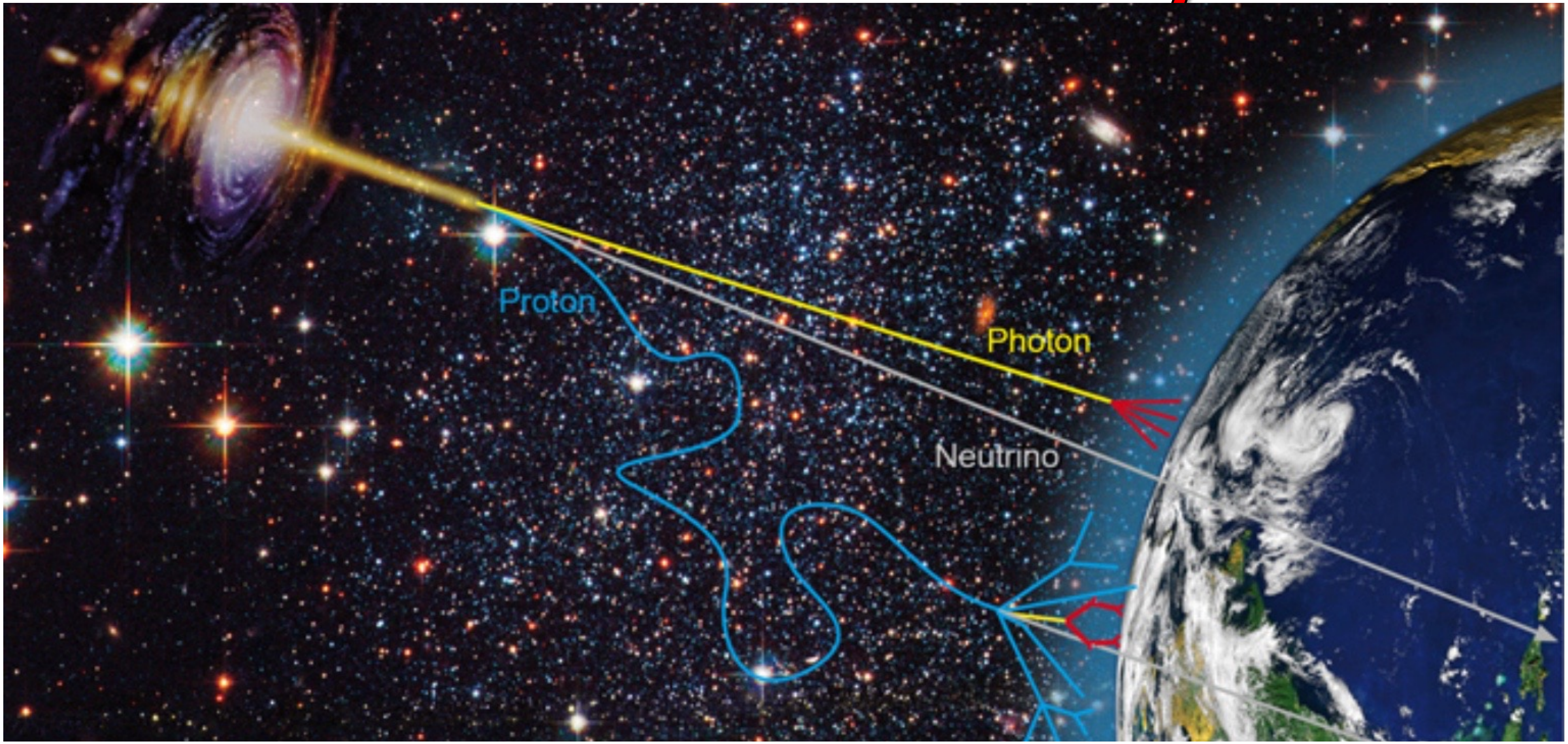
Multimessenger astrophysics: science of 21 sectury



Dmitri Semikoz
APC, Paris

Overview:

- *Introduction: optical astronomy*
- *Multi-wavelength astronomy*
- *Super-massive BH and AGN*
- *Uneasy messenger: cosmic rays*
- *New messenger – neutrinos*
- *Signal from first neutrino source*
- *Neutron stars, pulsars and BH*
- *New messenger – gravitational waves*
- *Gravitational Waves from binary neutron star merge and multi-messenger signal.*
- *Conclutions*

Introduction: optical astronomy

What Galileo Saw

Moons of Jupiter
The Earth is not the only center of motion.

Phases of Venus
Venus does not shine by its own light.
It goes around the Sun, not the Earth.

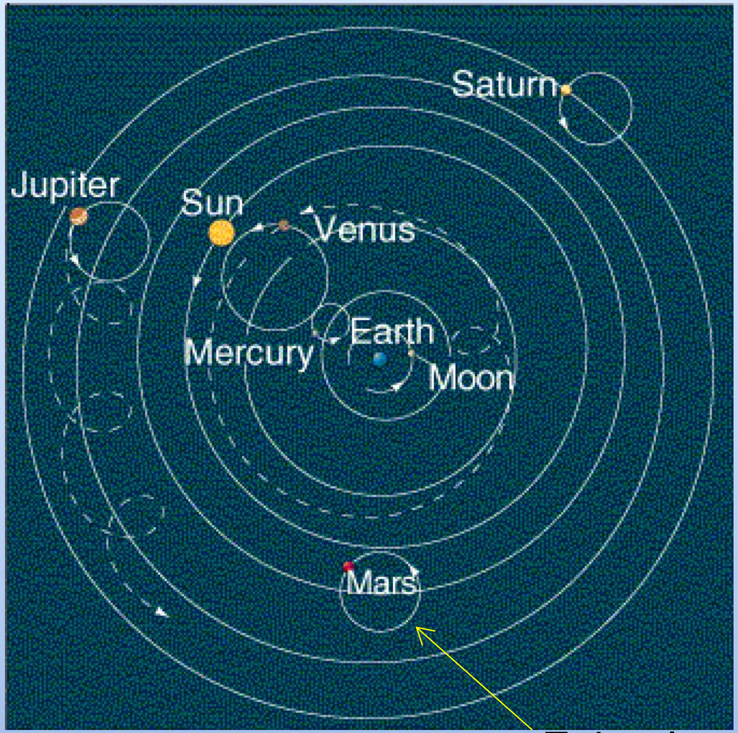
Craters & mountains on the Moon
The Moon is similar to the Earth.
The heavenly realm is not perfect.

Sunspots
The Sun is also imperfect, and is spinning.

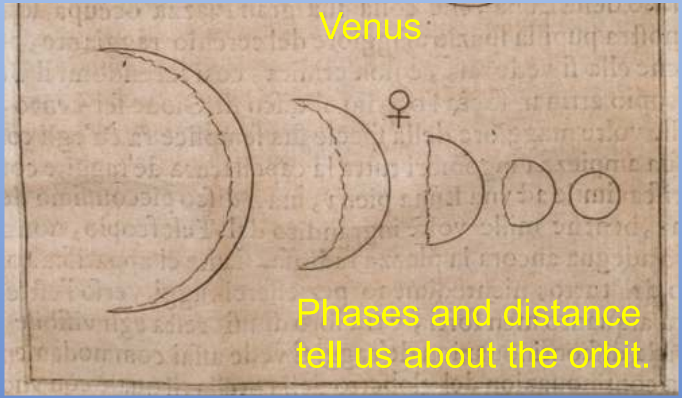
This (multiple centers or motion) was the final proof that Copernicus was right.
The Earth is not the center of the universe.

Most astronomers had already accepted the Copernican theory.

Ptolemaic Cosmology:



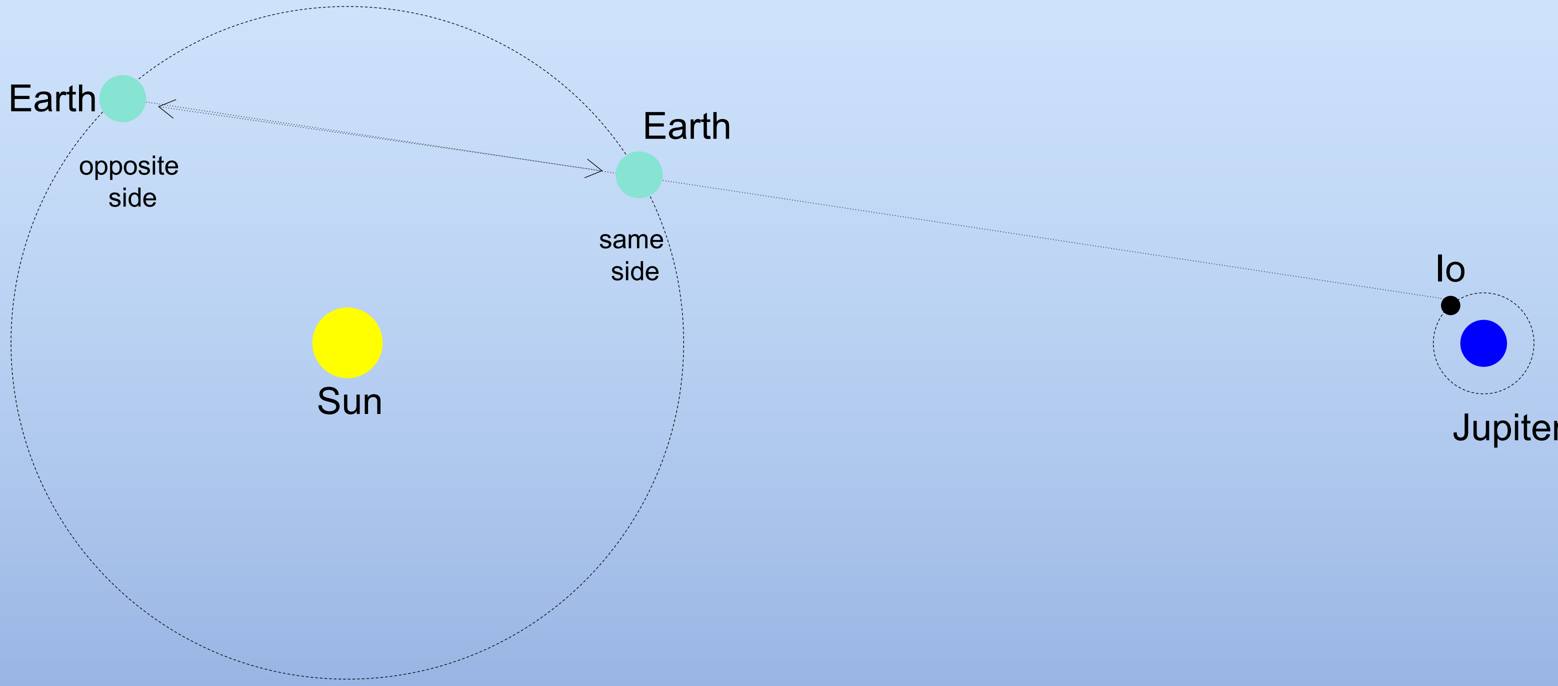
Epicycle



From J.**Thaler**

The Speed of Light

Between 1671 and 1690, Cassini, Römer, & Huygens studied discrepancies in the orbit of Io. They measured that when the Earth and Jupiter are on opposite sides of the Sun, the orbit lags by about 22 minutes, compared to when they are on the same side.



They attributed this to the time it takes light to travel across Earth's orbit.
Their answer, 132,000 mi/sec was about 30% smaller than the currently accepted value.
(Their time measurements were incorrect.)

Astronomy and physics have a continuing, close relationship.

From J.**Thaler**

The Rotation of the Earth

If you've ever used a telescope, you've noticed the annoying fact that the Earth rotates. Objects move out of the field of view.

For naked-eye observation, this is merely an annoyance.
For long exposure astrophotography, this is a disaster.

About a 30-minute exposure.

North pole

From J.**Thaler**

The Equatorial Mount

How to compensate for the Earth’s rotation:

Mount the telescope on an axle aligned with the Earth’s axis.
Rotate the axle counter to the Earth’s rotation.
This will stabilize the object in the vield of view, enabling more precise viewing.

To the north pole

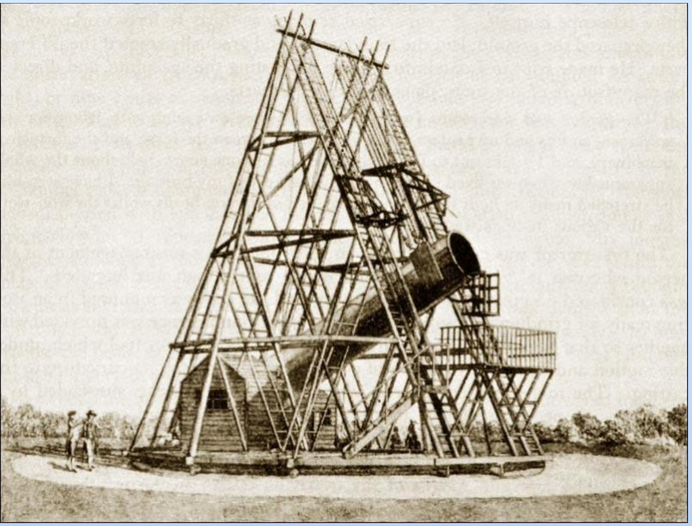
west

cm Cassegrain, at Sapporo

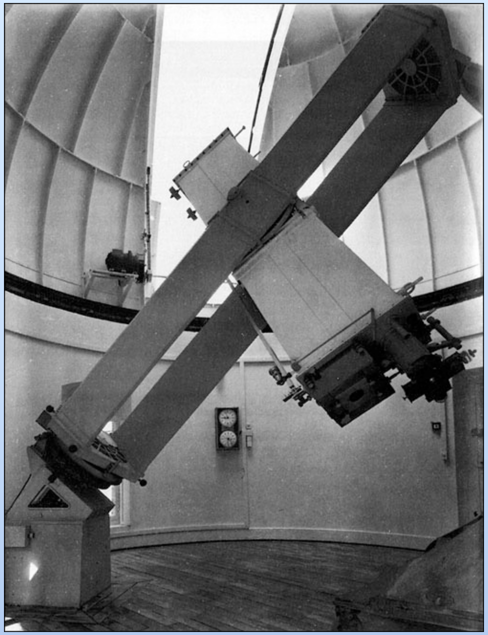
From J.**Thaler**

Hale 200” Cassegrain reflector on Mt. Palomar
(largest equatorial mount)

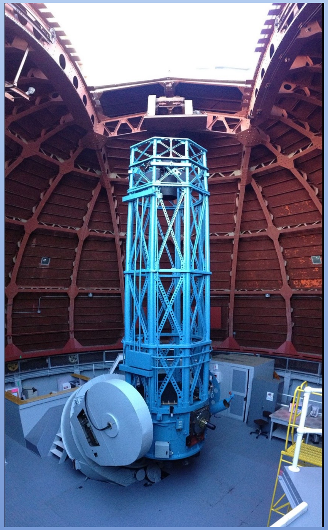
Historical telescopes



Herschel’s telescope 1788



Henry brother's photographic refractor, Paris observatory (ca. 1887)



The 60-inch reflector (Mount Wilson observatory) (ca. 1908)

Computers (1)

Computers and electronics enable several big advances:

- Bigger telescopes, using altitude-azimuth mounts.
  Following the circular path of a star with only horizontal and vertical controls is like drawing a circle with an Etch-a-Sketch. Computers are good at that.

- Better optics. A mirror or lens surface can be made (at some cost) with an arbitrary shape.

- Digital photography , using CCDs.
  - CCDs are more sensitive than film, and easier to calibrate.
  - Images can be transmitted to scientists over the internet.
    Some telescopes in Chile send their data to NCSA for analysis.
  - Digital images can be analyzed more quickly (by computer!).

- Large data sets
  The LSST camera will have 3 gigapixels, and each image will be 6 gigabytes. In 10 years, it will take nearly a million pictures.
  The final data set will be ~ 100 petabytes (100 million gigabytes).

About 300 times more than your 10 Megapixel camera.

Giga = billion
Tera = trillion
Peta = quadrillion

From J.**Thaler**

Computers (2)

- Robotic telescopes (no humans involved!)
  Example: The PROMPT project (led by UNC), is used for optical follow-up of gamma-ray bursts (huge explosions at the centers of galaxies). These bursts are very short, and a few-second response time is needed. The internet is required.

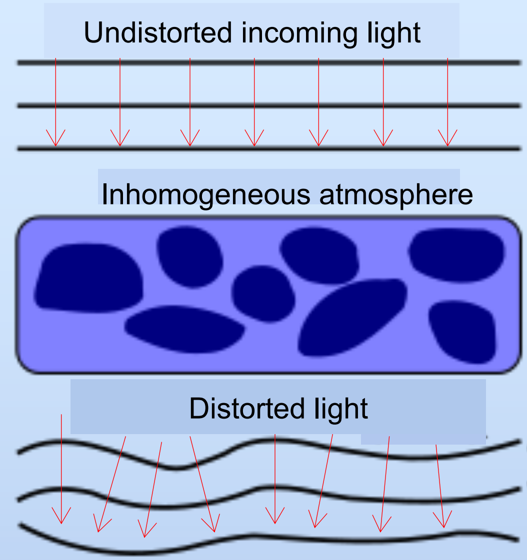
PROMPT, at Cerro Tololo, Chile

- Space-based astronomy.

The Hubble Space Telescope

From J.**Thaler**

Computers (3)



Adaptive optics:

Looking at stars through the atmosphere is like looking at objects
at the bottom of a swimming pool. If we can quickly measure the distortion (before the distortion changes), we can correct it.

This requires:

- Powerful computers (1000 measurements per second).
- Flexible mirrors, supported by computer controlled fingers,

r as needed.

mited) resolution.

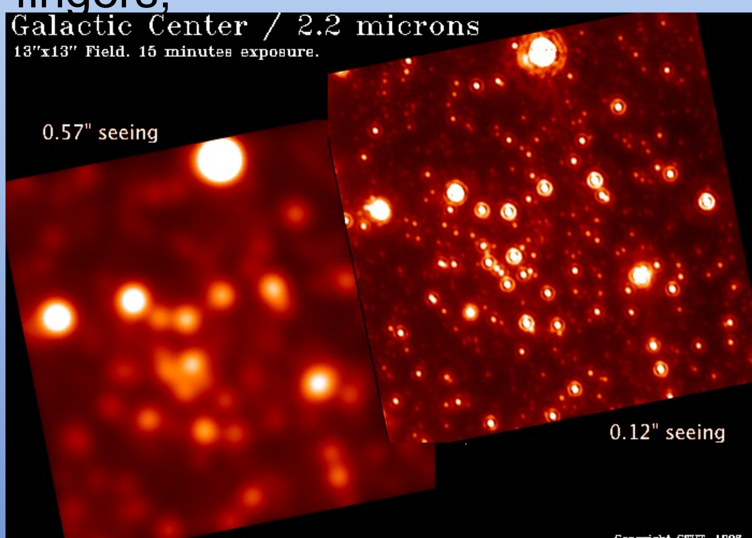
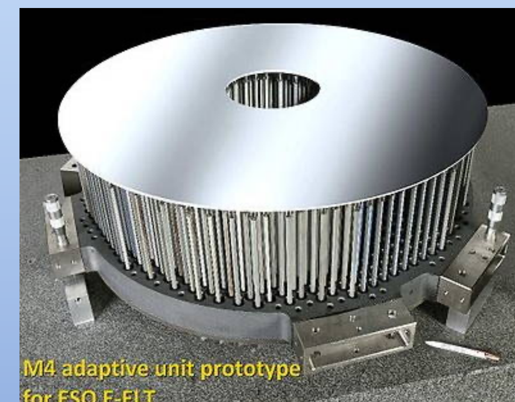
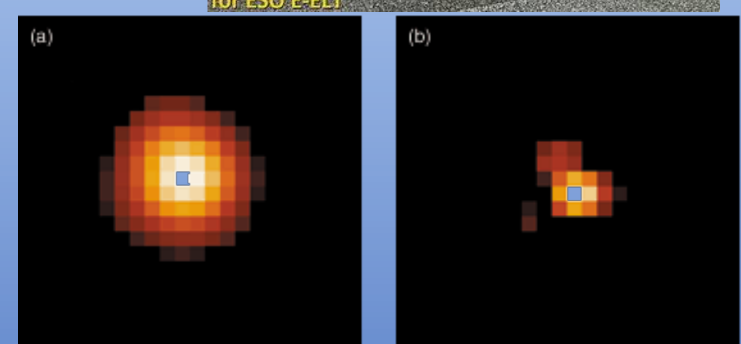


Image quality is crucial for exoplanet studies.

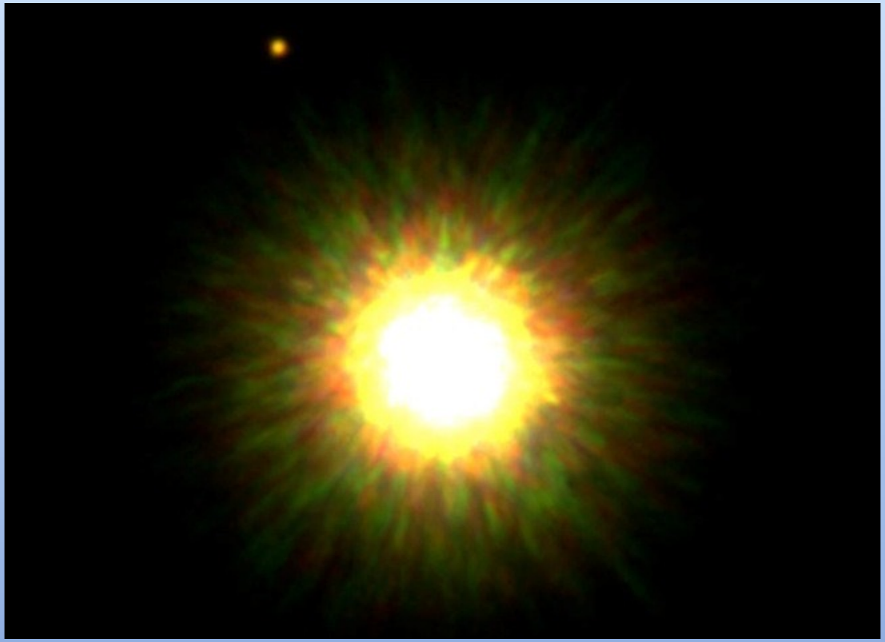


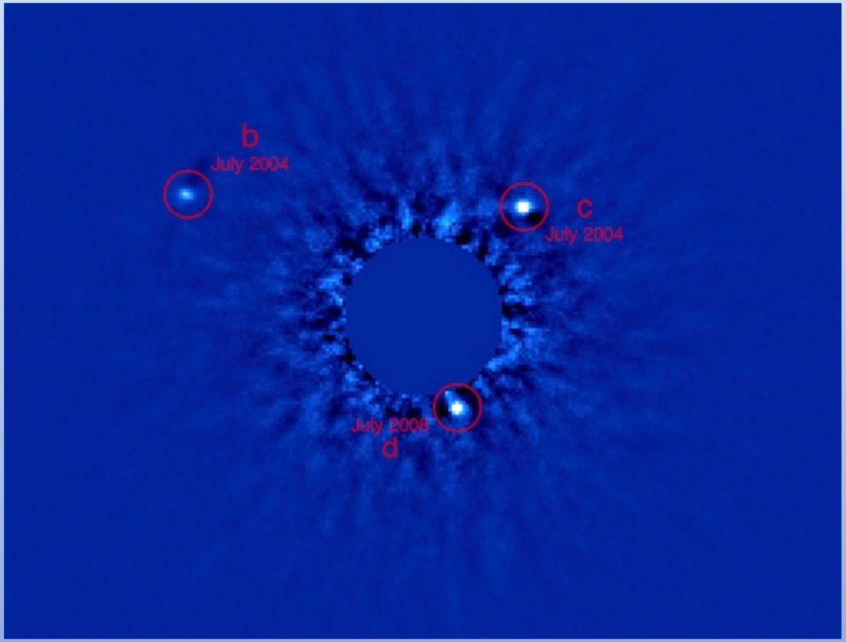


From J.**Thaler**

Exoplanet Images

These pictures were taken with 8-meter telescopes (one in Chile and one in Hawaii) without adaptive optics.
The point is, we can see exoplanets now. We'll study them with the next generation of very large telescopes.





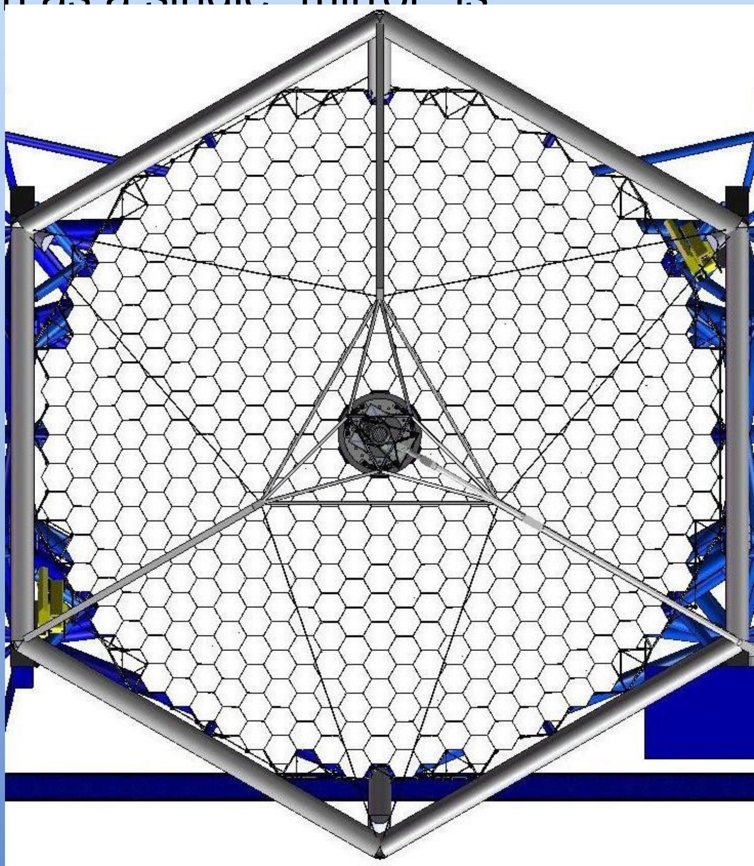
Both stars are sun-like and are a few hundred light-years away.
All four planets are super-Jupiters (8 to 70 times as massive). They are quite far from the star – comparable to or farther than the distance to Pluto.

From J.**Thaler**

Computers (4)

• Multiple mirrors. The Thirty Meter Telescope (TMT, construction about to begin)
will have a 30 m mirror that consists of 492 1.5 m hexagonal mirrors. It is not practical to consider a single 30 m (98 ft) piece of glass.

Alignment of the mirror segments so they function as a single “mirror” is similar to
adaptive optics.



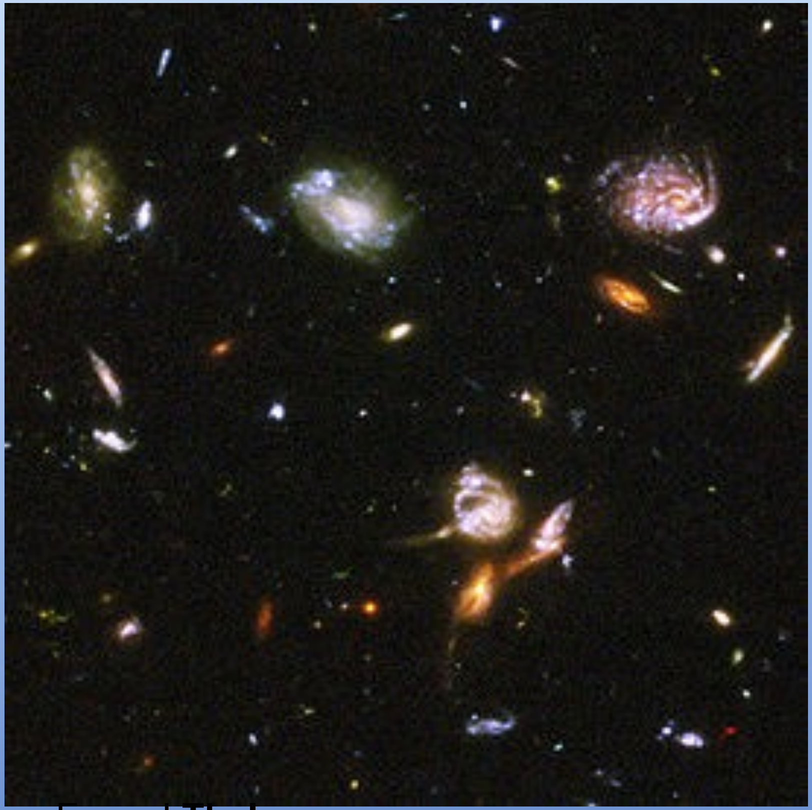
From J.**Thaler**

The Longest Photographic Exposure

In 2003, the Hubble Space Telescope's ACS camera took a one million second (about 11 days) exposure. There are very few stars in this photo, and about 10,000 galaxies, the faintest of which are about a billionth as bright as can be seen by eye.

We are seeing the light that they emitted about 13 billion years ago.
(because they are so far away)

The Hubble Ultra Deep Field

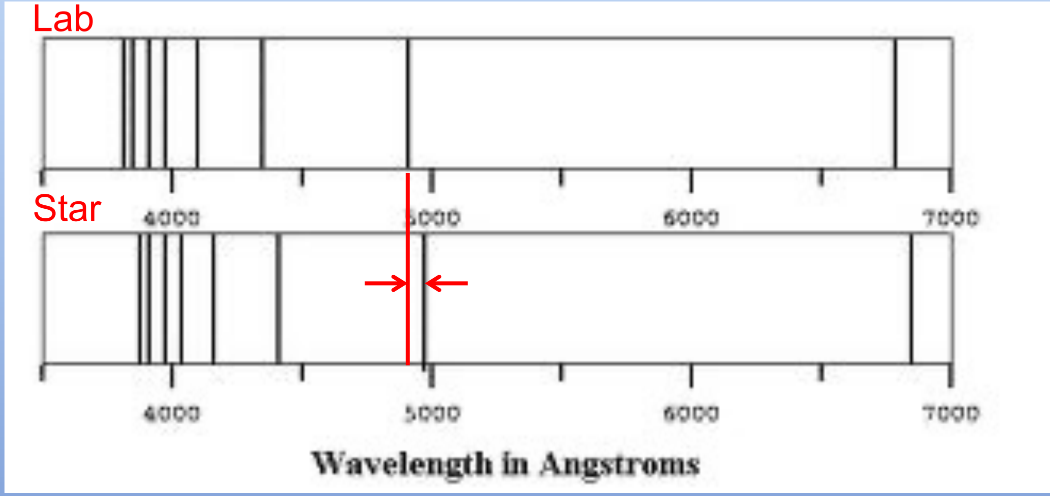


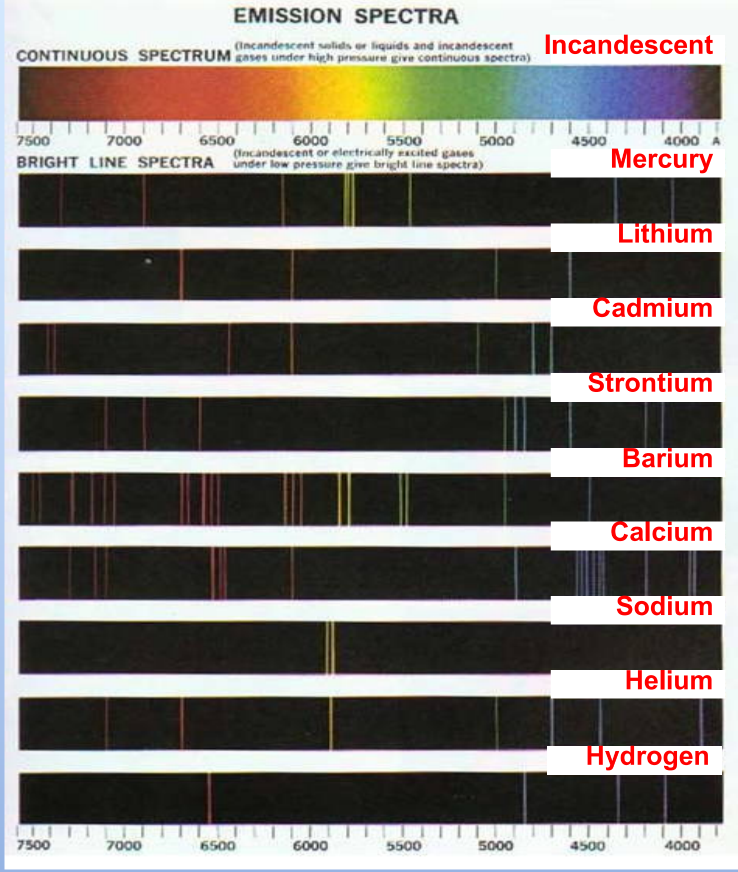
From J.**Thaler**

Spectroscopy

One can determine the chemical composition of astronomical objects by measuring the spectra of the light they emit.

One can also measure the speed toward or away from the telescope by observing the spectral (Doppler) shift.
The shift (to the red) shown here corresponds to 9% the speed of light away from the observer:



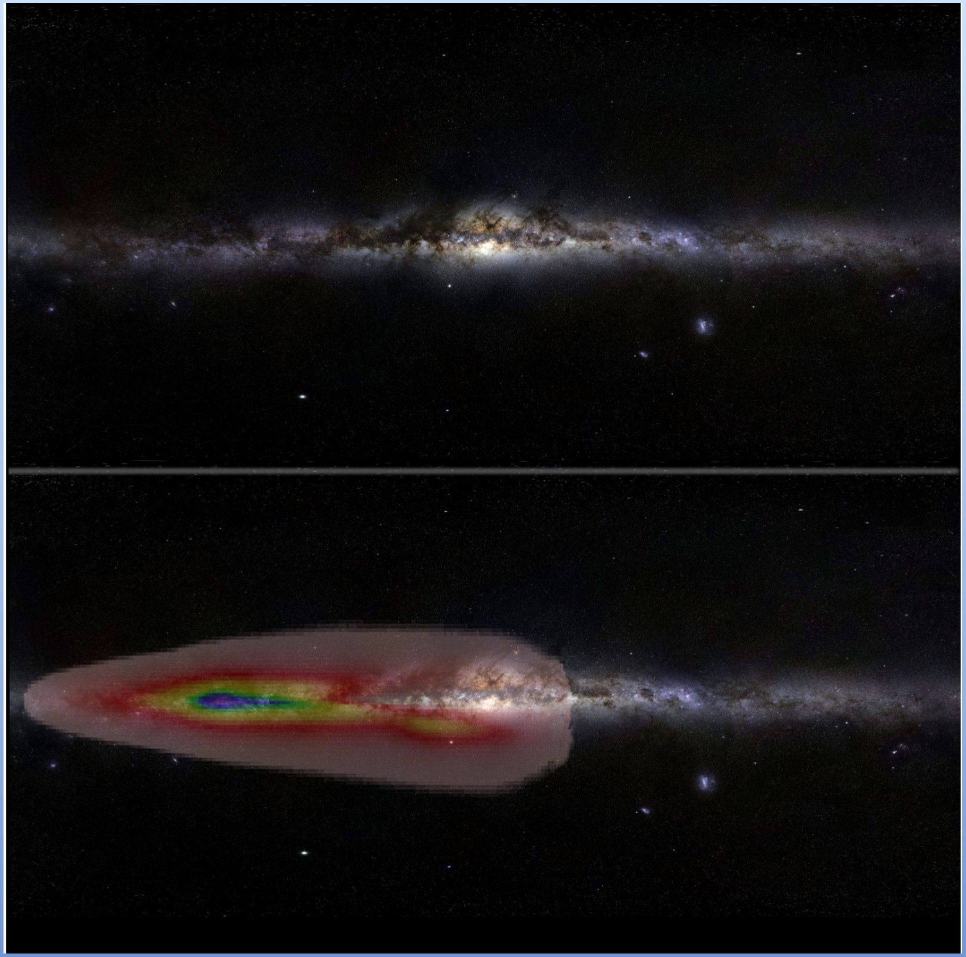


Spectroscopy requires a lot of light: Long exposures and large telescopes.

In cosmology, one talks about redshift, z, the fractional change of wavelength.

From J.**Thaler**

Gaia mission ESA



By naked eye 4500 stars

Small telescope 100 000

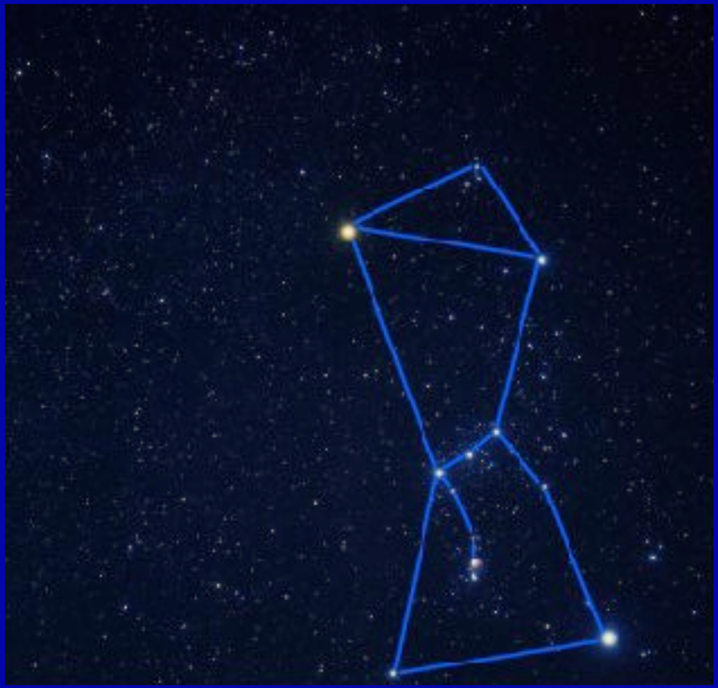
From Earth: millions

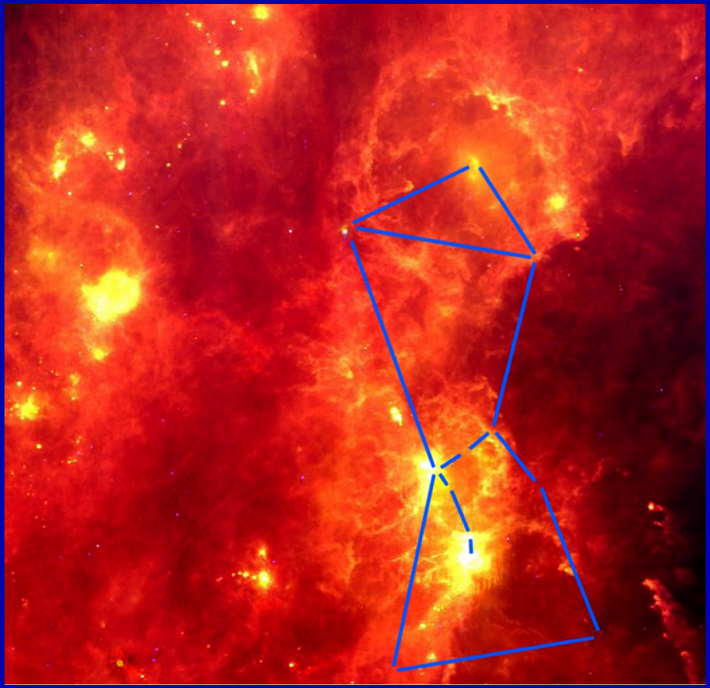
Gaia 1 500 000 000

Miky Way   250 000 000 000

Multi-wavelength astronomy

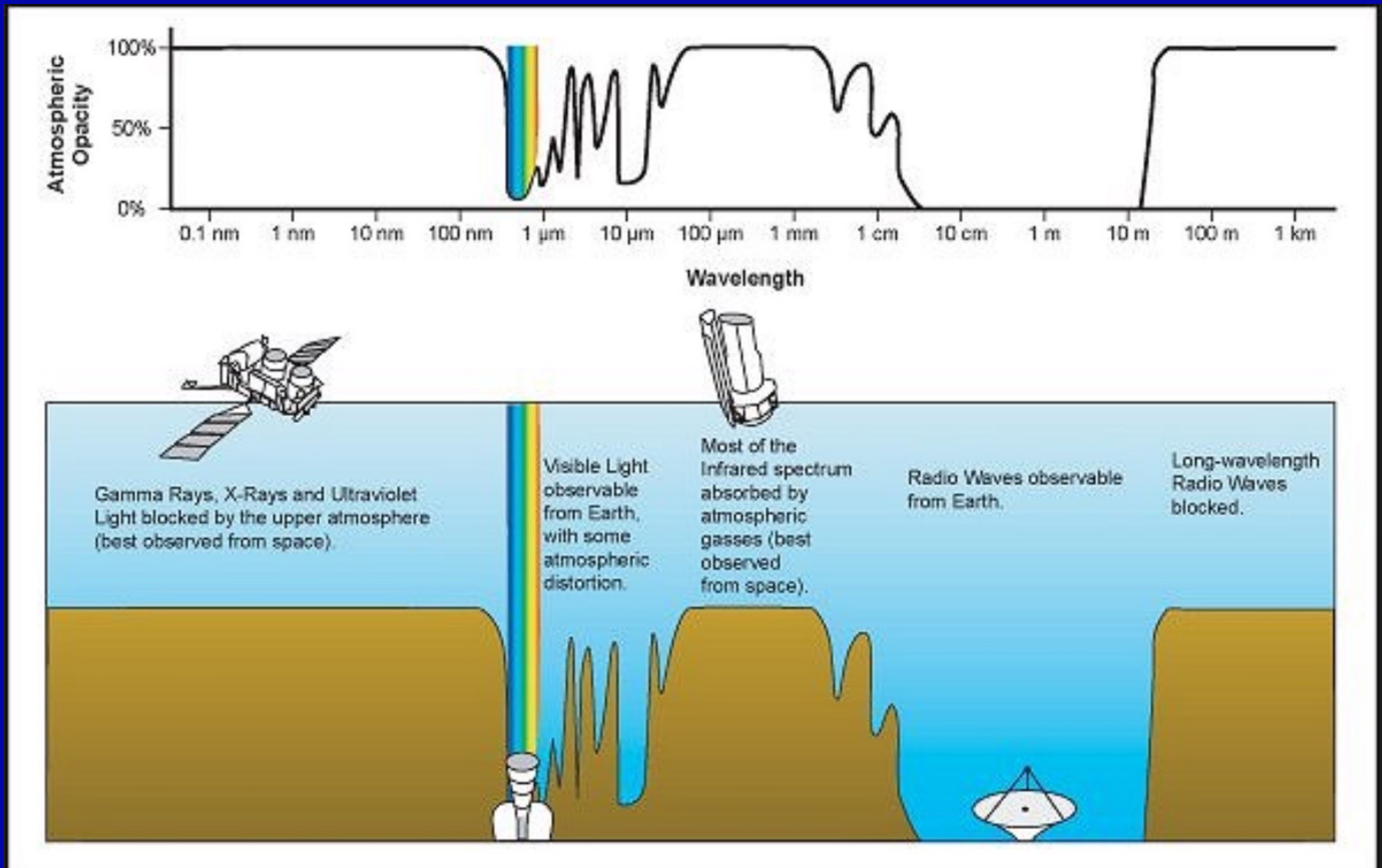
An object can appear radically different depending on the type of light collected from it:



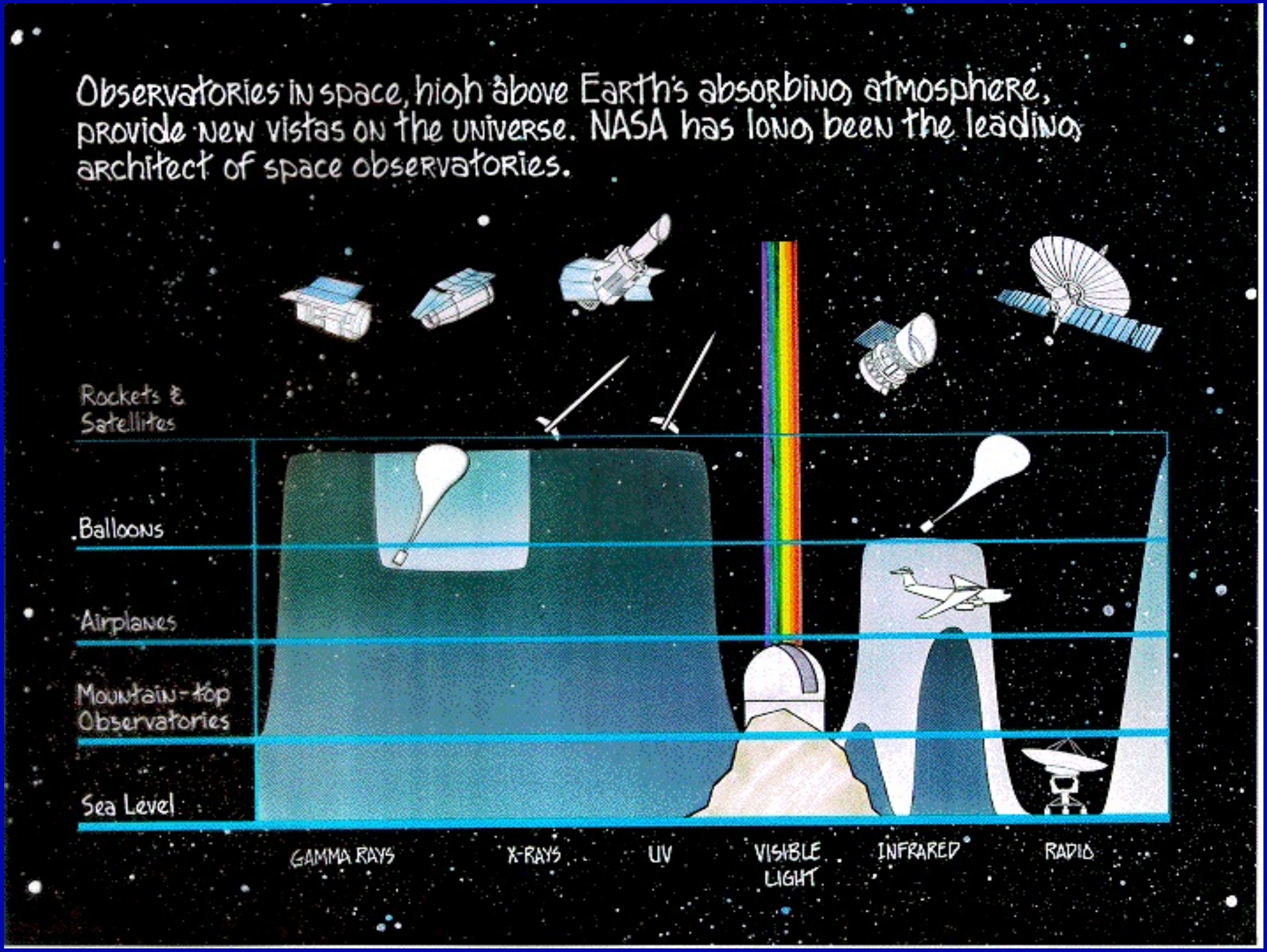


Constellation Orion
left: visual-wavelength view
right: far-infrared view

There's a problem for IR/UV, etc astronomy...

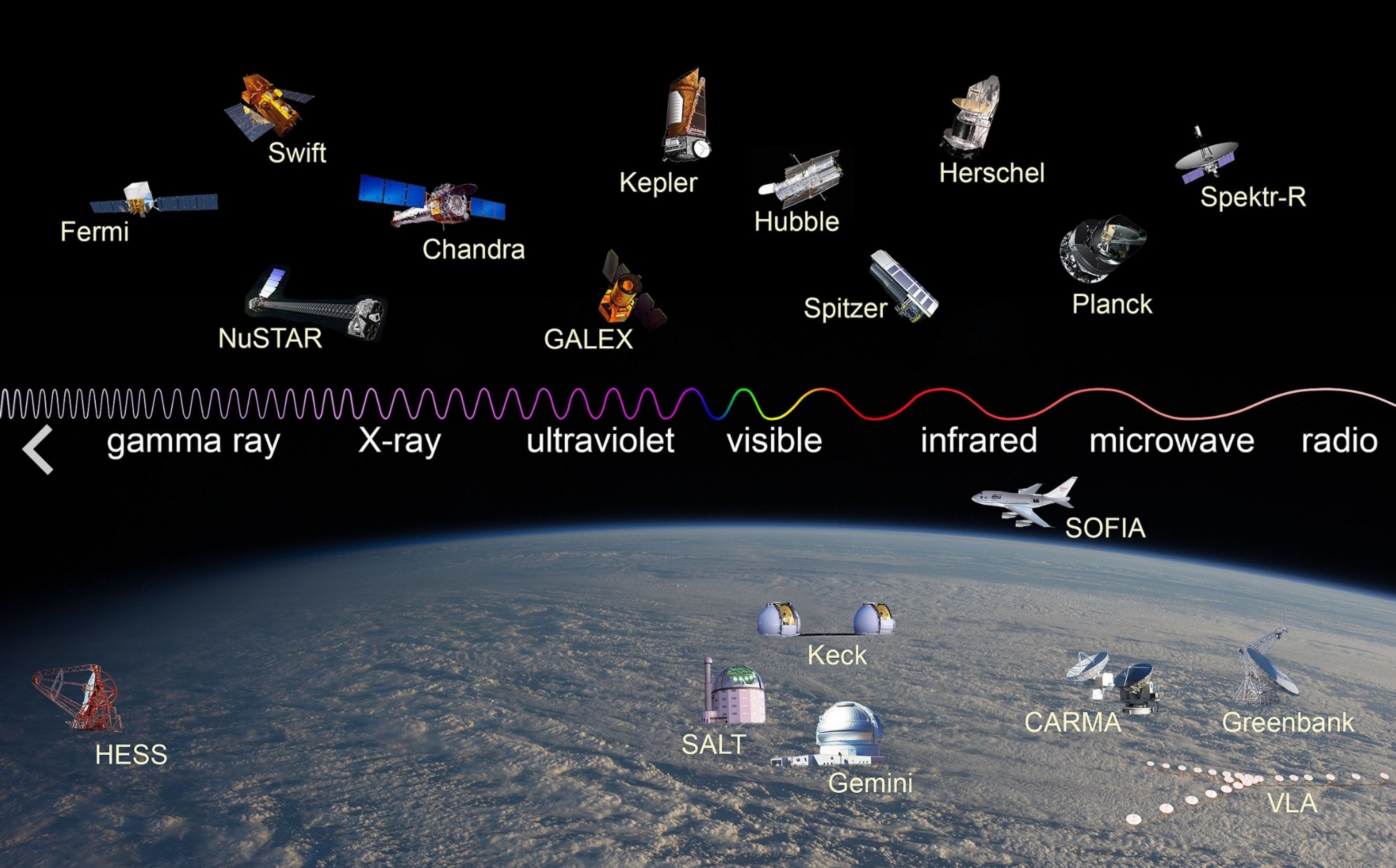


There's a problem for IR/UV, etc astronomy...



Multi-Wavelength Astronomy

MODERN TELESCOPES

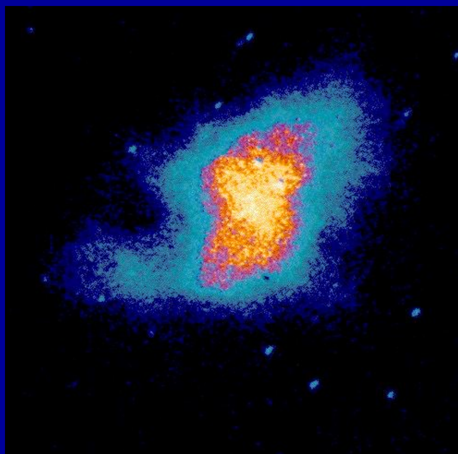


Multi-wavelength Astronomy

Waveband	Wavelength /Energy	Temperature	What can be studied
Gamma rays	100keV-100TeV	$>10^8$K	SN, pulsars, accretion disks, gamma-ray bursts
X-rays	<1-100keV	10^6-10^8K	Hot gas in clusters of galaxies, stellar coronae, accretion disks,
Ultra-violet	900-3000A	10^4-10^6K	Hot stars, white dwarfs, instellar gas
Optical	3000-10,000A	10^3-10^4K	Sun-like stars.
Infra-red	1-100 micron	10-10^3K	Dust, planets, brown dwarfs
Microwave	1cm	<10K	Background radiation of the Universe (remnant of Big Bang)
Radio	>1m	<10K	Radiation from electrons moving in a magnetic field: pulsars

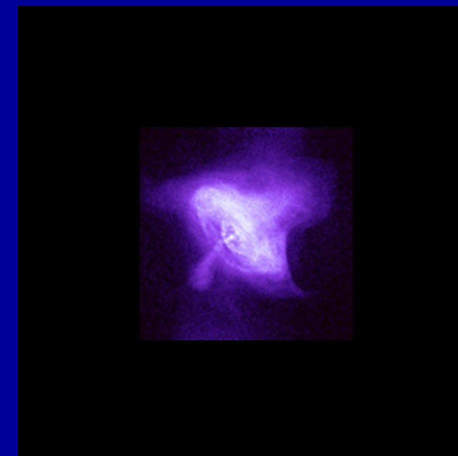
from M. Burleigh

Crab Nebula (SN 1054)

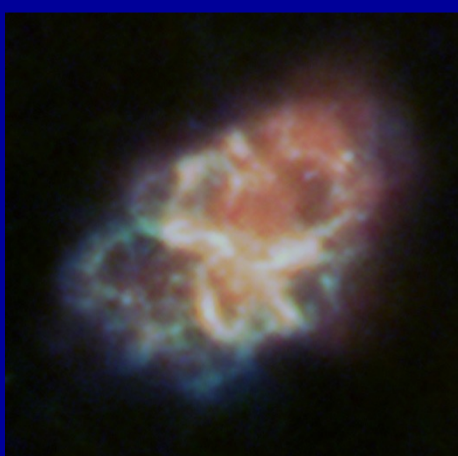


U5 (UIT)

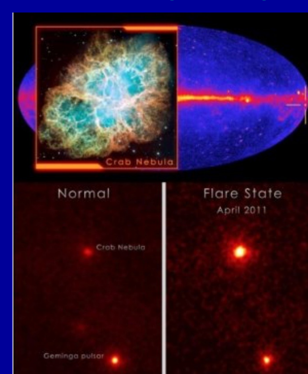
Crab (VLT)



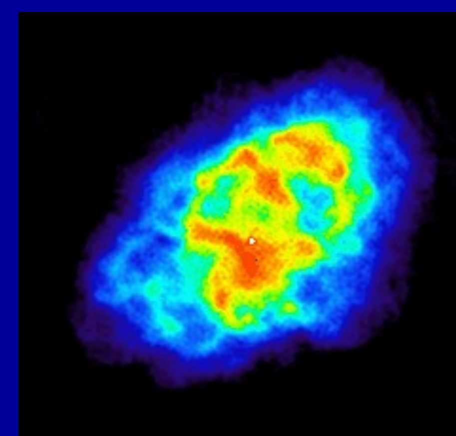
X4 (Chandra)



F7 (Herschel)

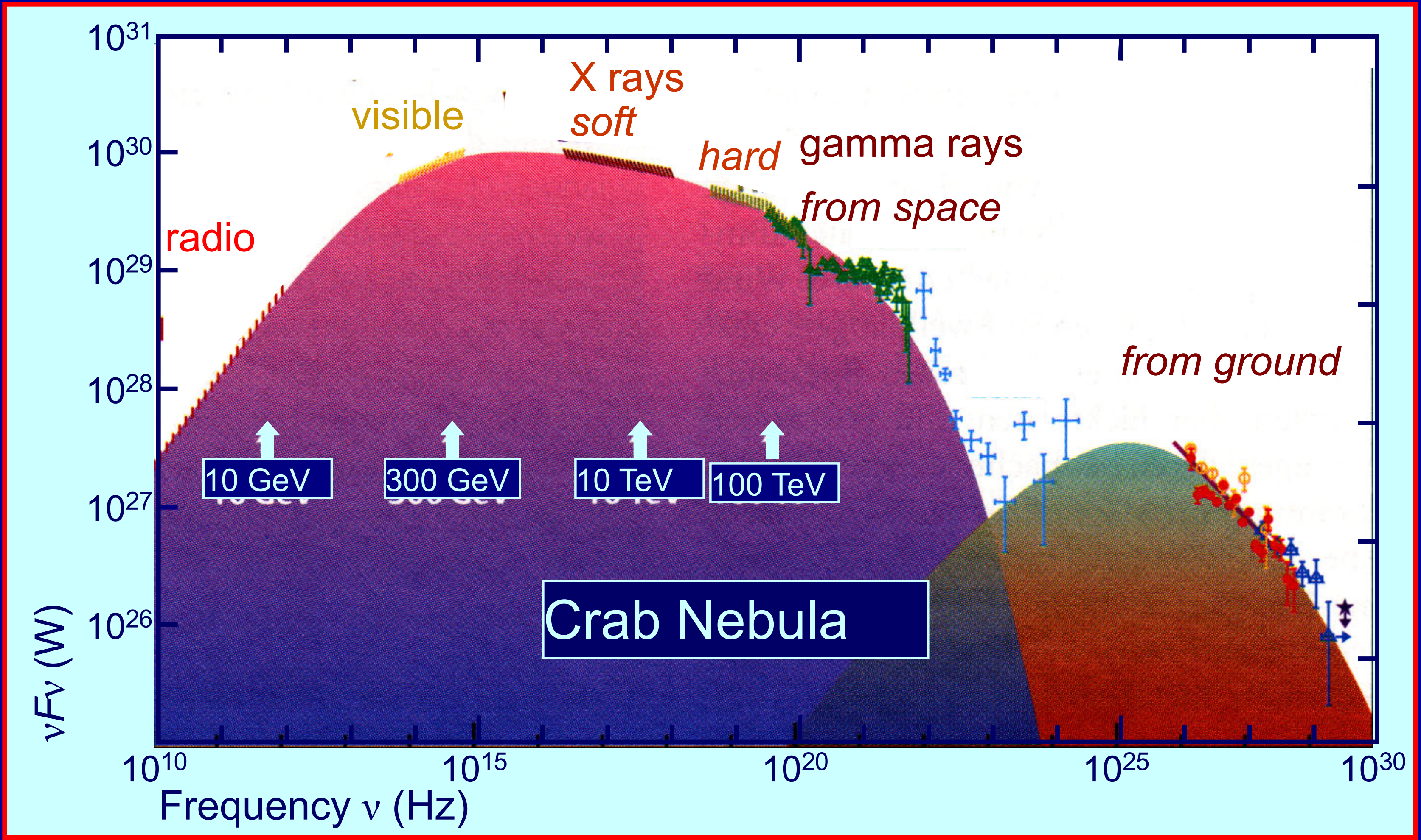


Crab (gamma)



R9 (NRAO)

Usefulness of multi-wavelength observations

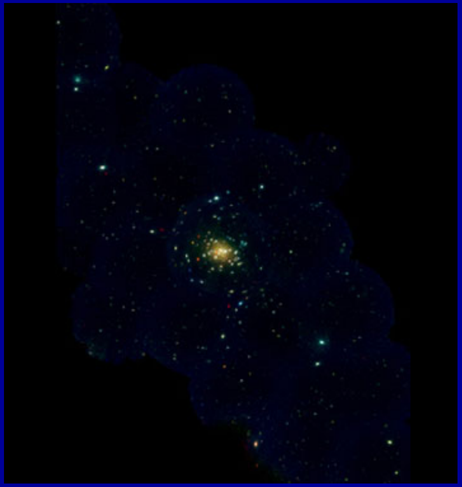


Thanks to the non-thermal nature of the emission processes gamma-ray sources can be **profitably** observed at longer wavelengths

Andromeda

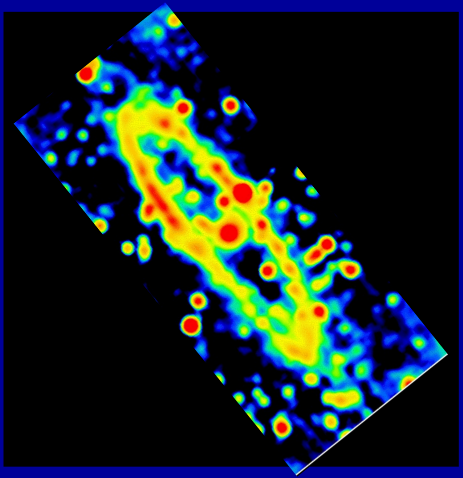
U3 (GALEX)

Andromeda (Gendler)



X7 (XMM-Newton)

F10 (Herschel)



R6 (Effelsberg)

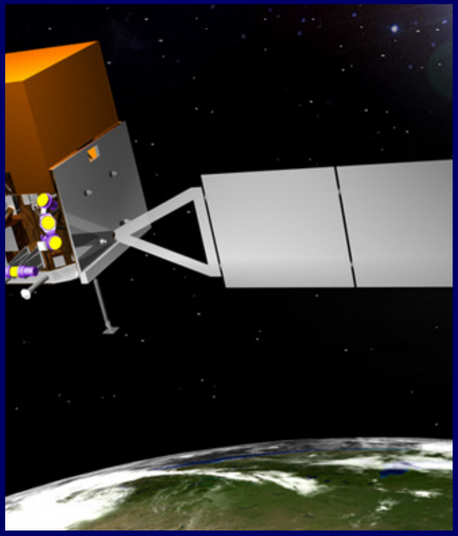
Multiwavelength

Exploring the gamma-ray domain

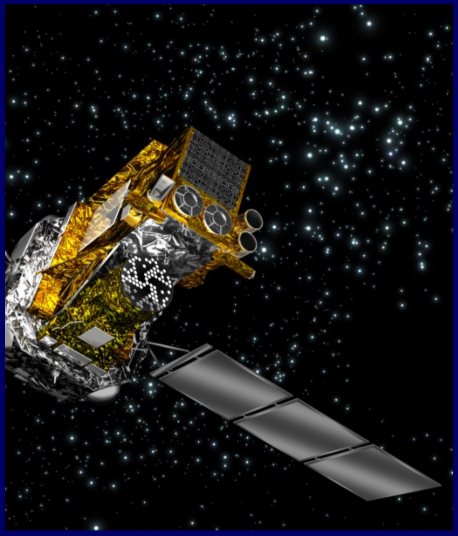
From ground

From space

HESS



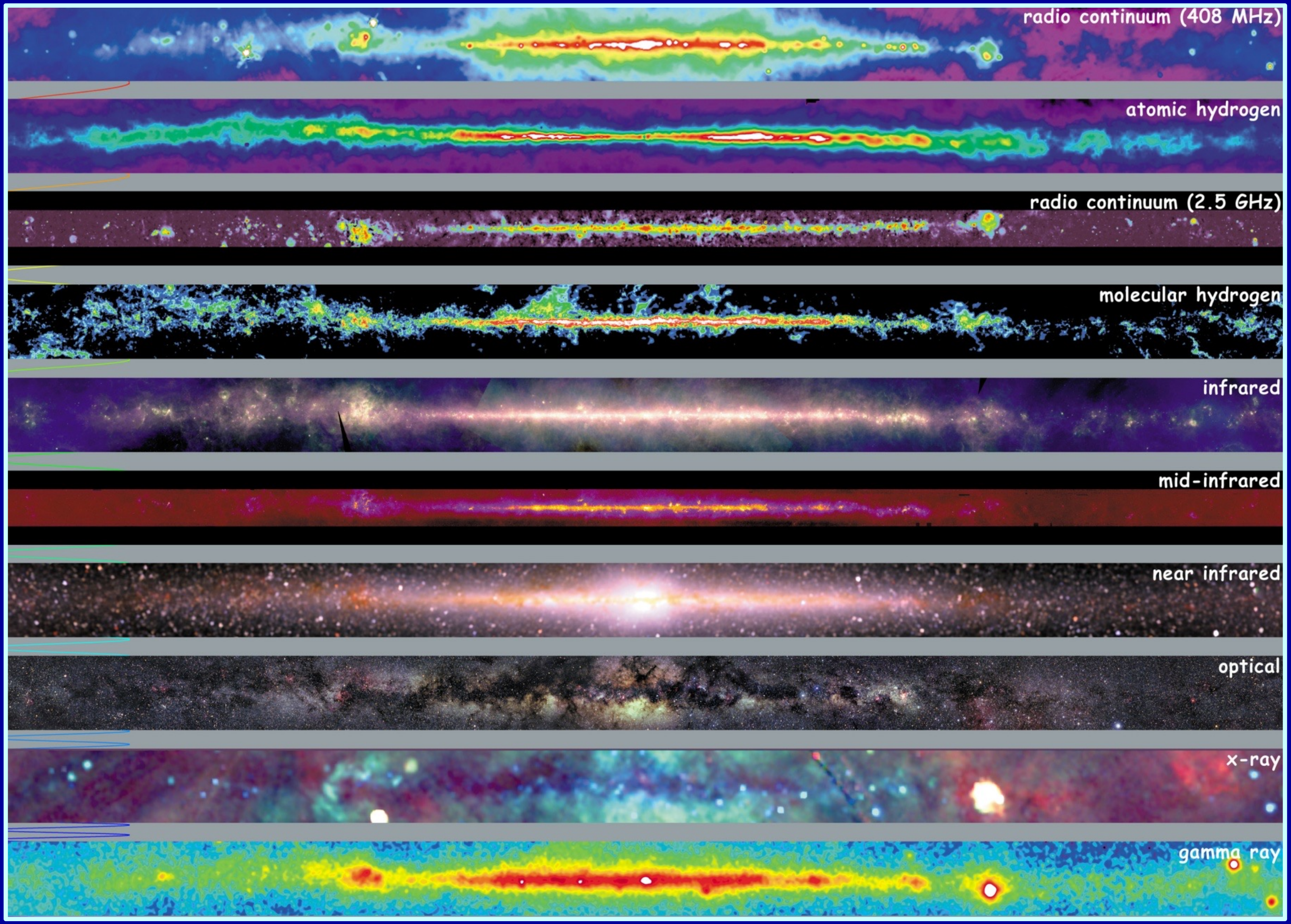
ermi



EGRAL

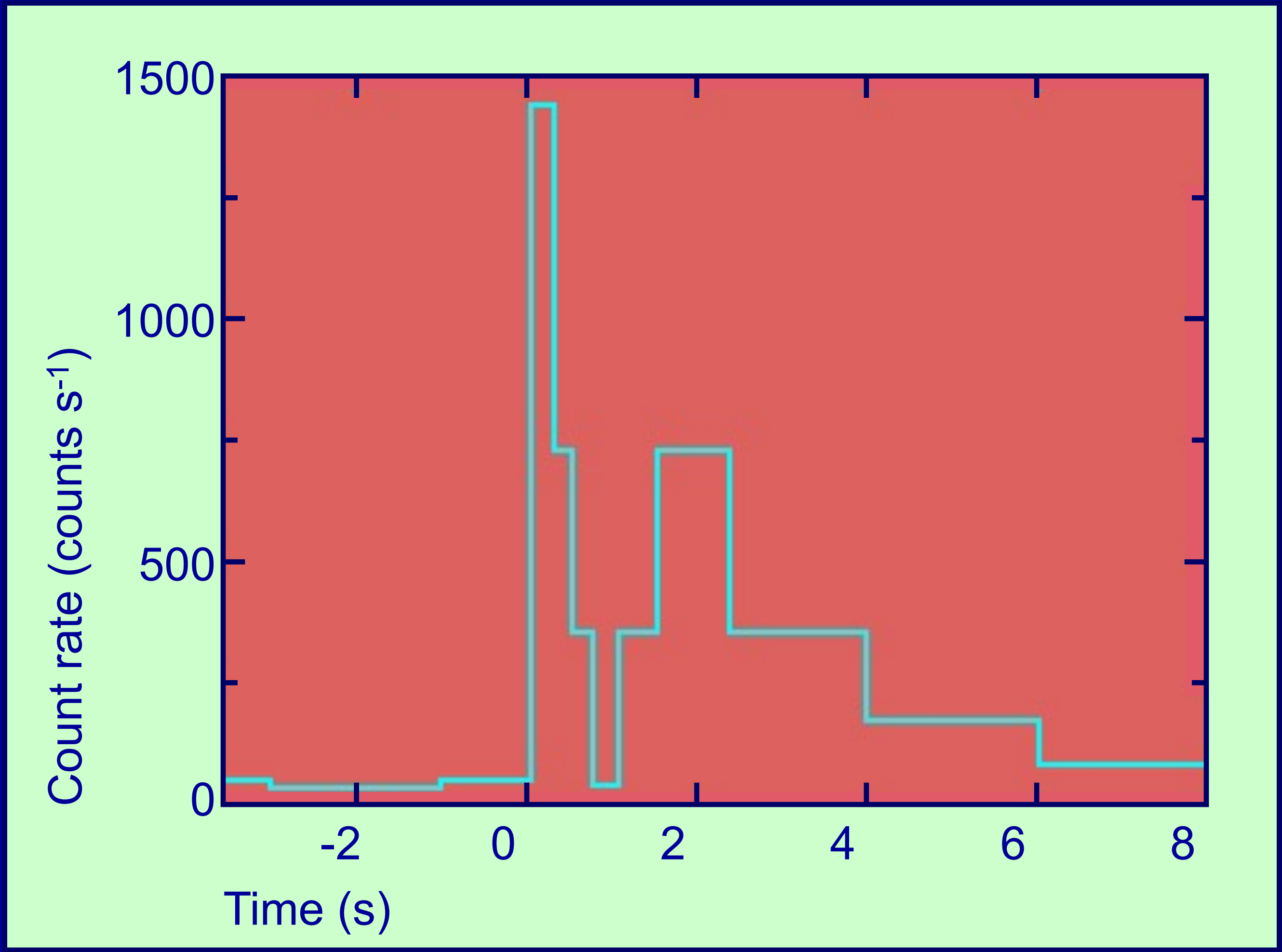
From J. Paul

Multi-wavelength view of the galactic disk



From J. Paul

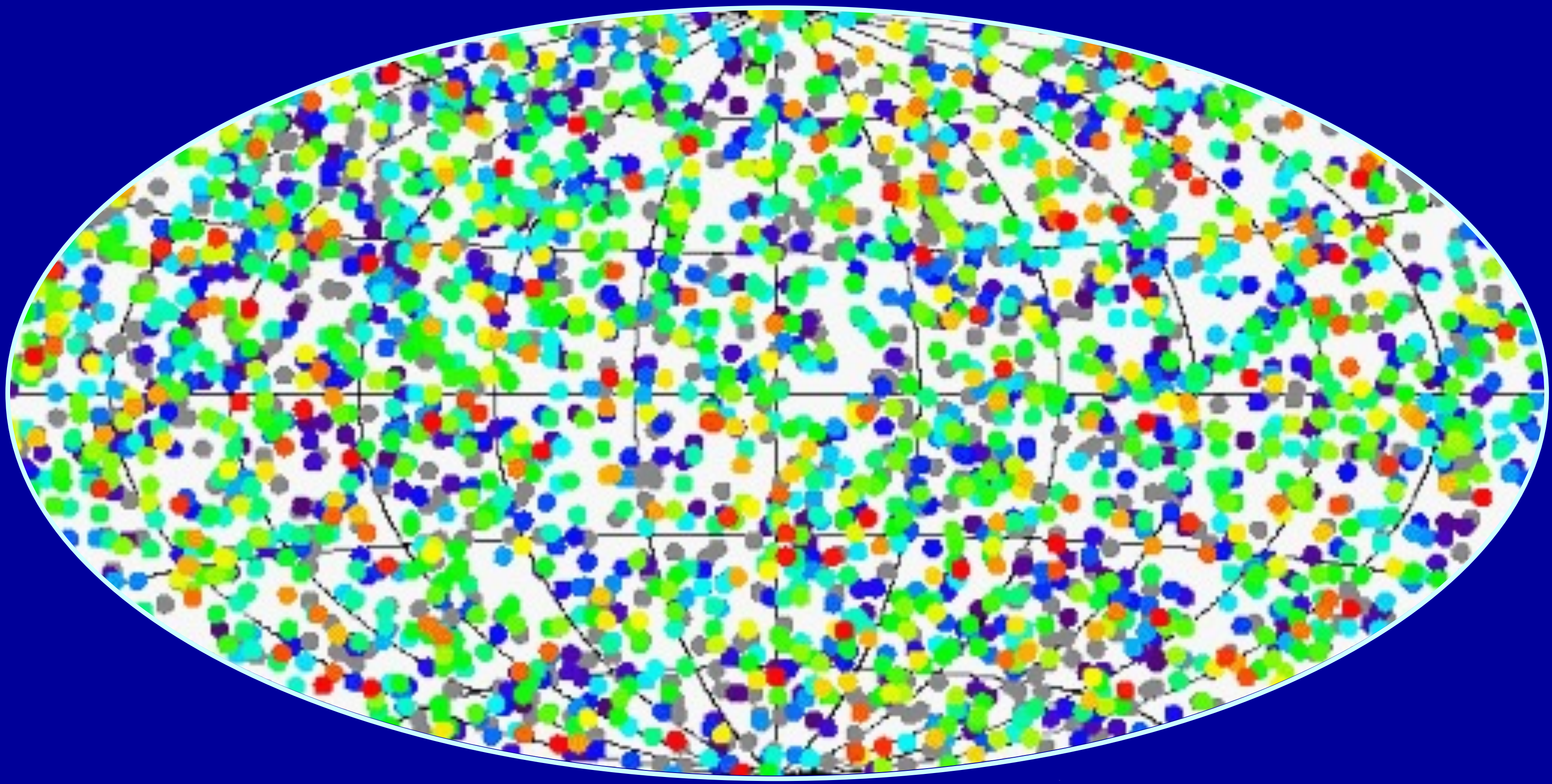
2 July 1967: First GRB ever detected



After Klebesadel et al. (1973), *ApJ*, vol. 182, p. L85.

From J. Paul

CGRO/BATSE: unprecedented statistics

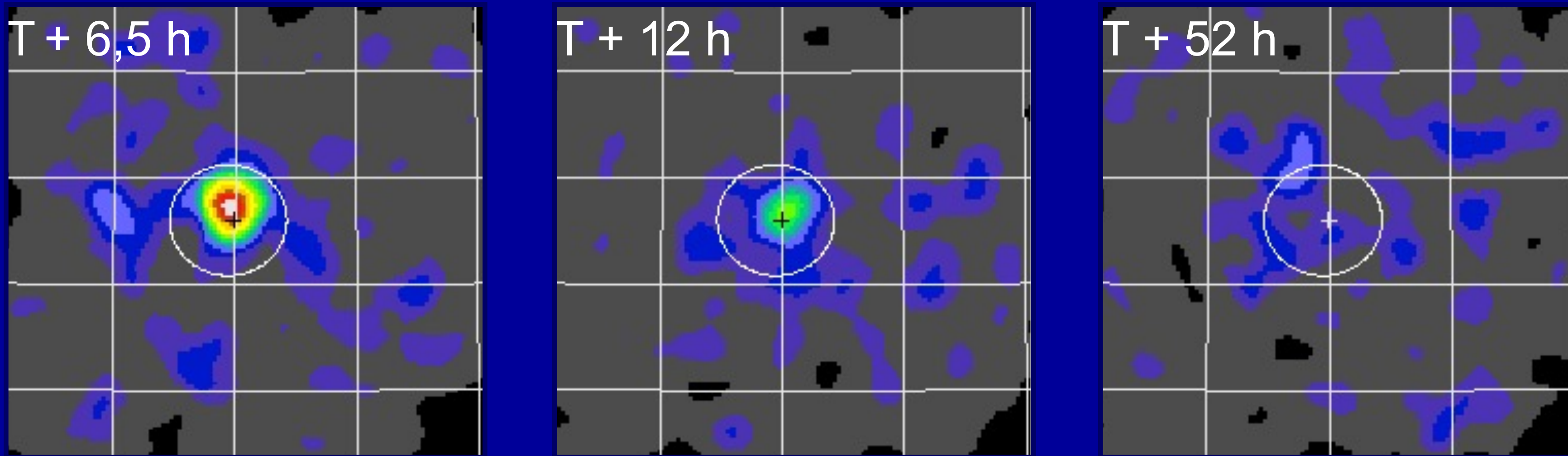


The 2704 GRBs detected by BATSE are uniformly distributed on the celestial sphere

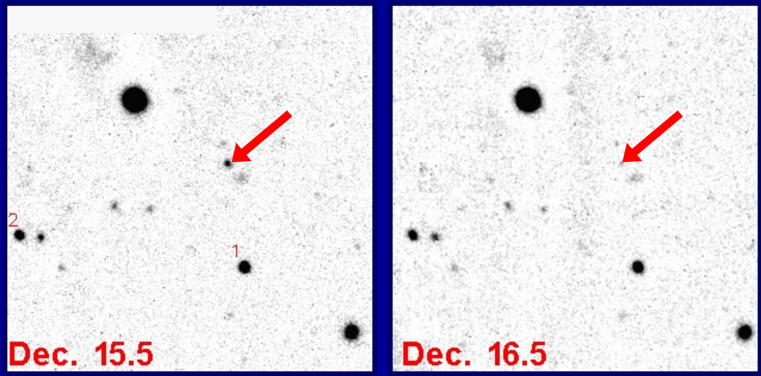
From J. Paul

Most GRBs are cosmological

Afterglow of GRB 971214 detected by BeppoSAX in the X-ray band



Afterglow in the visible band



- Detection of host galaxies
- Redshift measurements
- Cosmological distances
- Most energetic events
- 10^{44} J radiated in gamma rays

From J. Paul

Main processes used in gamma-ray astrophysics

$$\gamma + \gamma_B \Rightarrow e^- + e^+$$

$$e^{\pm} + \gamma_B \Rightarrow e^{\pm} + \gamma$$

$$e^{\pm} + B \Rightarrow e^{\pm} + \gamma_{synch}$$

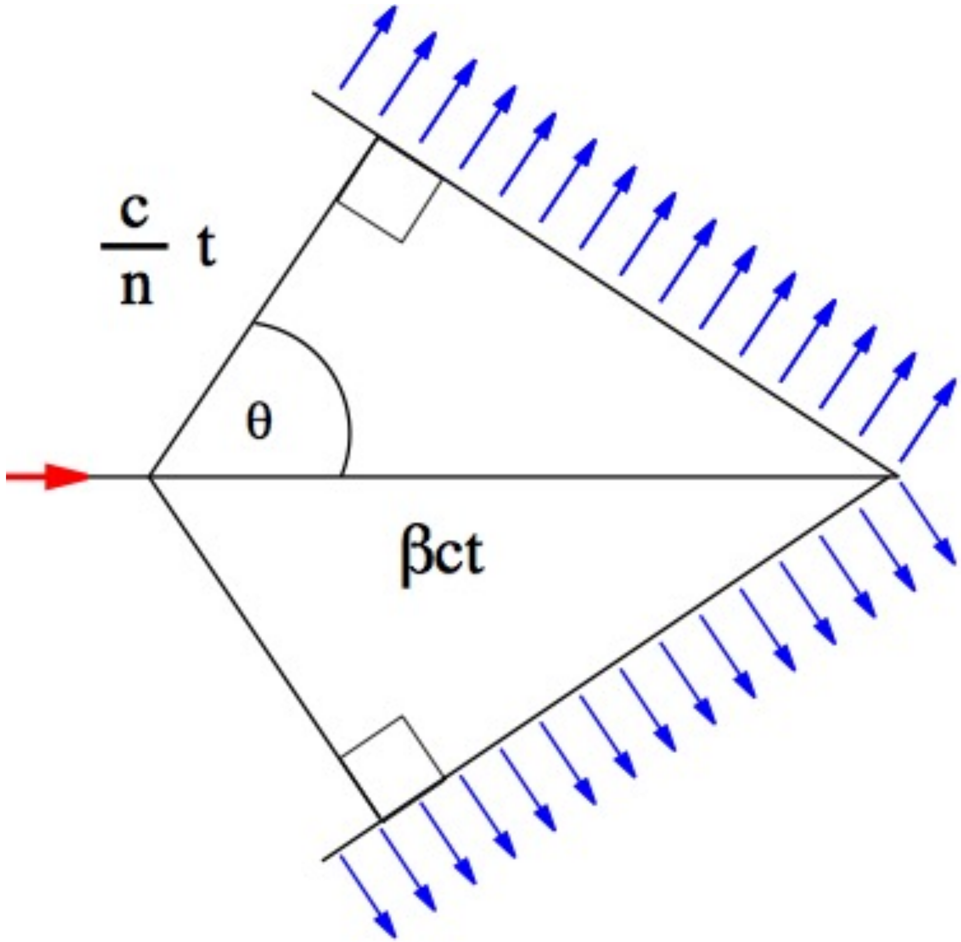
$$e^{\pm} + A_B \Rightarrow e^{\pm} + A_B + \gamma_{brems}$$

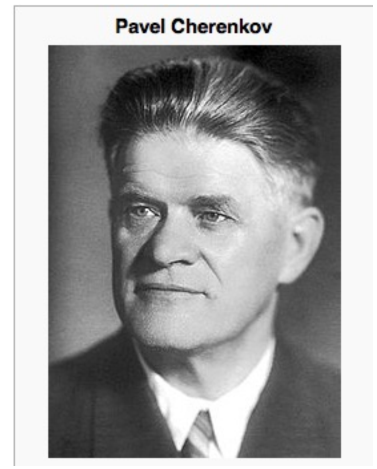
$$P + \gamma_B \Rightarrow N + \pi$$

$$P + P_B \Rightarrow N + N + \sum \pi$$

$$\pi^0 \Rightarrow 2\gamma$$

Cherenkov radiation





Discovery 1934
Nobel prize 1958

Cherenkov radiation

$$V > V_m = c / n$$

n is refractive index of medium

$n = 1.008$ air

$n = 1.33$ water

The charged particles polarize the molecules, which then turn back rapidly to their ground state, emitting prompt radiation

Cherenkov light is emitted under a constant Cherenkov angle with the particle trajectory, given by

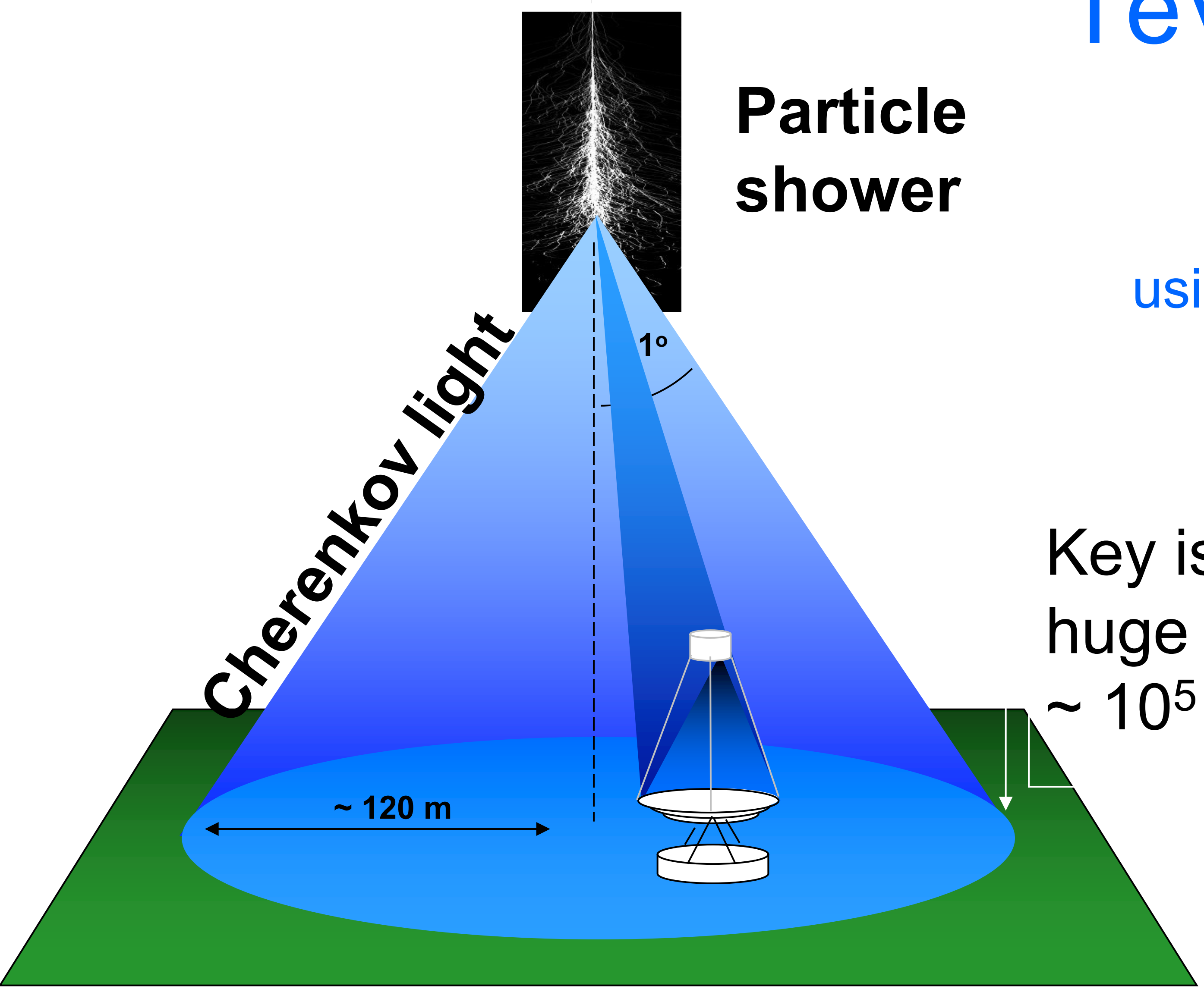
$$\cos\delta = \frac{V_m}{V} = \frac{c}{nV} = \frac{1}{\beta n}$$

Minimal energy of charge particle

$$\gamma_{\min} = \frac{n}{\sqrt{n^2 - 1}}$$

Detection of TeV gamma rays

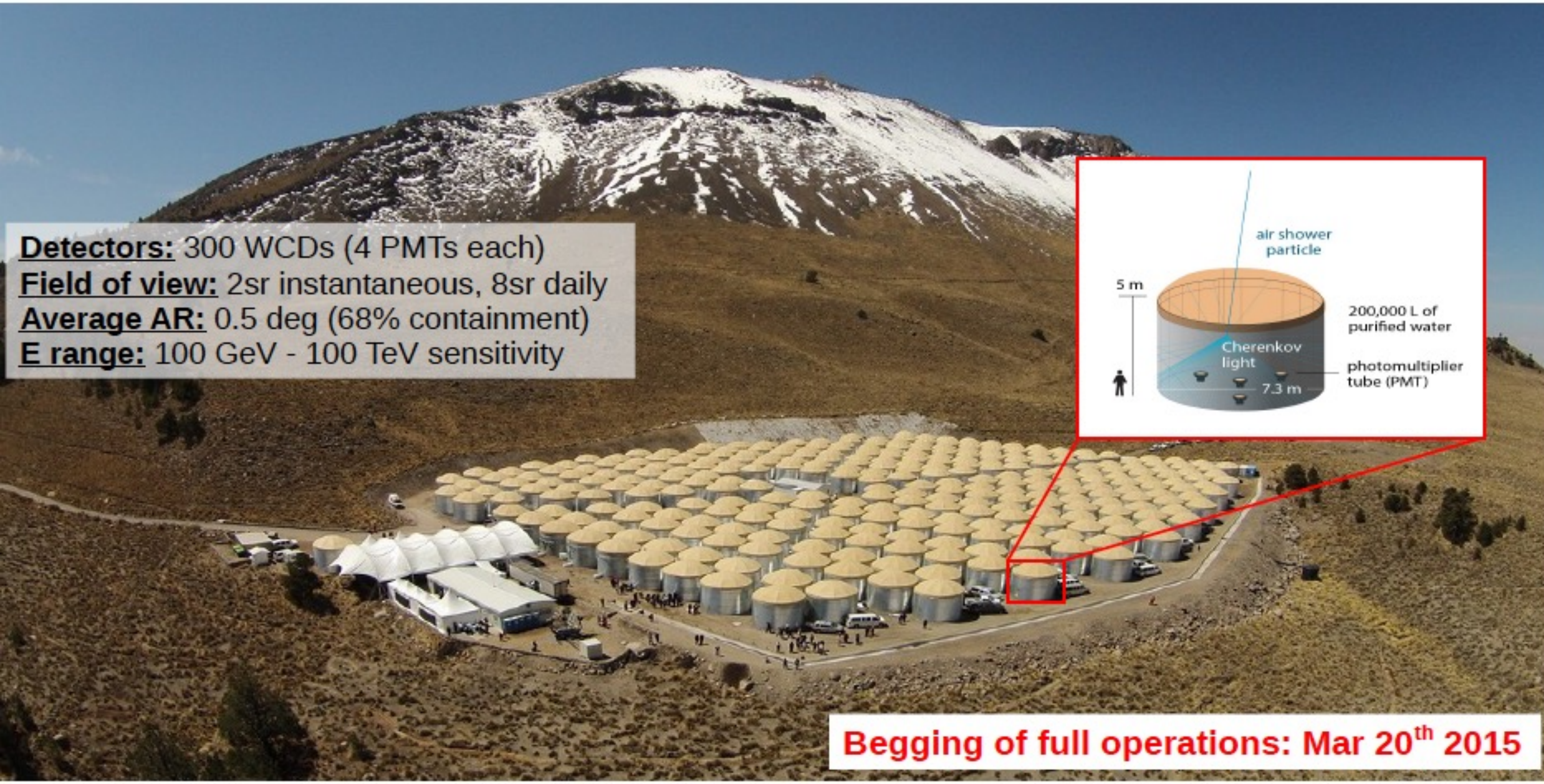
using Cherenkov telescopes



Key issue:
huge detection area
~ 10^5 m^2

From W.Hofman

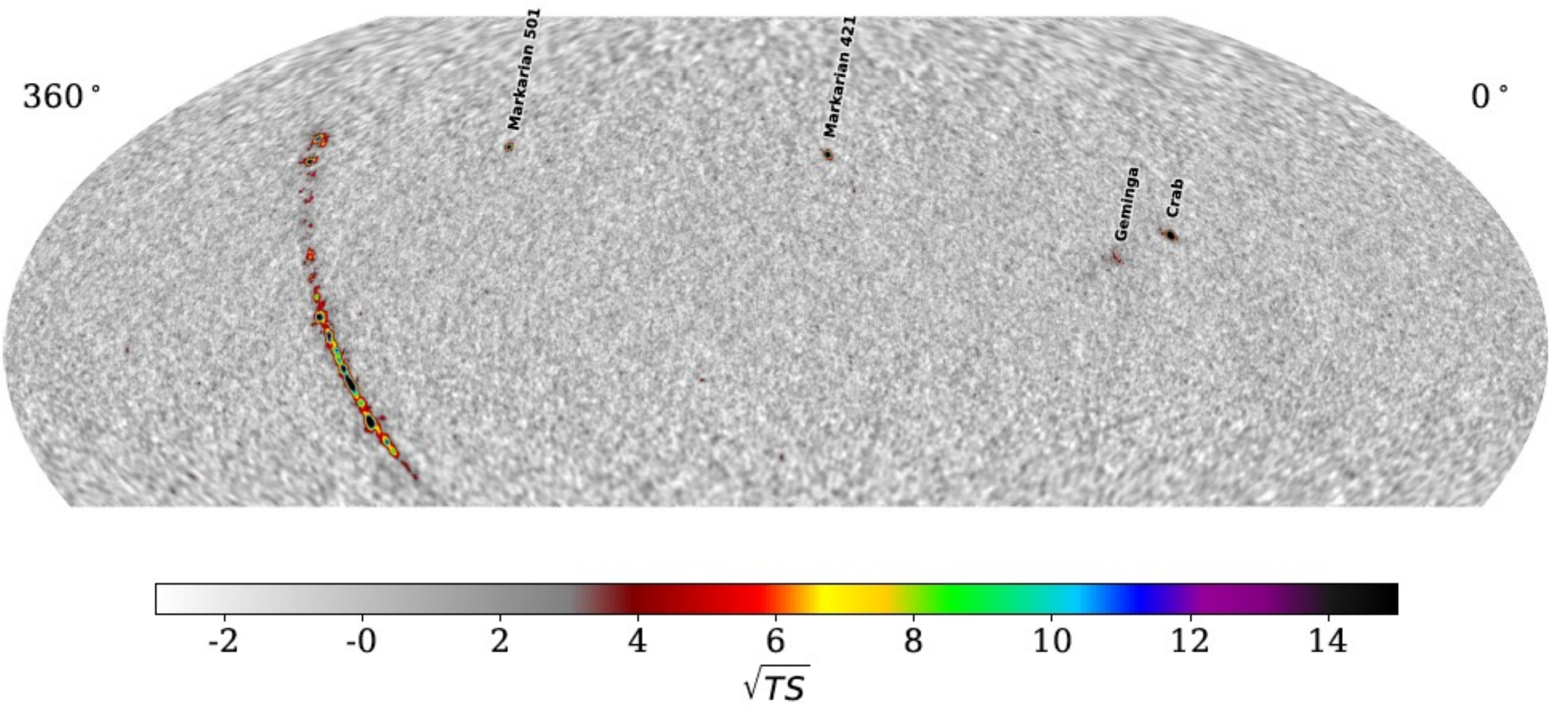
HAWC Inauguration



Detectors: 300 WCDs (4 PMTs each)
Field of view: 2sr instantaneous, 8sr daily
Average AR: 0.5 deg (68% containment)
E range: 100 GeV - 100 TeV sensitivity

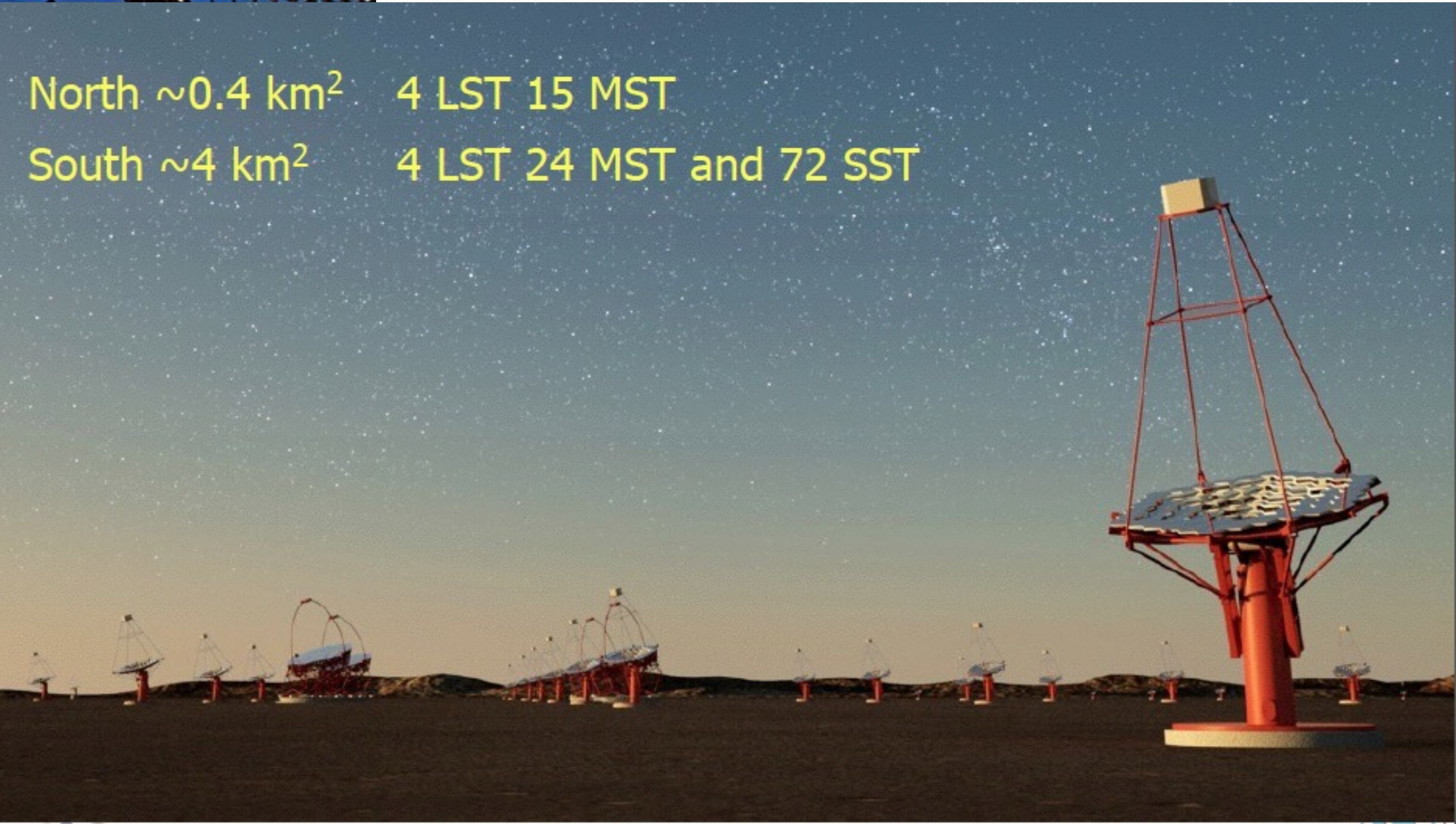
Begging of full operations: Mar 20th 2015

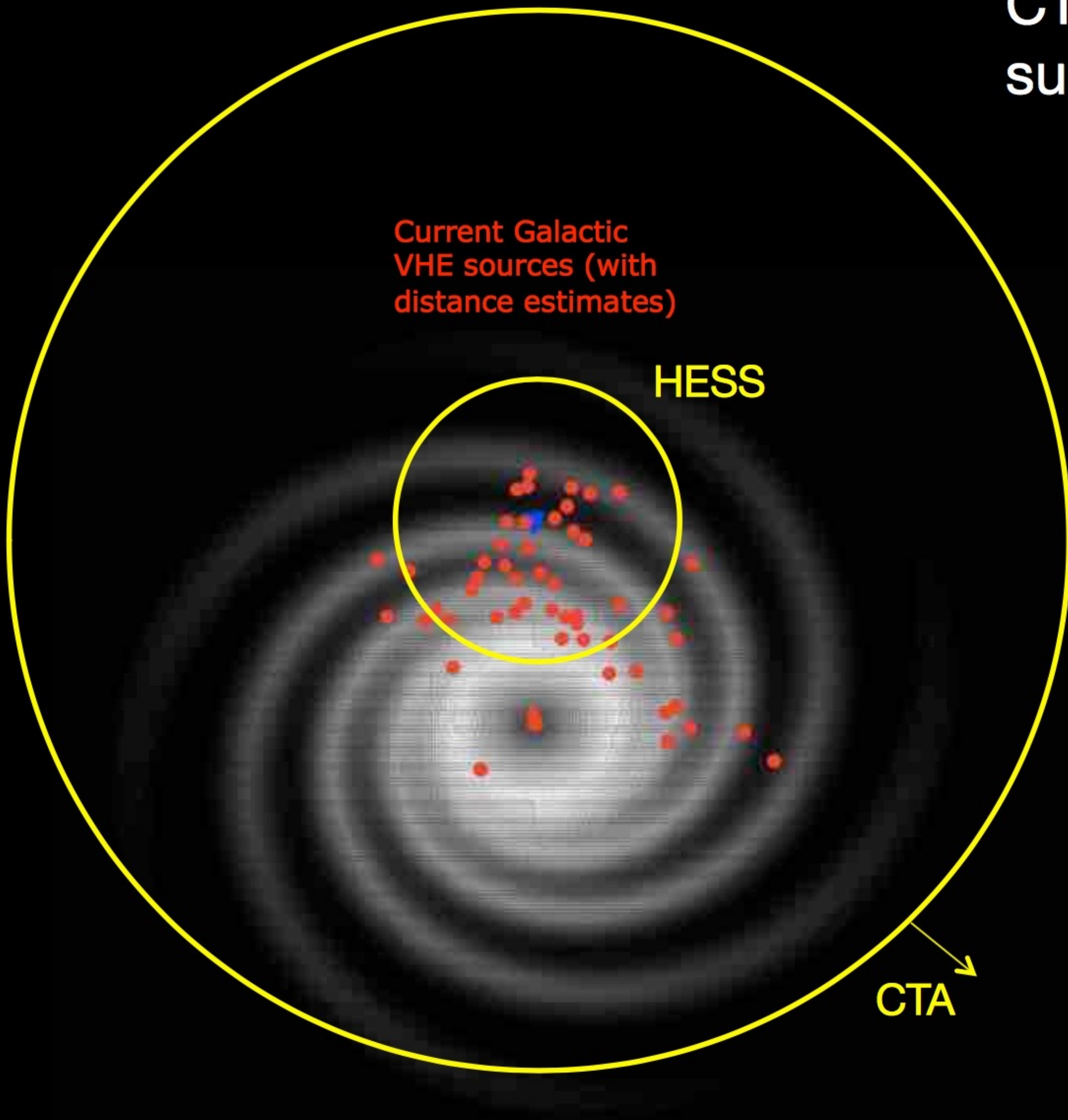
HAWC sky map


360°
0°
Markarian 501
Markarian 421
Geminga
Crab
-2
-0
2
4
6
8
10
12
14
√TS

CTA

The Next Generation: The Cherenkov Telescope Array





CTA as ultimate survey machine

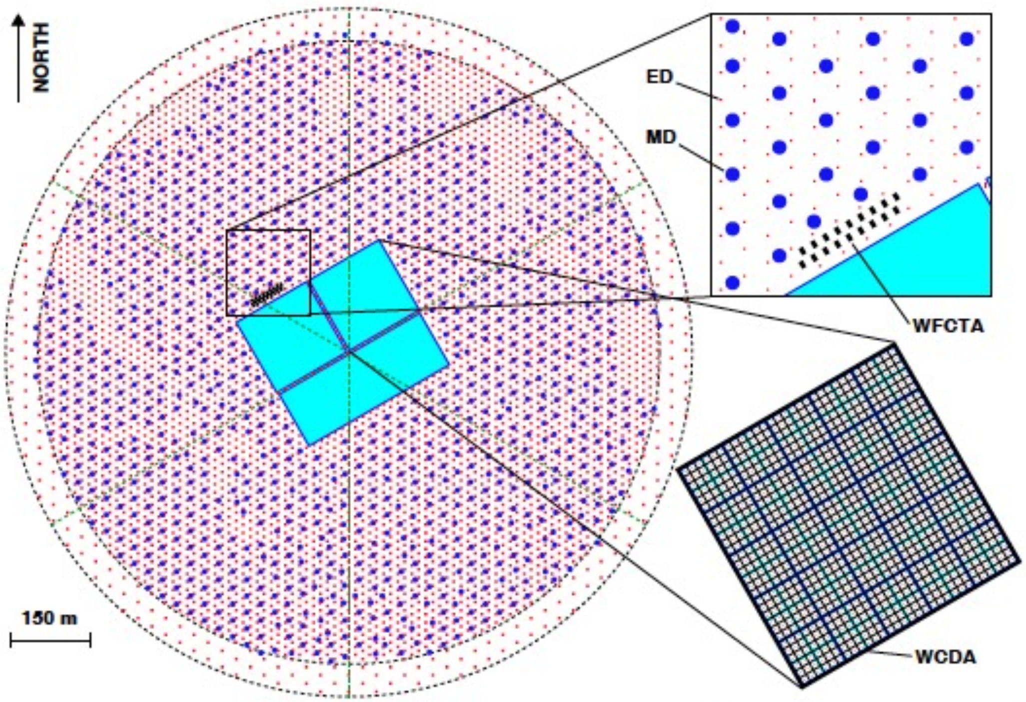
CTA as ultimate machine to study flares

at 25 GeV, for flares 10000 times more sensitive than Fermi

Coherent full-sky coverage from two sites

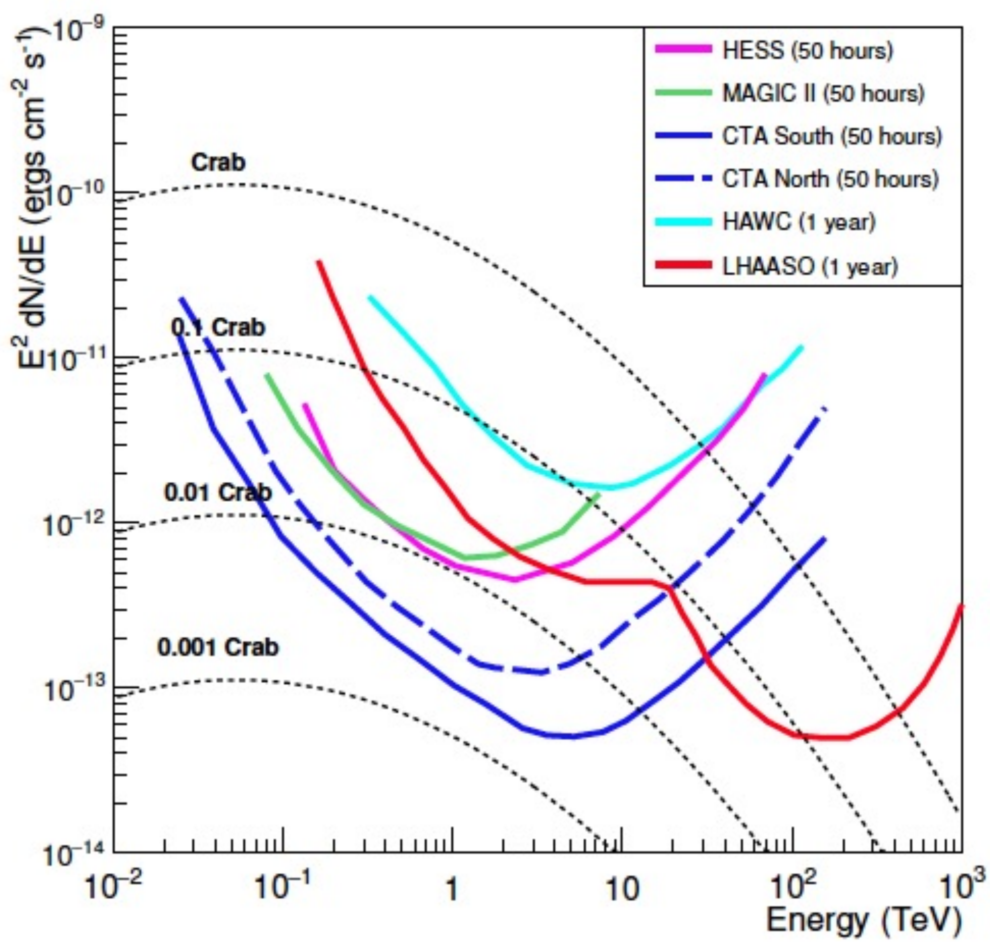
The LHAASO experiment

- 1 km^2 array, including 4941 scintillator detectors 1 m^2 each, with 15 m spacing.
- An overlapping 1 km^2 array of 1146, underground water Cherenkov tanks 36 m^2 each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m^2).

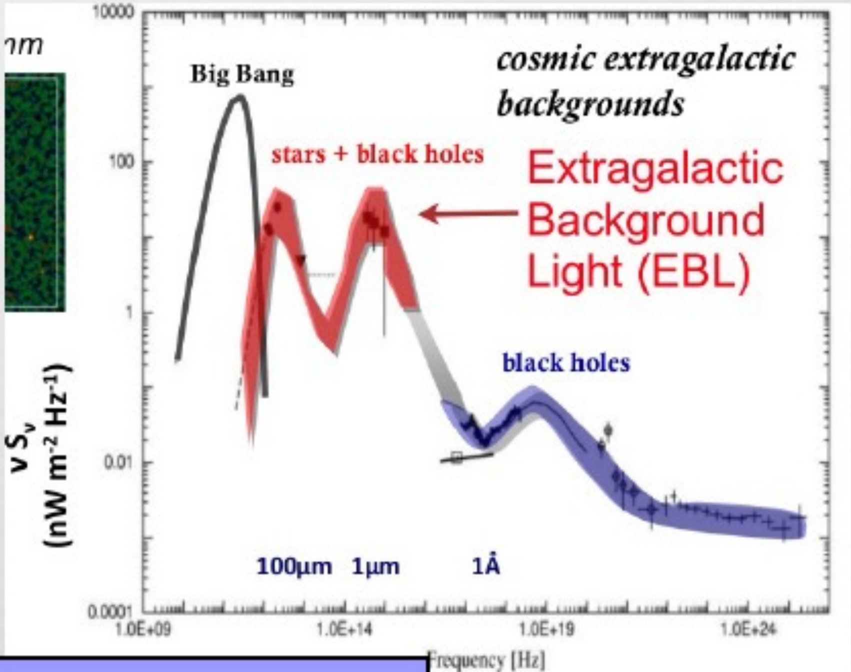


- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.

Sensitivity future detectors

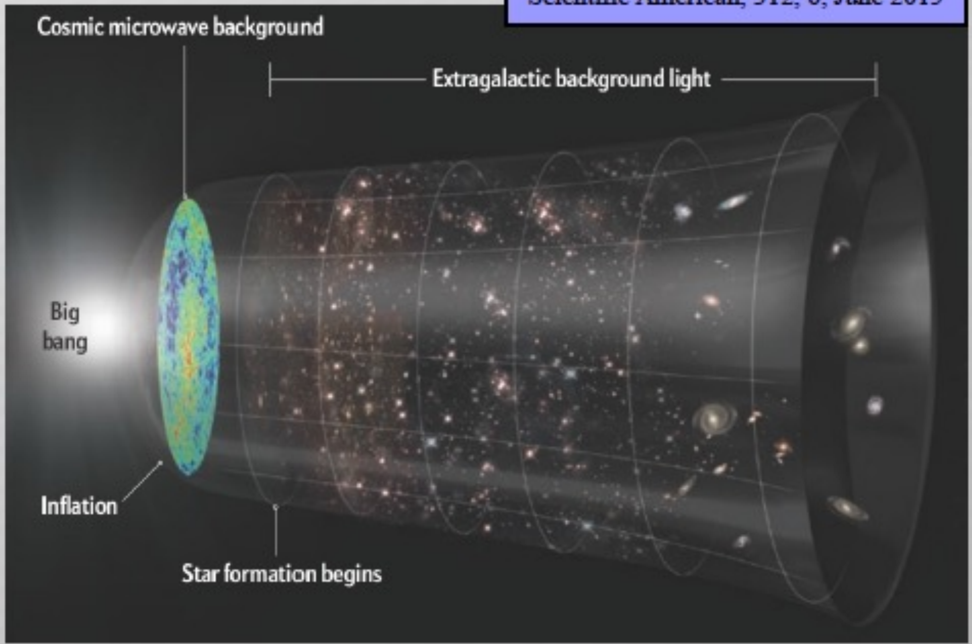


Diffuse extragalactic backgrounds



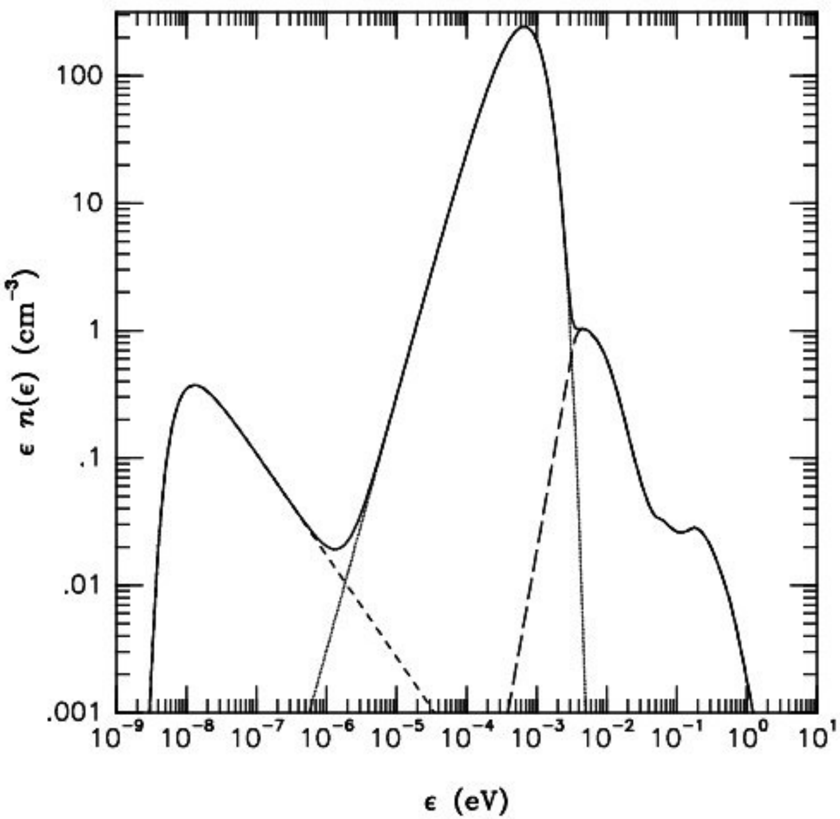
From Genzel's lecture @ 2013 Jerusalem Winter School

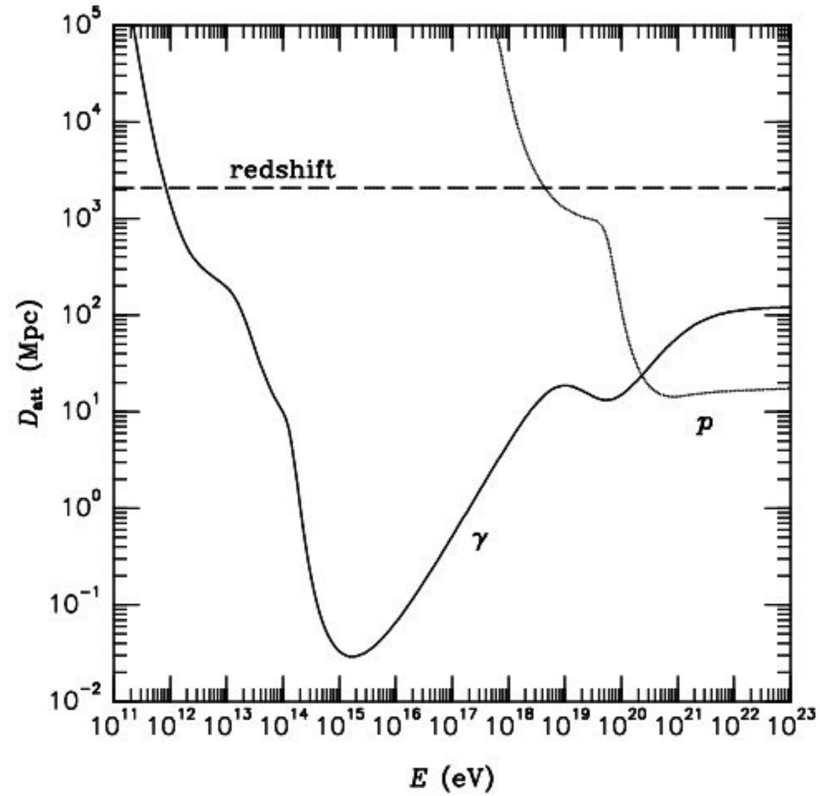
Scientific American, 312, 6, June 2015



- The EBL is the accumulated diffuse light produced by star formation processes and accreting black holes over the history of the Univere from the UV to the far-IR.
- It contains fundamental information about galaxy evolution, cosmology, and it is essential for the full energy balance of the Universe.

Diffuse backgrounds



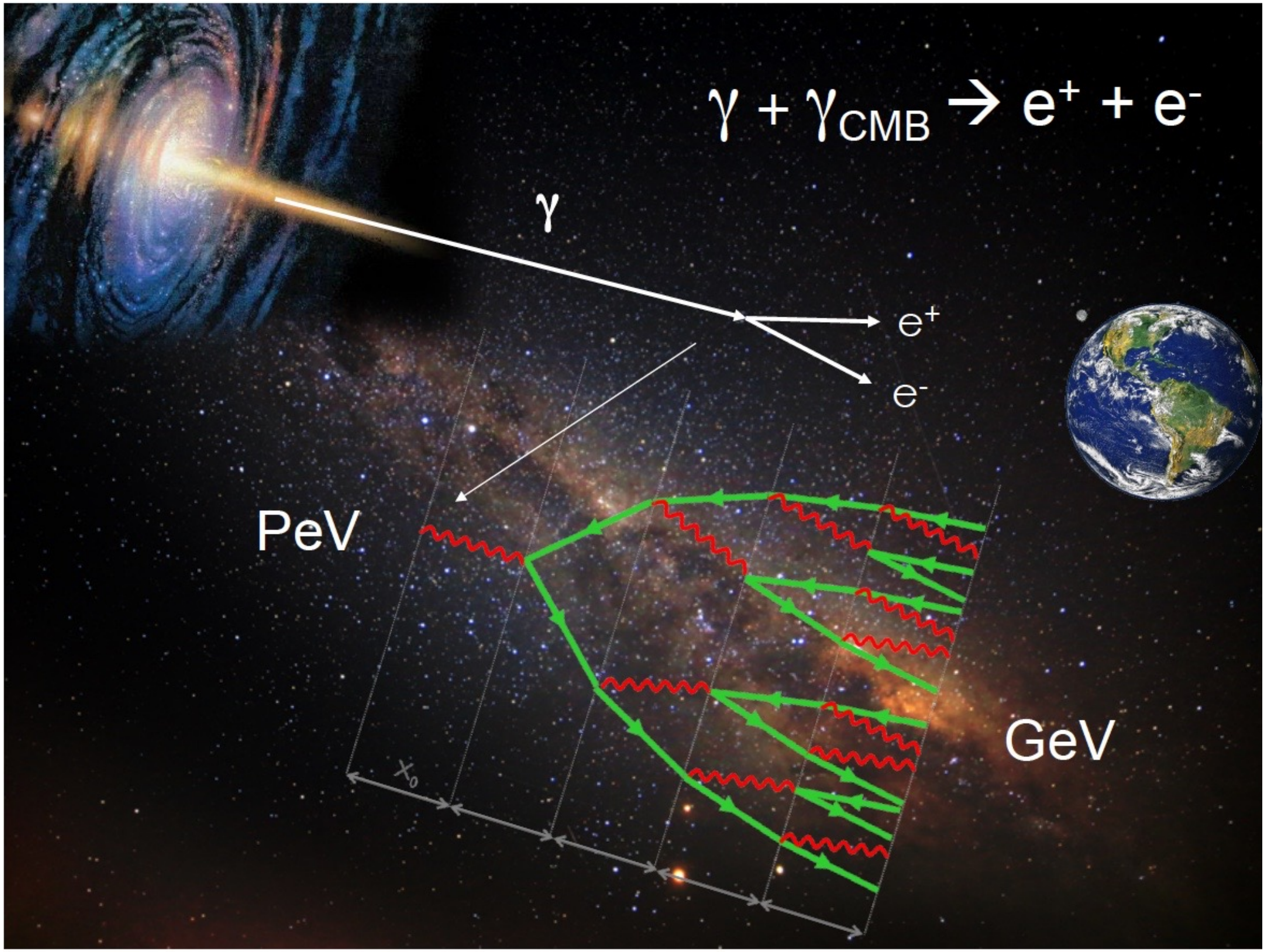


Electromagnetic cascade

$$\gamma + \gamma_B \Rightarrow e^- + e^+$$

$$e^\pm + \gamma_B \Rightarrow e^\pm + \gamma$$

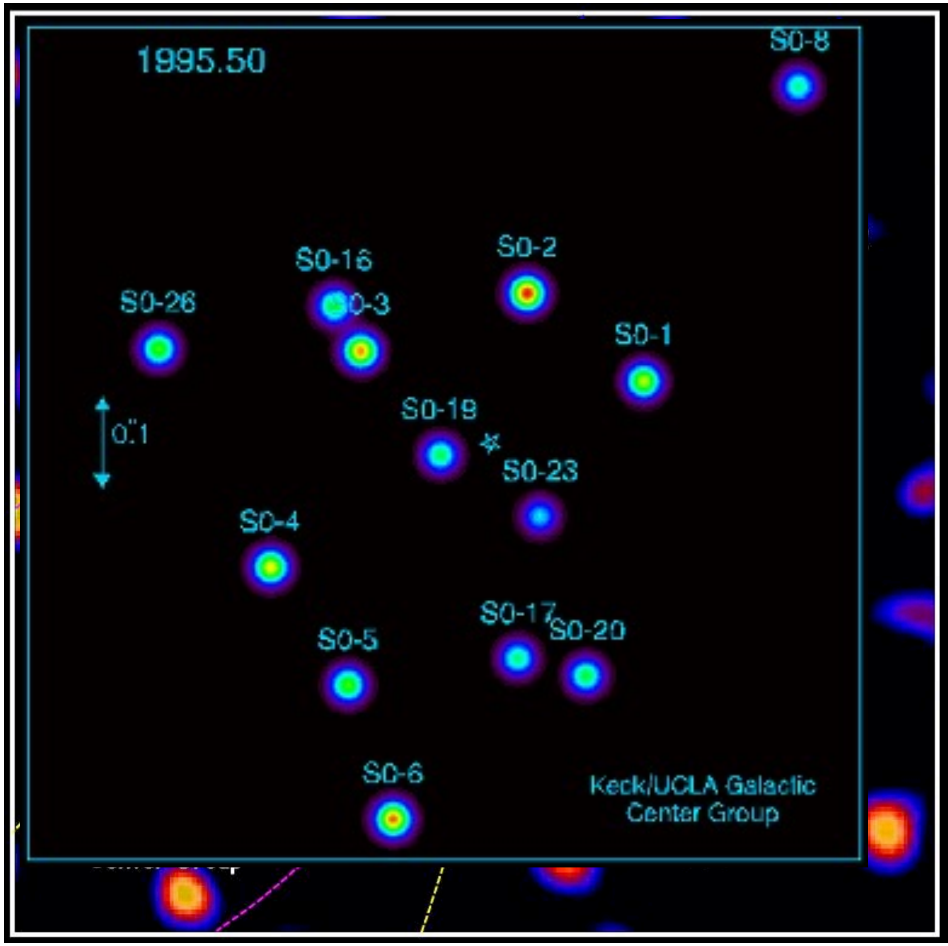
Electromagnetic cascade



Super-Massive Black Holes, AGNs

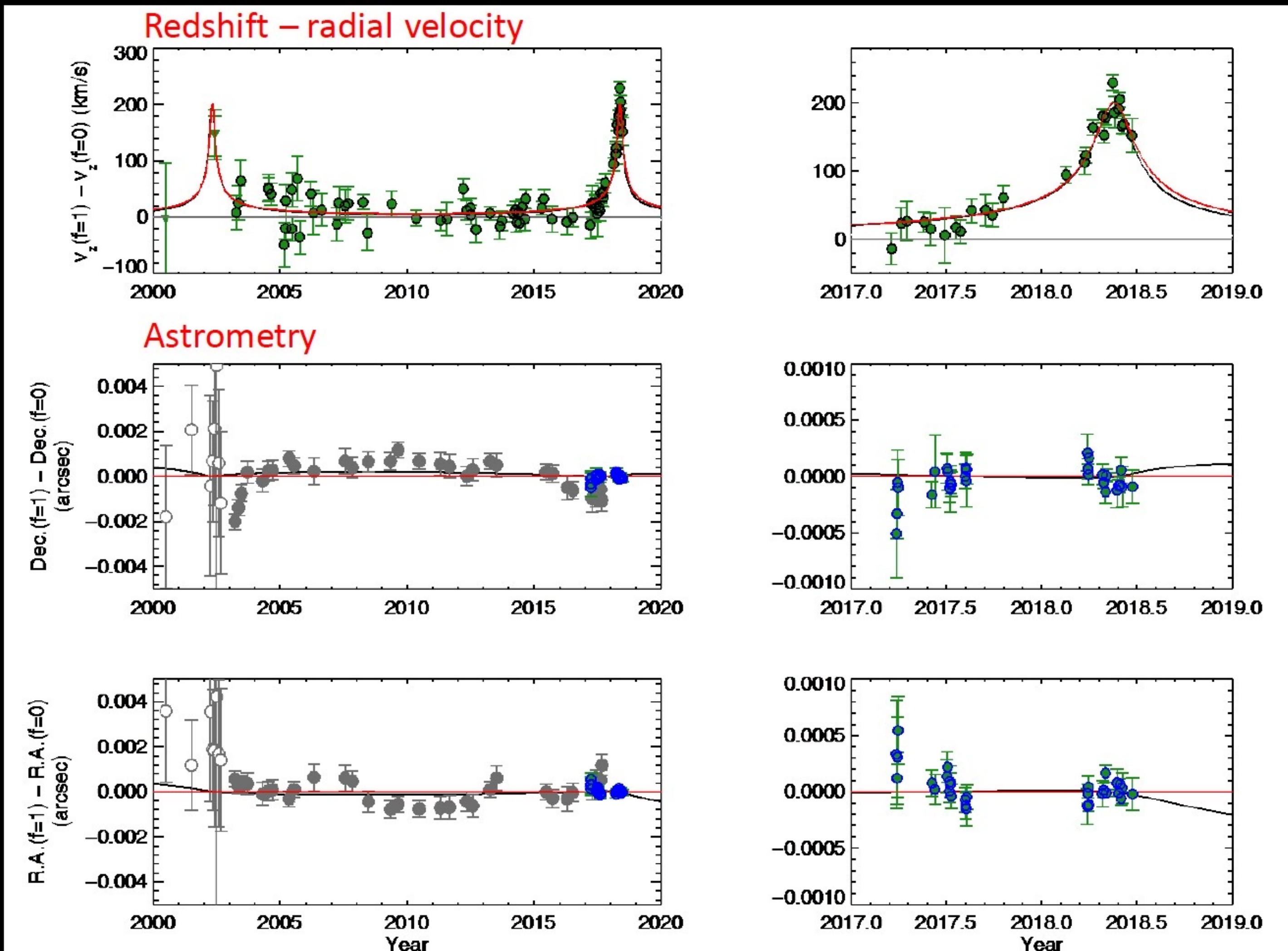
Center of the Milky Way: Sgr A*

- The center of our own Galaxy
  - Can directly observe stars orbiting an unseen object
  - Need a black hole with mass of 3.6+-0.4 million solar masses to explain stellar orbits
  - Best case yet of a black hole.



Ghez et al. (UCLA)

Fitting with a relativistic orbit



$f = 0$: Newton

$f = 1$: Einstein (post-newtonian approximation)

GRAVITY result:
$f = 0.94 \pm 0.09$

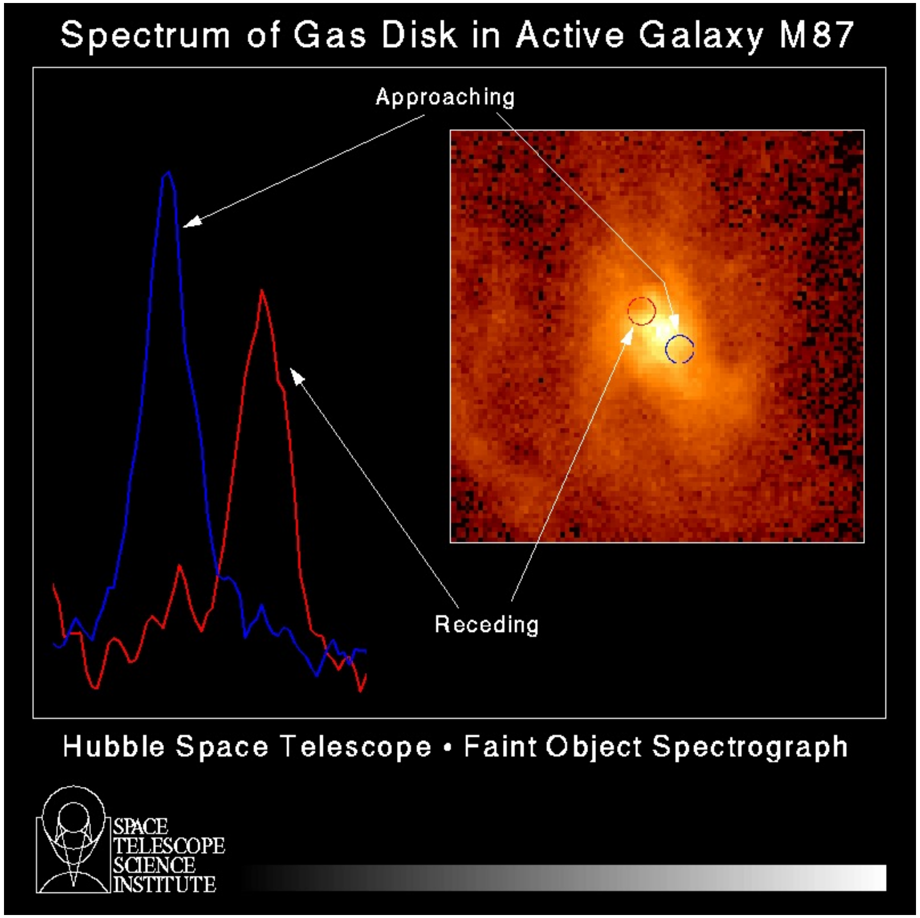
Mass of Sgr A*:
$4.11 \pm 0.03 \times 10^6$ $M_\odot$
(precision of 6×10^{-3})

Distance to Sgr A*:
8127 ± 31 pc
(precision of 4×10^{-3})

GRAVITY Collaboration, A&A 615, L15 (2018)

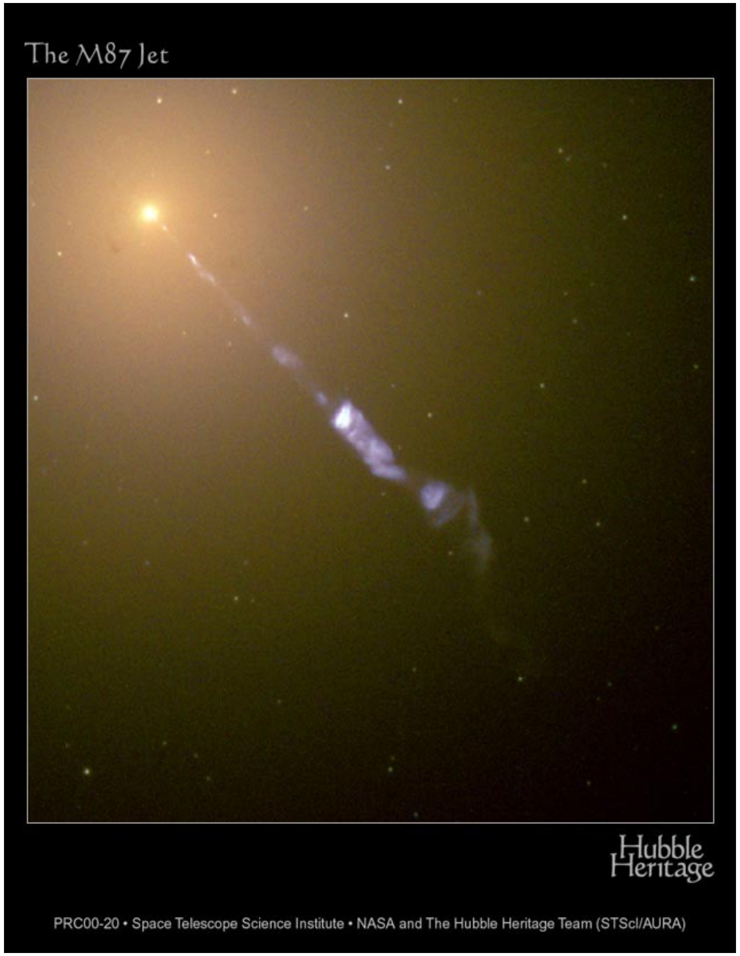
M87 Virgo cluster 20 Mpc

- Another example – the SMBH in the galaxy M87
  - Can see a gas disk orbiting galaxies center
  - Measure velocities using the Doppler effect (red and blue shift of light from gas)
  - Need a 3 billion solar mass SMBH to explain gas disk velocities



Active Galactic Nuclei

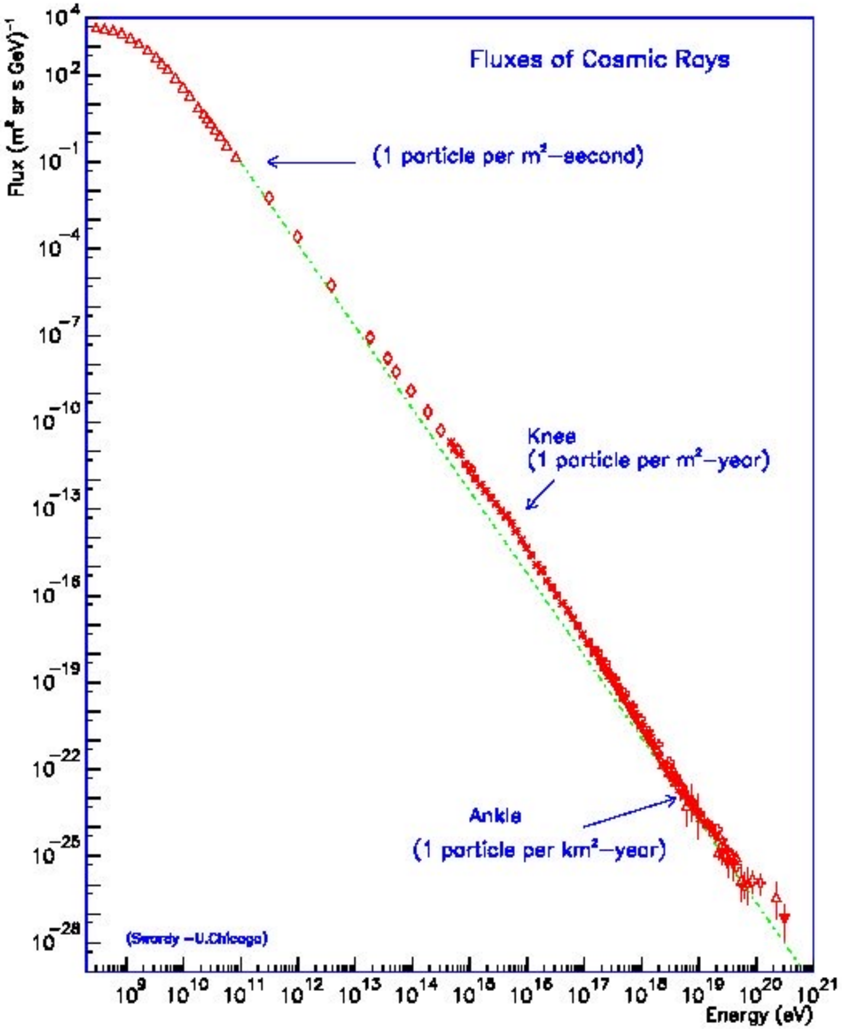
- M87 shows signs of "central activity"
- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor of >6
  - Powerful (probably as powerful as galaxy itself)
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole



Some Characteristic of AGN

- Super Bright: AGN 3C273 (an extreme example) is L = 4.8*10^12 L_{sun}.
- Along jet particles accelerated, secondary gamma-ray and neutrinos produced

Uneasy messenger: cosmic rays


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy – U.Chicago)
Energy (eV)
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹

Extensive air showers from cosmic rays

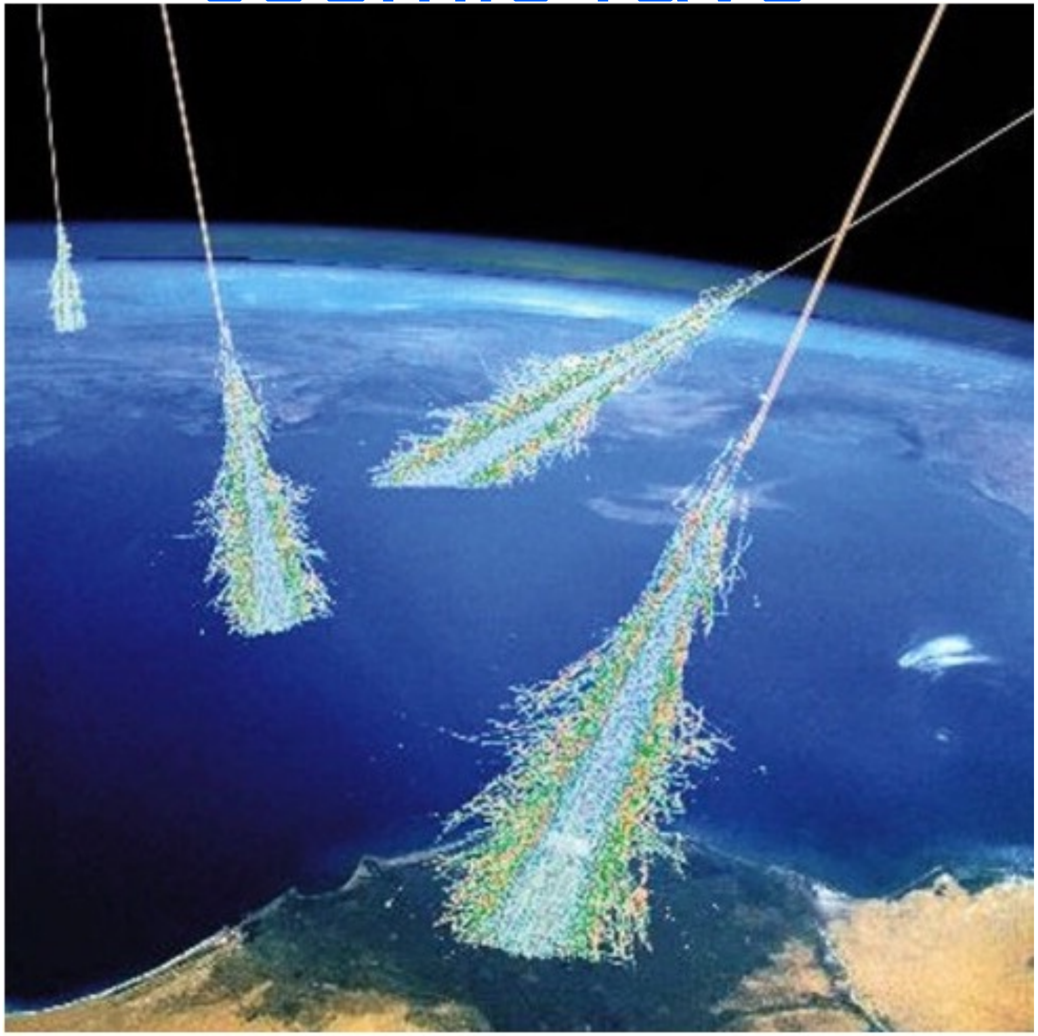
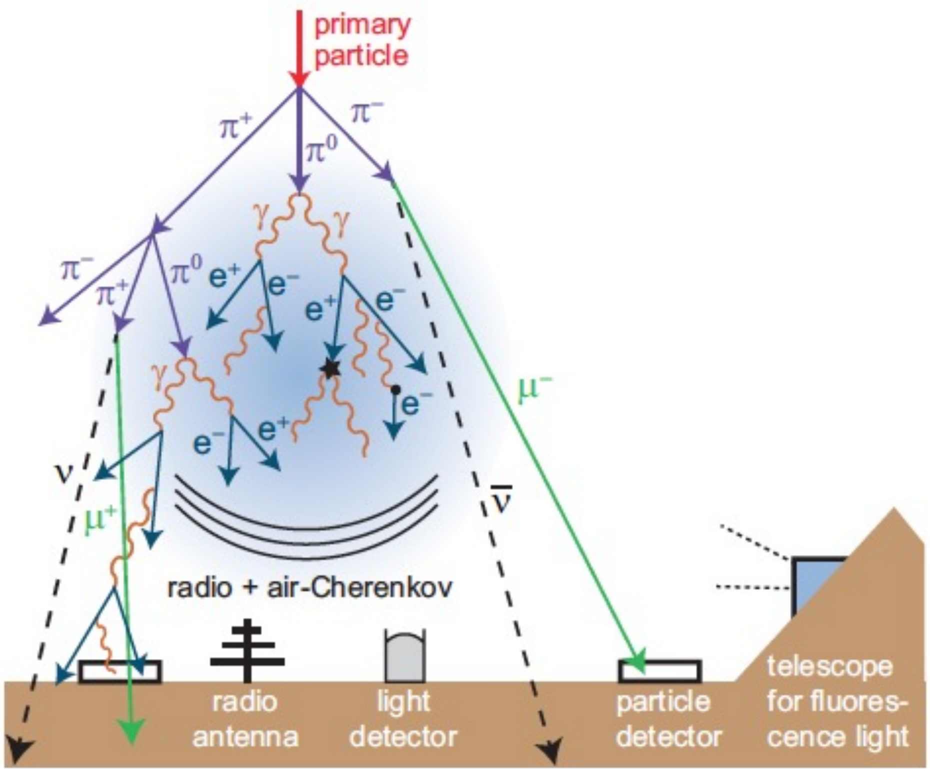
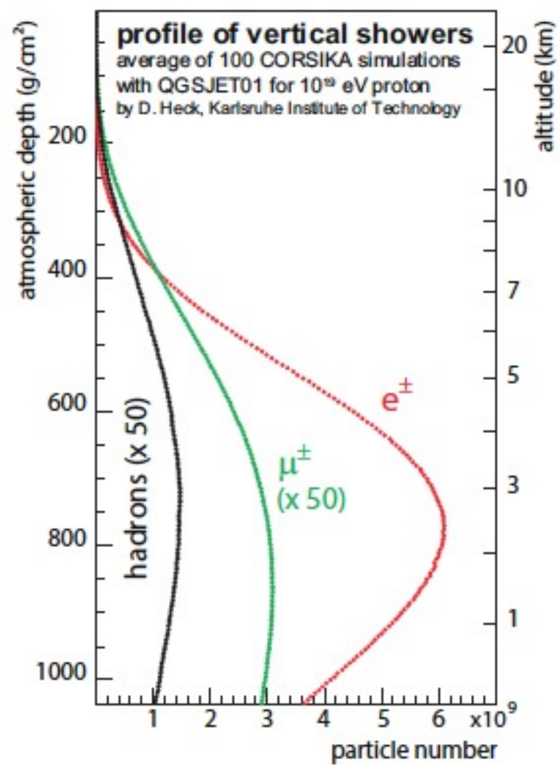


Illustration of extensive air-showers induced by UHECRs. Image credit: auger.org

Detection techniques

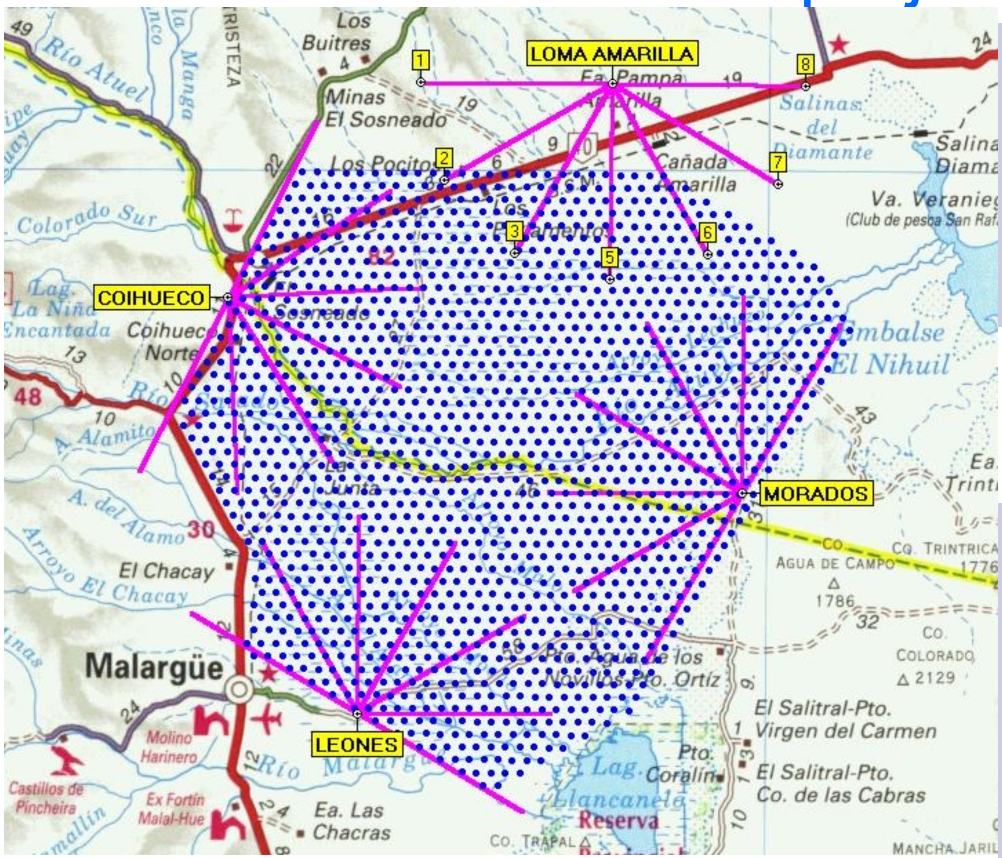




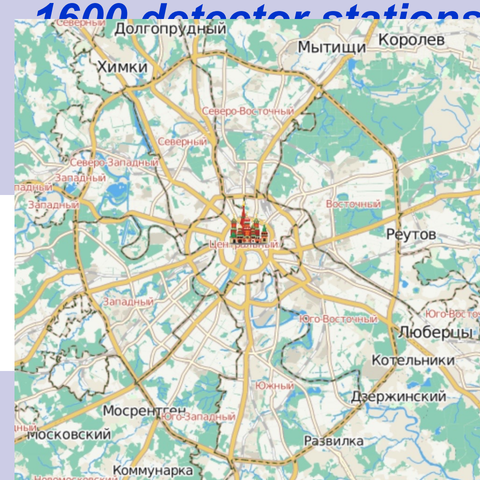
Pierre Auger Observatory

South site in Argentina almost finished

North site – project

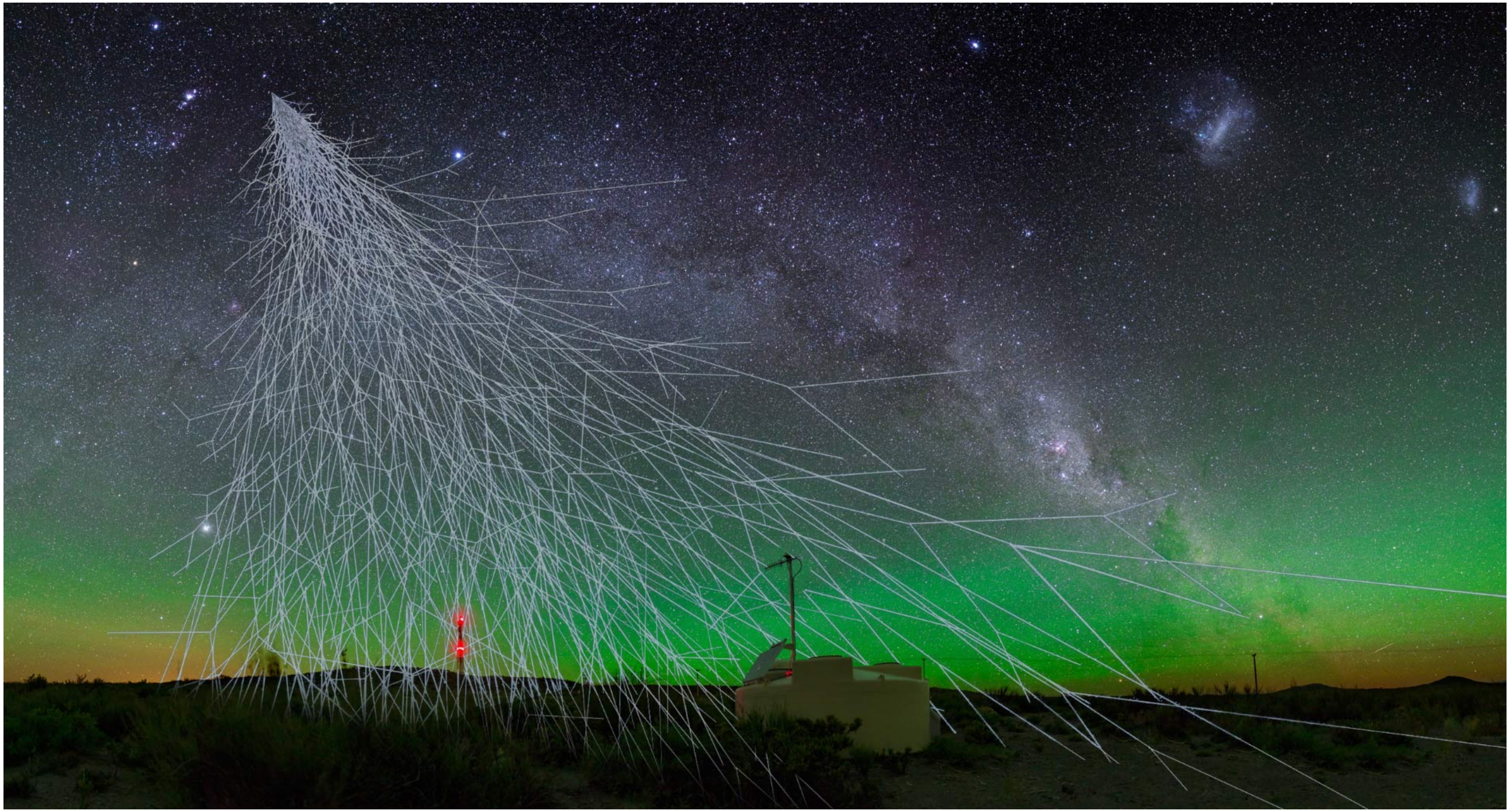


Surface Array

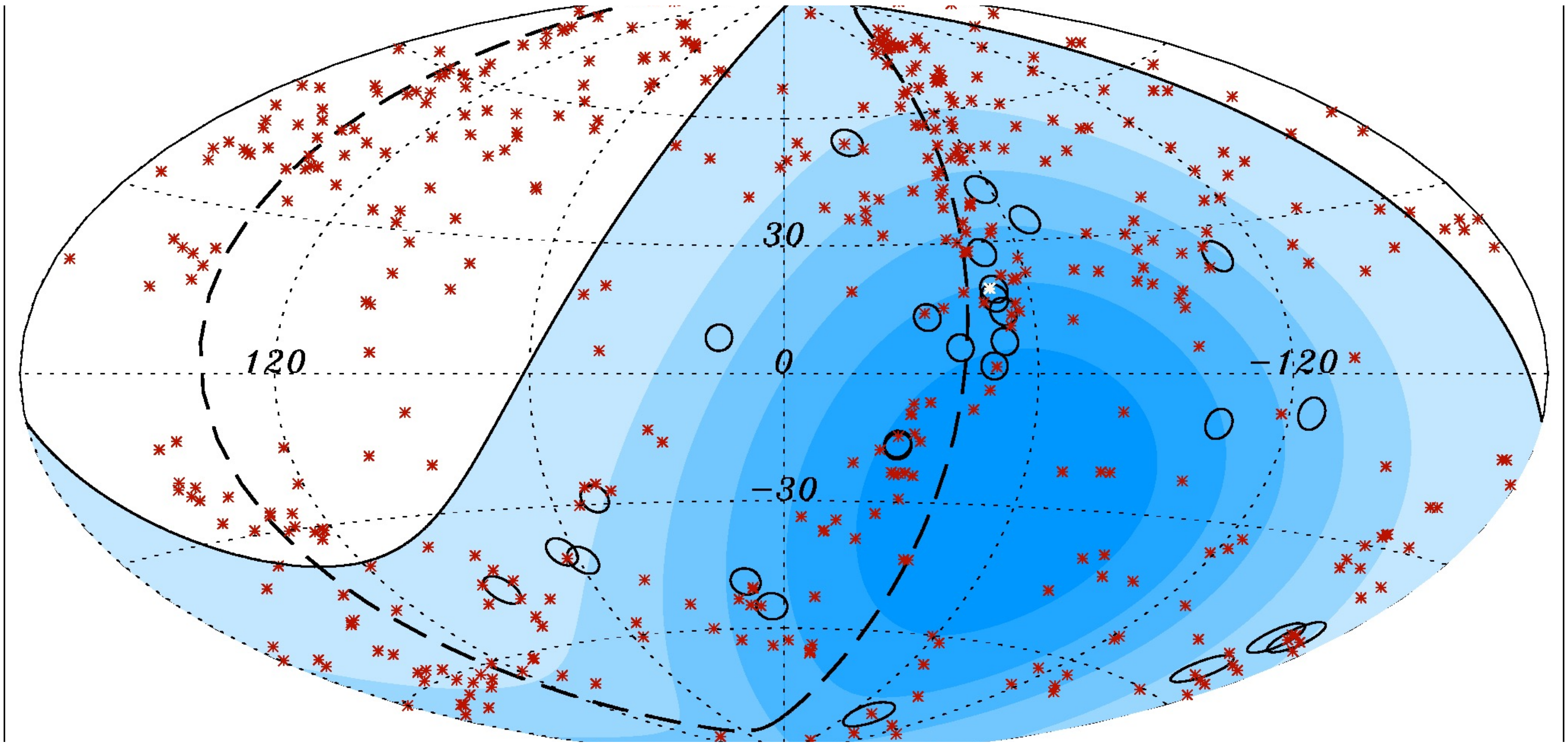


6 Telescopes per enclosure

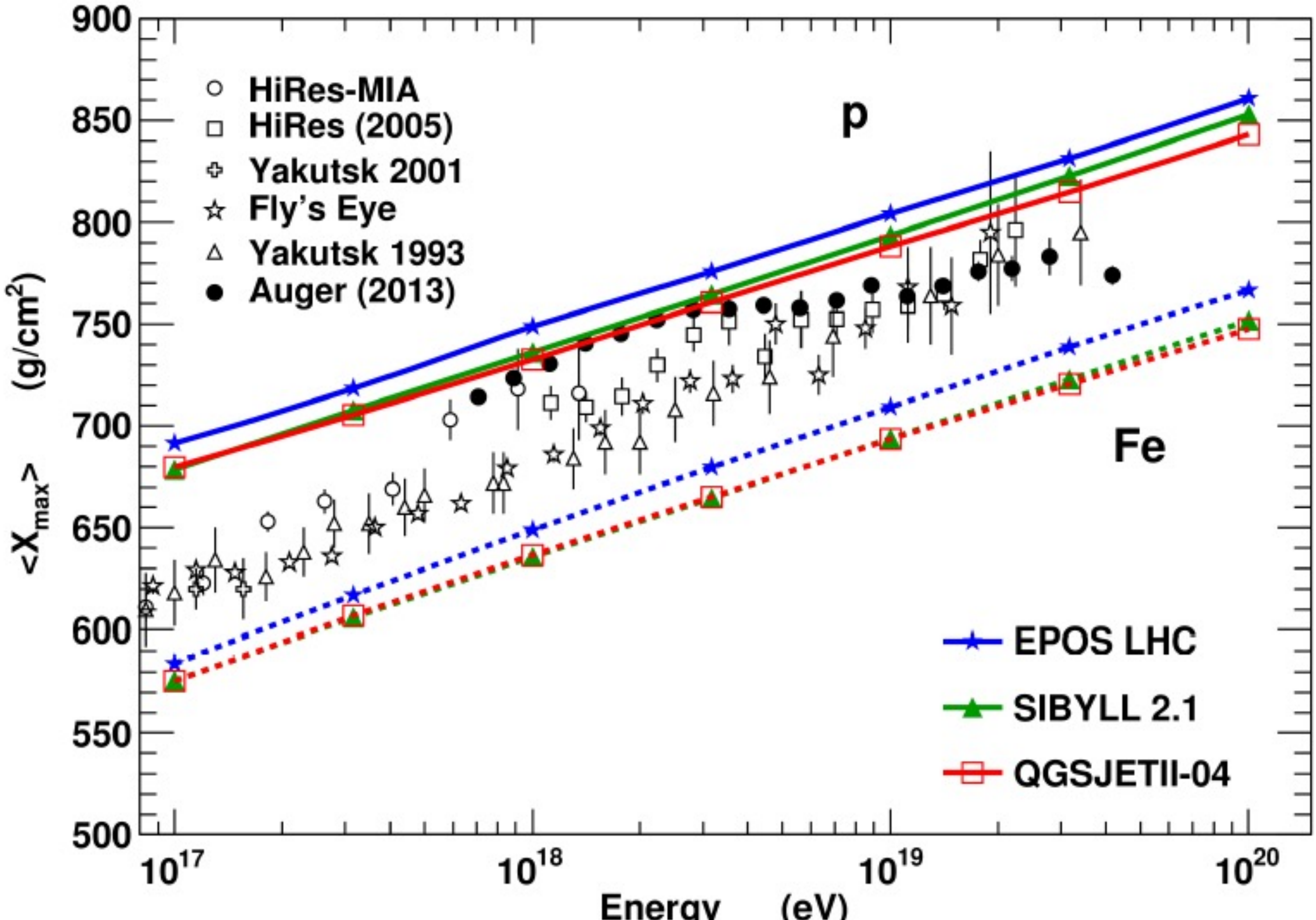
24 Telescopes total



Arrival directions for E>57 EeV in Auger



EAS with Re-tuned CR Models : X_{max}



Telescope Array

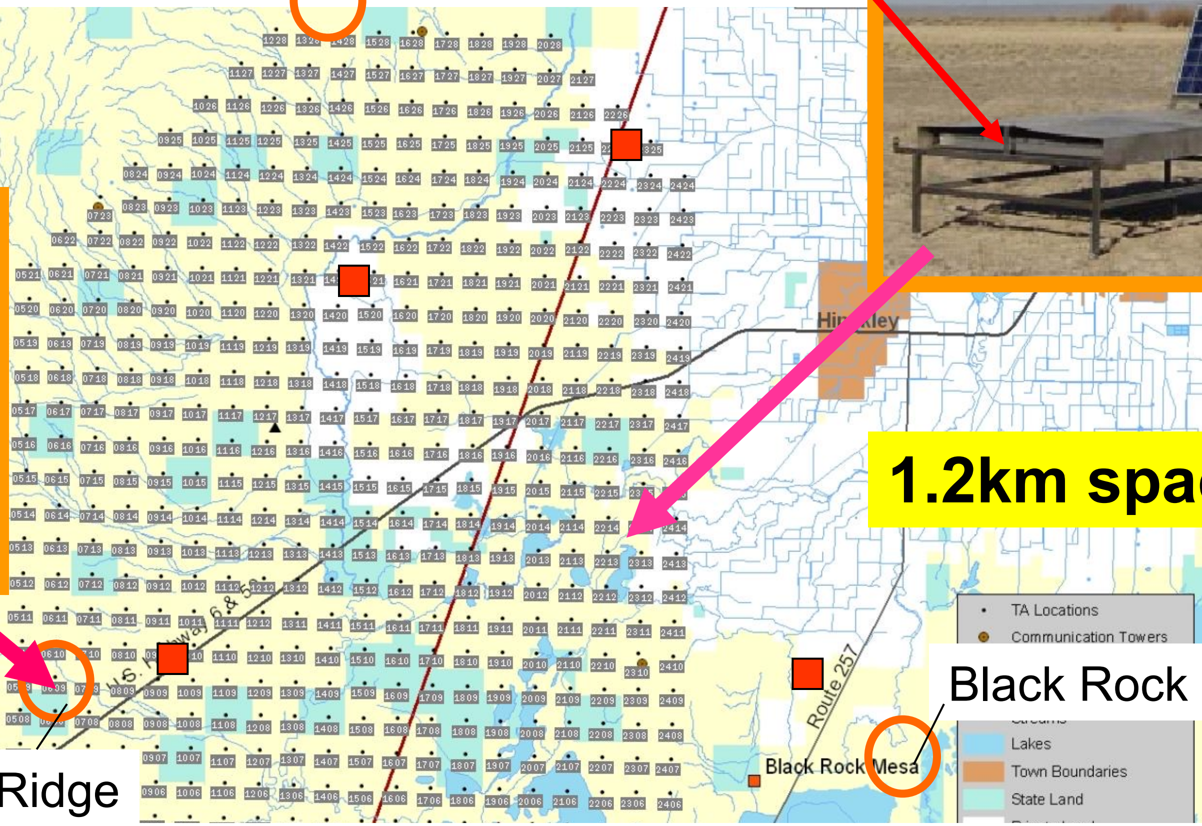
to astroparticle physic

576 plastic scintillation Surface Detectors (SD)

Atmospheric fluorescence telescope
3 stations **FD**

5 communication towers

3m^2 1.2cm t
two layers



1.2km spacing

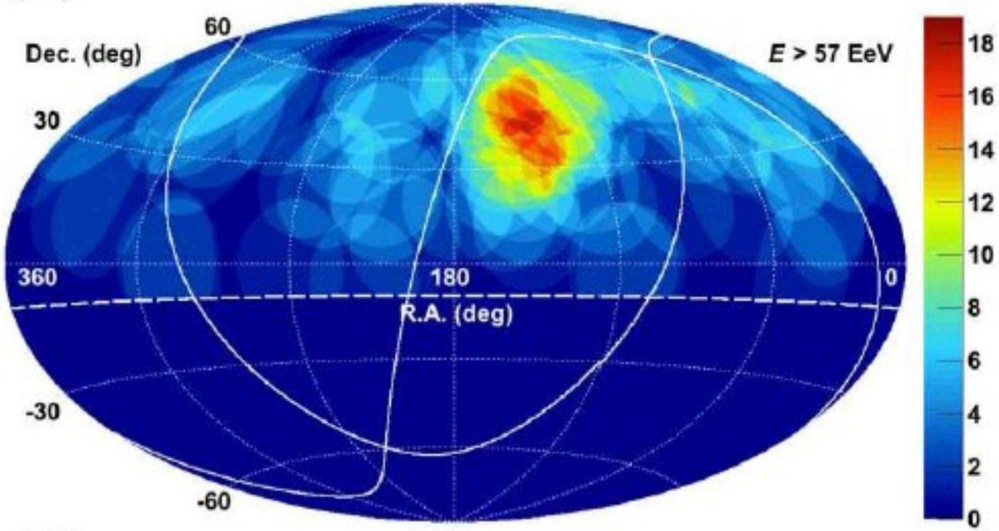
Long Ridge

Black Rock Mesa

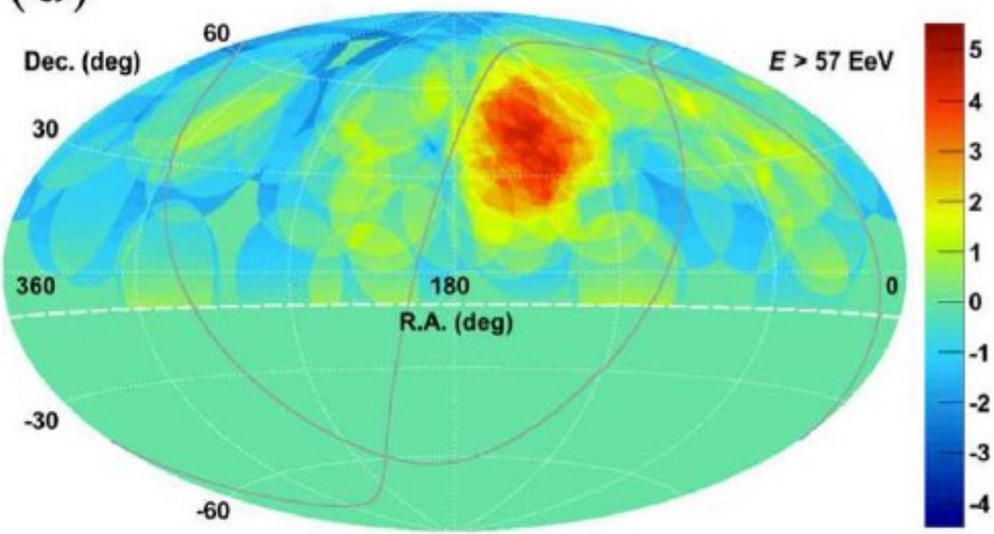
20km

Sensitivity of SD : ~9 x AGASA

(b)



(d)



Telescope Array

10^6 total events over 6 years

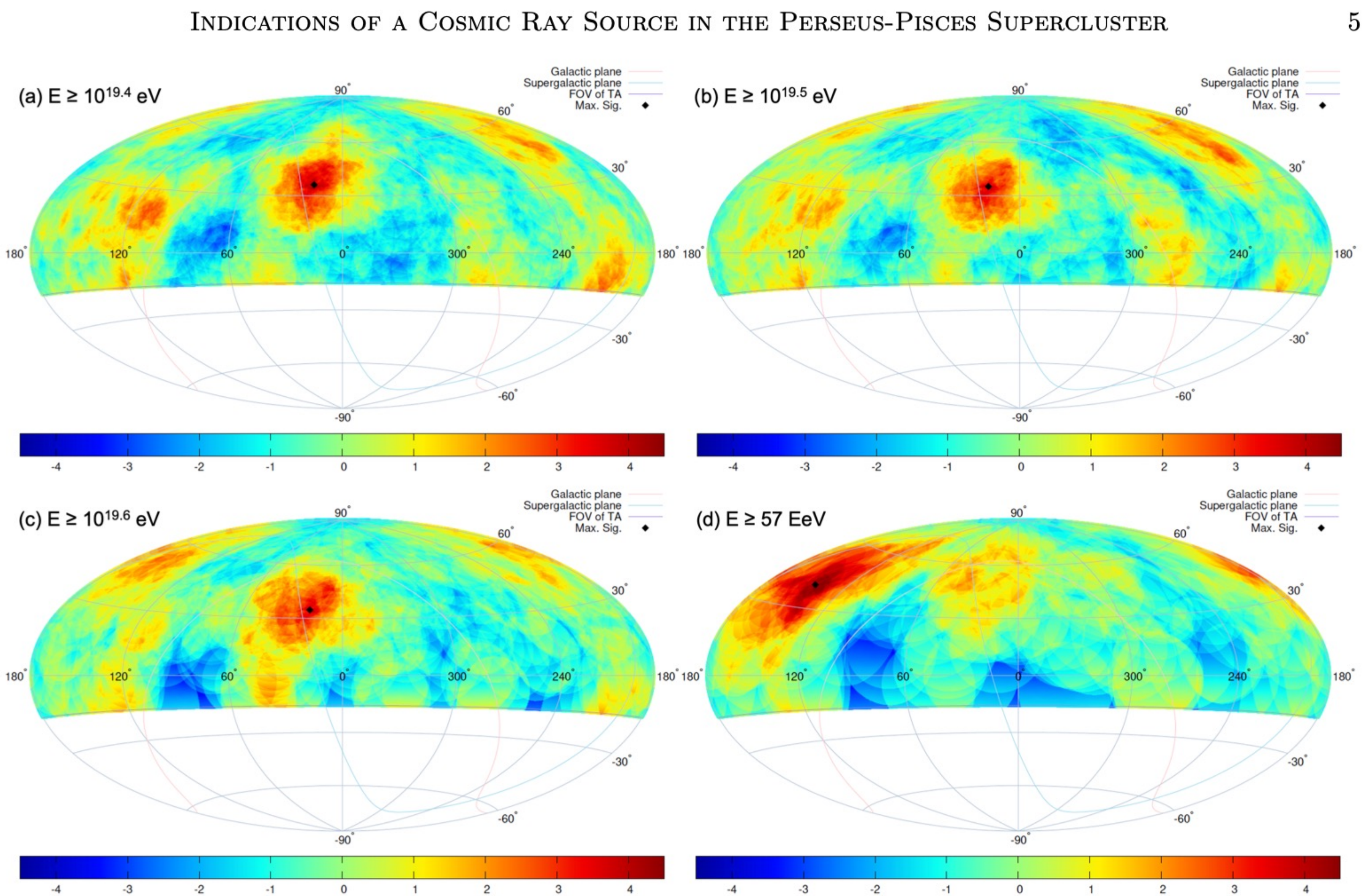
87 events > 57 EeV , < 60°

Shown: events within 20° of each point

Hot Spot at
RA= **148.4°** and dec= **+44.5°**
(*Mrk 421 is in the vicinity …)*

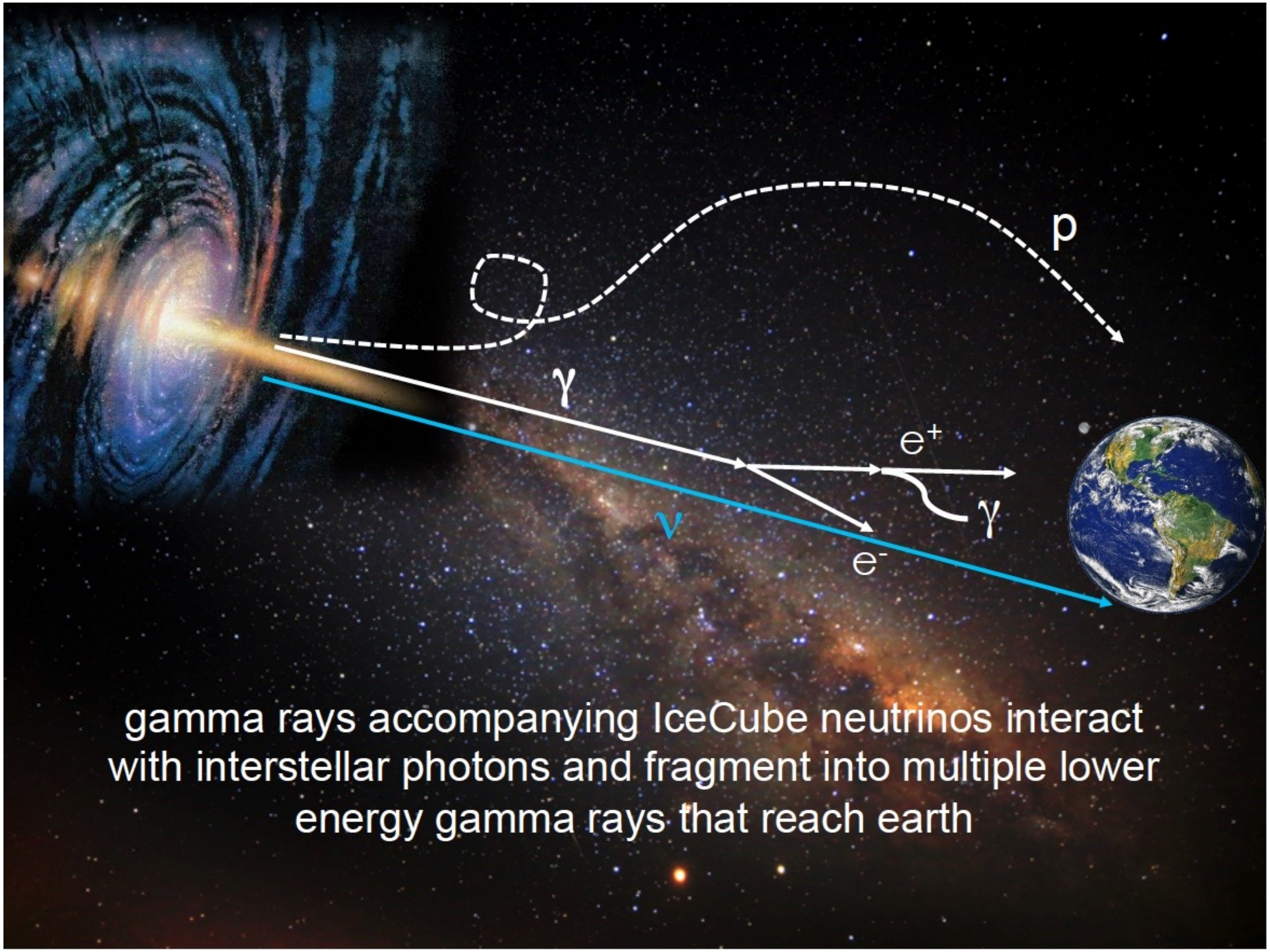
4.3 σ significance compared to isotropic fluctuation

R. Abbasi et al., Ap. J (Lett) ***790*** *(2014) L21; arXiv:1404.5890 [astro-ph.HE]*

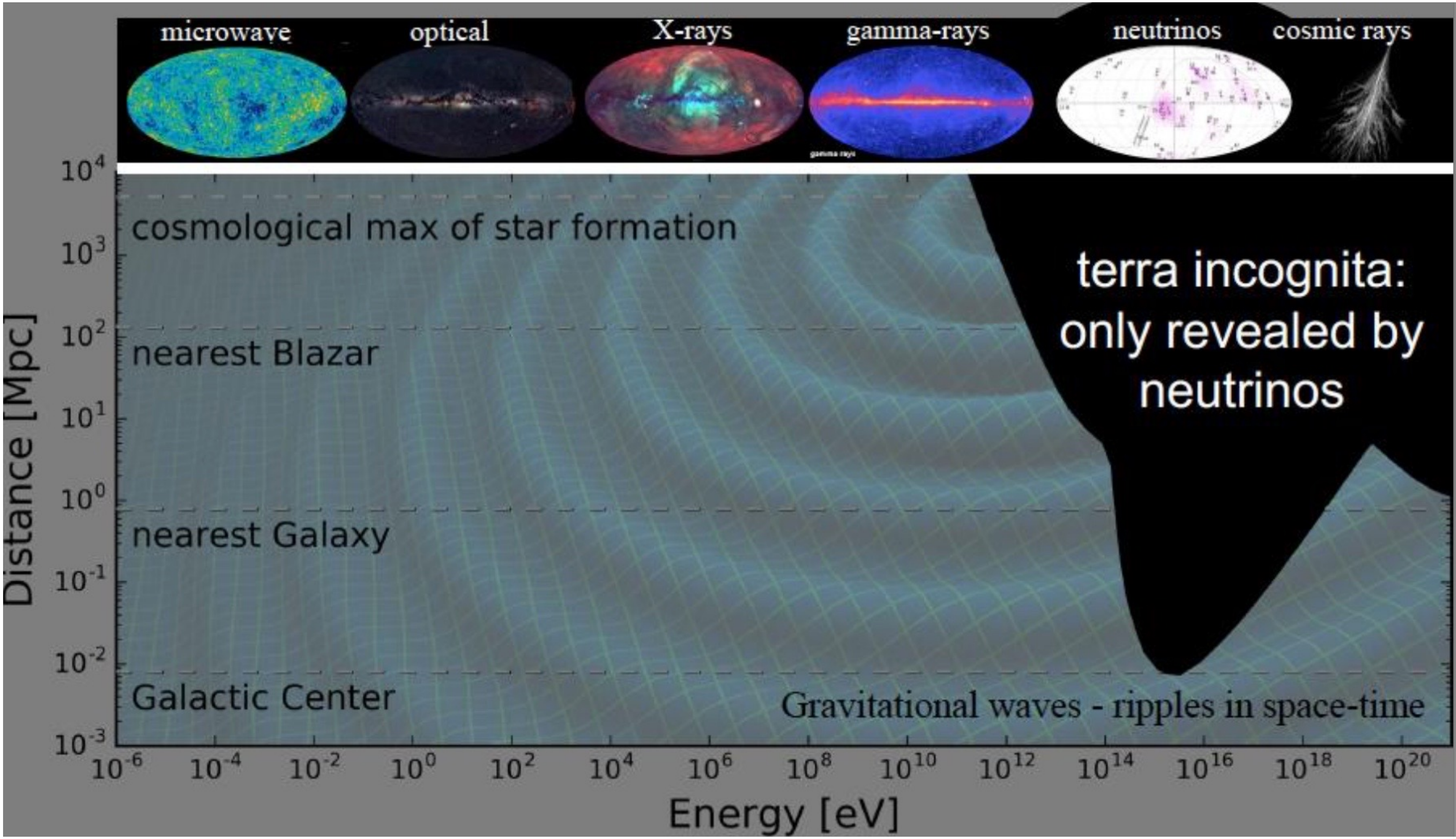


TA collaboration, 2110.14827

Gamma and neutrinos from source



From multi-wavelength to multi-messenger



From F.Halzen

New messenger: neutrinos

Simple facts

The Weak Nuclear Interactions concerns all Quarks and all Leptons

The Weak Interaction takes place whenever some conservation law (isospin, strangeness, charm, beauty, top) forbids Strong or EM to take place

In the Weak Interaction leptons appear in doublets:

Q	L(e) = +1	L(μ) = +1	L(τ) = +1
0	ν_e	ν_μ	ν_τ
-1	e^-	μ^-	τ^-

Doublets are characterized by electron, muon, tau numbers (each conserved, except in neutrino oscillations) → whose sum is conserved.

…and the relevant anti-leptons. For instance:

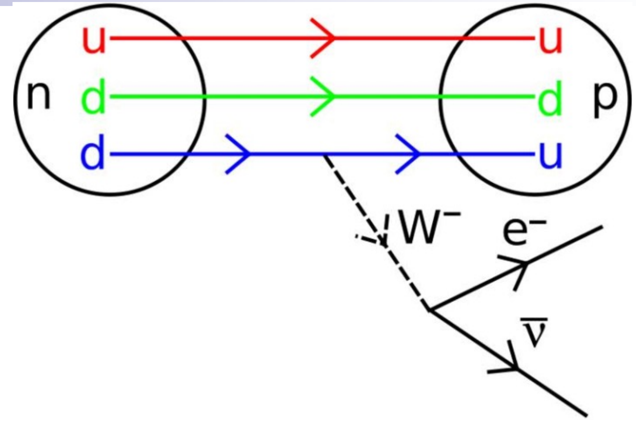
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Fermi Theory of the Beta Decay

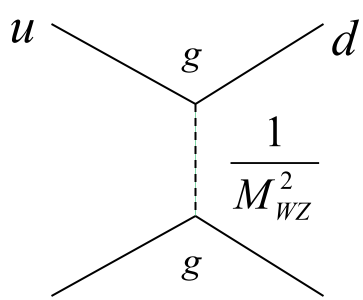
$$A(Z,N) \to A(Z+1,N-1) + e^- + \overline{\nu}_e$$

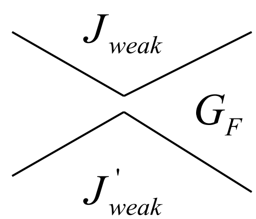
$$n \to p + e^- + \overline{\nu}_e$$

$$d \to u + e^- + \overline{\nu}_e$$



At the fundamental (constituents) level





$$L_{Fermi} \approx G_F\, J^{\mu} J'^{+}_{\mu} = \frac{g^2}{M_W^2} J^{\mu} J'^{+}_{\mu}$$

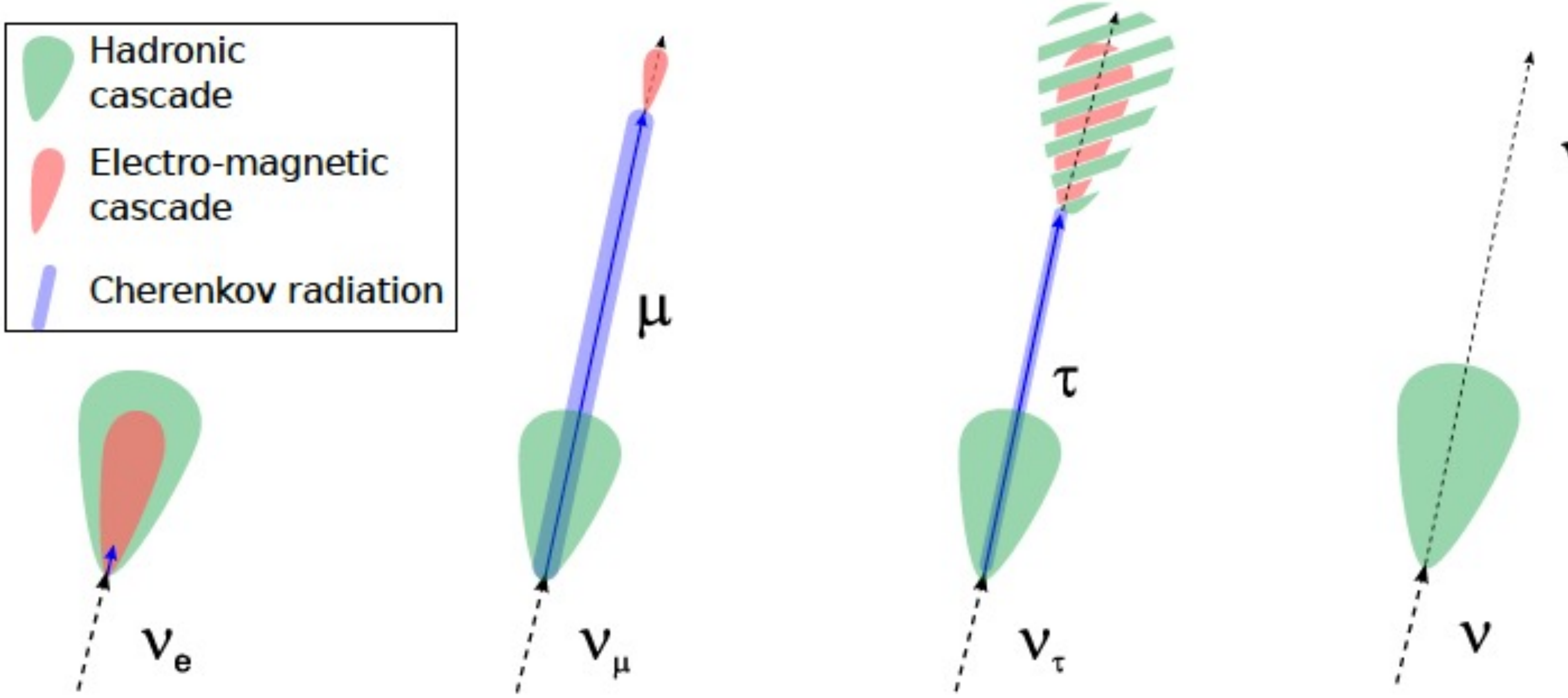
The rate of decay (transizions per unit time) will be:

$$W = \frac{2\pi}{\hbar} G_F^2 |M|^2 \frac{dN}{dE_0}$$

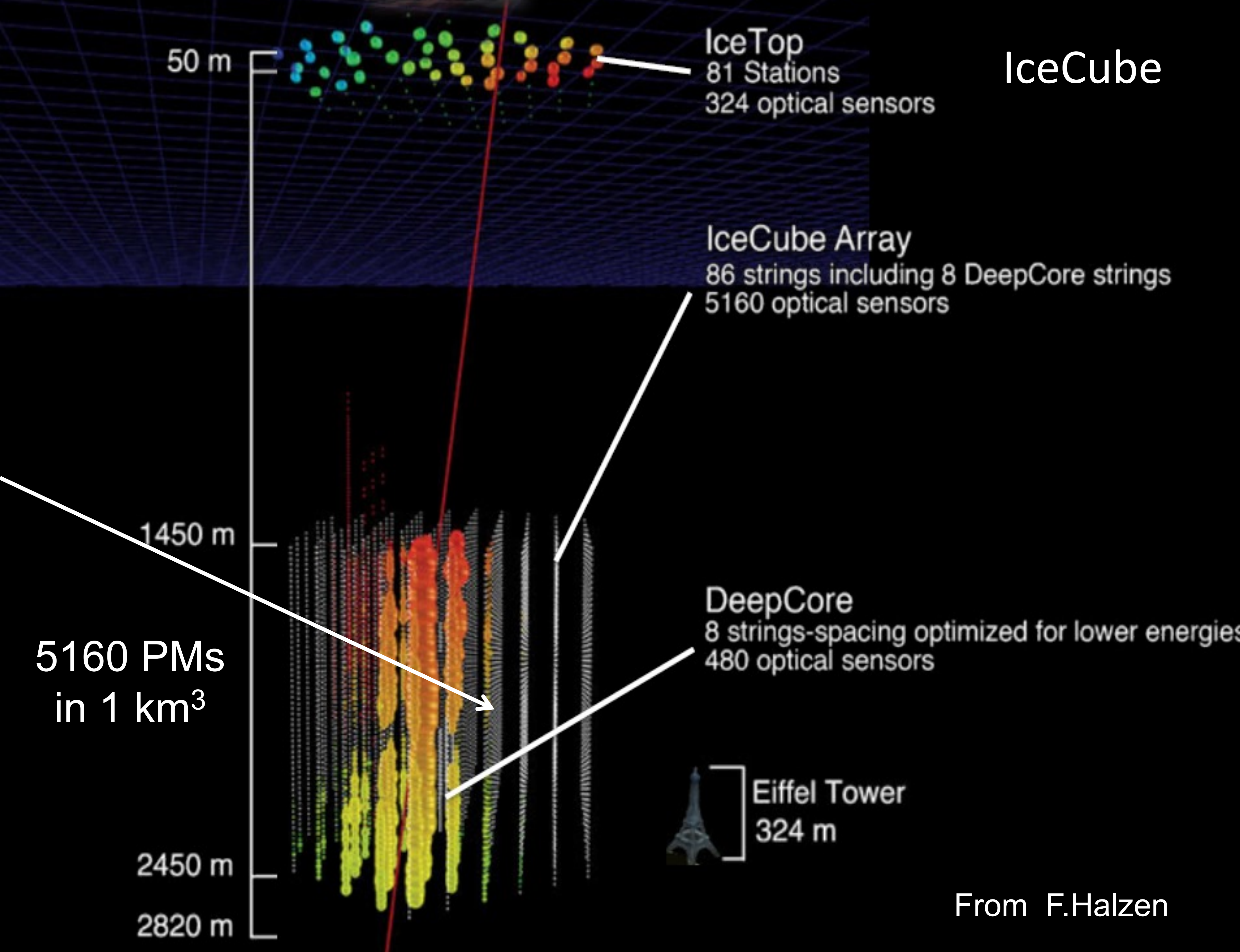
$|M|^2$ Integration over spins and angles

E_0 Energy of the final state

Detection of neutrino interactions



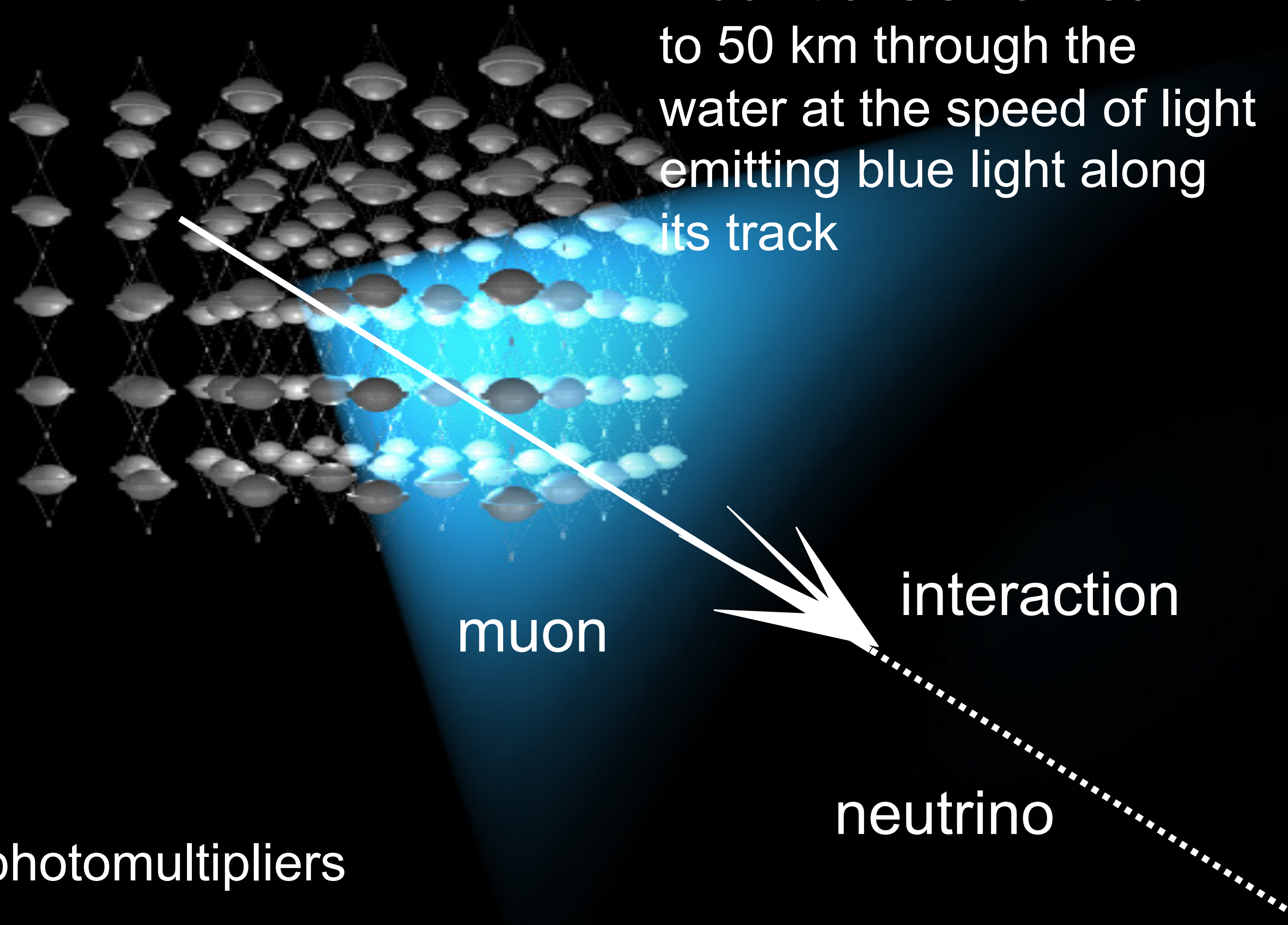
IceCube



5160 PMs
in 1 km^3

From F.Halzen

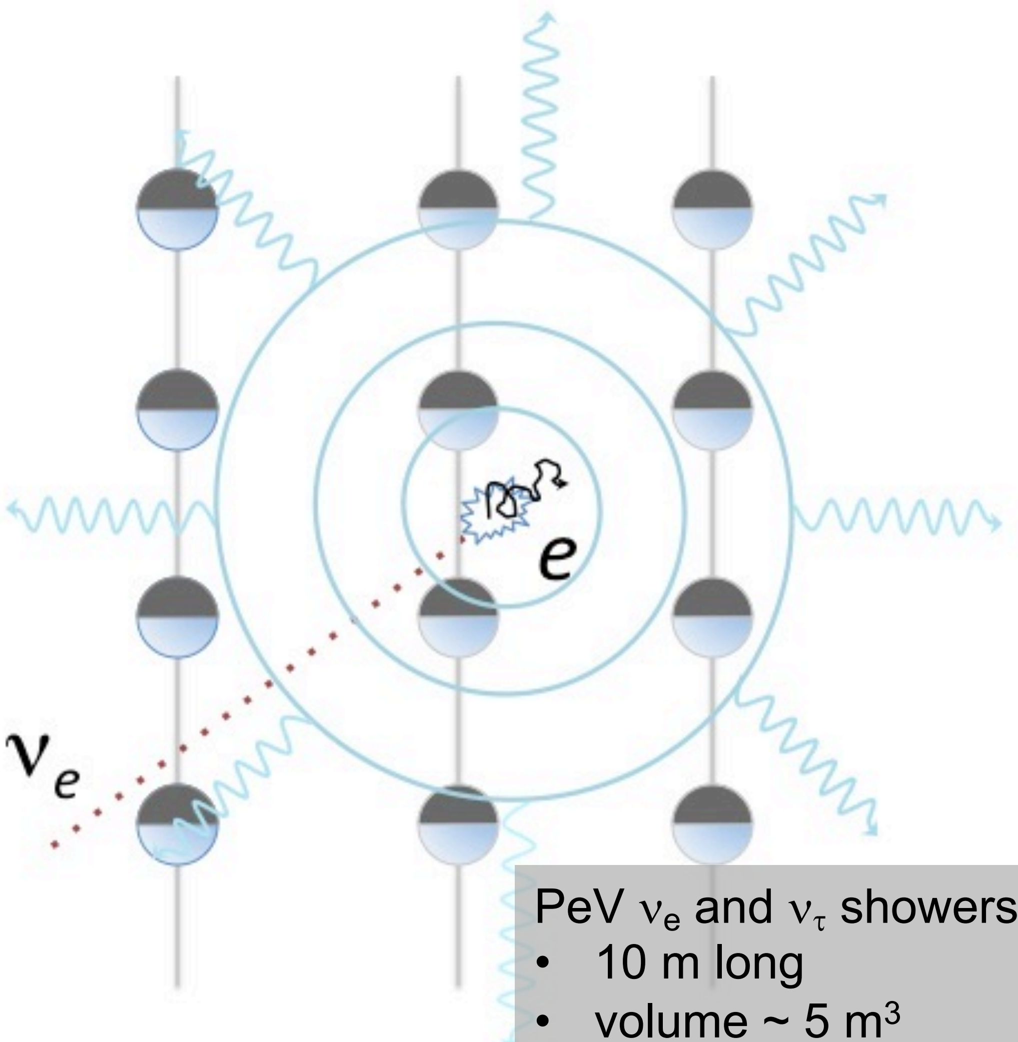
- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

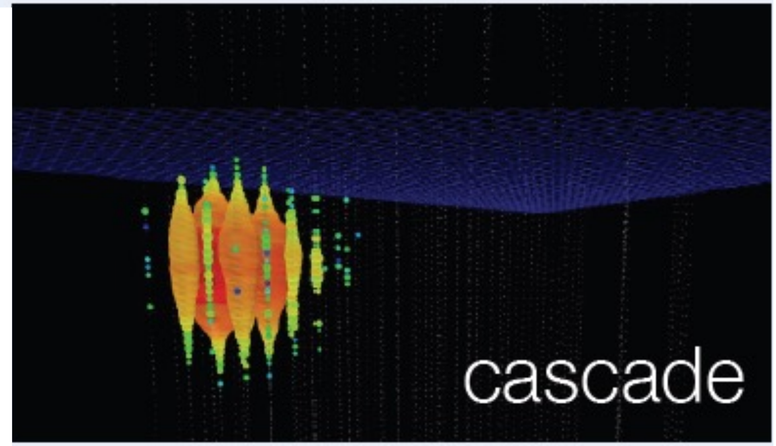


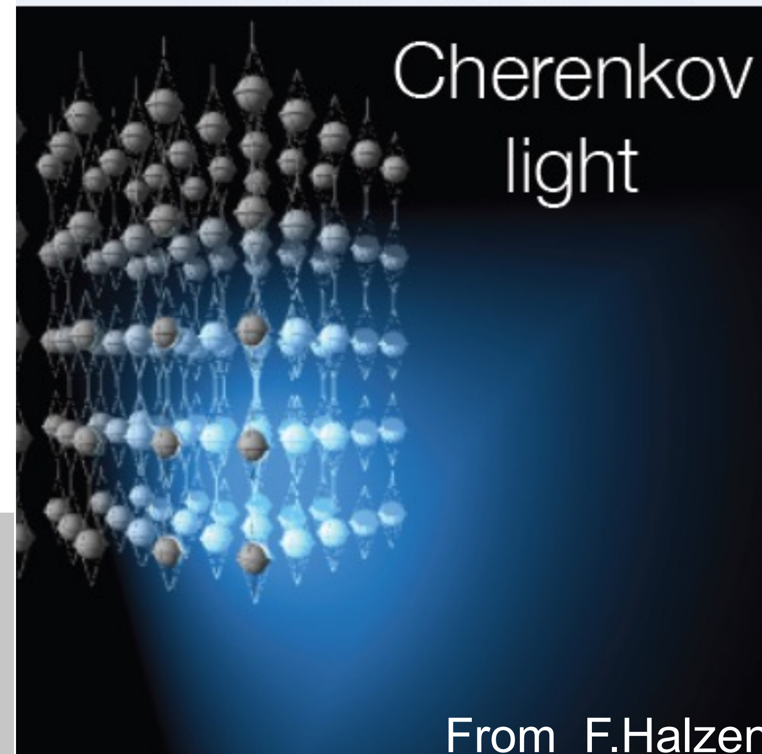
- lattice of photomultipliers

From F.Halzen

tracks and showers





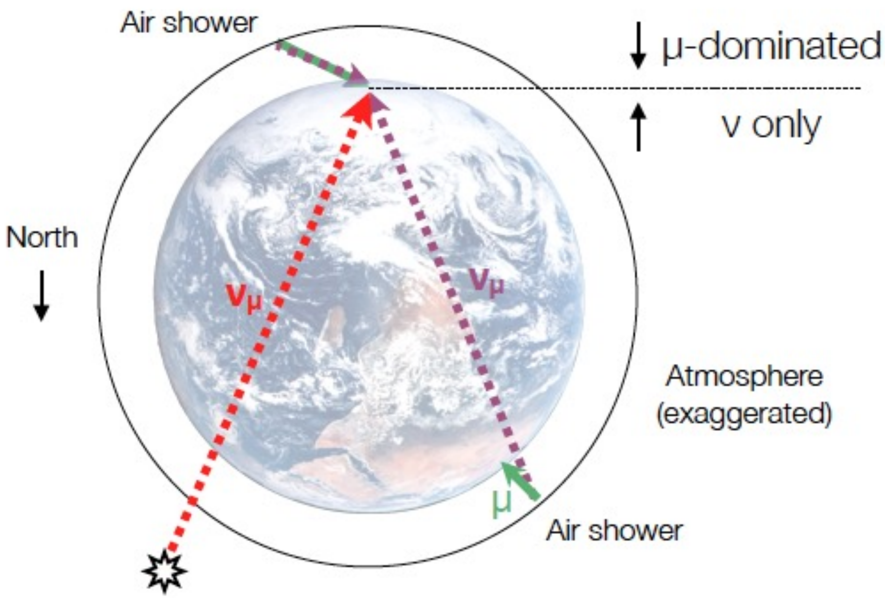


PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m

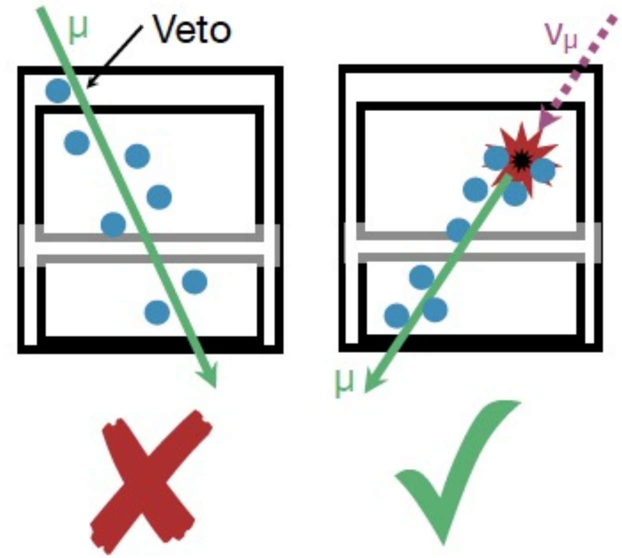
Isolating neutrino events: two strategies

Up-going tracks



- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
- Sensitive to half the sky

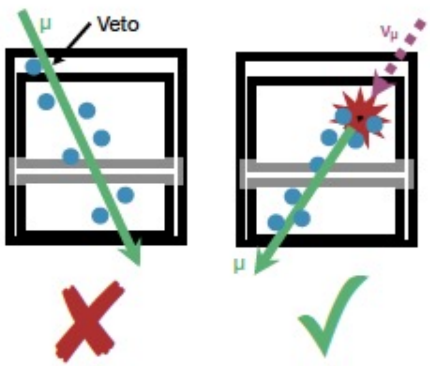
Active veto



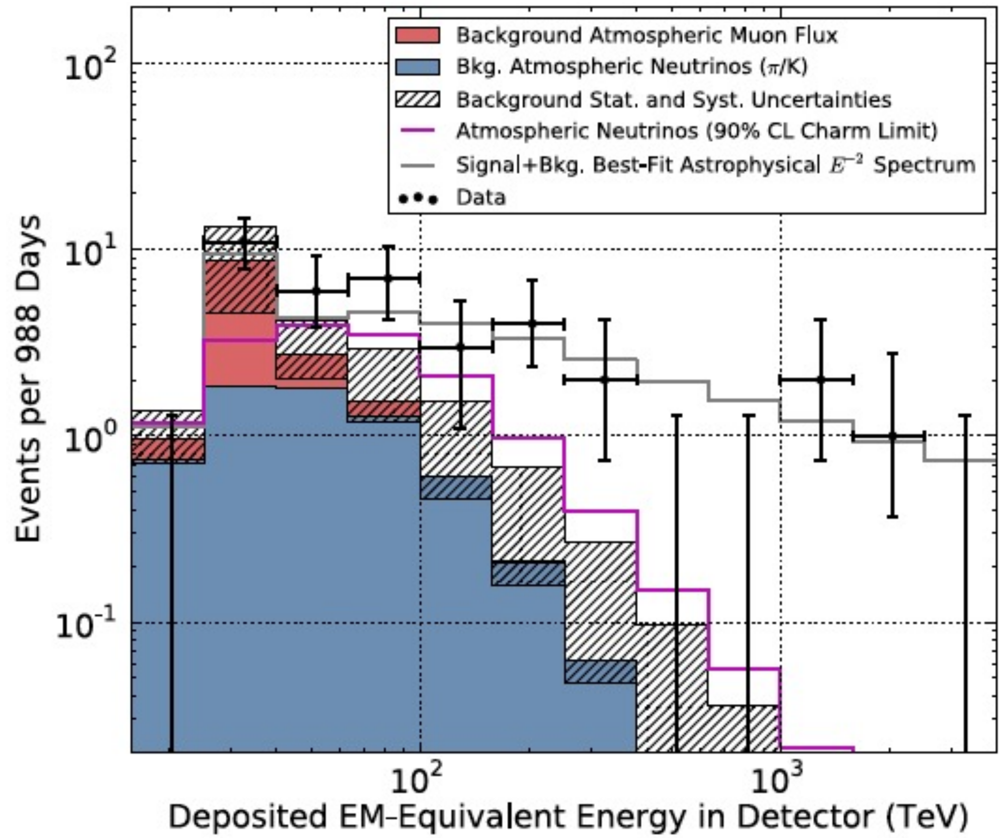
- Veto detects penetrating muons
- Effective volume smaller than detector
- Sensitive to all flavors
- Sensitive to the entire sky

Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



Deposited energy

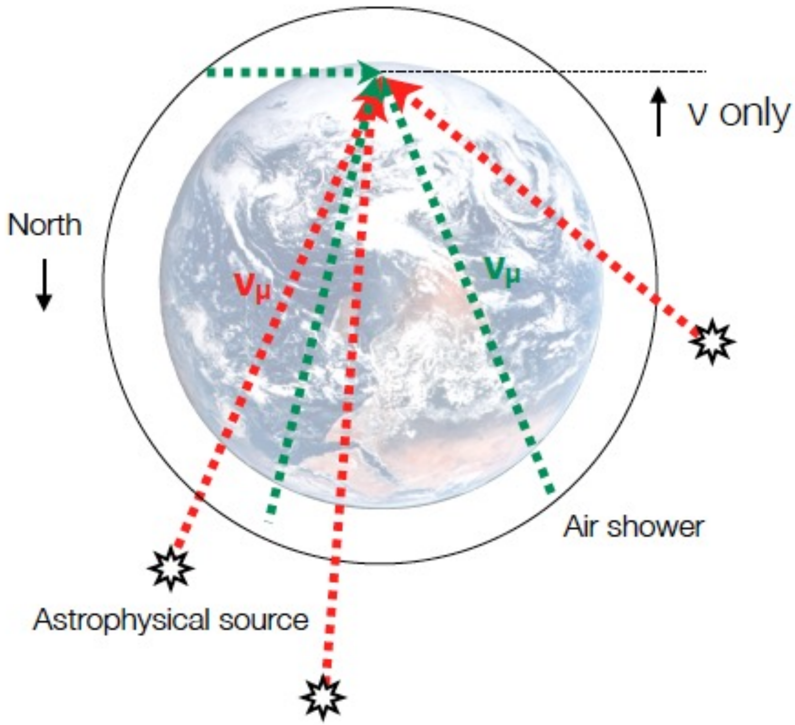


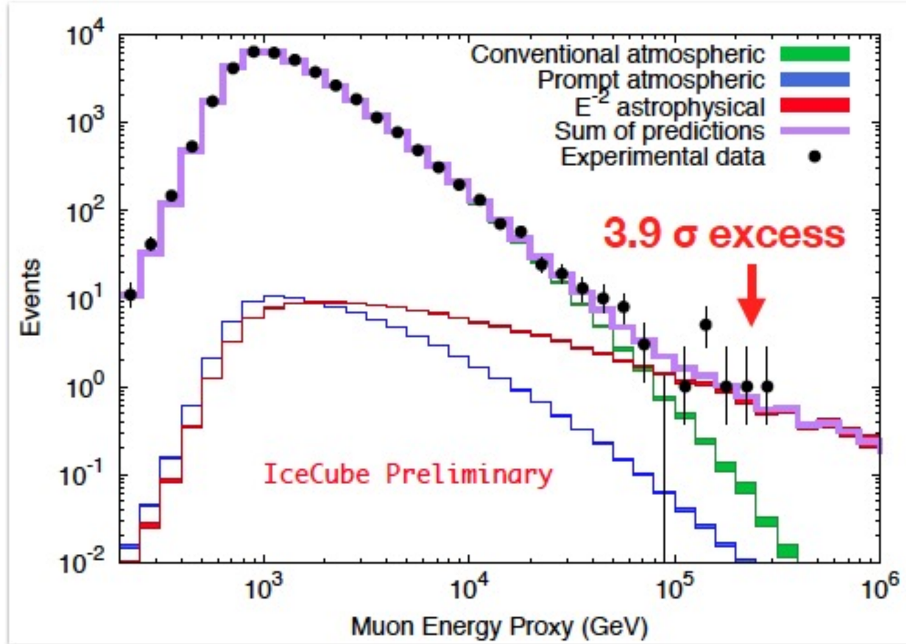
arXiv:1405.5303 (accepted for PRL)

- 3 cascades over 1 PeV in 3 years of data
- 5.7 σ evidence for astrophysical neutrinos

What about the northern sky and ν_μ?

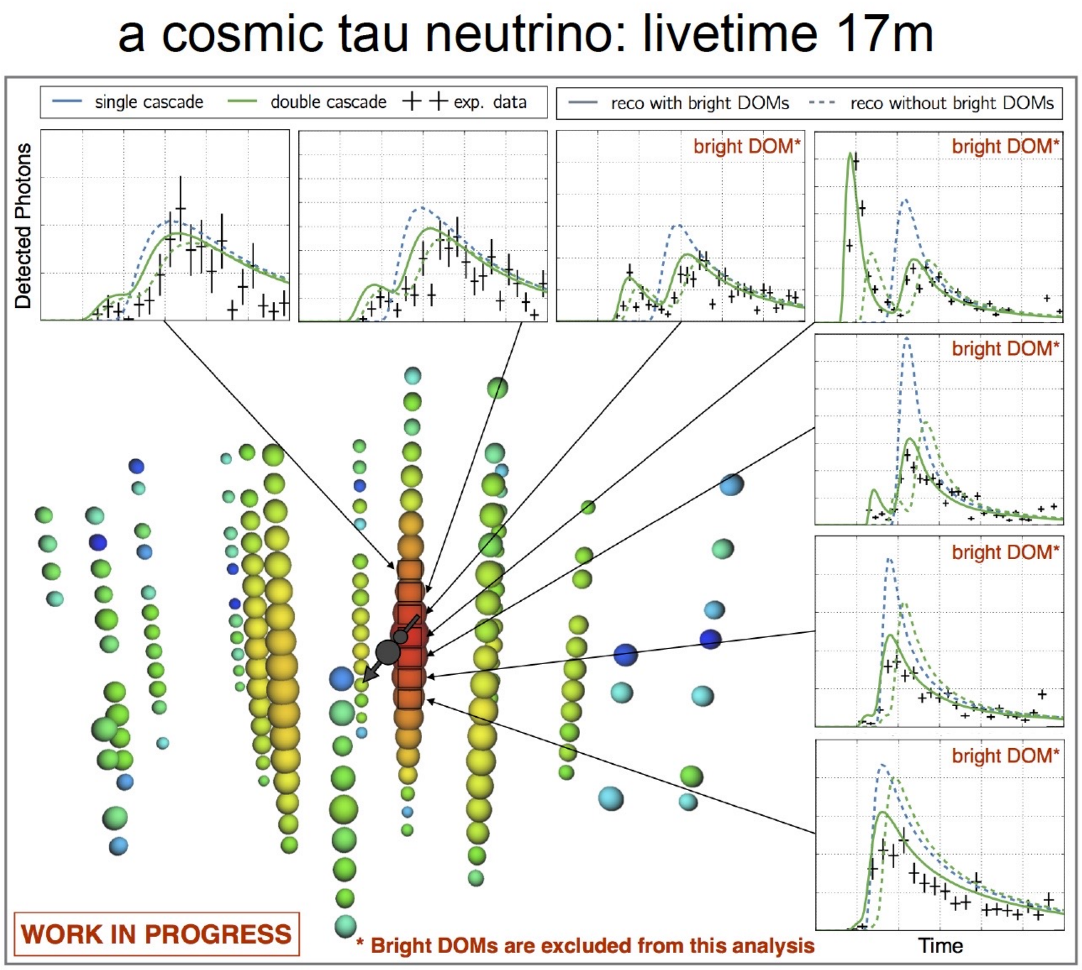
The high-energy starting event sample is dominated by cascades from the southern sky.



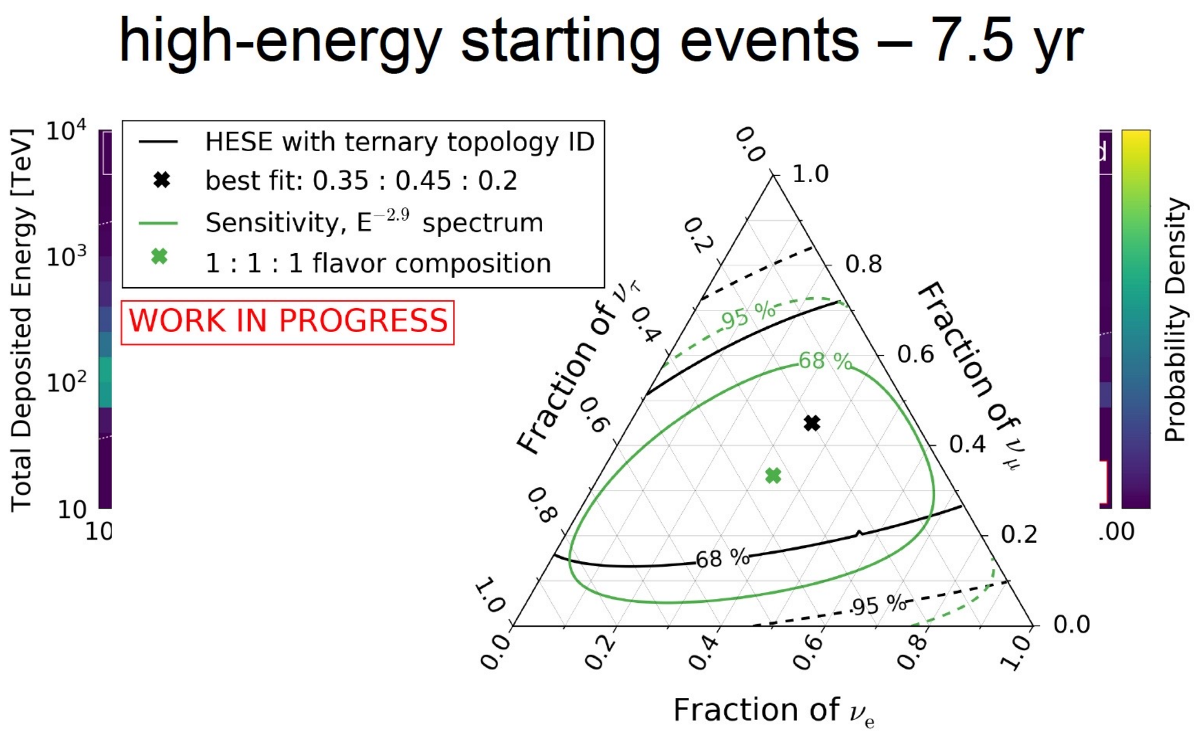


We look for the same excess in incoming muons from the northern sky
High-energy muons reach the detector from km away → large effective volume
Only sensitive to CC ν_μ → explicit handle on ν_μ flux

First tau events



Flavor content consistent with 1:1:1

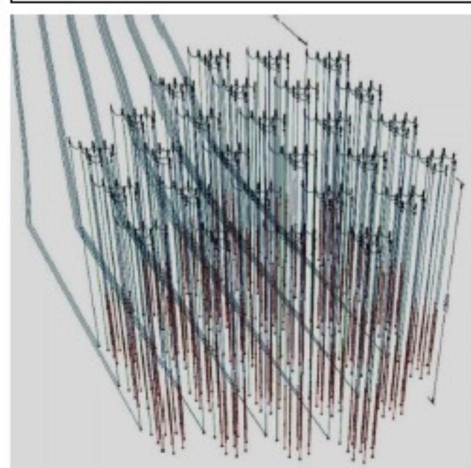


oscillations of PeV neutrinos over cosmic distances to 1:1:1

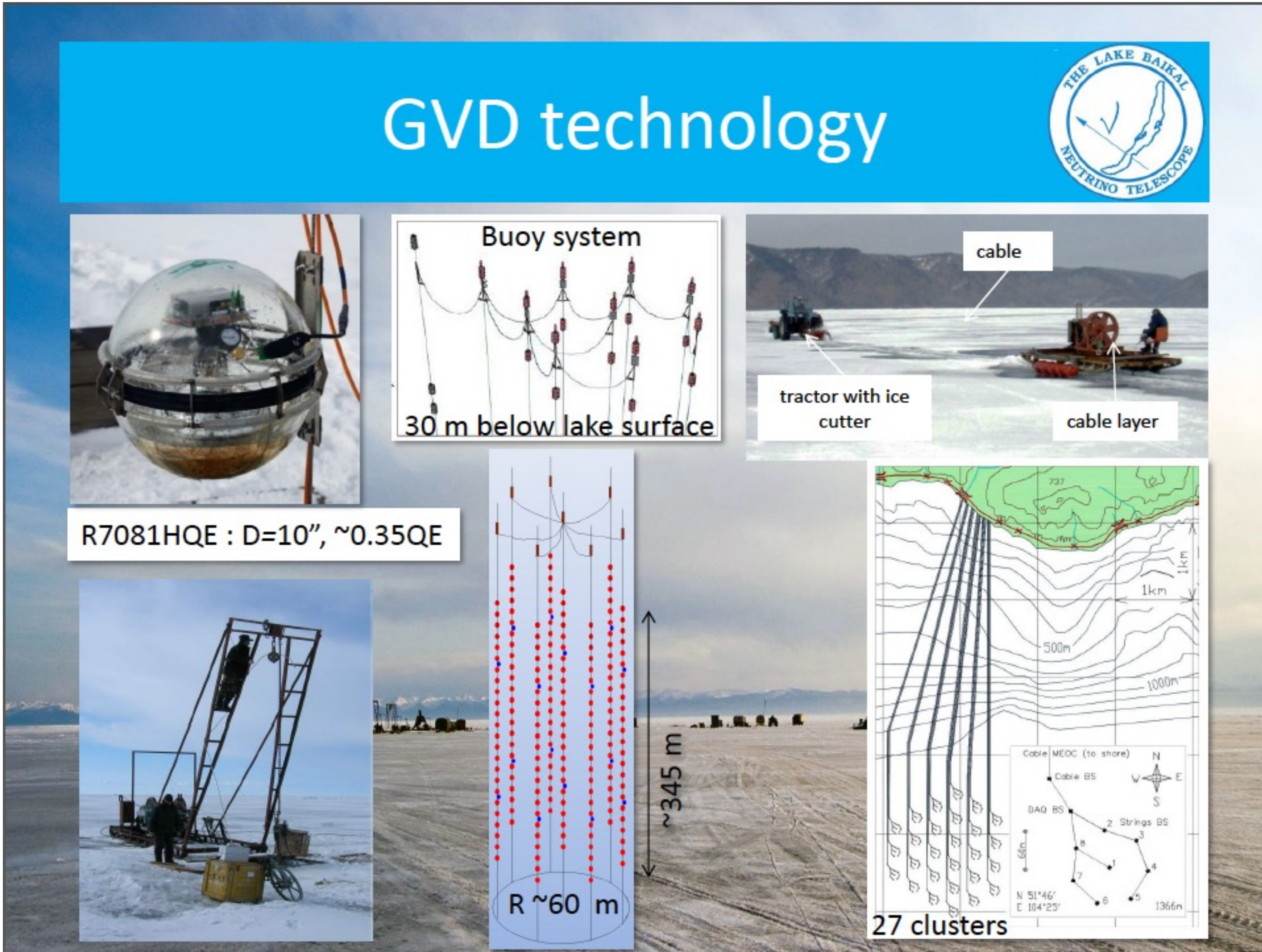
North detectors

Baikal-GVD

Environmental parameters	Telescope design
Lake Baikal - fresh water	~1.5 km3
distance to shore ~6 km →	27 shore-cables for 27 clusters
L_{abs} ~22-25 m	27*8=216 strings
L_{scat} ~30-50m	216*48=10368 OMs ¶
depth ~1360 m	deployment from icefloor
icefloor during winter →	*shallow water* DAQ infrastructure

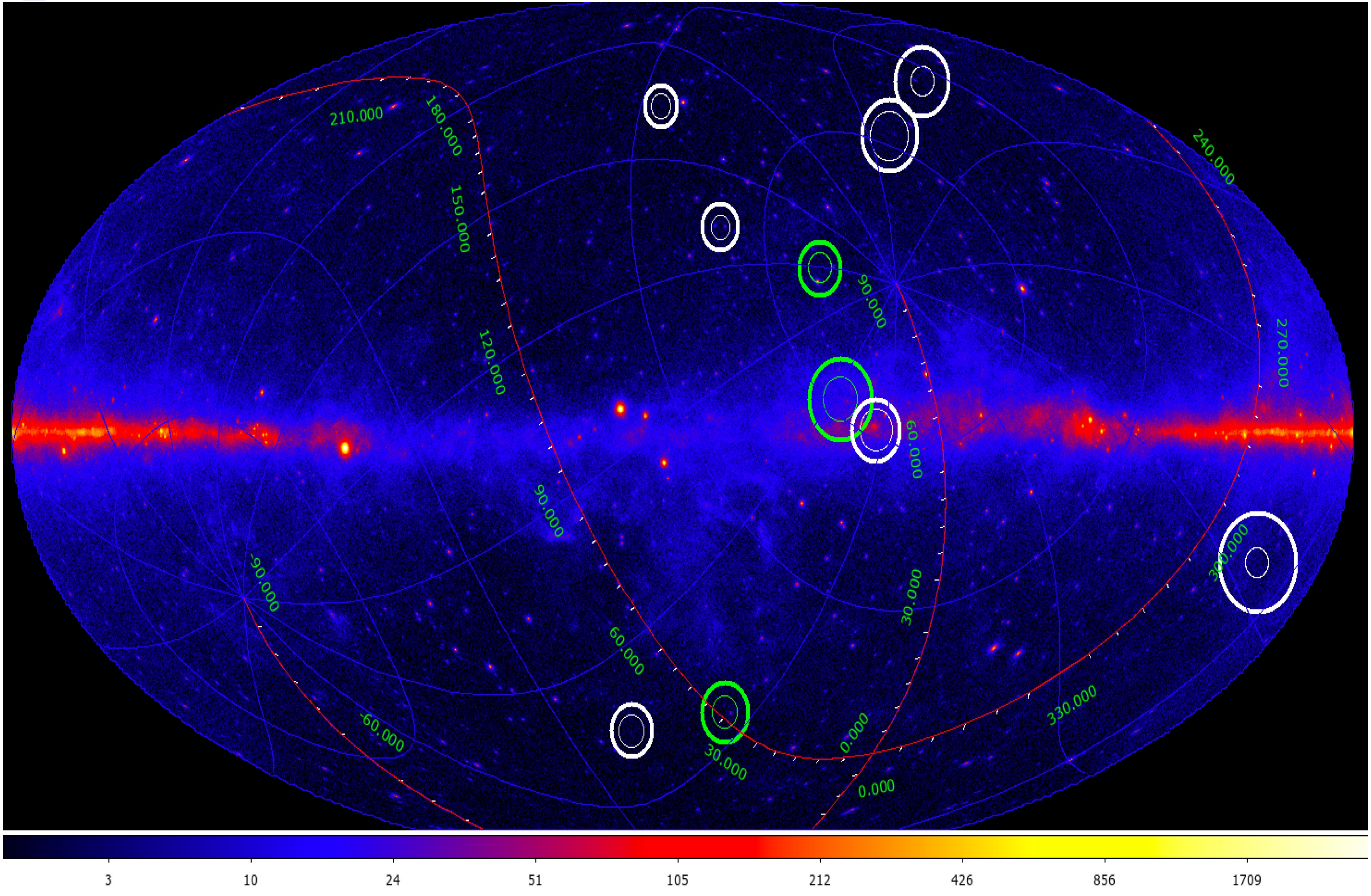


¶ OM – Optical Module


GVD technology
THE LAKE BAIKAL NEUTRINO TELESCOPE
Buoy system
30 m below lake surface
cable
tractor with ice cutter
cable layer
R7081HQE : D=10", ~0.35QE
~345 m
R ~60 m
1km
500m
1000m
Cable MEOC (to shore)
Cable BS
DAQ BS
Strings BS
N
W
E
S
N 51°46'
E 104°25'
27 clusters

Sky map with 10 events

Preliminary!

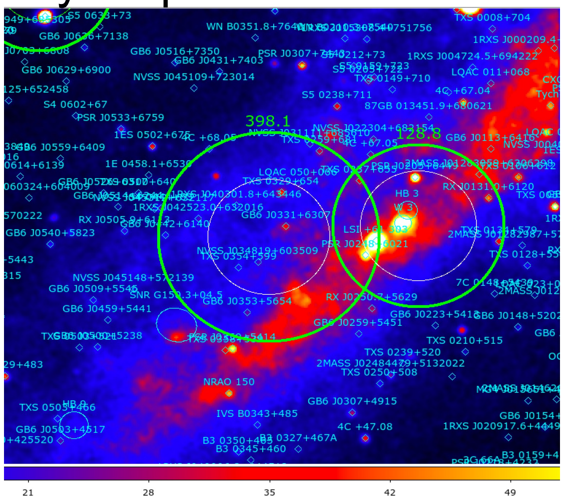


A. NERONOV talk

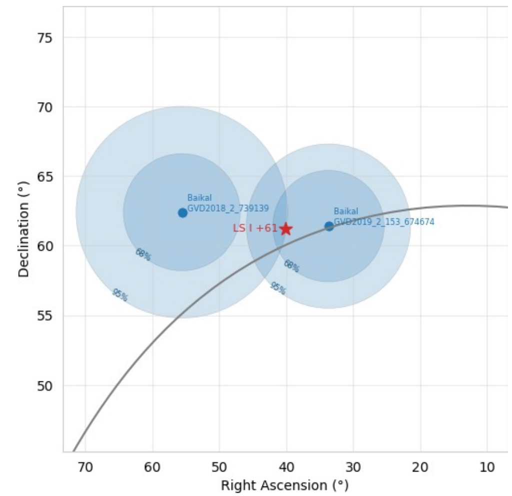
Preliminary!

Two close events at distance 10.3°: GVD_2018_656_N & GVD_2019_153_N

Sky map of Fermi sources



LSI +61 303 and two events



LSI +61 303 – at 3.1° and 7.4° from GVD_2019_153_N and GVD_2018_656_N

LSI +61 303 – microquasar, 26.5 day orbiting period of massive object

Using PSFs of all 10 events chance probability to observe such configuration was estimated:

p-value = 0.007

KM3NeT in the Mediterranean

Environmental parameters

Mediterranean Sea – salt water

3 installation sites

distance to shore ~40-100 km

L_{abs} ~60-100 m

L_{scat} ~50-70m

depths ~2500-4500 m

Telescope design

~3.5-6 km^3 (depending on spacing)

6 shore-cables for 6 building blocks

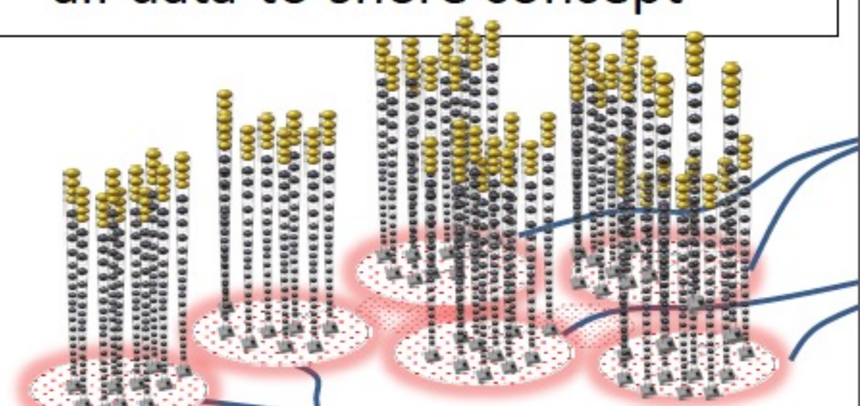
6 x 115 = 690 detection units

690 x 18 =12420 OMs

seabed data transmission infrastructure

installation requires ship + ROV

all-data-to-shore concept

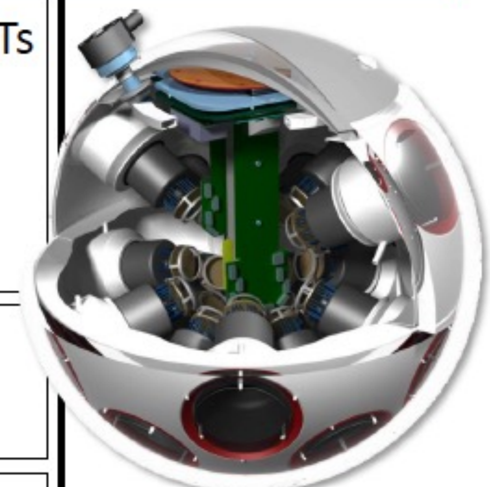


KM3NeT Optical Module

Segmented cathode area: 31 x 3” PMTs
Light concentrator ring
Cathode area: ~ 3 x 10-inch PMT
Custom low-power HV bases

LED & piezo inside
Compass and tiltmeter inside

PMT ToT measurements
FPGA readout, optical line terminator

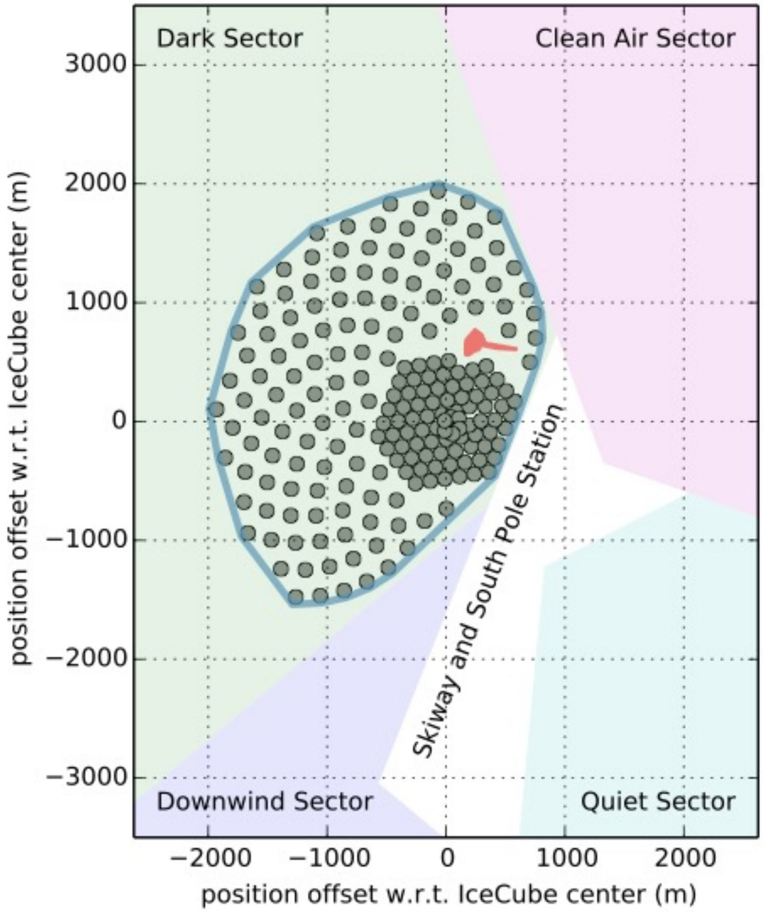


ETEL D792

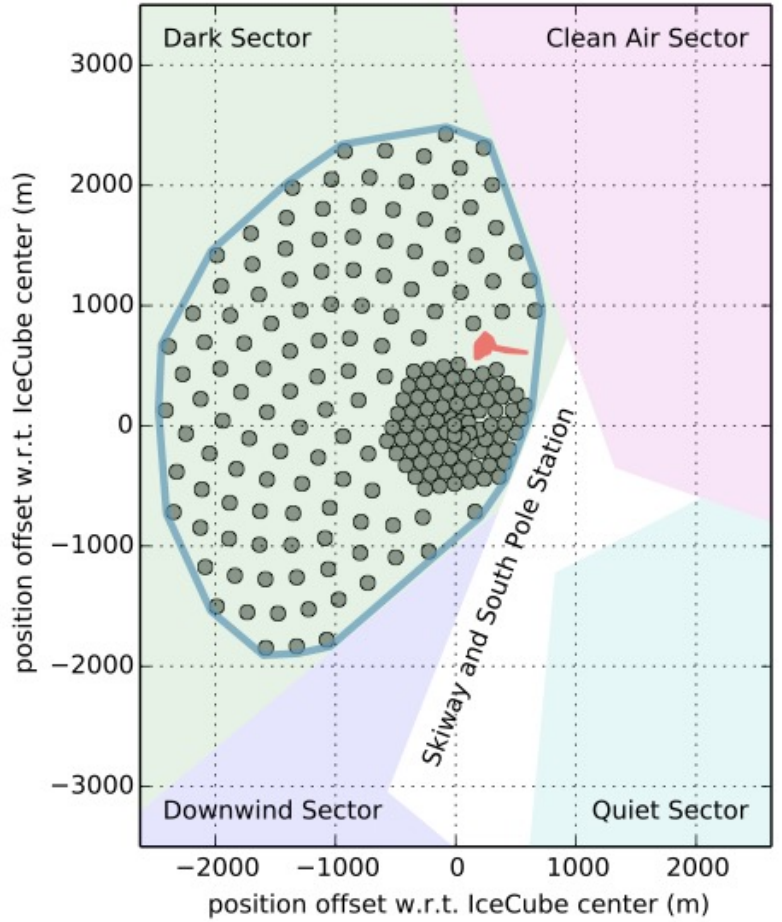
Hamamatsu R12199

HZC XP53B20

86 strings with 240-340 m spacing

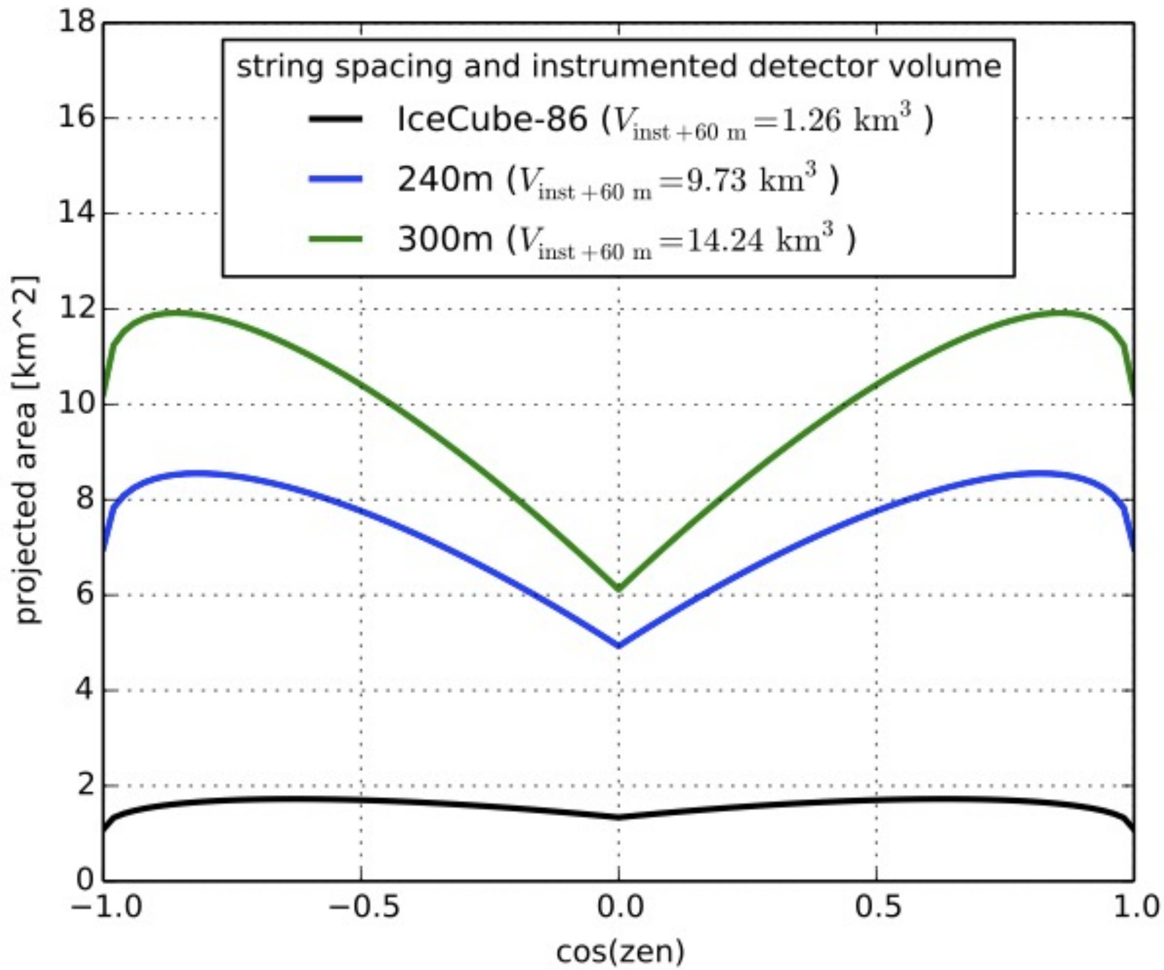


(a) 240 m string spacing (“benchmark”)



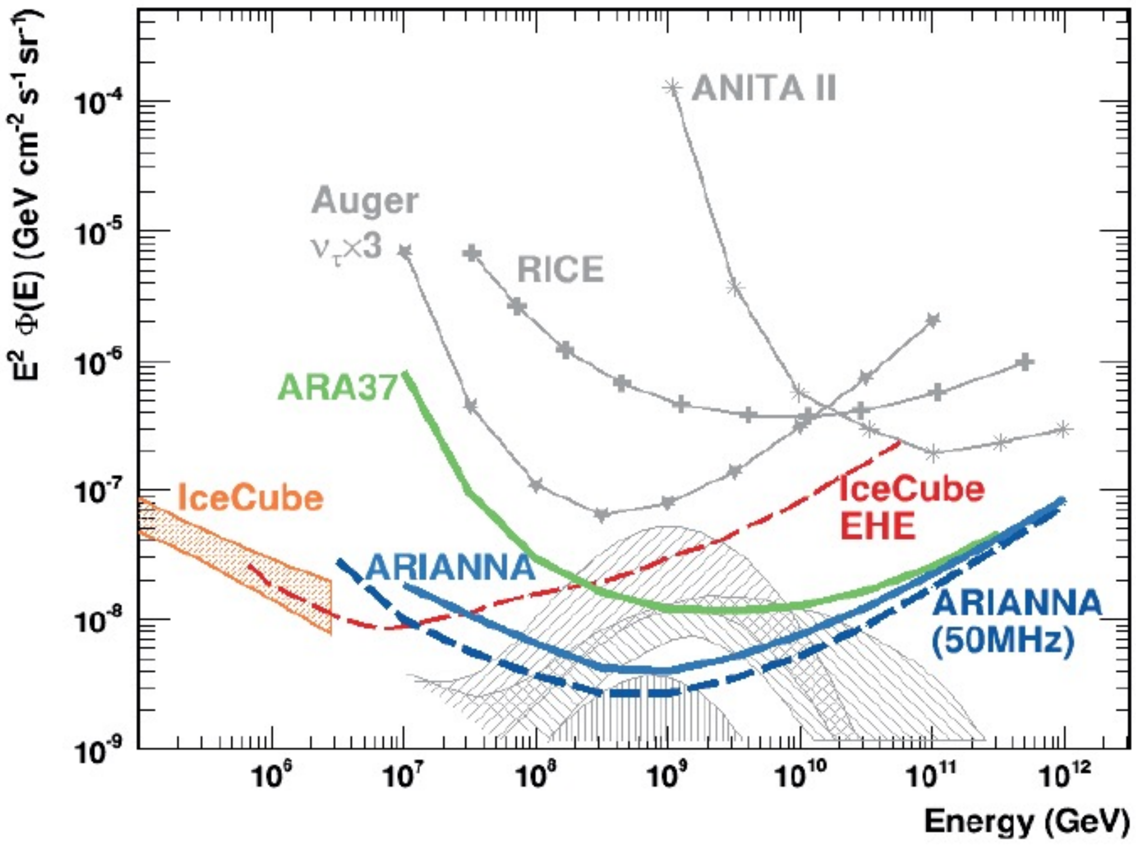
(b) 300 m string spacing

Effective volume



IceCube Collaboration, **arXiv:1412.5106**

Future radio detection

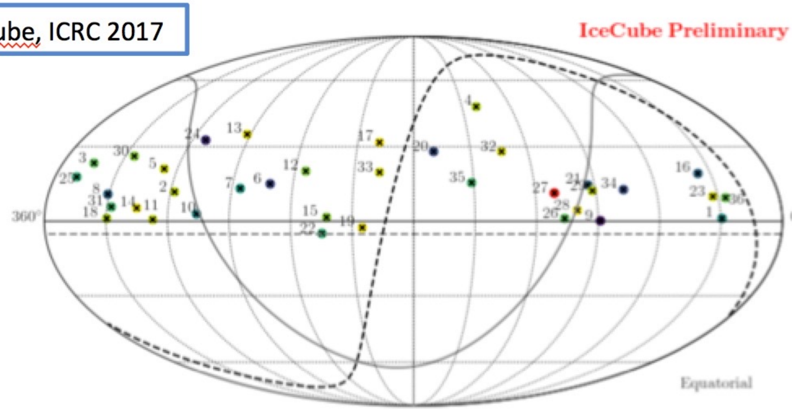


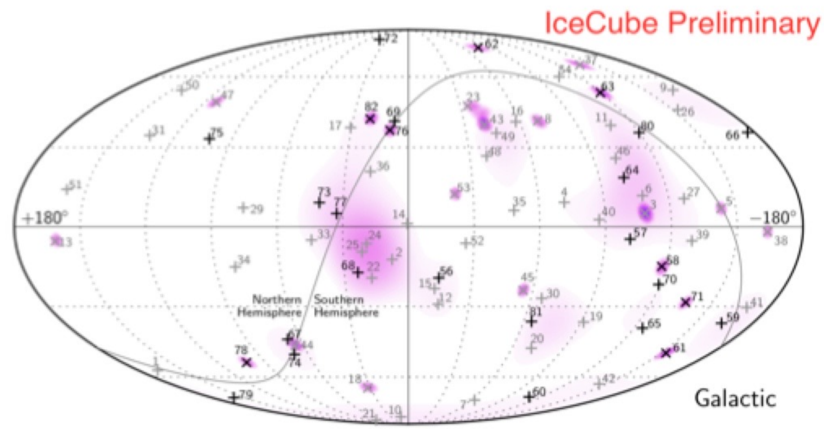
Astrophysical neutrinos: 6 years observations

IceCube ICRC 2017

Astrophysical neutrino signal

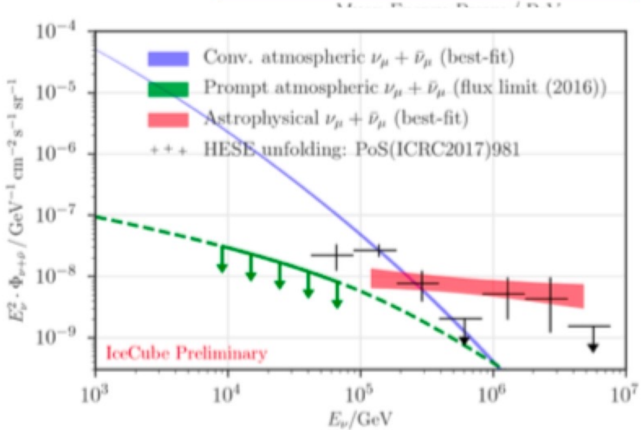
IceCube, ICRC 2017

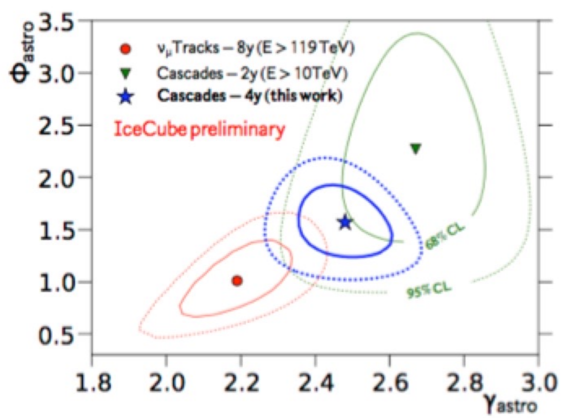


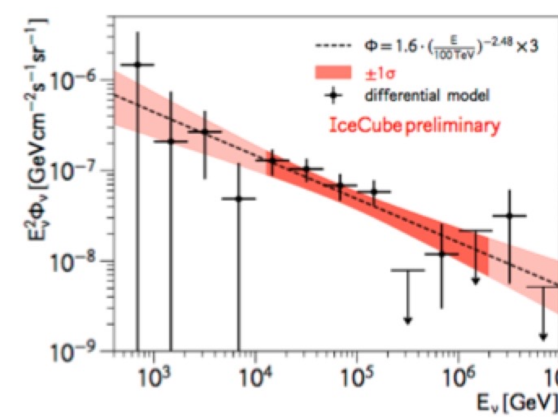


Muon neutrino sample

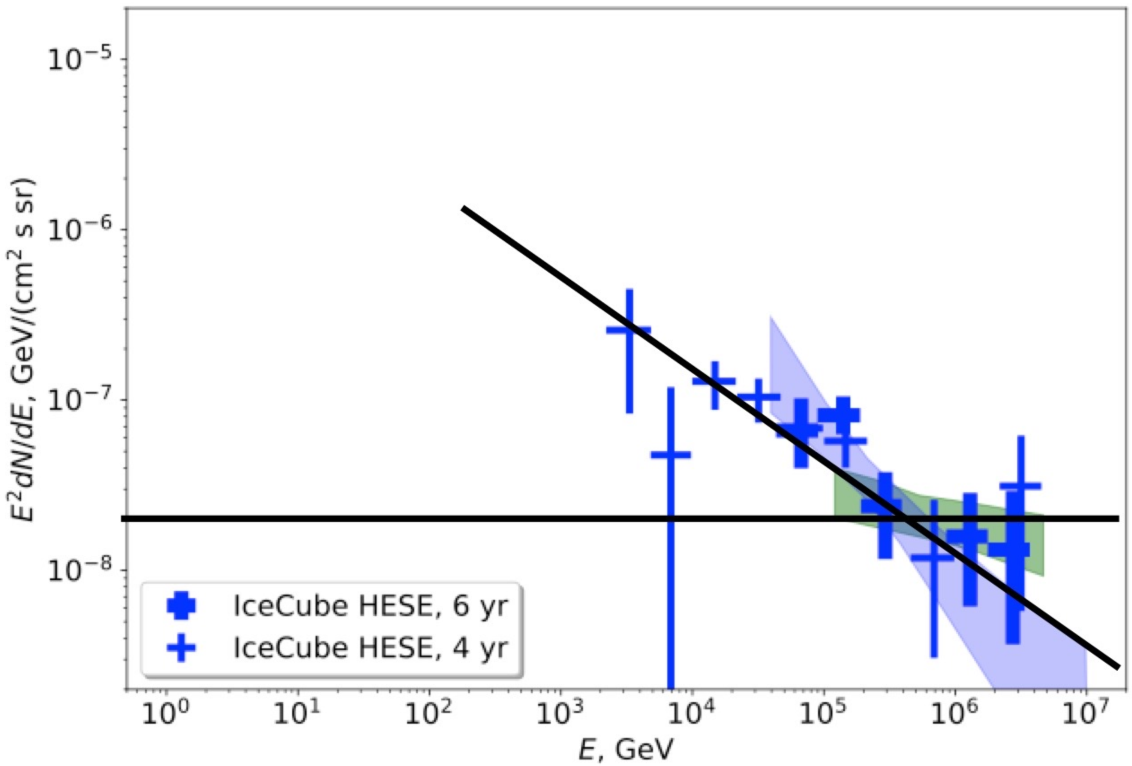
High Energy Starting Event neutrino sample



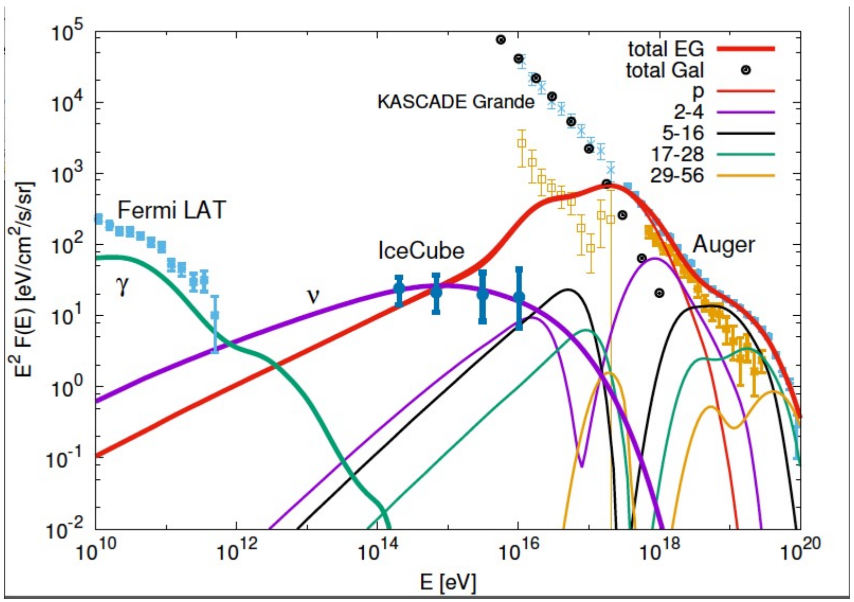


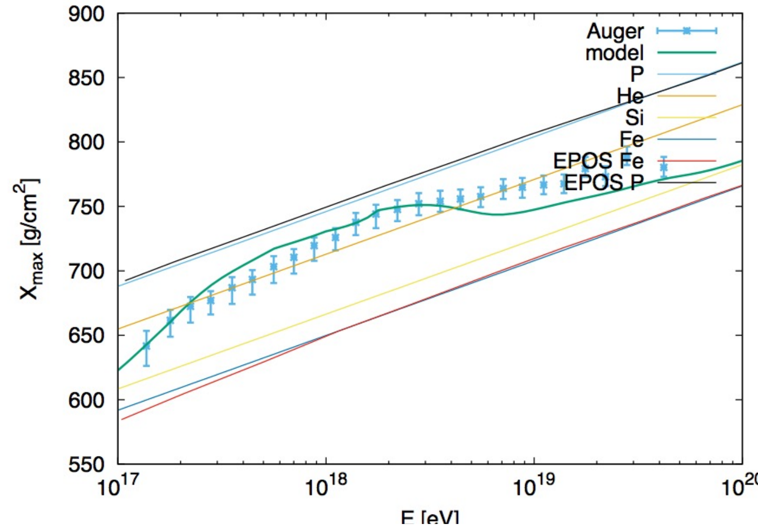


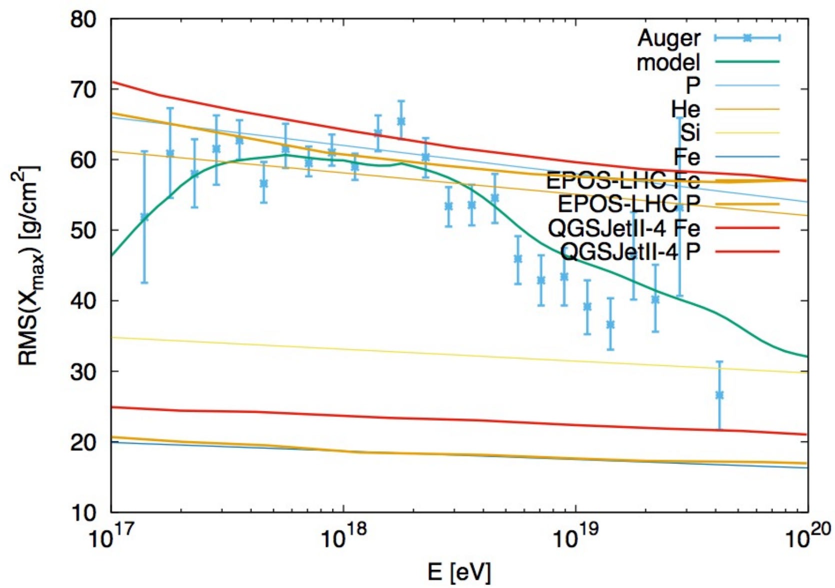
IceCube data



AGN's: P-gamma + Proton-proton interactions in the source region

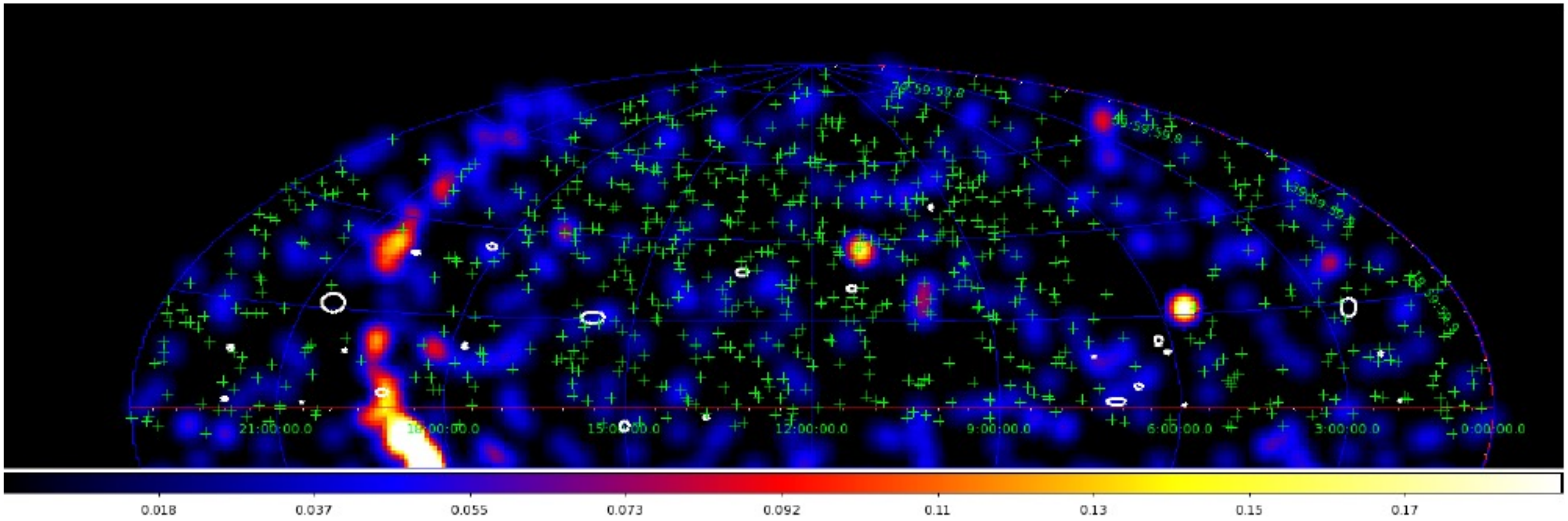






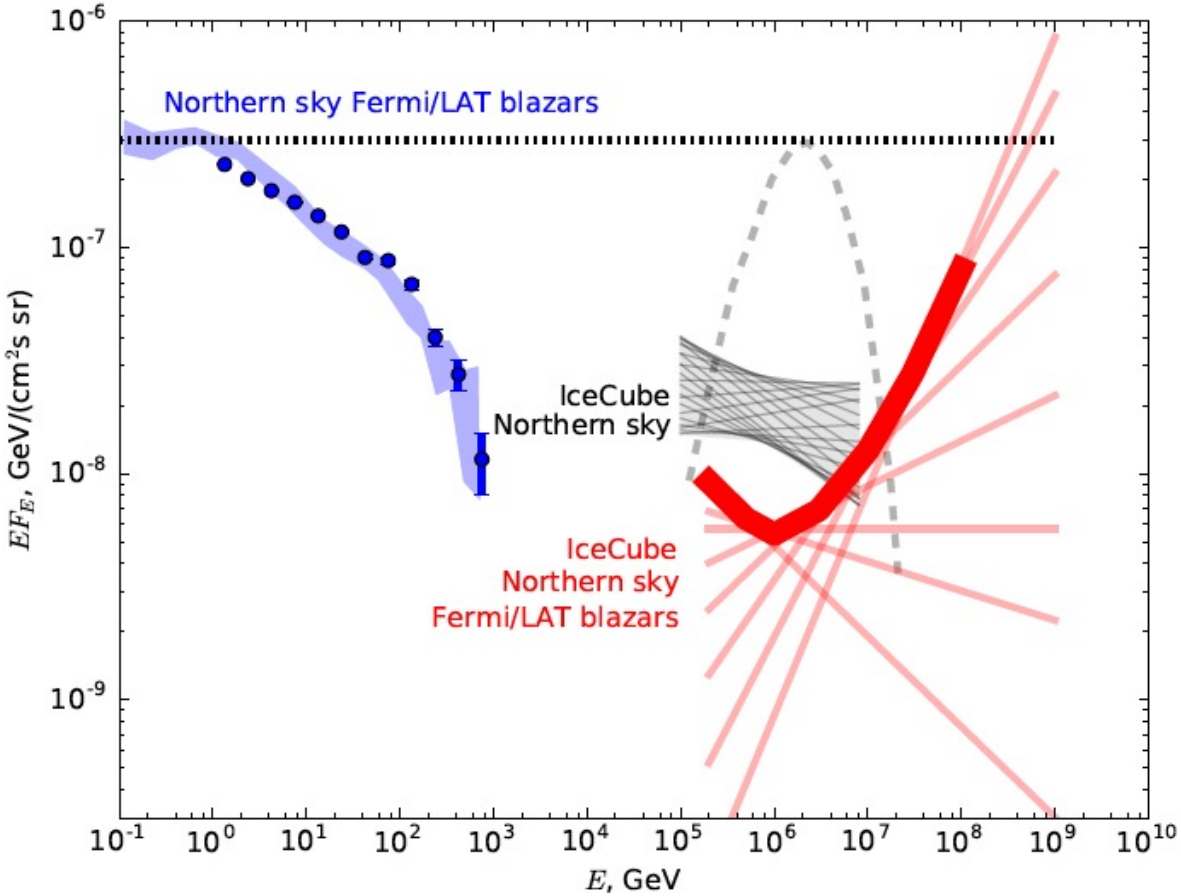
Kachelriess et al,   1704.06893

Fermi blazars and IceCube neutrinos



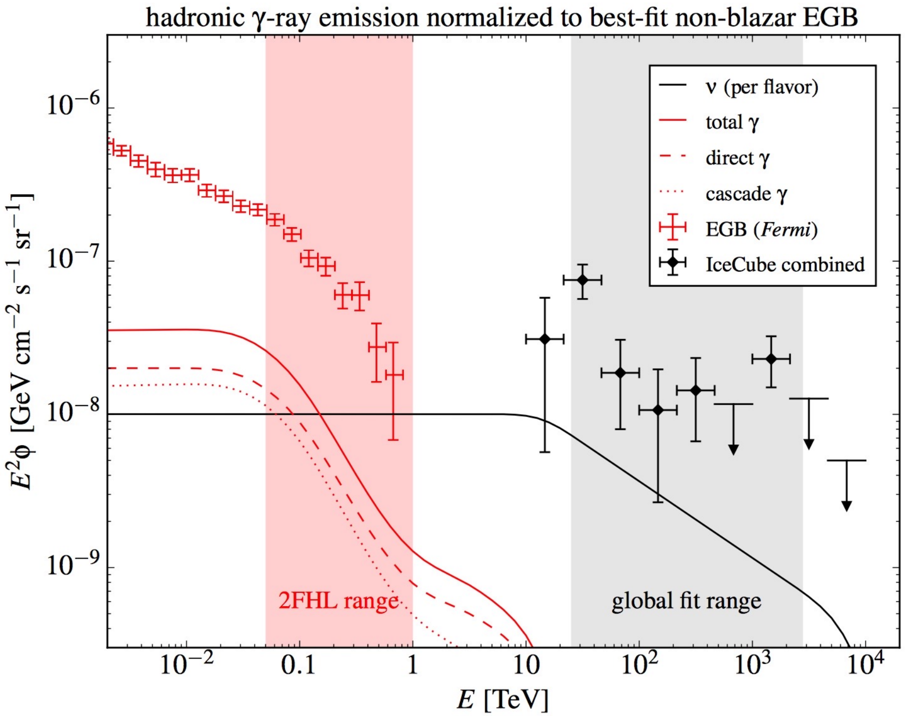
A.Neronov, K.Ptitsyna and D.S, arXiv:1611.06338

Neutrinos not from Fermi blazars



IceCube arXiv:1611.03874

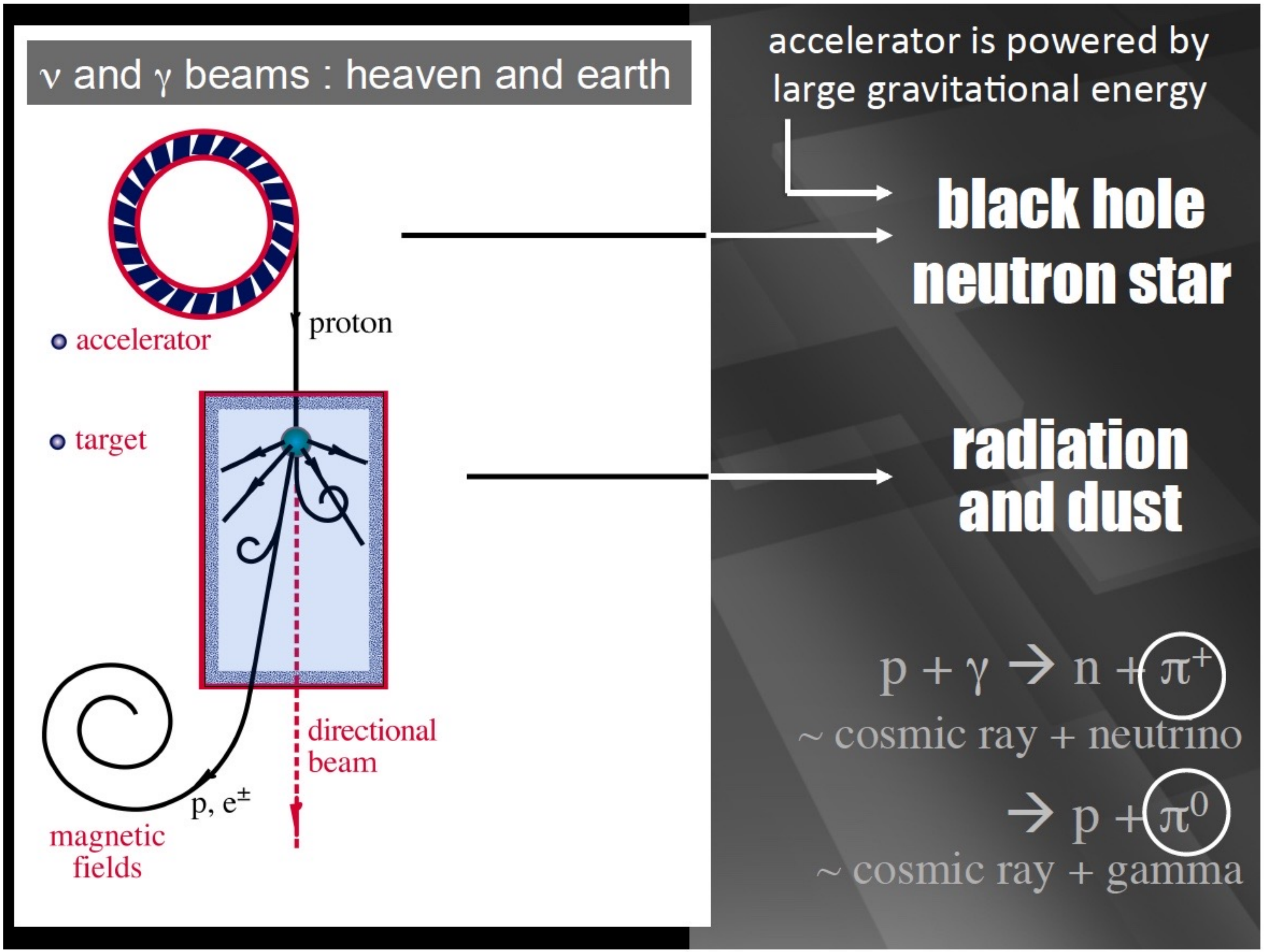
Self-consistent extragalactic sources: no blazars



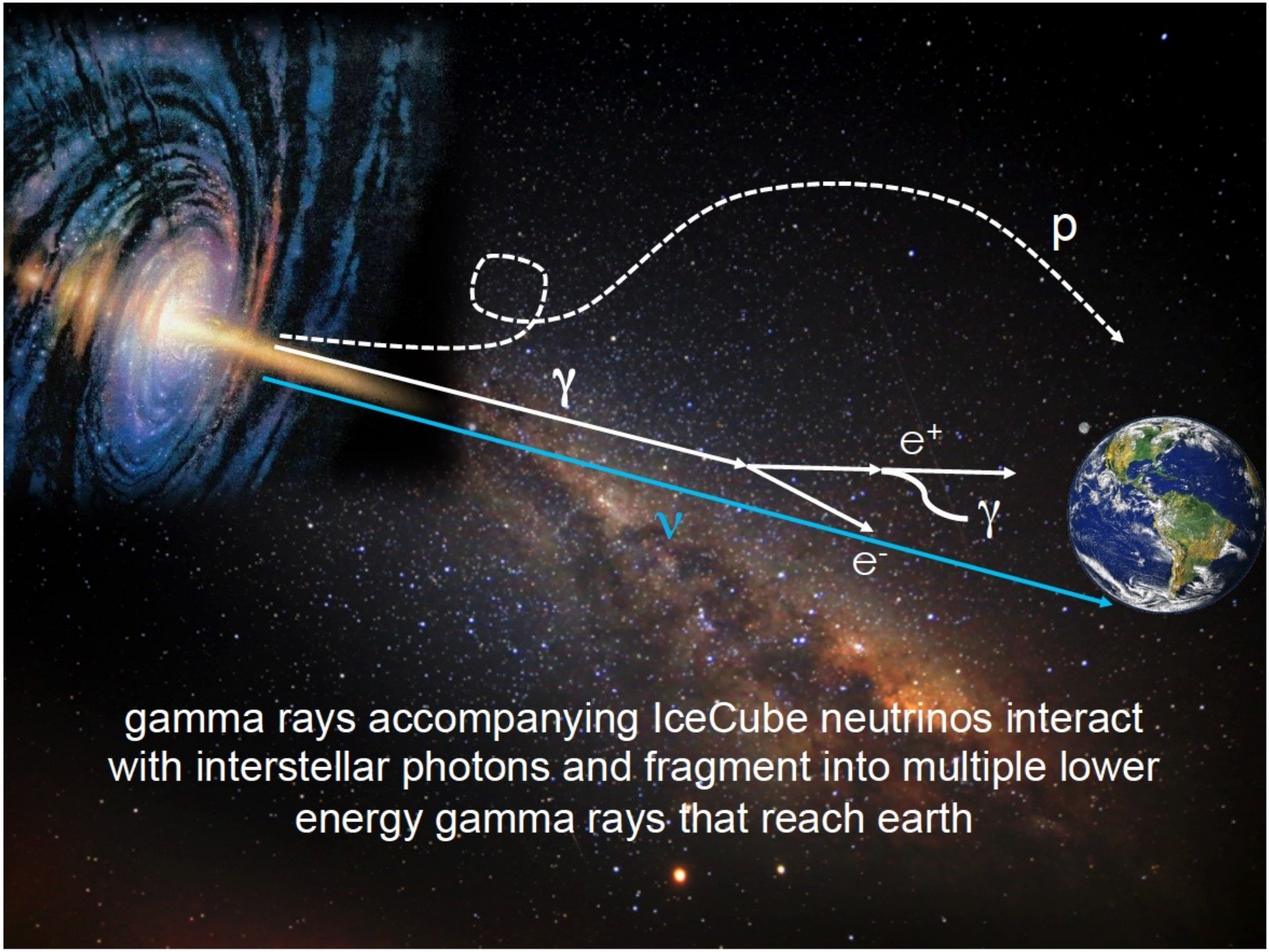
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Evidence for the first source

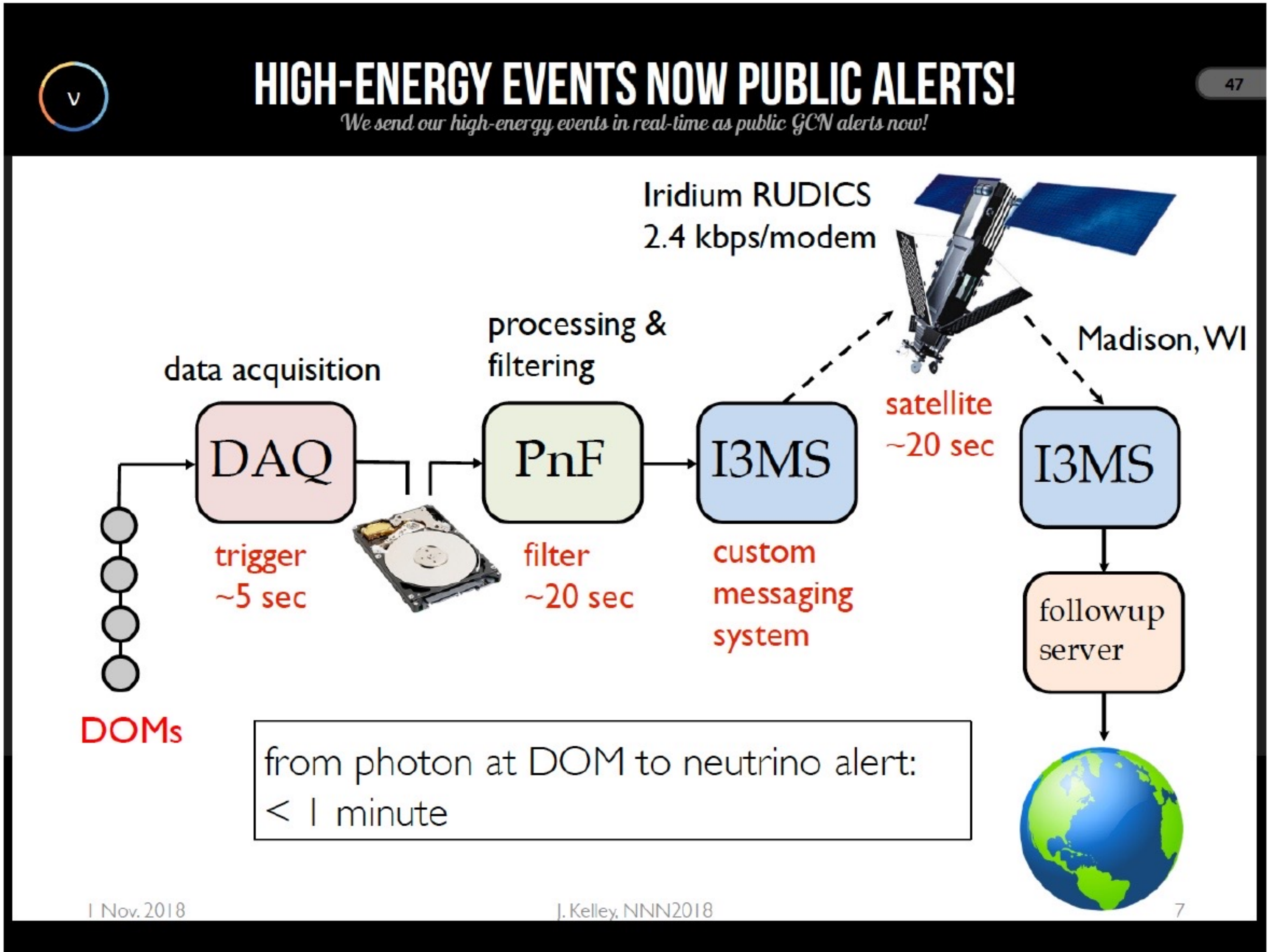
Gamma and neutrinos production



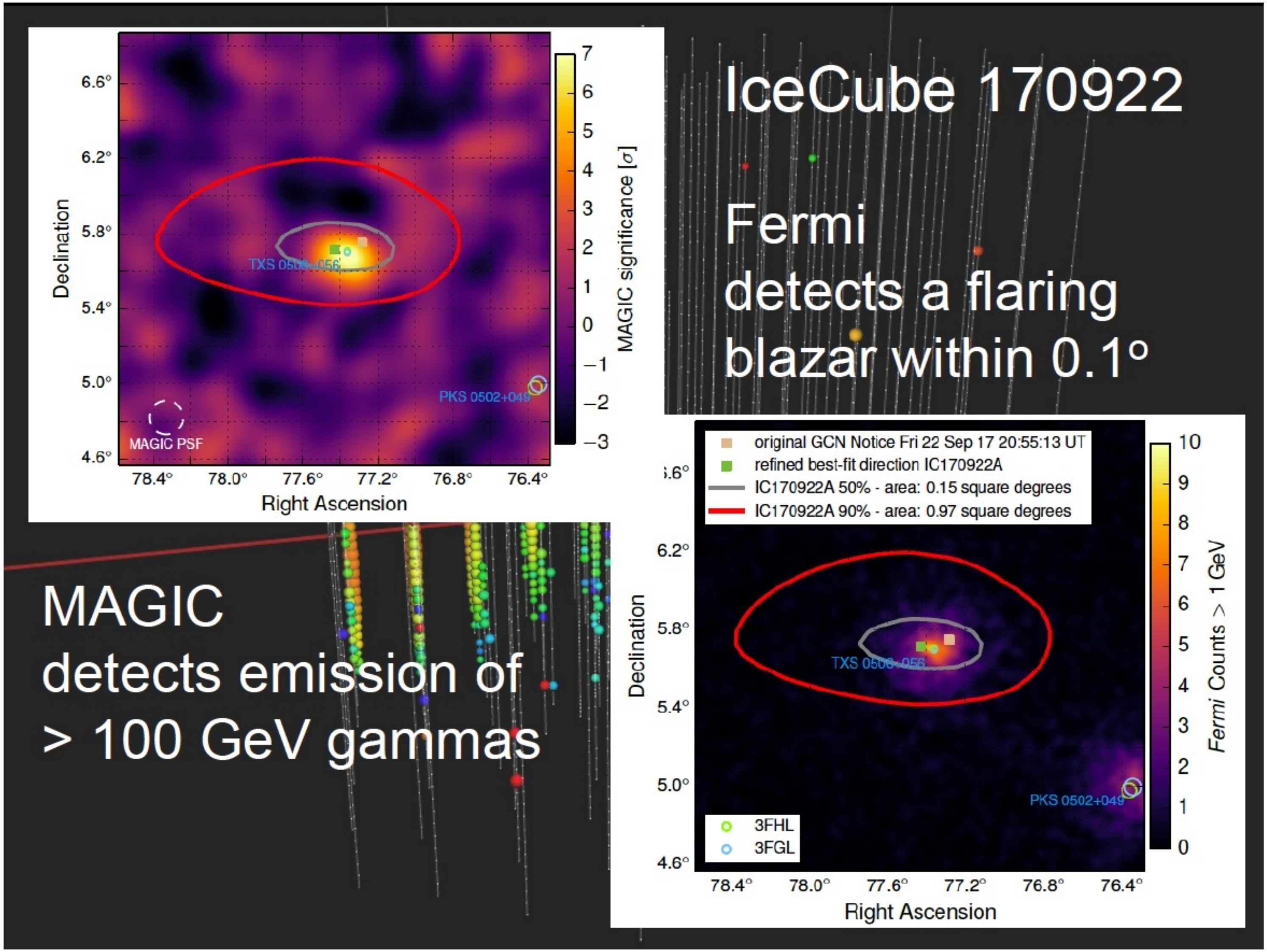
Gamma and neutrinos from source



Neutrino alert



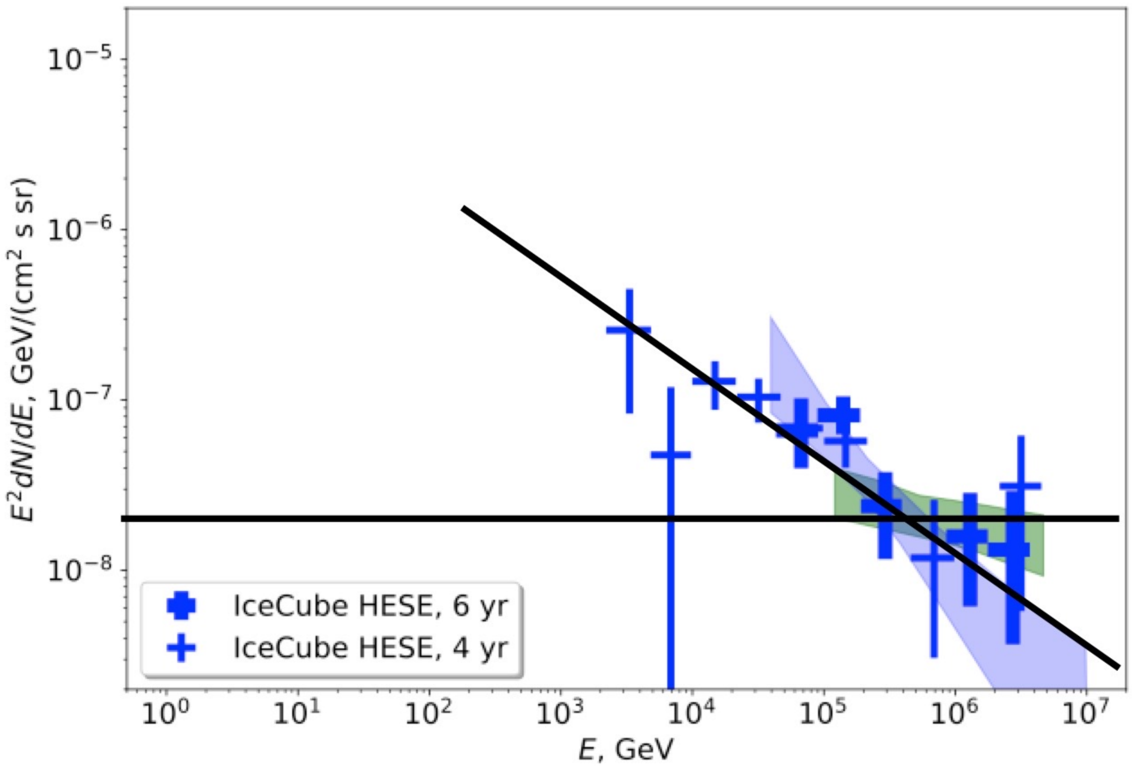
First neutrino source



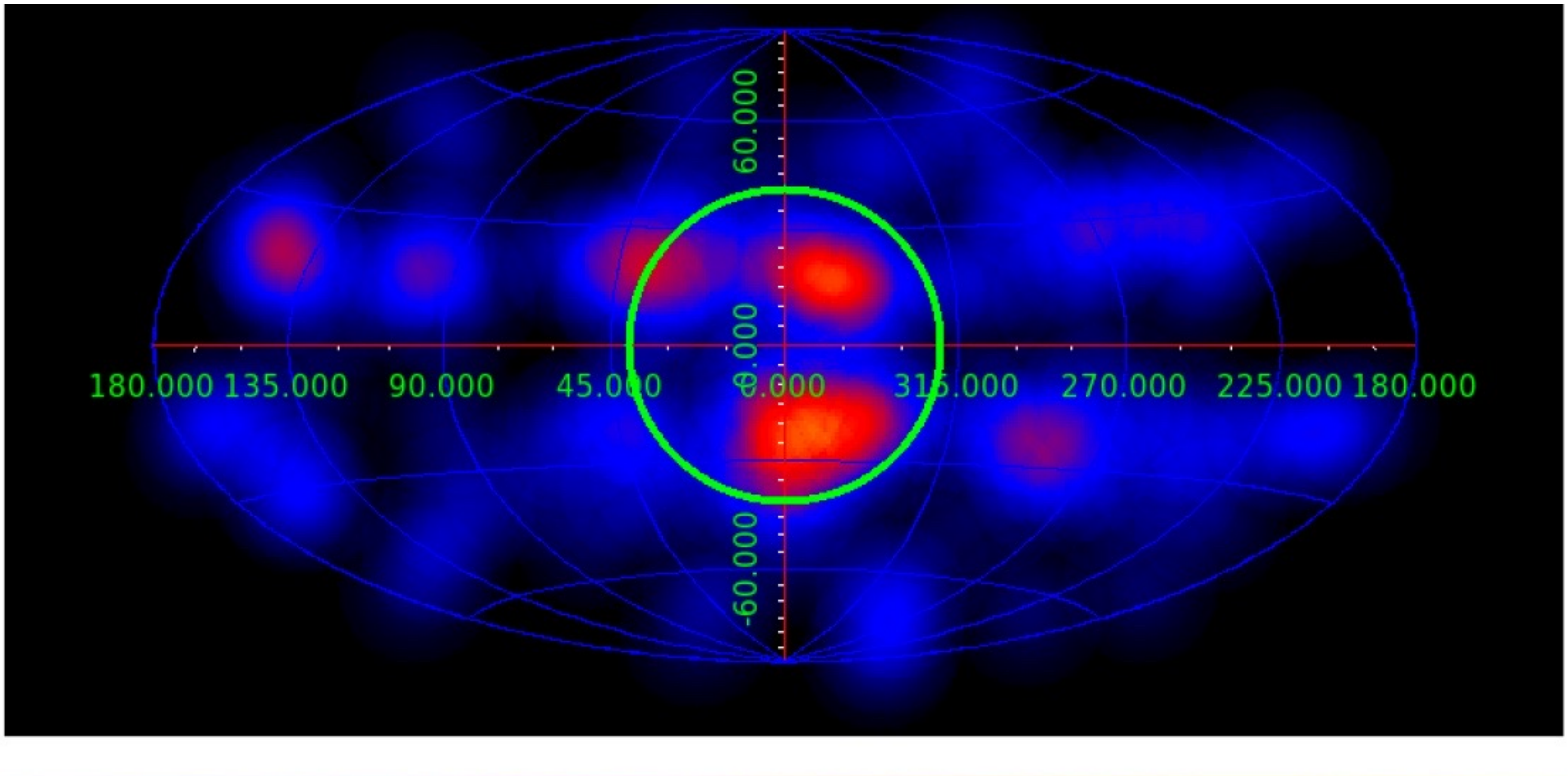
First neutrino source TXS 0506+056

- Blazar TXS 0506+056 is Fermi source, one of 50 bright sources , but not in first 20.
- Icecube event: IceCube-170922A Sept 22 2017
- Fermi detected activity of source in the same period.
- MAGIC detected flair Sept 28 2017
- TXS 0506+056 has redshift z=0.3365

IceCube data

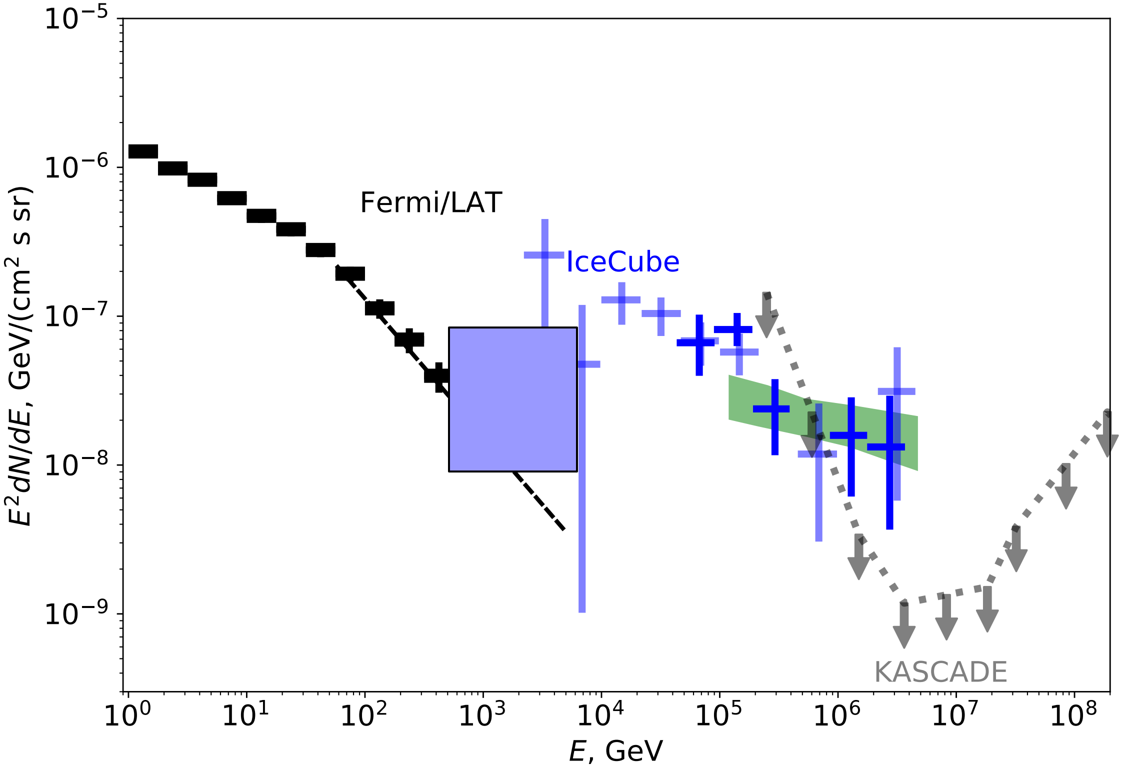


Sky map E> 1TeV no galactic plane |b|> 10 deg



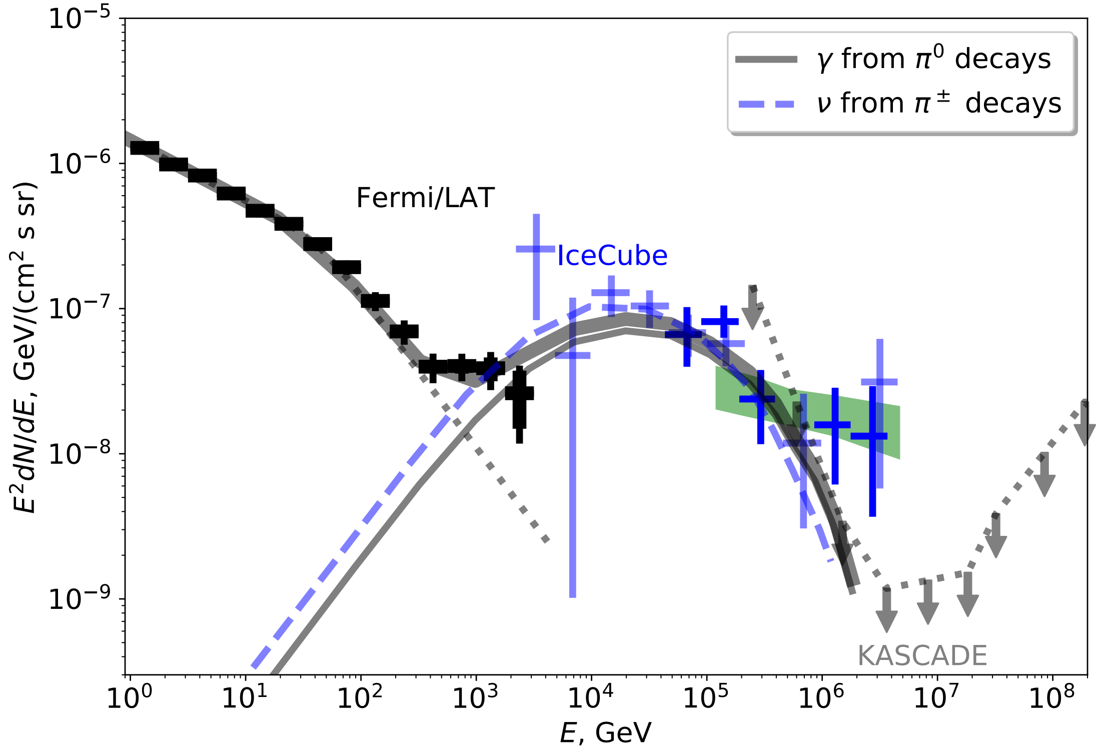
A.Neronov and D.S. , 2019 in preparation

IceCube + Fermi LAT high galactic latitude ÌbÌ>20 deg



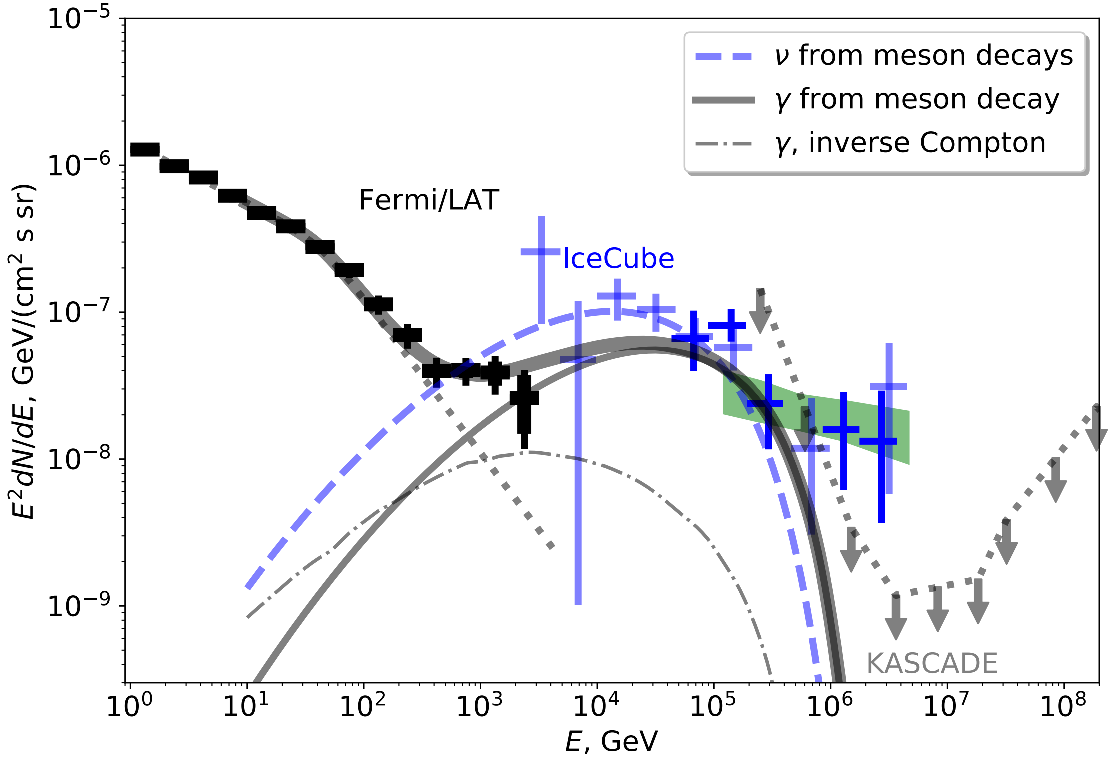
A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT : local source



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

IceCube + Fermi LAT Dark Matter m=5 PeV



A.Neronov, M.Kachelriess and D.S. , arXiv:1802.09983

Neutrino astrophysics

- IceCube detected first astrophysical neutrinos in 2013.
- First source – blazar TXS 0506+056 at redshift z=0.3 (1 Gpc)
- Distant bright blazars – main candidates for extragalactic neutrino sources
- There is Galactic contribution to neutrino flux, which come from local cosmic ray sources or heavy dark matter. Can be tested with gamma-ray search experiments like CARPET
- New neutrino detectors are in construction in Russia (lake Baikal) and in Mediterranean sea, IceCube detector will be updated in some years

Neutron stars, pulsars and BH

Baade & Zwicky (1934):

“With all reserve we advance the view that supernovae represent the transition from ordinary stars into *neutron stars*, which in their final stage consist of extremely closely packed neutrons.”

Supernova 1987A (23 Febr. 1987) in the Large Magellanic Cloud: before & after // Mass = $20M_o$

Sun: $R=10^5$km

density=6 gram/cm^3

Black hole: $R=3km*M/M_o$

. Mass > $3M_o$

Neutron `star' : R=20km

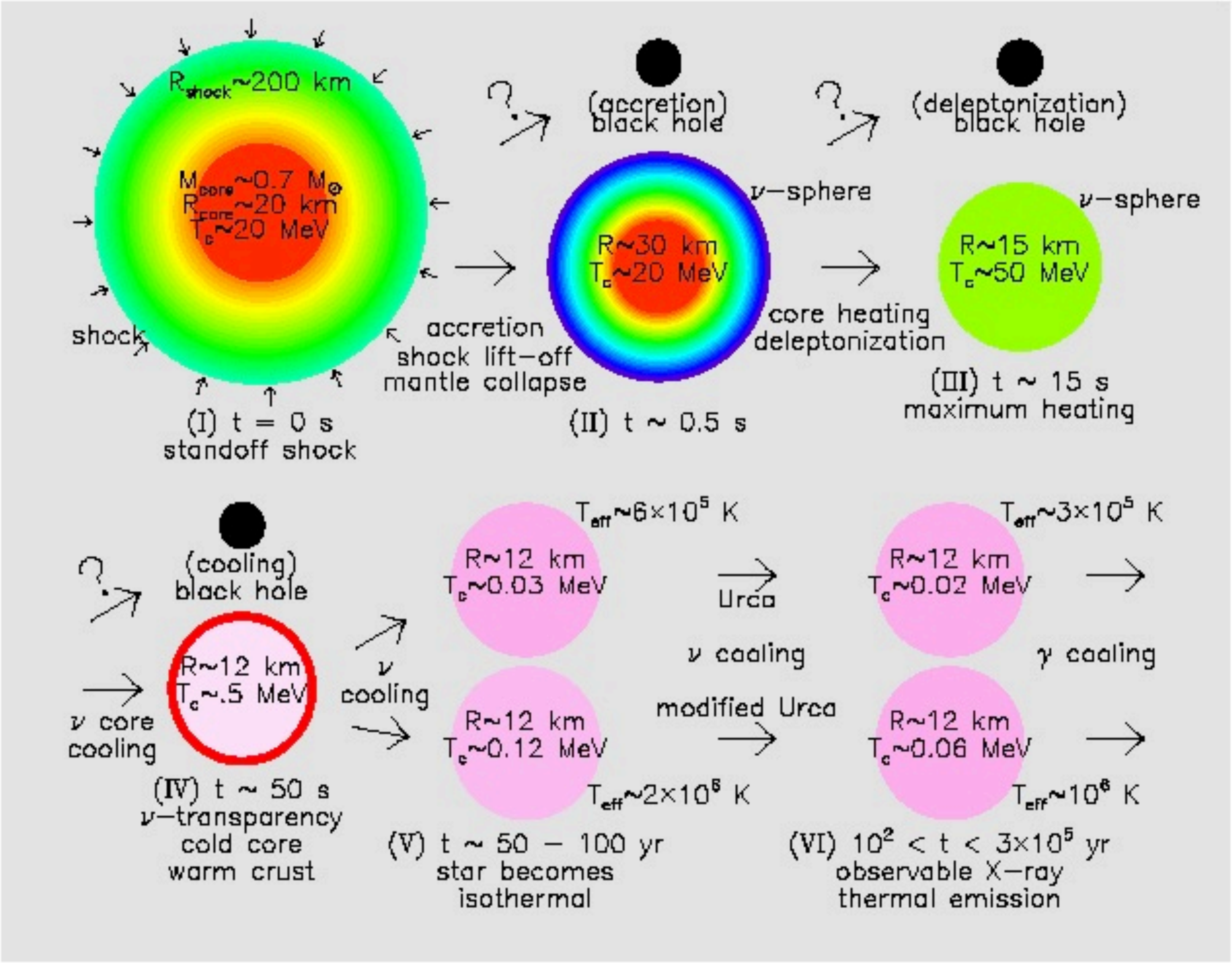
- density=10^{14}gram/cm^3

$3M_o$>Mass > $1.4M_o$

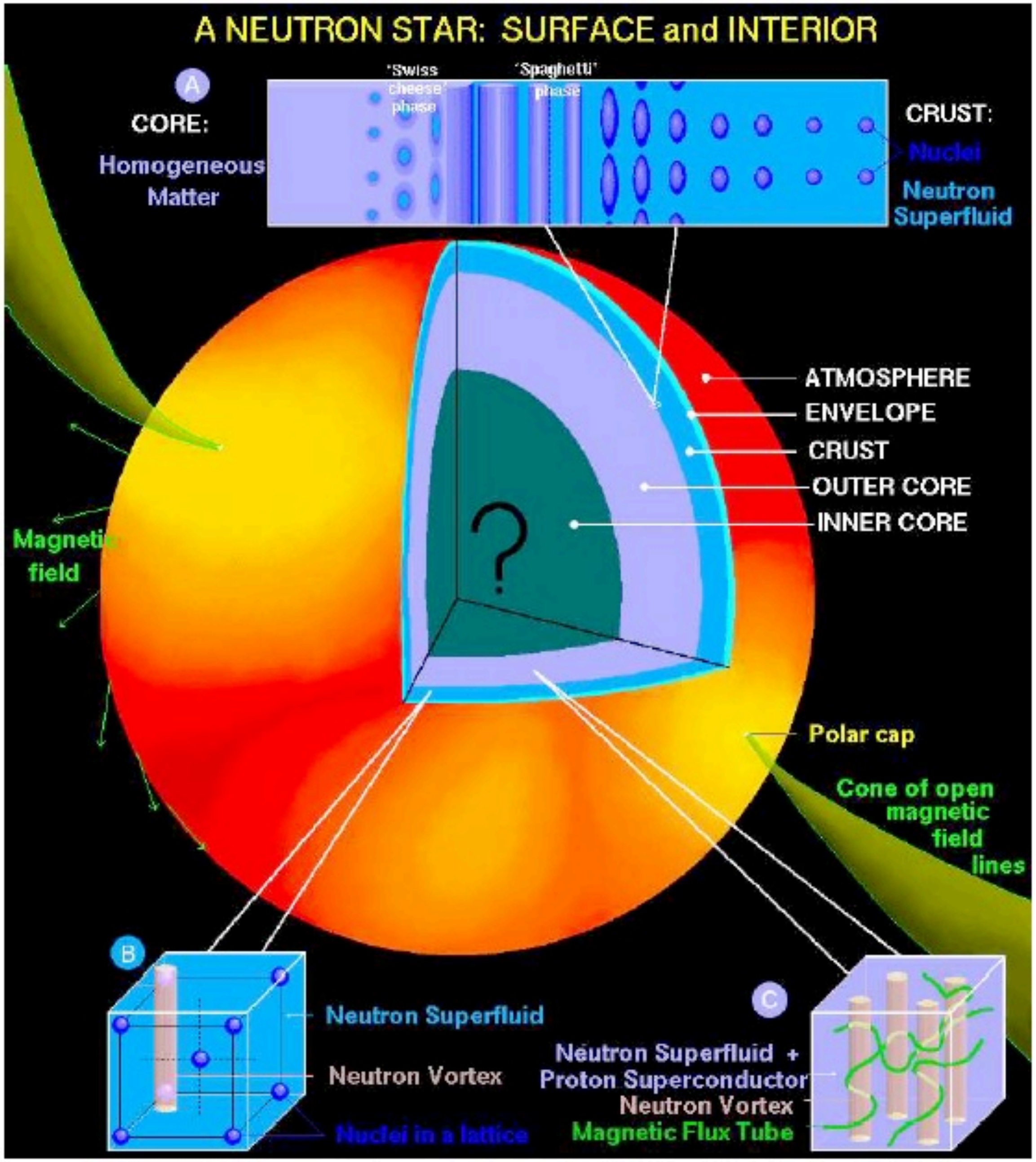
White Dwarf: R=6000km

density=10^6 gram/cm^3

Mass < $1.4M_o$



R_shock~200 km
M_core~0.7 M_⊙
R_core~20 km
T_c~20 MeV
shock
(I) t = 0 s
standoff shock
accretion
shock lift-off
mantle collapse
(accretion)
black hole
ν-sphere
R~30 km
T_c~20 MeV
(II) t ~ 0.5 s
core heating
deleptonization
(deleptonization)
black hole
ν-sphere
R~15 km
T_c~50 MeV
(III) t ~ 15 s
maximum heating
(cooling)
black hole
R~12 km
T_c~.5 MeV
ν core
cooling
(IV) t ~ 50 s
ν-transparency
cold core
warm crust
ν
cooling
T_eff~6×10^5 K
R~12 km
T_c~0.03 MeV
R~12 km
T_c~0.12 MeV
T_eff~2×10^6 K
(V) t ~ 50 - 100 yr
star becomes
isothermal
Urca
ν cooling
modified Urca
T_eff~3×10^5 K
R~12 km
T_c~0.02 MeV
γ cooling
R~12 km
T_c~0.06 MeV
T_eff~10^6 K
(VI) 10^2 < t < 3×10^5 yr
observable X-ray
thermal emission


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

- Conservation of angular momentum means:

$$L_{initial} = L_{final}$$

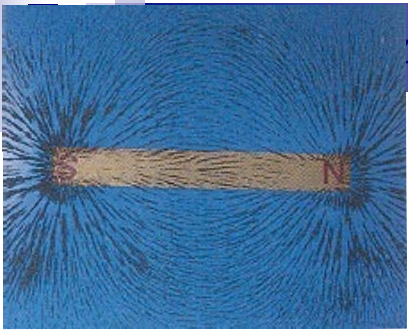
$$I_i \omega_i = I_f \omega_f$$

$$\frac{2}{5} M R_i^2 \omega_i = \frac{2}{5} M R_f^2 \omega_f$$

$$R_i^2 \omega_i = R_f^2 \omega_f$$

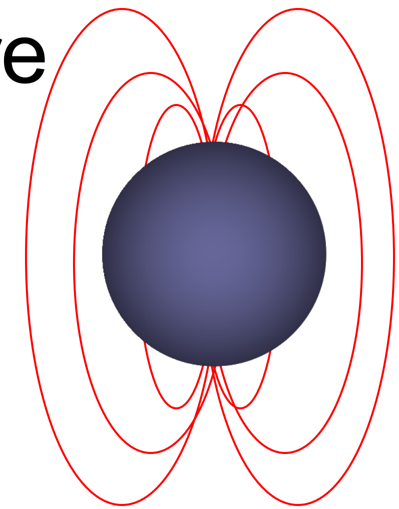
$$\omega_f = \frac{R_i^2}{R_f^2} \omega_i = \left(\frac{7 \times 10^5}{10} \right)^2 \omega_i = 4.9 \times 10^9 \omega_i$$

- Sun rotates at 1 rev/month. Compress it to 10km and conserve L, it will spin up to 1890 revolutions/second



Magnetic Fields

- Magnetic field lines are also conserved. When the core collapses, the field lines are

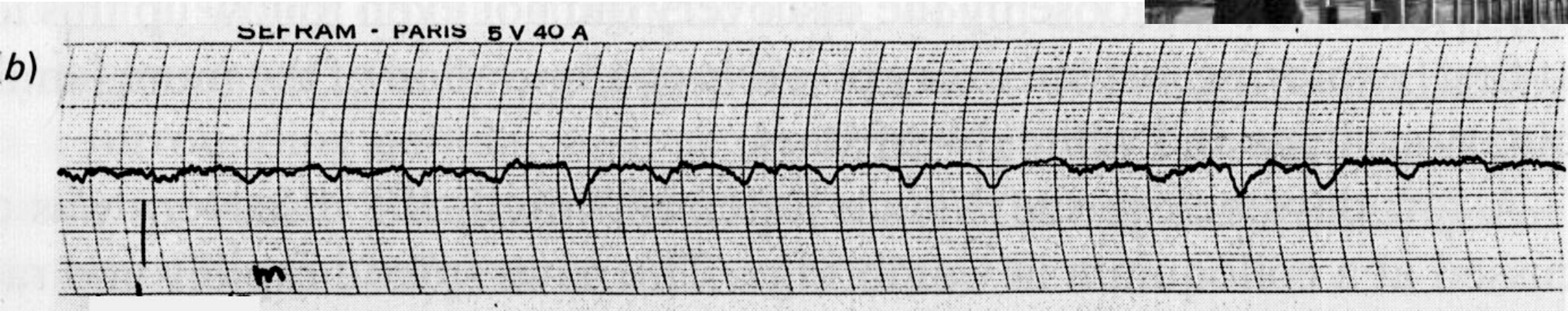


conserved, and the density of the field lines goes way up . This is the strength of the magnetic field.

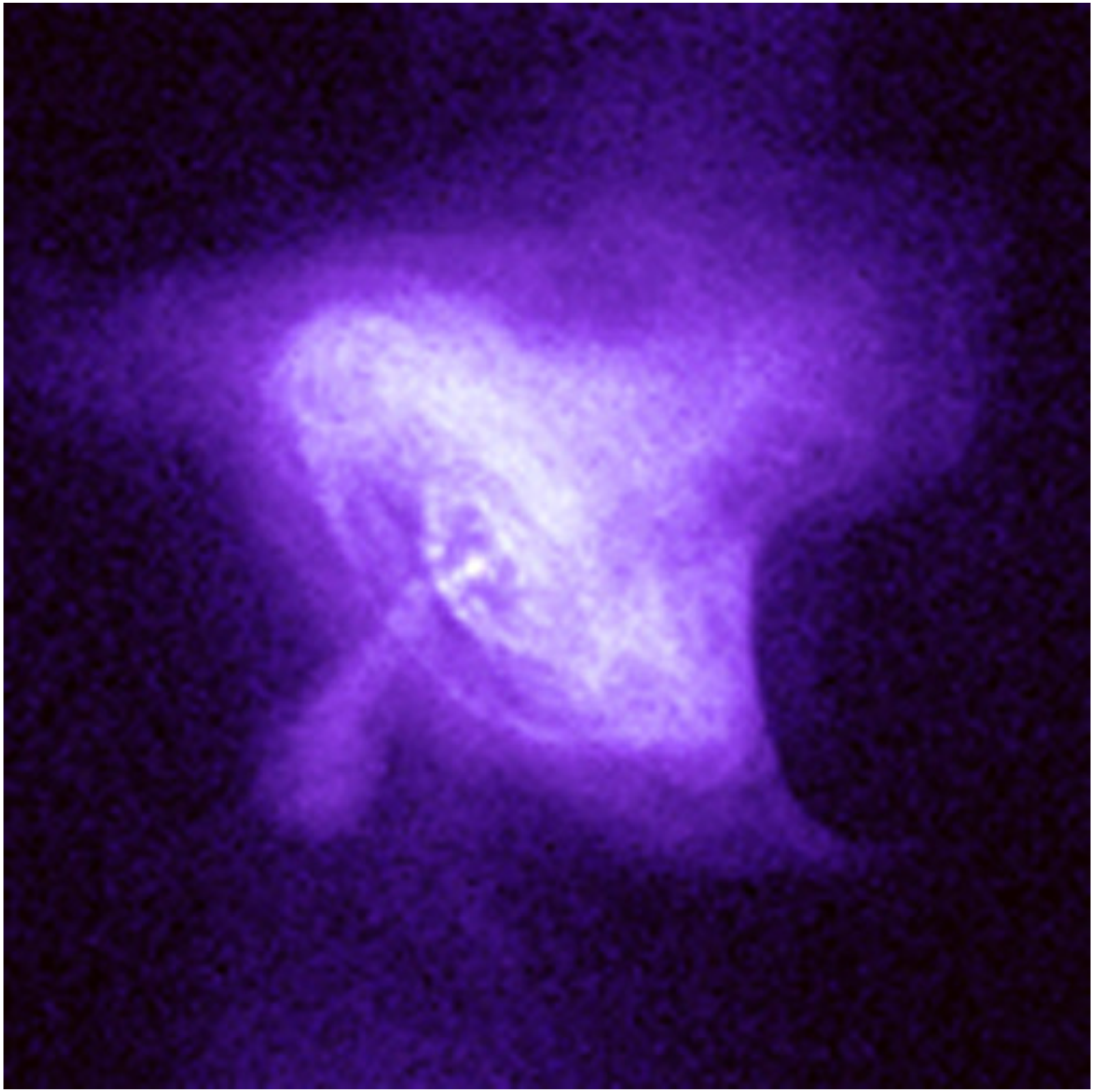
Pulsars: discovery

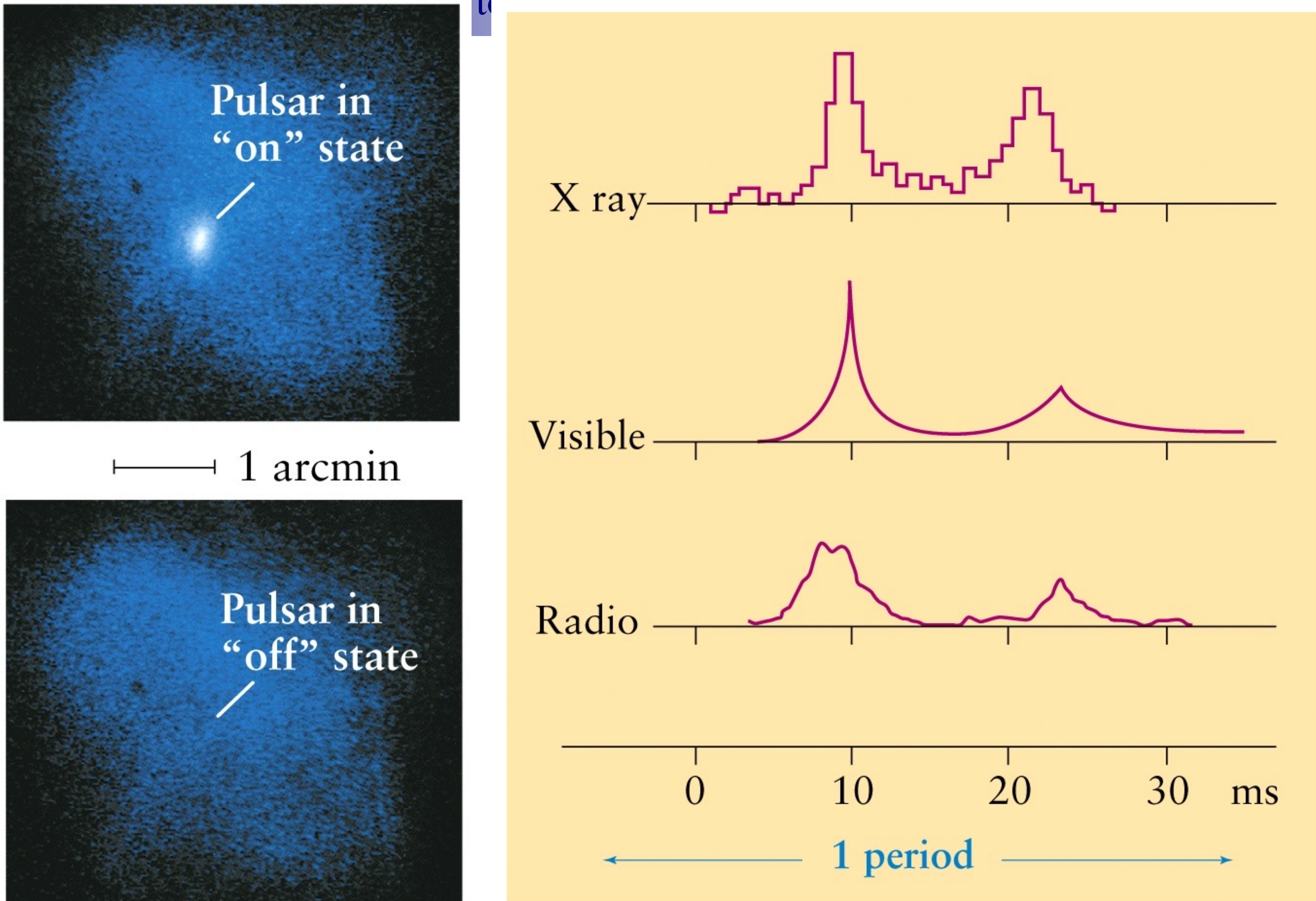
1967: PhD student **Jocelyn Bell** & her supervisor **Anthony Hewish** detect a very regular ***P**ulsating **S**ource of **R**adio* (PSR 1919+21) with P=1.377 s, initially “LGM 1”.

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html



Of Crabs, Shells and Plerions





a

b

X-ray image

How we know pulsars are NSs

- Association with supernova remnants (SNRs)
- Rotation of Crab pulsar $\Omega < \sqrt{GM/R^3} = \sqrt{4\pi G\bar{\rho}/3}$

$$\Rightarrow \quad \bar{\rho} > \frac{3\Omega^2}{4\pi G} \approx 10^{11}\ \frac{\text{g}}{\text{cm}^3}$$

  - Much faster ones (“millisecond pulsars”) found later
- Energy budget of SNR in rough agreement with energy lost from rotating NS.
- Very high-energy (non-thermal) emission: likely relativistic system
- Thermal emission (X-rays): emitting region ≤ 10 km

Masses of pulsars in binary systems

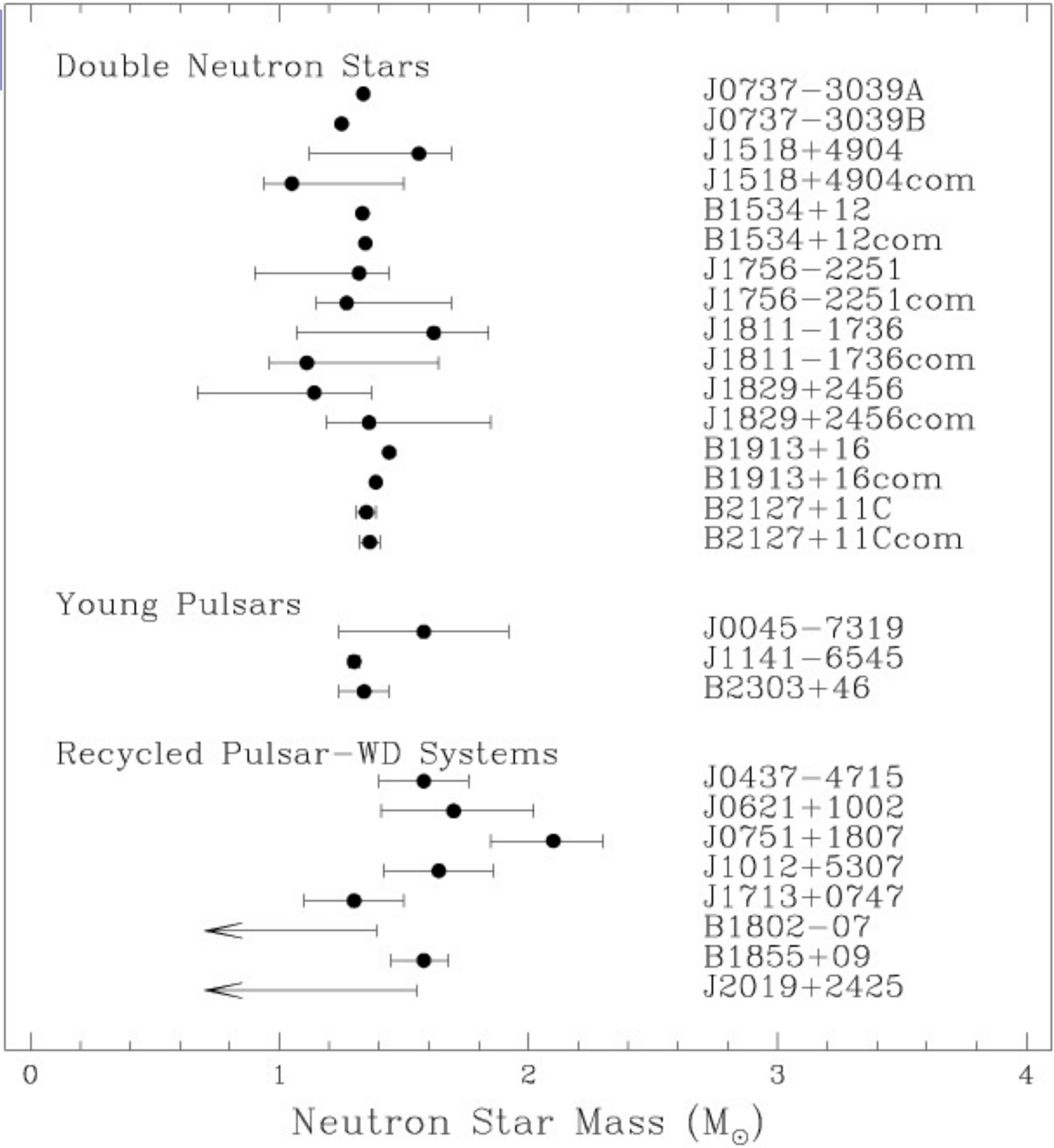
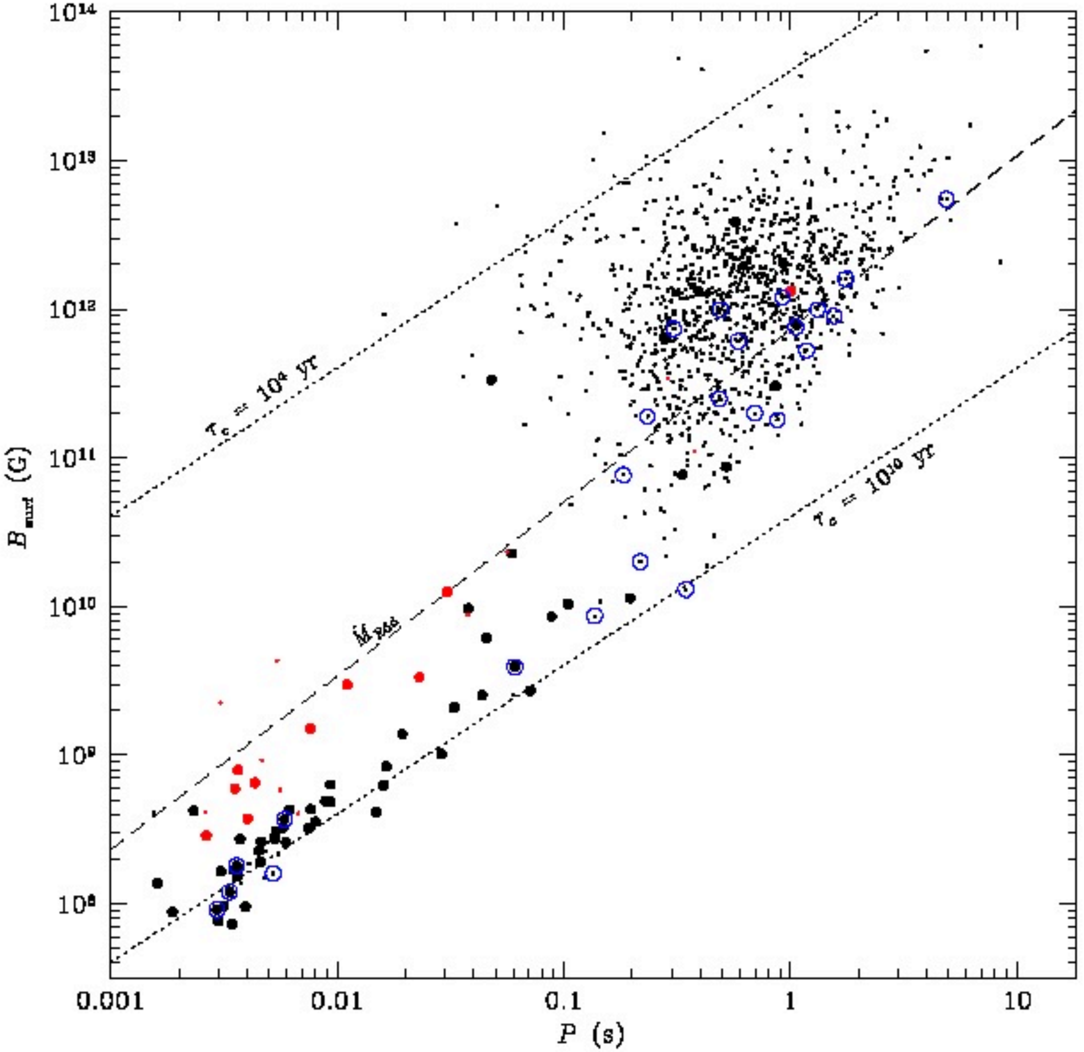


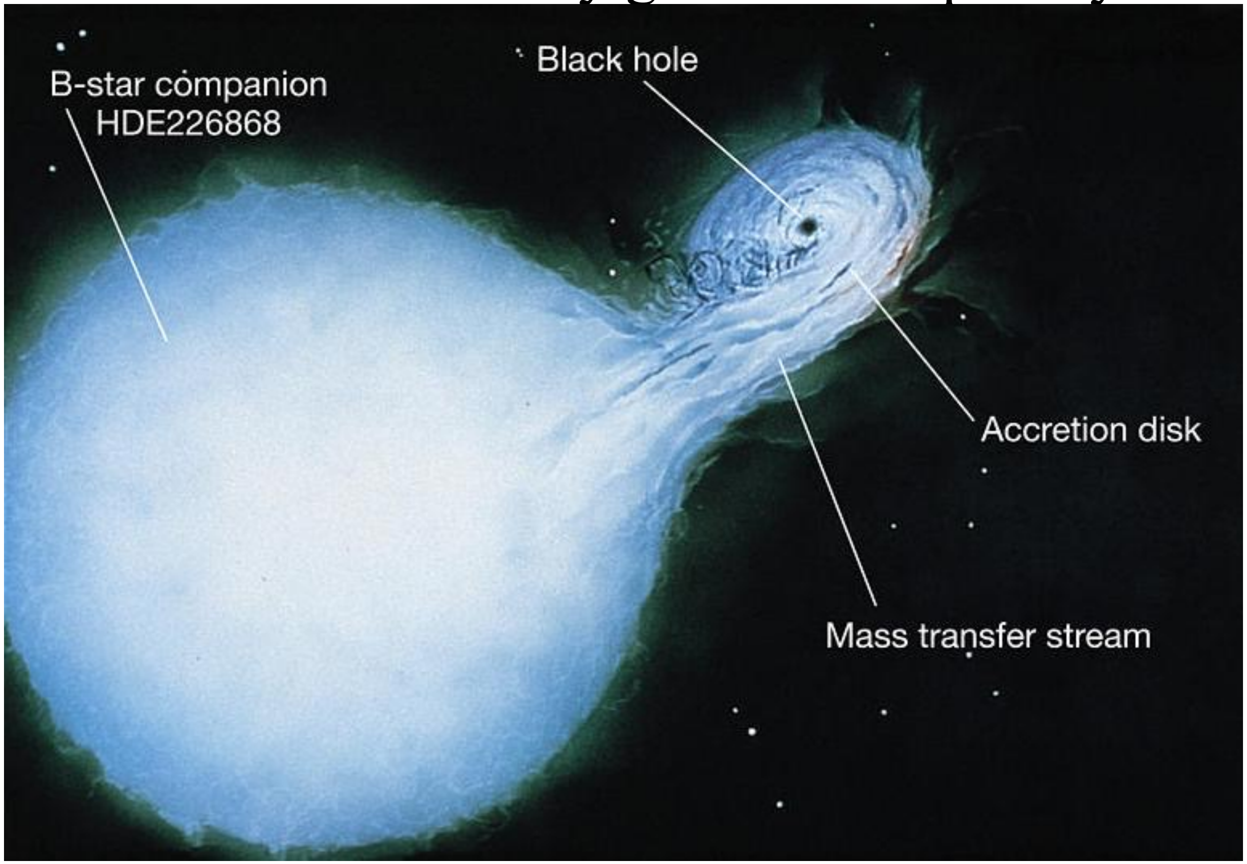
Fig. by I. Stairs, reproduced in Lorimer 2005

Pulsar P-Pdot Diagram



Accretion disc

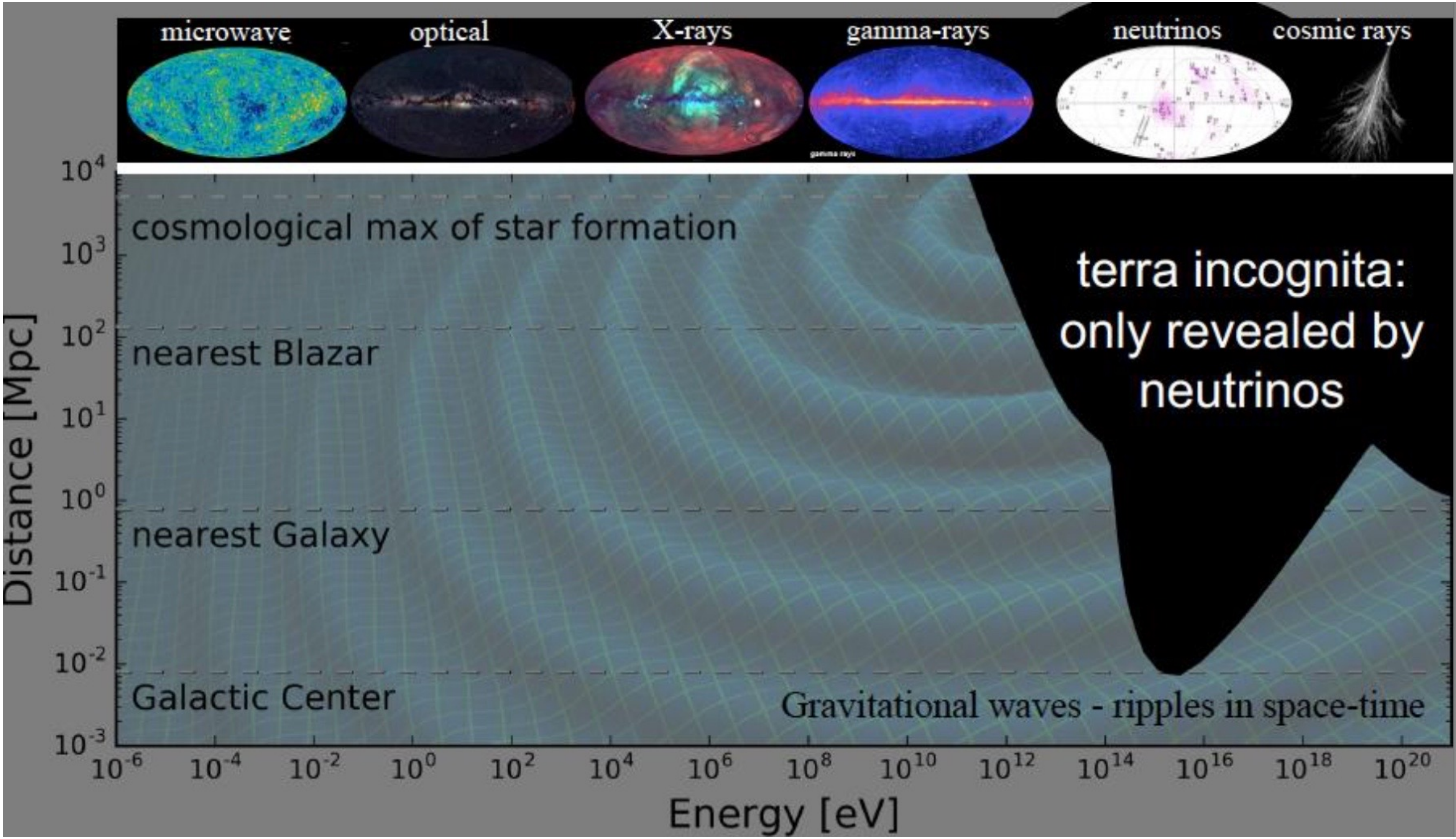
Stellar black holes observed in a *binary system,* i.e. where there is a companion star. This star can then literally get sucked apart by the black hole.



Cygnus X1:

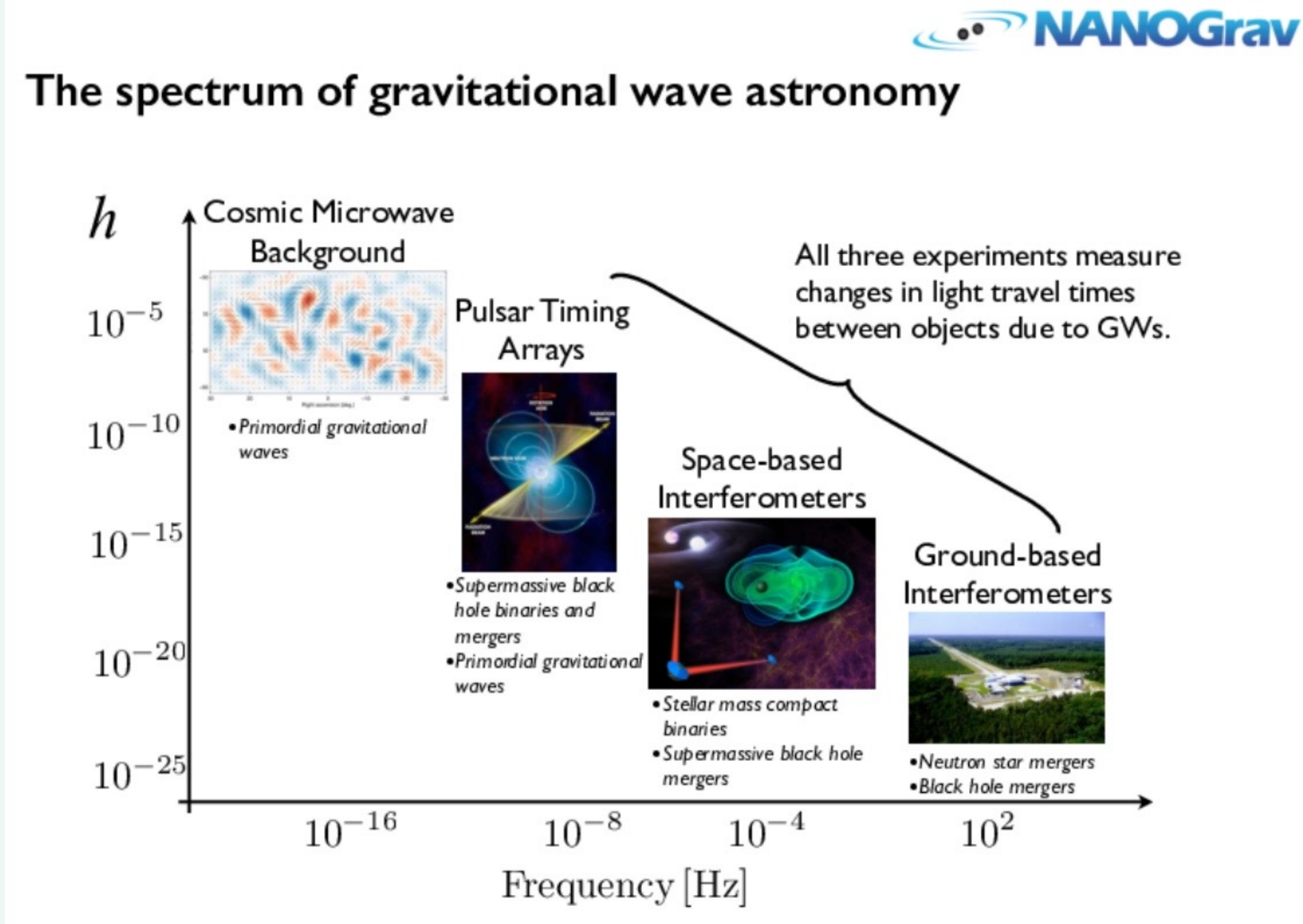
$M\_BH = 15M_o$

From multi-wavelength to multi-messenger



From F.Halzen

New messenger: Gravitational waves

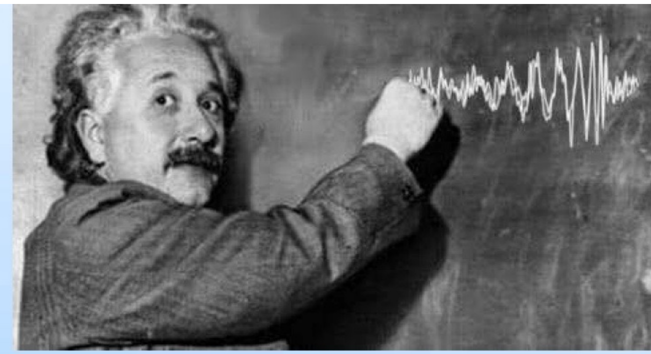


NANOGrav
The spectrum of gravitational wave astronomy
h
Cosmic Microwave Background
•Primordial gravitational waves
Pulsar Timing Arrays
•Supermassive black hole binaries and mergers
•Primordial gravitational waves
Space-based Interferometers
•Stellar mass compact binaries
•Supermassive black hole mergers
Ground-based Interferometers
•Neutron star mergers
•Black hole mergers
All three experiments measure changes in light travel times between objects due to GWs.
10^-5
10^-10
10^-15
10^-20
10^-25
10^-16
10^-8
10^-4
10^2
Frequency [Hz]

General Relativity

1915: Einstein's Theory of General Relativity

1916: Einstein paper on linear approximation to general relativity with multiple applications, including gravitational waves.



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Gravitational waves

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right) . \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"… in all conceivable cases, ***A*** must have a practically vanishing value."

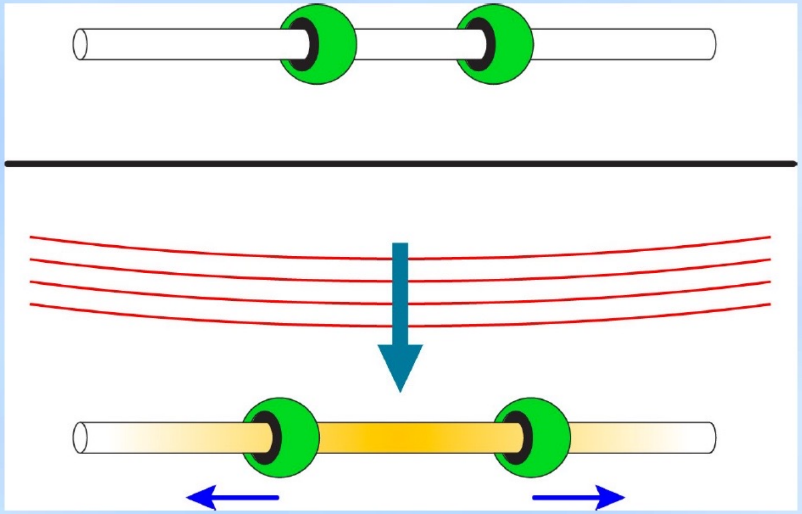
Gravitational waves are predicted by Einstein, but he recognizes that they are too small.

Are Gravitational Waves Real?

Continued debate on whether gravitational waves really exist up until 1957 Chapel Hill conference.

Felix Pirani paper and presentation: relative acceleration of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

Sticky bead (Felix Pirani, Richard Feynman, Hermann Bondi)

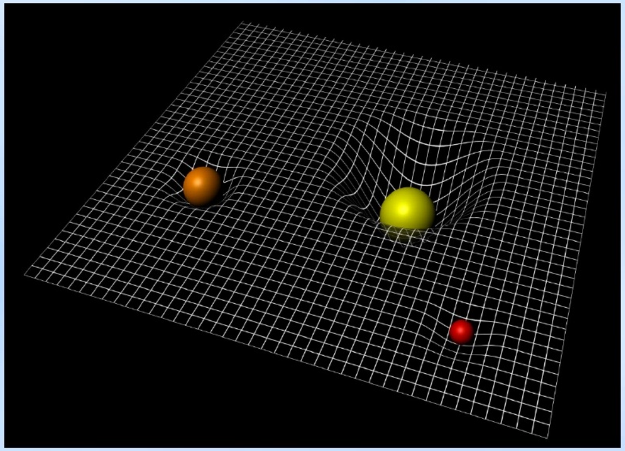


Joe Weber of the University of Maryland, and from this inspiration started to think about gravitational wave detection.

What Are Gravitational Waves?

- General relativity (1916) prediction.
- Gravity is not really a force in GR, but a space-time deformation.
- Masses locally deform space-time.
- Accelerated masses emit gravitational

waves, ripples in space time.



- Space-time is rigid:

The amplitude of the deformation is tiny.

Need cataclysmic events in order to

expect to measure something on Earth … h ~ 10^{-21}

- Gravitational Wave sources: mainly astrophysical in the 10 Hz -10 kHz bandwidth

Binary Pulsar PSR 1913+16

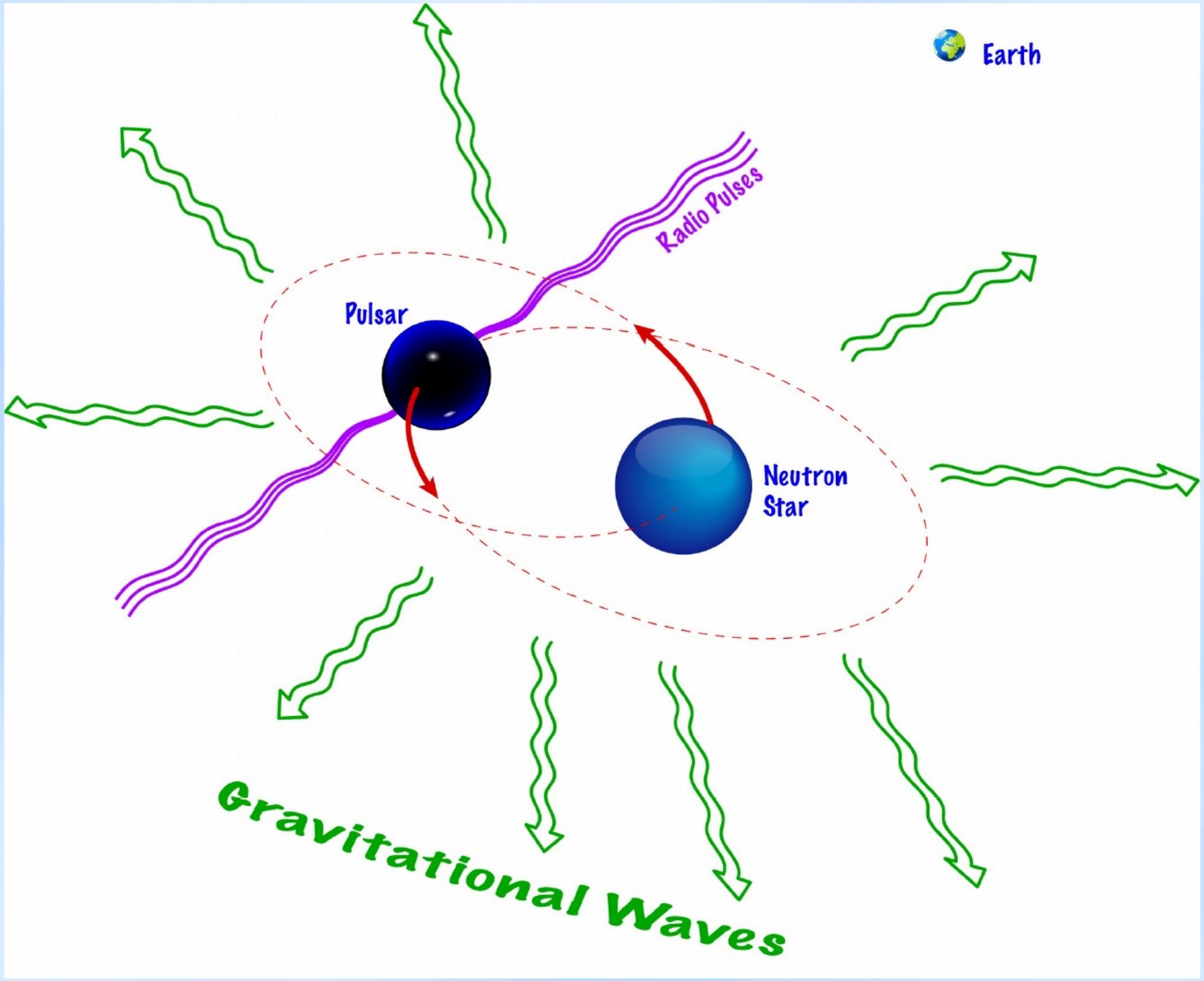
M1 = 1.438 M_o

M2 = 1.390 M_o

8 hour orbit

Orbit decays by 3mm per orbit.

Discovered in 1974 by Russell Hulse and Joseph Taylor, then at University Massachusetts.



First Proof That Gravitational Waves Exist - 1982

THE ASTROPHYSICAL JOURNAL, **253**:908–920, 1982 February 15

A NEW TEST OF GENERAL RELATIVITY: GRAVITATIONAL RADIATION AND THE BINARY PULSAR PSR 1913+16

J. H. TAYLOR AND J. M. WEISBERG
Department of Physics and Astronomy, University of Massachusetts, Amherst; and Joseph Henry Laboratories, Physics Department, Princeton University
Received 1981 July 2; accepted 1981 August 28

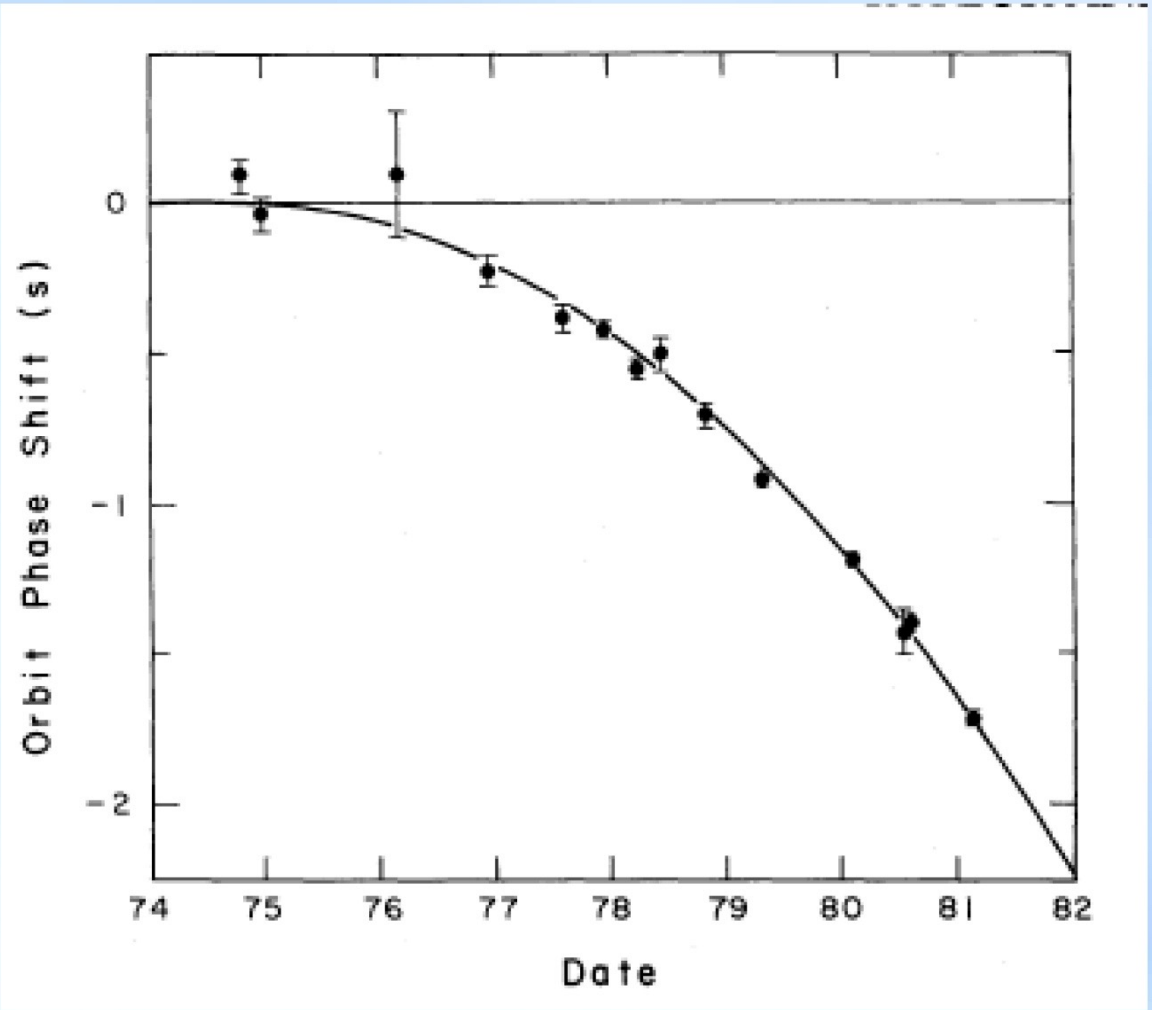
ABSTRACT

Observations of pulse arrival times from the binary pulsar PSR 1913+16 between 1974 September and 1981 March are now sufficient to yield a solution for the component masses and the absolute size of the orbit. We find the total mass to be almost equally distributed between the pulsar and its unseen companion, with $m_p = 1.42 \pm 0.06\ M_\odot$ and $m_c = 1.41 \pm 0.06\ M_\odot$. These values are used, together with the well determined orbital period and eccentricity, to calculate the rate at which the orbital period should decay as energy is lost from the system via gravitational radiation. According to the general relativistic quadrupole formula, one should expect for the PSR 1913+16 system an orbital period derivative $\dot{P}_b = (-2.403 \pm 0.005) \times 10^{-12}$. Our observations yield the measured value $\dot{P}_b = (-2.30 \pm 0.22) \times 10^{-12}$. The excellent agreement provides compelling evidence for the existence of gravitational radiation, as well as a new and profound confirmation of the general theory of relativity.

Subject headings: gravitation — pulsars — relativity

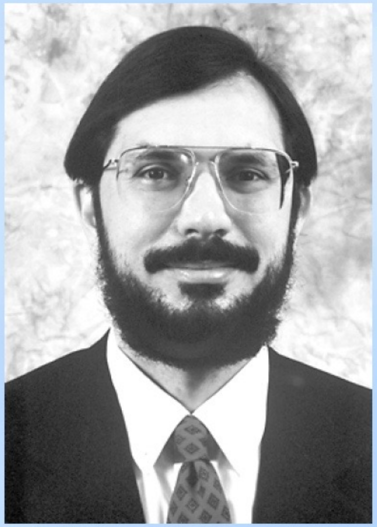
Prediction 1916 | Theoretical understanding 1957 | Indirect detection 1982

Gravitational Wave Proof



Taylor and Weisberg, 1982

A Nobel Prize for ...



“… for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.”
1993

For more on this Nobel, see, "The Nobel pulsar", Nelson Christensen. Science, Vol. 348 no. 6236 p. 766 (2015).

Binary Pulsar Studies Continue

THE ASTROPHYSICAL JOURNAL, 829:55 (10pp), 2016 September 20
doi:10.3847/0004-637X/829/1/55

RELATIVISTIC MEASUREMENTS FROM TIMING THE BINARY PULSAR PSR B1913+16

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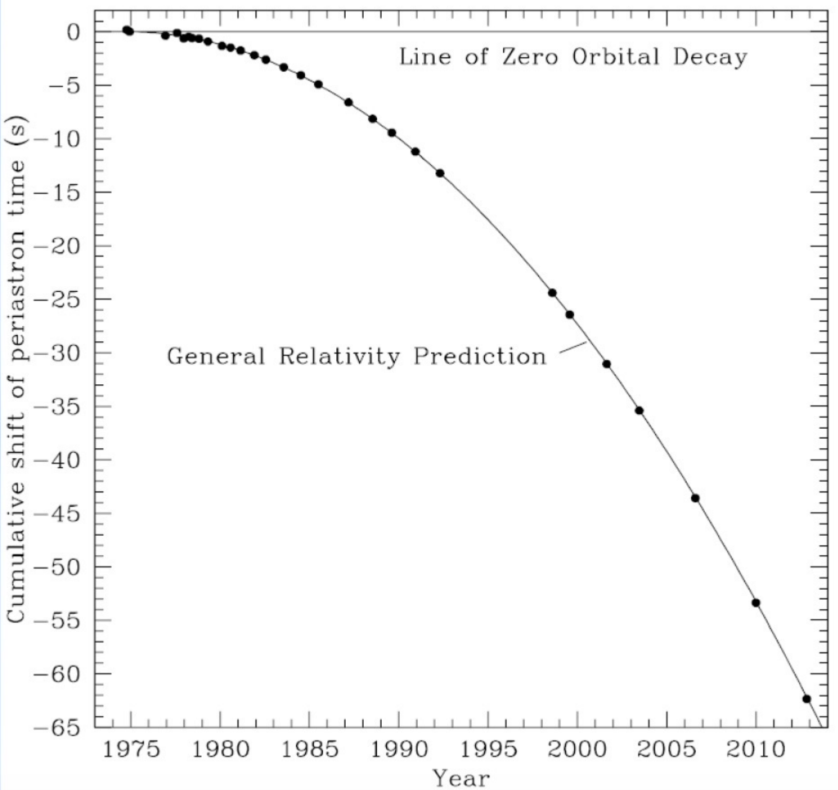
Department of Physics and Astronomy, Carleton College, Northfield, MN 55057, USA; jweisber@carleton.edu
Received 2016 January 19; revised 2016 April 20; accepted 2016 June 1; published 2016 September 21



"The points, with error bars too small to show, represent our measurements"

Gravitational Wave Detection

Inspired and motivated by the Chapel Hill Conference, Joe Weber of the University of Maryland constructs the first gravitational wave detectors.

"In 1958 I was able to prove, using Einstein's equations that a gravitational wave would change the dimensions of an extended body."

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

K. Thorne 1980

1960s & 70s: Detection claims and theoretical studies on sources

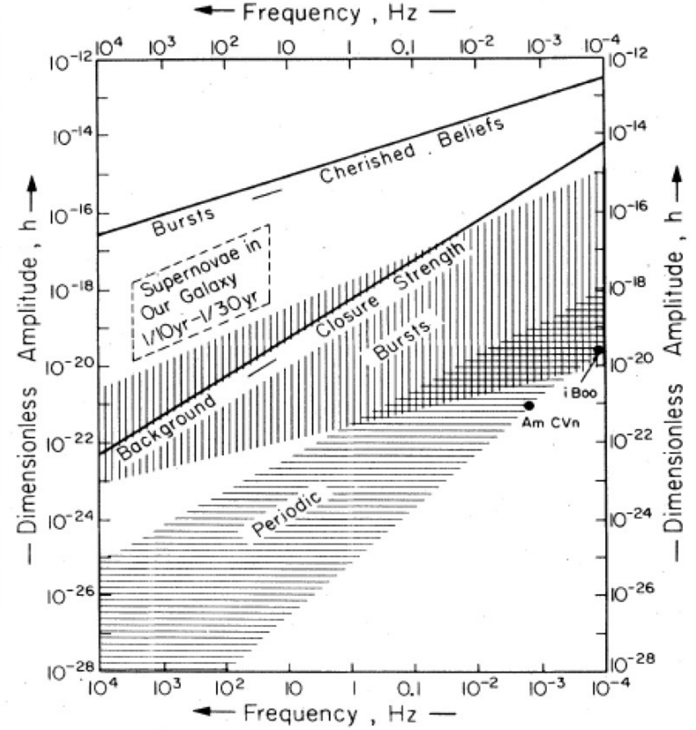


FIG. 3. Estimates of the strengths of the gravitational waves that bathe the Earth. See text for explanation of the lines and hatched regions.

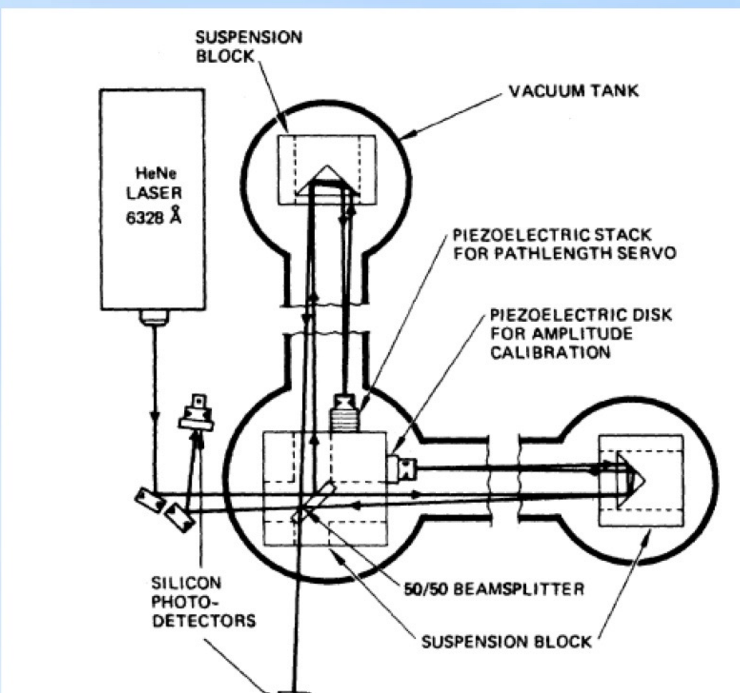
The future looks promising—but by no means certain! The search for gravitational waves is a game requiring long, hard effort with a definite risk of total failure—but with very great payoff if it succeeds.

Interferometric GW Detectors

First suggestion: 1962 two Soviet physicists, V.I. Pustovoit and M.E. Gertsenshtein, noted that the use of a Michelson interferometer would be a possible means to detect gravitational waves over a frequency range that was broader than the Weber bars.

1970's, Robert Forward (student of Weber) at Hughes Air Michelson interferometer to search for gravitational wave (MIT) and astronaut Philip Chapman (also at MIT) for ins

The wideband interfe



VII. CALIBRATION OF EAR

When the interferometer was working well, we were able to hear single-frequency 3- to 10-kHz tones of 10-fm rms amplitude introduced into the interferometer by the piezoelectric displacement transducer.

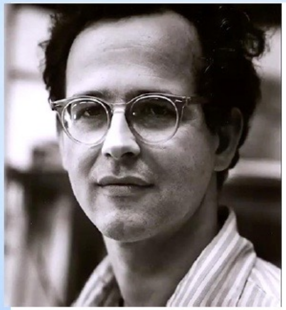
Since the noise level of the interferometer in that band is about 0.9 fm/Hz$^{1/2}$, this means that the audio system, including our ear-brain combination, had an effective detection bandwidth of about 120 Hz.

Rai Weiss Interferometer Study

1972: Weiss produces the first detailed study for a realistic interferometric gravitational wave detector.

Systematically addresses a number of realistic noise sources:

- Amplitude Noise in the Laser Output Power
- Laser Phase Noise or Frequency Instability
- Mechanical Thermal Noise in the Antenna
- Radiation-Pressure Noise from the Laser Light
- Seismic Noise
- Thermal-Gradient Noise
- Cosmic-Ray Noise
- Gravitational-Gradient Noise
- Electric Field and Magnetic Field Noise



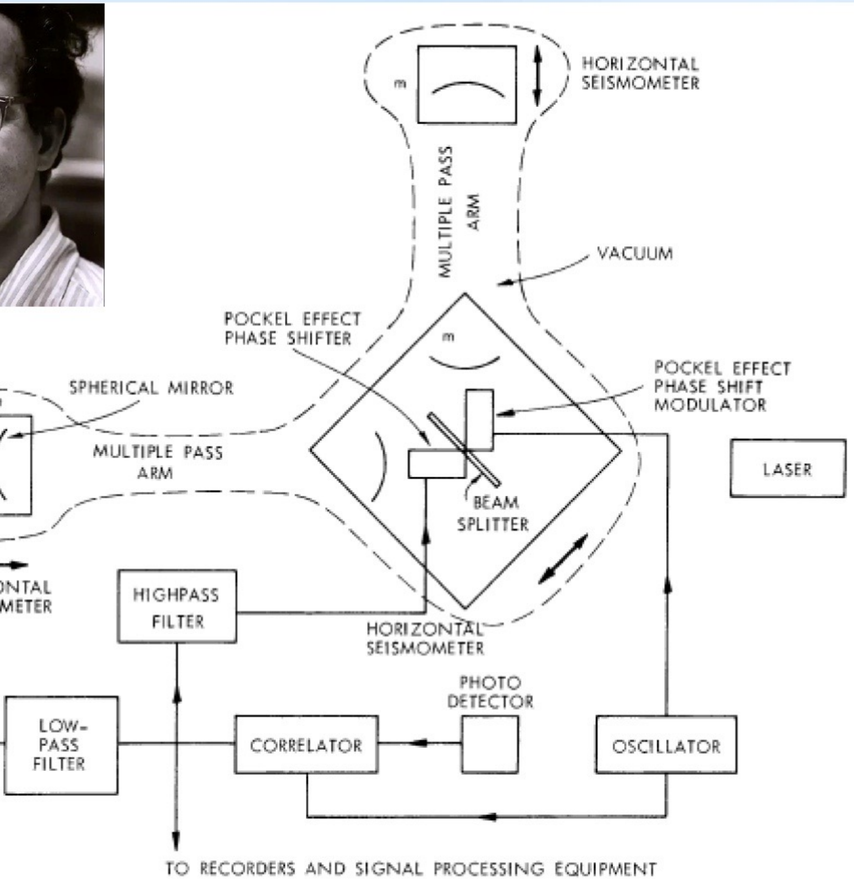
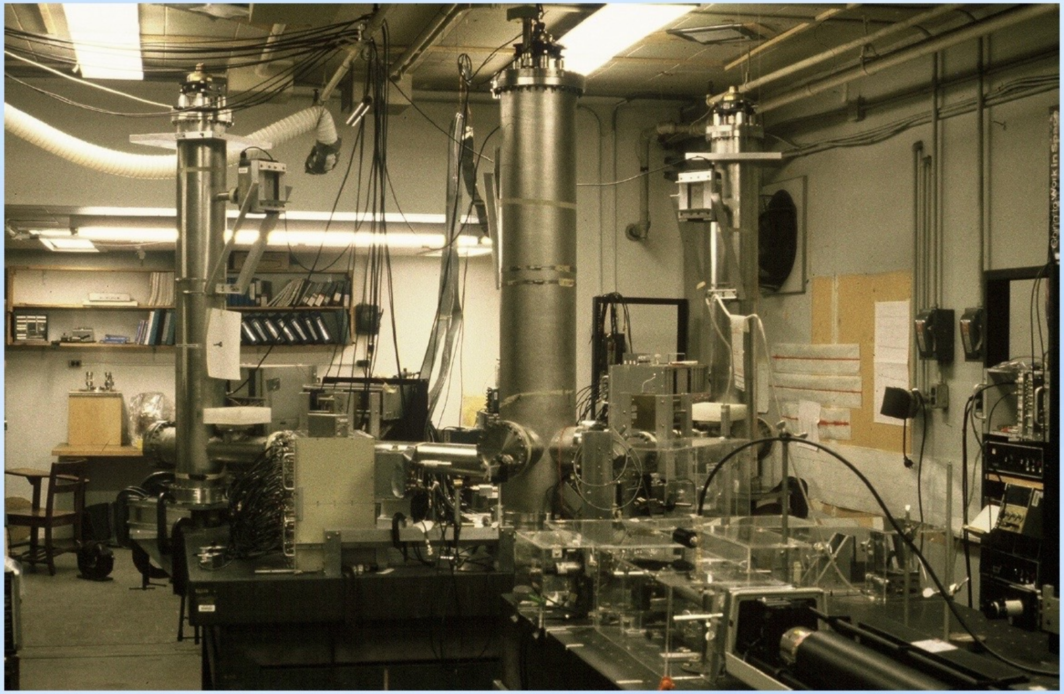


Fig. V-20. Proposed antenna.

Prototype Interferometric Detectors



MIT 1.5 m delay line Michelson Interferometer

1970s and 80s:
Interferometers constructed at
Garching
Glasgow
MIT
Caltech

The interferometer technology started progressing rapidly.

1980s LIGO is Born

Thorne, Drever (Caltech)

Weiss (MIT)

National Science Foundation

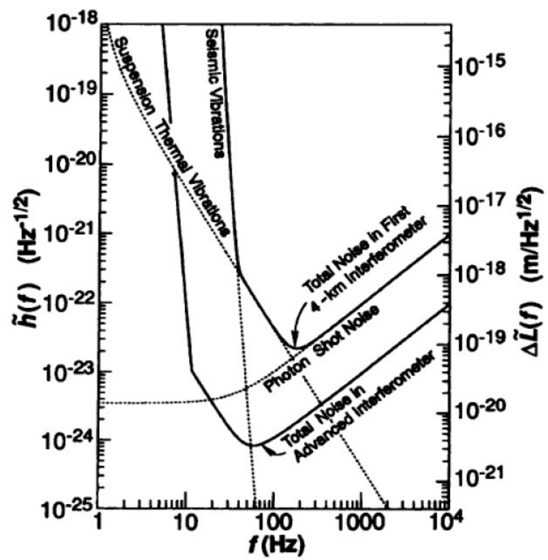


Fig. 7. The expected total noise in each of LIGO's first 4-km interferometers (upper solid curve) and in a more advanced interferometer (lower solid curve). The dashed curves show various contributions to the first interferometer's noise.

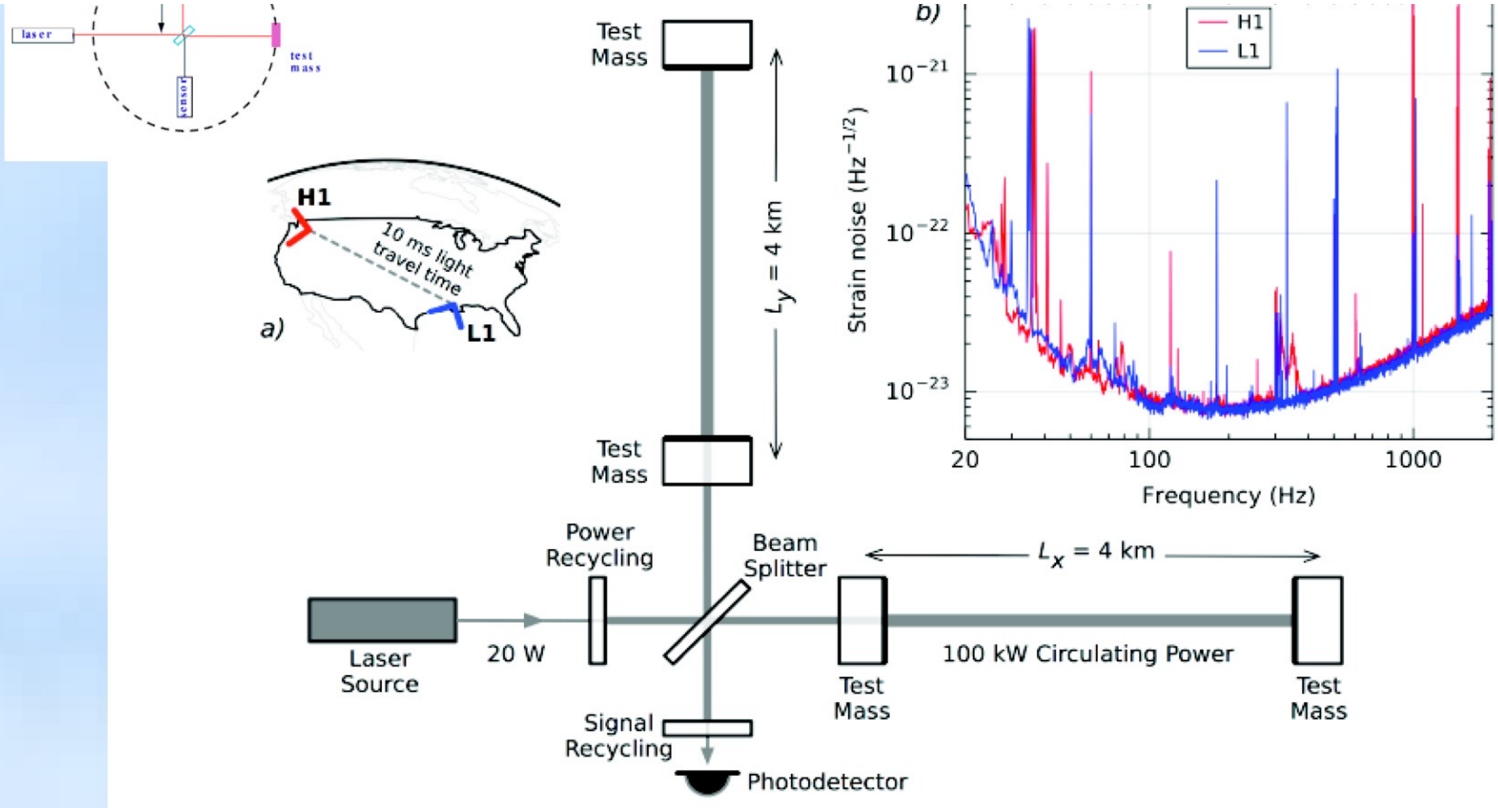
SCIENCE • VOL. 256 • 17 APRIL 1992

While in Europe … Virgo

A. Brillet (Orsay, Nice)
Lasers, Optics

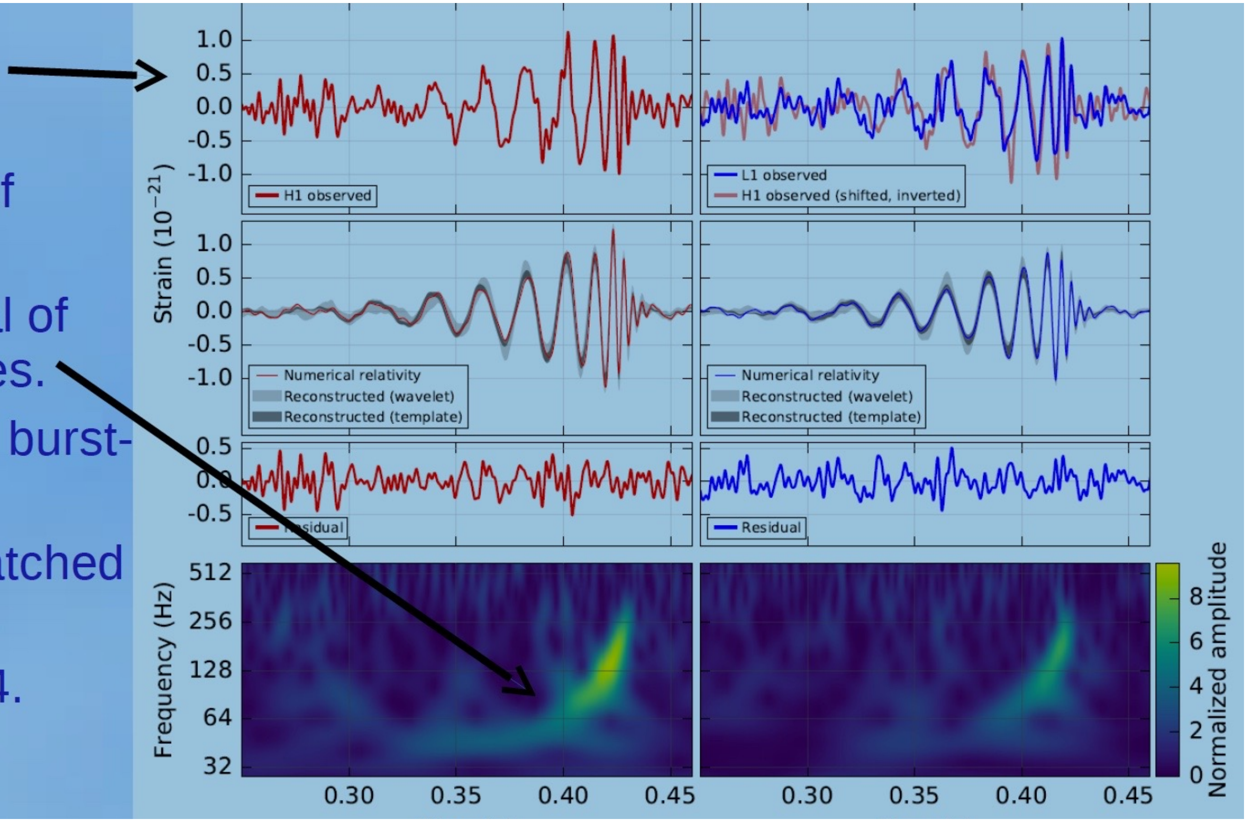
A. Giazotto (Pisa)
Vibration Isolation

The Detectors



GW150914

- Band-pass filter:
  35-350 Hz
- L1-H1 time delay of about 7ms.
- Chirp signal, typical of binary coalescences.
- Detected by online burst-search pipelines.
- Confirmed later matched template searches.
- Combined SNR: 24.



The Results

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

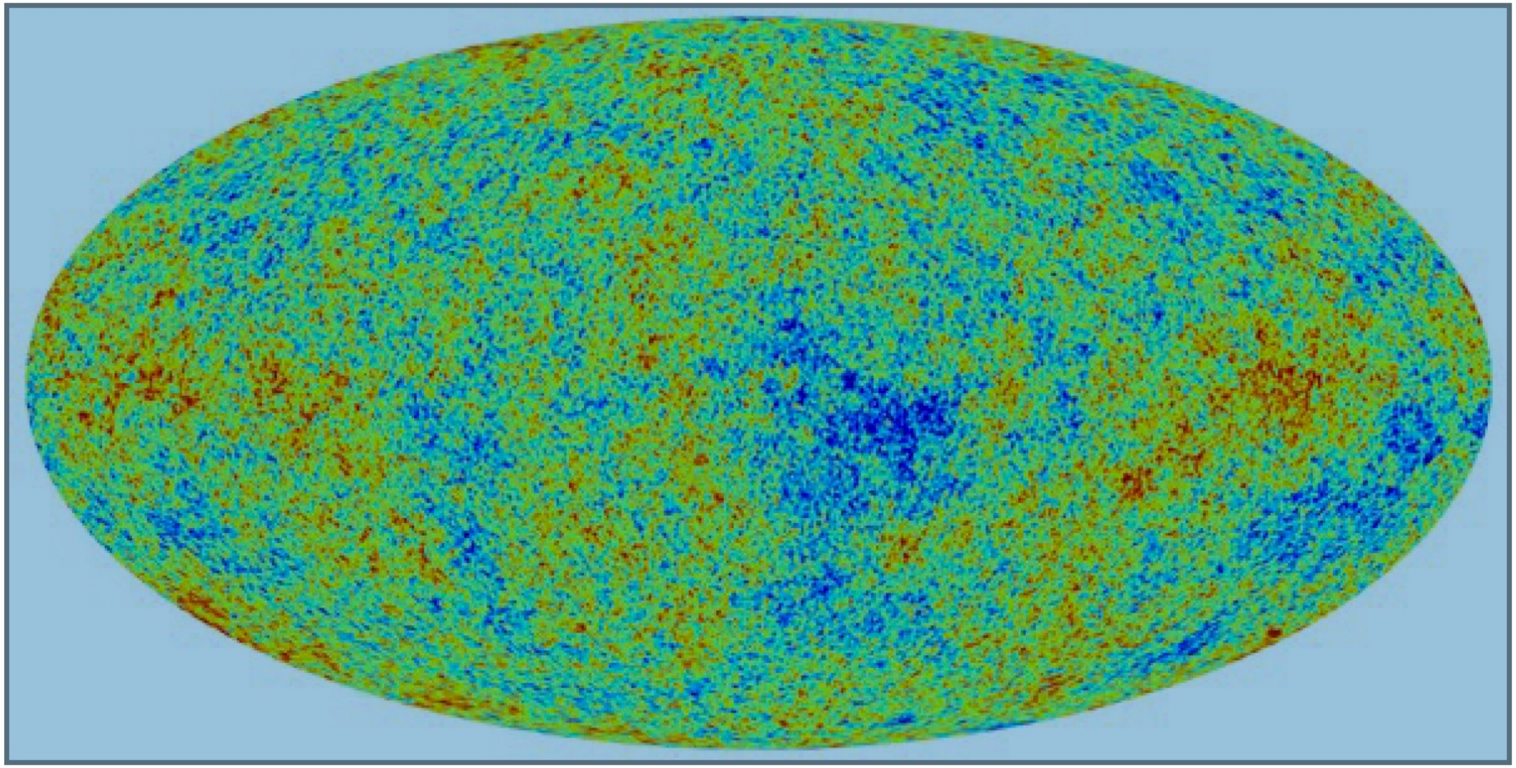
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

10.00 x 7.50 in

Phenomenology of GW

Primordial gravitational waves / Quantum fluctuations:

<< 1 sec from Big Bang, due to INFLATION of the Universe
Freq. ~ 10^-16 – 10^2 Hz
extremely “faint” (small amplitude)



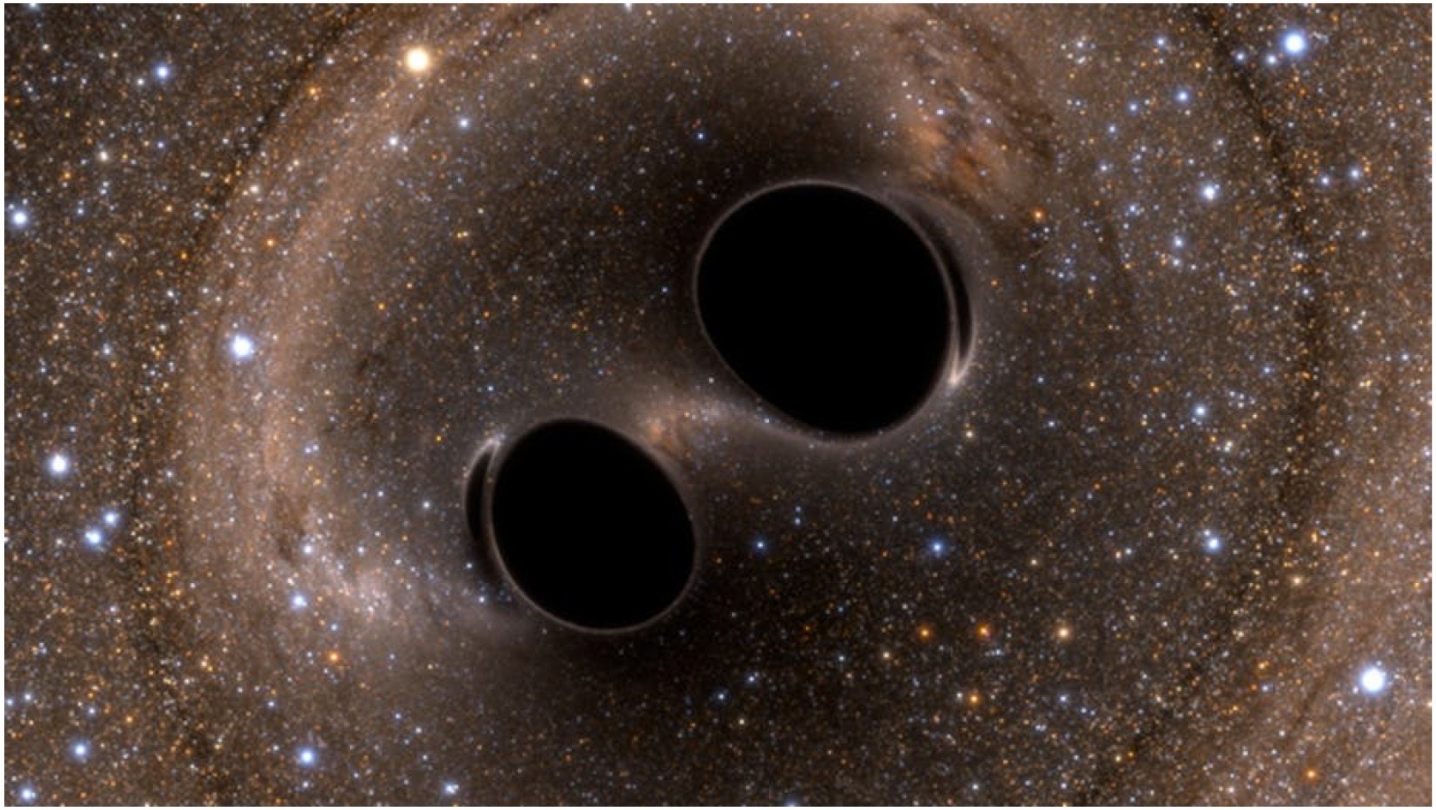
Mergers of super-massive black holes (SMBHs, >10^5 Msun):

Black holes at centre of galaxies might form Keplerian binaries and might merge
Freq. ~ 10^-10 – 0.1 Hz

Mergers of compact object binaries (black holes <10^5 Msun, neutron stars):

Black holes (BHs) and neutron stars (NSs) born from stars might merge

Freq. ~ 10^-4 – 10^3 Hz

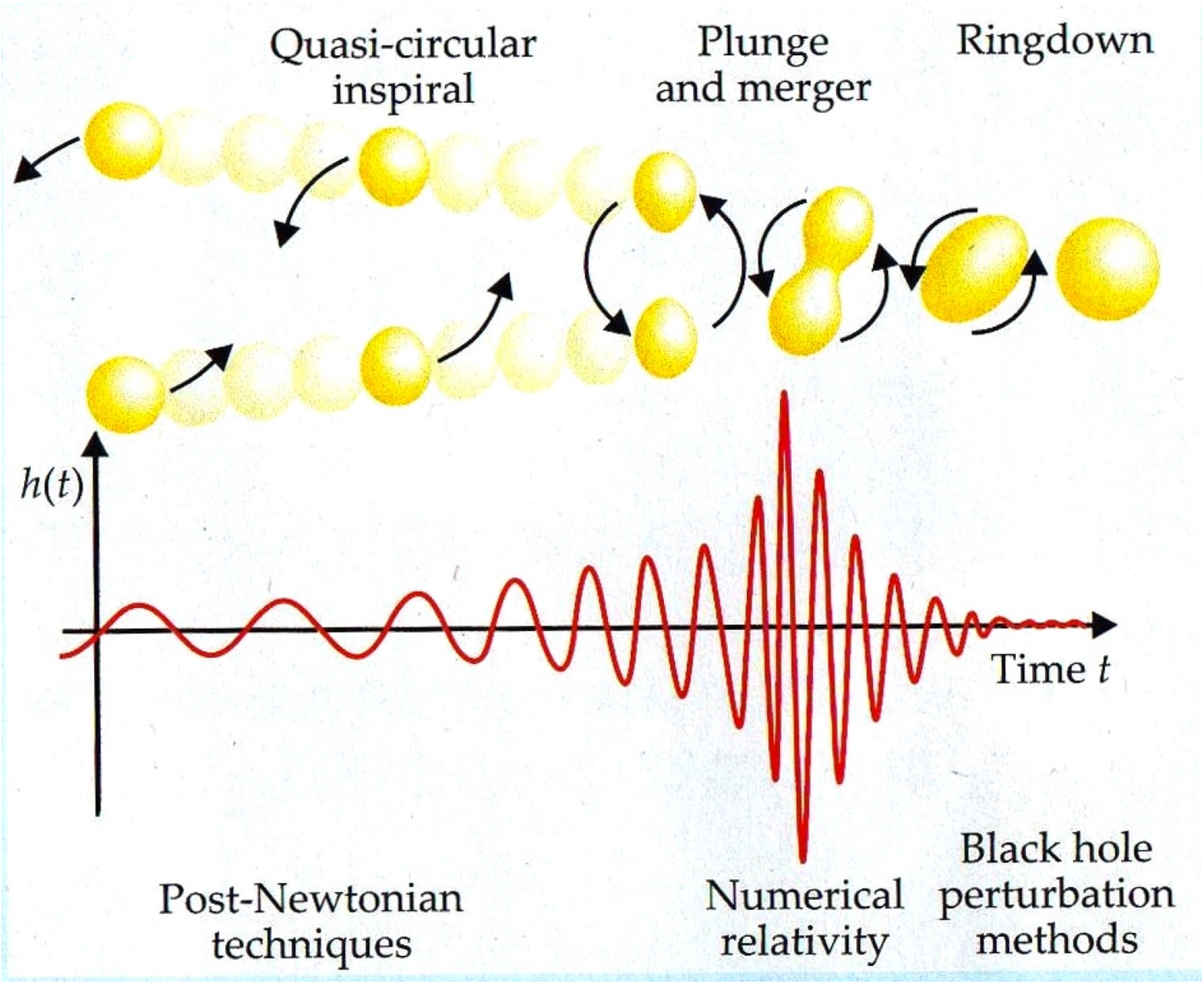


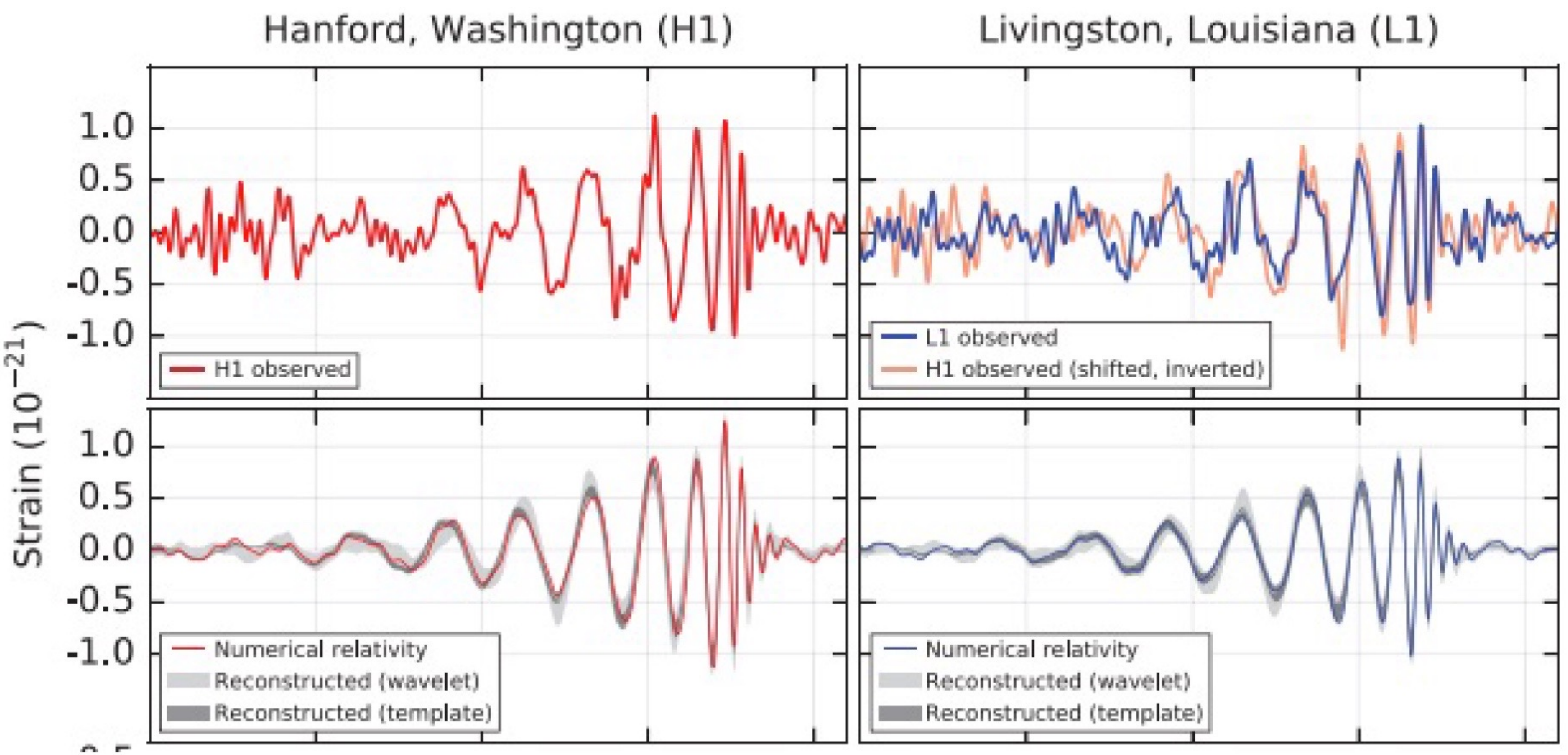
– **EMISSION of GWs implies LOSS of ORBITAL ENERGY:**

$$E_{orb} = -\frac{G\, m_1\, m_2}{2\, a}$$

THE BINARY SHRINKS WHILE EMITTING GWs TILL IT MERGES

https://www.youtube.com/watch?v=g8s81MzzJ5c


Quasi-circular inspiral
Plunge and merger
Ringdown
h(t)
Time t
Post-Newtonian techniques
Numerical relativity
Black hole perturbation methods



Abbott et al. 2016

Detectors:

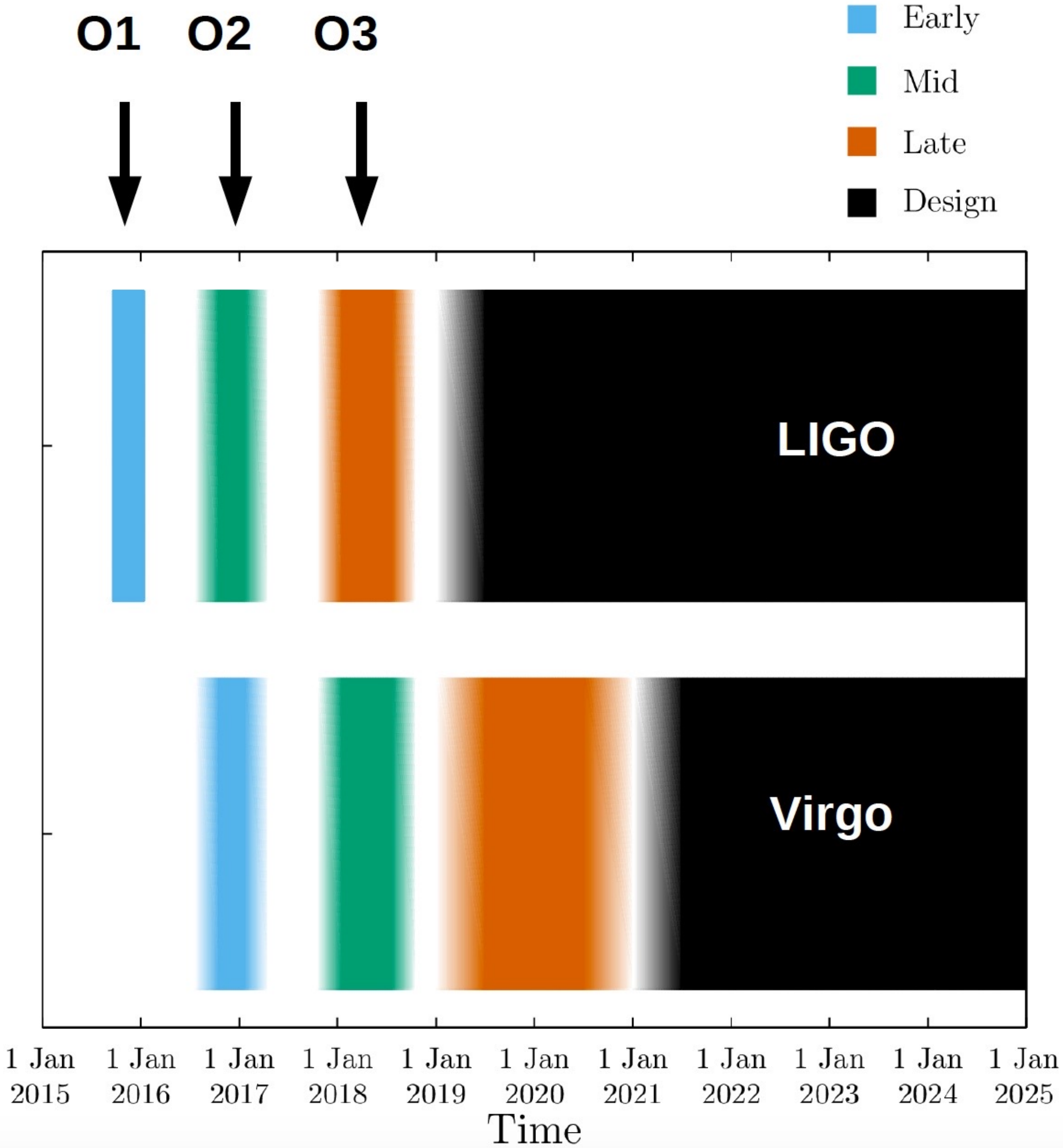
Advanced LIGO (Livingstone + Hanford, US)
Advanced Virgo (Pisa, Italy)

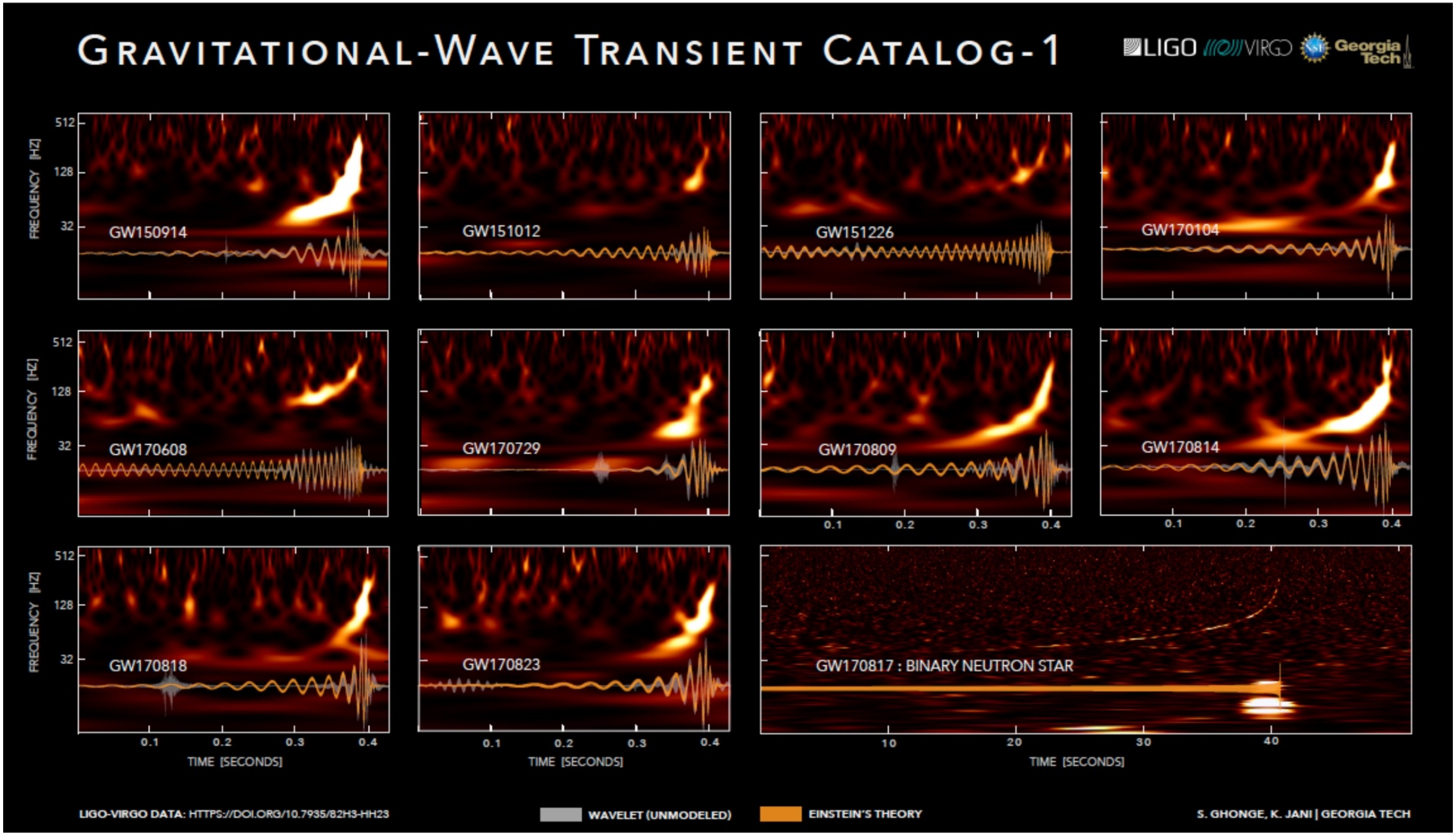
LIGO Lab/Virgo

Michelson interferometers

Design started in the '90s
First science runs ~ 2007 (no detection)
Being upgraded in 2007 – 2015
First run advanced detectors 2015

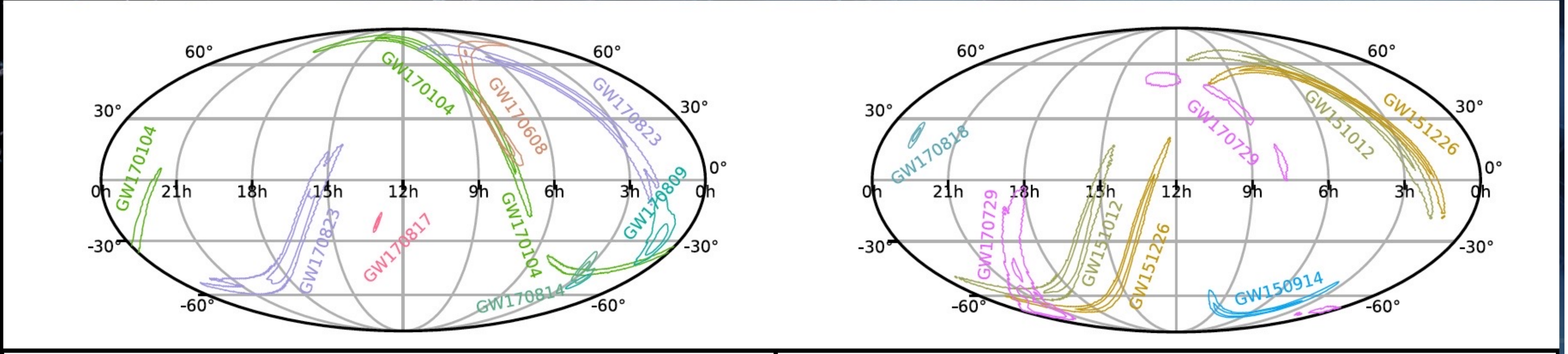
Time schedule





GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

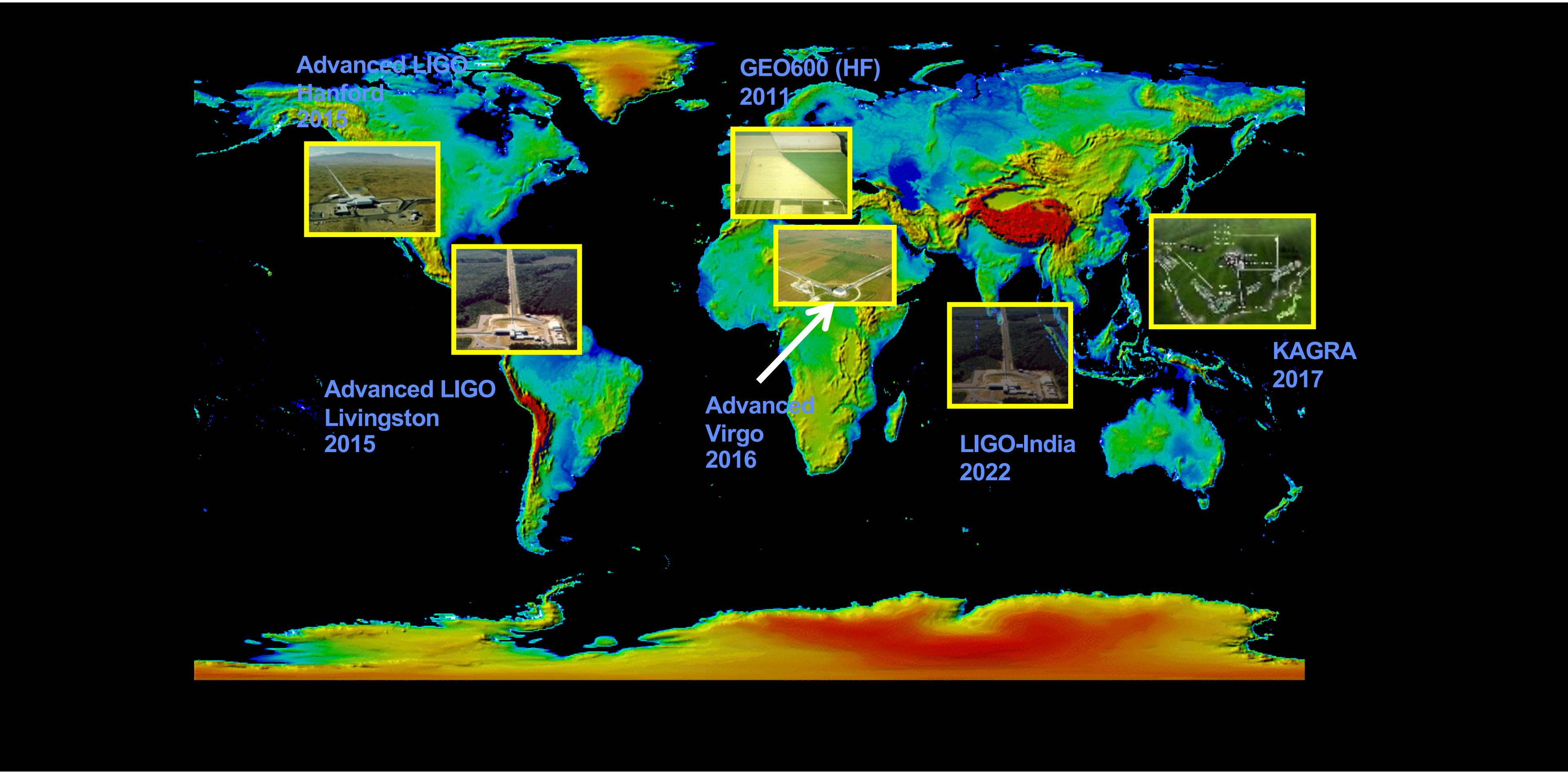
Sky location



O2 GW events for which alerts were sent to EM observers.	O1 + GW170729, GW170818 (not previously released to EM observers)

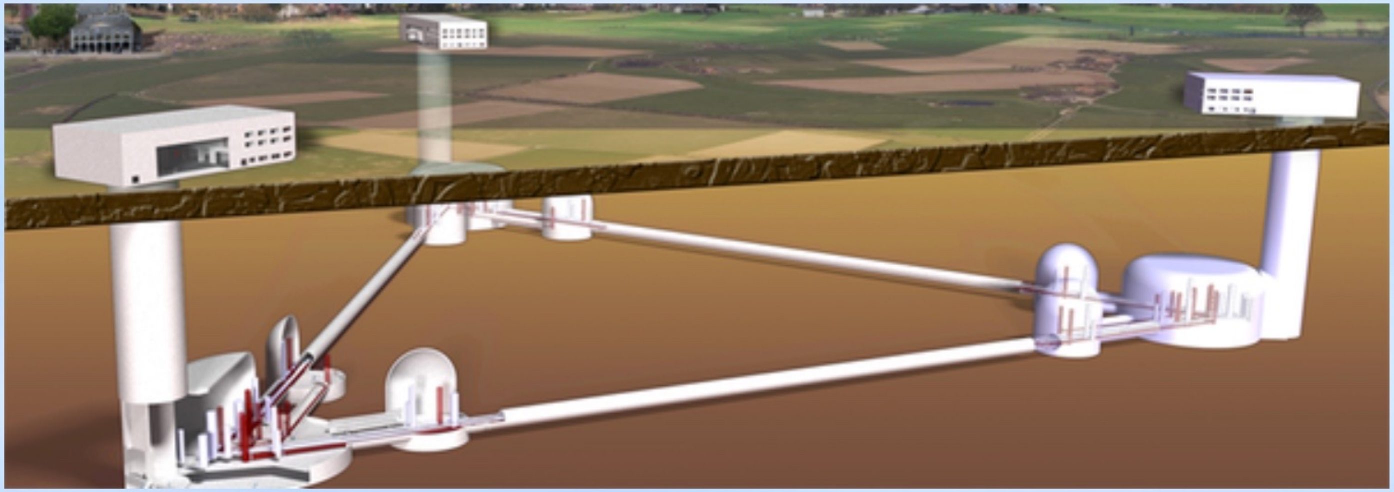
- **Inclusion of Virgo improves sky localization:** importance of a global GW detector network for accurate localization of GW sources
- **GW170818** (LV) is best localized BBH to date: with a 90% area of 39 deg^2
- GW170729 was not identified by the low-latency searches
- Virgo trigger was not included in the significance estimation of GW170818, so as L-only trigger it did not pass the false alarm threshold of the online searches

GW detector network: 2015-2025



Third Generation Gravitational Wave Detectors

Einstein Telescope



Underground to reduced seismic noise.
10 km arms
Cryogenic mirrors
Lower frequency limit – 1 Hz
10 x better sensitivity than 2nd generation detectors
Farther back in the universe

M. Punturo talk

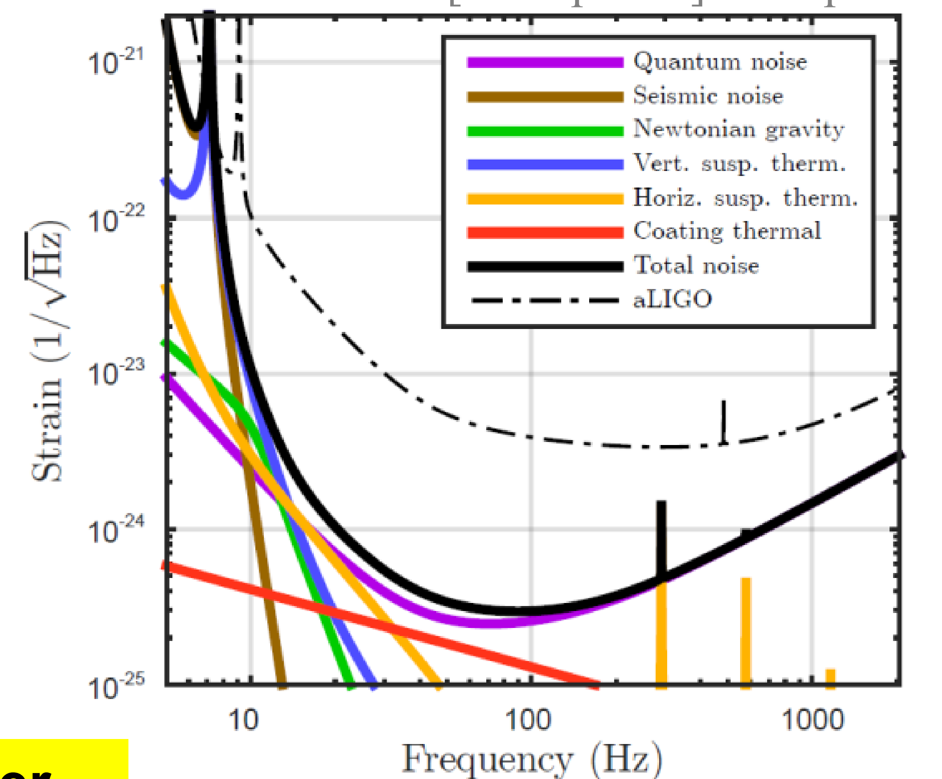
Cosmic Explorer

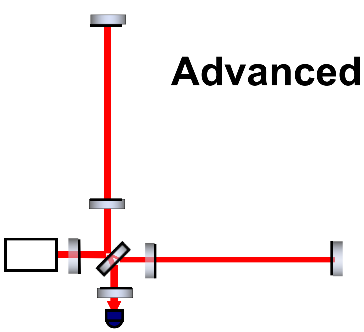
Preliminary Concept

The Cosmic Explorer: x10 aLIGO

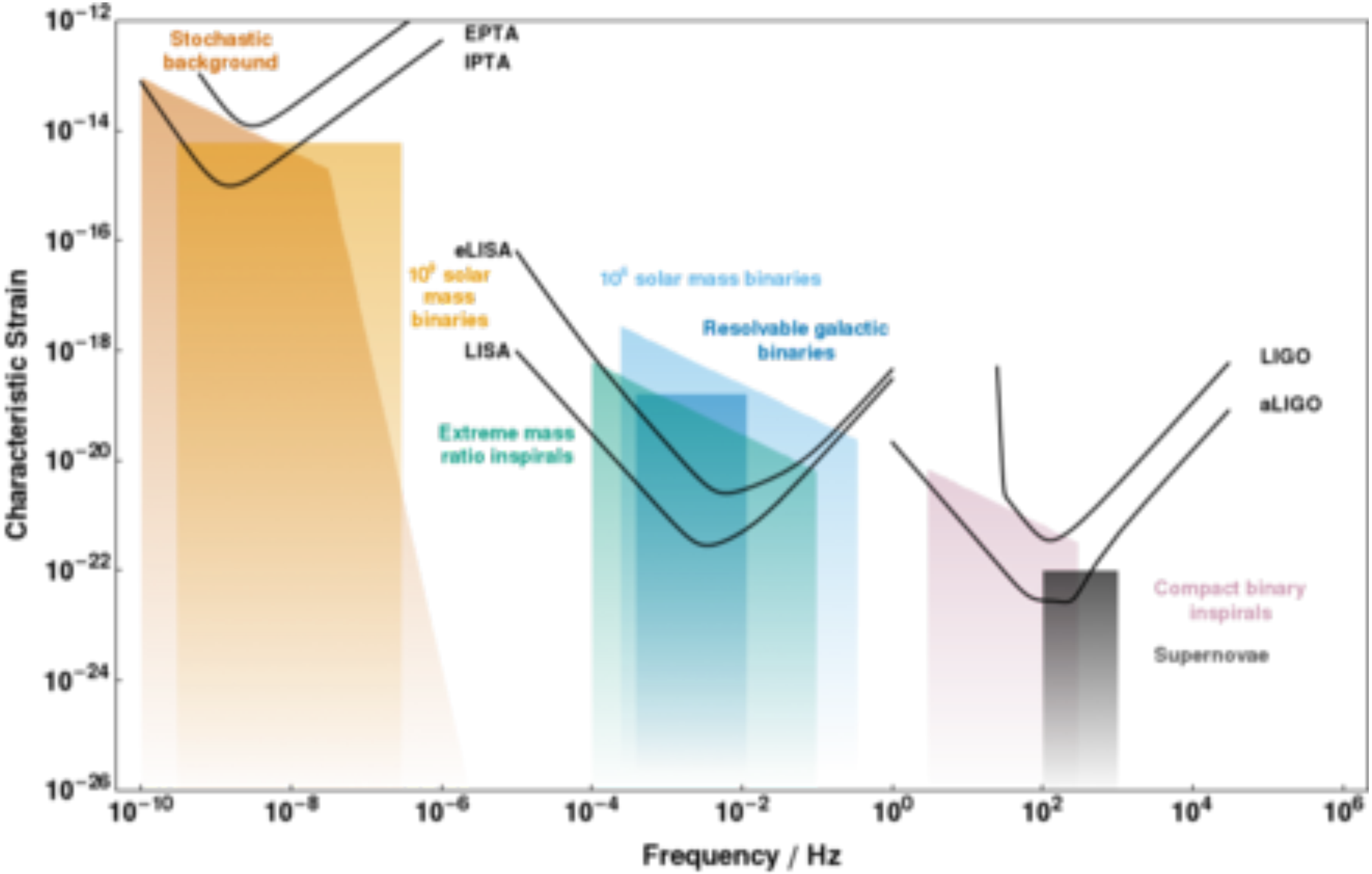
- Earth's Surface;
- 40 km arms
- Advanced LIGO Technology +
- Squeezed Light

arXiv:1607.08697v3 [astro-ph.IM] 11 Sep 2016



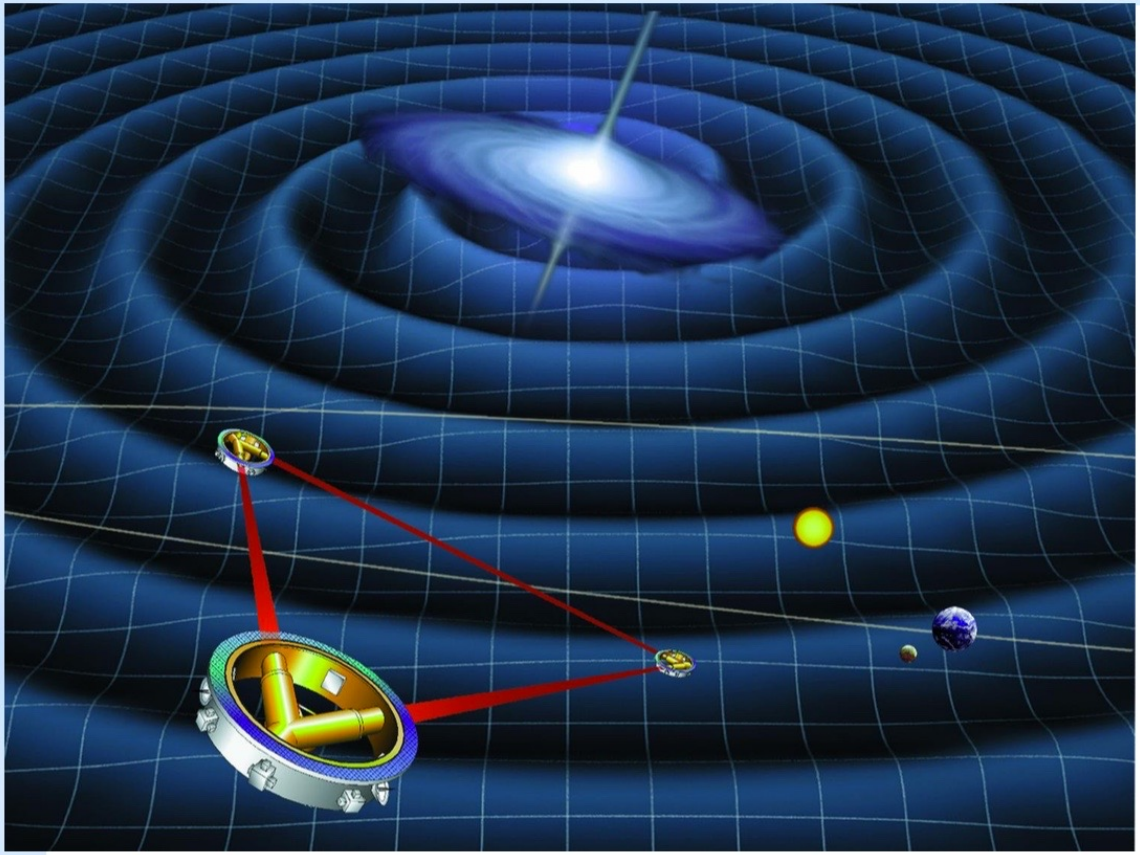


GW detection



Space missions

Laser Interferometer Space Antenna - LISA



Present plan: 3 Interferometers
2.5 x 10^6 km arm lengths

ESA – All Systems GO!

Recent "Call" for mission

Acceptance - soon?

Planned launch 2034

NASA coming back

Earlier launch? 2028?

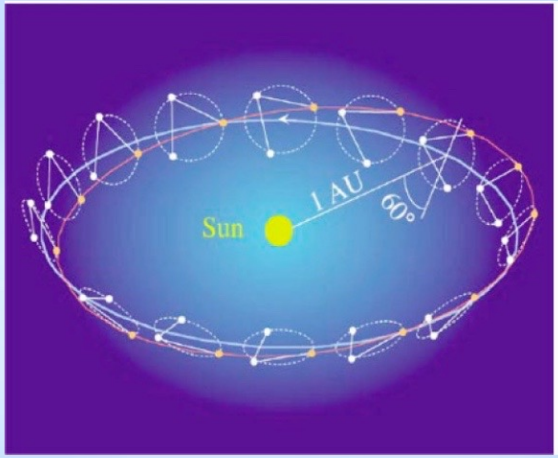
LIGO GW events and Lisa Pathfinder success have helped significantly

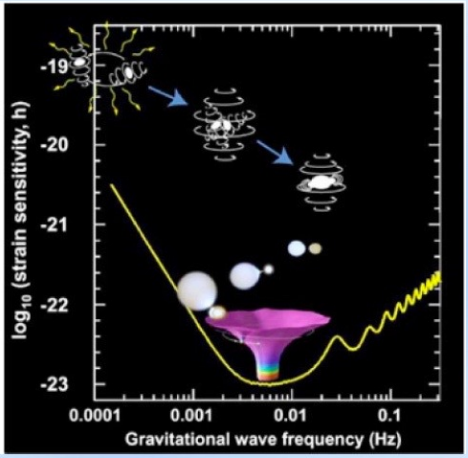
Tremendous activity at present

LISA physics

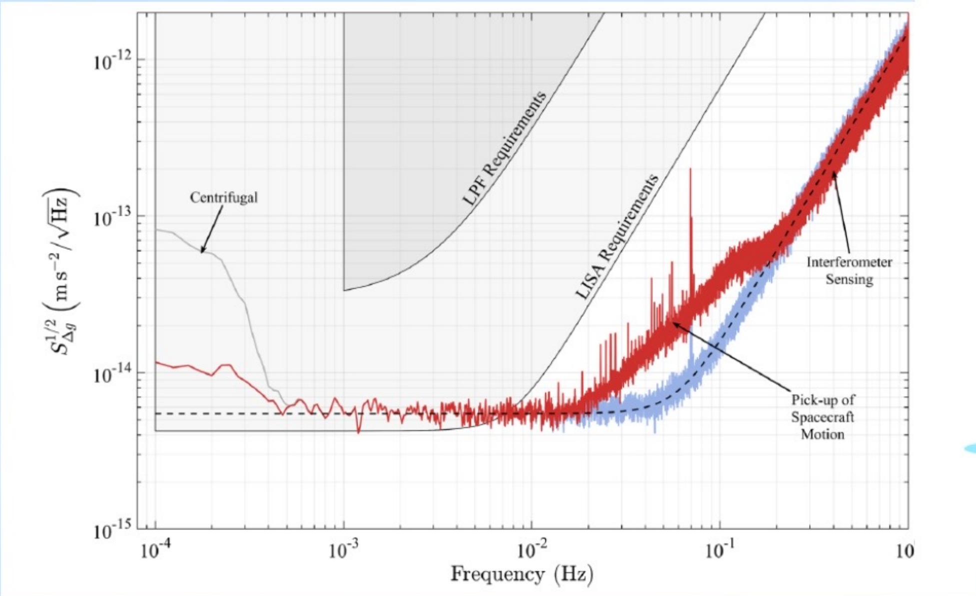
- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

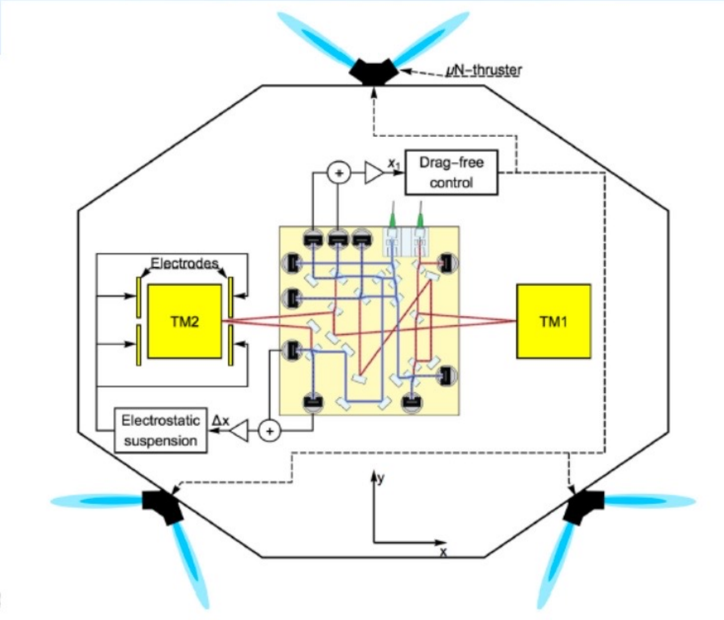
Gravitational Observatory Advisory Team – GOAT (ESA web site)





LISA Pathfinder – Demonstrating LISA Technology



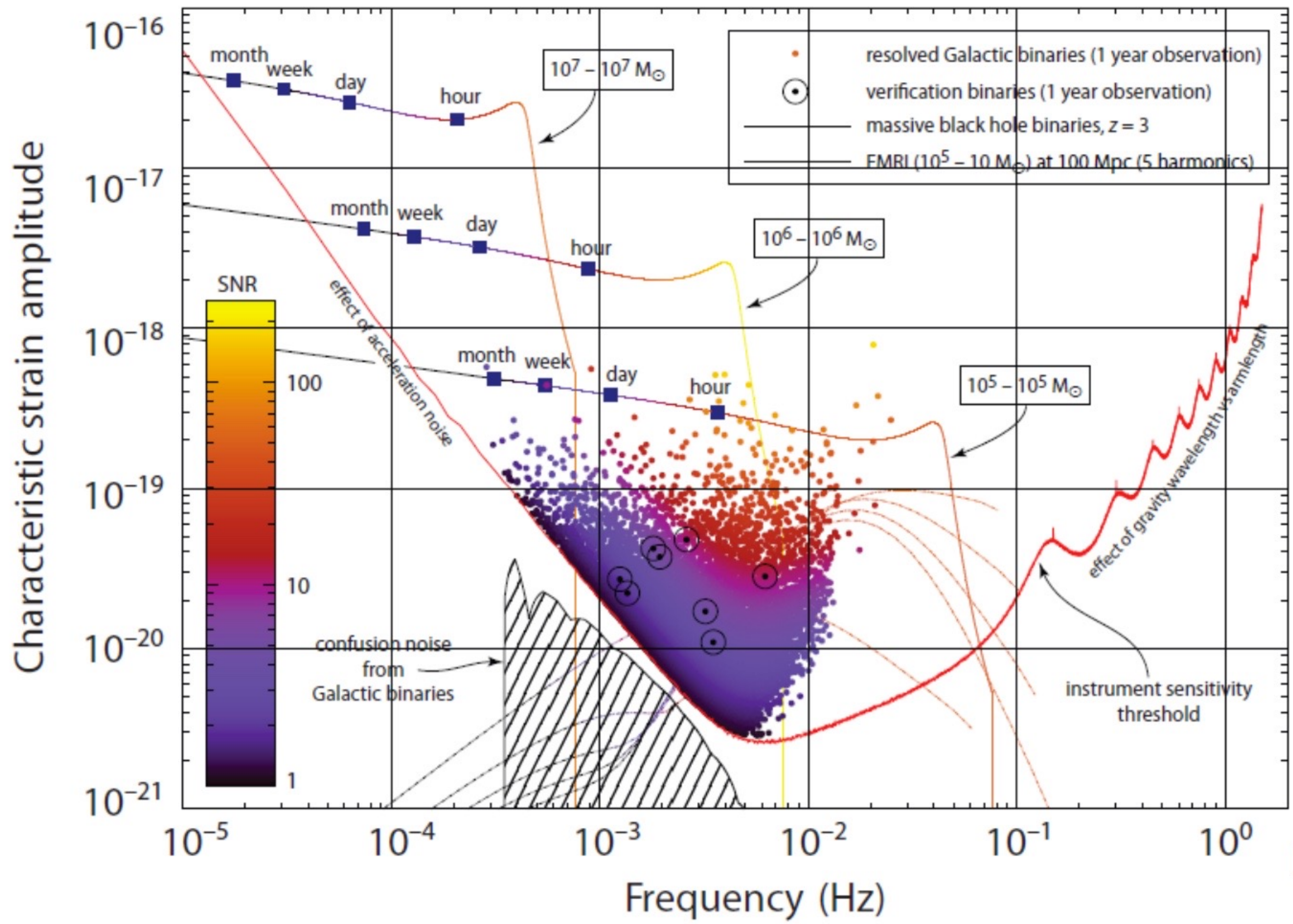


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

A set of cold gas micro-newton thrusters to ensure the spacecraft follows TM1. A second control loop forces TM2 to stay at a fixed distance from TM1 and thus centered in its own electrode housing.

PRL **116**, 231101 (2016)

LISA Physics



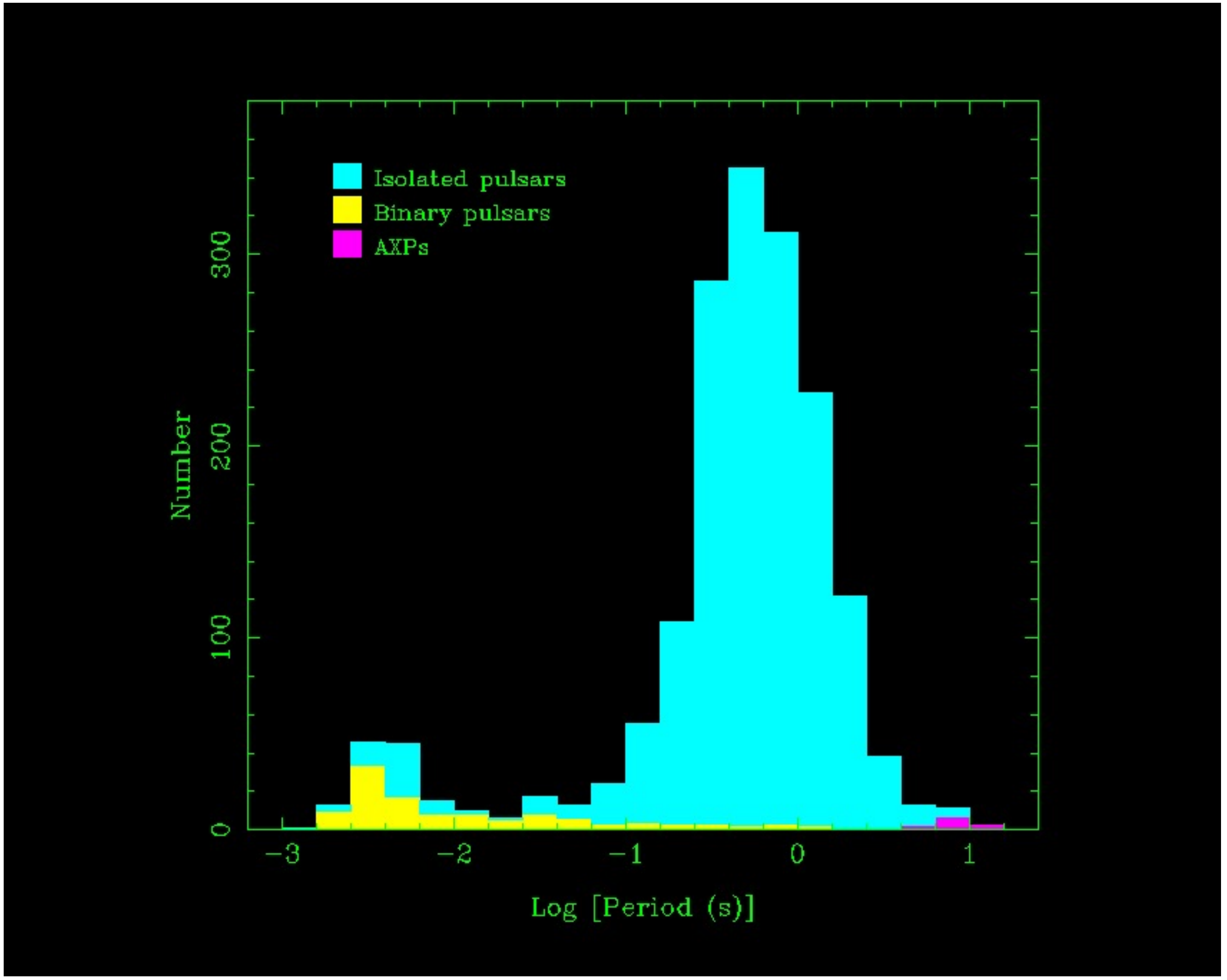
LISA GOAT

Characteristic strain amplitude versus frequency for a space-based laser interferometry mission (armlength 10^6 km, 1-yr observations). Objects expected to be strong gravitational wave sources over this frequency range.

Pulsar Timing Arrays

Spin-Powered Pulsars: A Census

- Number of known pulsars: 1765
- Number of millisecond pulsars: 170
- Number of binary pulsars: 131
- Number of AXPs: 12
- Number of pulsars in globular clusters: 99*
- Number of extragalactic pulsars: 20

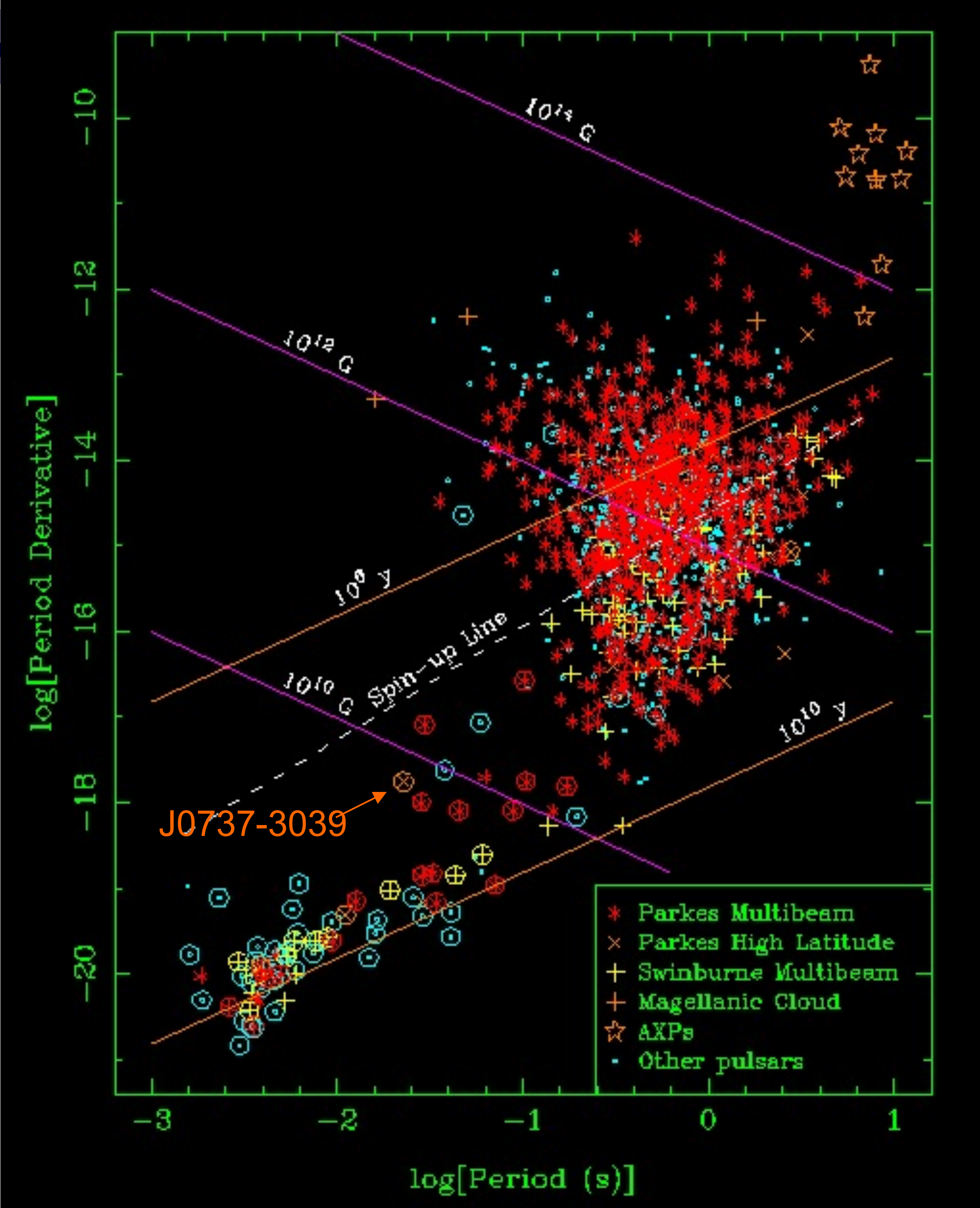


* Total known: 129 in 24 clusters (Paulo Freire's web page)

Data from ATNF Pulsar Catalogue, V1.25 (www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)

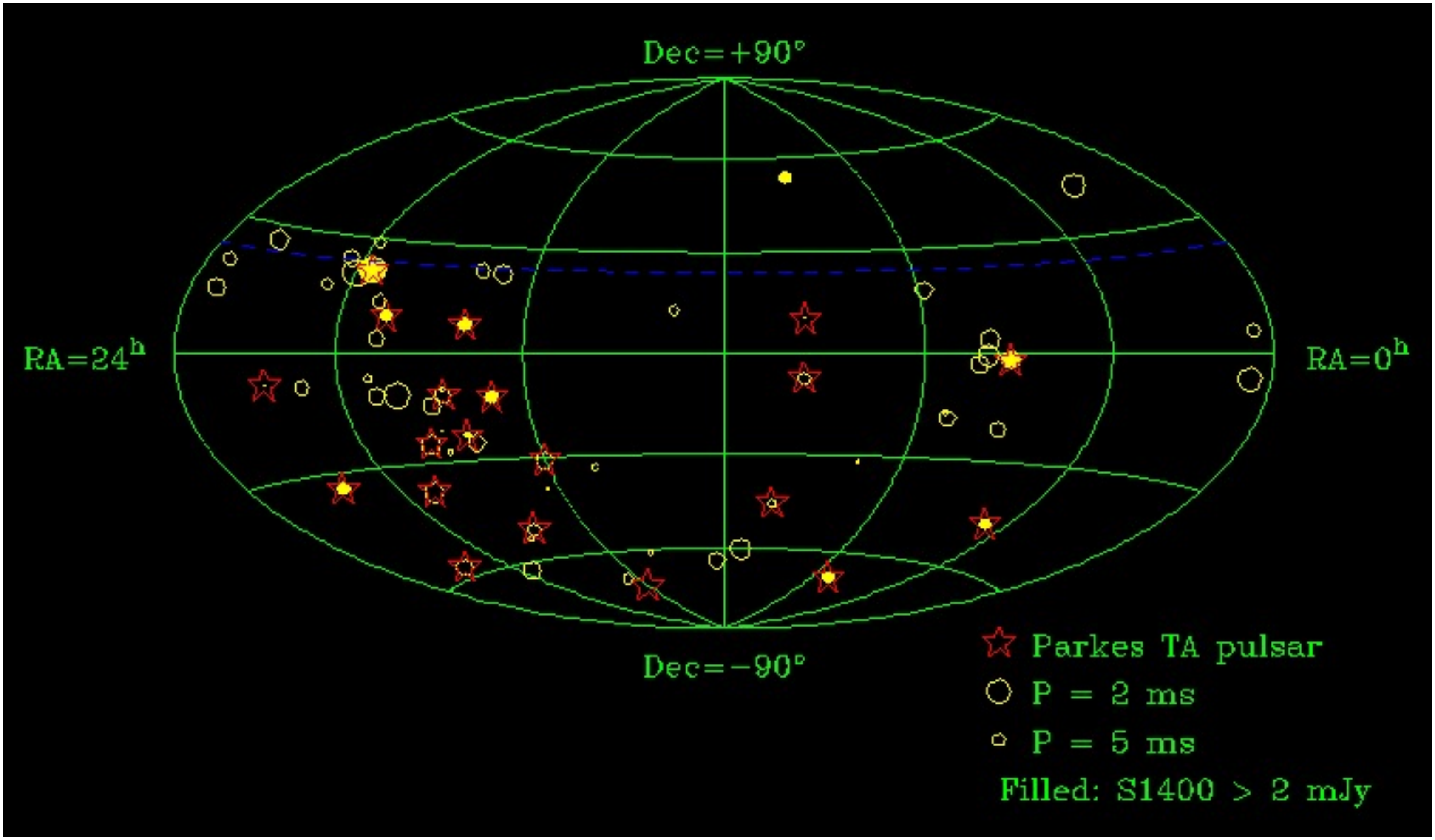
P - P Diagram

- Millisecond pulsars have very low P and are very old
- Most MSPs are binary
- MSPs are formed by ‘recycling’ an old pulsar in an evolving binary system
- ‘Normal’ pulsars have significant period irregularities, but MSP periods are very stable



Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters



PPTA Pulsars

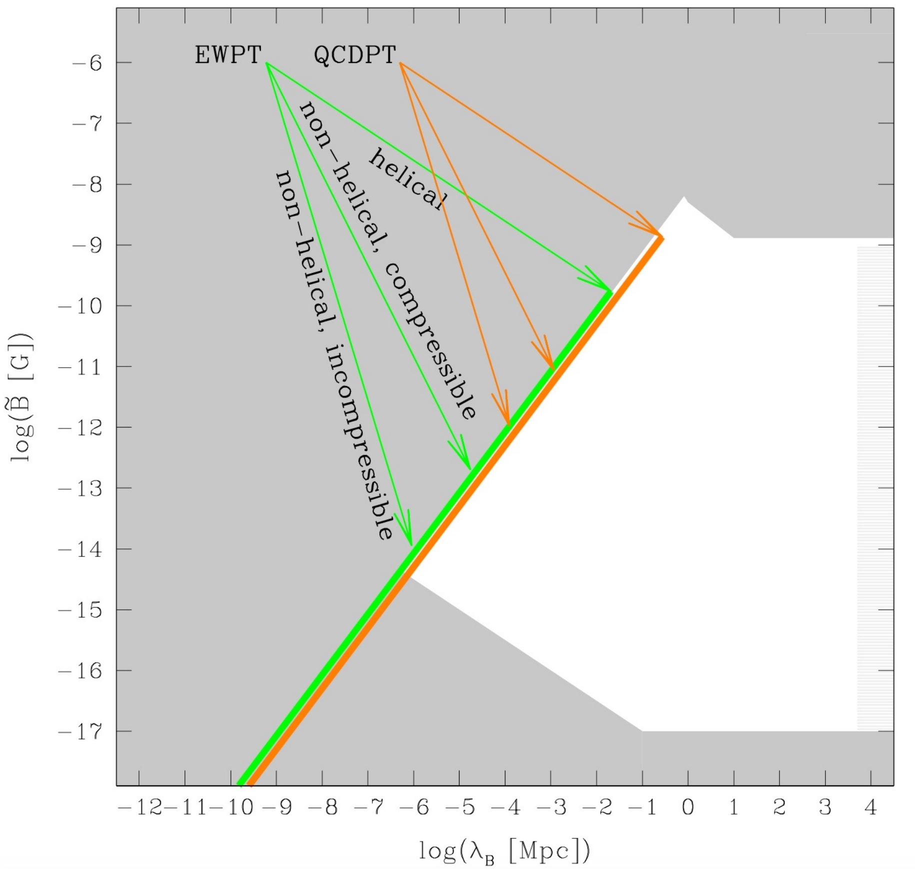
- 20 MSPs - all in Galactic disk except J1824-2452 (B1821-24) in M28
- Two years of timing data at 2 -3 week intervals and at three frequencies
- Uncorrected for DM variations and polarisation calibration
- Five pulsars with rms timing residuals < 500 ns, all < 2.5 μs
- Best results on J0437-4715 (120 ns) and B1937+21 (170 ns)

Still have a way to go!

Name	Period (ms)	DM (cm^{-3} pc)	Orbital period (d)	Rms Residual (μs)
J0437-4715	5.757	2.65	5.74	0.12
J0613-0200	3.062	38.78	1.20	0.83
J0711-6830	5.491	18.41	-	1.56
J1022+1001	16.453	10.25	7.81	1.11
J1024-0719	5.162	6.49	-	1.20
J1045-4509	7.474	58.15	4.08	1.44
J1600-3053	3.598	52.19	14.34	0.35
J1603-7202	14.842	38.05	6.31	1.34
J1643-1224	4.622	62.41	147.02	2.10
J1713+0747	4.570	15.99	67.83	0.19
J1730-2304	8.123	9.61	-	1.82
J1732-5049	5.313	56.84	5.26	2.40
J1744-1134	4.075	3.14	-	0.65
J1824-2452	3.054	119.86	-	0.88
J1857+0943	5.362	13.31	12.33	2.09
J1909-3744	2.947	10.39	1.53	0.22
J1939+2134	1.558	71.04	-	0.17
J2124-3358	4.931	4.62	-	2.00
J2129-5721	3.726	31.85	6.63	0.91
J2145-0750	16.052	9.00	6.84	1.44

Multi-messenger observation of signal from QCD phase transition

IGMF from phase transitions



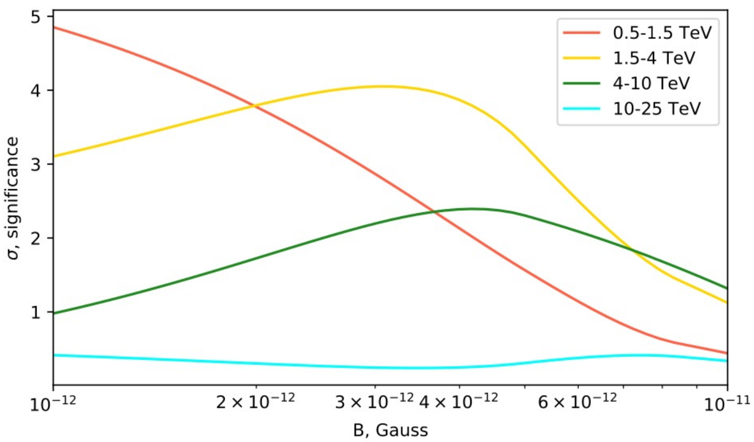
R.Durrer and A.Neronov, A&A Rev. 21 62, [1303.7121].

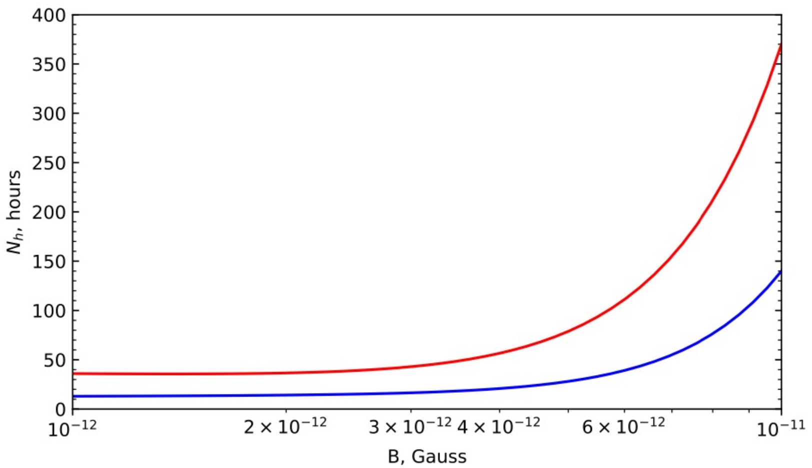
H0 with PMF 10-50 pG

	Planck ΛCDM	Planck+H3 ΛCDM	Planck+H3 M1	Planck+H3 M2
$\Omega_b h^2$	0.02237 ± 0.00015	0.02263 ± 0.00014	$0.02270^{+0.00014}_{-0.00016}$	0.02280 ± 0.00016
$\Omega_c h^2$	0.1200 ± 0.0012	0.1172 ± 0.0011	0.1216 ± 0.0014	0.1191 ± 0.0012
τ	0.0546 ± 0.0075	$0.0629^{+0.0075}_{-0.0087}$	0.0555 ± 0.0073	$0.0607^{+0.0071}_{-0.0085}$
n_s	0.9651 ± 0.0041	0.9721 ± 0.0040	0.9628 ± 0.0040	0.9734 ± 0.0042
$b^{(a)}$	-	-	$0.61^{+0.16(0.35)(0.57)}_{-0.20(0.33)(0.42)}$	$0.30 \pm 0.11(0.22)(0.34)$
H_0	67.37 ± 0.54	68.70 ± 0.50	71.03 ± 0.74	69.81 ± 0.62
Ω_m	0.3151 ± 0.0074	0.2977 ± 0.0064	0.2873 ± 0.0064	0.2926 ± 0.0064
σ_8	0.8113 ± 0.0060	0.8080 ± 0.0064	0.8265 ± 0.0079	0.8192 ± 0.0075
S_8	0.831 ± 0.013	0.805 ± 0.012	0.809 ± 0.012	0.809 ± 0.012
z_*	1089.91 ± 0.26	1089.35 ± 0.24	$1107.9^{+4.2}_{-3.6}$	$1096.8^{+2.6}_{-2.0}$
r_*	144.44 ± 0.27	144.96 ± 0.25	142.22 ± 0.65	143.69 ± 0.48
$z_{\rm drag}$	1059.94 ± 0.30	1060.33 ± 0.29	$1076.9^{+3.8}_{-3.4}$	$1067.4^{+2.4}_{-2.0}$
$r_{\rm drag}$	147.10 ± 0.27	147.55 ± 0.25	144.89 ± 0.64	146.28 ± 0.49
$r_{\rm drag} h$	99.11 ± 0.93	101.36 ± 0.87	102.91 ± 0.92	102.11 ± 0.89
$\chi^2_{\rm lensing}$	9.23 ± 0.70 (8.73)	9.6 ± 1.2 (8.74)	9.20 ± 0.66 (8.91)	9.33 ± 0.80 (9.39)
$\chi^2_{\rm plik}$	2359.5 ± 6.2 (2347.6)	2364.0 ± 6.6 (2350.93)	2366.2 ± 6.7 (2355.6)	2367.4 ± 7.1 (2359.2)
$\chi^2_{\rm lowl}$	23.40 ± 0.86 (23.18)	22.36 ± 0.72 (22.76)	24.30 ± 0.97 (24.0)	22.37 ± 0.72 (21.9)
$\chi^2_{\rm simall}$	397.0 ± 1.8 (396.0)	399.0 ± 3.3 (397.2)	397.0 ± 1.7 (395.6)	398.2 ± 2.7 (396.3)
$\chi^2_{\rm prior}$	11.6 ± 4.6 (4.46)	11.6 ± 4.6 (4.38)	11.6 ± 4.5 (4.21)	11.9 ± 4.6 (3.42)
$\chi^2_{\rm CMB}$	2789.1 ± 6.4 (2775.5)	2794.9 ± 7.2 (2779.7)	2796.8 ± 6.9 (2784.2)	2797.3 ± 7.3 (2786.8)
$\chi^2_{\rm H3}$	-	22 ± 4 (24.92)	6.1 ± 3.4 (5.74)	12.9 ± 4.2 (9.62)
$\chi^{2({\rm tot})}_{\rm bestfit}$	2779.9	2809.0	2794.1	2799.9

K.Jedamzik and L. Pogosian 2004.09487

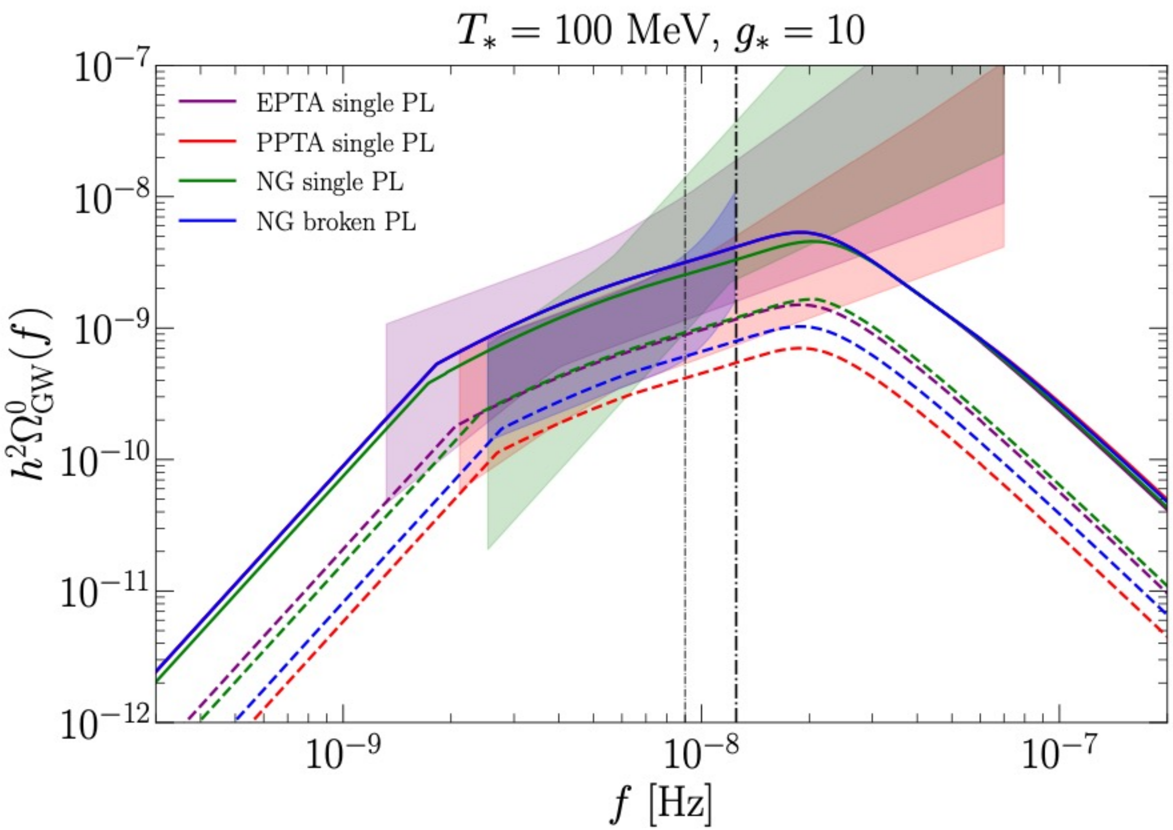
Detection of extended emission around Mkn 501 by CTA North for 1-10 pG IGMF





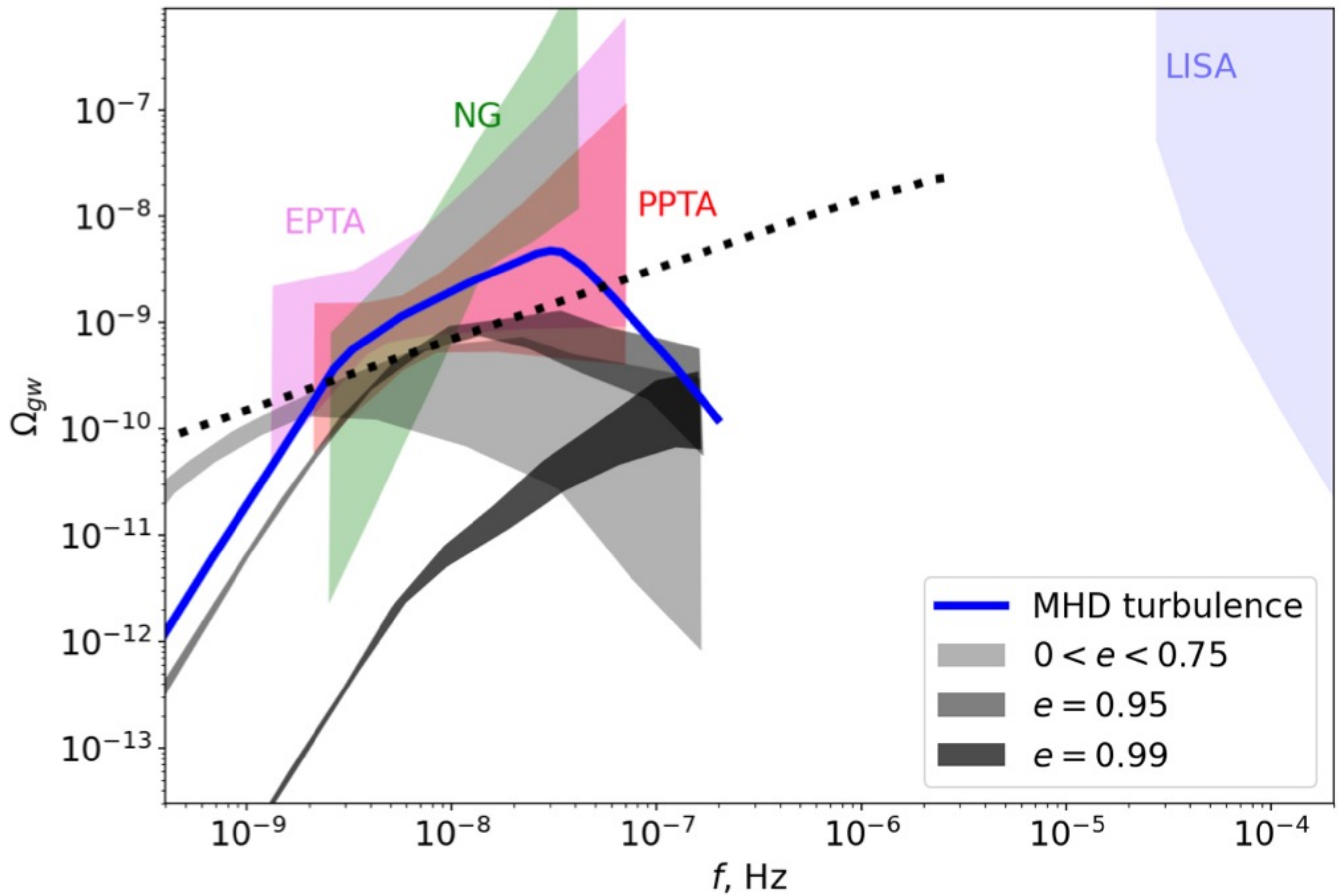
Kalashev et al, 2007.14331

Pulsar Timing Arrays GW QCD



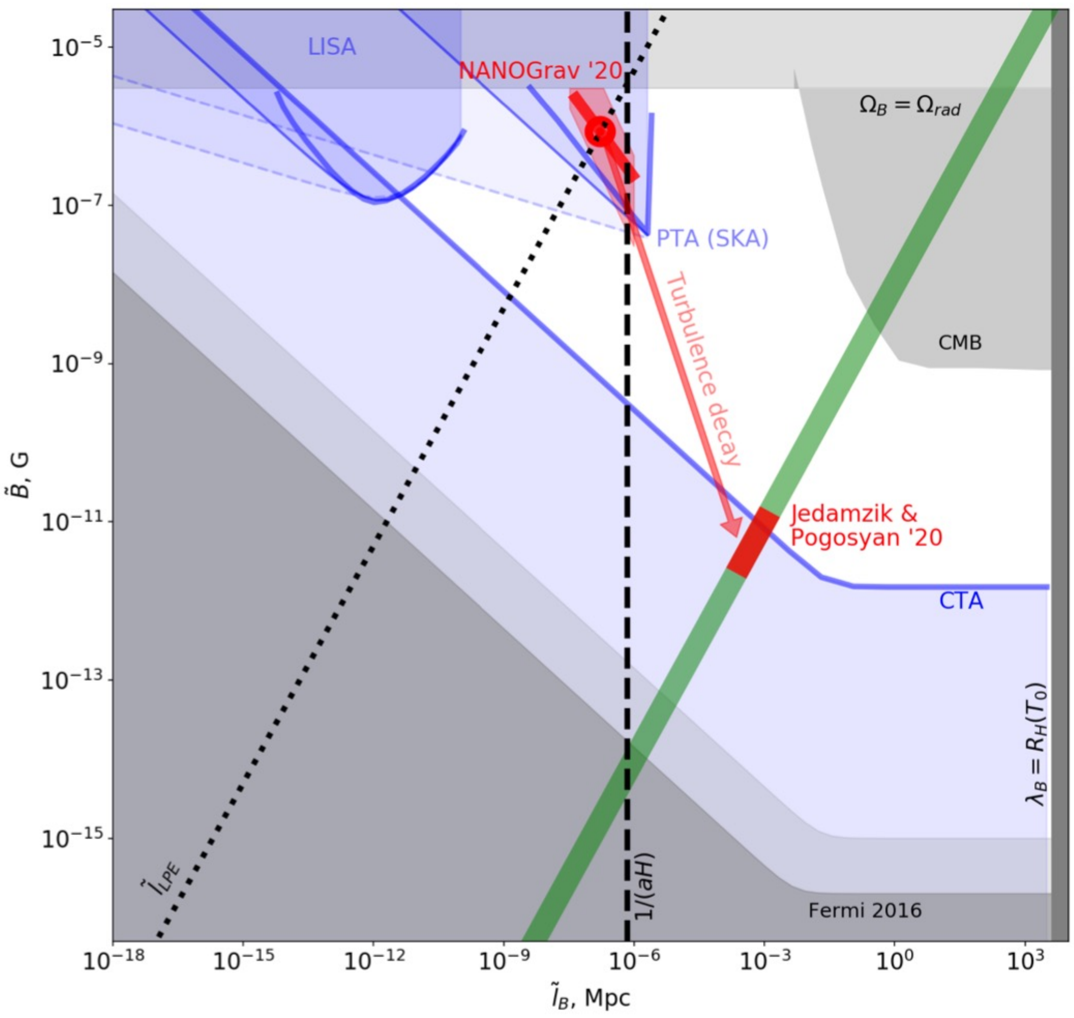
A. Neronov et al., 2201.05630

Pulsar Timing Arrays GW BH



A. Neronov et al., 2201.05630

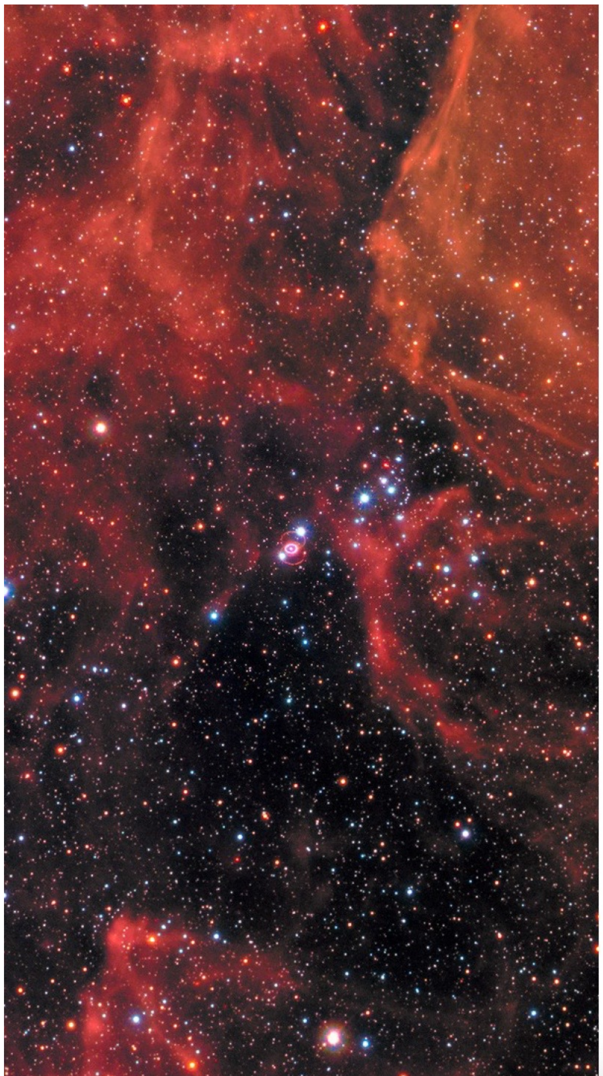
IGMF from QCD phase transition



A. Neronov et al., 2009.14174

Multi-messenger observation of binary neutron star collision

First multi-messenger observation: SN1987A



Annu. Rev. Astron. Astrophys. 1989. 27: 629–700

SUPERNOVA 1987A

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1. INTRODUCTION

On February 23.316 UT, 1987, light and neutrinos from the brightest supernova in 383 years arrived at Earth, shocking astrophysicists into a frenzied state of activity. Since that time Supernova 1987A (SN 1987A) has taken its pla… astronomy, but also as one of the most thoroughly studied objects outside the solar system. Detected by instruments on the ground, below the ground, in space, and from … from all continents, including Antarctica. Studied at all wavelengths from radio through gamma rays, SN 1987A is the only object besides the Sun to have been detected in neutrinos. From these extensive observations has emerged

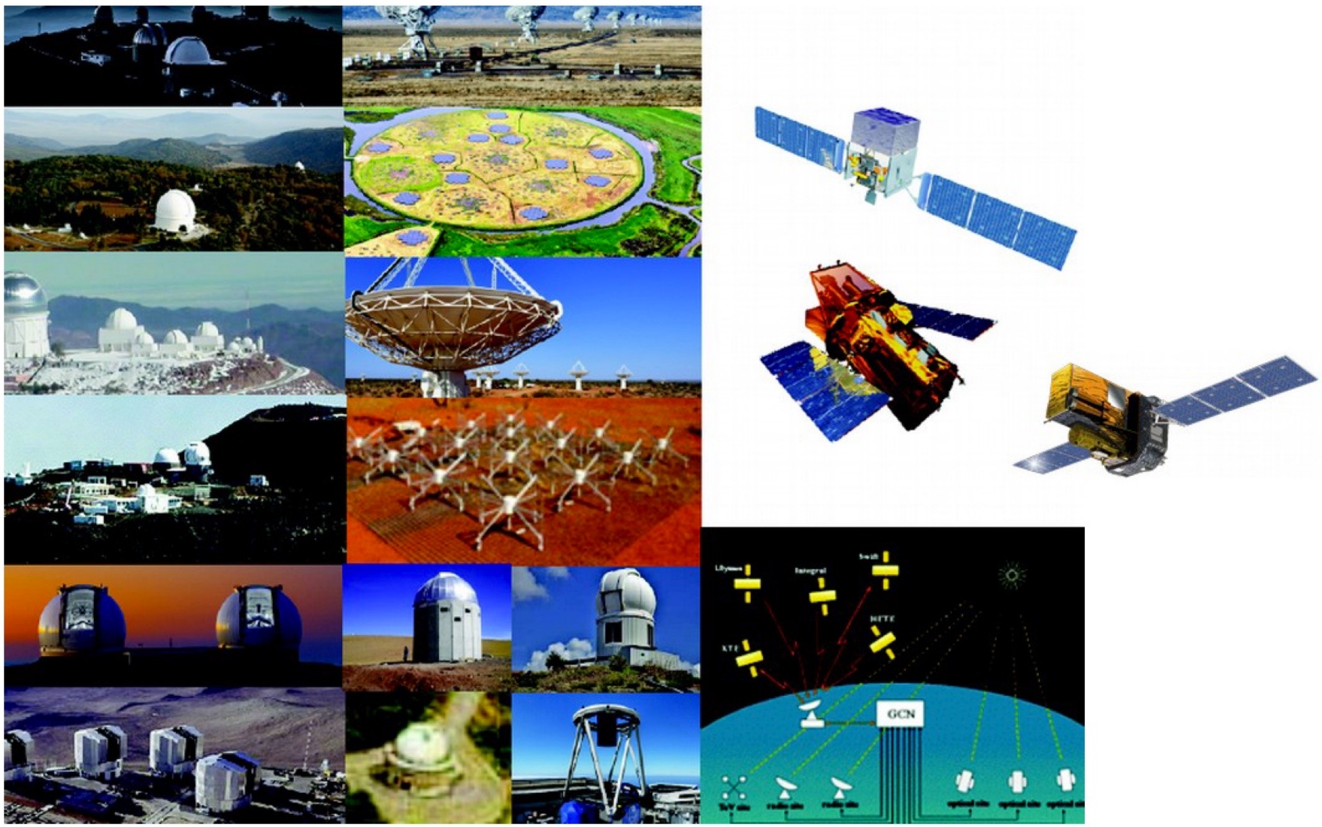
“Multimessenger”

Neutrinos and photons

1300 papers on SN1987A

Binary neutron stars

Network for multi-messenger observations with GW



2009 – Prototype demonstration of online analysis and alert testing
2013 – Initiate global discussion about GW-EM follow-up program
2017 – Memoranda of Understanding signed with **90+ groups around the globe**

Observation of binary neutron star merger

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
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Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of $\sim$1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_\odot$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at $\sim$40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over $\sim$10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position $\sim$9 and $\sim$16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

1. Introduction

Over 80 years ago Baade & Zwicky (1934) proposed the idea of neutron stars, and soon after, Oppenheimer & Volkoff (1939) carried out the first calculations of neutron star models. Neutron stars entered the realm of observational astronomy in the 1960s by providing a physical interpretation of X-ray emission from

Heuvel 1975; Massevitch et al. 1976; Clark 1979; Clark et al. 1979; Dewey & Cordes 1987; Lipunov et al. 1987; for reviews see Kalogera et al. 2007; Postnov & Yungelson 2014). The Hulse-Taylor pulsar provided the first firm evidence (Taylor & Weisberg 1982) of the existence of gravitational waves (Einstein 1916, 1918) and sparked a renaissance of observational tests of general relativity (Damour & Taylor 1991, 1992;

56 teams and collaborations

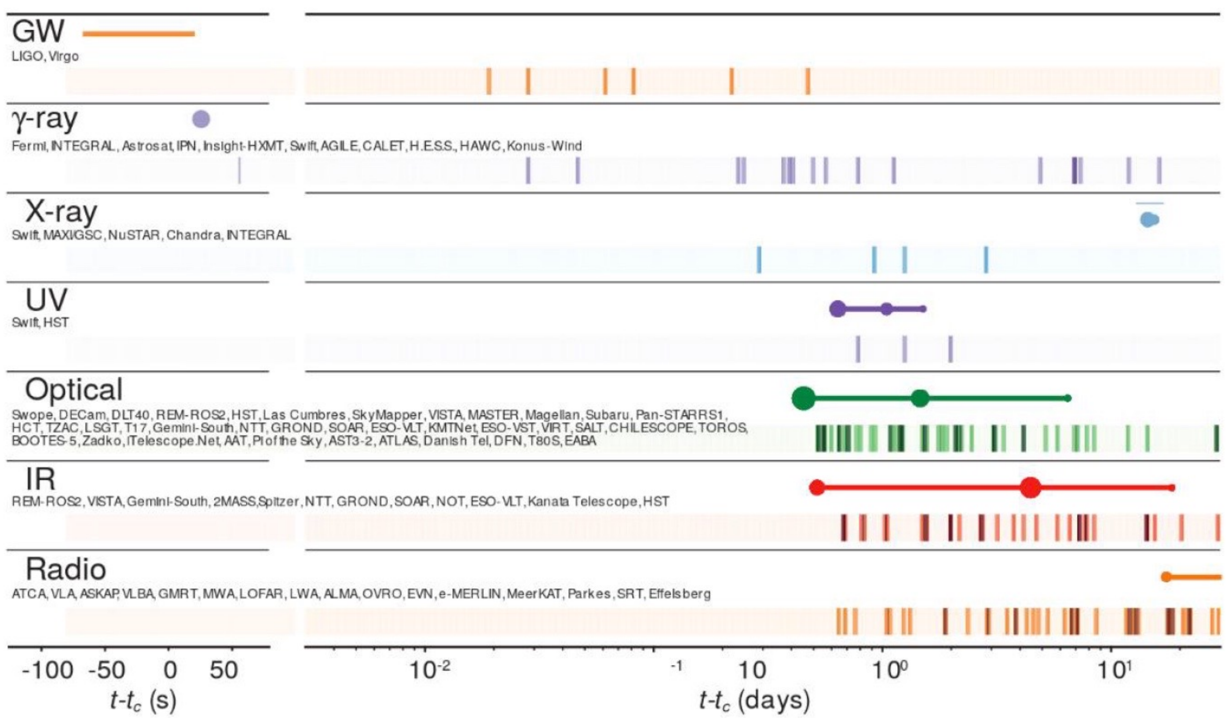
3600 co-authors, 900 institutes

What is the sequence of observations?

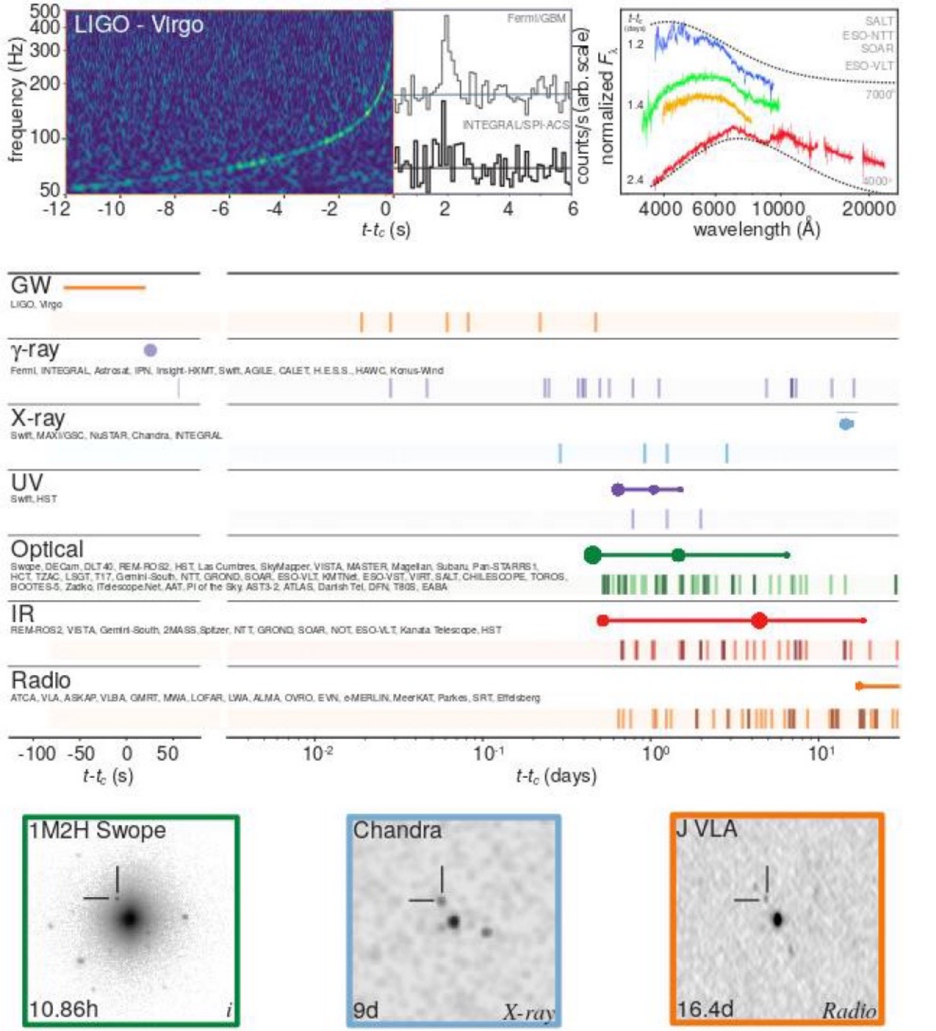
First hints of interpretation

« The big picture »

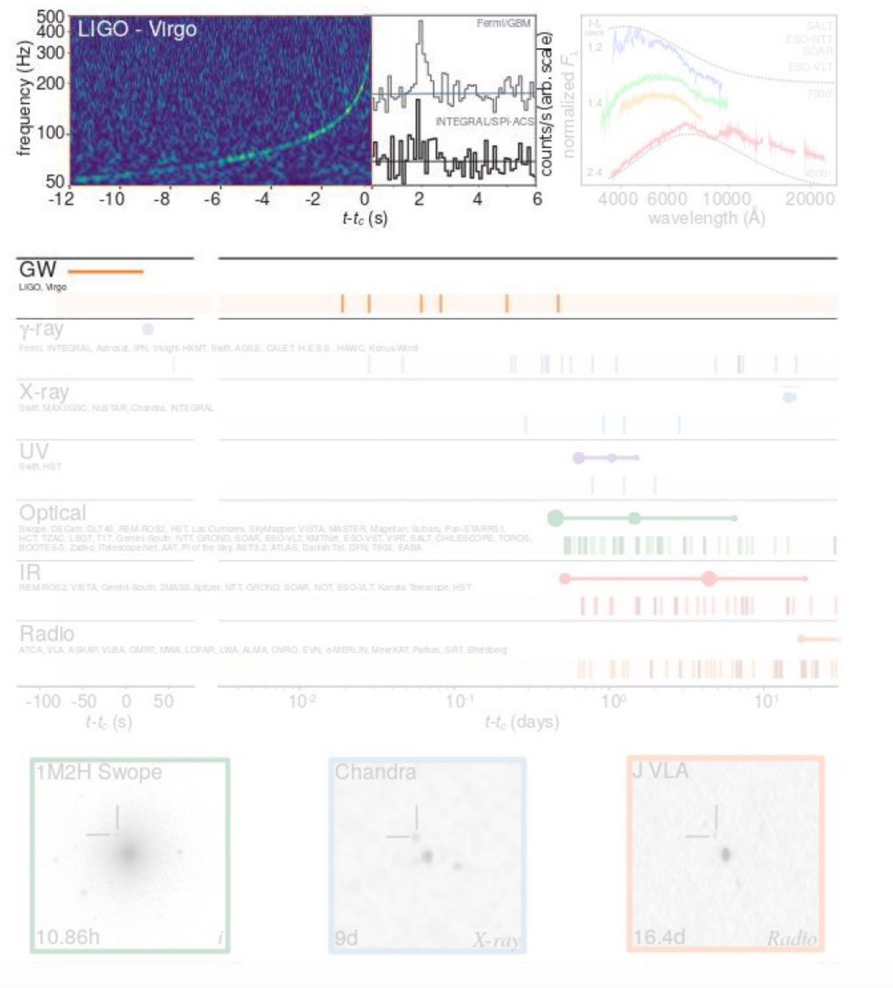
- A guide to the jungle of **80+ articles**
- An exhaustive record for the **192 ! GCN Notices** exchanged about GW170817



Main discoveries

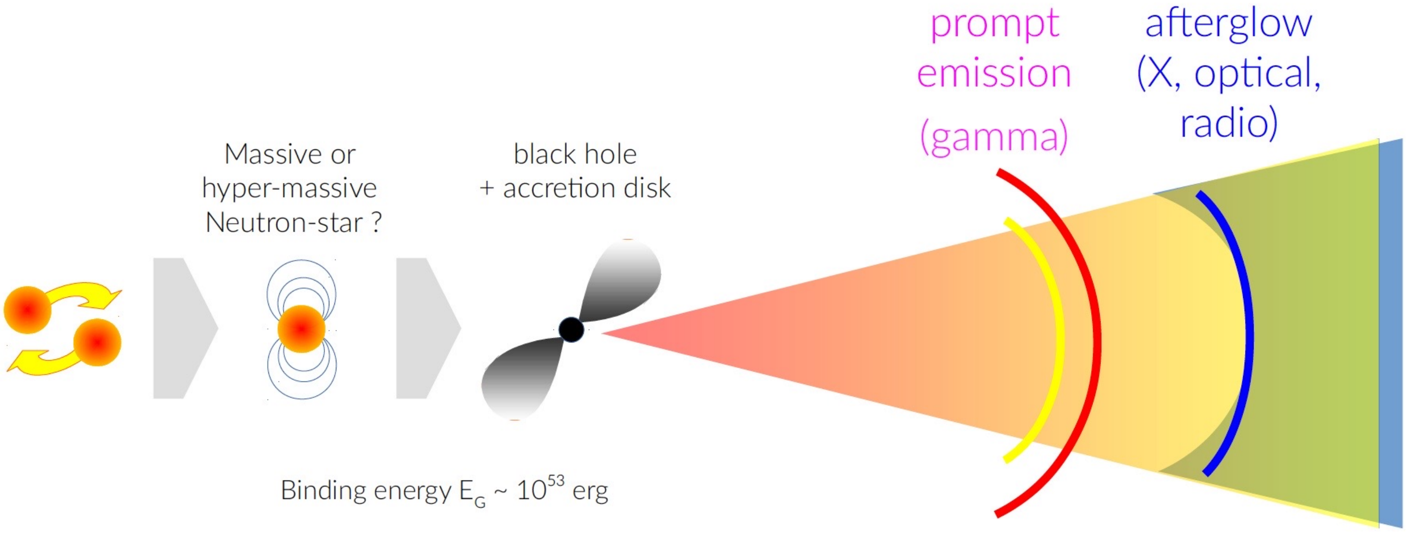


Main discoveries (1)



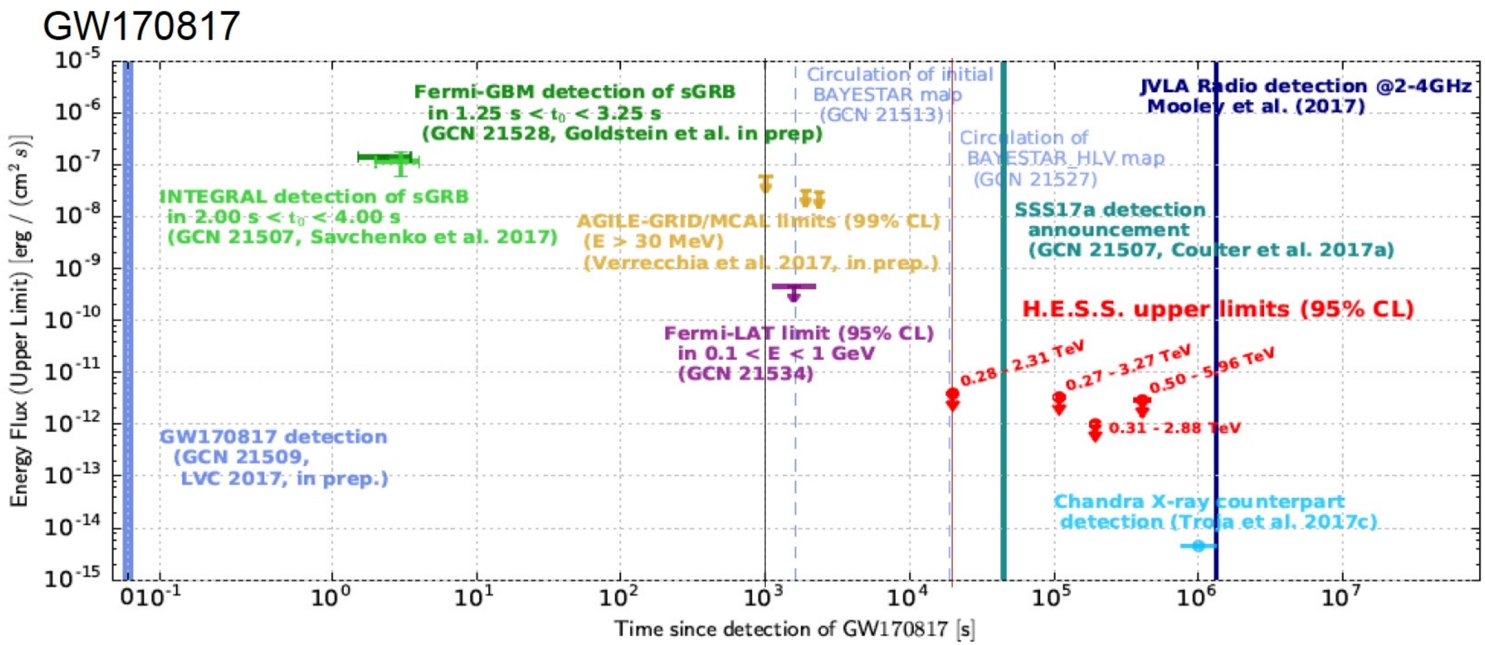
Short gamma-ray burst – GRB170817A

"Fireball model"



- E_{iso} ~ 5 x 10^{46} erg, 10,000 x less than usual
  - This is **not a standard "on-axis"** short GRB – Off-axis ?
- 1.7 s after the merger
  - Favors hyper massive neutron star (life time ~ seconds)

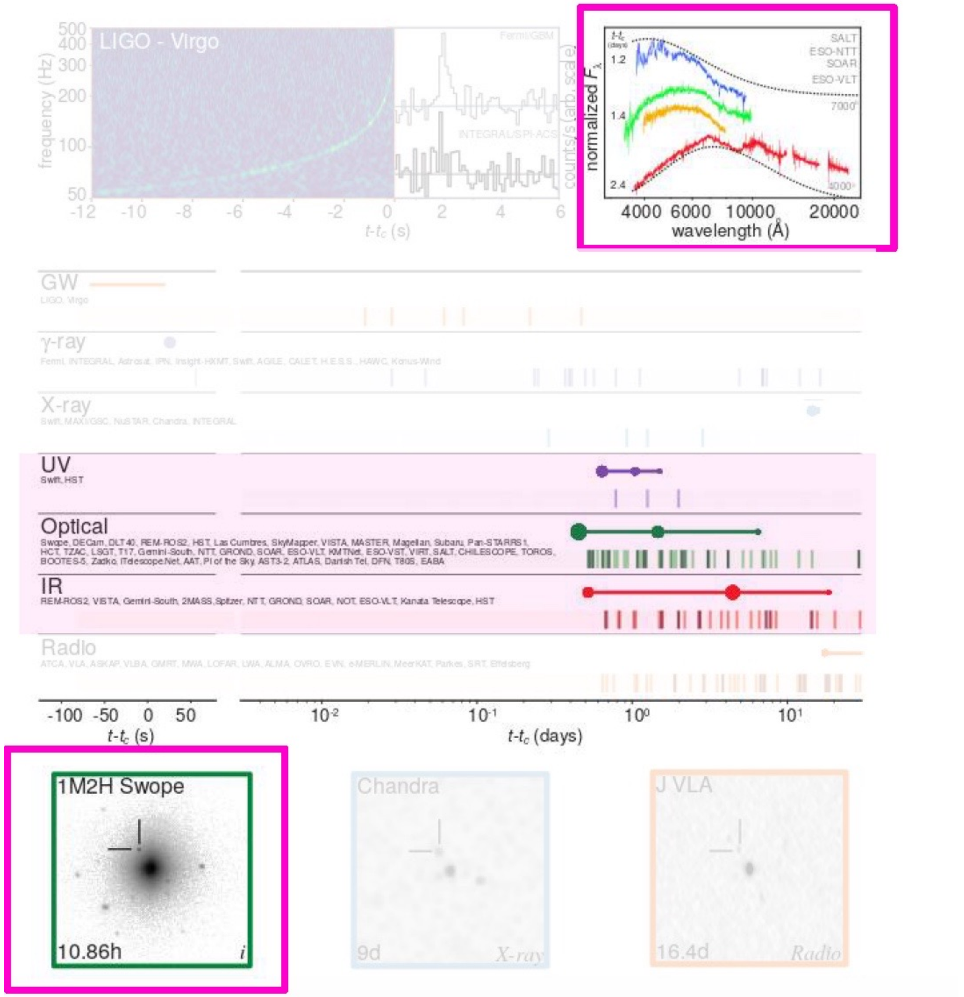
Gamma-ray follow-up observations of GW170817



- 27 min after GW170817 : First GW map : uncertainty covering 24,200 deg^2 at 90% containment : not suitable for scheduling follow-up observations with H.E.S.S.

- 5h later (LIGO+VIRGO map) : uncertainty covering 31 deg^2 at 90% containment
  → HESS follow-up observations first night : only 35 min to derive pointing strategy before visibility window. 3 observations of 28 min each (with CT5)
  → Shortest time delay by any ground based pointing instrument participating in the follow-up of GW170817

Main discoveries (2)



The race to 1st optical detection

t_c + 40 min: 1st LV announcement
candidate BNS associated with GRB

t_c + 1h05 : Fermi report
preliminary localization = 1100 deg^2

t_c + 1h30 min: LV update
H1-only loc. and distance = 37 ± 12 Mpc

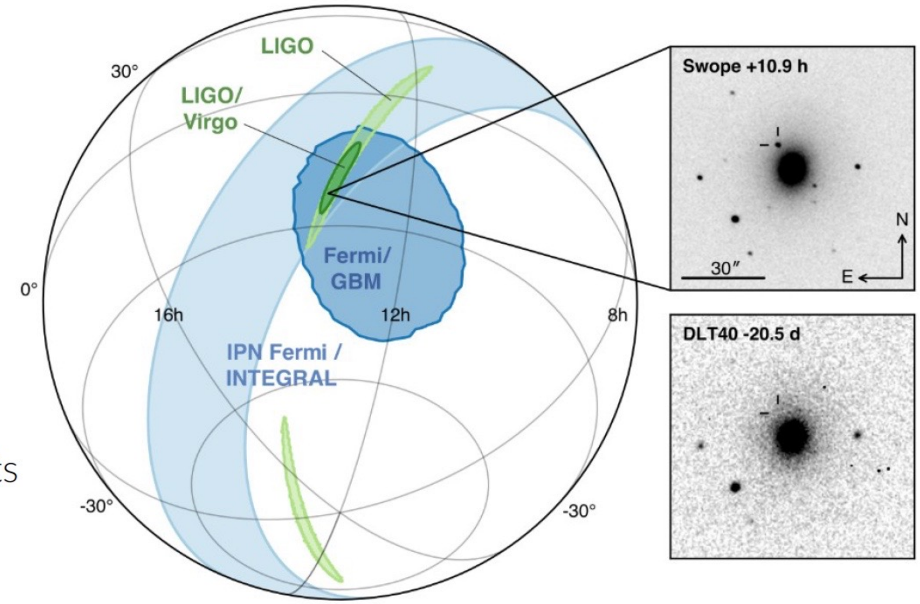
t_c + 5h : LIGO Virgo loc. = 30 deg^2
distance = 40 ± 8 Mpc
Too late for Australia and South Africa

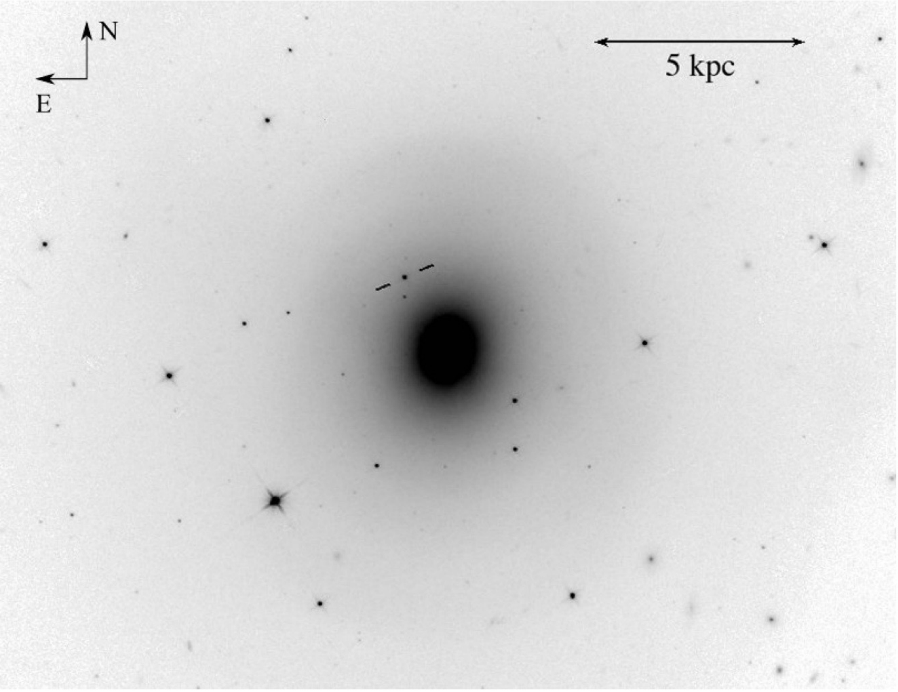
t_c + 11h : Swope detects SSS17a and its host galaxy **NGC4993**
9th field taken at 20:33 LT, Las Campanas Obs
180 galaxies at ~40 Mpc in the error box

+ 5 more independent detections in the following hour

t_c + 13h: Swope announcement
GCN Circular #21529

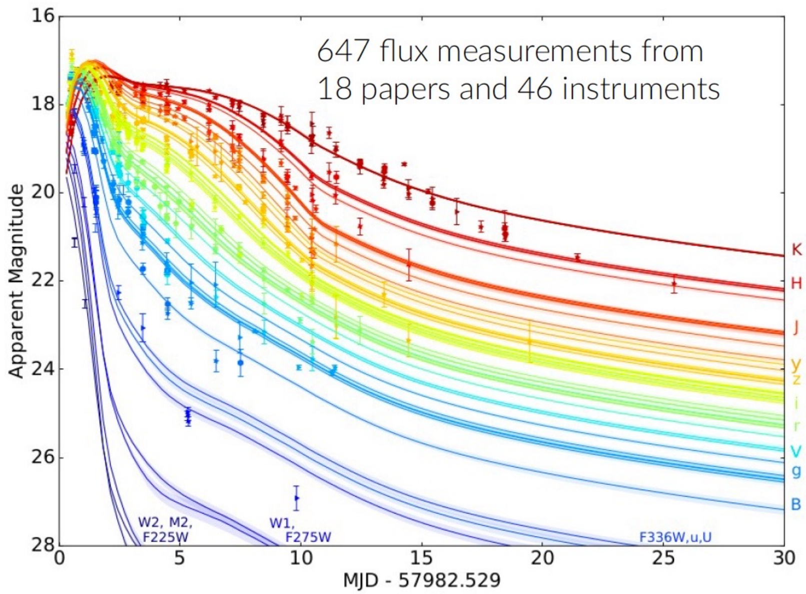
t_c + 17h: 1st report on spectroscopic obs.
(GCN Circular #21547)

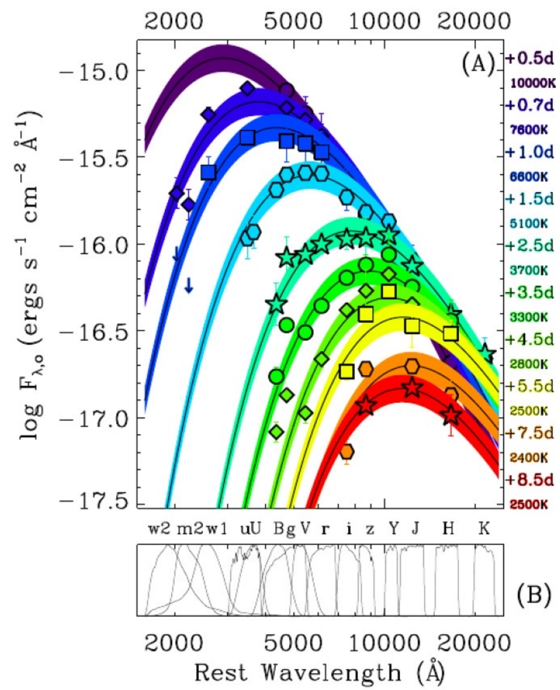




HST/WFC3-IR F110W t_c+4.79d Tanvir et al, ApJL 848:L27 2017

Photometry



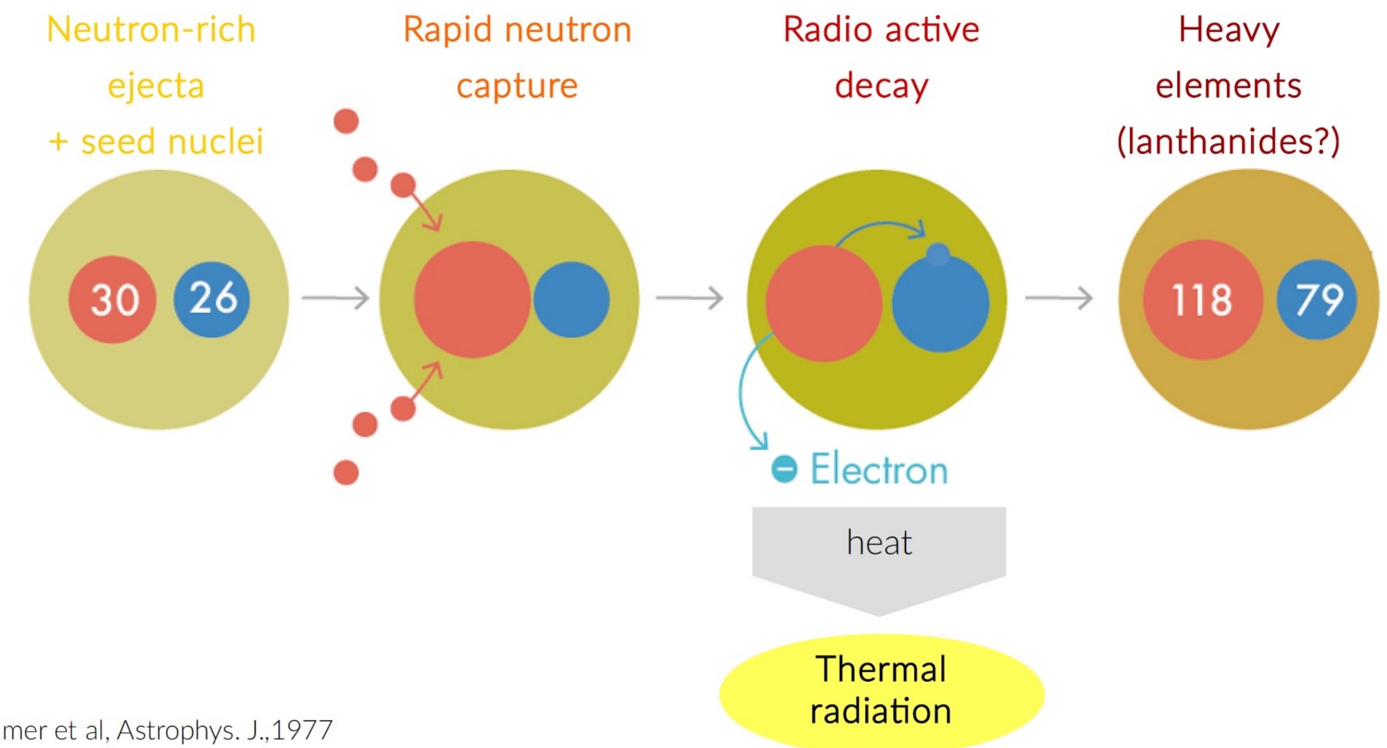


Discovery: 17.48 mag (*i* band*)*
Rapidly rise and fading after ~1 day
Decline faster in the blue band, 1.5 mag/day
SED shifts from near-UV to near-IR in 8 days – hot ejecta and rapid cooling

V. Ashley Villar et al, arXiv:1710.11576

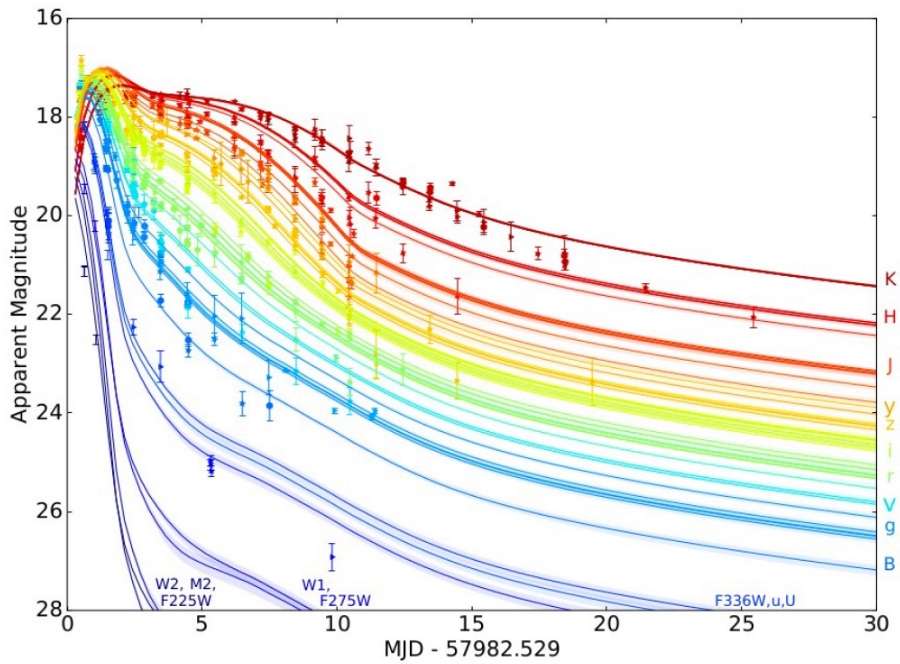
Drout et al, Science, 2017

Kilonova model (r-process)



Lattimer et al, Astrophys. J.,1977
Eichler et al, Nature 1989
Li & Paczynsky, Astrophys. J. 1998

Inferring the kilonova model



$M_{ej} \sim 0.02 M_\odot$

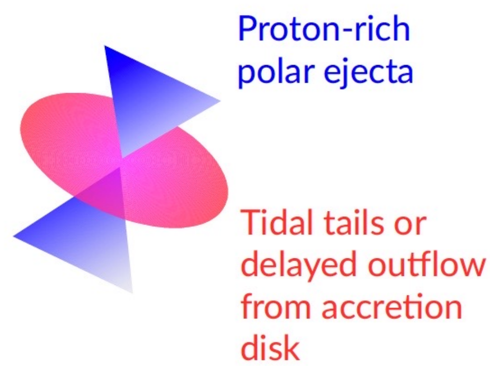
$v_{ej} \sim 0.26\, c$

$M_{ej} \sim 0.04 M_\odot$

$v_{ej} \sim 0.15\, c$

$M_{ej} \sim 0.01 M_\odot$

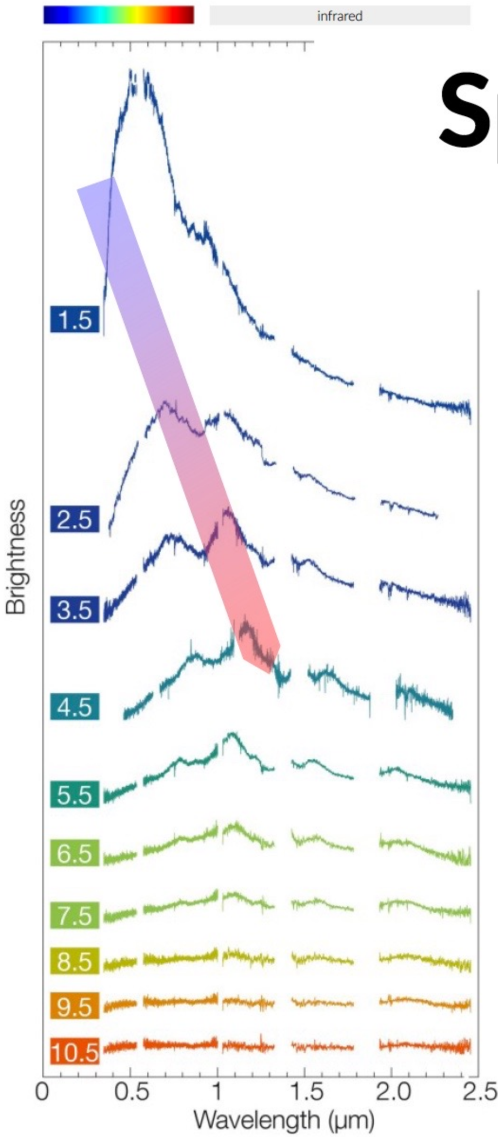
$v_{ej} \sim 0.14\, c$



- Best fit has three components
  - Lanthanide-poor (blue, 0.5 cm²/g), intermediate (magenta, 3 cm²/g) and lanthanide-rich (red, , 10 cm²/g)
- Good fit provides **evidence for heavy-element nucleosynthesis and ejection**
  - Supernova models (^{56}Ni decay, Fe opacity) do not fit

V. Ashley Villar et al, arXiv:1710.11576

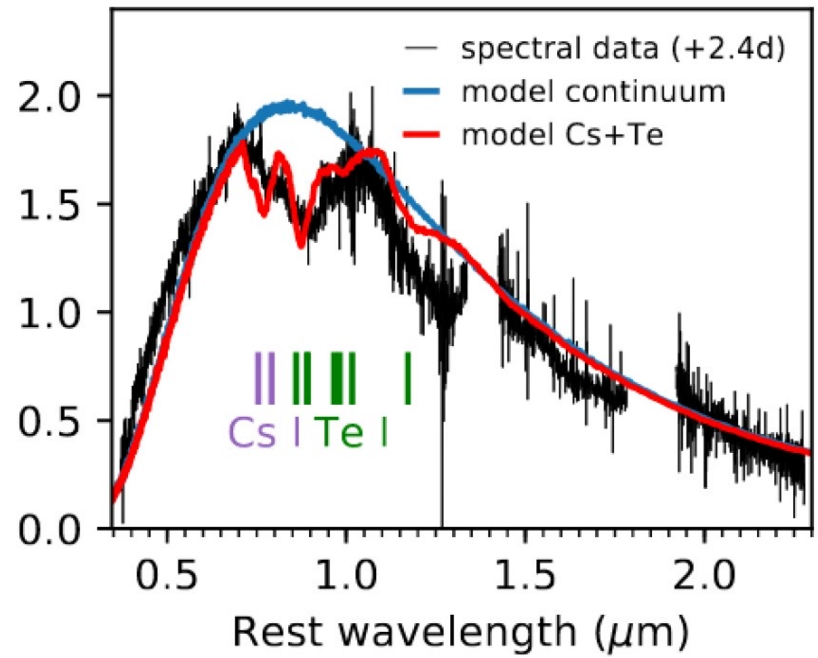
Spectrometry



Pian et al, Nature, 2017

ESO VLT – X-shooter

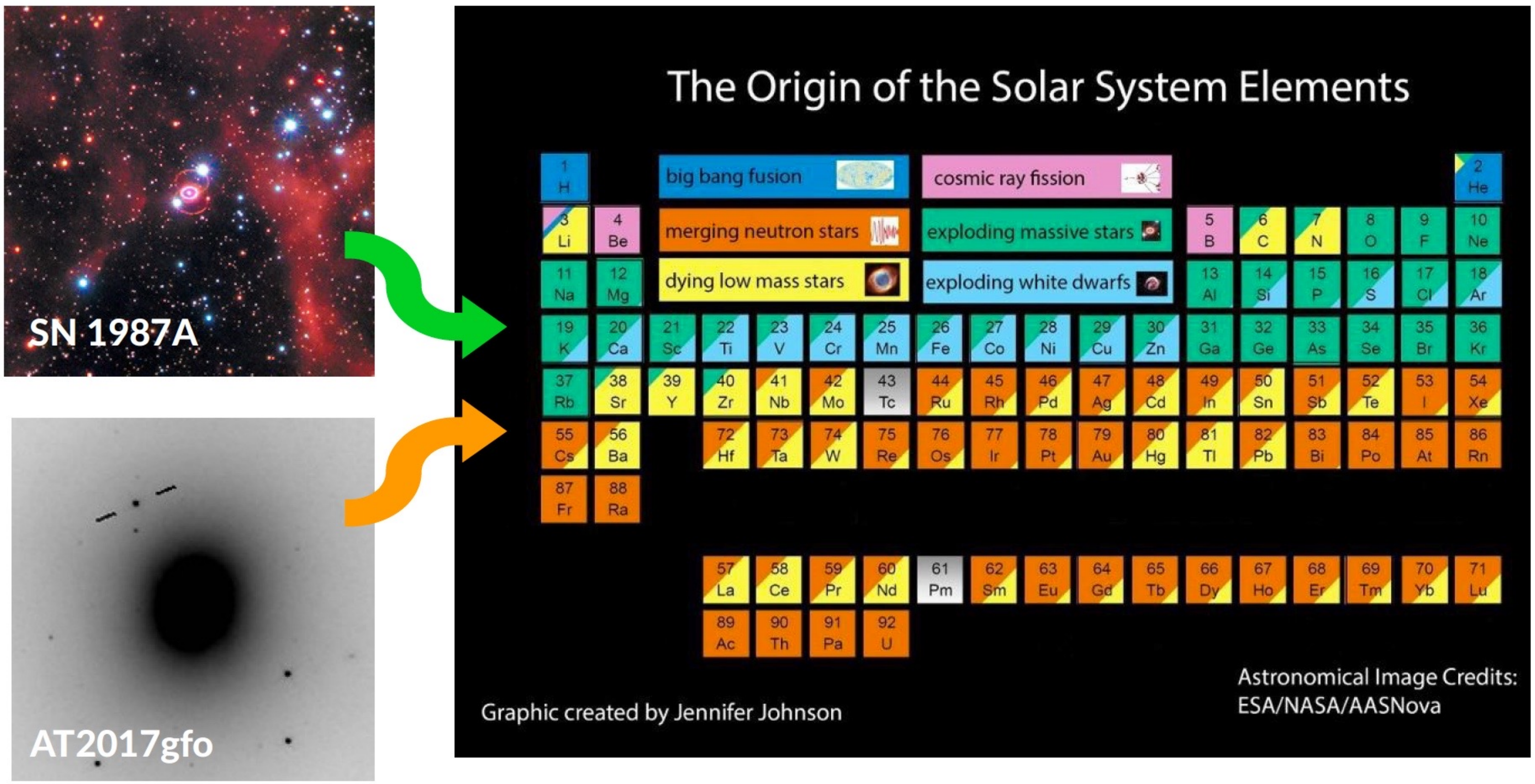
Absorption lines consistent with Cesium and Tellurium



Smartt et al, Nature, 2017

ESO VLT – X-shooter

Kilonova –Nucleosynthesis (1)



Kilonova –Nucleosynthesis (2)

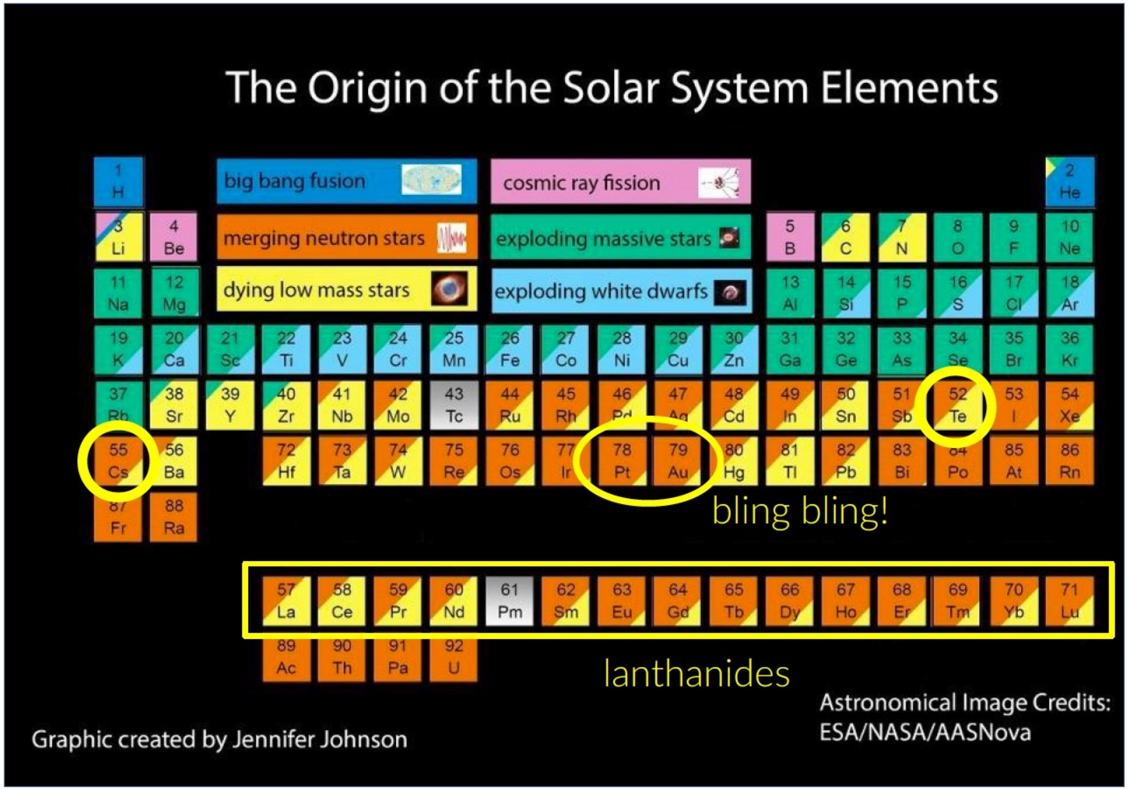
$16\,000\ \mathrm{M}_\oplus$

of heavy elements

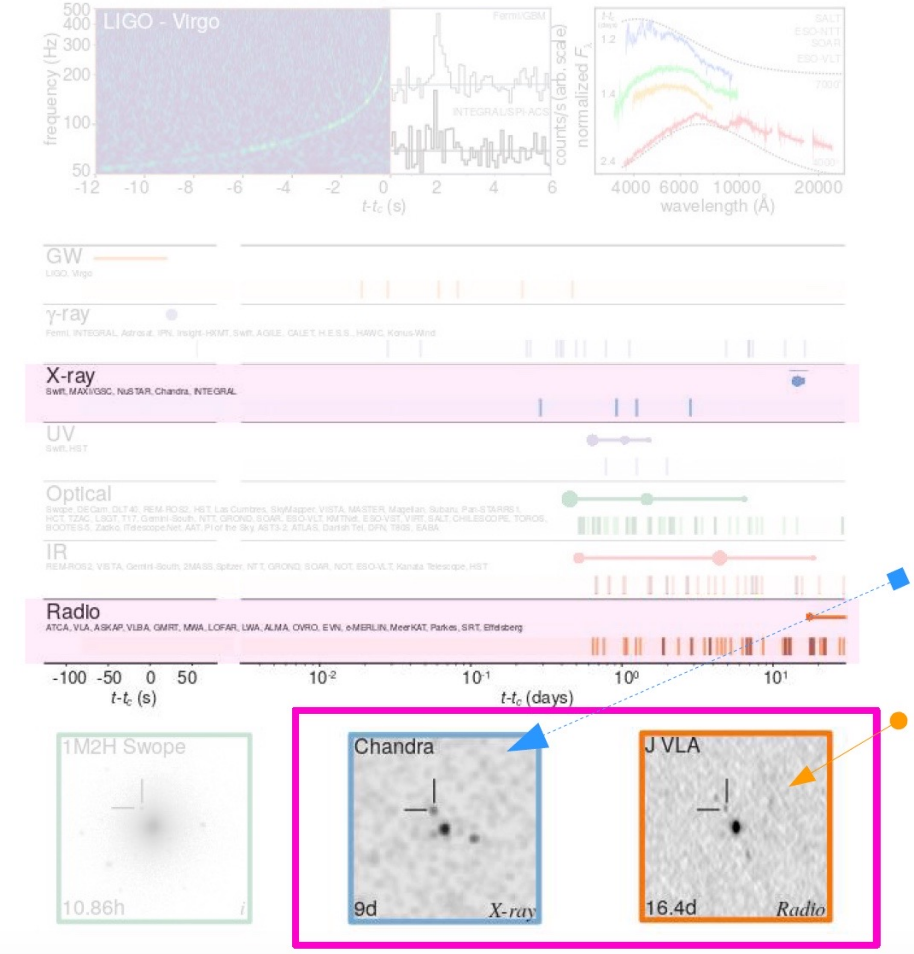
$10\ \mathrm{M}_\oplus$

in gold and platinum

(according to Edo Berger)



Main discoveries (3)

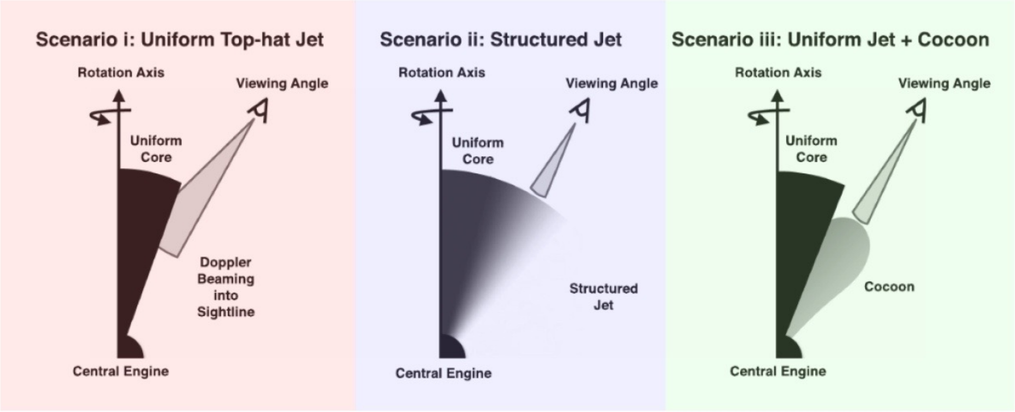


X-rays: 10^{39} erg/s at t_c + 9d (!)
Troja et al, 2017

Radio (6 GHz): ~28 uJy at t_c + 16 d
Hallinan et al, 2017

Decoupled from the kilonova

So far, no convincing global model



X-ray and radio counterparts are likely afterglows (synchrotron)

A. Jet off-axis by ~5 deg → excluded
   - 1.7 s delay is too short (delay to medium transparency)
   - Delayed X-rays require viewing angle ~ 13 deg
   - Radio flux x 10 larger if true

B. Structured jet (same conclusion)

C. “Hot cocoon”
   - Kilonova shows that a lot of material surrounds the binary. Jet drills into the ejecta.

Summary

- *99 years after prediction by Einstein, gravitational waves was detected from 2 black holes merger in 2015.*
- *In 2017 extraordinary event of binary NS merger proved heavy element production and challenge gamma-ray models.*
- *Pulsar timing arrays found signal in 2020, probably signal from QCD phase transition*
- *This field has great future, first detections just started.*