Recent Progress in Particle Astrophysics And Cosmology

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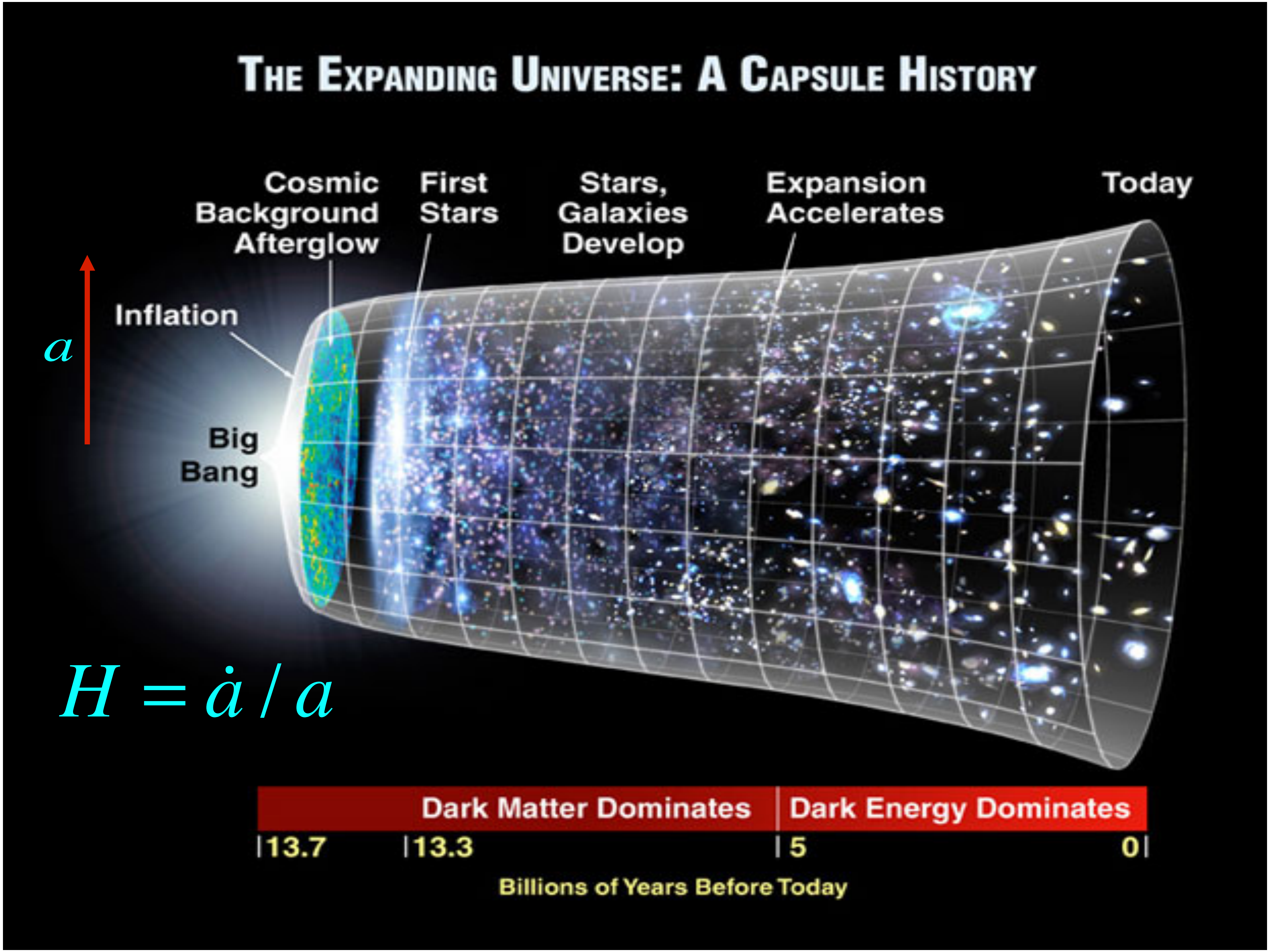
National Taiwan University (NTU)
Leung Center for Cosmology and Particle Astrophysics (LeCosPA) established November 13, 2007

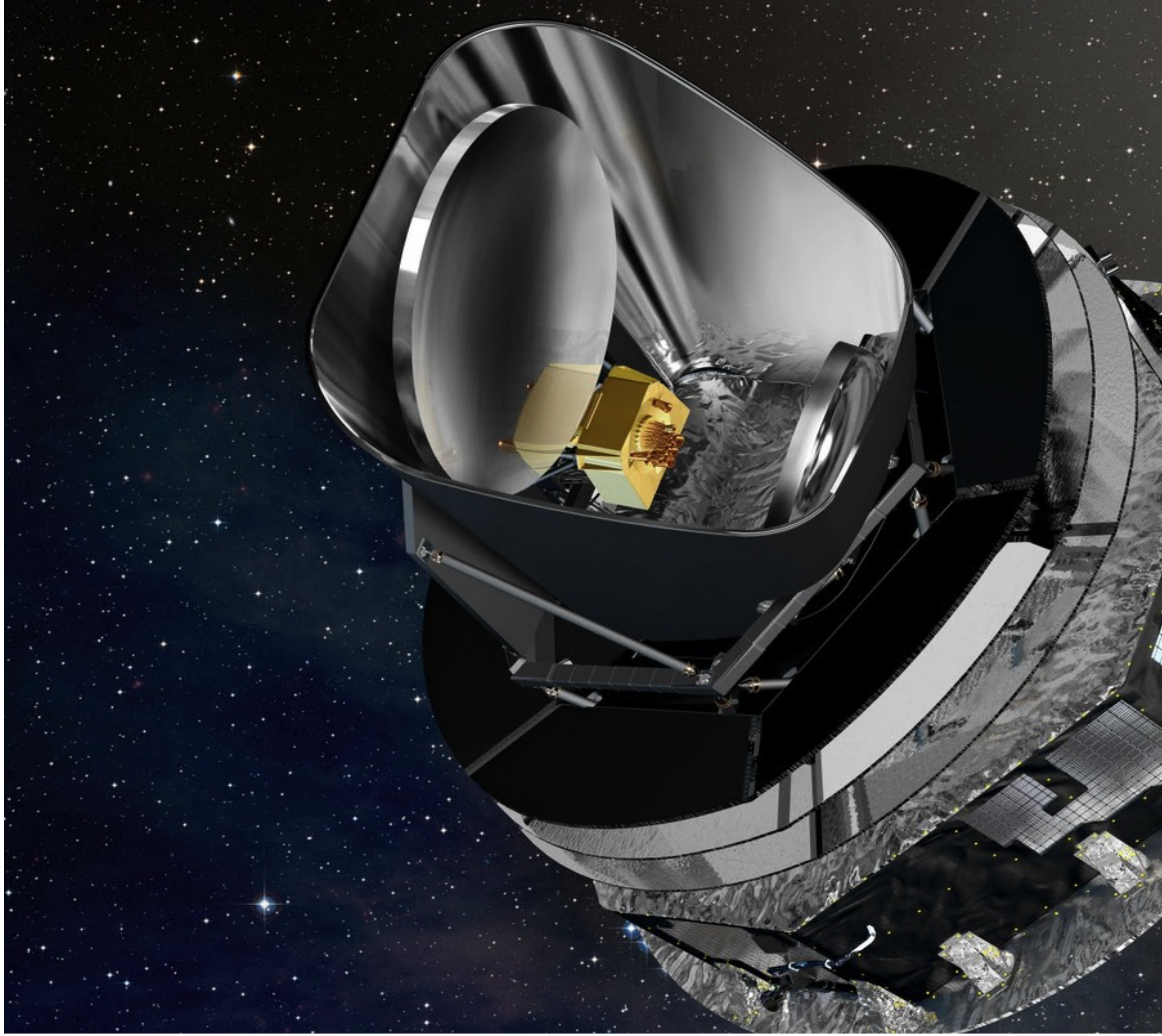
On June 21, 2012, Leung and NTU signed another contract to further donate US$19M to turn LeCosPA into a permanent center

LeCosPA Building on NTU site under planning


THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
a
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

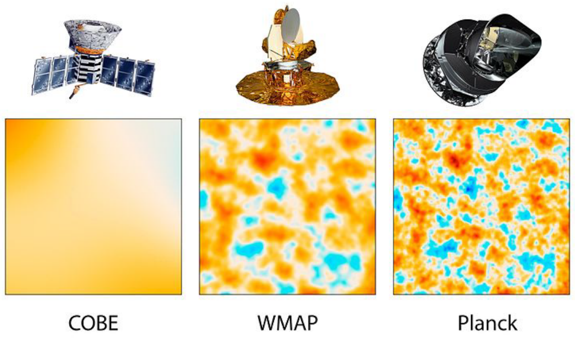
$$H = \dot{a} / a$$

Universe after Planck



Max Planck
(1858-1947)

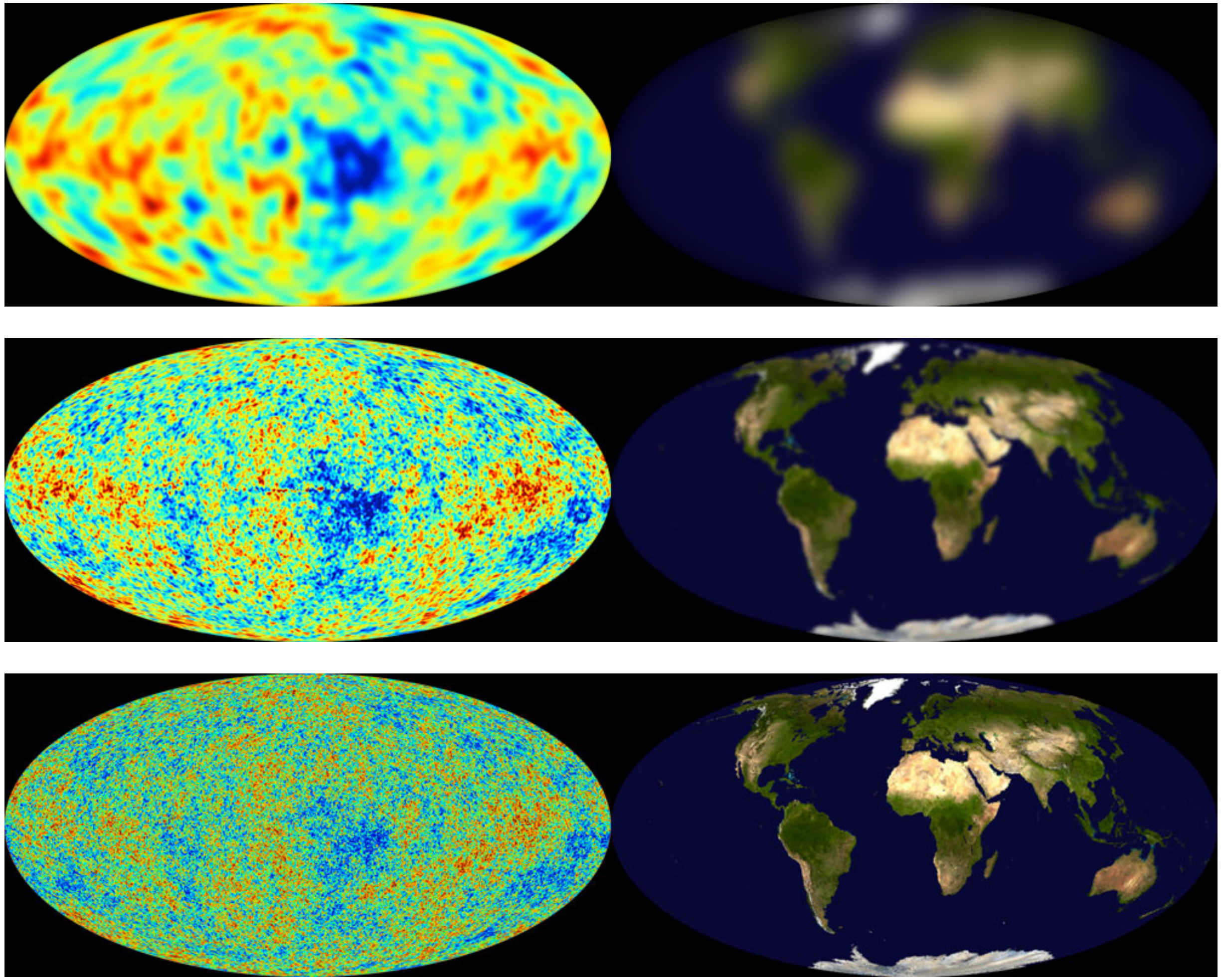
CMB Anisotropy



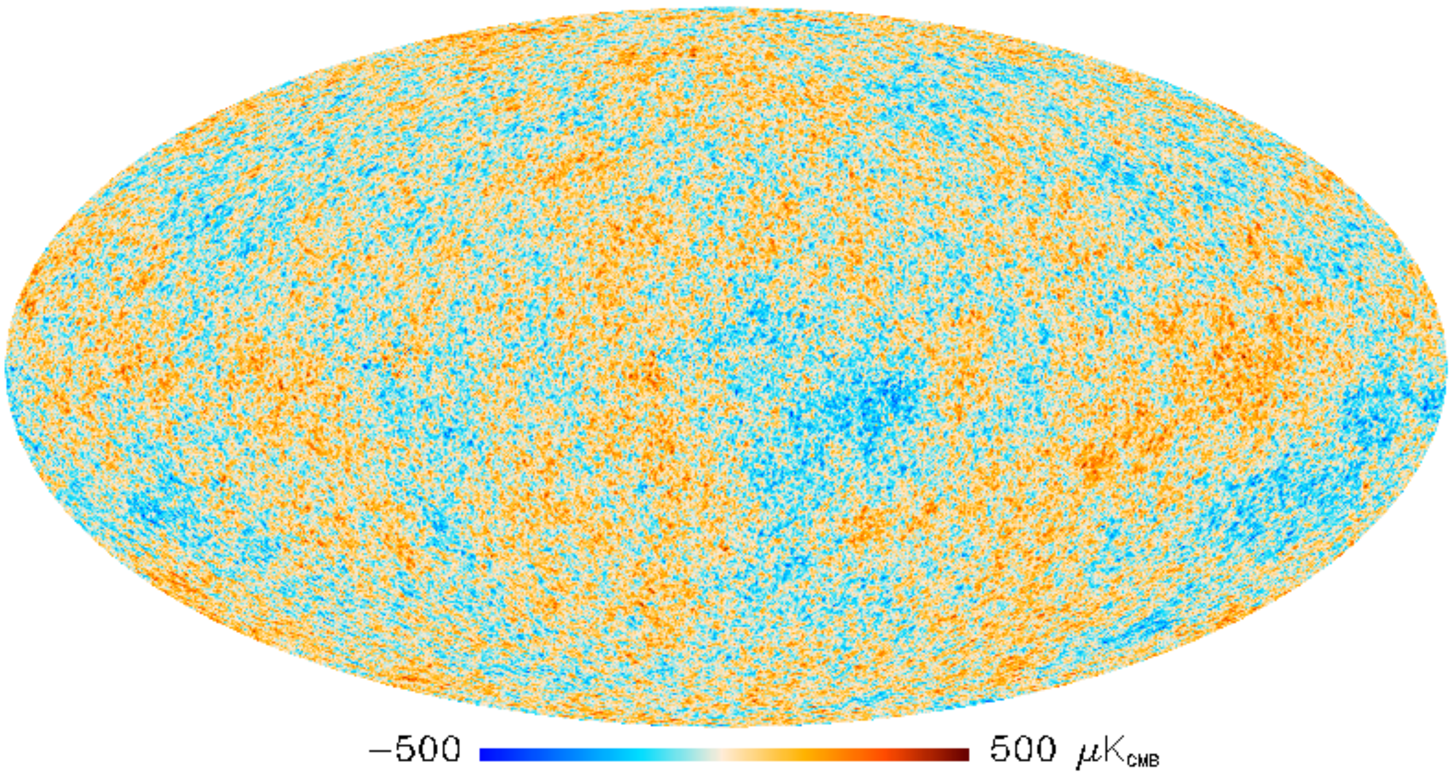
COBE

WMAP

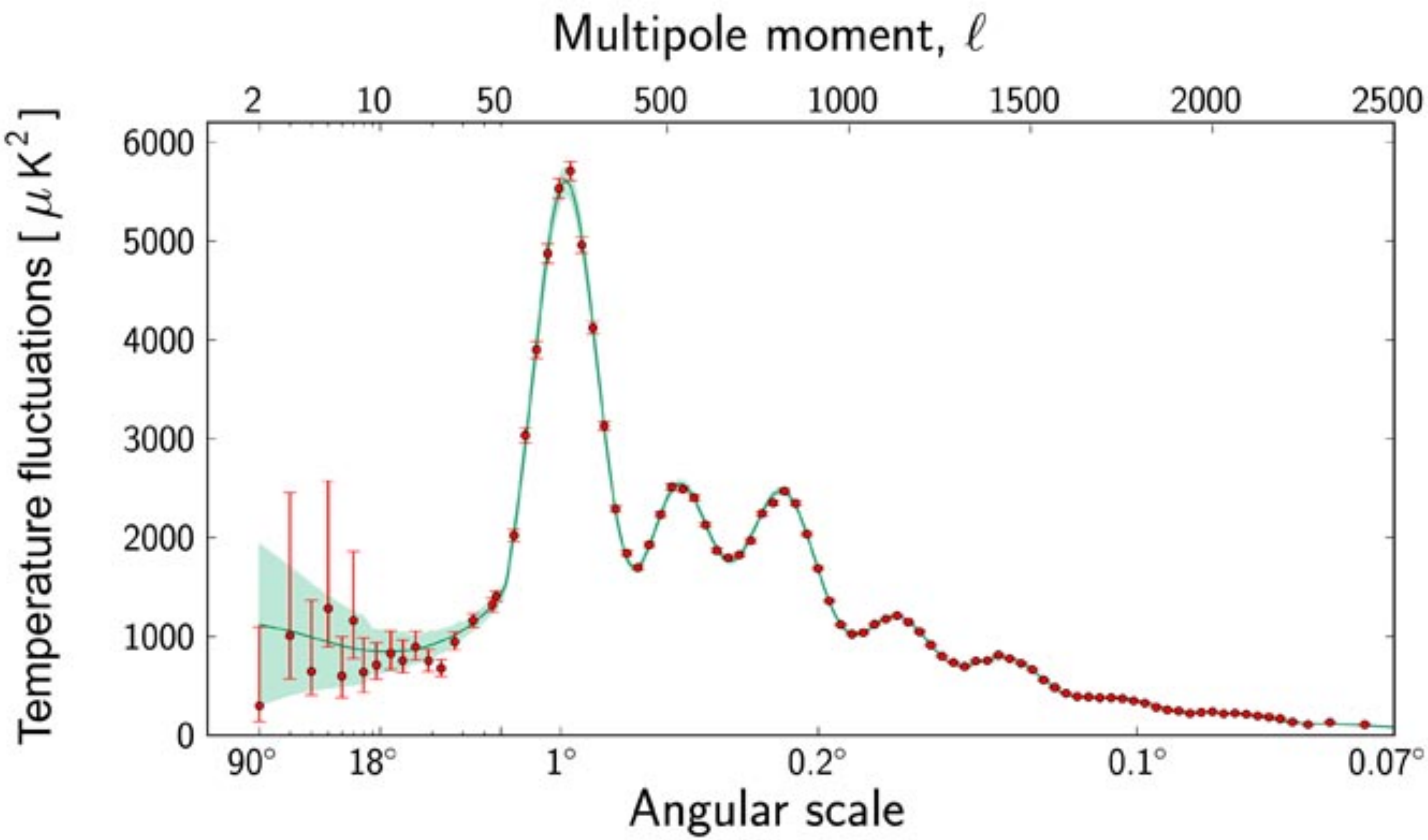
Planck



CMB anisotropy measured by Planck

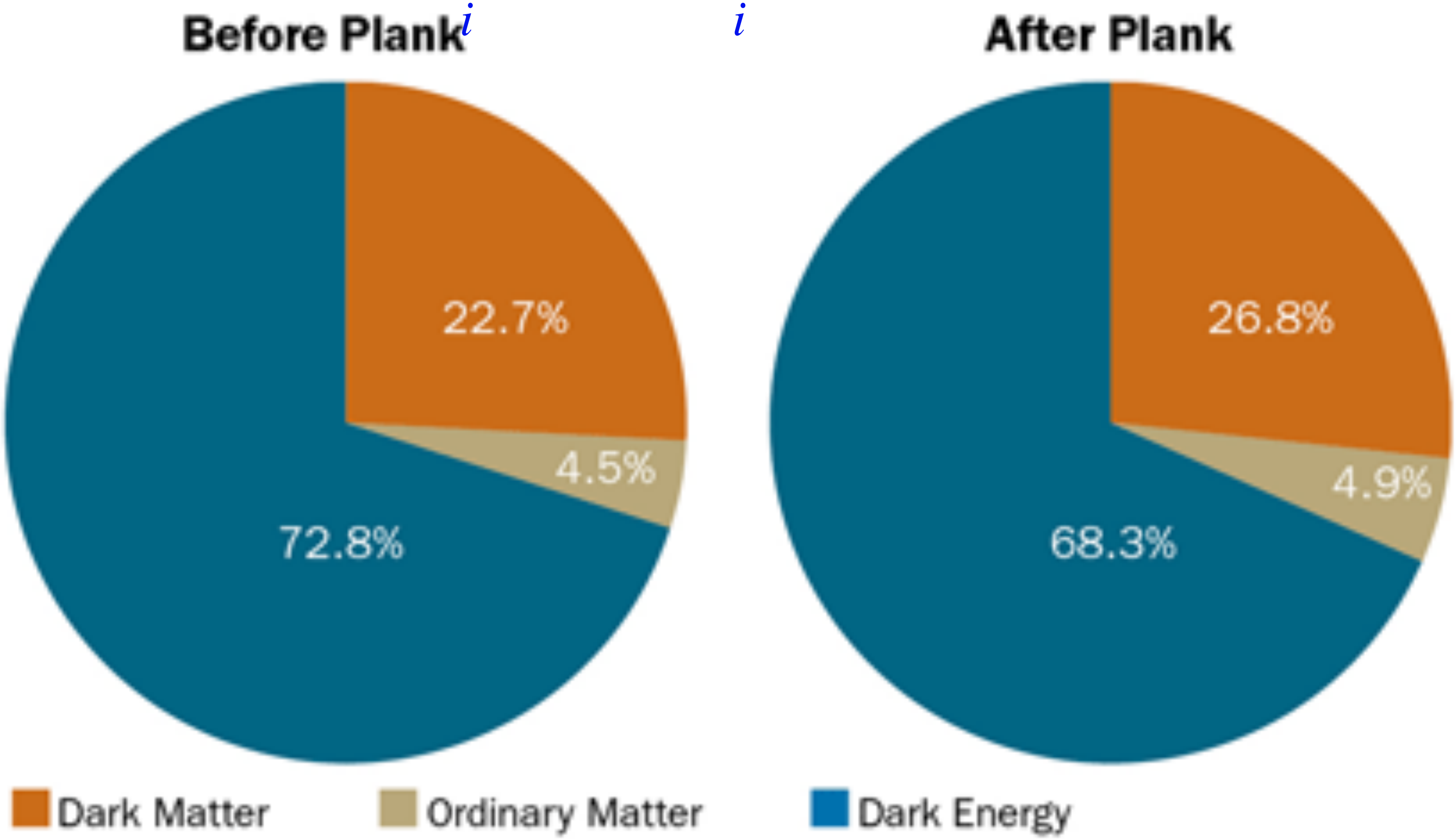


Power spectrum angular scale



Composition of the Universe

$$\Omega = \sum_i \Omega_i = \sum_i \rho_i / \rho_{critical} = 1$$



Summary of Planck Results

1. The Universe is expanding slower [Hubble parameter: 67.3 ± 1.2 km/s/Mpc] than previously thought.

2. The universe has slightly more dark matter and slightly less dark energy than previously estimated [68-to-69% instead of 73%].

3. There are likely 3 neutrinos [instead of 4 as previously suggested]. The sum of their masses is very small [less than 0.18 eV]. No evidence for sterile neutrino, though not conclusively excluded.

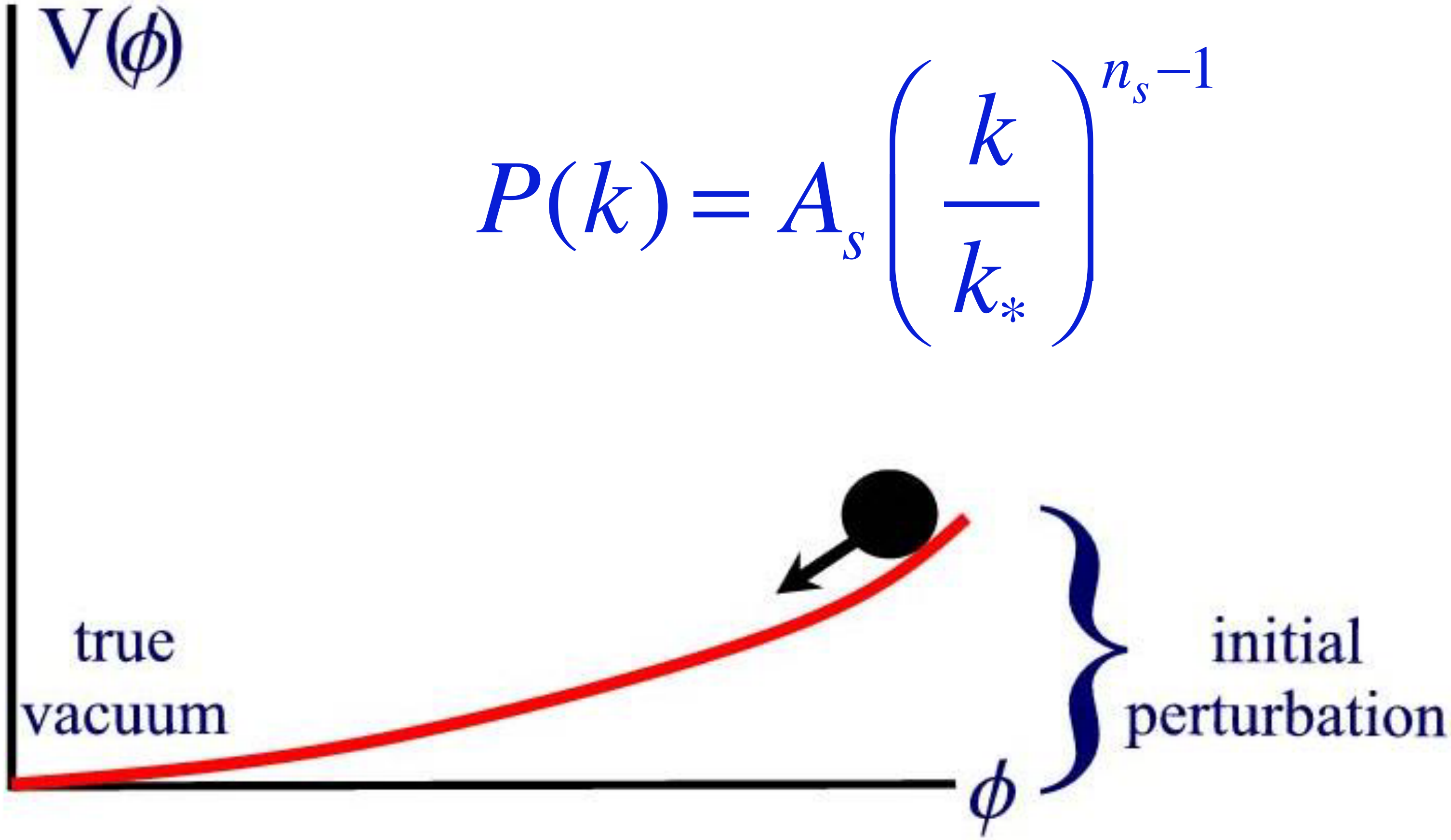
4. Simplest inflation models [$V(\phi) \propto \phi^n$, $n>1$] are disfavored.

5. CMB anisotropy is found lower than expected at large scales.


Early Universe

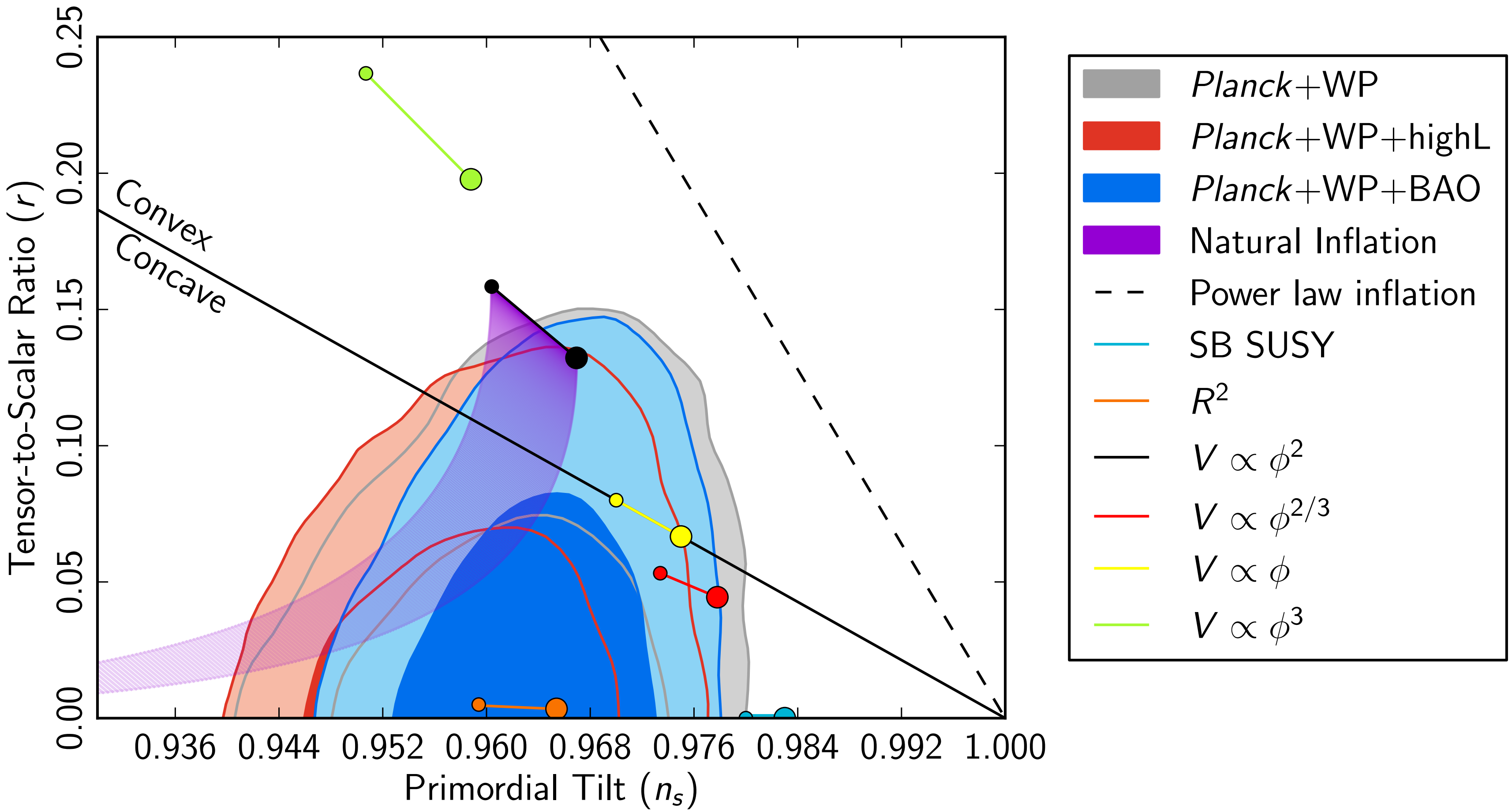
Inflation

$$P(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$



Some inflation potentials disfavored

In addition, NO obvious non-Gaussianity → single field



New Mystery:
Large-Small Scale Tension

- 5-10% deficit in lower mode ($l < 40$) power spectrum compared to expectation from ΛCDM cosmology

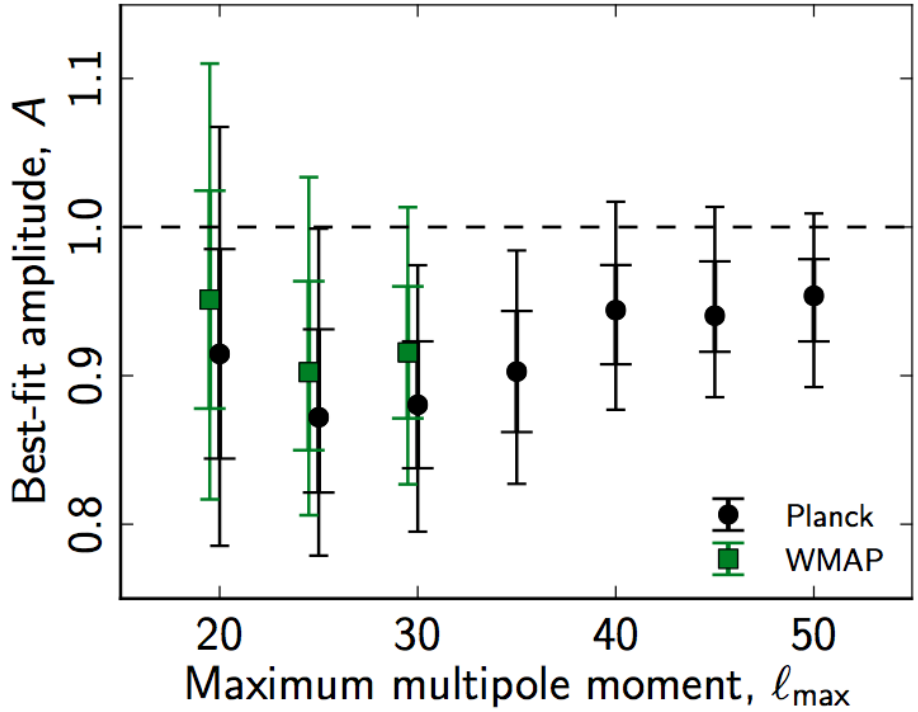


Figure 39. Power spectrum amplitude, q, relative to the best-fit *Planck* model as a function of ℓ_{max}, as measured by the low-ℓ *Planck* and *WMAP* temperature likelihoods, respectively. Error bars indicate 68 and 95% confidence regions.


Dark Energy

Dark Energy: Dynamical Field vs. Cosmological Constant

DE eq. of state:

$$p = w\rho,$$

Hubble expansion can be expressed in terms of the rate of change of the scale factor a:

$$H \equiv \dot{a} / a$$

According to the Friedmann eq., the accelertion)or deceleration) of the universe, i.e., the rate of change of H, is governed by

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{1}{3}\Lambda,$$

where Λ is the CC. Either $\Lambda > 0$ or $\rho + 3p < 0$ will induce accelerated expansion.

Dark Energy: Dynamical Field vs. Cosmological Constant

DE eq. of state: $p = w\rho, \quad w = w_0 + w_a(1-a).$

$w_0 = -1.04^{+0.72}_{-0.69}, \; w_a < 1.32$ (95%; Planck+WP+BAO)

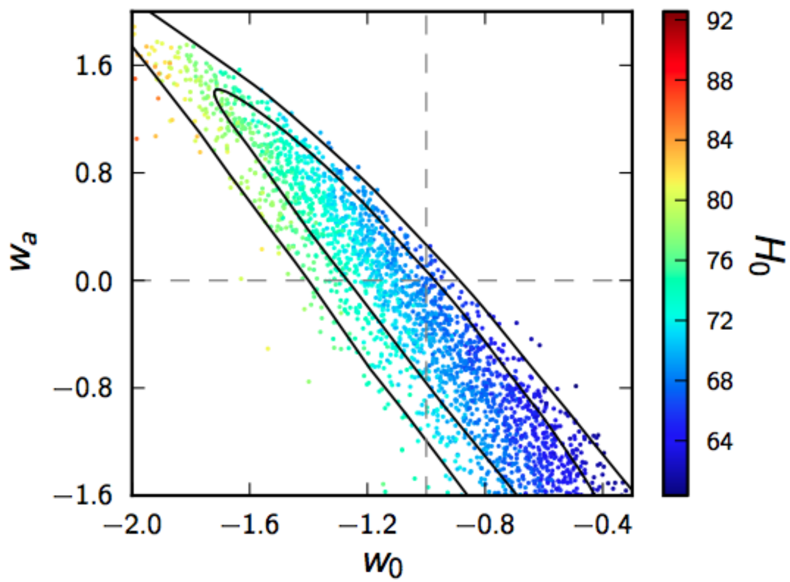


Fig. 35. 2D marginalized posterior distribution for w_0 and w_a for *Planck*+WP+BAO data. The contours are 68% and 95%, and the samples are colour-coded according to the value of H_0. Independent flat priors of $-3 < w_0 < -0.3$ and $-2 < w_a < 2$ are assumed. Dashed grey lines show the cosmological constant solution $w_0 = -1$ and $w_a = 0$.

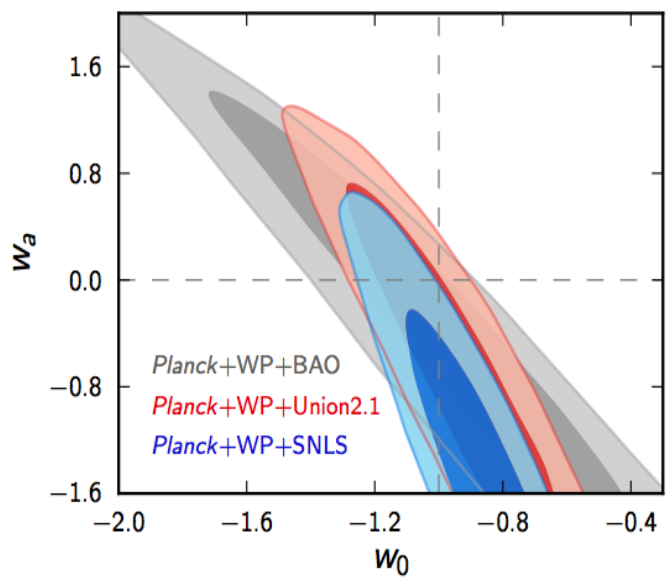


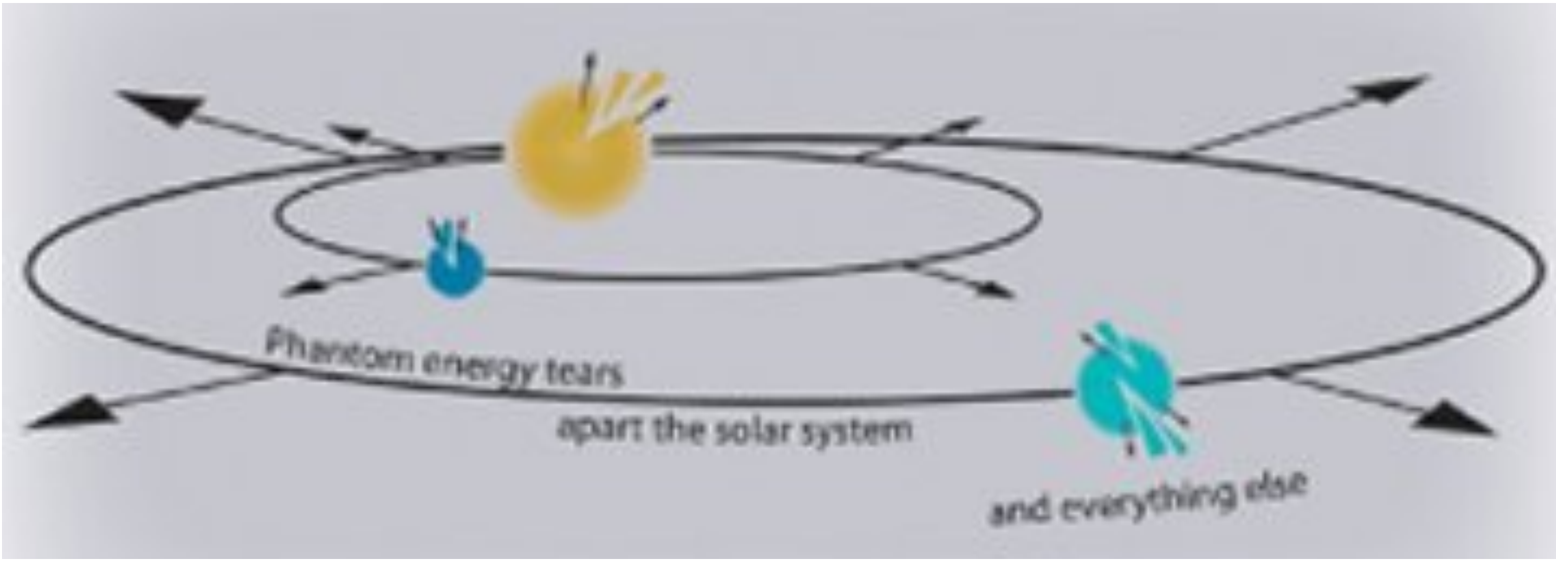
Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the cosmological constant solution.

Cosmic Acceleration

Quintessence: $-1 < w < -1/3$

Cosmological constant: $w = -1$

Phantom energy: $w < -1$



The Big Rip: Universe ends at age 35By; Milky Way rips apart 60My before the end

Case for Cosmological Constant

- CC remains a viable and simplest candidate for dark energy.
- CC Problem: In GR, anything that contributes to the energy density of the vacuum acts like CC.
- Quantum vacuum energy with cutoff at Planck scale gives

$$\rho_V \sim M_{Planck}^4 \sim (10^{28} eV)^4 \gg \rho_{DE} \sim \rho_c \sim (10^{-3} eV)^4 \,!$$

Cosmological Constant Problem

- Surely quantum vacuum energy should not gravitate. But why not?
- A possible solution:

  CC as a constant of integration in an alternative gravity theory

Case 1: Unimodular Gravity

Proposed in early 80s (van der Bij, Weinberg, Wilzcek-Zee, etc.)

Revived after 2000 (Finkelstein, Ellis, etc.)

- Idea:

  - Same action as Einstein-Hilbert,

$$S_{EH} = \frac{1}{8\pi G}\int dx^4 \sqrt{-g}R,$$

  but with constraint

$$\sqrt{-g} = 1$$

  - Conservation of stress energy tensor separately imposed.

- Outcome:

  - CC identified as the constant of integration.

- Implications:

  - CC disengaged from quantum vacuum energy.
  - Can accommodate inflation (G. Ellis, arXiv:1306.3021)
  - Fine-tuning problem: why is CC so small?

Case 2: Higher-Order (Gauge Theory of) Gravity

- Idea:
  - Replace Einstein-Hilbert action with quadratic contraction of Riemann tensors

(Stephenson, Kilmester, Newman, Yang, Camenzind,Cook, PC)

  - Affine connection as dynamical variable

- Outcome:
  - 2 integration constants: C_1:=CC, C_2:= dark radiation

- Implications: (PC-Izumi-Tung, PRD, arXiv:1304.6334)
  - Extra bonus: dark radiation ($\Omega_{DR} \propto 1/a^4$)
  - Camenzind's matter current is problematic (not general covariant)
  - Ghosts exist, but can be ameliorated (PC,arXiv:1002.4275)

Smallness of DE based on Holographic Principle

- Cohen-Kaplan-Nelson (99), Horava-Minic (00) Thomas (02), Miao Li (04, 12).
- Quantum zero-point energy caused by short-distance cutoff inside a region L must be bounded by mass of black hole at same size:

$$L^3 \rho_\Lambda \le L M_p^2 \qquad (M_p^2 \equiv 1/8\pi G)$$

- Identifying L with Hubble radius at present, i.e.,

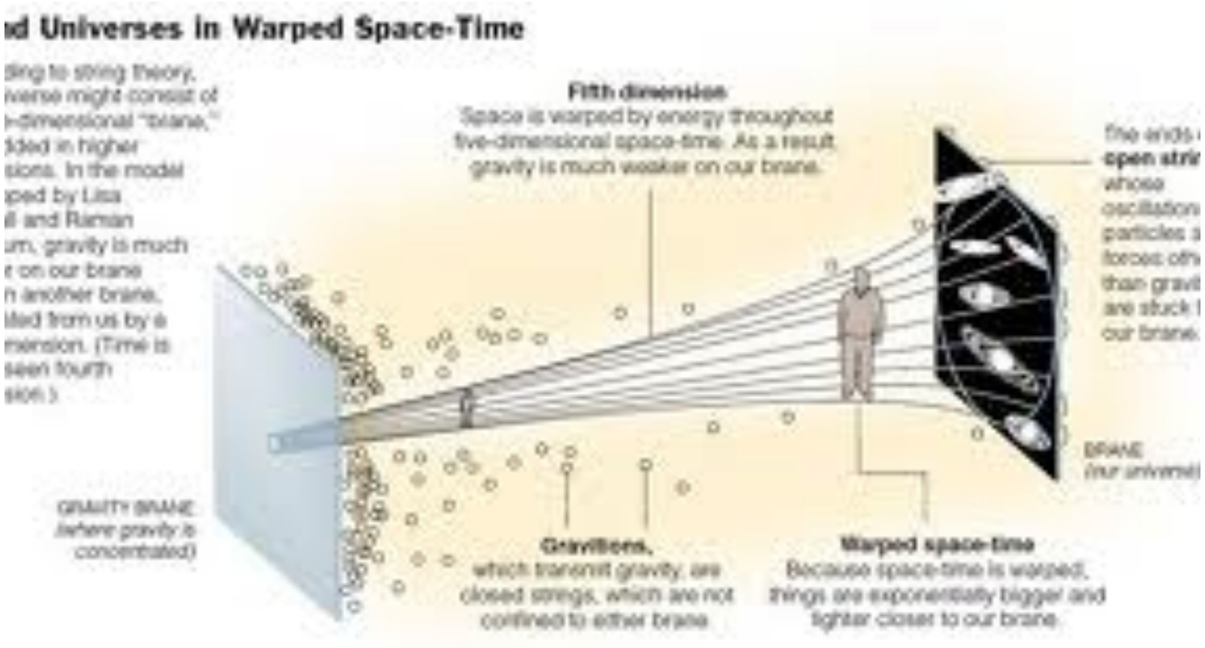
$L = 1/H_0 \sim 10^{28} cm$, one readily finds

$\rho_\Lambda \sim 10^{-10} eV^4$, just right for DE.

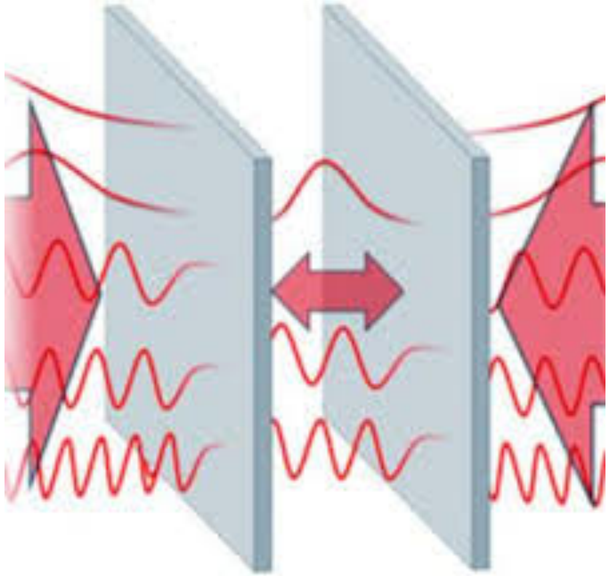
BUT why is the present so special in history of universe?

Smallness due to double gauge hierarchy: Casimir energy in extra-dimension

Randall-Sundrum model: brane-world in 4+1 d



Casimir energy

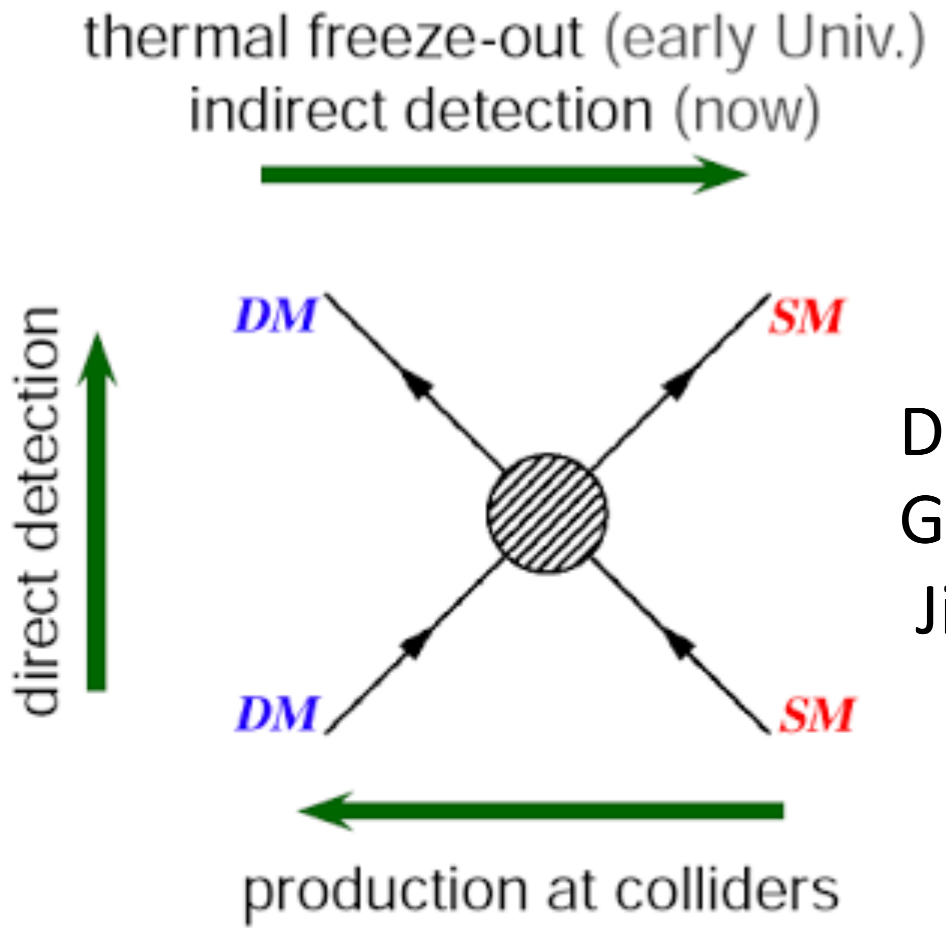


$$\rho_{DE} \sim (M_{SM} / M_p)^2 M_p$$

This approach can also make CC small, but without the strange concordance. (PC , Gu, Shao, 2010)

Dark Matter

Direct vs. Indirect Search of DM

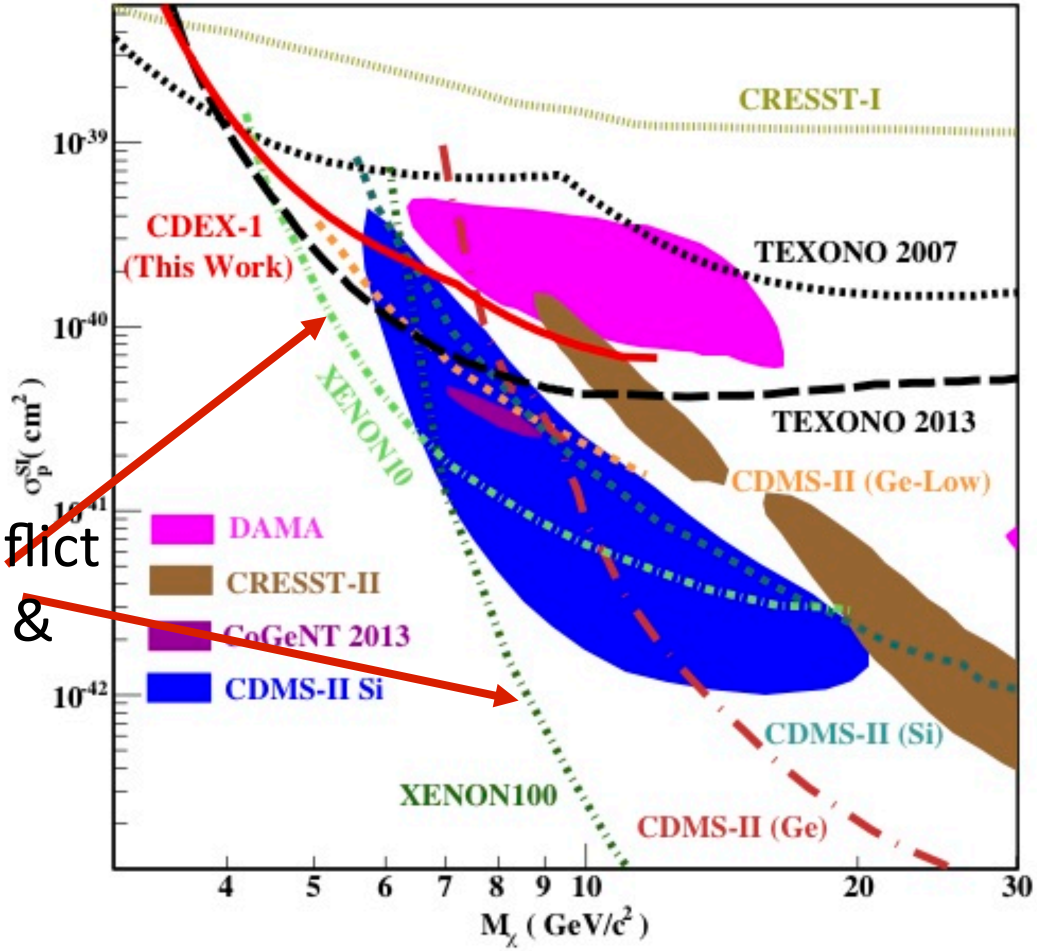


Direct search underground:
Gran Sasso, Sudan Mine,
Jingping Shan, etc.

Direct Detection:
Hints on Light(er) WIMP DM

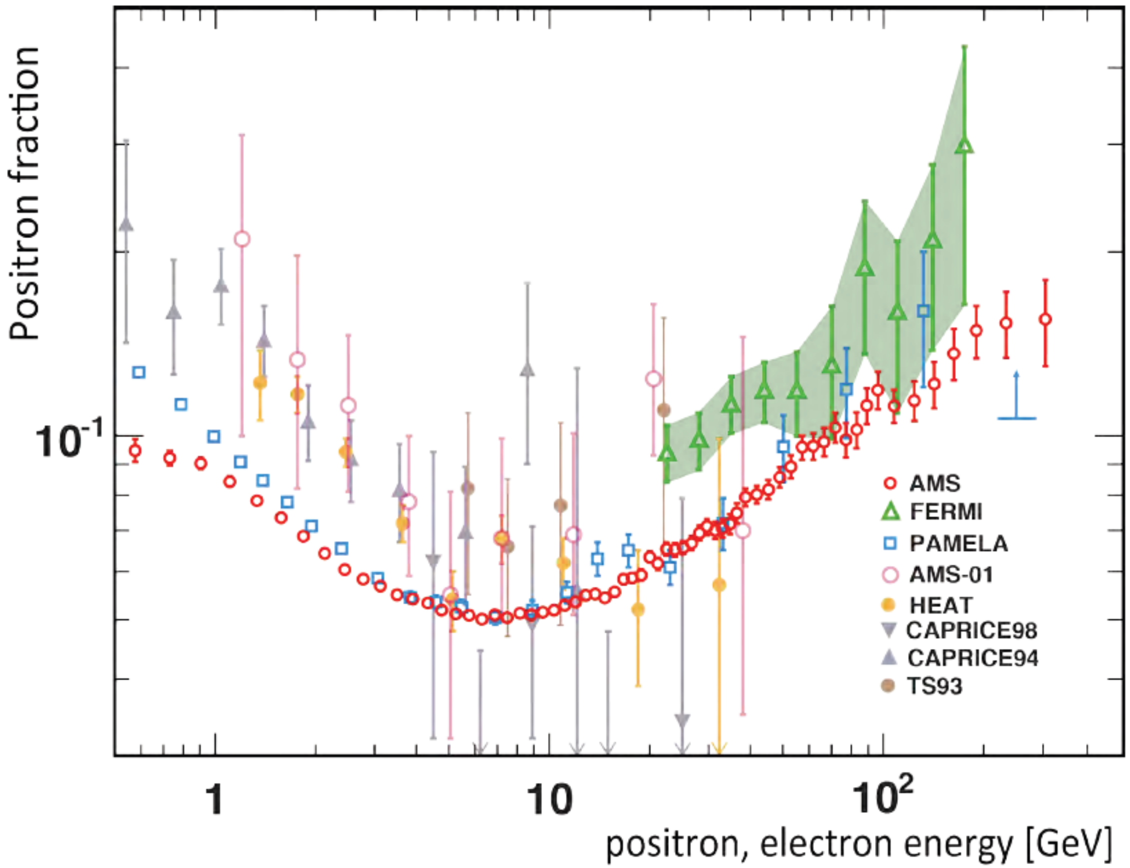
Exciting news from CoGeNT, CRESST, and CDMS that confirms the earlier finding of DAMA/LIBRA, evidence of DM

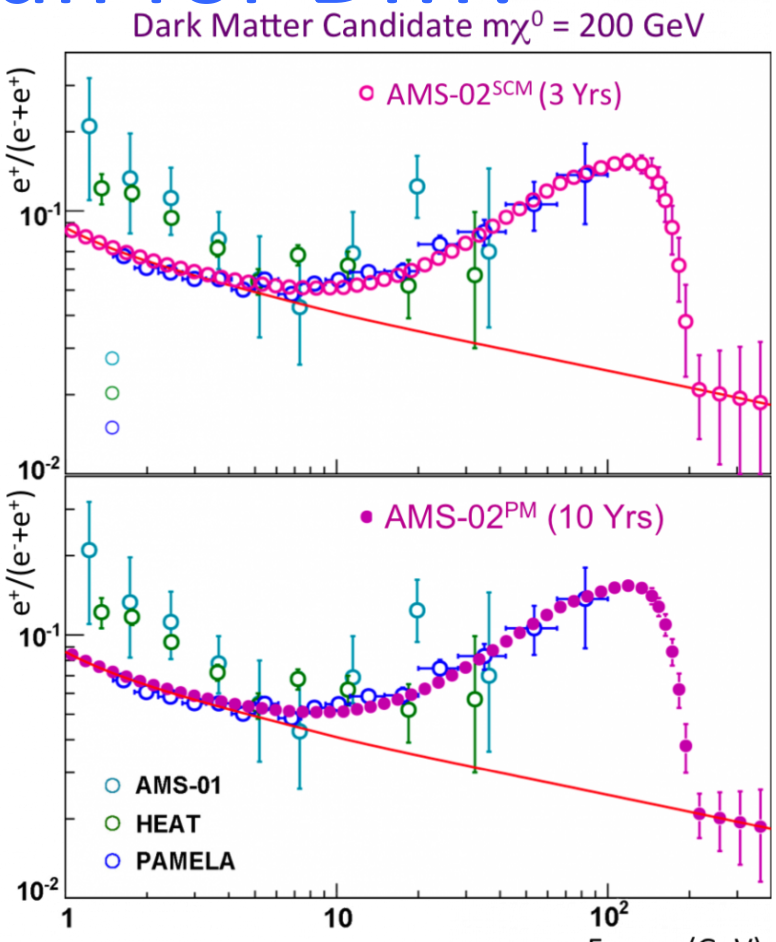
$m_{DM} \sim 8.6GeV$



In seeming conflict with XENON10 & XENON100

Indirect Detection: AMS confirms positron excess(>10GeV) Another smoking gun for DM?



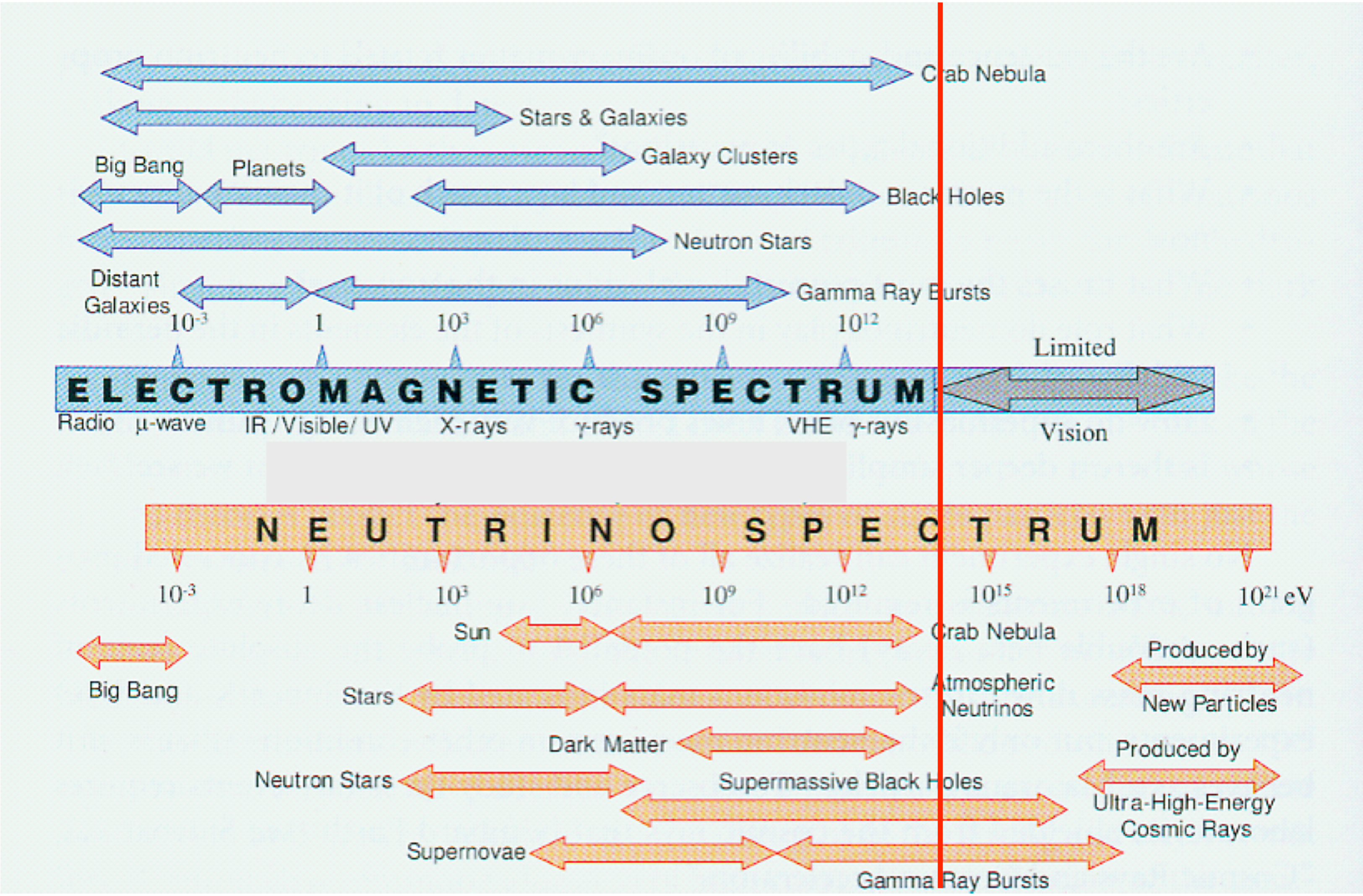


Collider Search: No evidence of SUSY from LHC

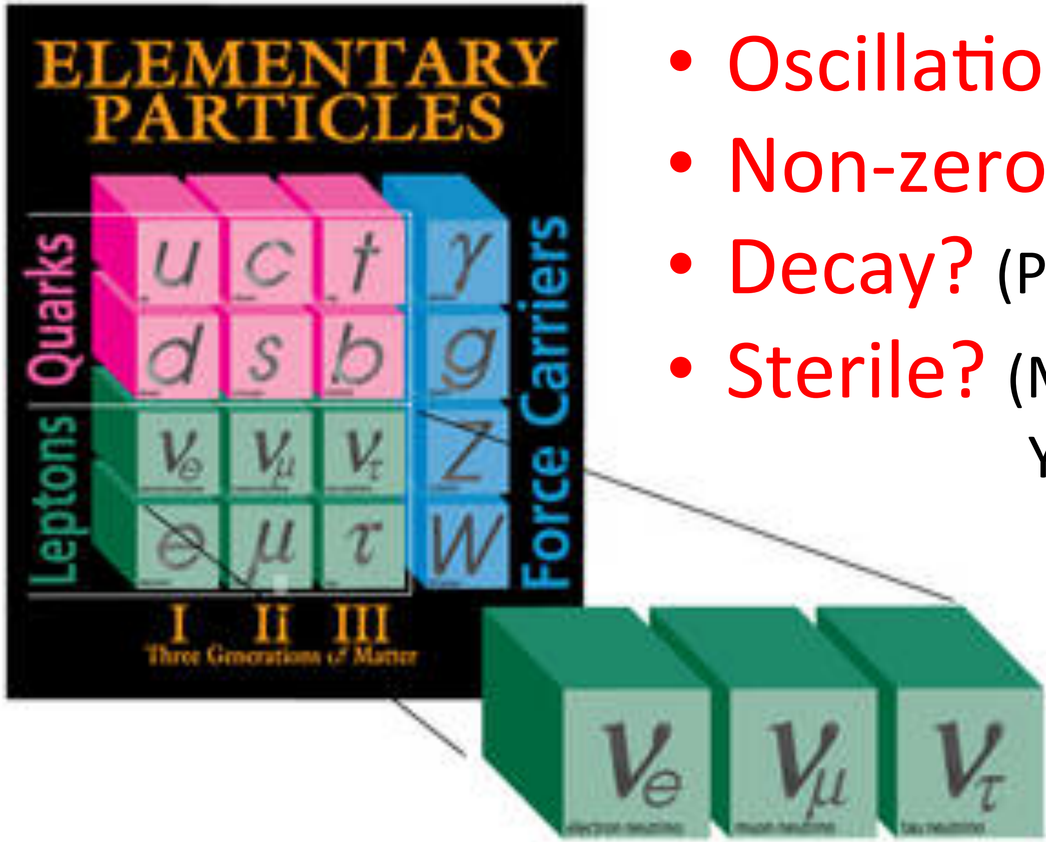
- Lightest stable particle in SUSY has been a popular candidate for WIMP DM.
- However SUSY has not (yet) been found at LHC.
- This, plus the discovery of Higgs at 126 GeV have imposed constraints on Constrained Minimal Supersymmetric Standard Model (CMSSM).
- It was suggested recently that the Next-to-MSSM (NMSSM) may be able to contrive light-mass DM


Cosmic Neutrinos

Unique window for the UHE cosmos

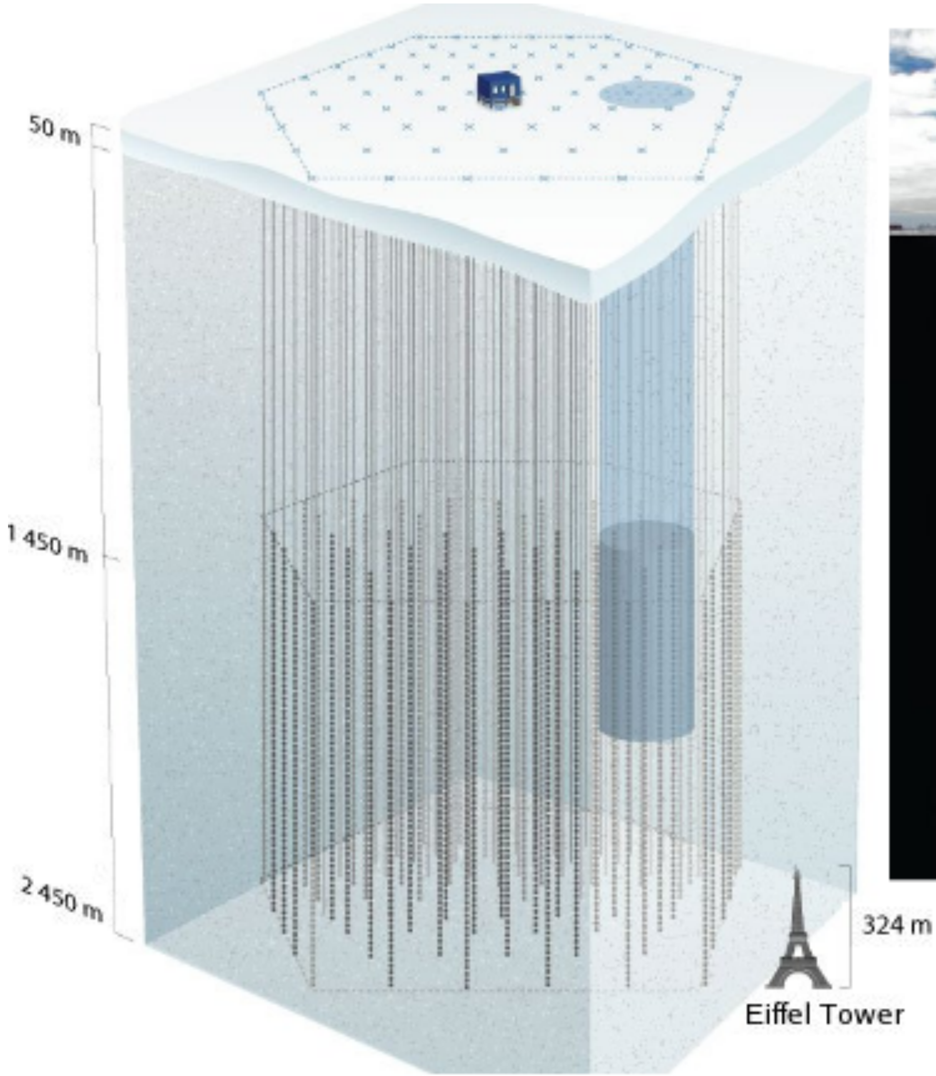


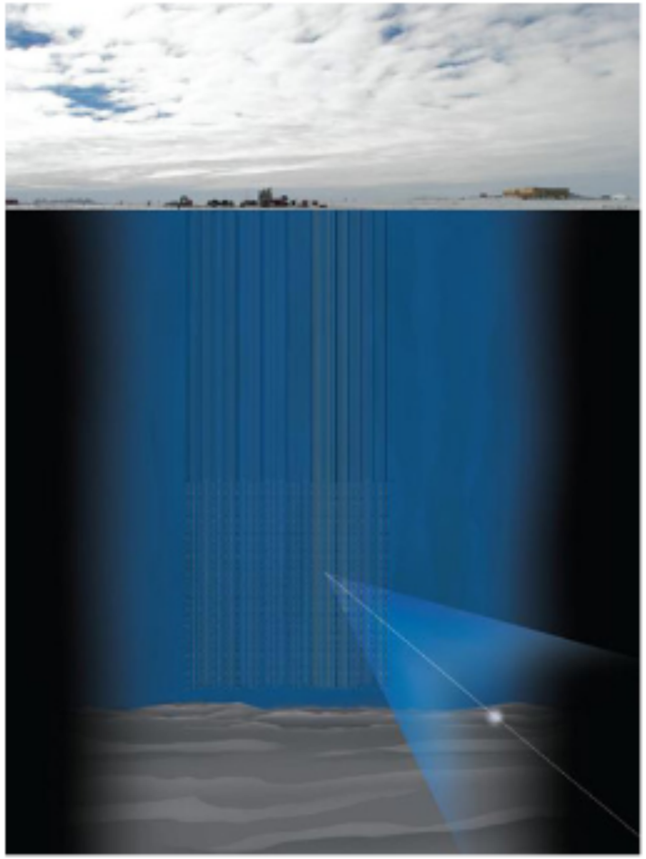
Among all elementary particles, neutrinos are the least understood.



- Oscillations
- Non-zero masses
- Decay? (Pakvasa, Beacom, Hooper, PC)
- Sterile? (Motohashi, Starobinsky, Yokoyama, PRL 13)

Detection of Ultra-High Energy Cosmic Neutrinos (IceCube 2013)



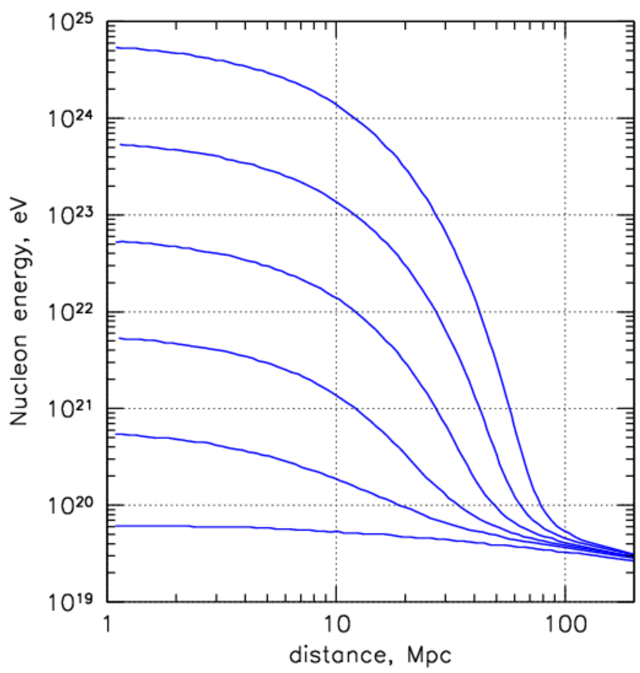


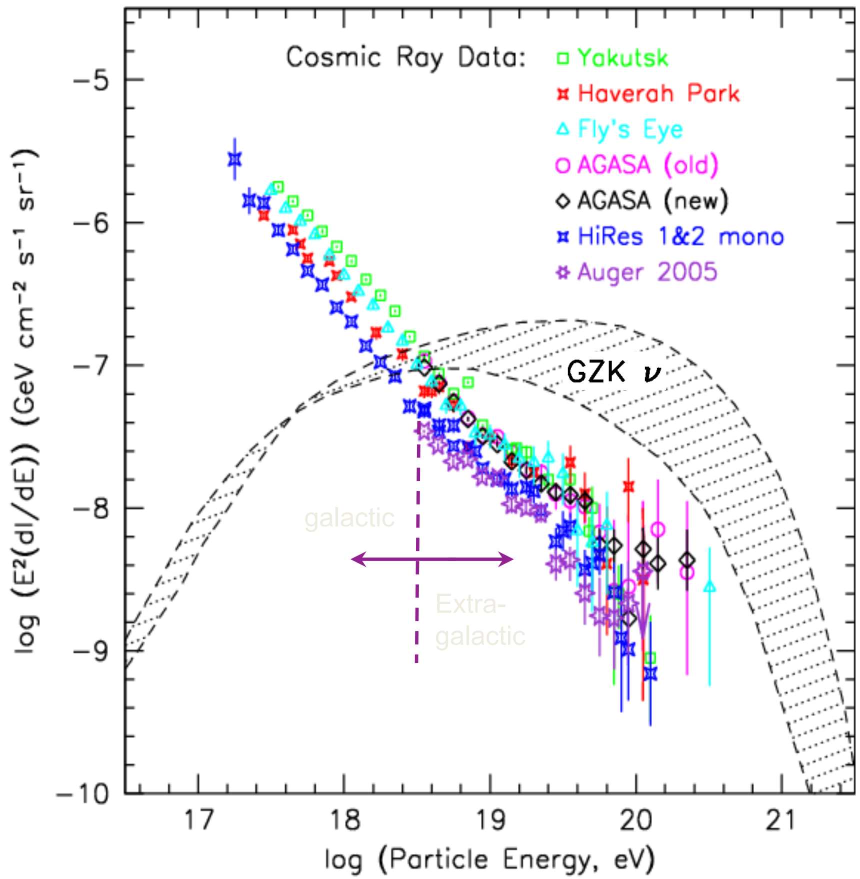
ICECUBE

Ultra-High Energy Cosmic Neutrinos

"GZK" Neutrinos: Result of UHECR and CMB Collision

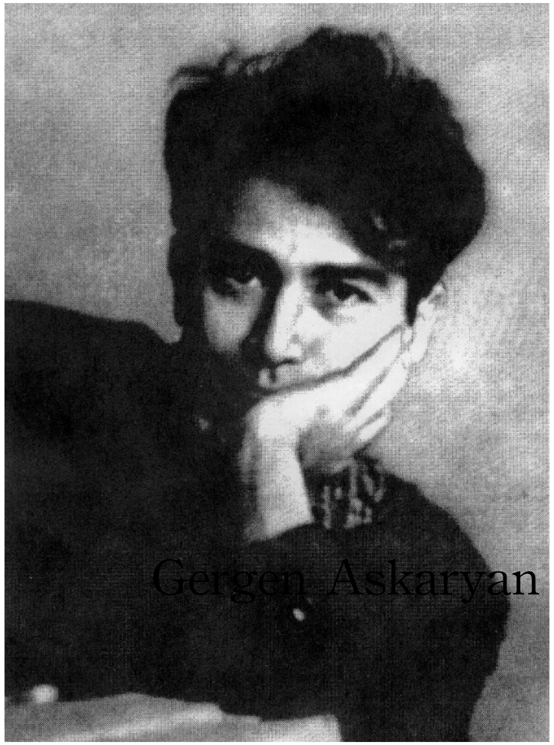
$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$

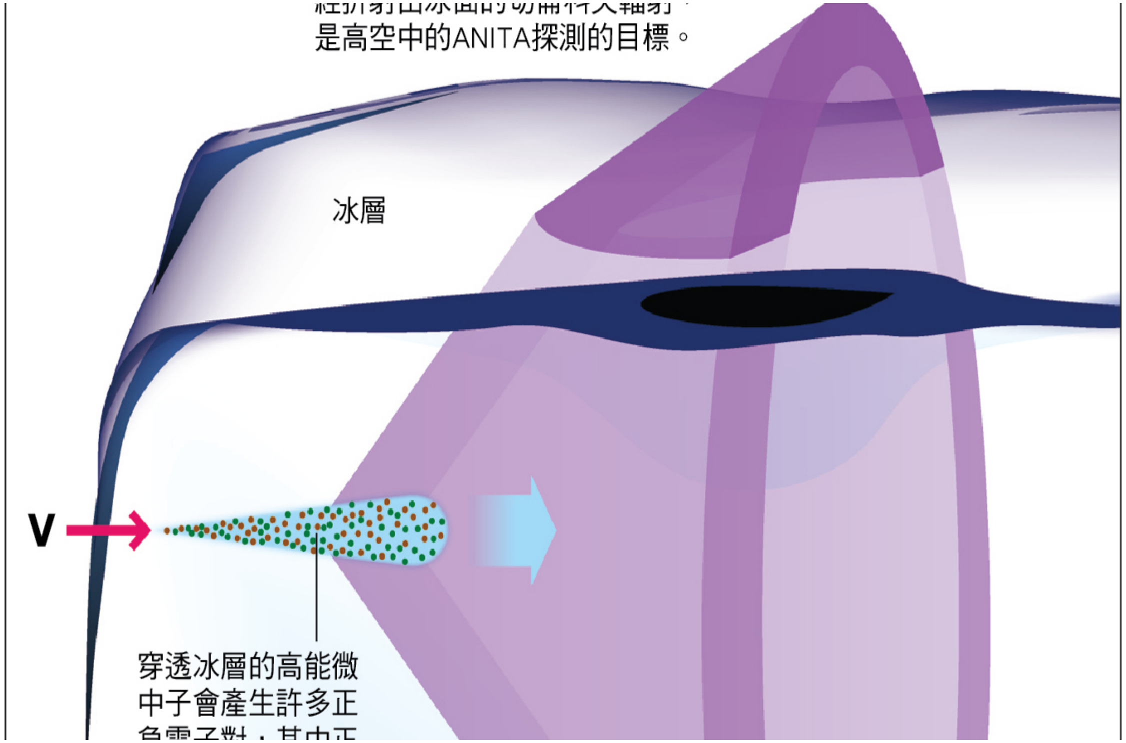




What goes beyond IceCube?

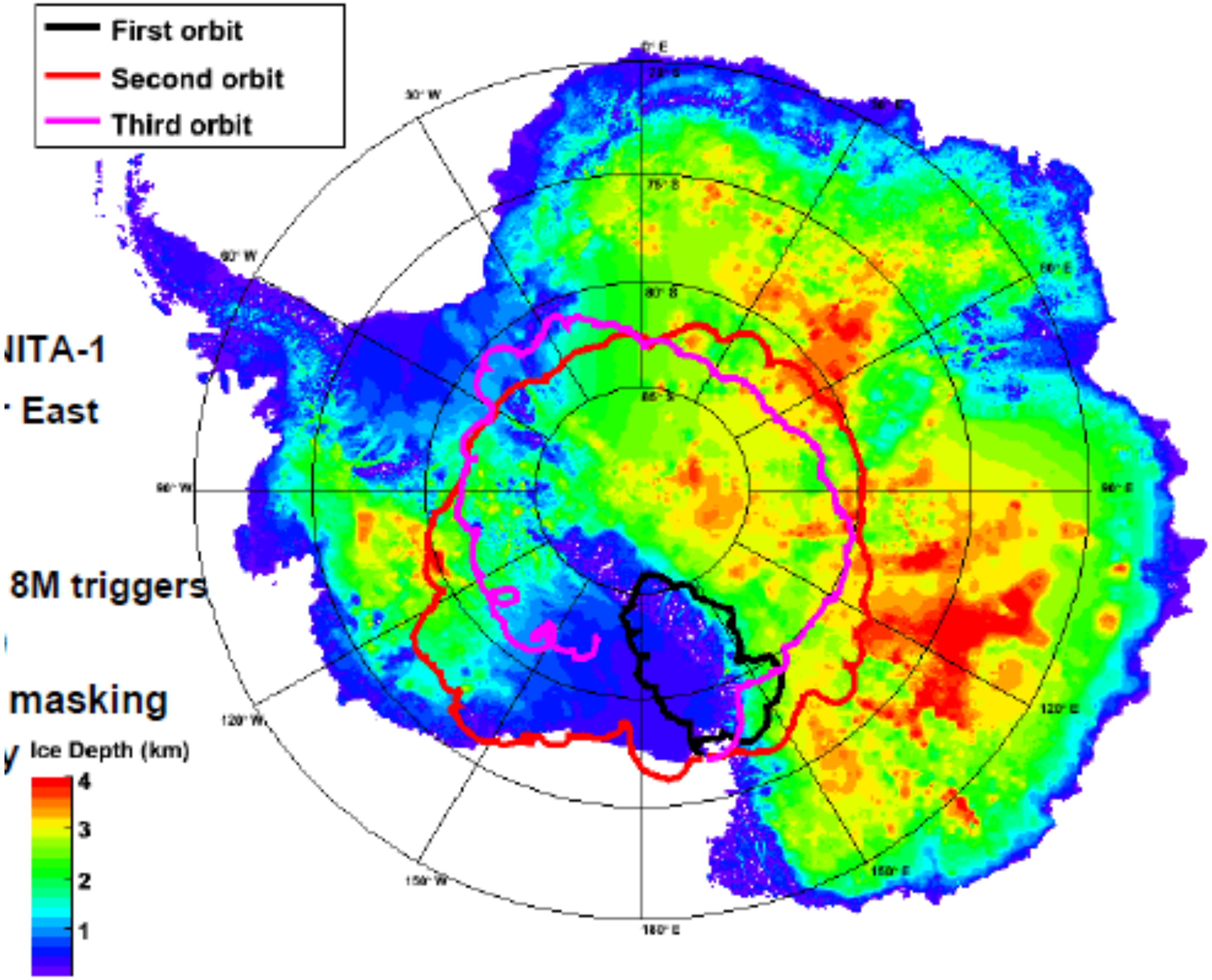
Much larger detection volume based on Askaryan effect





ANITA-2

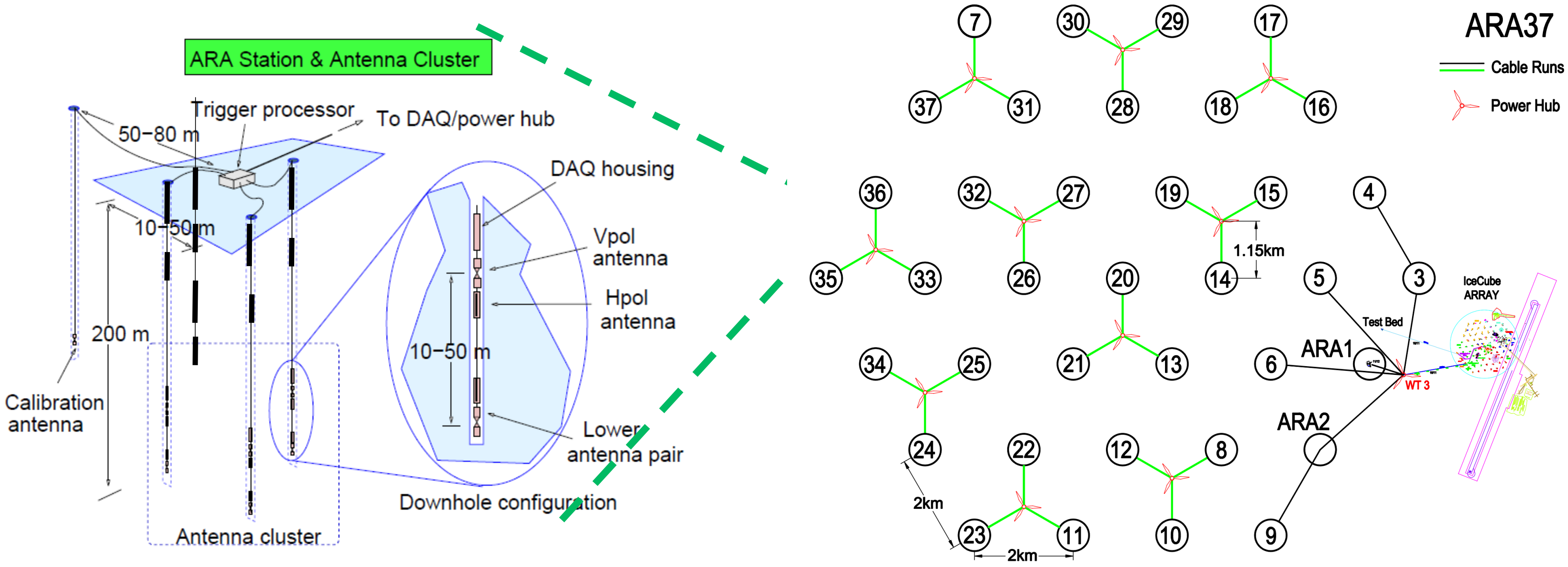
One candidate GZK event found (2010)!



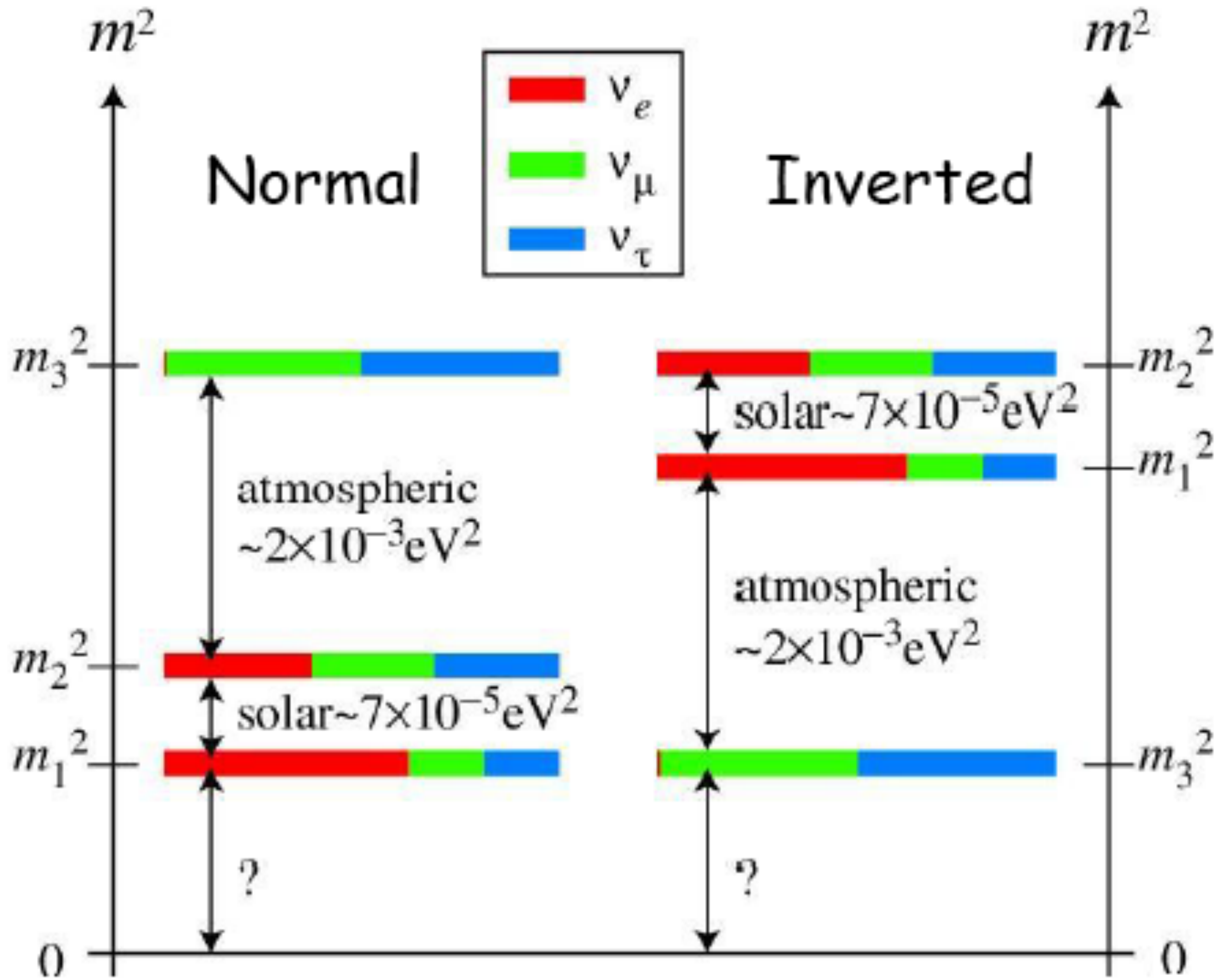
Beyond ANITA: Askaryan Radio Array (ARA)

37 4-string, 16-antenna stations covering 100km^2 w. 3-5 ν/yr

Taiwan team will contribute 10 stations, or ¼ of ARA.



in the 3-neutrino picture



Evolution of ν Flavors In-flight: Neutrino Oscillates and Decays

Two major discoveries about neutrinos in the past 20 years:

1. Neutrinos oscillate;
2. Neutrinos have mass.

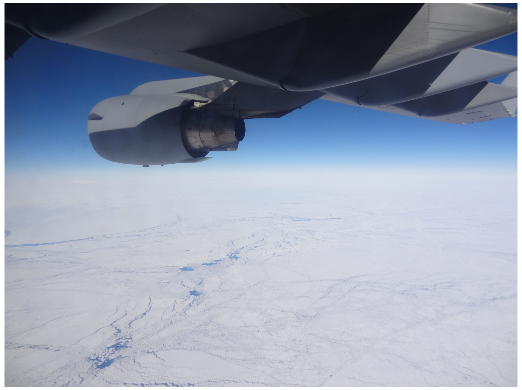
2. Neutrino Decay [Learned & Pakvasa (1995), Beacom et al. (2003)]

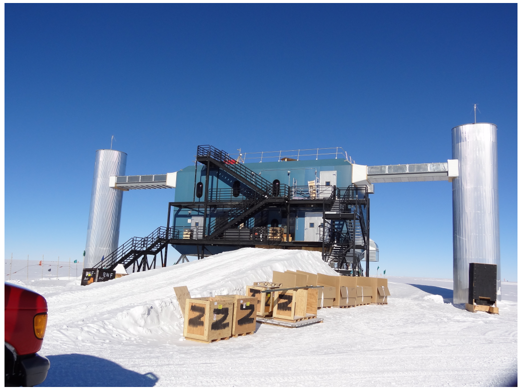
Normal Hierarchy: $f_e^E : f_\mu^E : f_\tau^E = 6 : 1 : 1$

Inverted Hierarchy: $f_e^E : f_\mu^E : f_\tau^E = 0 : 1 : 1$

Deployment of ARA1 at South Pole 2011

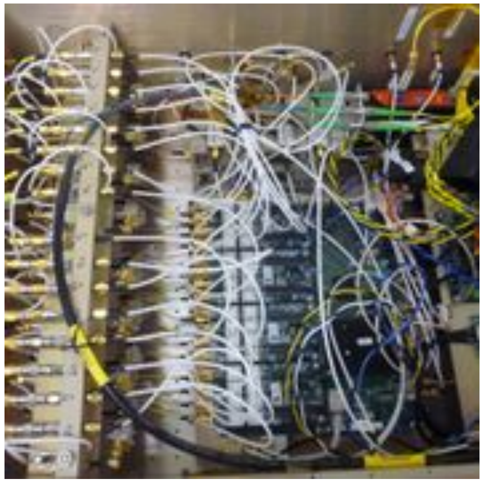
South Pole Expedition 2011-2012





Expedition 2012-2013: Deploy two new antenna stations

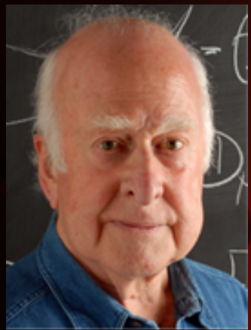




Laboratory Astrophysics Using High Intensity Lasers

I ZEST
International Zeta-Exawatt Science Technology

IZEST



"The discovery of this particle is potentially the beginning of another road, which is to explore what lies beyond the Standard Model"

- Peter Higgs

"I realized there would be many applications for the laser, but it never occurred to me that we'd get such power from it!"

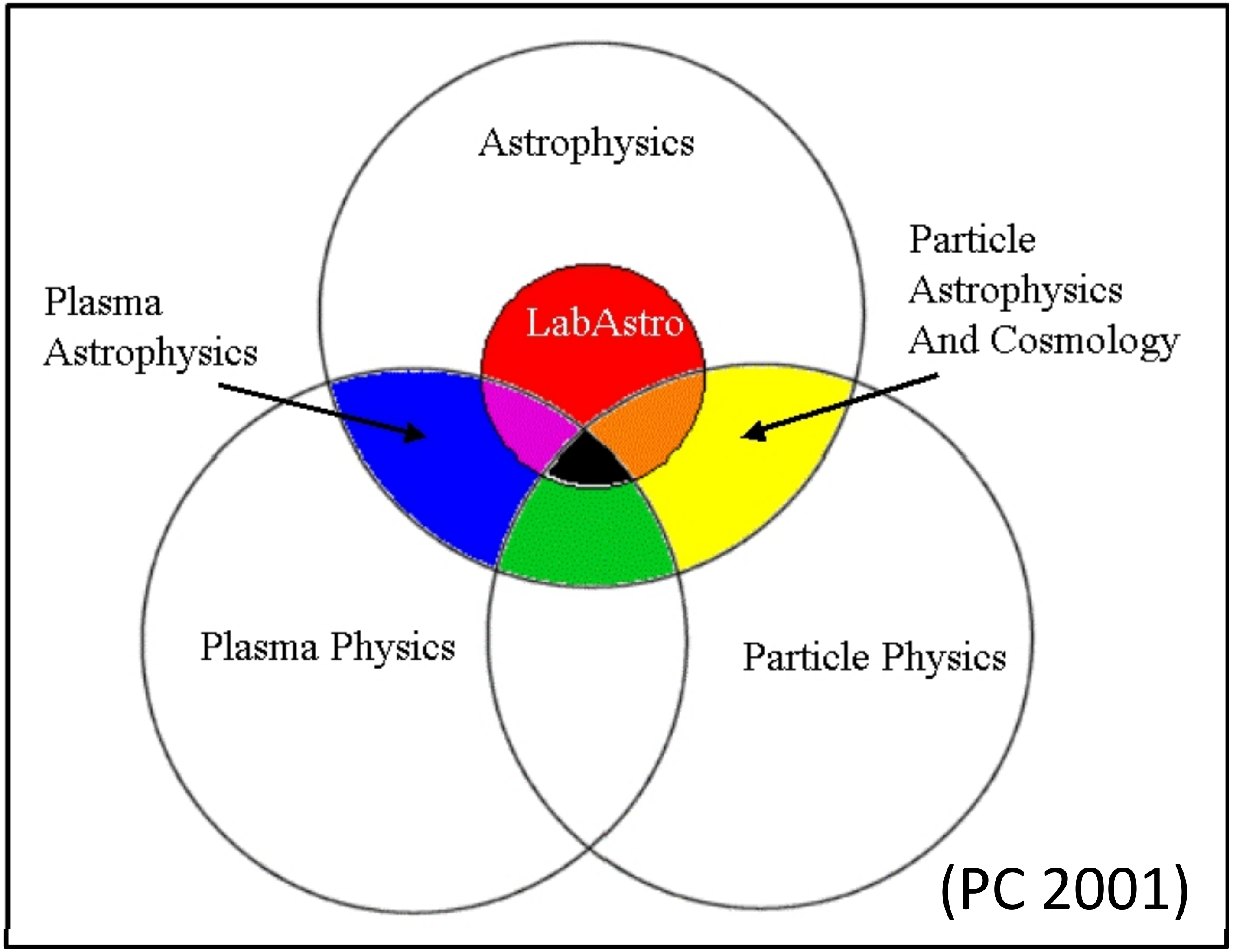
- Charles H. Townes

Gerard Mourou
IZEST Ecole Polytechnique – Paris – France

150th Anniversary of Politecnico di Milano

LABORATORY ASTROPHYSICS

Its relationship with Astrophysics, Particle Physics, and Plasma Physics



National Research Council Committee on the Physics of the Universe:

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

- What is the dark matter?
- What is the nature of the dark energy?
- How did the universe begin?
- Did Einstein have the last word on gravity?
- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
- How do cosmic accelerators work and what are they accelerating?
- Are protons unstable?
- Are there new states of matter at exceedingly high density and temperature?
- Are there additional spacetime dimensions?
- How were the elements from iron to uranium made?
- Is a new theory of matter and light needed at highest energies?

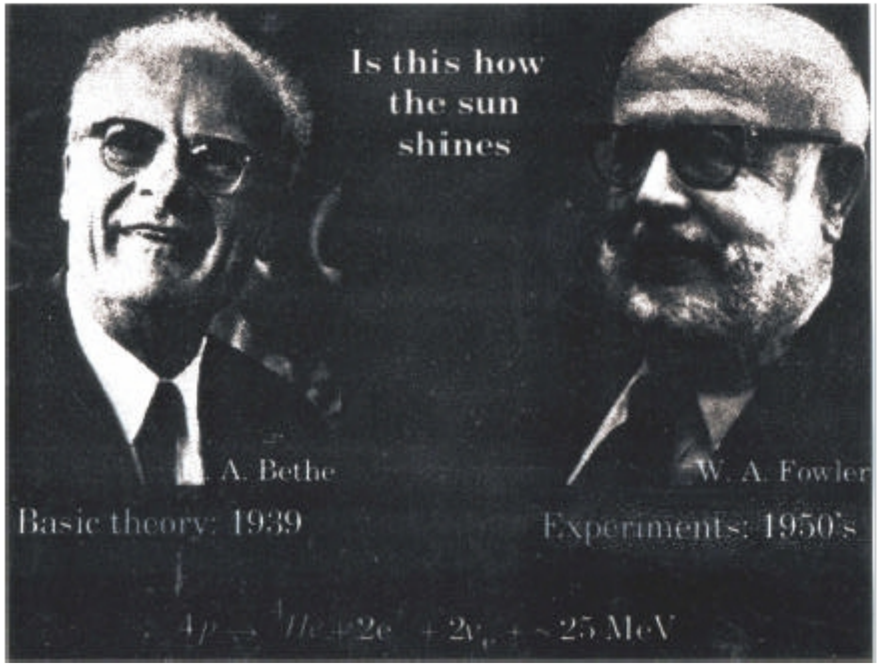
"Eleven Science Questions" and Extreme Astrophysical Conditions

- Extremely high energy events, such as ultra high energy cosmic rays (UHECR), neutrinos, and gamma rays
- Very high density, high pressure, and high temperature processes, such as supernova explosions and gamma ray bursts (GRB)
- Super strong field environments, such as that around black holes (BH) and neutron stars (NS)

Particle astrophysics and cosmology *partially overlaps with* high energy-density physics *through some of these connections*

Symbiosis between Direct Observations and Laboratory Investigations

Classic example: Laboratory determination of stellar evolution



$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + \sim 25 \text{ MeV}$$

Symbiosis should still be true for Particle Astrophysics and Cosmology

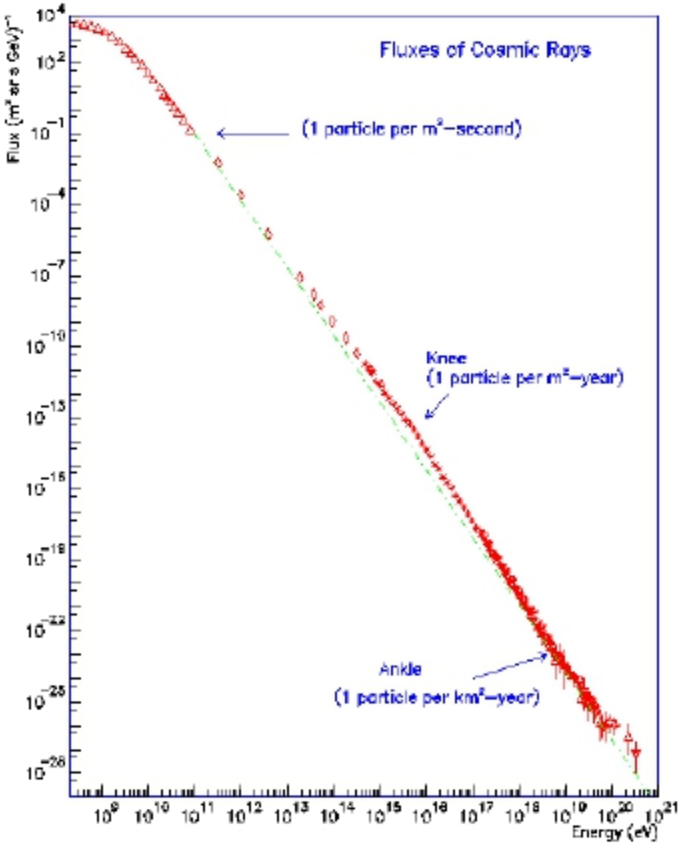
Three Categories of LabAstro

-Using Lasers and Particle Beams as Tools -

1. Calibration of observation
   - Precision measurements to calibrate observation processes
   - Development of novel approaches to astro-experimentations
   - Though mundane, value to astrophysics most certain
2. Investigation of dynamics
   - Astro-conditions hard to recreate in lab
   - Many MHD or plasma processes scalable by extrapolation
   - Value lies in revelation of dynamical underpinnings
3. Probing fundamental physics
   - Underlying physical principles may yet to be developed
   - Extreme limits render signatures faint; viability uncertain
   - Issues at stake too fundamental to be ignored for experimentation

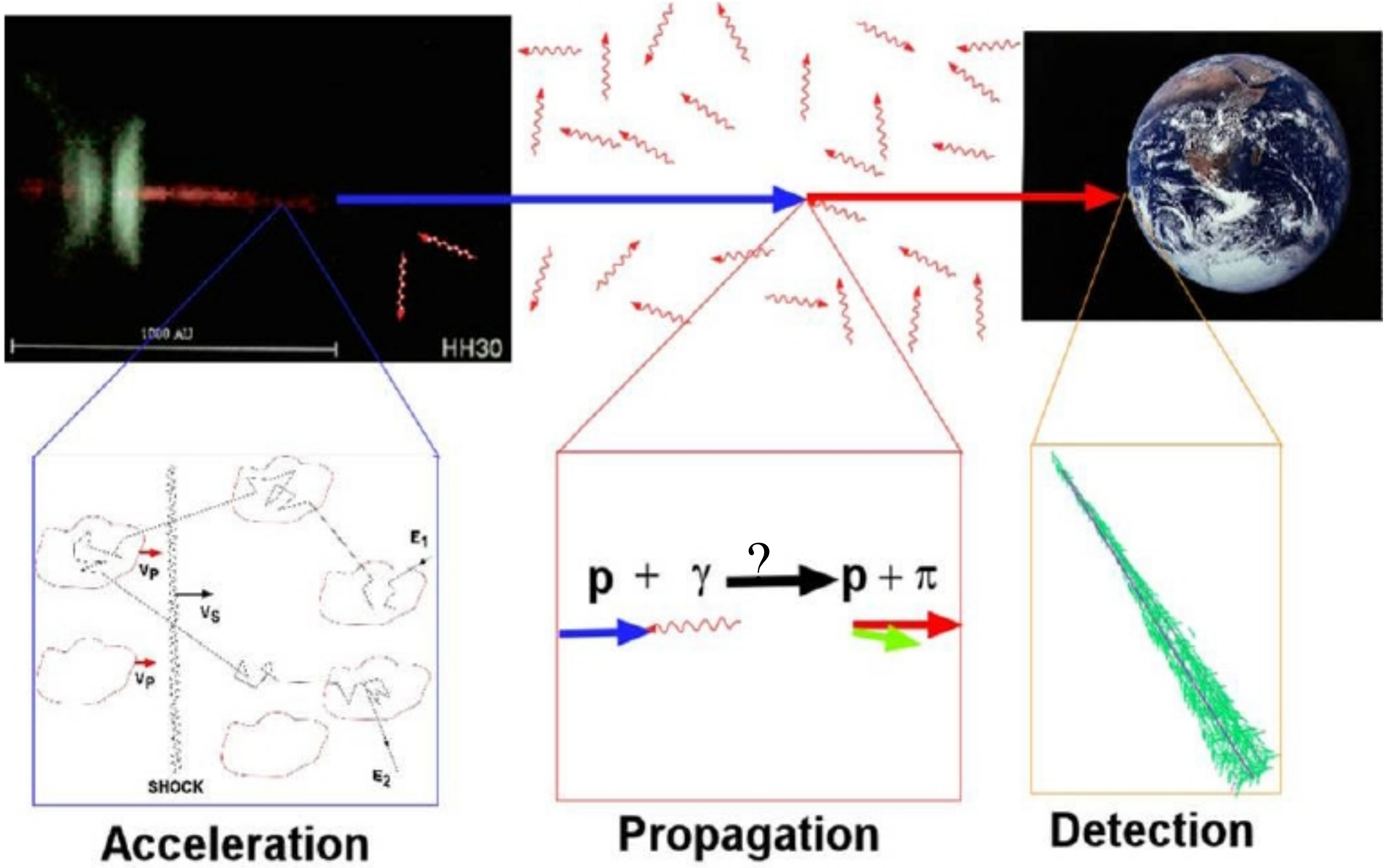
UNIVERSE AS A LABORATORY
- Extremely High Energy Events -

- Ultra High Energy Cosmic Rays (UHECR)
  - "Knee" and "ankle" in UHECR spectrum
  - Events beyond GZK-limit found
- Very high energy ?'s and ?'s
  - ? masses and oscillations
  - Extremely high energy ?: violation of Lorentz invariance?



"Is a new theory of matter and light needed at the highest energies?"

UHECR: From Source to Detection



"How do cosmic accelerators work and what are they accelerating?"

Cosmic Acceleration Mechanisms

- Conventional cosmic acceleration mechanisms encounter limitations:
  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)
  - Diffusive shock acceleration (70s) (a variant of Fermi mechanism)

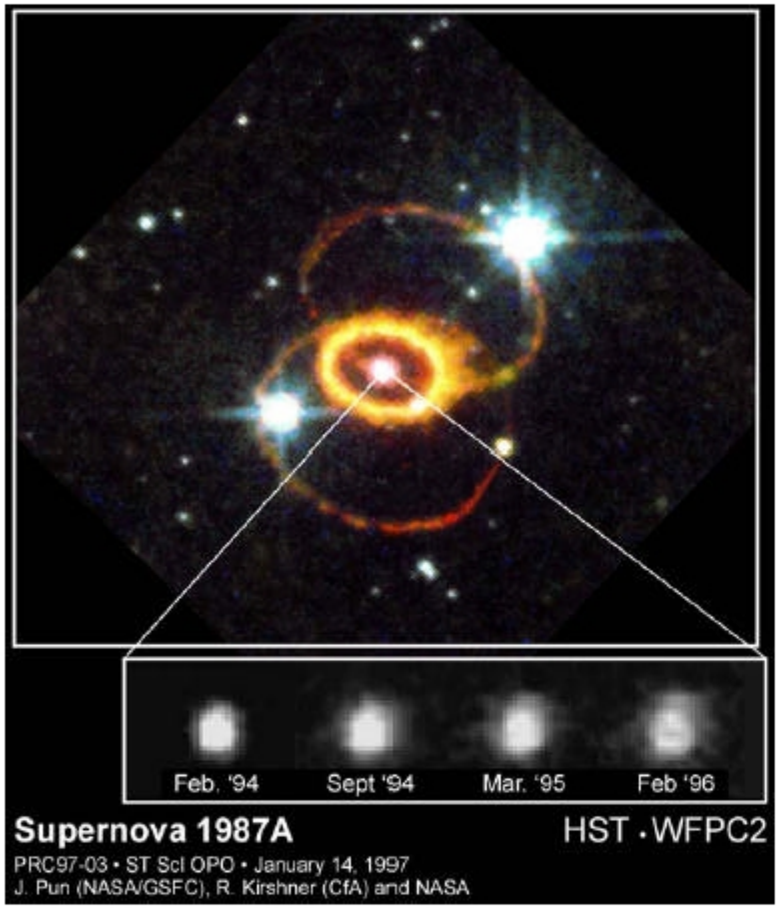
    Limitations for UHE: field strength, diffusive scattering inelastic
  - Eddington acceleration (= acceleration by photon pressure)

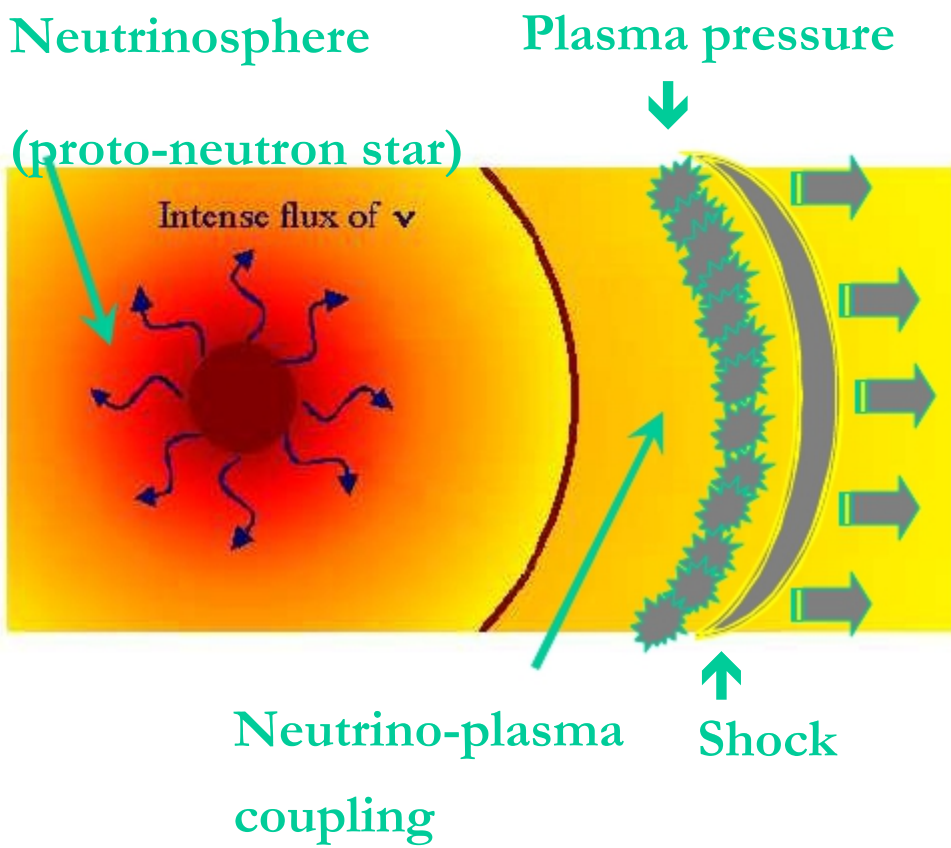
    Limitation: acceleration diminishes as 1/?
- New thinking:
  - Zevatron (= unipolar induction acceleration) (R. Blandford)
  - Alfven-wave induced wakefield acceleration in relativistic plasma

    (Chen, Tajima, Takahashi, Phys. Rev. Lett. 89 , 161101 (2002).)
  - Additional ideas by M. Barring, R. Rosner, etc.

UNIVERSE AS A LABORATORY
- Ultra High Energy-Density Processes -

- Supernova explosion



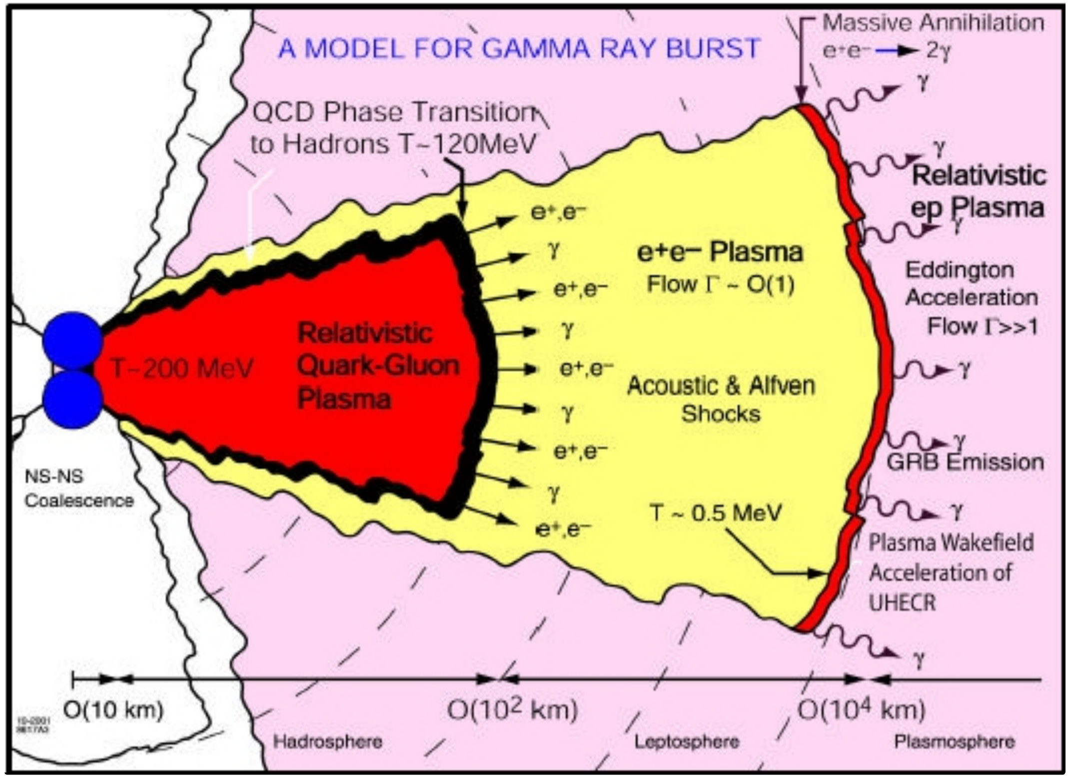


Bingham, Dawson, Bethe,
Phys. Lett. A, 220, 107 (1996)

Phys. Rev. Lett., 88, 2703 (1999)

Gamma Ray Burst

- Release of ~ 10^{52} erg/sec (short bursts)!
- "Standard" relativistic fireball model (Rees-Meszaros, 92, 93)
- Extended model invokes quark-gluon plasma (Chen et al., 01)



"Are there new states of matter at exceedingly high density and temperature?"

UNIVERSE AS A LABORATORY
- Super Strong Field Environment -

- Black holes and strong gravitational field
  - Testing general relativity

  "Did Einstein have the last word on gravity?"
- Neutron stars and strong EM fields
  - Schwinger critical field: $B_c \sim 4\times10^{13}$G or $E_c \sim 10^{16}$ V/m
  - QED Vacuum unstable

UNIVERSE AS A LABORATORY

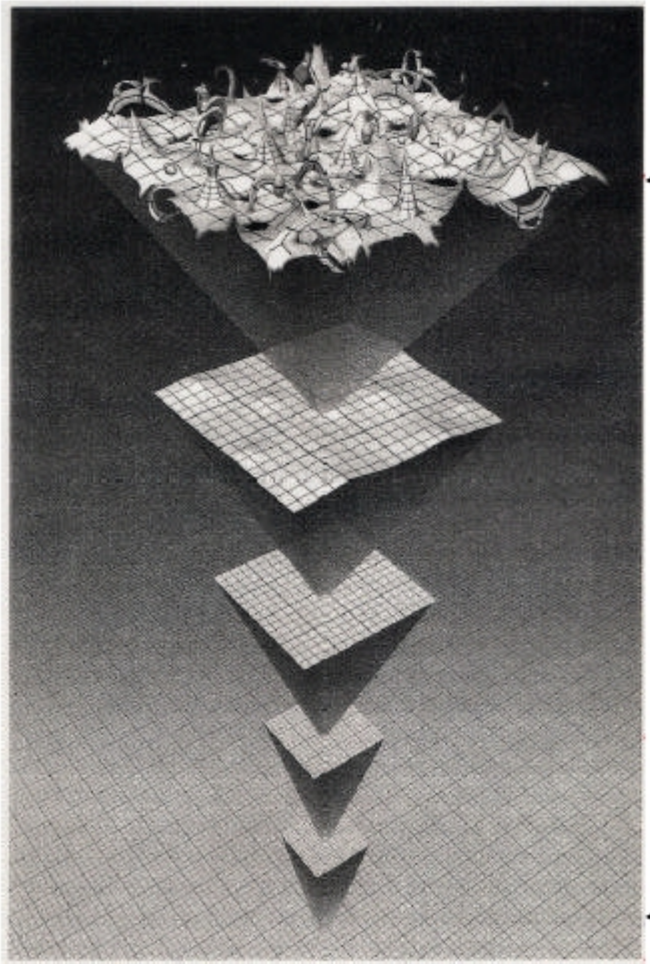
- Extreme Limits of Spacetime and Vacuum -

- ~2/3 of the present energy density of the universe is in "dark energy".

"What is the nature of dark energy?"

- Quantum effects of gravity becomes sizable, or spacetime becomes unrest, at Planck scale.

"Are there additional spacetime dimensions?"



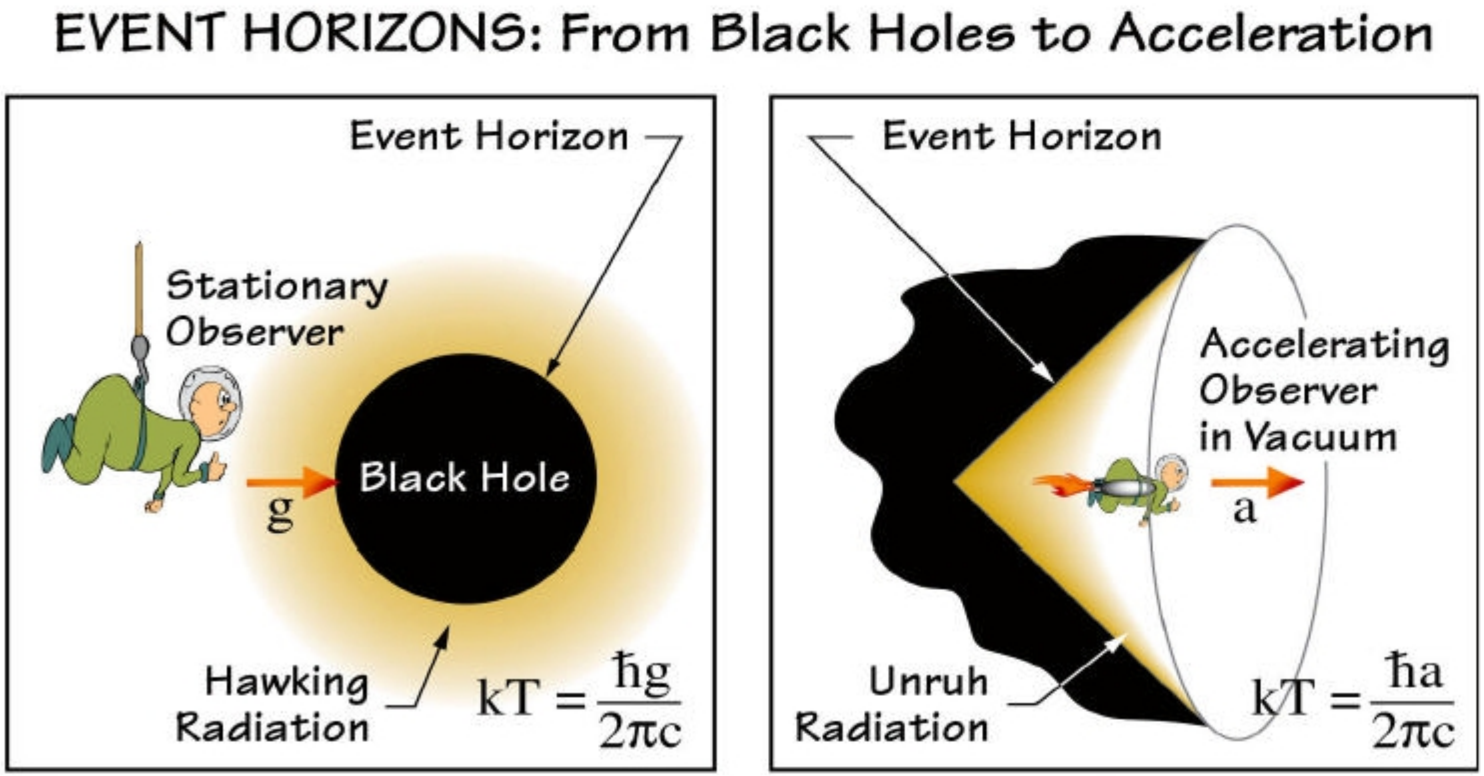
Planck Scale ~10^{-35}m

Human scale ~ 1m

LABORATORY STUDIES OF THE UNIVERSE

- Probing Fundamental Physics -

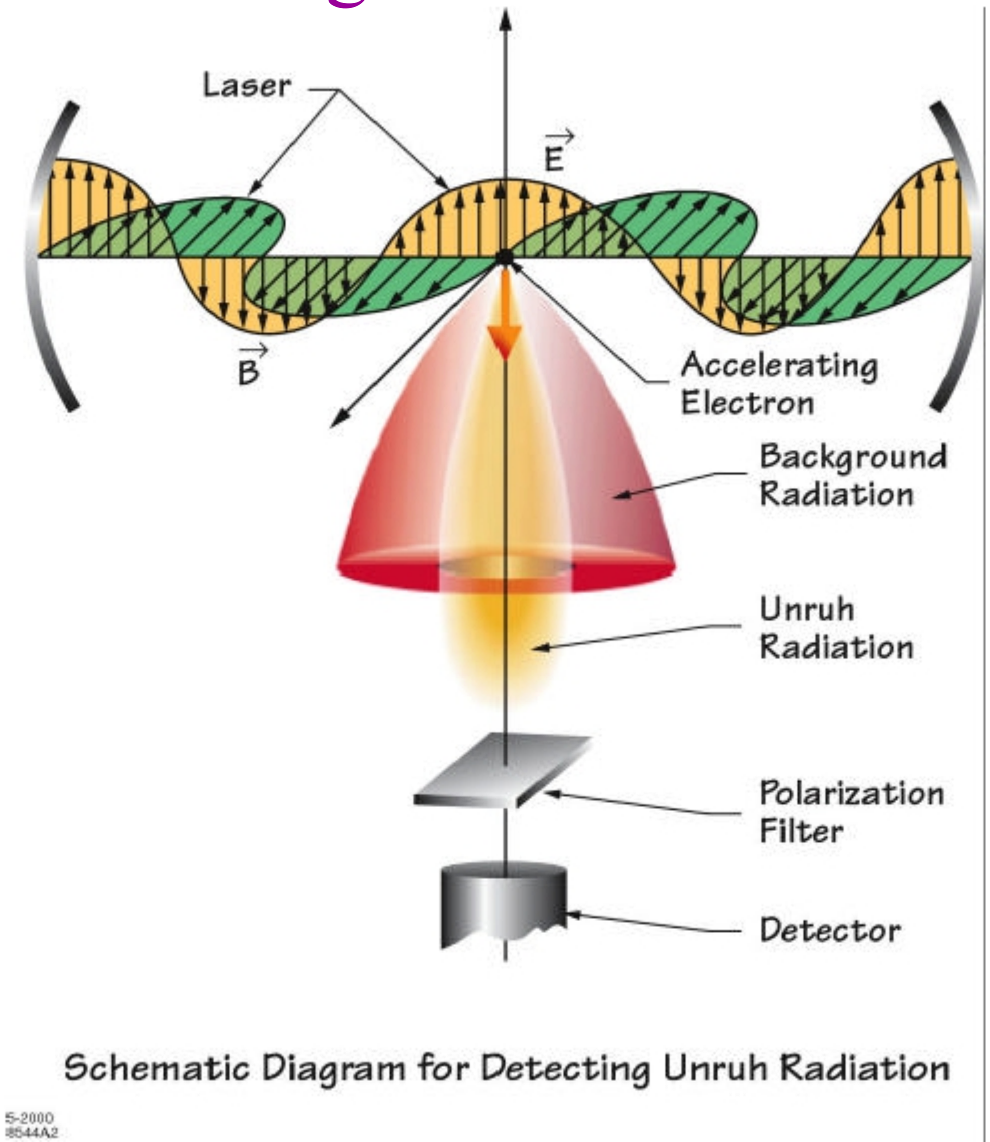
1. Event Horizon Experiment (Chen and Tajima, 99)



A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

A Conceptual Design of an Experiment for Detecting the Unruh Effect



Schematic Diagram for Detecting Unruh Radiation

Laser-driven Unruh effect

- Laser-induced nonuniform acceleration does not have a horizon, but does reveal a vacuum temperature nonetheless. (Doukas et al. 2013)
- Effective Unruh temperature :

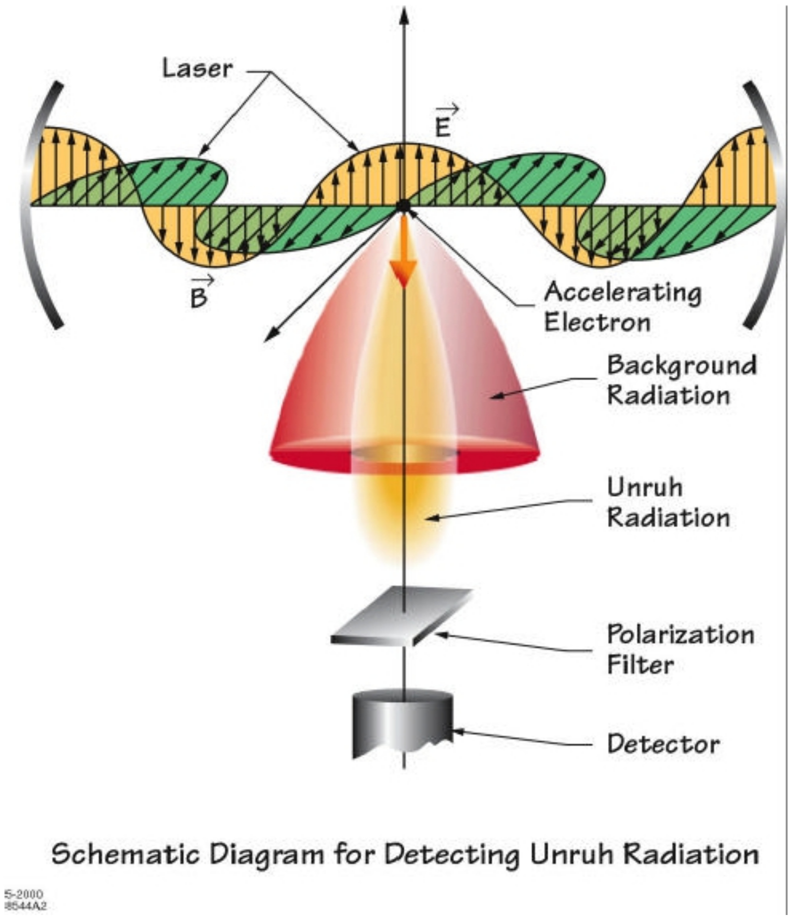
$$\bar{a} = \frac{\omega \sinh^{-1} 2a_0}{F(\pi/2, -4a_0^2)}$$

- Approaches bone fide Unuh effect when $\bar{a} \gg 1$.
- The higher the laser peak power the better!

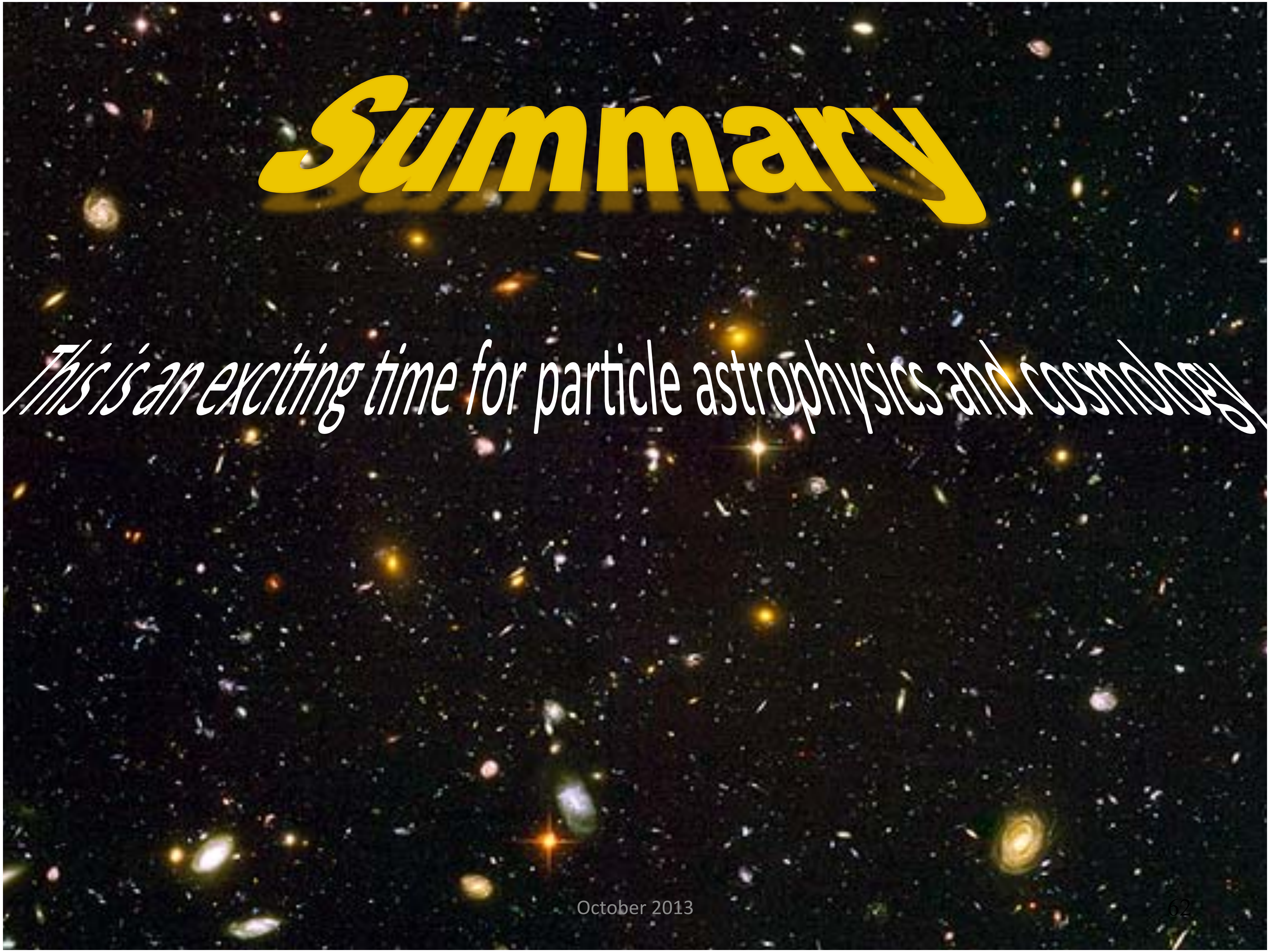
IZEST is the promise!

2. Boiling the Vacuum (Nonlinear QED)

- The same setup can be used for "boiling the vacuum" when the laser power is at the IZEST- XCELS level.
- The EM-field intensity is so high to exceed the Schwinger critical field under which copious *e+e-* pairs spontaneously created (Sauter, Euler-Heisenberg, Schwinger, Narozhny, Chen-Pellegrini, etc.)



Schematic Diagram for Detecting Unruh Radiation


Summary
This is an exciting time for particle astrophysics and cosmology