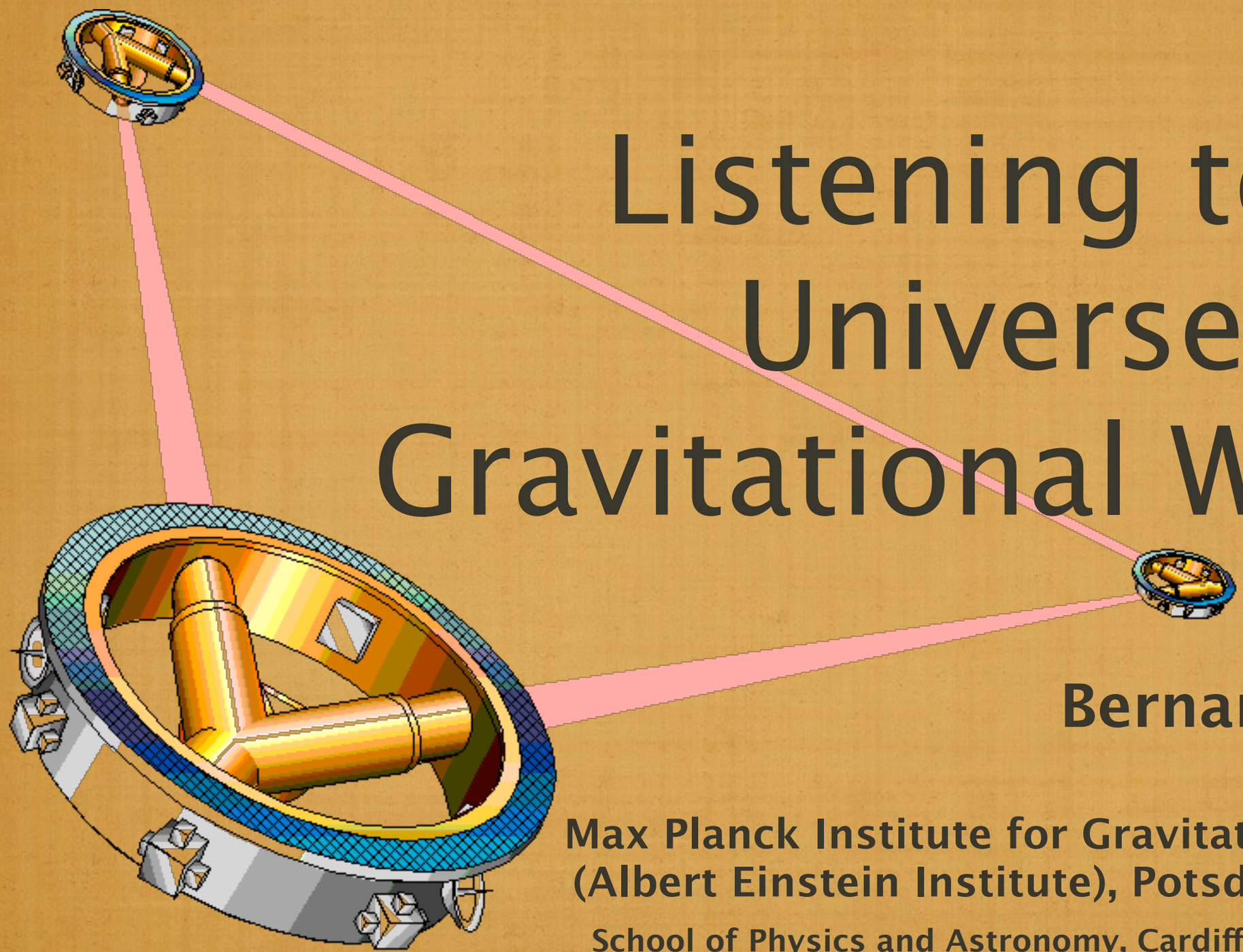

Listening to the Universe with Gravitational Waves

Bernard Schutz

Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany
and
School of Physics and Astronomy, Cardiff University, Wales

Gravitational Waves

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Gravitational Waves

$$\text{Gauge:} \qquad h^{\mu}{}_{\mu} = 0, \quad \partial^{\alpha} h_{\alpha\beta} = 0$$

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{\alpha\beta} = 0$$

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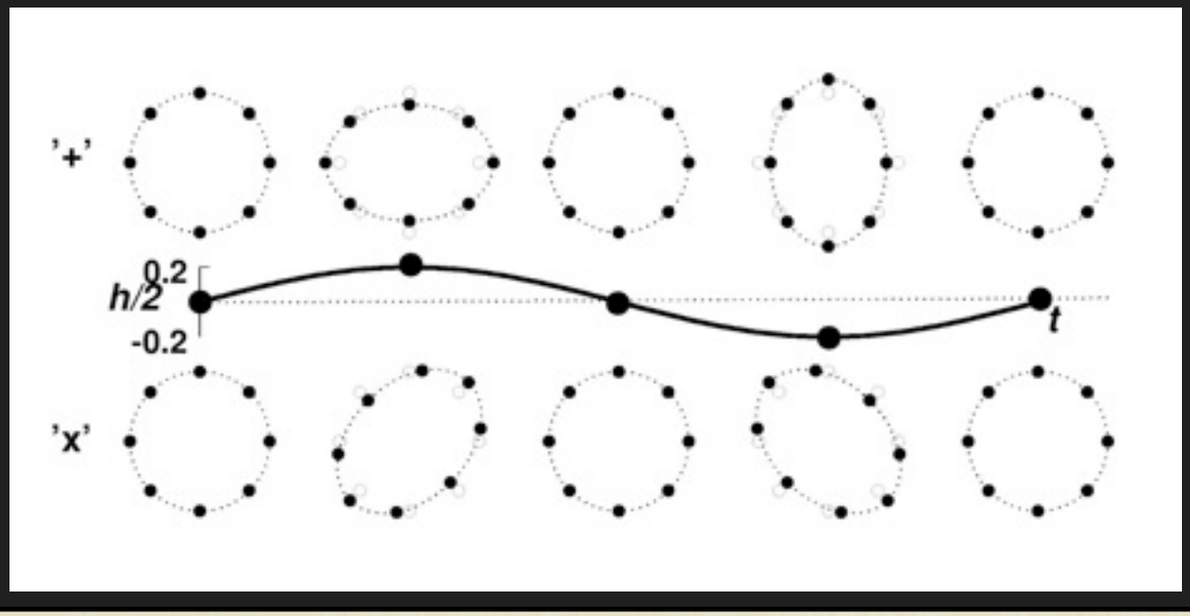

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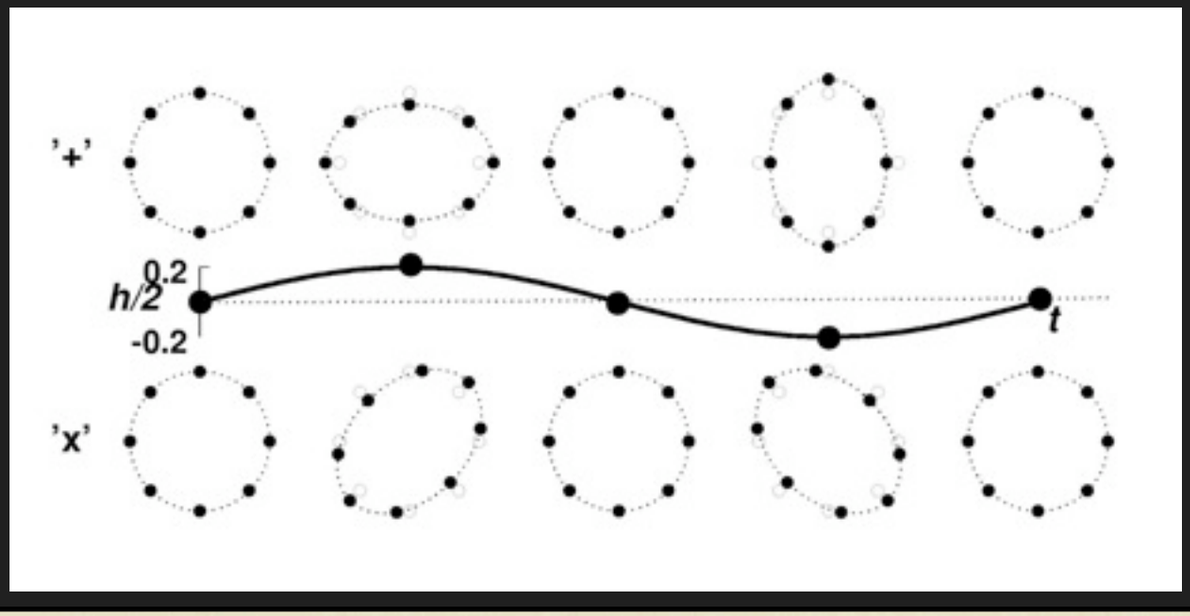

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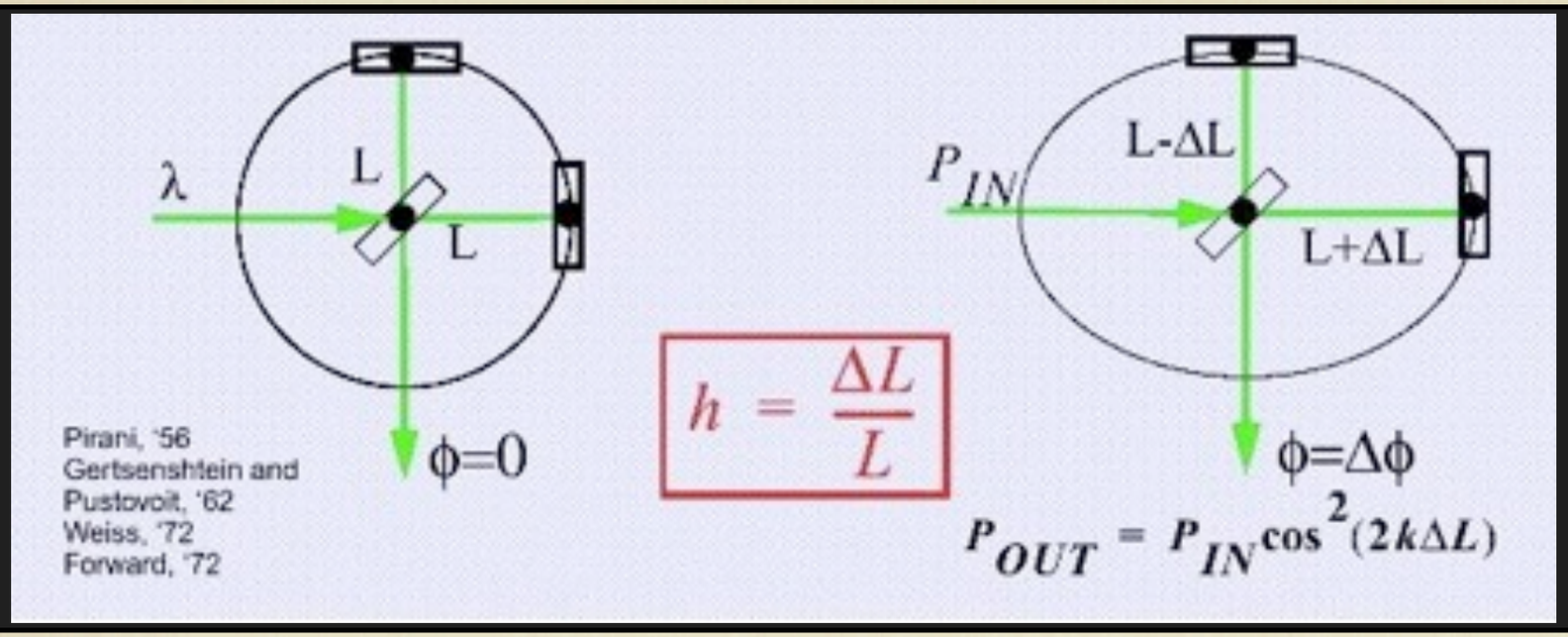

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  - The most sensitive detectors are interferometers; linearly polarized

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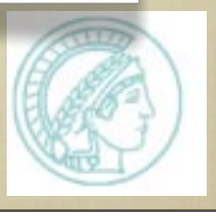

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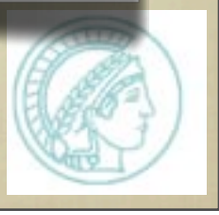

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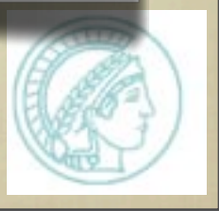

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   - ☑ *GWs excite detectors that directly measure waves'* amplitude, phase

Global interferometer network

LSC

- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction

The Alphabet Soup

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  - Includes two data producers, LIGO (Hanford & Louisiana) and GEO600 (Germany)
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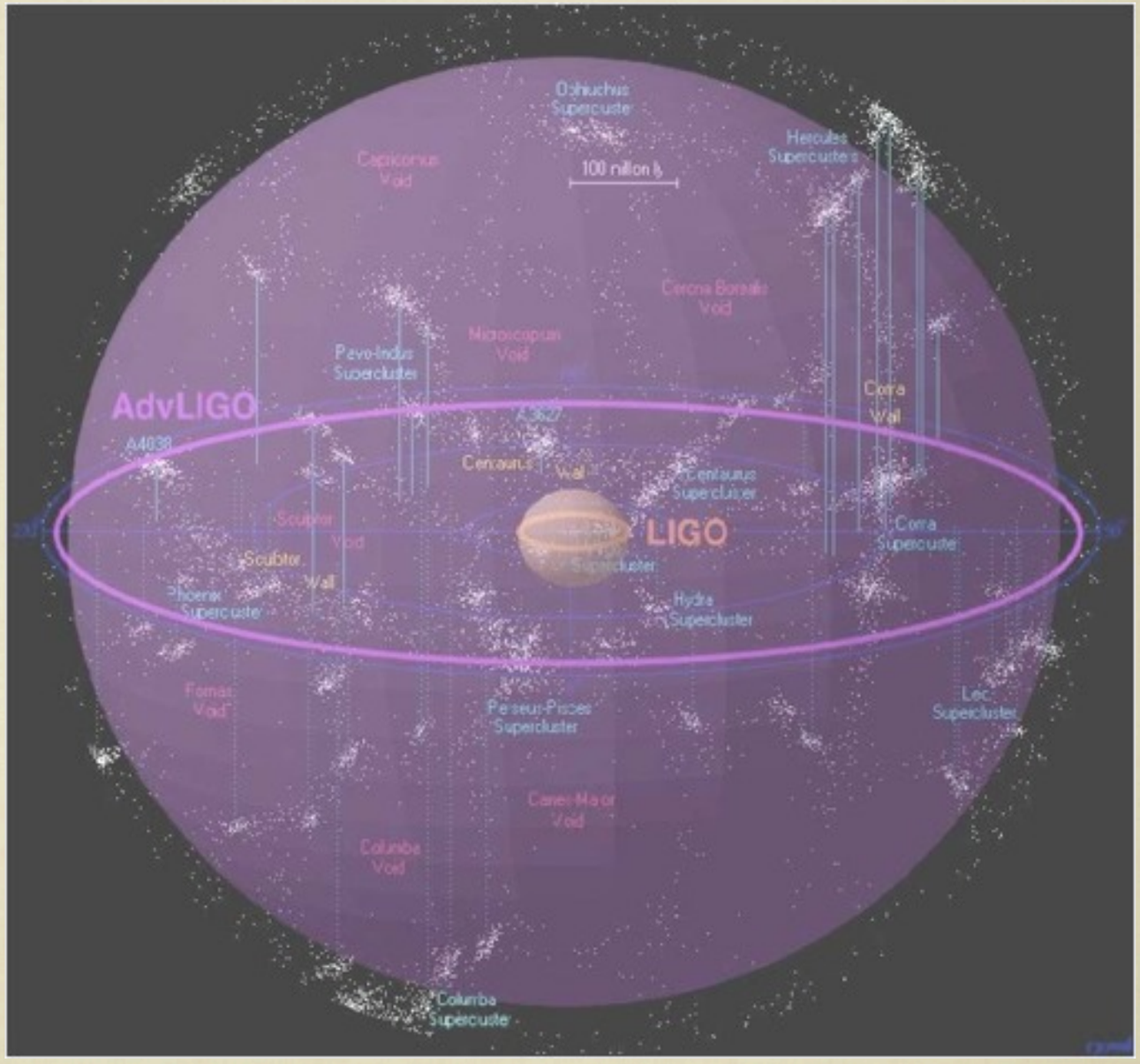

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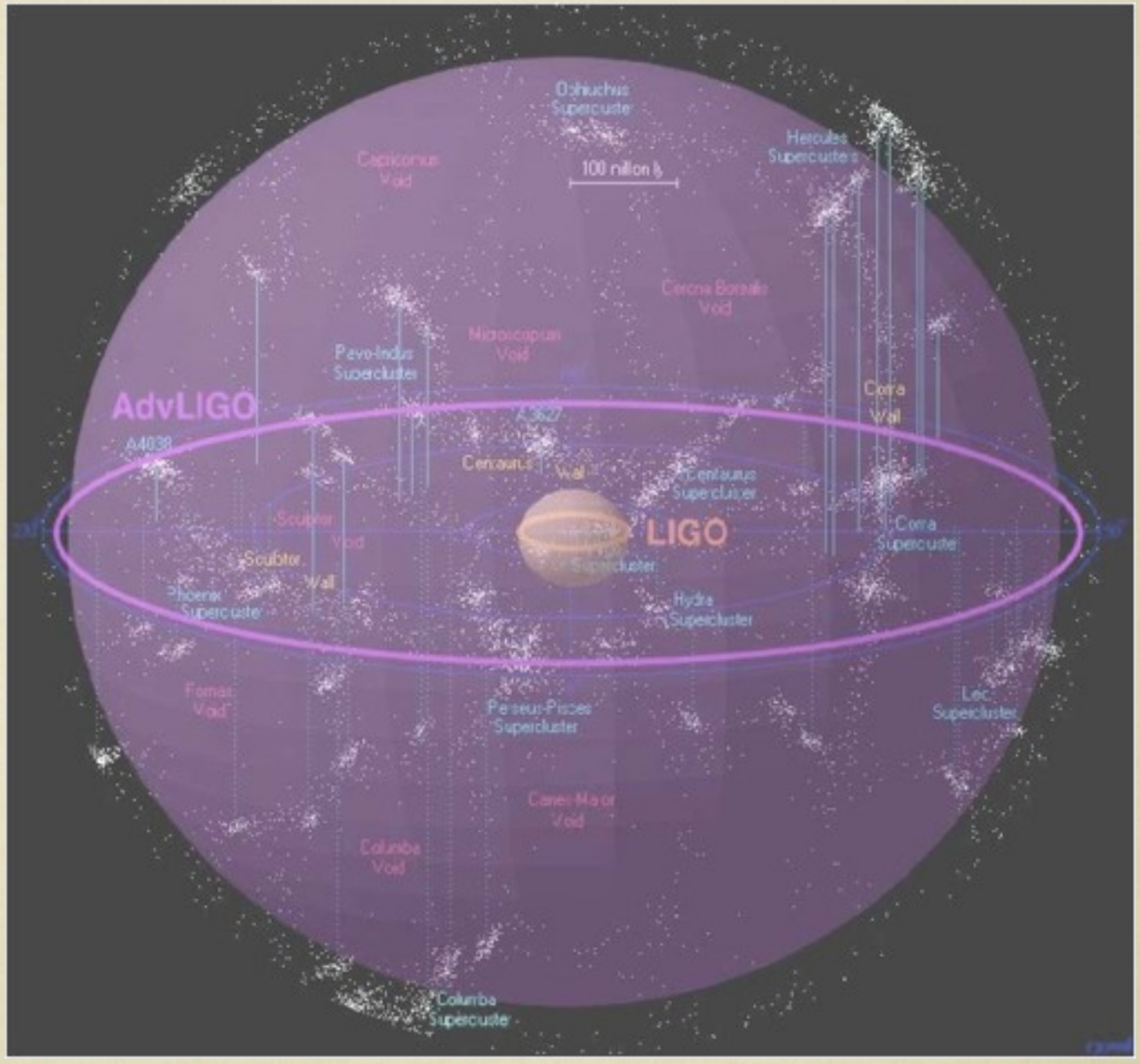

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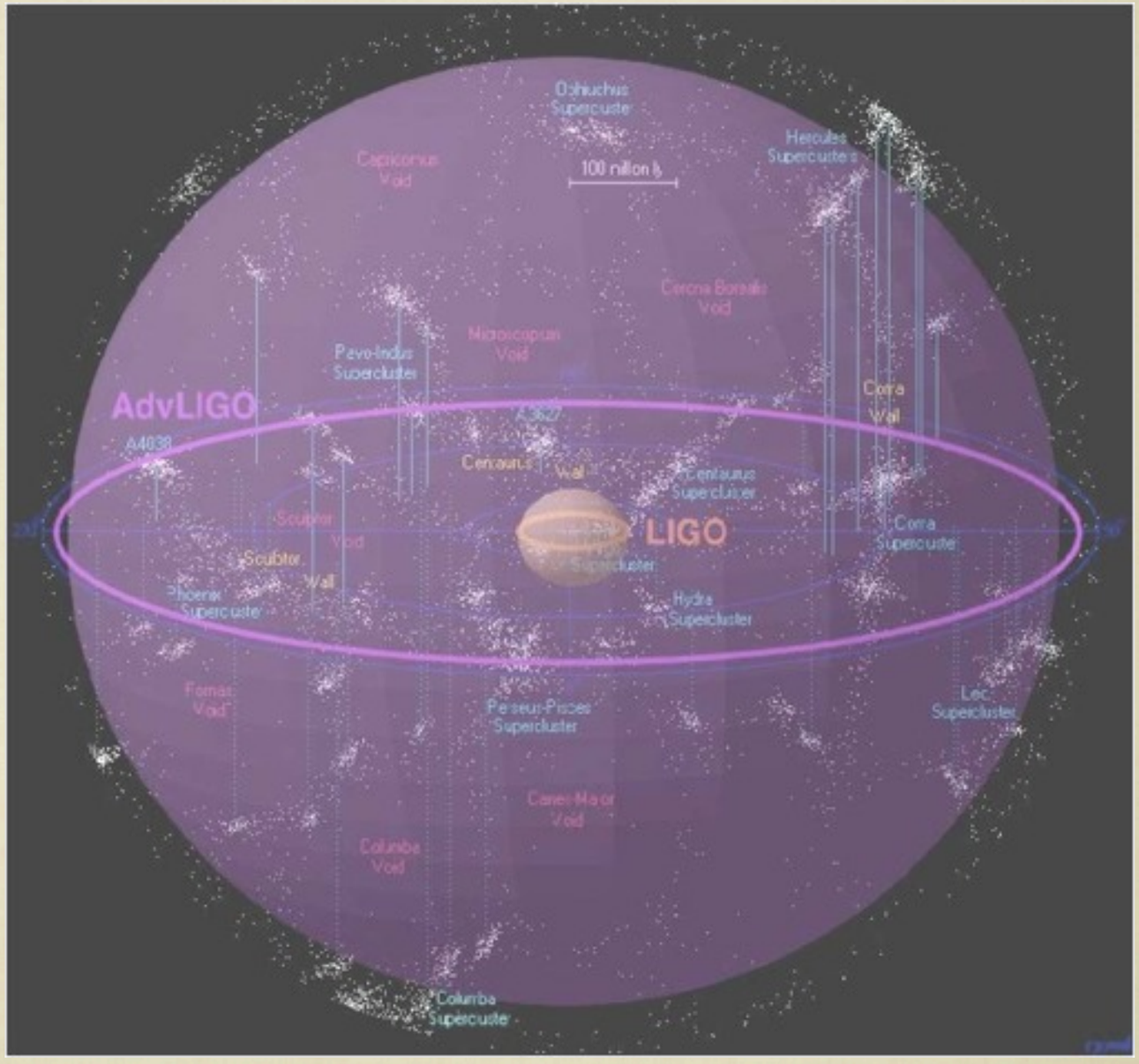
- 2017+: Continuing upgrades of sensitivity, releases of data to community. LCGT joins network.



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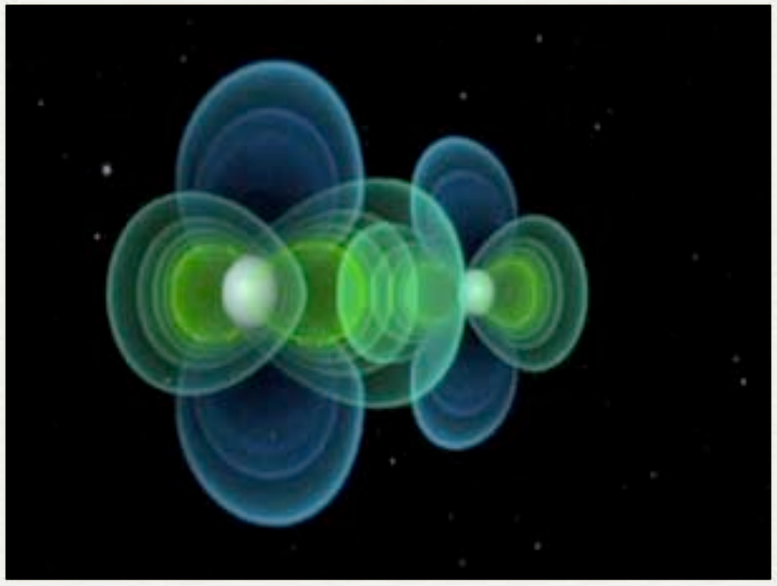

BH-BH merger

Expect ~20/yr, rising to ~150. Range beyond z =1. Science: BH population statistics, stellar evolution, tests of GR, (H_0, w).

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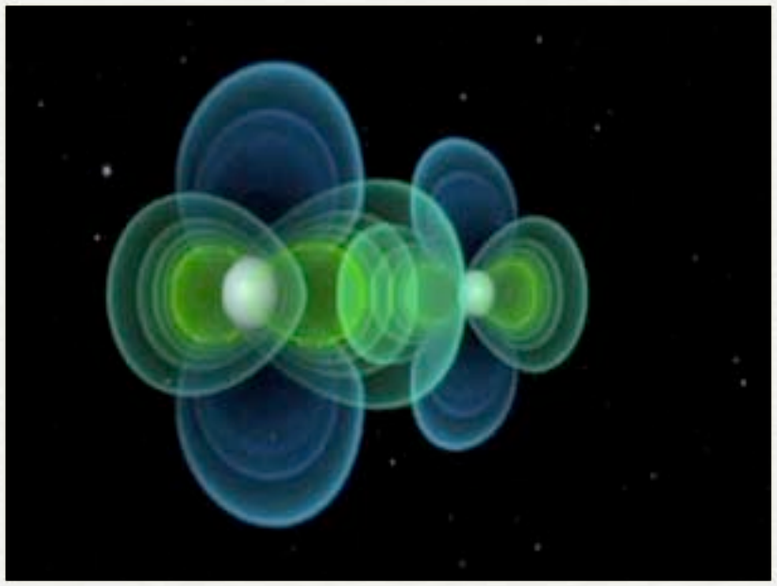

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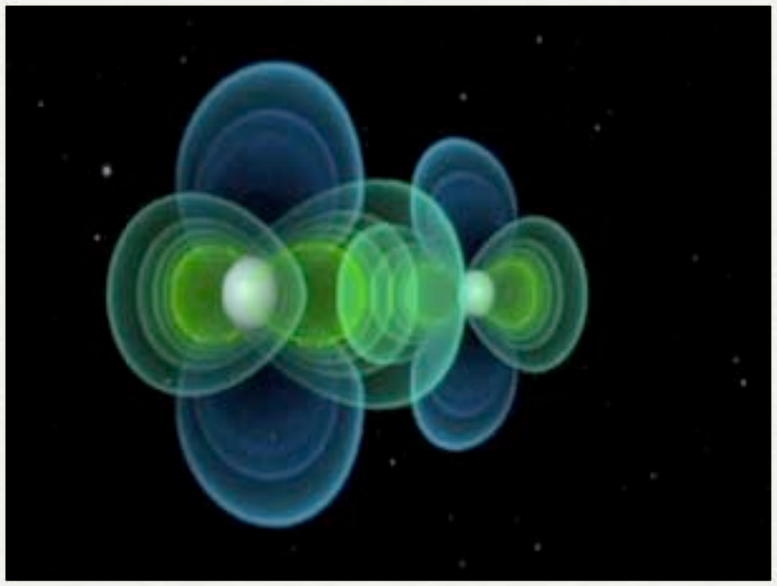

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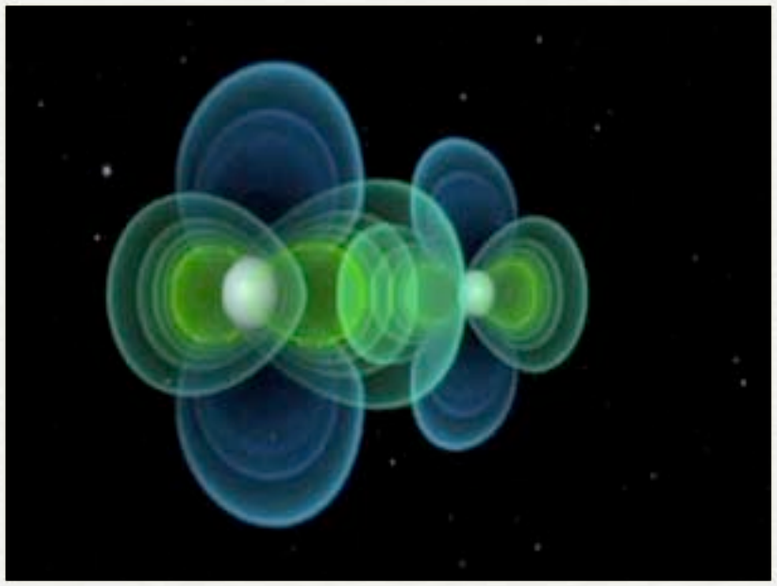

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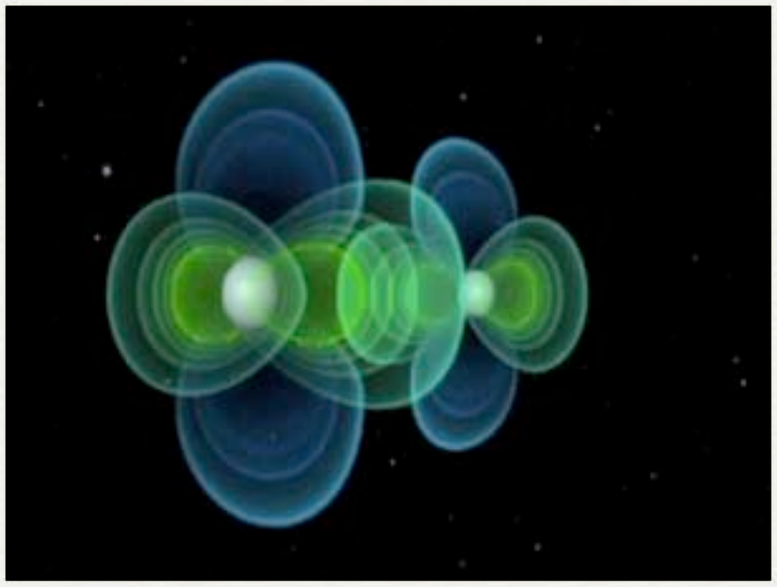

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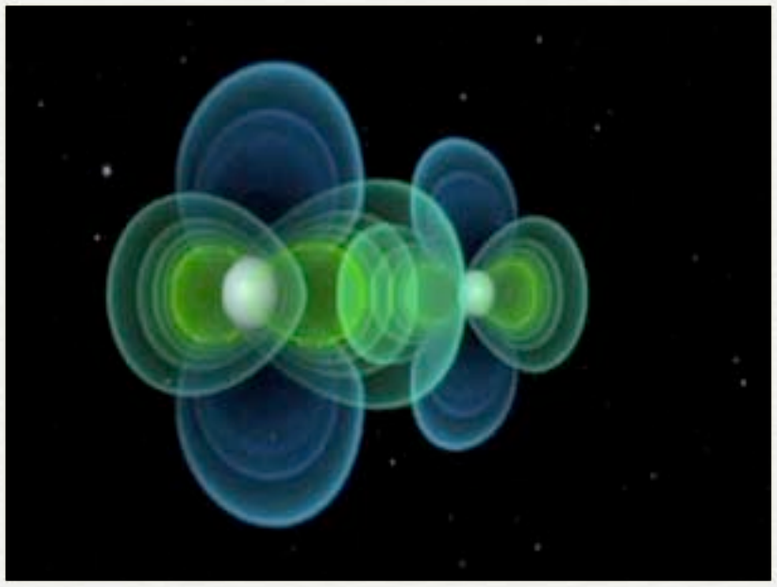

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THE GRAVITATIONAL WAVE SPECTRUM

SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy

and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period

AGE OF THE UNIVERSE

YEARS

HOURS

SECONDS

MSEC

Frequency (Hz)

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

DETECTORS

Cosmic microwave polarisation

Pulsar timing arrays (2006-) SKA (2020?)

LISA (ESA/NASA, 2020)

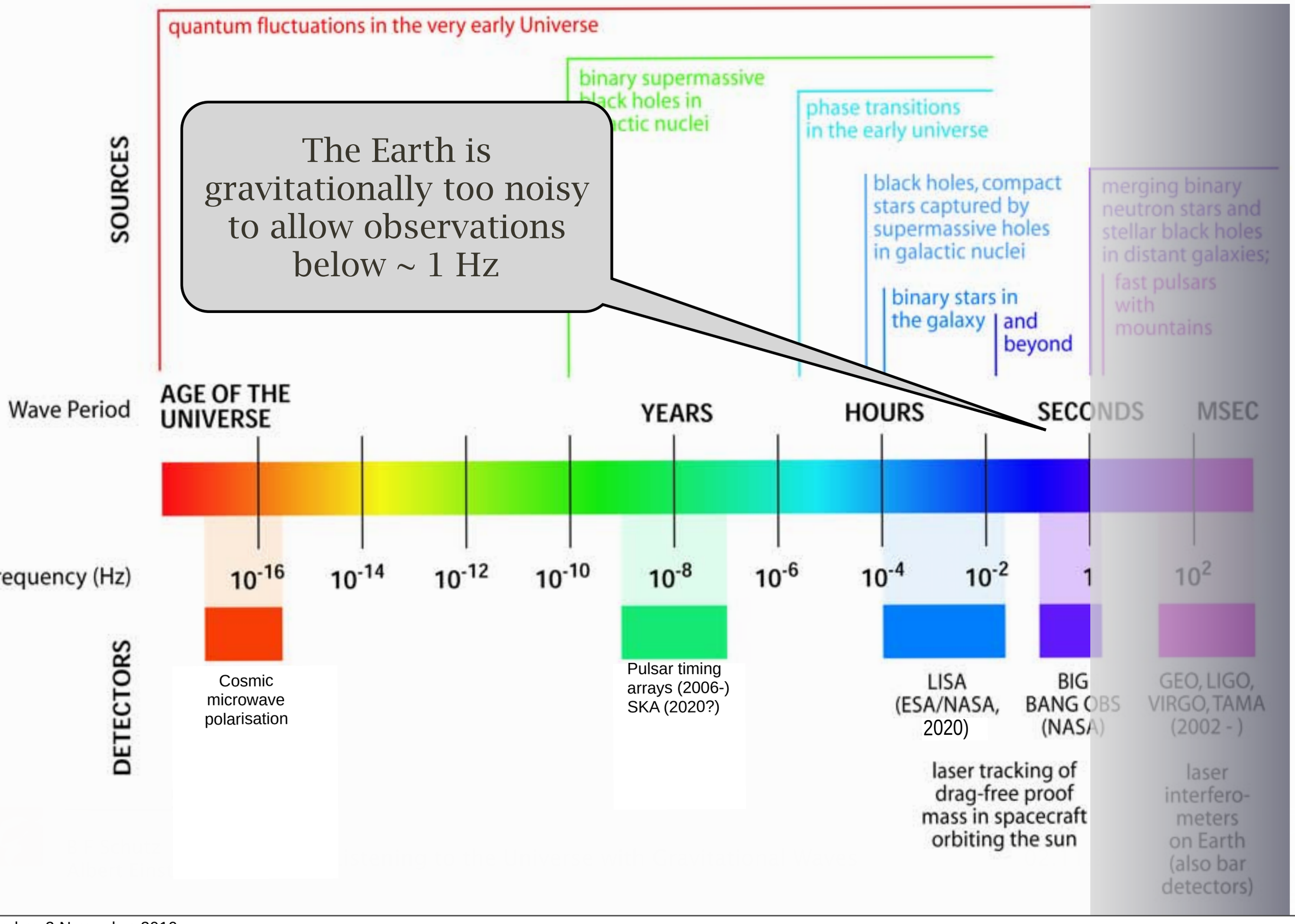
laser tracking of drag-free proof mass in spacecraft orbiting the sun

BIG BANG OBS (NASA)

GEO, LIGO, VIRGO, TAMA (2002 -)

laser interfero-meters on Earth (also bar detectors)

THE GRAVITATIONAL WAVE SPECTRUM



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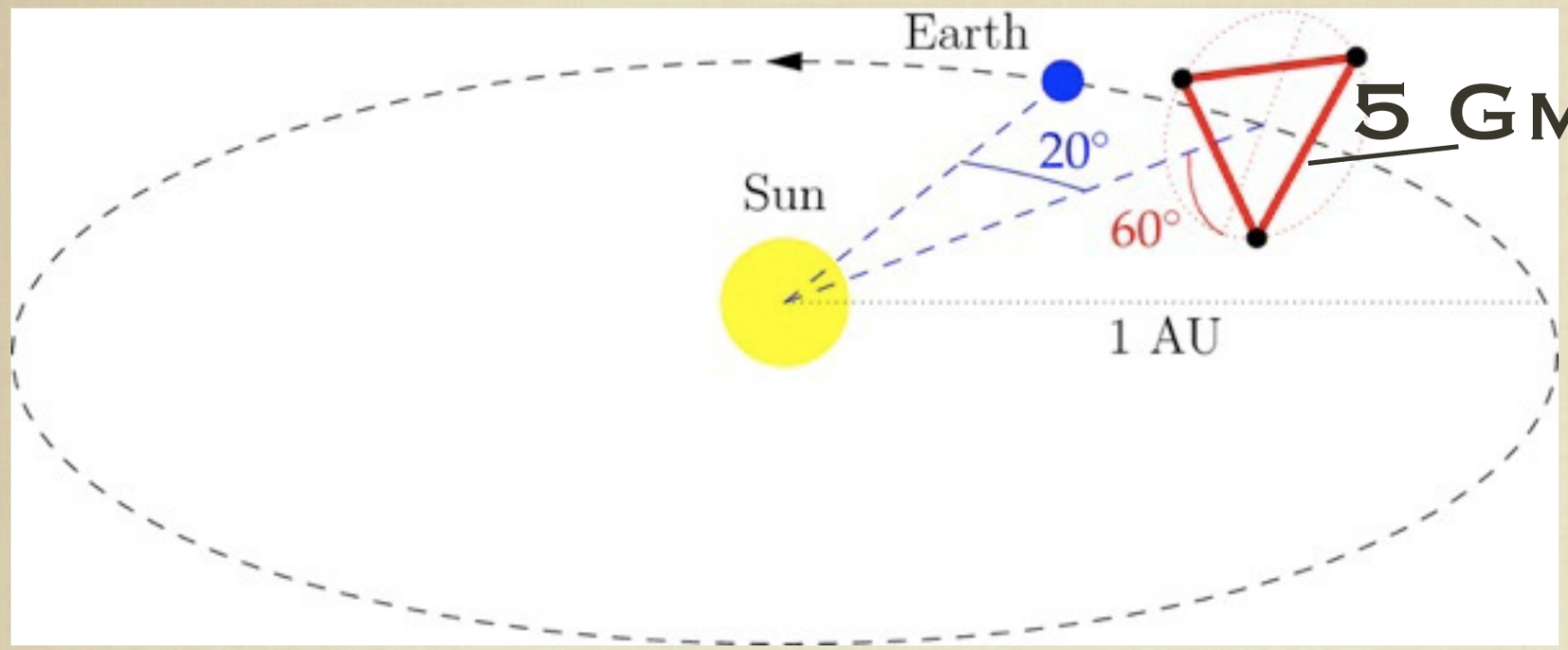

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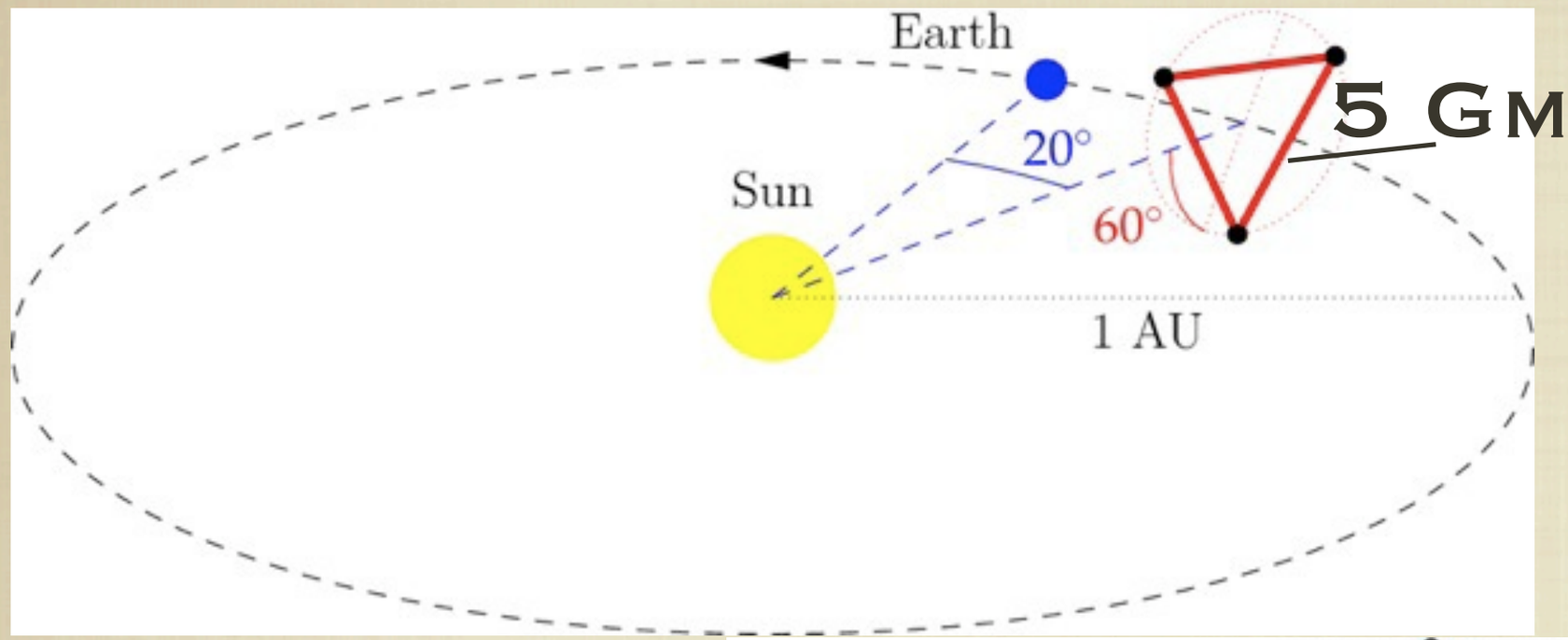

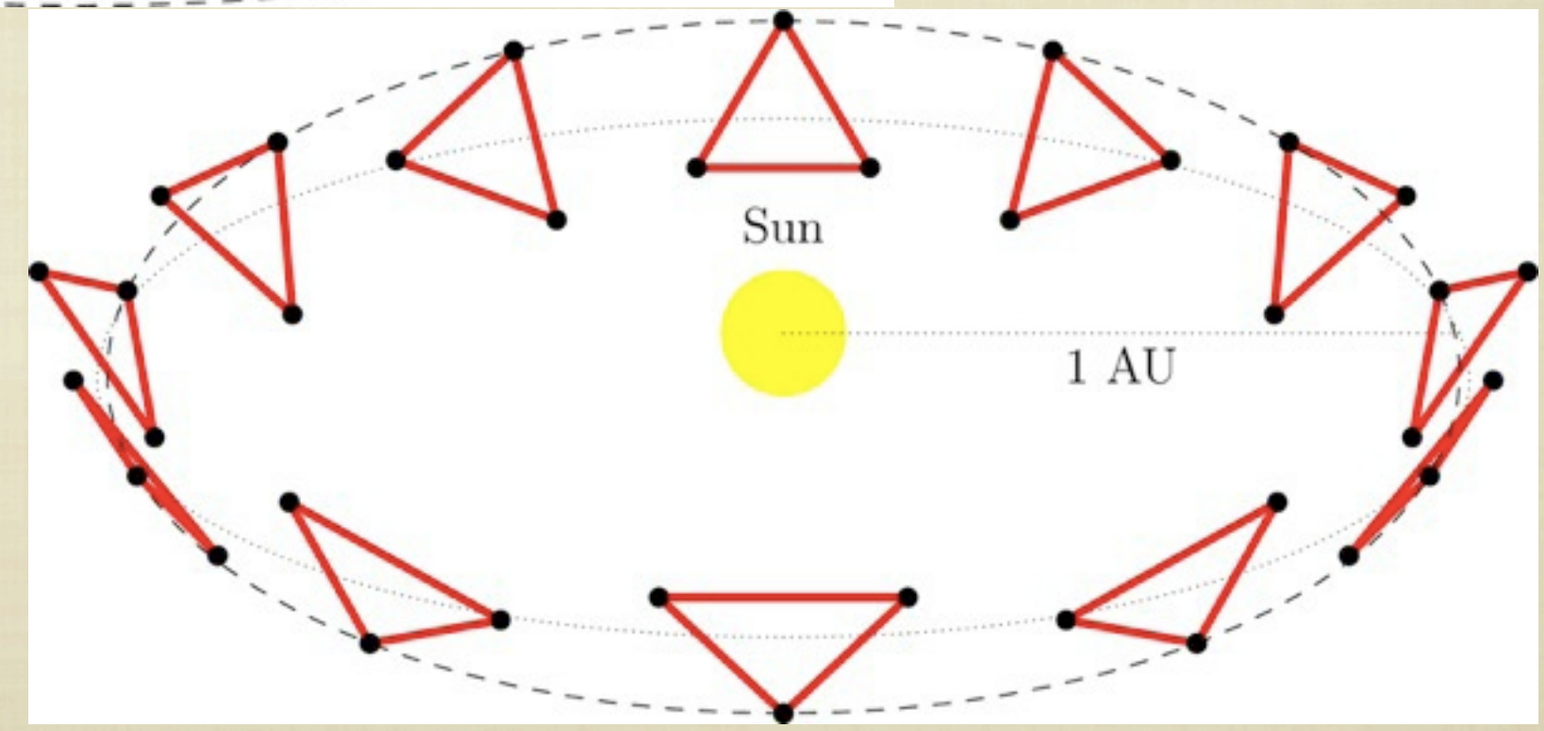

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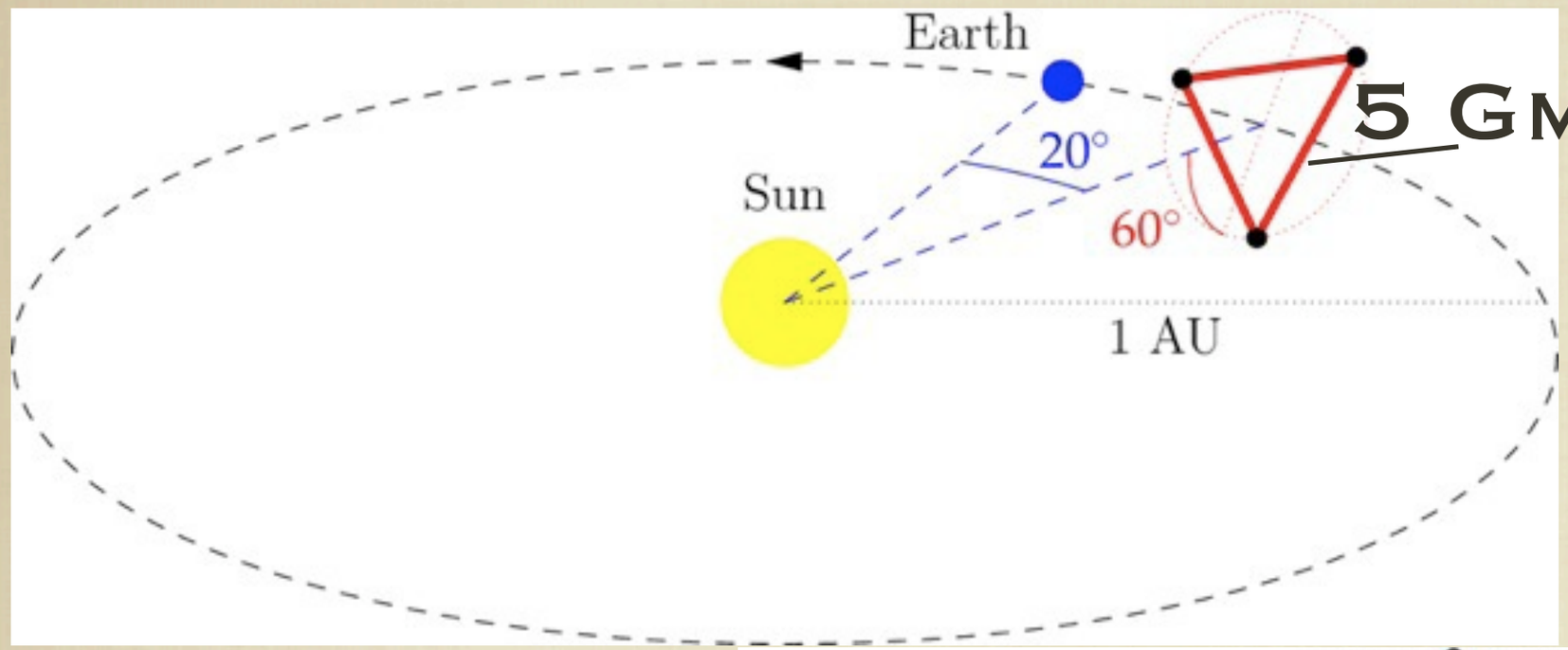

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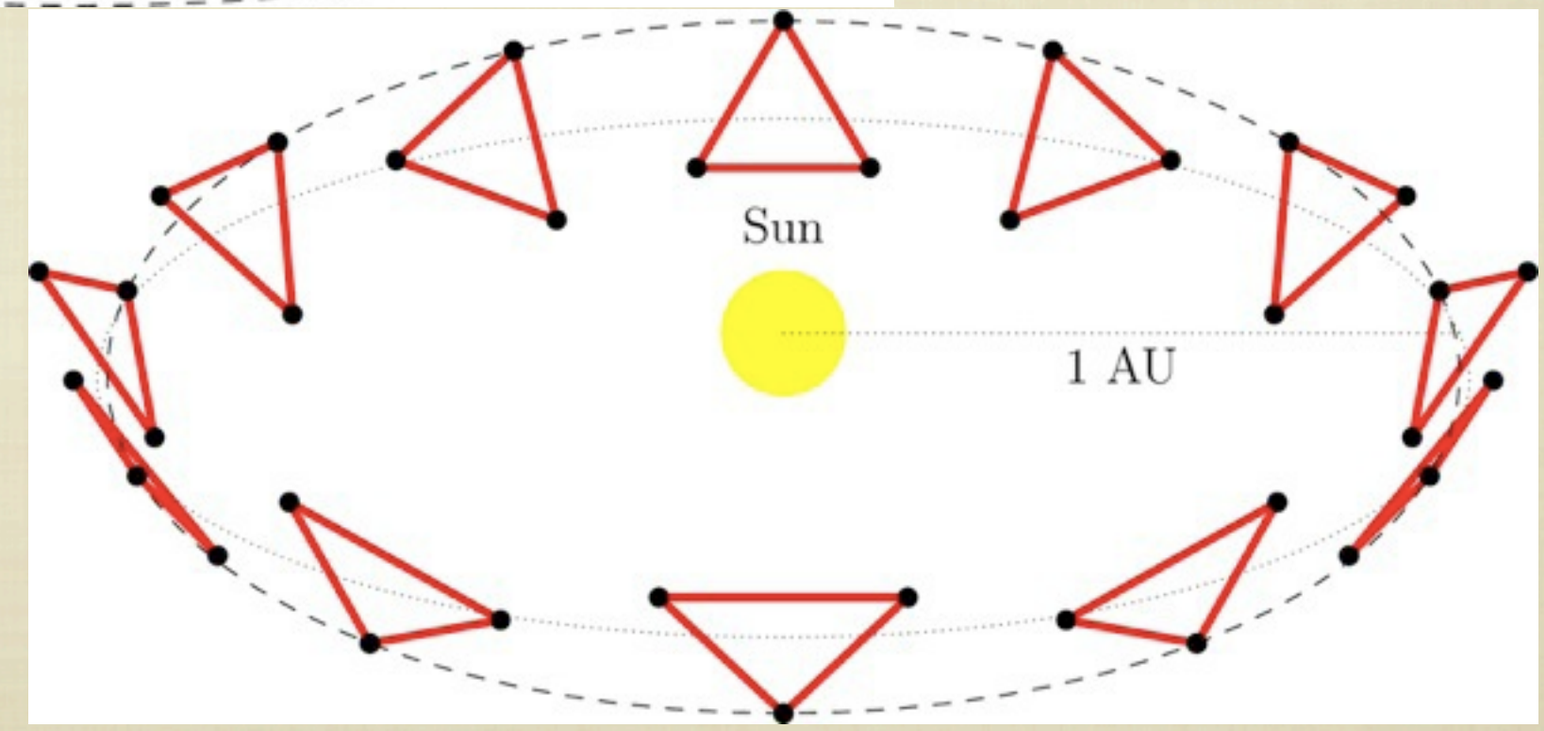

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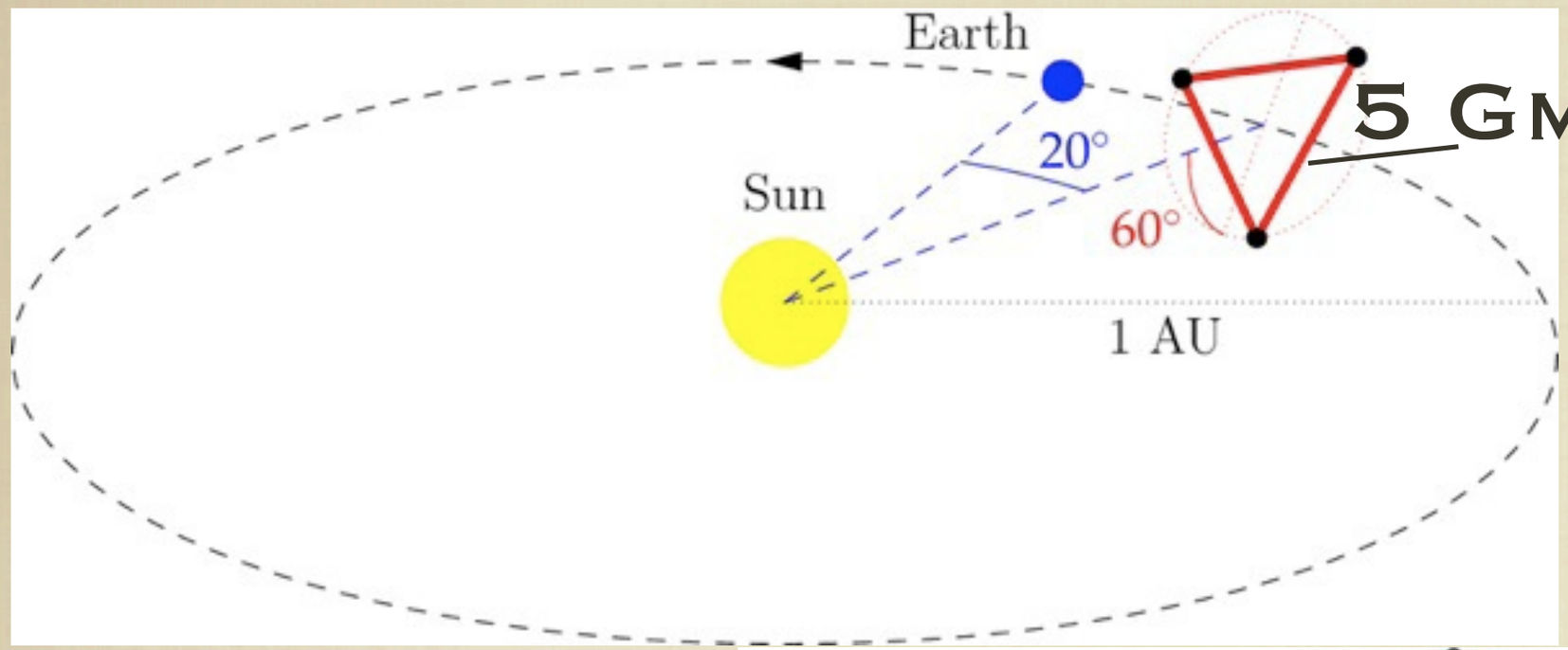

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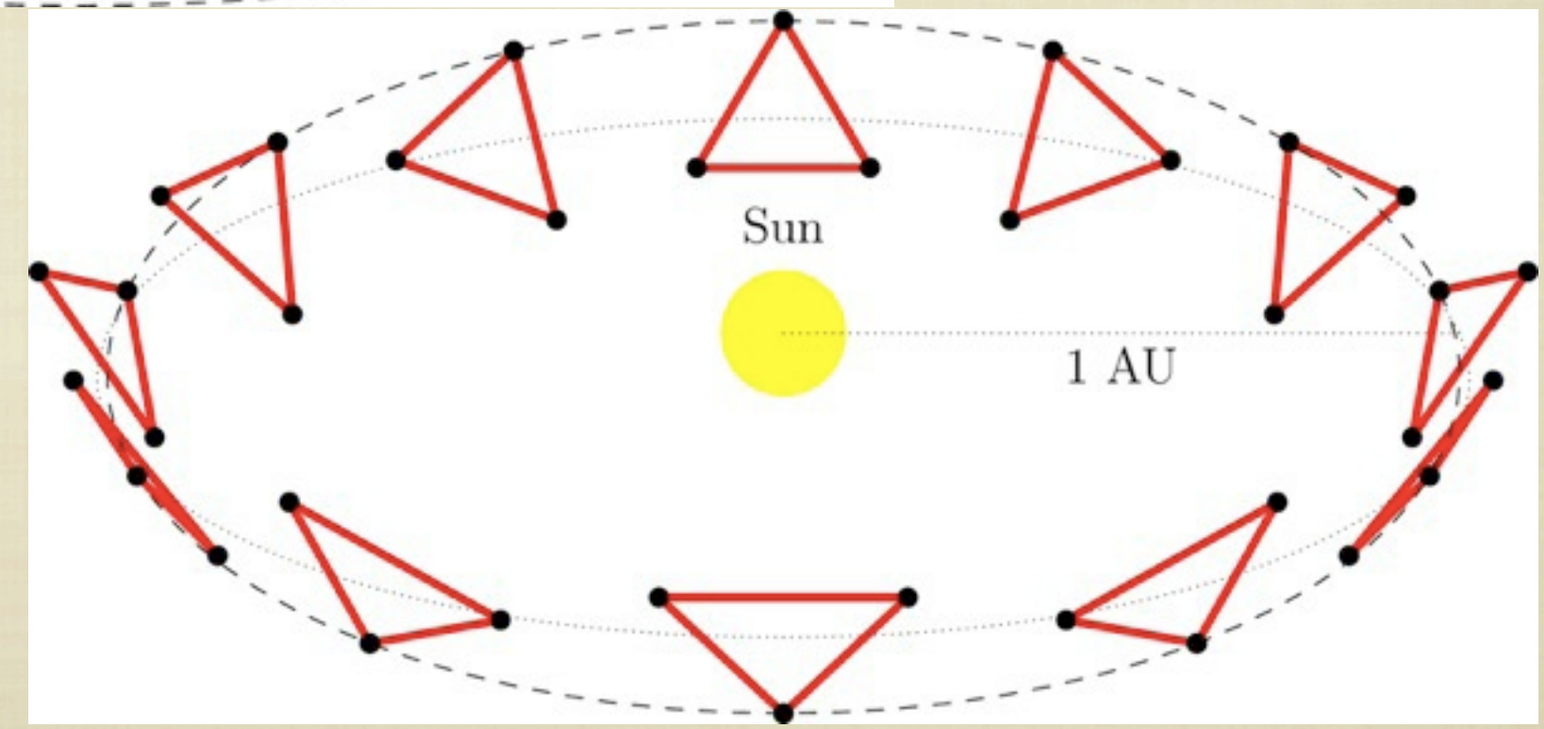

- In practice, LISA does no station-keeping, so its interferometry has to cope with MHz fringe-counting rates. It does this using UHS oscillators on-board.

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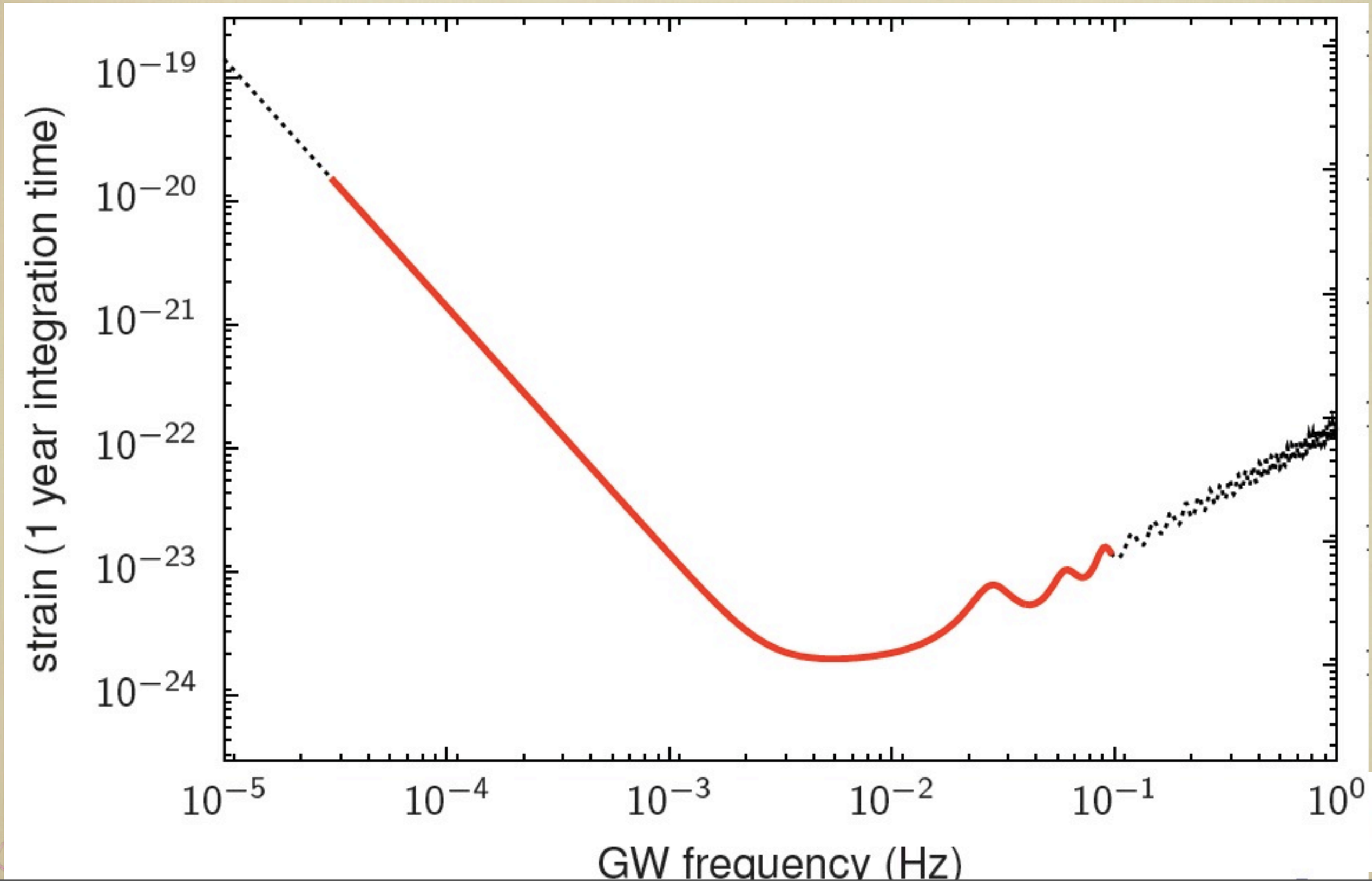

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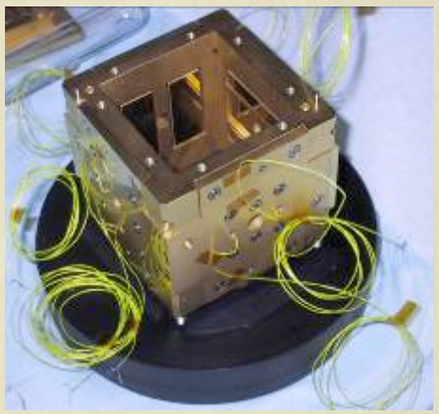

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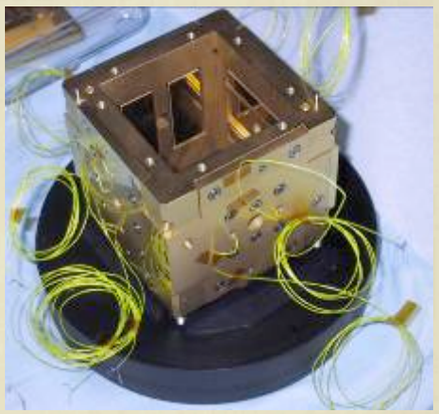

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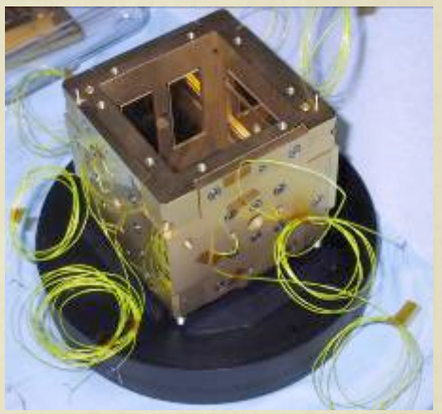

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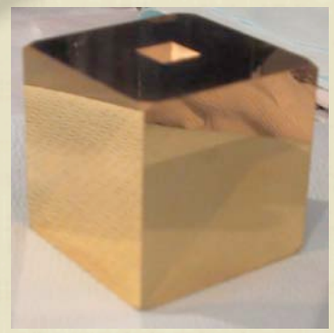

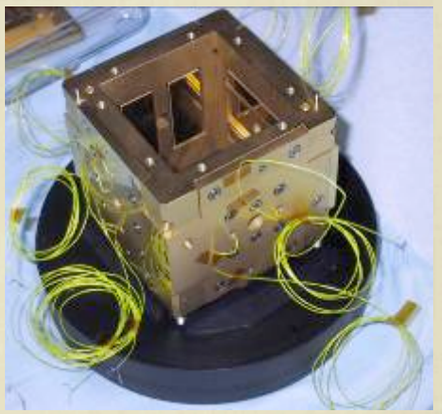

- LISA's technology of stillness will be tested by the LISA Pathfinder mission (2012)

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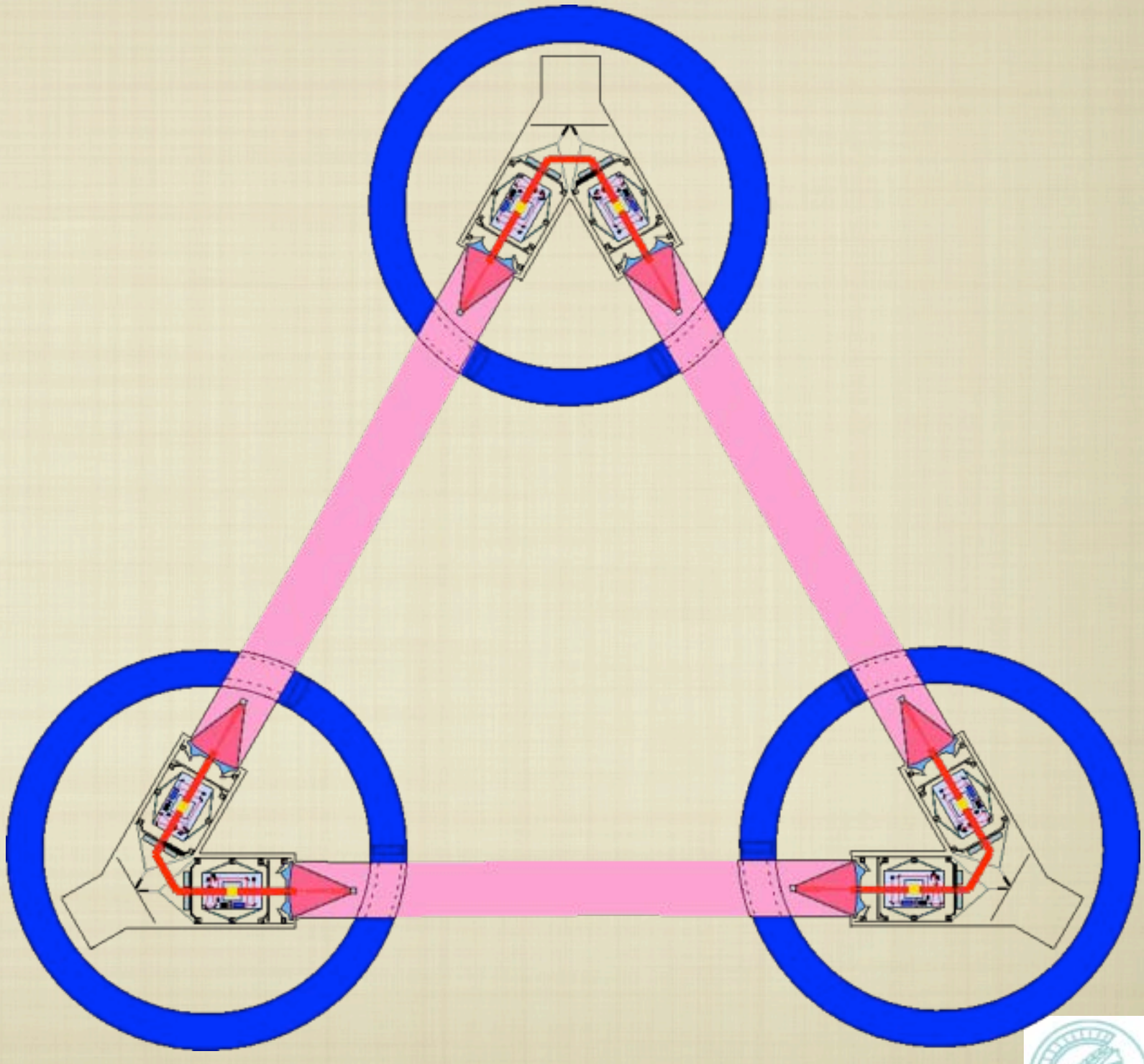

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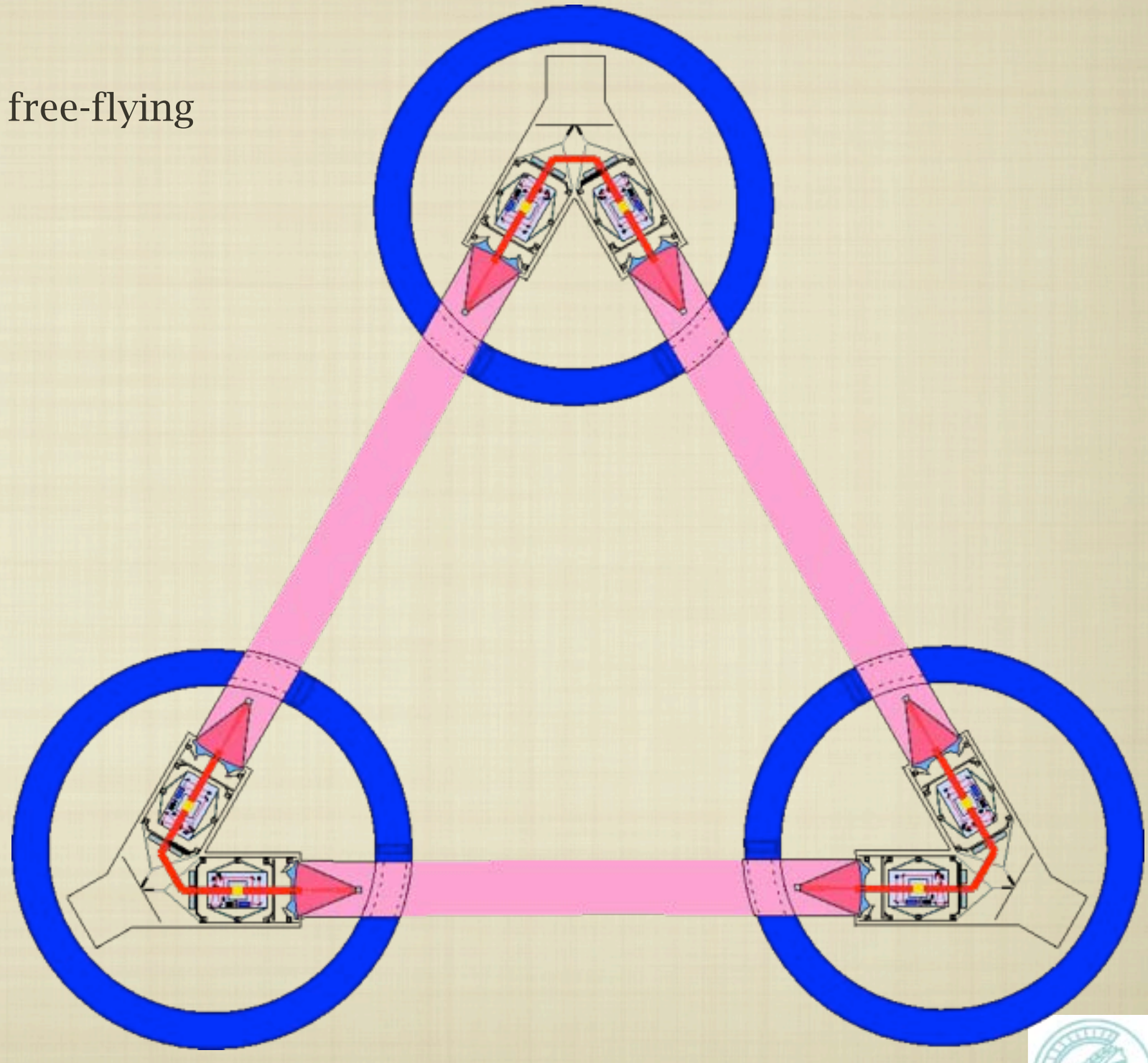

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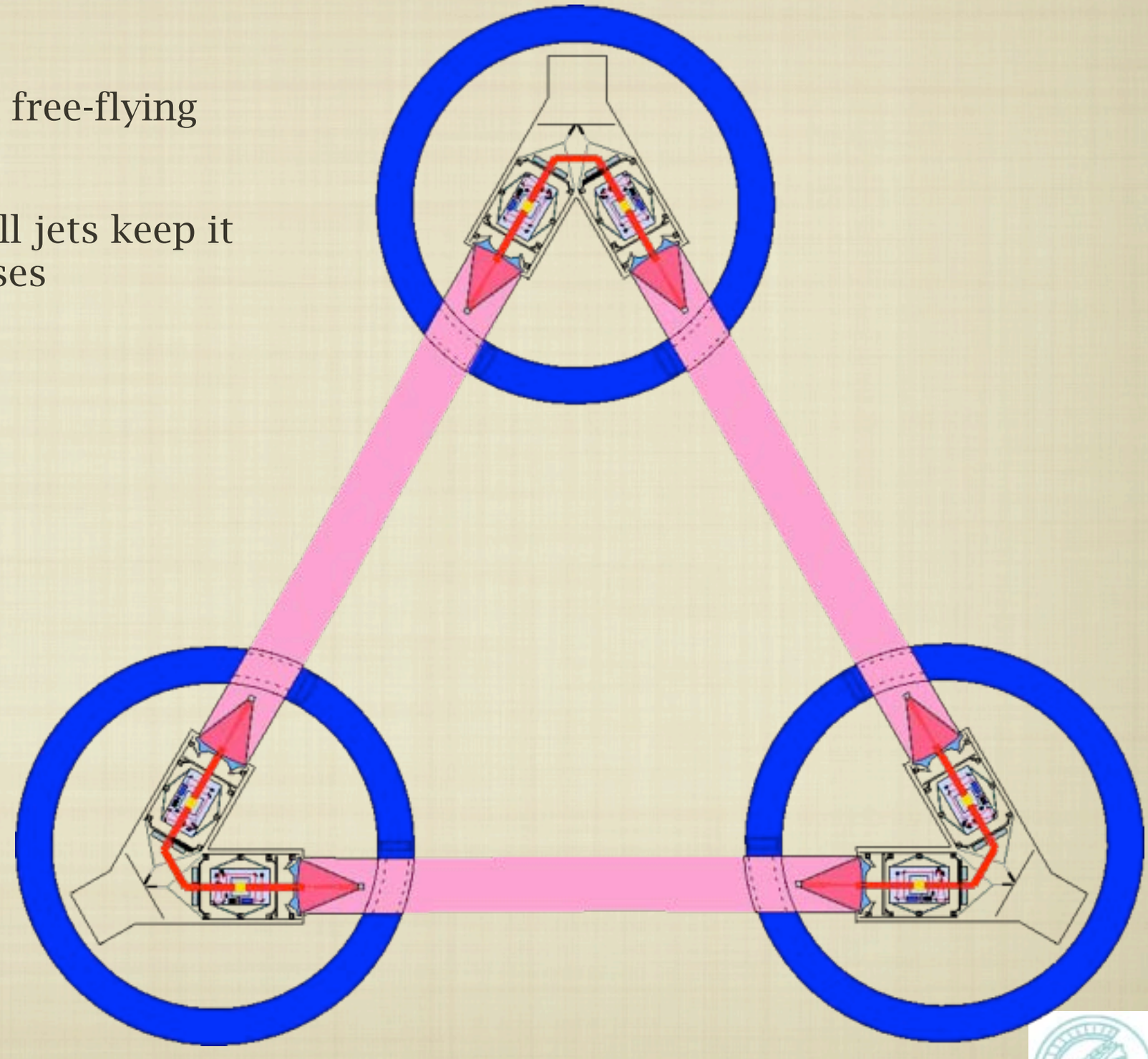

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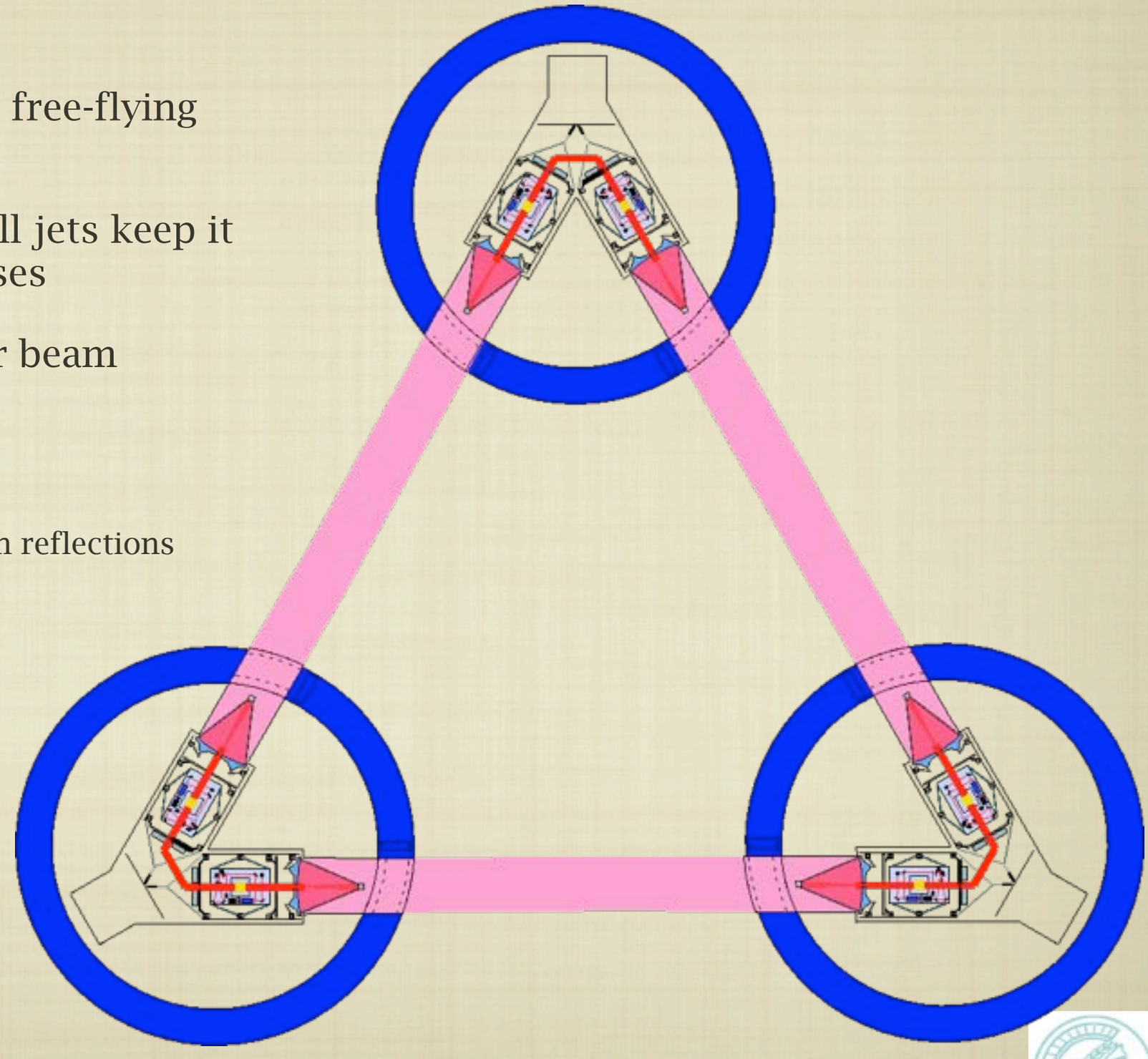

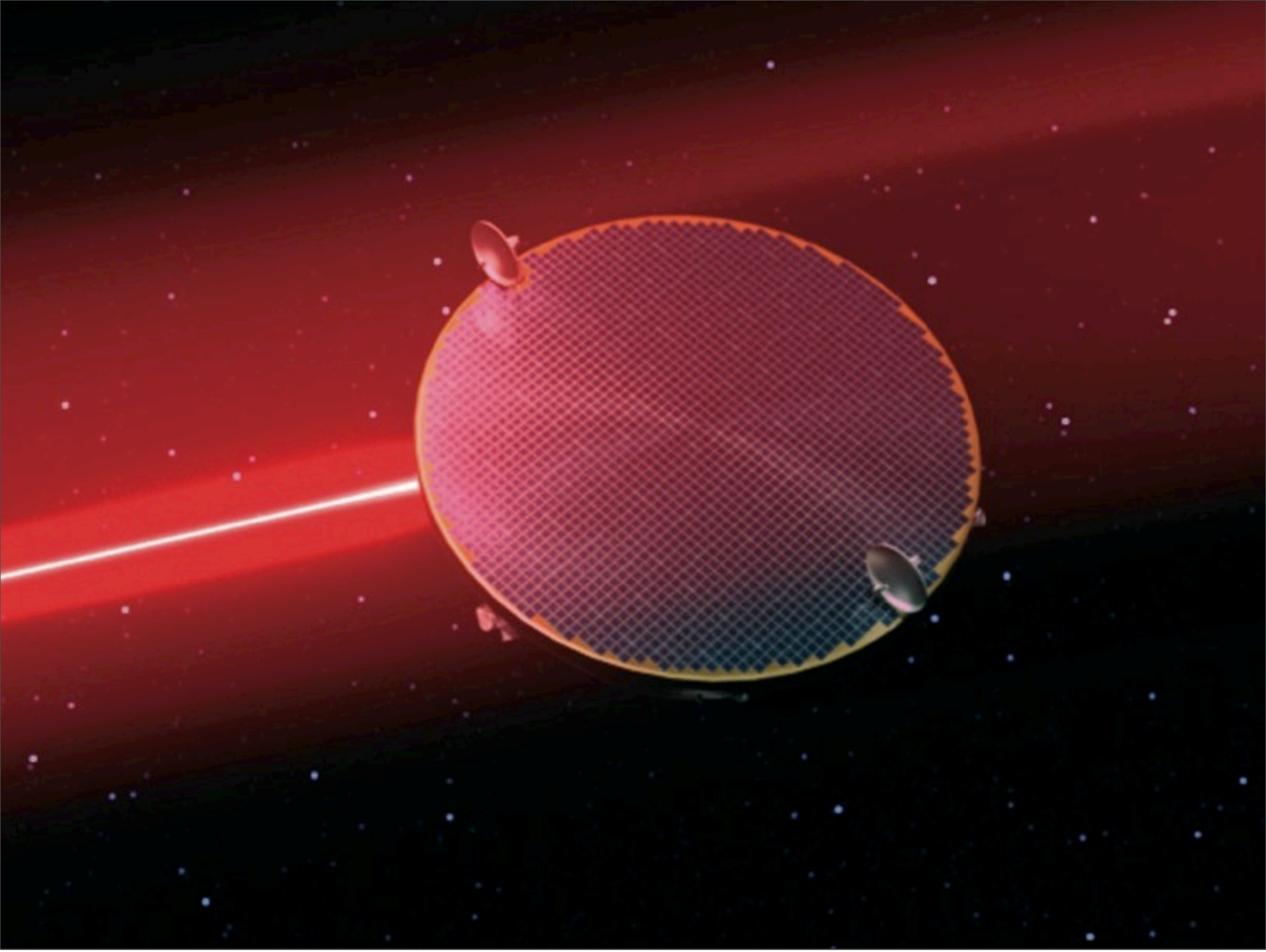

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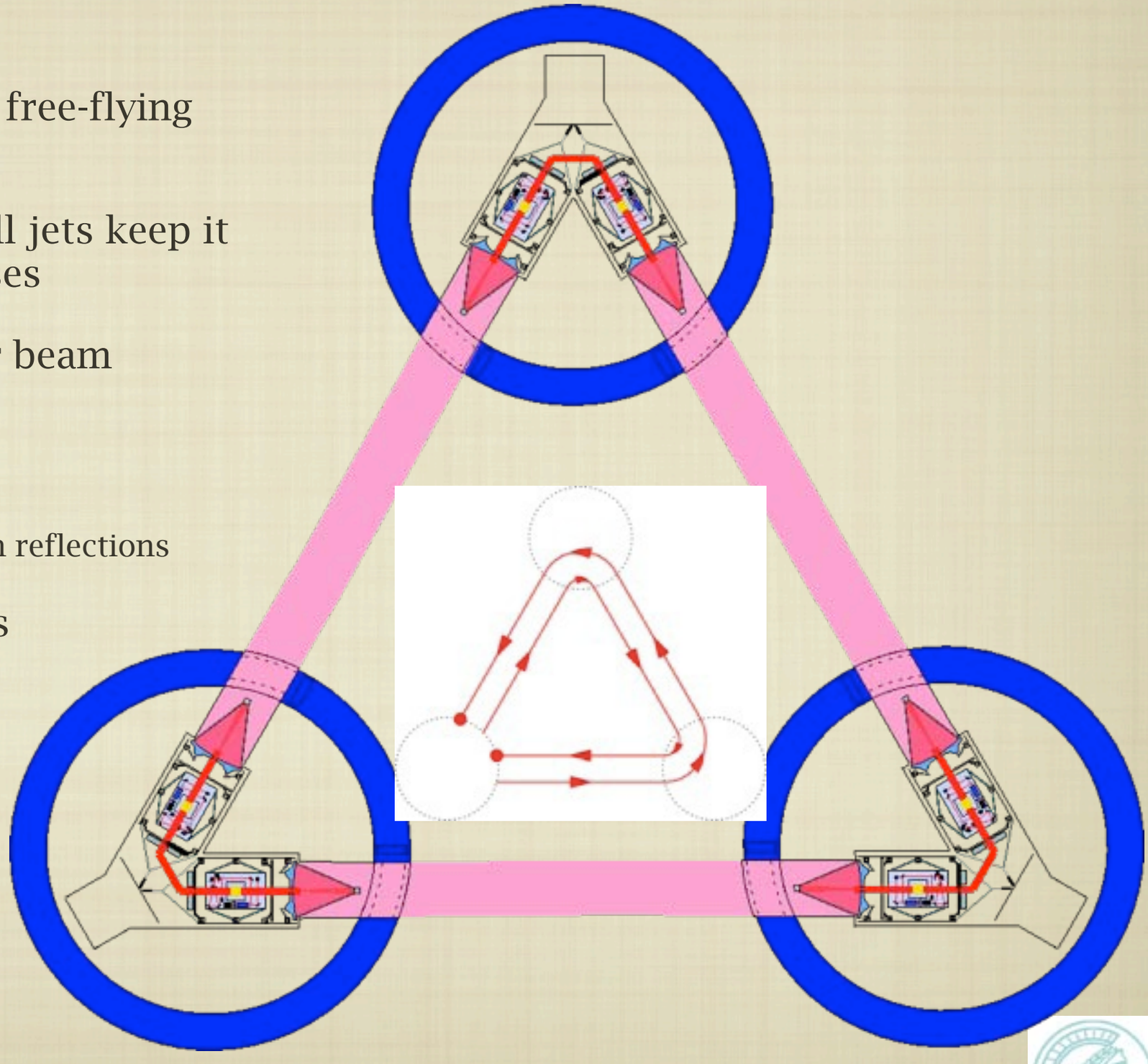

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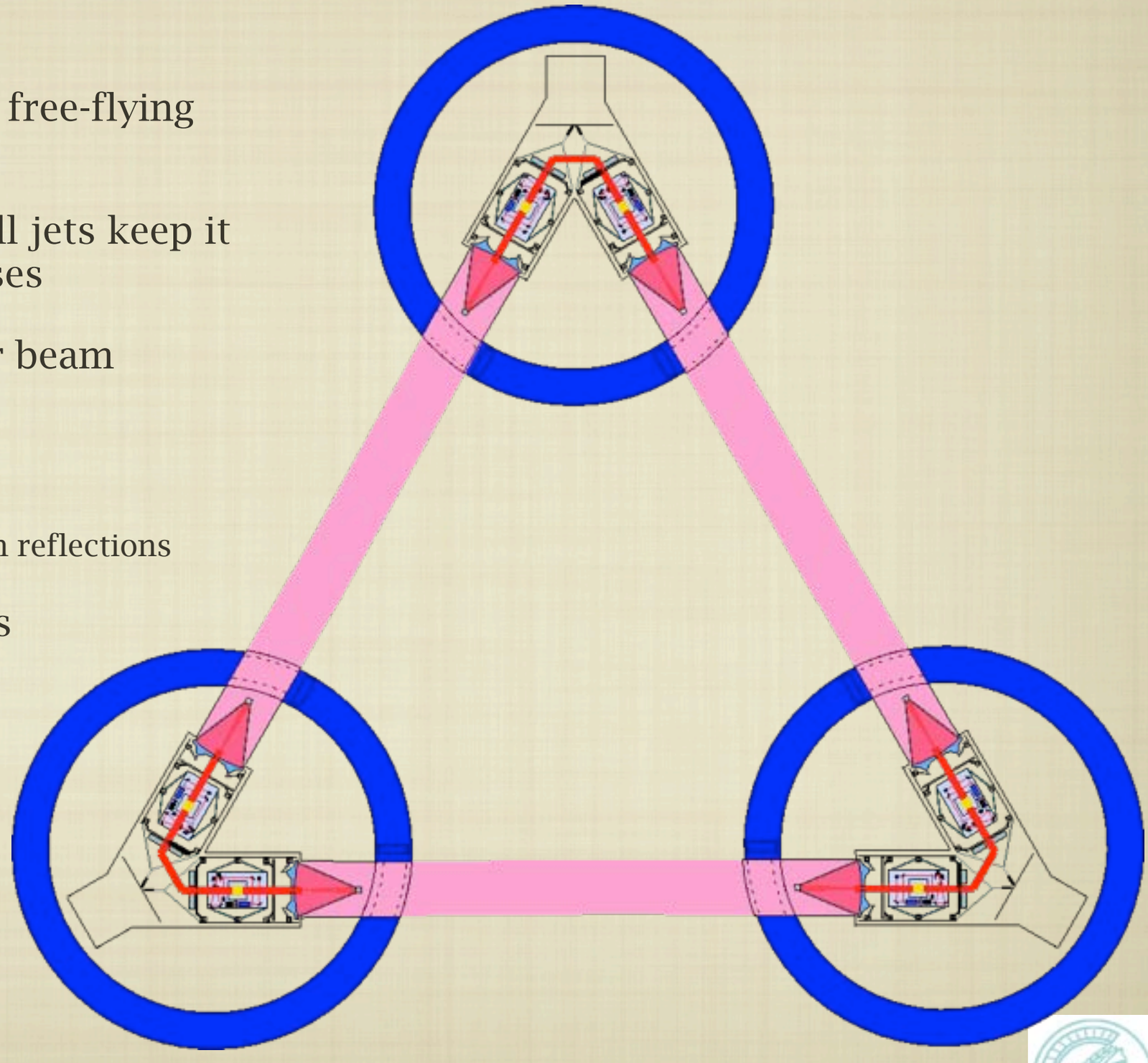

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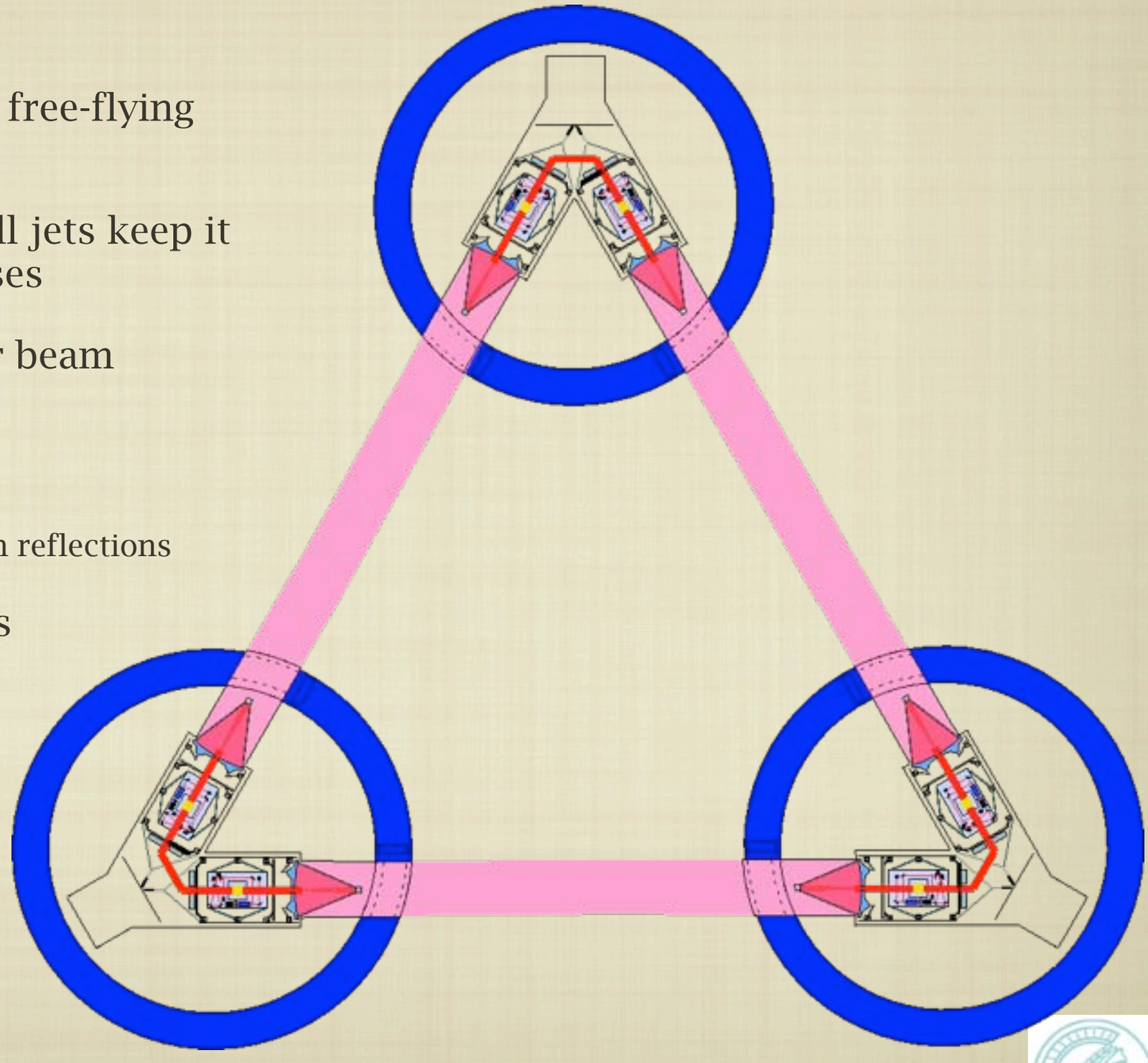

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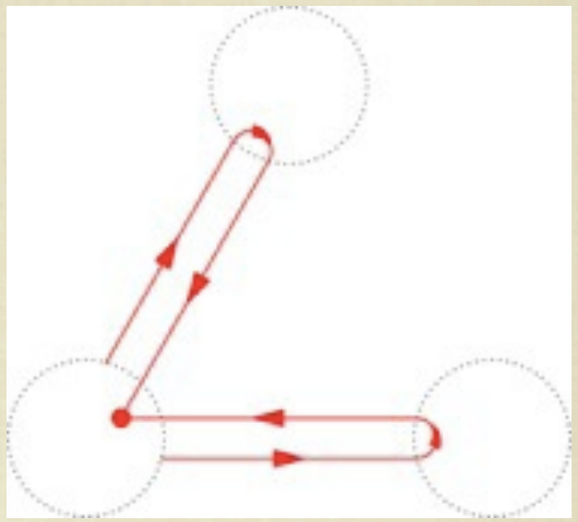

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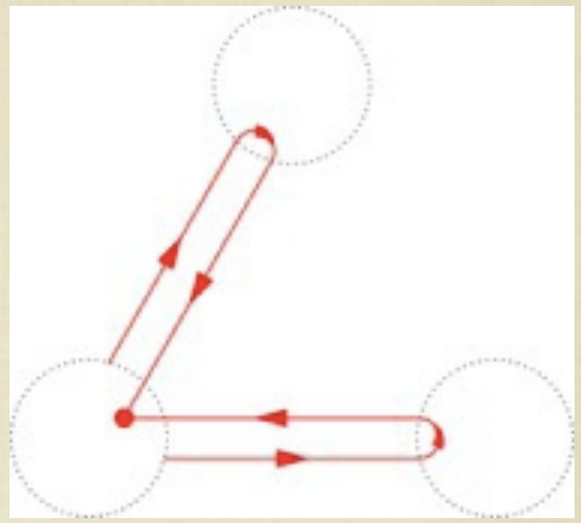

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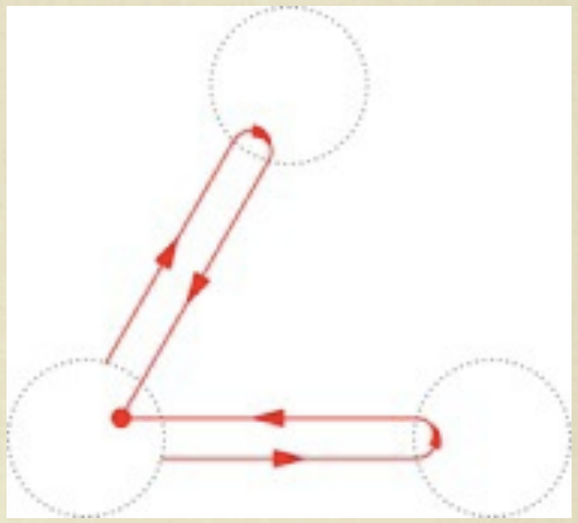

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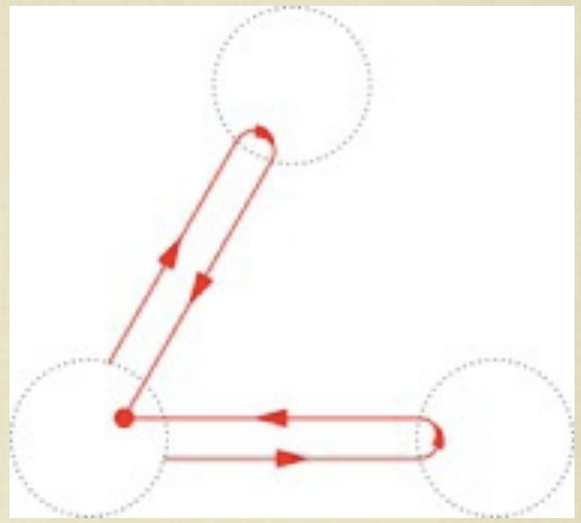

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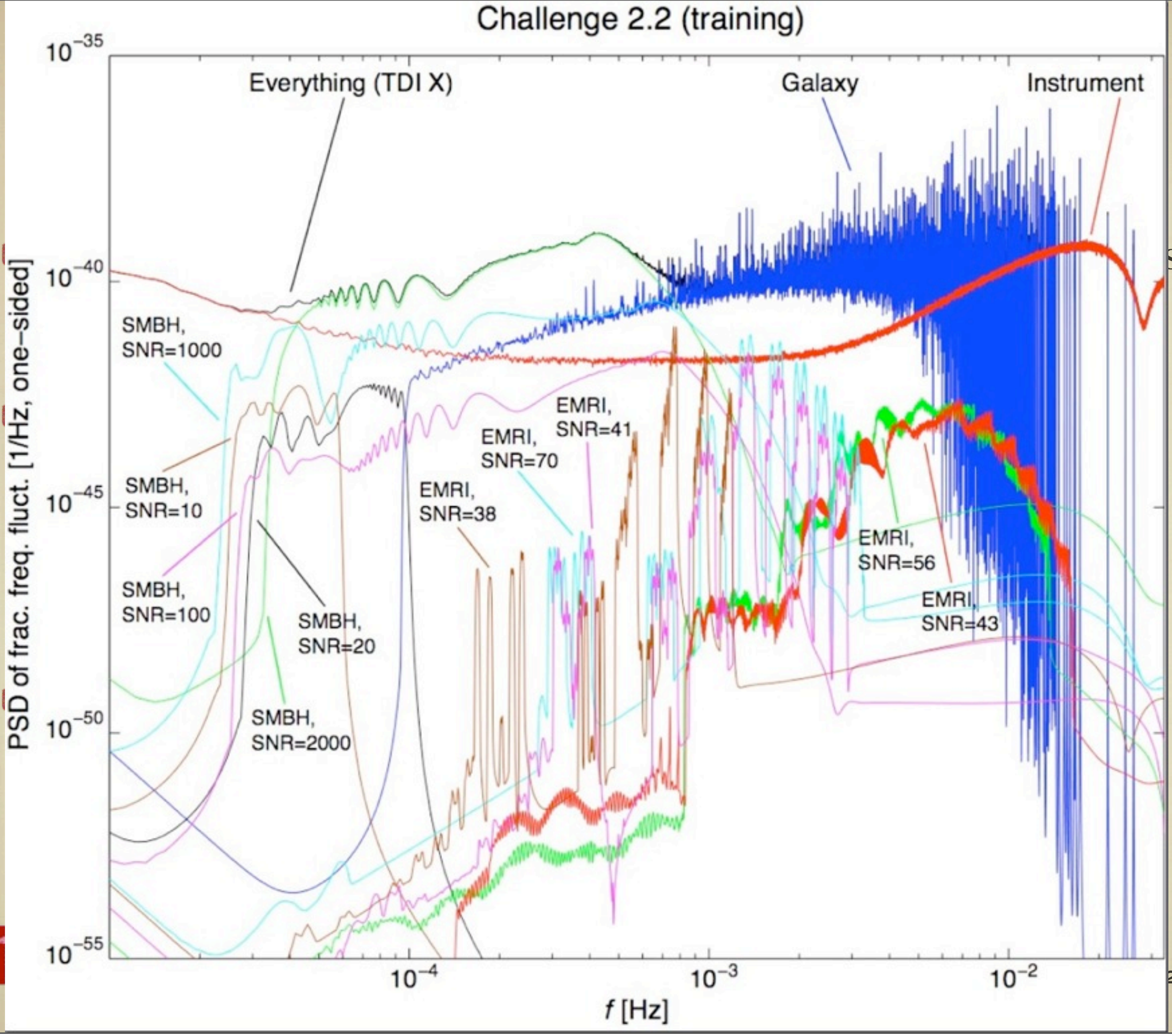
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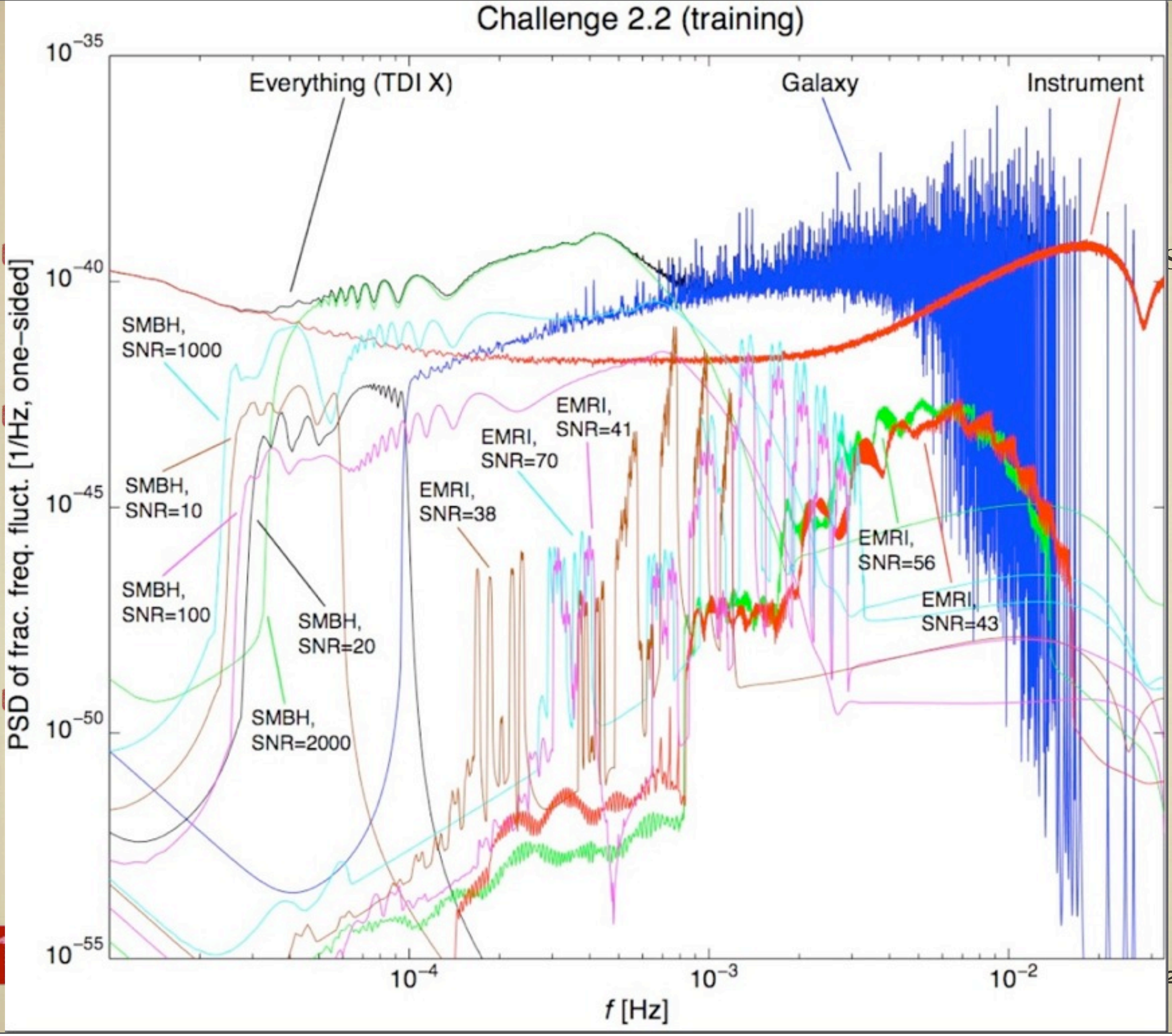
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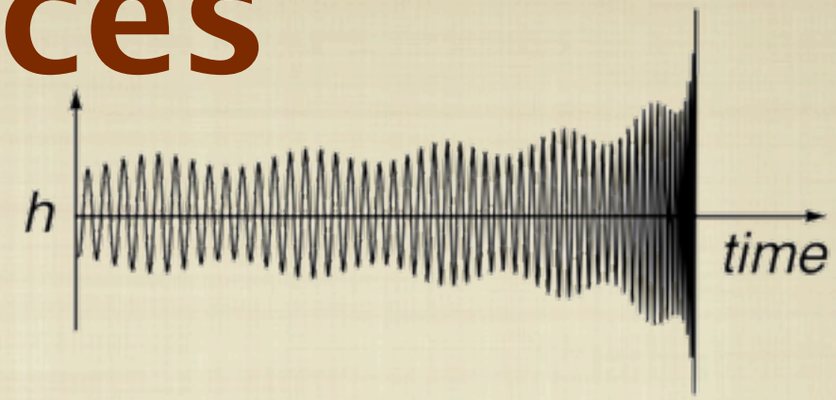
  - Distances to 5%, limited by weak lensing, which distorts intrinsic amplitude

Absolute Distances

Waveforms of black hole binaries give precise distances to high redshift, no calibration or distance ladder needed



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- Can be used for cosmology (Hubble constant, dark energy) if either (a) number of events is large or (b) identifications are possible to get redshifts.

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- Possible detection of shortest period BH-BH binary.

Science from LISA: Verification

Known Binaries in the Galaxy

Class	Source	*f* (mHz)	Strain *h* (10^{-23})
WD+WD	WD 0957-666	0.38	40
	WD 1101+364	0.16	20
	WD 1704+481	0.14	40
	WD 2331+290	0.14	> 20
WD+sdB	KPD 0422+4521	0.26	60
	KPD 1930+2752	0.24	100
LMXB	4U1820-30	3.0	2
	4U1626-67	0.79	0.6
W Uma	CC Com	0.105	60

Class	Source	*f* (mHz)	Strain *h* (10^{-23})
AM CVn	RXJ0806.3+1527	6.2	40
	RXJ1914+245	3.5	60
	KUV05184-0939	3.2	9
	AM CVn	1.94	20
	HP Lib	1.79	20
	CR Boo	1.36	10
	V803 Cen	1.24	10
	CP Eri	1.16	4
	GP Com	0.72	3

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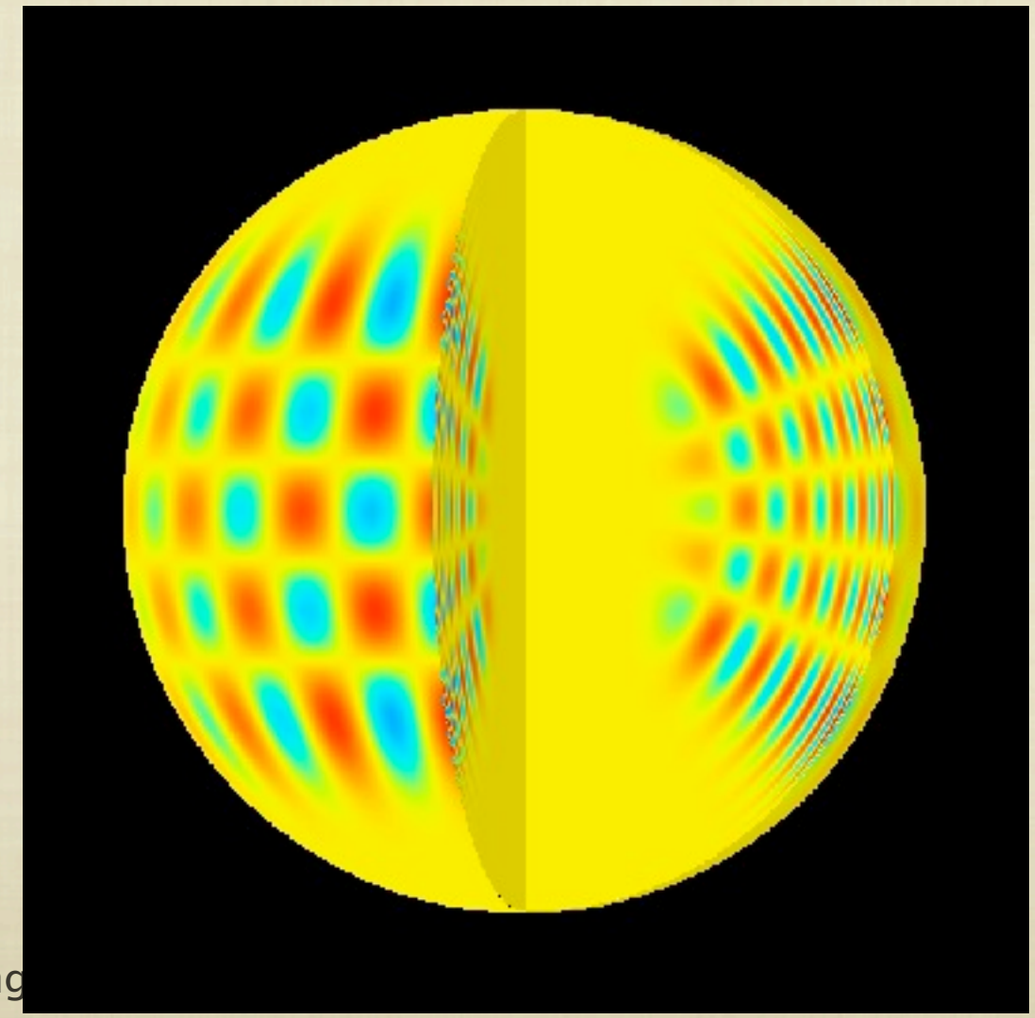

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- Signature in LISA would be distinct from GWs: no doppler modulation.
- Not a guaranteed source, since nobody can predict amplitude: depends on unknown excitation mechanisms. (Polnarov et al 2009)

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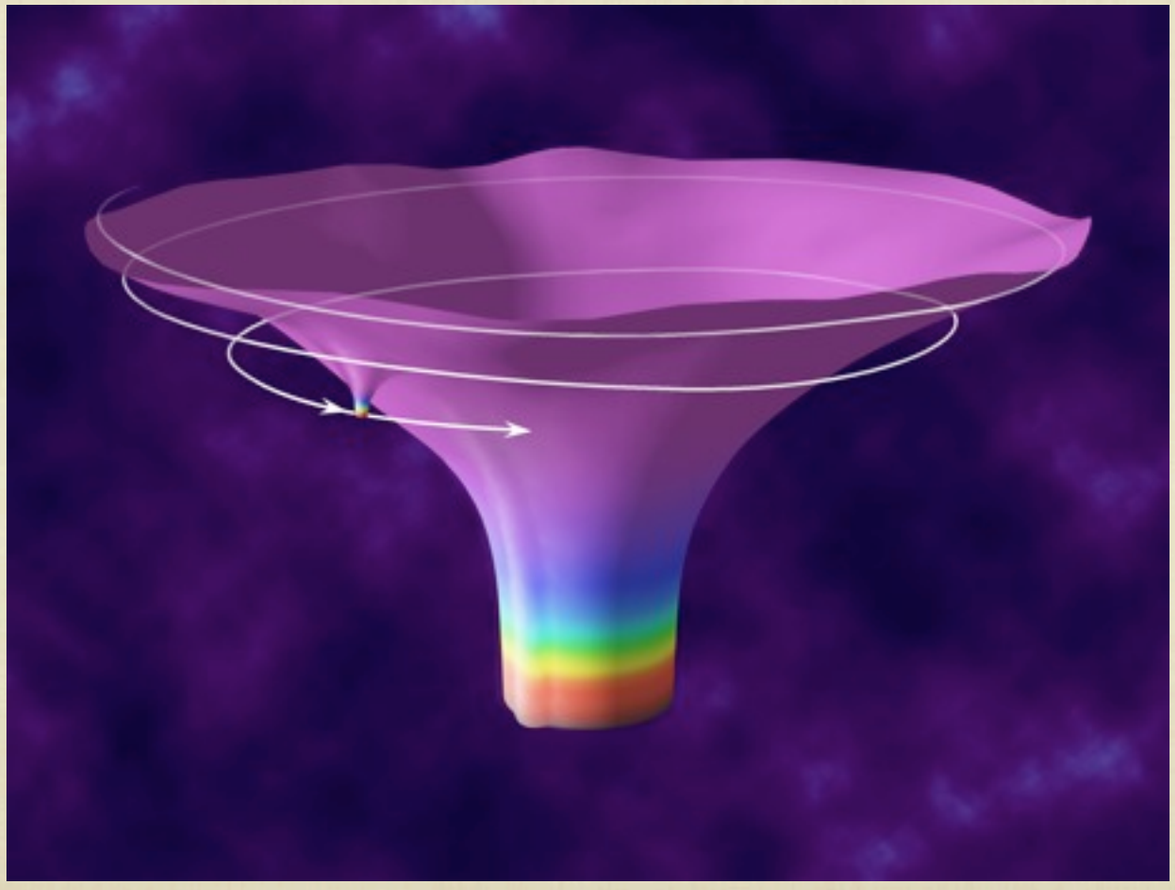

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EMRI signal: Mock LISA Data Challenge

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- Distances are measurable from observed orbital decay, which leads to determination of local Hubble constant (to z ~ 0.1) to better than 1%. (Hogan and McCleod 2008)

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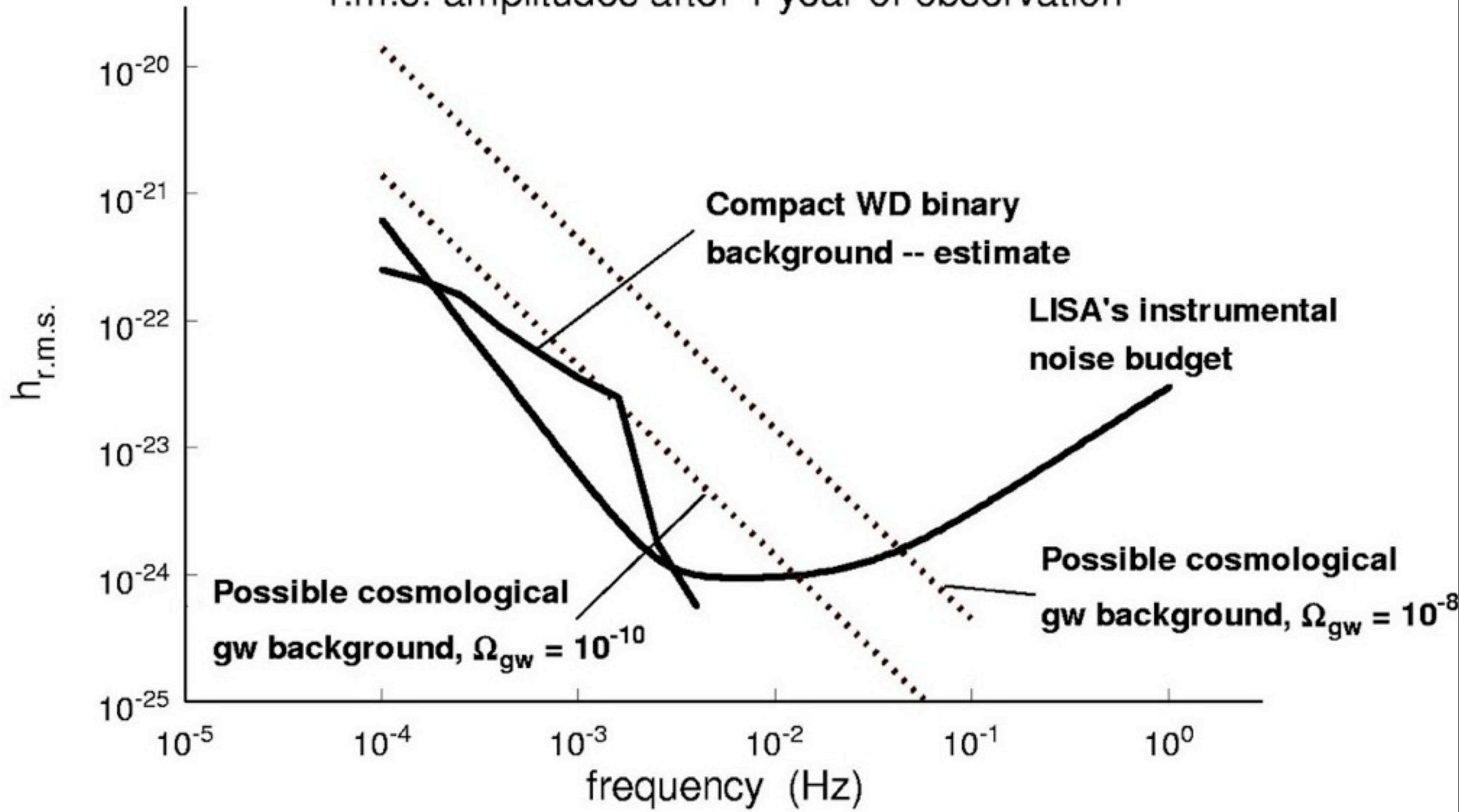
LISA and GW Background Radiation

r.m.s. amplitudes after 1 year of observation



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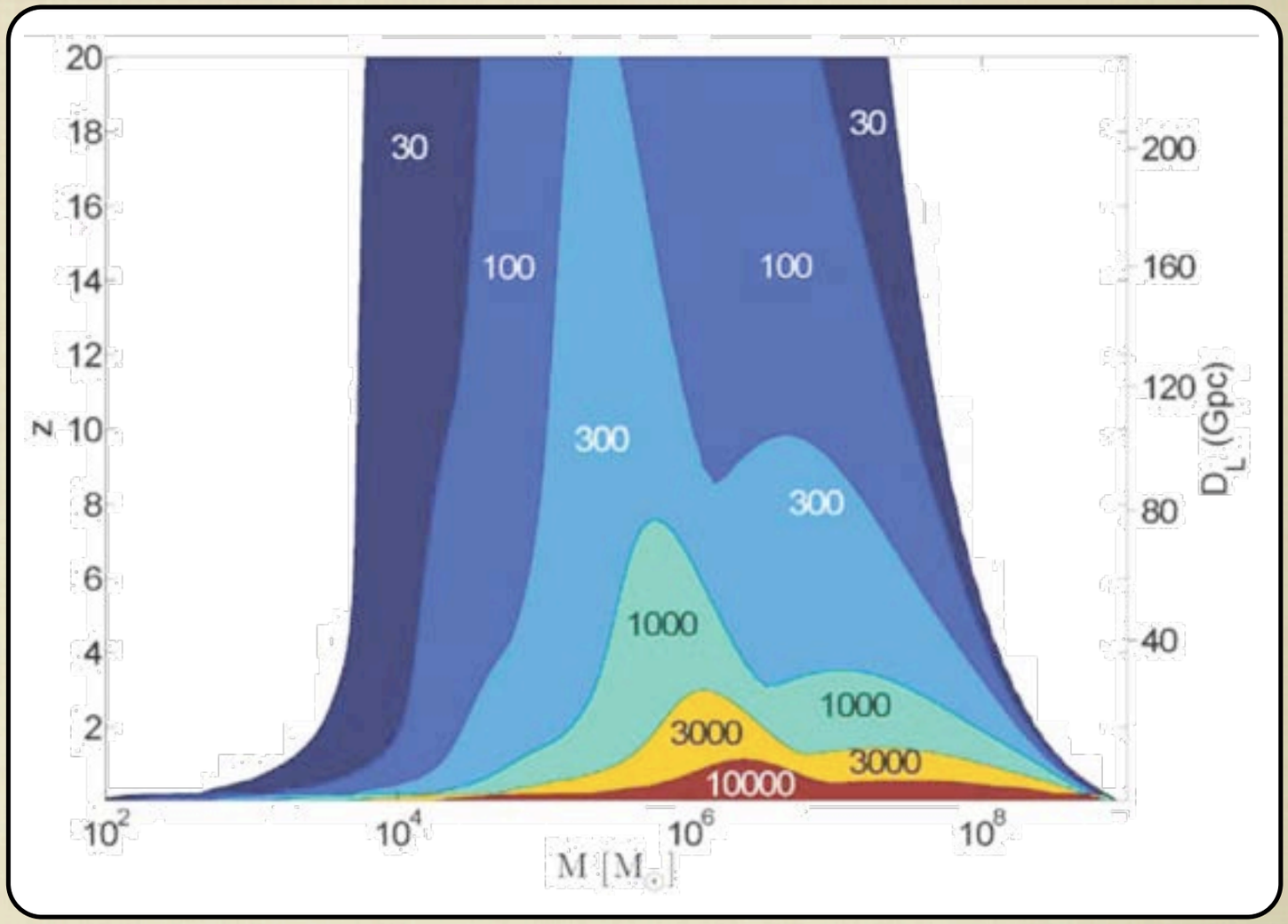

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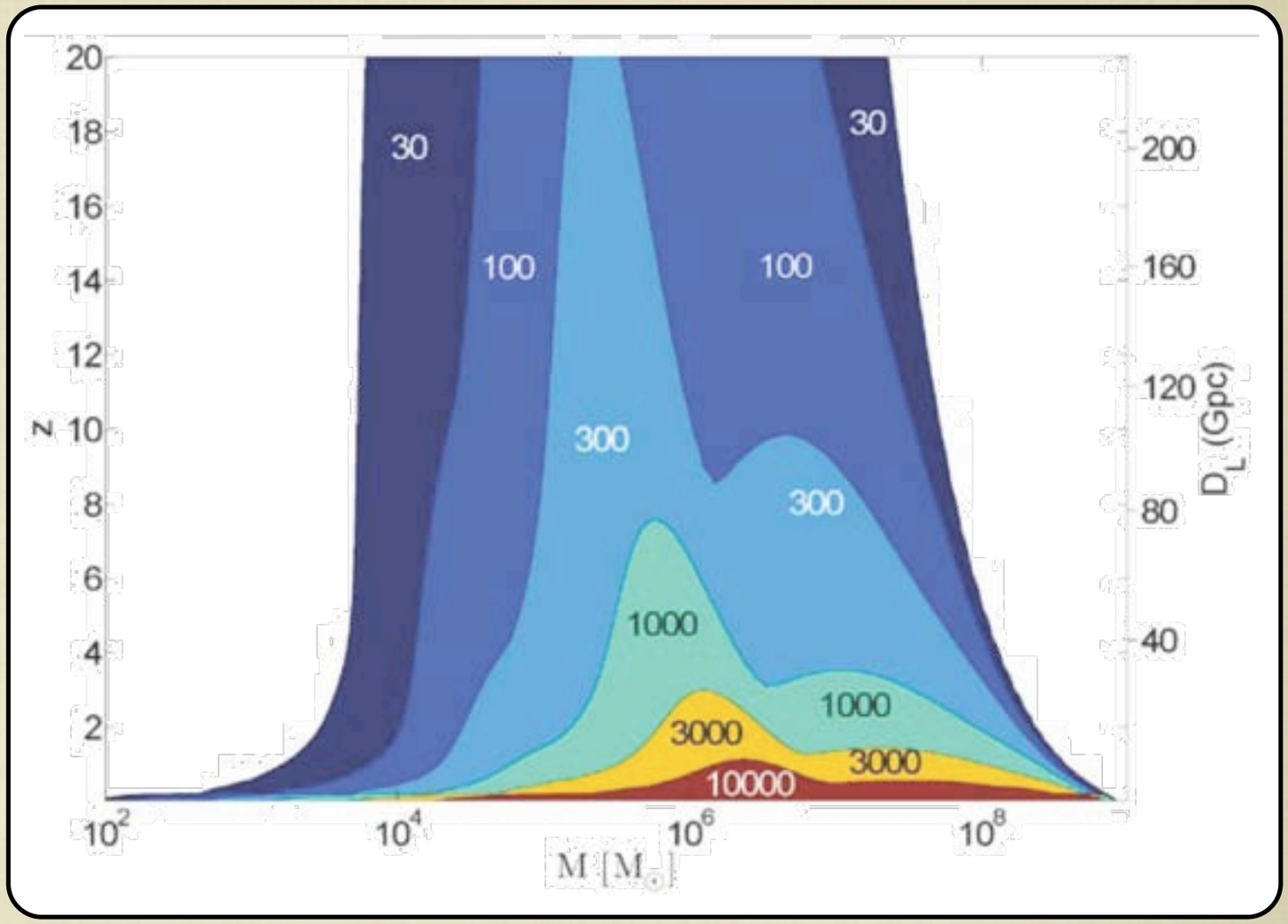

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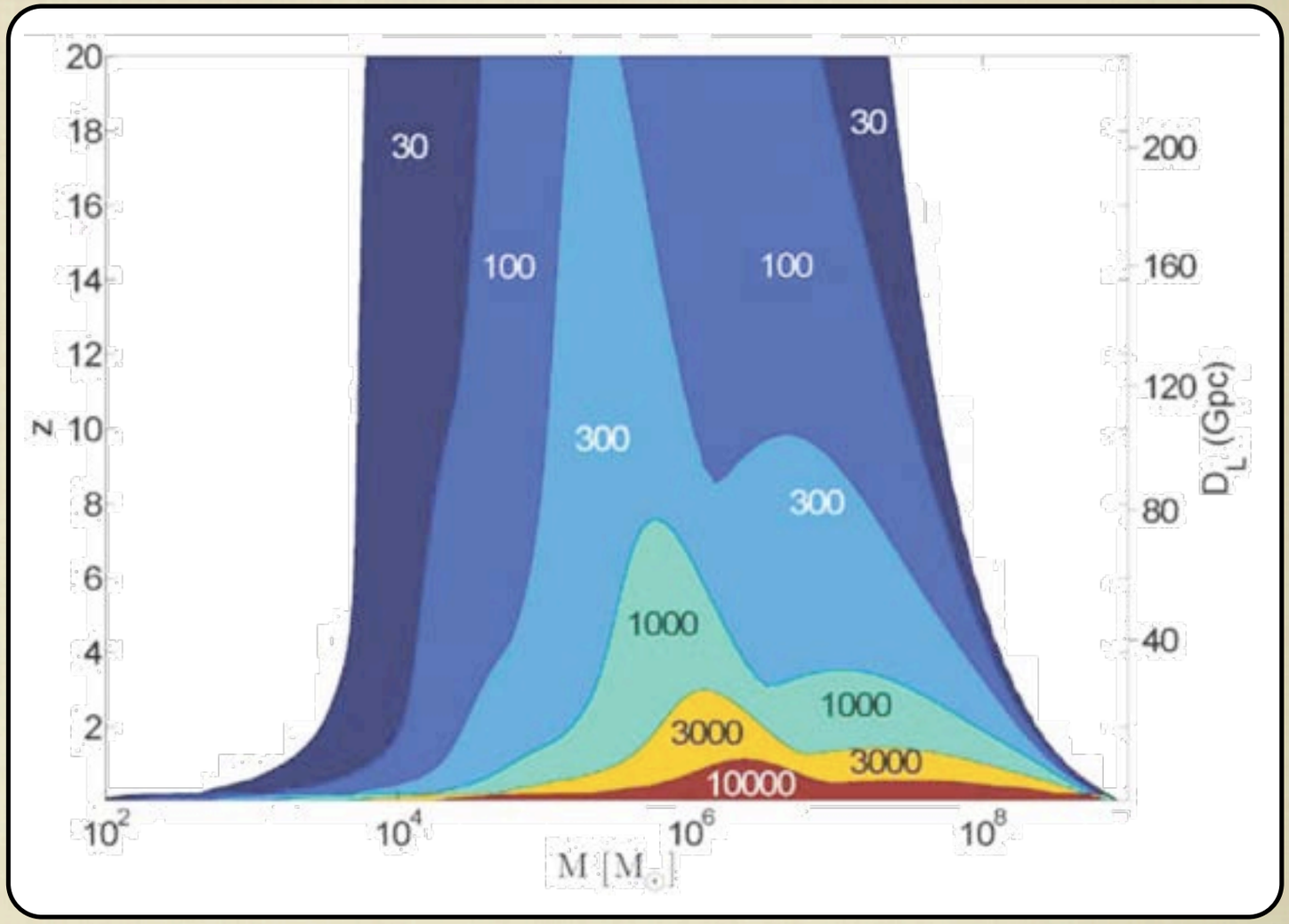

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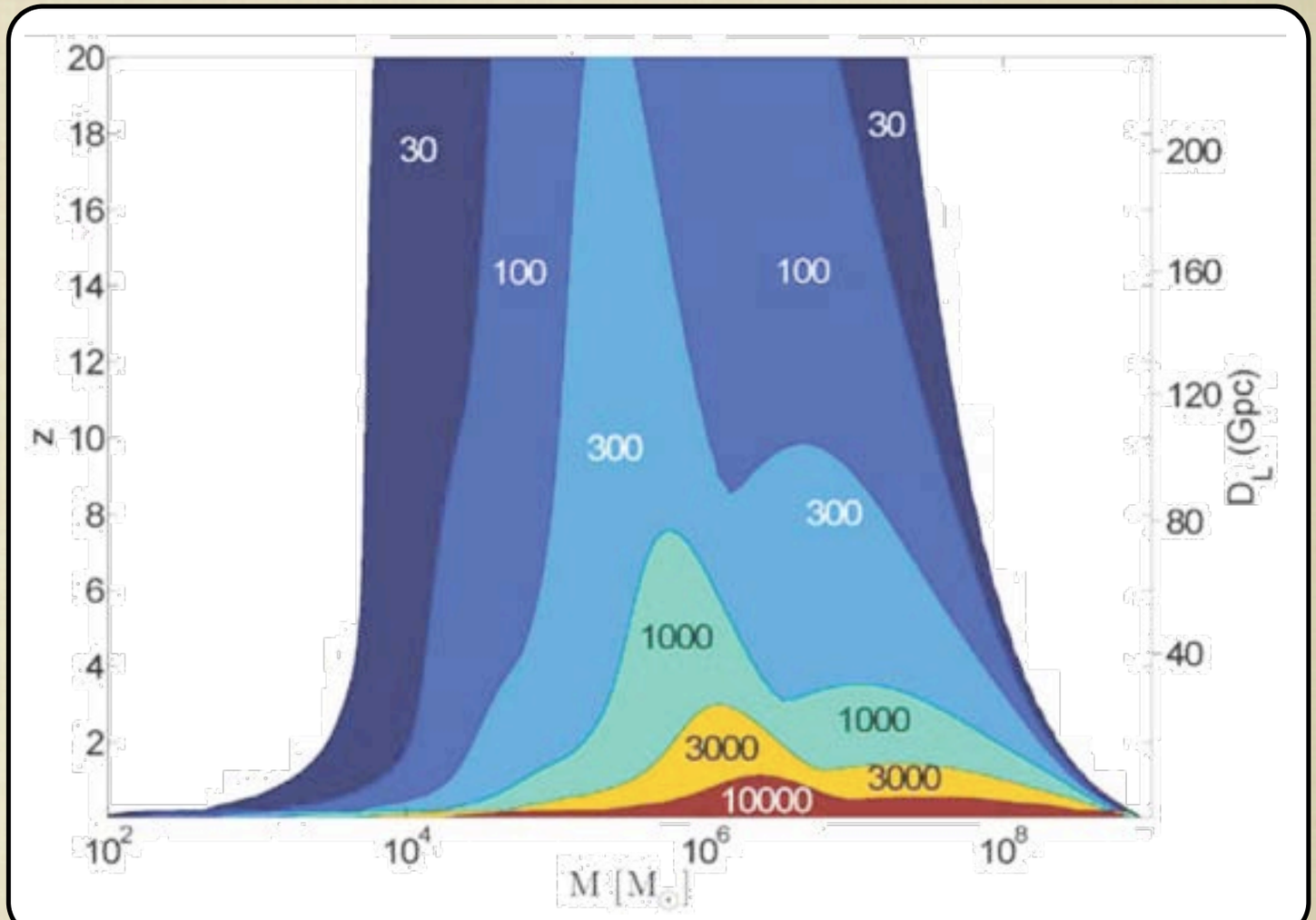
- Cosmology: determination of Hubble constant, dark energy parameter *w*, even perhaps d*w*/d*t* at z = 1.



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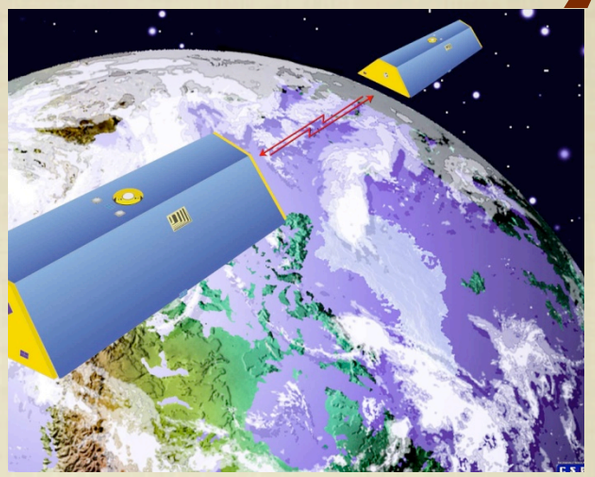

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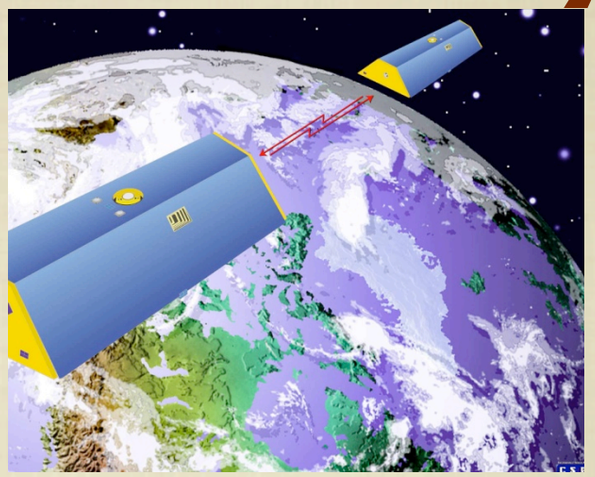

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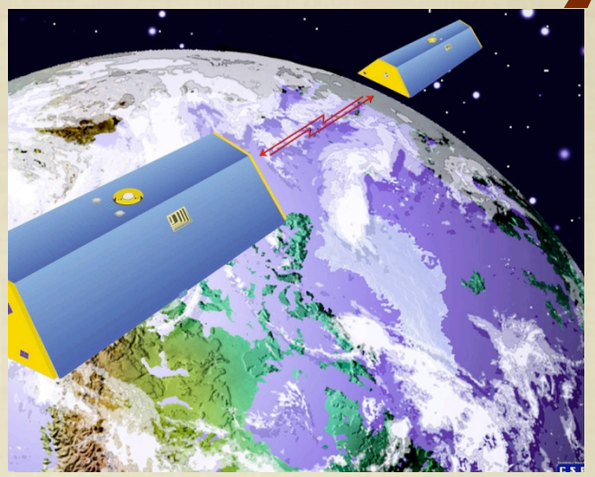

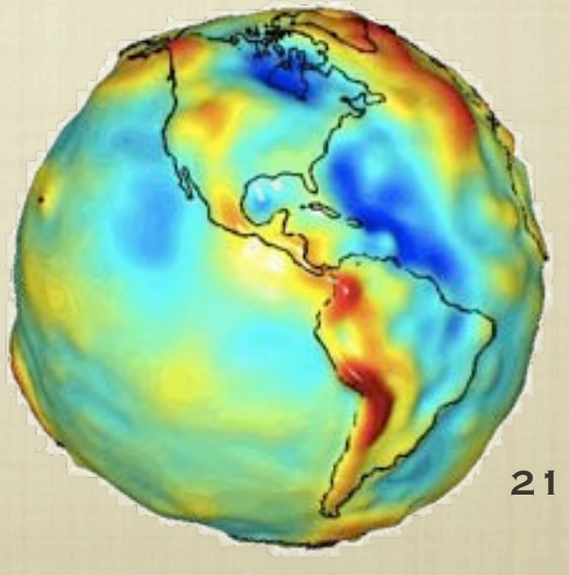

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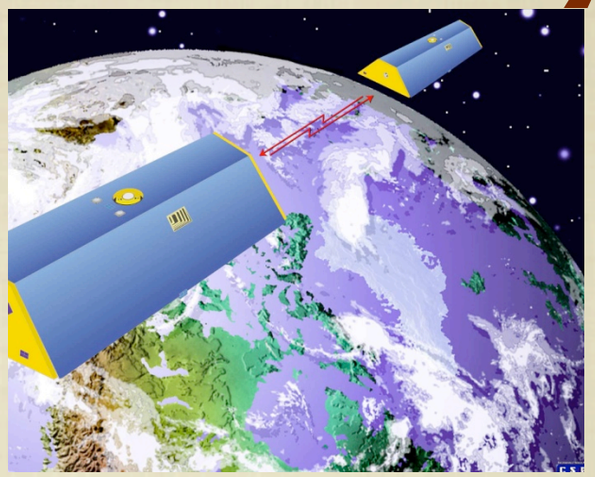

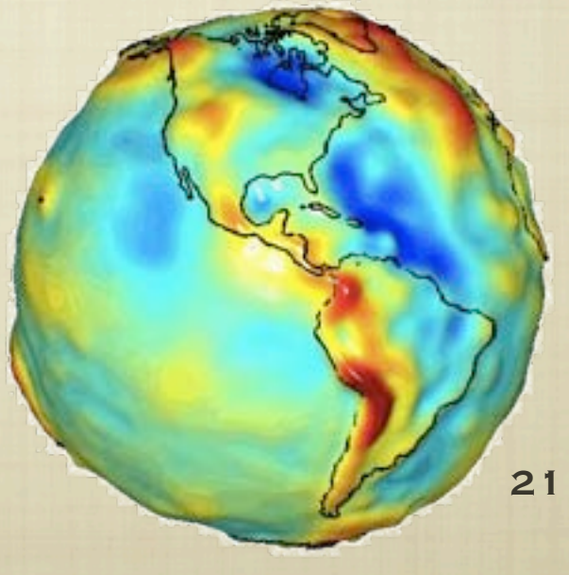

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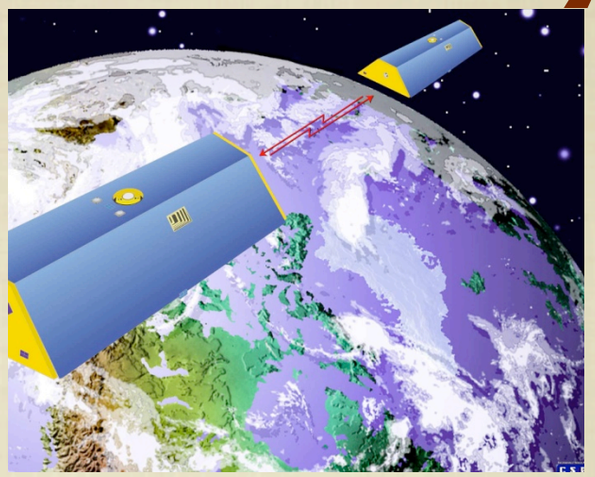

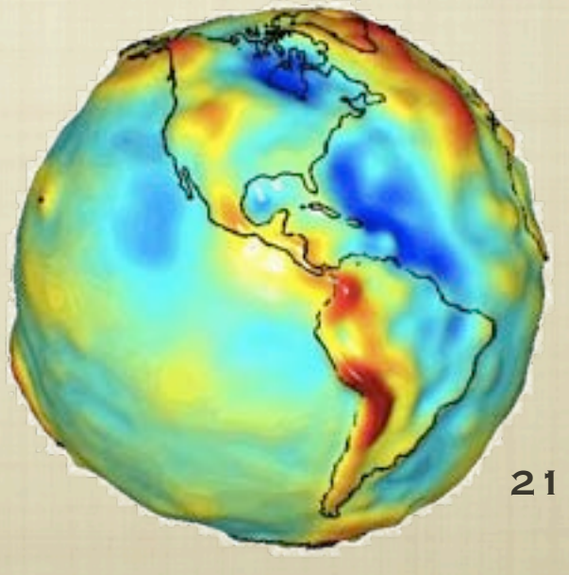

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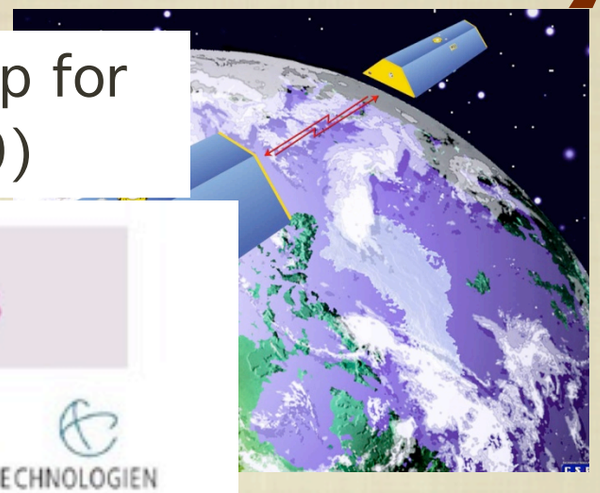
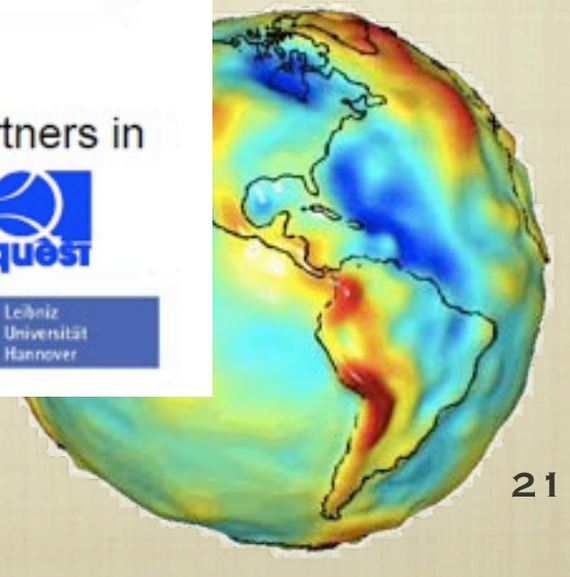
Müller, et al, at the meeting "Towards a Roadmap for Future Satellite Gravity Missions" (Graz 2009)





Project Areas and Participating Teams

control systems

DLR/ZARM*
control systems

GEOTECHNOLOGIEN

GIS
orbit design, formations

IFR
control systems, inertial sensors

Astrium

APMG
gravity recovery optimization

IFE*
sensor optim., integration

MenloSyst
frequency combs

STI
system budgets, cost, risks

Kayser-Th
fs-laser metrology

satellite systems

GFZ
full scale simulations

IAPG
sensor analysis

AEI/MPG/IQ*
laser metrology, LISA, matter waves

TimeTech
µwave metrology

geodesy/science

sensors

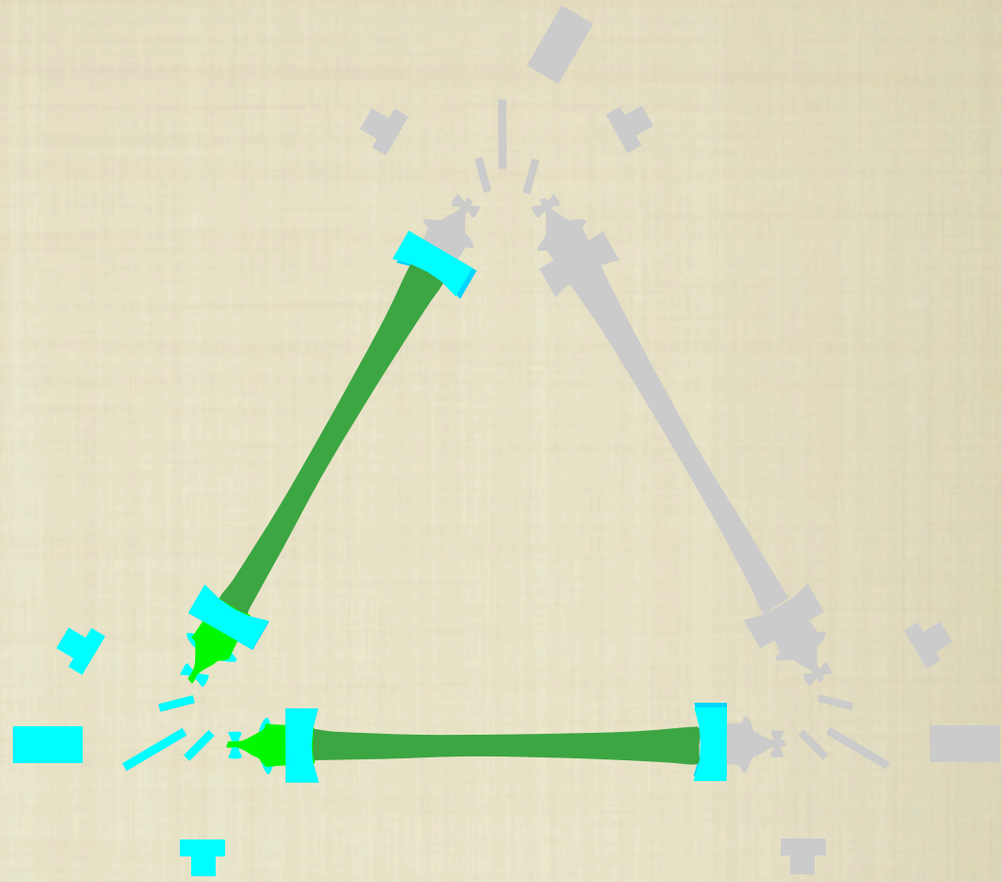
*partners in

quest

ife

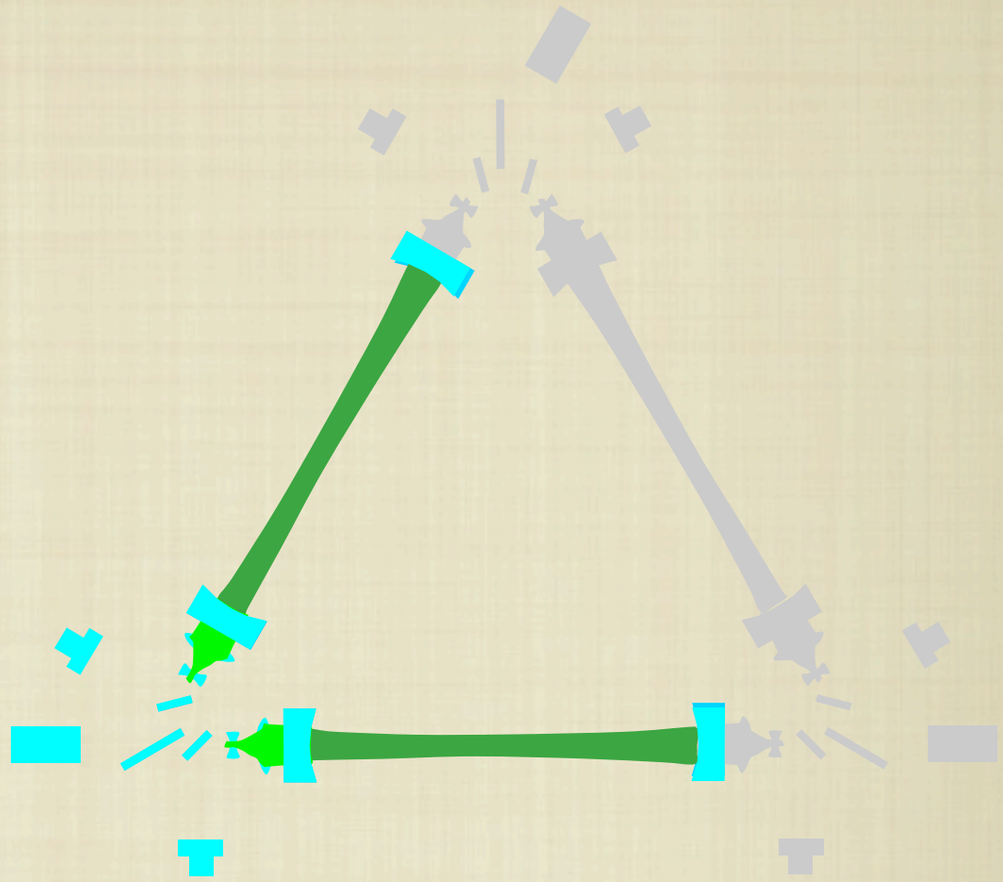
Leibniz Universität Hannover

After LISA: DECIGO



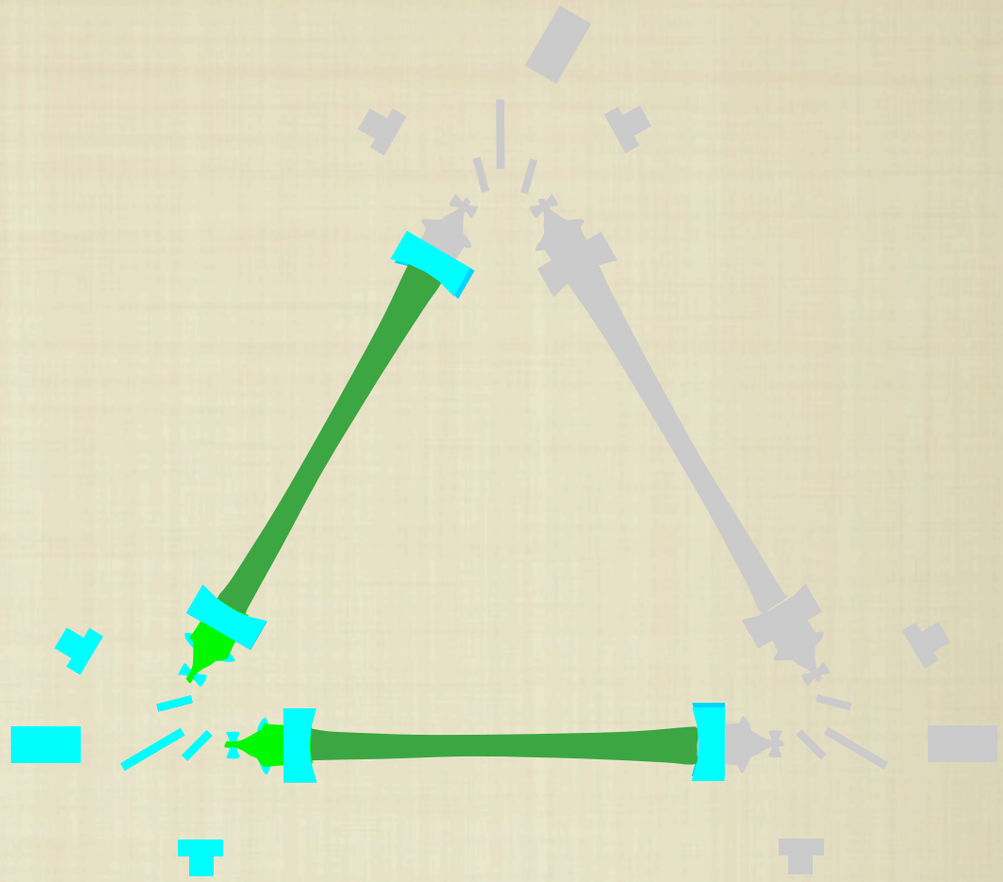
After LISA: DECIGO

- Decigo is a Japanese proposal for a differential Fabry-Perot interferometer (reflecting, not transponding)



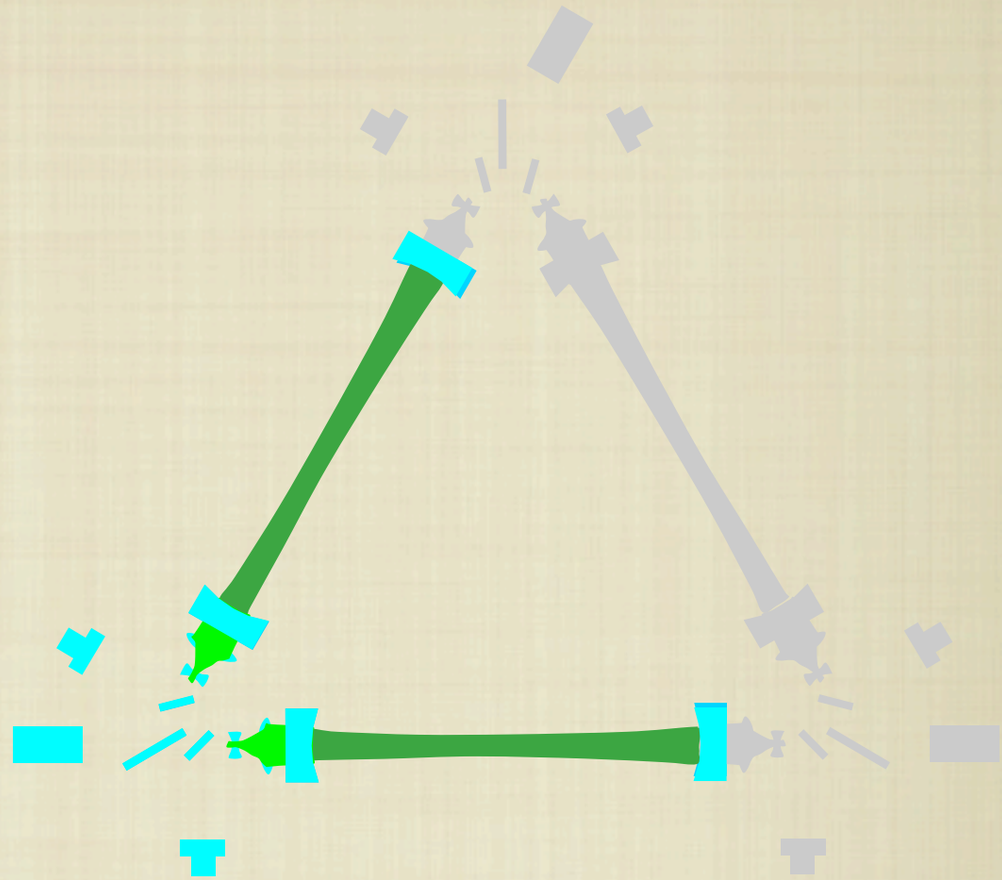
After LISA: DECIGO

- Decigo is a Japanese proposal for a differential Fabry-Perot interferometer (reflecting, not transponding)
  - Arm length 1000 km



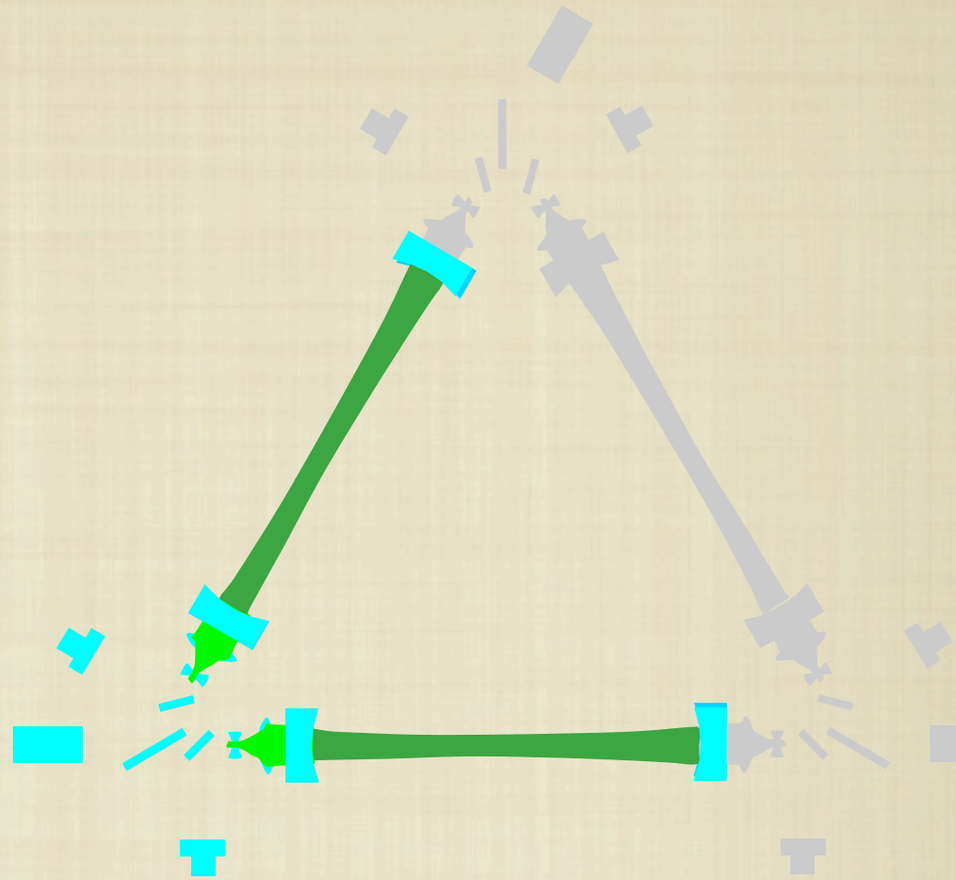
After LISA: DECIGO

- Decigo is a Japanese proposal for a differential Fabry-Perot interferometer (reflecting, not transponding)
  - Arm length 1000 km
  - Laser: green (0.532 μm)



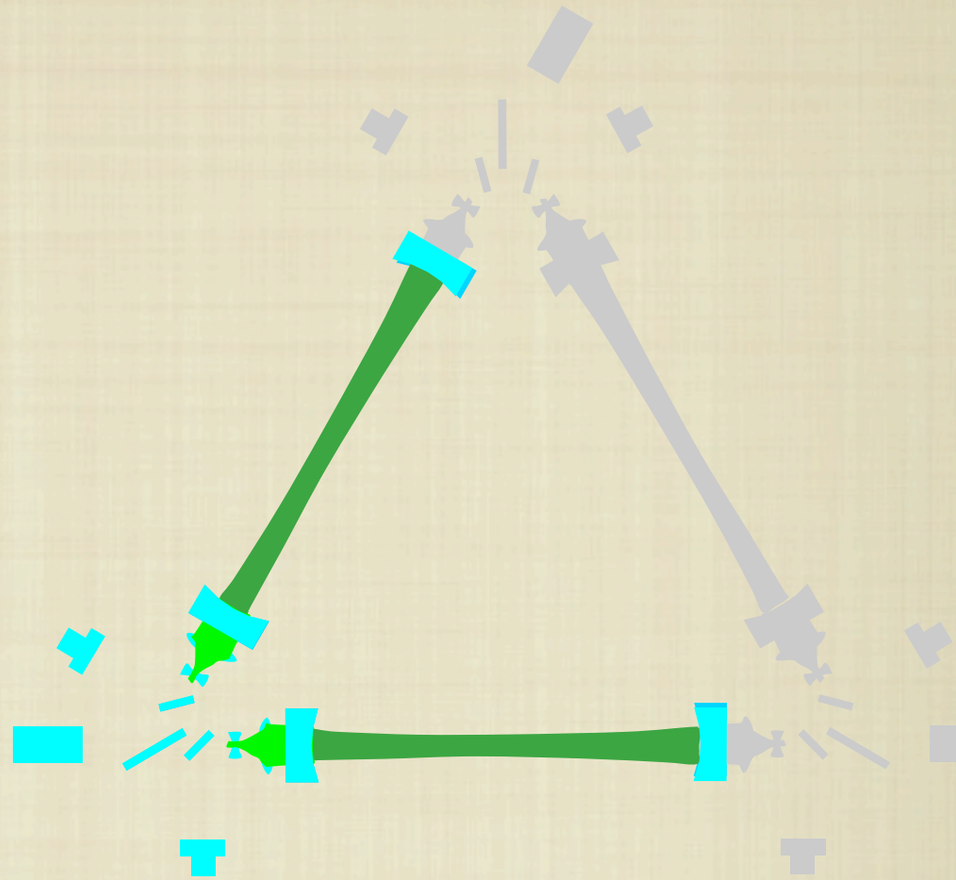
After LISA: DECIGO

- Decigo is a Japanese proposal for a differential Fabry-Perot interferometer (reflecting, not transponding)
  - Arm length 1000 km
  - Laser: green (0.532 μm)
  - Laser power: 10 W



After LISA: DECIGO

- Decigo is a Japanese proposal for a differential Fabry-Perot interferometer (reflecting, not transponding)
  - Arm length 1000 km
  - Laser: green (0.532 μm)
  - Laser power: 10 W
  - Finesse: 10



After LISA: DECIGO

- Decigo is
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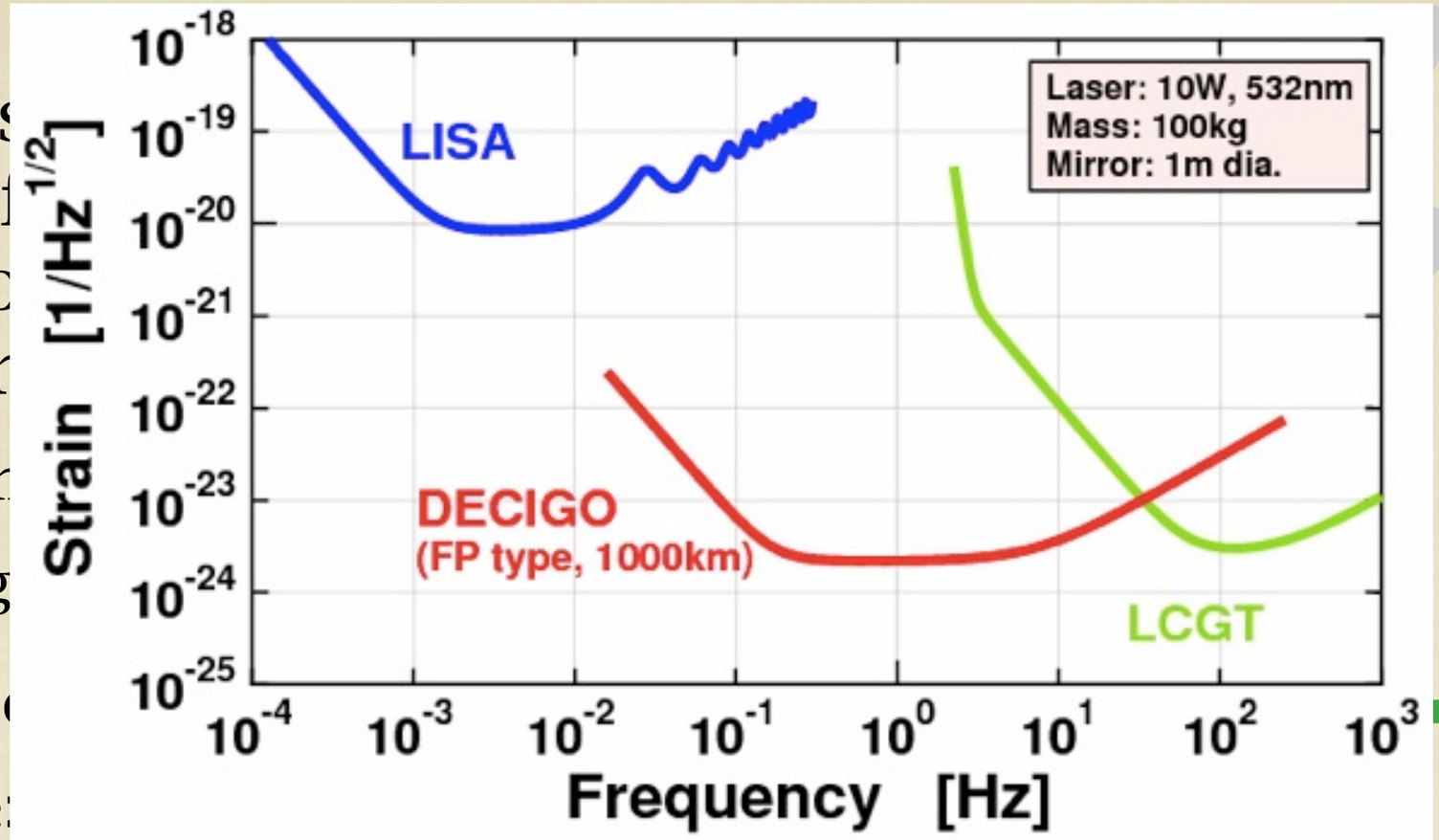
  - Laser: g
  - Laser p
  - Finesse:
- Sensitivity band: between LISA and ground-based detectors, ie 0.1- 10 Hz.



After LISA: DECIGO

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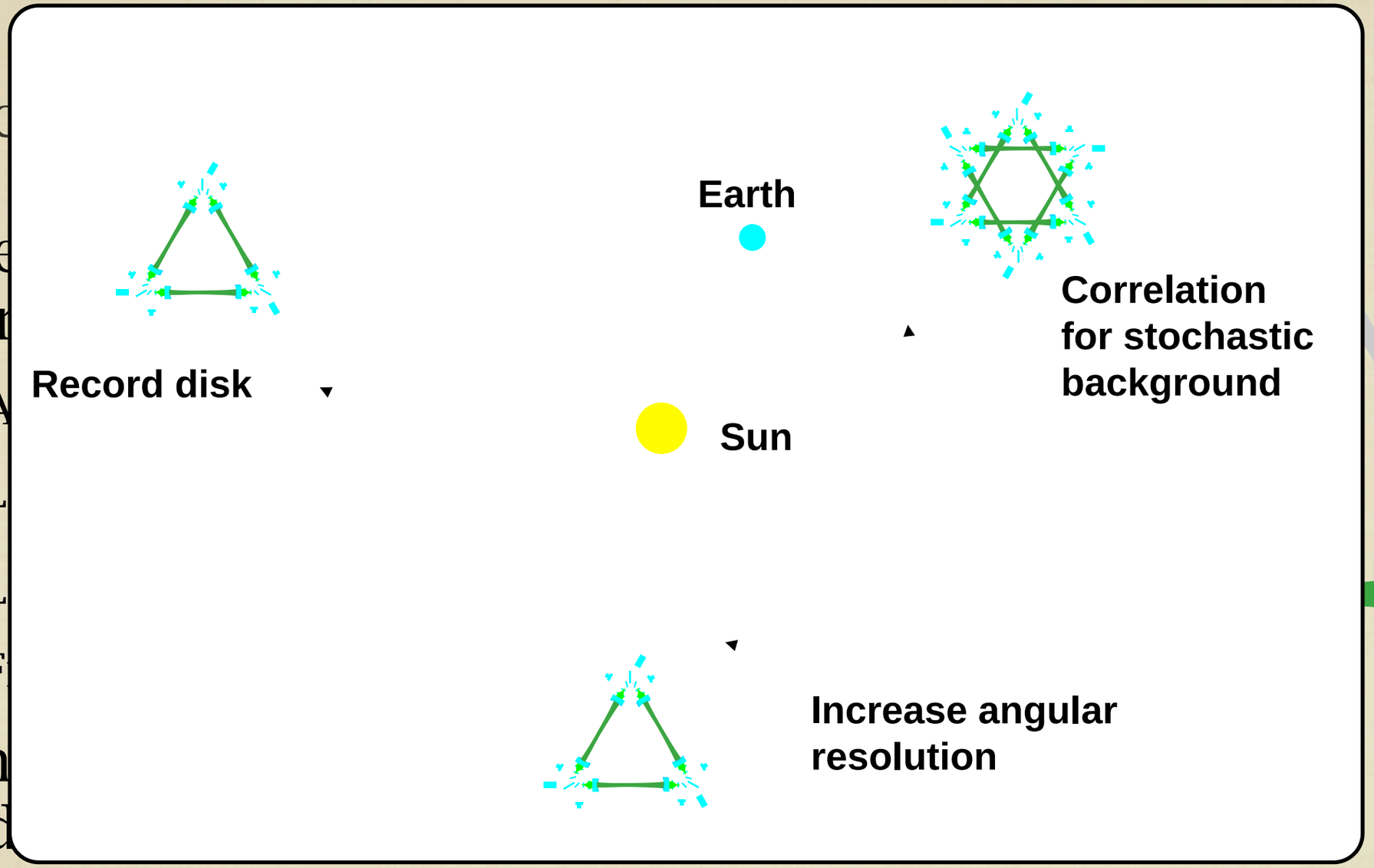
- Sen
  and
  0.1- 10 Hz.
- Ambitious constellation!



Summary

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- Technologies converging: study GWs, the gravity of the Sun, or the gravity of the Earth
  - Laser ranging
  - Drag-free S/C with microthruster control

Summary

- Technologies converging: study GWs, the gravity of the Sun, or the gravity of the Earth
  - Laser ranging
  - Drag-free S/C with microthruster control
- The driver is GW Astronomy:
  - Black holes back to the beginning of galaxy formation
  - Populations of massive black holes in galaxies
  - Populations of compact white-dwarf binaries
  - Possible observations of backgrounds, cosmic strings, other exotica
  - Strong tests of GR