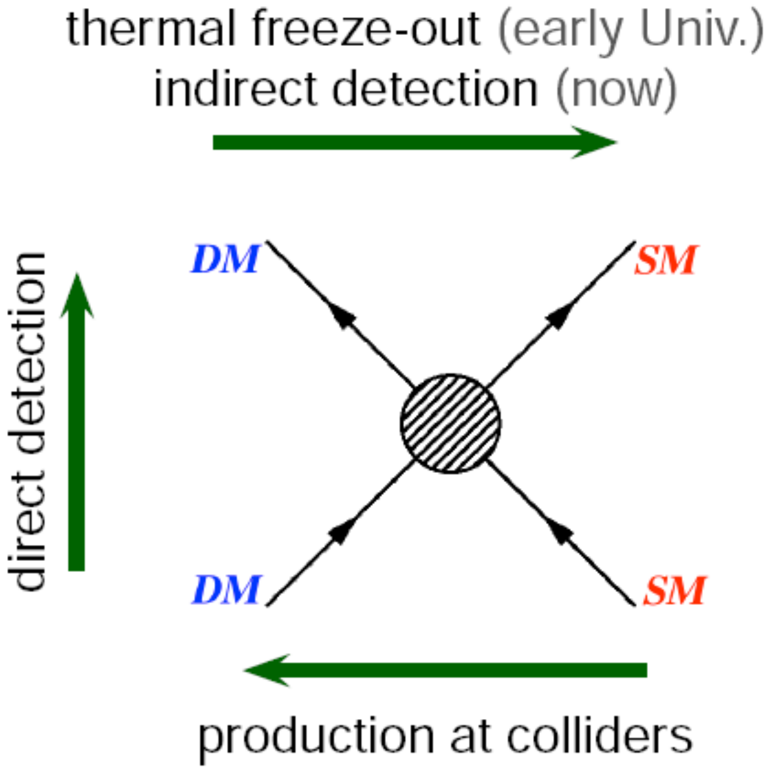
Dark Matter

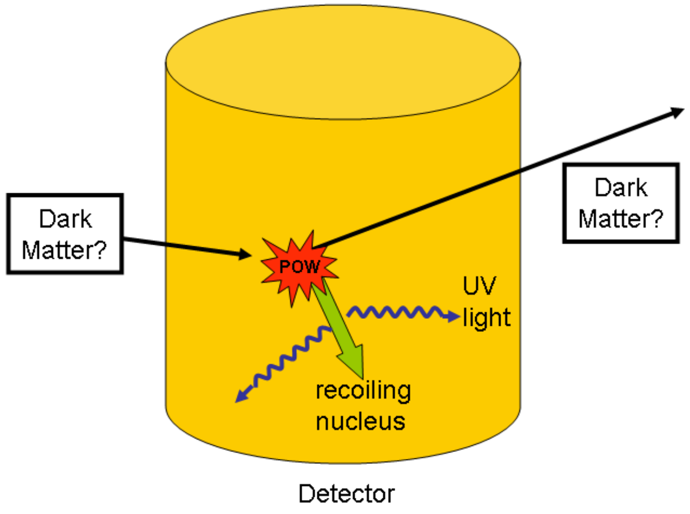
The hunt for dark matter particles

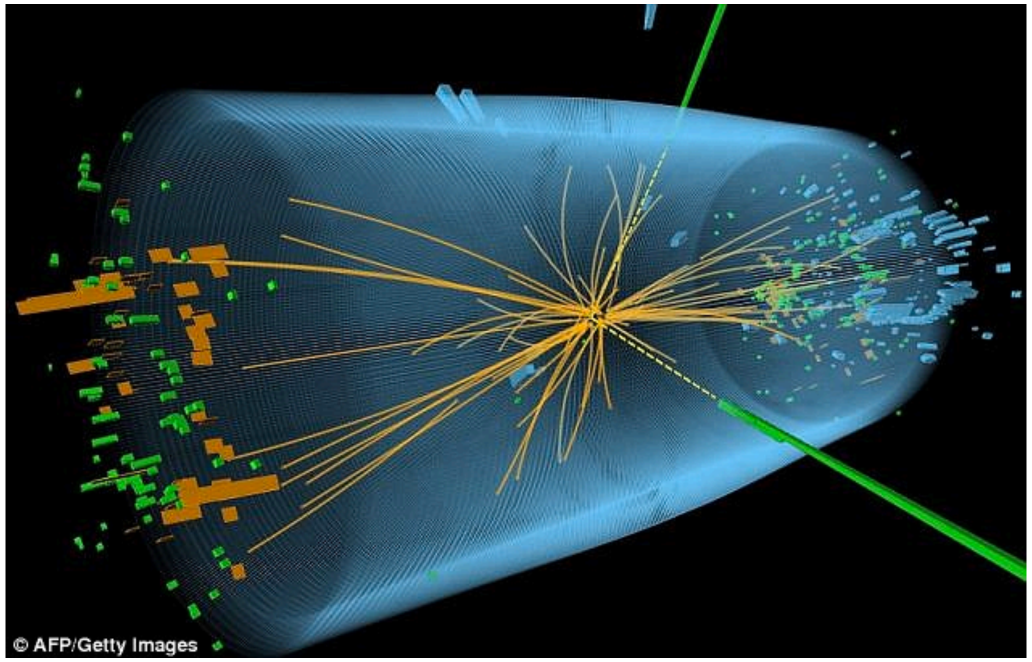

thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

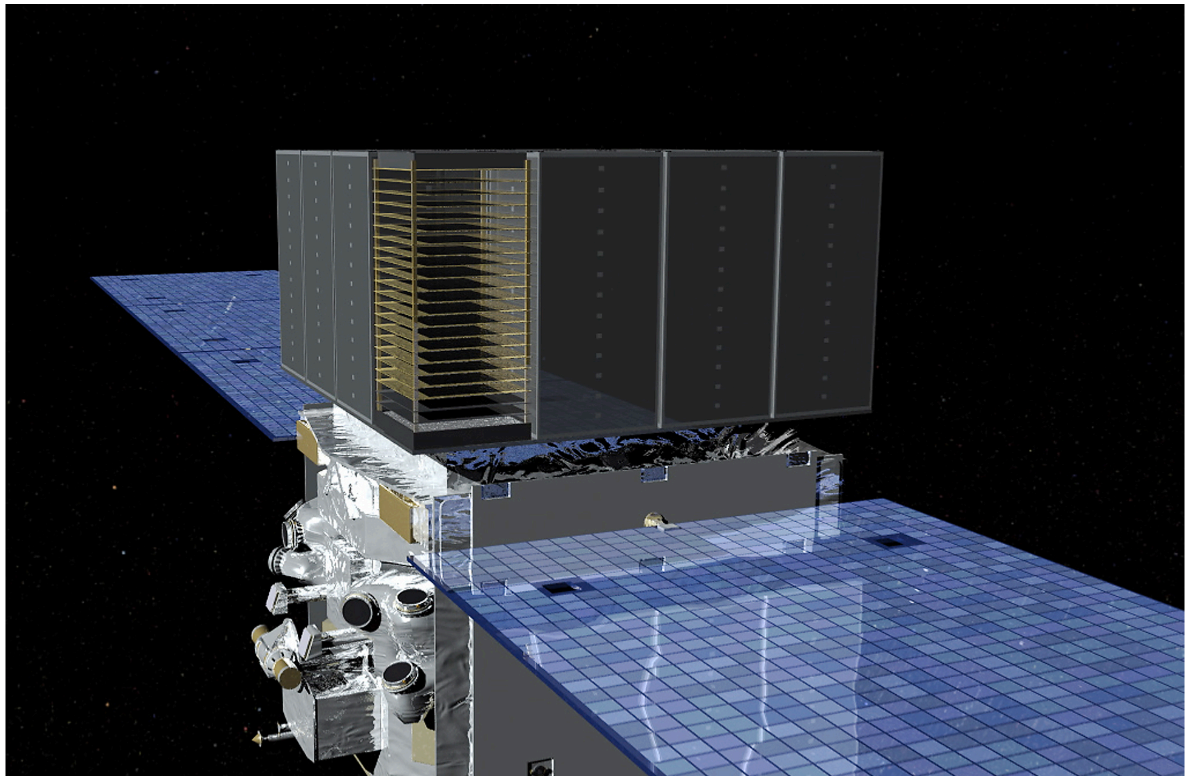
production at colliders

direct searches




© AFP/Getty Images

collider searches



indirect searches

We don’t know yet what DM is... but we do know many of its properties

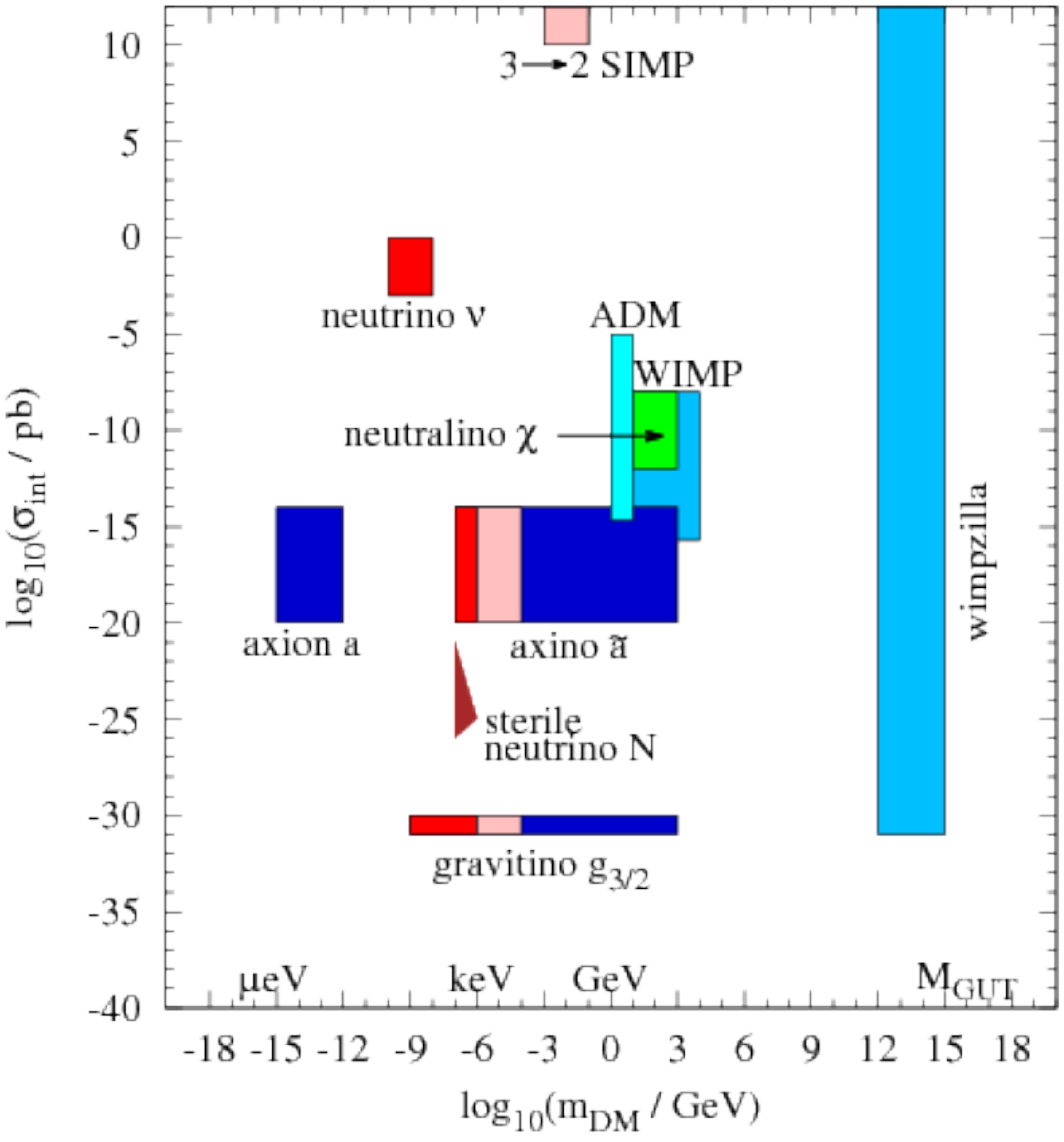
Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...

Baer et al. 2014



... they have very **different** properties

Current challenges for DARK MATTER

- **Experimental detection:**
  Does DM feel other interactions apart from Gravity?
  Is the Electro-Weak scale related somehow related to DM?
  How is DM distributed?

- **Determination of the DM particle parameters:**
  Mass, interaction cross section, etc…

- **What is the theory for Physics beyond the SM:**
  DM as a window for new Physics
  Can we identify the DM candidate?

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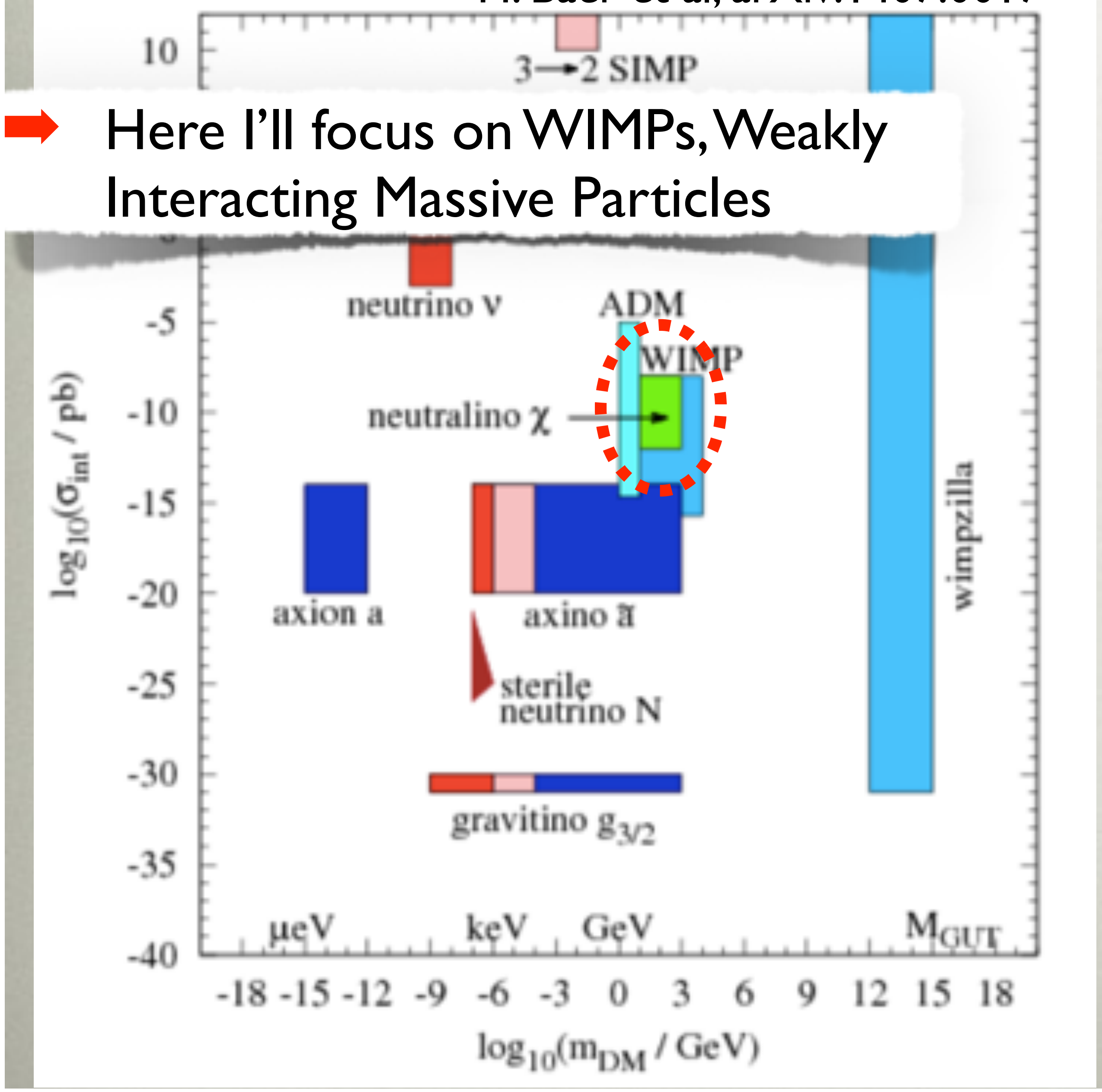
Supersymmetry is a well motivated extension of the SM

- **Solution to the hierarchy problem?** Low mass Higgs with SM-like couplings
- **Dark Matter candidates**

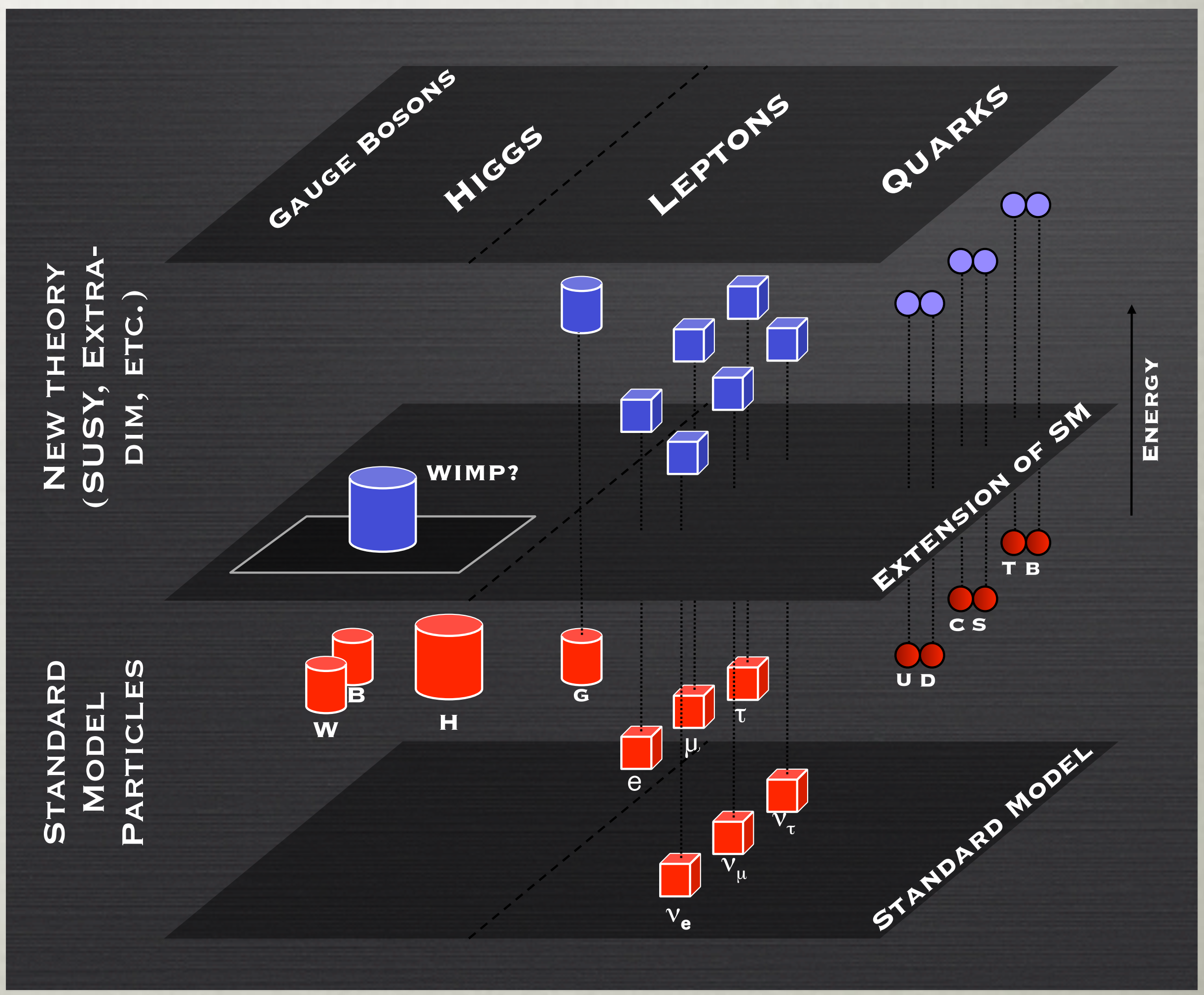
DARK MATTER CANDIDATES

- Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates

H. Baer et al, arXiv:1407.0017

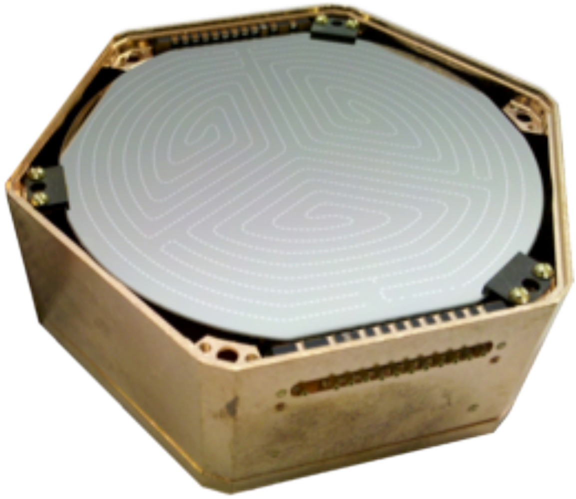


➡ Here I'll focus on WIMPs, Weakly Interacting Massive Particles

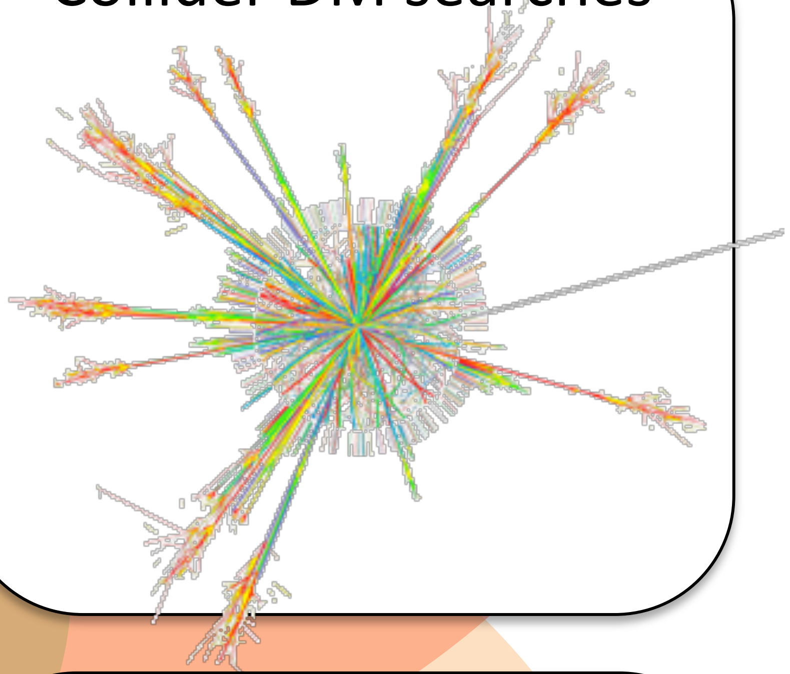


Dark matter MUST BE searched for in different ways...

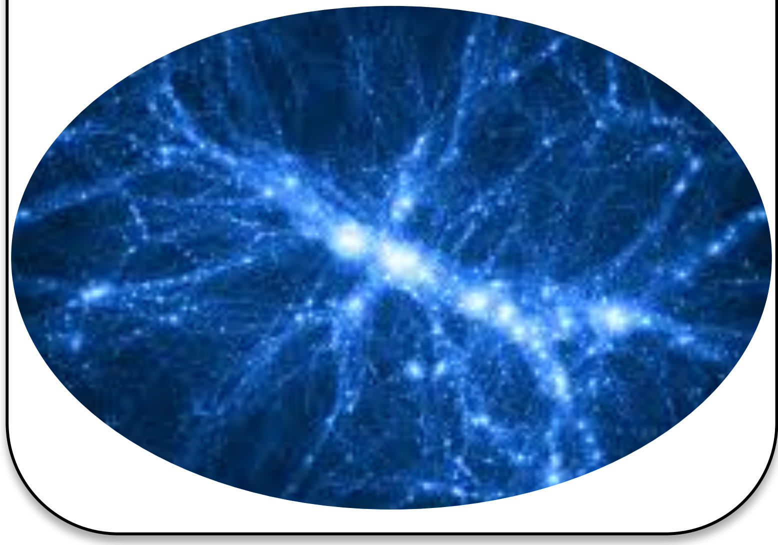
Direct DM detection



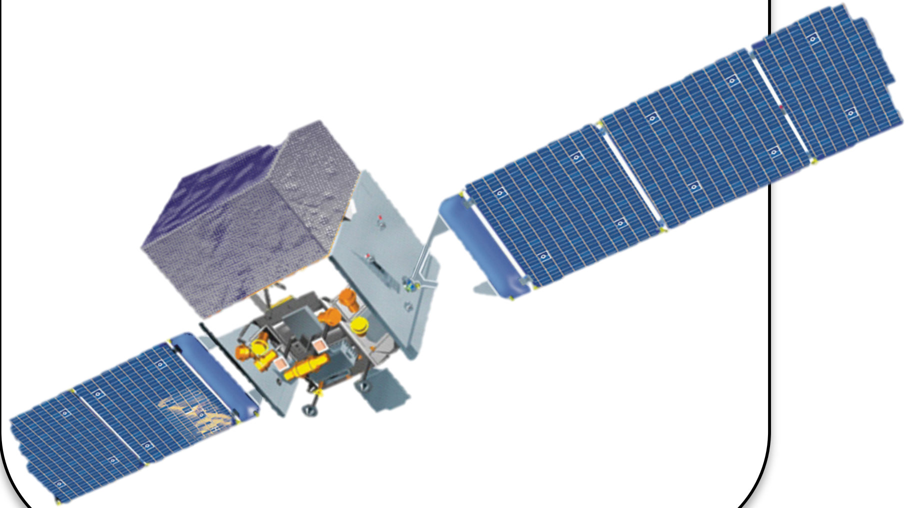
Collider DM searches



Astro/Cosmo probes

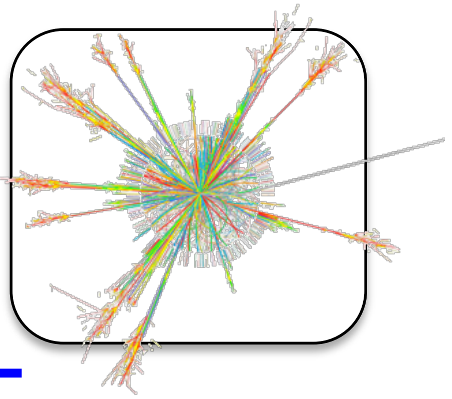


Indirect DM detection

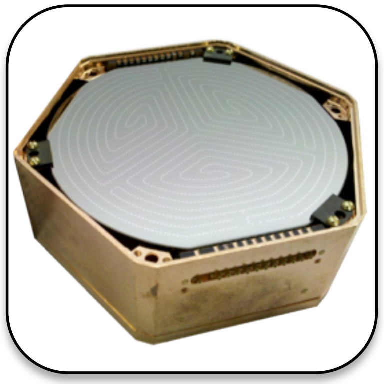


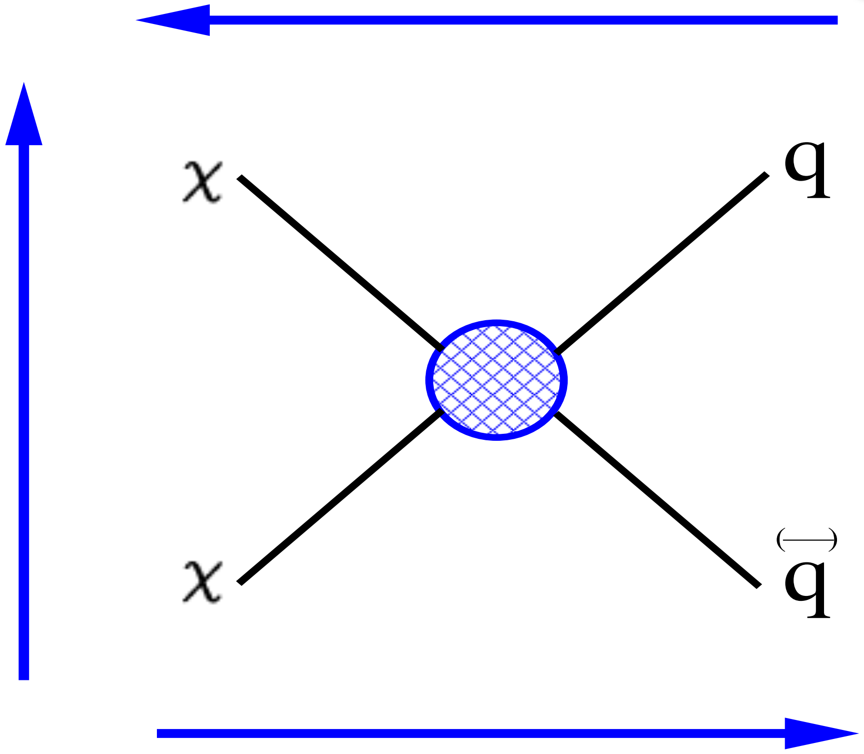
... probing **DIFFERENT** aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection (scattering)

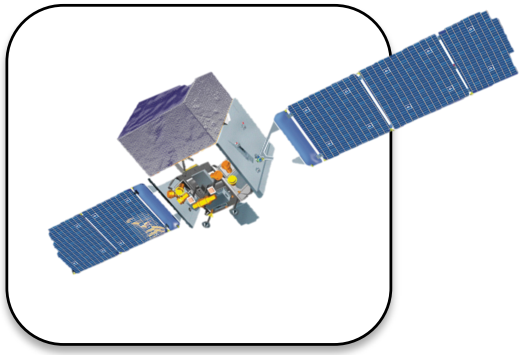




Constraints in one sector affect observations in the other two.

"**Redundant**" detection can be used to extract DM properties.

Indirect Detection (annihilation or decay)



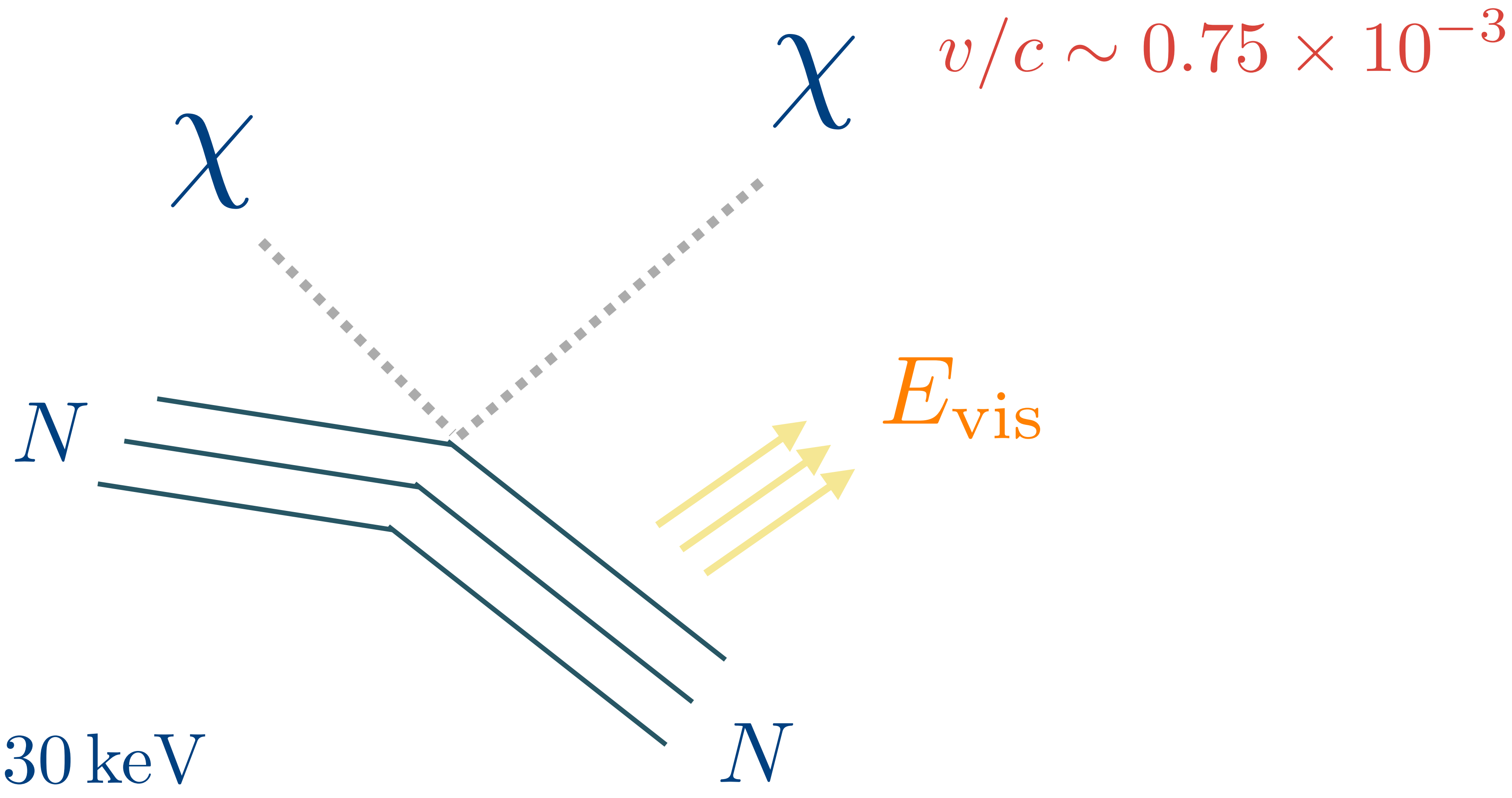
Direct detection

Physics aim of direct detection experiments

Observe WIMP dark matter via elastic scattering off atomic nuclei

Momentum transfer ~ few tens of MeV

Energy deposited in the detector ~ few keV - tens of keV

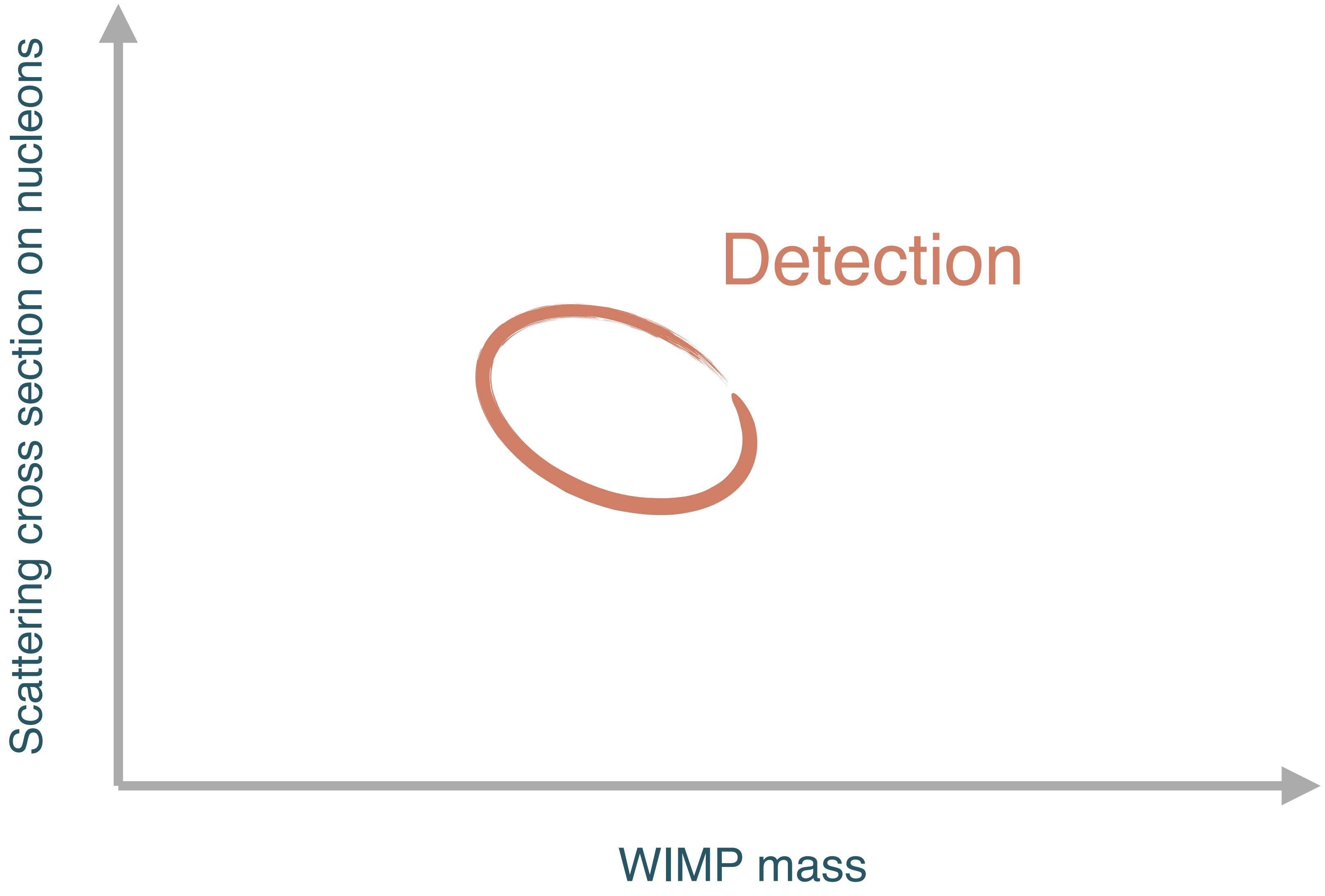


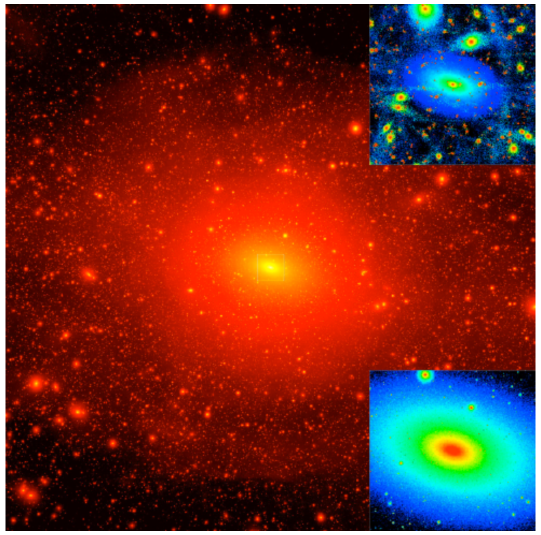
$$E_R = \frac{q^2}{2m_N} < 30\,\text{keV}$$

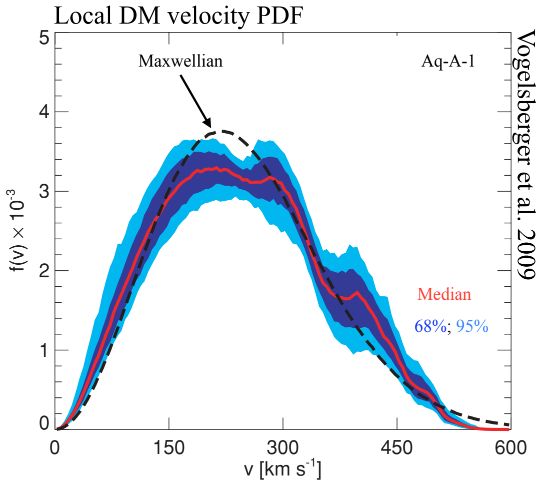
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$







Vogelsberger et al. 2009

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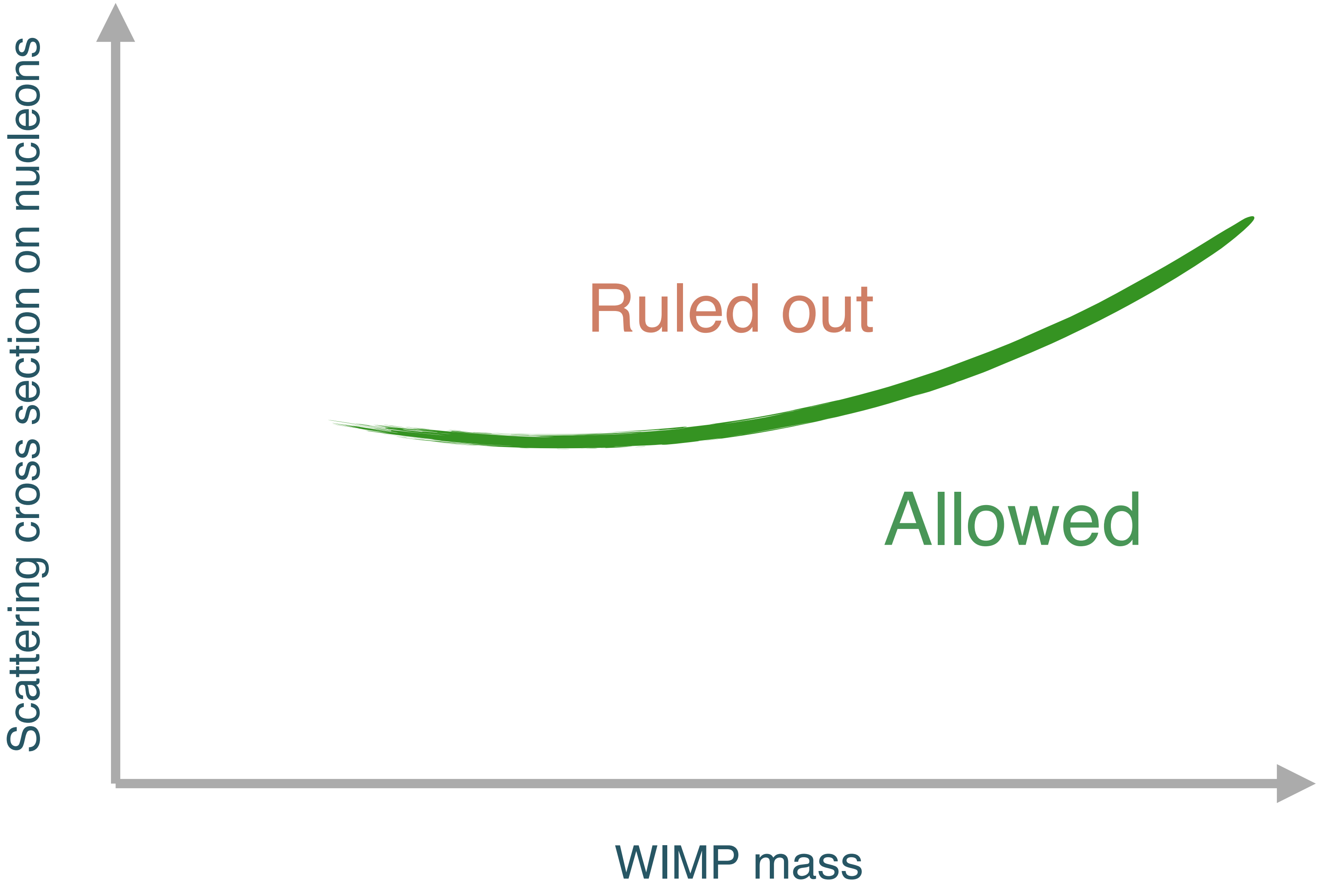
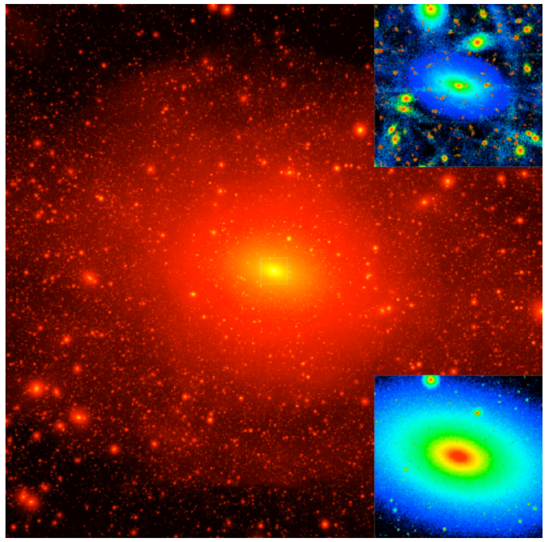
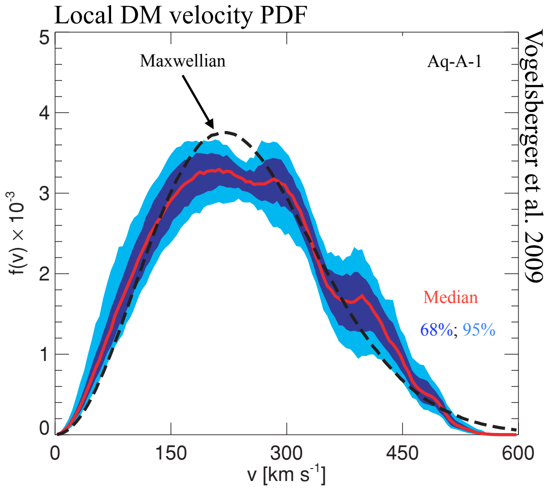
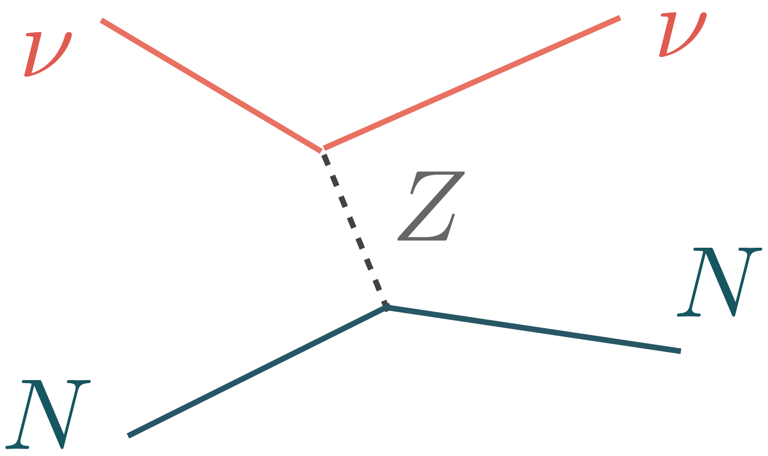


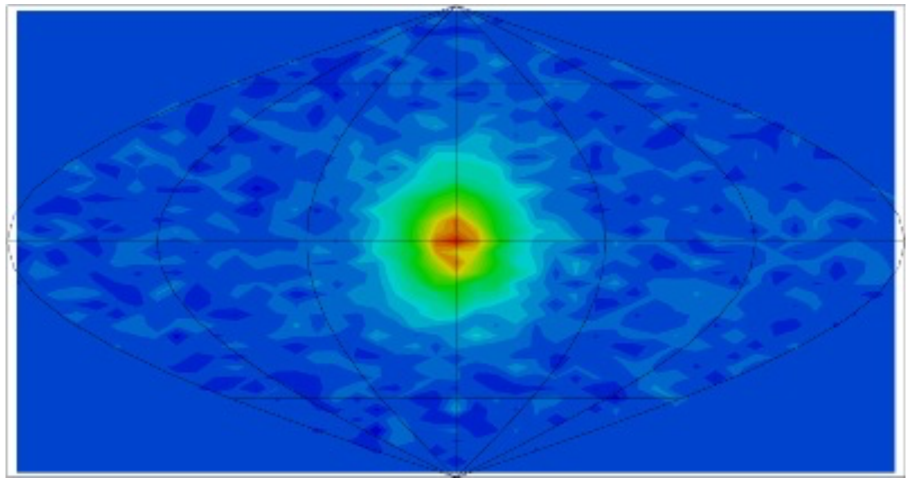


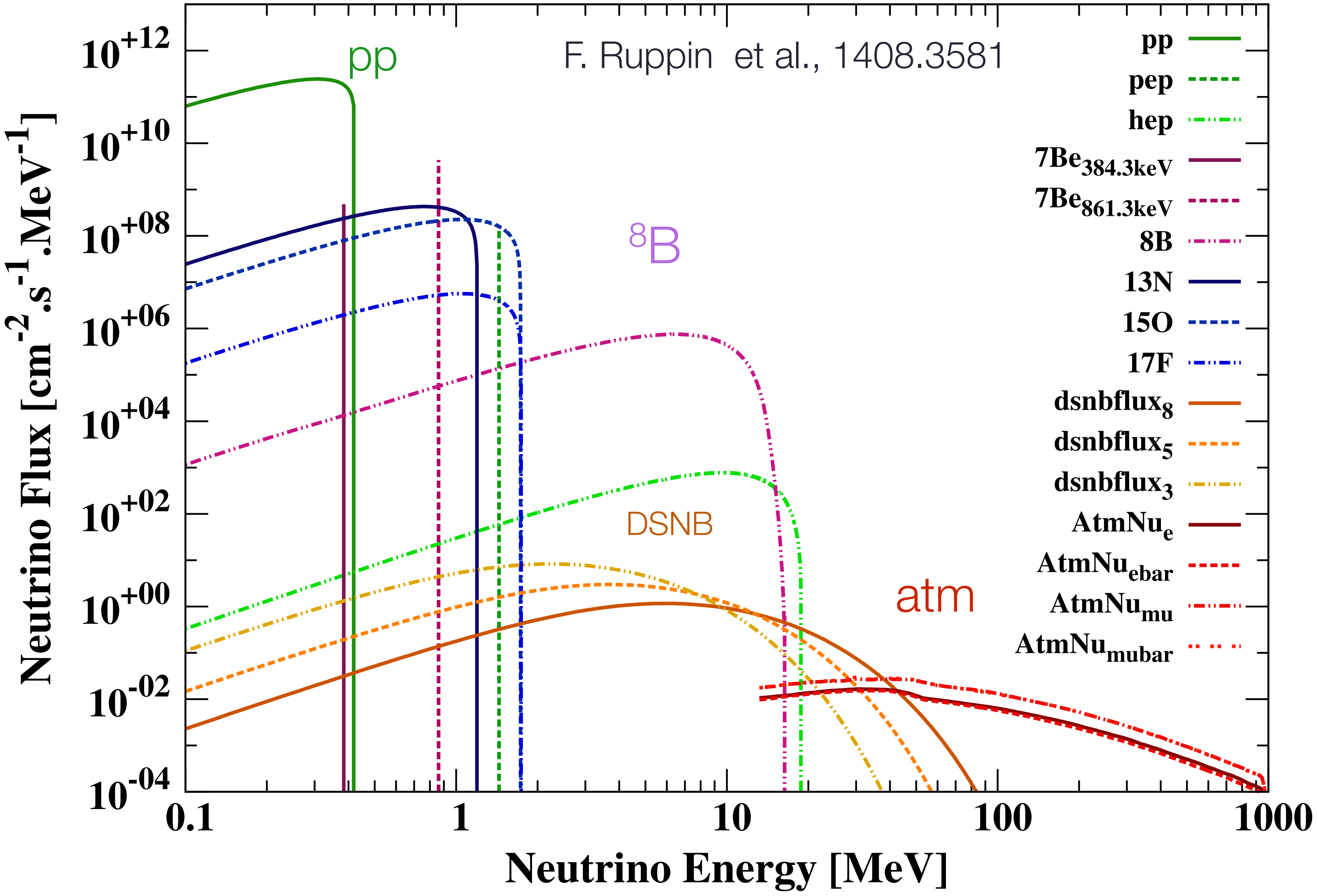


Backgrounds

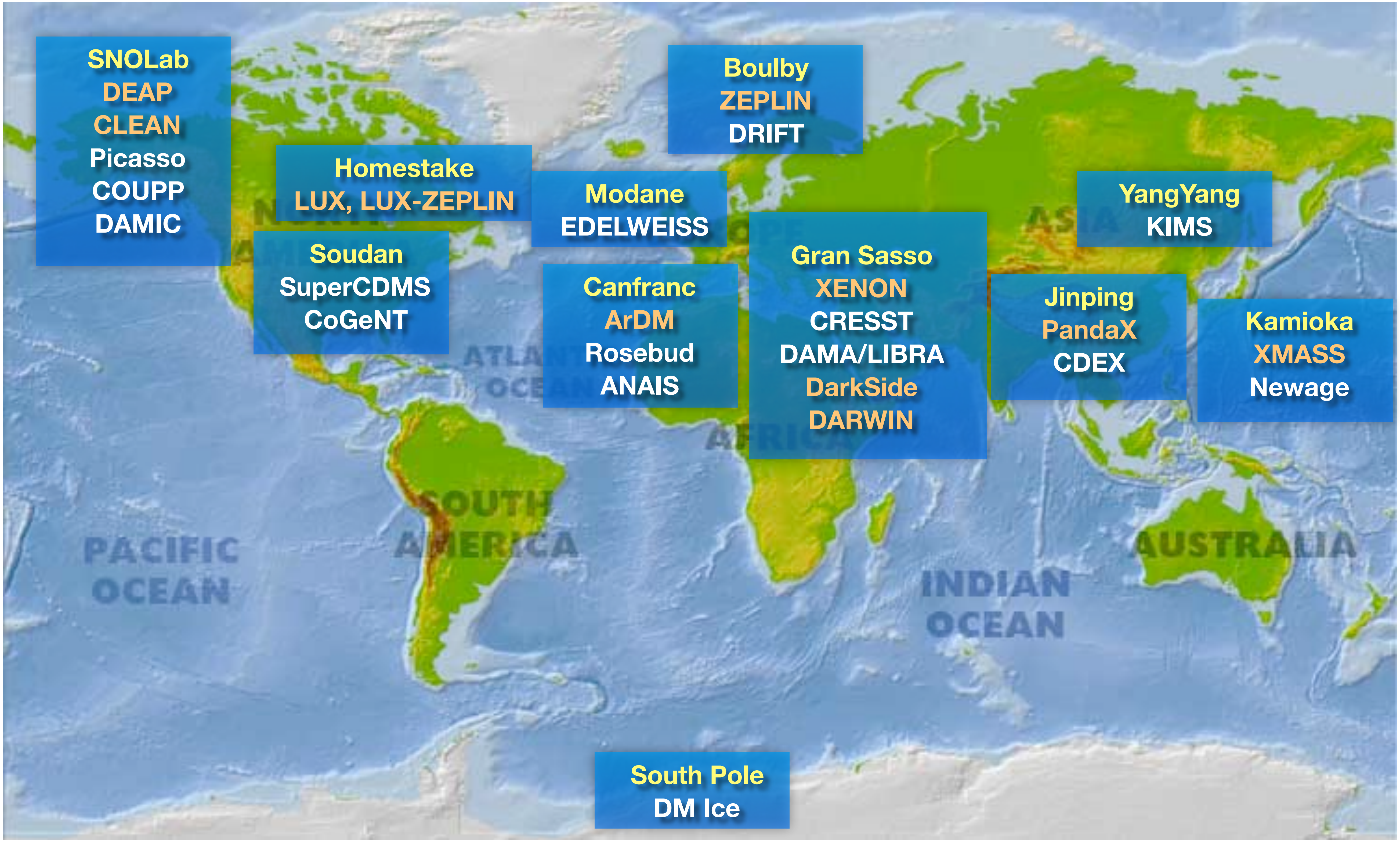
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**







A world-wide effort to search for WIMPs

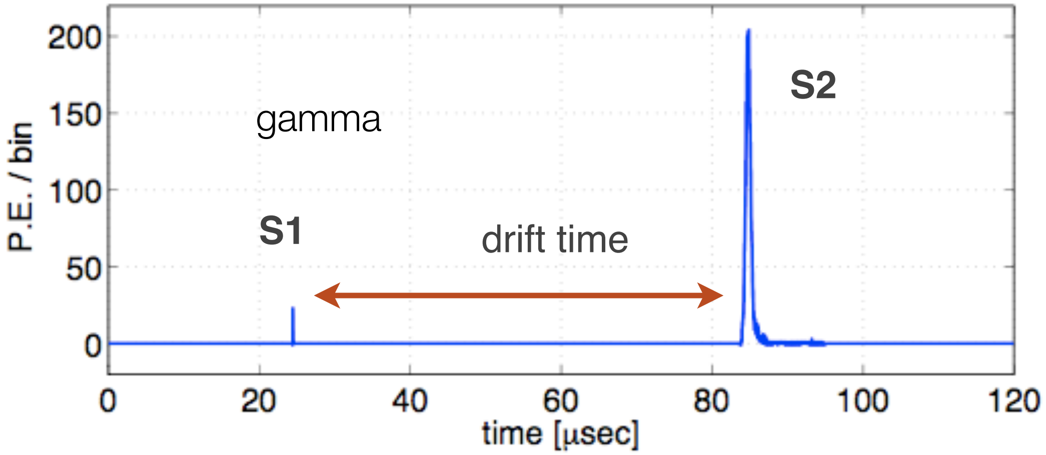


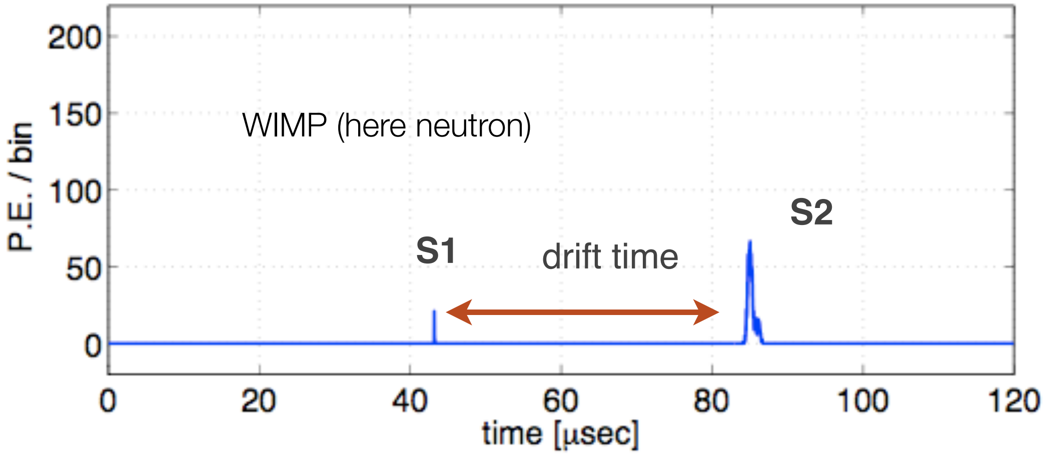
The Double-Phase Detector Concept

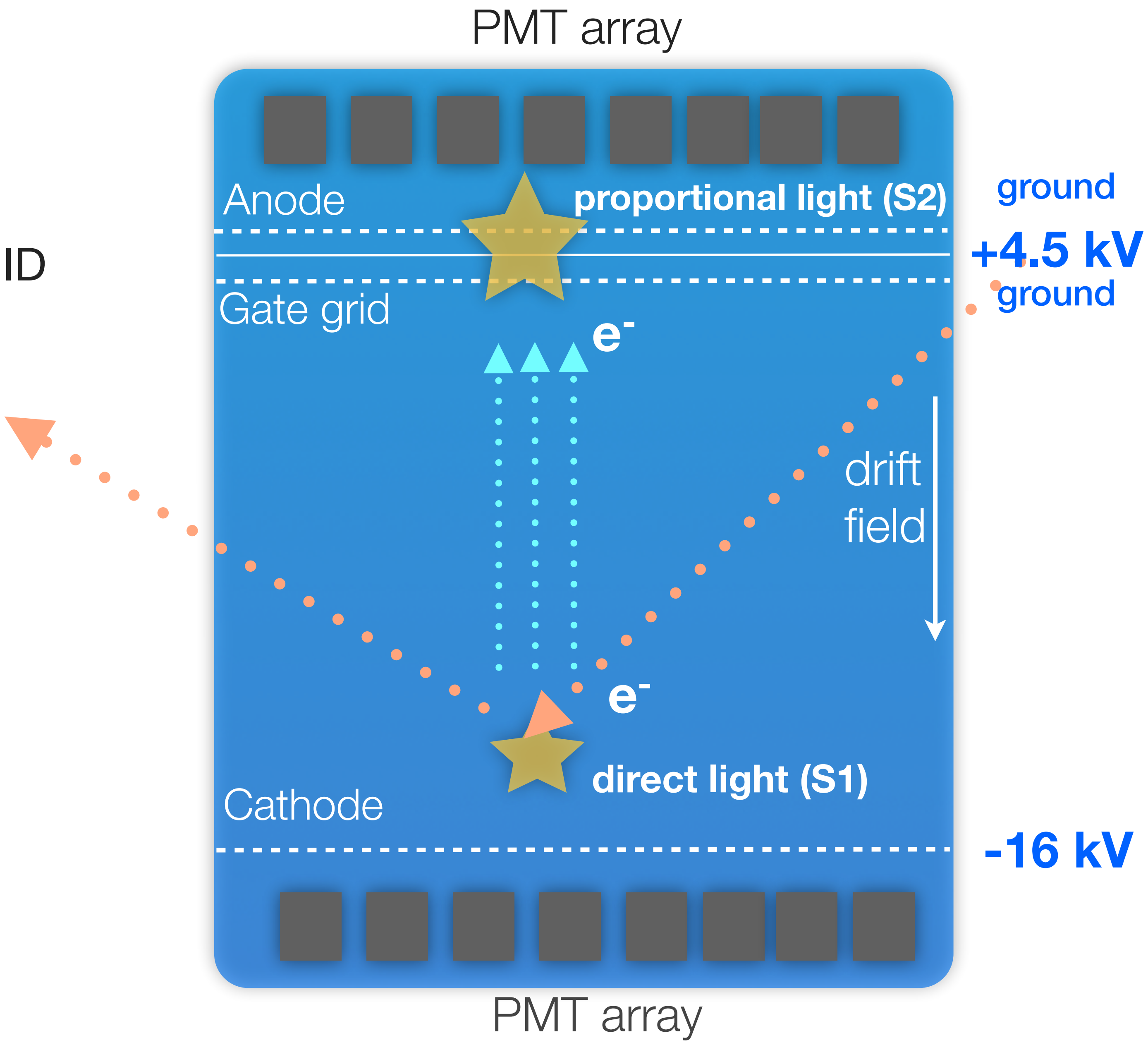
- Particle interaction in the active volume produces *prompt scintillation light (S1)* and ionisation electrons
- Electrons drift to interface (E= 0.53 kV/cm) where they are extracted and amplified in the gas. Detected as *proportional scintillation light (S2)*
  - $(S2/S1)_{\mathrm{WIMP}} << (S2/S1)_{\mathrm{Gamma}}$
  - 3-D position sensitive detector with particle ID

position resolution:

<3mm in x-y; < 0.3 mm in z

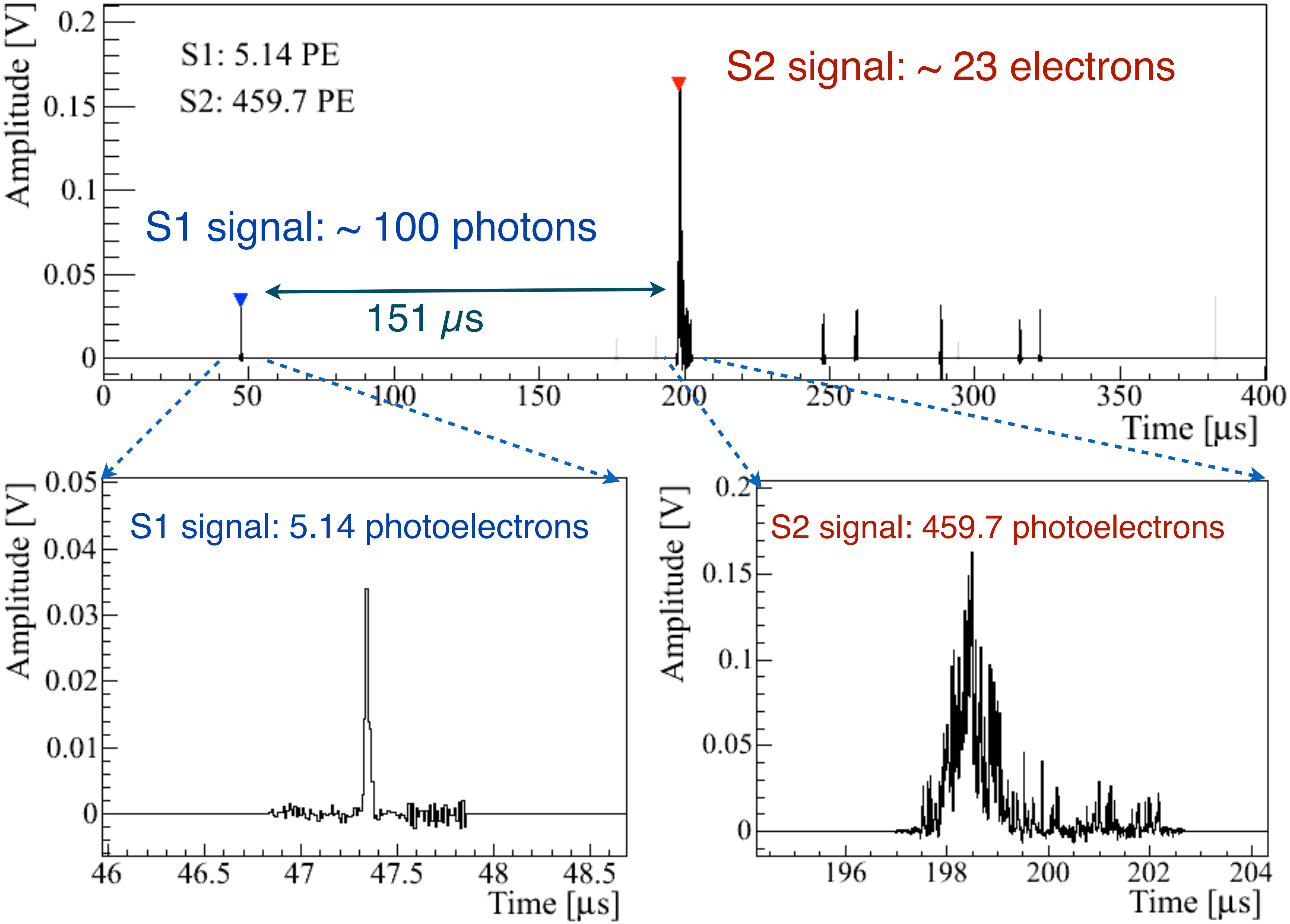






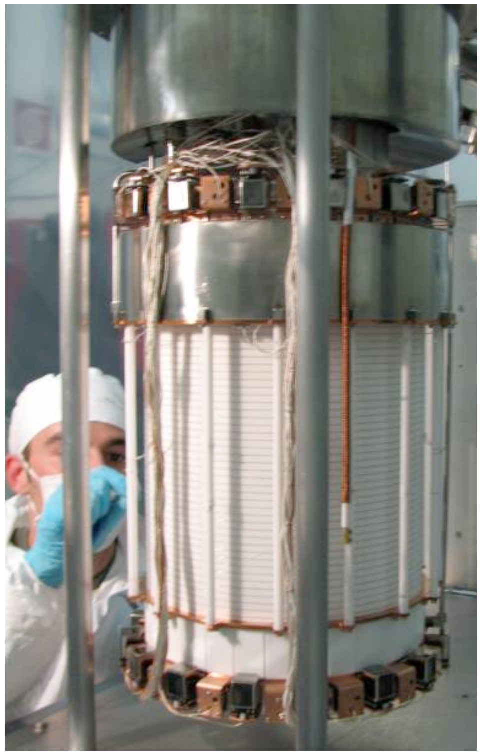
Example of a low-energy event in XENON100

The maximum electron drift time at 0.53 kV/cm is 176 μs



Time projection chambers: xenon

See talk by L. Bütikofer



XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs

results from run II
calibration data (YBe, ^{83m}Kr, CH_3T, ^{220}Rn) etc

S. Fiorucci, Patras 2016

LUX at SURF:

350 kg LXe
(100 kg fiducial)

122 2-inch PMTs

re-analysis of 2013 data (run 3)
first result from run 4 by the end of this year

X. Ji, UCLA DM 2016

PandaX at Jinping:

500 kg LXe
(306 kg fiducial)

110 3-inch PMTs

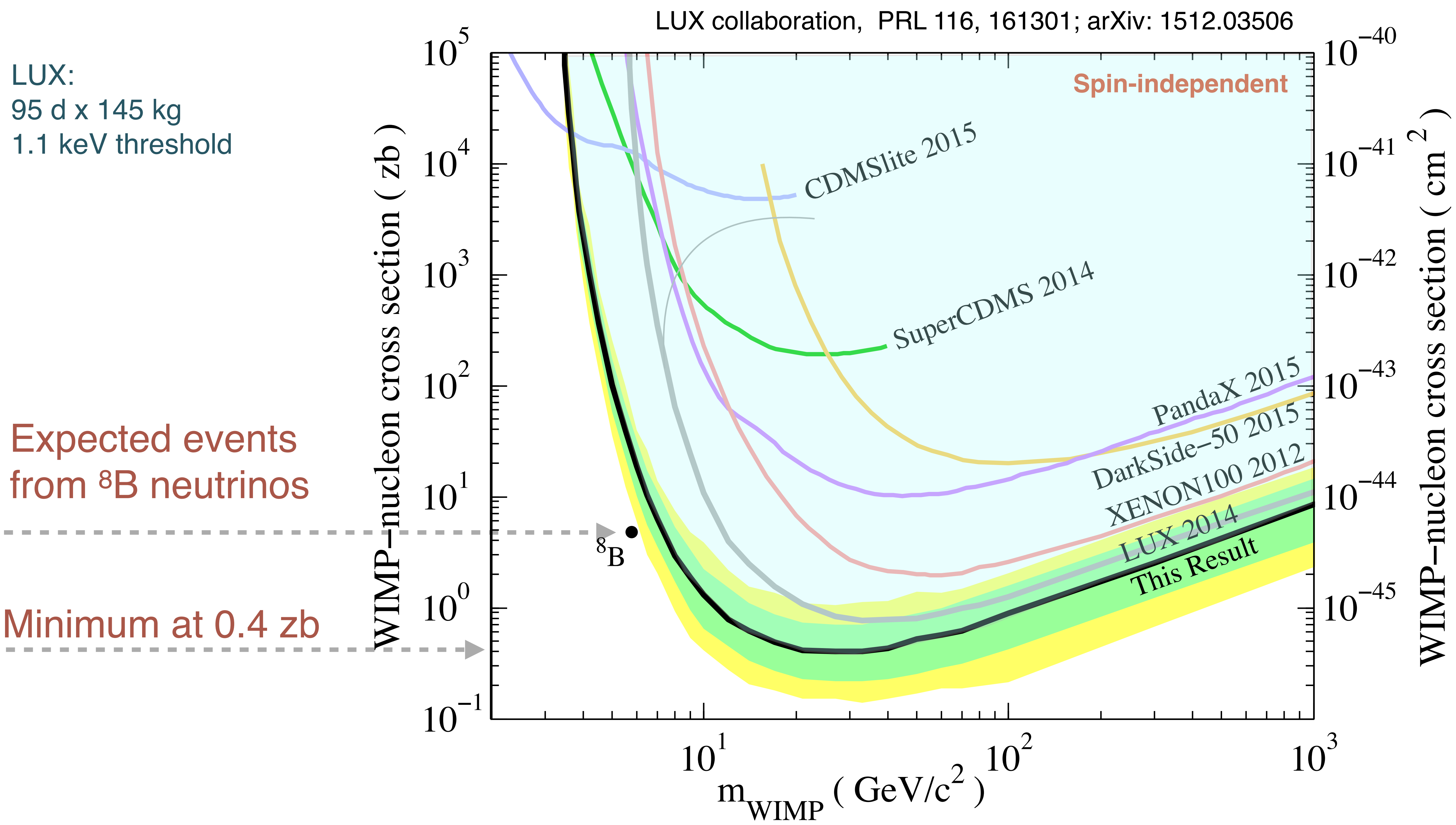
first commissioning run
science data since spring 2016

Recent results: no evidence (yet) for WIMPs

LUX:
95 d x 145 kg
1.1 keV threshold

Expected events from ^{8}B neutrinos

Minimum at 0.4 zb

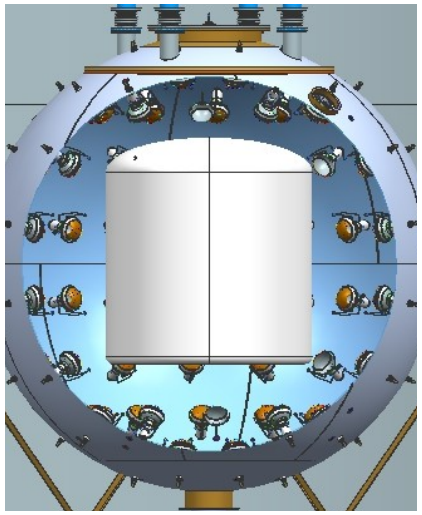


1 b = 10^{-24} cm^2 z=Zepto 10^{-21}

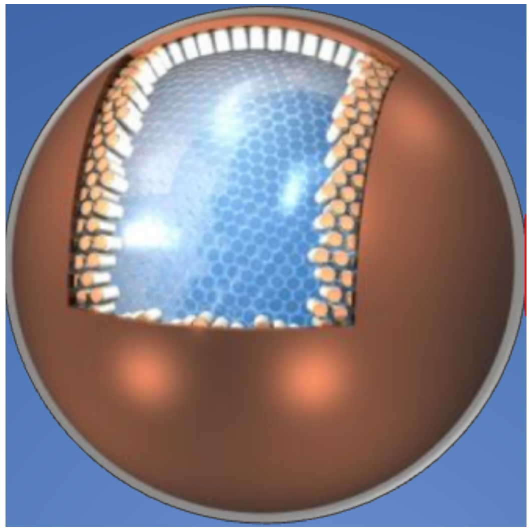
New and future noble liquid detectors

- **Under commissioning: XENON1T (3.5 t LXe) at Gran Sasso**
- Planned LXe: LUX-ZEPLIN 7t, XENONnT 7t, XMASS 6t
- Proposed LAr: DarkSide 20 t, DEAP 50 t
- Design & R&D stage: DARWIN 50 t LXe; ARGO 300 t LAr

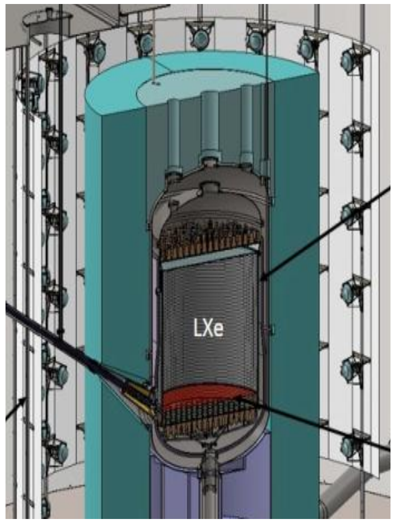
XENONnT: 7t LXe



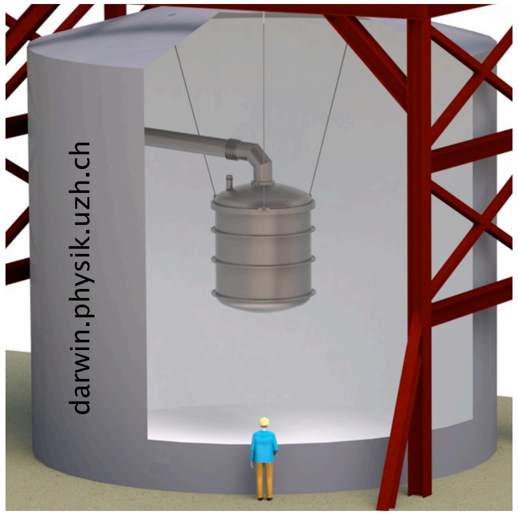
DarkSide: 20 t LAr



XMASS: 6t LXe



LZ: 7t LXe



DARWIN: 50 t LXe

The XENON1T experiment

See talk by P. Pakarha

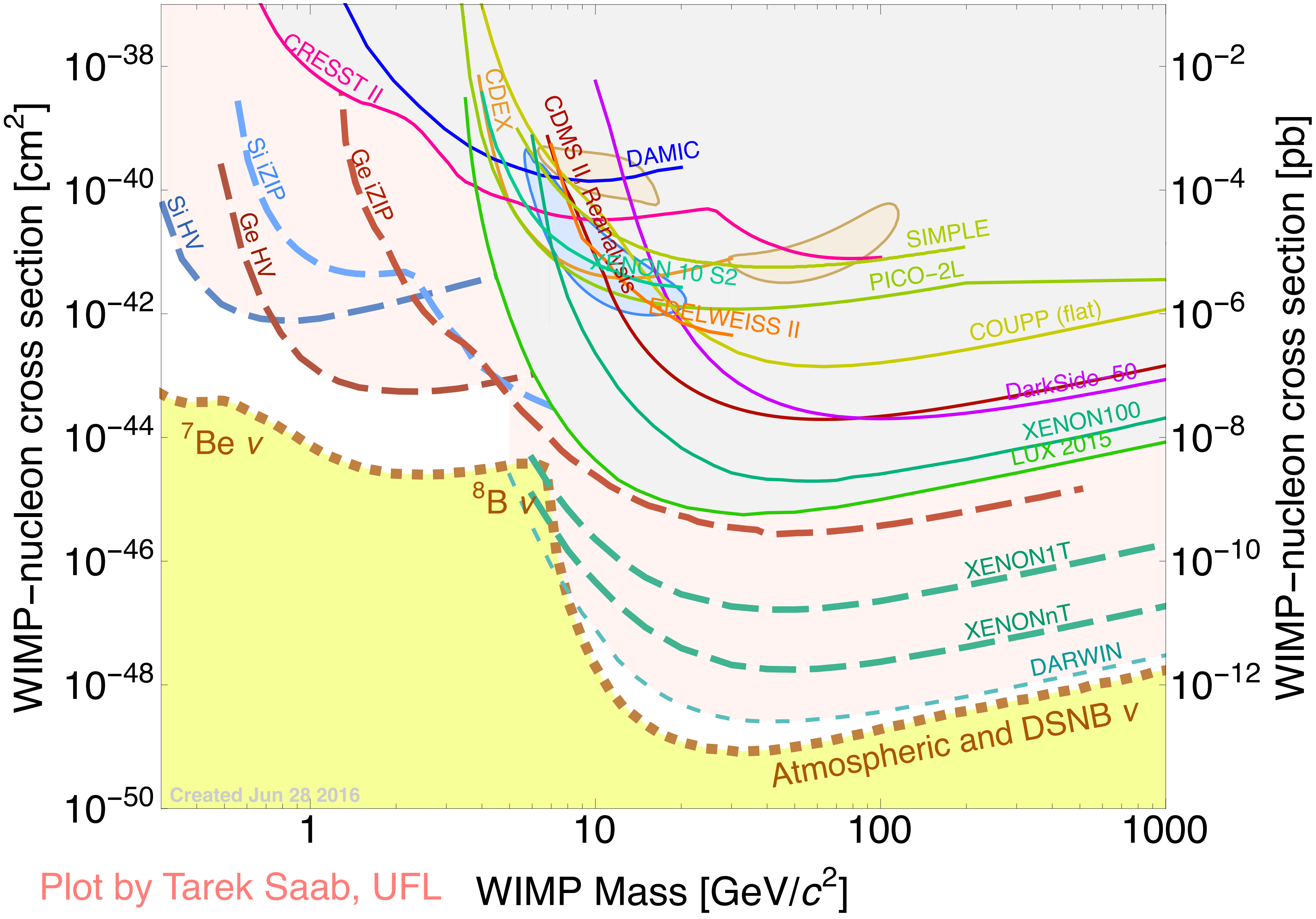
- Total (active) LXe mass: 3.5 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)

xenon1t.org

The end

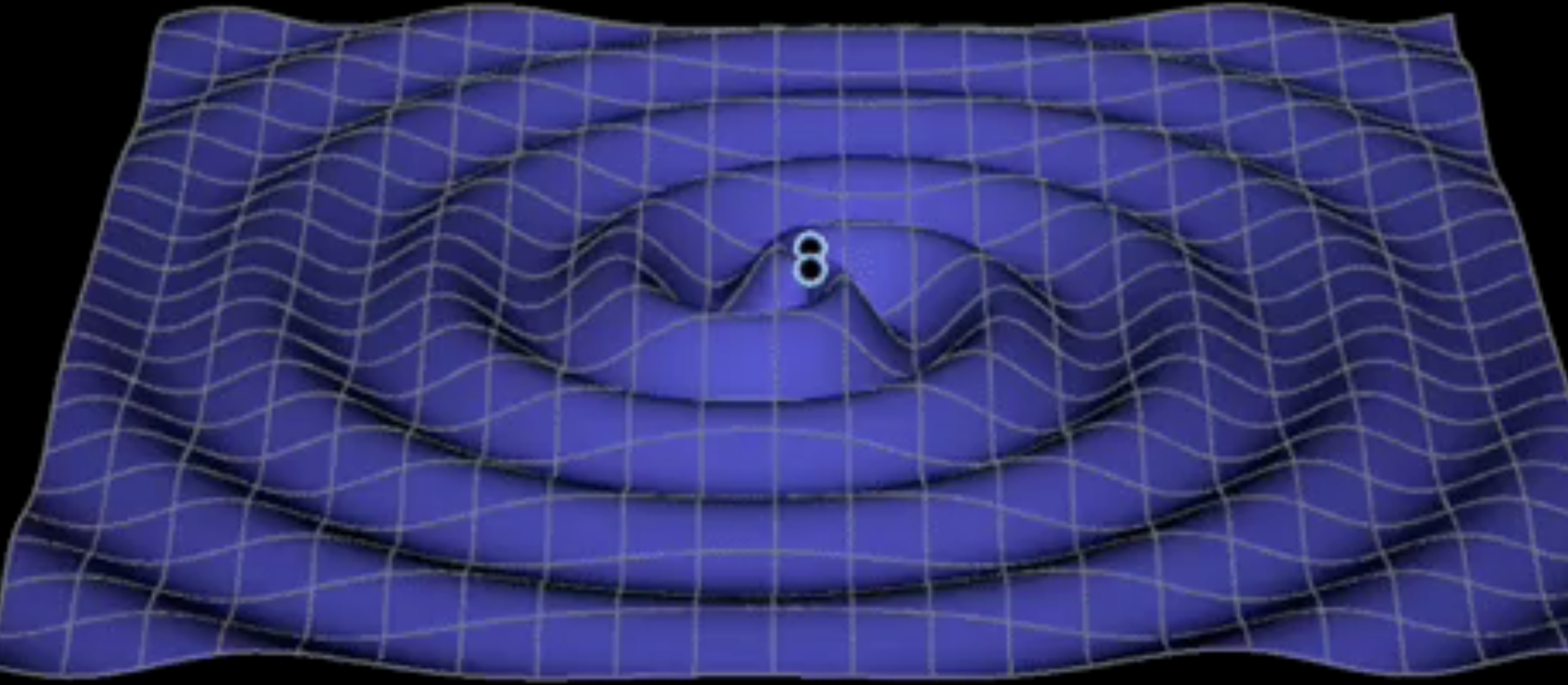
Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

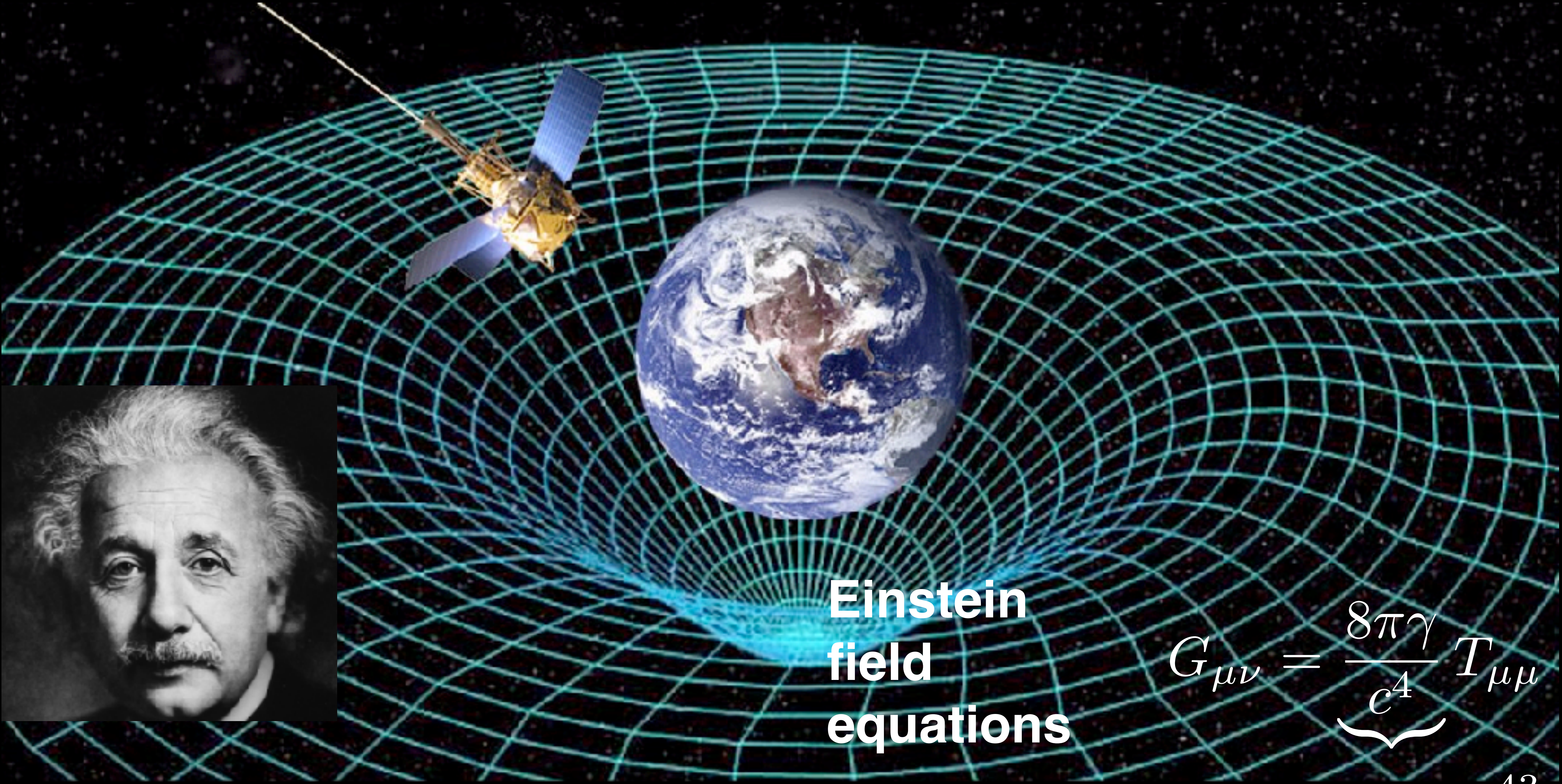


Plot by Tarek Saab, UFL

Gravitational Waves



General Relativity



Einstein field equations

$$G_{\mu\nu} = \underbrace{\frac{8\pi\gamma}{c^4}}_{\approx 10^{-43}} T_{\mu\mu}$$

Albert Einstein
1879 - 1955

GWs in linear gravity

- We consider weak gravitational fields:

$$g_{\mu\nu} \approx \underset{\substack{\uparrow \\ \text{flat Minkowski metric}}}{\eta_{\mu\nu}} + h_{\mu\nu} + \mathcal{O}(h^2_{\mu\nu})$$

- The GR field equations in vacuum reduce to the standard wave equation:

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) h^{\mu\nu} = \Box h^{\mu\nu} = 0$$

- Comment: GR gravity like electromagnetism has a “gauge” freedom associated with the choice of coordinate system. The above equation applies in the so-called “transverse-traceless (TT)” gauge where

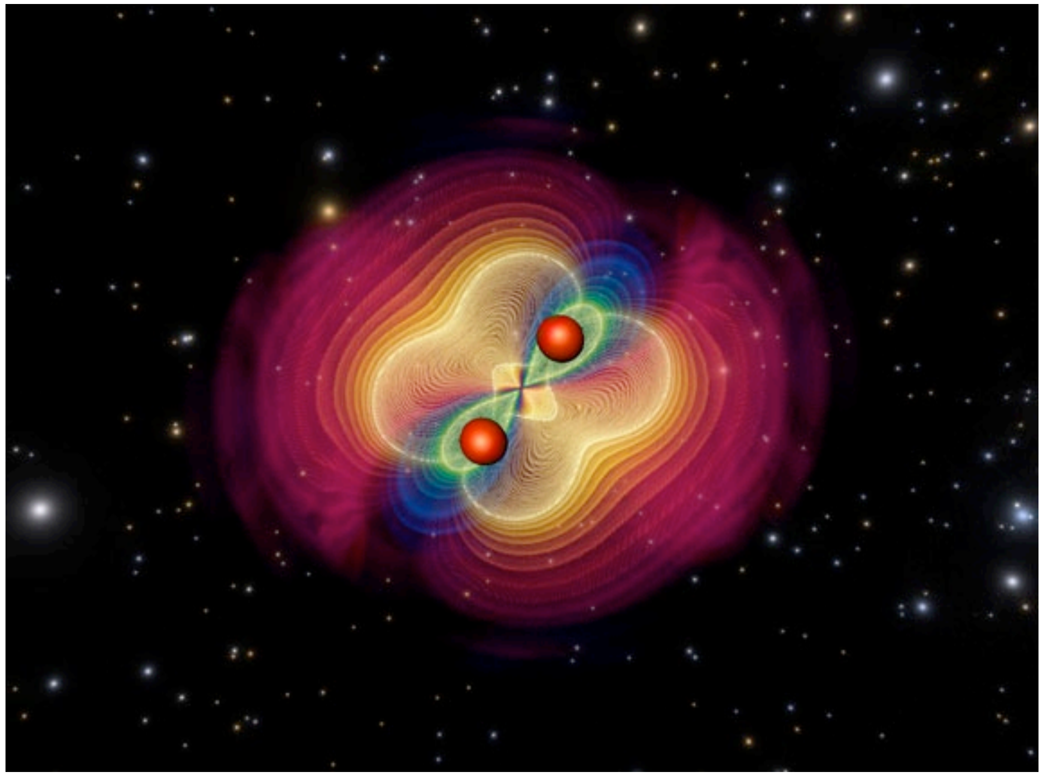
$$h_{0\mu} = 0, \qquad h^{\mu}_{\mu} = 0$$

Newtonian vs General Relativistic gravity

Newtonian field equations	**GR field equations**
$\nabla^2\Phi = 4\,\pi G\rho$	$G^{ab} = \frac{8\pi G}{c^4} T^{ab}$
Source: mass density Gravitational field: scalar Φ	Source: energy-momentum tensor (includes mass densities/currents) Gravitational field: metric tensor g_{ab}

GWs: origins

- Electromagnetism: accelerating charges produce EM radiation.



- Gravitation: accelerating masses produce gravitational radiation.
(another hint: gravity has finite speed.)

GWs in linear gravity

- We consider weak gravitational fields:

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu} + \mathcal{O}(h^2_{\mu\nu})$$

$\uparrow$

flat Minkowski metric

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$$h_{0\mu} = 0, \qquad h^\mu_\mu = 0$$

Wave solutions

- Solving the previous wave equation in weak gravity is easy. The solutions represent “plane waves”:

$$h_{\mu\nu} = A_{\mu\nu} e^{ik_a x^a}$$

wave-vector

- Basic properties: $A_{\mu\nu} k^\mu = 0, \qquad k_a k^a = 0$

transverse waves

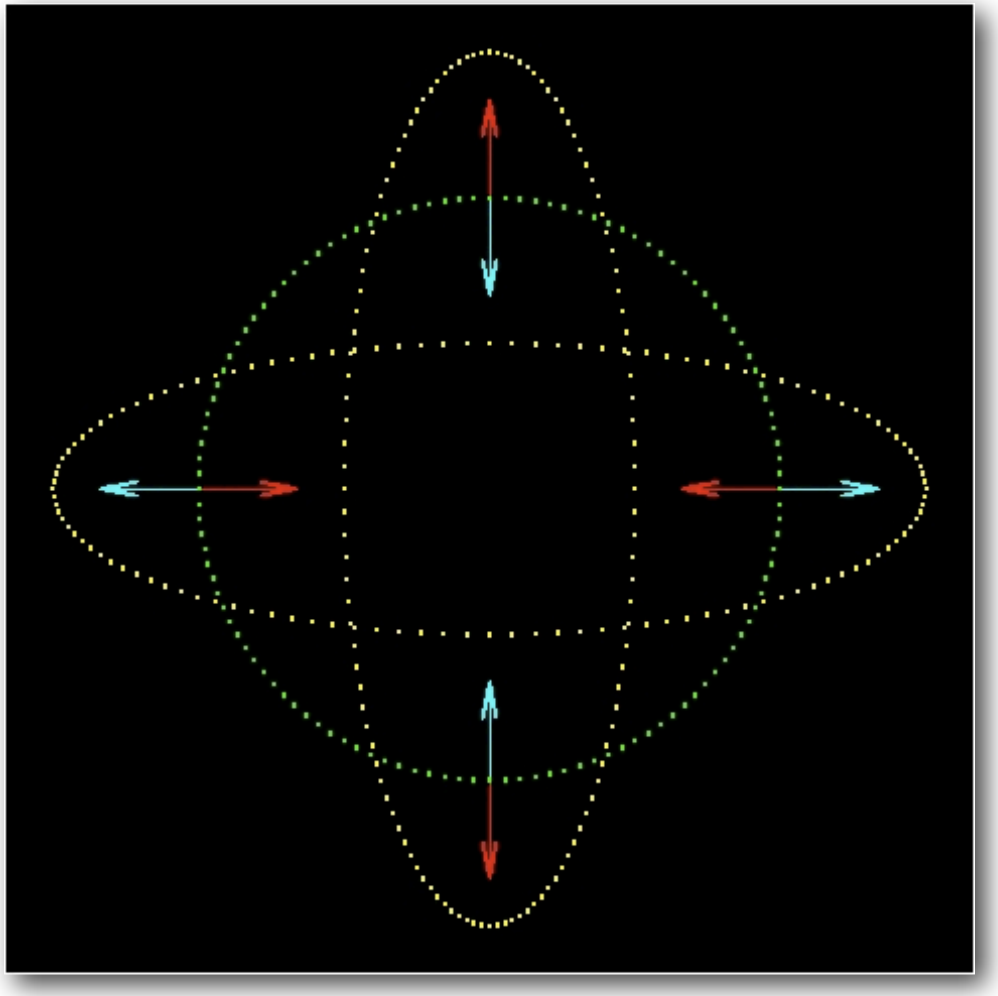
null vector = propagation along light rays

- Amplitude: $A^{\mu\nu} = h_+ e_+^{\mu\nu} + h_{\mathrm{x}} e_{\mathrm{x}}^{\mu\nu}$

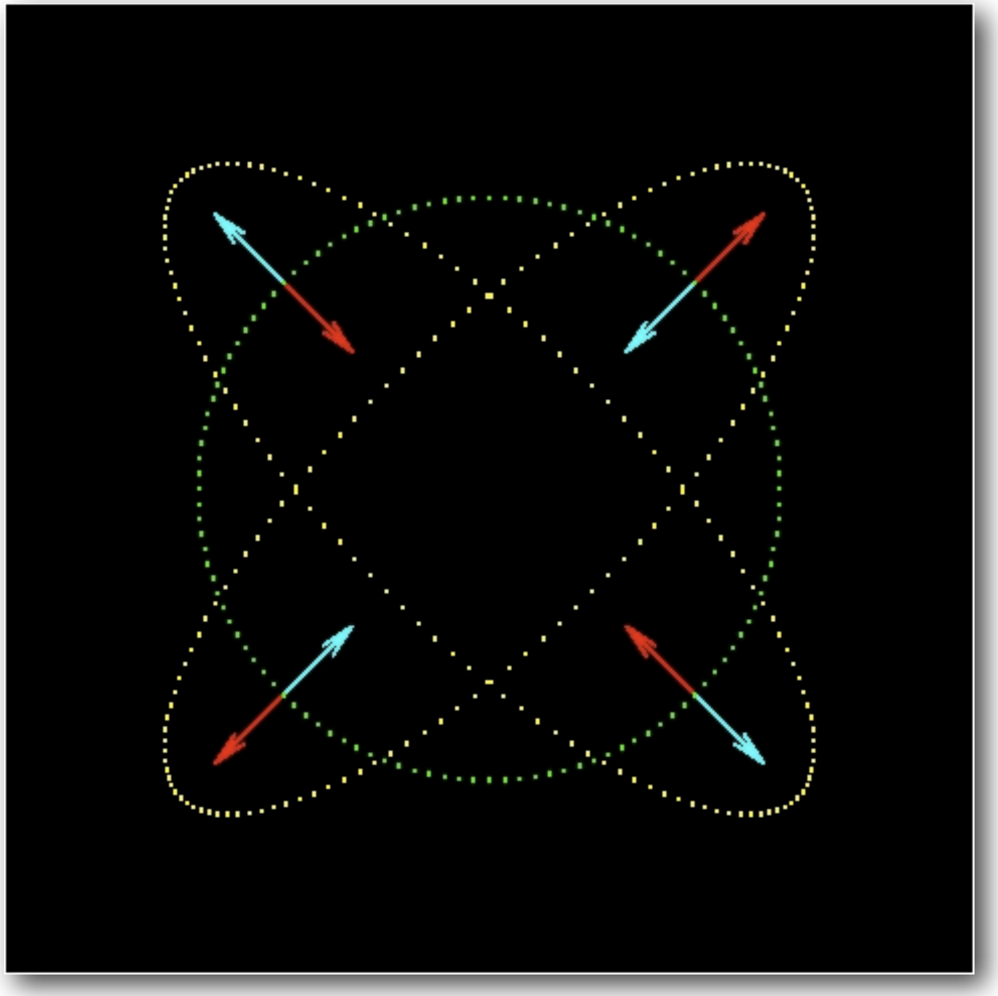
two polarizations

GWs: polarization

- GWs come in two polarizations:



“+” polarization



“x” polarization

GWs vs EM waves

- Similarities:

✓ Propagation with the speed of light.

✓ Amplitude decreases as ~ 1/r.

✓ Frequency redshift (Doppler, gravitational, cosmological).

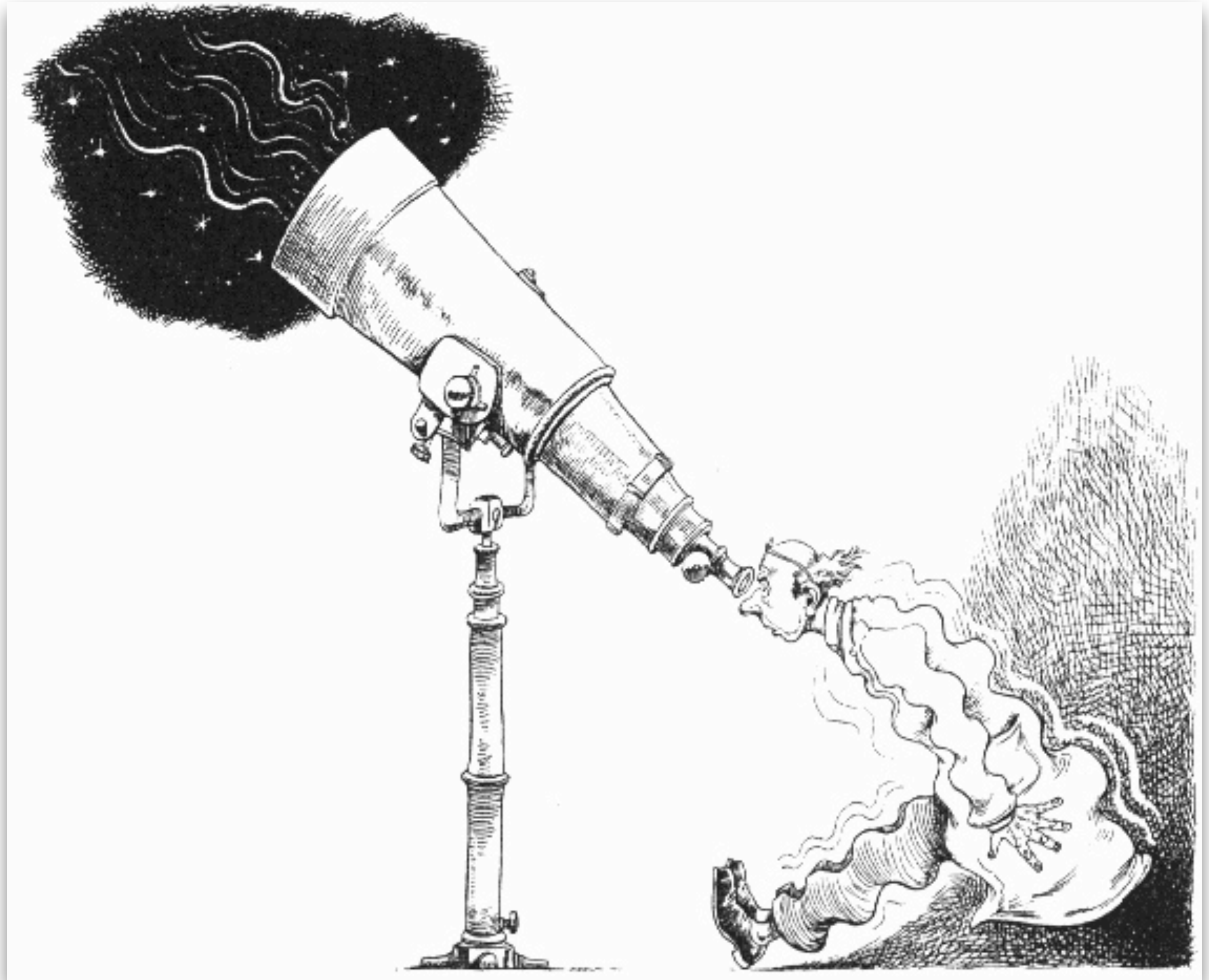
- Differences:

✓ GWs propagate through matter with little interaction. Hard to detect, but they carry uncontaminated information about their sources.

✓ Strong GWs are generated by bulk (coherent) motion. They require strong gravity/high velocities (compact objects like black holes and neutron star).

✓ EM waves originate from small-scale, incoherent motion of charged particles. They are subject to "environmental" contamination (interstellar absorption etc.).

Detection of GWs

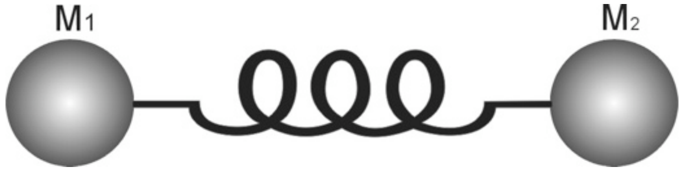


GW detectors: prehistory

- For decades after the formulation of Einstein's GR the notion of GWs was a topic for speculations and remote from real astrophysics.
- Joe Weber pioneered the construction of the first "primitive" bar detector. However, his claims of a GW detection were never verified ...
- Theoretical work in the 1970s-1990s (and the discovery of the Hulse-Taylor pulsar) advanced the popularity of GWs.
- GW astronomy is expected to become reality in the present decade.

A toy model GW detector

- Consider a GW propagating along the z-axis (with a "+" polarization and frequency ω), impinging on an idealized detector consisting of two masses joined by a spring (of length L) along the x-axis



- The resulting motion is that of a forced oscillator (with friction τ, natural frequency ω_0):

$$\ddot{\xi} + \dot{\xi}/\tau + \omega_0^2 \xi = -\frac{1}{2}\omega^2 L h_+ e^{i\omega t}$$

- The solution is:

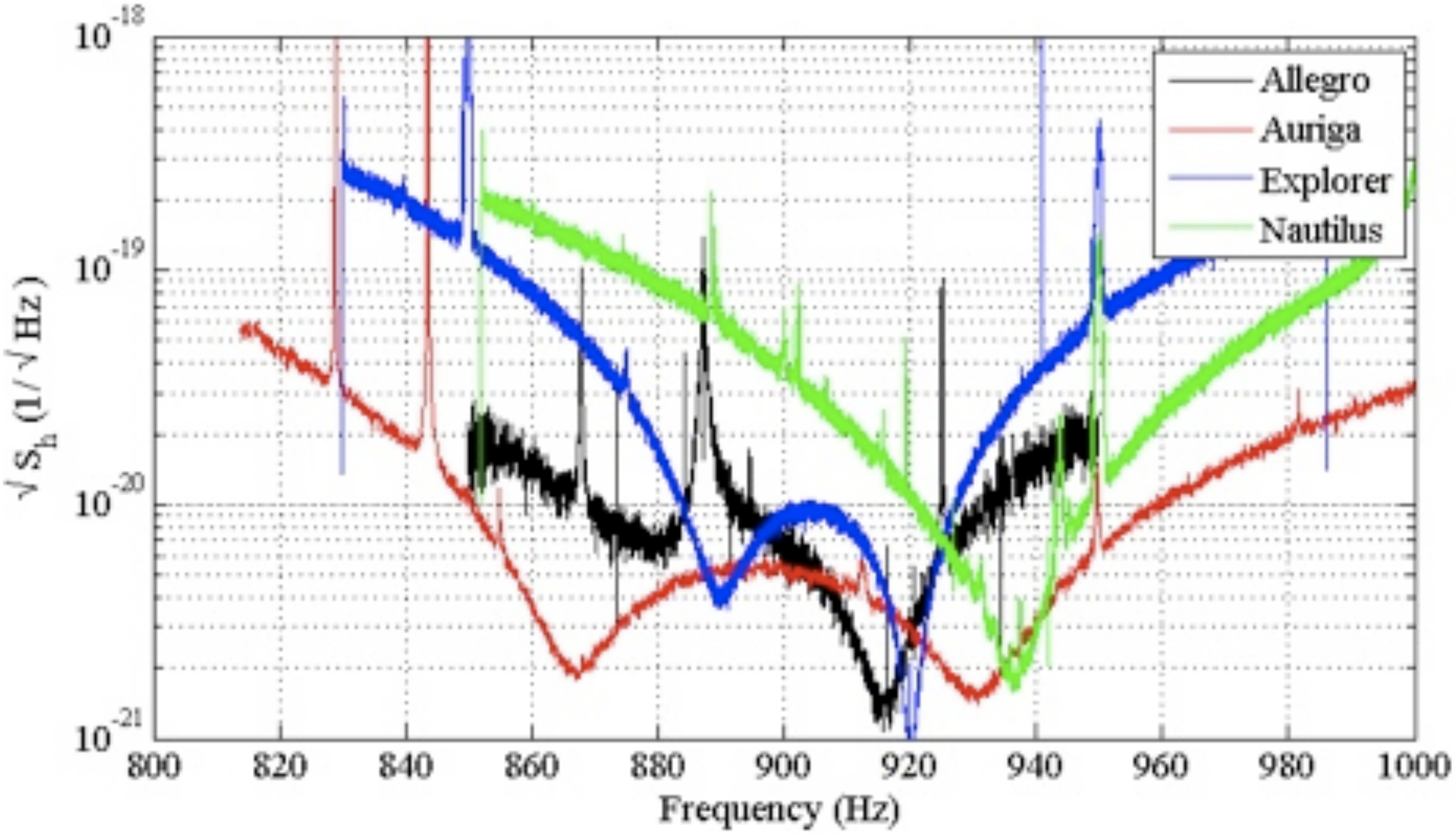
$$\xi = \frac{\omega^2 L h_+}{2(\omega_0^2 - \omega^2 + i\omega/\tau)} e^{i\omega t}$$

- The maximum amplitude is achieved at $\omega \approx \omega_0$ and has a size: $\xi_{\max} = \frac{1}{2}\omega_0 \tau L h_+$

- The detector can be optimized by increasing $\omega_0 \tau L$.

Bar detectors

- Bar detectors are narrow bandwidth instruments (like the previous toy-model)

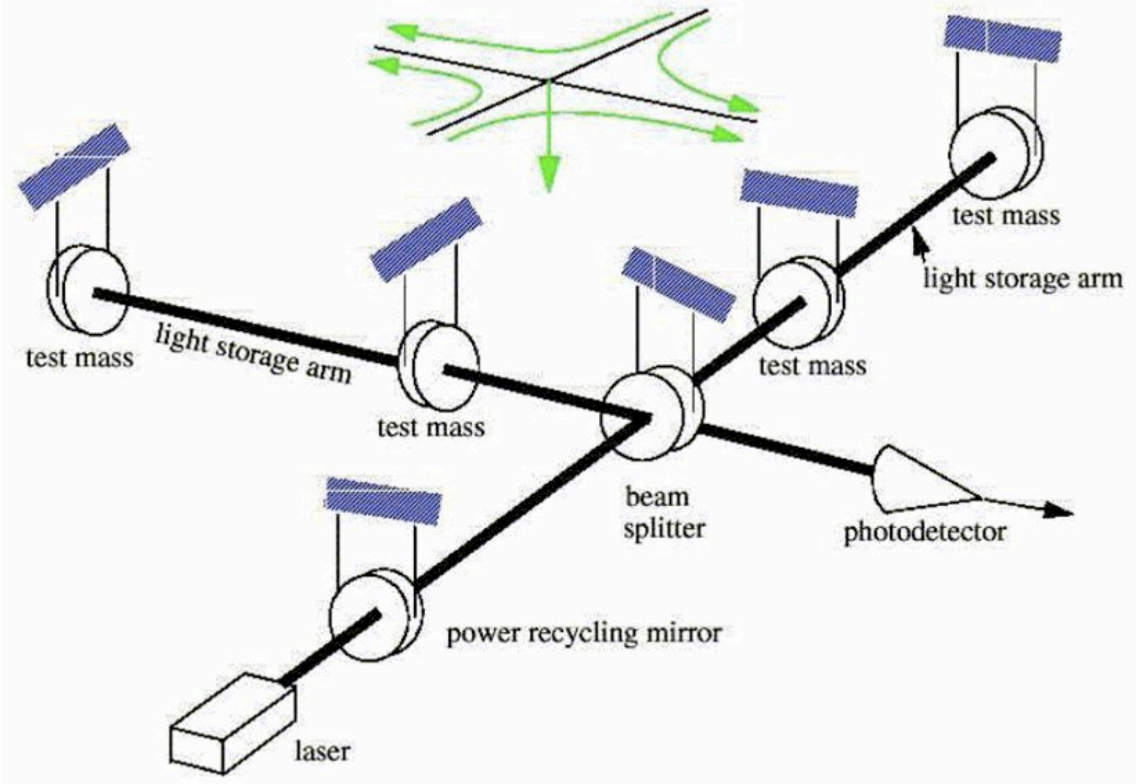


Sensitivity curves of various bar detectors

Detectors: laser interferometry

- A laser interferometer is an alternative choice for GW detection, offering a combination of very high sensitivities over a broad frequency band.

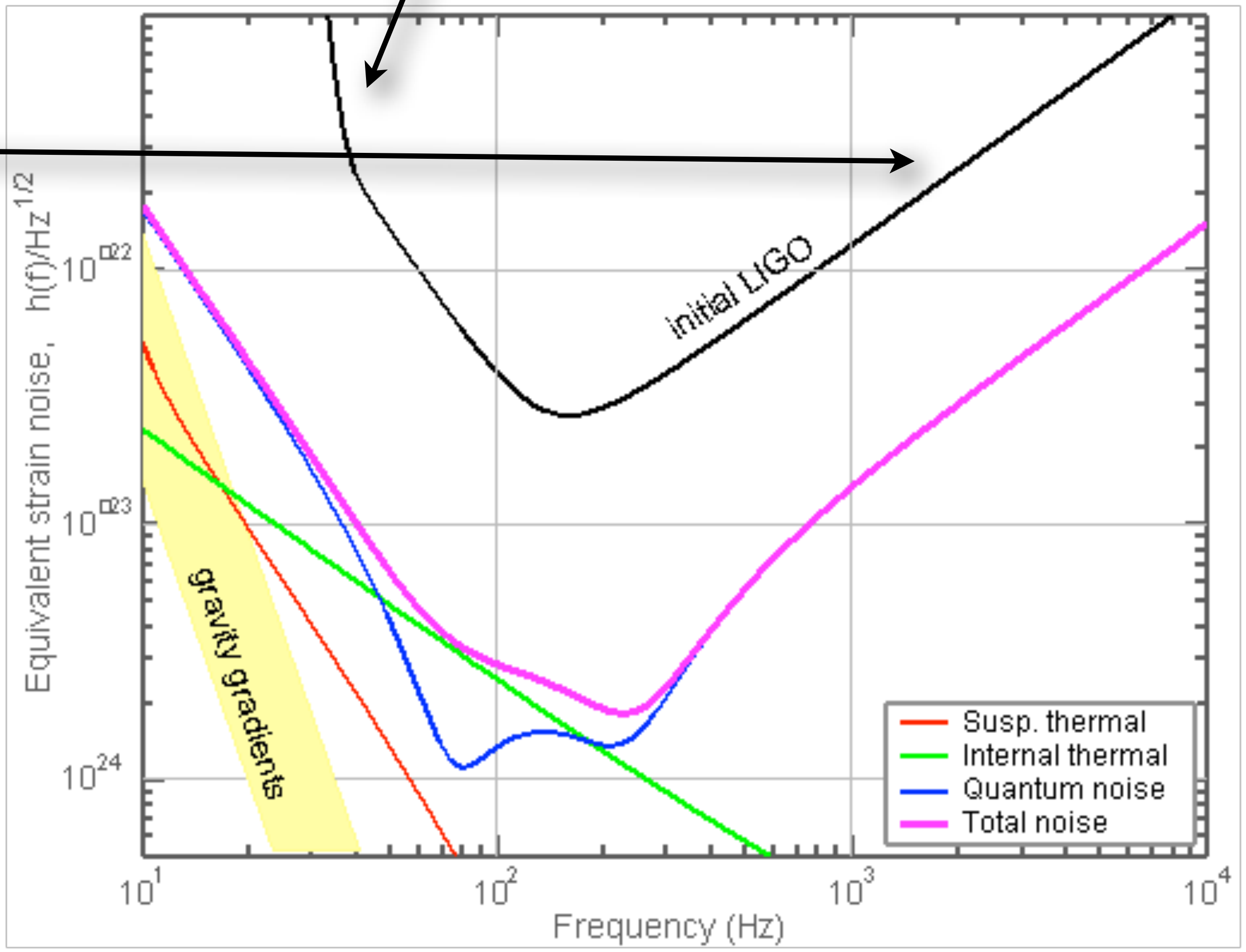
- Suspended mirrors play the role of “test-particles”, placed in perpendicular directions. The light is reflected on the mirrors and returns back to the beam splitter and then to a photodetector where the fringe pattern is monitored.



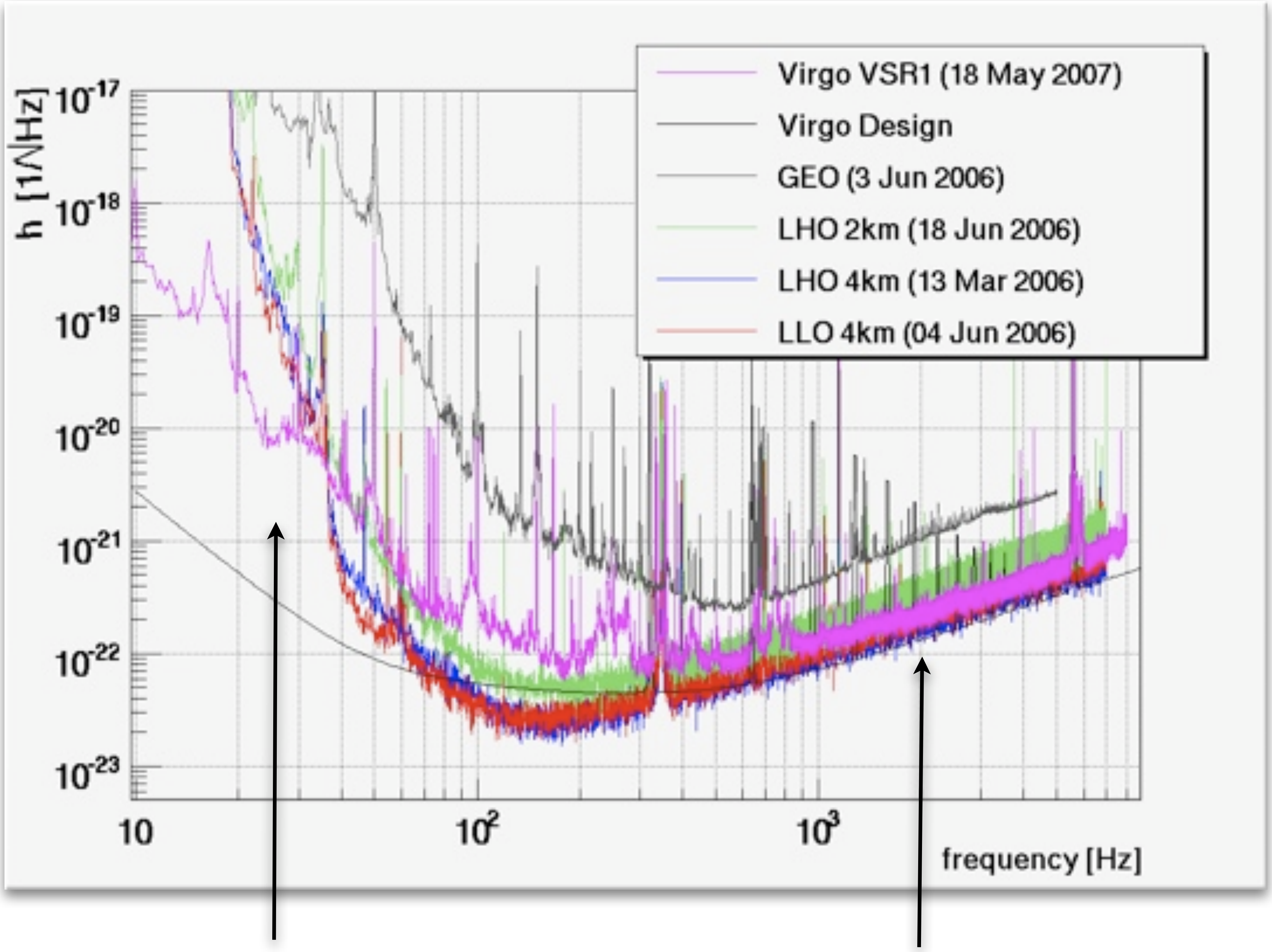
Noise in interferometric detectors

- Seismic noise (low frequencies). At frequencies below 60 Hz, the noise in the interferometers is dominated by seismic noise. The vibrations of the ground couple to the mirrors via the wire suspensions which support them. This effect is strongly suppressed by properly designed suspension systems. Still, seismic noise is very difficult to eliminate at frequencies below 5-10 Hz.

- Photon shot noise (high frequencies). The precision of the measurements is restricted by fluctuations in the fringe pattern due to fluctuations in the number of detected photons. The number of detected photons is proportional to the intensity of the laser beam. Statistical fluctuations in the number of detected photons imply an uncertainty in the measurement of the arm length.



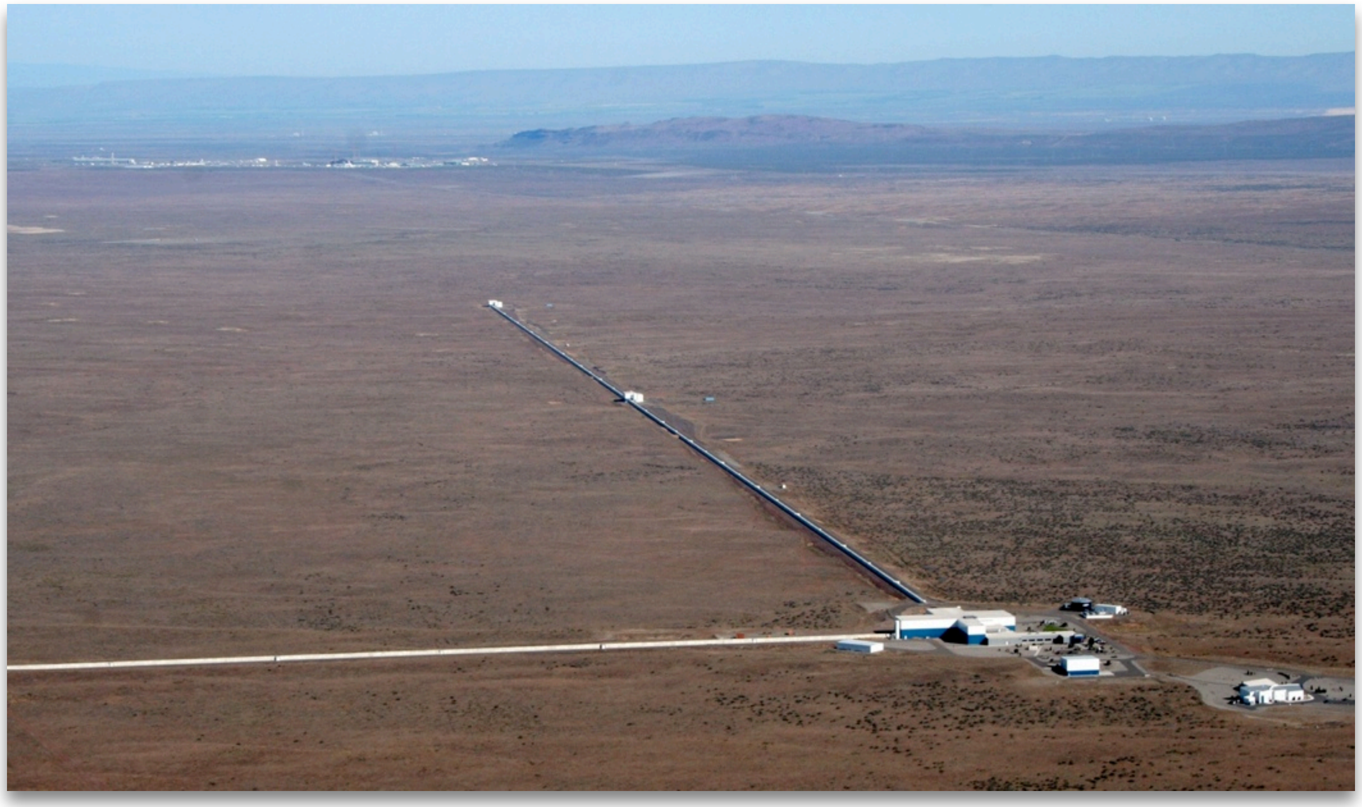
Detectors: real-life sensitivity



Seismic noise

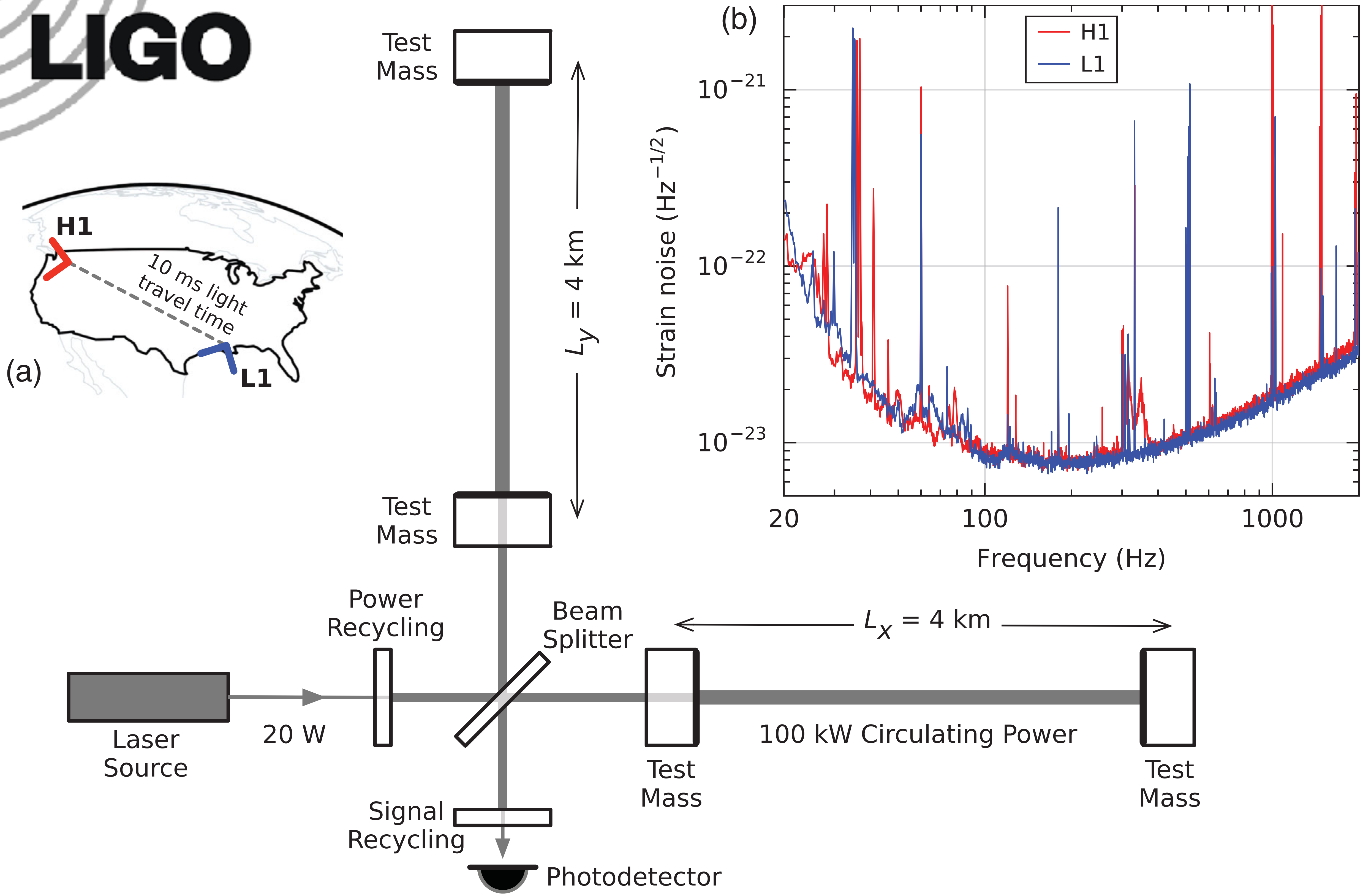
laser photon noise

Detectors: the present (I)



The twin LIGO detectors (L = 4 km) at Livingston Louisiana and Hanford Washington (US).

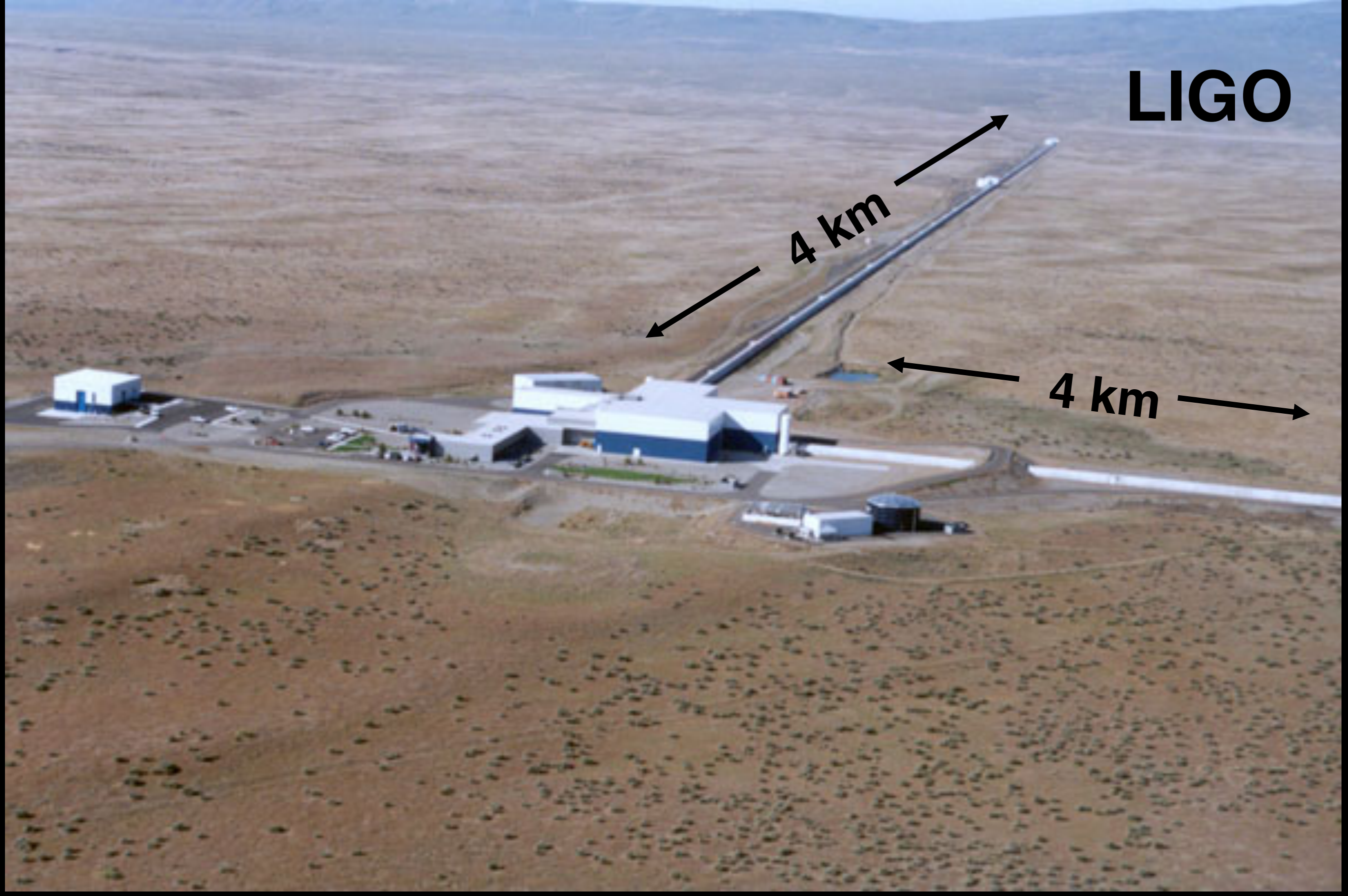
LIGO


(a)
H1
10 ms light travel time
L1
Test Mass
L_y = 4 km
Test Mass
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)

Detectors: the present (II)

The VIRGO detector (L= 3 km) near Pisa, Italy

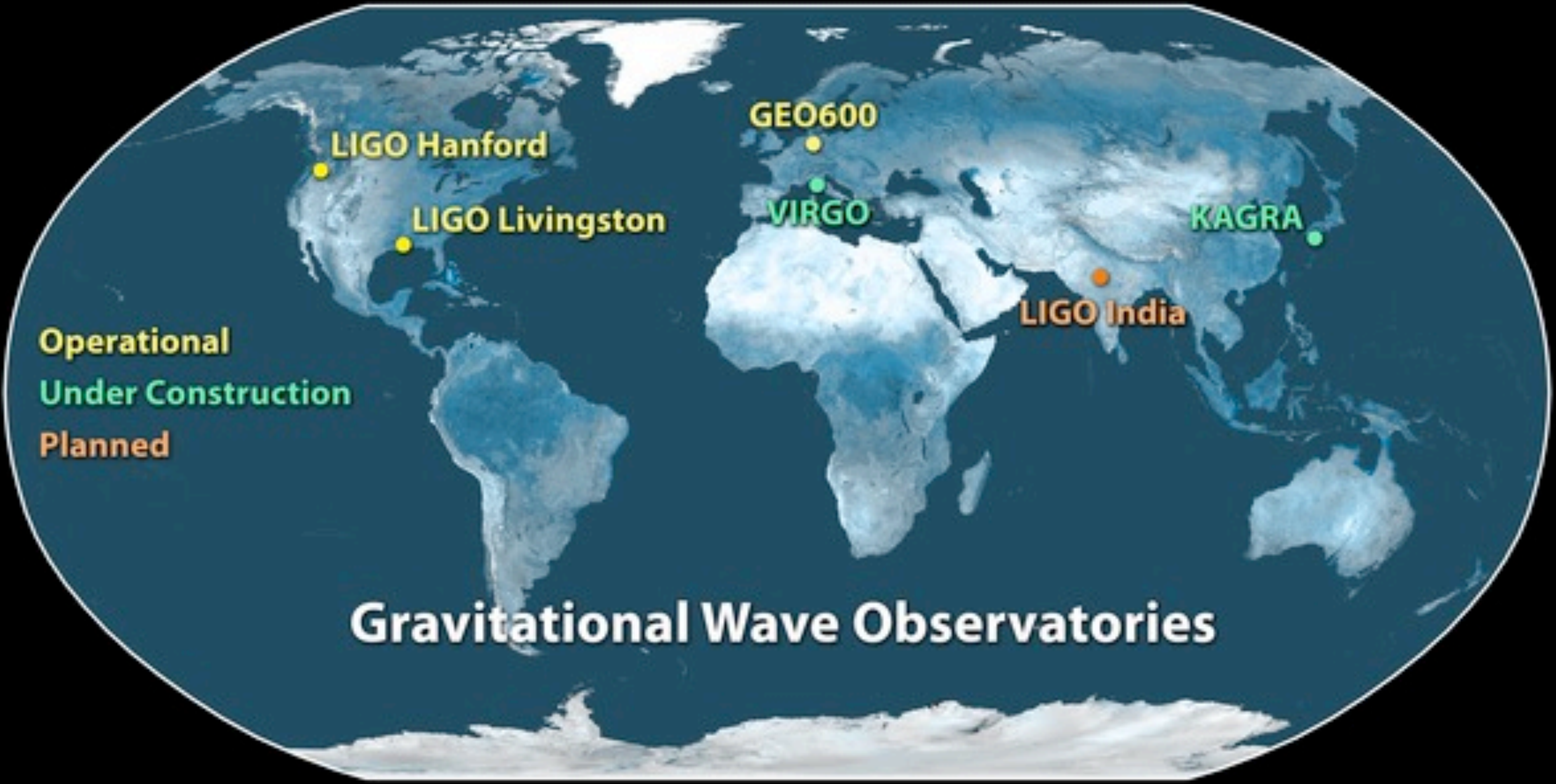

VIRGO
GEO 600

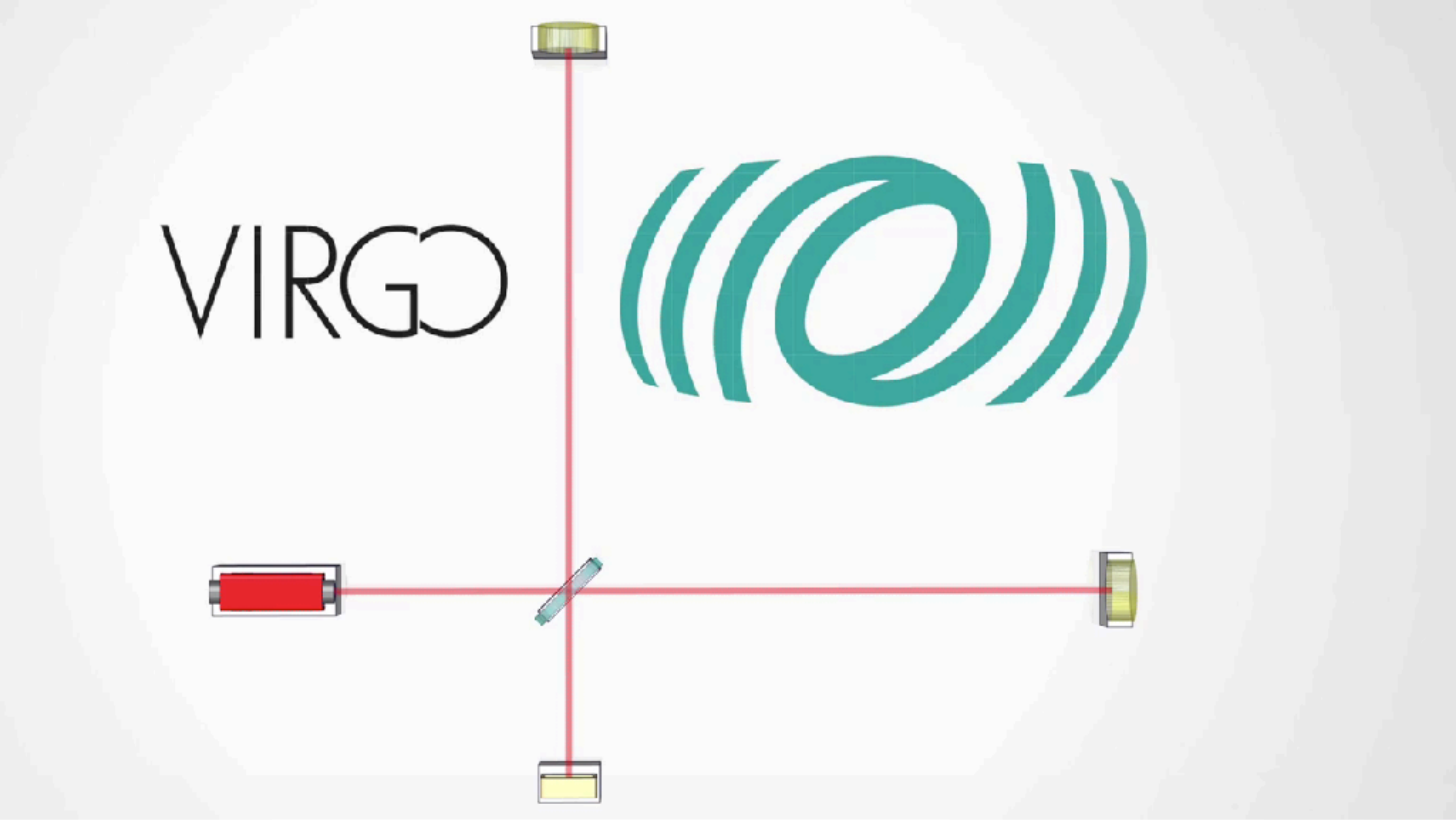

LIGO
4 km
4 km


LIGO

LIGO Livingston, Louisiana

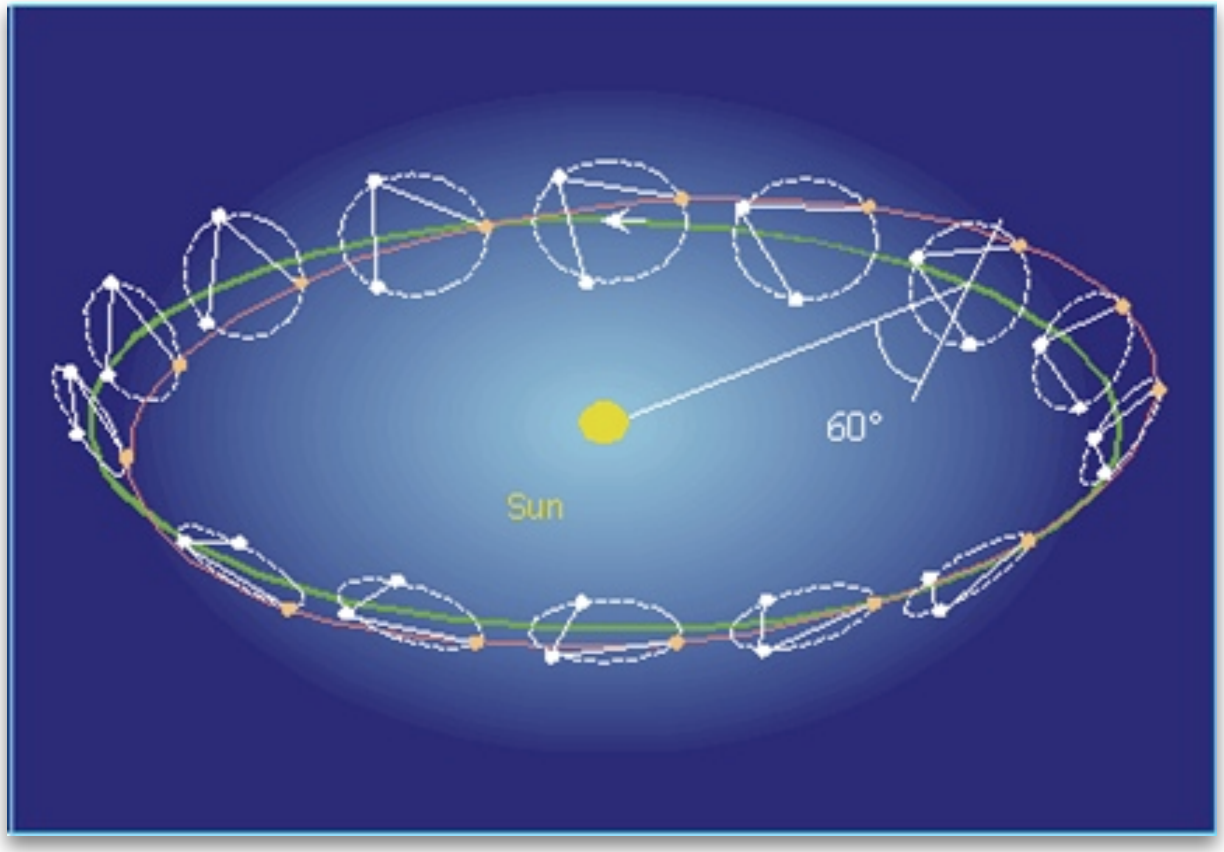
LIGO Livingston, Louisiana

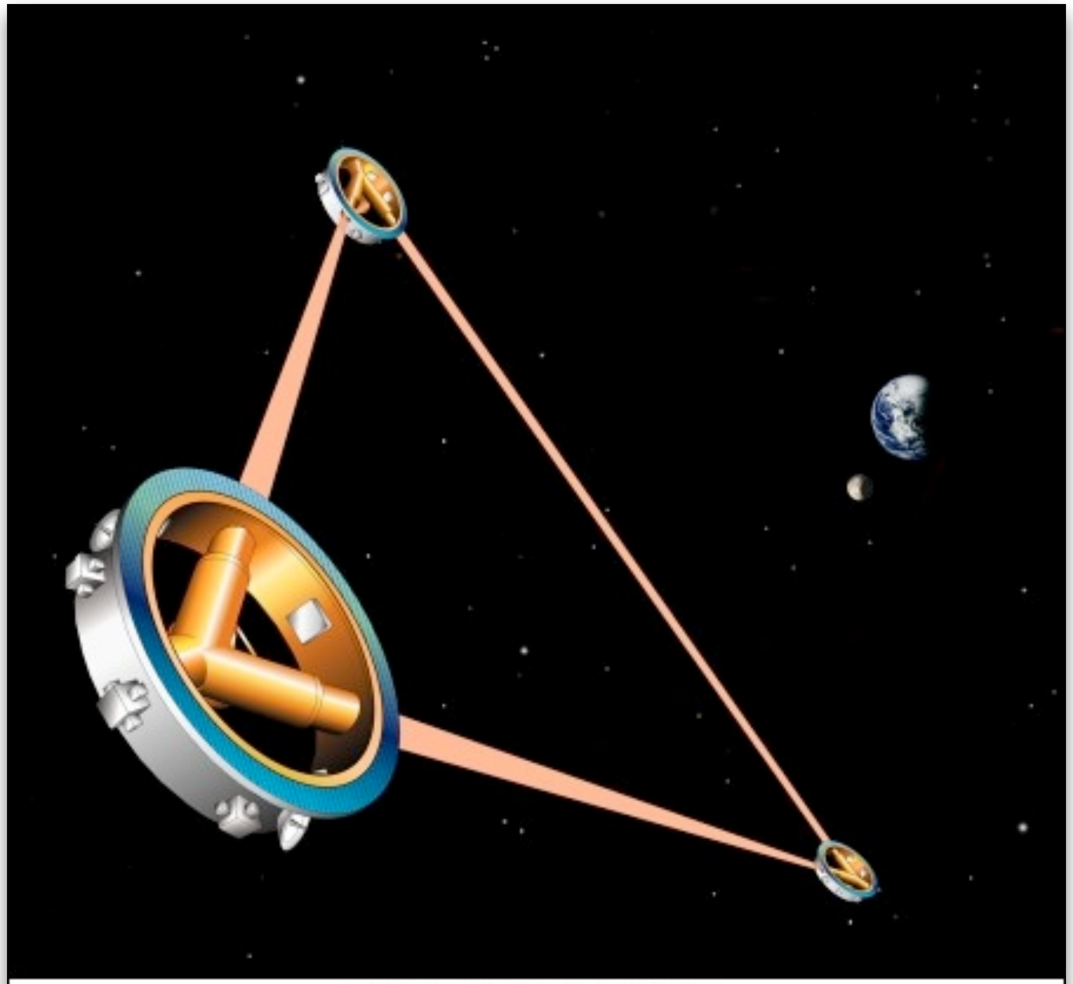

GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories


VIRGO

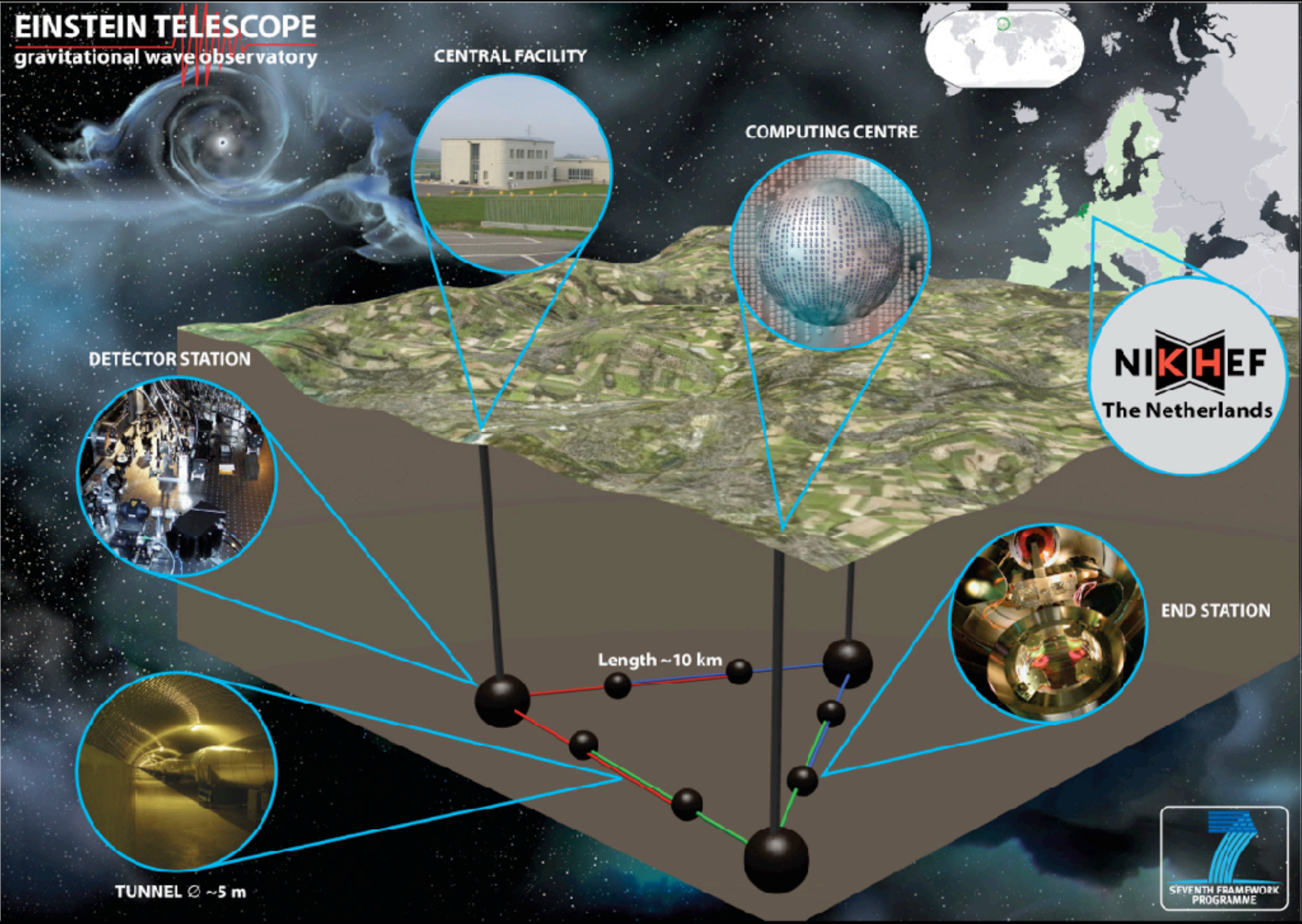
Going to space: the LISA detector

- Space-based detectors: “noise-free” environment, abundance of space!
- Long-arm baseline, low frequency sensitivity
- LISA: Up until recently a joint NASA/ESA mission, now an ESA mission only. To be launched around 2020.





LISA (NASA-ESA)


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
NIKHEF
The Netherlands
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

GWs detectors: ground and space