Multimessenger astronomy

Sergey Troitsky
(INR RAS & MSU Phys. Dept.)

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Cosmic messengers = carriers of information about astro objects and media

- Photons
  - all “conventional” astronomy goes here
- Neutrinos
- Gravitational waves
- Cosmic rays
  - all not included above goes here

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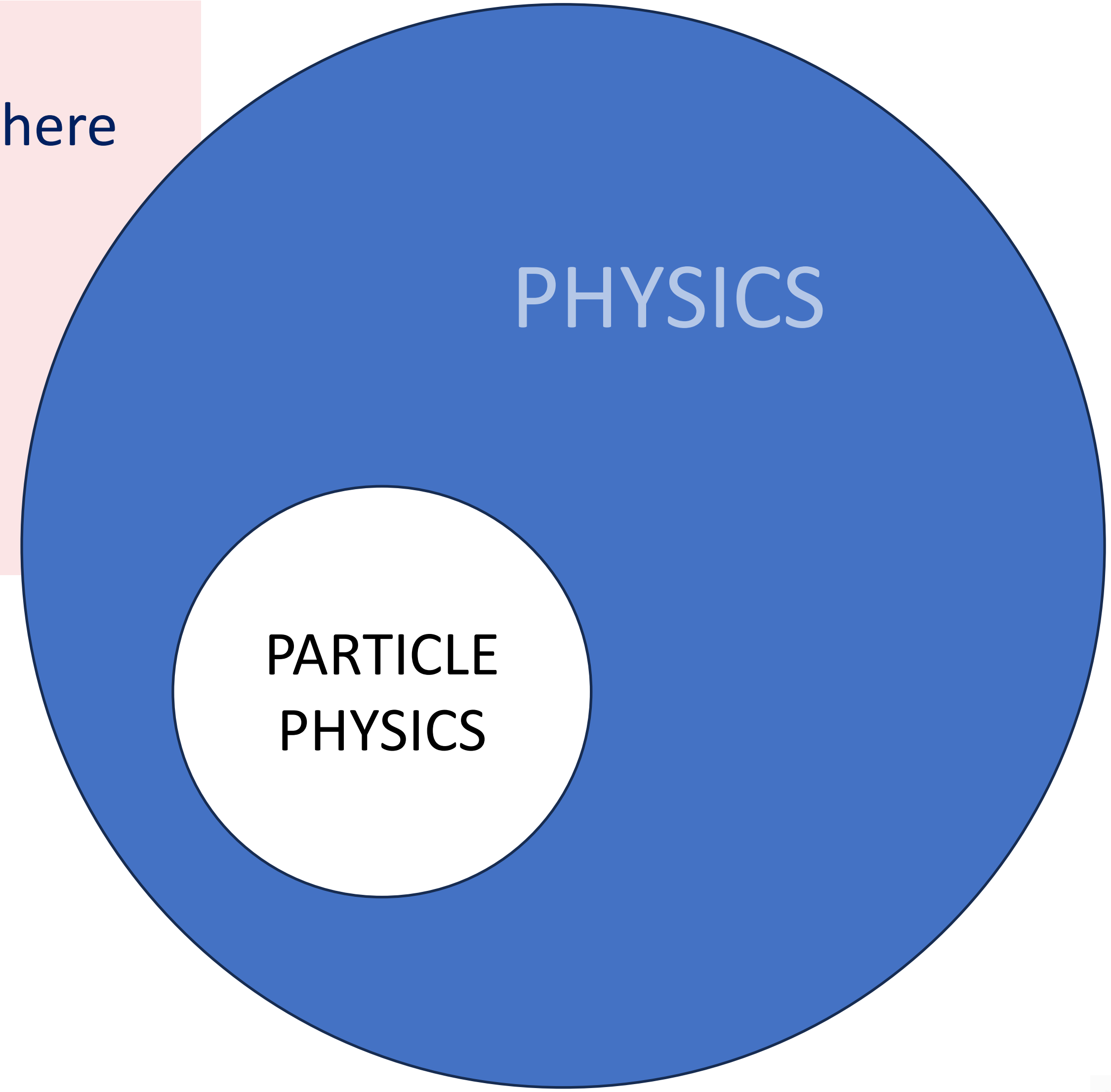

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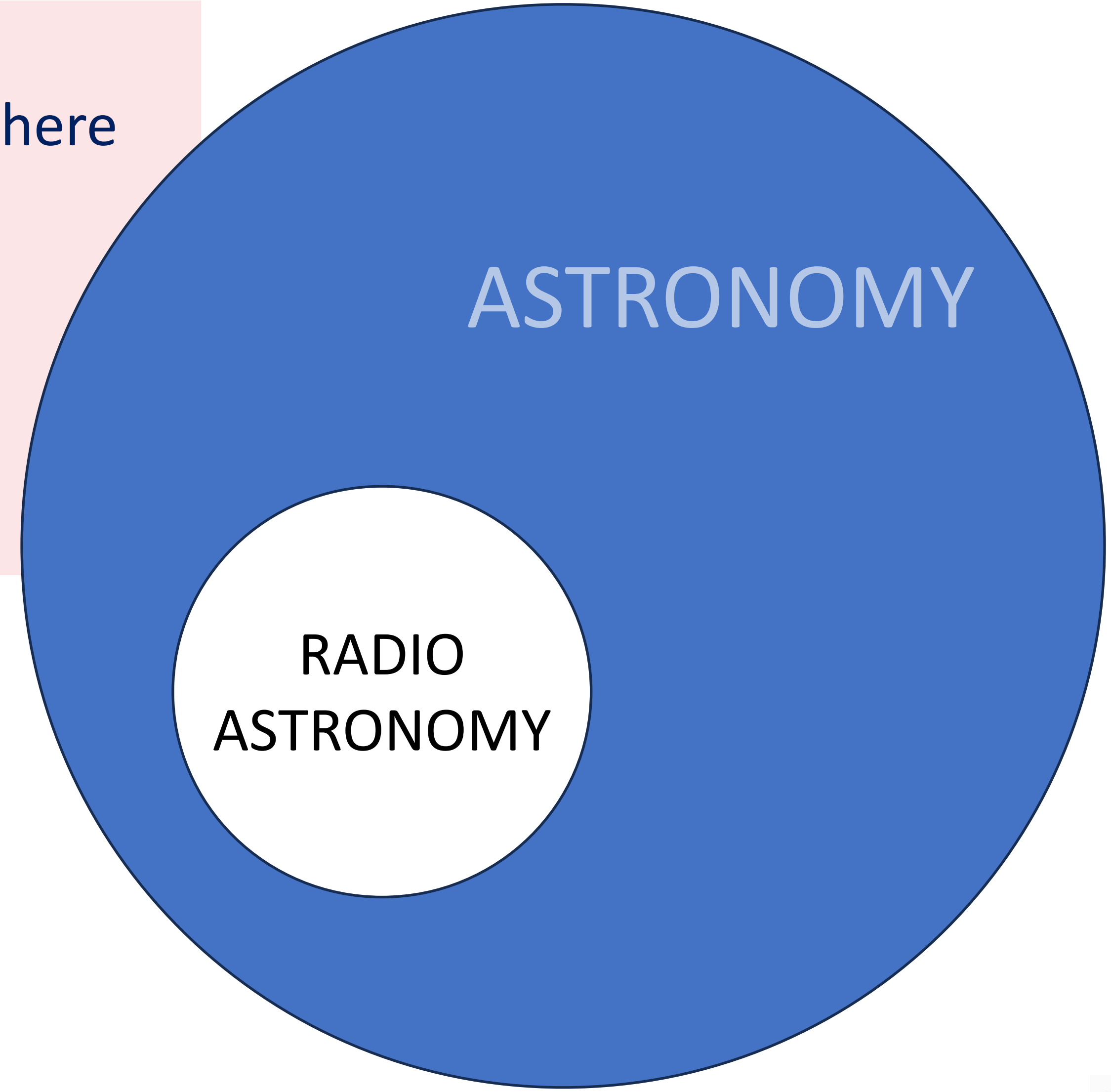

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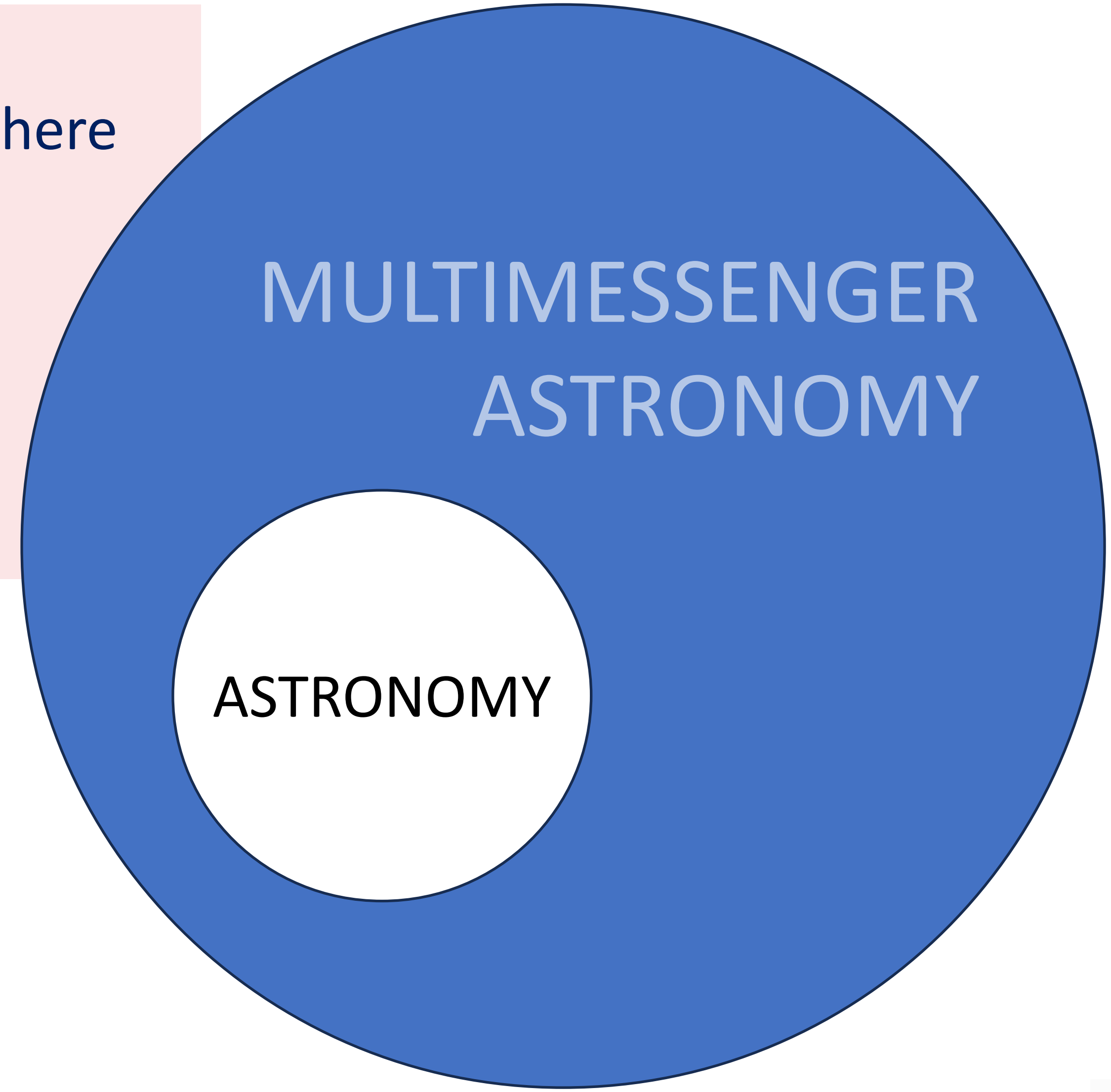
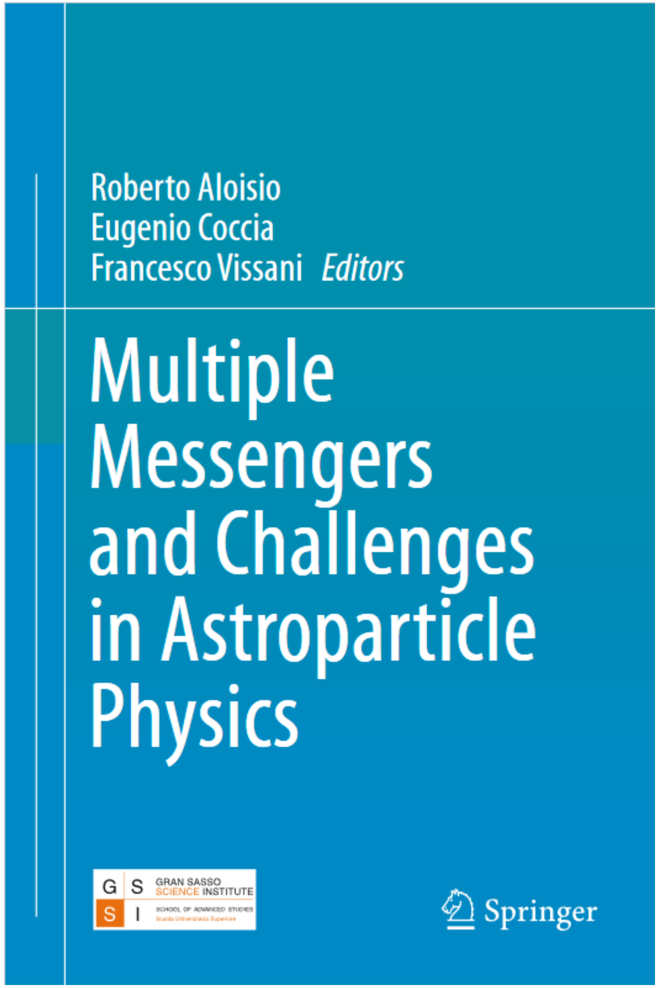


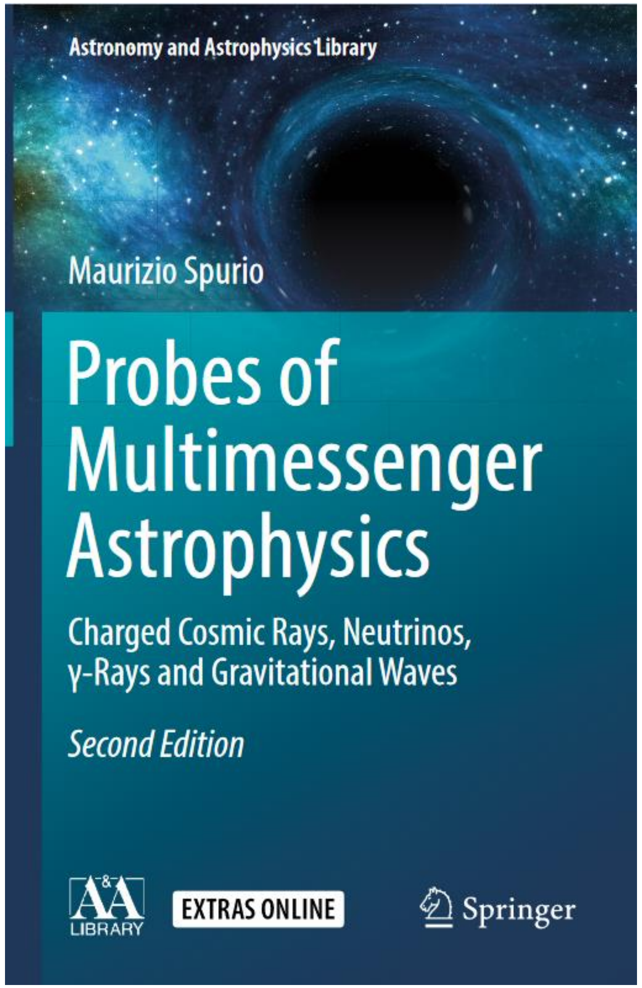
Multimessenger astronomy: more than astronomy

- Not a direct sum of messengers
  - ➢ advantages of combined analyses

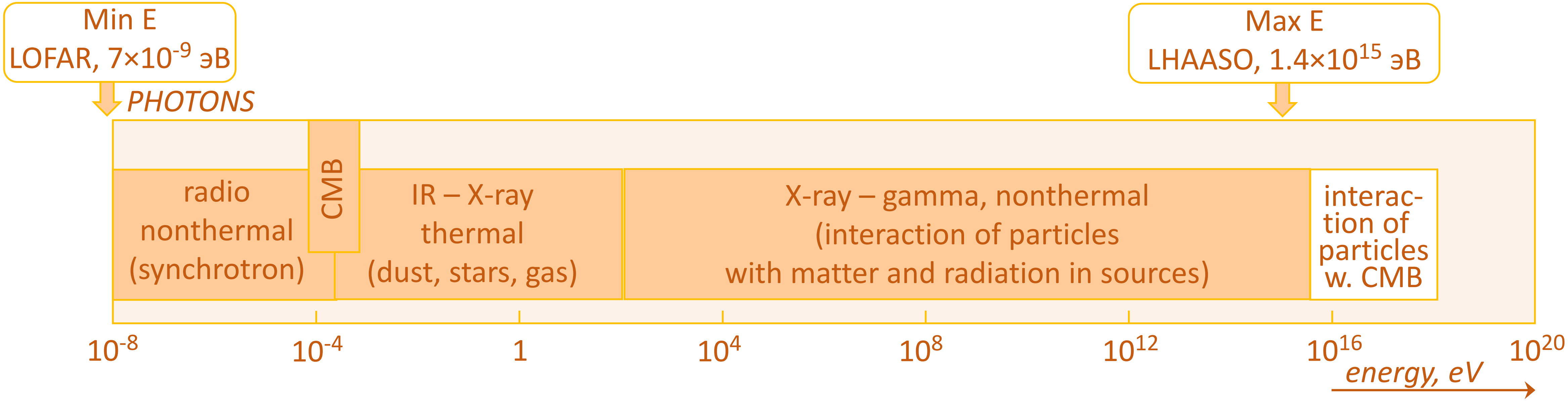
- Important implications for fundamental physics
  - ➢ the Universe as a laboratory…

Multimessenger astronomy: not in one lecture...



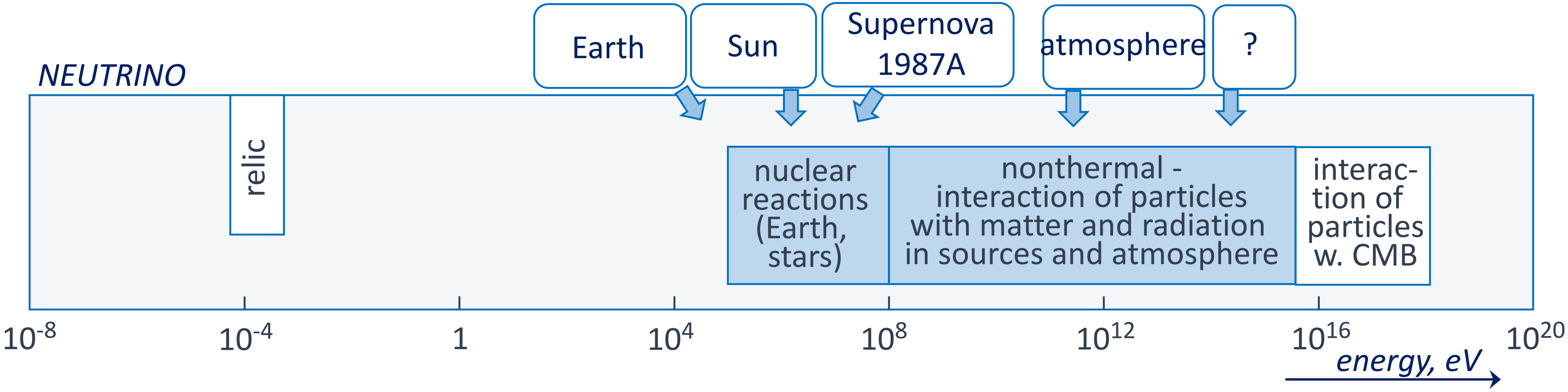


Cosmic messengers: photons



This is the standard astronomy. But highest-energy photons are different.

Cosmic messengers: neutrinos



Neutrinos are very different from photons. Many lectures about them here...

Cosmic messengers: gravitational waves

electromagnetic field:

$$\partial_\mu F^{\mu\nu} = j^\nu$$

Maxwell equations

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

they are **linear**!

solution = plane waves

$$A_\mu(x) = A^0_\mu \mathrm{e}^{[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]}$$

gravitational field:

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein equations

they are **nonlinear**!

linearize: $g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x), \quad |h_{\mu\nu}(x)| \ll 1$

$$\Box h_{\mu\nu}(x) = -16\pi G S_{\mu\nu}(x),$$

$$S_{\mu\nu}(x) \equiv T_{\mu\nu}(x) - \frac{1}{2}\eta_{\mu\nu} T^\lambda{}_\lambda(x).$$

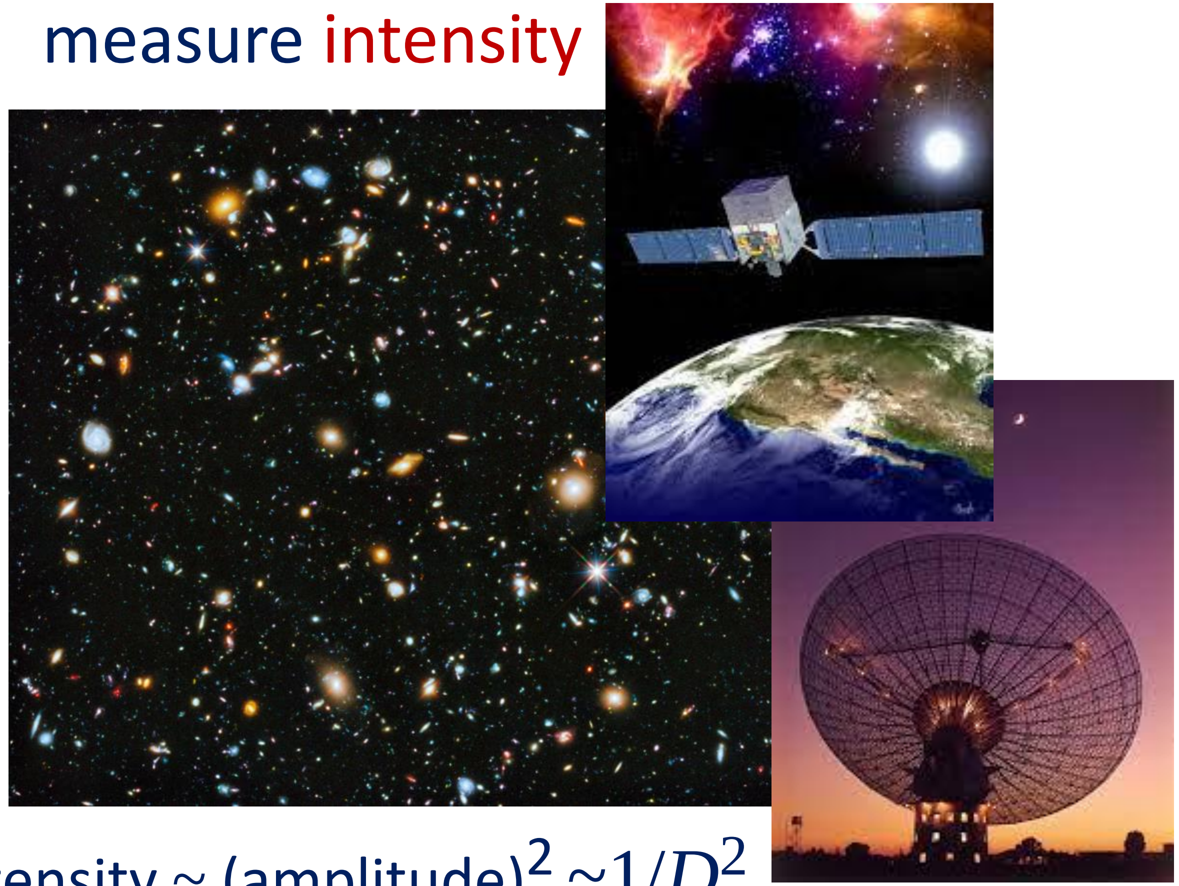
solution = plane waves

$$h_{\mu\nu}(\mathbf{x}) = h^0_{\mu\nu} e^{[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]}$$

Cosmic messengers: gravitational waves

- electromagnetic waves:

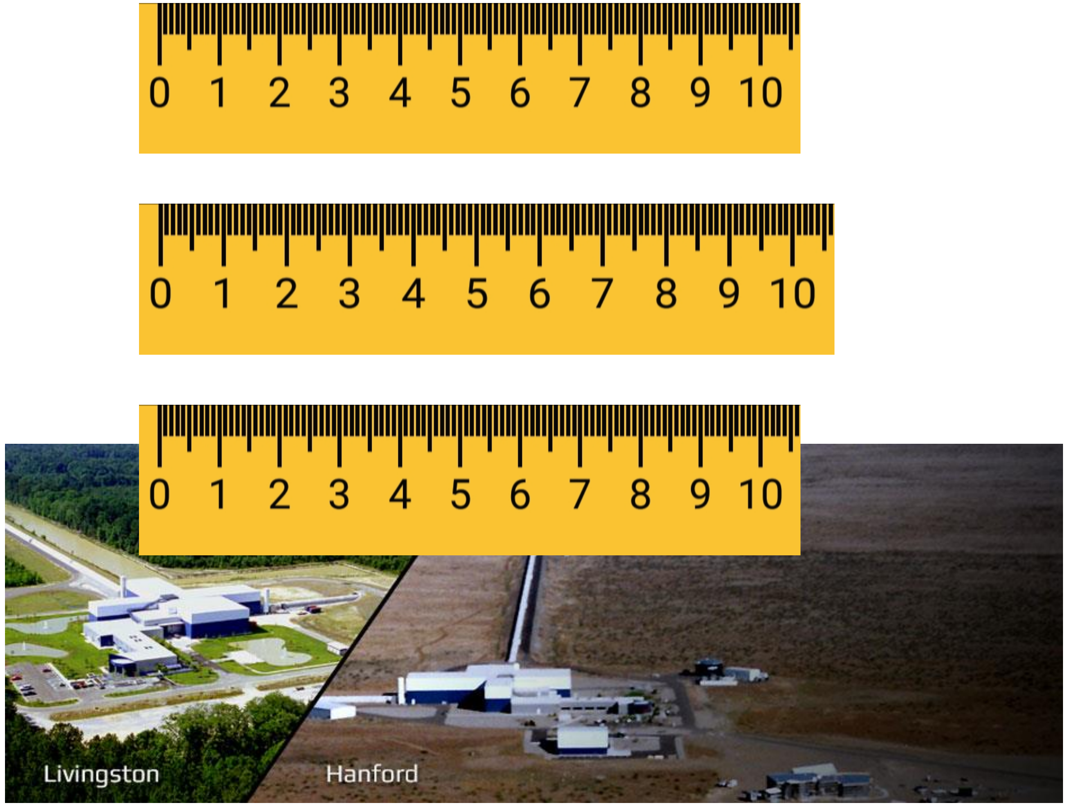
measure intensity



intensity ~ (amplitude)^2 $\sim 1/D^2$

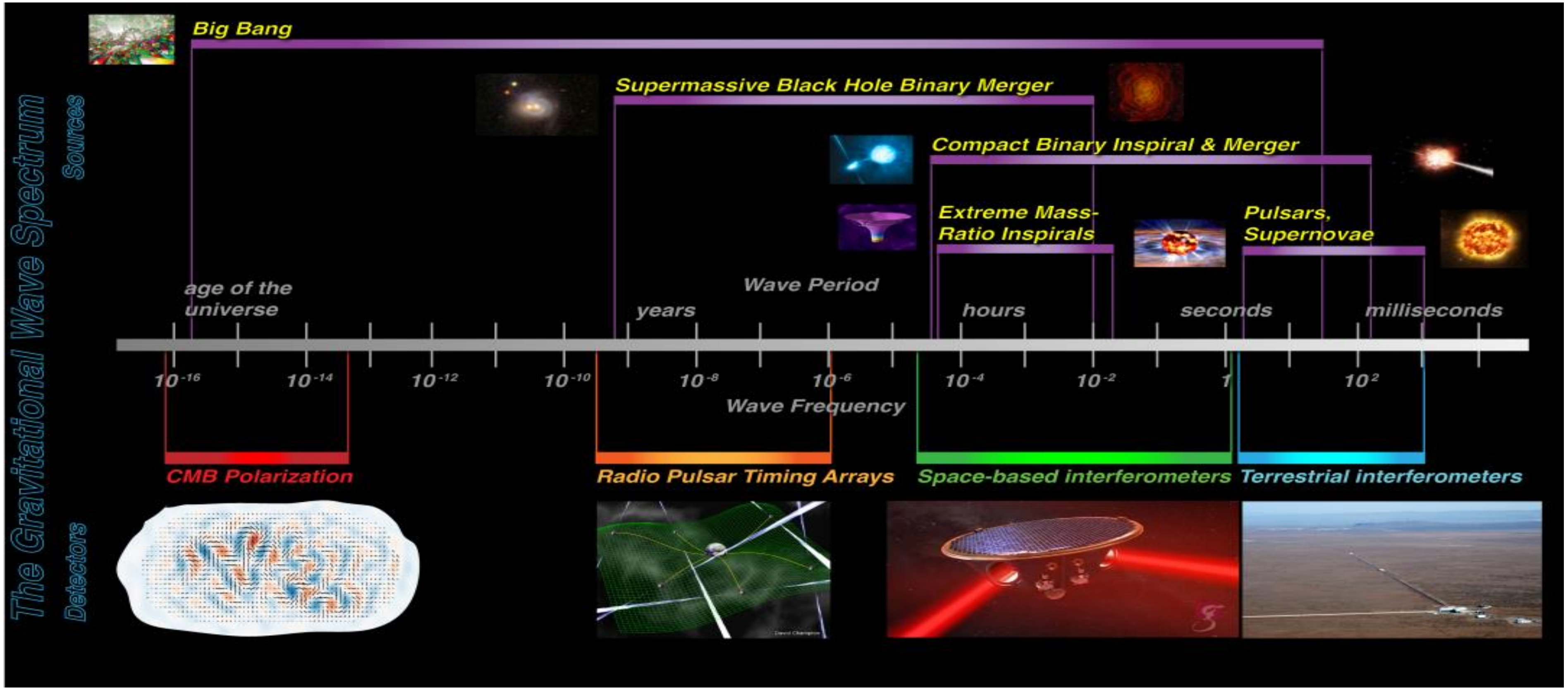
- gravitational waves:

measure amplitude



amplitude $\sim 1/D$

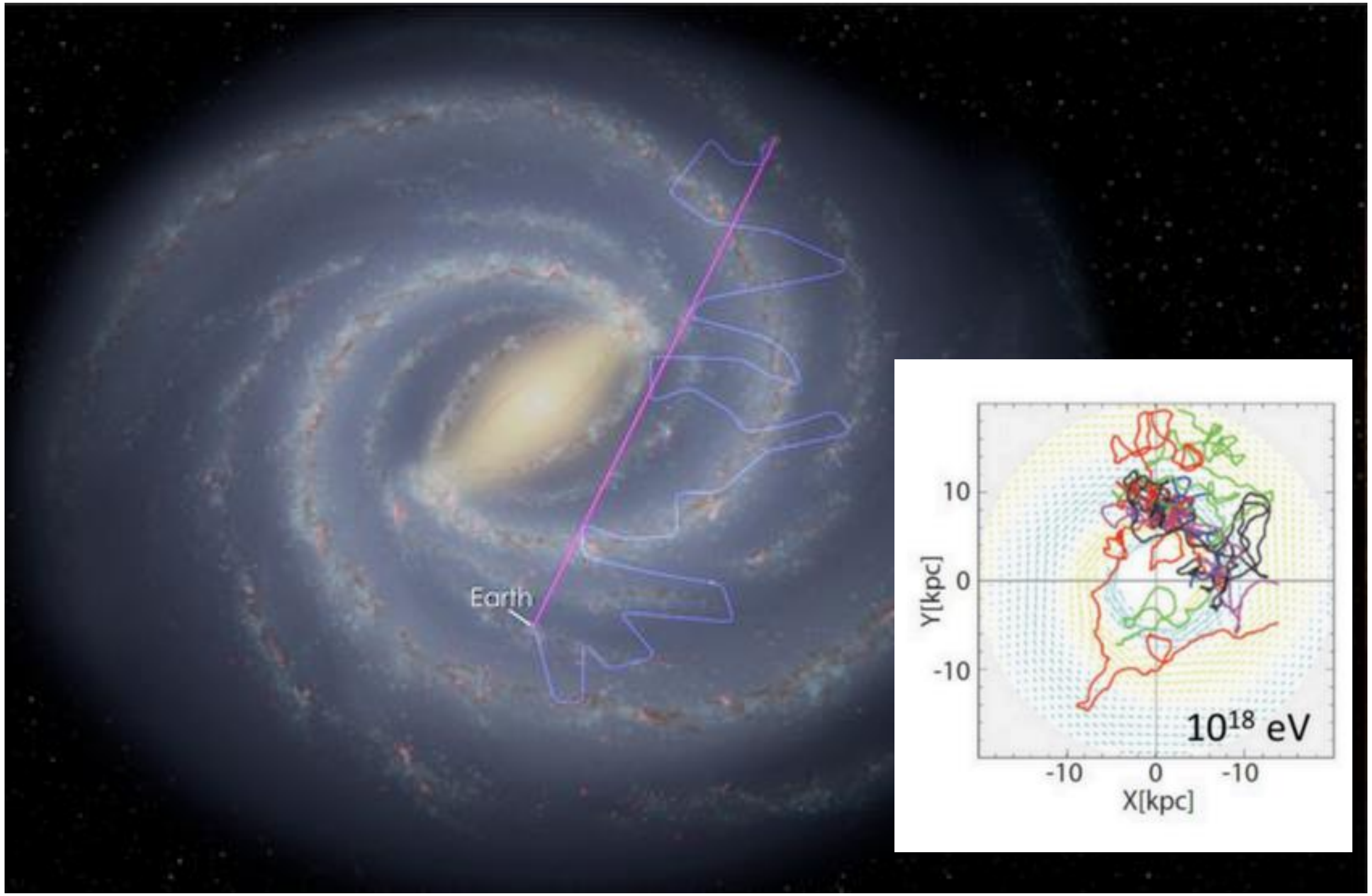
Cosmic messengers: gravitational waves



Gravitational waves also come at very different frequencies, with very different detection methods

Cosmic messengers: cosmic rays

- everything not included above
  - ➢ electrons, protons, nuclei, …
- mostly charged particles
  - ➢ deflections in magnetic fields
  - ➢ loss of direction, time delay



“Simple” examples: single event, two messengers

- supernova 1987A
  - photons + neutrinos

- merging of 2 neutron stars, GRB170817
  - gravitational waves + photons

NB: some people think that the multimessenger astronomy = simultaneous observations like these two. We will shortly see that it is richer.

SN 1987A

- birthday of modern astroparticle physics
  - photons + neutrinos brought info about the stellar explosion
  - serious implications for particle physics

NB: this day is celebrated as a fest day of astroparticle physicists every year

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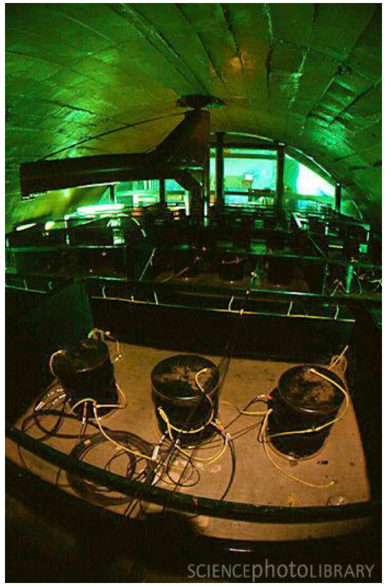
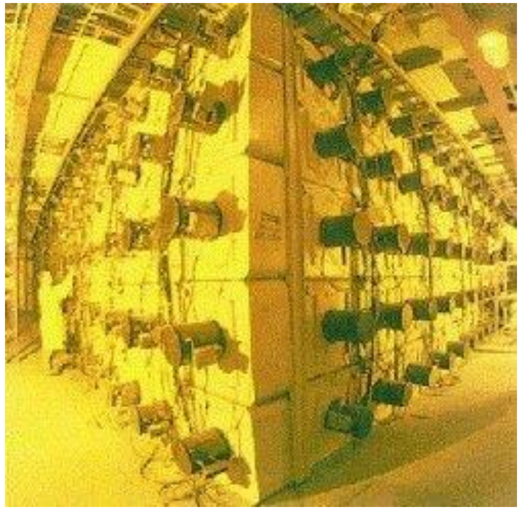
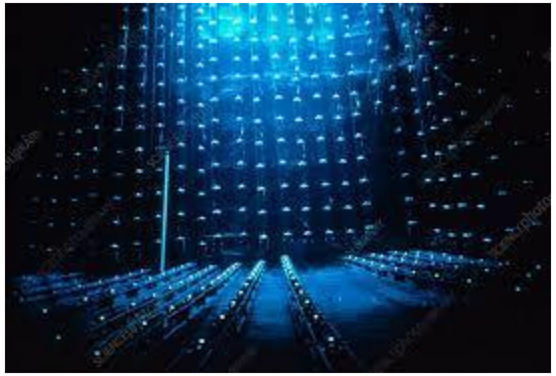
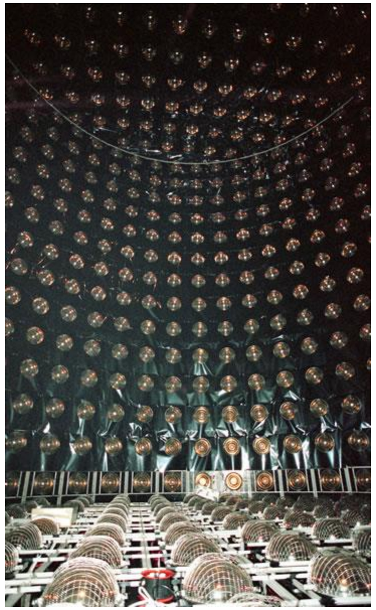
SN 1987A

- core-collapse supernovae
  - ➢ death of an old, heavy star
  - ➢ most energy carried out by neutrinos (a few hours before the visible flare)
- neutrino detectors are waiting for such events for decades…



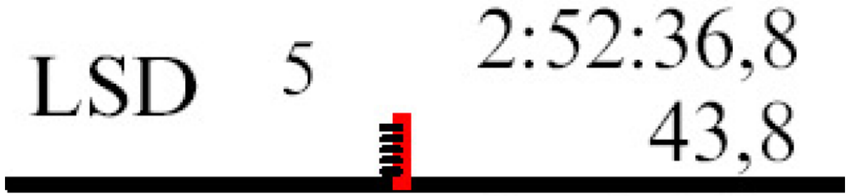




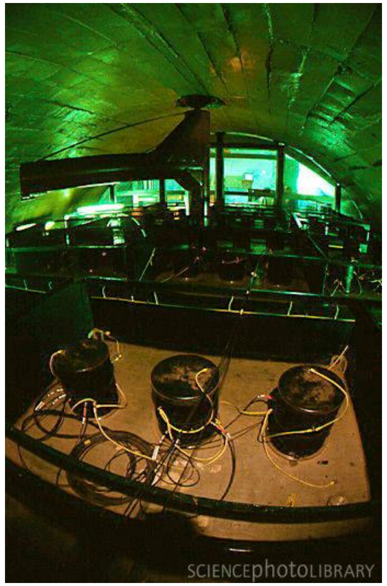
SN 1987A

Feb 23, 1987
Large Magellanic Cloud

SN 1987A

Feb 23, 1987





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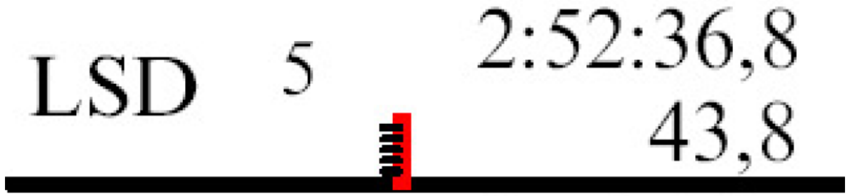

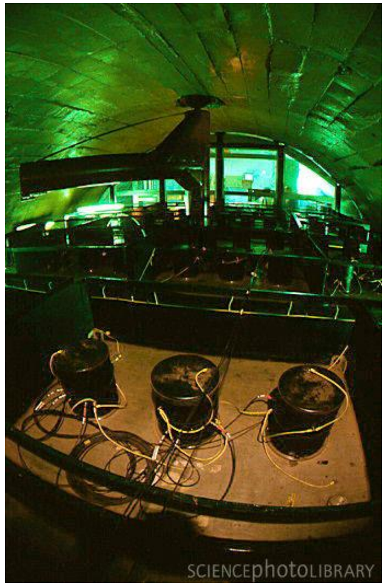

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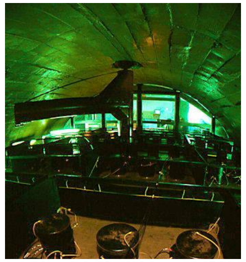

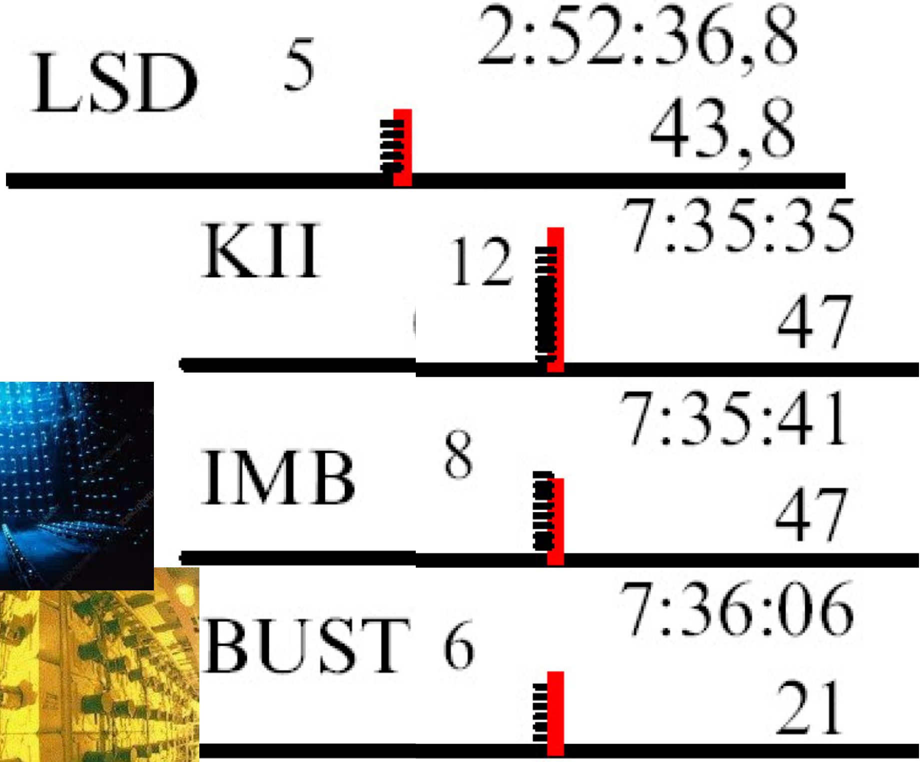

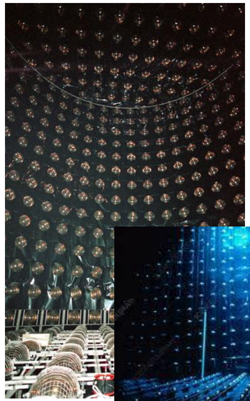

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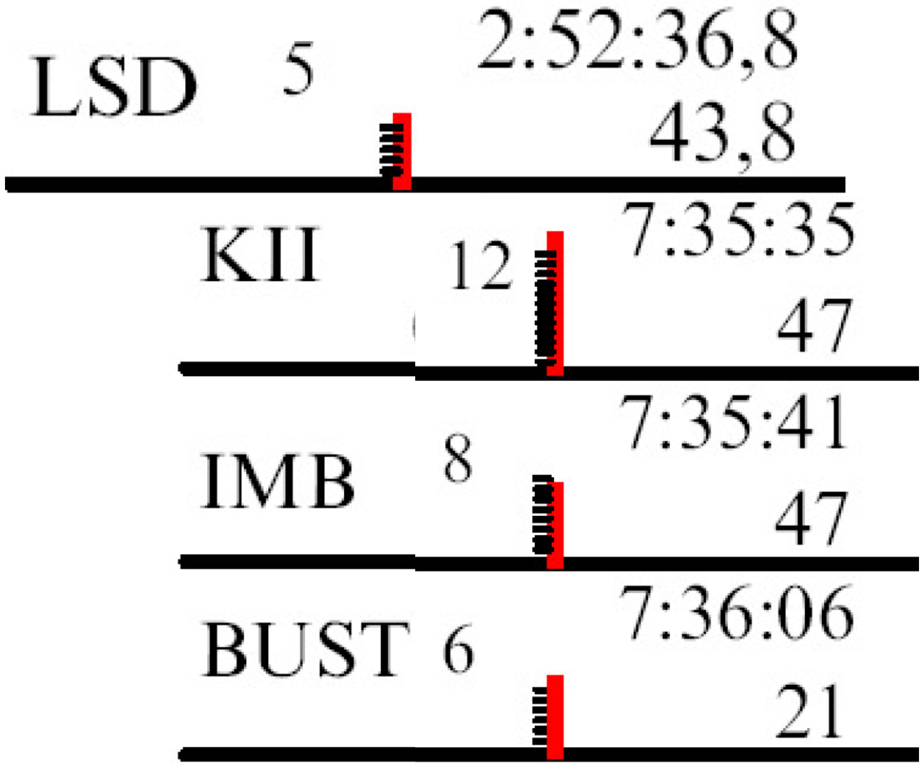

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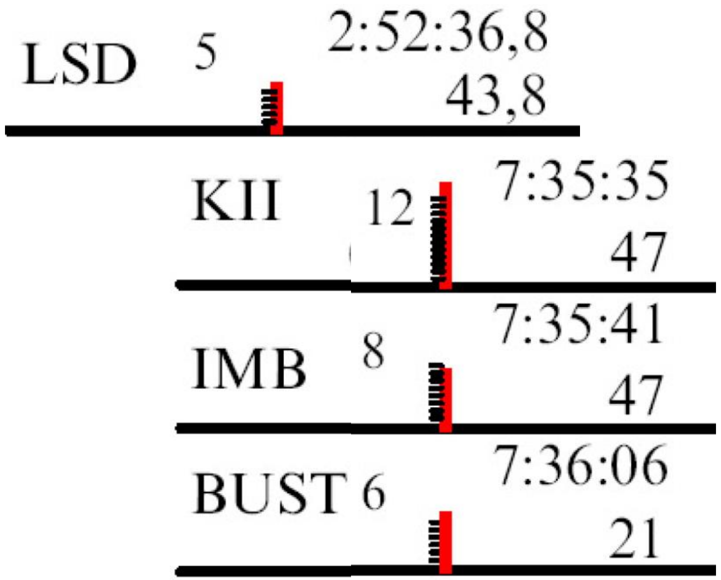
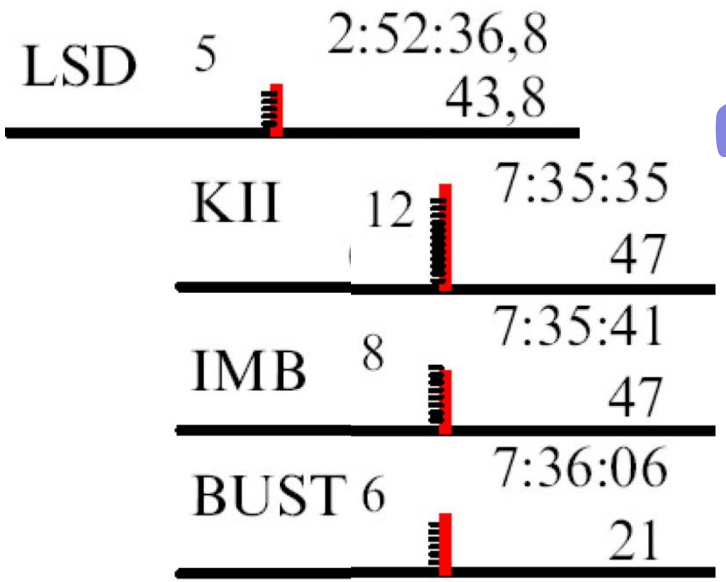
SN 1987A



- neutrino flux
- neutrino energies
- duration of the neutrino flare
- interval to the visible flare

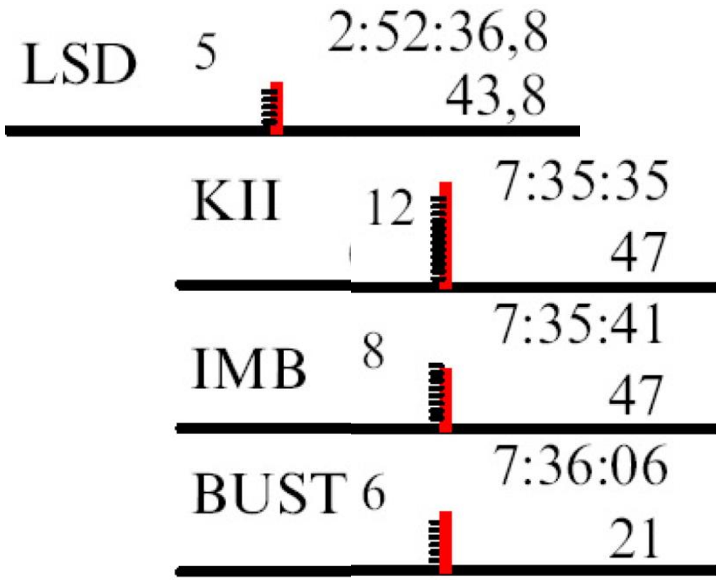
all confirm qualitatively theory of the core-collapse SN explosion

SN 1987A



double neutrino signal remains unexplained!

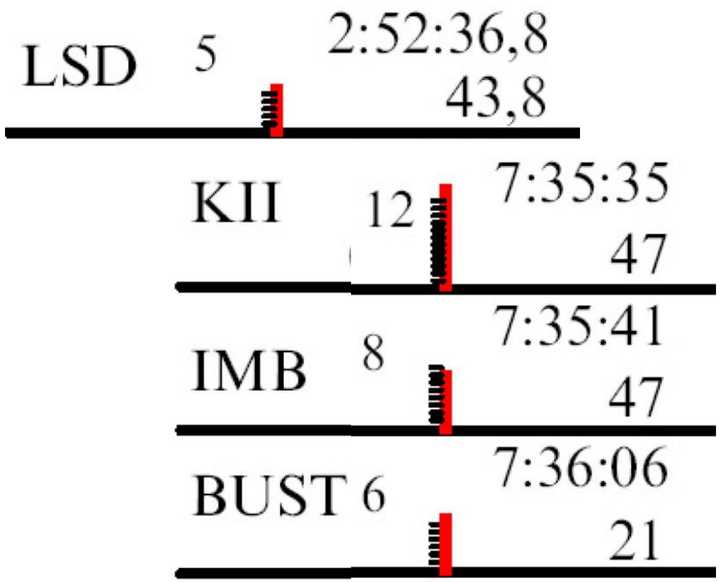
SN 1987A



constraints on neutrino properties:

- mass
- charge
- oscillation parameters
- magnetic moment
- velocity…

SN 1987A



constraints on neutrino properties:

- mass
- charge
- oscillation parameters
- magnetic moment
- velocity…

OPERA 2011 : $(v – c)/c \sim 10^{-5}$

SN 1987A : $(v – c)/c < 10^{-9}$

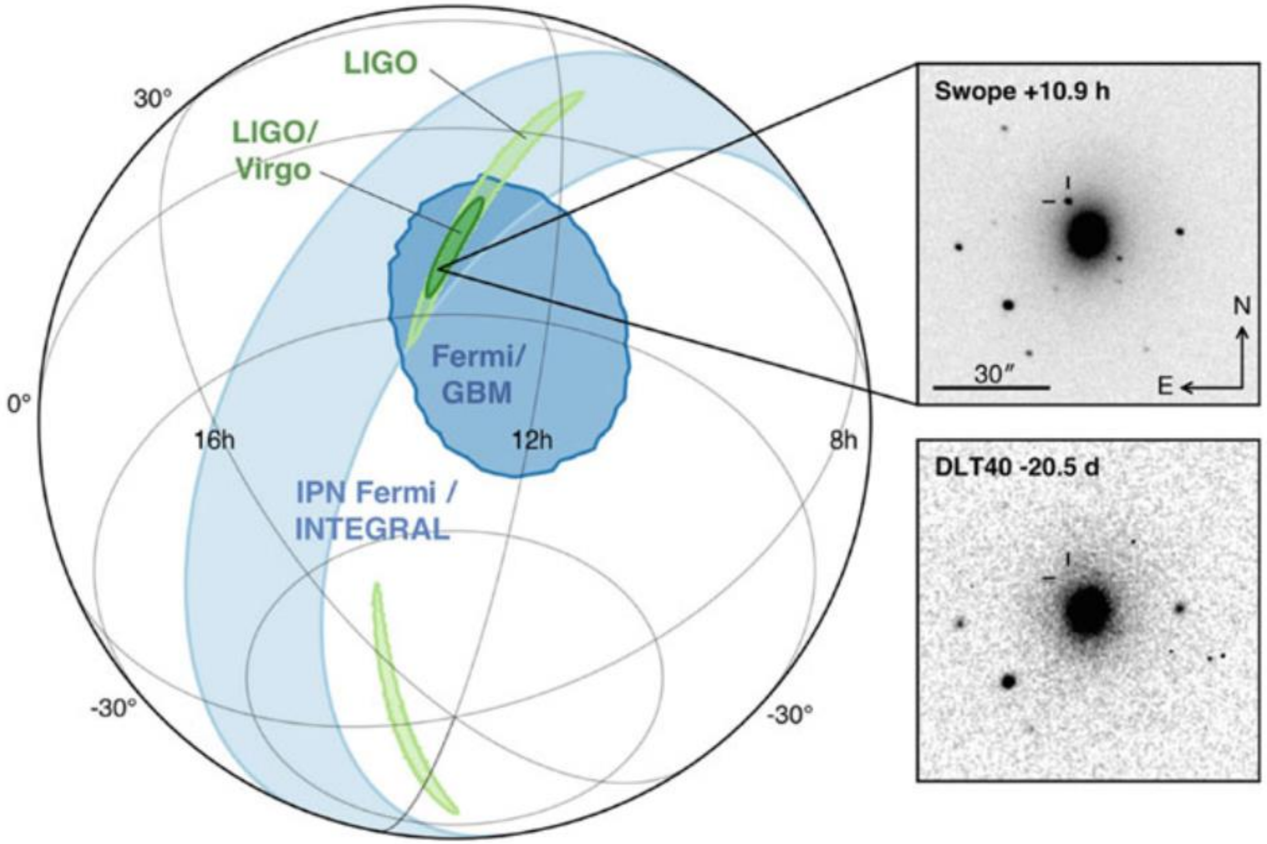
!

GW 170817

- gravitational + electromagnetic waves brought info about the coalescence of two neutron stars
- serious implications for fundamental physics

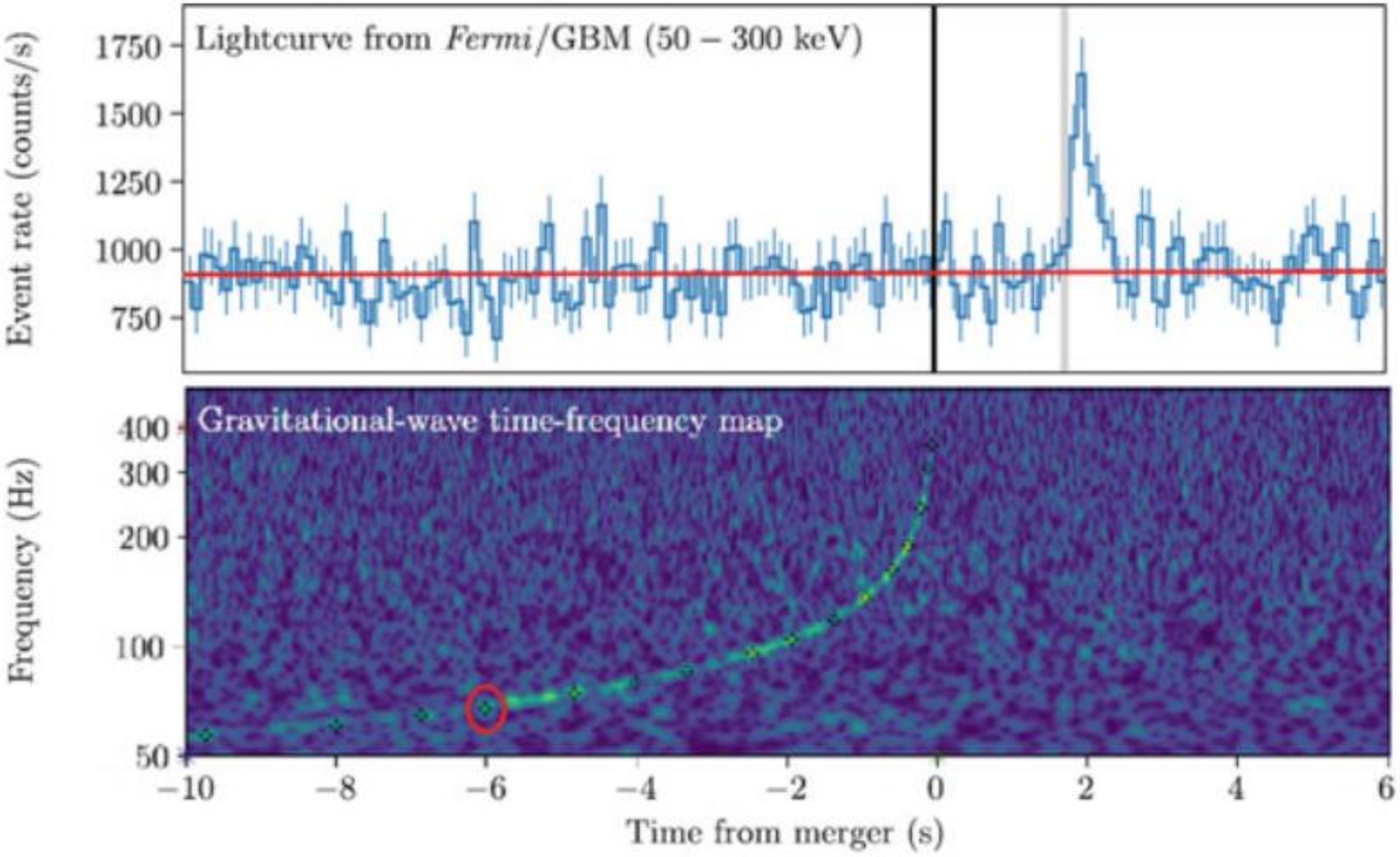
GW 170817

- find it in the sky!



GW 170817

- in a close binary system, gravitational waves are emitted at the frequency = ½ of orbital



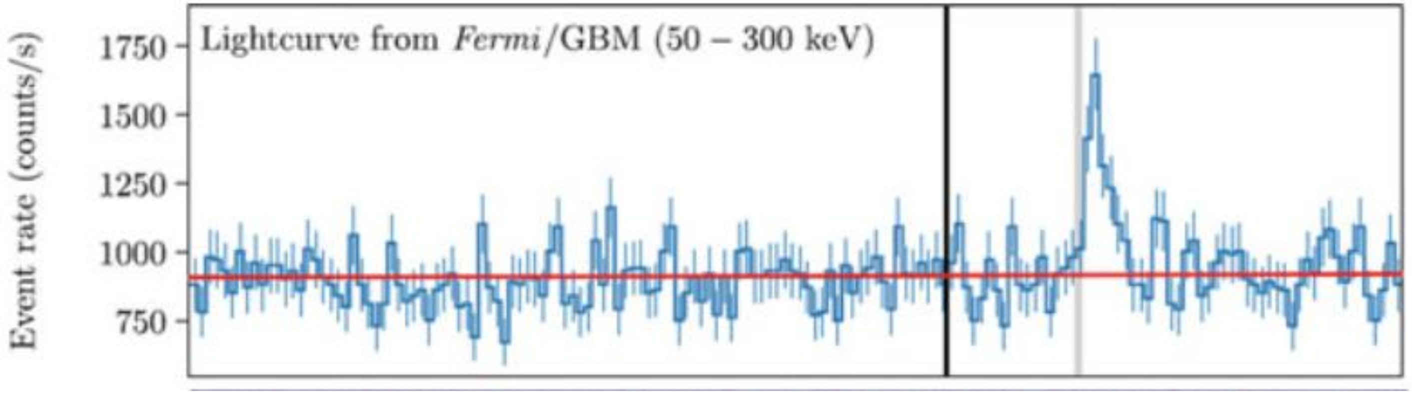
Δt (s)	ν_{gw} (Hz)	$\dot{\nu}_{gw}$ (Hz s^{-1})	$\mathcal{M}$ (kg)	$\mathcal{M}/M_\odot$	R (km)
−9.74	57.1	–	–	–	166
−6.87	64.8	2.7	2.1E+30	1.0	153
−4.83	74.3	4.7	2.2E+30	1.1	140
−3.33	85.7	7.6	2.1E+30	1.1	127
−2.45	95.7	11.4	2.1E+30	1.1	118
−1.93	104.7	17.2	2.2E+30	1.1	111
−1.37	118.2	23.8	2.1E+30	1.0	102
−0.94	136.3	42.8	2.1E+30	1.1	93
−0.59	163.1	75.1	2.0E+30	1.0	83
−0.21	239.7	201.1	1.6E+30	0.8	64
−0.06	359.9	810.0	1.5E+30	0.7	49

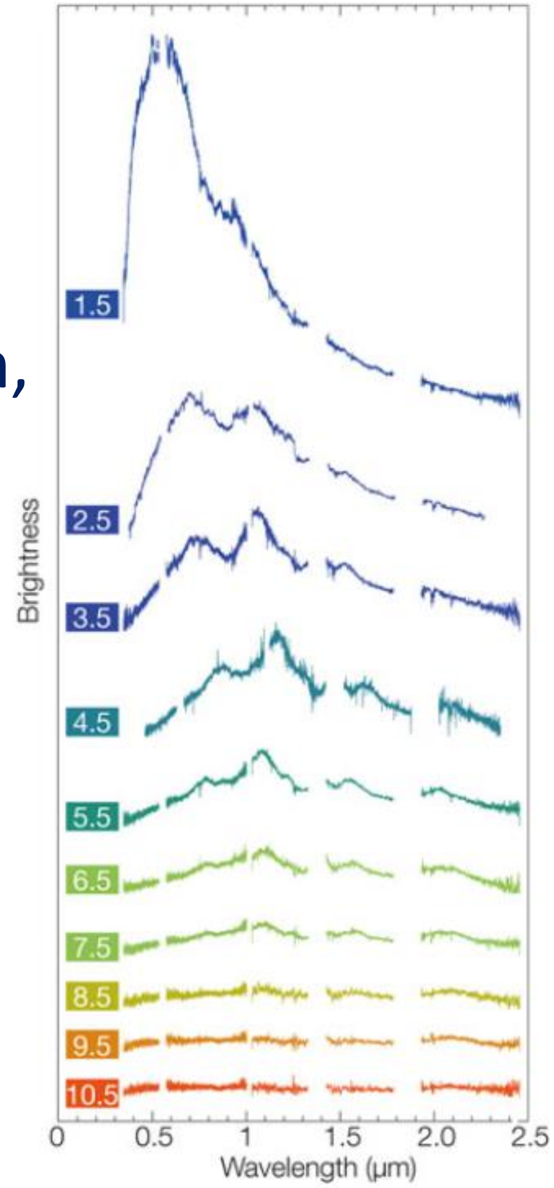
GRB 170817

it was a typical short gamma-ray burst!

prompt emission,
seconds

afterglow emission,
days

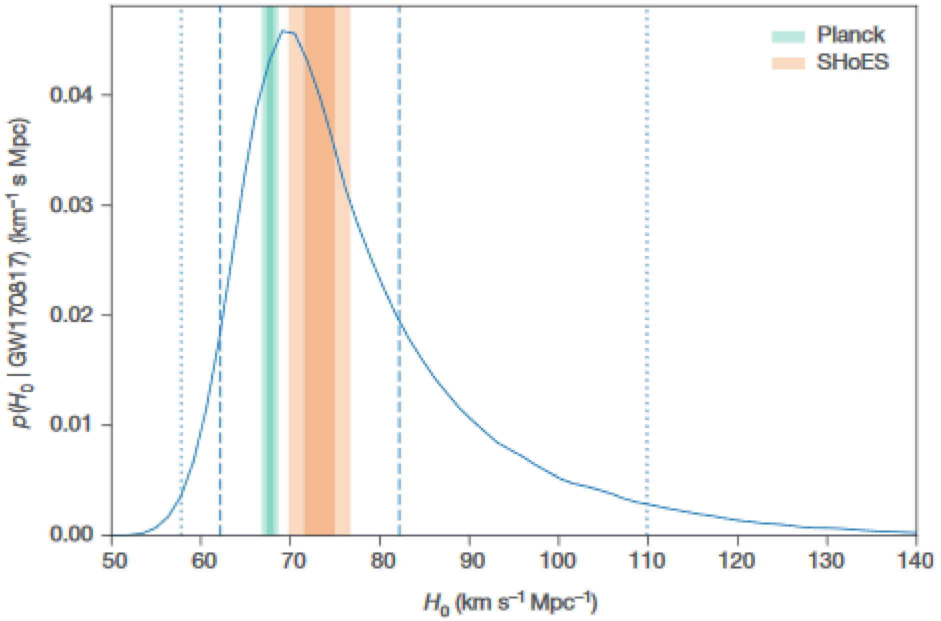




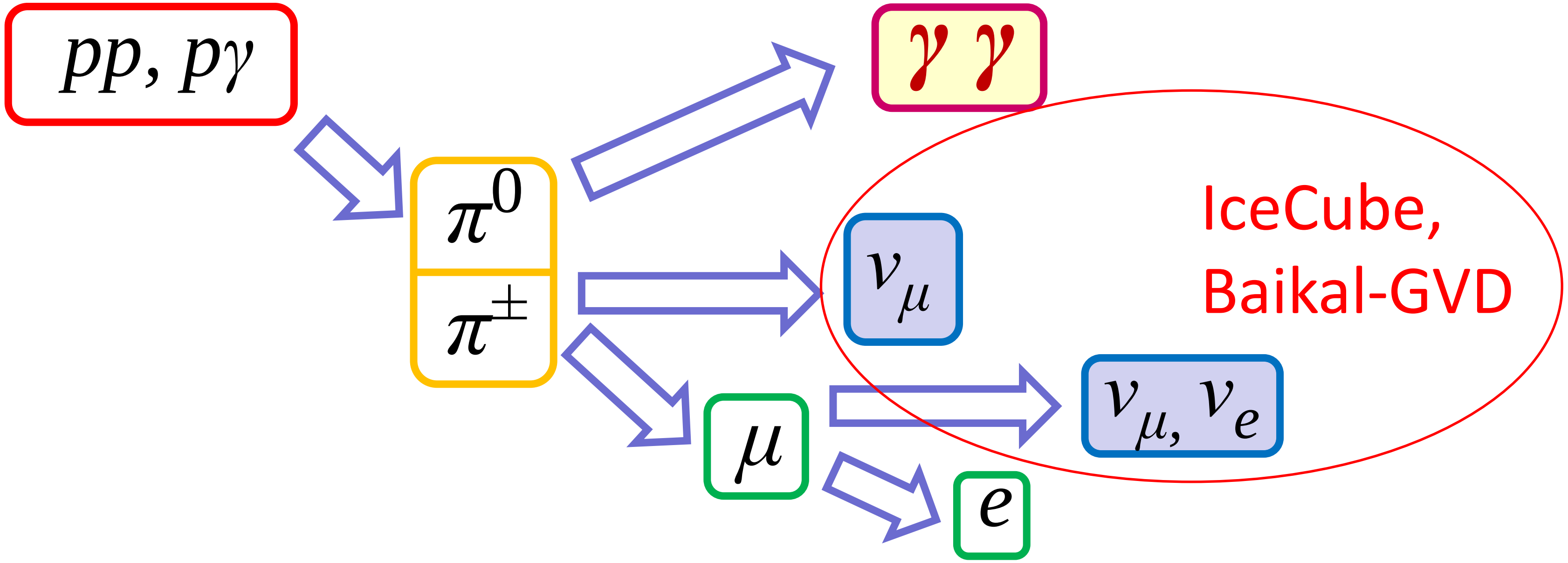
confirmation of the short GRB/kilonova model

GW 170817

- implications
  - velocity of the gravitational waves (=c in GR)
  - cosmology: standard sirens (an independent way to determine the Hubble constant)
  - (future): neutron-star equation of state



High-energy neutrinos, photons and cosmic rays

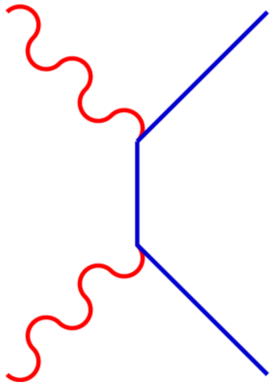


- ✓ Energies above 1 ТэВ – nonthermal origin
- ✓ Standard physics – only processes with accelerated hadrons

Neutrino is a marker of relativistic protons and nonthermal processes

Pair production: the Universe is opaque to gamma rays

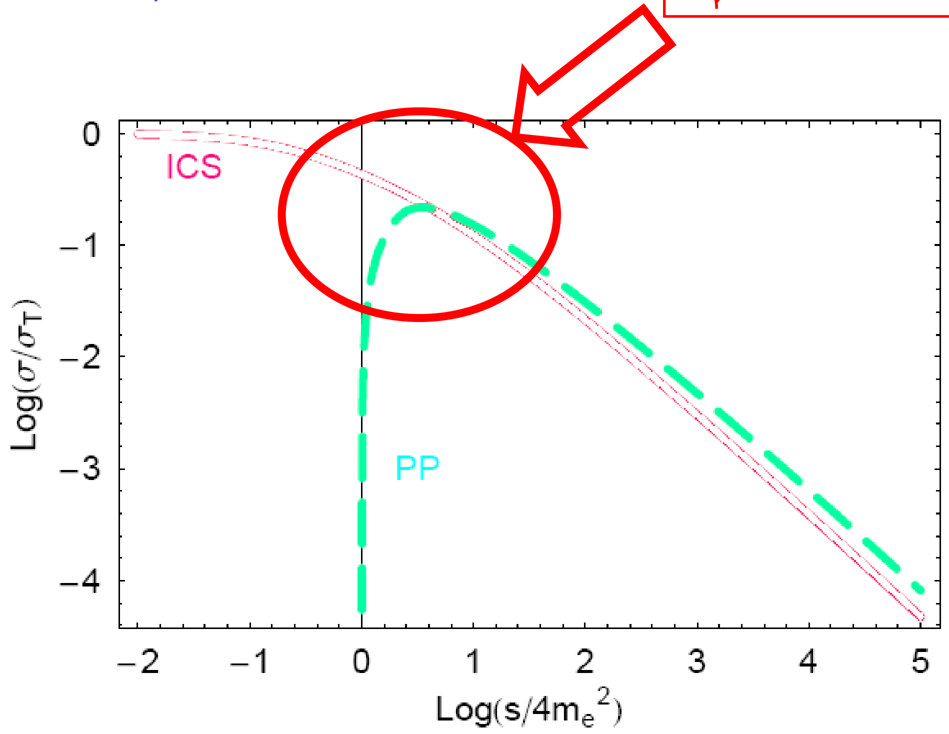
Nikishov 1962

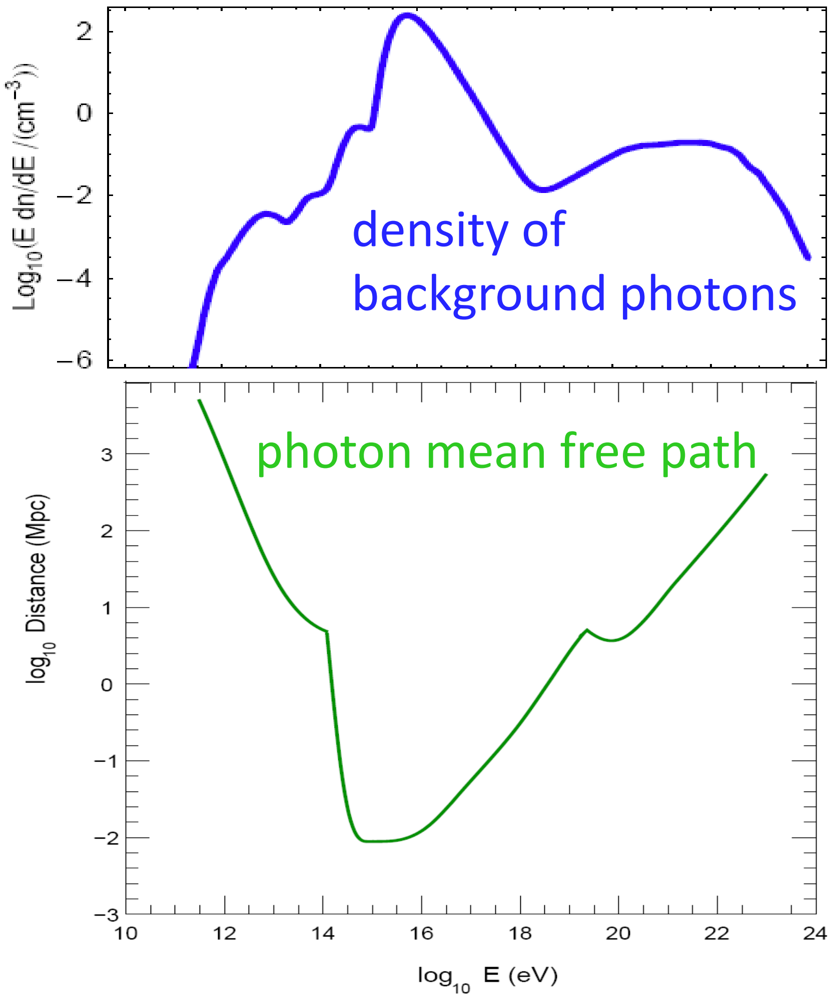


the most intense pair production:

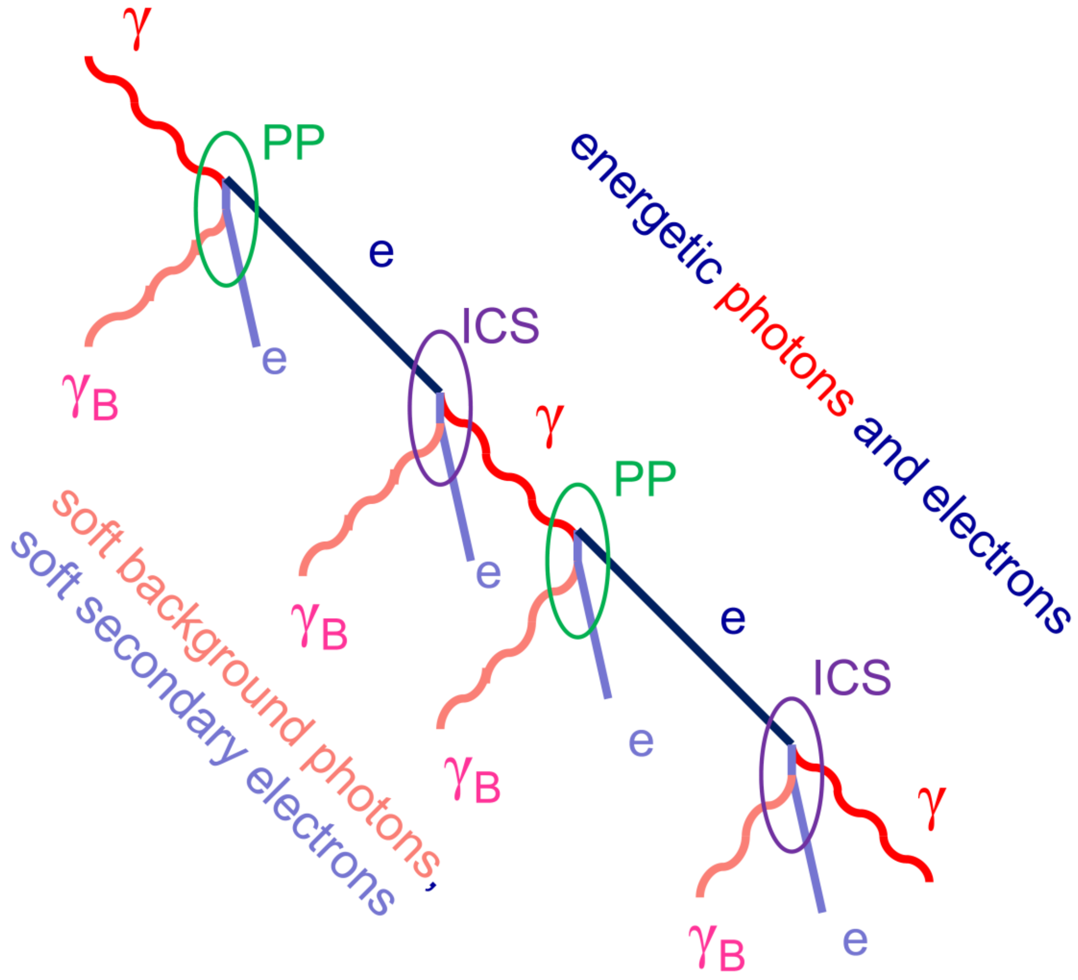
$s/4m_e^2 \sim 2\ldots4$

$E_\gamma \sim 5\times10^{11}\,(\omega/\text{eV})^{-1}$ eV





Fate of photons

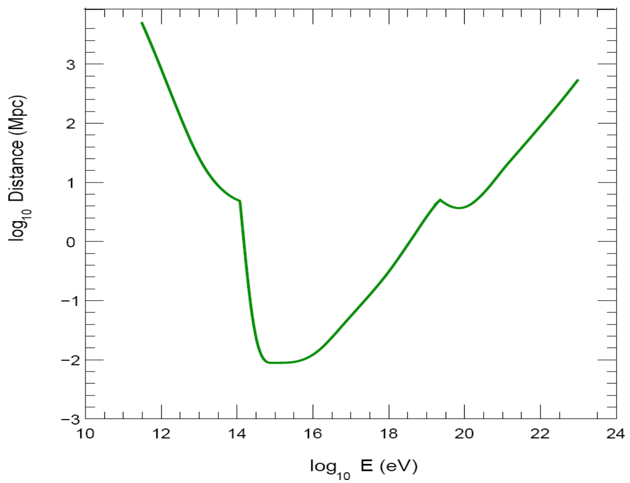


Electromagnetic cascades:

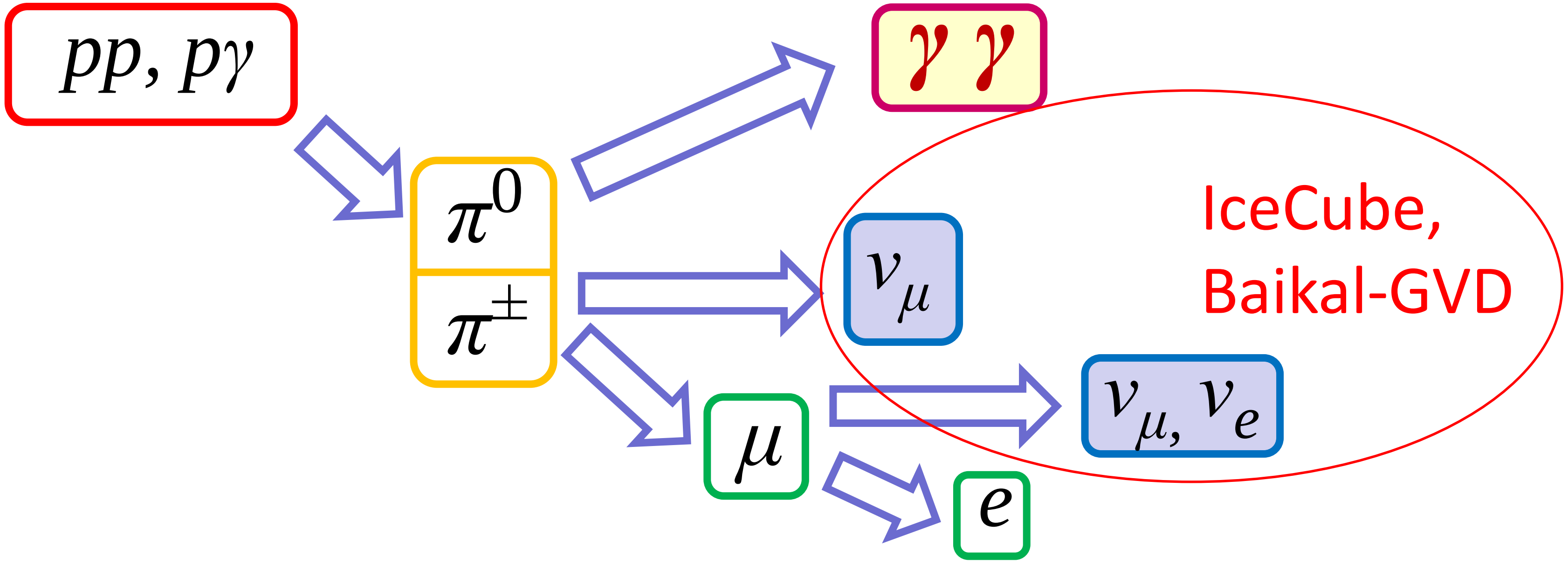
- pair production
- inverse Compton scattering

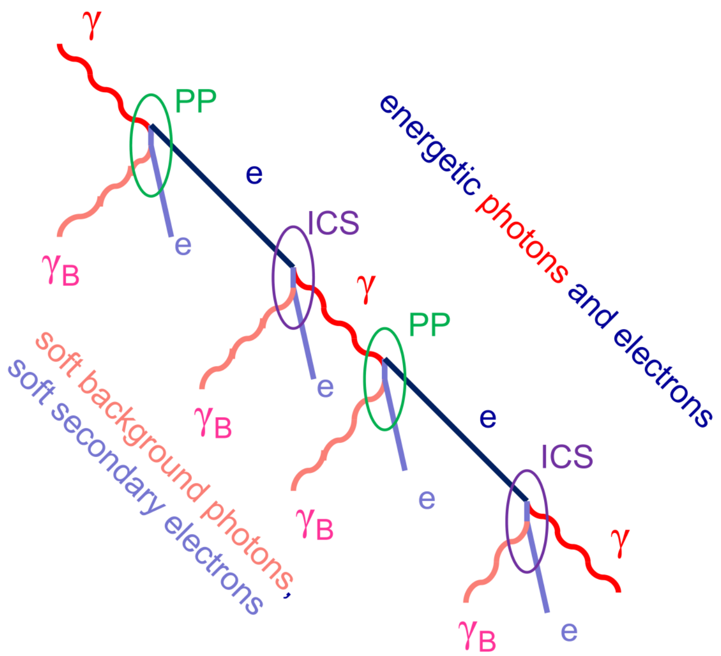
the energy is conserved, directions change

energy of all sources in the Universe re-emitted in diffuse ~GeV gamma rays



Neutrino astronomy and gamma rays





✓ High-energy (E>100 TeV) astrophysical neutrinos are accompanied by high-energy photons, if they are born in π-meson decays

✓ Cascades on CMB ⇨ (for extragalactic sources) the energy is transferred to the GeV band

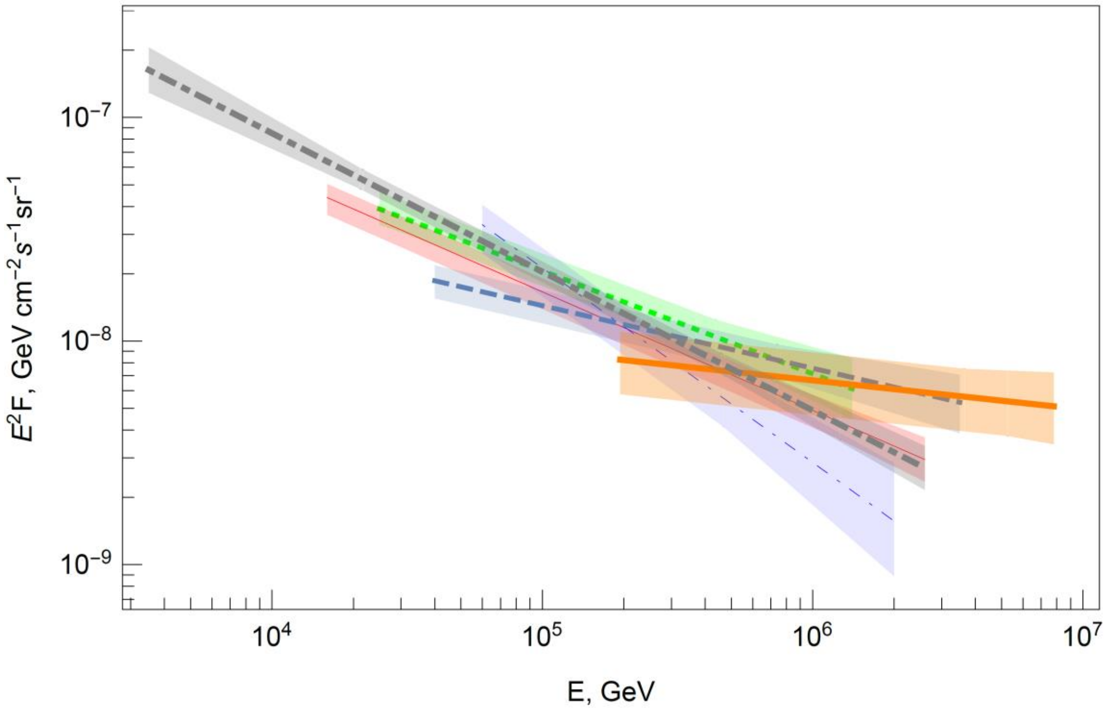
✓ Nonthermal radiation (radio and gamma) accompanies the acceleration of particles to the required energies

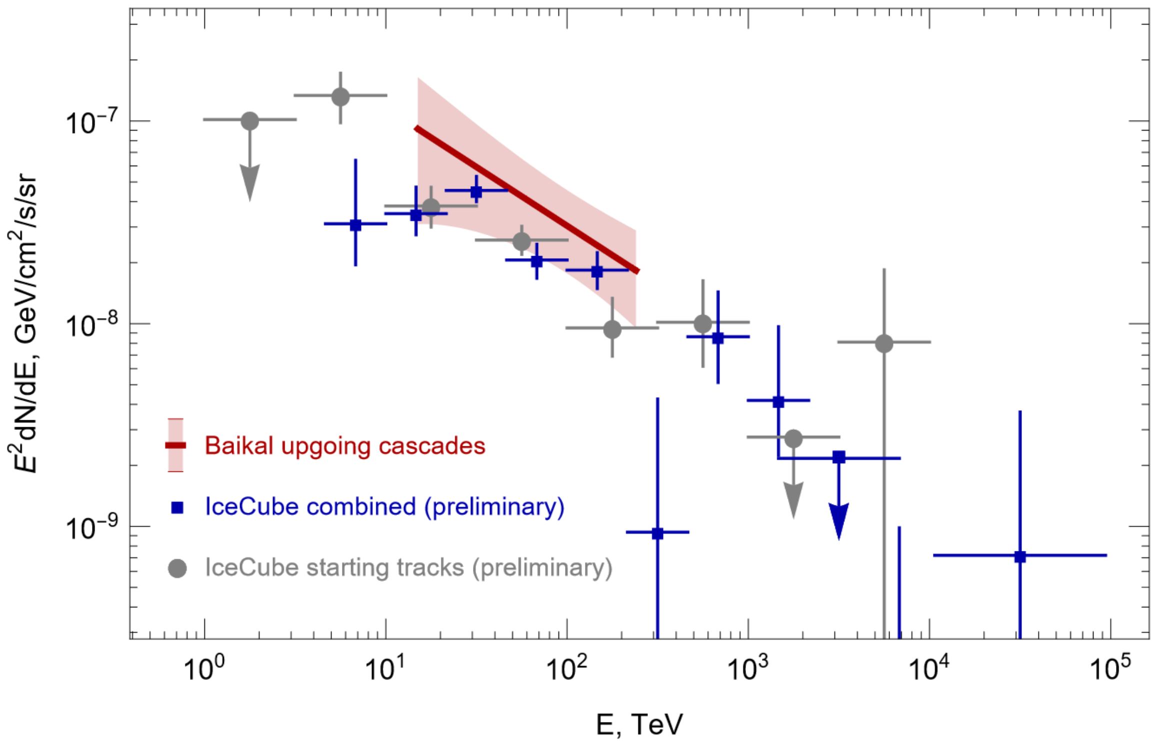
⇩

Search for high-energy photons = a tool to understand the neutrino origin

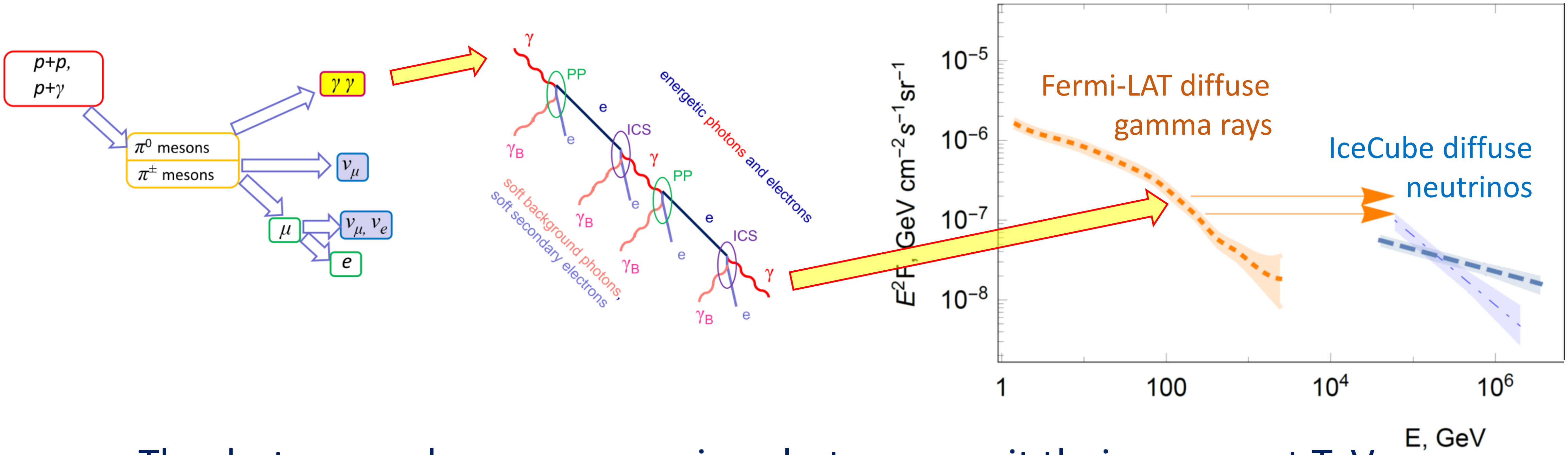
High-energy neutrino spectra

high-energy slope is flat,
different analyses suggest softer spectrum, higher fluxes, at lower energies





A Galactic component?



- Thanks to cascades, accompanying photons reemit their energy at TeV and overshine Fermi-LAT measured fluxes
- Galactic sources are too close, no time to develop cascades – no tension
- But then 100-TeV Galactic gamma rays should be observed!

Galactic neutrinos and Galactic photons

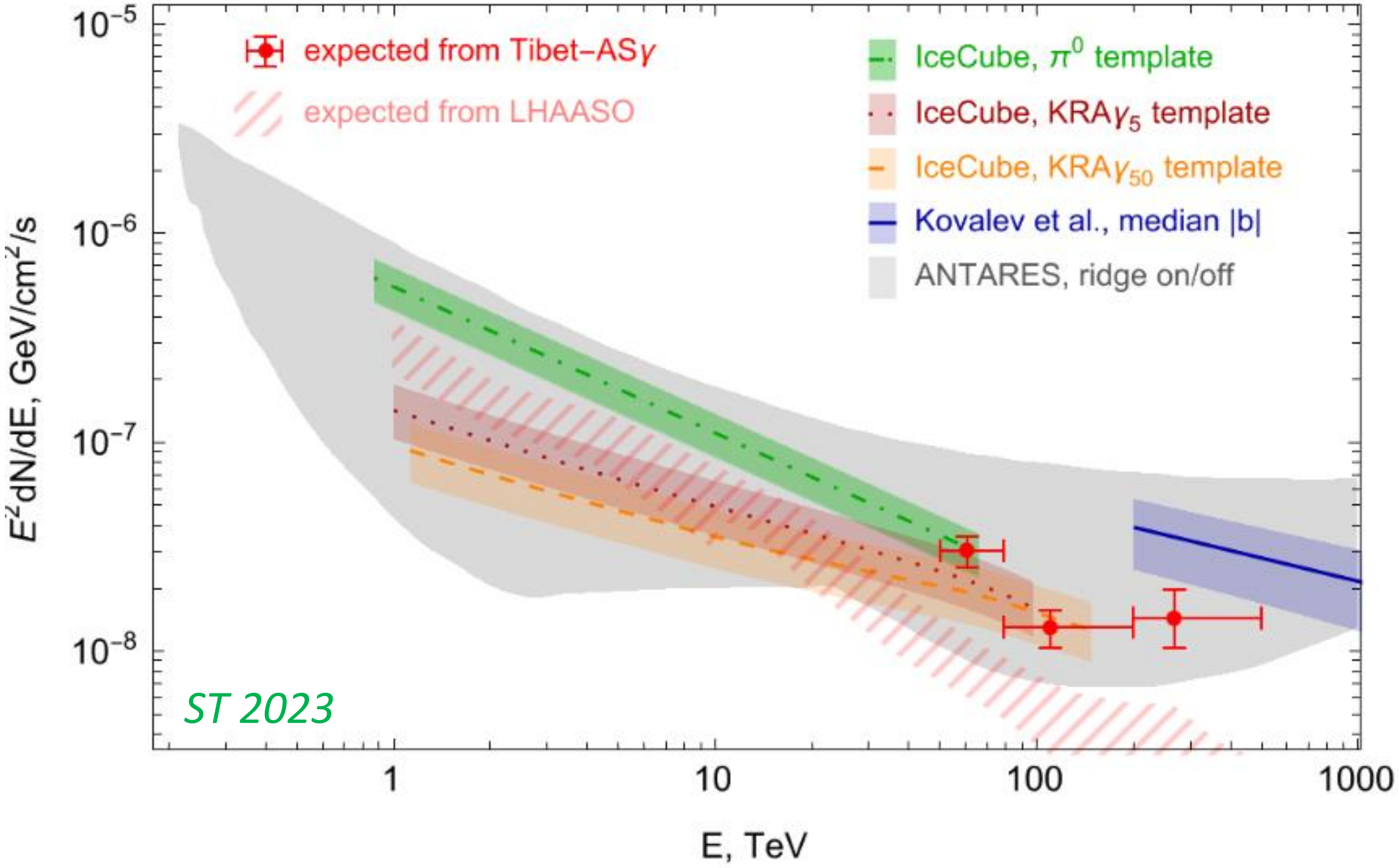
- Galactic neutrinos observed in 2022-2023
  - comparison of 3 analyses (IceCube HE tracks, ANTARES, IceCube cascades)

Analysis	Energies	Method	Significance
Kovalev et al., 2022 ApJL	$\gtrsim$ 200 ТэВ	median of $\|b\|$ distribution	4.1σ
ANTARES, 2022 PLB	$\sim 1-100$ TeV	on/off, ridge	2.0σ
IceCube, 2023 Science	$\sim 1-100$ TeV	templates	4.5σ

- Galactic diffuse gamma rays observed in 2021-2022 (Tibet-ASγ, LHAASO)
  - do they match?

Galactic neutrinos and Galactic photons

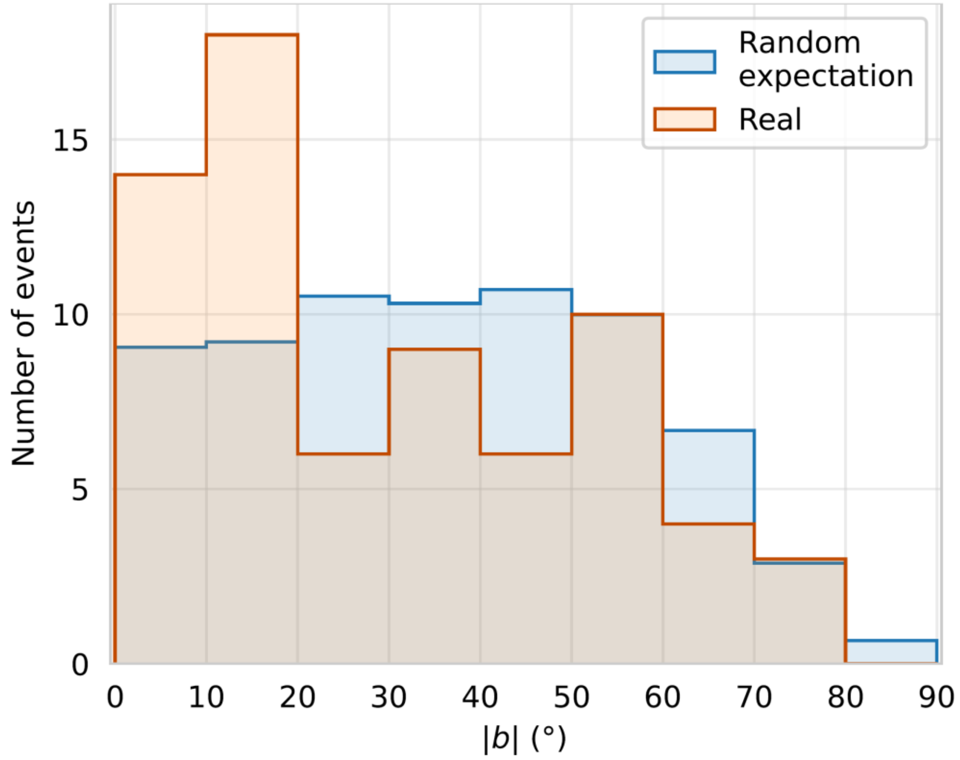
Neutrinos and gamma rays match quite well!

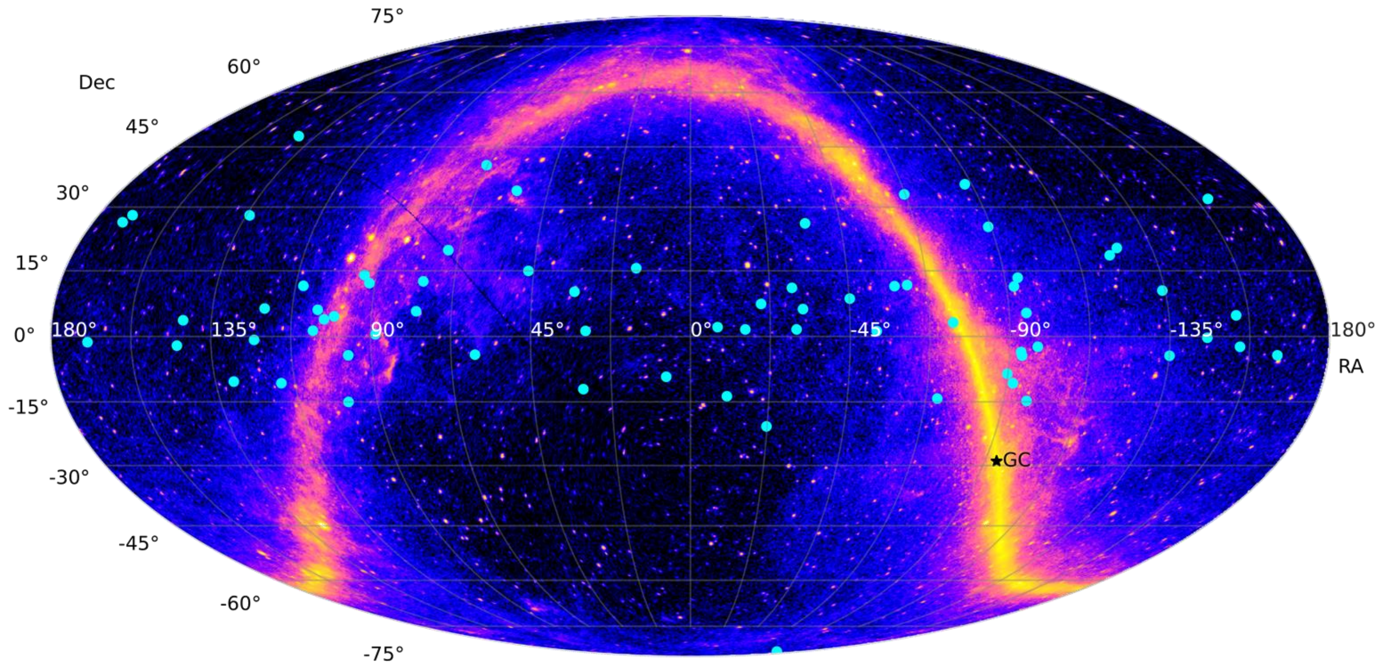


Note: contribution of point sources to the Galactic neutrino flux is expected

Comparison: arrival directions (width of the Milky Way)

Kovalev et al. 2022 : Milky Way in neutrinos looks wider than expected!

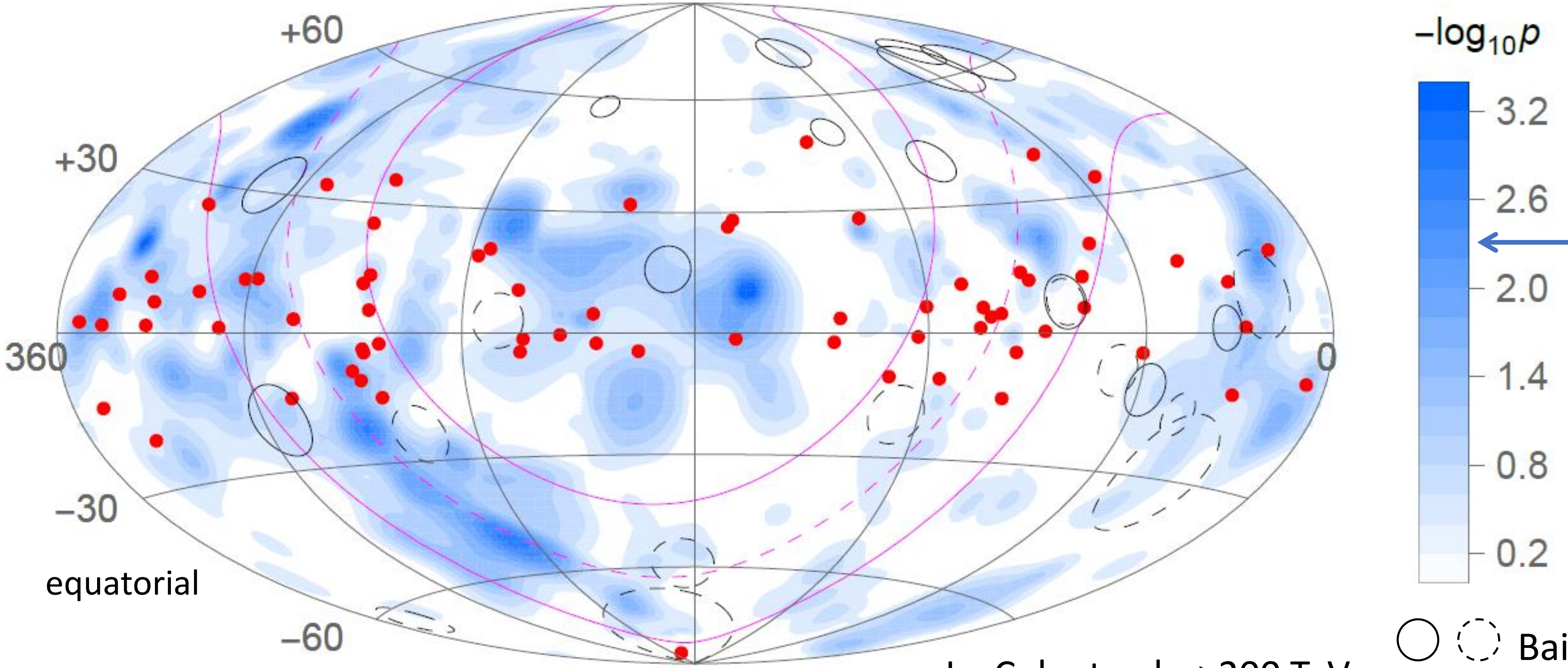




Comparison: arrival directions (width of the Milky Way)

[note: directional accuracy ~10-15° for IceCube cascades]

Galactic plane ± 20°



shading: IceCube cascades *IceCube 2023*

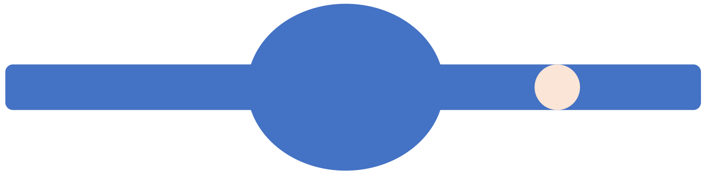
equatorial

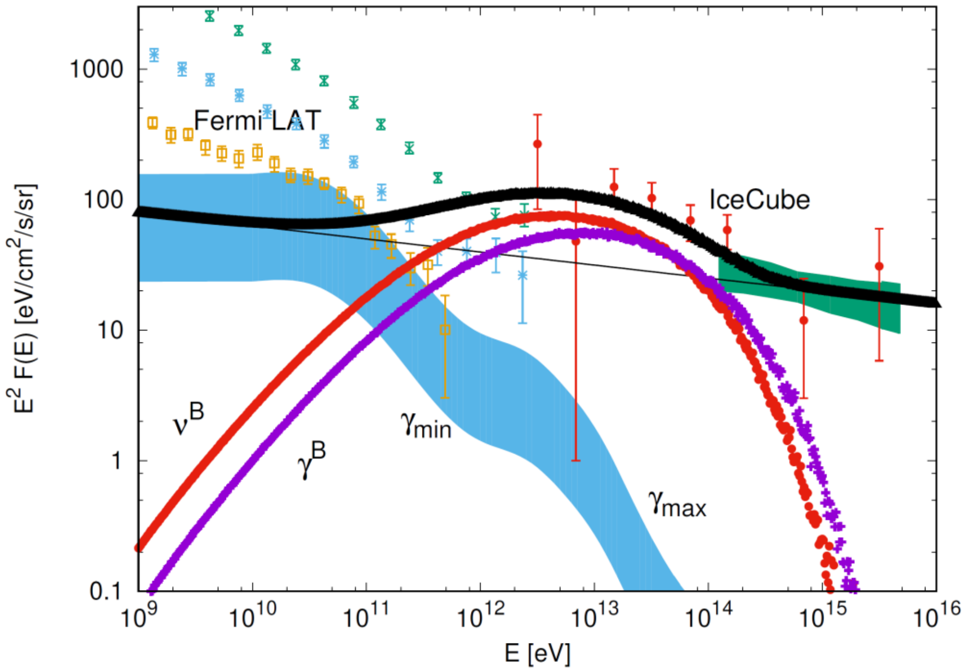
ST 2023

● IceCube tracks >200 TeV used by *Kovalev+ 2022*

◯ ◌ Baikal-GVD cascades *Baikal-GVD 2022*

Contribution of a local origin?

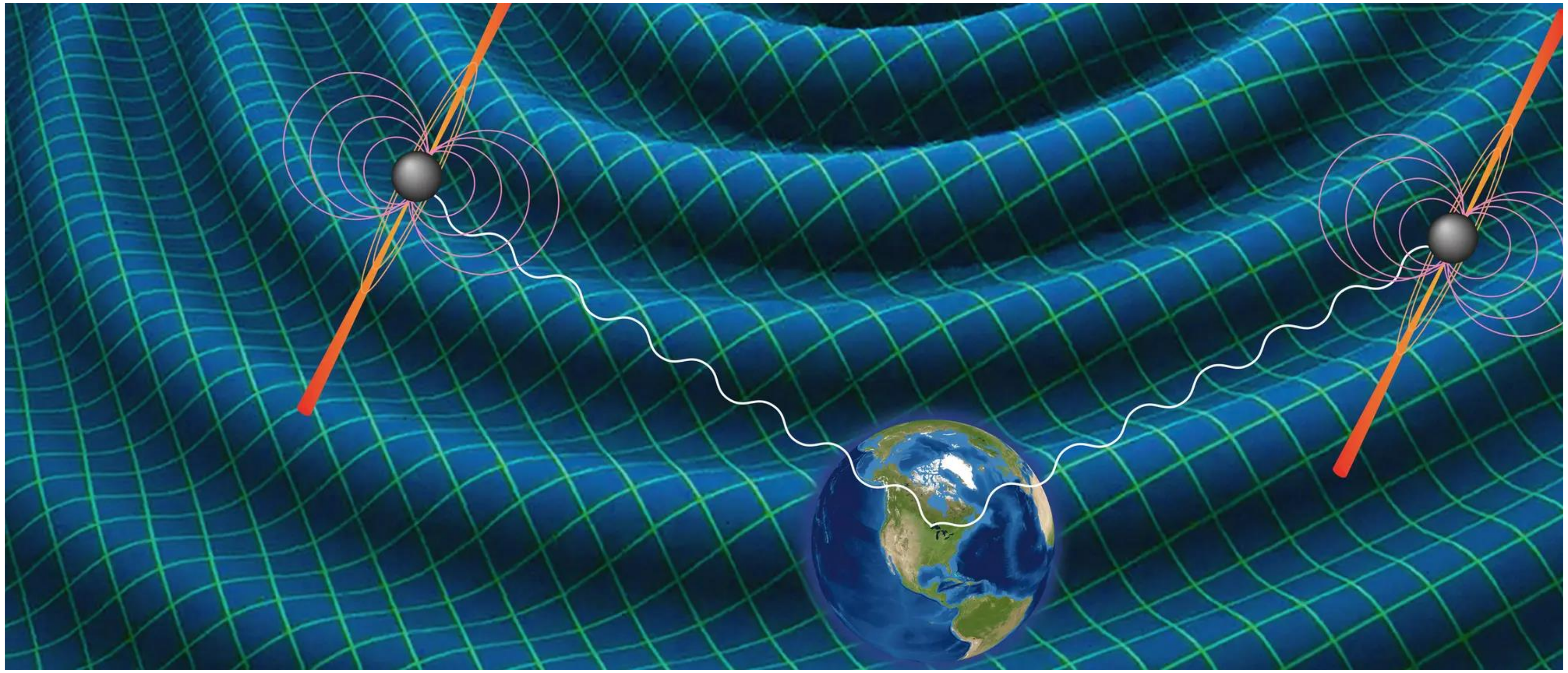




- "Local Bubble" – 100 pc, the Sun in the center (several supernovae?)
- high-energy photons and neutrinos from the bubble walls? (plus a local CR source)
  Bouyahiaoui, Kachelriess, Semikoz 2018, 2020
  Neronov, Kachelriess, Semikoz 2018
- disk contribution (including other bubbles) + Local Bubble
- add the isotropic component (atmosphere, blazars, contribution of other similar galaxies)…

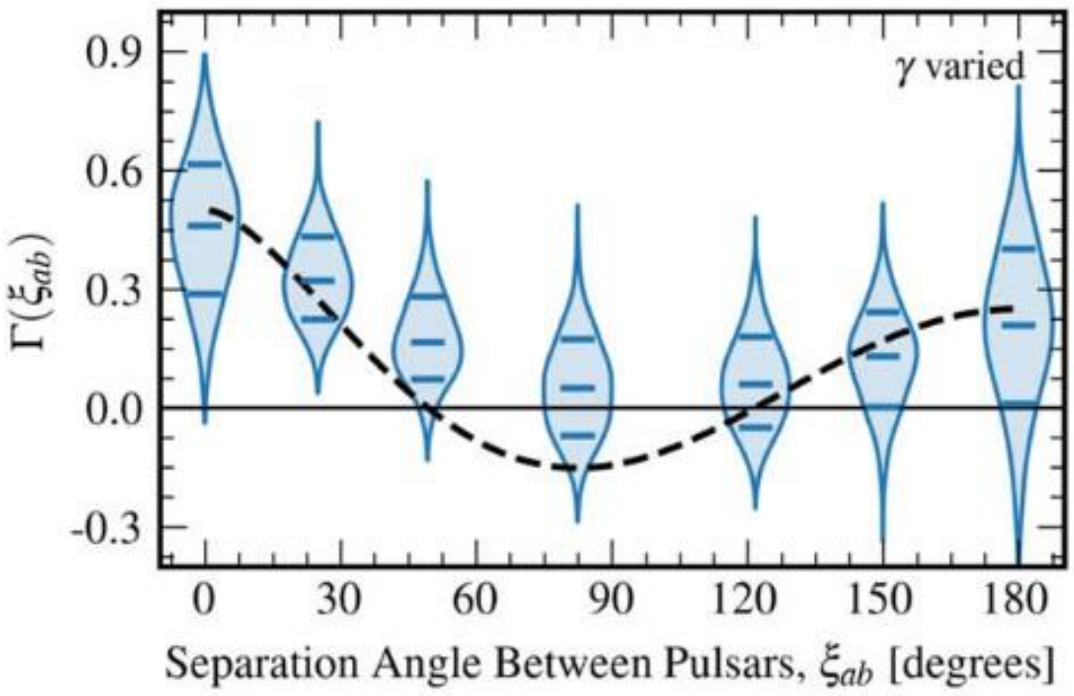
A better model of cosmic rays in the Galaxy is needed!

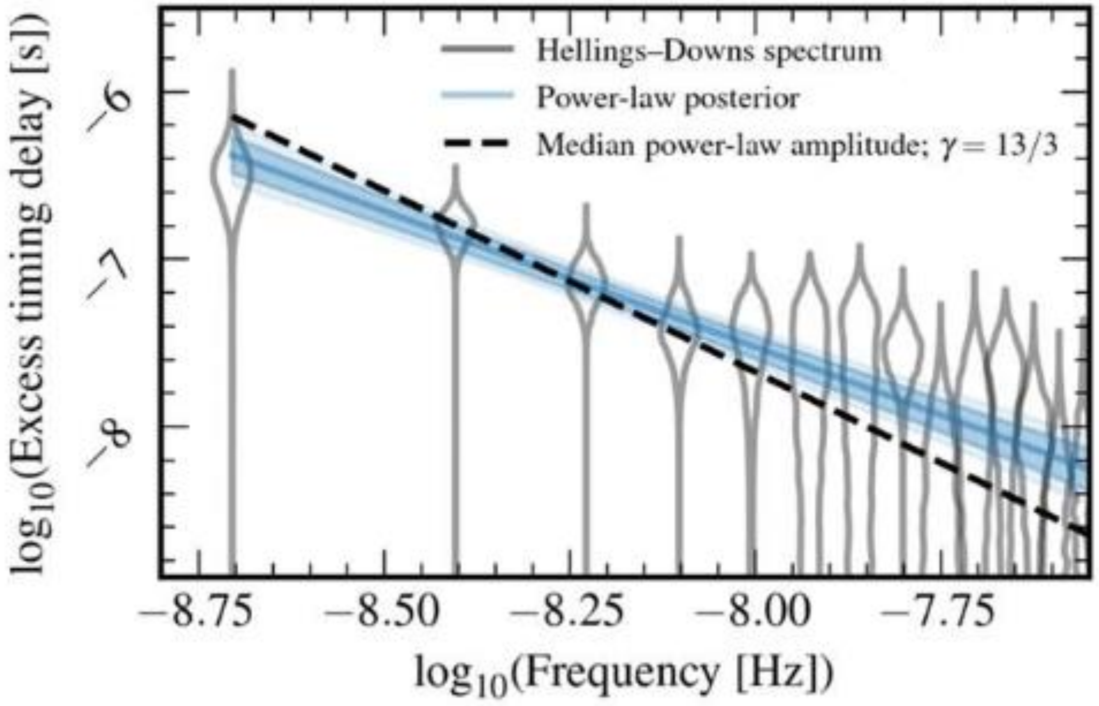
What about the gravitational-wave background?



- Pulsars are excellent natural clocks
- Gravitational waves change spacetime metrics
- A gravitational wave passing through the Earth changes observed timing of all pulsars coherently

Gravitational-wave background found in 2023





- Angular correlations consistent with GW passing through the Earth
- Spectrum differs from the one expected from black-hole mergers
- A plenty of possibilities for astro, cosmo and particle theorists!

Conclusions

- Astronomy is now multimessenger. Classical astronomy is only a part of it.
- Messengers include electromagnetic waves (photons), neutrinos, gravitational waves and ~~everything else~~ cosmic rays
- MM astronomy is more than a direct sum of messengers: combination of the signals has much stronger constraining power
- MM astronomy works for the total signals of populations of sources, not only for particular events observed in different channels simultaneously
- These observations have deep implications for fundamental physics

Question

- Why only one event – not more – has been observed so far in electromagnetic and gravitational waves simultaneously?