Multimessenger strategies for the study of the macrocosm and microcosm

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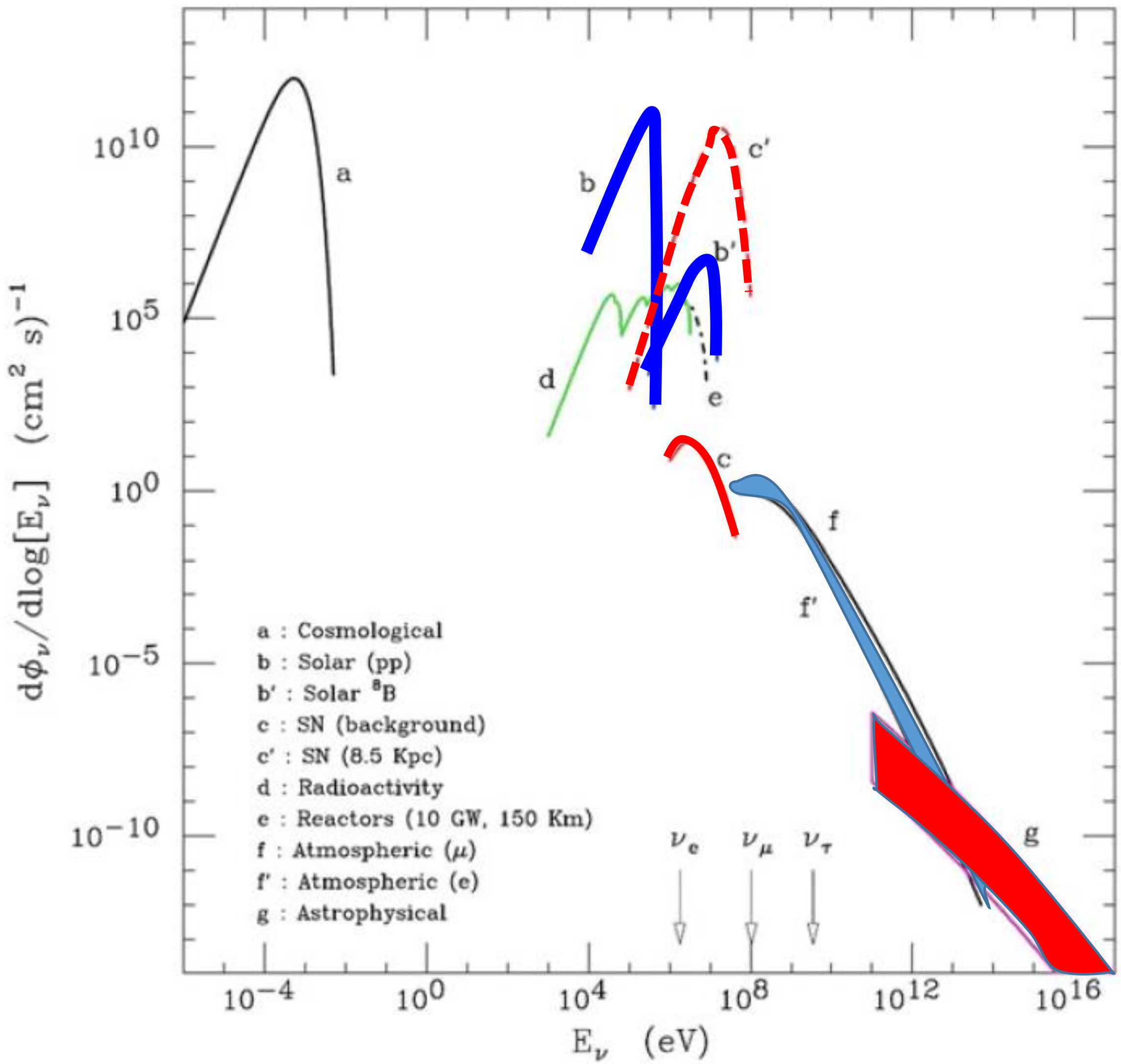
Few, selected topics

PART II.

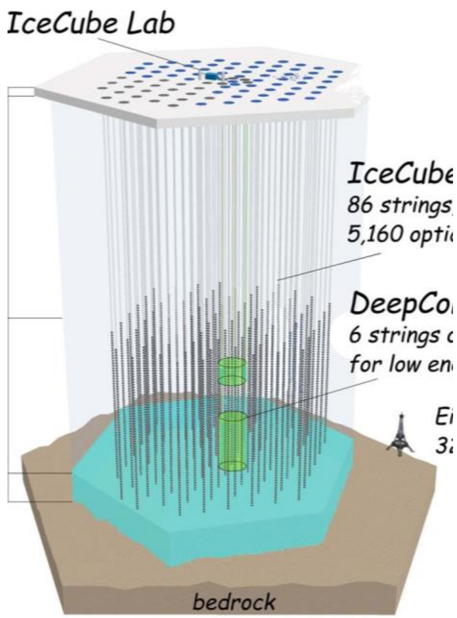
1. Some open questions in neutrino astrophysics
   - Why we do not have a “neutrino map”?
   - Correlation with UHECRs and Neutrinos
   - About **Galactic** sources
   - Detecting **extragalactic** sources
2. Extragalactic objects
   - Gamma-ray bursts and consequences
   - Fast Radio Bursts
3. The multimessenger role of Gravitational waves
   - Importance for **particle physics**
   - Importance for **cosmology**
   - Importance for **astrophysics**

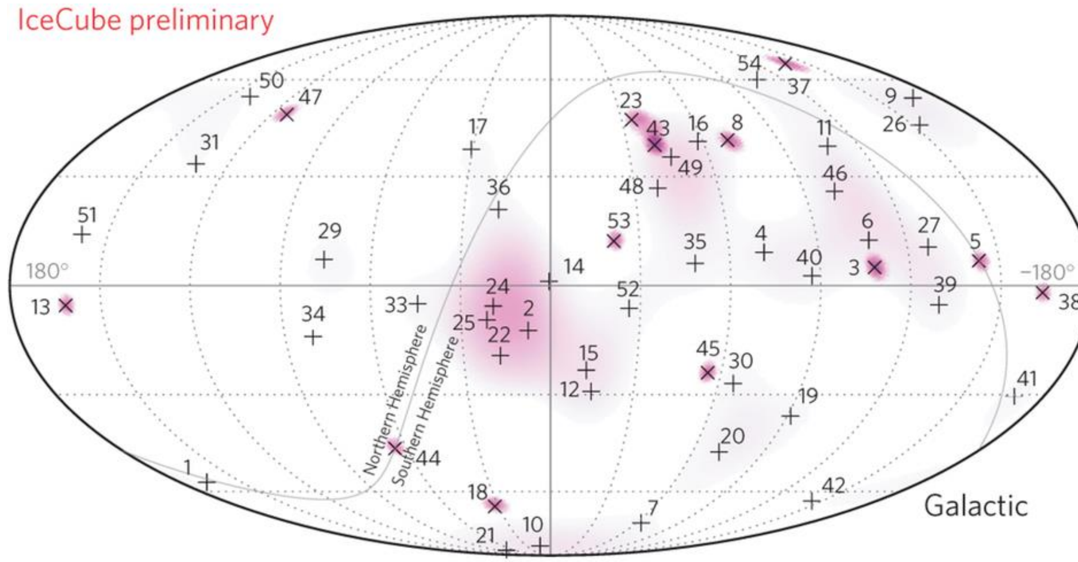
Neutrini from the Cosmos

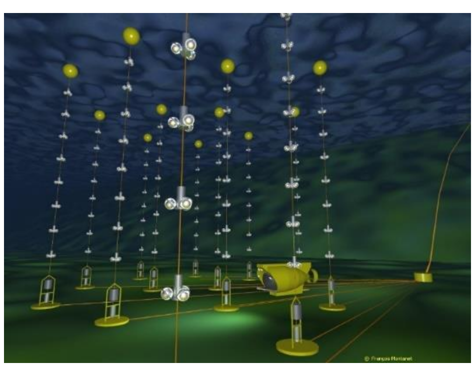


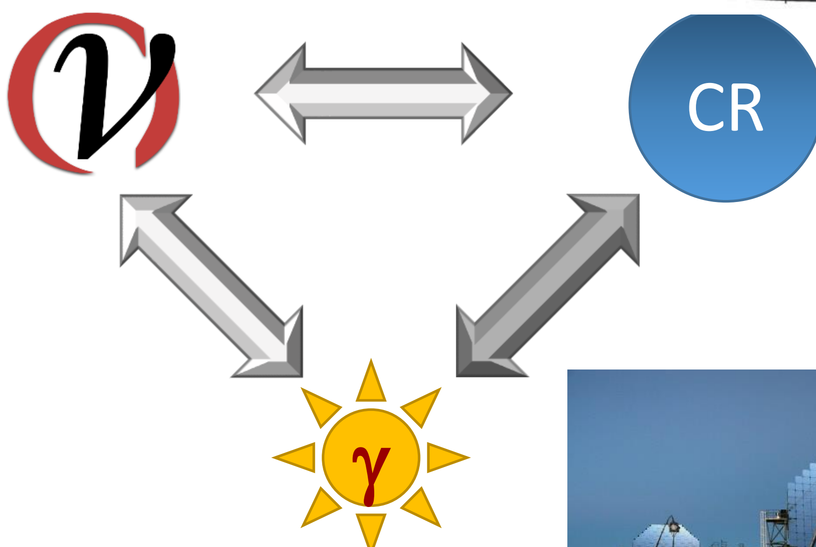
- Flux of neutrinos at the surface of the Earth.
- The three *arrows* near the *x*-axis indicate the energy thresholds for CC production of the charged lepton

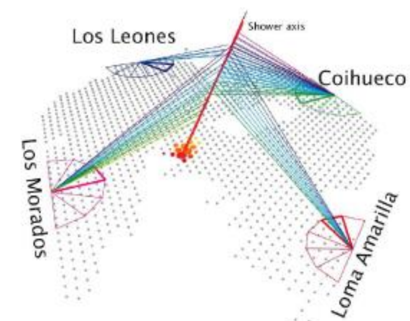
1) Open questions for neutrino astrophysics











1) Open questions for neutrino astrophysics

- Origin of IceCube's HE astrophysical neutrinos?
- Evidence of galactic "TeVatron" from γ-rays (e, p or both?). But, for p and nuclei, no "LHC" o "PeVatrons" observed
- Neutrino: fundamental probe to identify **galactic** and **extragalactic** CR sources
- Disentangle astrophysical models with multimessenger observations: i.e., GRBs with GW, HEN and traditional astronomy (useful also in case of no ν observation)
- Production mechanisms of high energy cosmic particles **(jets?)**
- Study of galactic (and extragalactic?) propagation of CR, with neutrinos as tracers
- **Test the neutrino sector of the SM and BSM physics**

Advantages of neutrino telescopes

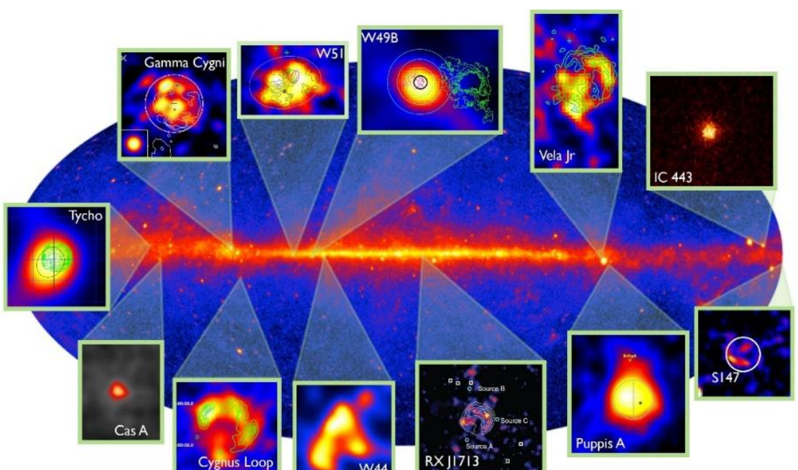
- Very high **duty cycle** (almost 100%)
- Large observation **solid angle** (2π or 4π: different resolutions)
- **Complementary f.o.v.** for Mediterranean and South Pole detectors
- Adequate **angular resolution**, depending on the ν direction, medium and track/shower (0.1^o → 10^o)
- **Online analysis**, fast response (few seconds), immediate alert
- (Neutrinos): no **significantly attenuated**, no **deflected**, during propagation
- (Neutrinos): not significantly absorbed by Earth for E_ν<100 TeV

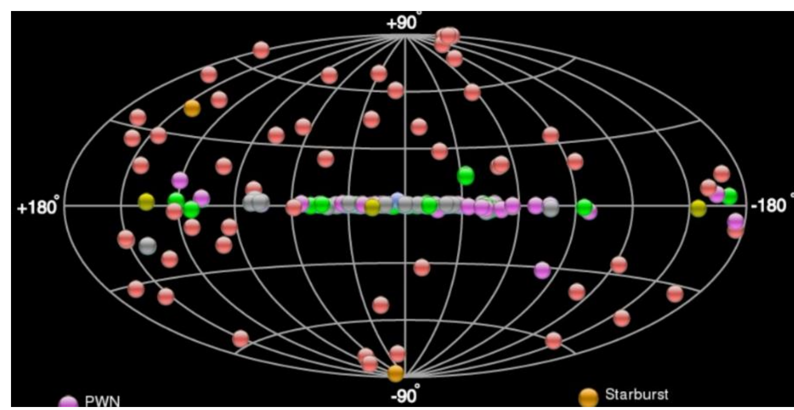
γ-ray telescopes

(Remember)

- Fermi-LAT (GeV)

IACTs (TeV





The “effective area” A_{eff}: quality response

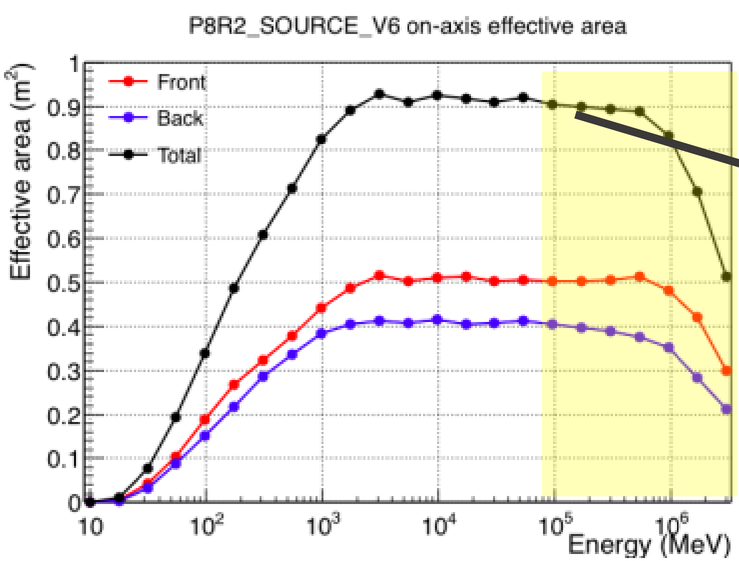
- The rate of observable events [N_{obs} (s^{-1})] in a detector is given by

$$N_{obs} = \int \frac{dN}{dE} \cdot A_{eff} \cdot dE$$

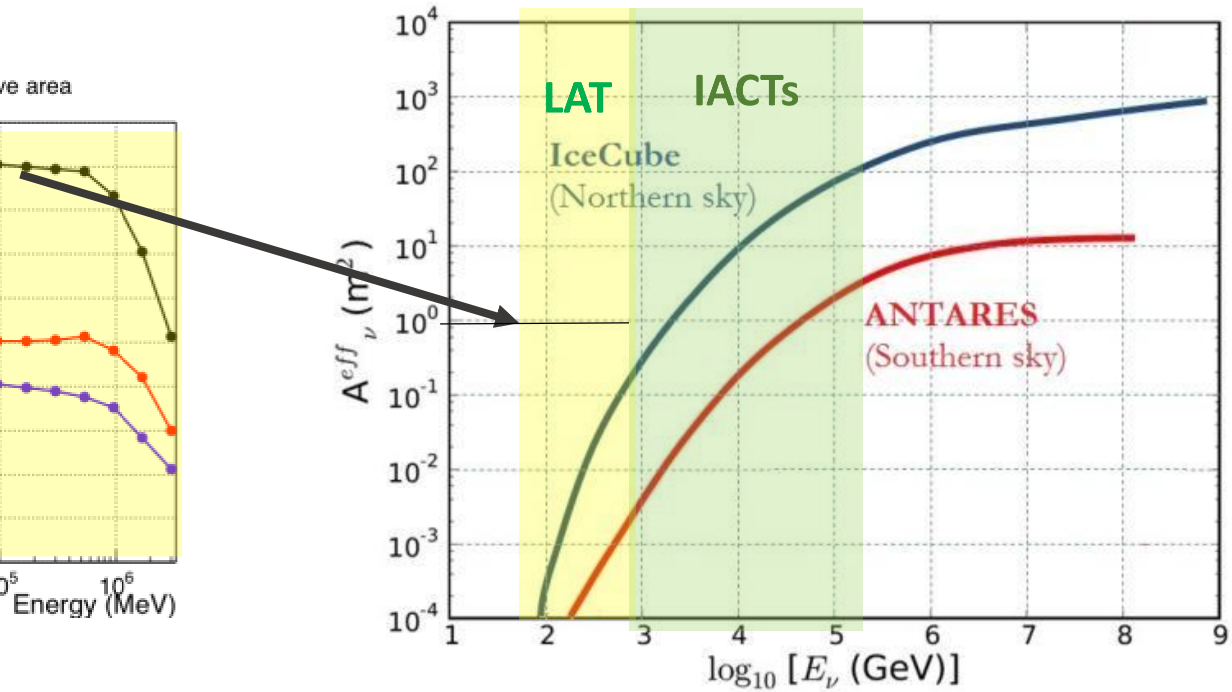
- where $\frac{dN}{dE}$ is the the flux ($cm^{-2}\ s^{-1}\ GeV^{-1}$) of γ or ν;
- The effective area, A_{eff} , depends on the particle cross-section, energy, direction, and analysis cuts (efficiencies)
- A_{eff} must computed by experiments

Drawbacks of ν detector (cross section and…)

- Large background
  - Downward going atmospheric muons
  - Irreducible: atmospheric neutrinos
- **Effective area A_{eff}**: strong function E_ν , analysis-dependent
- Energy range of neutrino telescopes partially overlapping with γ-ray observatories (LAT and IACTs)



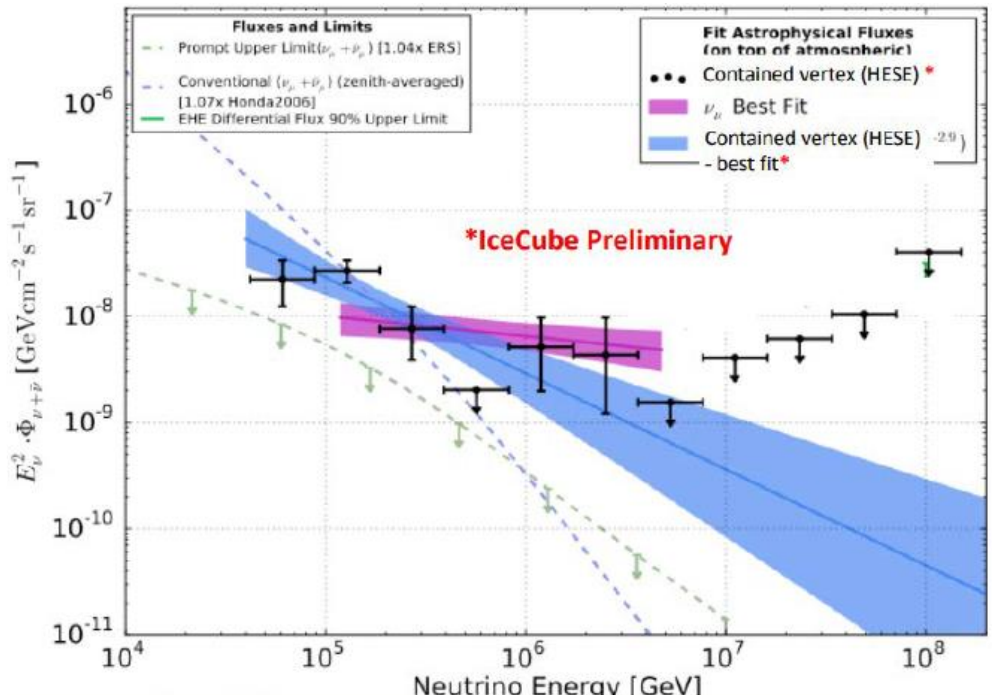
Fermi-LAT **A_{eff}** *vs. E*



ANTARES, IceCube **A_{eff}** *vs. E*

Detecting **cosmic** neutrinos: a threefold way

1. Excess of HE neutrinos over the background of atmospheric events. Measurement of the ν **energy**

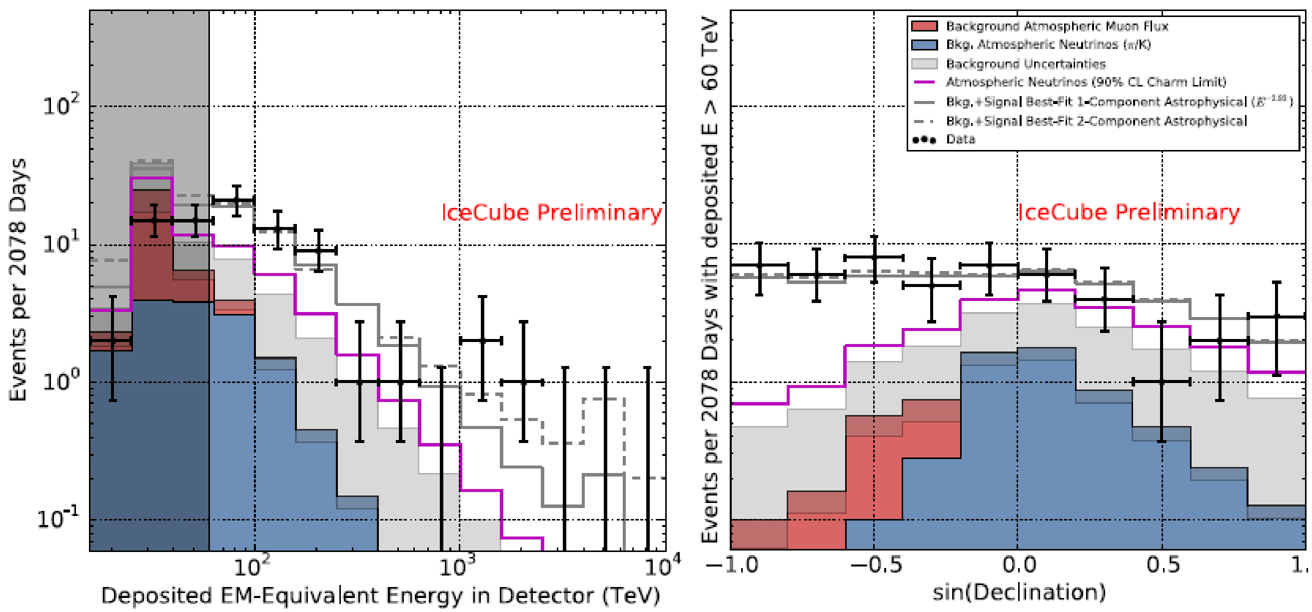


2. Point-like events, significant excess in the sky map. Measurement of the **neutrino direction**

3. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts. Relaxed energy/direction measurement + **transient/ multimessenger** information

IceCube signal: High Energy Starting Events

- «Contained» events (veto outside a fiducial volume), 6 y of data
- Mostly cascased events (ν_e and NC) with poor angular determination
- Good energy estimate, **isotropic**
- Excess over the energy distribution expected for background events
- Excess fitted with a power-law: $\boldsymbol{\Phi_\nu = \Phi_o E^{-\Gamma}}$



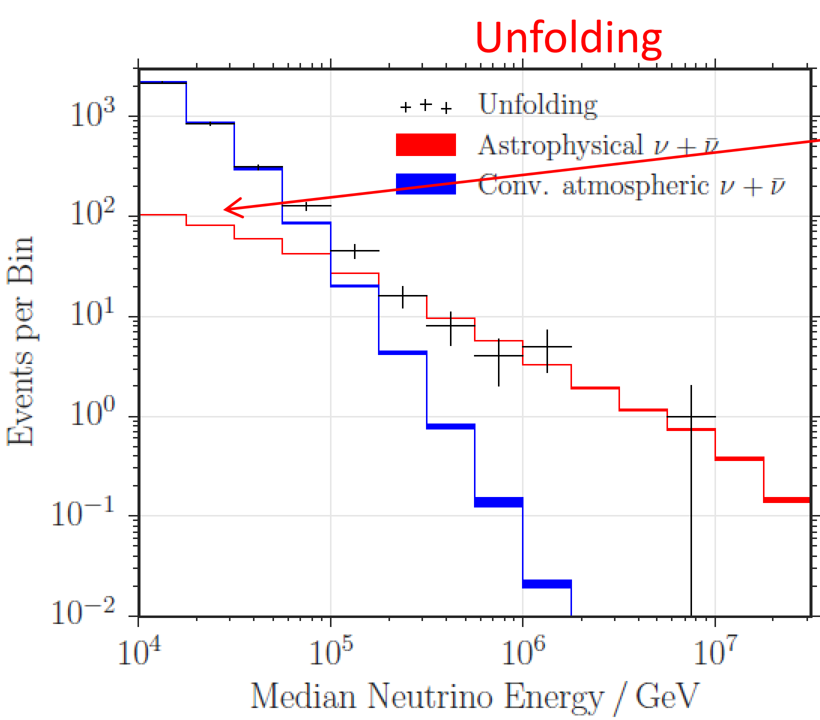
(a) deposited energies

(b) arrival directions

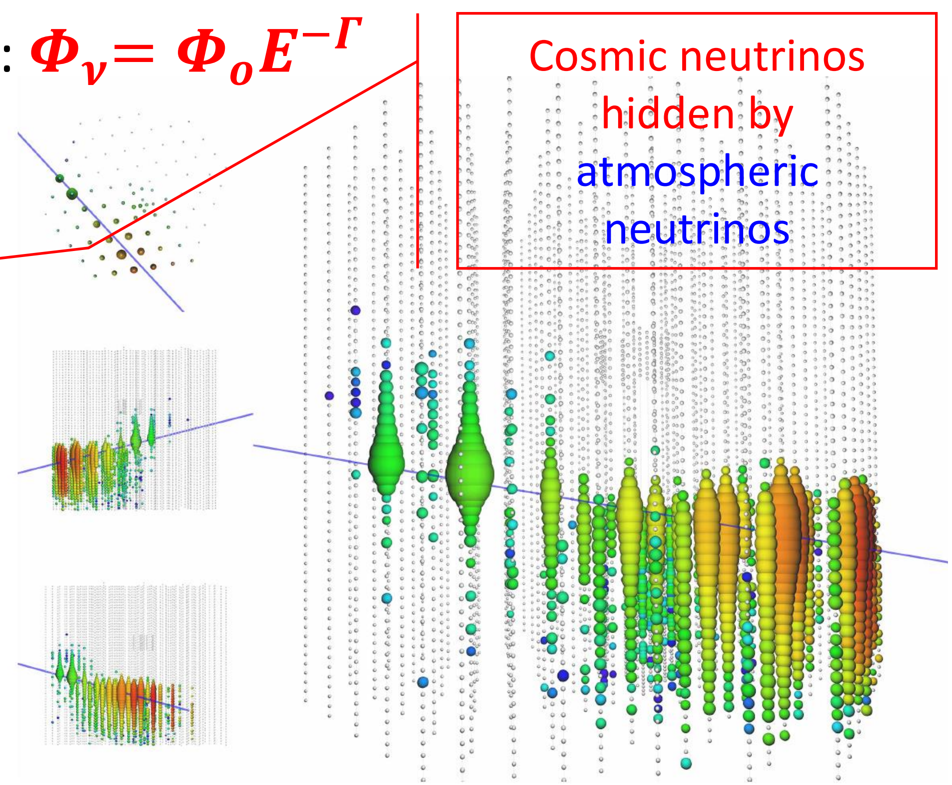
PoS(ICRC2017)981

IceCube signal: up-throughgoing muons

- Tracks produced by ν_μ interactions outside the volume, 6 y of data
- Relatively poor (good) energy (direction) estimate
- Only upgoing → from the Northern sky
- Excess over the energy distribution expected for background events
- Excess fitted with a power-law: $\Phi_\nu = \Phi_o E^{-\Gamma}$

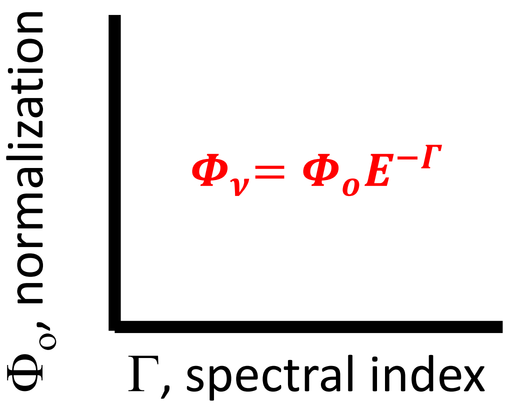


M. G. Aartsen et al. ApJ, 833:3 (2016)



The IceCube spectral anomaly

- A ~3σ discrepancy between sample using the same $\Phi_\nu = \Phi_o E^{-\Gamma}$
- Harder spectrum (Γ~ 2.1) in the Northern Hemisphere
- Softer spectrum in the Southern (Γ~ 2.9)
- A possible explanation: [A. Palladino, MS, F. Vissani JCAP 1612 (2016)]
  - Extragalactic hard spectrum (N+S)
  - + Galactic soft component



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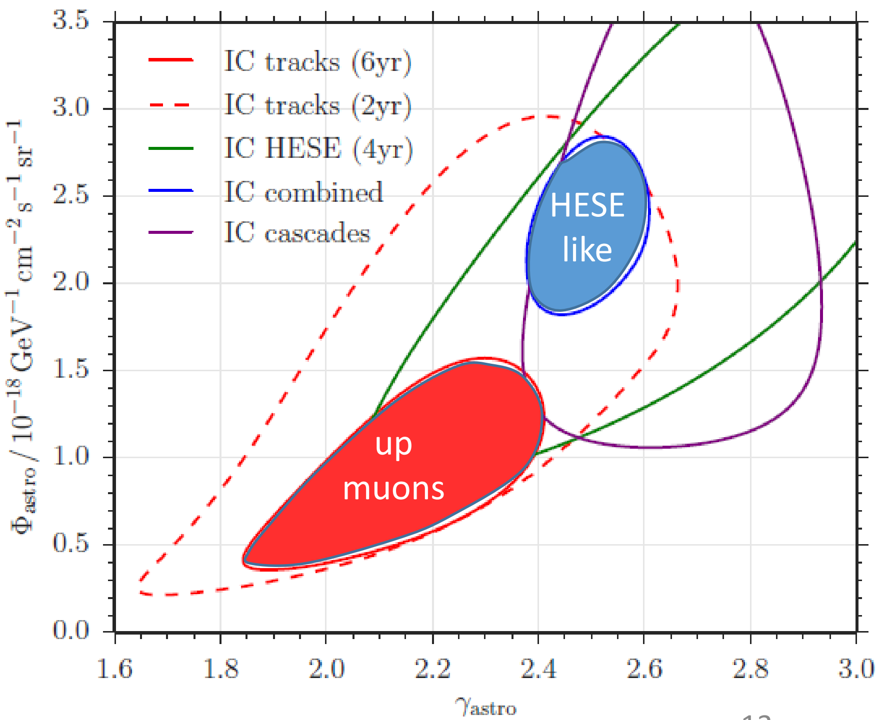
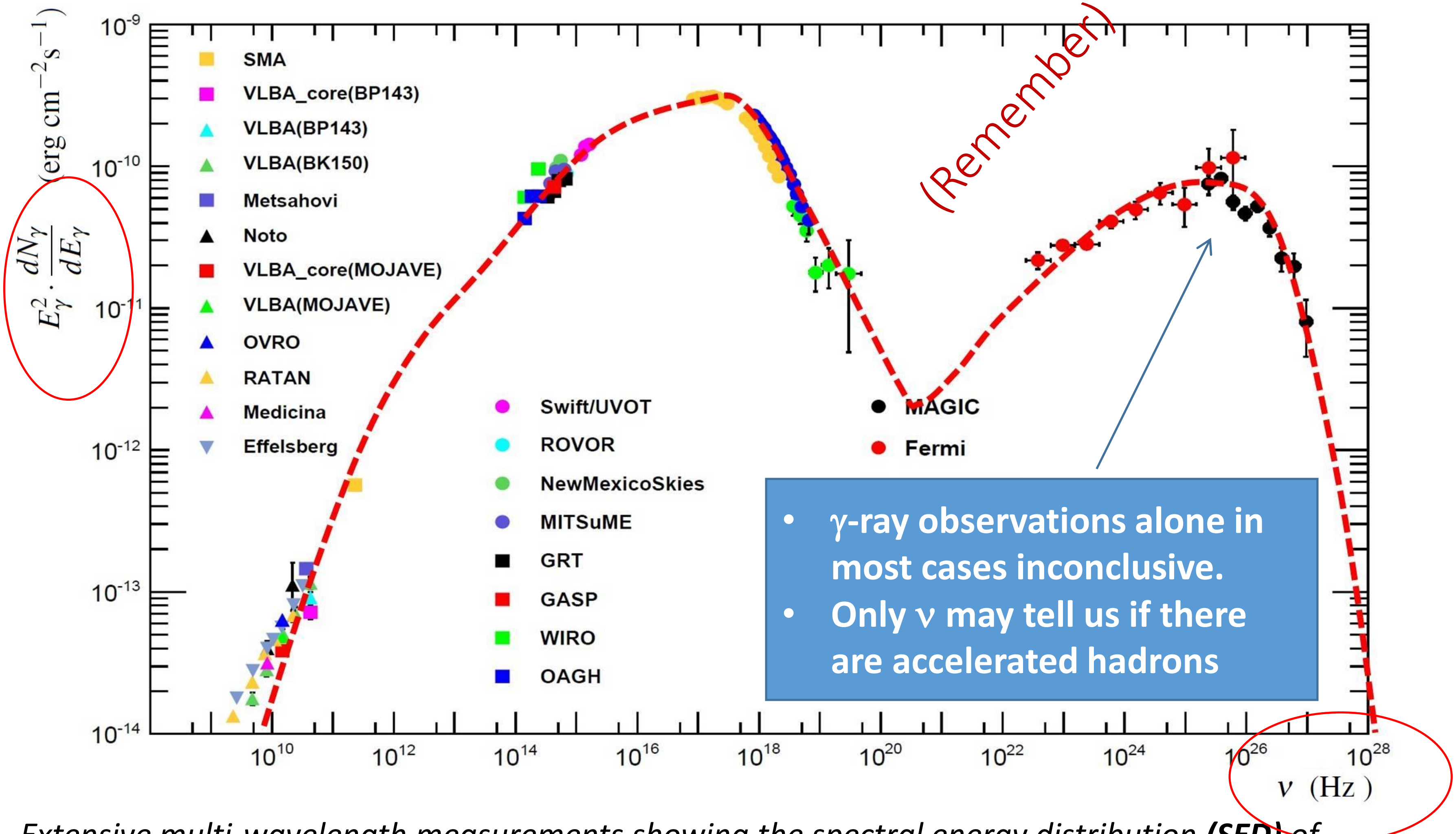


1.I) Why we do not have a "neutrino map"?

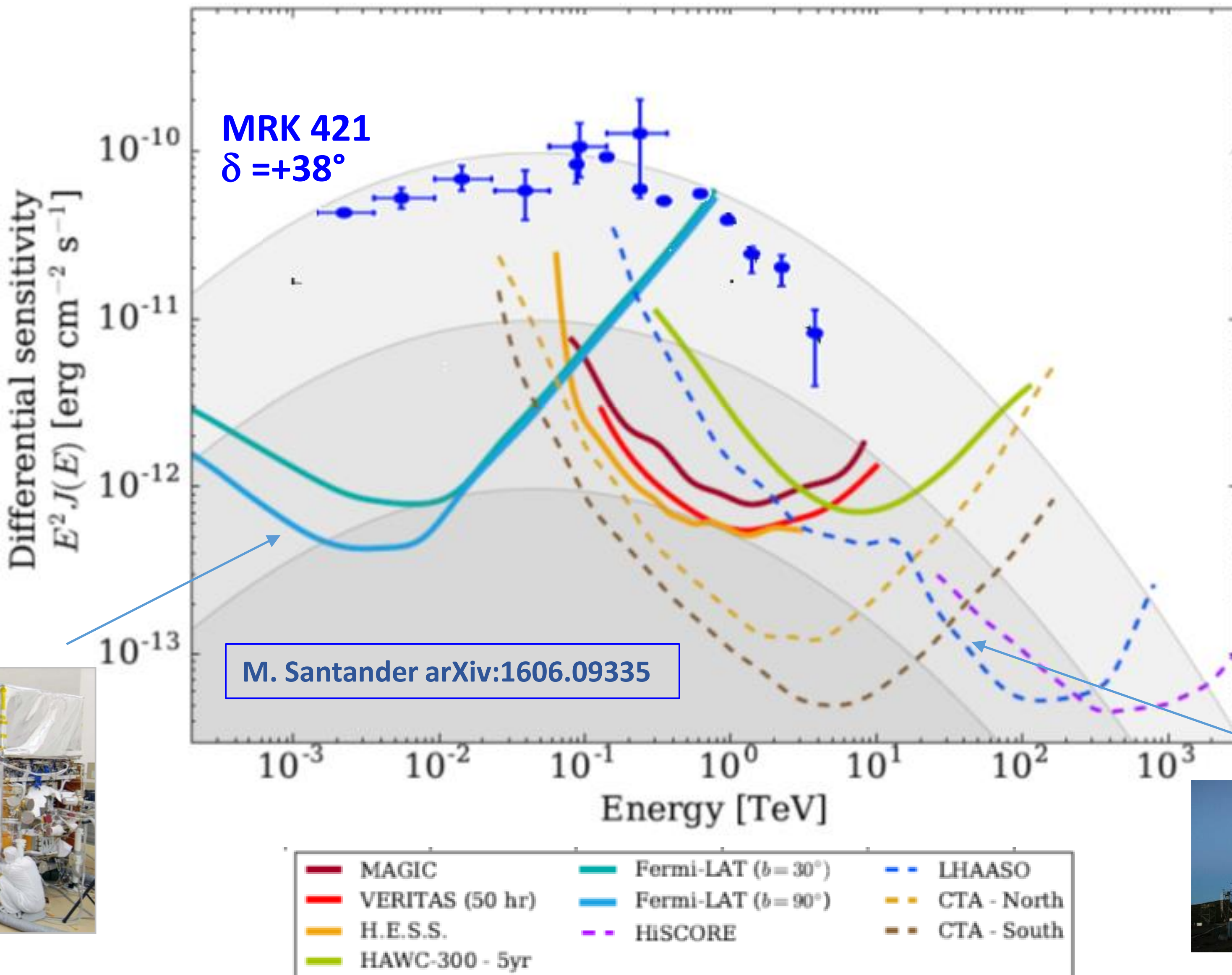
Multi-wavelength observation: Mrk421



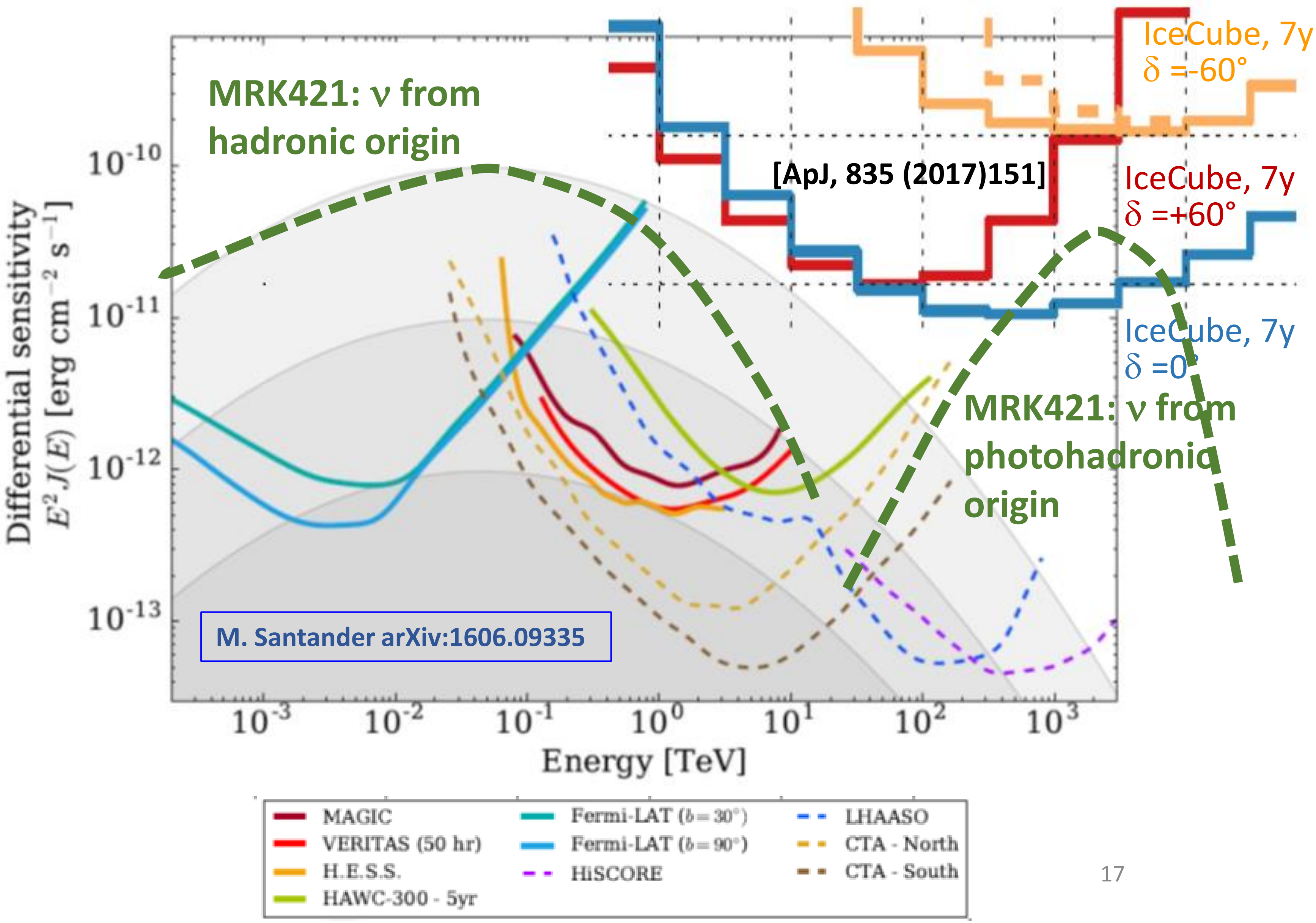
- γ-ray observations alone in most cases inconclusive.
- Only ν may tell us if there are accelerated hadrons

Extensive multi-wavelength measurements showing the spectral energy distribution ***(SED)*** *of* ***Markarian 421 from*** *observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data*

γ and ν discovery potential



γ and ν discovery potential



(Previous plots)

I. **Differential** **<u>5σ sensitivity</u>** of **current** (solid) and **future** (dashed lines) γ-ray observatories.
   - **Fermi-LAT**: curve for a **10 year exposure**.
   - **VERITAS, MAGIC, H.E.S.S. and CTA**: **50 h** of observation.
   - **HAWC 300, HiScore and LHAASO** arrays: **5-year exposure**.
   - **Shaded grey regions**: 100%, 10%, and 1% levels of the Crab

II. **Measurement of the MK421 flux (LAT+Magic)**

III. **7y** **<u>Discovery potential</u>** **(5σ)** for IceCube [ApJ, 835 (2017)151] analysis in different bins of neutrino energy E using an E^{-2} spectrum. Three different declinations are shown: Up-going **(δ=+60°)**, horizontal **(blue, δ = 0°)**, and down-going **(yellow, δ = −60°)** events.

IV. Neutrino flux from **pp** or **pγ** models

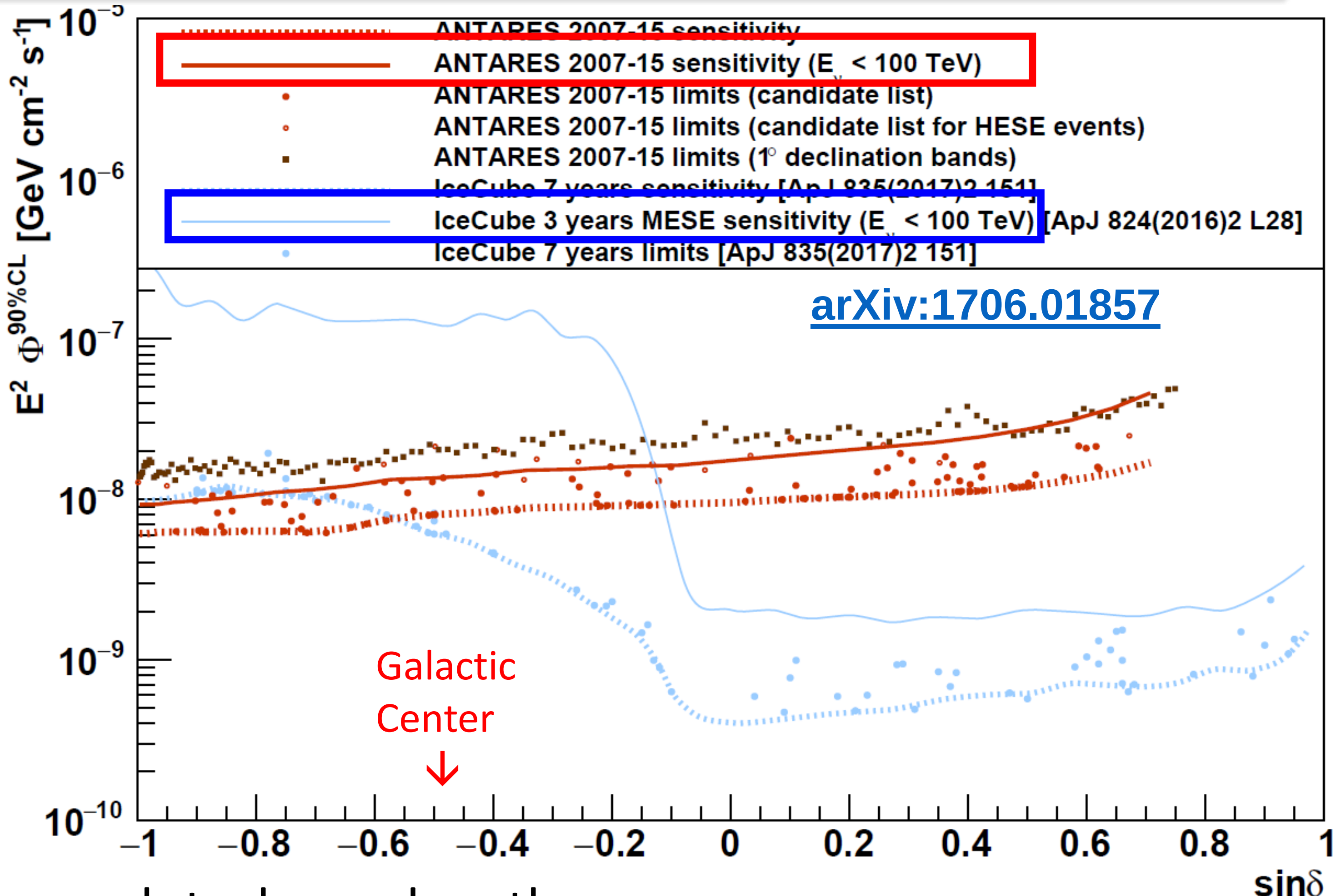
U.L. and Sensitivities (also E_ν<100 TeV)

IC signal:

1 p. source →

10 p. sources →

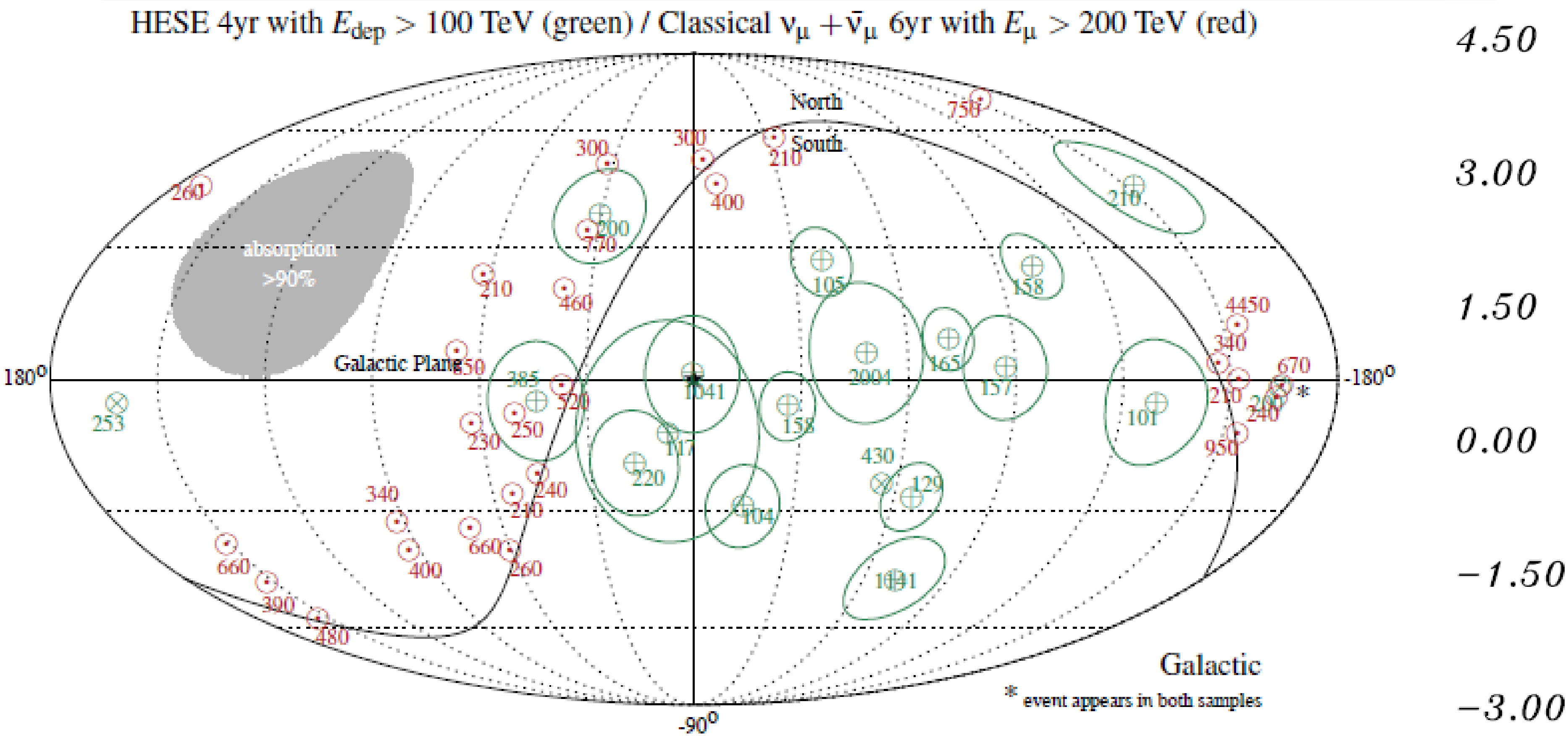
100 p. sources→



Note: these plots depend on the

- assumed **spectral index** of the source
- differential **energy sensibility** of the detector

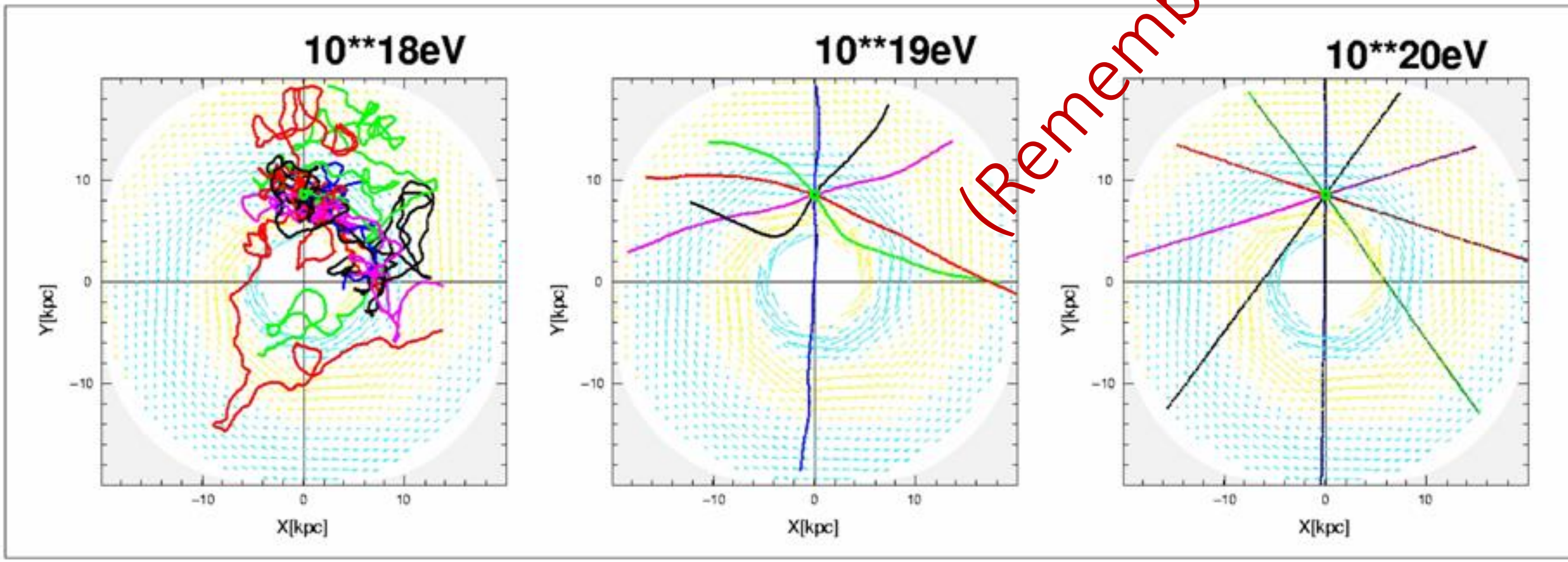
1.II) Correlation UHECRs and Neutrinos



- Map in Galactic coor. of the significances of excesses in 12°-radius windows for E>54 EeV **PAO** events. Dashed line=super-Galactic plane; white star= Cen A
- IceCube cascades (plus signs) and high-energy tracks (crosses), and of the UHECRs detected by **PAO** (circles) and **TA** (triangles).

CR confinement in our Galaxy

(Remember)

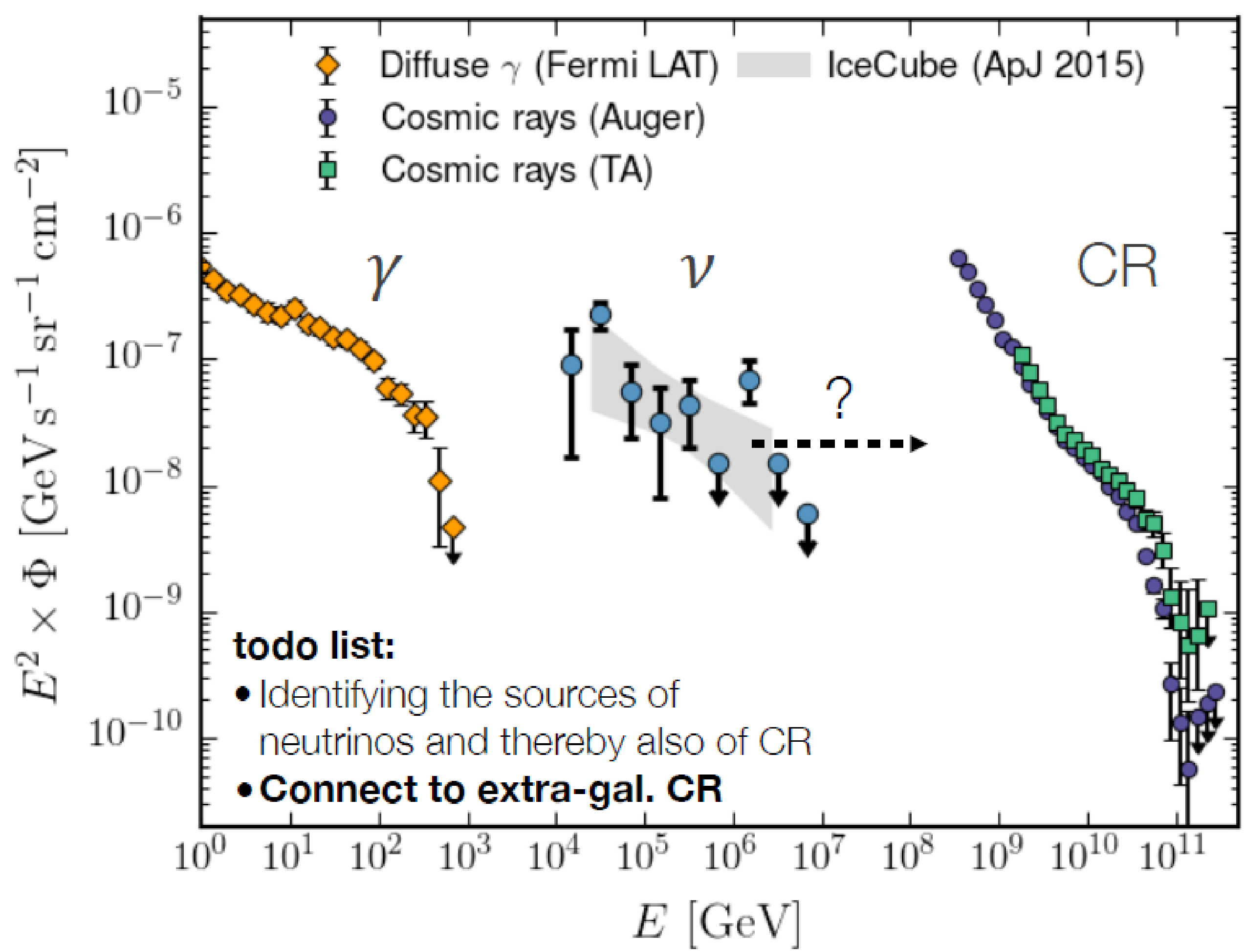


~ 10^{18} eV: RC well confined within our Galaxy

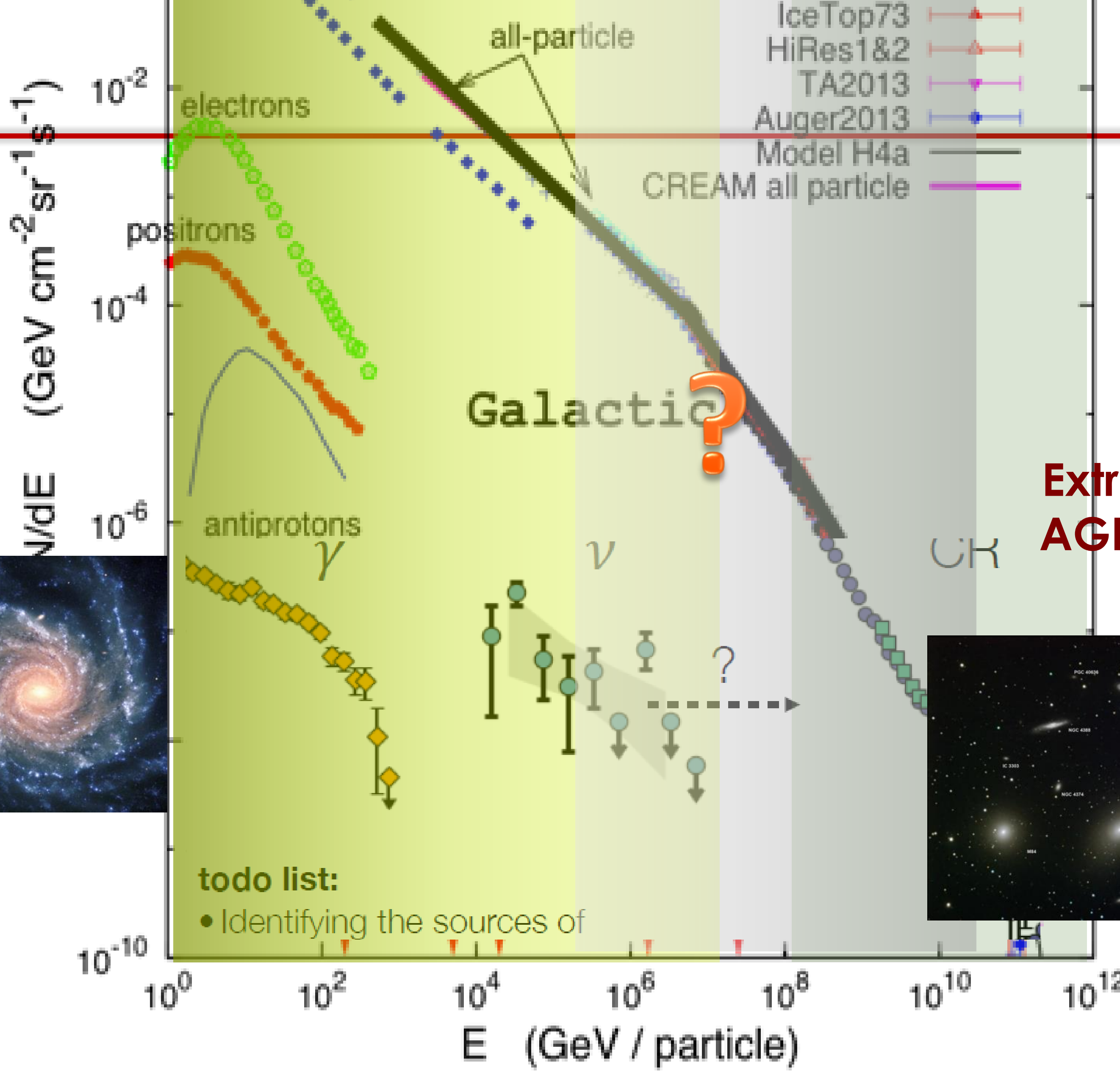
$\gtrsim 10^{19}$ eV: probably of extragalactic origin (@ 10^{20} eV deviation in our Galaxy smaller than 1°)

$$r(kpc) \cong \frac{E(EeV)}{ZB(\mu G)}$$

- At the highest energies, huge experiments are necessary to detect few CRs
- Flux @10^{20} eV ~ **1 particle/century/km²** .


Diffuse γ (Fermi LAT)
IceCube (ApJ 2015)
Cosmic rays (Auger)
Cosmic rays (TA)
γ
ν
CR
?
todo list:
• Identifying the sources of neutrinos and thereby also of CR
• Connect to extra-gal. CR
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}

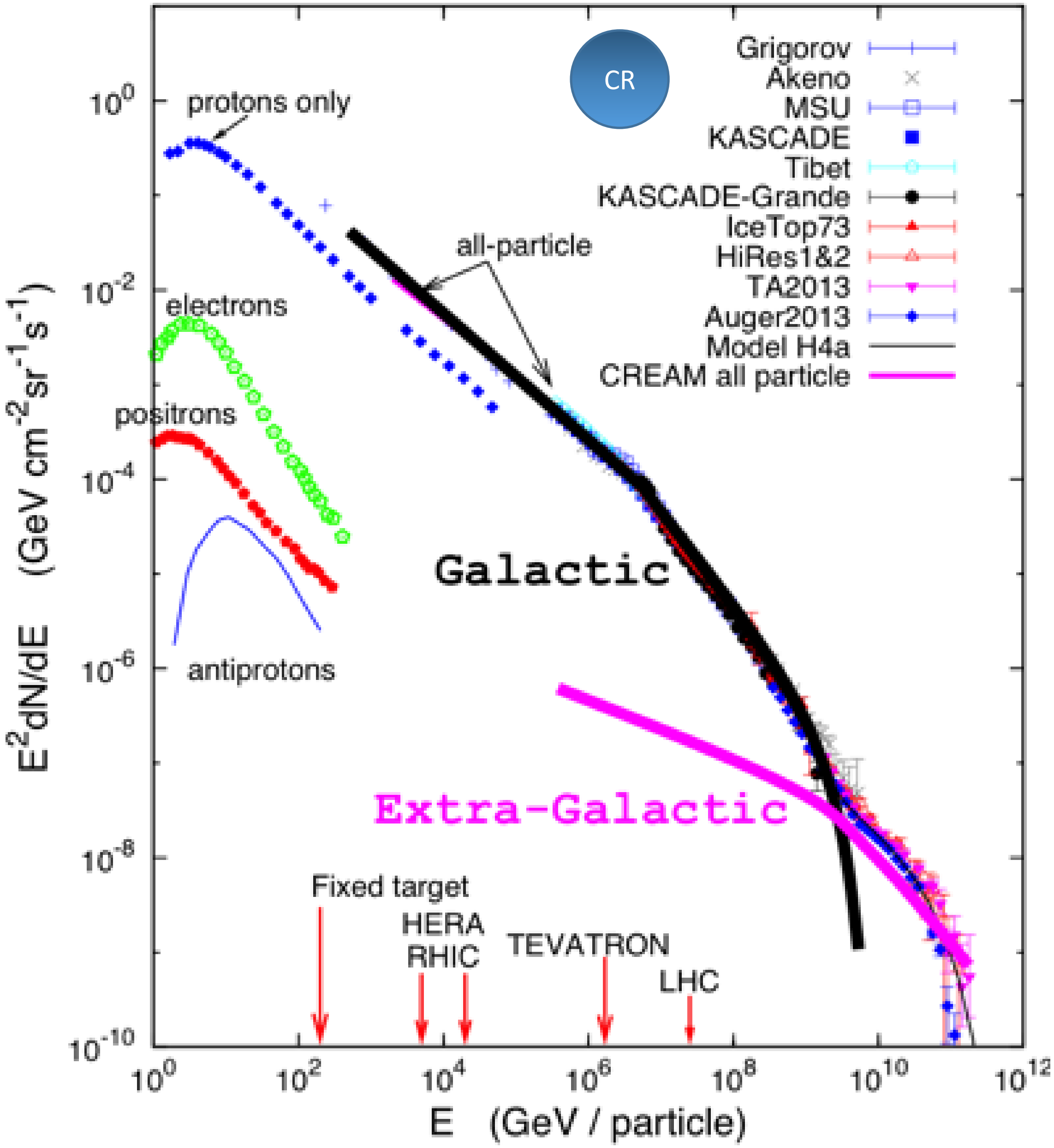
CR

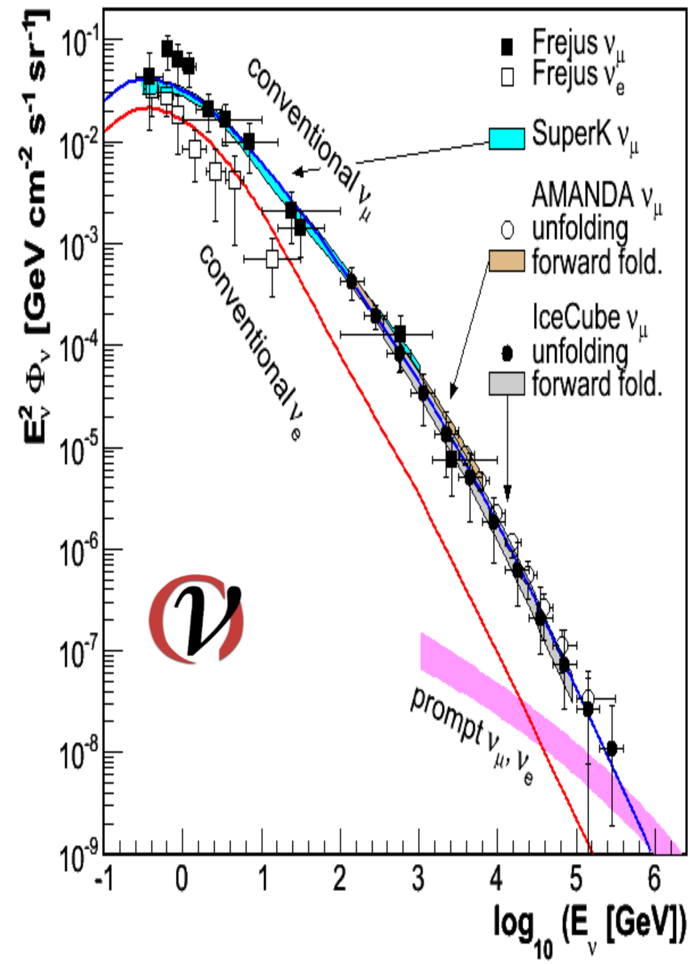


Galactic SNRs (?)

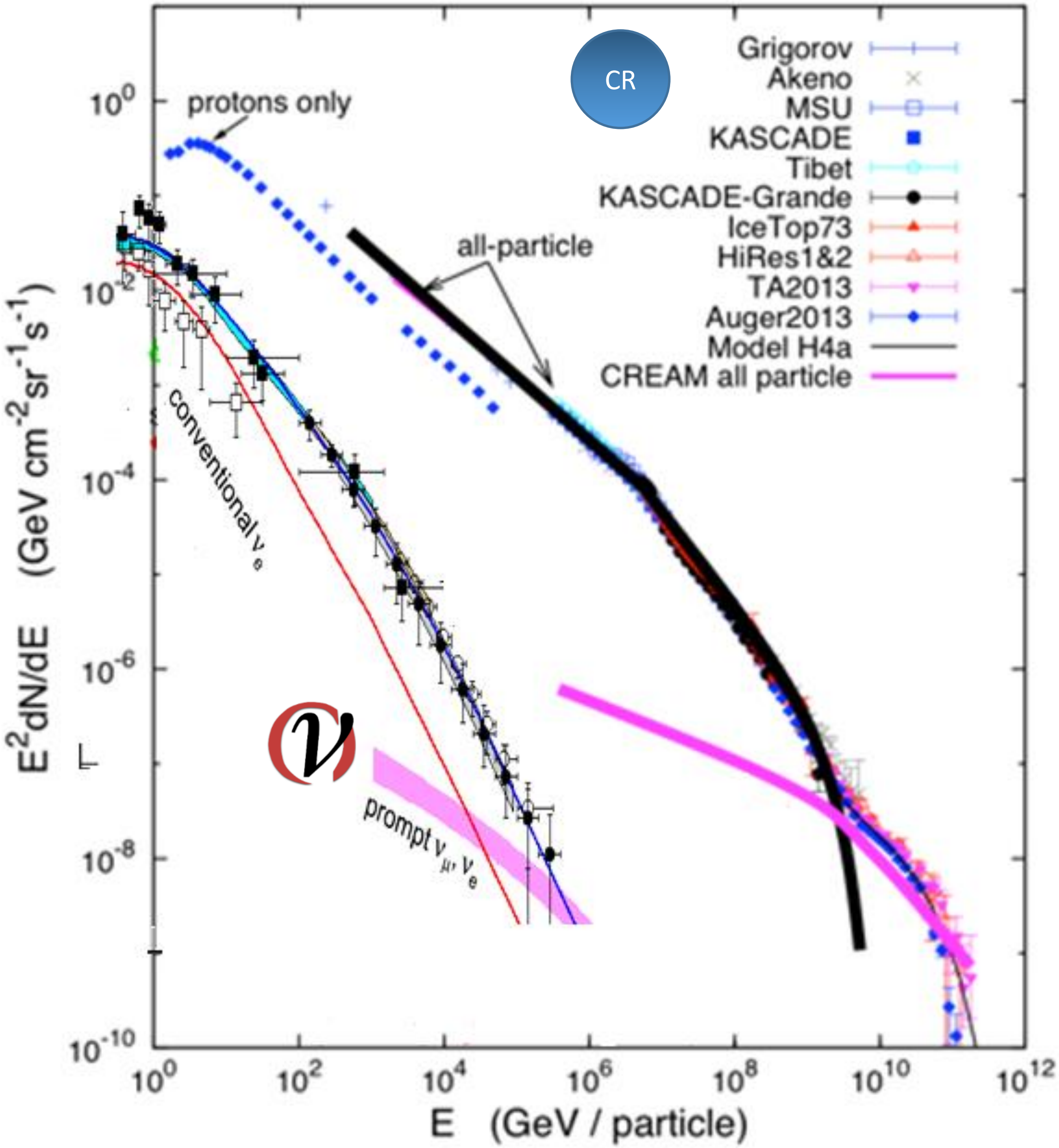
ExtraGalactic AGN, GRBs (?)

Cosmic rays and atmospheric neutrinos

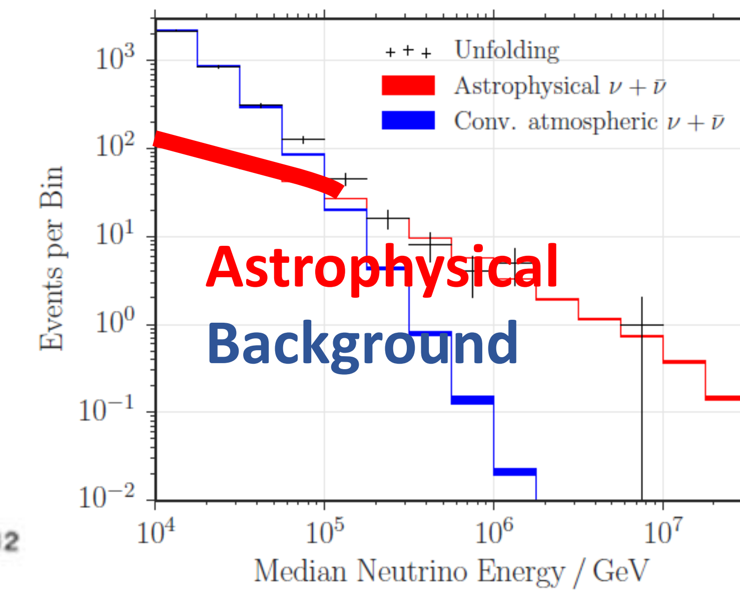




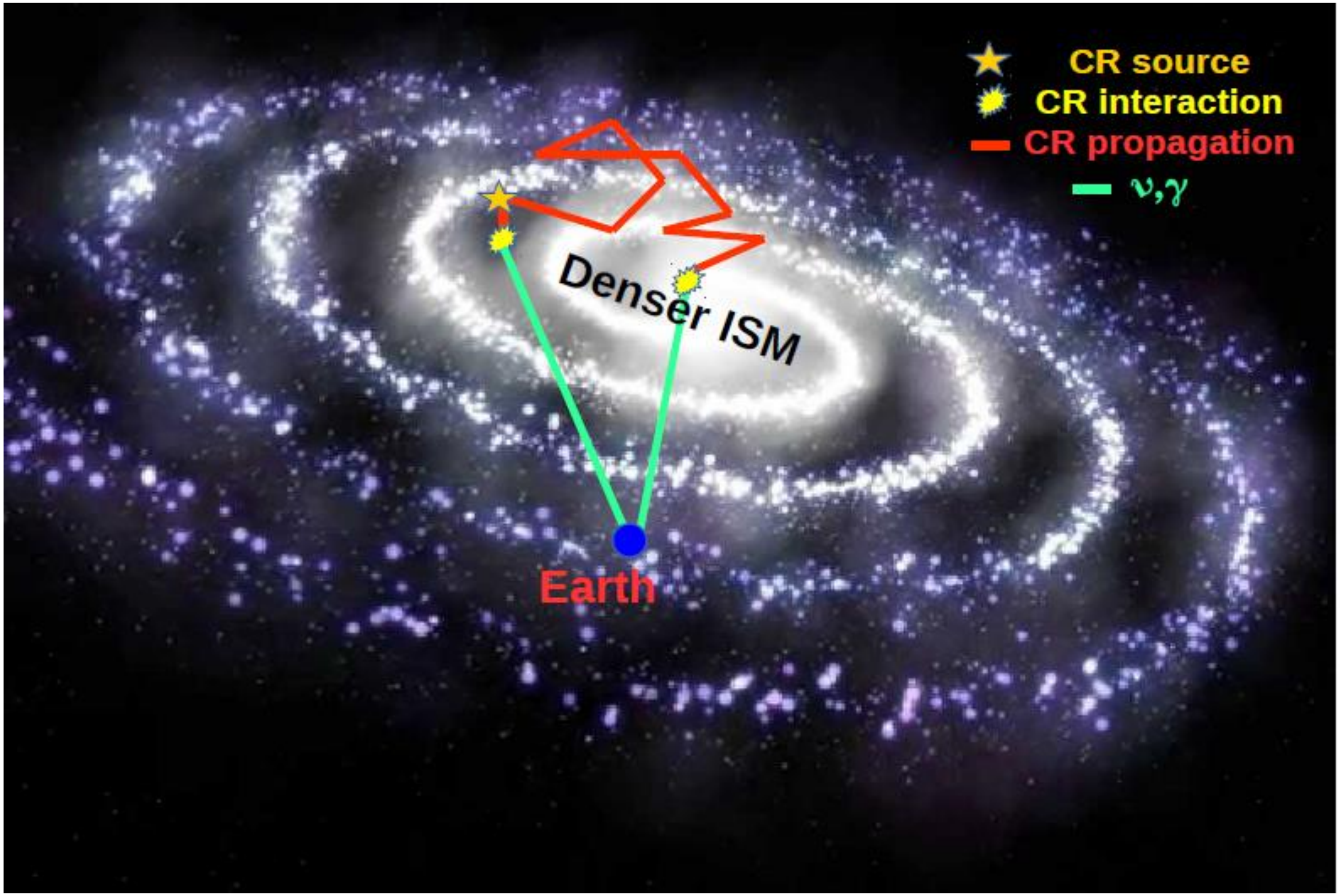
Cosmic rays and atmospheric neutrinos



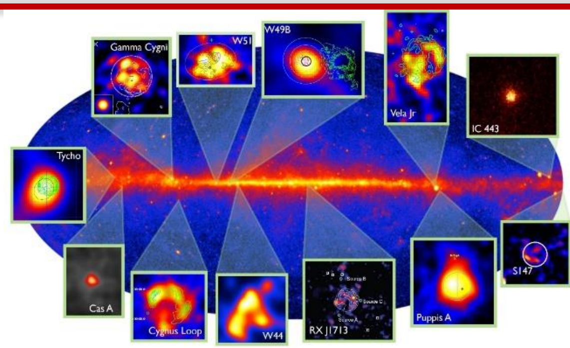
- PeVatrons in our Galaxy?
- Disantangle among lepton and hadrons not assured with γ-rays alone
- CR origin of the **ν signal** near source, origin of the **ν background** on Earth!



1.III) About **Galactic** neutrinos



Models of CR propagation in the Galaxy



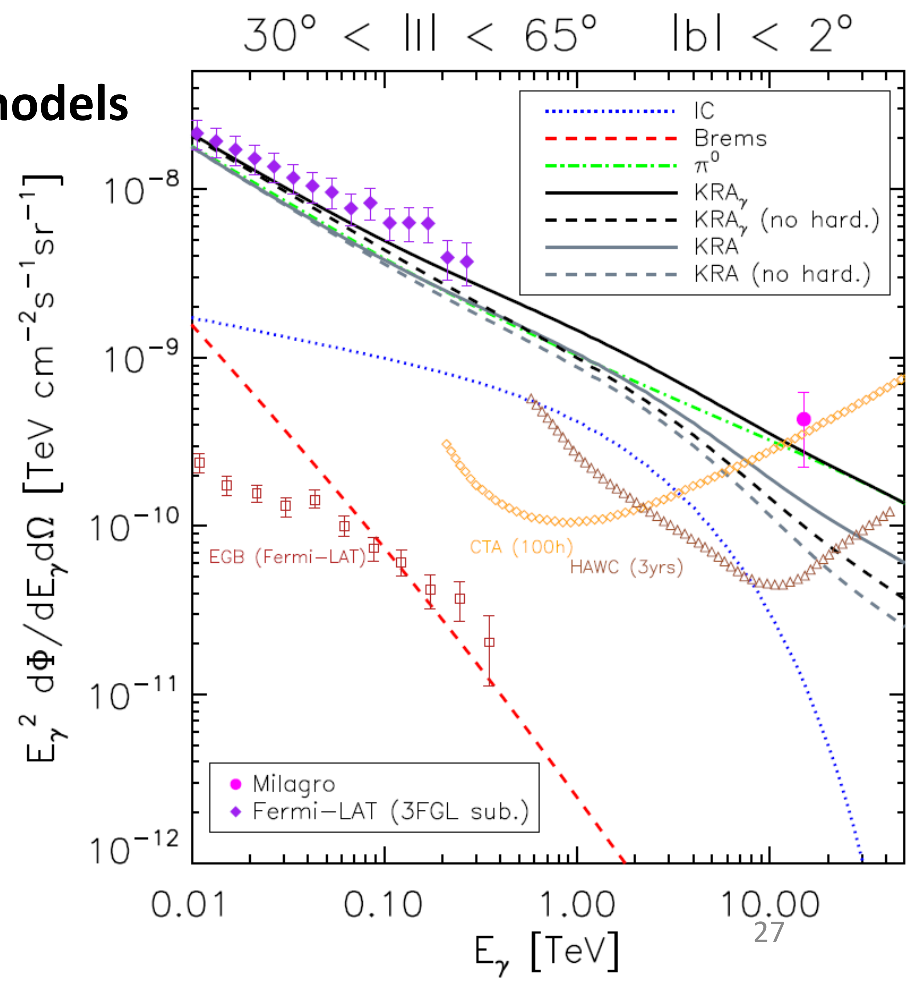
CR → **Diffuse γ-rays**

Input Ingredients of diffusive transport models

- Distribution of source
- Galactic magnetic field
- Distribution of matter in the Galaxy
- Interaction models and cross sections

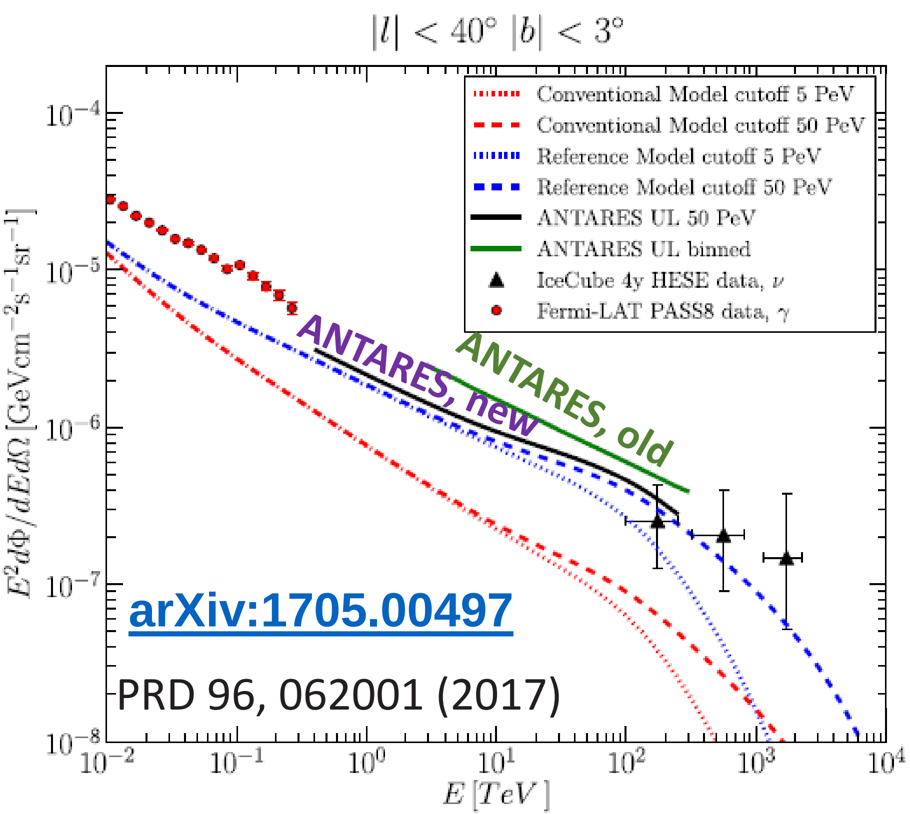
..and must reproduce data on

- Secondary nuclei
- Antimatter
- Diffuse γ-rays
- Diffuse neutrinos (still undetected)

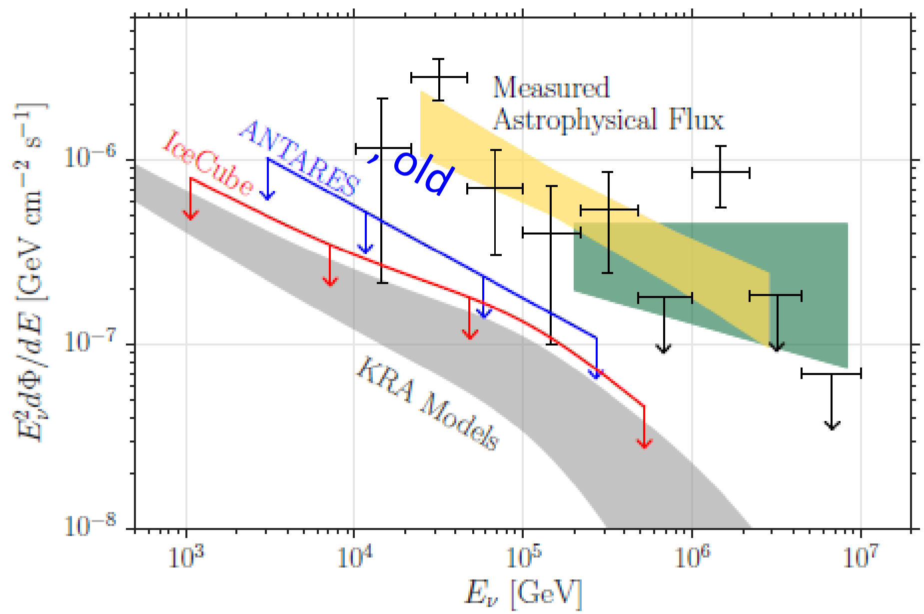


CR propagation: a fundamental test

- Neutrinos and γ-rays produced during **CR** diffusion in the Galaxy
- Model reproduces diffuse **γ-rays** observed by LAT, HESS, Milagro
- No excess of neutrino events observed by ANTARES/IC



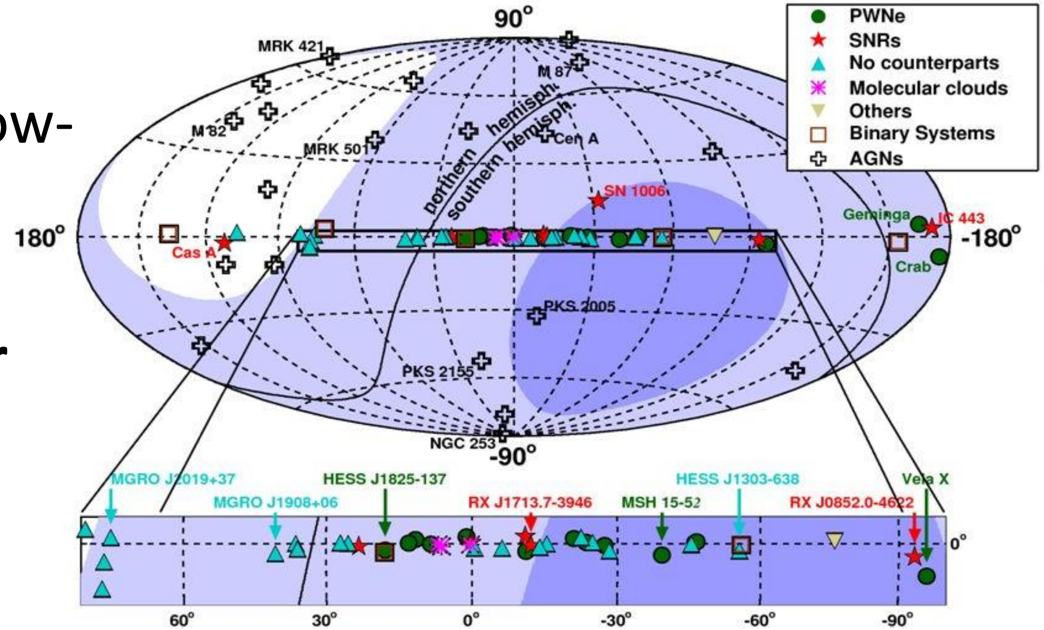
arXiv:1707.03416



CR → **Diffuse ν ' s**

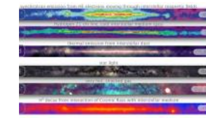
Mediterranean vs. South Pole telescopes

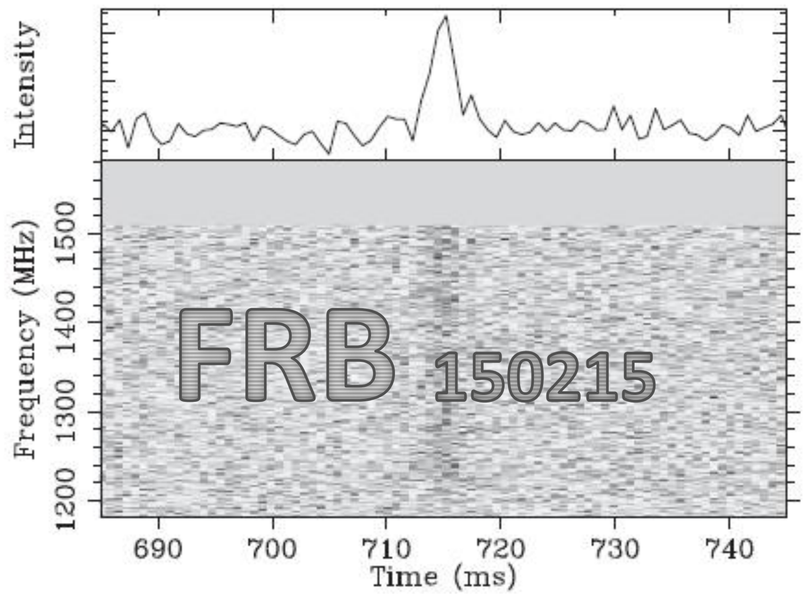
- Most **galactic sources** produce upgoing events in the "**golden channel**" (ν_μ)
- Larger depth (~2.5 km for ANTARES, ~3.5 km for KM3NeT/ARCA) allows larger reduction of atmospheric muons
- KM3NeT: OM segmentation with small PMTs (further background reduction)
- **Looser cuts** select more low-energy events
- Lower scattering in water w.r.t. ice → better **angular resolution** $\Delta\theta$;
- Signal/background $\propto \Delta\theta^{-2}$

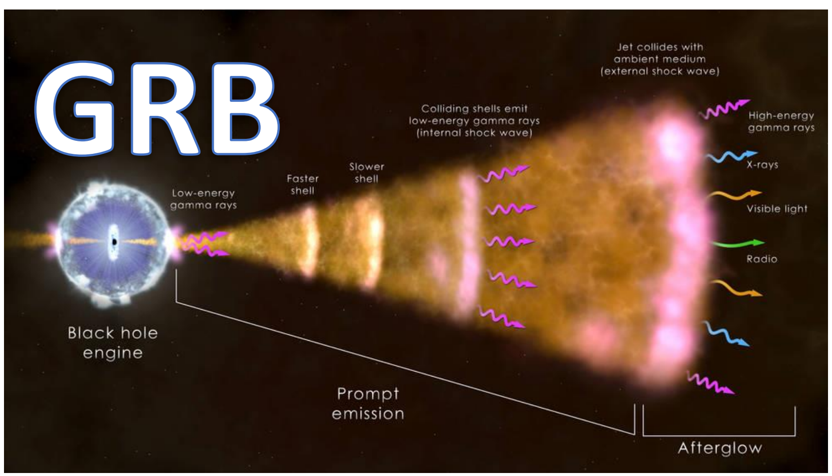


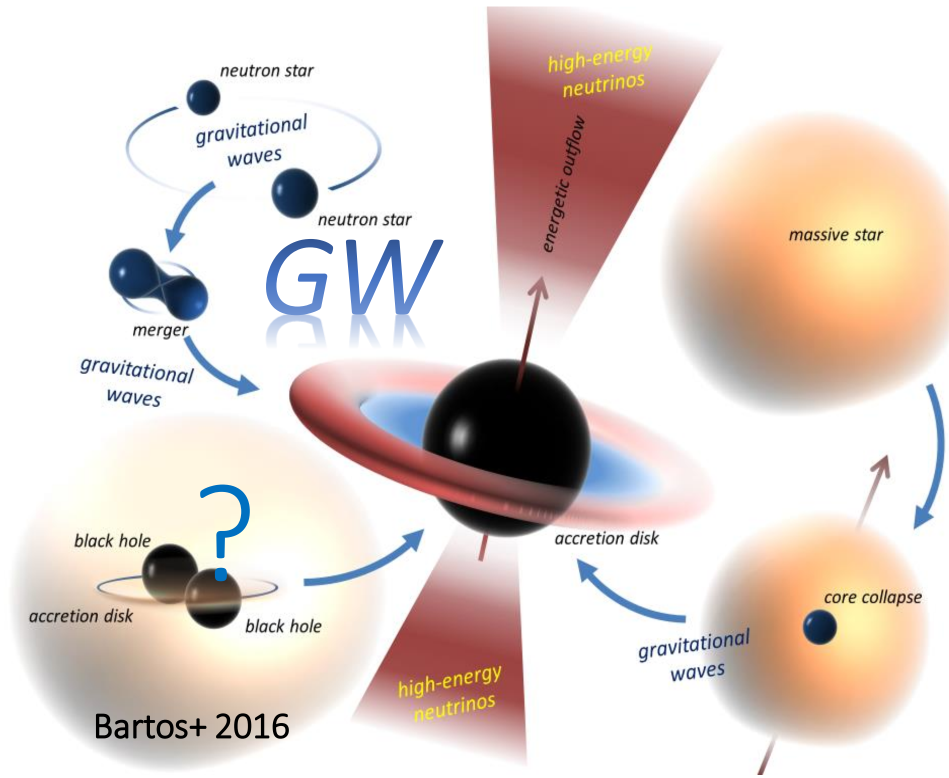
(see J. Zornoza)

2) About **ExtraGalactic** sources







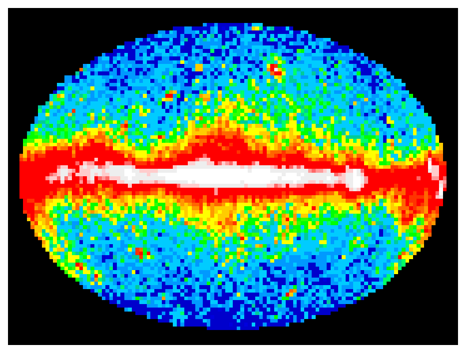


2.I) Gamma Ray Bursts (GRBs)

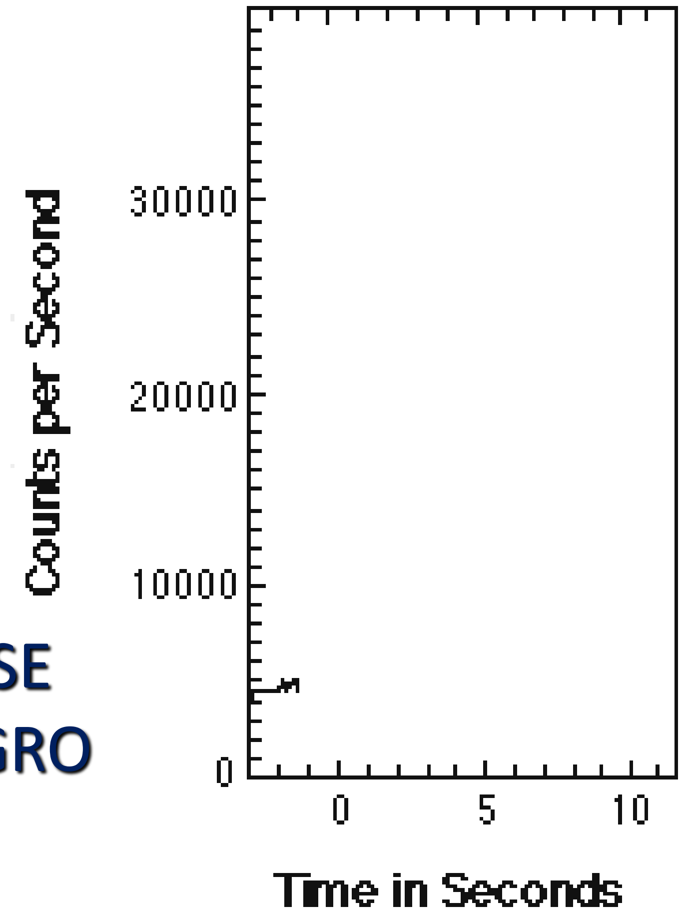
- Until ~20 y ago, GRBs were the first unknown in HE astronomy.
- They were discovered serendipitously in the late 1960s by U.S. military satellites looking for Soviet nuclear testing in violation of the atmospheric nuclear test ban treaty.

- These satellites carried γ-ray detectors since a nuclear explosion produces γ–rays.

- **GRBs are short-lived bursts of γ–rays.**
- At least some of them are associated with a special type of Sne;
- GRBs shine hundreds of times brighter than a typical SN, making them the brightest source of γ–rays in the observable Universe.

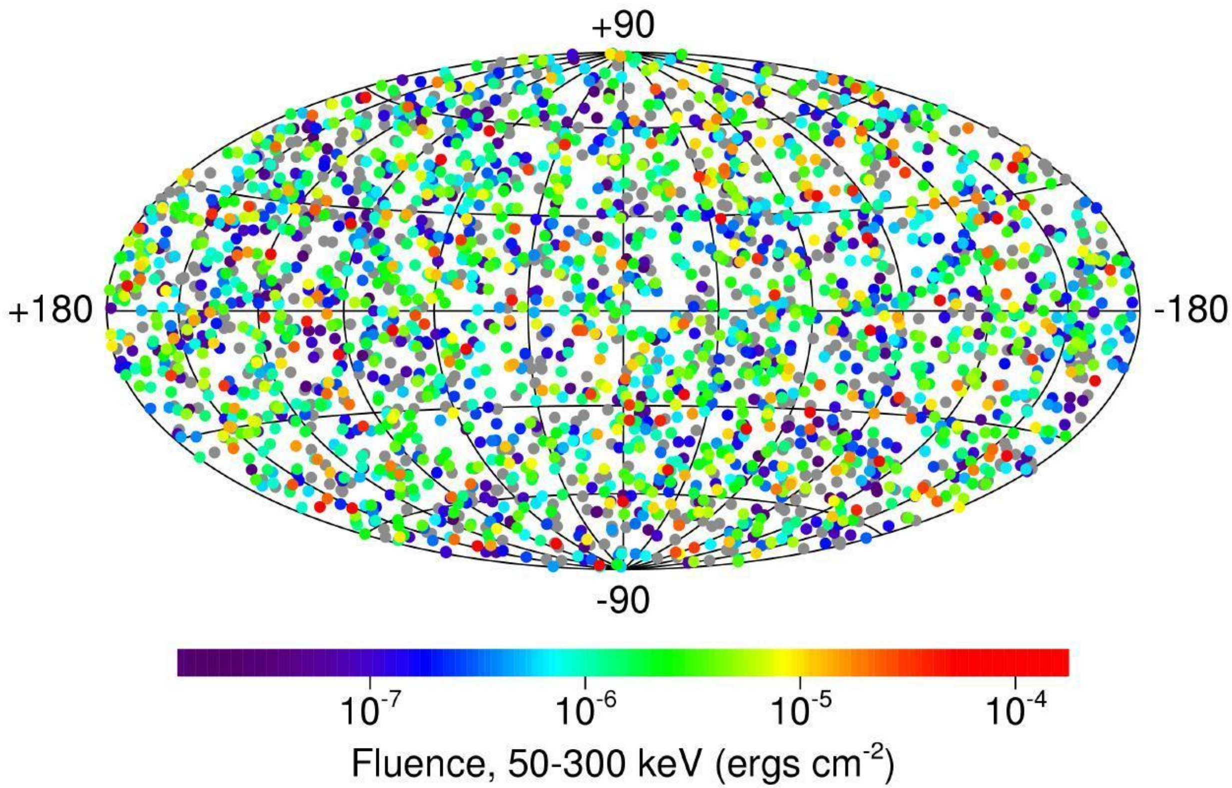


BATSE
on CGRO



The 2704 BATSE GRBs

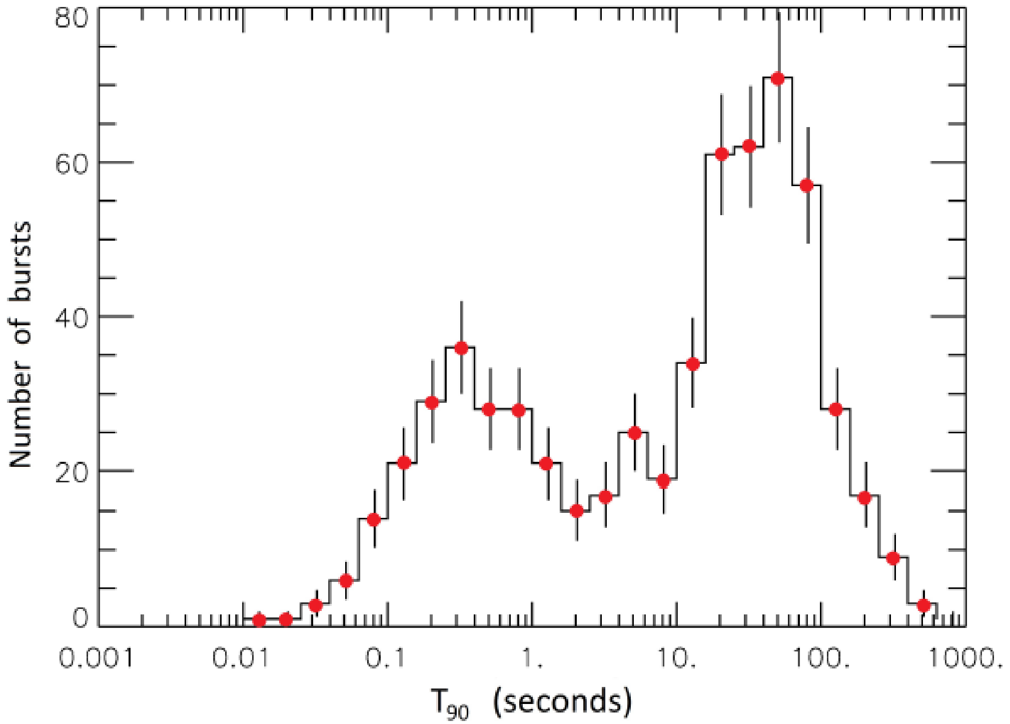
- Map of the locations of a total of 2704 GRBs recorded with the **BATSE** on board NASA's CGRO during the nine-year mission.
- GRBs are detected roughly once per day, from random directions in the sky by satellite experiments;



- The isotropy of the GRB distribution is evident from this figure.
- The projection is in galactic coordinates; the plane of the Milky Way Galaxy is along the horizontal line at the middle of the figure

Long and short GRBs

- As recently as the early 1990s, astronomers didn't even know if GRBs originated in our Galaxy or at cosmological distances
- Two classes of GRBs: **long- and short-duration bursts**.
- Long GRBs last more than 2 s; short-duration ones less than 2 s;
- Long and short duration GRBs are created by fundamentally different physical properties

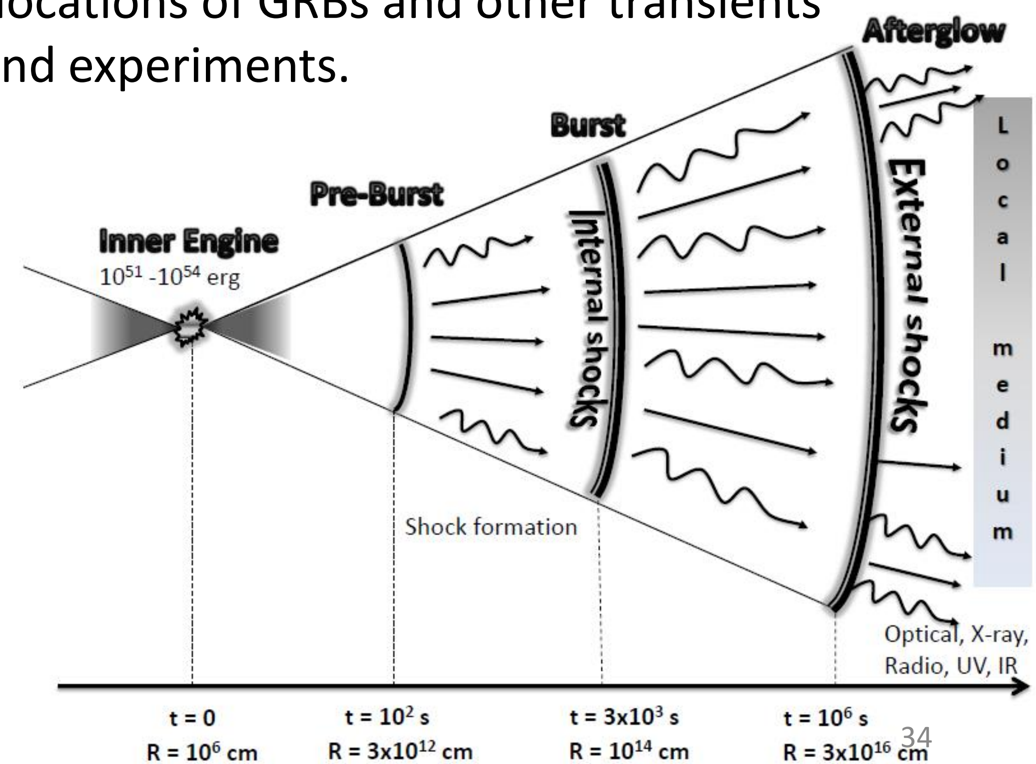


- Possible candidates for **long GRBs are core collapse of a special kind of very massive star**. This core collapse occurs while the outer layers of the star explode in an especially energetic supernova (the “hypernova”, 100 times the SN).
- Possible candidates for **short GRBs are mergers of neutron star binaries (**or NS-BH), which lose angular momentum and undergo a merger (kilonova)

Why they were so important?

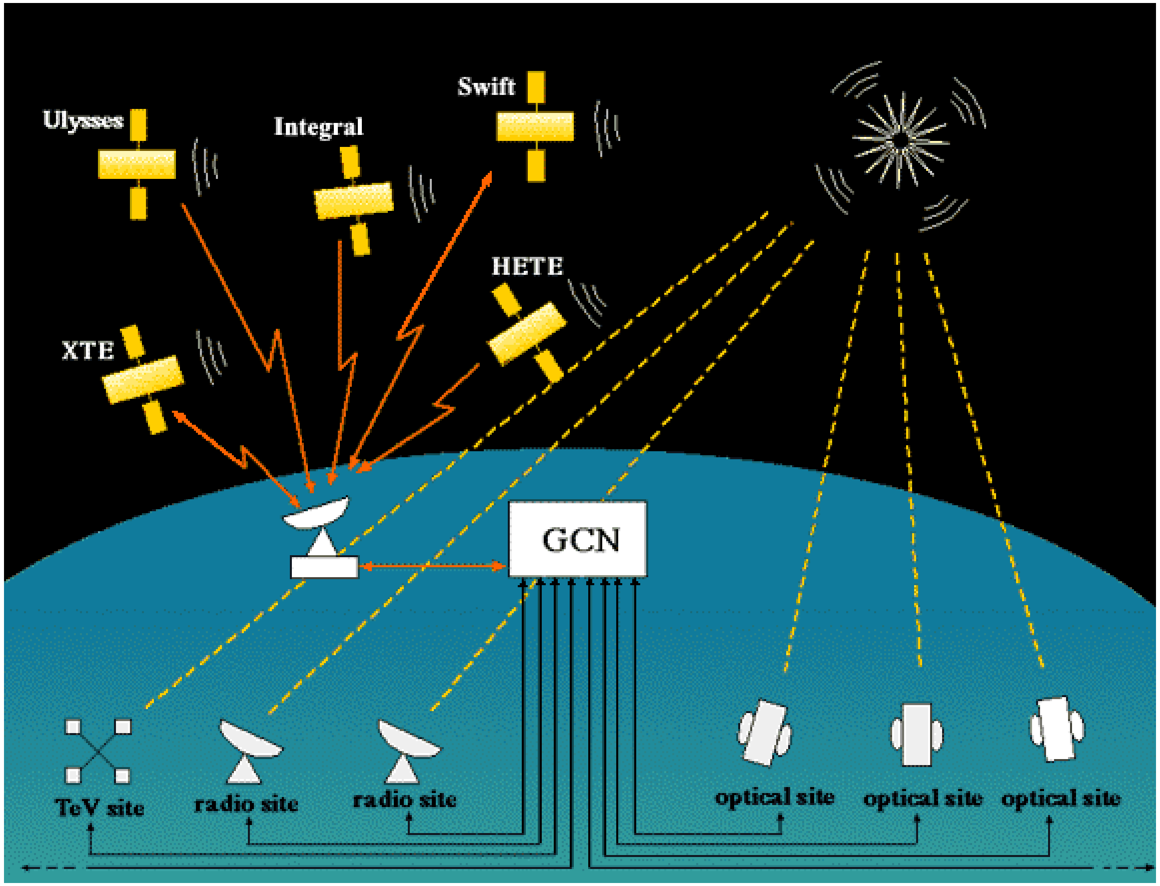
- GRBs are the most energetic transient eruptions observed in the Universe
- GRBs are observed up to z ~ 9
- The discovery of GRBs stimulated a series of space experiments dedicated for their searches that greatly improved our knowledge during the last 20 y;
- As transient, a dedicated network of observatories was created: the **GCN (Gamma-ray burst Coordinates Network)**
- The GCN system distributes the locations of GRBs and other transients detected by spacecraft and ground experiments.

- The Fireball model is the most widely used theoretical framework to describe the physics of the GRBs.
- It originates from considerations on the total energy release of a GRB and its extremely short variability time



The GCN network

- The **GCN** is a system that distributes information about the location of GRB, called *notices*, when a burst is detected by various spacecraft.
- The GCN also automatically receives and distributes messages, called *circulars*, about follow-up observations to interested individuals and institutions.
- Follow-up observations may be made by ground-based and space-based optical, radio, X-ray and meutrino observatories

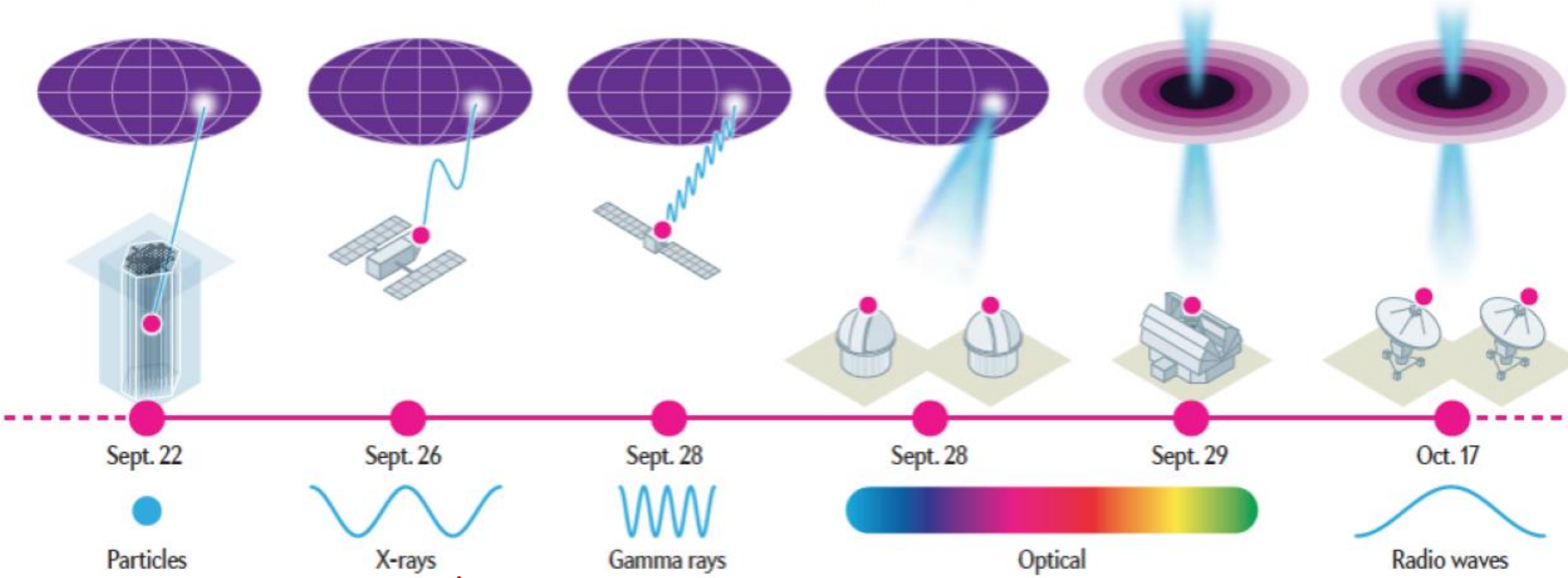


Breaking news

Many Messengers

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.



(see J. Zornoza)

Finkbeiner (Scientific American)

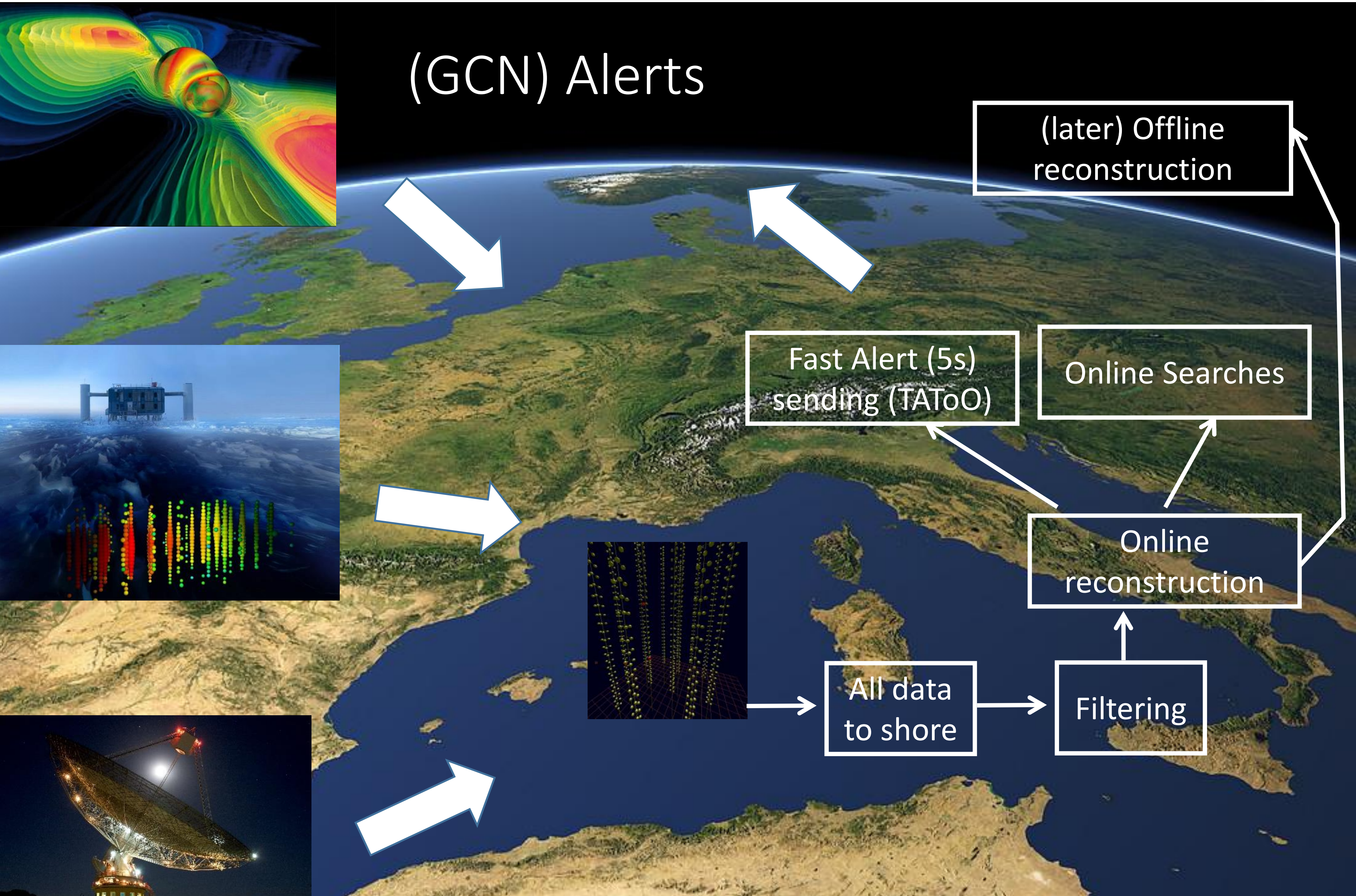
…and, what FRBs are?



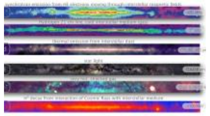
- Distance: same history of GRBs before Beppo-SAX
- Distance: dispersion measure DM*. *Cosmological distances*

  *total column density of free electrons between the observer and the source
- Identification of host Galaxy: only one case FRB121102*
  - White dwarf at z=0.19
- Repetition: only one case FRB121102, no other EM counterparts
- **Progenitors**: nearby extragalactic origin (100-200 Mpc)
  - Supergiant flares in the magnetosphere of young (<100 y) and fast (ms) rotating NS embedded in a dense environment
- **Progenitors**: cosmological origin (1-20 Gpc)
  - Massive NS’s collapse: magnetic blast wave, shock front within the SNR.
  - Merger: Magnetic reconnection between the two merging magnetospheres.
  - Magnetar: flares in the magnetosphere of a magnetar (associated to SGR).
- Neutrino production mechanism?

Time-domain astroparticle physics



ANTARES Multimessenger program



Up to Feb.2018:

Real-time (follow-up of the selected neutrino events):

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER] → 272 alerts sent
- X-ray telescope [Swift/XRT] → 14
- Soft γ-rays [INTEGRAL] → 4
- GeV-TeV γ-ray telescopes [HESS, HAWC] → 2
- radio telescope [MWA] → 22
- Online search of fast transient sources [GCN, Parkes]

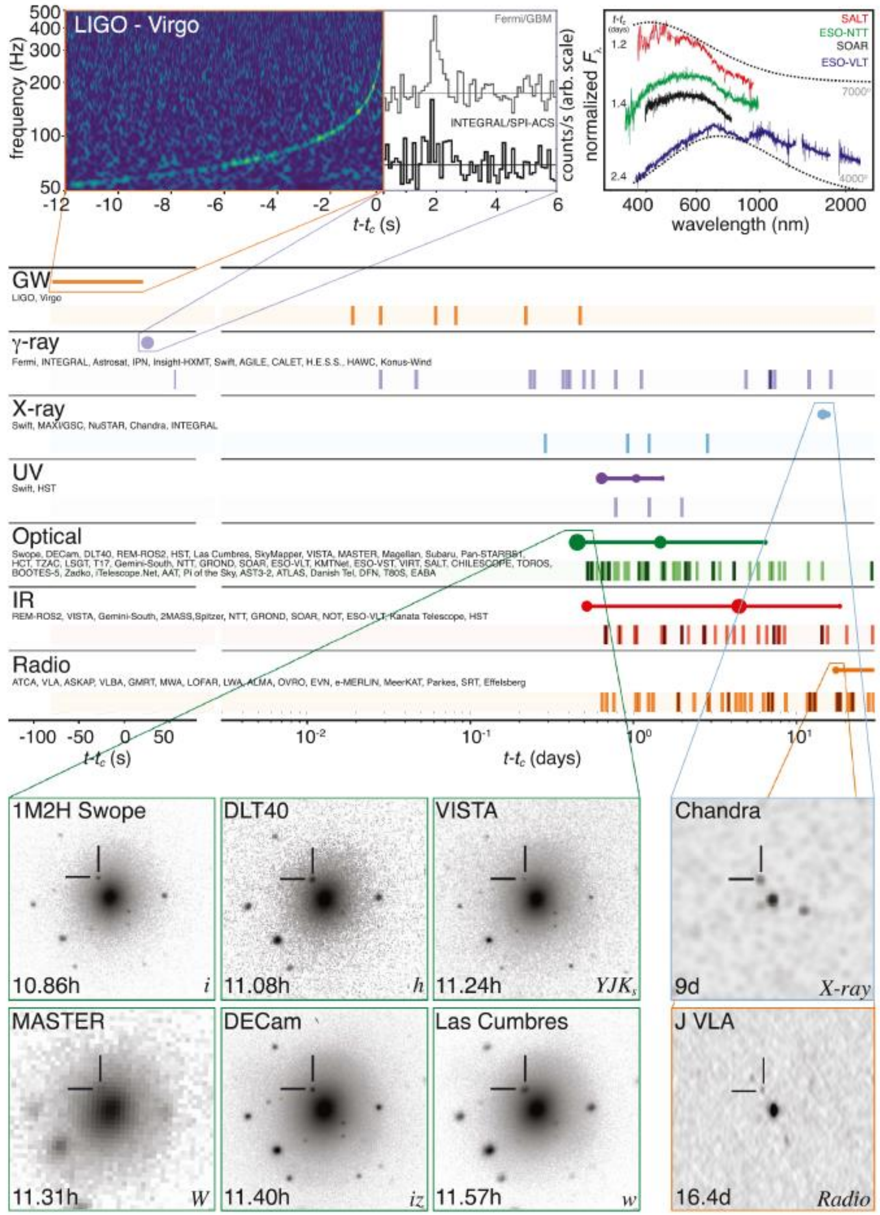
Multi-messenger correlation with:

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]
- Neutrinos [IceCube]

Time-dependent searches:

- GRB [Swift, Fermi, IPN] MNRAS 469, 906–915 (2017)
- Fast radio burst [Radiotelescopi] MNRAS 475, 1427–1446 (2018)
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]

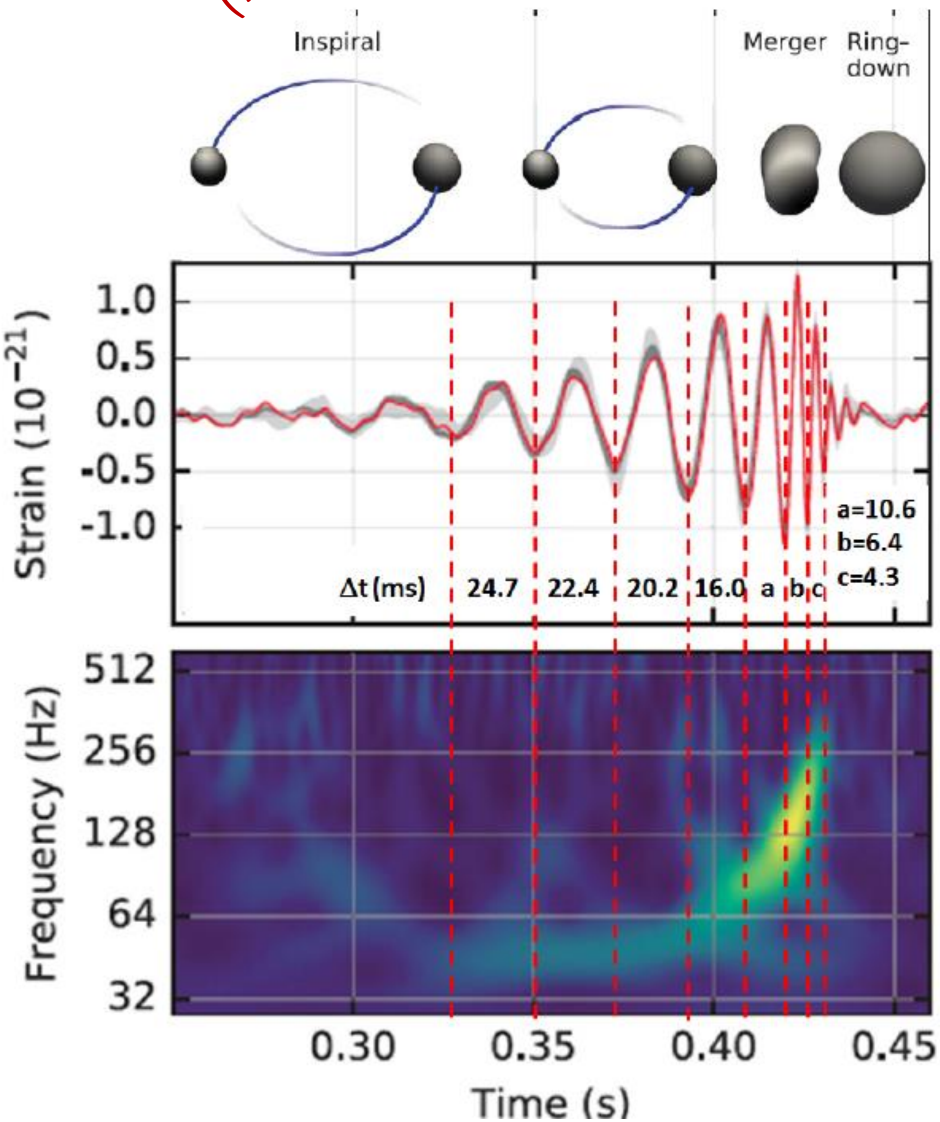
3) The multimessenger role of GWs waves



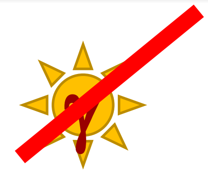
EM vs Gravitational waves

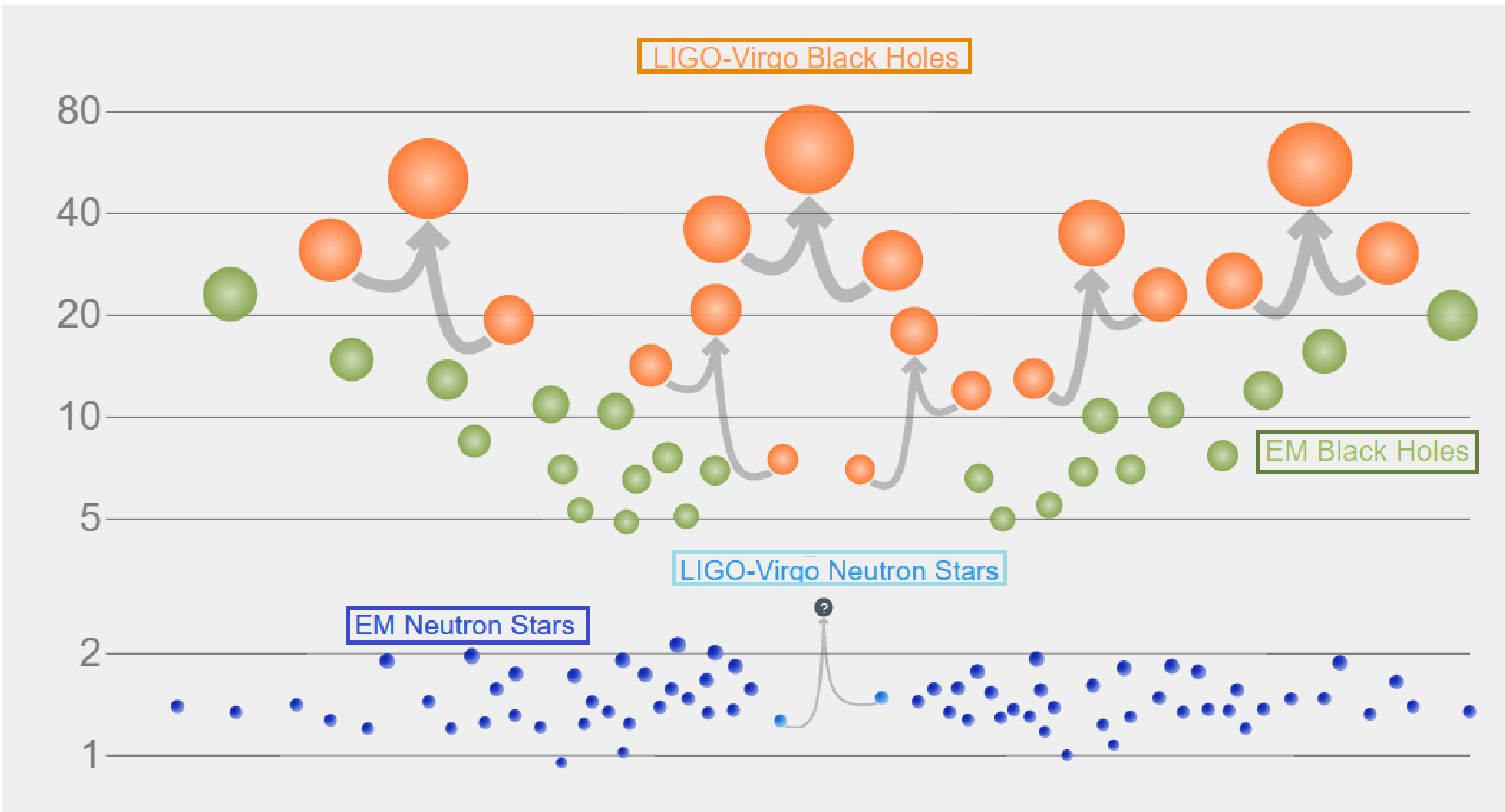
(Remember)

- The **EM radiation** emitted is an incoherent superposition from sources >> λ;
- **GW radiation** comes from systems with sizes R << λ. Hence, the signal reflects the coherent motion of extremely massive objects.
- Effect of EM radiation falls as $\mathbf{1/r^2}$ **(intensity)**. GWs as **1/r (phase)** .
- GWs suffer a very small absorption when passing through ordinary matter.
- **Experimental methods** complementary to that developed in particle physics and traditional astronomy
- The **observables** contain direct information on **mass, distance, spin**



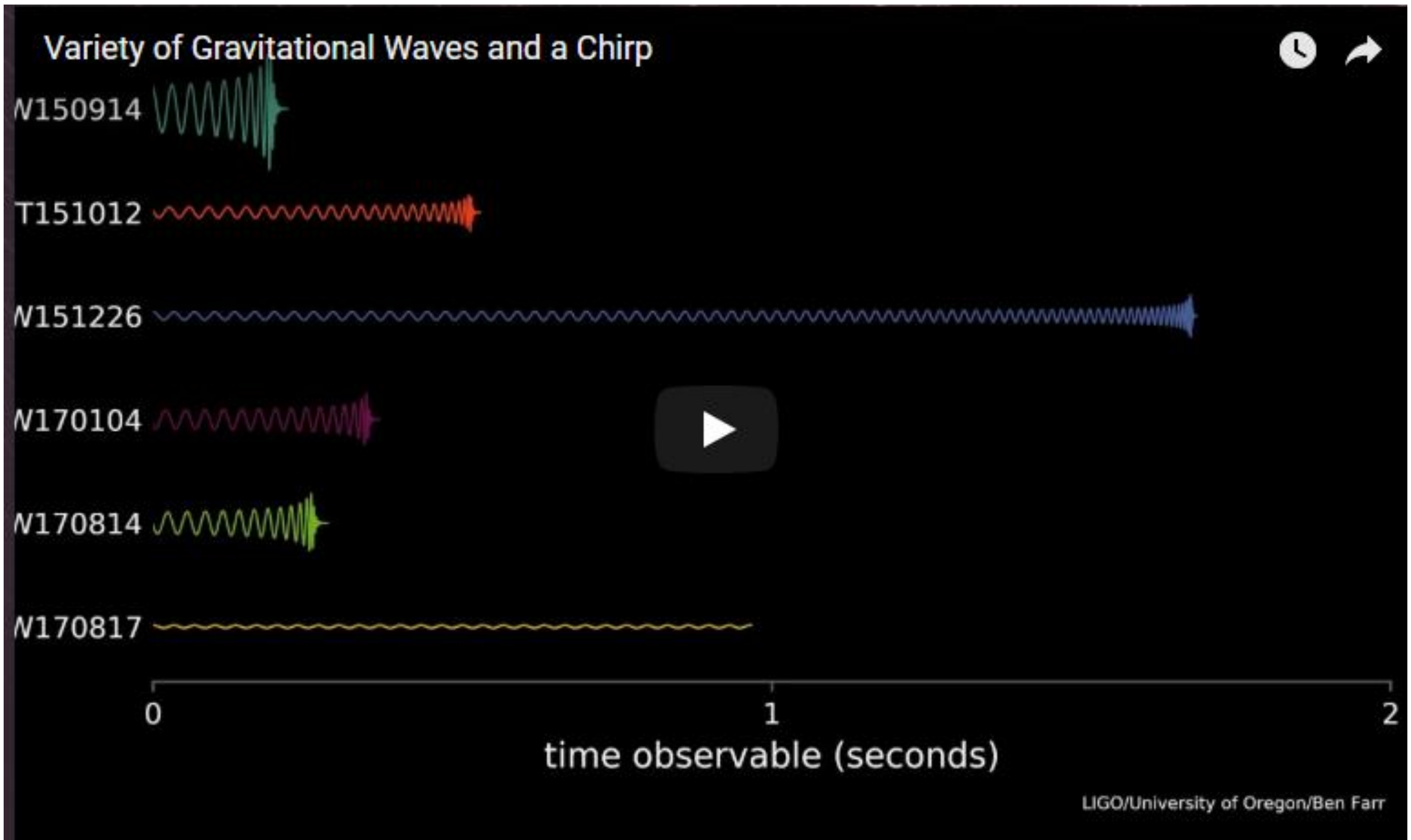
The role of Gravitational waves

- BH+BH =   

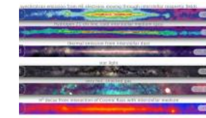


NS + NS =

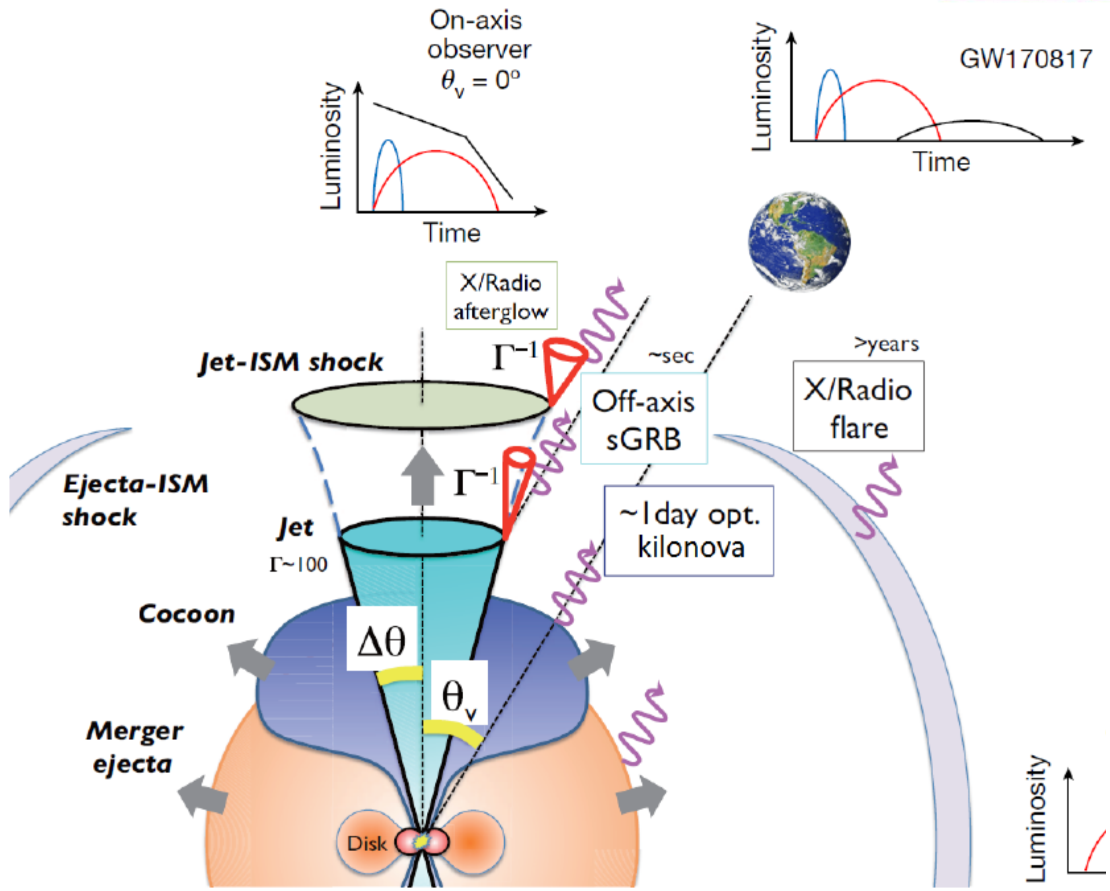
For the movie:
https://www.ligo.caltech.edu/video/ligo20171016v3



The most wanted object: NS+NS (NS+BH)



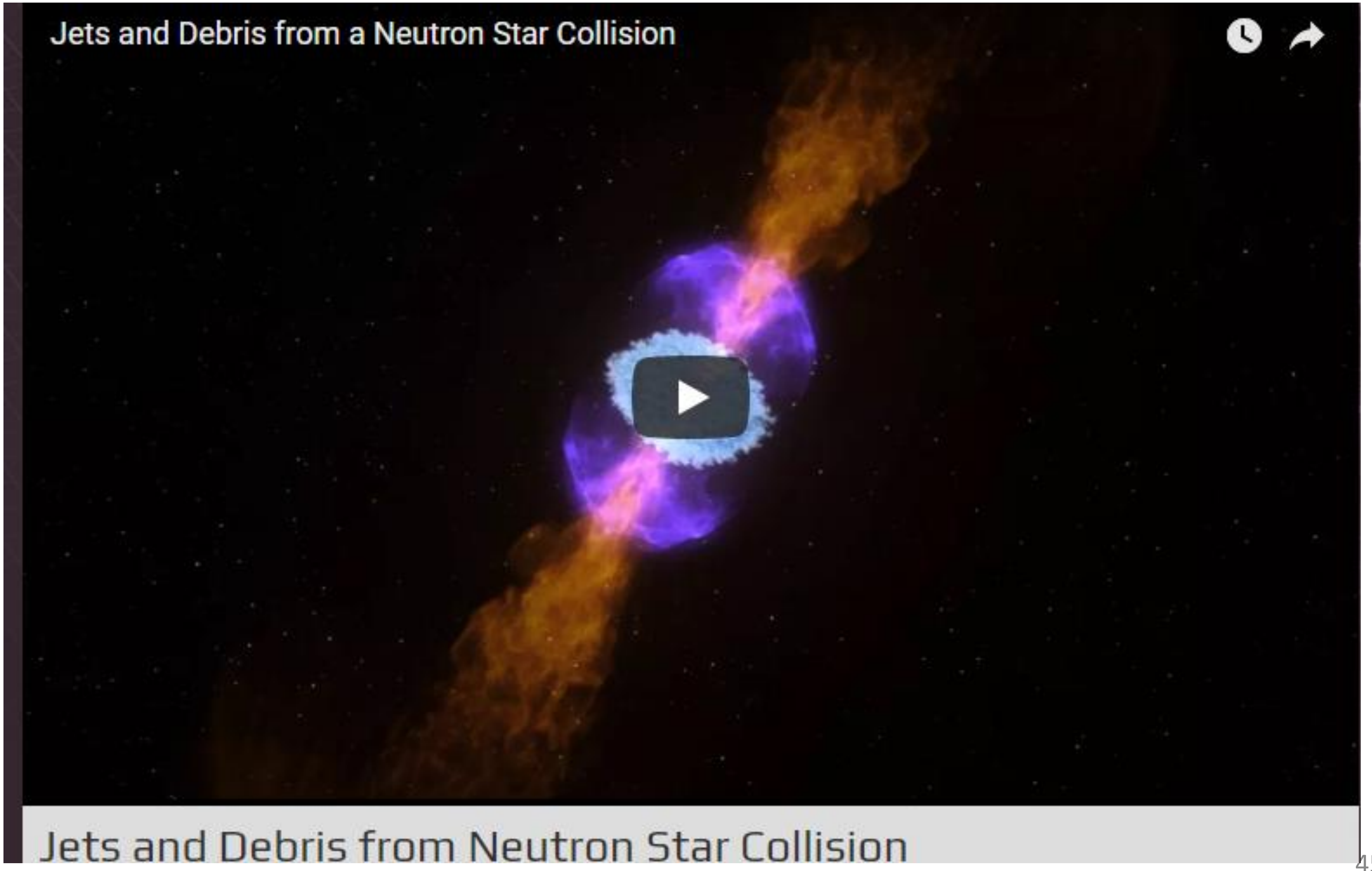
- A rich variety of phenomena in the case of NS-NS merging
- *GW* standard "sirene"
- Neutrinos
- EM counterpart
  - Fast emission (GRB)
    - Beamed emission
    - Afterglow (X-ray,...)
  - Kilonova (*)
    - Isotropic emission
    - Neutron-rich ejecta
  - Radio emission
- UHECR's acceleration?



(*) By radioactive decay of heavy elements produce via r-process nucleosynthesis in the neutron-rich merger ejecta

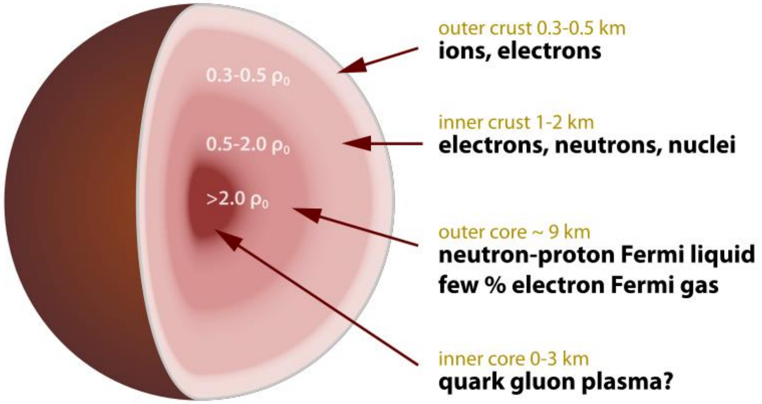
The most wanted object: NS+NS (NS+BH)

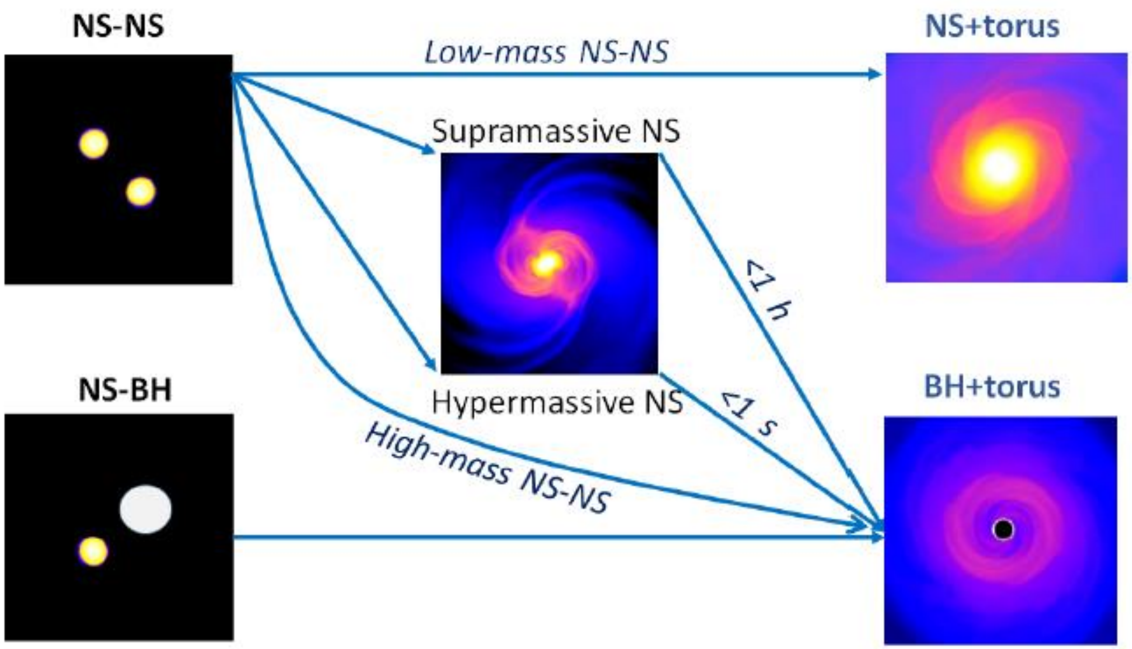
https://www.ligo.caltech.edu/video/ligo20171016v2



Particle physics with GWs (from NS+NB/BH)

- Tidal effects are important because they contain information on the nuclear equation of state (EOS) for NSs.
- Tidal effects affect the phase of the GW and become significant above f> 600 Hz, potentially observable by interferometers.
- Unfortunately, in the O2 run, they were not sufficiently sensitive above 400 Hz.



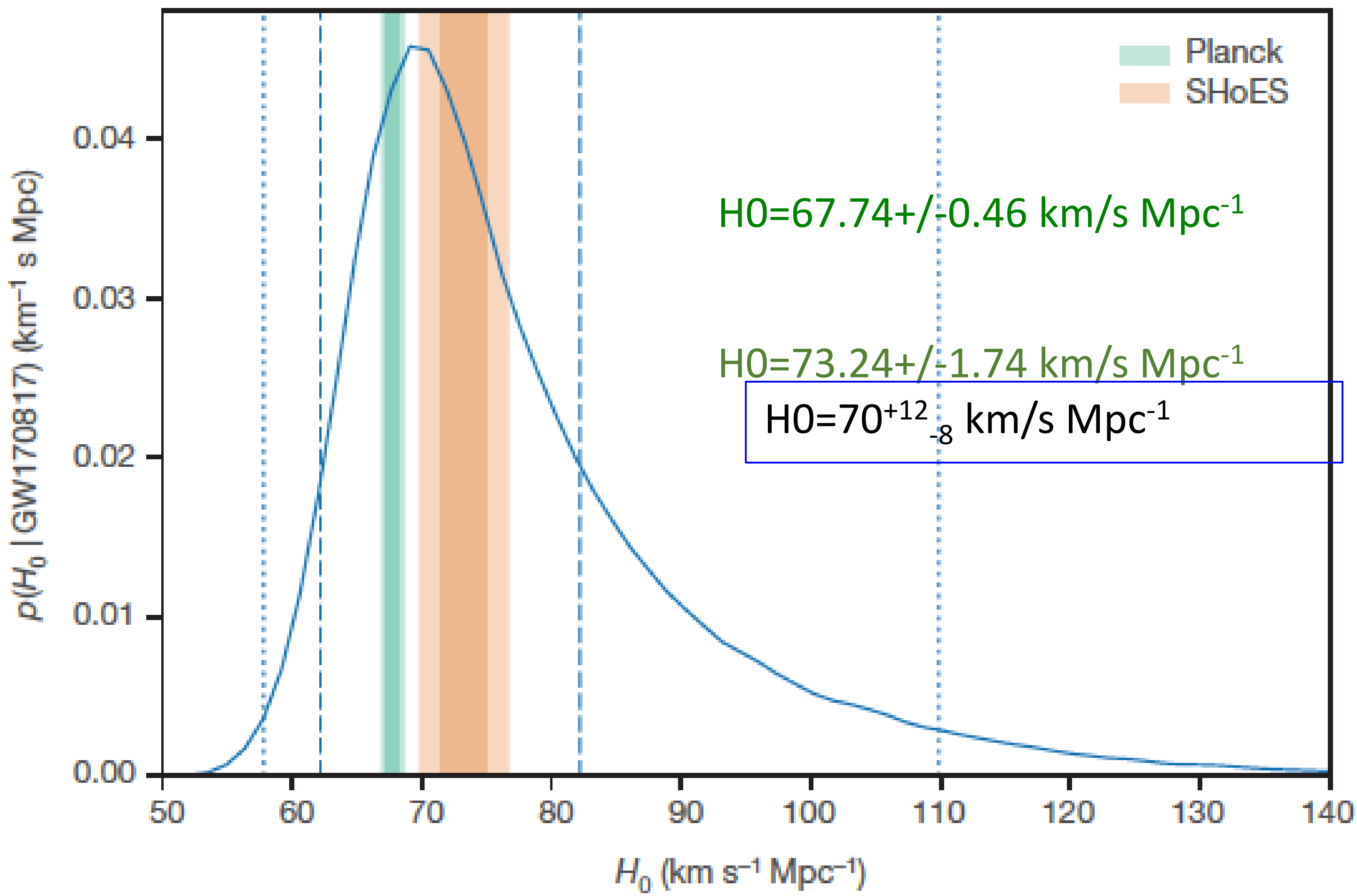


- For GW170817, data disfavor EOS that predict less compact stars;
- objects more compact than NS, such as **quark stars**, black holes, or more exotic objects, are not excluded

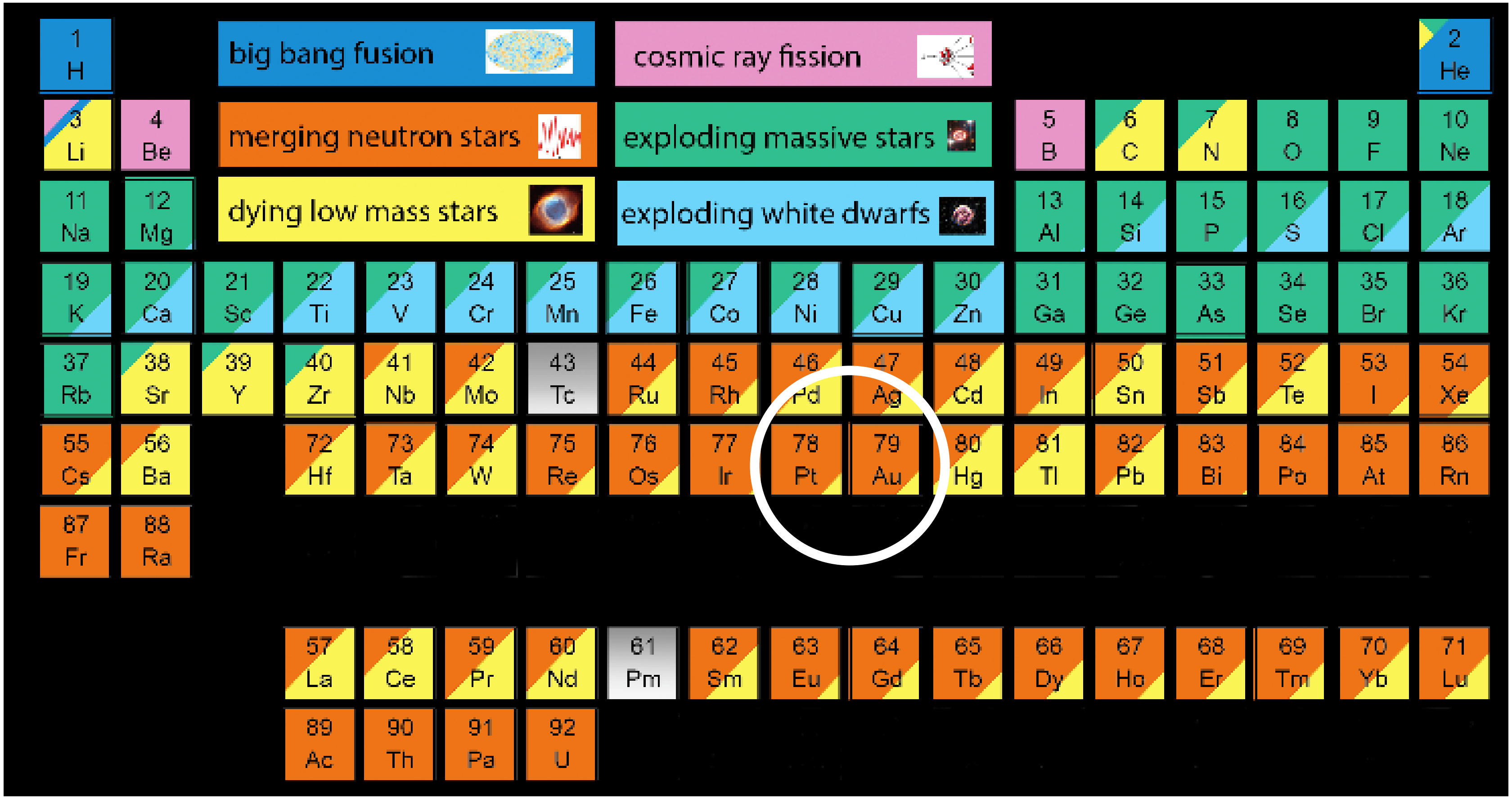
Cosmology with the "standard sirene"

- Type I SNe → Electromagnetic ***"standard candles"*** in cosmology
- Schutz (1986) recognized that NS+NS can be precise **luminosity distance indicators,** via measurement of GW signal during the inspiral and merger.
- GWs can act as "***standard sirens"*** as cosmological probes, although the NS+NS do not **require any assumption to be made about their intrinsic 'luminosity'**
- A realistic target for the upcoming global network of advanced detectors is measurement of the Hubble constant, *H*0, using standard sirens.
- A standard siren measurement of *H*0 **will present a major multi-messenger challenge.** To estimate the Hubble constant **requires comparison of distance with redshift**, and the latter will not generally be measurable from GW data alone
- This measurement of course first **requires the prompt observation of an EM counterpart** and the unique identification of the host galaxy (as GW170817)
- The expected reach of advanced detectors will be too shallow to permit exploration of **dark energy models** and the accelerated expansion of the Universe

Hubble's constant measured with GW170817

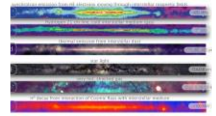


The reason why kilonovae are so important

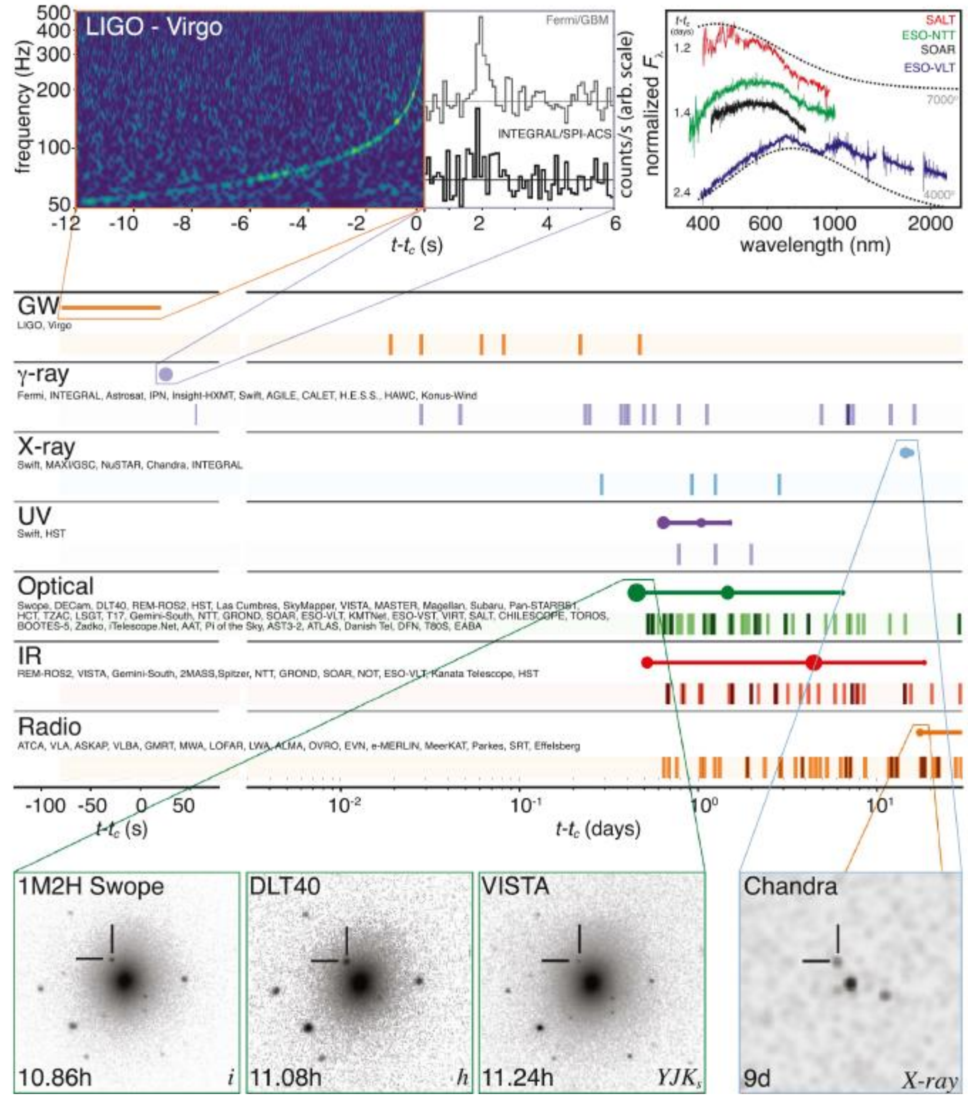


***Isaac Newton** Master of the Royal Mint*

NS + NS =



- The GW signal was the input for the EM follow-up
- A simultaneous short GRB was observed by FERMI-GBM and INTEGRAL satellites. Alone, these signals are not sufficient to trigger EM position (position not known)
- The network of GW observatories can provide directionality information on the event position
- The observation of a coincident neutrino can provide directionality information as well
- In addition, ν's can provide additional info on the acceleration mechanism
- The key of the success: we know the kinematics of the merging objects, and the energy loss in GW



For the future (optimistic)

- We know that SNe explode in Nature
- SNe do not explode in computer
  - i.e., we do not know the details of the dynamic process
  - We do not know exactly the GW signal of a SN
  - It is difficult to search for SN in the laser interferometers
- Neutrinos can be detected for a SN in our Galaxy (or in neighbouring satellite galaxies)
  - The neutrino signal can provide information on t_0
  - It can provide some directional information
  - Neutrino can be detected also if the light is obscured
- The neutrino can trigger an off-line search of the SN signal in the GW data
  - Retrive information of the dynamic process of SN explosion

Conclusions

- Multi-messenger is a young field
- Combine the information from traditional astronomy, γ-rays, charged cosmic-rays, neutrinos and gravitational waves
- Use information from instruments (close) to the technology limits
- New instruments:
  - SKA (radio), Webb (IR), CTA (TeV)
  - aLIGO, adVIRGO: Astrophysics with GW signals
  - Neutrino telescopes with multi-km3 effective volumes
- Different opportunities for **particle physics**
  - Dark matter searches
  - Mass of the neutrino
  - Propagation of neutral particle (Transparency of the Universe)
  - Energy of the vacuum - axions;
  - Tests of Lorentz Invariance; Quantum gravity (space time structure of vacuum)
  - …
- **cosmology**
  - Alternative measurement of the cosmological parameters
- and **astrophysics**
  - Sources of Galactic CRs
  - Origin on cosmic neutrinos observed by IceCube
  - Origin and type of UHECRs
  - …