המכללה האקדמית להנדסה
אורט בראודה
ORT BRAUDE COLLEGE

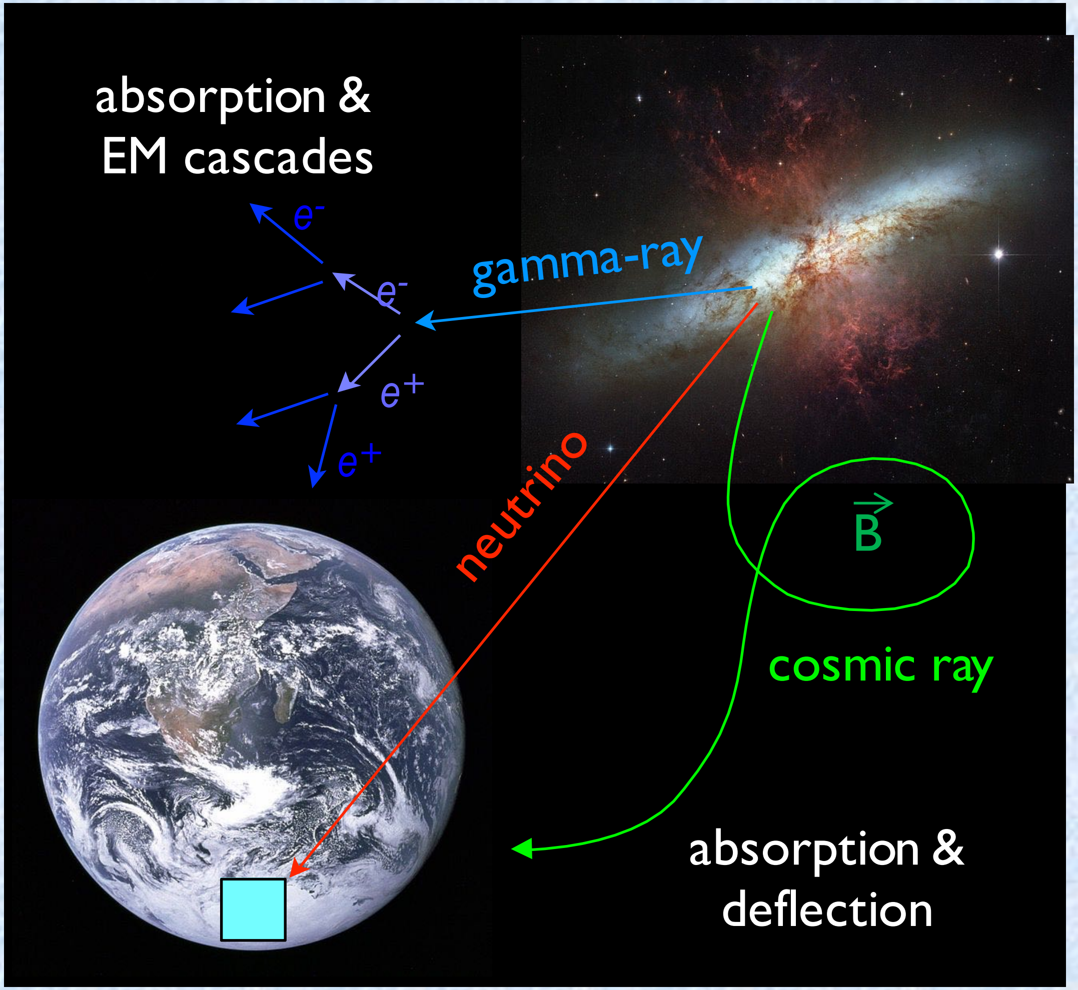
Multimessenger Probes of High-energy Sources

Dafne Guetta

Multi-Messenger Astronomy

Cosmic Messengers:

- ✓Cosmic Rays
- ✓ Gamma-Rays
- ✓ Neutrinos
- ✓ Gravitational Waves



→ Neutrino astronomy:

- ✓ closely **related** to cosmic rays (CRs) and γ-rays
- ✓ **weak interaction and ossillation** during propagation
- ✓ **exclusive messenger** for 10 TeV-10 EeV telescopes

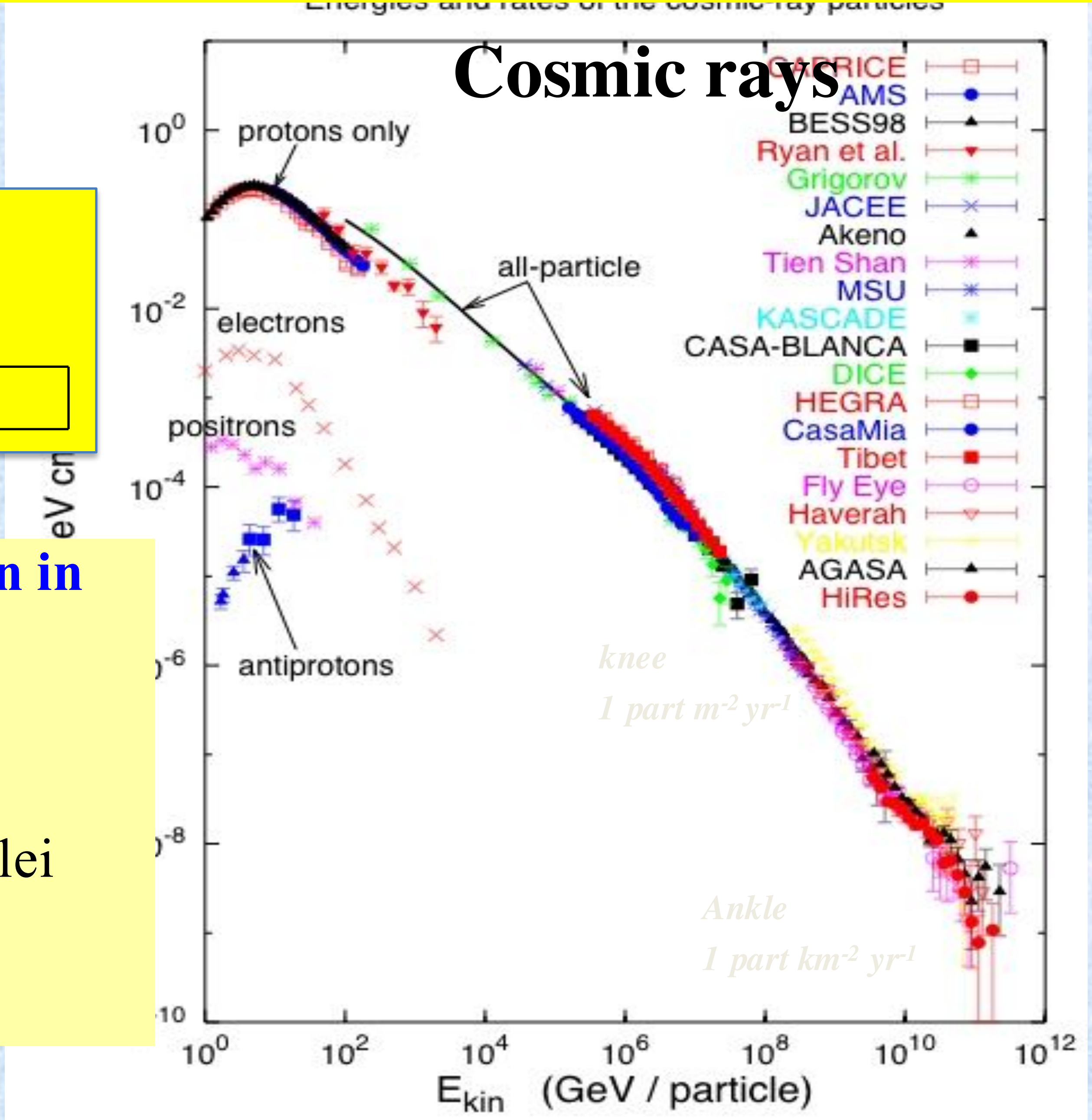
Challenges:

- x **low** statistics
- x **large** backgrounds

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$



Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

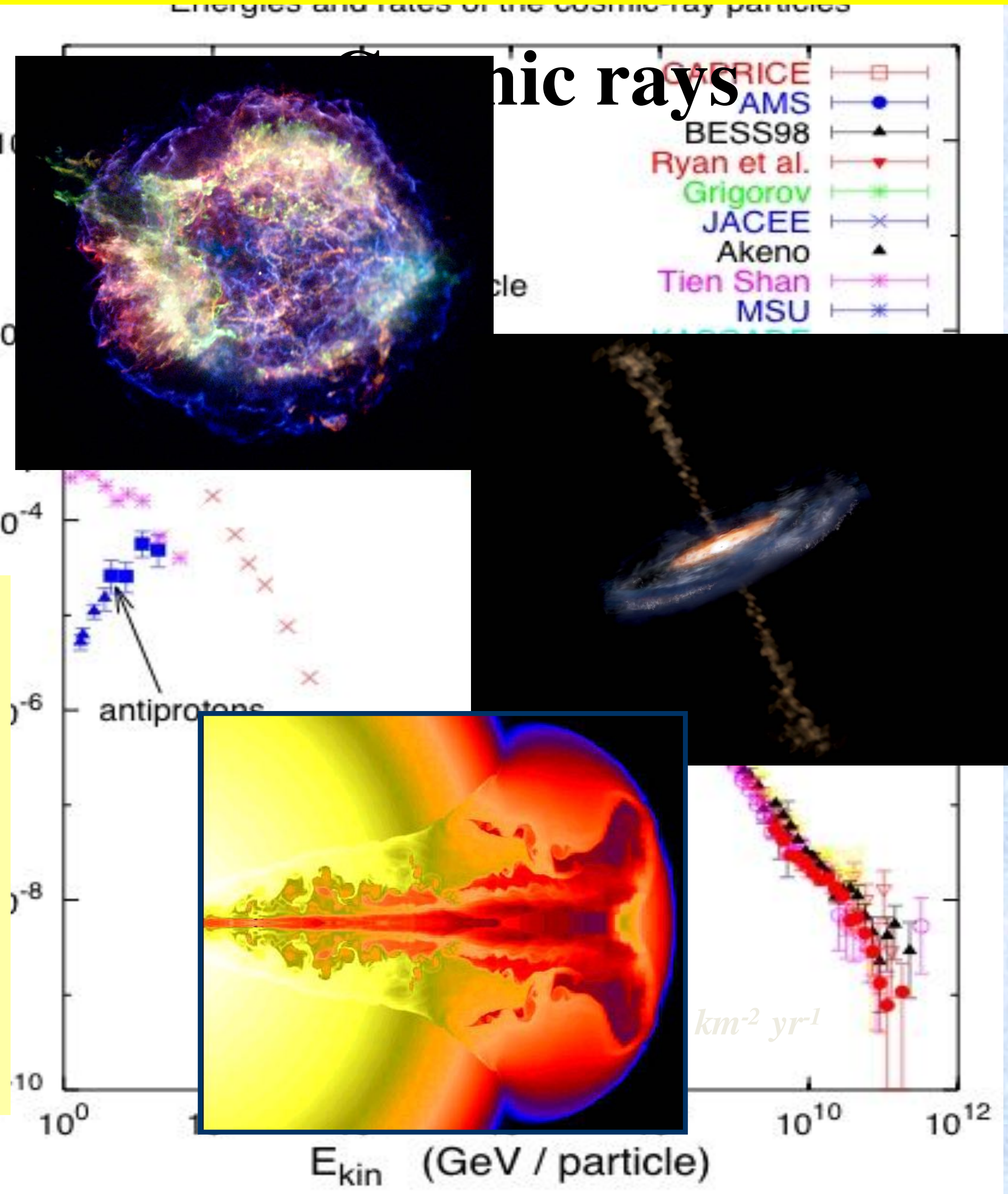
Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
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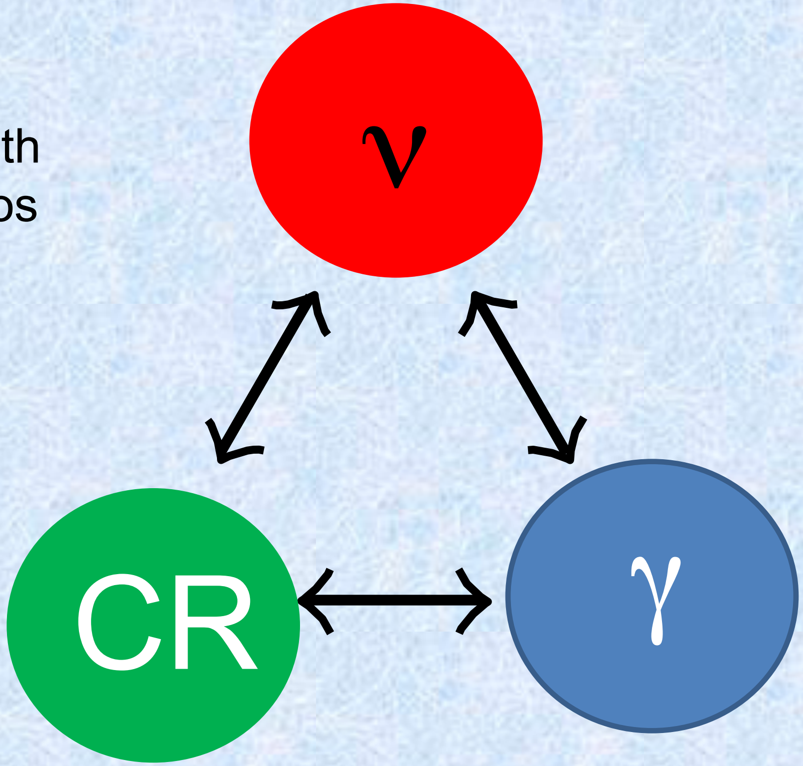
Multi-messenger Paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

‹ pion production in CR interactions with gas (“*pp*”) or radiation (“*p*γ “) ⇨ neutrinos with about 5% of CR nucleon energy

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ -rays

‹ **very interesting** energy range:
  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?



Advantages of the Multi-Messenger Approach

Assuming that different messengers (all or some of them, depending on the model and on the type of source) are produced/accelerated in the same astrophysical site, the Multi-Messenger Approach:

- increases the discovery potential, by observing the same source with different probes (noteworthy for transient or flaring sources)
- improves the statistical significance of the observations, by coincident detection (sustained by the development of alert systems between the experiments)
- improves the detection efficiency, by profiting of relaxed cuts (exploiting the advantages of time-dependent analysis)
- Give information on the nature of the accelerated particle

This is valid in particular for Neutrino detectors, since potential astrophysical sources are predicted to emit faint signals and the presence of an isotropic flux of atmospheric background requires the development of effective search strategies.

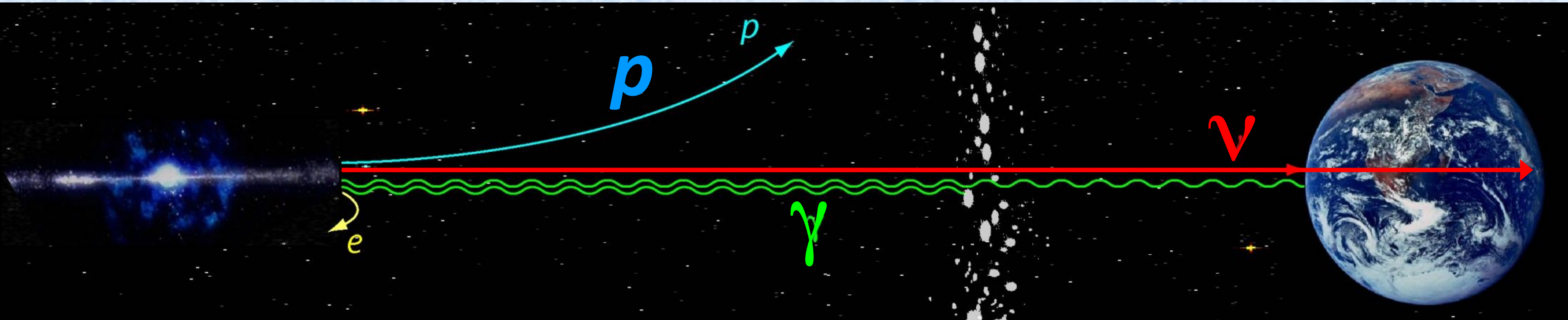
Cosmic neutrinos?

Why look for them?

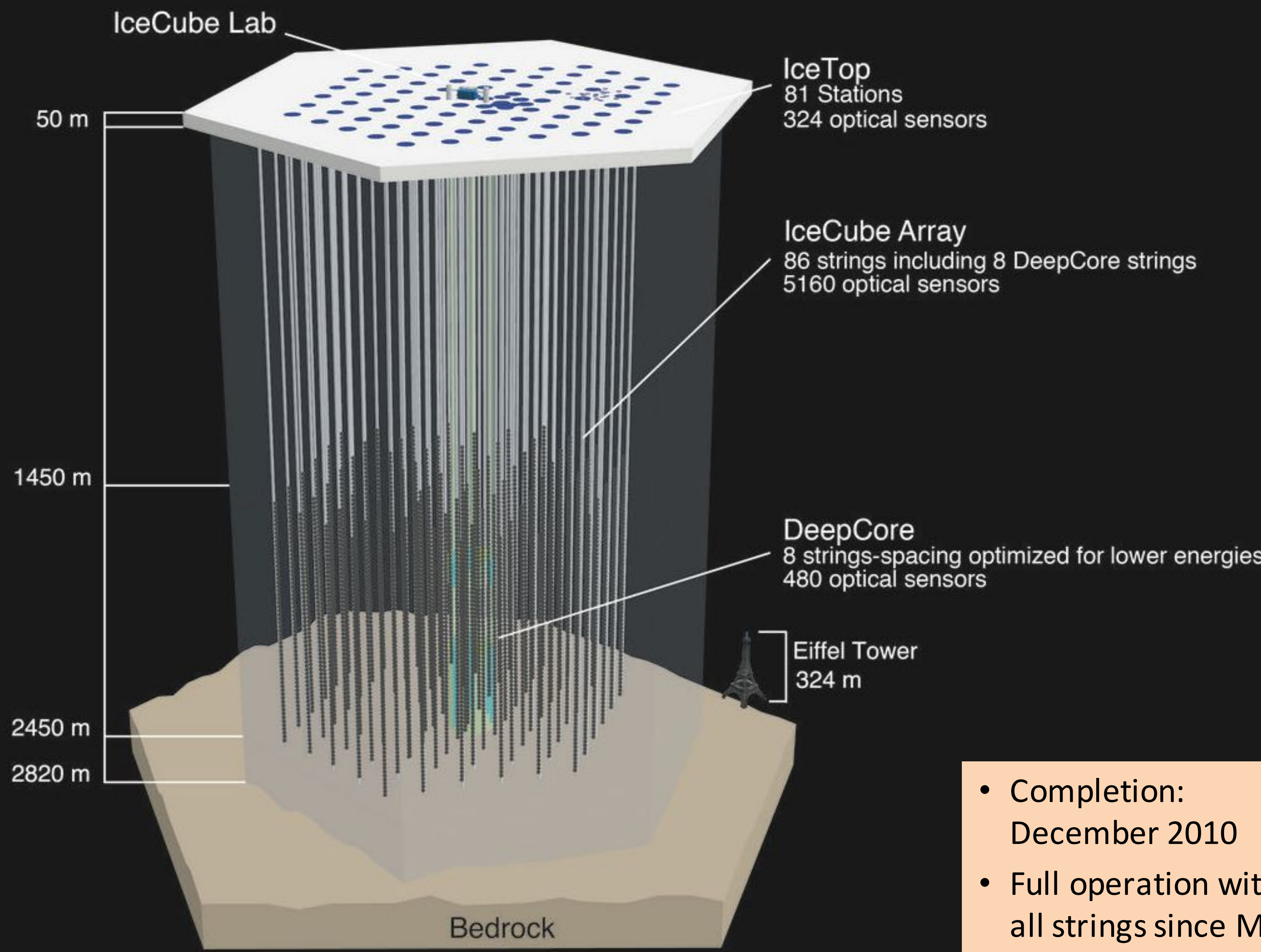
- They could tell us about the origin of high energy cosmic rays, which we know exist.
  - There are numerous ways how neutrinos can tell us about fundamental questions in nature: dark matter, supernova explosions,
  - Composition of astrophysical jets, physics of the source core
  - Neutrino astronomy represents a unique tool within multimessenger astrophysics to probe the most extreme cosmic processes.

Can they reach us?

- High energy neutrinos will pass easily and undeflected through the Universe
  - That is **not** the case for other high energy particles: such as photons or other cosmic rays, eg protons.

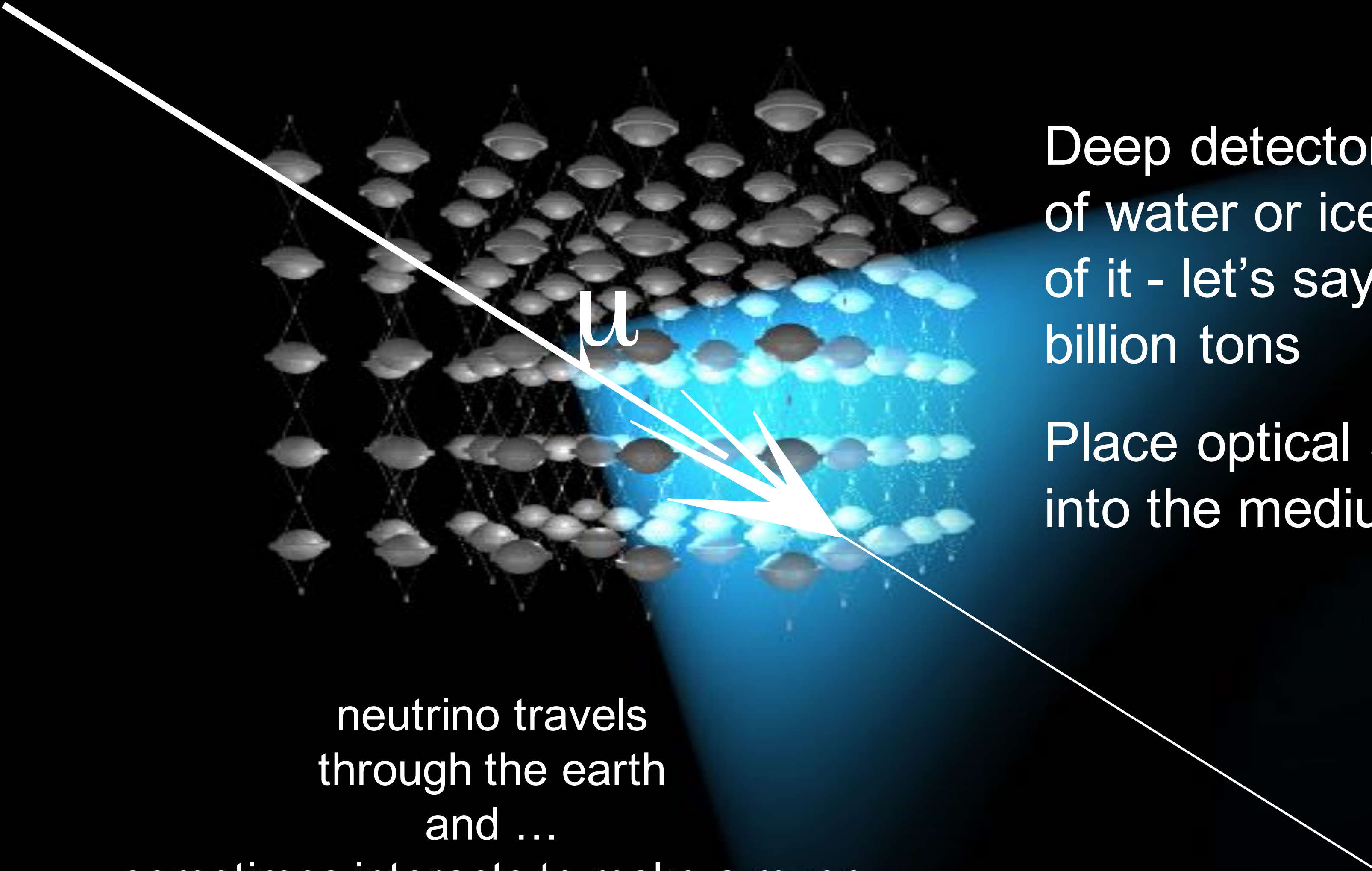


IceCube



- Completion: December 2010
- Full operation with all strings since May 2011.

How to catch them?
Detection principle

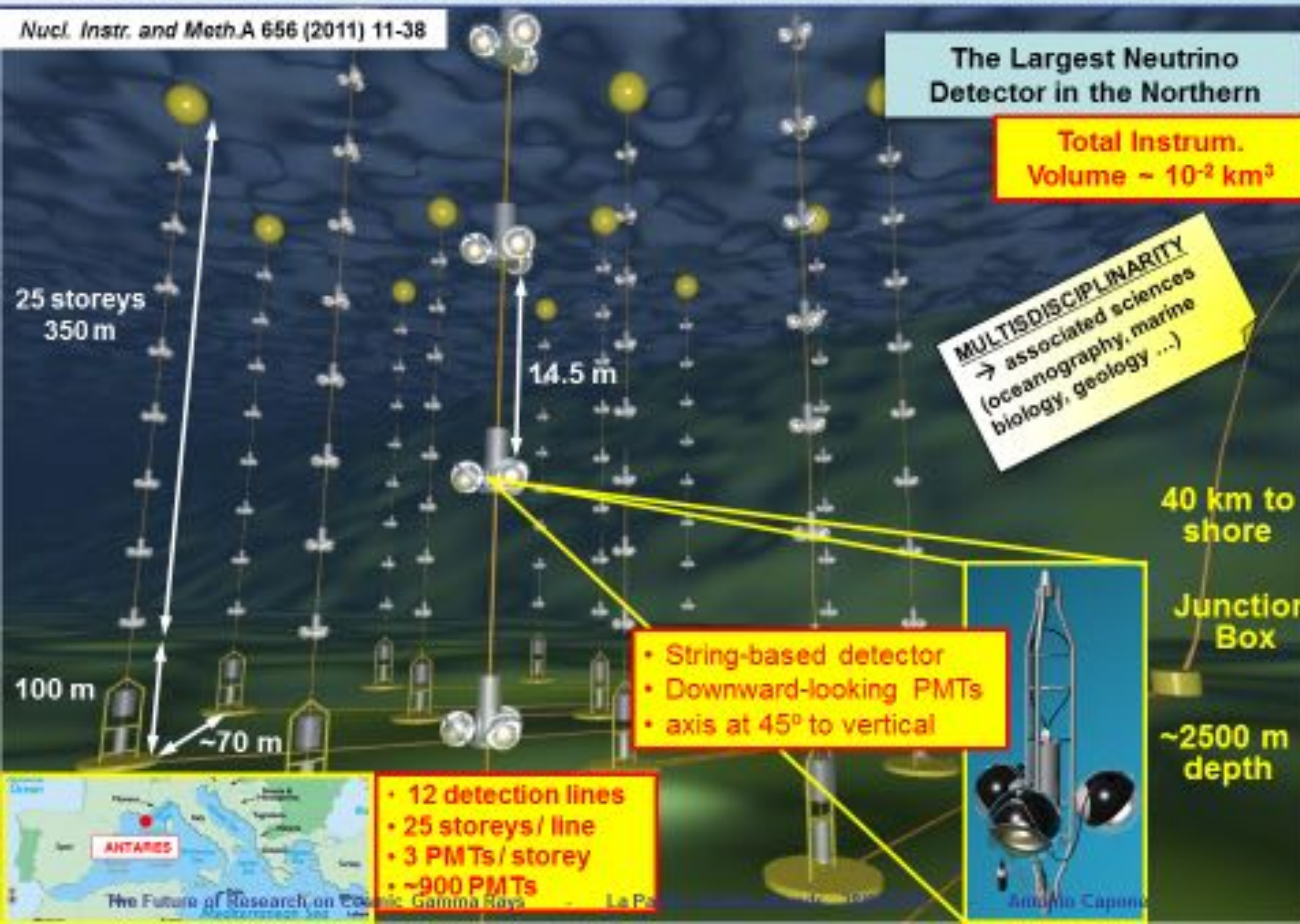


Deep detector made of water or ice – lots of it - let's say 1 billion tons

Place optical sensors into the medium

neutrino travels through the earth and …
sometimes interacts to make a muon that travels through the detector

ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch



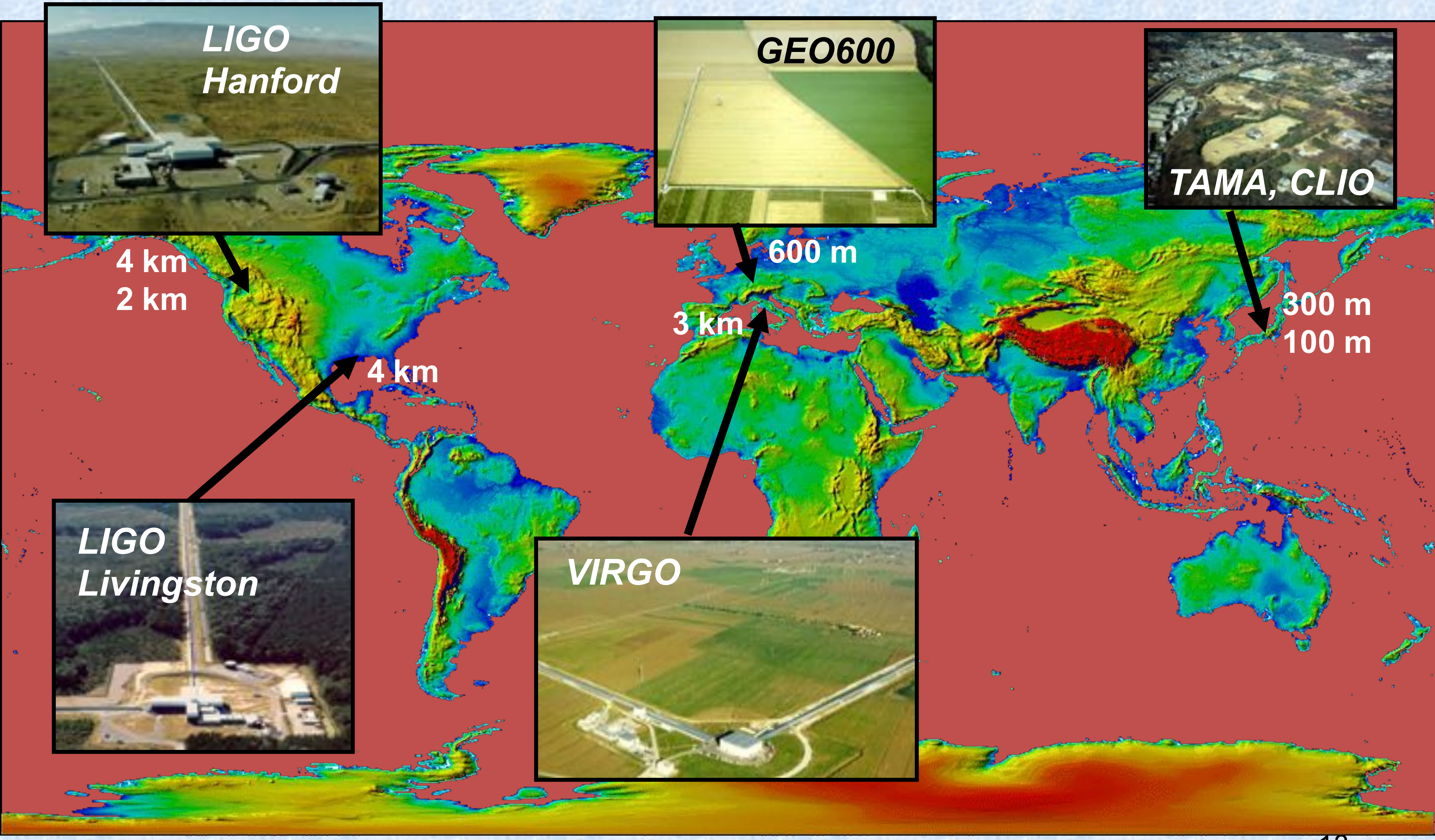
Future telescopes

- IceCube plans to extend to 10 km^3 of glacial ice at the South Pole, improving IceCube's sensitive volume by an order of magnitude. Expected thousands events per year over several years.
- On the other side of the world in the Mediterranean sea. ANTARES is currently the only deep sea high energy neutrino telescope that is operating in the Northern hemisphere.
- ANTARES is planned to be followed by a multi-cubic-kilometer detector in the Mediterranean sea called KM3NeT in the next few years. (Capo Passero, Sicily).
- **The realization of next generation high energy detectors like CTA for TeV photons, KM3Net and IceCube-Gen2 for higher energy neutrinos and the improving sensitivity of Gravitational Waves detectors will open a new era in multimessenger astrophysics**

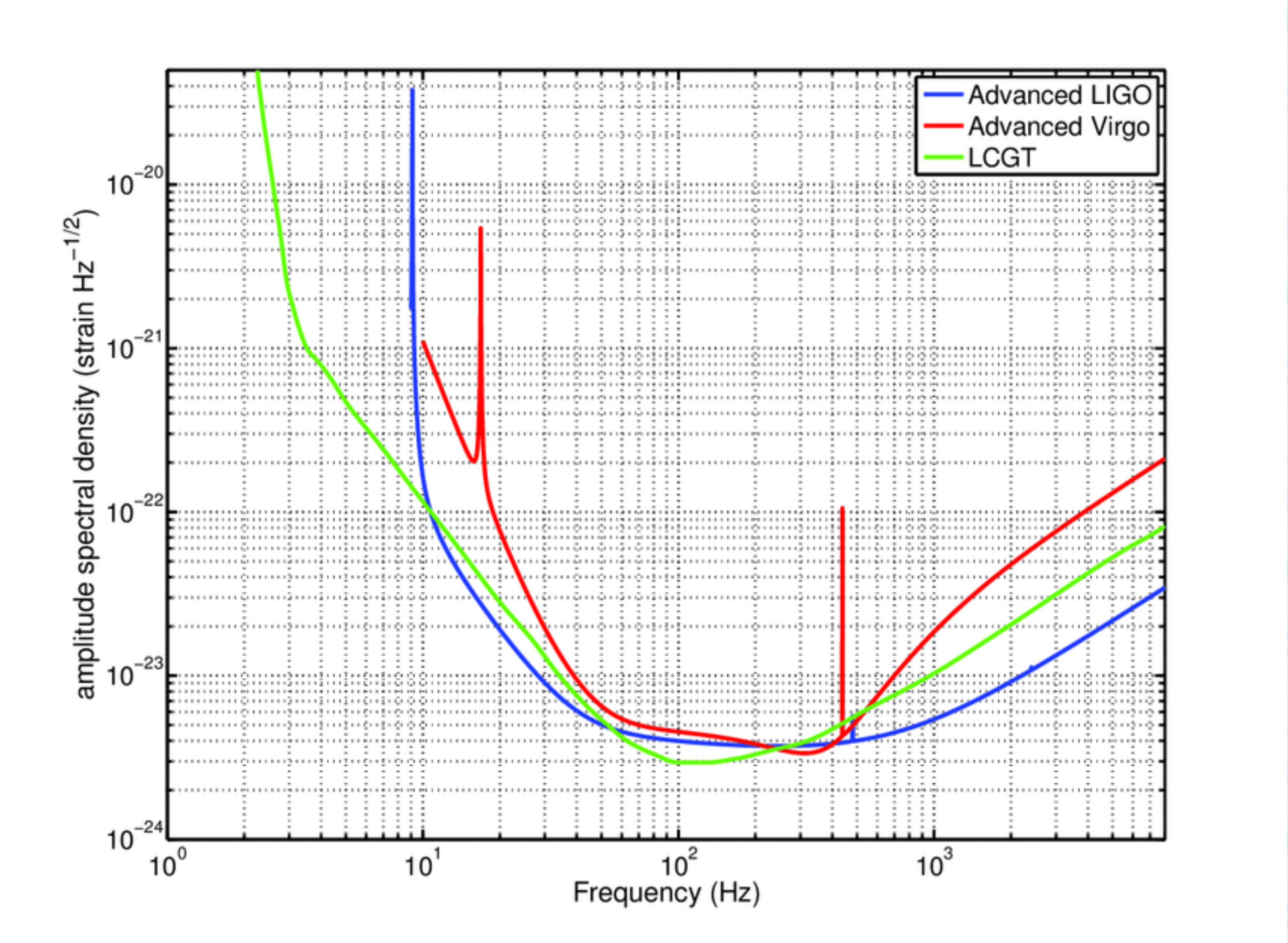
Gravitational-Waves

- Typical frequencies of electromagnetic waves range from (10^7 Hz – 10^{20} Hz) whereas GW frequencies range from ~ (10^{-9} Hz – 10^4 Hz). They are more like sound waves.
- Combining information from GW detections with electromagnetic and neutrino observations allows us to gain a fuller understanding of some of the most extreme cosmic processes .
- **GWs are indicative of:** source dynamics, such as the formation, evolution and interaction of compact objects. These compact objects are anticipated to play a central role in astrophysical particle acceleration and high-energy emission, making GW observations directly relevant for neutrino and in general high-energy astroparticle studies

The Worldwide Network of Gravitational Wave Interferometers

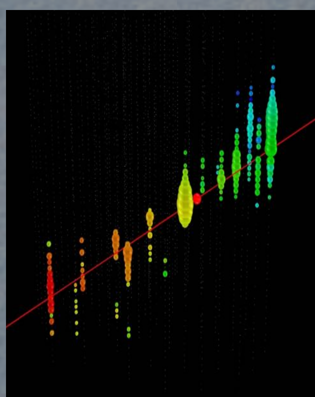


Advanced LIGO and Virgo



Neutrino Event Signatures (IceCube)

CC Muon Neutrino

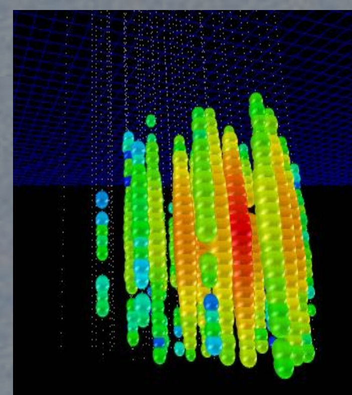


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 0.5° angular resolution

Neutral Current /Electron Neutrino



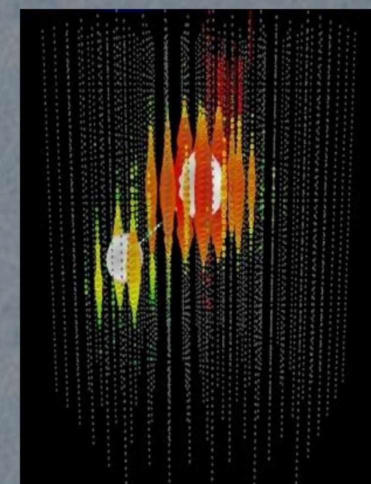
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies $\gtrsim$ 100 TeV)

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

(not observed yet)

An astrophysical neutrino flux?!

- IceCube data provide strong evidence for an astrophysical neutrino flux
- Consistent with:
  - 1:1:1 all flavor neutrino flux – as expected for astrophysical sources
  - Isotropic distribution, north, south – specifically no evidence for galactic association.

The data suggest that we see an extragalactic neutrino flux.
The level of this flux is exactly, and thus intriguingly so, at the level of the Waxman-Bahcall upper bound.
- Is it a clue for it's origins?

Open Questions

- Cosmic ν origin expected level.
- Starbursts galaxies, galaxy clusters/groups, Active Galaxies, Gamma-Ray Bursts, Supernovae pulsars
- pp or pγ?
- UHECR connections (compatible with CR-related bounds)
- γ-ray connection (compatible with Fermi γ-ray flux)

What is the Origin?

What is the Origin?

New mystery (probably need to identify single sources)

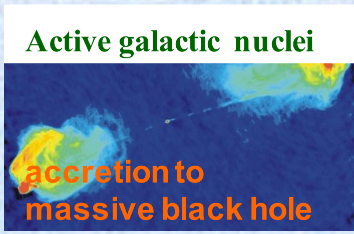
Requirements: isotropic flux w. $E_\nu^{\,2}\,\Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
break/cutoff around PeV for hard spectra

Extragalactic
- γ-ray burst jets (ex .Yacobi, Guetta, Behar 2014 ApJ, Cholis & Hooper 13 JCAP)
- active galaxies (ex. Stecker 13 PRD, Dermer, Murase & Inoue 14 JHEAP, Kimura, KM & Toma 15)
- starburst galaxies (ex. Murase, Ahlers & Lacki 13 PRDR, Tavecchio, Ghisellini, Guetta 14)
- galaxy clusters/groups (ex. Murase, Ahlers & Lacki 13 PRDR, Dobardzic & Prodanovic 14)

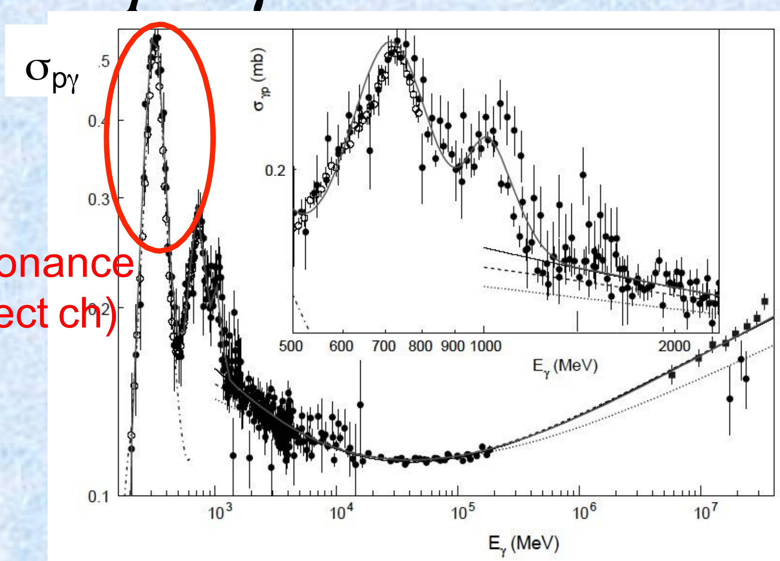
Galactic (as mostly subdominant contributors)
- Unresolved sources (supernova/hypernova remnants, microquasars)
- Extended sources (Fermi bubbles, Galactic halo)
(Anchordoqui+ 14 PRD, Razzaque 13 PRDR, Ahlers & Murase 14 PRD, Lunardini+ 14 PRD)

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



$$p+\gamma \rightarrow N\pi + X$$



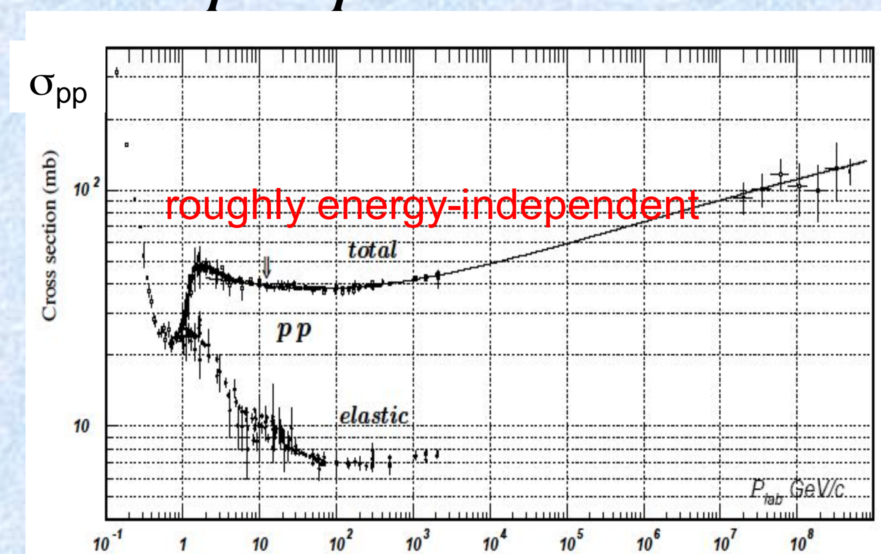
Δ-resonance
(+ direct ch)

$\sigma_{p\gamma}$~$\alpha\sigma_{pp}$~0.5 mb

$\varepsilon'_p\varepsilon'_\gamma$ ~0.16 GeV^2

Cosmic-ray Reservoirs

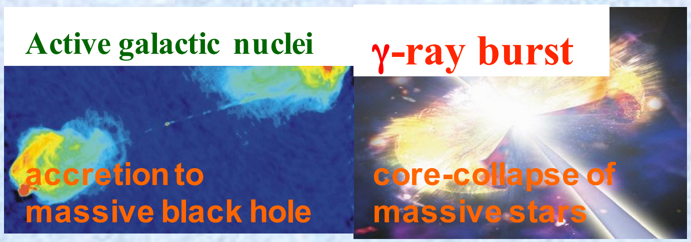
$$p+p \rightarrow N\pi + X$$



σ_{pp}~$1/m_\pi^2$~30 mb

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



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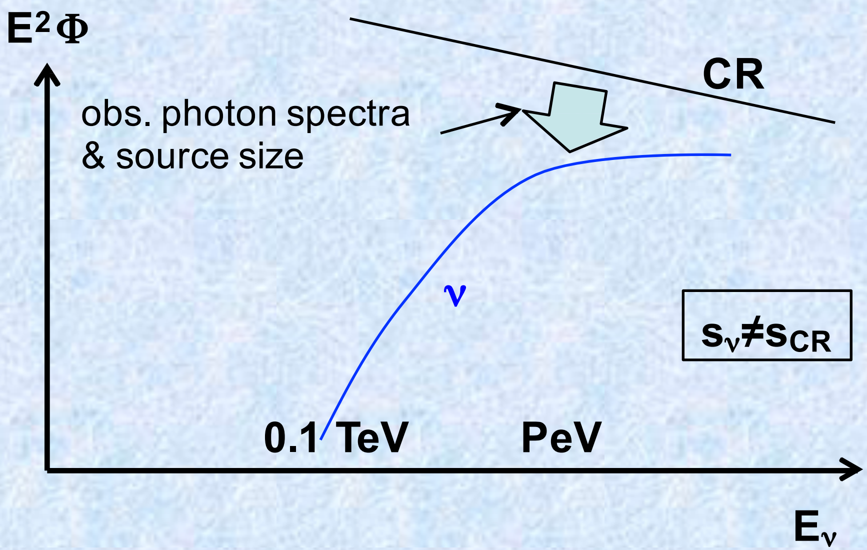
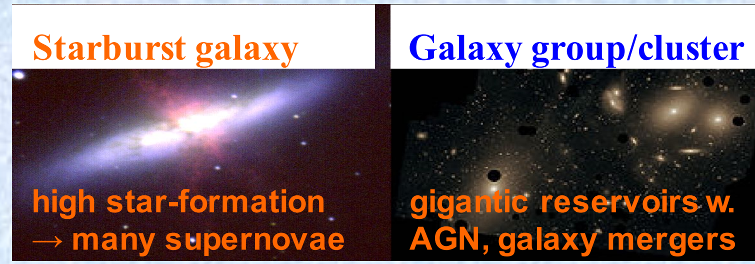


Cosmic-ray Reservoirs



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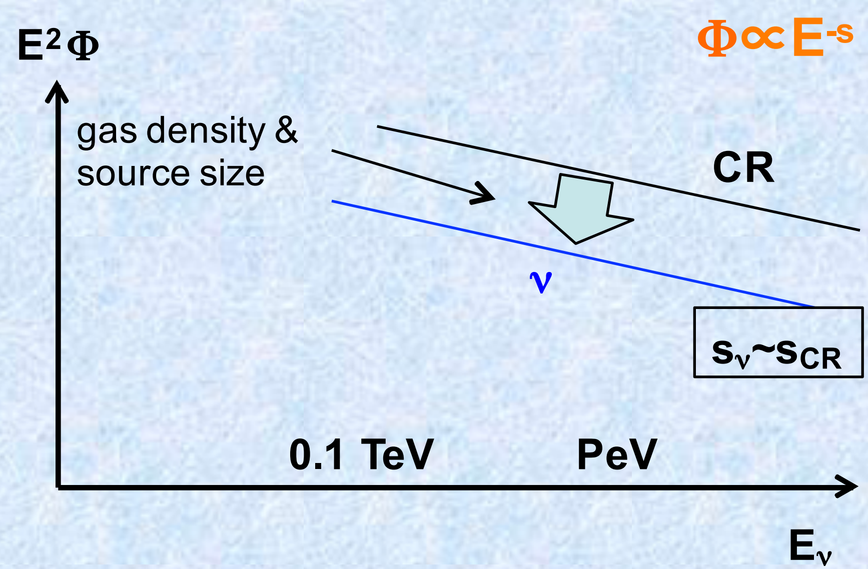

$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Astrophysical Extragalactic Scenarios

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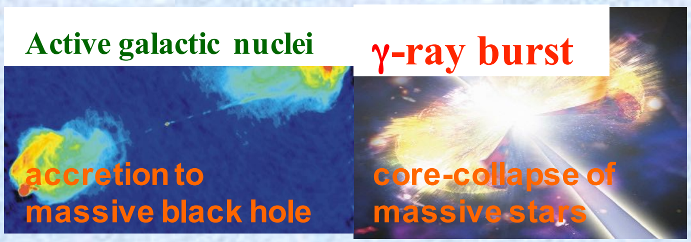
Cosmic-ray Accelerators (ex. UHECR candidate sources)



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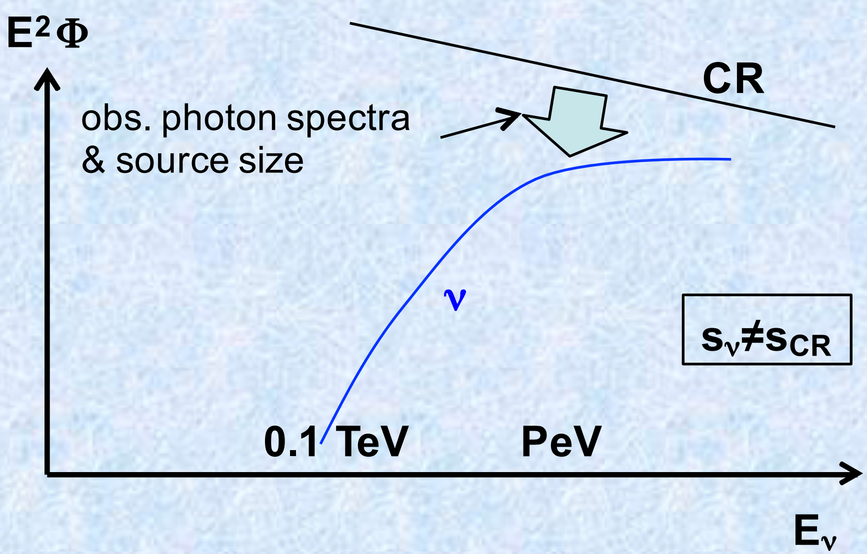
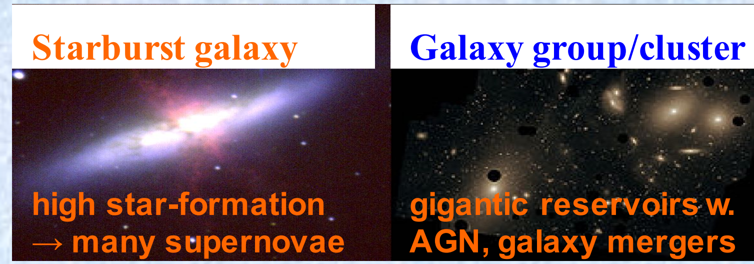


Cosmic-ray Reservoirs



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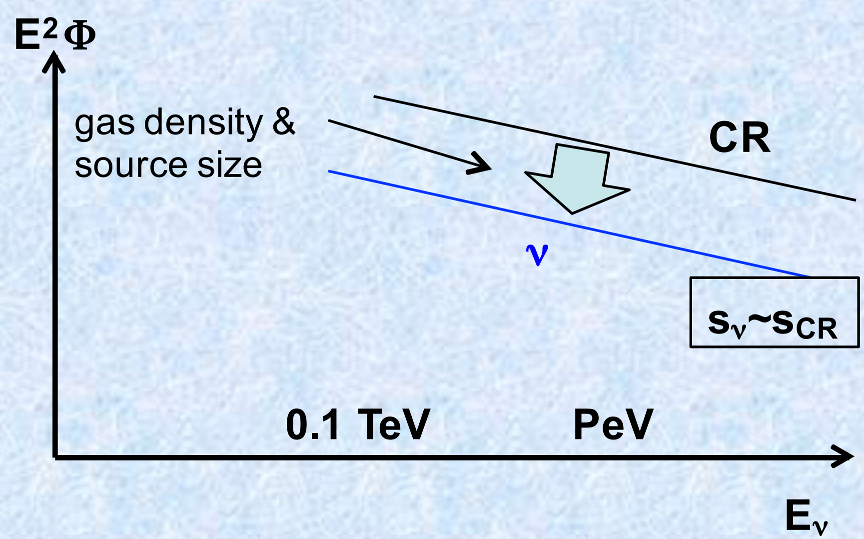
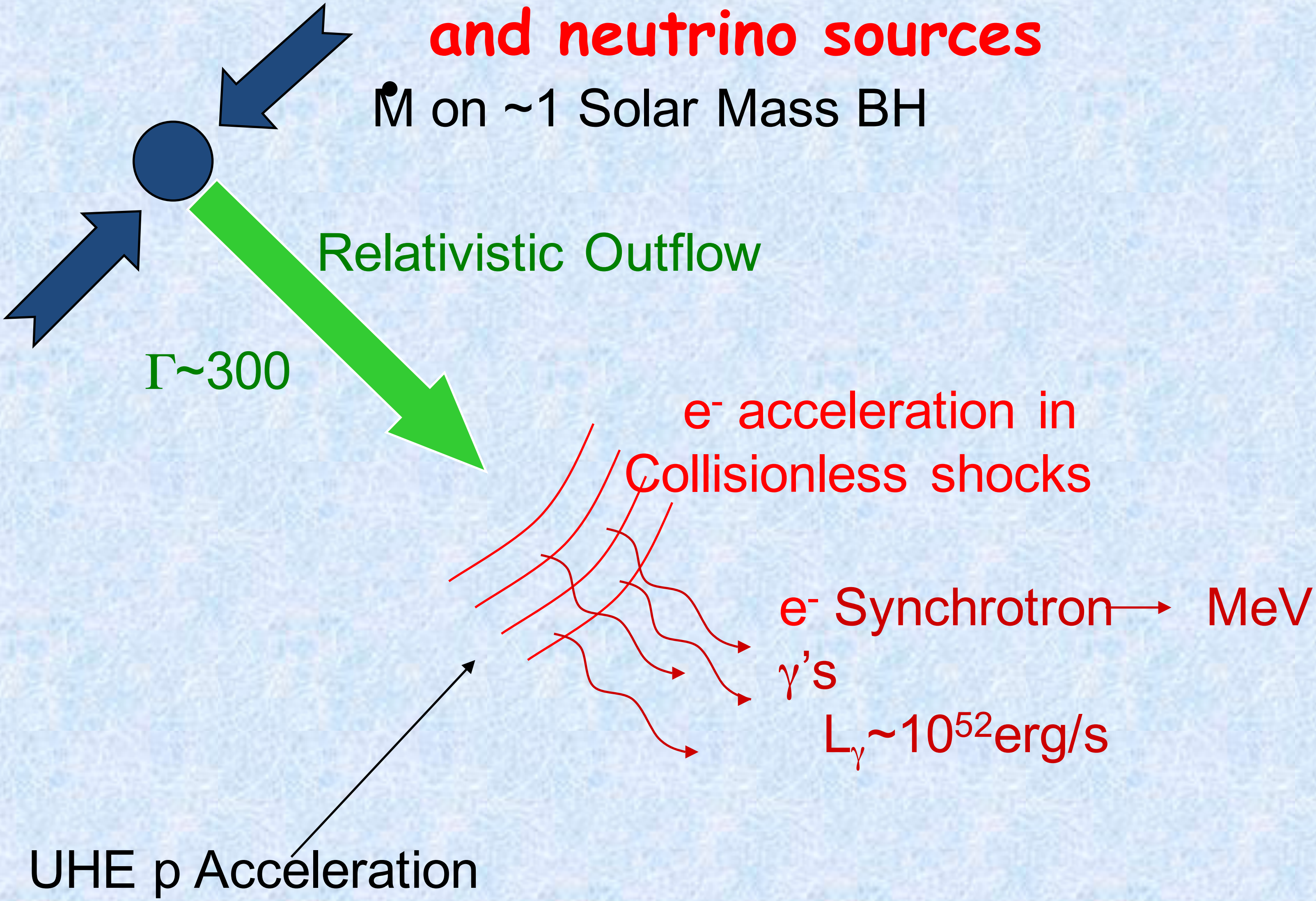
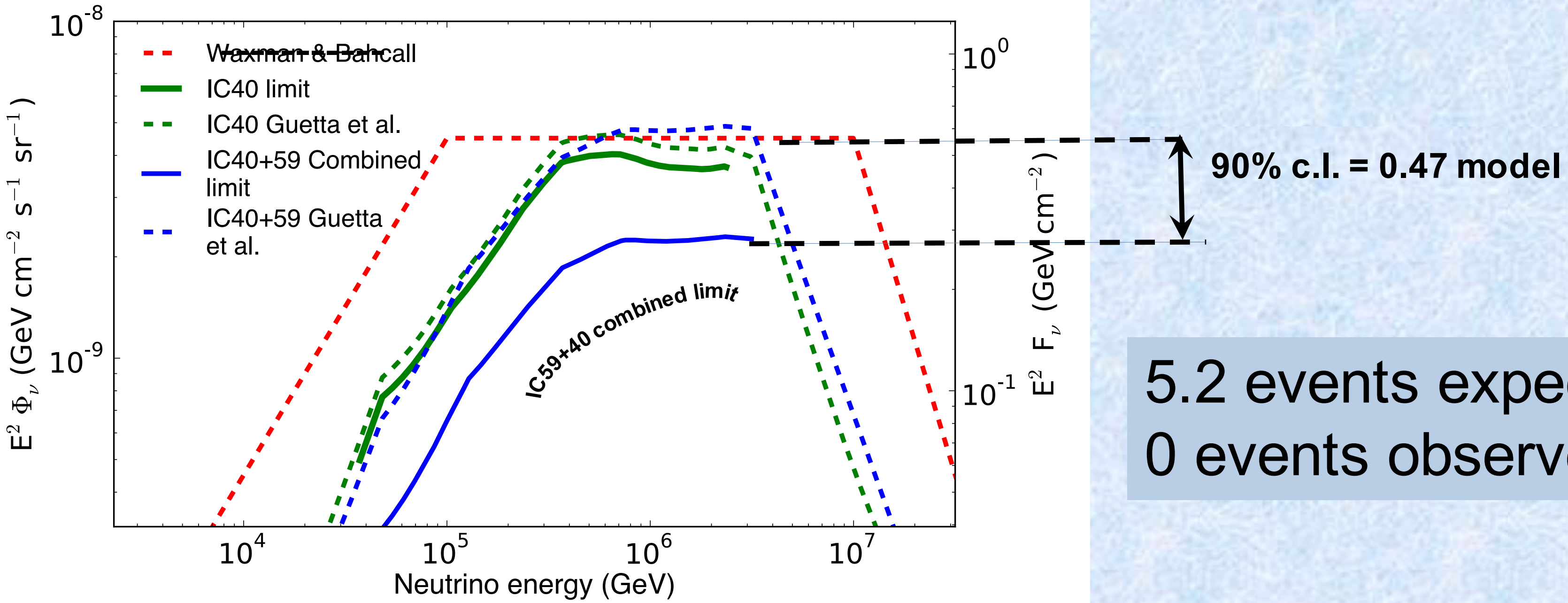


$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Gamma-ray Bursts as particle accelerators and neutrino sources



(No) neutrinos in coincidence with gamma ray bursts

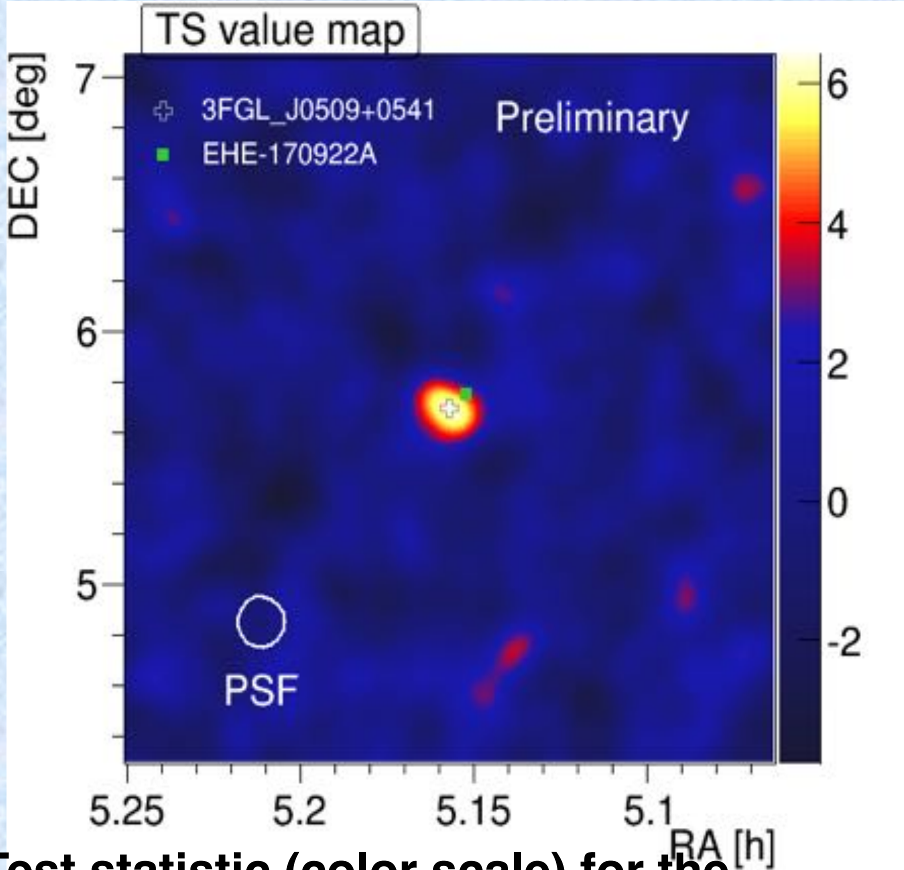


5.2 events expected
0 events observed

Abbasi et al. Nature Vol **484**, 351 (2012)

GRB fireball neutrino models tested.
From this analysis GRBs fireball model strongly constrained (Hummer, Baerwald & Winter 2012) and GRBs as the primary source of highest energy CR strongly disfavored for classes of models (neutron escape)
GRBs can contribute to 1% of the ν
Blazars also strongly constrained

Neutrinos from blazars IC170922A



Test statistic (color scale) for the MAGIC observation of gamma rays in the direction of IceCube alert IC170922A (green square).

Evidence was found for a spectacular burs of 14 high-energy (~300 TeV) neutrinos in 110 days. It dominates the flux of the source over the last 9.5 years for which we have data

For the first time, telescopes detected a source aligned with the cosmic neutrino within less than **0.1°.** They identified a flaring blazar at redshift ~0.34, called **TXS0506+056, also known as 3FGL J0509+0541**. Originally detected by NASA's Fermi and Swift satellite telescopes, the alert was followed up by the MAGIC air Cherenkov telescope, MAGIC detected a very hard photon spectrum in gamma rays with energies exceeding 400 GeV. Several other telescopes subsequently observed the flaring blazar.

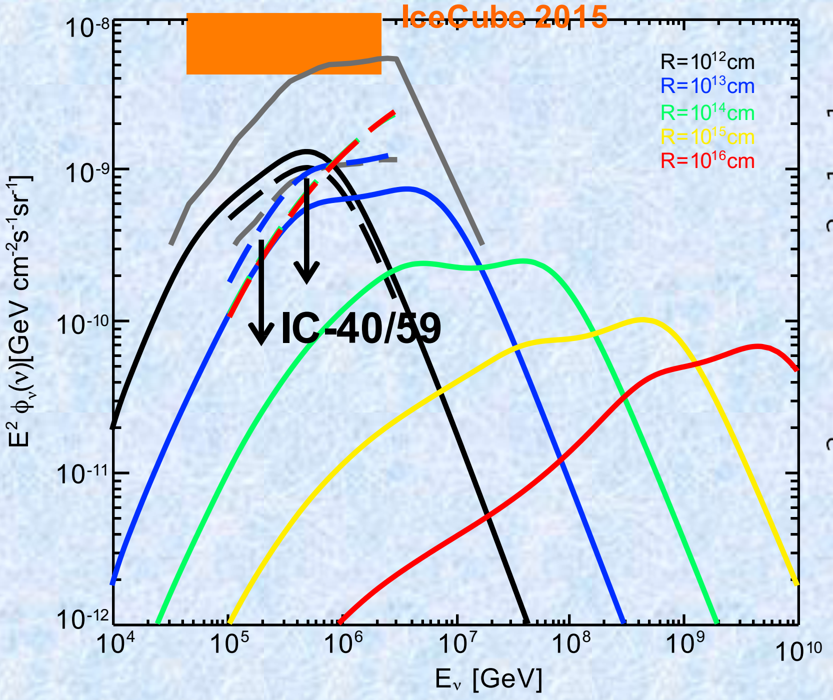
Objective: model the rich multiwavelength data provided by this event. The challenge is that the blazar jet must have a sufficiently dense photon target to produce the neutrinos seen by IceCube and, at the same time, be transparent to the TeV photons implied by the MAGIC observation and the large redshift of the source

HE Neutrinos from GRBs and AGN

Standard jet models as the cosmic ν origin: ruled out by multi-messenger obs.

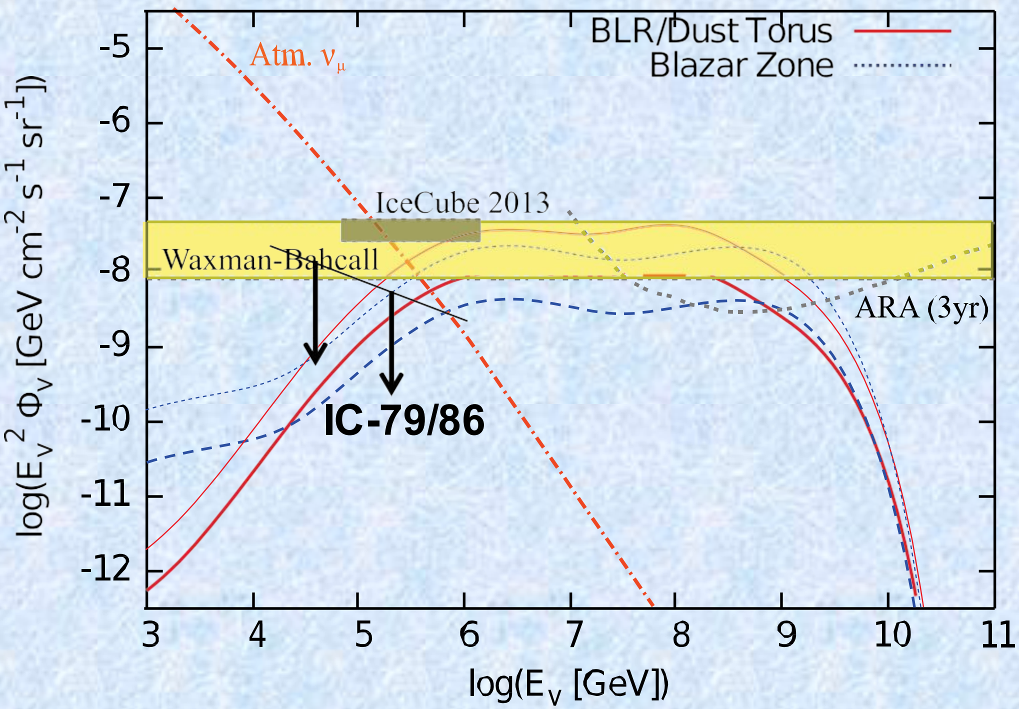
- Classical GRBs: constrained by stacking analyses **<~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}**
- Blazars: spectral shape, point-source limits Murase & Waxman 15
- **Maybe low luminous GRBs and AGN or Hidden sources (Murase Guetta Ahlers 2015)**

Classical GRBs



He+ KM 12 ApJ

Blazars



KM, Inoue & Dermer 14 PRD

Extragalactic Gamma-Rays

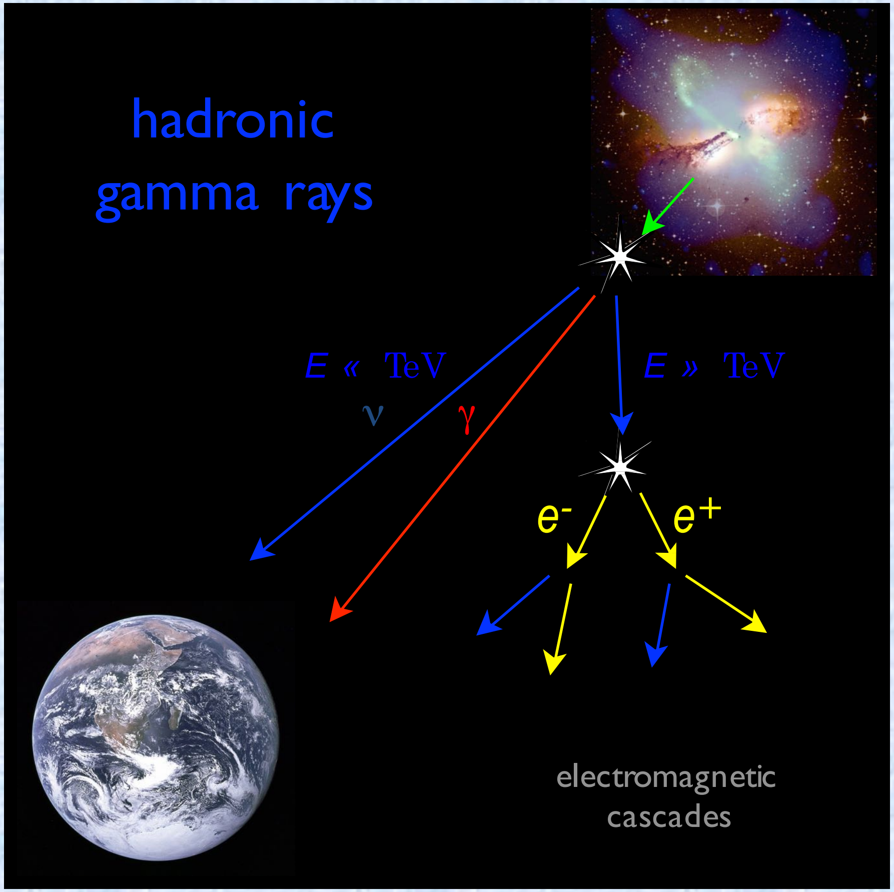
- **hadronic** γ -rays:
  pion production in CR interactions
  $\pi^0 \rightarrow \gamma\gamma$

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_\mu \nu_e$

Cross correlation of γ-ray and neutrino sources

x electromagnetic cascades of super-TeV γ-rays in CMB, EBL intrasource cascade can prevent γ-ray to escape

✓ If escape can contribute to the Isotropic Diffuse Gamma-Ray Background (IGRB) constraints the energy density of hadronic's origin γ-rays & neutrinos



How to Test?: Multi-Messenger Approach

$$\boxed{\pi^0 \rightarrow \gamma + \gamma}$$

$p + \gamma \rightarrow N\pi + X$ $\pi^\pm:\pi^0 \sim 1:1 \rightarrow$ $\mathbf{E_\gamma^2\, \Phi_\gamma \sim (4/3)\, E_\nu^2\, \Phi_\nu}$

$p + p \rightarrow N\pi + X$ $\pi^\pm:\pi^0 \sim 2:1 \rightarrow$ $\mathbf{E_\gamma^2\, \Phi_\gamma \sim (2/3)\, E_\nu^2\, \Phi_\nu}$

>TeV γ rays interact with CMB & extragalactic background light (EBL)

$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^+ + e^-$

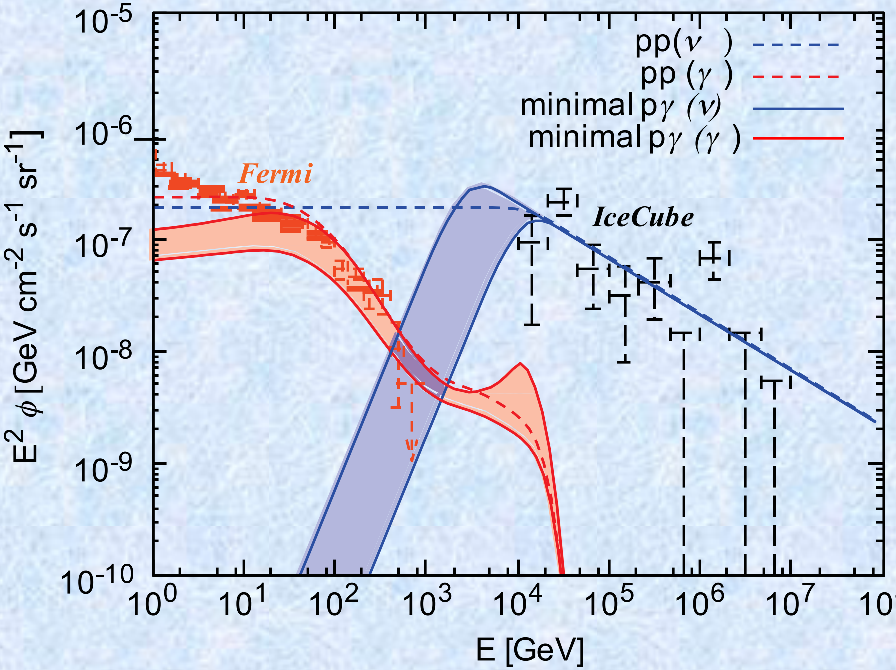
ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center

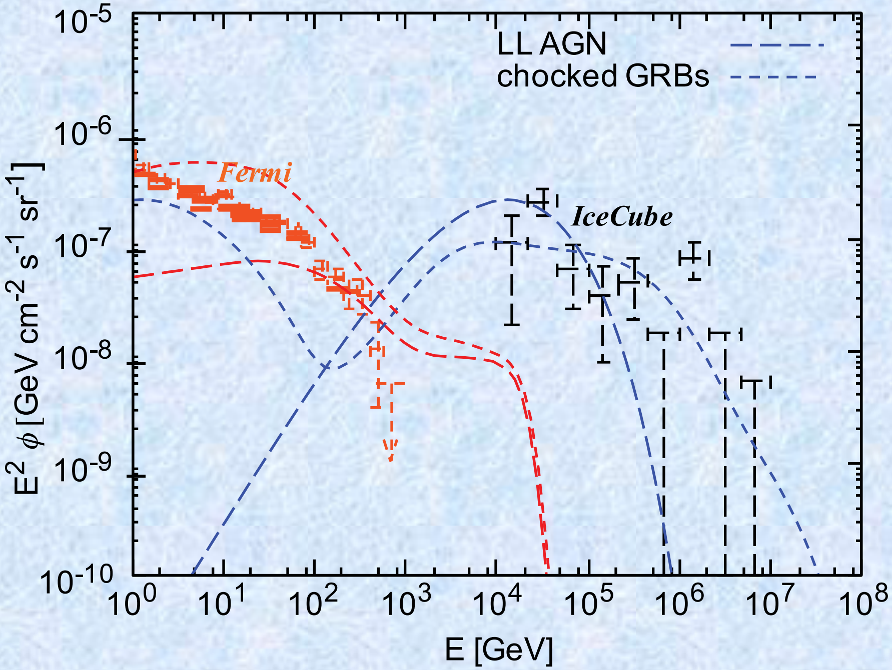
airshower detectors

Fermi satellite

Difficulty of Gamma-ray Transparent Sources (Murase, Guetta, Ahlers 2015)

~Minimal pγ with $\varepsilon_\nu \le \varepsilon_{b\nu} \le$ 25 TeV produced by CR at the pion prod. threshold $E^2\phi \sim \varepsilon_\nu^2$ for $\varepsilon_\nu \ge \varepsilon_{b\nu}$ $E^2\phi \sim \varepsilon_\nu^{2-s'}$ where s'~2.5 from IC data





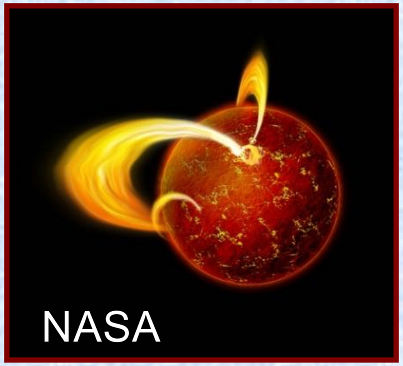
- γ-ray transparency → tensions w. diffuse γ-ray background
- Minimum pγ: if $\varepsilon_{b\nu}$~ 25 TeV→50% IGRB if $\varepsilon_{b\nu}$~ 6 TeV→100% IGRB γ-ray spectrum power law with HE cutoff
- 30TeV data indicate the existence of hidden CR accelerators

Possible GW sources: Bursts

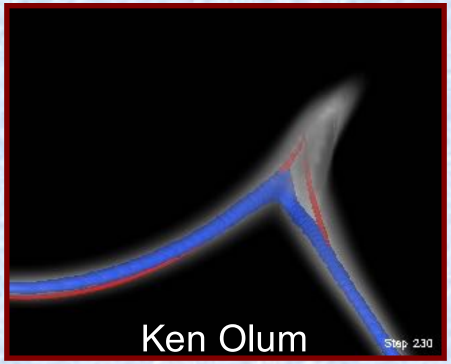
- Transient (usually less than 1 second)
- Waveform not known in advance (could be modeled)
- Zoo of potential sources:
  - Core collapse supernovae
  - Merger of two compact objects (e.g. short GRBs)
  - Neutron star instabilities
  - Cosmic string cusps and kinks

supernova remnant

gamma ray burst
(artist's conception)

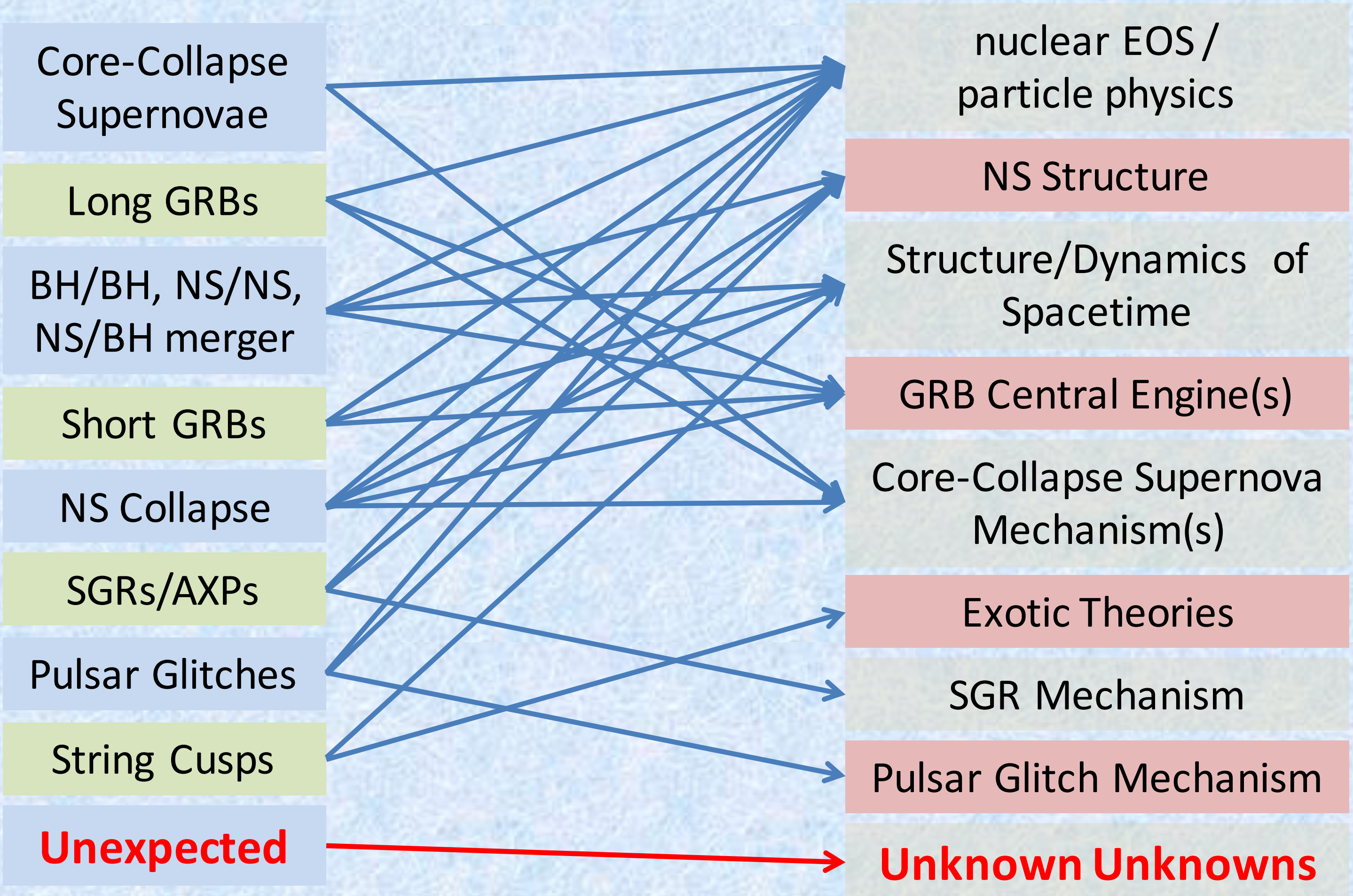


magnetar
(artist's conception)

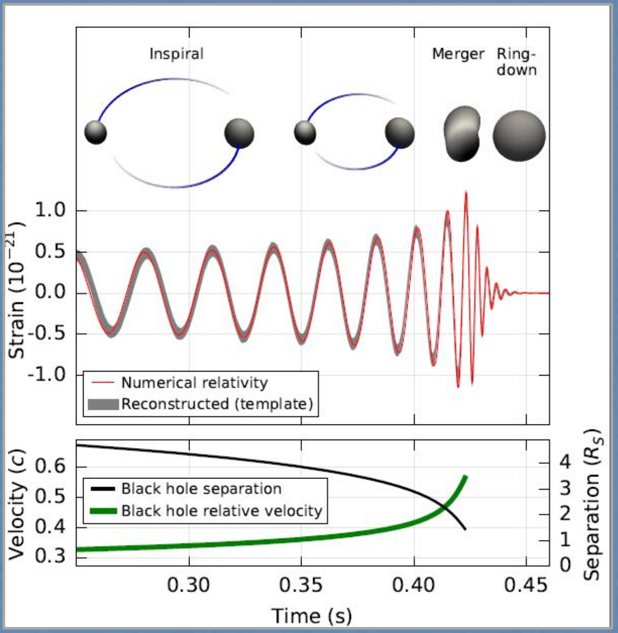


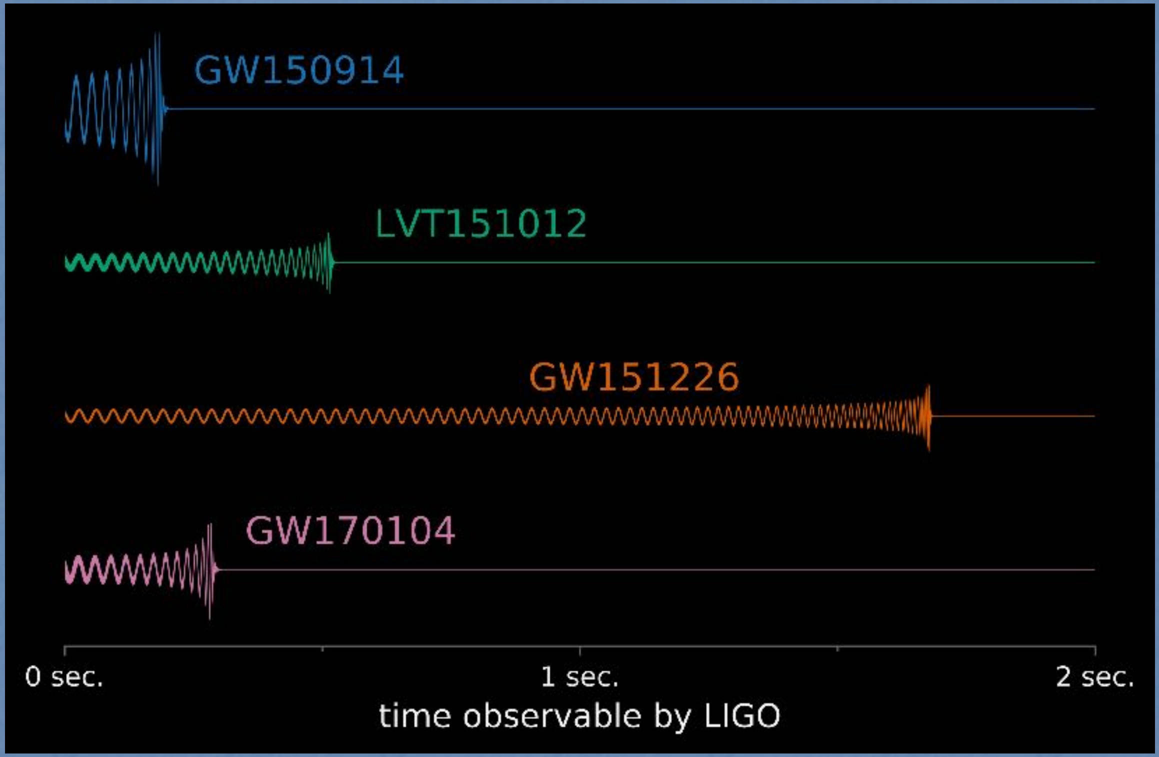
cosmic string cusp
(computer simulation)

GW Burst Sources and Science Payoff:



After a Century, Gravitational Waves Detected on Earth





Electromagnetic follow-ups

With the onset of GW observations, there has been a significant effort to search for electromagnetic and neutrino emission from GW sources

Gravitational wave and electromagnetic emission from the same source is not guaranteed, but many candidates exist (GRBs, SN, SGR….) and science payout could be huge:

Gravitational Wave Signal

- Bulk motion dynamics
- Luminosity distance
- Progenitor mass

Light curve and spectrum

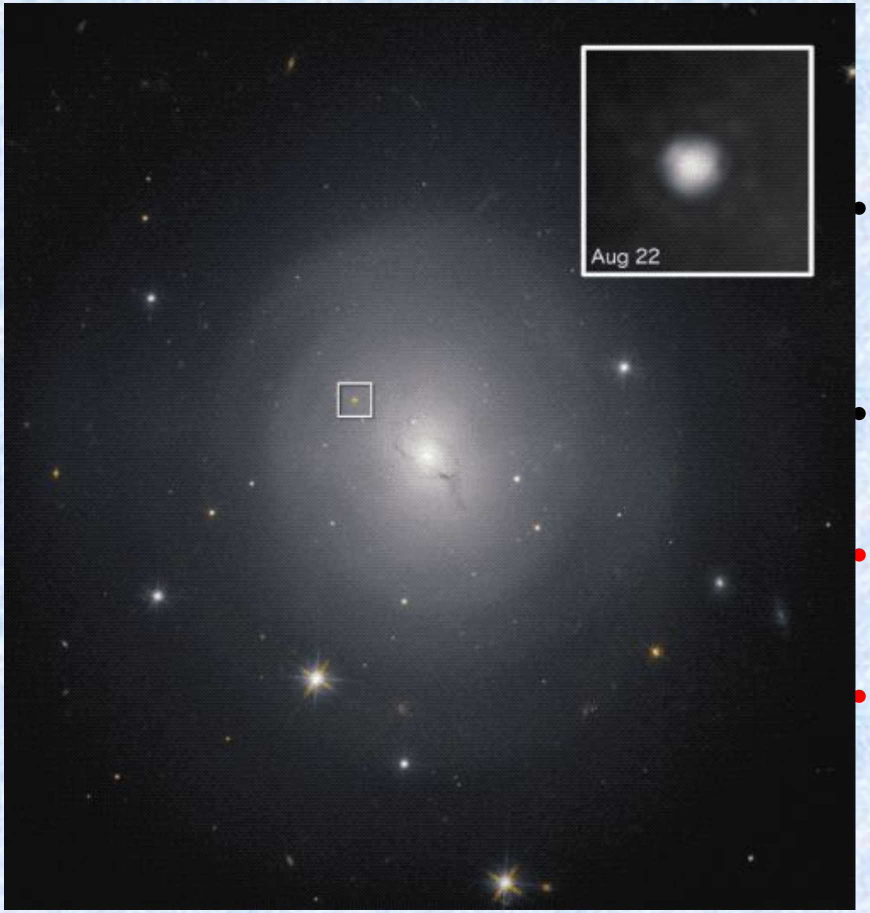
- Host galaxy
- Gas environment
- Red shift distance
- **Confirm GW detection**

Multi-messenger astrophysics!!

Map compact object hosts

Full picture of progenitor physics

GRB 170817A



- Short, hard gamma-ray burst
  - Leading model for short GRBs: binary merger involving a neutron star
- Position (from gamma-ray satellite data) is consistent with being in NGC4993 D=40MpC
- Result from LIGO data analysis: GW signal found!!!
- Evidence of Kilonova the source of Gold!
- https://www.youtube.com/watch?v=qJj32mr2Z0M

Constraints: Granot,Guetta & Gil ApJ 2017

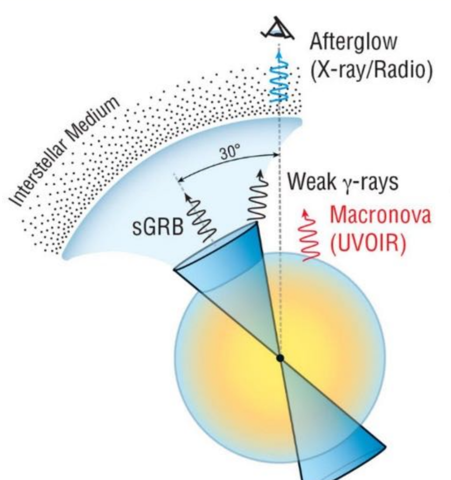
Kilonova Rate (2018)
Della Valle, Guetta et al. MNRAS in press

https://www.space.com/-38471
-crashes-star-neutron-waves-gravitational
explained.html-discovery

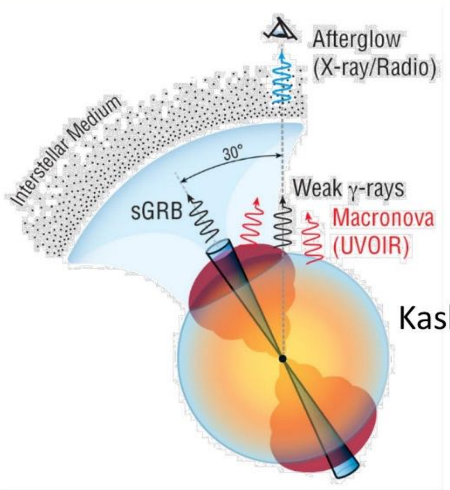
GRB 170817A
The multimessenger view

Information from GRB & afterglow

- Weak GRB --- orders of magnitude below weakest detected.
- Delayed afterglow (9/15 days for X-ray/radio) --- off axis?
- Afterglow brightness grows until ~200 days.
    - Simple (on-axis, “top-hat”) models ruled out.
    - Outflow is structured likely due to interaction with kilonova ejecta.

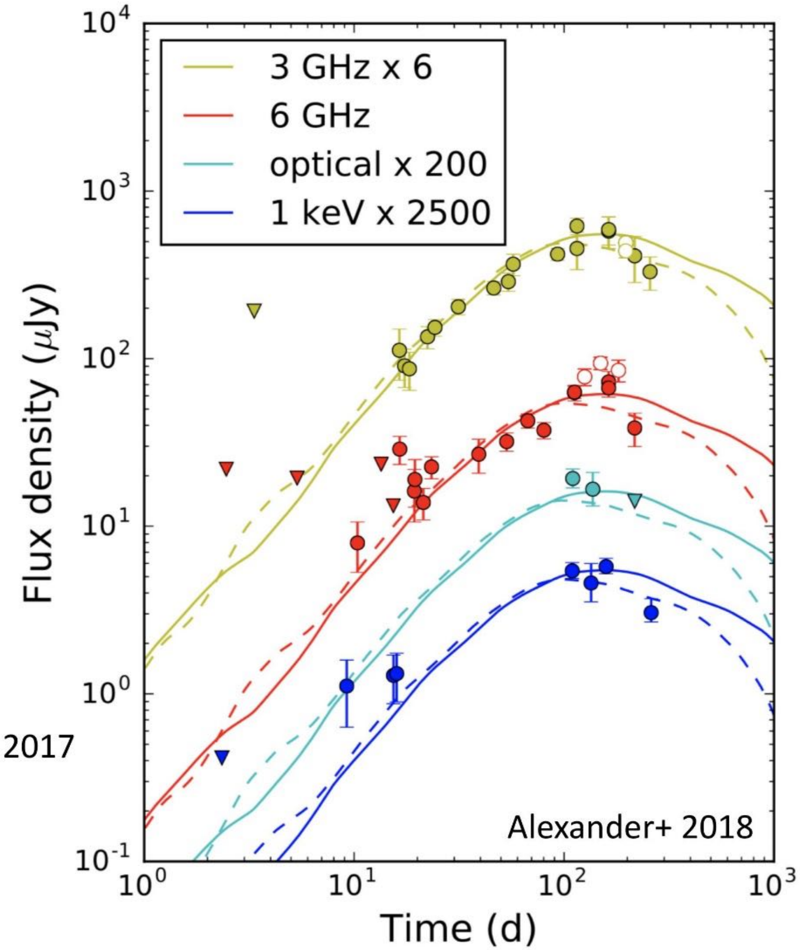


Structured jet
(e.g. Lazzati+2017, Margutti+ 2018)



“Cocoon”
(e.g. Gottlieb 2017, Mooley 2018)

Kasliwal+ 2017



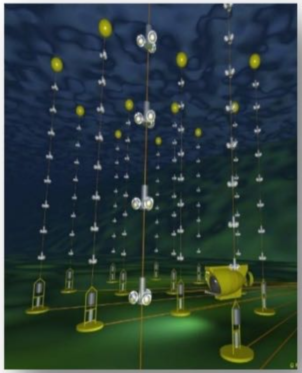
High-energy emission (neutrinos)

Rationale:

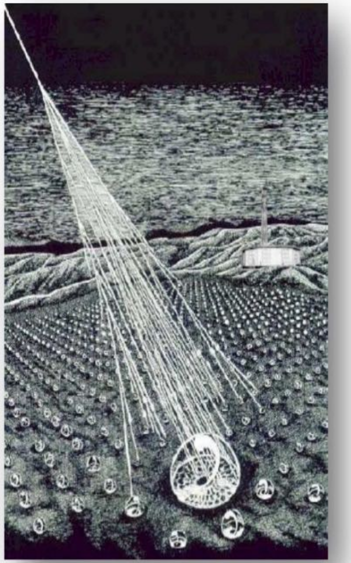
- <u>Very nearby GRB</u> – potentially strong emission.
- <u>GRB model unclear</u> (e.g. structured vs cocoon, on-axis / off-axis) – neutrinos may help differentiate.
- <u>Interaction between GRB and kilonova ejecta</u> --- interesting site for neutrino production.

Multi-messenger search:

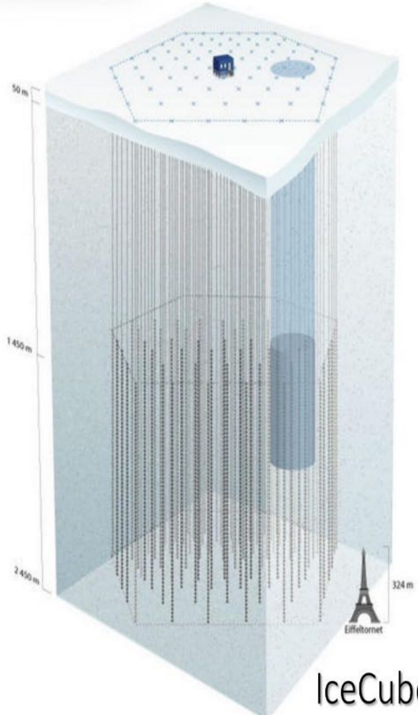
- Rapid reaction is critical – joint event can immediately help localization.
- Required close collaboration of multiple observatories – logistics, data sharing, etc.
- Participating observatories: ANTARES, IceCube, Pierre Auger.



ANTARES

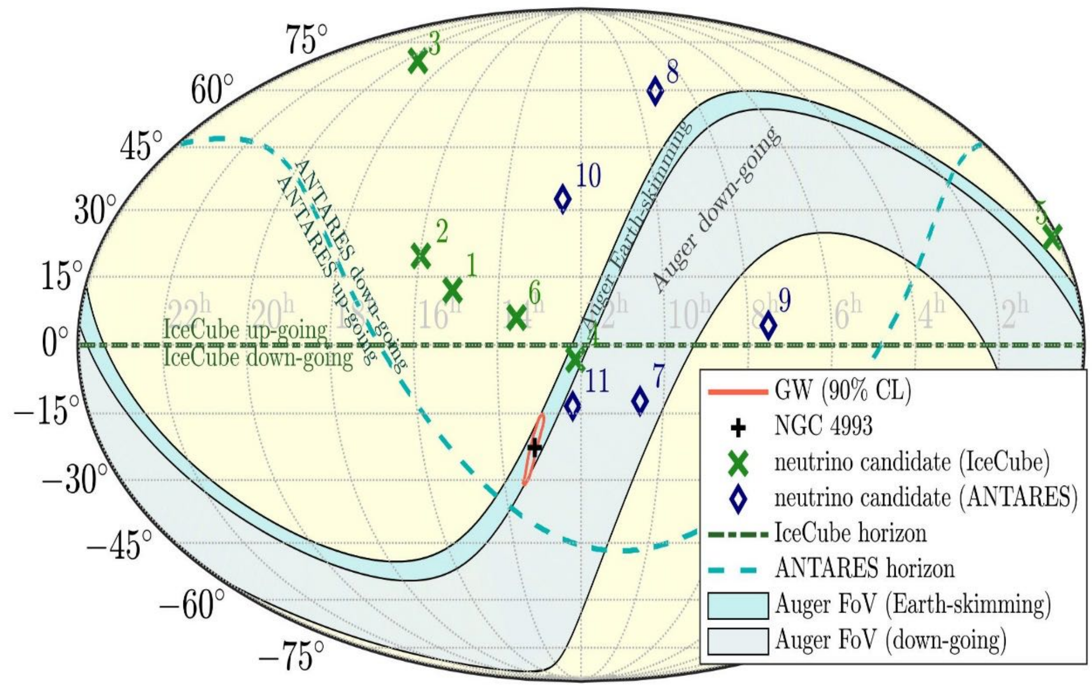


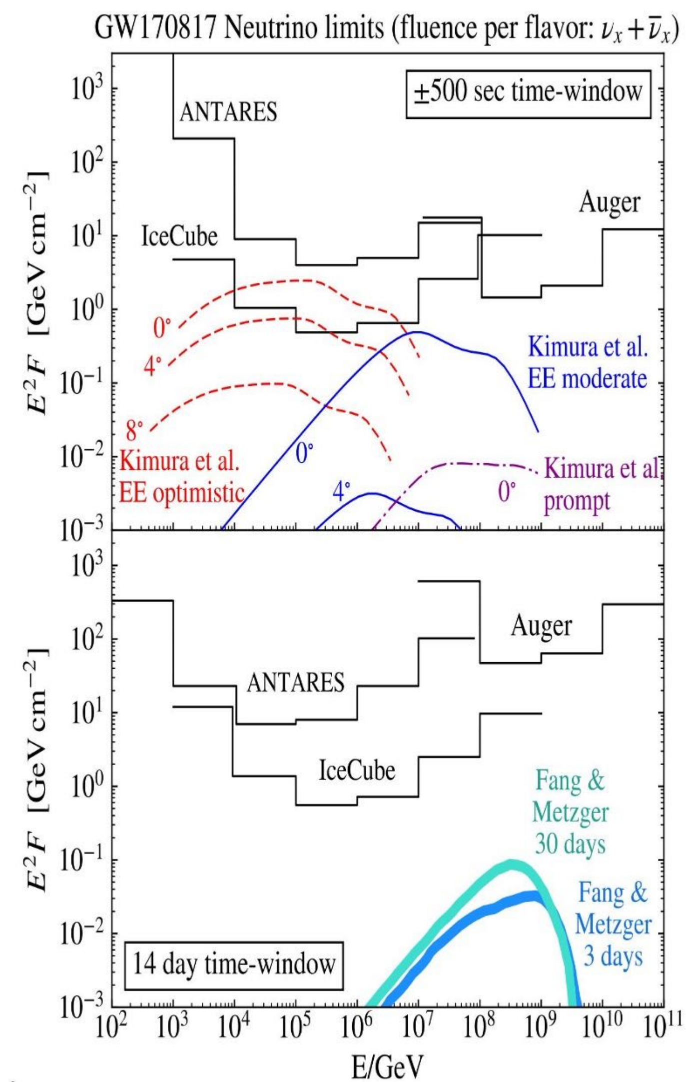
Pierre Auger



IceCube

Search for high-energy neutrinos

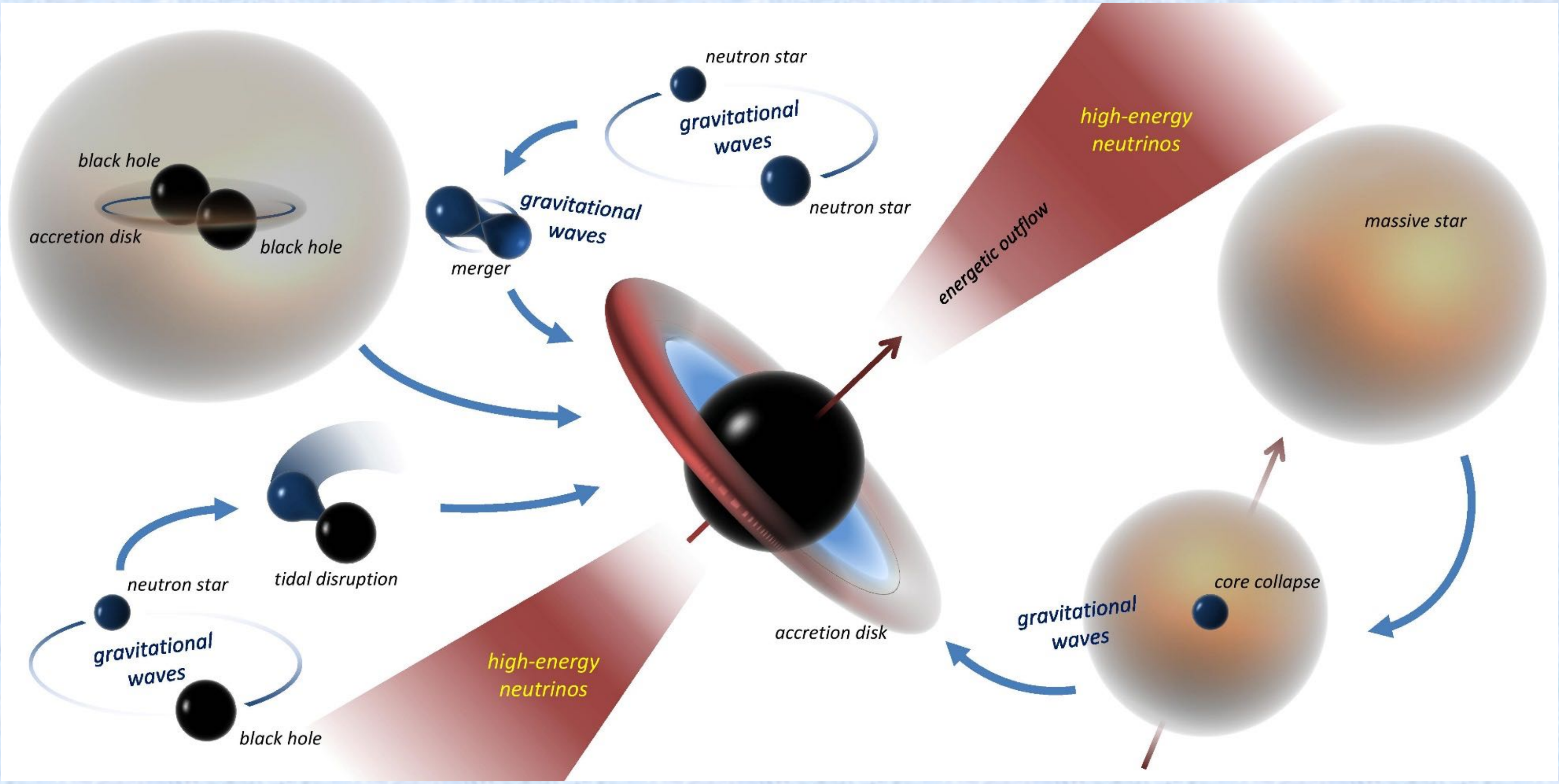




- Search within <u>1000 s</u> and <u>2-week</u> time windows (model motivated).
- Complementary sensitivity from the three detectors.
- No significant coincident detection.
- On-axis emission could have produced detectable emission in some models.

ANTARES, IceCube, Auger, LIGO, Virgo 2017

Multimessenger sources of GWs and high-energy neutrinos



Conclusions

- The study of common sources of GWs, neutrinos and gamma-rays requires a broad understanding of the emission processes and detection technique.
- It is fundamental that multimessenger predictions and observational planning are performed within the same theoretical framework, instead of combined from different studies that have a diverse set of assumptions.
- How effective multimessenger searches will be in yielding astrophysical insights strongly depends on how well we understand the sources we are searching for, and how much information on these sources we incorporate in searches.

Comments & Consequences

What is the origin of cosmic ν signals?

pp: Strong limits apply to CR calorimeters like starbursts galaxies or galaxy clusters

mostly isotropic & diffuse TeV-PeV γ-ray limits $\rightarrow$ extragalactic pp scenarios: $s<2.2$ & >30% to the diffuse sub-TeV γ-ray bkg.

If radio-loud AGN are the main sources of IGRB little room to CR reservoirs, strong constraints.

Direct γ-ray emission can be reduced in $p\gamma$ scenarios: classical GRBs & blazars are subdominant → hidden CR accelerators (ex. low-power GRBs/AGN)?

For power-law target photon spectra that extend to low energy $\tau_{\gamma\gamma}>1$ at TeV too

Hidden CR accelerators are suggested at least for ~10-100 TeV neutrinos

- tension w. diffuse sub-TeV γ-ray bkg. & optical depth argument
- Search for neutrino counterparts in other bands X-ray, Optical