המכללה האקדמית להנדסה
אורט בראודה
ORT BRAUDE COLLEGE

Multimessenger Probes of High-energy Sources

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THESEUS Conference 24/03/2021

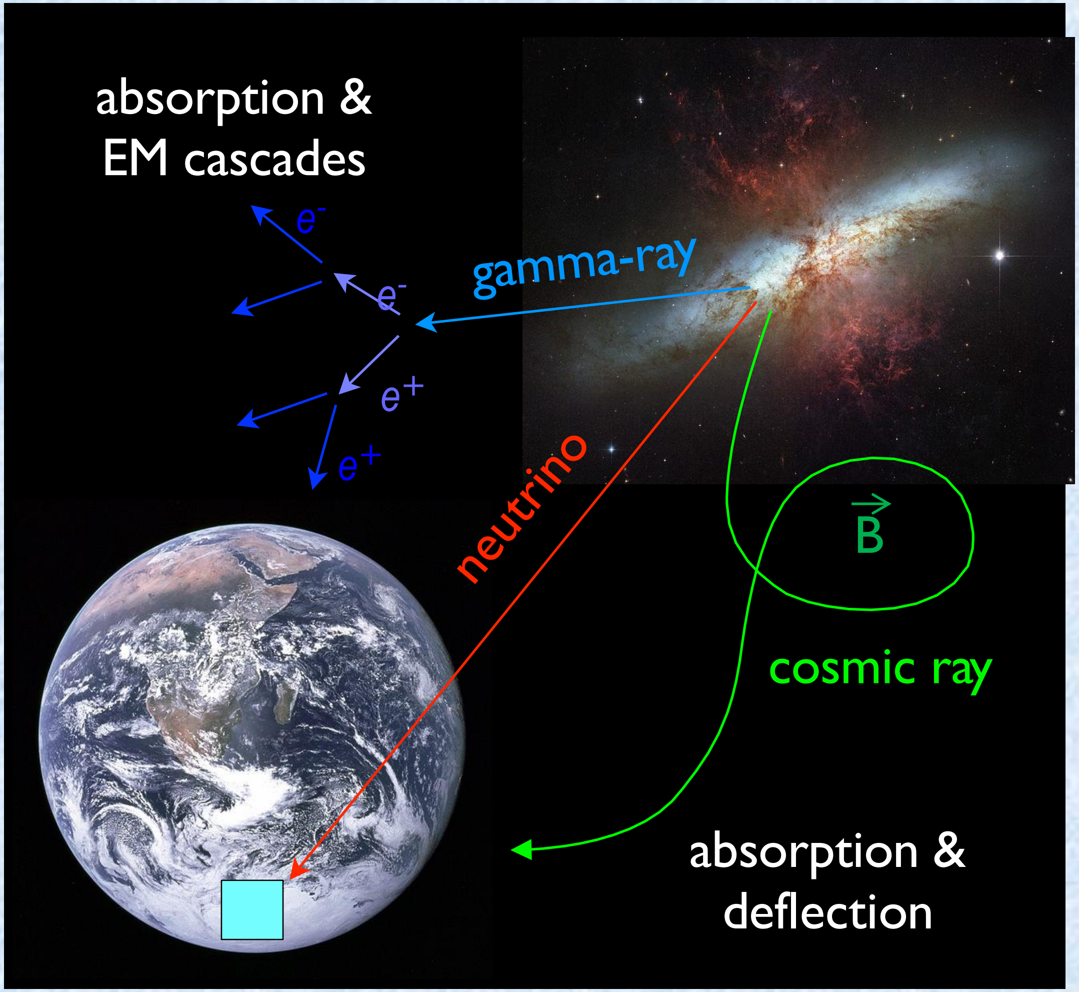
Multi-Messenger Astronomy

Cosmic Messengers:

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

→ Neutrino astronomy:

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



Challenges:

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

Cosmic Rays and Neutrino Sources

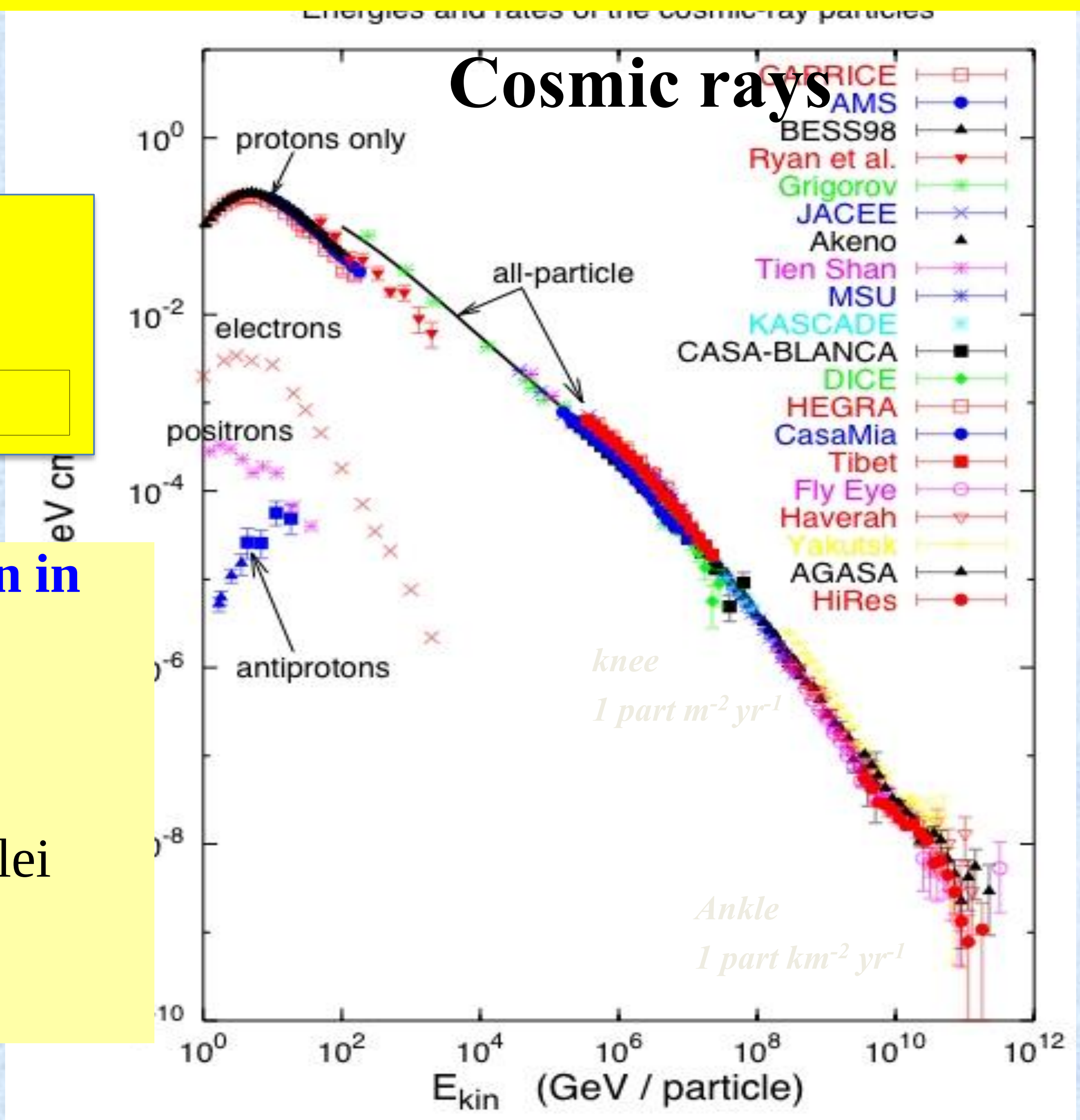
Can neutrinos reveal origins of cosmic rays?

$$pg \to pp^0, np^+$$

Cosmic ray interaction in accelerator region

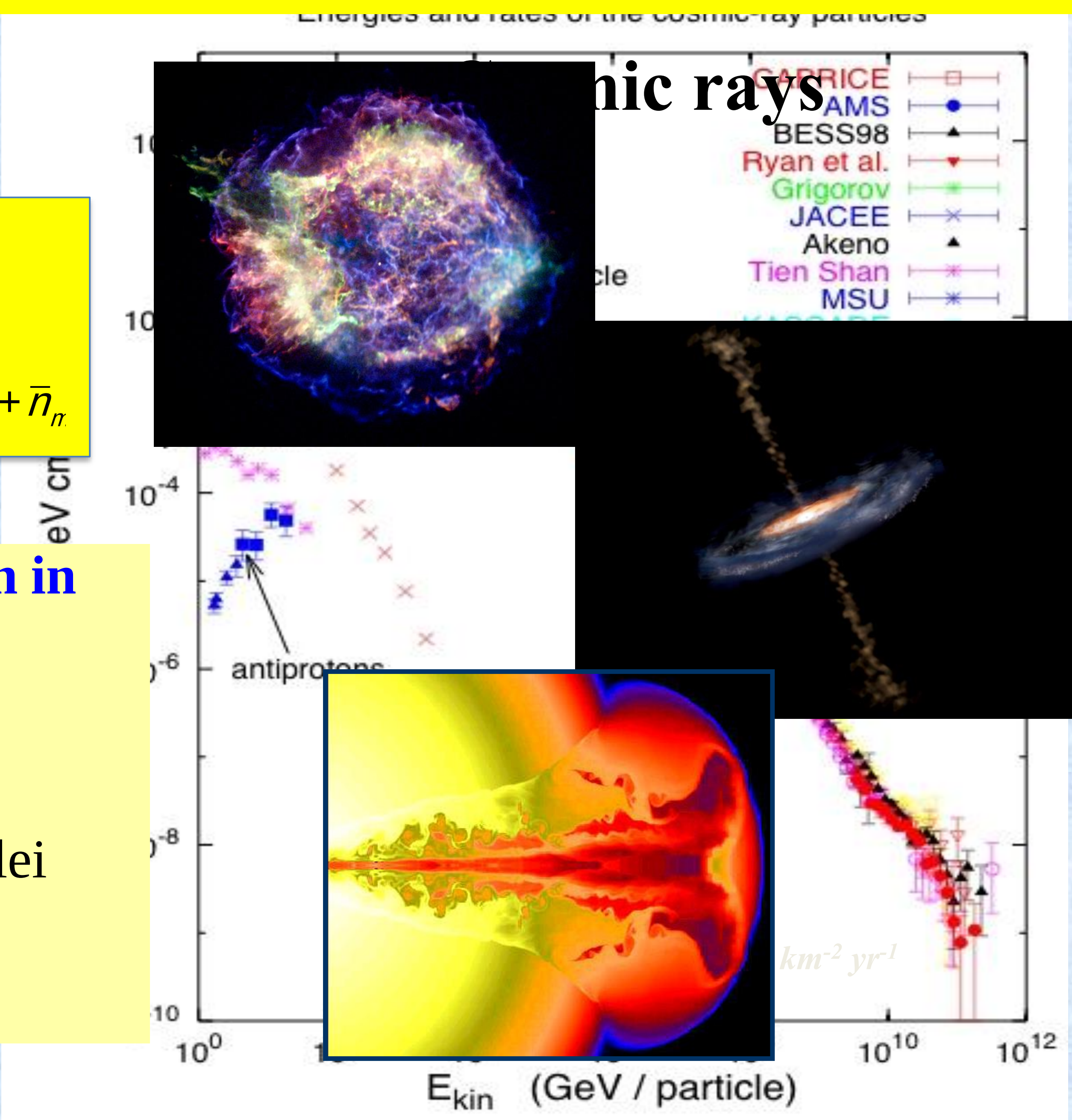
Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts



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
- Gamma Ray Bursts

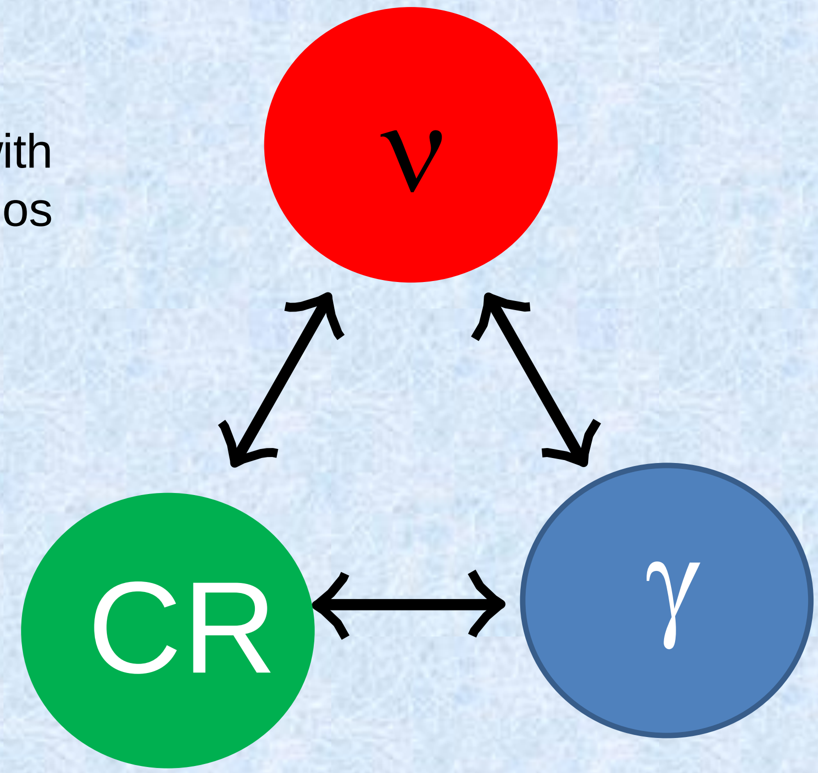
Multi-messenger Paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and γ -rays. **Hunting for EM counterpart !!!**

‹ pion production in CR interactions with gas (“*pp*”) or radiation (“$p\gamma$ “) ⇨ 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:



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.

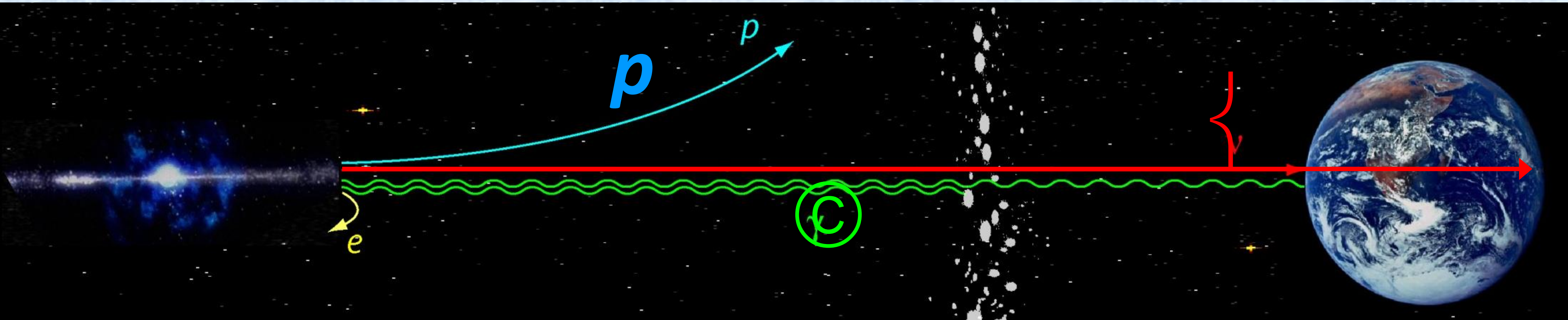
Cosmic neutrinos?

Why look for them?

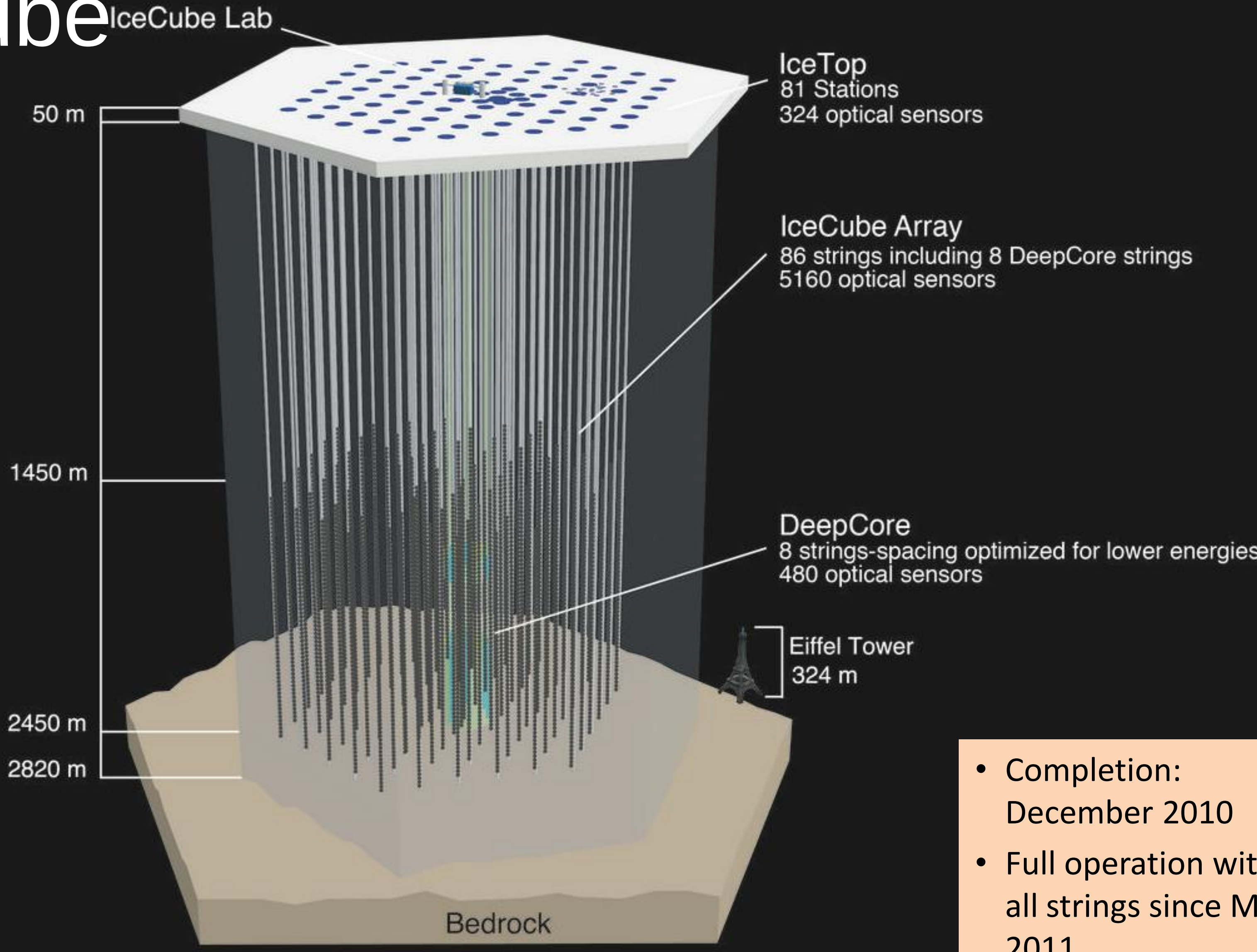
- They could tell us about the origin of high energy cosmic rays, which we know exist.
  - There are numerous ways how neutrinos can tell us about fundamental questions in nature: dark matter, supernova explosions,
  - Composition of astrophysical jets, physics of the source core
  - Neutrino astronomy 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.

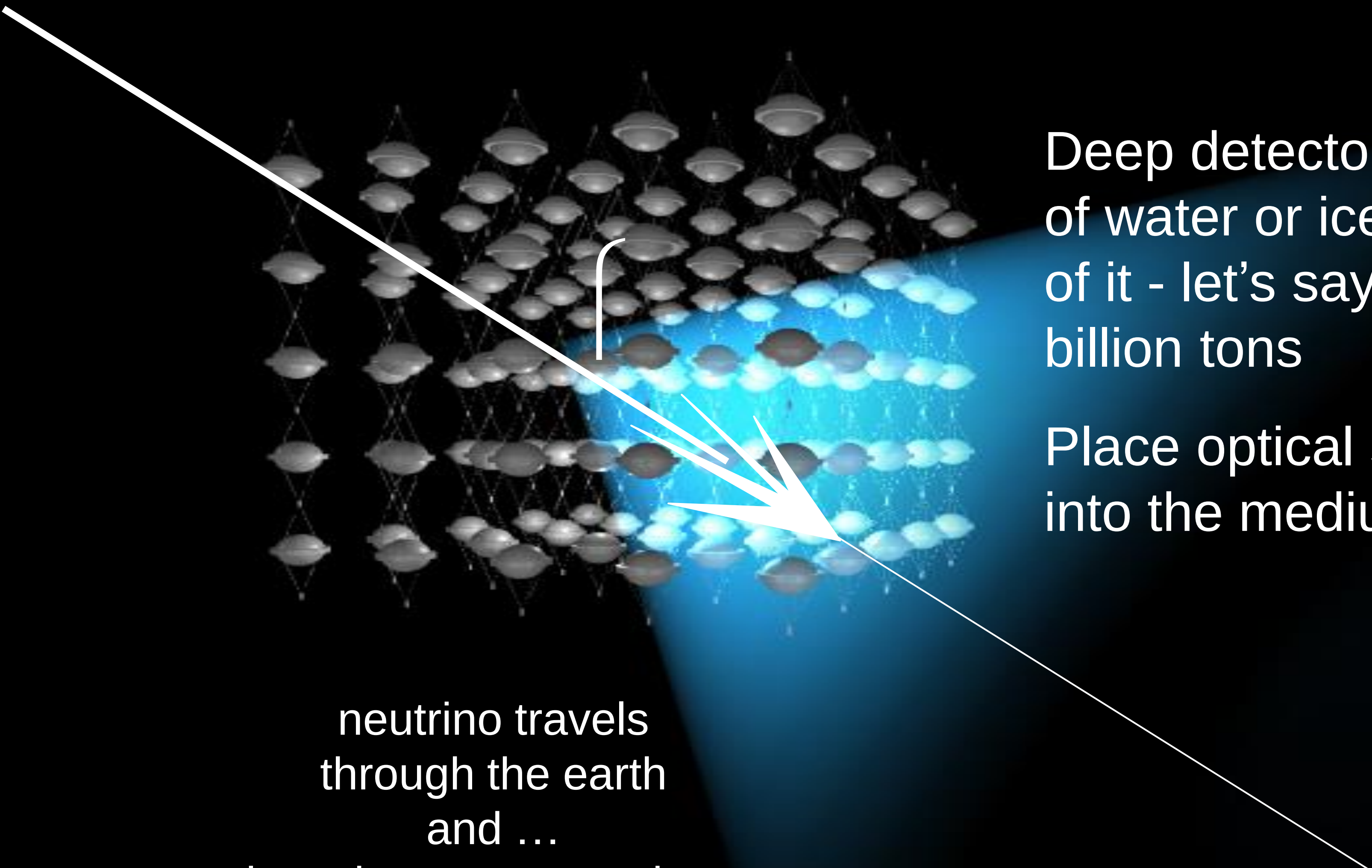


Telescopes: Spurio's talk
IceCube



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

How to catch them?
Detection principle

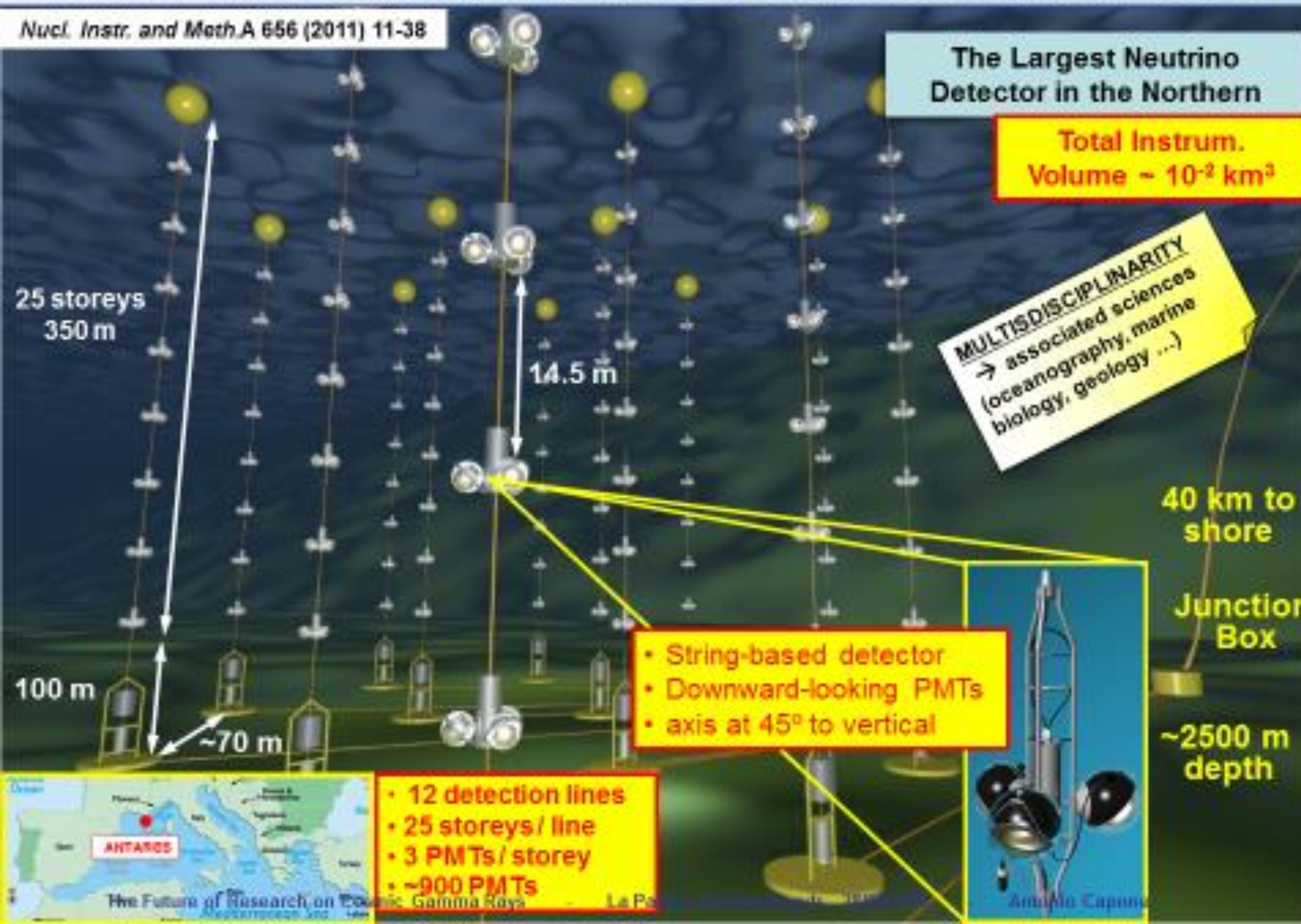


Deep detector made of water or ice – lots of it - let's say 1 billion tons

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

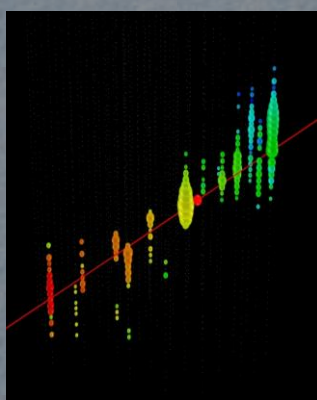


Future telescopes

- 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**
- **THESEUS synergy with future neutrinos facilities (Giulia's talk)**

Neutrino Event Signatures (IceCube)

CC Muon Neutrino

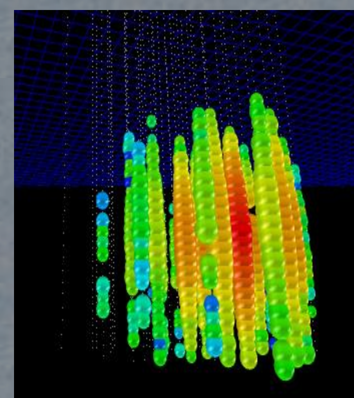


$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 0.5° angular resolution

Neutral Current /Electron Neutrino



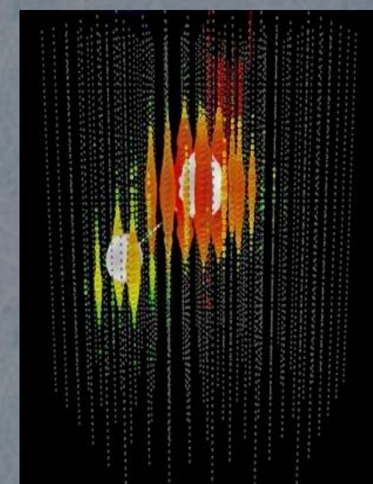
$$\nu_{\mathrm{e}} + N \to \mathrm{e} + X$$

$$\nu_{\mathrm{x}} + N \to \nu_{\mathrm{x}} + X$$

cascade (data)

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

CC Tau Neutrino



$$\nu_\tau + N \to \tau + X$$

“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?

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)

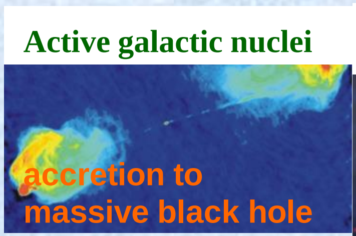
Galactic (as mostly subdominant contributors)

- Unresolved sources (supernova/hypernova remnants, microquasars)
- Extended sources (Fermi bubbles, Galactic halo)

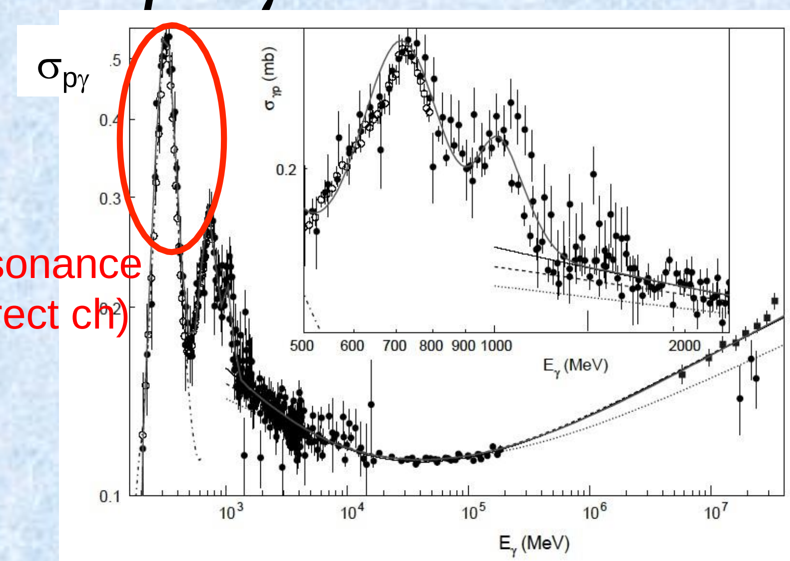
(Anchordoqui+ 14 PRD, Razzaque 13 PRDR, Ahlers & Murase 14 PRD, Lunardini+ 14 PRD)

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators (ex. UHECR candidate sources)



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



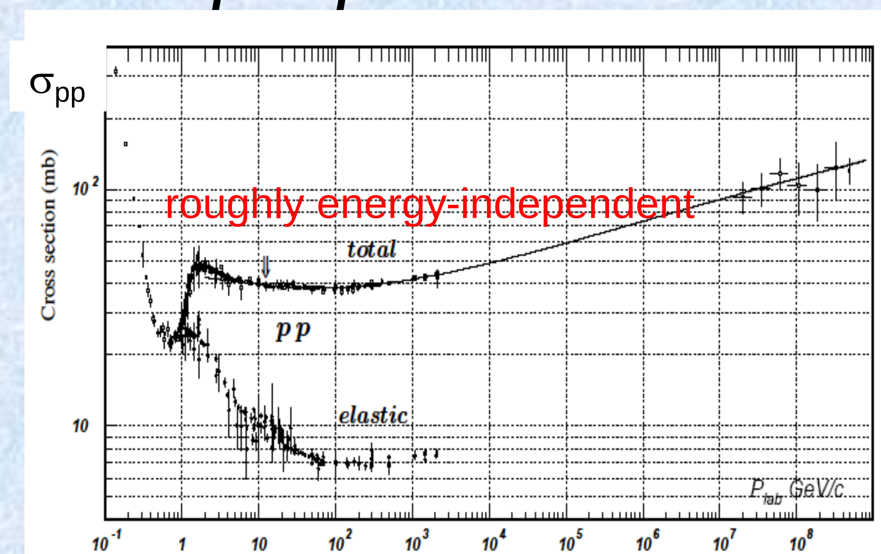
Δ-resonance
(+ direct ch)

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

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

Cosmic-ray Reservoirs

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



$\sigma_{pp} \sim 1/m_\pi^2 \sim 30$ mb

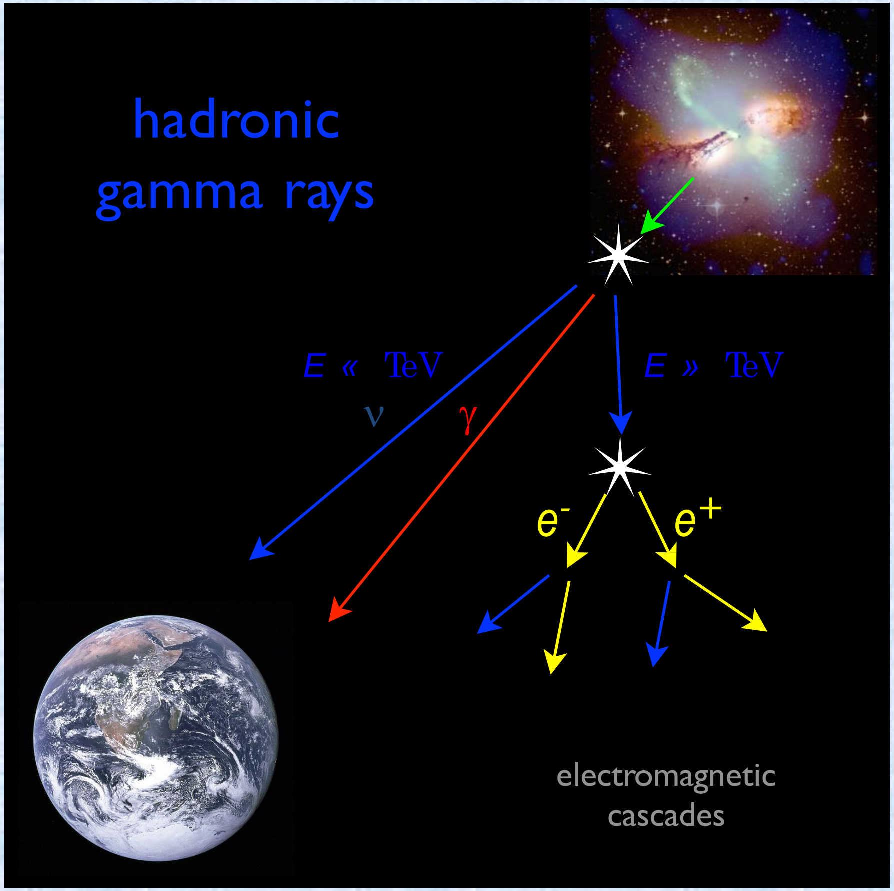
Extragalactic Gamma-Rays

- **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

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

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

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

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

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

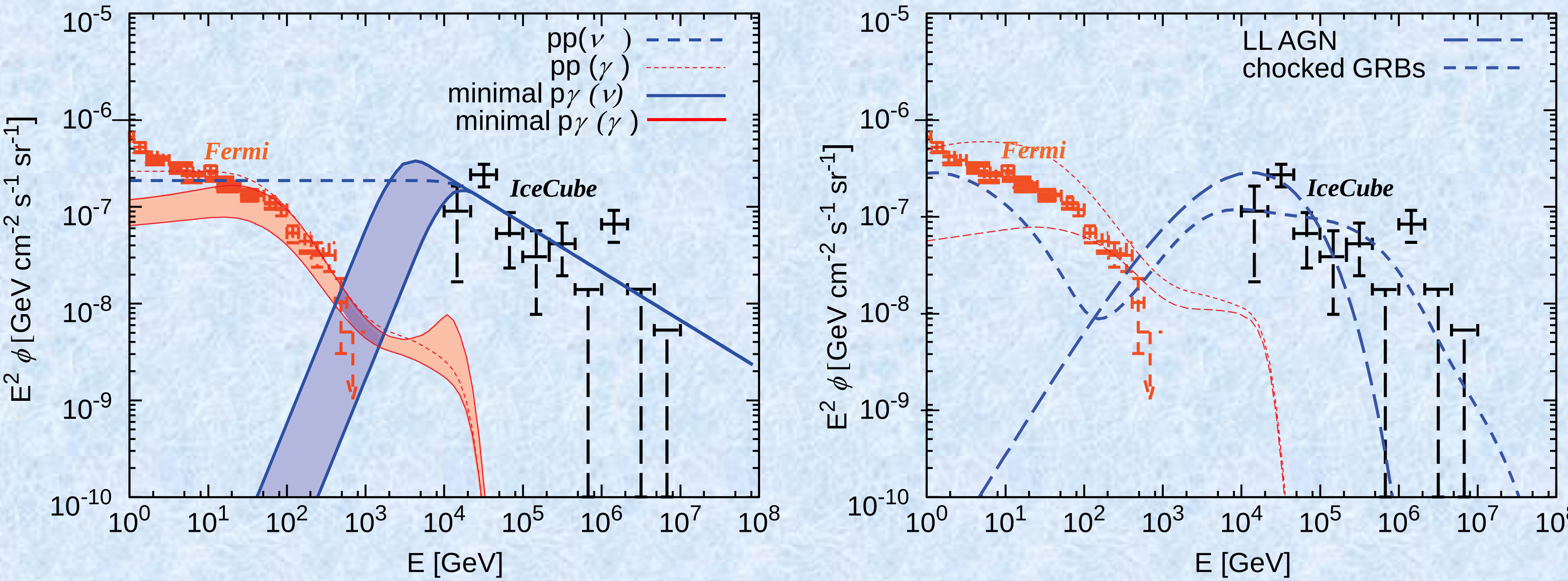
ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center

airshower detectors

Fermi satellite

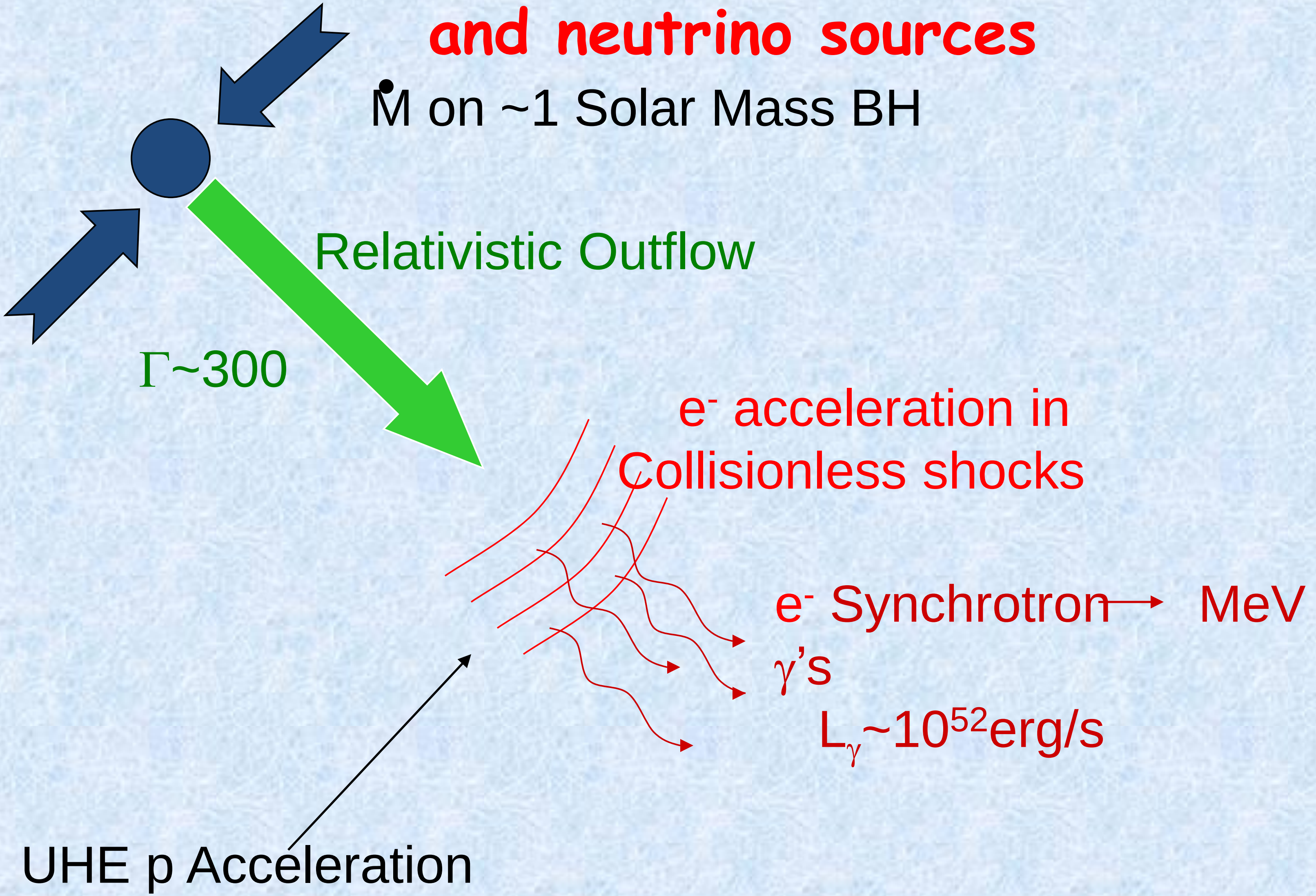
Difficulty of Gamma-ray Transparent Sources (Murase, Guetta, Ahlers 2015)

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

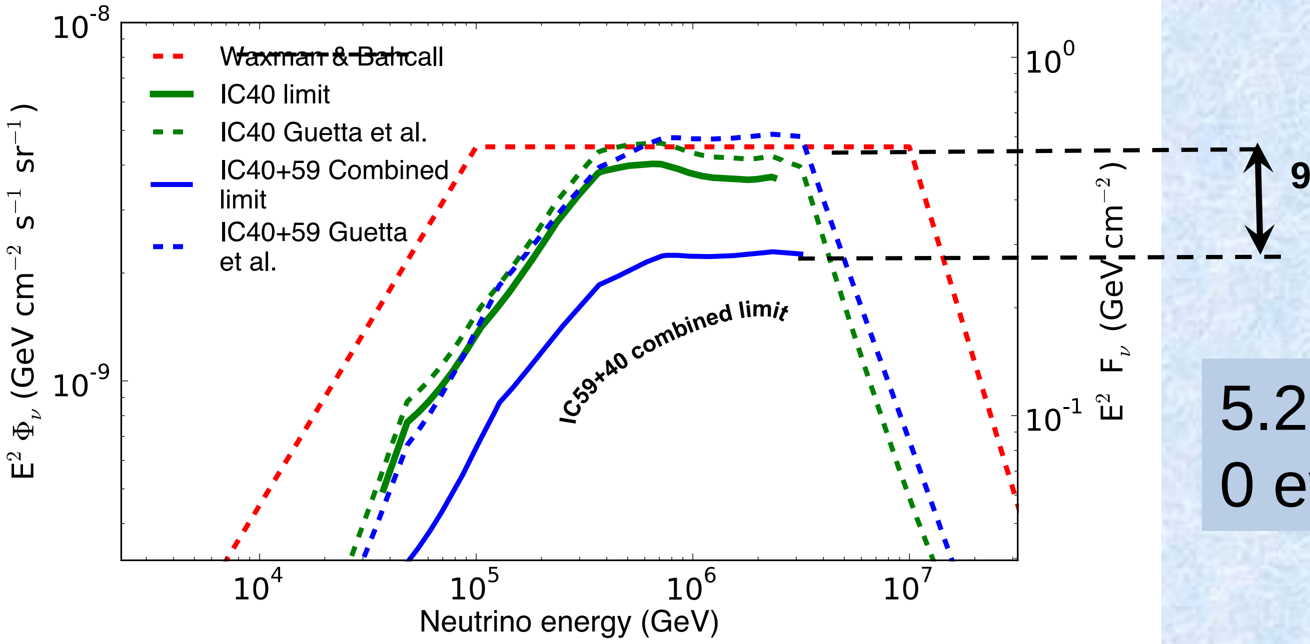


- γ-ray transparency → tensions w. diffuse γ-ray background
- Minimum pγ: if $\varepsilon_{b\nu}$~ 25 TeV→50% IGRB if $\varepsilon_{b\nu}$~ 6 TeV→100% IGRB γ-ray spectrum power law with HE cutoff
- 30TeV data indicate the existence of hidden CR accelerators

Gamma-ray Bursts as particle accelerators and neutrino sources



(No) neutrinos in coincidence with gamma ray bursts

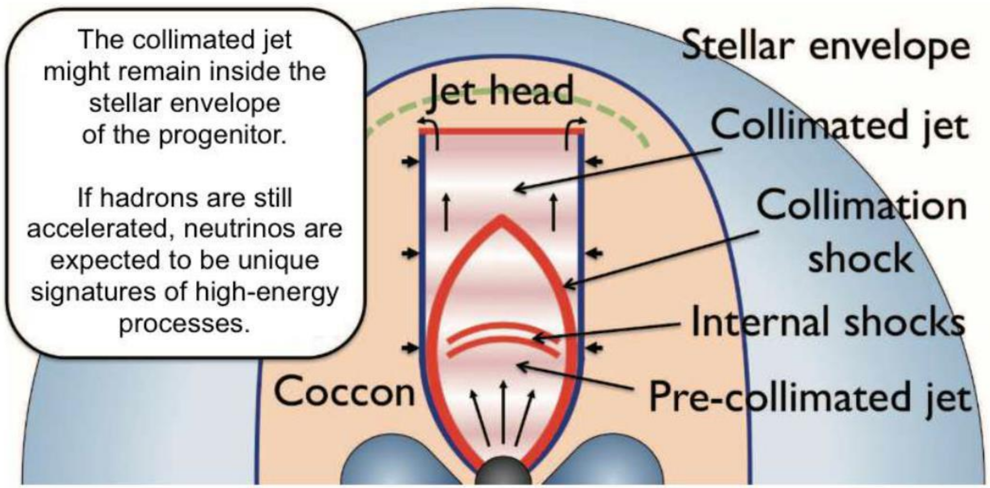


5.2 events expected
0 events observed

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 **(association not sure Giulia's talk)**
Look for other counterparts not gamma-rays!

Neutrinos from choked GRBs (Guetta et al. 2020, Fasano et al 2021)



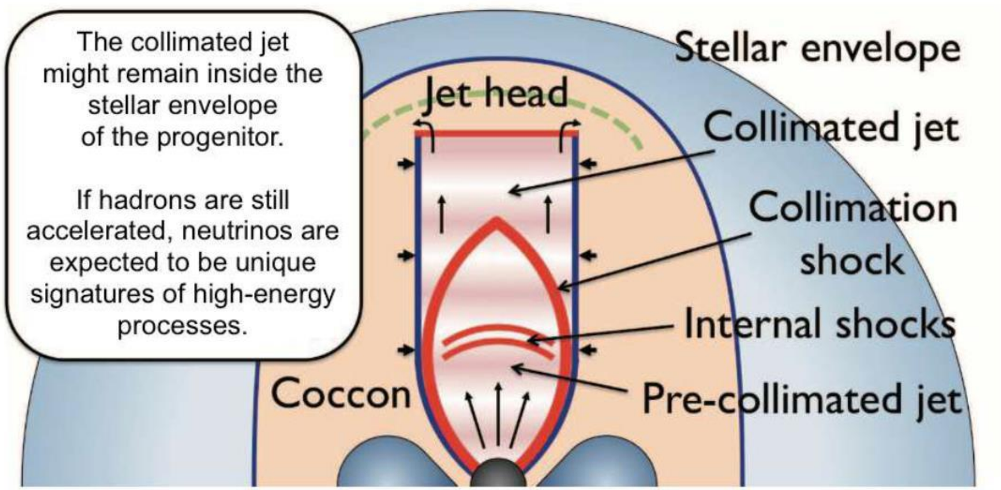
K. Murase & K. Ioca, PRL 111 (2013) 121102

Choked GRBs are **unsuccessful jets**, produced in the collapse of massive stars ending their life in type SNe Ic or Sne II still with an extended hydrogen envelope around (~10^{13} cm).

The jet is unable to penetrate the envelope, hence it deposits all of its energy in a cocoon (Lazzati, Piran, Nakar papers), that will afterwards break out of the star releasing energetic material at sub-relativistic speeds.

We may have X-ray and UV emission from these objects

Neutrinos from choked GRBs



Particle acceleration model from He et al., ApJ 856 (2018) 119

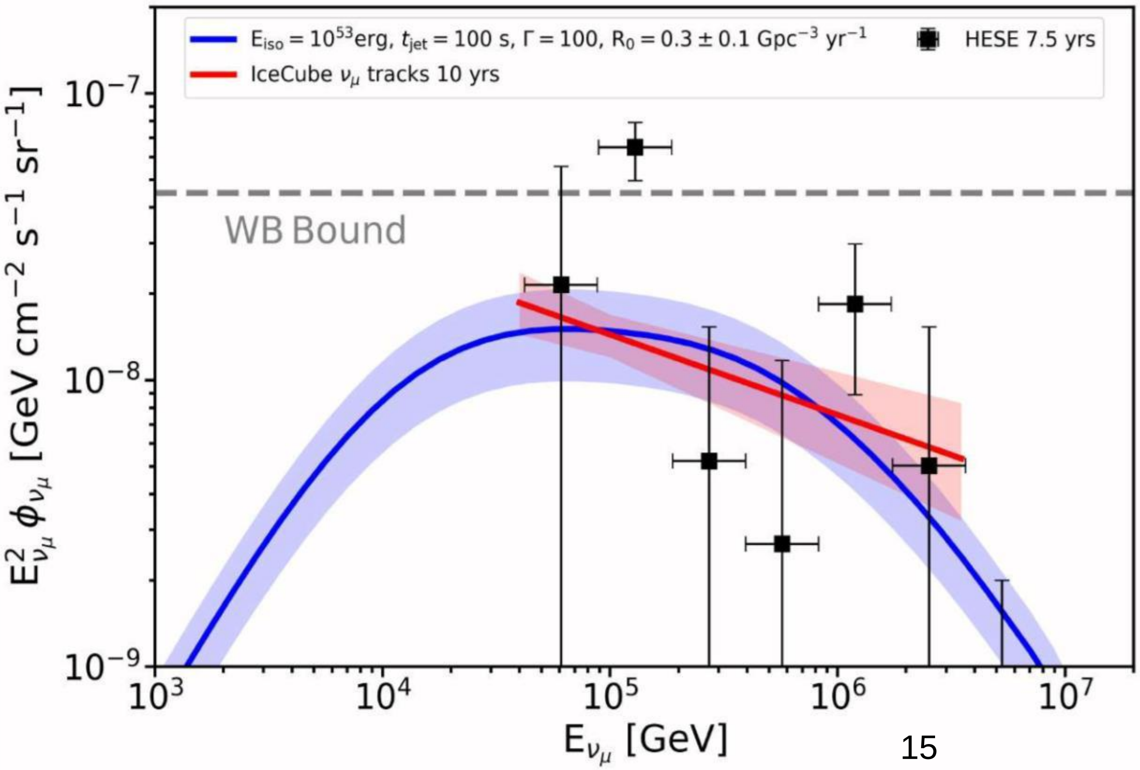
Thermalized photons in the reverse shock have typical temperatures of ~ keV

Protons accelerated in the Internal Shock region interact with the thermalized photons and may produce neutrinos: photomeson interactions

Neutrinos from choked GRBs

2. CONTRIBUTION TO THE DIFFUSE NEUTRINO FLUX

We choose a set of parameters that satisfy the conditions to have internal shocks inside a collimated jet



Implying a local rate of choked GRBs of

R_0 = (1-1000) Gpc^{3}yr^{-1}

Depend on the energy released in protons If 100% Rate similar to normal GRBs

Fasano et al., arXiv:2021:03502

X-ray emission from the chocked jet

- Soft X-ray Instrument (SXI) on THESEUS (0.3-5 keV energy band) may detect the ~ keV emission from the chocked jet region (cocoon)
- Electromagnetic signal X-ray from a neutrino source may be a smoking gun for the identification of the IceCube neutrino sources (Giulia's talk but X-ray)
- The study of common sources of UV, X-ray neutrinos and gamma-rays requires a broad understanding of the emission processes and detection technique.
- **O'Brien talk:** "A search for electromagnetic counterparts of multi-messenger astronomy has begun to provide a new window on the universe"

Conclusions

- The origin of IC neutrinos remains so far elusive, though overall a major contribution from EG sources appears preferable;
- Upper limits derived in the stacking searches of ANTARES and IceCube disfavor GRBs as major contributors of the cosmic diffuse neutrino flux (<1%);
- Choked GRBs appear a viable alternative, possibly dominating the IC flux. The chocked GRB rate depend on the fraction of energy released in protons.
- If so, searching for a gamma-ray counterpart would be inconclusive. Lower frequency radiation appears to be better suited for such a search, X-ray, UV.

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.