Sources of ultra high energy cosmic rays

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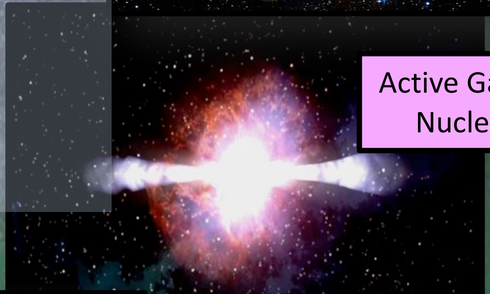
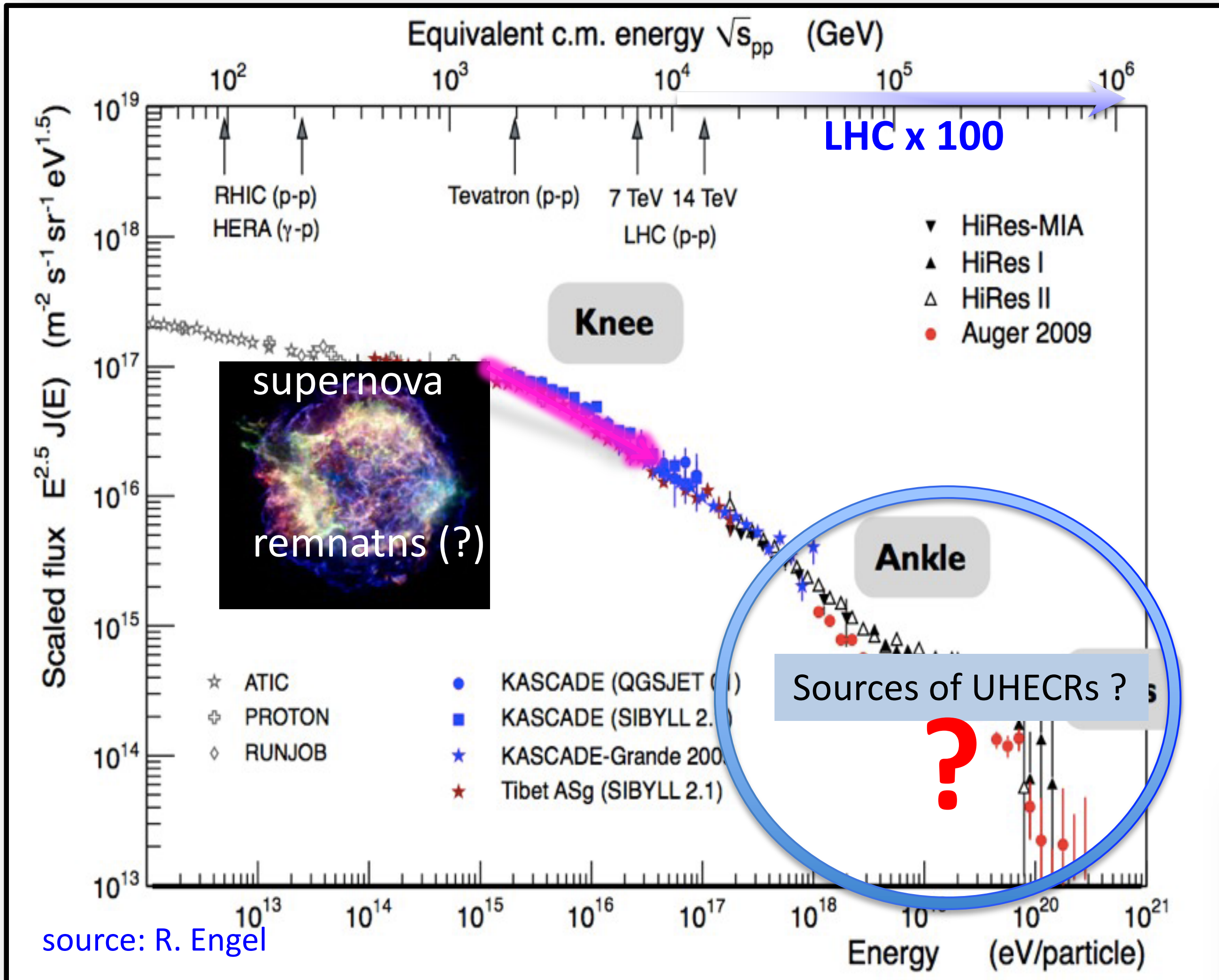
Outline:
- Spectrum, propagation of UHECRs, Hillas diagram,..
- Sources of UHECRs: GRB, AGNs, LL-GRB, TDEs,..
- Multi-messenger approach and UHECRs



The Ultra-High-Energy Cosmic Ray mystery



> What's their composition?

> Where do they come from?

→ *anisotropies weakly correlated to known possible sources: active galactic nuclei, gamma-ray burst,…*

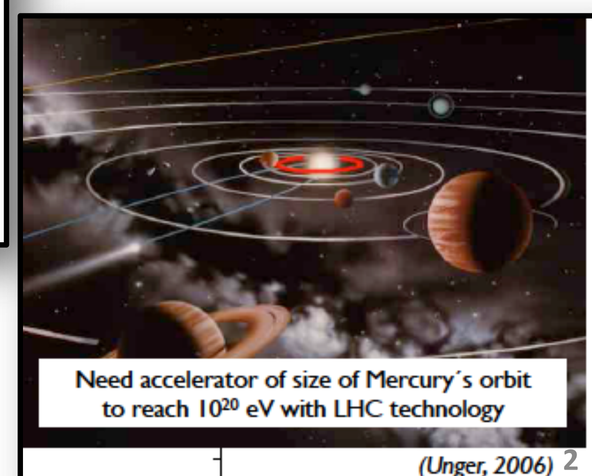
> How do they reach such tremendous energies?

Spectrum suppression:

in the past: *the GZK cut-off*

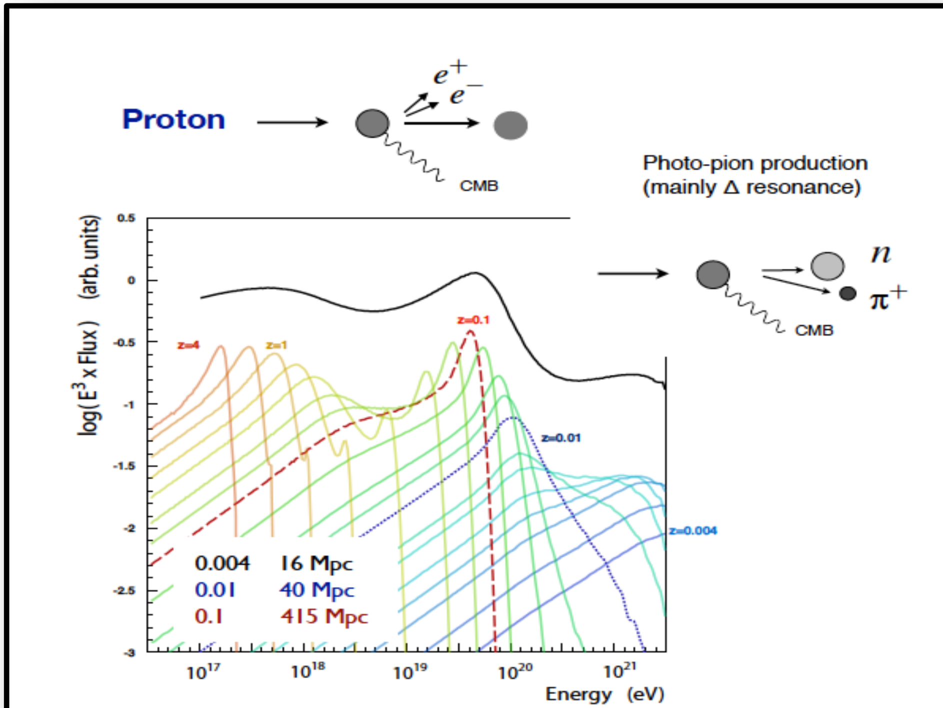
now: *rather the efficiency limit of particle acceleration by sources*

Particle physics beyond the reach of colliders



UHECRs propagation to Earth

Photo-pion production



(Bergmann et al., PLB 2006)

Greisen-Zatsepin-Kuzmin (GZK) effect (1966)

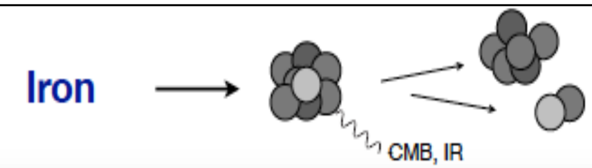
cosmic ray absorption

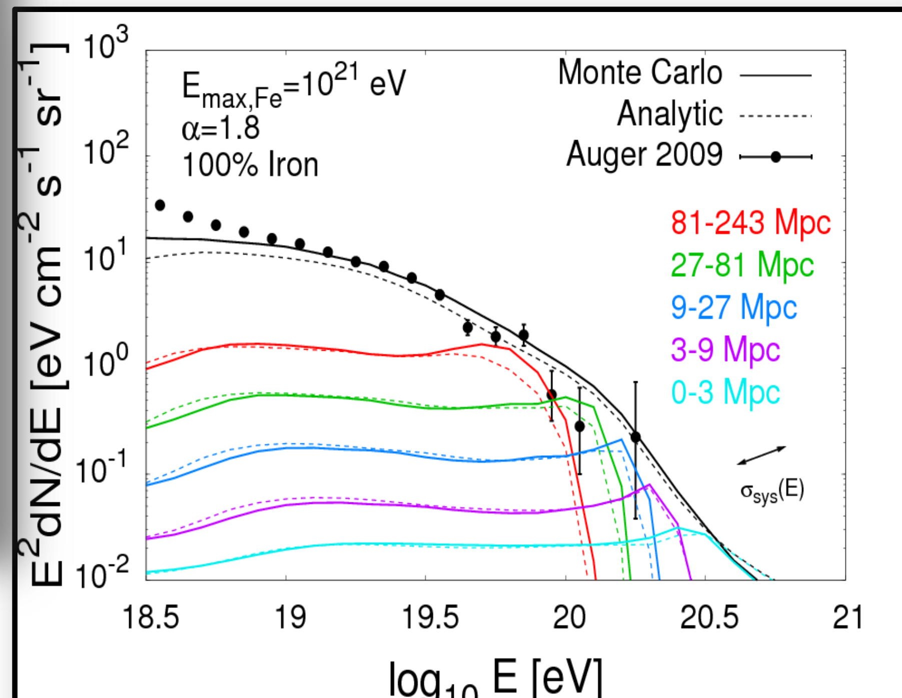
in Cosmic Mirowave Background CMB (1965)

> suppression of cosmic ray flux above energy of 4 x 10^{19} eV (GZK-cut-off), maximum source distance of 50-100 Mpc

Photo - nuclear interactions

photon-disintegration, hadronphotoproduction,...





(Hooper, Taylor et al., PRD 2008)

> disruption of higher mass nuclei into lower mass fragments (nuclear cascade)

see more in J. Stasielak talk

Acceleration requirements:

> The first condition for successful acceleration:

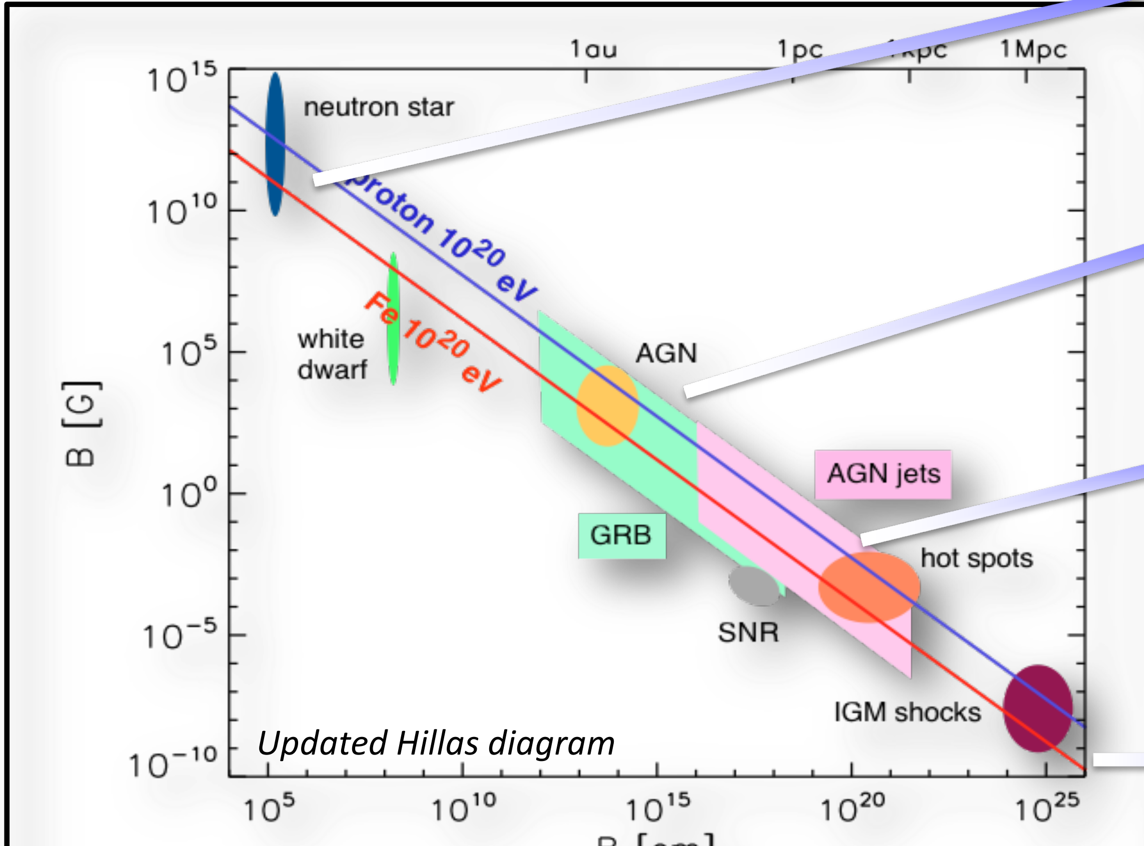
$$\mathbf{r_L < R_{Size-of-source}}$$

$$E \leq E_{\max} \sim 10^{15}\ \mathrm{eV} \times Z \left(\frac{B}{1\ \mu\mathrm{G}}\right)\left(\frac{R}{1\ \mathrm{pc}}\right)$$

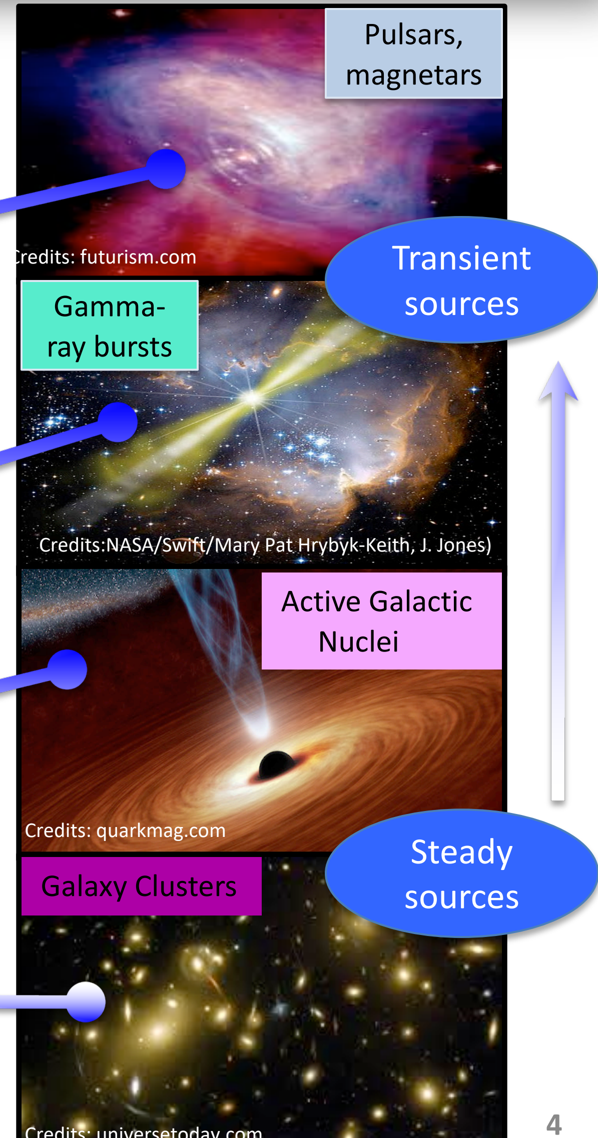
Larmor radius:

$$r_L = 1.08\ \mathrm{Mpc}\, Z^{-1} \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)\left(\frac{B}{1\ \mathrm{nG}}\right)^{-1}$$

particle charge | particle energy | source mag. field



source: K.Kotera & A. Olinto 2011



A luminosity bound

> The second condition for successful acceleration:

$$t_{\rm acc} < t_{\rm dyn} \sim R/\beta_{\rm W}\Gamma_{\rm W}c$$

The dynamical time (time scale of energy loss)

Schock velocity

Lorentz factor

The acceleration time: depends on acceleration mechanism and environments

The luminosity that a source must possess in order to be able to accelerate particles up to $E_{20}= E/10^{20}$ eV

$$L > L_B \equiv \Gamma_{\rm W} R^2 B^2/2 > 10^{45}\, Z^{-2} E_{20}^2 \ {\rm erg\ s^{-1}}$$

Lemoine & Waxman 2009

> The third condition:

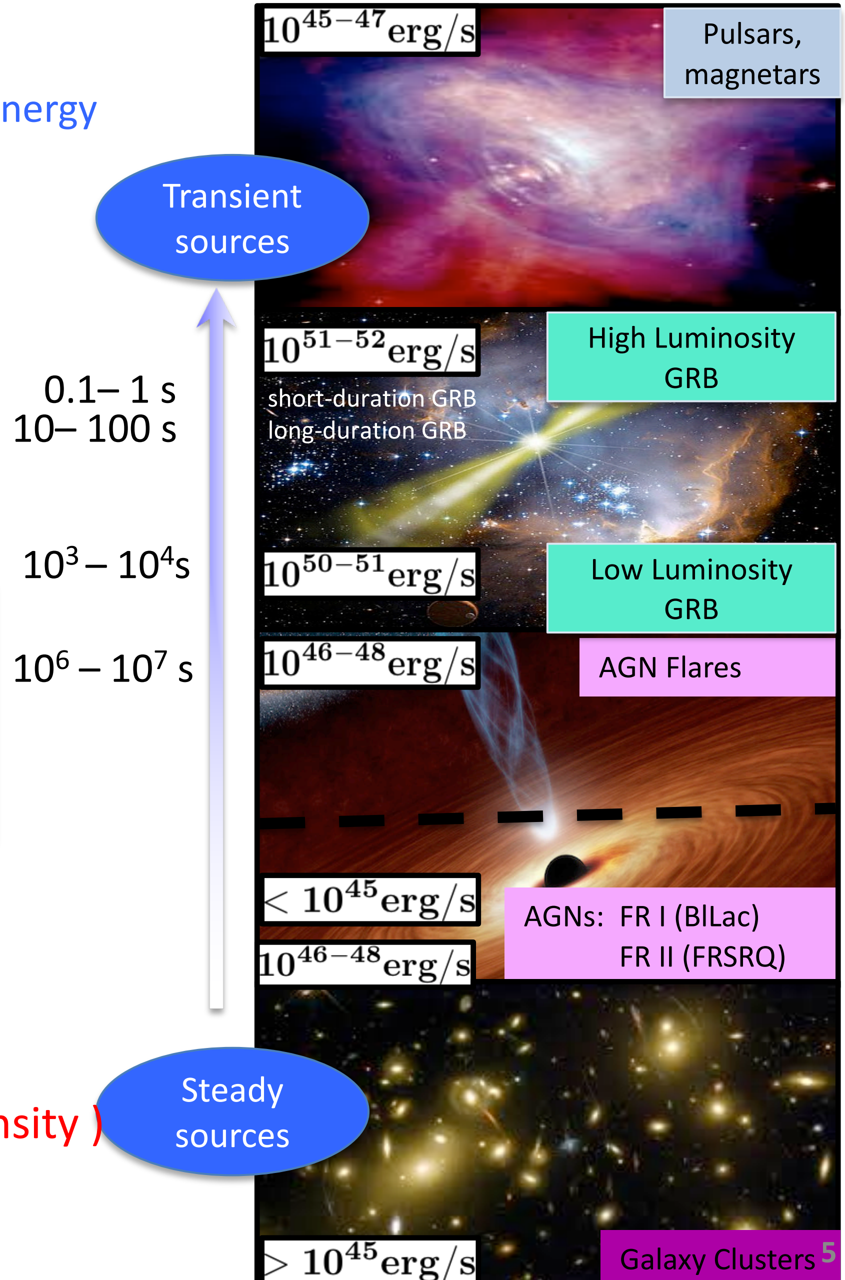
sources must possess the required energy budget to produce the observed UHECRs flux

($E_{UHE}\, Q_{EUHE}$ > 5 x 10^{43} erg s^{-1} yr^{-1}) (enough sources density)

See for more details:

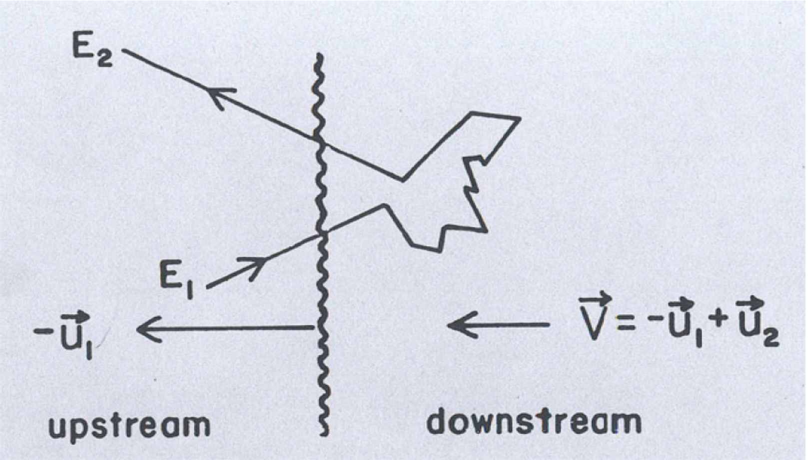
K.Komiko A . Kotera Annu. Rev. Astron. Astrophys 2010

Luminosity



First order Fermi acceleration

Proces Fermiego 1. rzędu



$$\frac{\Delta E}{E} = \xi \propto \frac{u_1 - u_2}{c} \qquad E_n = E_0(1+\xi)^n = E_0(1+\xi)^{t/T_c}$$

przyspieszanie stopniowe - limit energii

widmo całkowe $\propto E^{-\gamma+1}$

dla gazu jednoatomowego $\gamma - 1 \approx 1 + 4/M^2$ $M = u_1/c_1$ liczba Macha

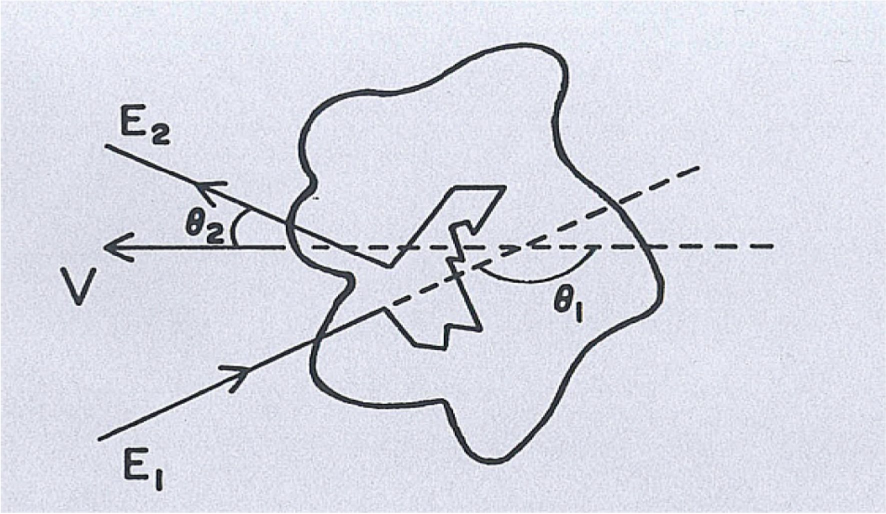
obs. $F(E) \sim E^{-1.7}$ $\rightarrow$ u źródła $Q(E) \sim E^{-\gamma+1+\delta} \sim E^{-1.1}$

$E_{max} \sim Z\, 10^{14}$ eV

Second order Fermi acceleration

Proces Fermiego 2. rzędu

przyspieszanie cząstek w zderzeniach z obłokami magnetycznymi



$$E_1' = \gamma E_1 (1 - \beta \cos\theta_1)$$

$$E_2 = \gamma E_2' (1 + \beta \cos\theta_2')$$

$$E_2' = E_1' \qquad \beta = v/c$$

przyrost energii w jednym cyklu

$$\frac{\Delta E}{E} = \xi \propto \beta^2$$

proces powolny

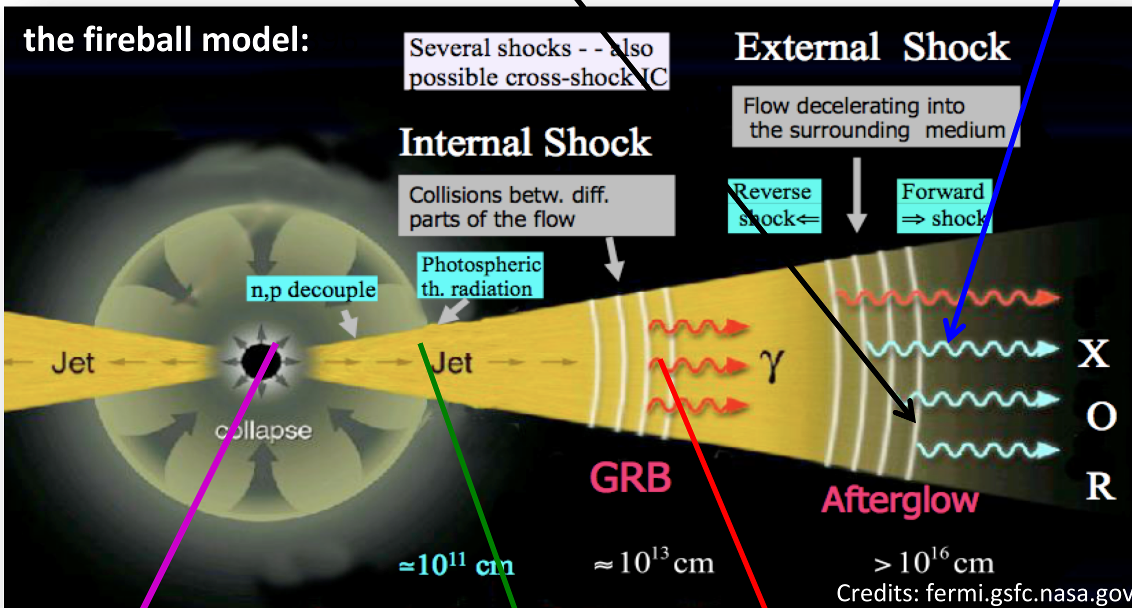
GRBs and SuperNovas (time scale of seconds/minutes)

> 'long GRBs' > few seconds
as a source of high energy neutrinos

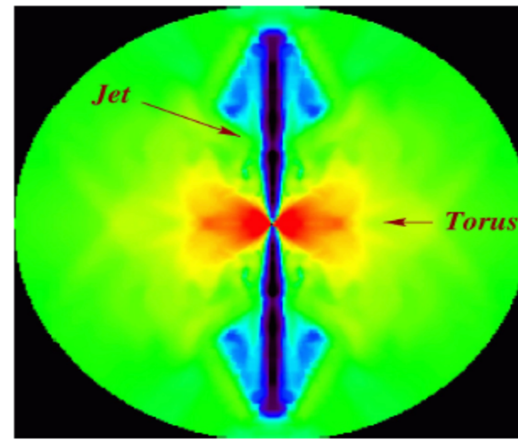
> SNII neutrinos (choked jets)
S. Ando, J.F. Beacom 2005

EeV neutrinos from external shocks
Dermer 2001
Waxman & Bahcall 2000

PeV-EeV neutrinos from flares
Murase &Nagataki



$$p\,\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$$
$$p\,p \rightarrow \pi, K$$
$$\pi^+ \rightarrow \nu_\mu\,\mu^+ \rightarrow \nu_\mu\; e^+\;\nu_e\,\bar{\nu}_\mu$$



MeV neutrinos at collapse

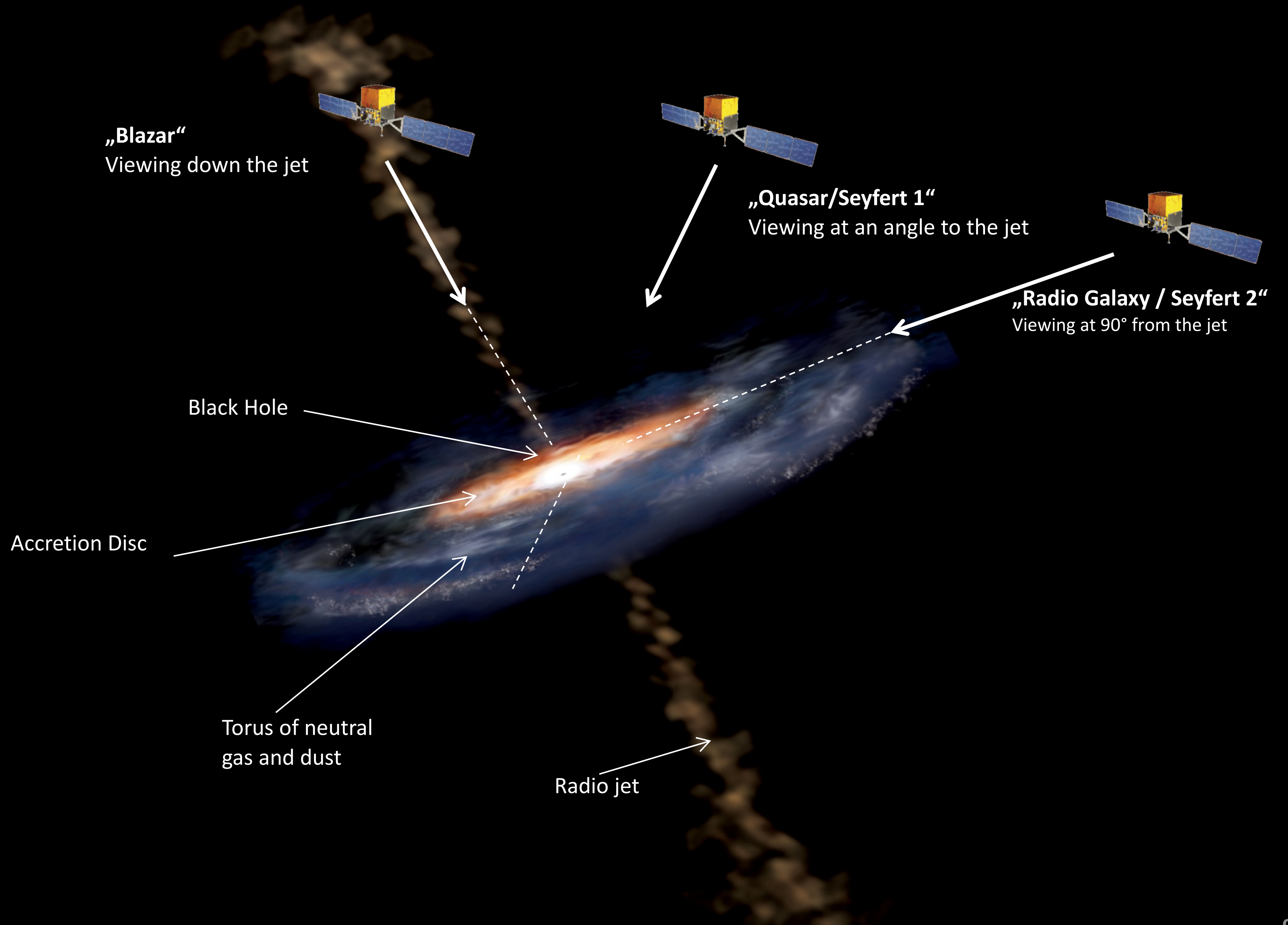
TeV neutrinos at collapse
Meszaros & Waxman, 2001
Razzaque et al. 2003

PeV neutrinos from internal shock
Waxman & Bahcall, 1997
Gupta &Zhang 2006
Murase &Nagataki 2006

Less relativistic jet than for GRBs and the jet inside the star envelope

> The different shock waves will be traveling at different relativistic speeds, and it is the interaction between these different shock fronts that cause the energetic gamma-ray/neutrino emissions.

Active Galactic Nuclei (AGN)



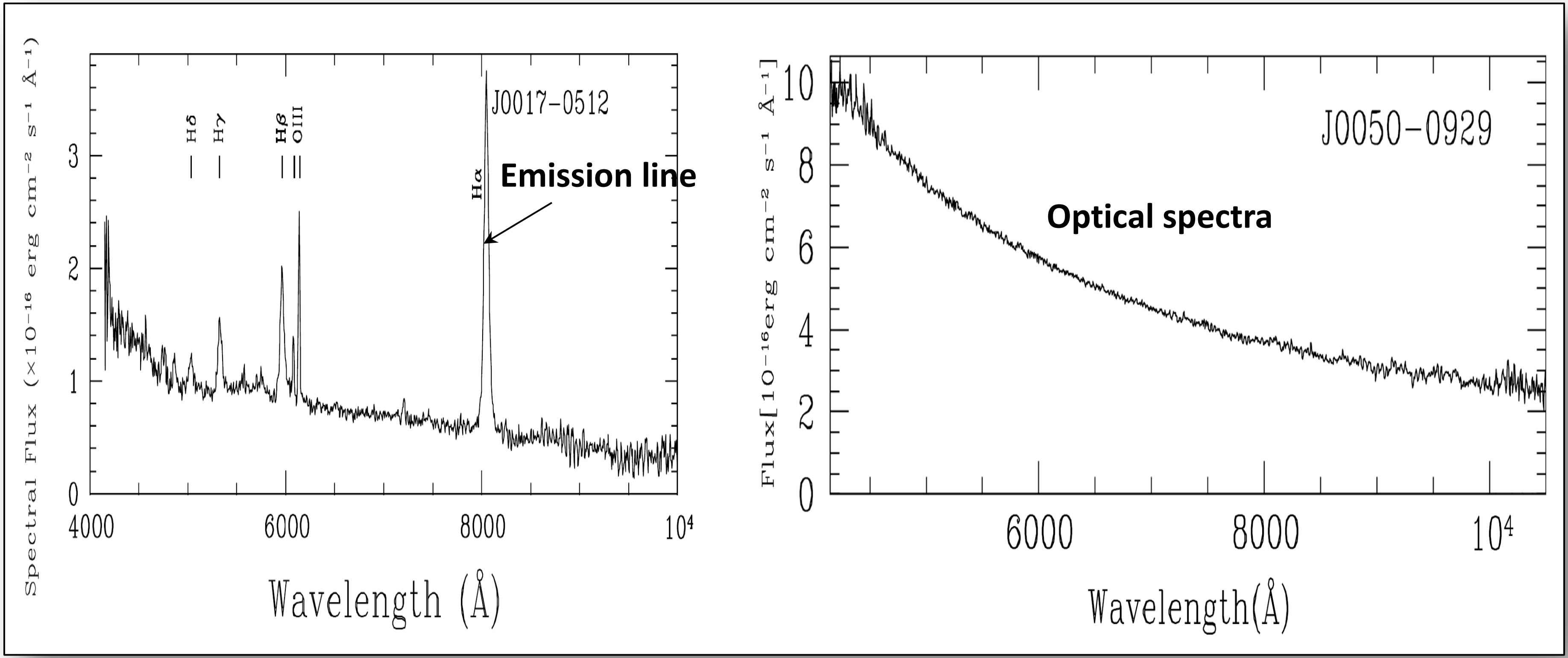
Credit: Aurore Simonnet, Sonoma State University

Blazars

FSRQ (Flat Spectrum Radio Quasar):

shows strong atomic lines in their optical and UV spectra **Quasar)**

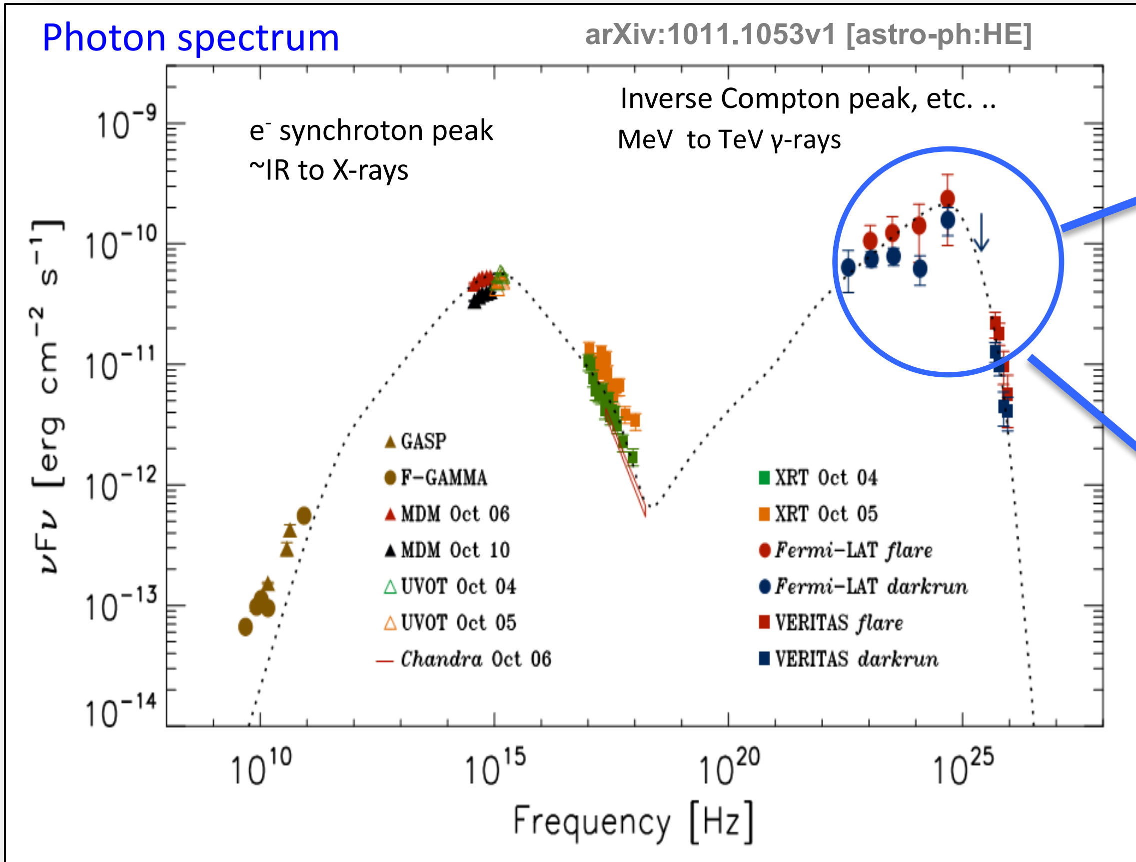
BL Lac



arXiv:0908.2996v1 [astro-ph:HE]

Blazars

The spectral energy distribution (SED) 3C 66A (BL Lac)



Hadronic models:

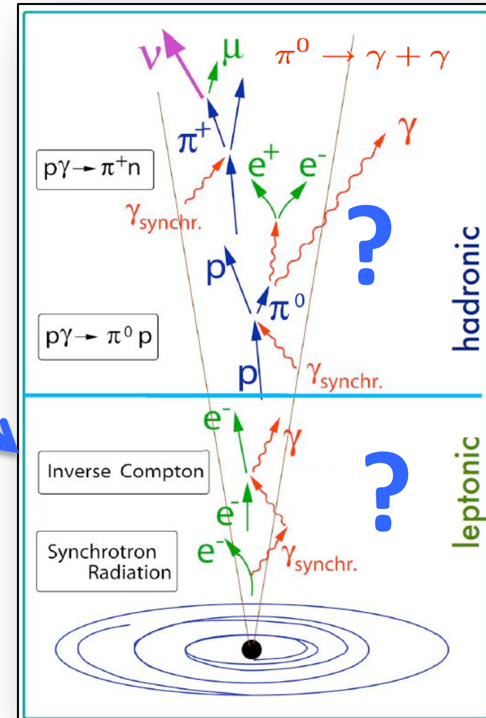
1) Photo-meson production:

$$p\gamma \rightarrow \Delta^{+} \rightarrow n\pi^{+}$$
$$p\gamma \rightarrow p + \pi^{0}$$

2) p-p interaction:

$$pp \rightarrow \pi^{\pm,0} \rightarrow \nu, e^{\pm}, \gamma$$

or/and



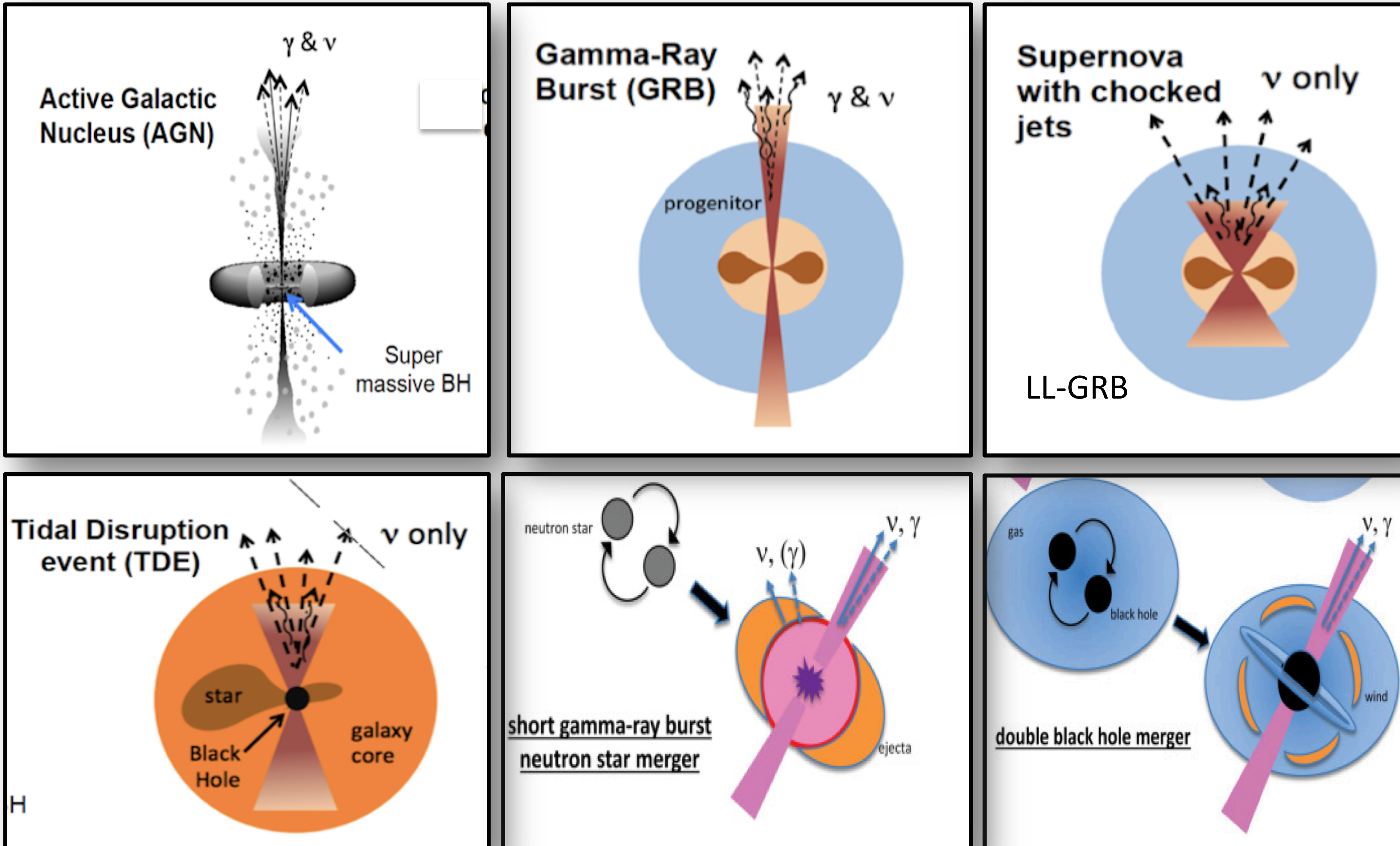
Leptonic models:

Synchroton self-Compton (SSC) models,..

Hadronic models predict
neutrino flux correlated with photon flux

Different Scenarios with varying degree of jet formation

Jets are great astroparticle accelerators



Source: I. Bartos and M. Kowalski, 2017

But,

there is only weak evidence that AGNs are sources of UHECRs

The Pierre Auger Observatory search for UHECR correlation with:

> γ-ray detected Active Galactic Nuclei

- 2FHL AGNs (*Fermi*-LAT)
- 17 objects within 250 Mpc

significance 2.7σ

Astrophysical Journal Letters, 853:L29 (2018)

> Starburst Galaxies

- *Fermi*-LAT search list for star-formation objects
- 23 objects within 250 Mpc

significance 3.9σ

The Pierre Auger Observatory search for UHECR correlation with:

> **Starburst Galaxies**

- *Fermi*-LAT search list for star-formation objects
- 23 objects within 250 Mpc

$f_{anisotropy}$ = 10%, Ψ = 13°
significance 3.9σ

> **γ-ray detected Active Galactic Nuclei**

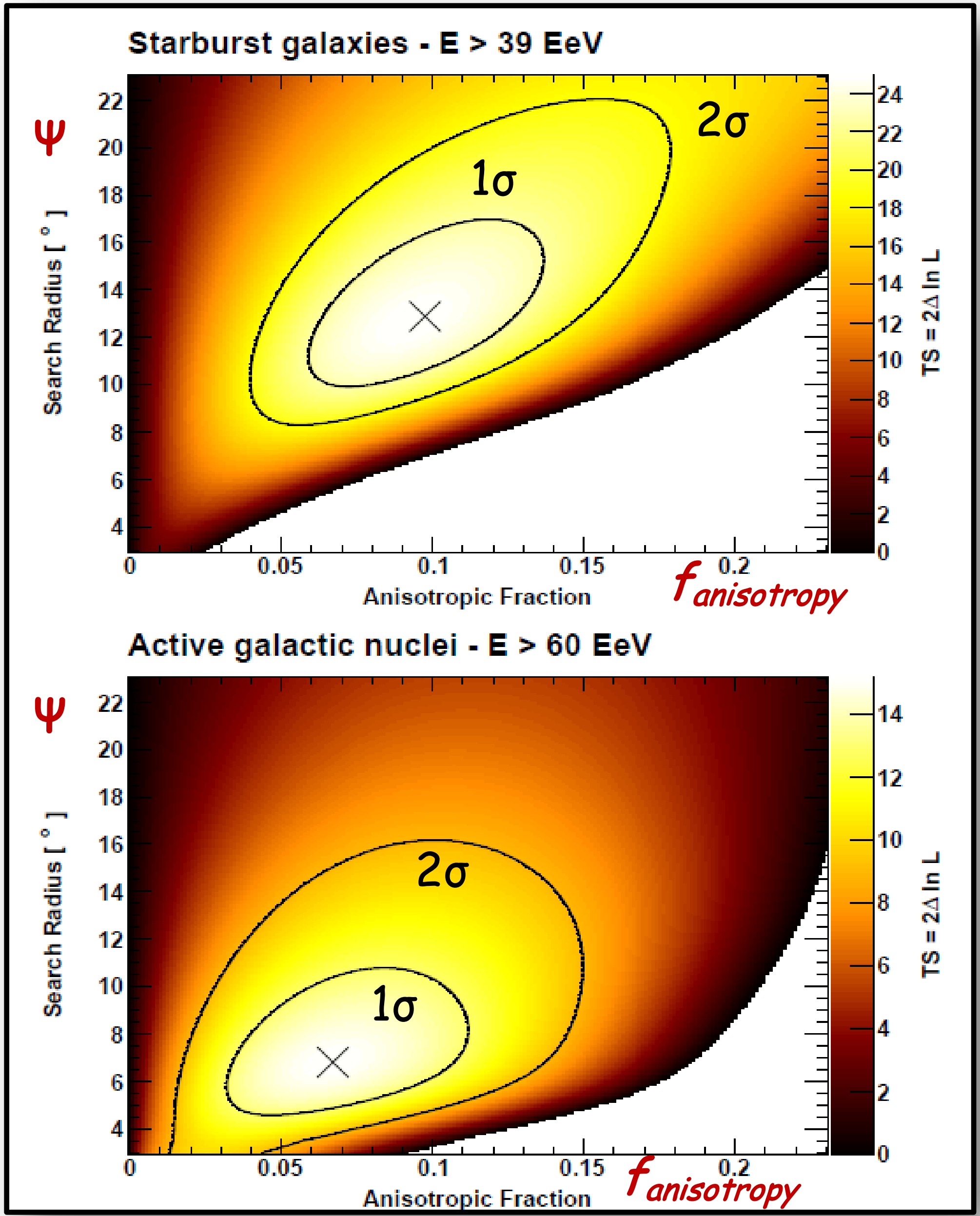
- 2FHL AGNs (*Fermi*-LAT)
- 17 objects within 250 Mpc

$f_{anisotropy}$ = 7%, Ψ = 7°
significance 2.7σ

Likelihood ratio analysis

- correlation angle Ψ (takes into account the unknown deflections of the UHECRs in the magnetic field)
- H_0: isotropy
- H_1: (1-f) x isotropy + f x fluxMap(Ψ)
- Test Statistic = 2 log(H_1 / H_0)

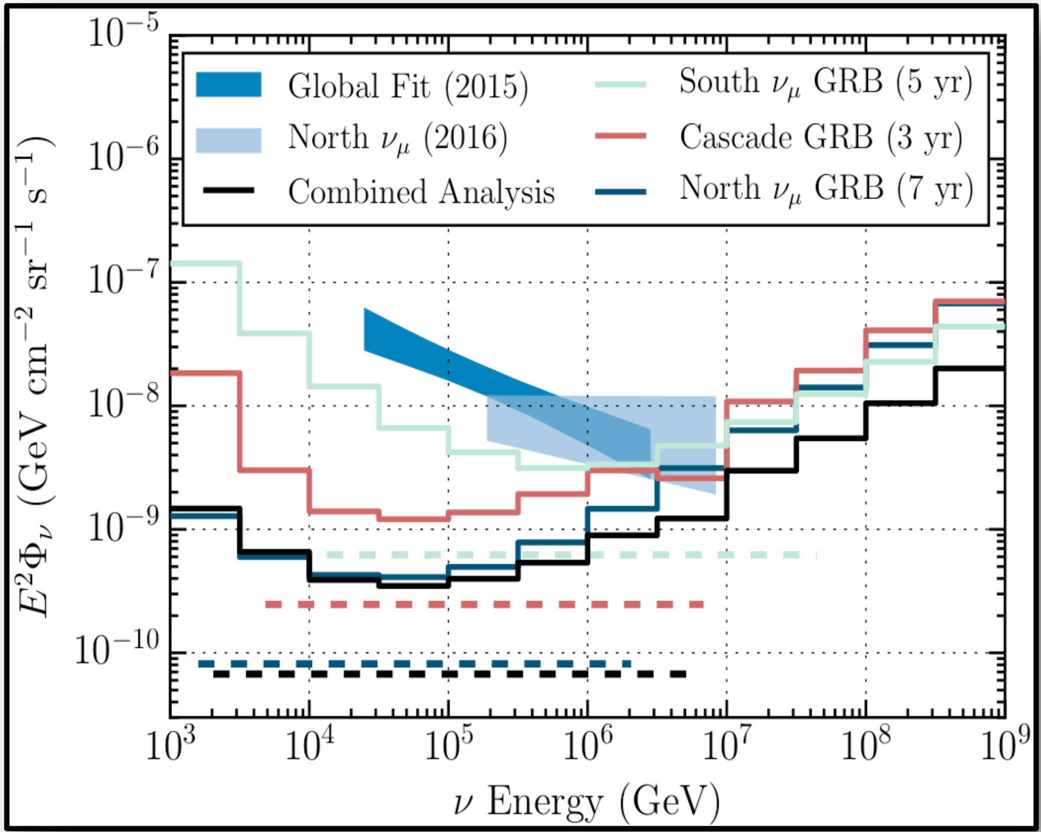
Astrophysical Journal Letters, 853:L29 (2018)



Also classical GRBs do not fully explain the origin of UHECRs

IceCube: AGNs and GRBs analysis

IceCube Collab., The Astrophysical Journal, 843, no. 2 , p.13



Using the timing and position information of each GRB, IceCube put the limit on GRB associated neutrinos

—> GRB cannot be a source of observed neutrinos*

** The analysis focus only on the prompt phase (afterglow GRB phase is not included)*

> IceCube searches constrain the maximum contribution of blazars (for steady emission) in the Fermi - LAT 2LAC catalogue to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV, assuming equi-partition of flavors at Earth and a single power-law spectrum.

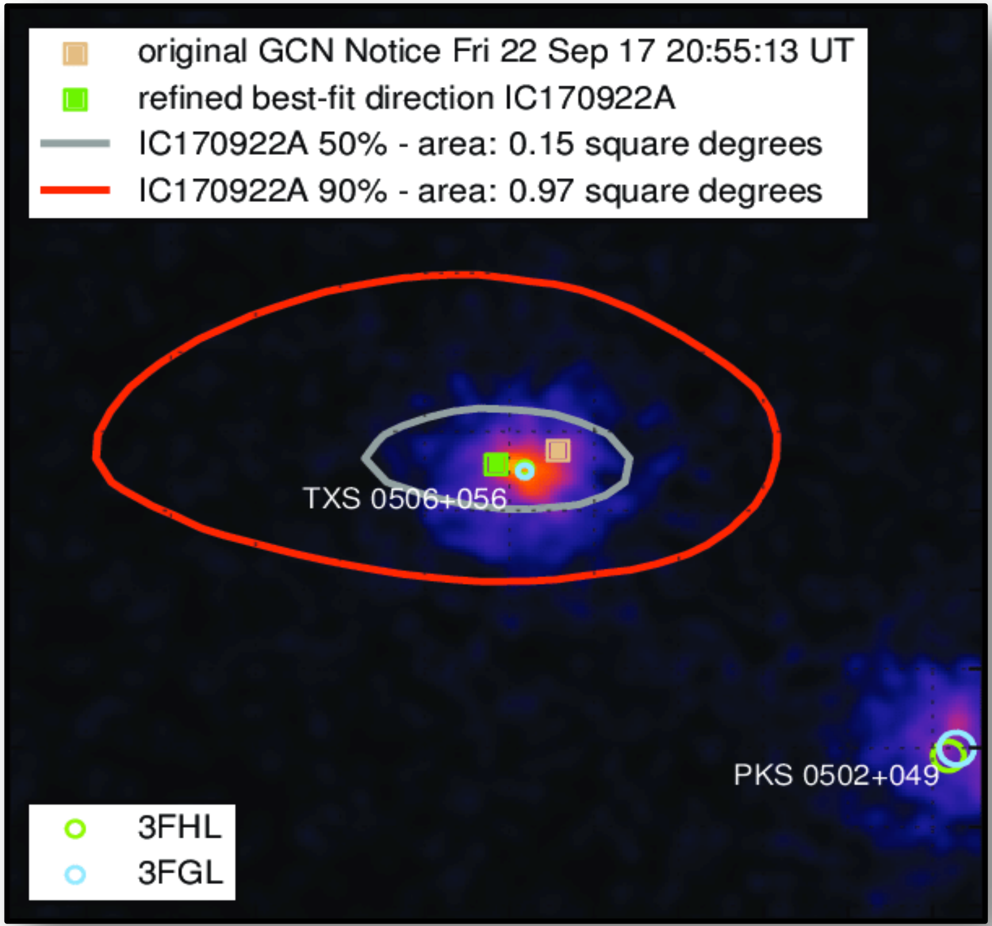
IceCube Collab., Astrophysical Journal 835, no. 1, p. 45

… but TXS 0506+056 is also the first source of UHECRs ?

> A high-energy neutrino event detected by **IceCube** on 22 September 2017 was coincident in direction and time with a gamma-ray flare **(Fermi, MAGIC)** from the blazar **TXS 0506+056**

> In addition an excess of high - energy neutrino events at the position of **TXS 0506+056** between Sept. 2014 and March 2015.

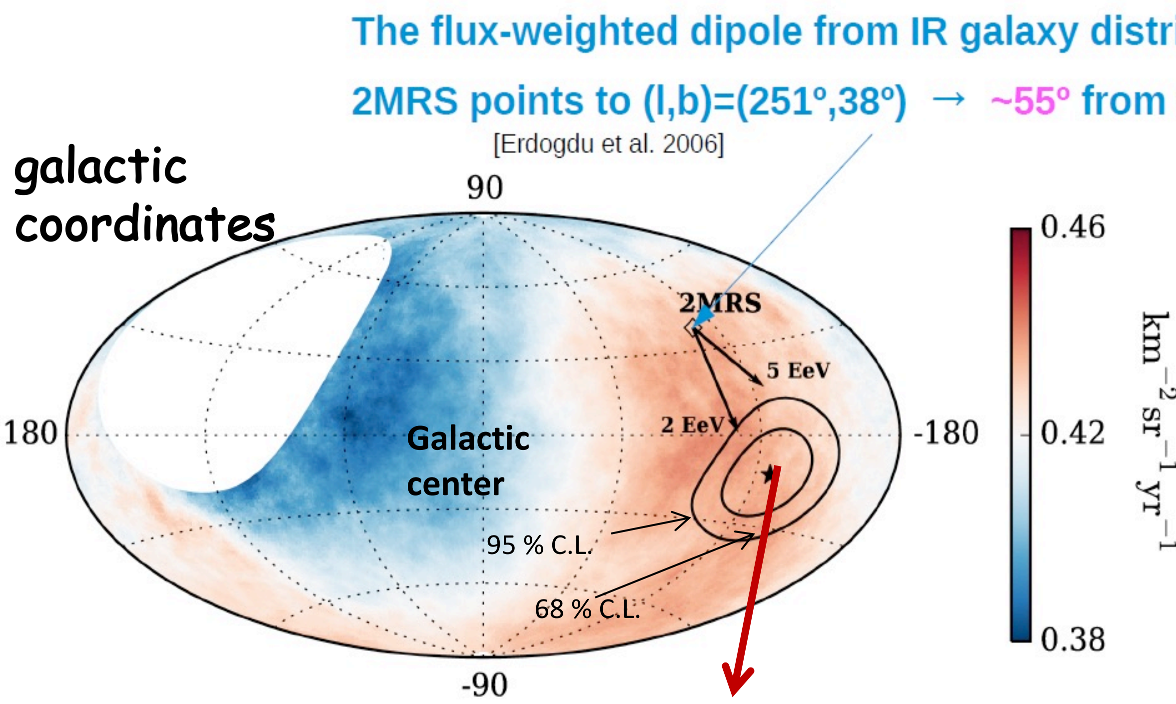
> 3.5σ evidence for neutrino emission from the direction of **TXS 0506+056**, independent of and prior to the 2017 flaring episode.



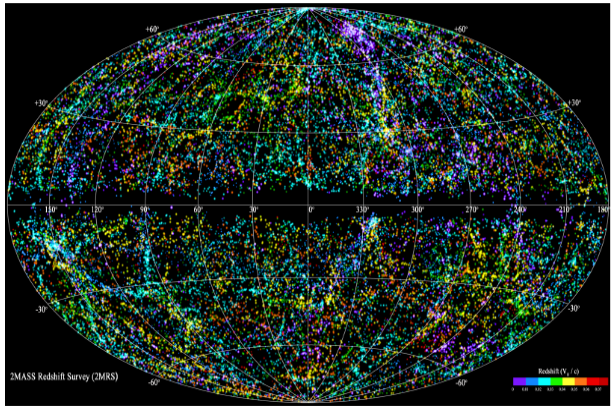
IceCube, Fermi, MAGIC, …, Science. 361 (6398): 147–151.

This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux, but the neutrinos and the bulk of the gamma rays observed from TXS 0506+056 cannot have been initiated by the same process --> more sophisticated AGNs jet models required

Auger observation of dipolar anisotropy above 8 EeV

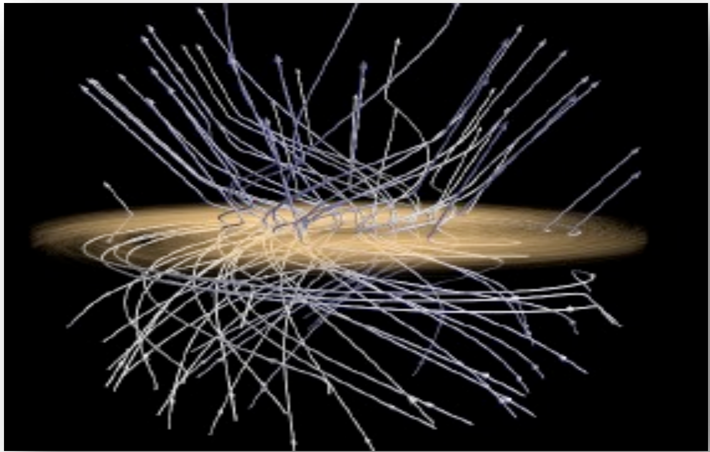


Distribution of of galaxies in the nearby Universe : 2MRS catalog



Observed dipole, Gal. coord. (l, b) = (233°, −13°), ~120° away from GC -> disfavours galactic origin

Traces of CRs in the galactic magnetic field

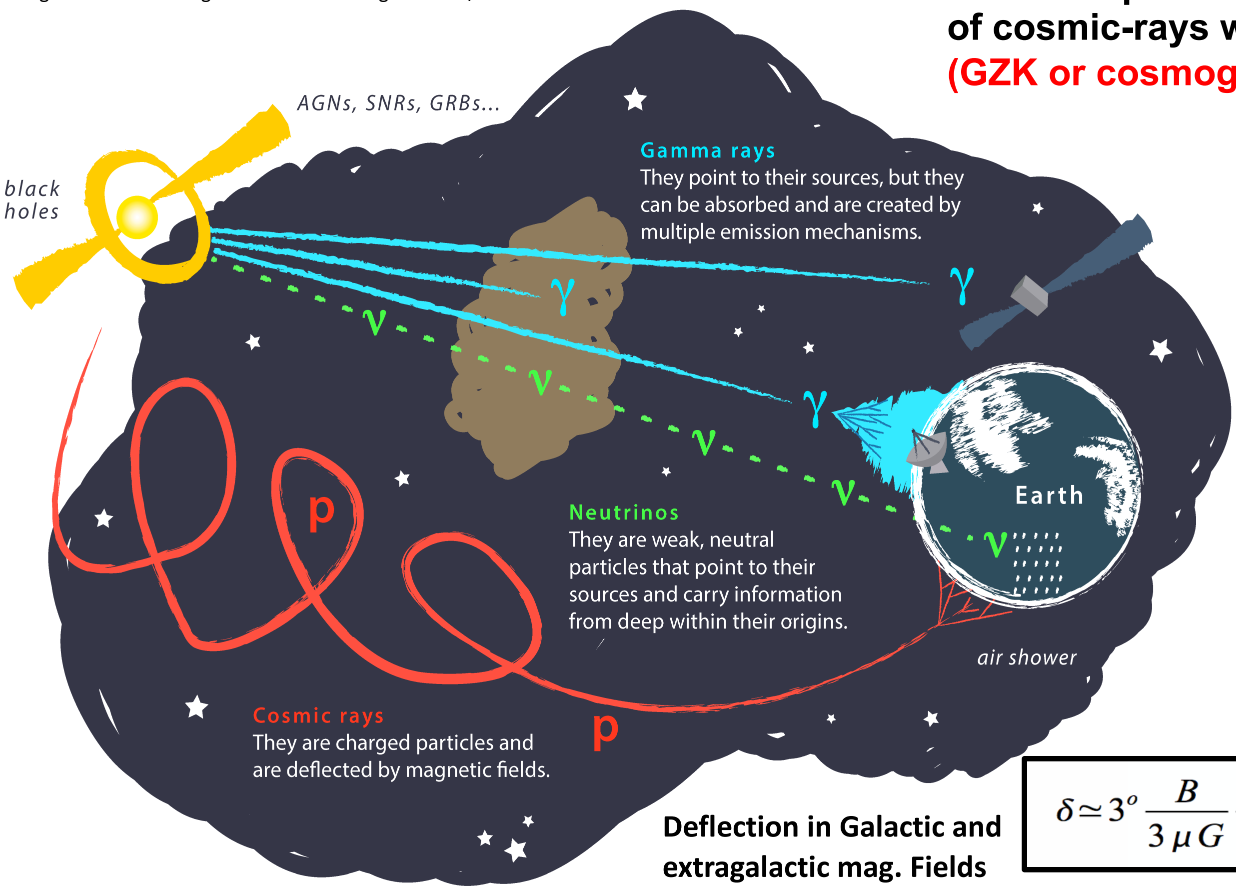


Large-scale anisotropy can arise from:
> inhomogeneous large-scale distribution on sources
> diffusion in extragalactic magnetic fields from dominant nearby sources

The Pierre Auger Collaboration, Science 357 (2017)

Multi-messenger approach and UHECR propagations

Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC



Deflection in Galactic and extragalactic mag. Fields

$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$

> **Neutrinos/photons are also produced from interaction of cosmic-rays with CMB**
> **(GZK or cosmogenic neutrinos/photons)**

> **UHE neutrinos arise from decays of charged pions:**

$$p + p(\gamma) \to \pi^{\pm} + X$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$$

> **Photons arise from decays of neutral pions:**

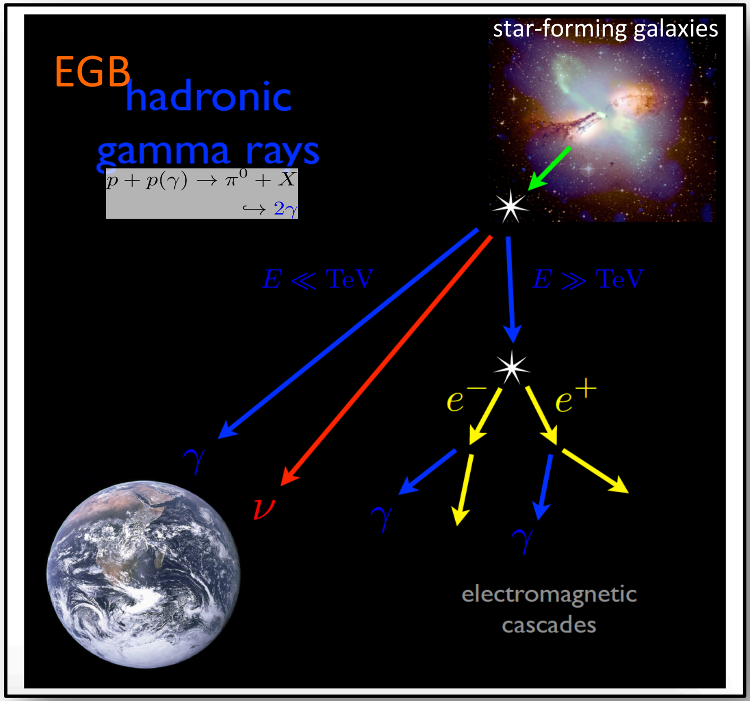
$$p + p(\gamma) \to \pi^0 + X$$
$$\hookrightarrow 2\gamma$$

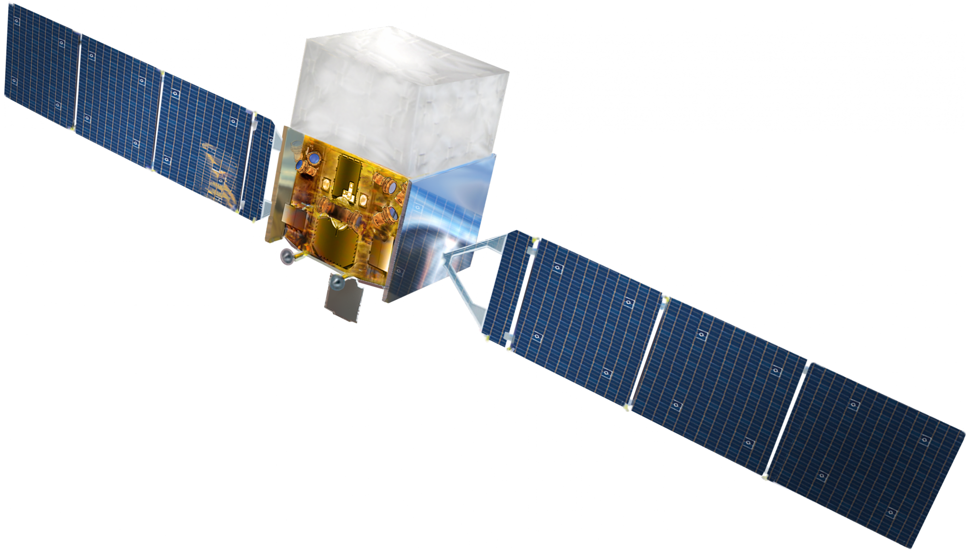
> The determination of the origin of CRs is a difficult task since CRs are deflected during propagation and the extent of this angular deflection is still poorly constrained.

> On the other hand, neutrinos propagate unaffected from their sources to us. They can deliver potentially valuable information on the sources of the most energetic CRs.

Extragalactic gamma-ray Background (EGB)

> Extragalactic gamma-ray Background (EGB) measured by Fermi-satellite constraints the energy density of hadronic gamma-rays & neutrinos





pp model -> Γ< 2.1 - 2.2

K. Murase, M. Ahlers, B. Lacki PRD D88 121301

(arxiv/1511.00688)

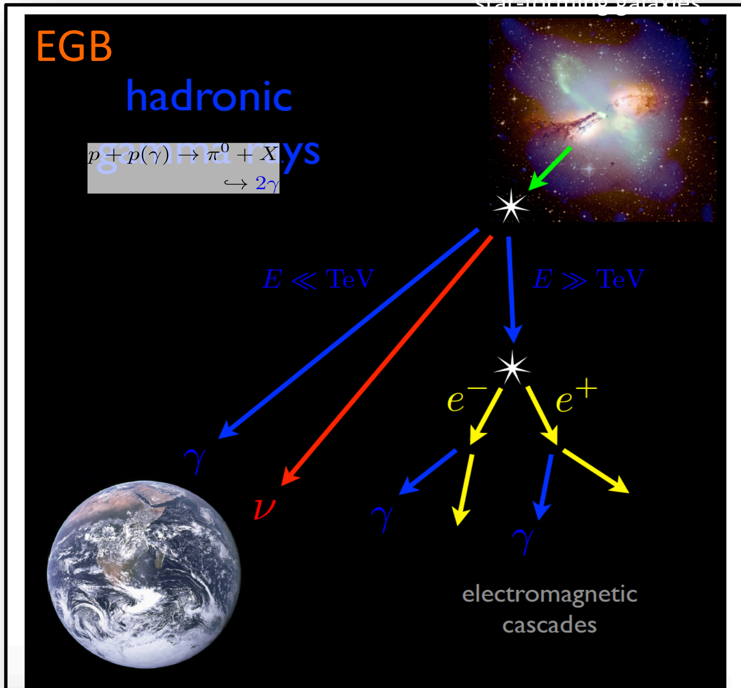
> such studies can place also the limit on spectral index of neutrino sources, Importance of sources with hard spectrum, Second Fermi Hard Source List (2FHL)

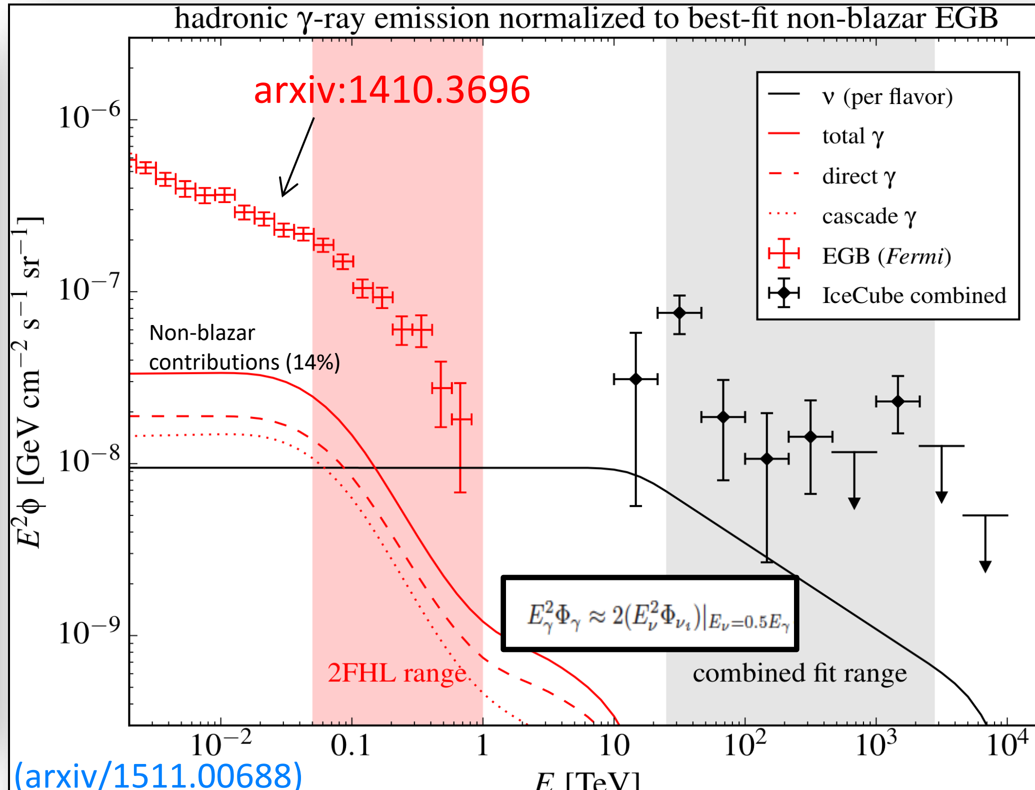
Extragalactic gamma-ray Background (EGB)

> Extragalactic gamma-ray Background (EGB) constraints the energy density of hadronic gamma-rays & neutrinos

> Cosmic-ray induced gamma-ray emission in star-forming galaxies as the dominat source of HESE (arxiv/1306.3417), but in (arxiv/15.11.00688) evidence against star-forming galaxies

$$E_\nu^2 \Phi_{\nu_i} \approx \frac{c t_H \xi_z}{4\pi} \frac{1}{6} \min[1, f_{pp}](E_p Q_{E_p})$$





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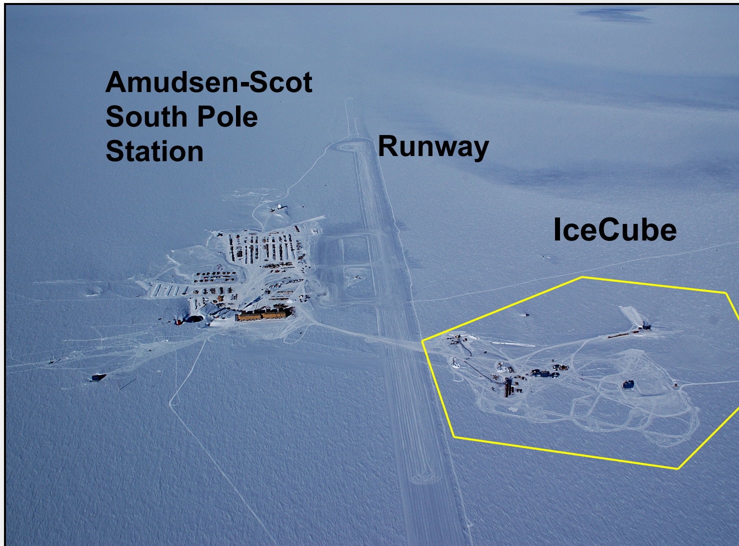
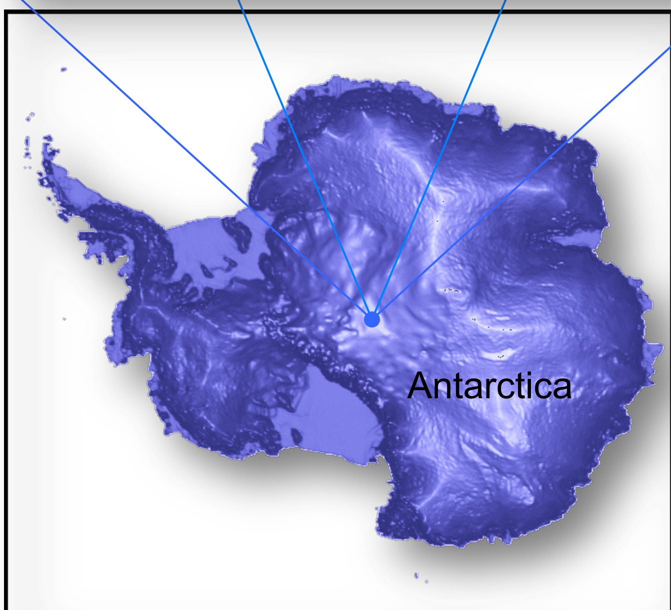
IceCube-Detector





Construction:

2005: 1st String

2006: +8 = 9 strings

2007: +13 = 22 strings

2008: +18 = 40 strings

2009: +19 = 59 strings

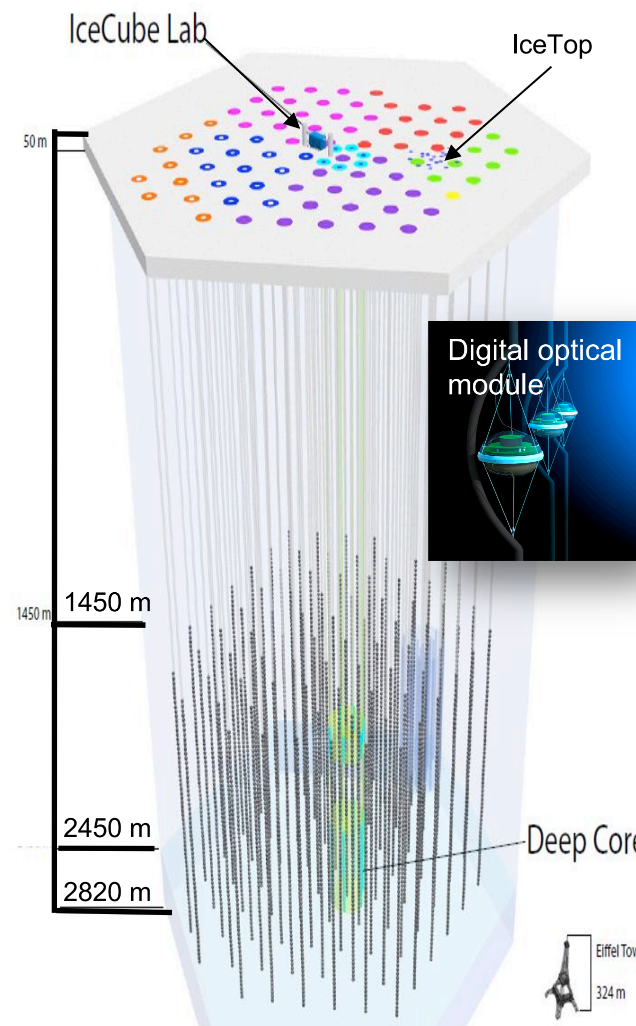
2010: +20 = 79 strings

2011: +8 = 86 strings

60 Digital Optical Modules per string

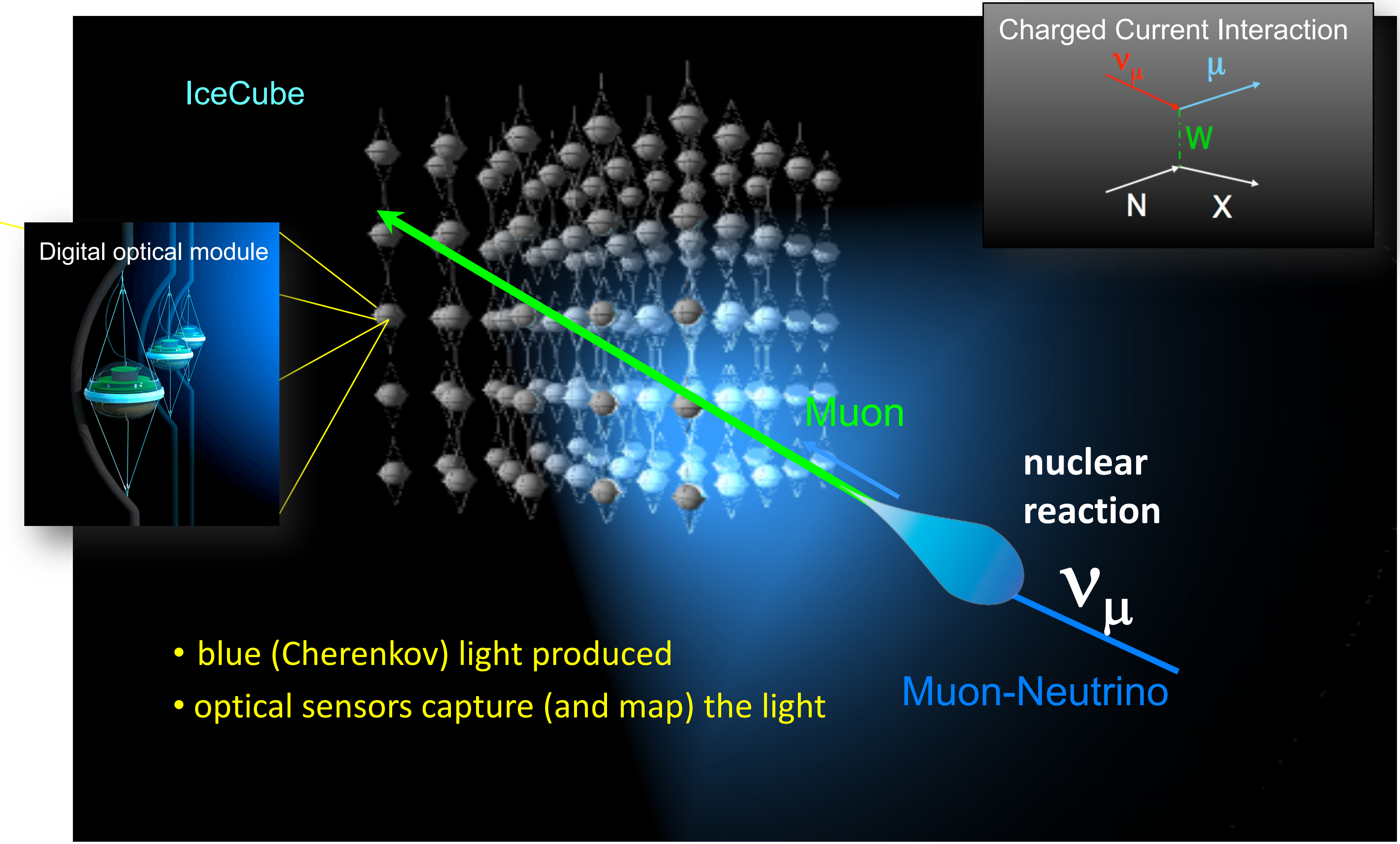
5160 modules in Ice
1 km^3 instrumented volume

IceTop:
81 stations
324 modules total
1 km^2 surface array



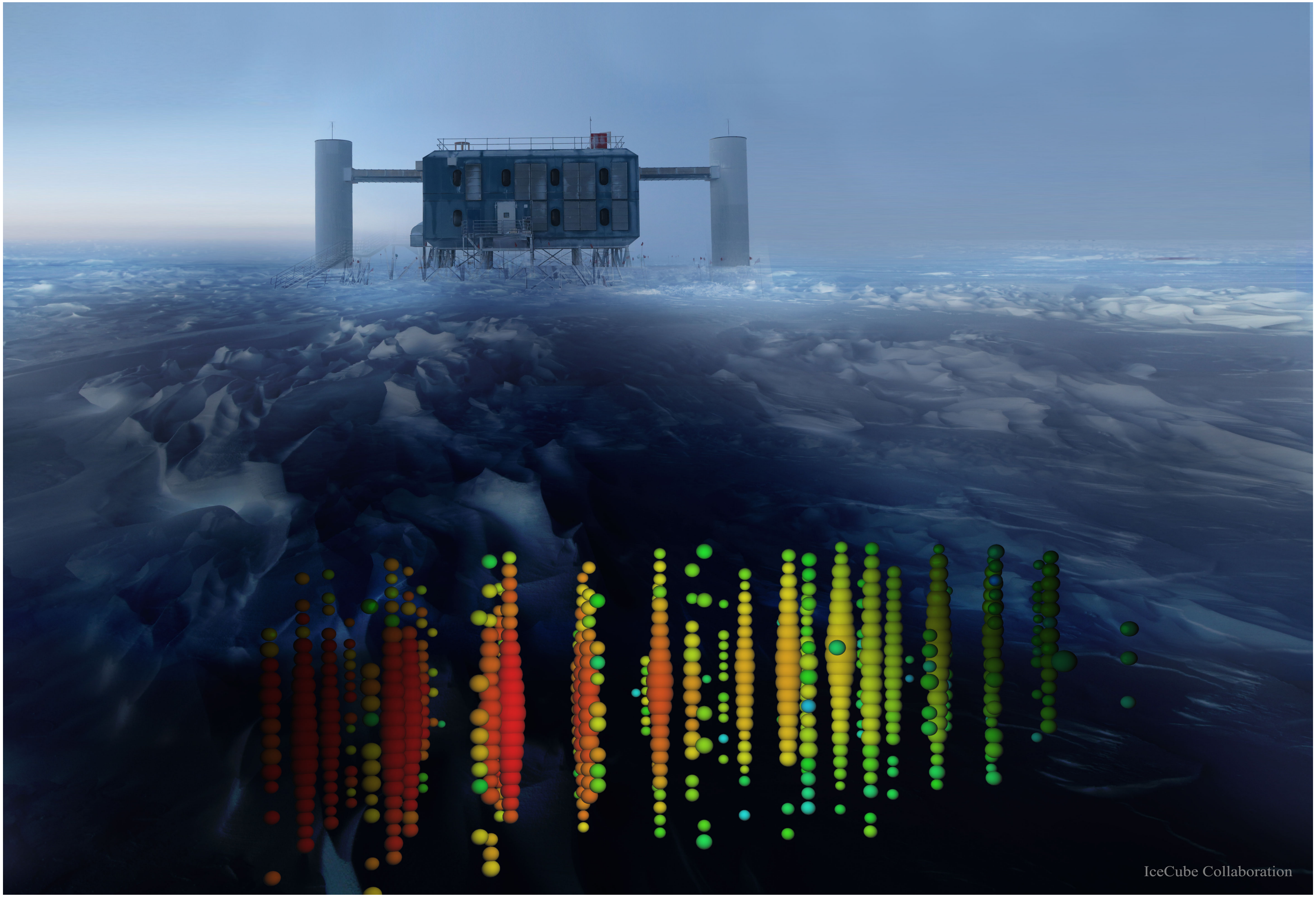
Construction finished December 2010

IceCube-Detector (basic detection principe)

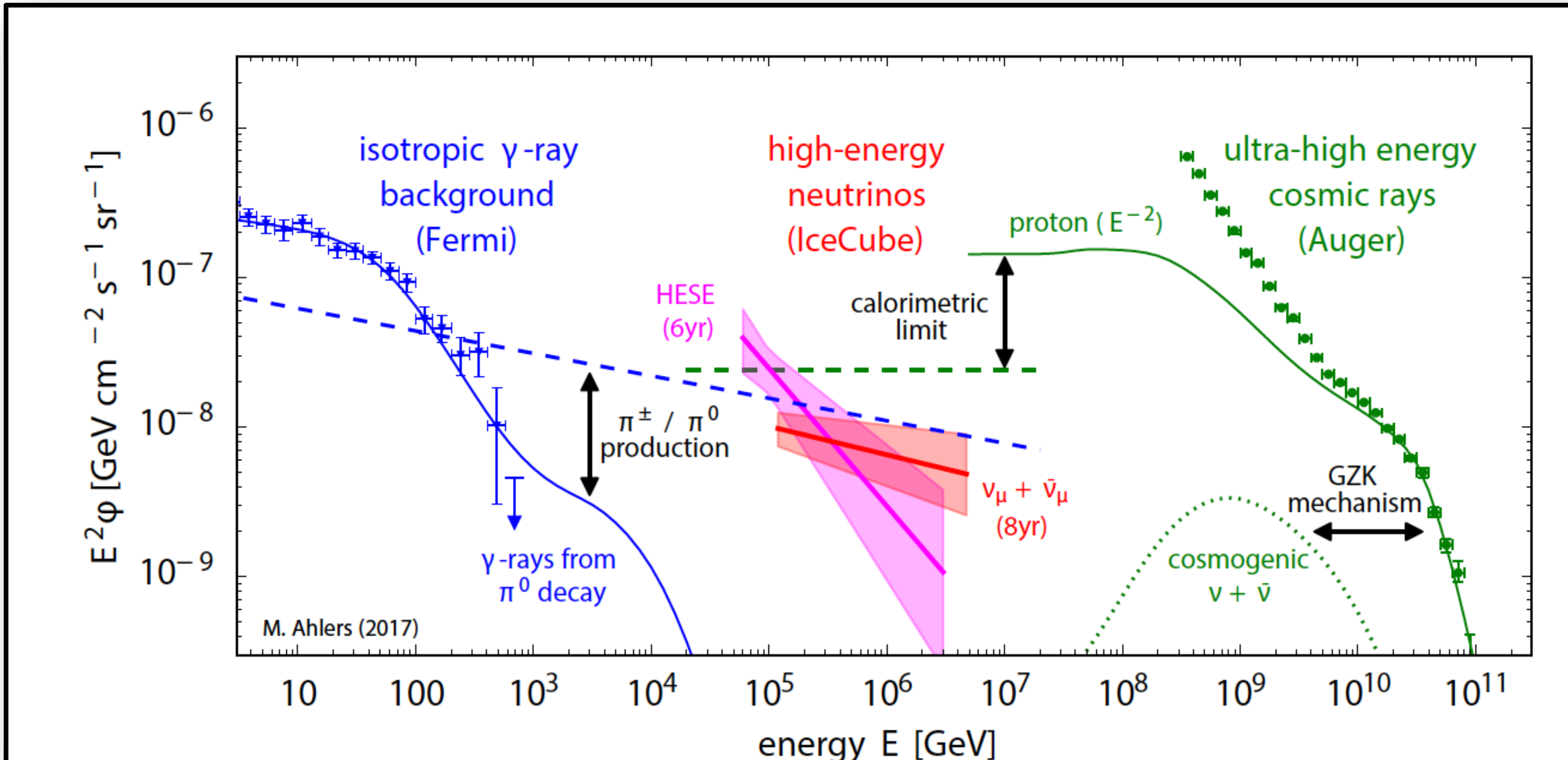


Detection principle: Cherenkov light from charged particles produced in neutrino interaction

IceCube-Detector (~ 1 PeV event)



Global picture – energy density and multi-messenger physics



> Despite ten orders of magnitudes difference in energy, UHECRs, IceCube neutrinos, Fermi non-blazar EGB share similar energy injection rate.

Murase, Ahlers , B.C. Lacki, PRD (2013) E. Waxman 1312.0558 Giacin et al (2015) Murase & Waxman PRD (2016) , Wang & Loeb PRD (2017)

Energy density per decade similar in all three messenger particles

$$\rho_{\rm decade} = \int_{\rm decade} E \frac{dN}{d\ln E} \, d\ln E$$

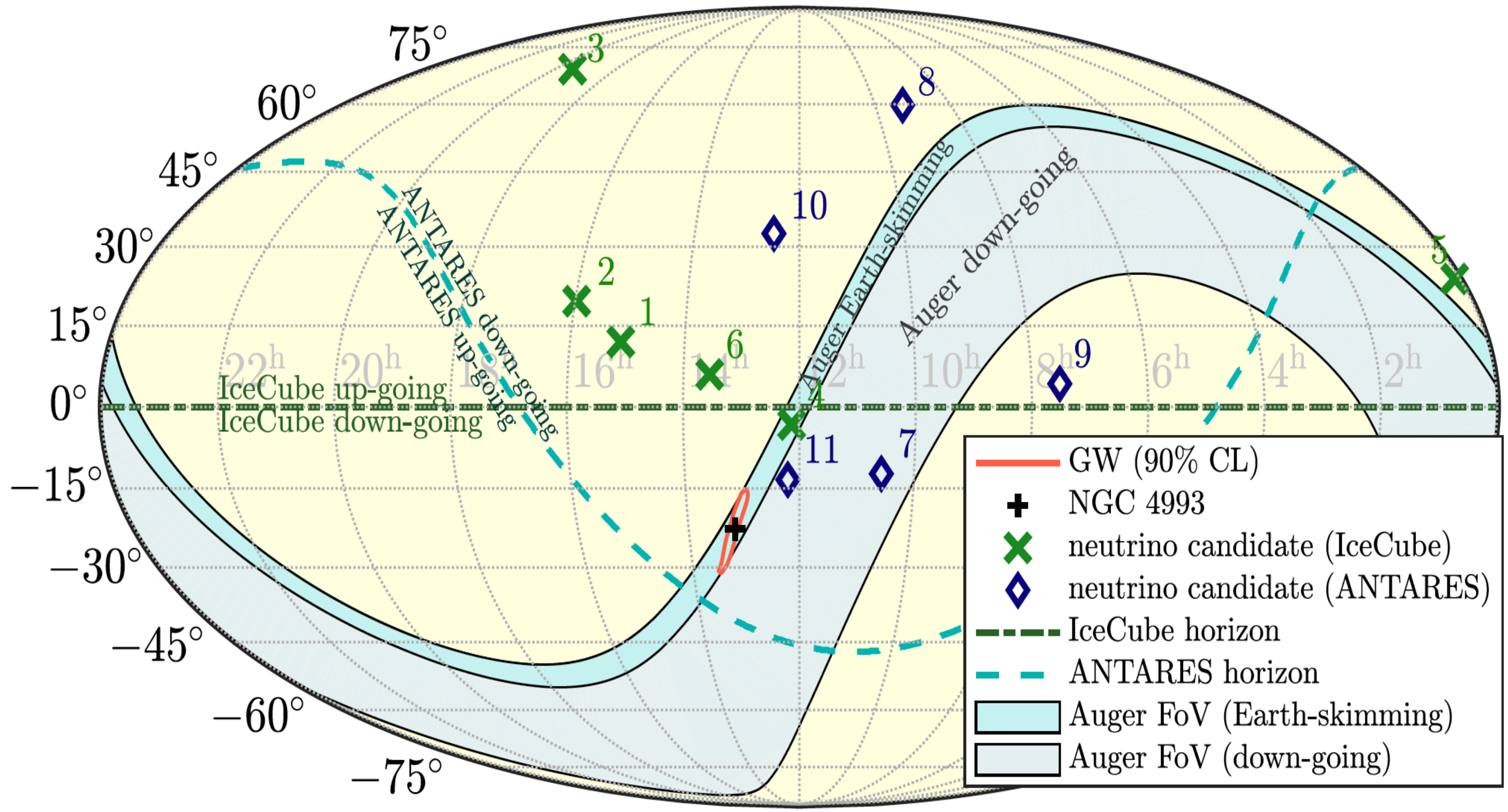
→ This may indicate a common origin of these signals, which provides excellent conditions for multi-messenger studies

Example of follow-ups of astrophysical transients: GW170817

Energy range of Auger: $E_\nu > 10^{17}$ eV

Zenith angle of optical counterpart within ± 500 s: $(90.4^\circ; 93.3^\circ)$, Earth-skimming

Search results: no candidates in time windows ± 500 s, $+14$ days



Choked Jets and Low-Luminosity GRBs

> **AGNs,GRBs, Star-form./burst galaxies do not explain the IceCube neutrino signal**
...IceCube neutrinos are also not traced by extragalactic γ-emitters* (VERITAS, MAGIC, Fermi) ➔ IceCube neutrinos could originate from environments with high γ-ray opacity

> **Choked jets and Low Luminosity GRBs as hidden neutrino sources**
N. Senno, K. Murase, P. Meszaros Phys. Rev. D 93, 083003 (2016); E. Nakar, The Astrophysical Journal, 807 2 (2015) ->LL GRB 060218/SN 2006 AJ, * except **TXS 0506+056**

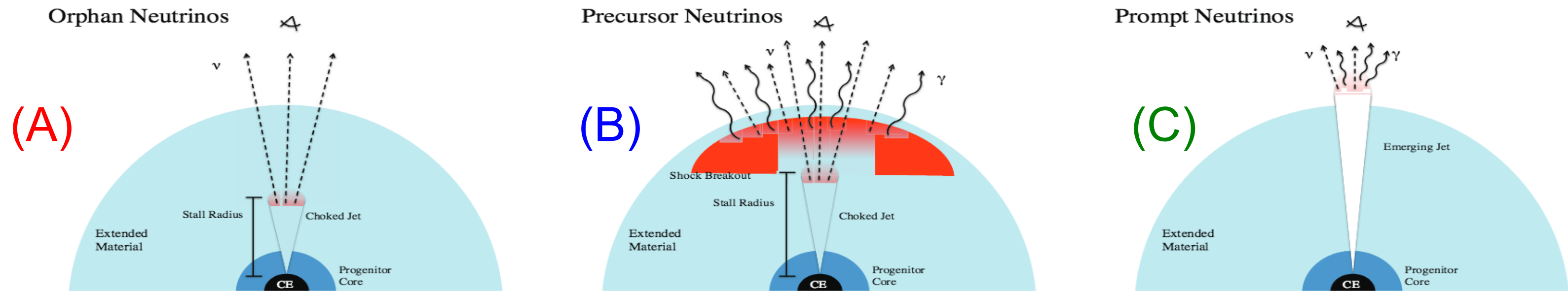


FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic SNe are driven by choked jets. Choked jets produce precursor neutrinos since the gamma-ray emission comes from the SN shock breakout later than the neutrinos (e.g., [25]). **Right panel:** The emerging jet model for GRBs and LL GRBs. Both neutrinos and gamma rays are produced by the successful jet, and both messengers can be observed as prompt emission.

- Neutrinos
- γ-ray absorbed
- Time scale: $10^{1.5}$ - $10^{2.5}$ s

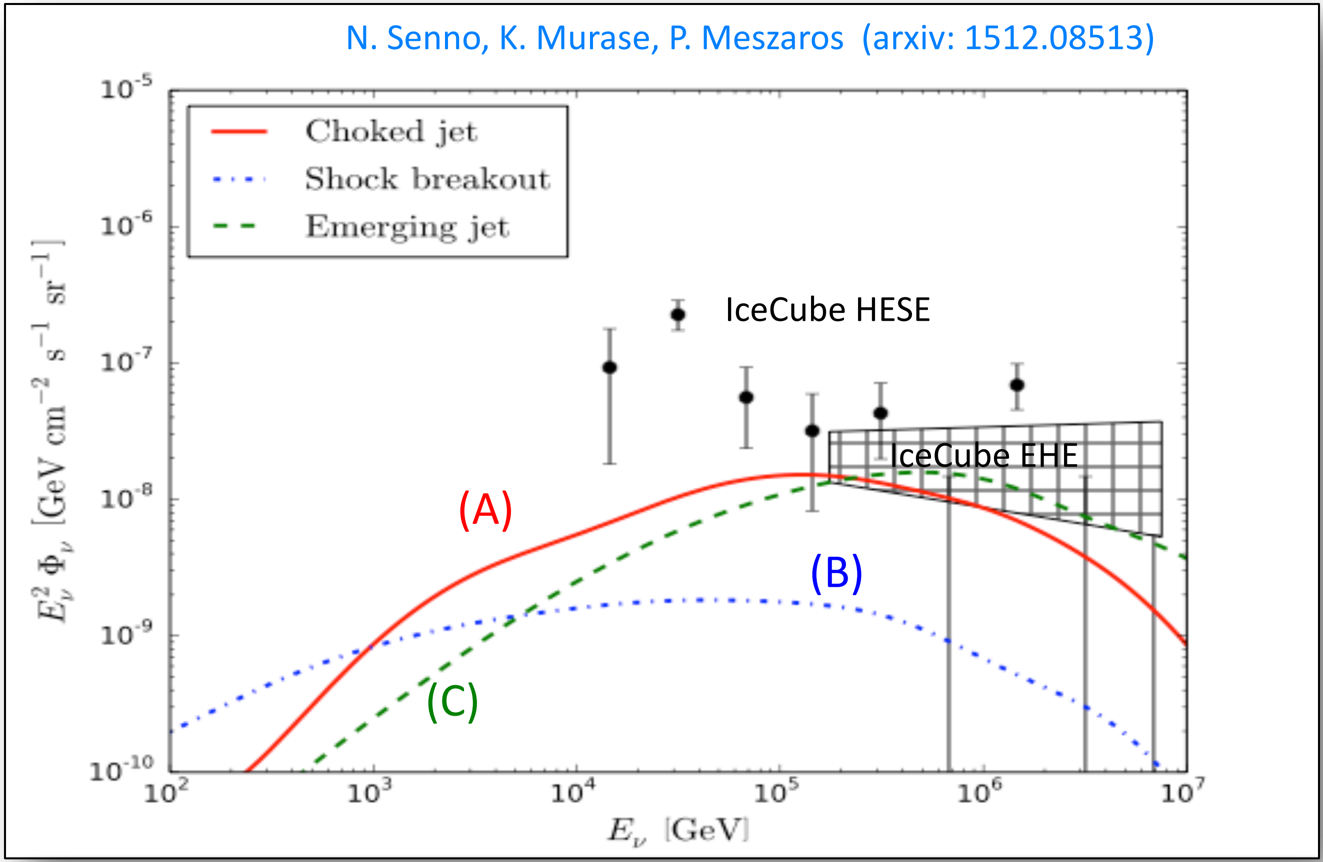
- neutrino precursor
- Later γ-ray counterpart
- Time scale: 10 - 1000 s

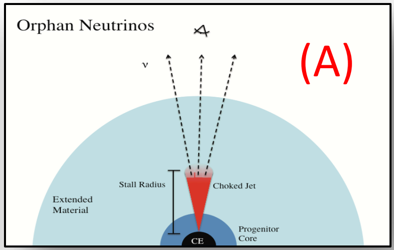
- neutrinos
- γ-ray emission
- Time scale: $10^{3.5}$ s

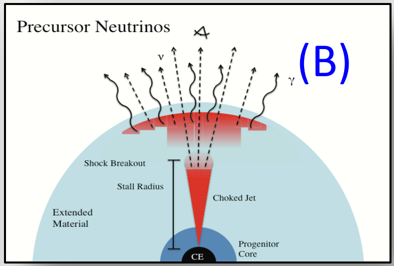
> **UHECRs produced in the nuclear cascade in the jets of LL-GRBs can describe the UHECR** spectrum and composition, and at the same time, the diffuse neutrino flux at the highest energies. D.Boncioli, D. Biehl, W. Winter The Astrophysical Journal, 872, 1

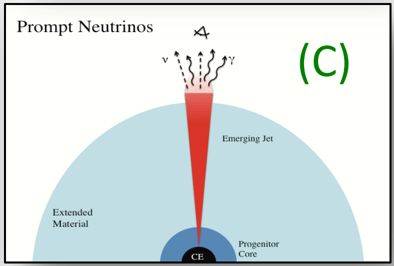
Choked Jets and Low-Luminosity GRBs

➢ Choked jets sources are dark in GeV-TeV gamma rays, so only neutrino are predicted







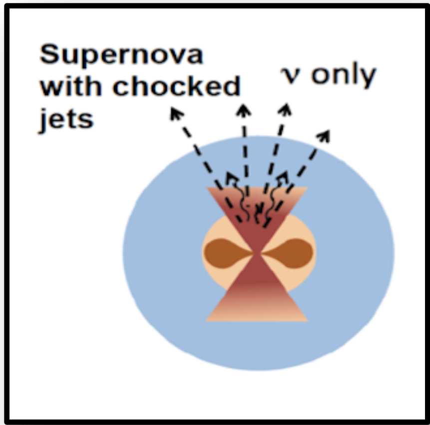


> Tidal disruption jets (TDEs) of supermasive black holes ➔hidden neutrino sources ➔ can also explain IceCube neutrinos, but again dark in GeV-TeV γ-rays (arxiv:1512.08596)

Low-Luminosity GRBs and Tidal Disruptions Events

> **Choked jets and Low Luminosity GRBs as hidden neutrino/UHECR sources**

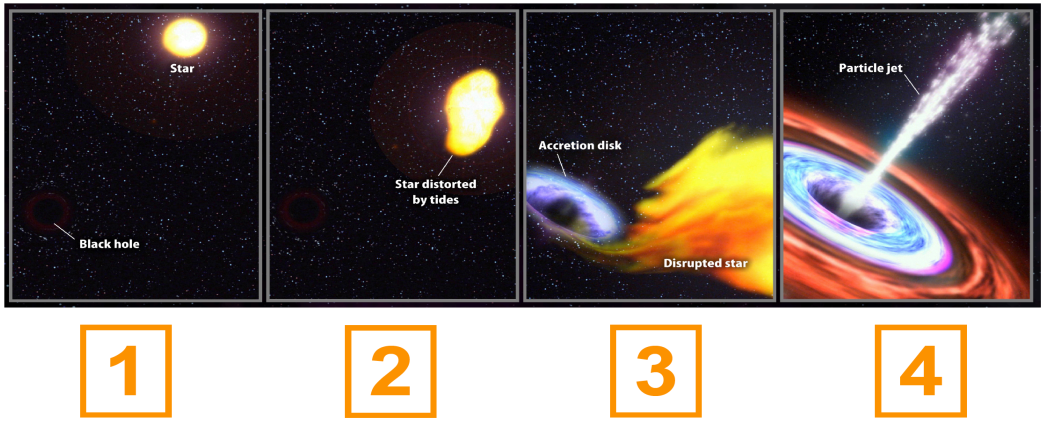
N. Senno, K. Murase, P. Meszaros Phys. Rev. D 93, 083003 (2016); E. Nakar, The Astrophysical Journal, 807 2 (2015) ->LL GRB 060218/SN 2006 AJ,



> **UHECRs and neutrinos from Tidal Disruptions by Massive Black Holes**

Stars that pass within the tidal radius of a super-massive black hole are disrupted and a large fraction of the resulting debris gets accreted onto the black hole.

-> outside the black hole horizon
a luminous flare of thermal emission
is emitted



> **UHECRs produced in the nuclear cascade in the jets of LL-GRBs/TDEs can describe the UHECRs**
spectrum and composition, and at the same time, the diffuse neutrino flux at the highest energies D.Boncioli, D. Biehl, W. Winter The Astrophysical Journal, 872, 1

C. Guépin et al. A&A 616, A179 (2018)

UHECRs and neutrinos from Tidal Disruptions by Massive Black Holes

> *Stars that pass within the tidal radius of a super-massive black hole are disrupted and a large fraction of the resulting debris gets accreted onto the black hole.*

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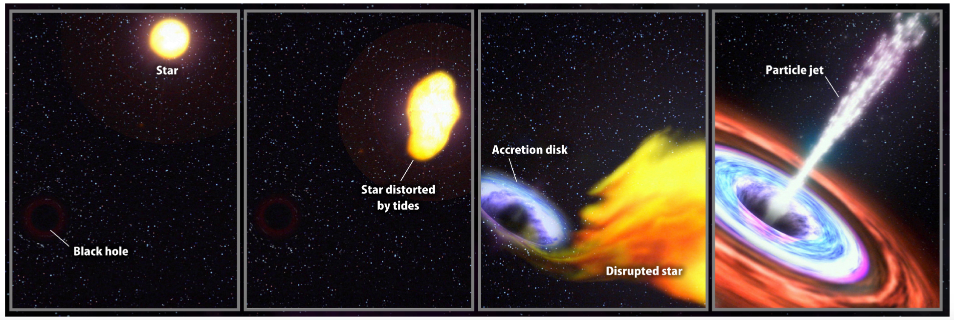
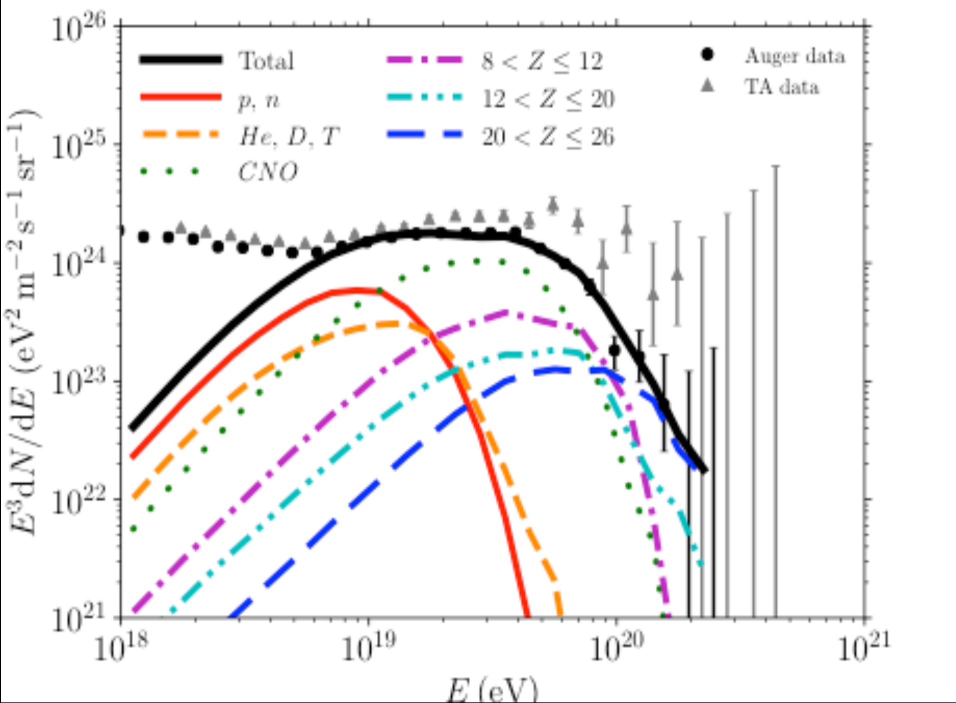
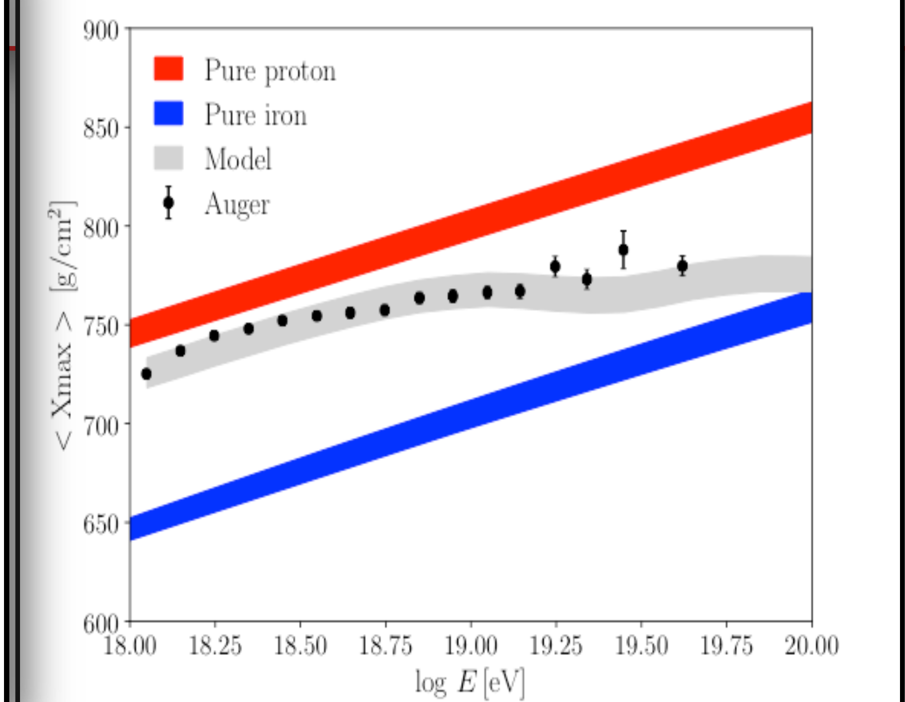
What are Tidal Disruption Events?



Injection of 70% Si and 30% Fe



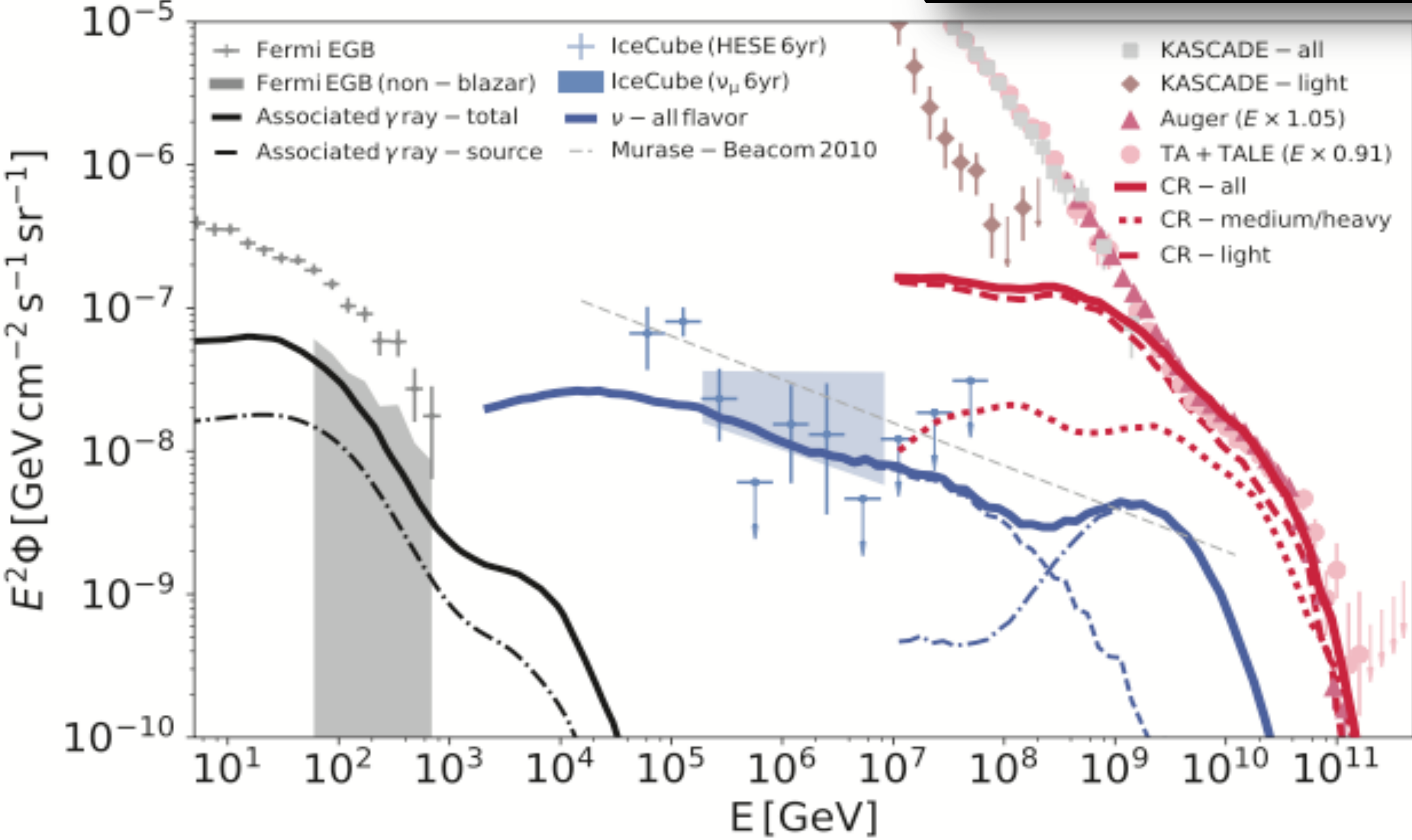


C. Guépin et al. A&A 616, A179 (2018)

See more for Auger mass composition in J. Stasielak talk

Black hole Jets in Clusters of Galaxies

K. Fang and K. Kotera, Nature Phys. 14 (2018) 396



> Black hole jets embedded in galaxy clusters can simultaneously explain UHECRs, high-energy neutrinos, and the non-blazar component of isotropic gamma-ray background

Summary

> Still there are open questions about the origin of UHECRs
  - classical AGNs, GRBs, star-form./burst galaxies do not yet fully explain the origin of UHECRs

  but ..
  - *the first source of CRs is TXS 0506+056 and it is a blazar*
  - *first time detection of a GRB at sub-TeV energies by MAGIC (GRB 190114C, ATel #12390)*

  On the other hand
  - UHECRs/neutrinos could originate from environments with high γ-ray opacity like LL-GRBs, TDEs, ...

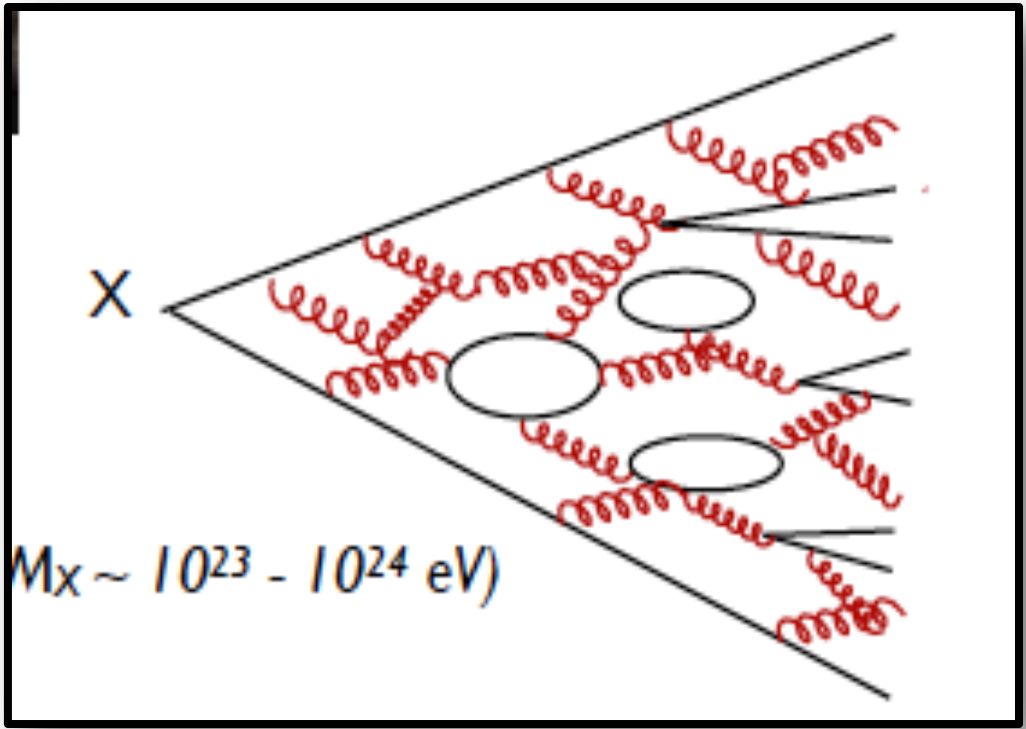
> Era of multi-messenger physics
  - black hole jets embedded in galaxy clusters can simultaneously explain UHECRs, high-energy IceCube neutrinos, and the non-blazar component of isotropic gamma-ray background measured by Fermi satellite.

  K. Fang and K. Kotera,Nature Phys. 14 (2018) 396

Top-down models of UHECRs

- Sources of UHECR and astrophysics

X-particles from:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces



QCD: ~ E-1.5 energy spectrum
QCD+SUSY: ~ E-1.9 spectrum