# Theory of Cosmic Ray Origin

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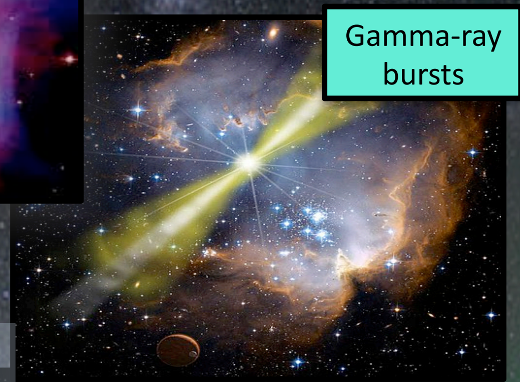
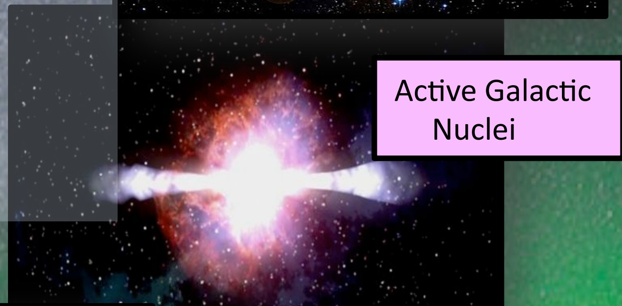


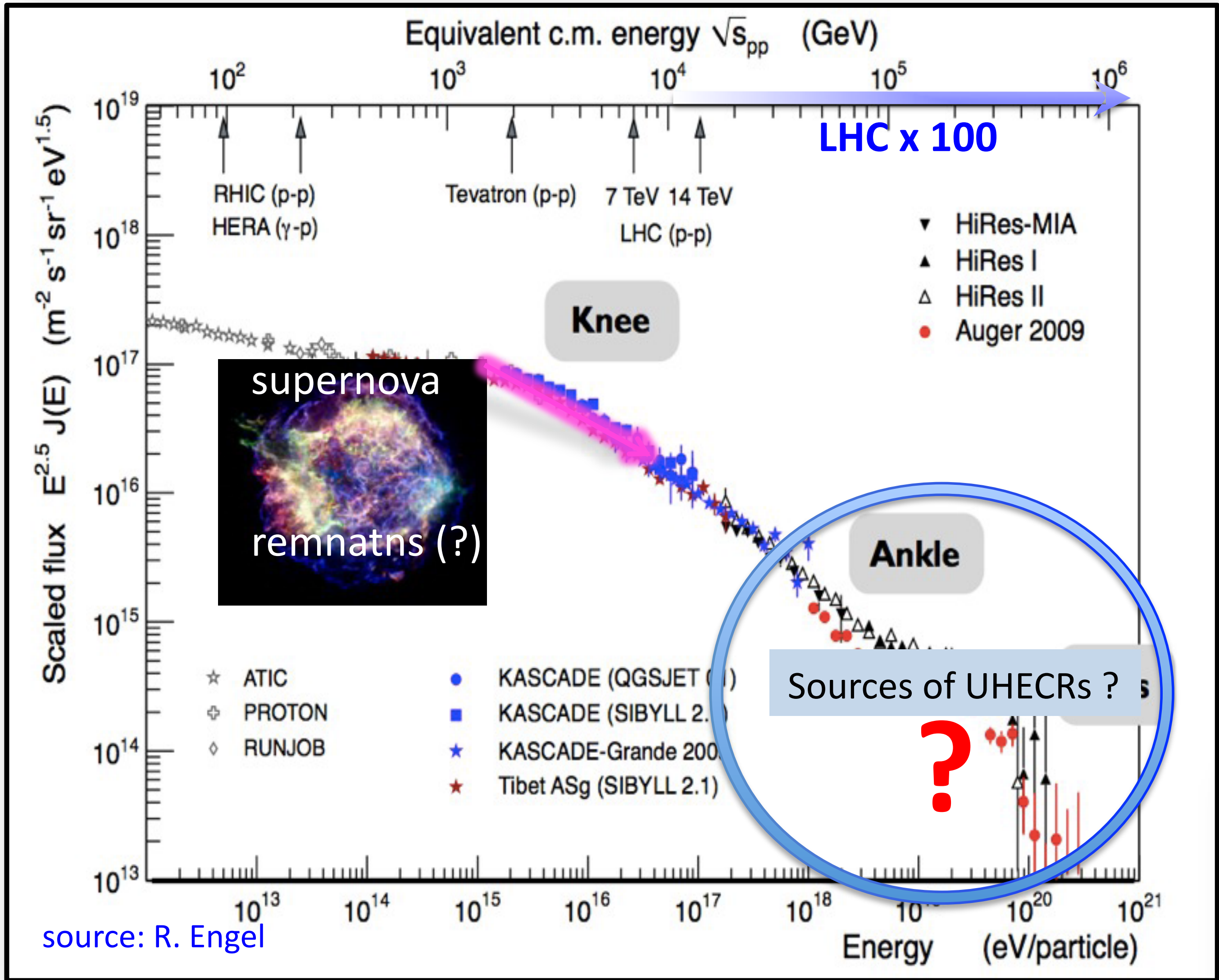

Outline:
- Spectrum, propagation of UHECRs, Hillas diagram,..
- Sources of UHECRs: GRB, AGNs, LL-GRB, TDEs,..
- Multi-messenger approach and UHECRs






Particle Astrophysics in Poland, Warszawa 20-21 Maj 2019

# 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,…*

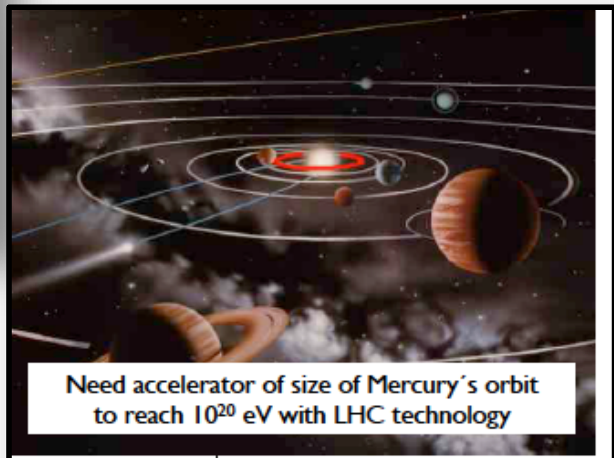
> How do they reach such tremendous energies?

**Spectrum suppression:**

**in the past**: *the GZK cut-off*

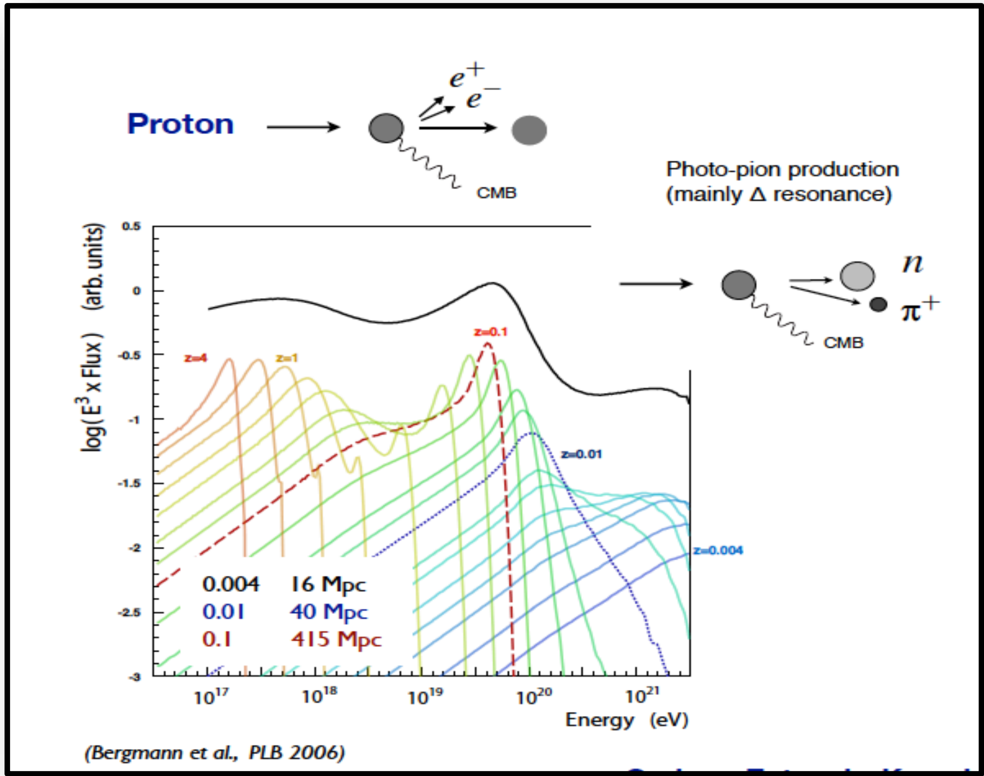
**now**: *rather the efficiency limit of particle acceleration by sources*

Particle physics beyond the reach of colliders



# UHECRs propagation to Earth

## Photo-pion production




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

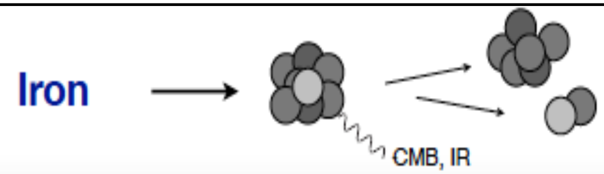
*cosmic ray absorption*

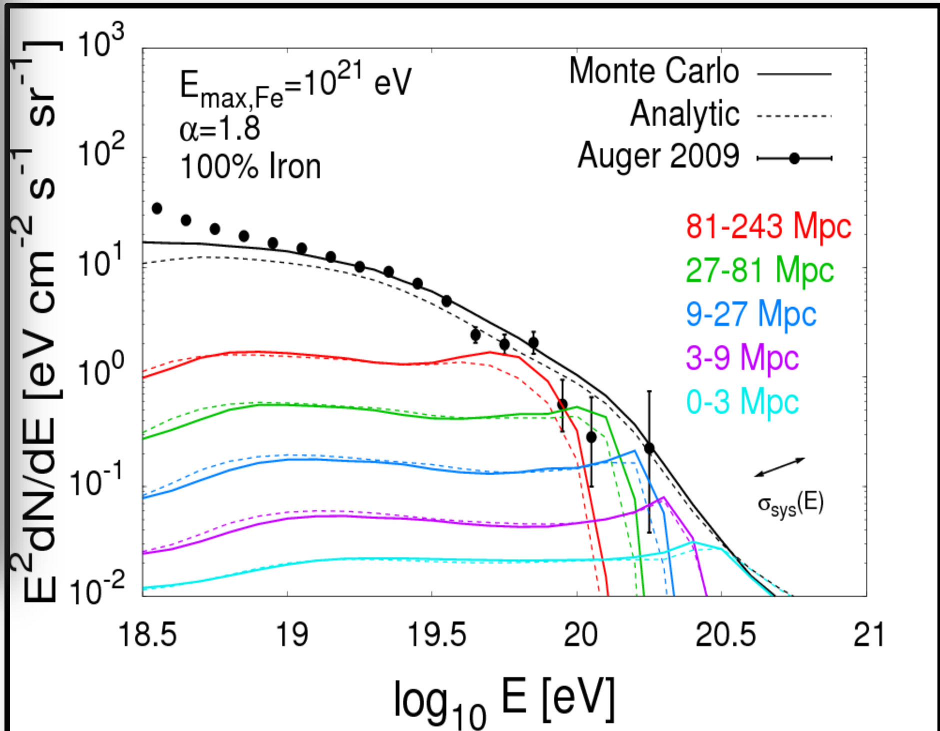
*in Cosmic Mirowave Background CMB (1965)*

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

## Photo - nuclear interactions

**photon-desintegration, 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:

Larmor radius:

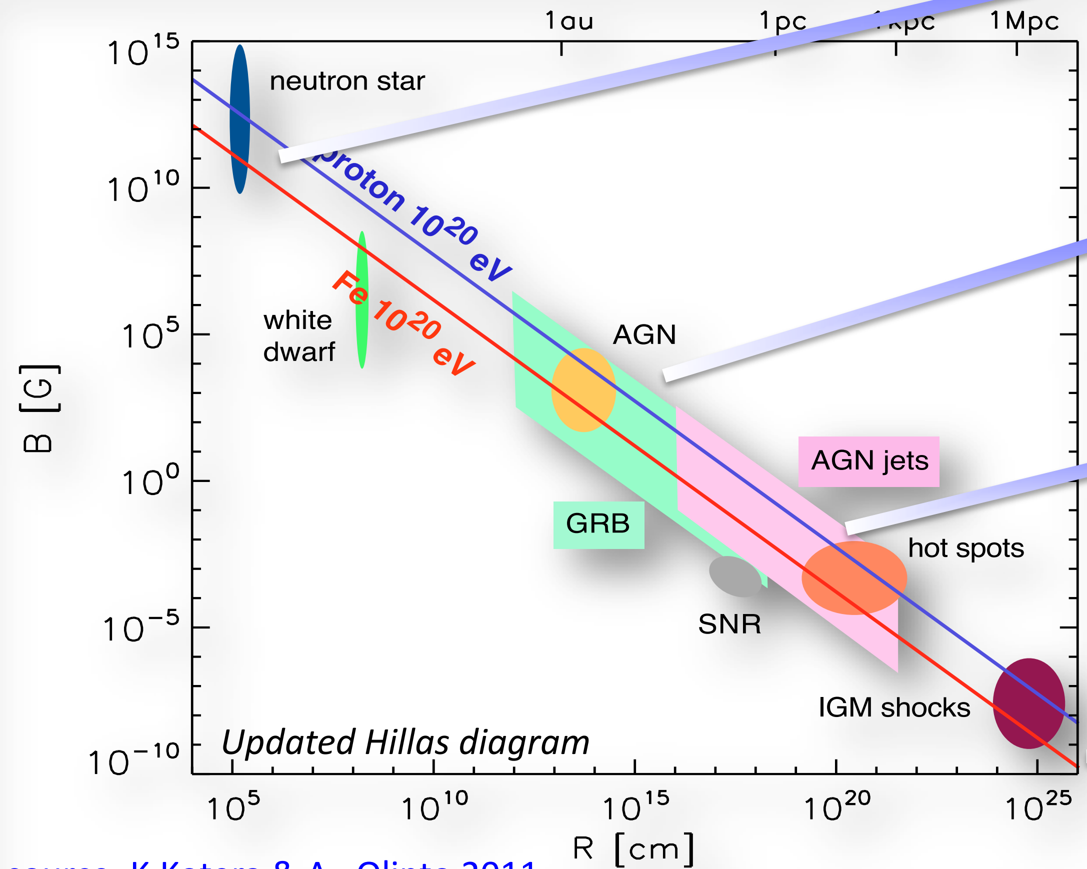
$$r_L = 1.08\ \mathrm{Mpc}\ Z^{-1} \left(\frac{E}{10^{18}\ \mathrm{eV}}\right) \left(\frac{B}{1\ \mathrm{nG}}\right)^{-1}$$

particle charge — particle energy — source mag. field

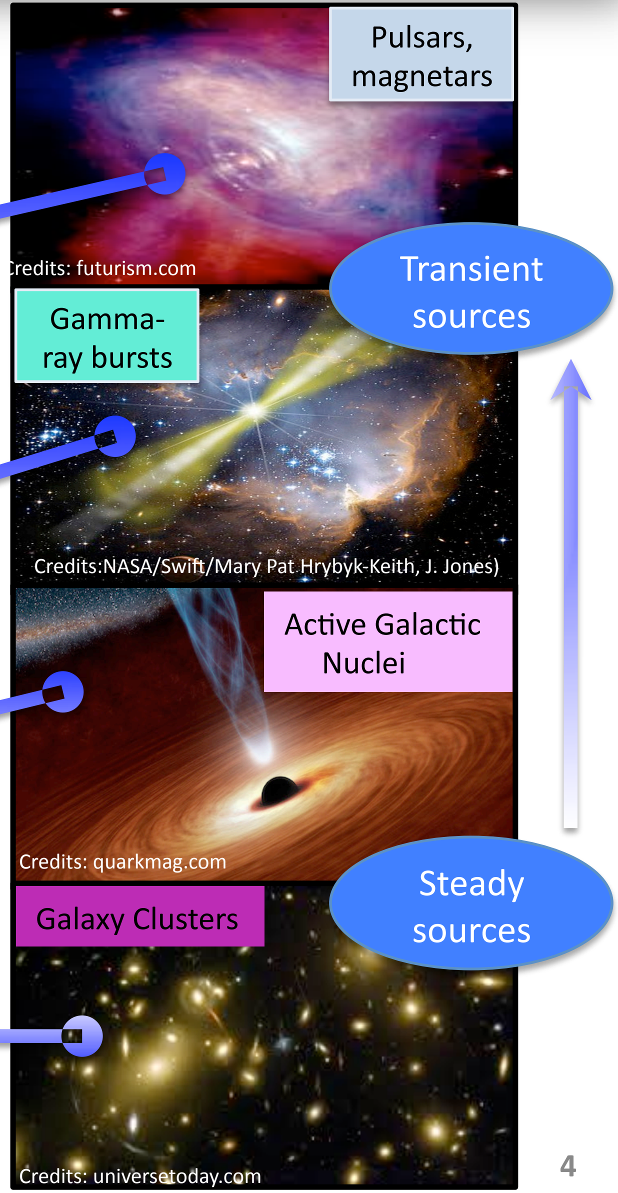
> The first condition for successful acceleration:

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

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




source: K.Kotera & A. Olinto 2011



# A luminosity bound

> The second condition for successful acceleration:

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

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

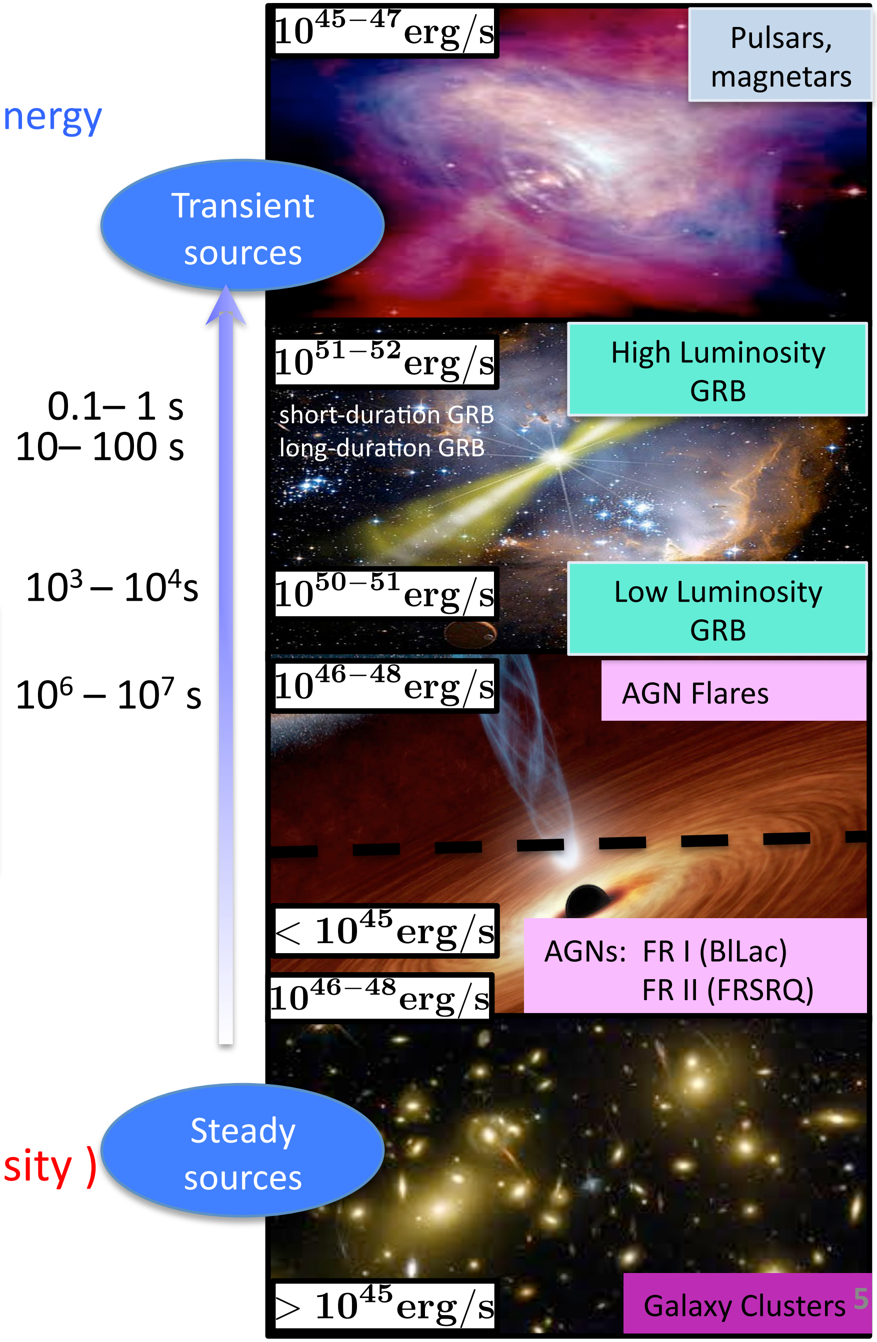
$$L > L_B \equiv \Gamma_{\mathrm{W}} R^2 B^2/2 > 10^{45}\, Z^{-2} E_{20}^2 \ \mathrm{erg\ s^{-1}}$$

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

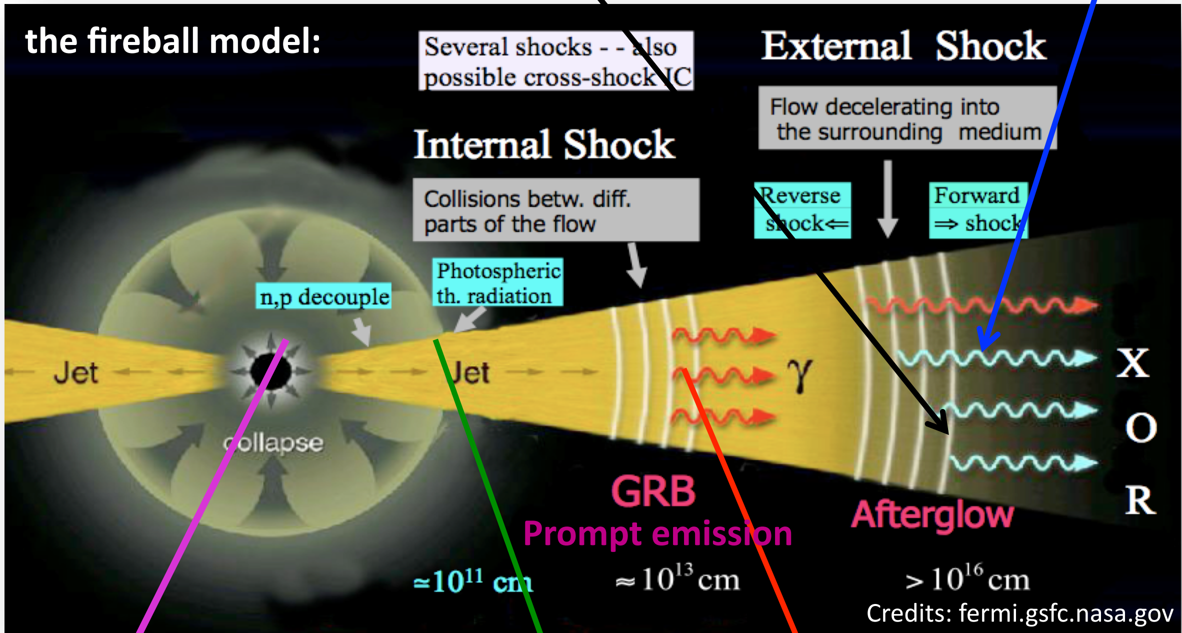


# GRBs and SuperNovas (time scale of seconds/minutes)

> GRBs are extremely energetic explosions caused by ultrarelativistic jet launched by the collapse of masive star or merger of two compact binary objects.

**PeV-EeV neutrinos from flares**
Murase &Nagataki

**EeV neutrinos from external shocks**
Dermer 2001
Waxman & Bahcall 2000




**MeV neutrinos at collapse**

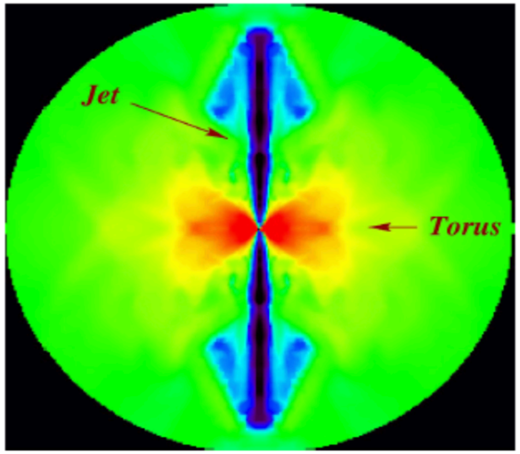
**TeV neutrinos at collapse**
Meszaros & Waxman, 2001
Razzaque et al. 2003

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

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

**Hadronic model:**

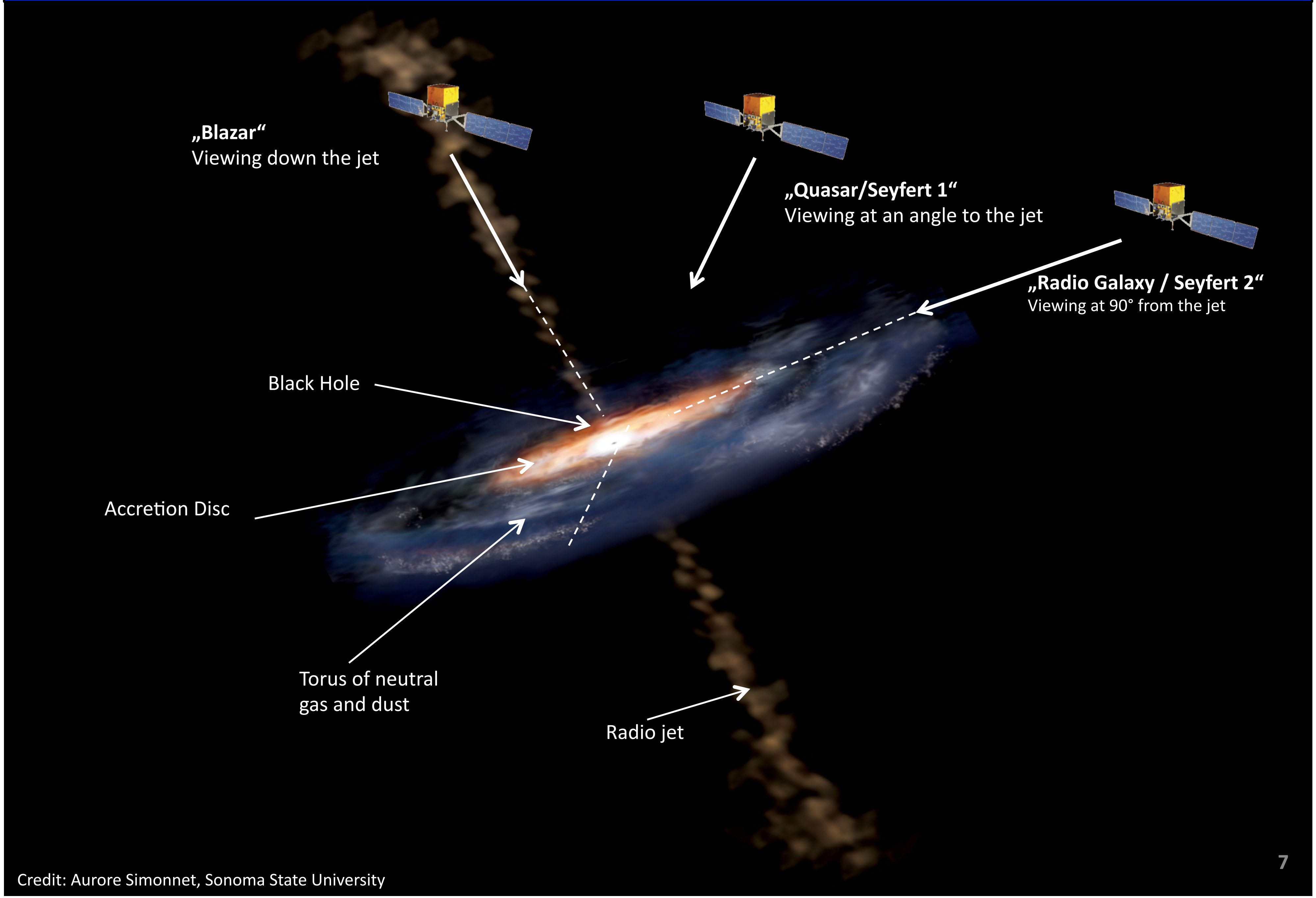
$$p\,\gamma \rightarrow \Delta^{+} \rightarrow n\,\pi^{+}$$
$$p\,p \rightarrow \pi, K$$
$$\pi^{+} \rightarrow \nu_{\mu}\,\mu^{+} \rightarrow \nu_{\mu}\,e^{+}\,\nu_{e}\,\bar{\nu}_{\mu}$$




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)

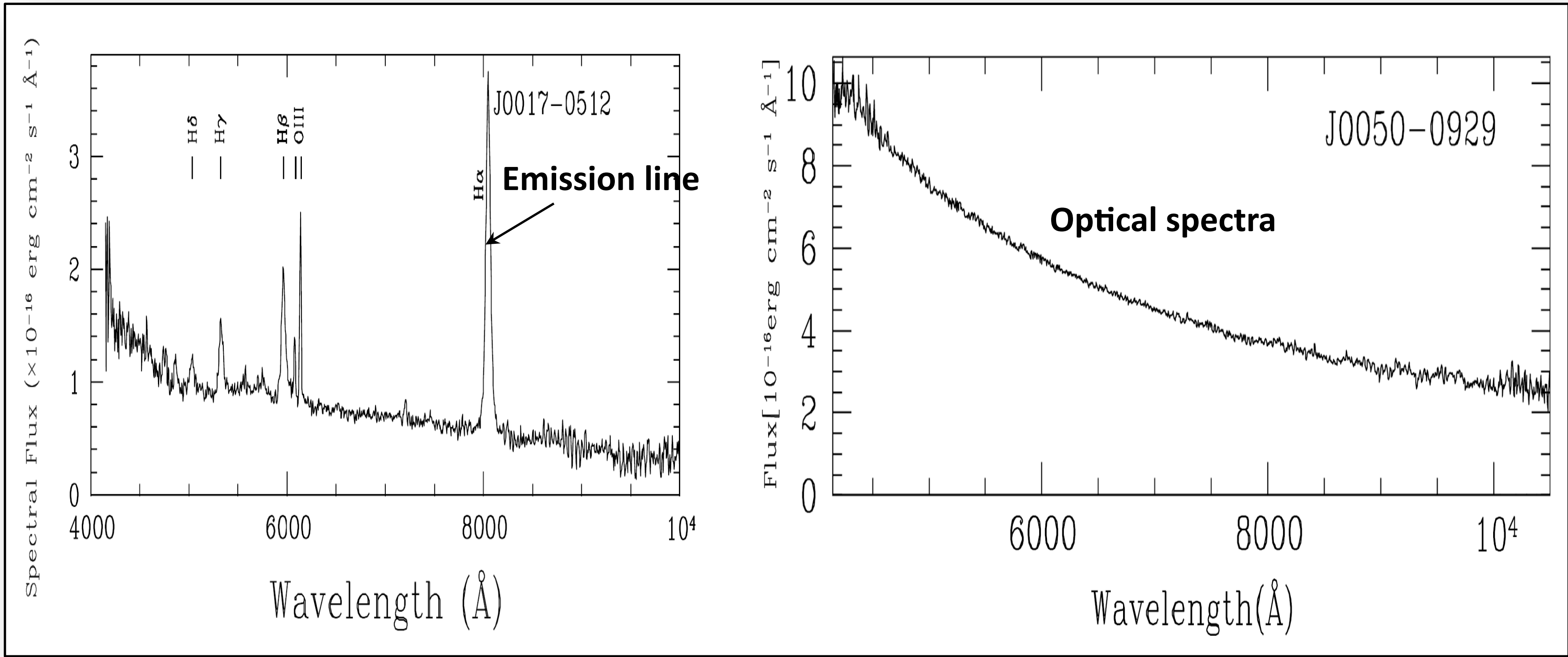



Credit: Aurore Simonnet, Sonoma State University

# Blazars

**FSRQ (Flat Spectrum Radio Quasar):**
shows strong atomic lines in their optical and UV spectra **Quasar)**

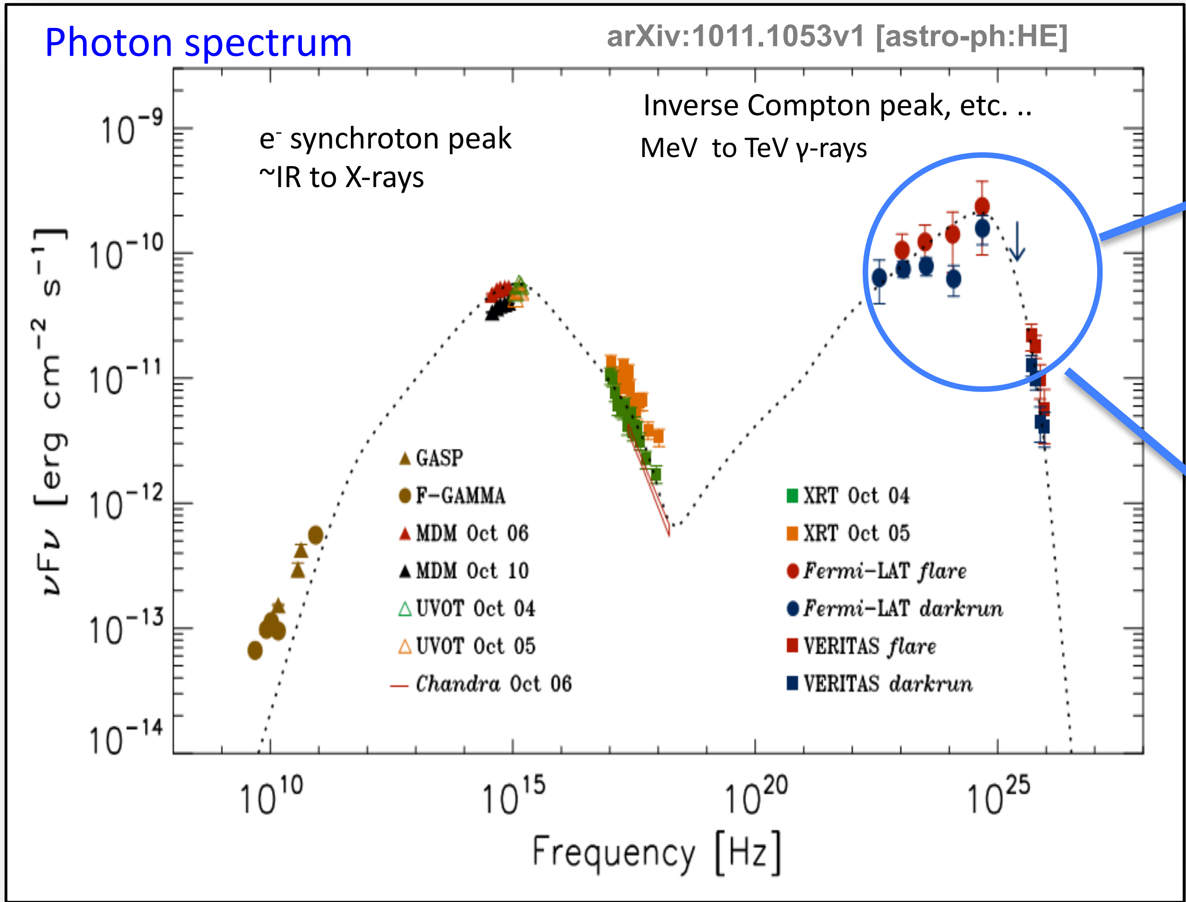
**BL Lac**




arXiv:0908.2996v1 [astro-ph:HE]

# Blazars

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




**Hadronic models:**

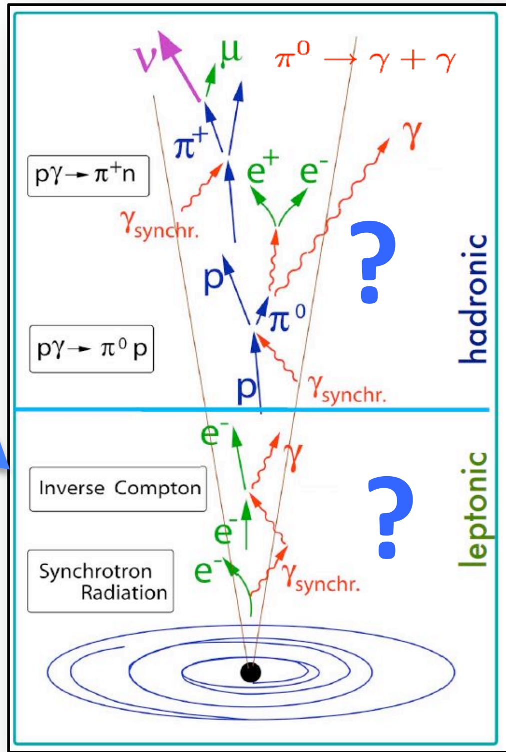
1) Photo-meson production:

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

2) p-p interaction:

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

**or/and**



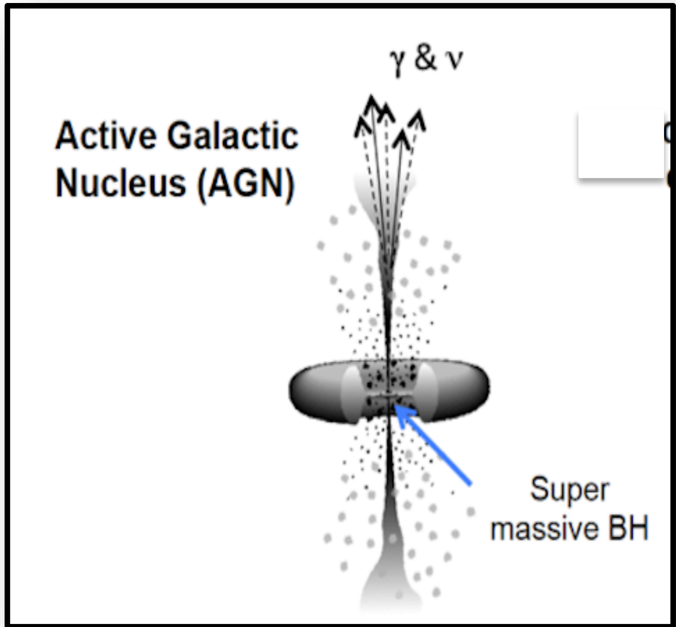

**Leptonic models:**

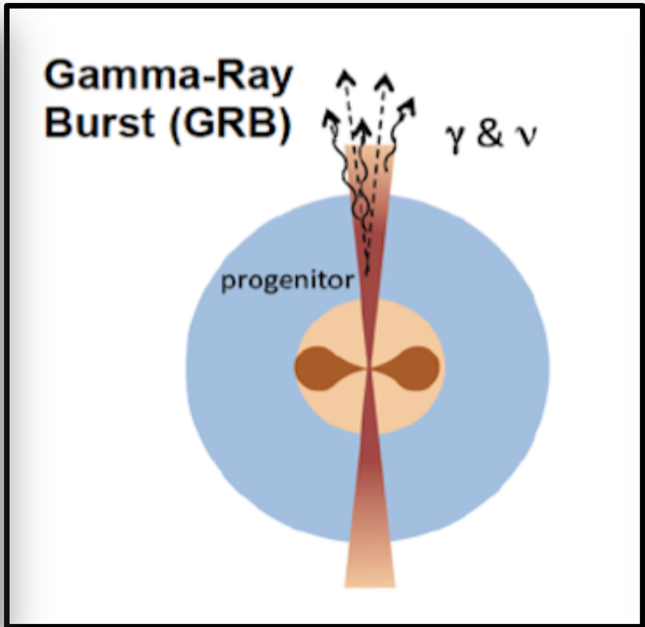
Synchroton self-Compton (SSC) models,..

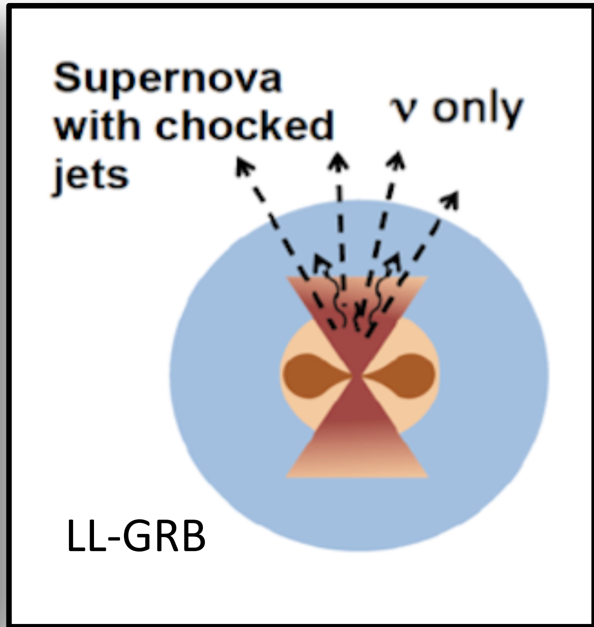
Hadronic models predict
neutrino flux correlated with photon flux

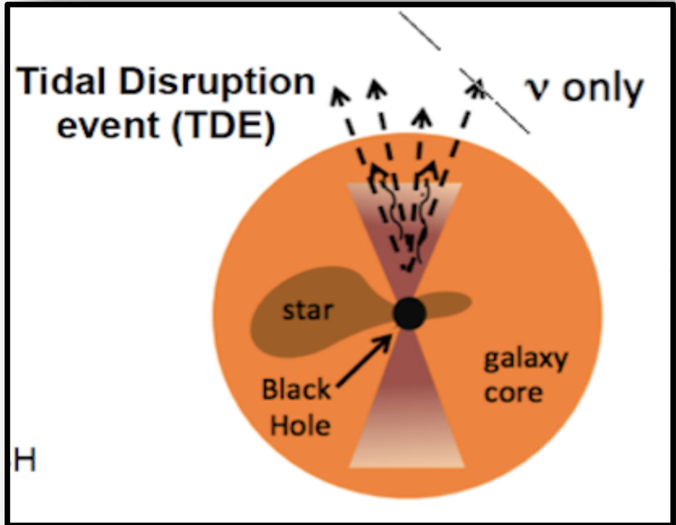
# Different Scenarios with varying degree of jet formation

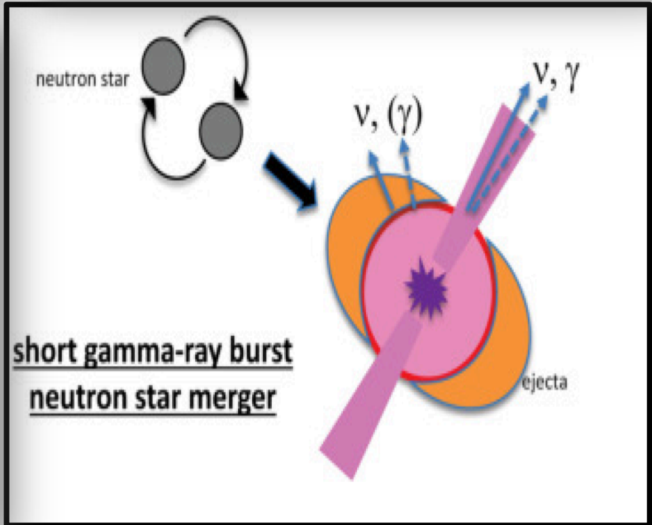
Jets are great astroparticle accelerators

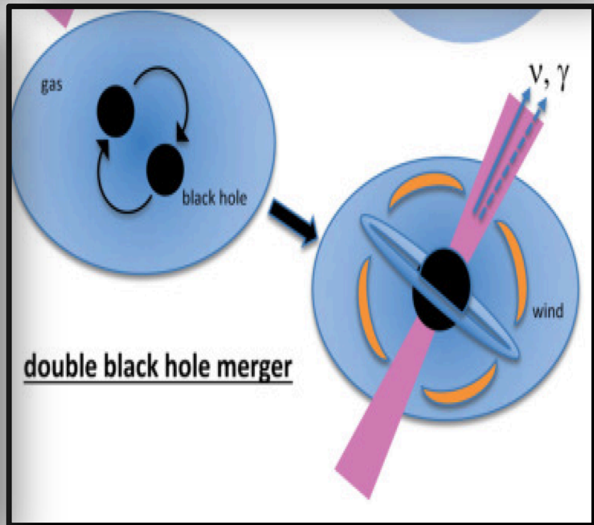



Source: I. Bartos and M. Kowalski, 2017

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

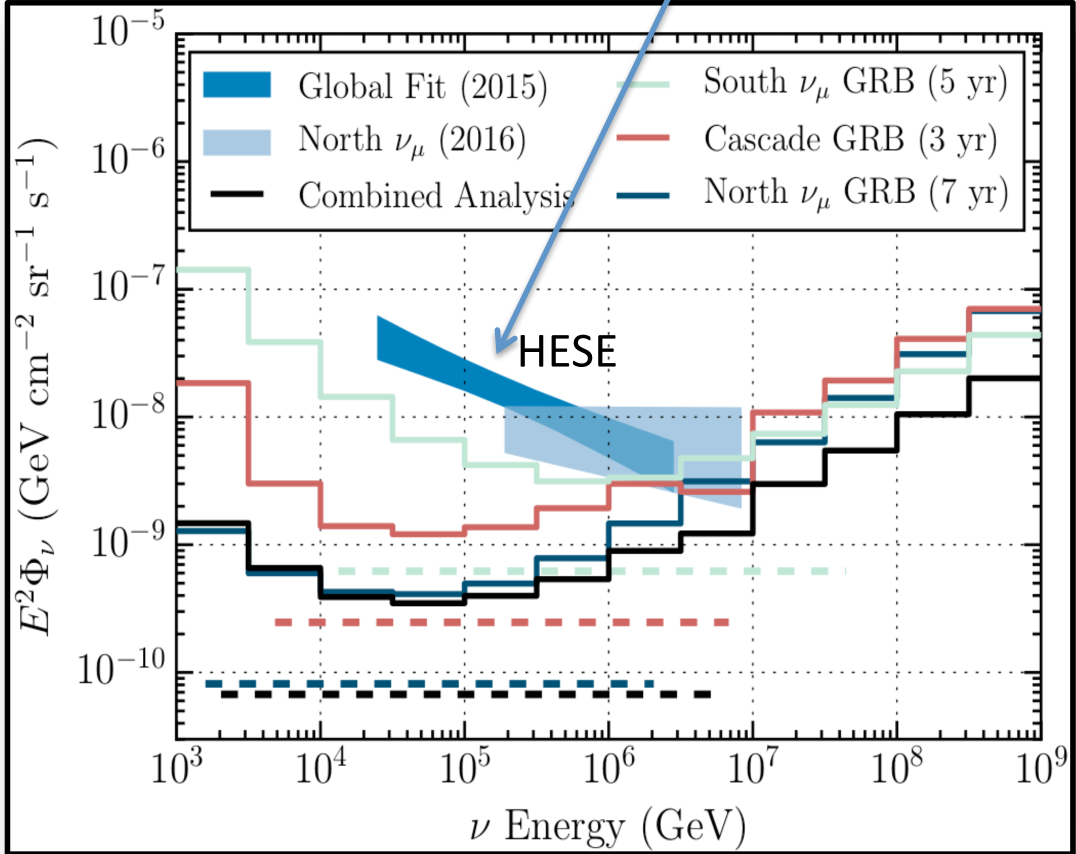
**significance 3.9σ**

**see more about this in J. Stasielak talk**

Also classical GRBs do not fully explain the origin of UHECRs

# IceCube: AGNs and GRBs analysis

IceCube: 82 high energy starting events (HESE) neutrino candidates (30 – 2000 TeV)
PoS(icrc2017)981




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

> 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

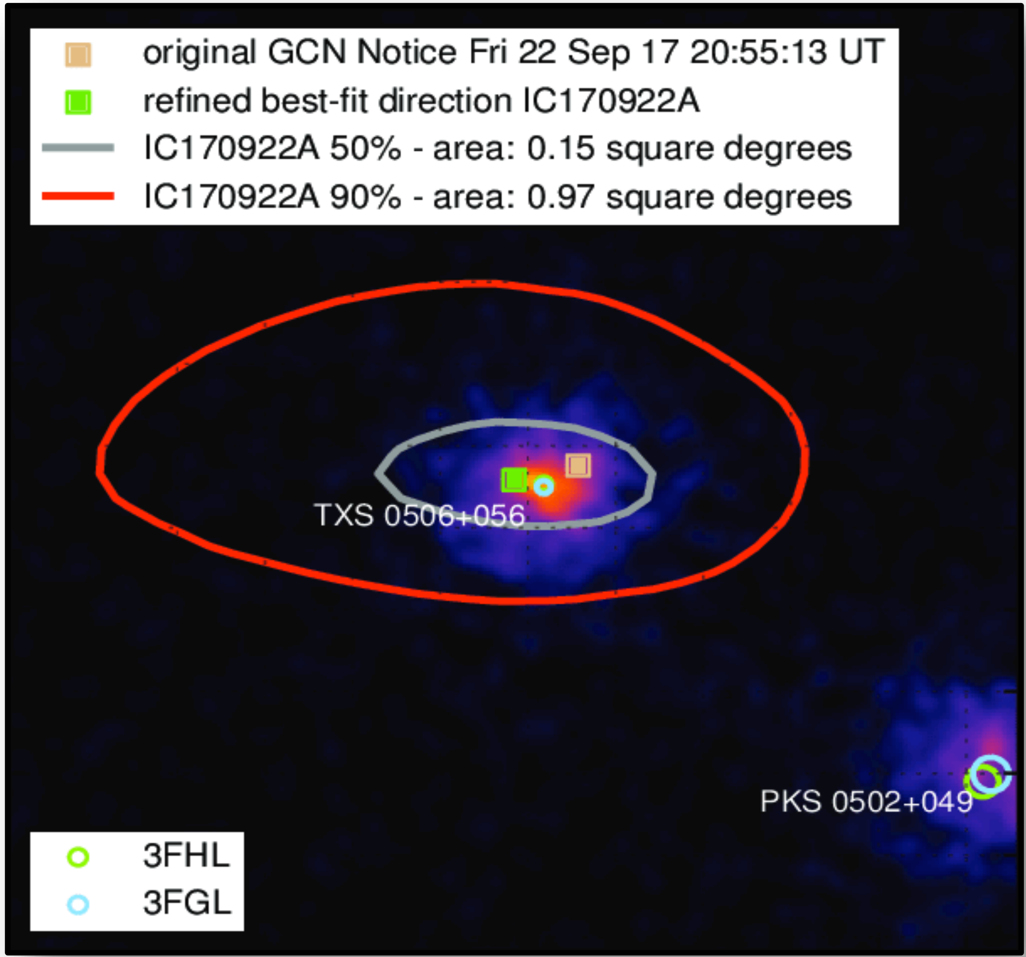
# … but TXS 0506+056 is also the first source of UHECRs ?

> 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.

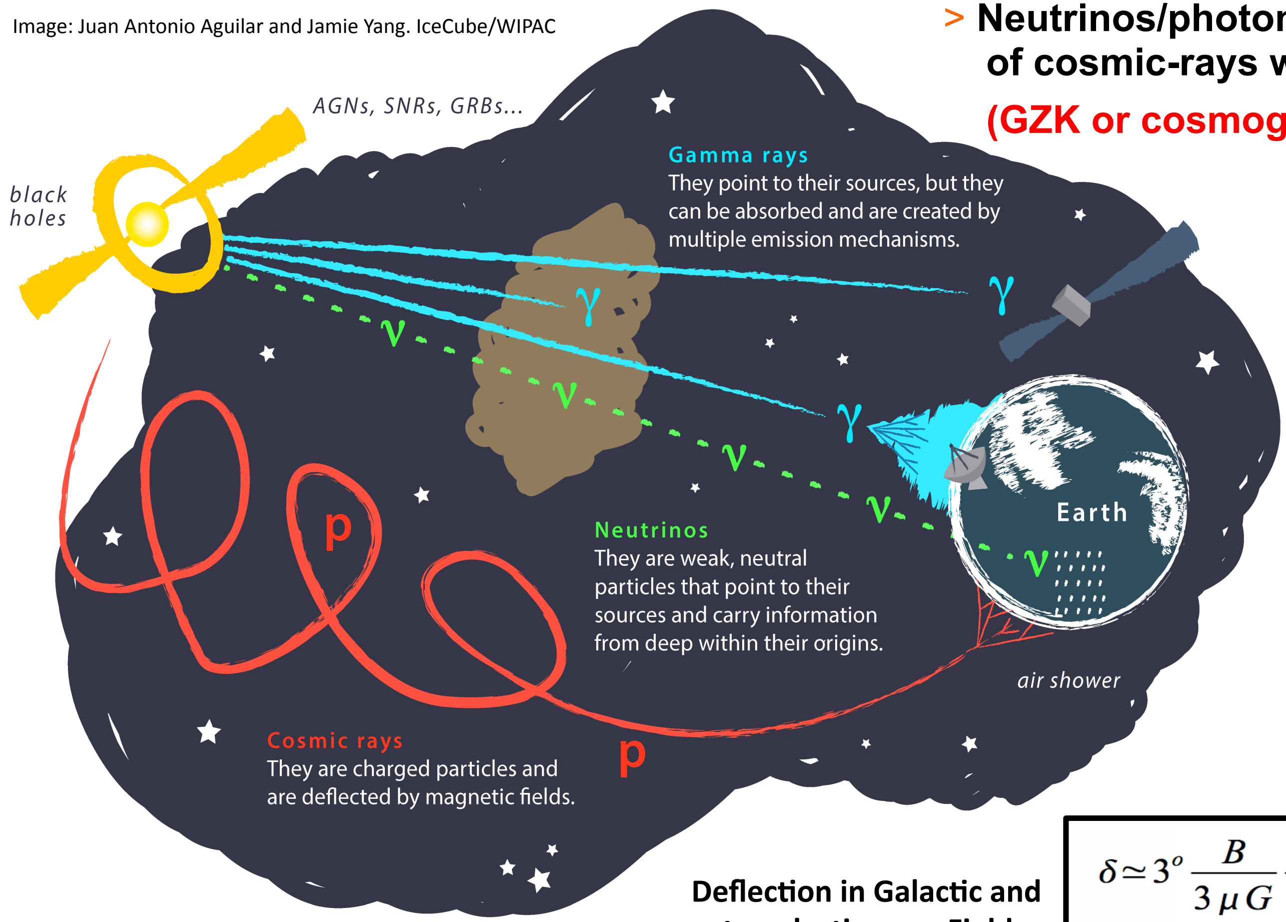
IceCube, Fermi, MAGIC, …, Science. 361 (6398): 147–151.




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

# Multi-messenger approach and UHECR propagations

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




> **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:**

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

**Deflection in Galactic and extragalactic mag. Fields**

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

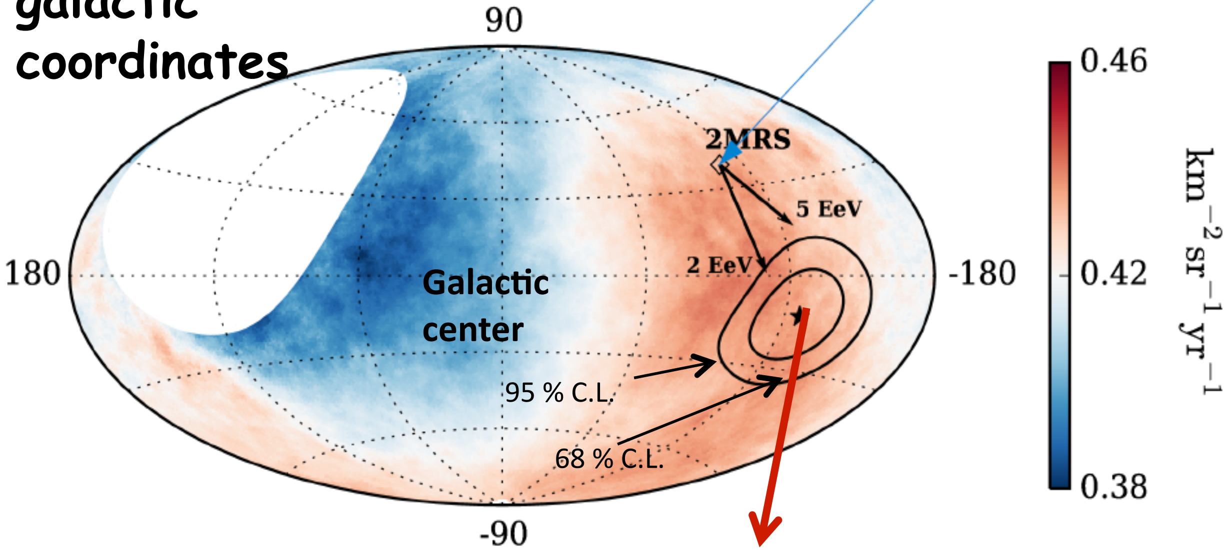
> The determination of the origin of CRs is a difficult task since CRs are deflected during propagation and the extent of this angular deflection is still poorly constrained.

> 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.

# Auger observation of dipolar anisotropy above 8 EeV

The flux-weighted dipole from IR galaxy distribution in 2MRS points to (l,b)=(251°,38°) → ~55° from observed

[Erdogdu et al. 2006]

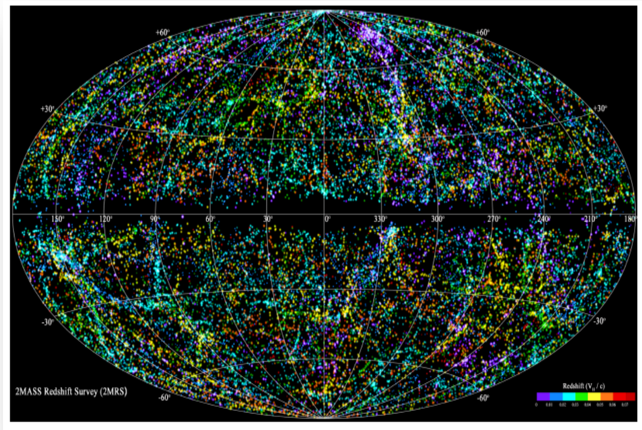



Observed dipole, Gal. coord. (l, b) = (233°, −13°), ~120° away from GC -> disfavours galactic origin

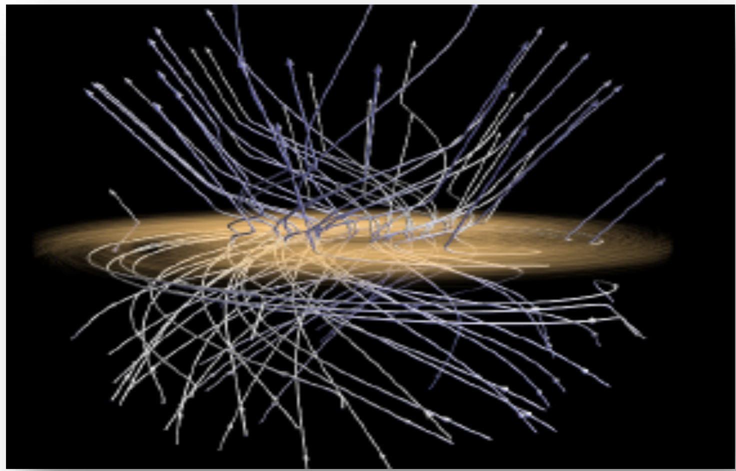
Large-scale anisotropy can arise from:
> inhomogeneous large-scale distribution on sources
> diffusion in extragalactic magnetic fields from dominant nearby sources

The Pierre Auger Collaboration, Science 357 (2017)

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



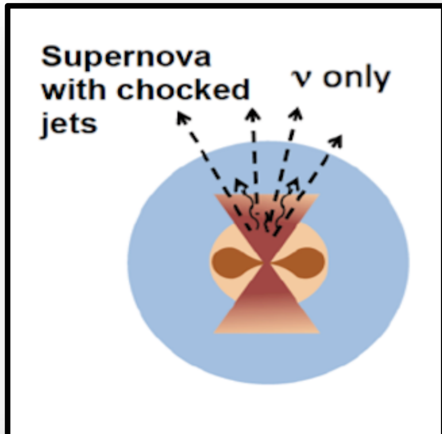

Traces of CRs in the galactic magnetic field



# Low-Luminosity GRBs and Tidal Disruptions Events

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

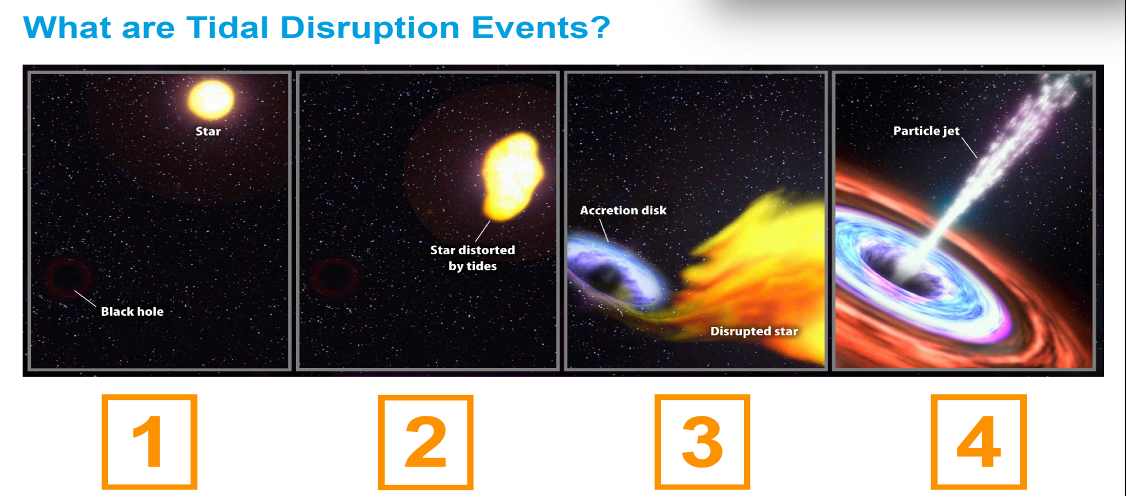
N. Senno, K. Murase, P. Meszaros Phys. Rev. D 93, 083003 (2016); E. Nakar, The Astrophysical Journal, 807 2 (2015) ->LL GRB 060218/SN 2006 AJ,




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

*Stars that pass within the tidal radius of a super-massive black hole, located in center of galaxy, 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 (measured by Auger), and at the same time, the diffuse neutrino flux at the highest energies from ICeCube

D.Boncioli, D. Biehl, W. Winter The Astrophysical Journal, 872, 1

C. Guépin et al. A&A 616, A179 (2018)

# 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, ...

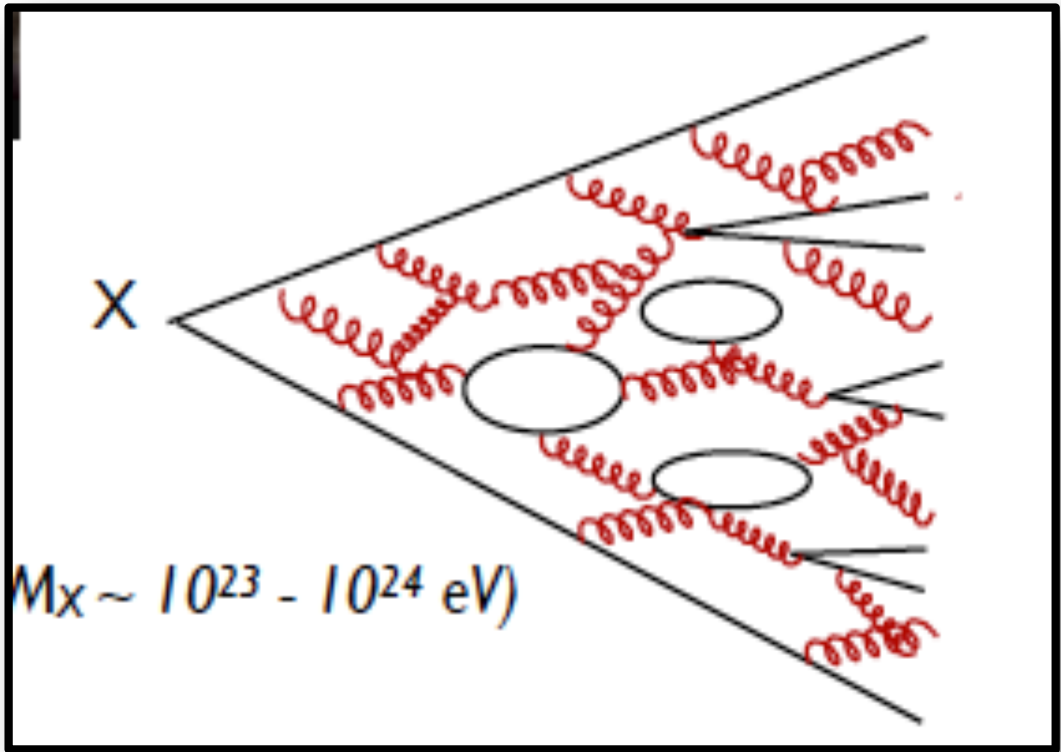
> Era of multi-messenger physics
  - black hole jets embedded in galaxy clusters can simultaneously explain UHECRs, high-energy IceCube neutrinos, and the non-blazar component of isotropic gamma-ray background measured by Fermi satellite.

  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

# The Pierre Auger Observatory search for UHECR correlation with:

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

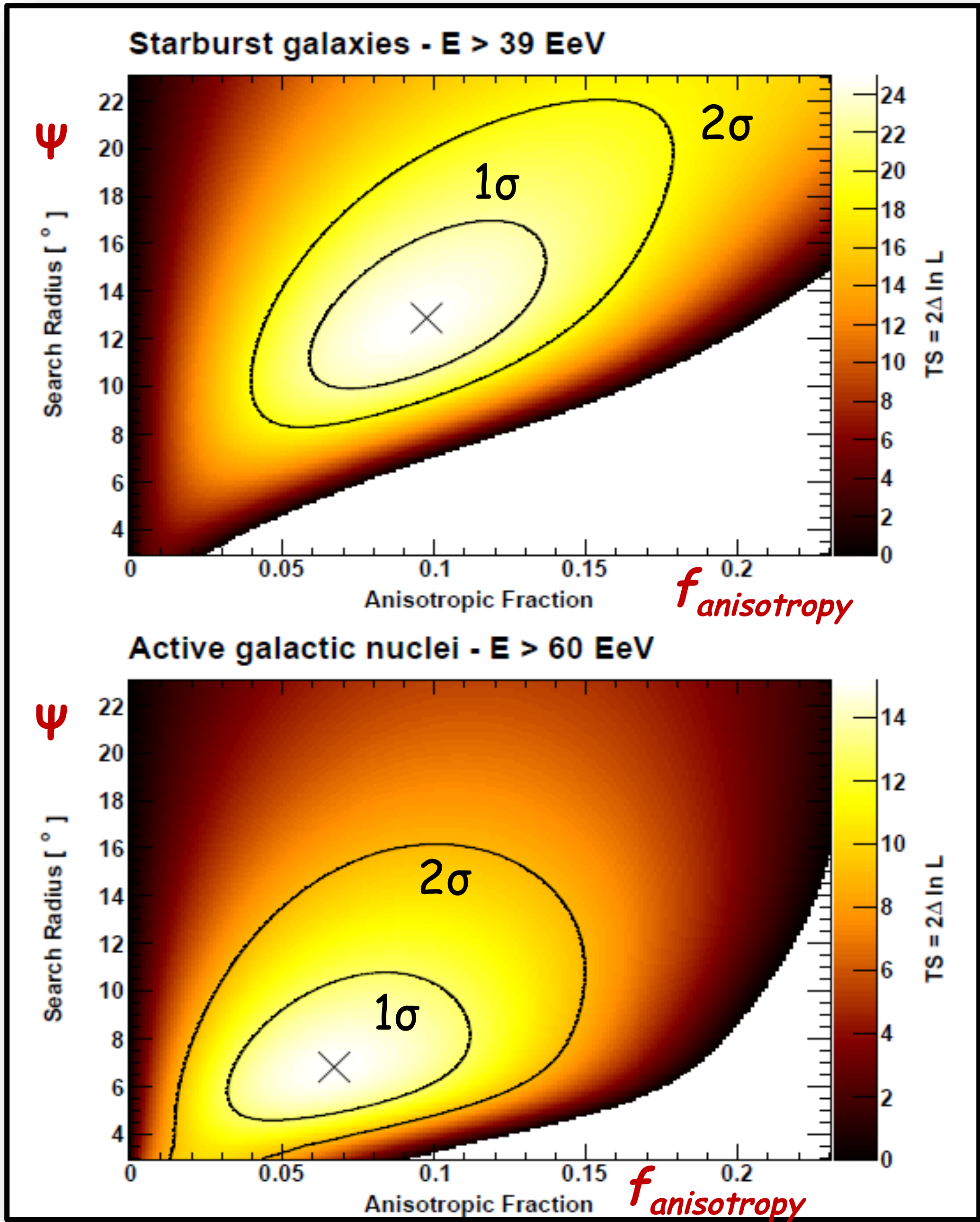
***$f_{anisotropy}$ = 10%, Ψ = 13°***
**significance 3.9σ**

**> 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)*



# 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**

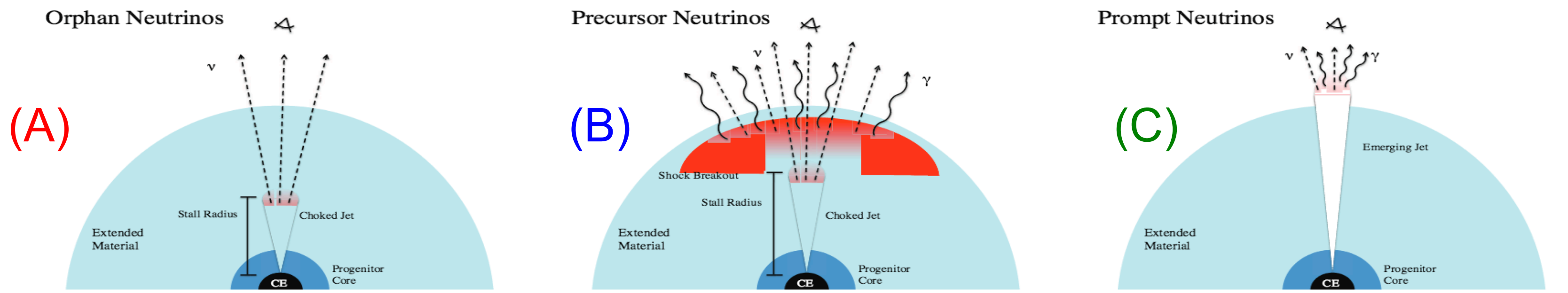



FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic SNe are driven by choked 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

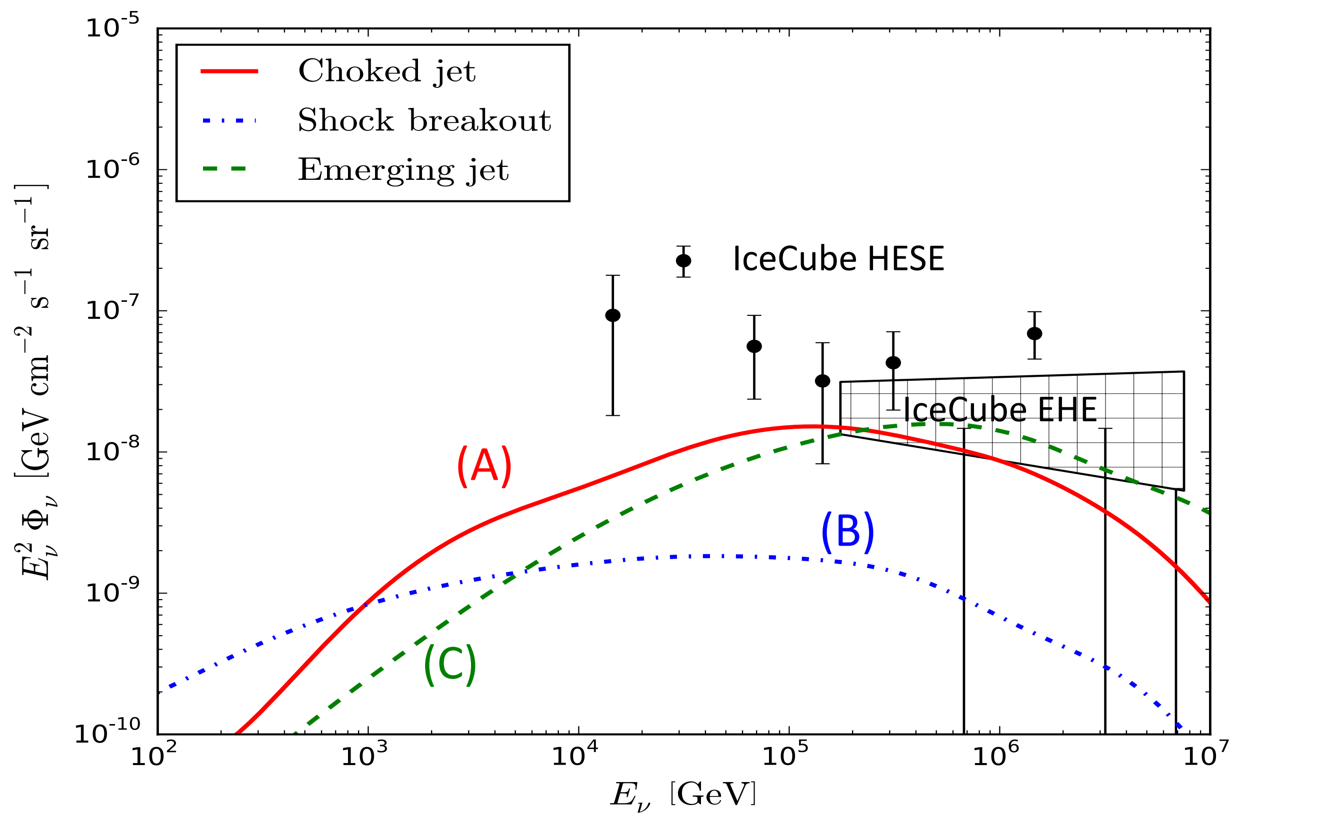
- neutrinos
- γ-ray emission
- Time scale: $10^{3.5}$ s

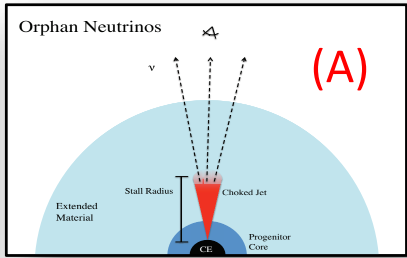
**> UHECRs produced in the nuclear cascade in the jets of LL-GRBs can describe the UHECR** spectrum and composition, and at the same time, the diffuse neutrino flux at the highest energies. D.Boncioli, D. Biehl, W. Winter The Astrophysical Journal, 872, 1

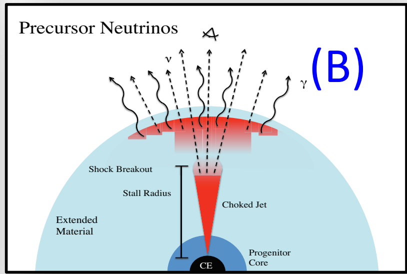
# Choked Jets and Low-Luminosity GRBs

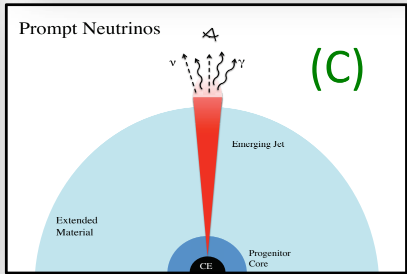
- Choked jets sources are dark in GeV-TeV gamma rays, so only neutrino are predicted

N. Senno, K. Murase, P. Meszaros (arxiv: 1512.08513)



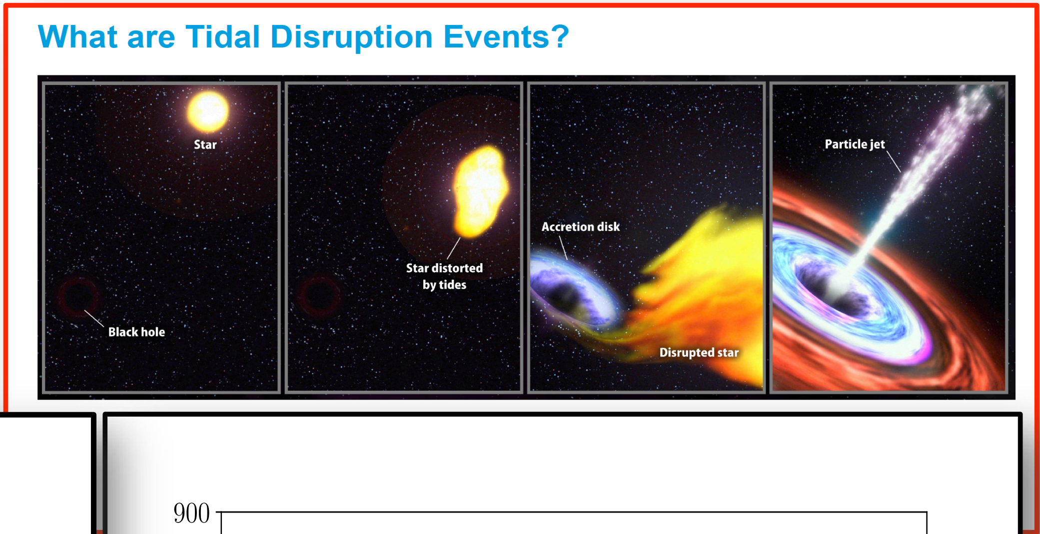



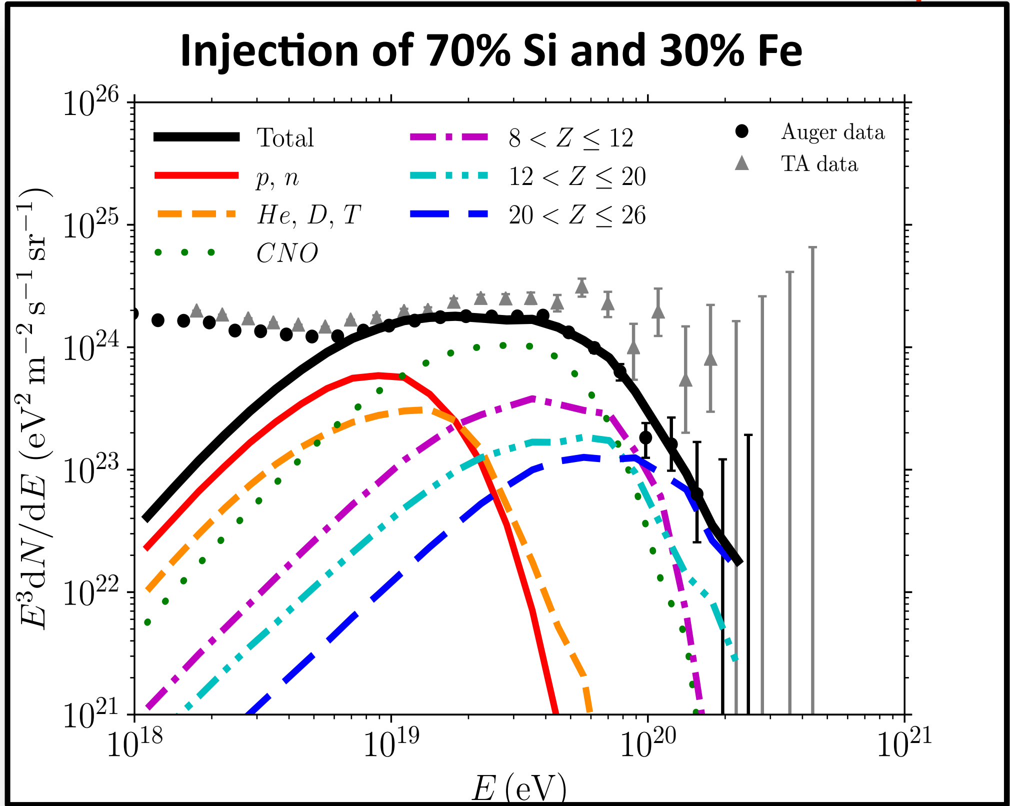

> Tidal disruption jets (TDEs) of supermasive black holes ➔hidden neutrino sources ➔ can also explain IceCube neutrinos, but again dark in GeV-TeV γ-rays (arxiv:1512.08596)

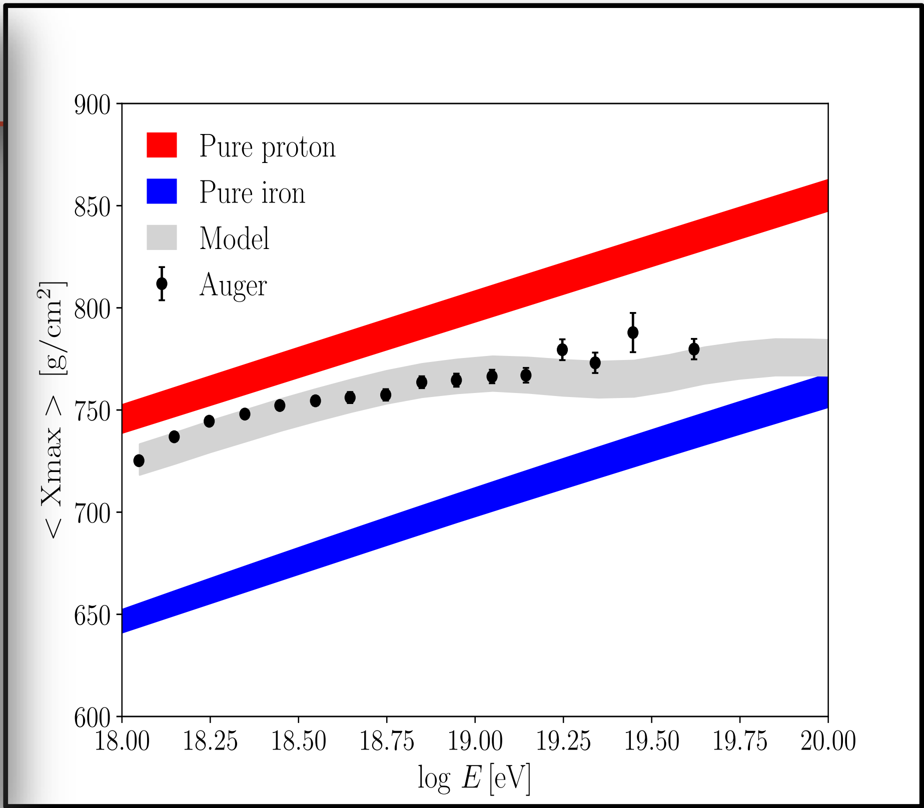
# UHECRs and neutrinos from Tidal Disruptions by Massive Black Holes

> *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



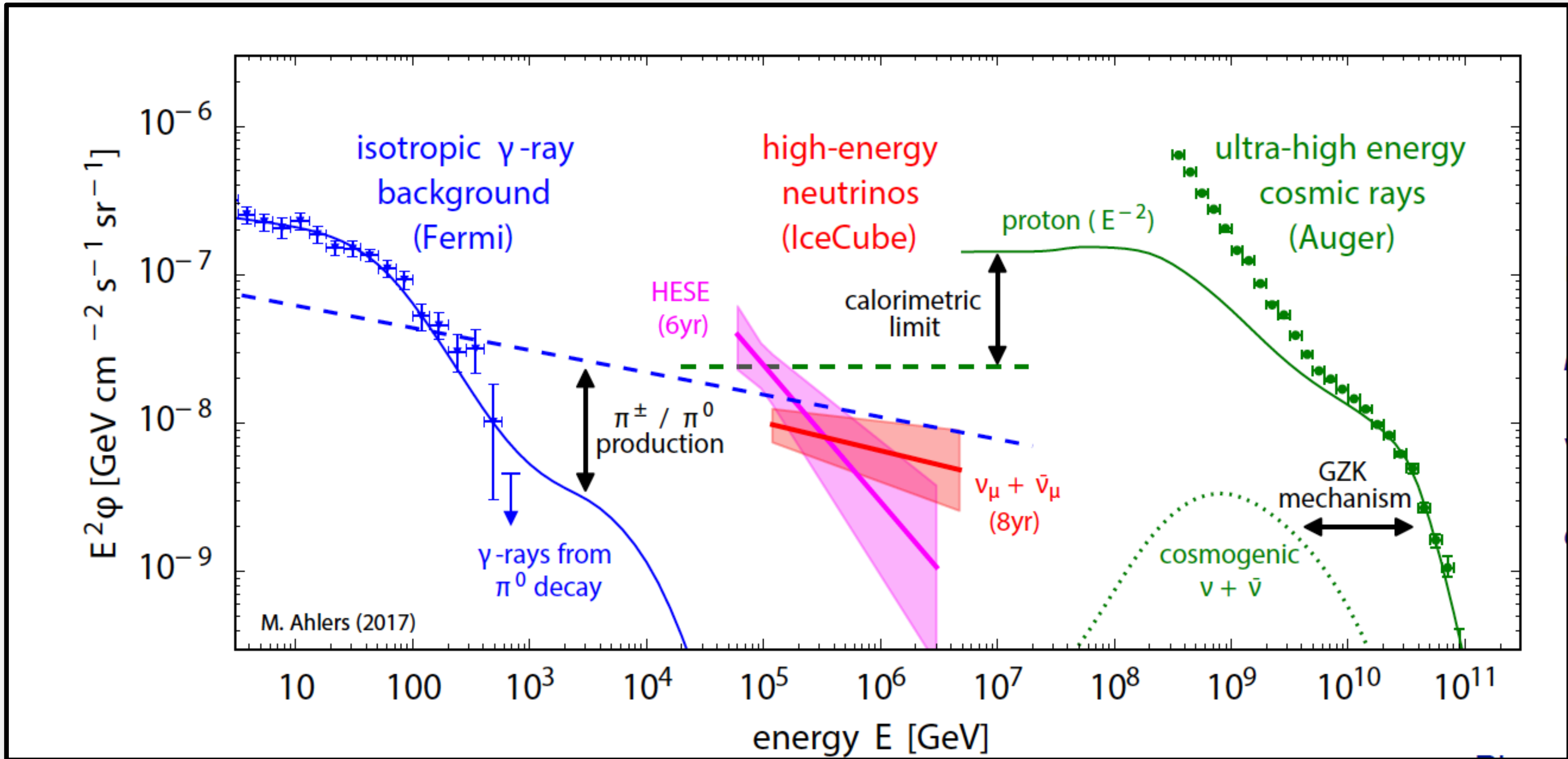




C. Guépin et al. A&A 616, A179 (2018)

See more for Auger mass composition in J. Stasielak talk

# 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

$$\rho_{\mathrm{decade}} = \int_{\mathrm{decade}} E \frac{\mathrm{d}N}{\mathrm{d}\ln E}\, \mathrm{d}\ln E$$

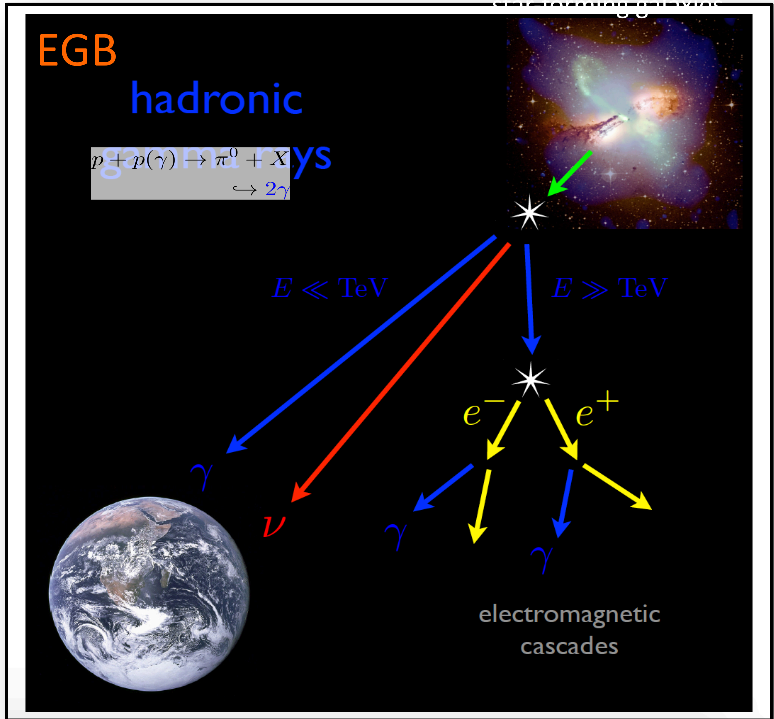
→ This may indicate a common origin of these signals, which provides excellent conditions for multi-messenger studies

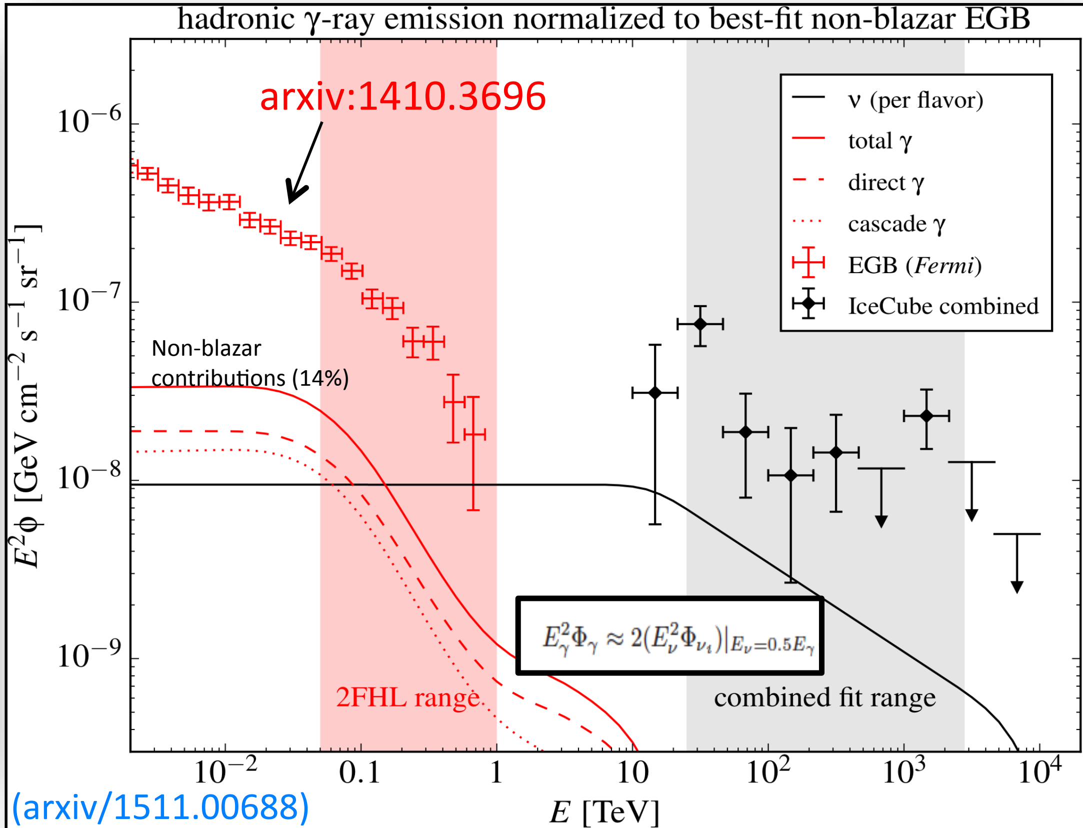
# Extragalactic gamma-ray Background (EGB)

> 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

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



(arxiv/1511.00688)

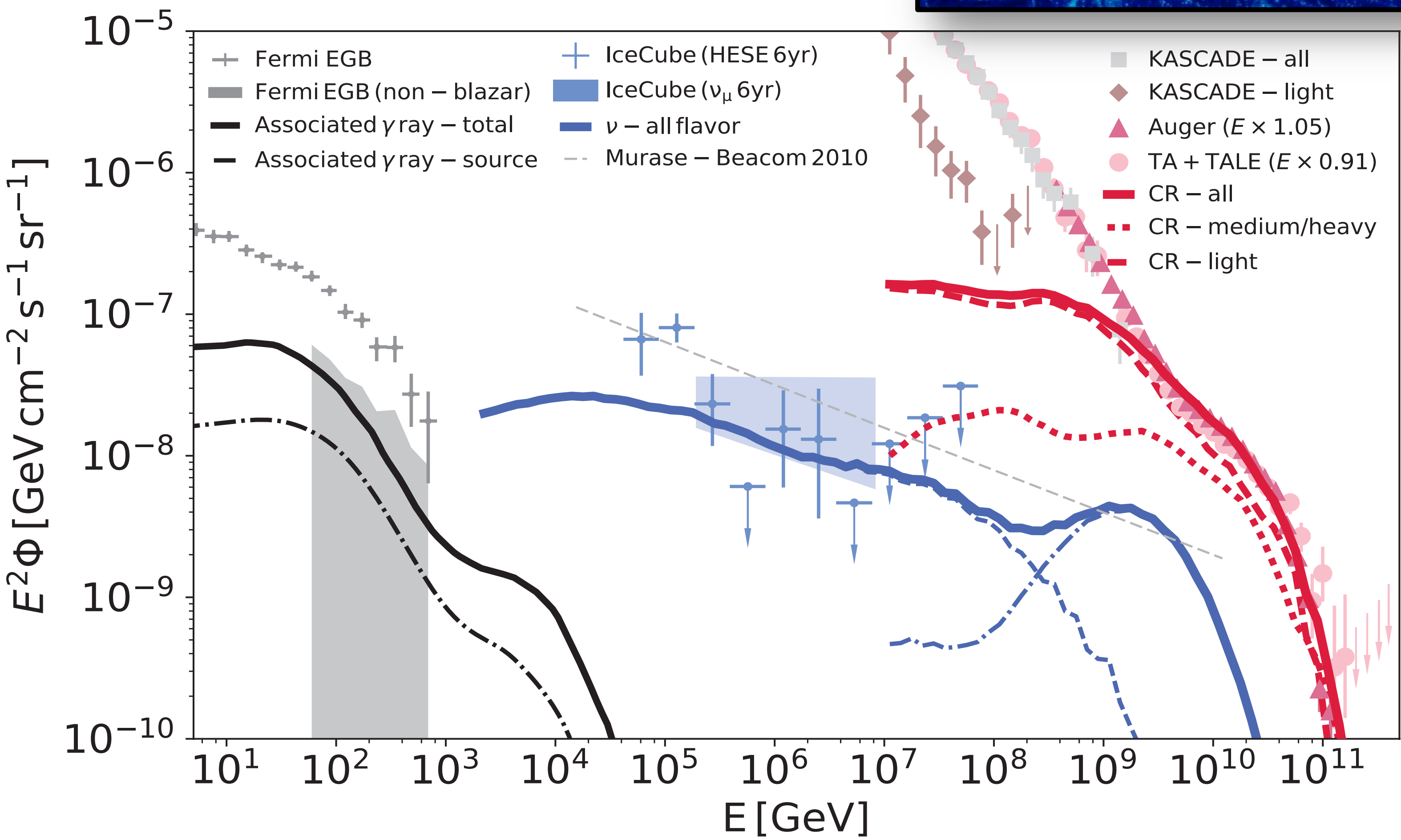
pp model -> Γ< 2.1 - 2.2

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

> 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)

# 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