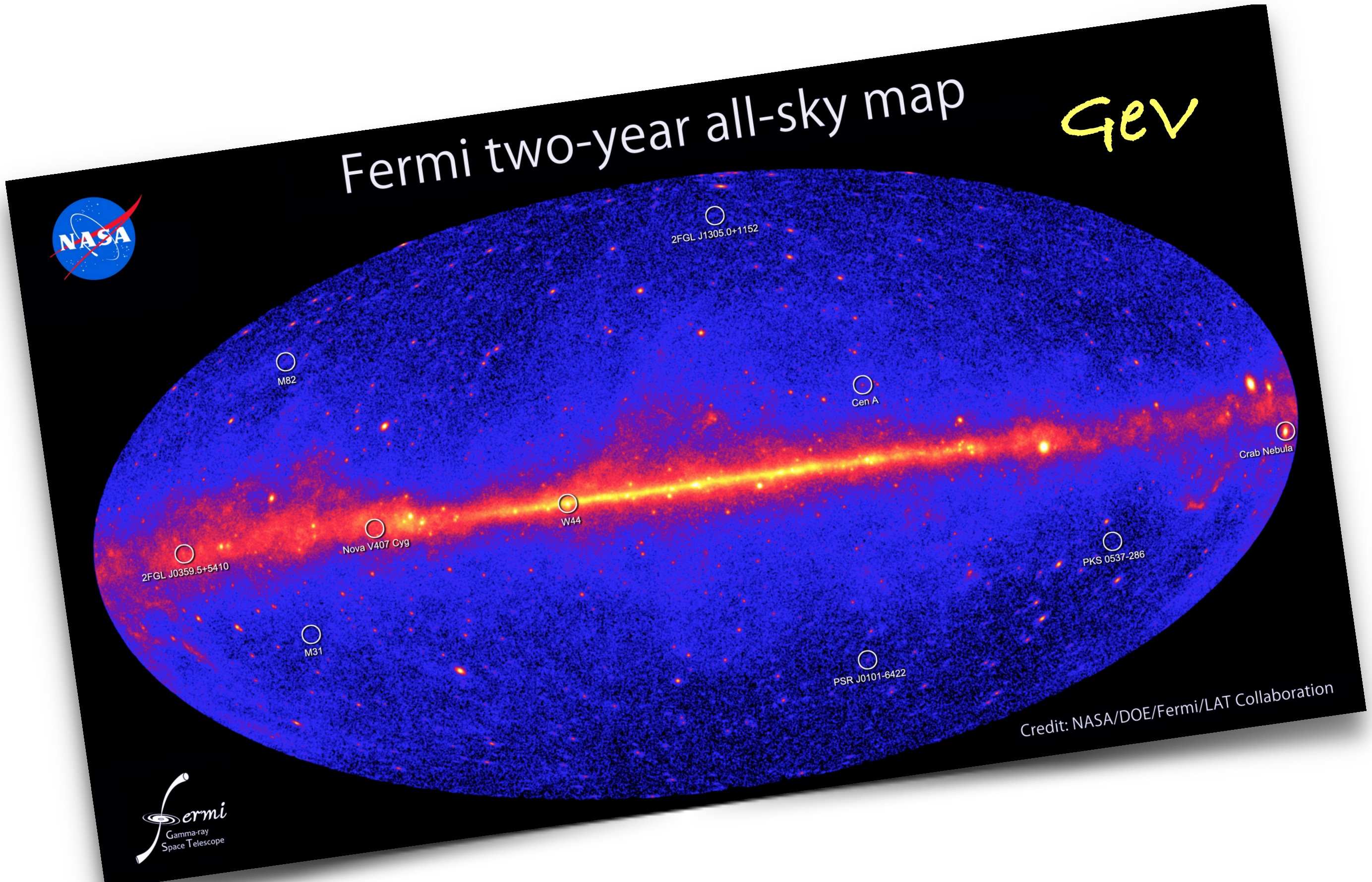
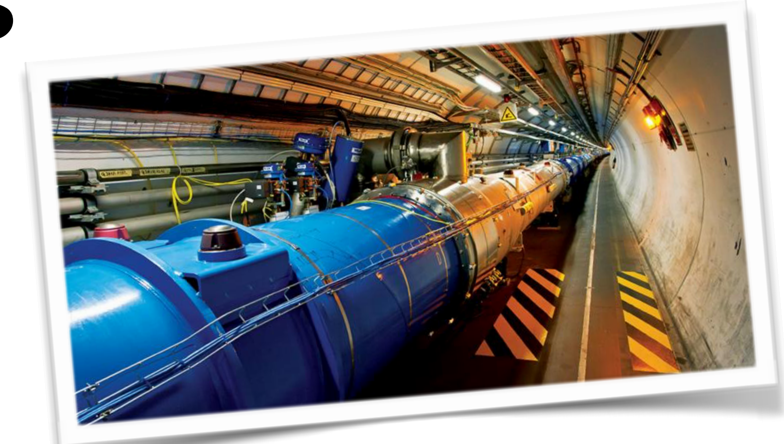
High-energy neutrinos from blazars

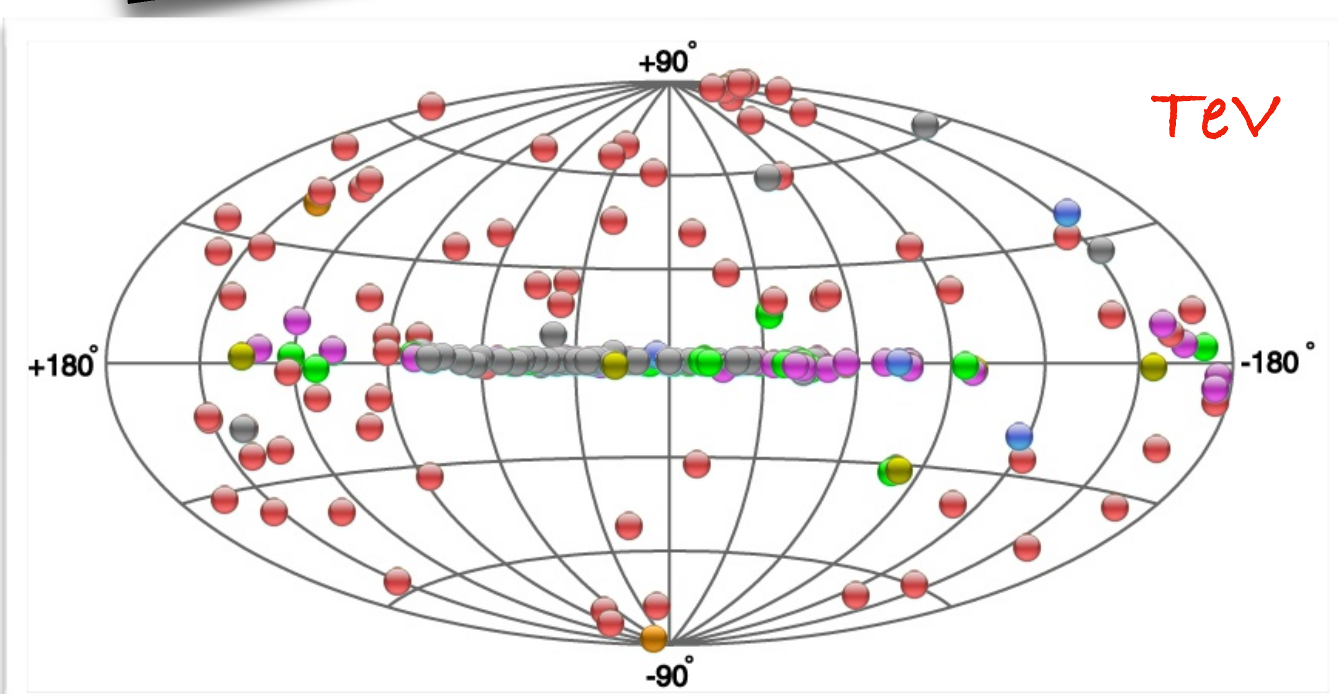
Fabrizio Tavecchio
INAF-OAB

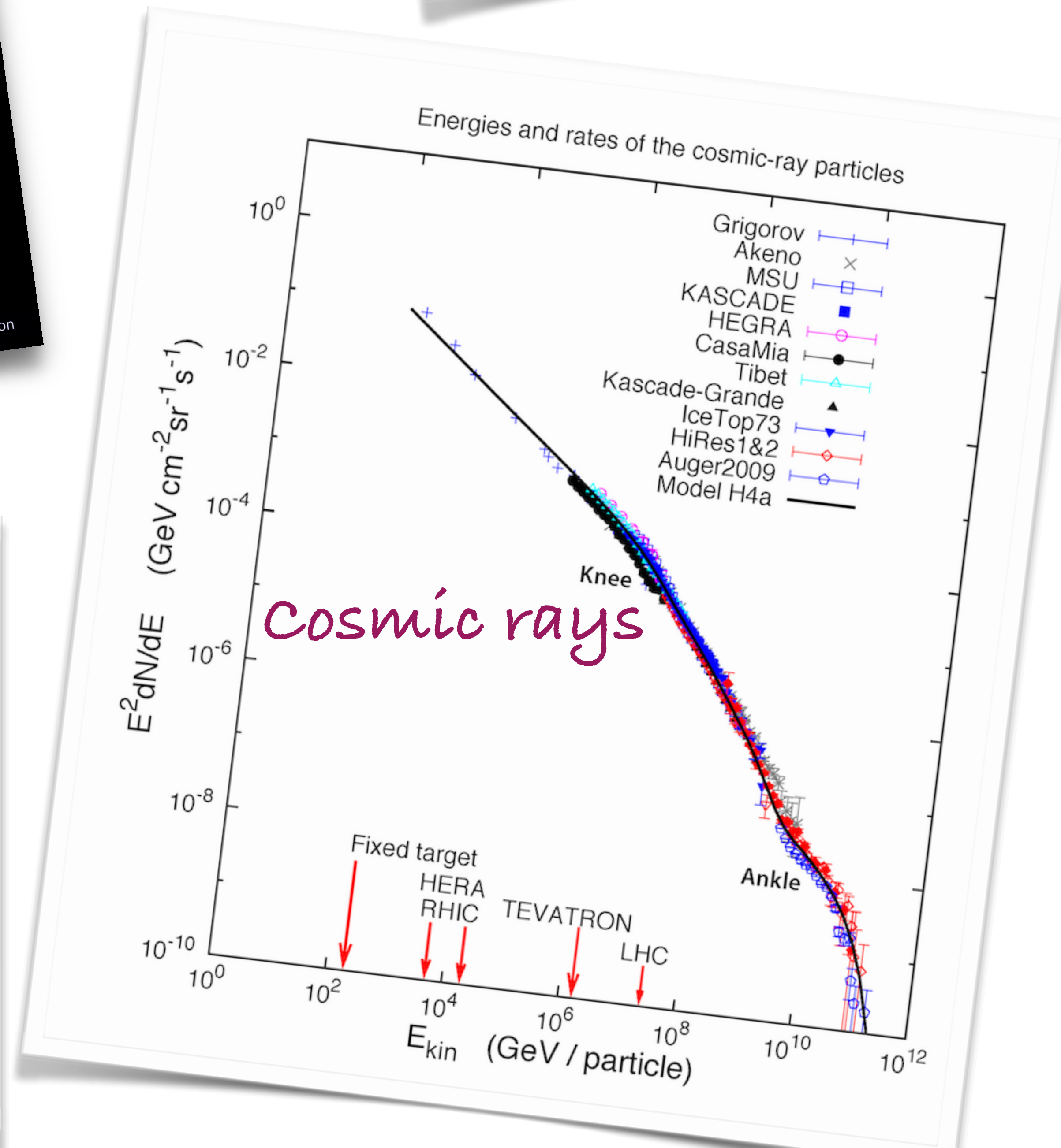
Active Galactic Nuclei 13
BEAUTY and the BEAST
...when the Super Massive Black Hole ...
has a crush on the galaxy

Cosmic accelerators









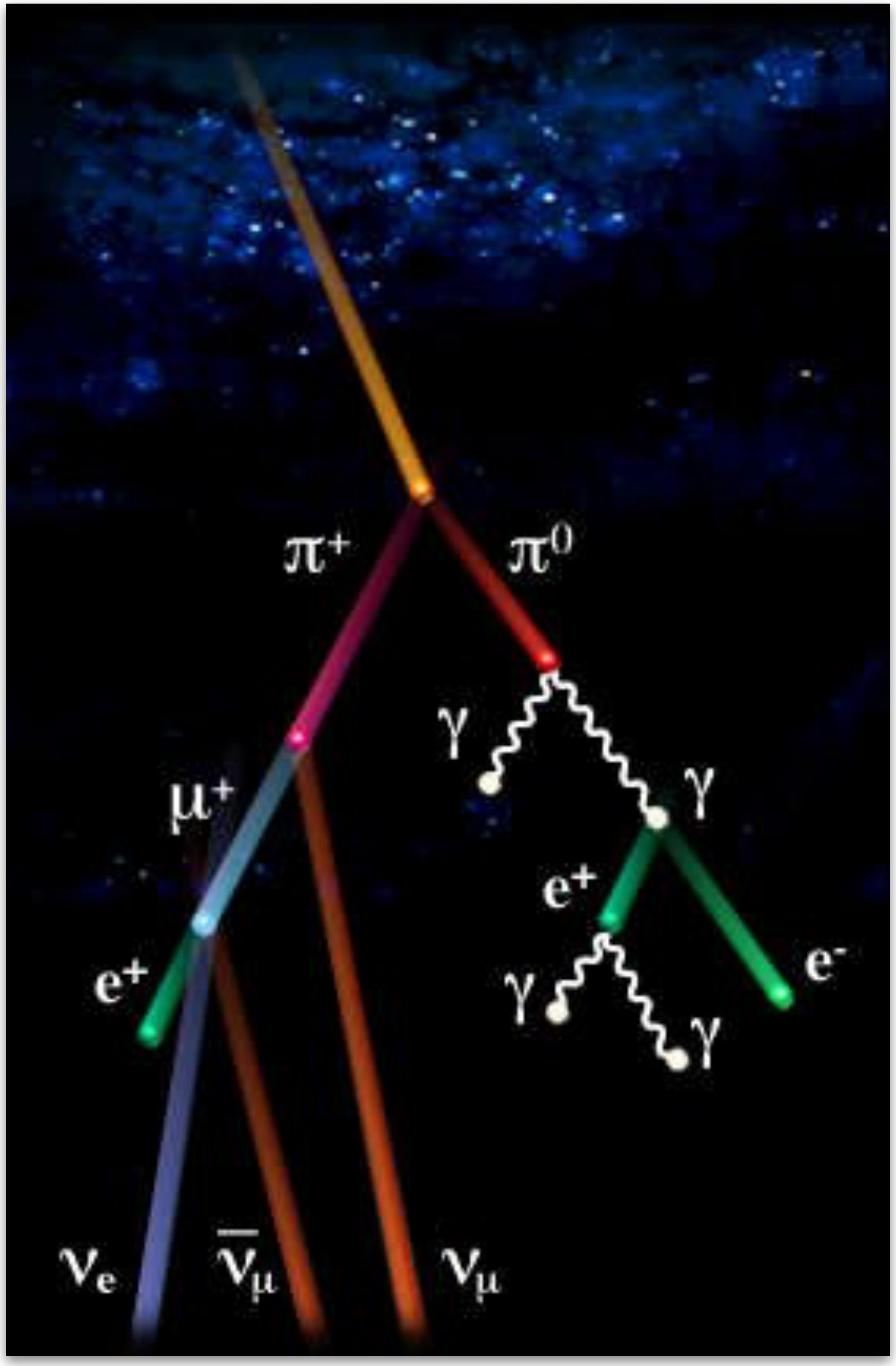
HE neutrinos: probes of extreme accelerators

Ingredients:

high-energy protons (nuclei)

+

Targets: matter, photons



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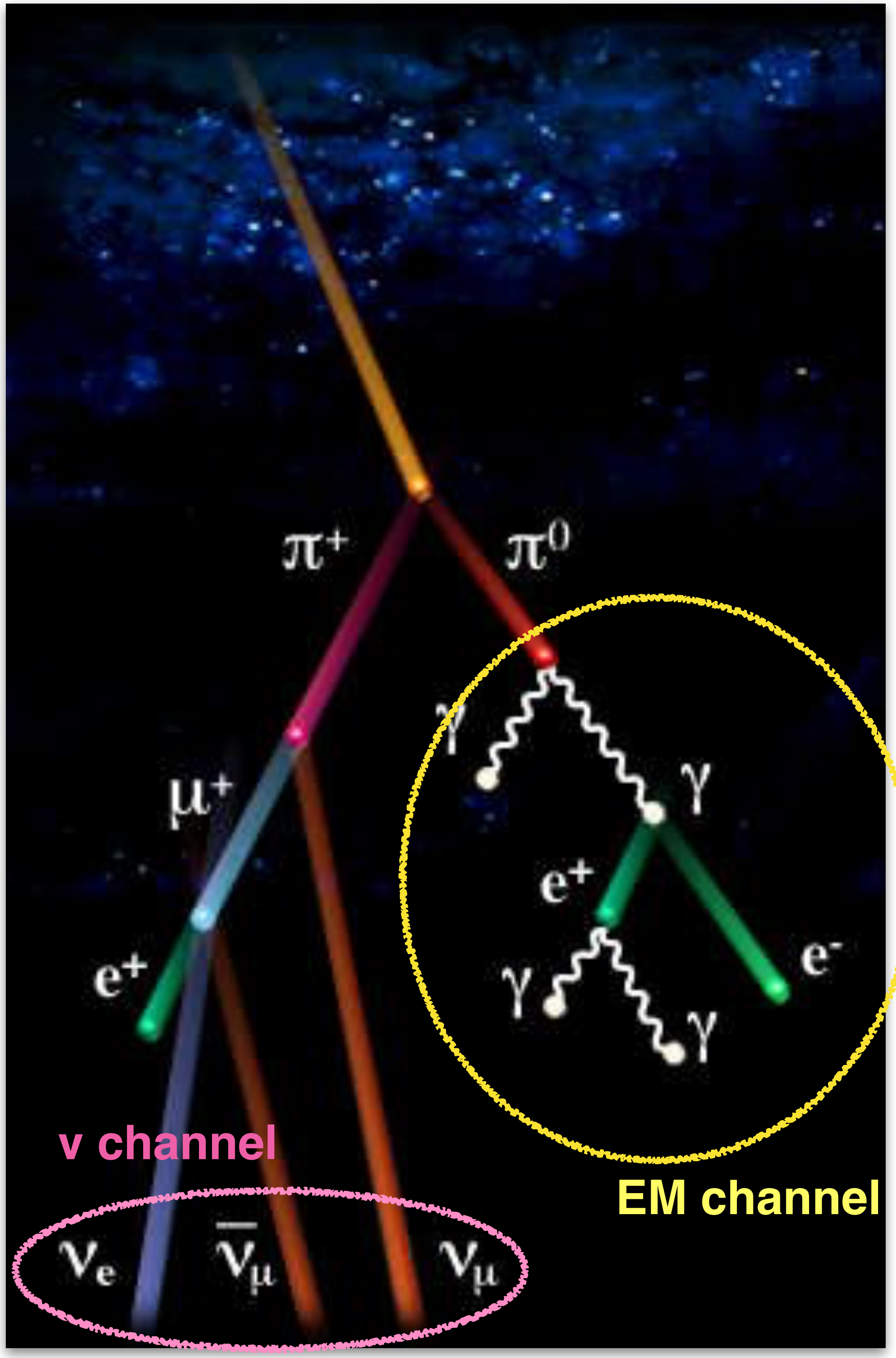
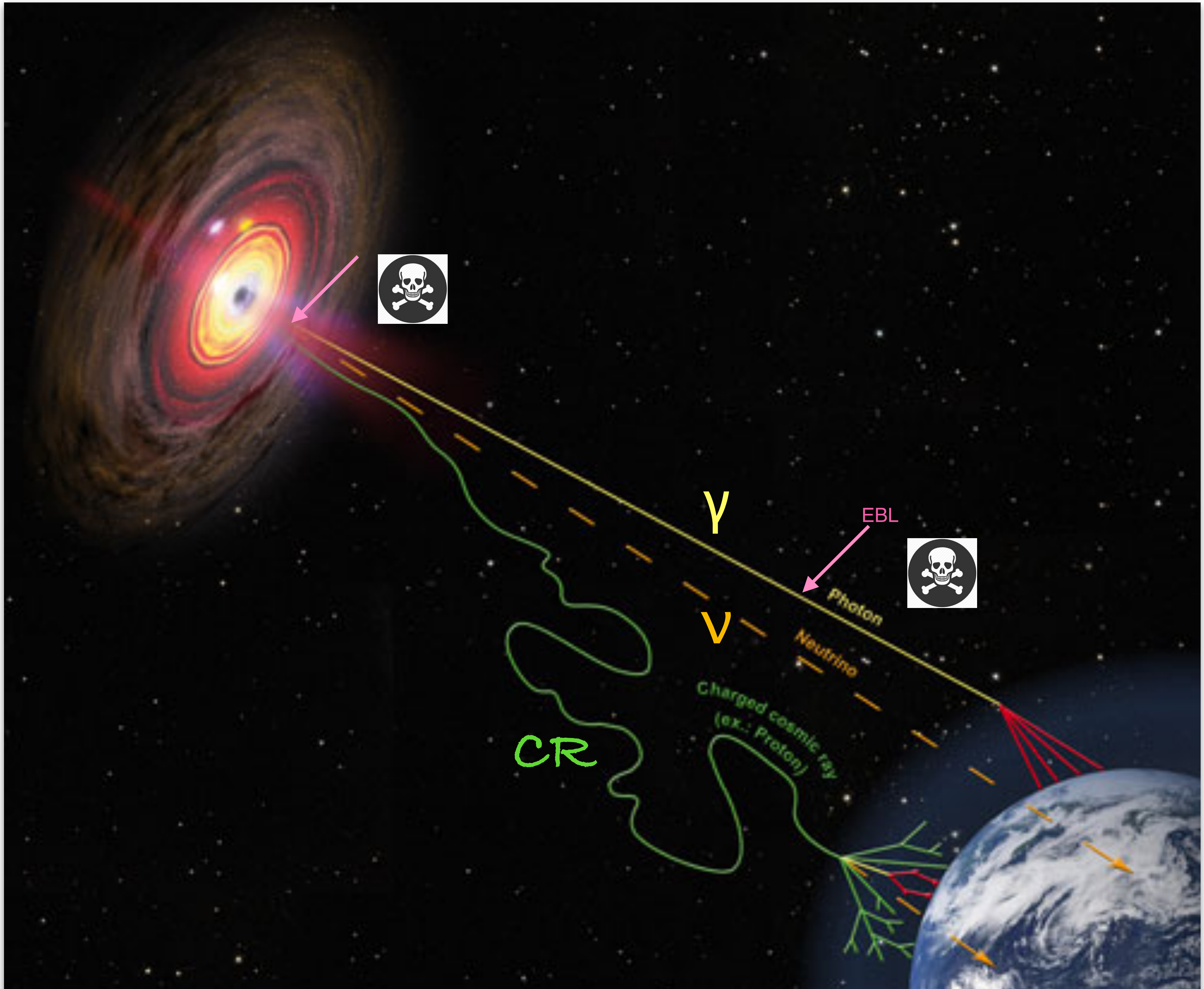


→ Tracers of very-high energy cosmic ray acceleration (and propagation)

HE neutrinos: probes of extreme accelerators



Astrophysical production in a nutshell

proton-proton (pp)

$$p + p \to \pi + X$$

proton-photon (pγ)

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \bar{\nu_e} + \bar{\nu_\mu} + \nu_\mu$$

$$p + \gamma \to n + \pi^+$$

$$\pi^0 \to 2\gamma$$

$$p + \gamma \to p + \pi^0$$

Astrophysical production in a nutshell

proton-photon (pγ)

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

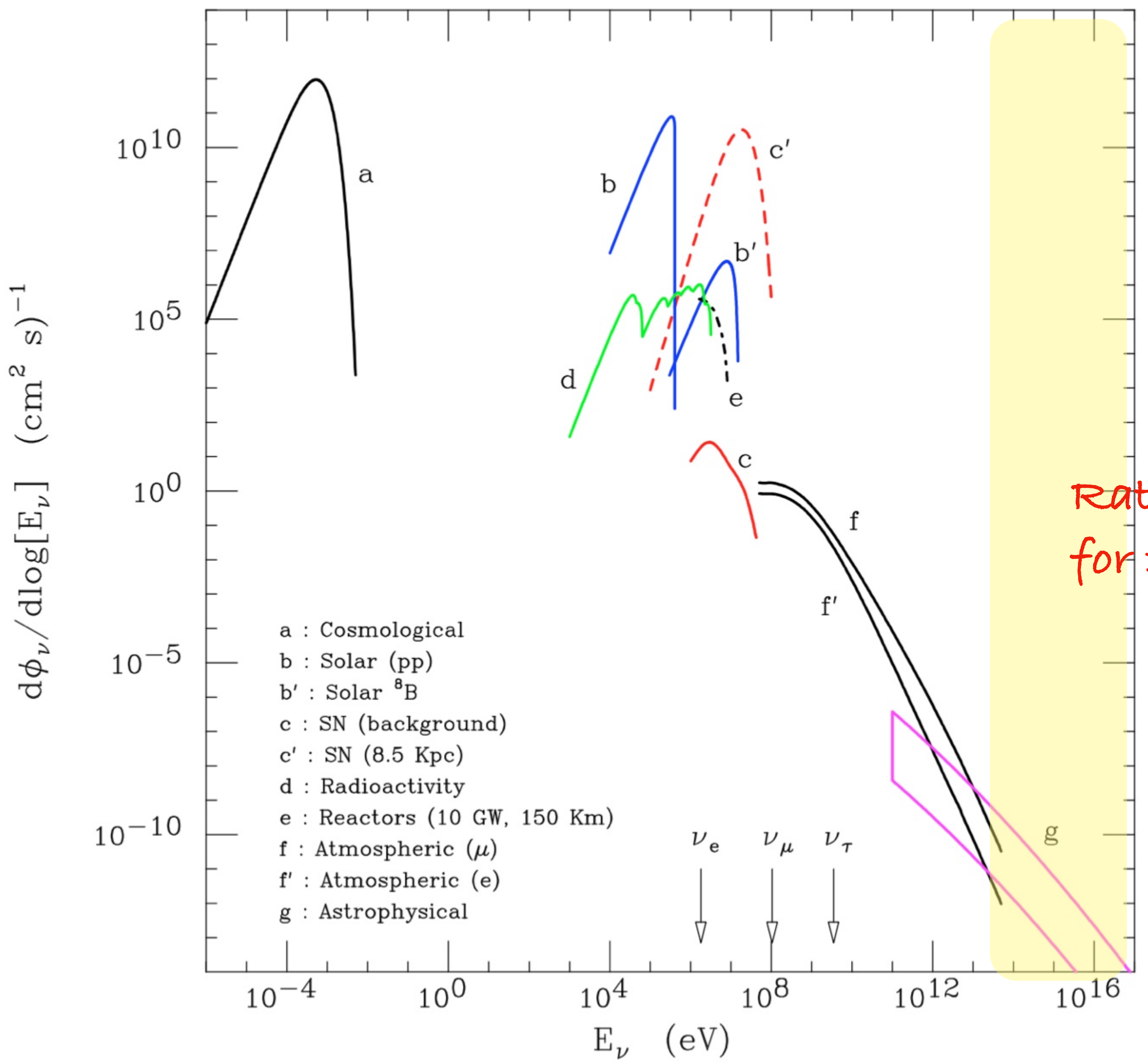
$$p + \gamma \rightarrow p + \pi^0$$

$$E_{\rm th} = \frac{2m_p m_\pi + m_\pi^2}{4\epsilon} \simeq 7 \times 10^{16} \left(\frac{\epsilon}{\rm eV}\right)^{-1} \rm eV$$

Ep~20 Ev

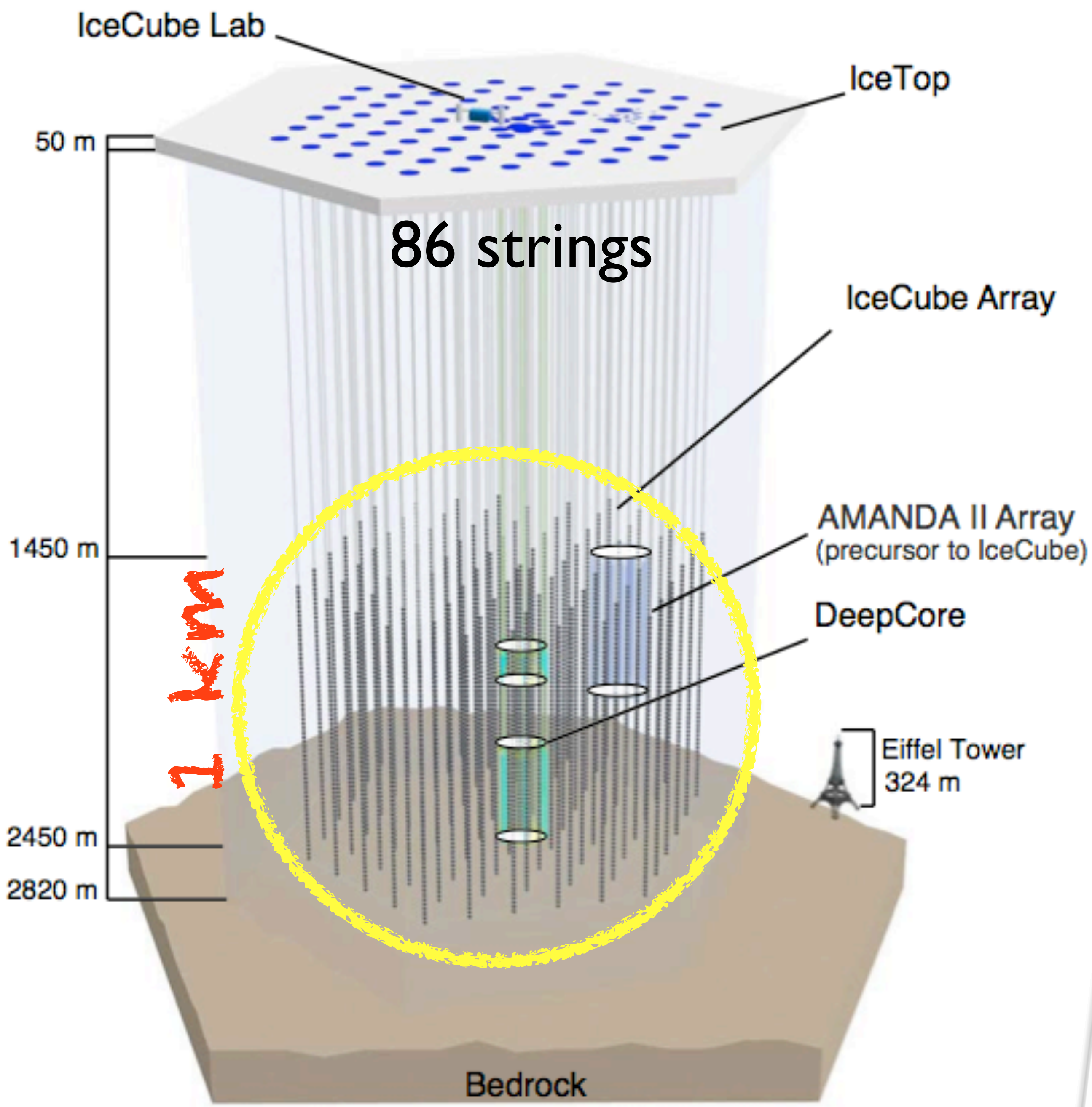
Lγ~Lν

E> 100 TeV



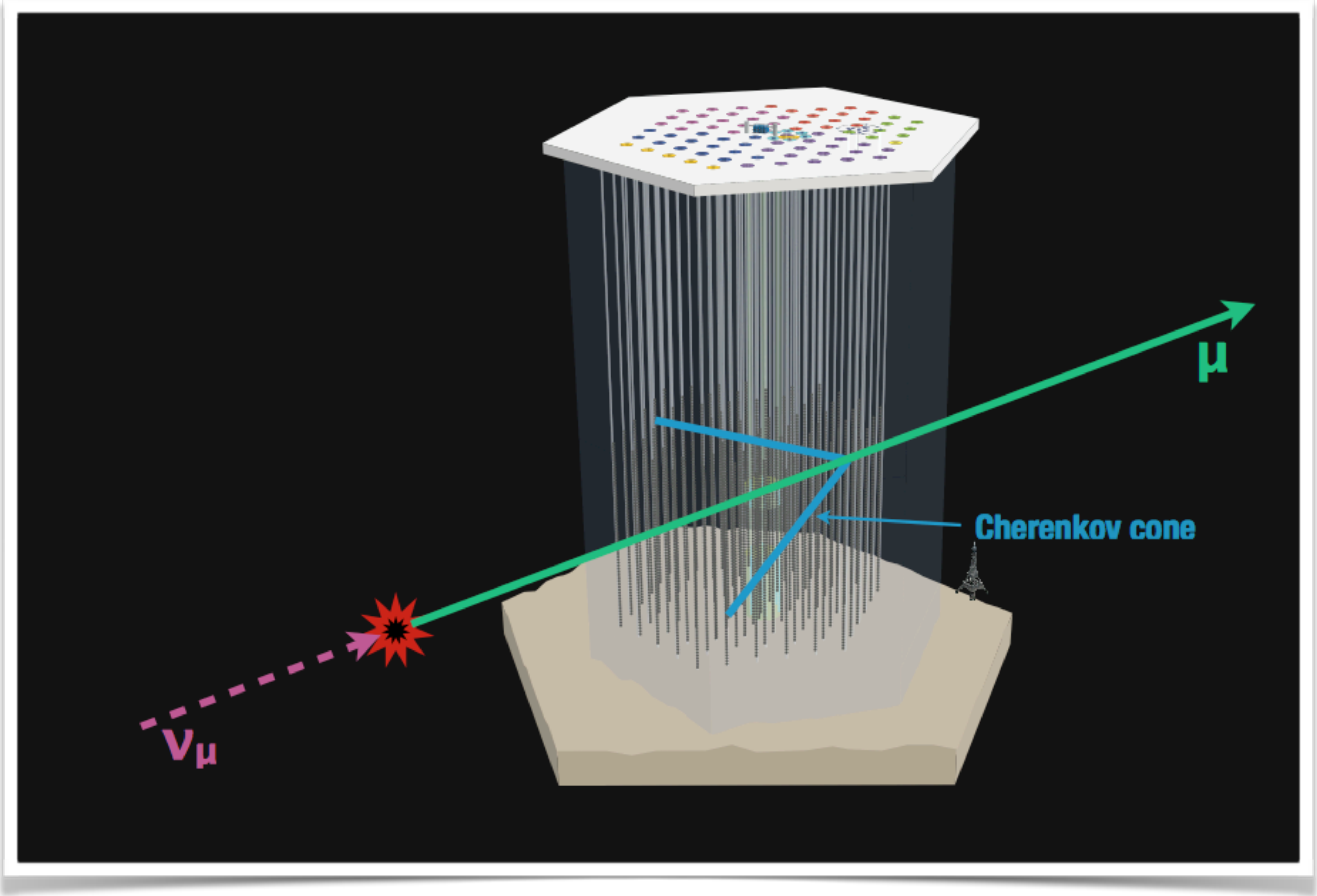
Rate~few tens/y
for 1km3

IceCube



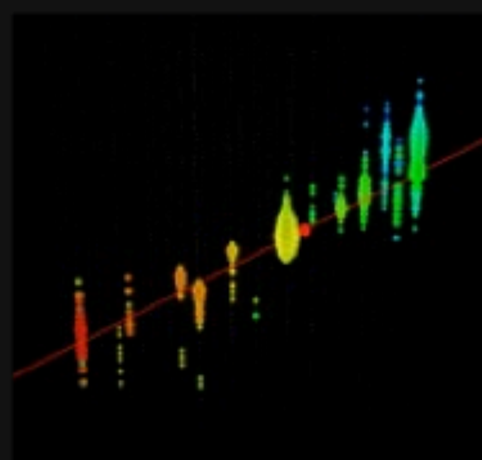
@ South Pole
(Amundsen-Scott)

IceCube



IceCube

CC Muon Neutrino

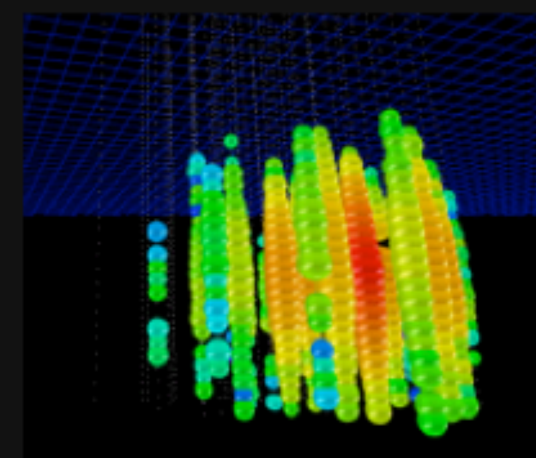


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



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

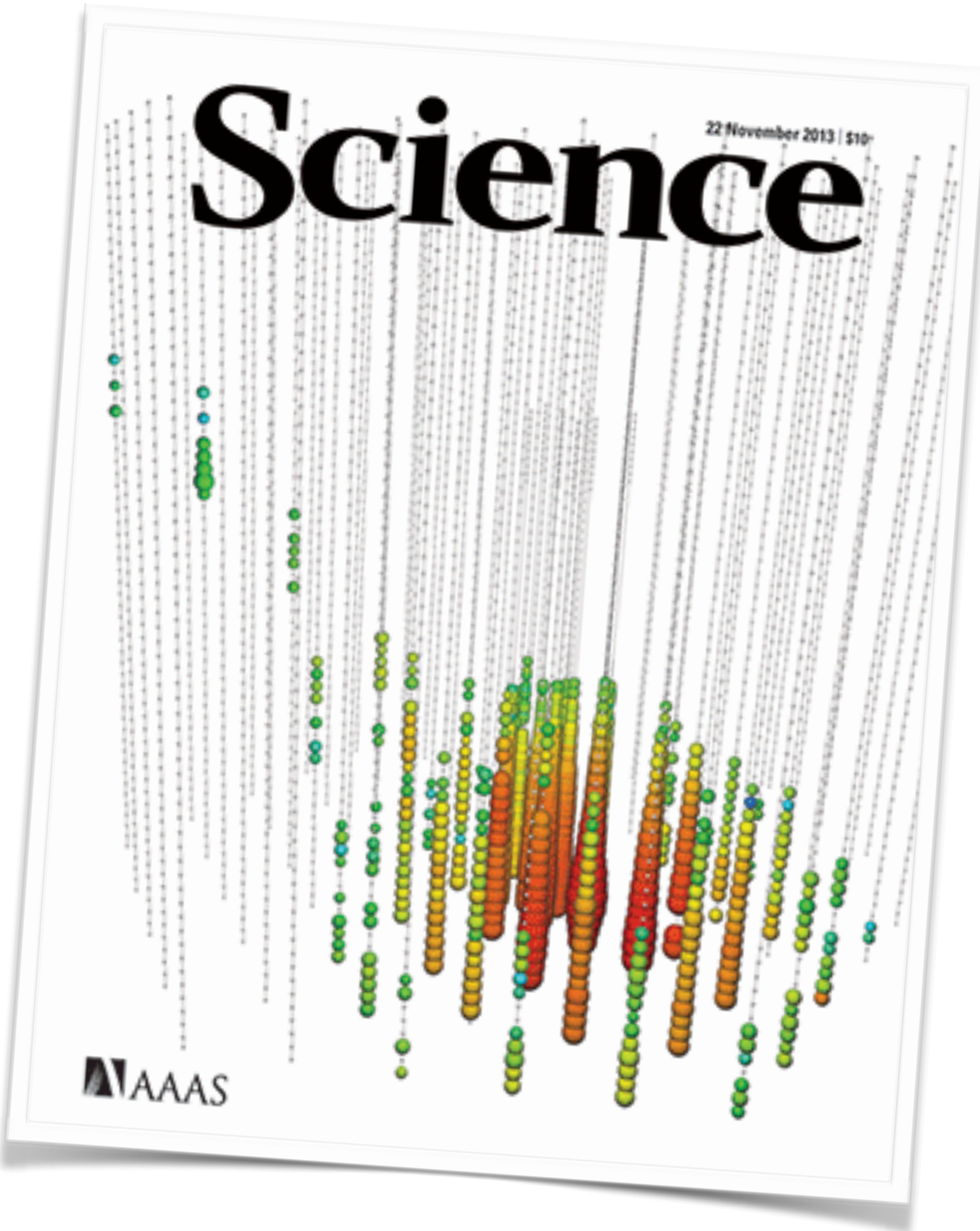
$$\nu_x + N \rightarrow \nu_x + X$$

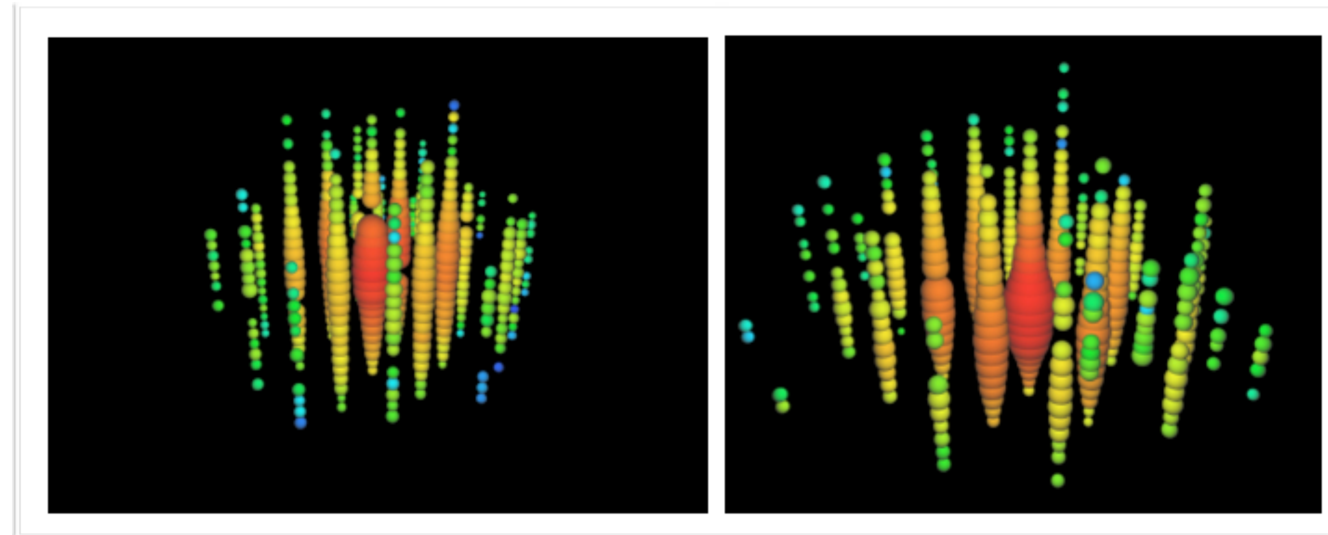
cascade (data)

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

Kopper 2014

Discovery of high-energy neutrinos



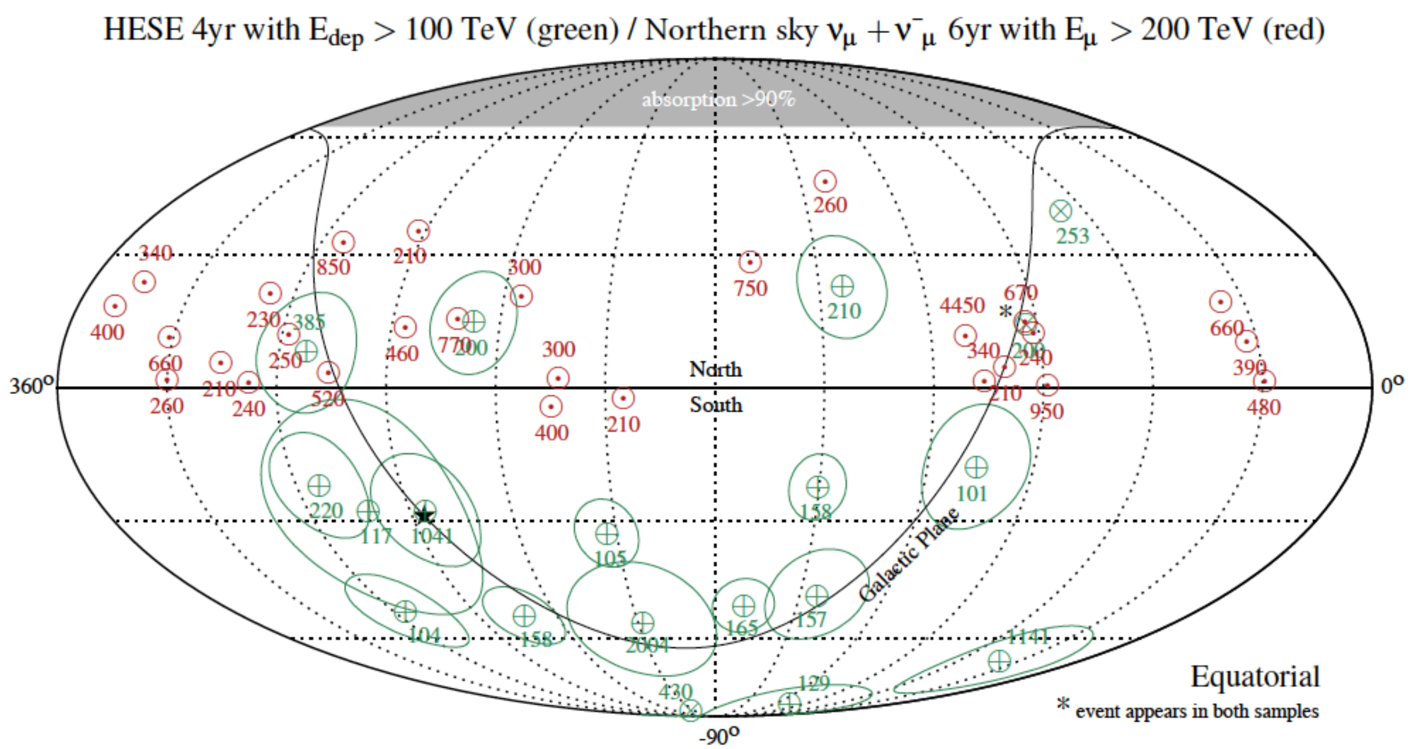


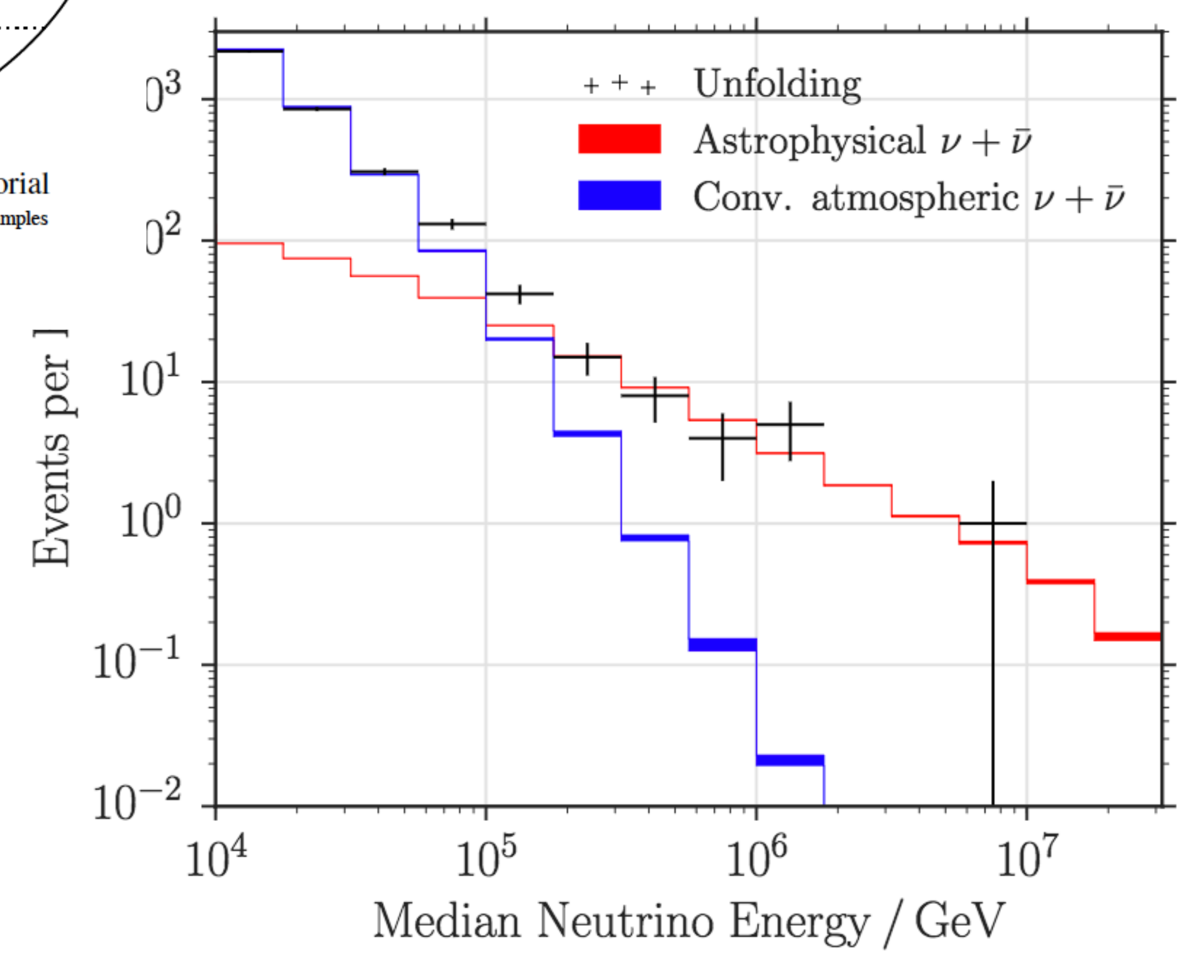
28 events (21 shower)
May 2010-May 2012

First evidence (4.3 sigma) of HE extraterrestrial (i.e. non atmospheric) neutrinos!

Abbasi et al. 2013

Current status



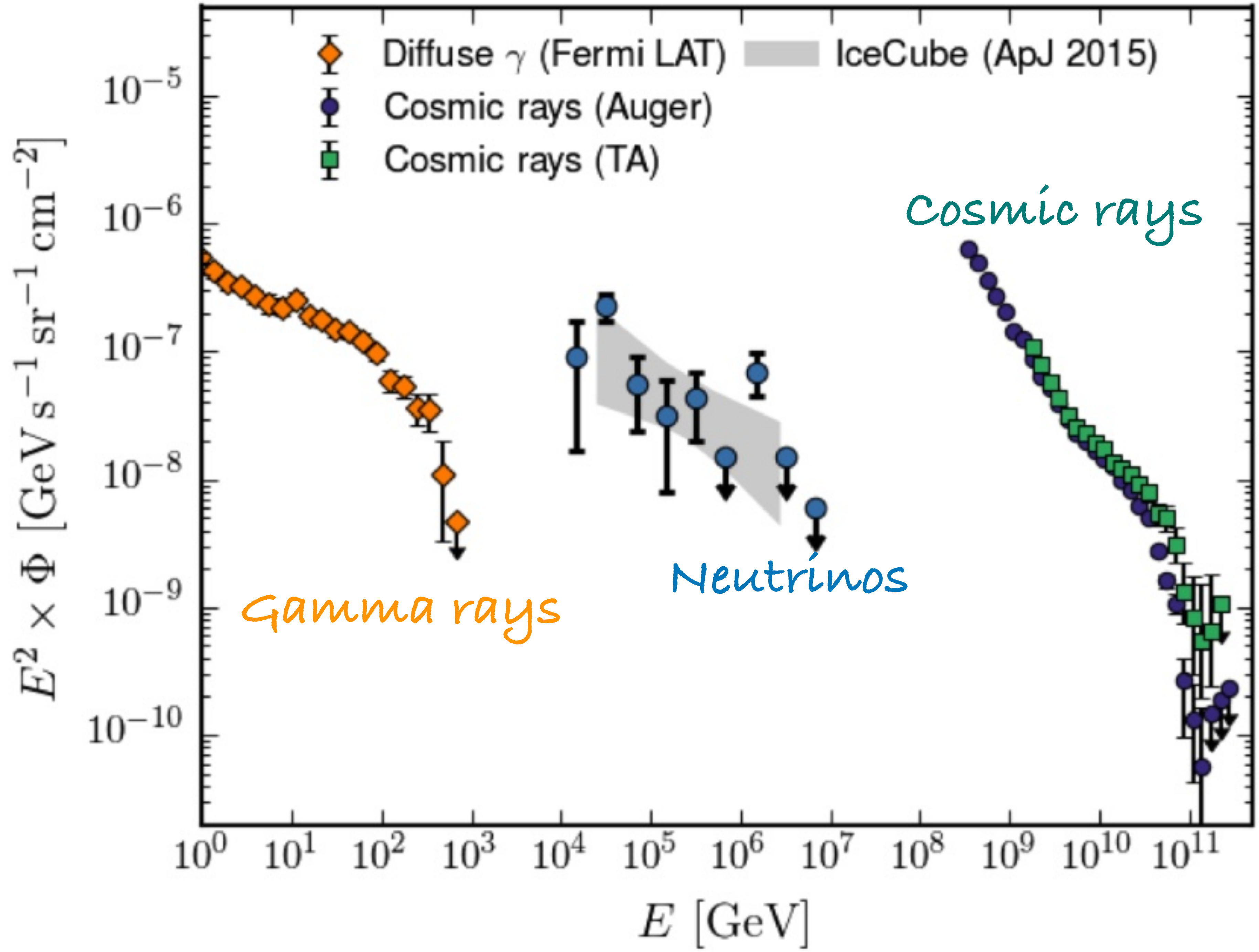


Aartsen et al. 2016

About ~60 TRACKS events

Current status

Gaisser 2018



“Multimessenger sky background”

Potential source(s)

Ingredients:

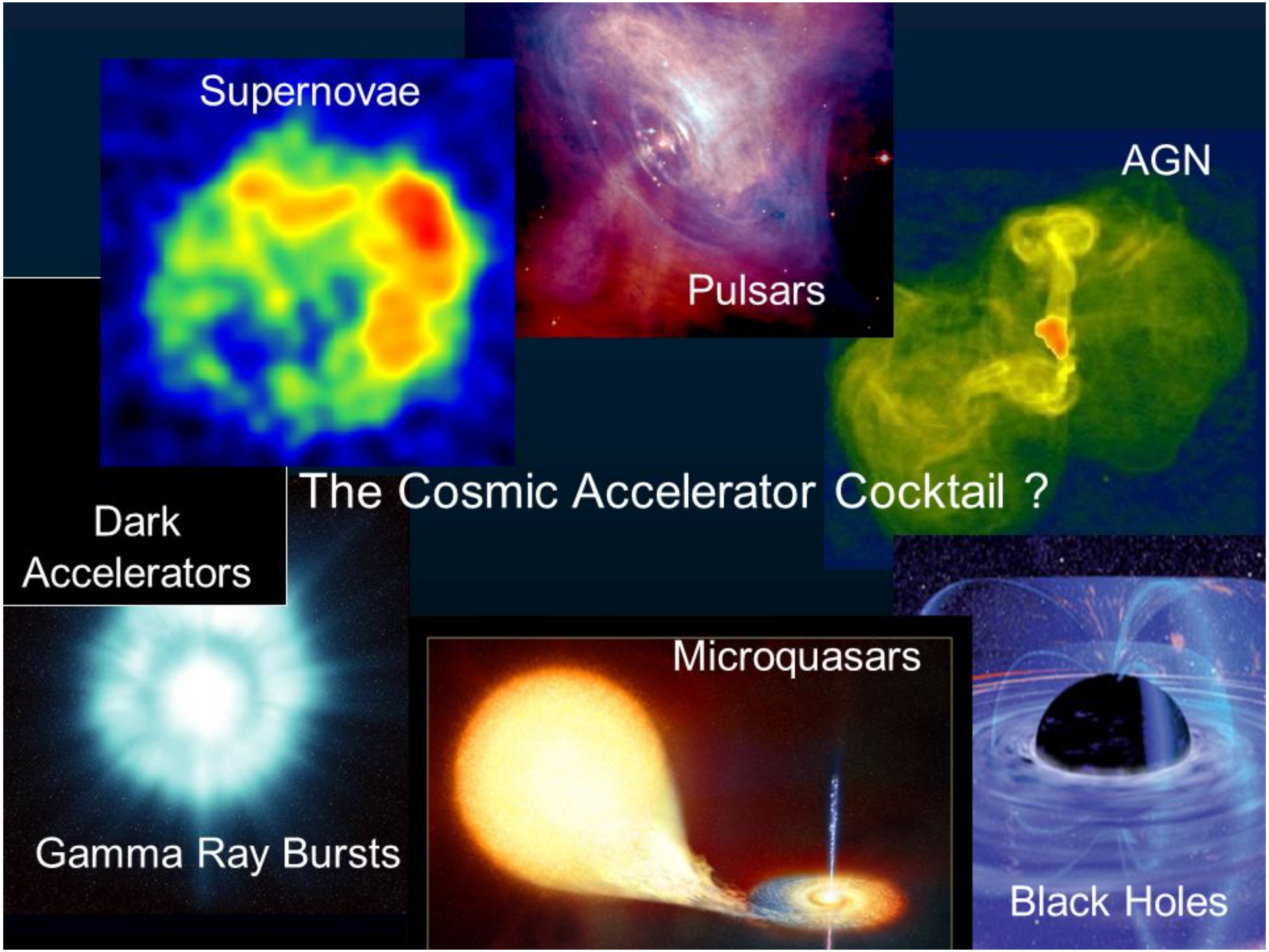
high energy protons (nuclei) → Injected luminosity, spectrum, maximum energy

+

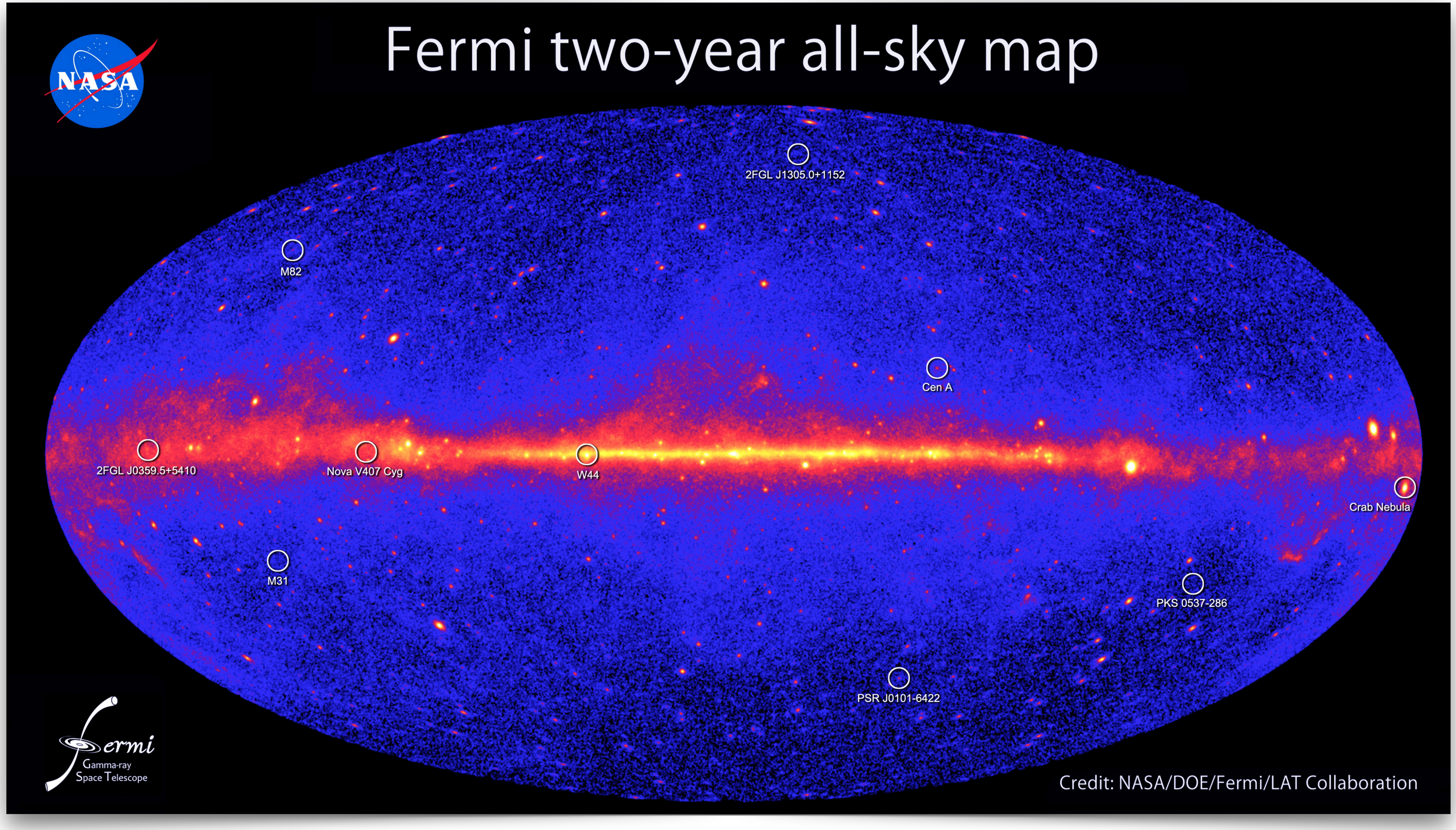
Targets: matter, photons

⇒ Candidate source: potential site of **CR** acceleration with substantial density of **matter** and/or **photons**

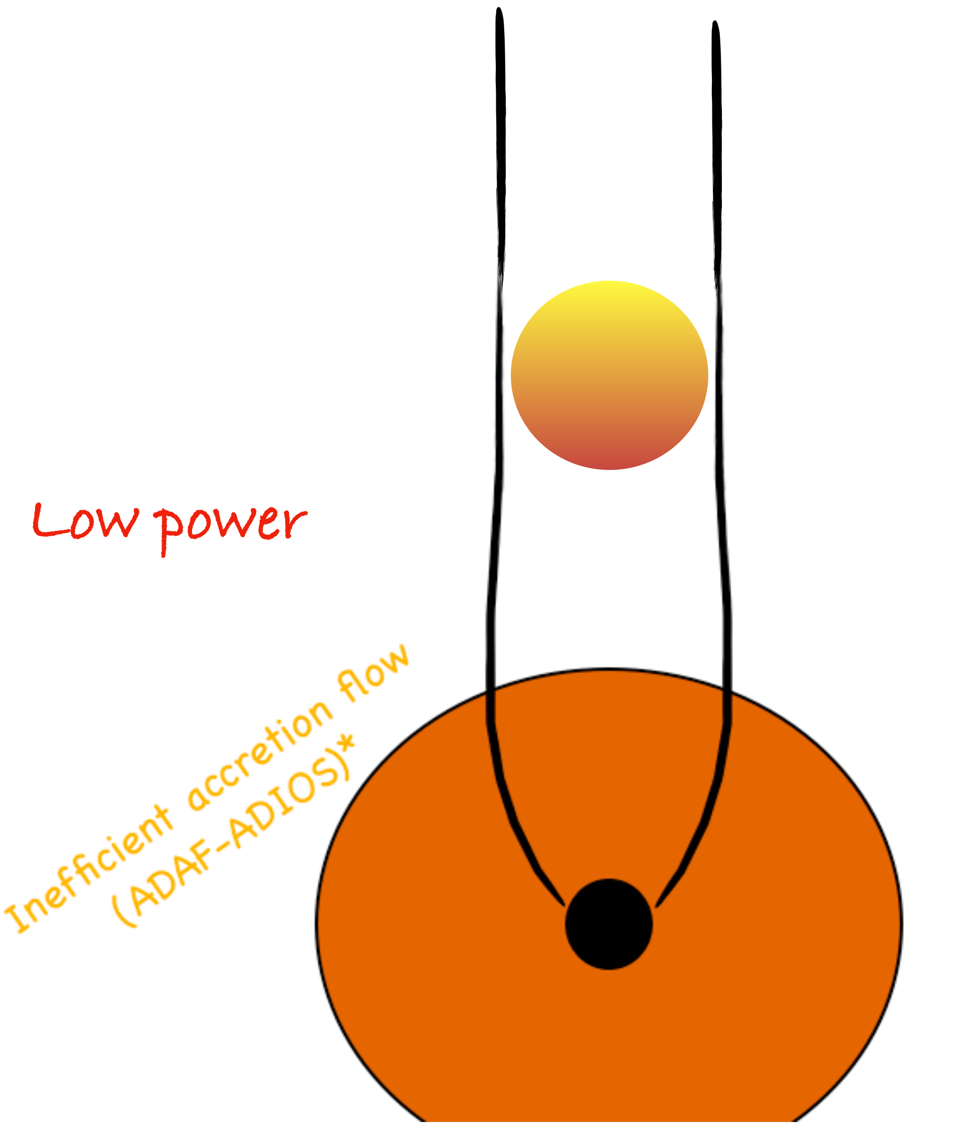
Potential source(s)



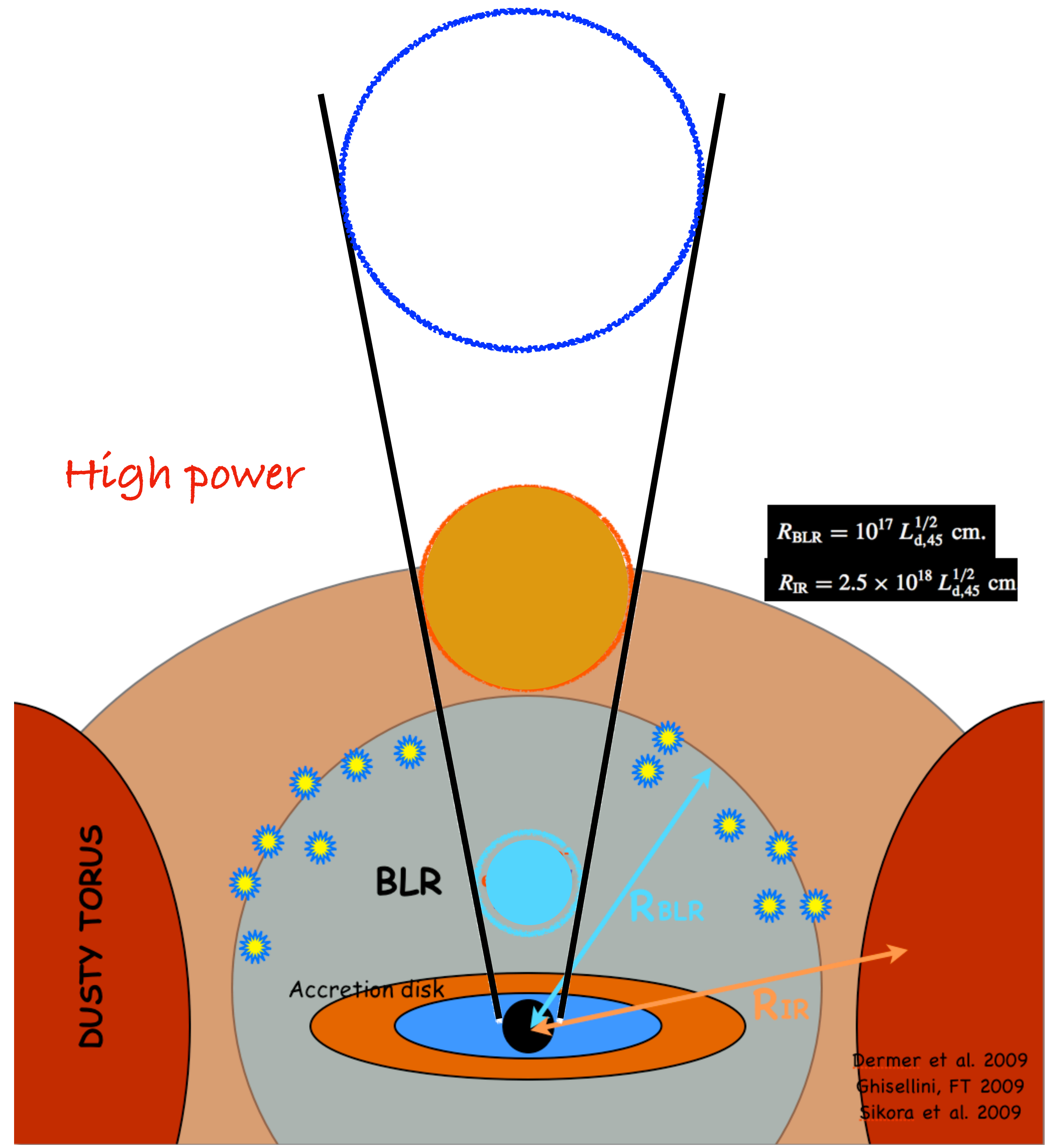
Neutrinos from blazar jets?



BL Lacs: “naked” jets

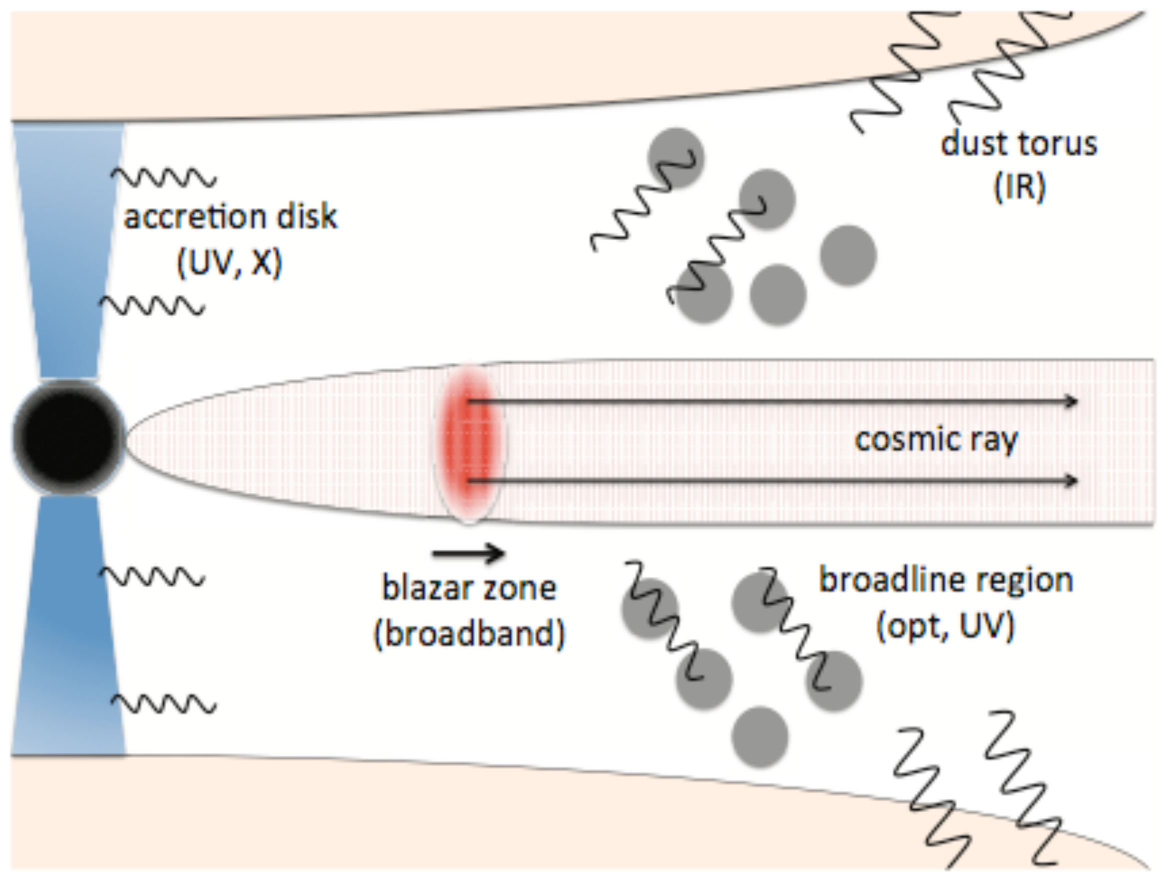


FSRQ: “dressed” jets



The prime suspects

Relativistic jets: blazars?

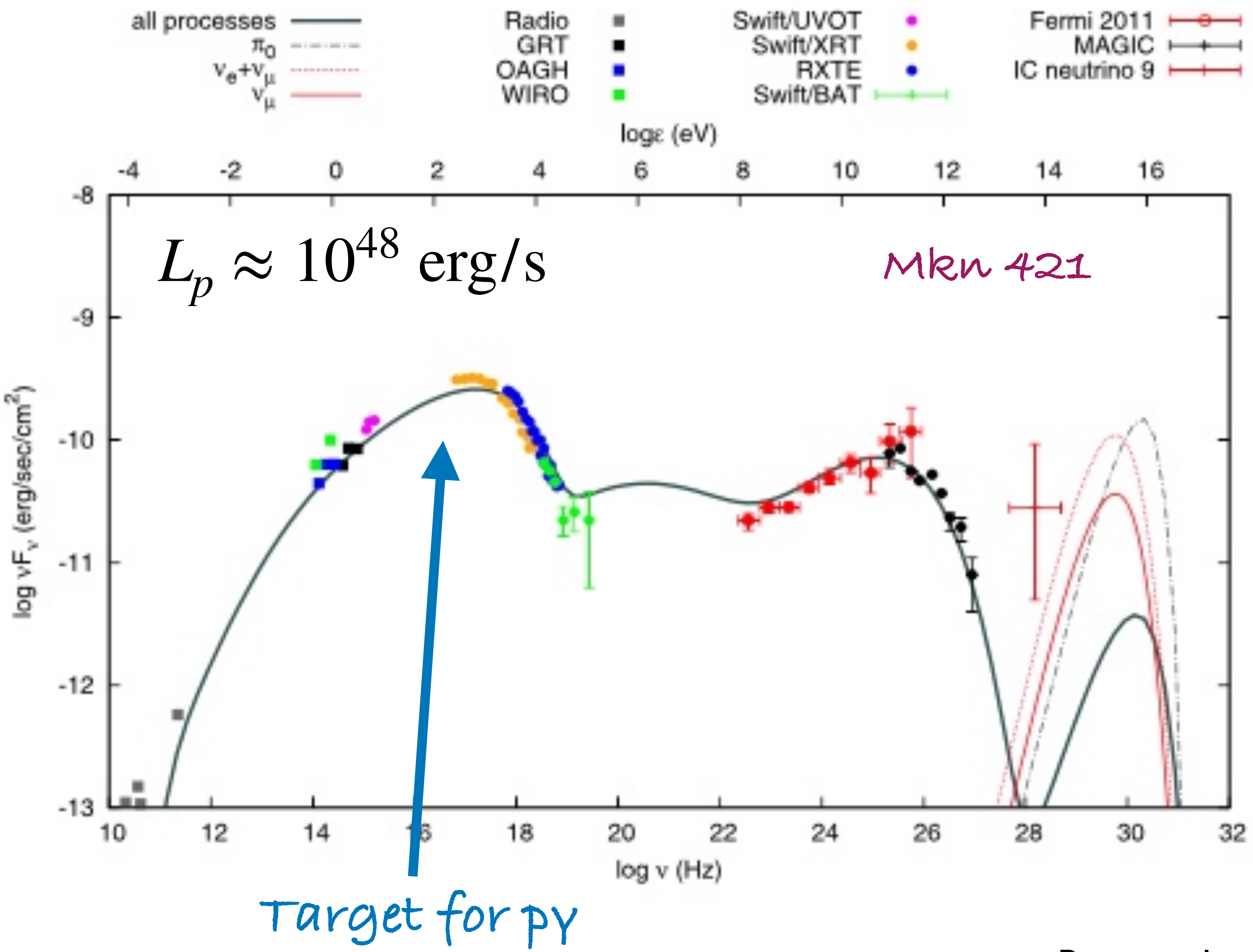


Photomeson production strongly favored

Murase, Inoue & Dermer 2014

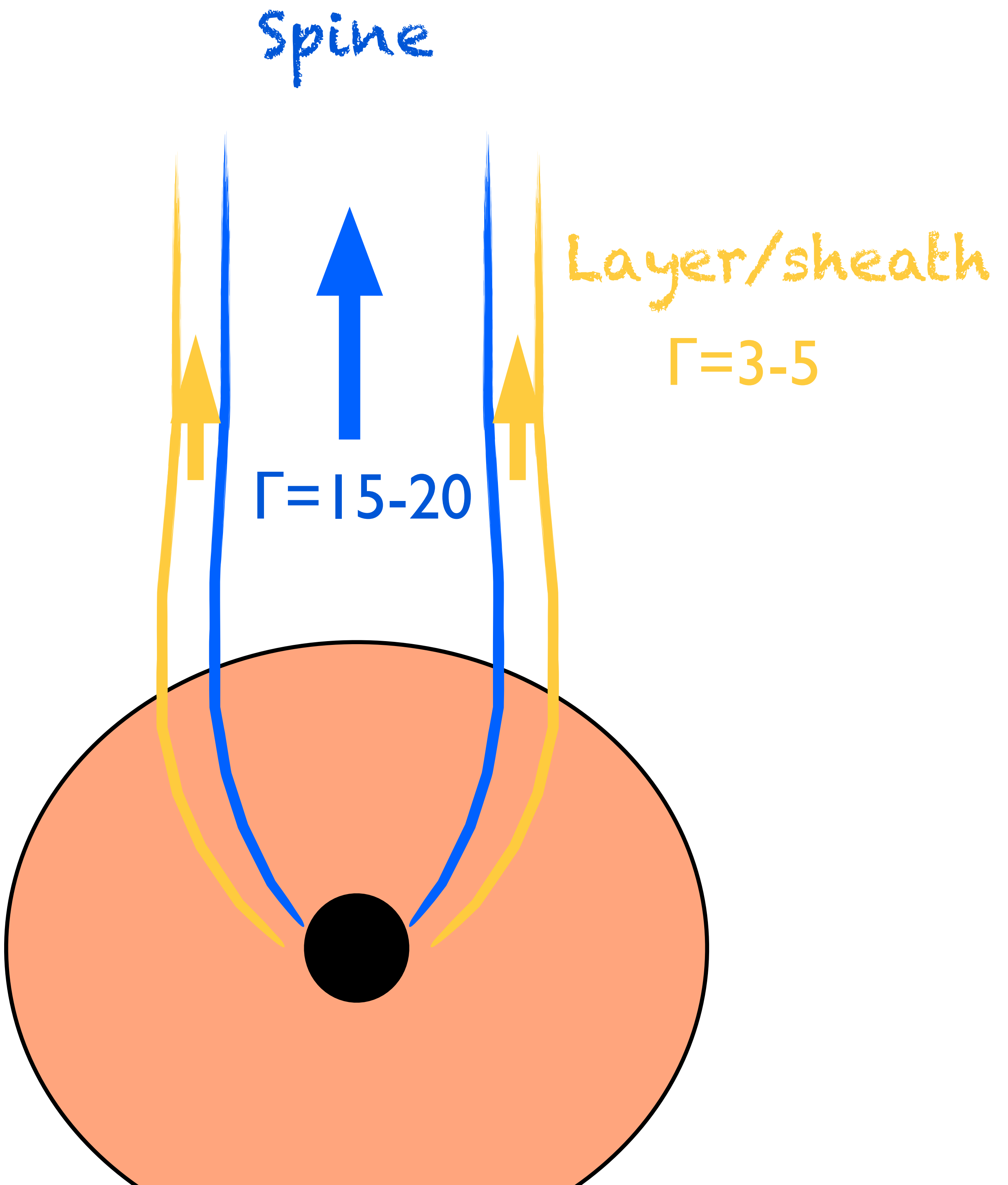
Neutrino from BL Lacs?

One-zone models



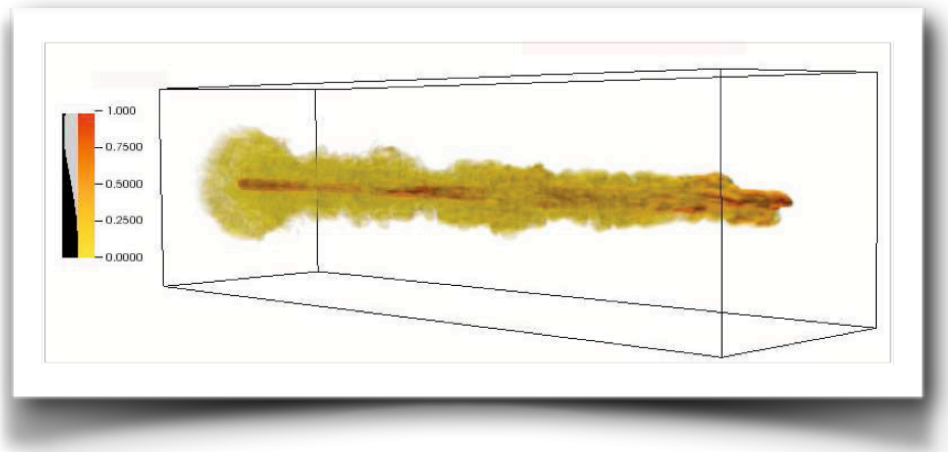
e.g., Petropoulou et al. 2015, 2016

Structured jets in BL Lacs



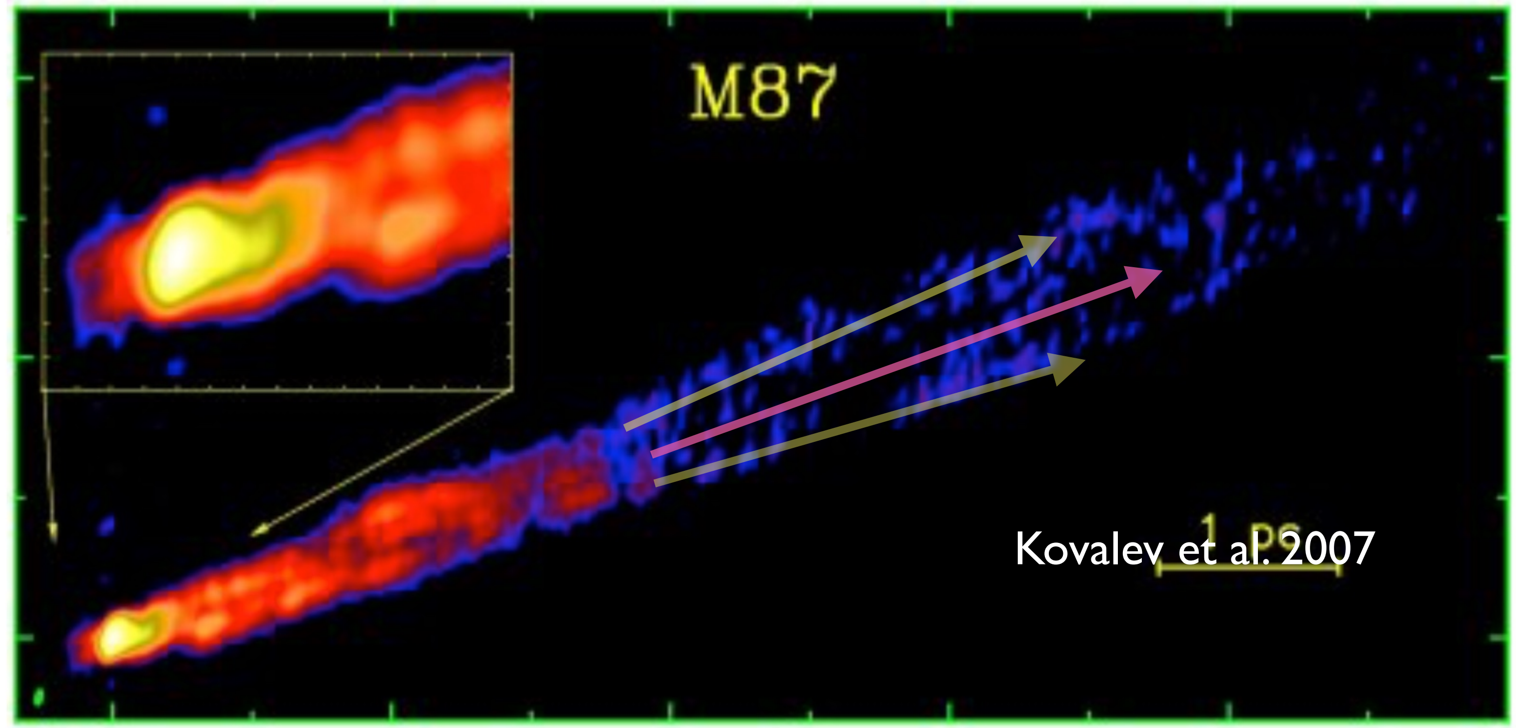
Ghisellini, FT and Chiaberge 2005
Tavecchio & Ghisellini 2008

Structured jets in BL Lacs



Simulations **predict spine-layer structure**

Entrainment/instability e.g. Rossi et al. 2008
Acceleration process e.g. McKinney 2006

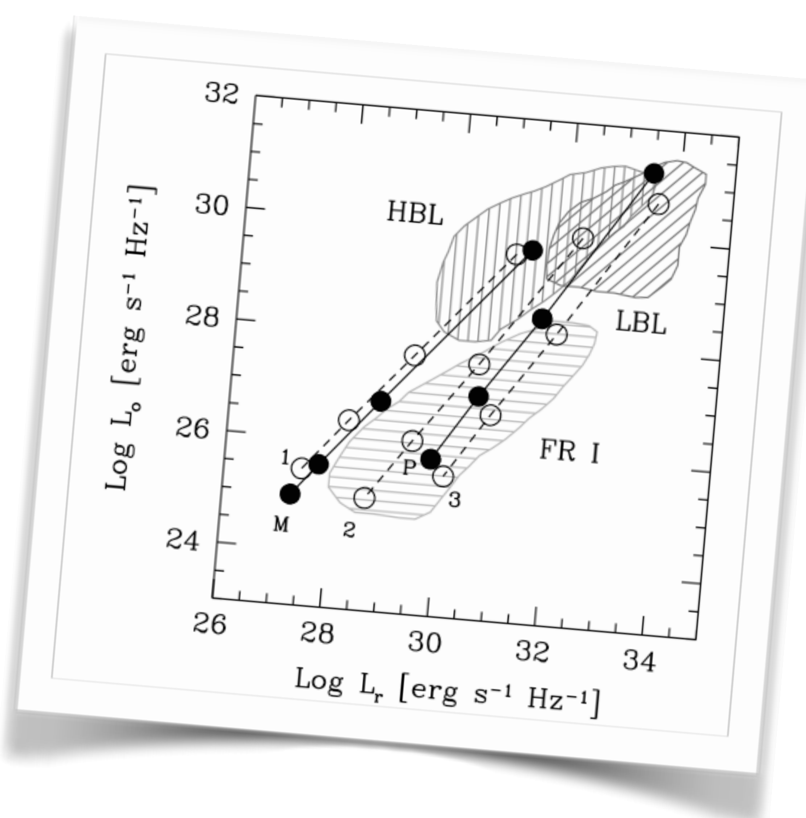


Limb brightening
Mkn 501, Mkn 421, M87, NGC 1275

Laing 1996
Giroletti et al. 2004
Piner & Edwards 2014
Pushkarev et al. 2005
Clausen-Brown 2011
Murphy et al. 2013

Unification requires velocity structures

Chiaberge et al. 2000
Meyer et al.
Sbarrato et al. 2014

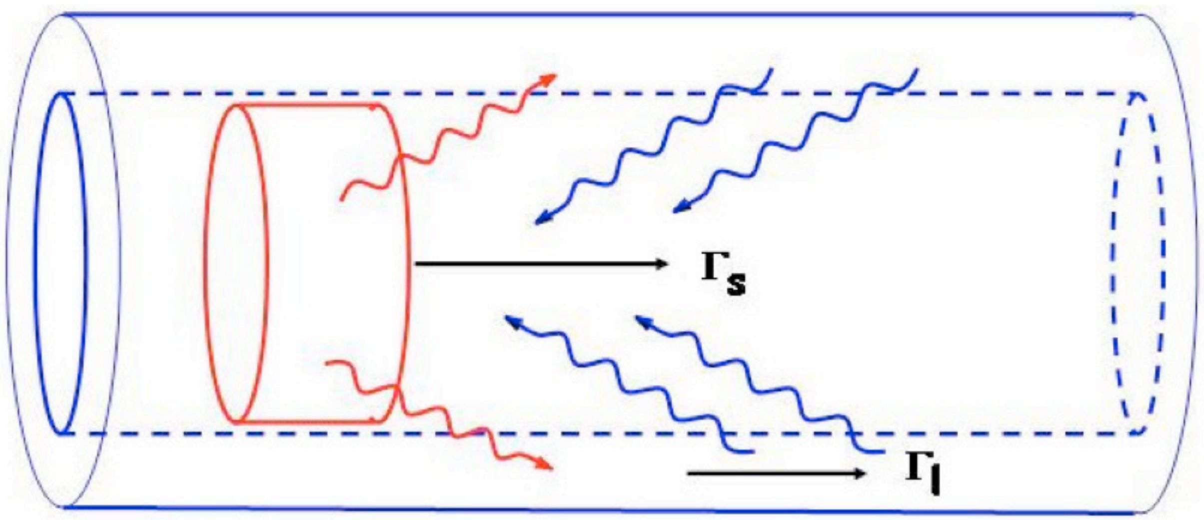


Similar suggestions for GRBs...

Structured jets in BL Lacs

$$\Gamma_{\rm rel} = \Gamma_{\rm s}\Gamma_{\rm l}(1-\beta_{\rm s}\beta_{\rm l})$$

$$U' \simeq U\Gamma_{\rm rel}^2$$



★ The spine "sees" an enhanced u_{rad} coming from the layer

Rates of processes involving soft photons are enhanced w.r.t. to the one-zone model

Both IC and neutrino emission!

Structured jets in BL Lacs

$$L_\nu \approx \frac{3}{8} f_{p\gamma} L_p$$

$$f_{p\gamma} \propto n_{soft}$$

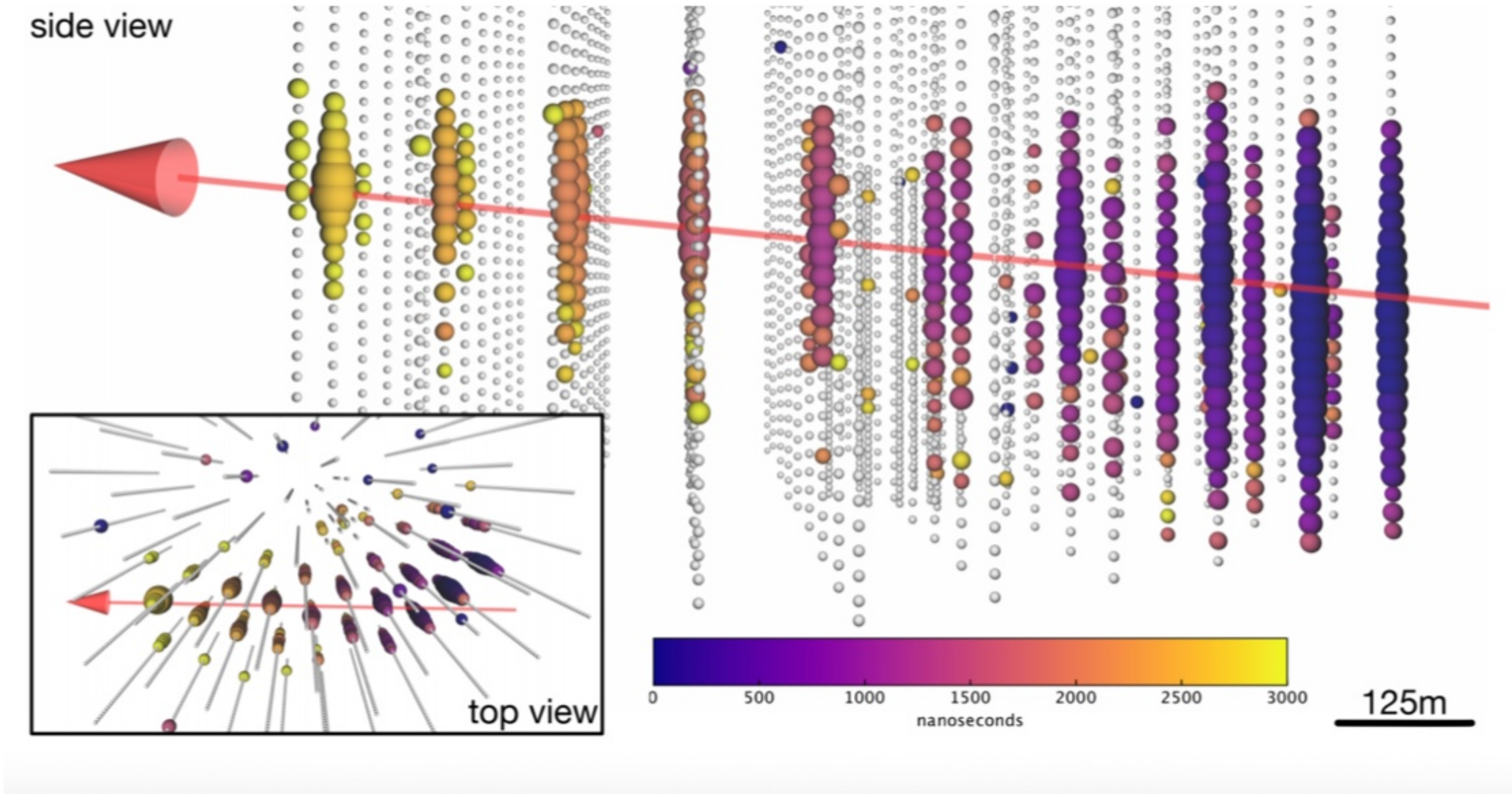
Increased target density

⇒ Reduced proton luminosity

FT et al. 2014, 2015
Righi FT, Guetta 2017

TXS 0506+056 & IC-170922A

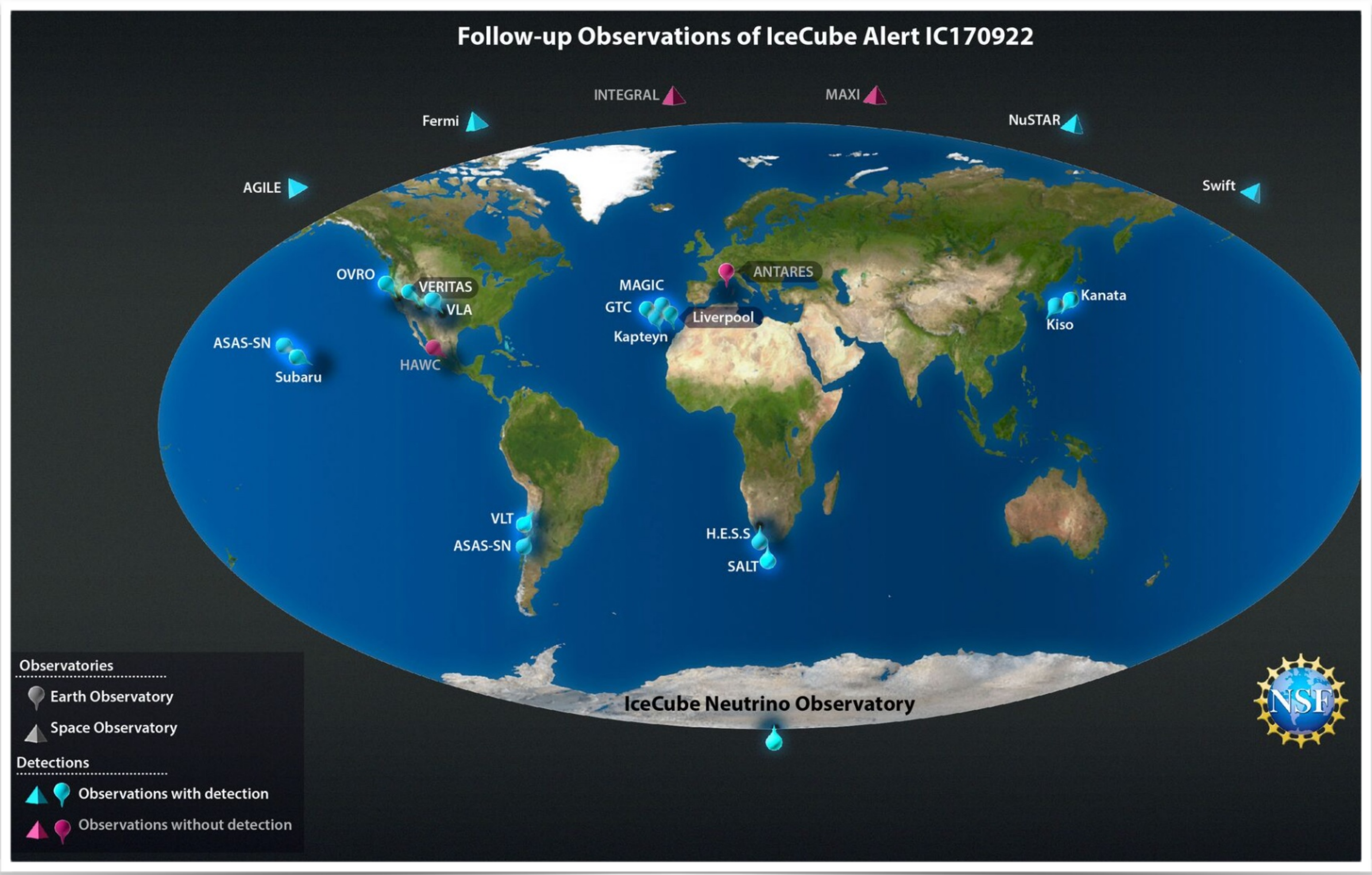
2017 september 22



TXS 0506+056 & IC-170922A

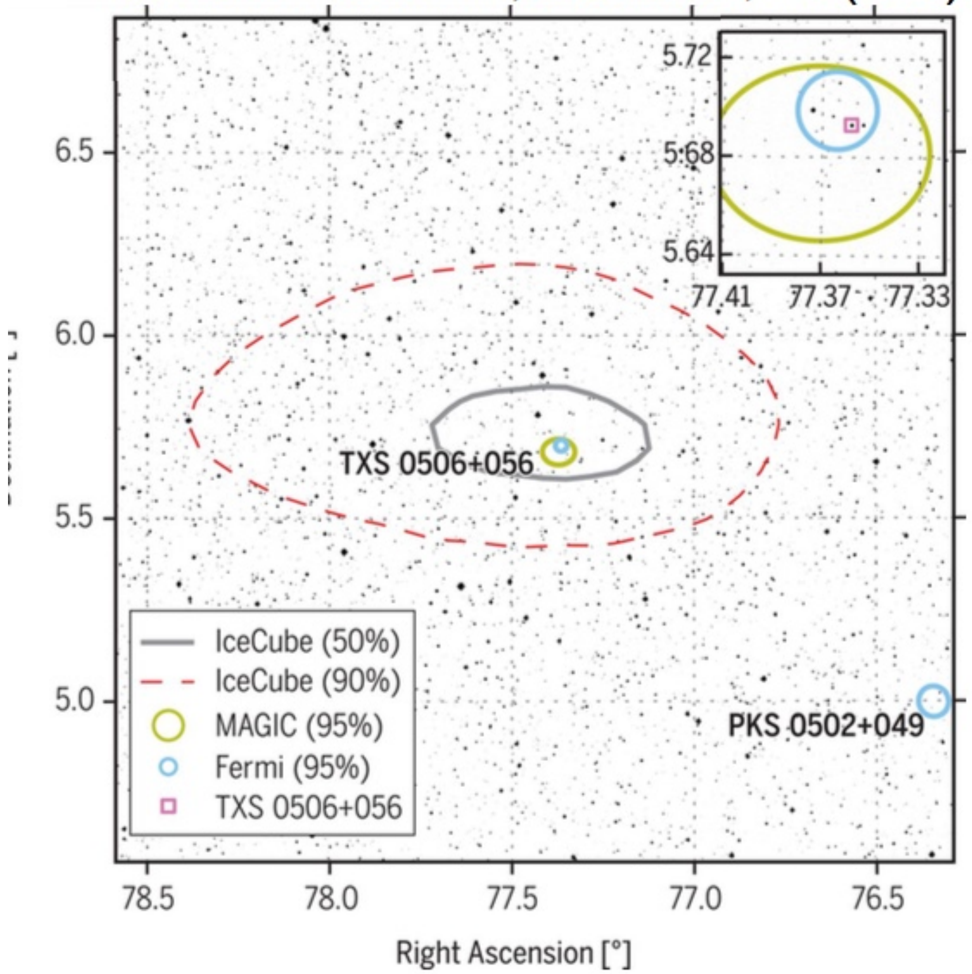
2017 september 22

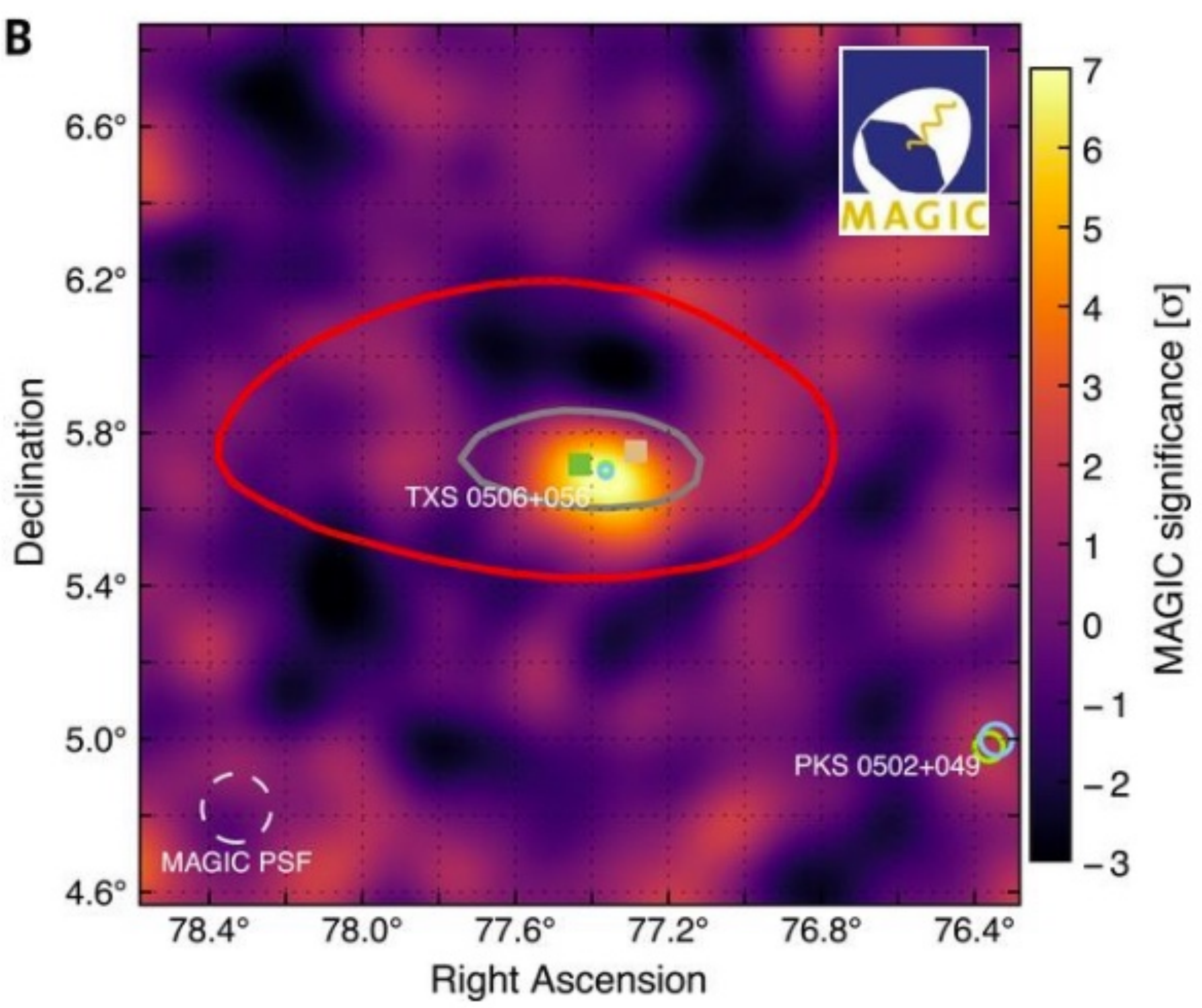
TXS 0506+056 & IC-170922A



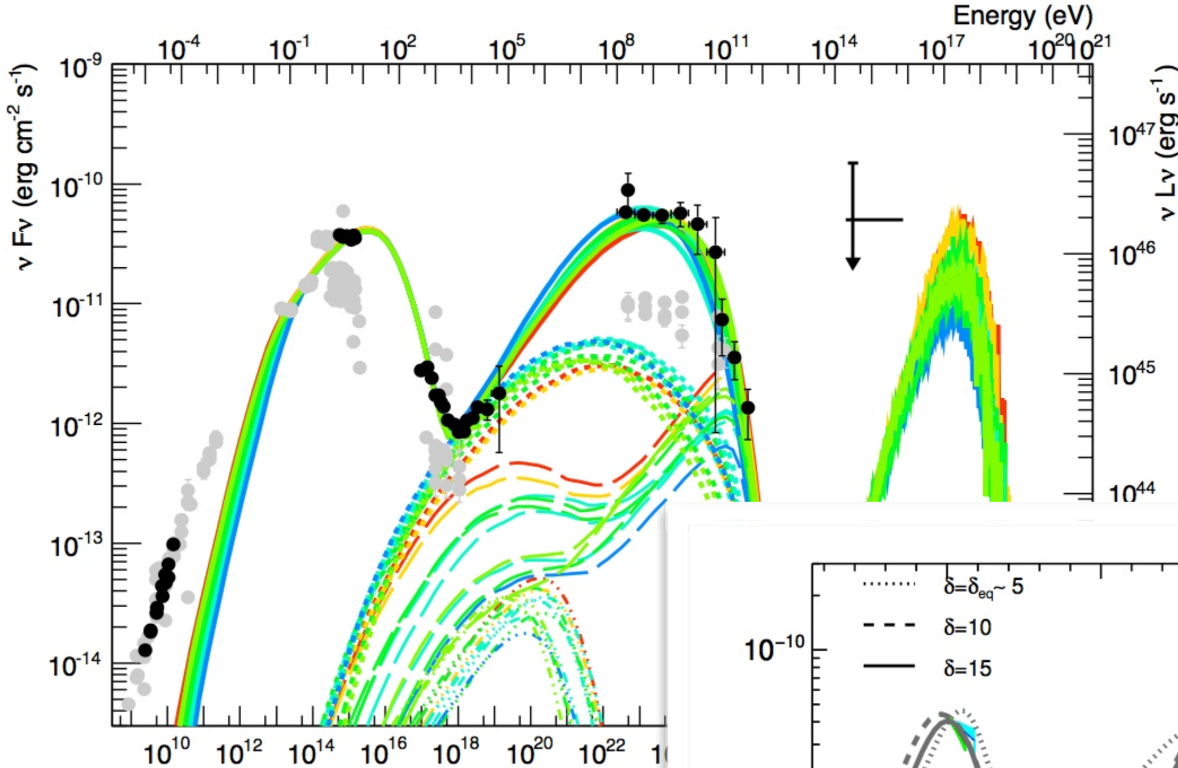
TXS 0506+056 & IC-170922A

IC+Fermi+MAGIC++., Science 361, 146 (2018)

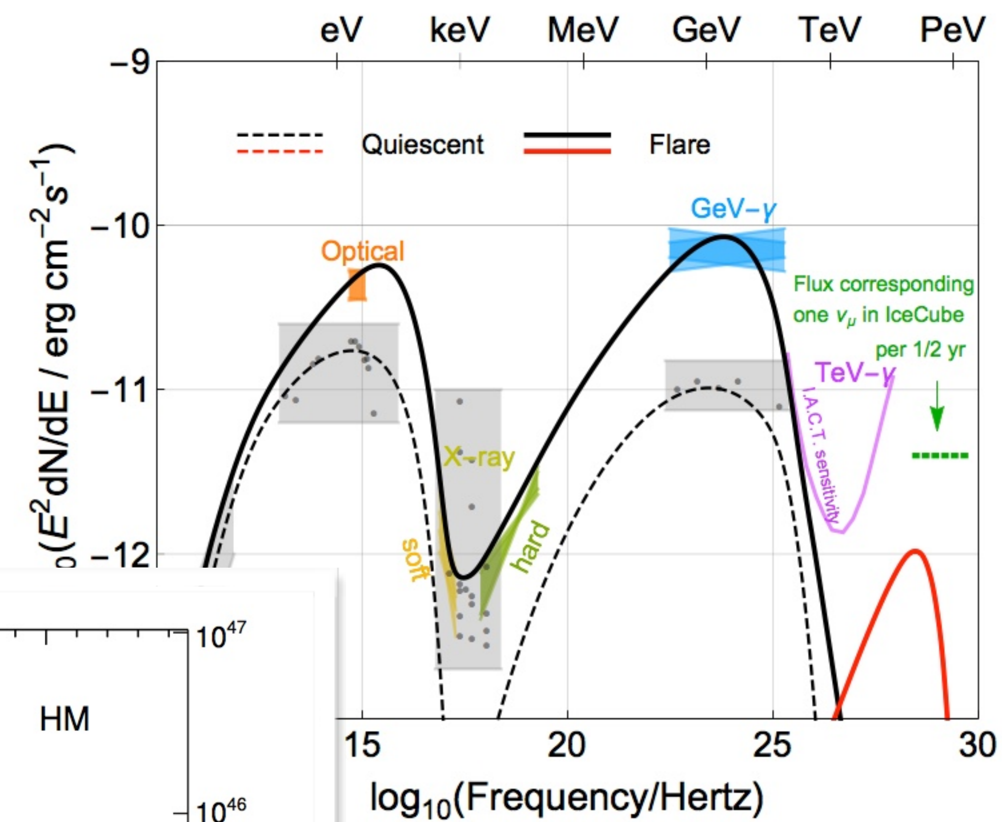




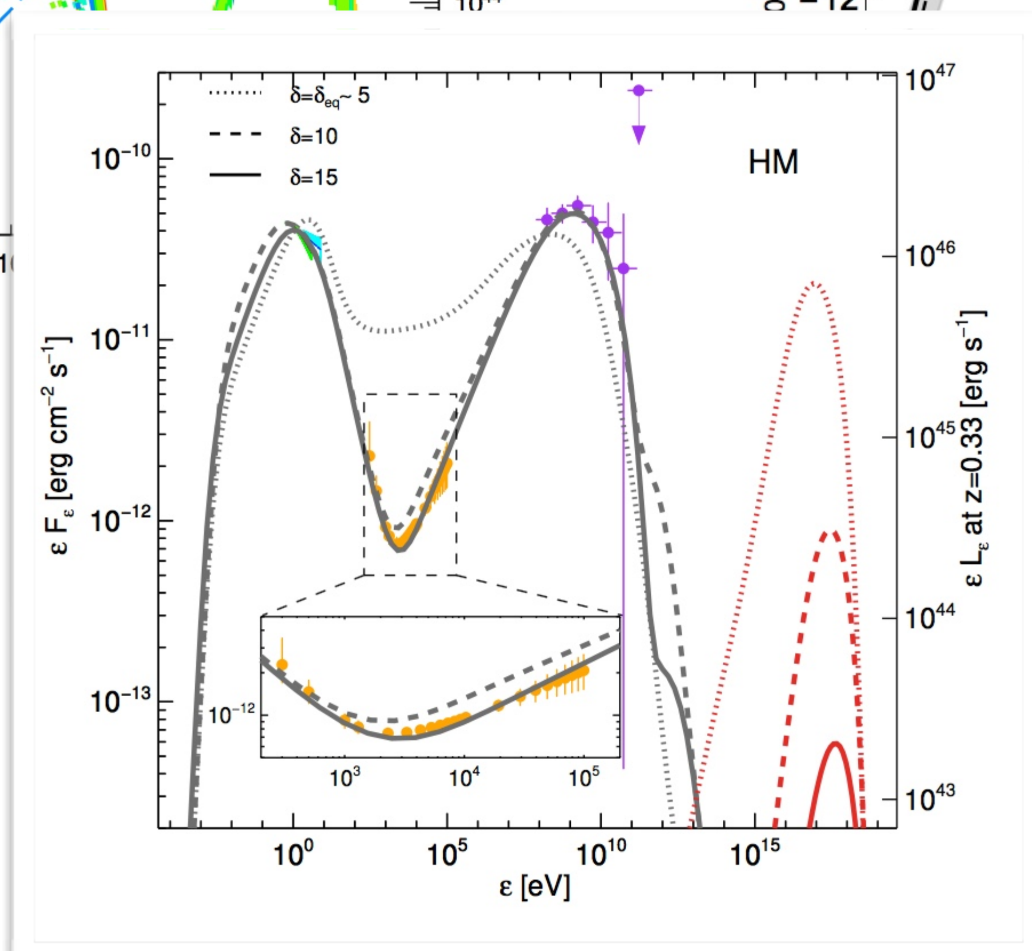
A burst of models …



Cerruti et al. 2018



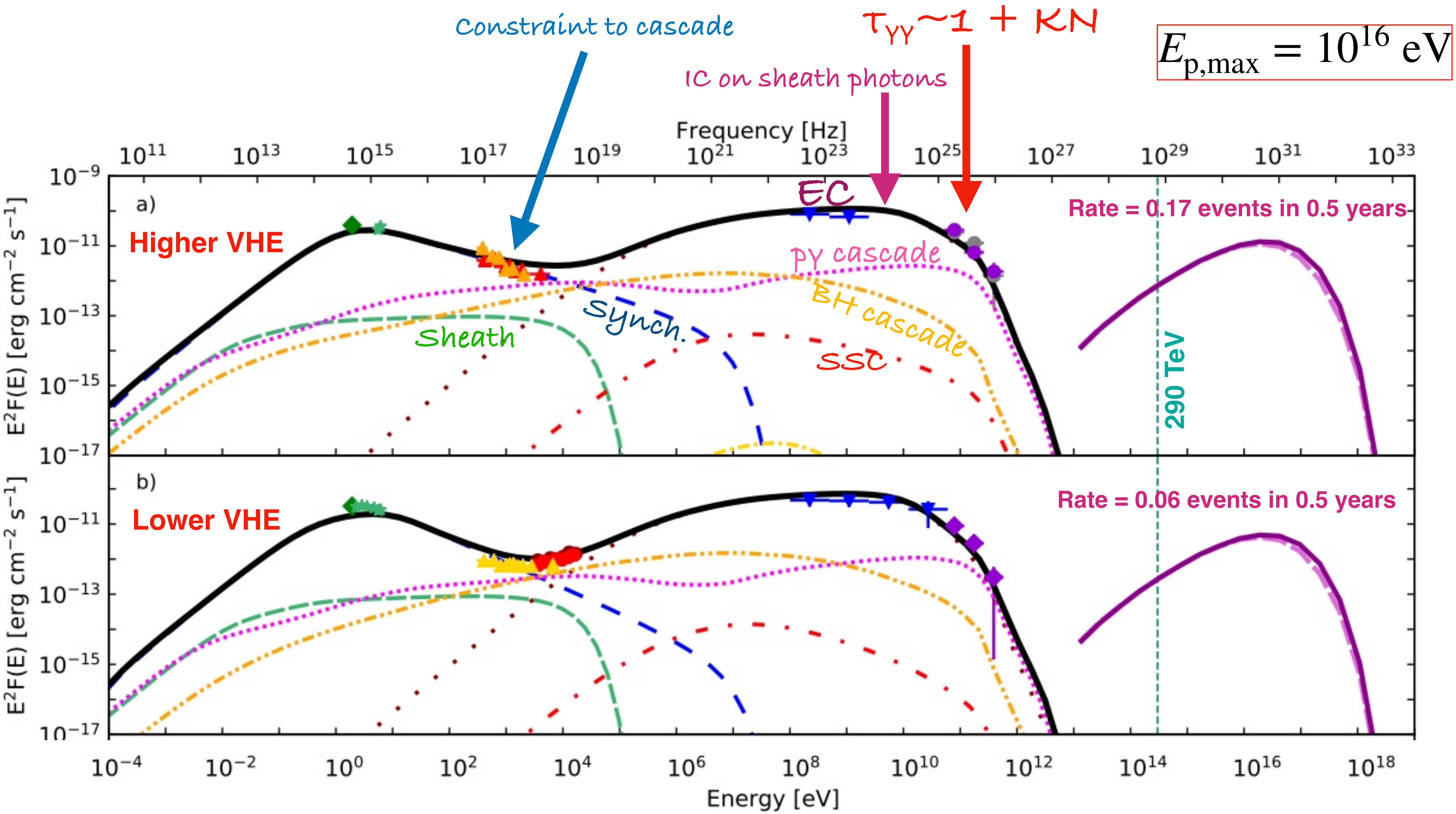
Gao et al. 2018



Keivani et al. 2018

But the jet power is very large!

Jet-sheath model

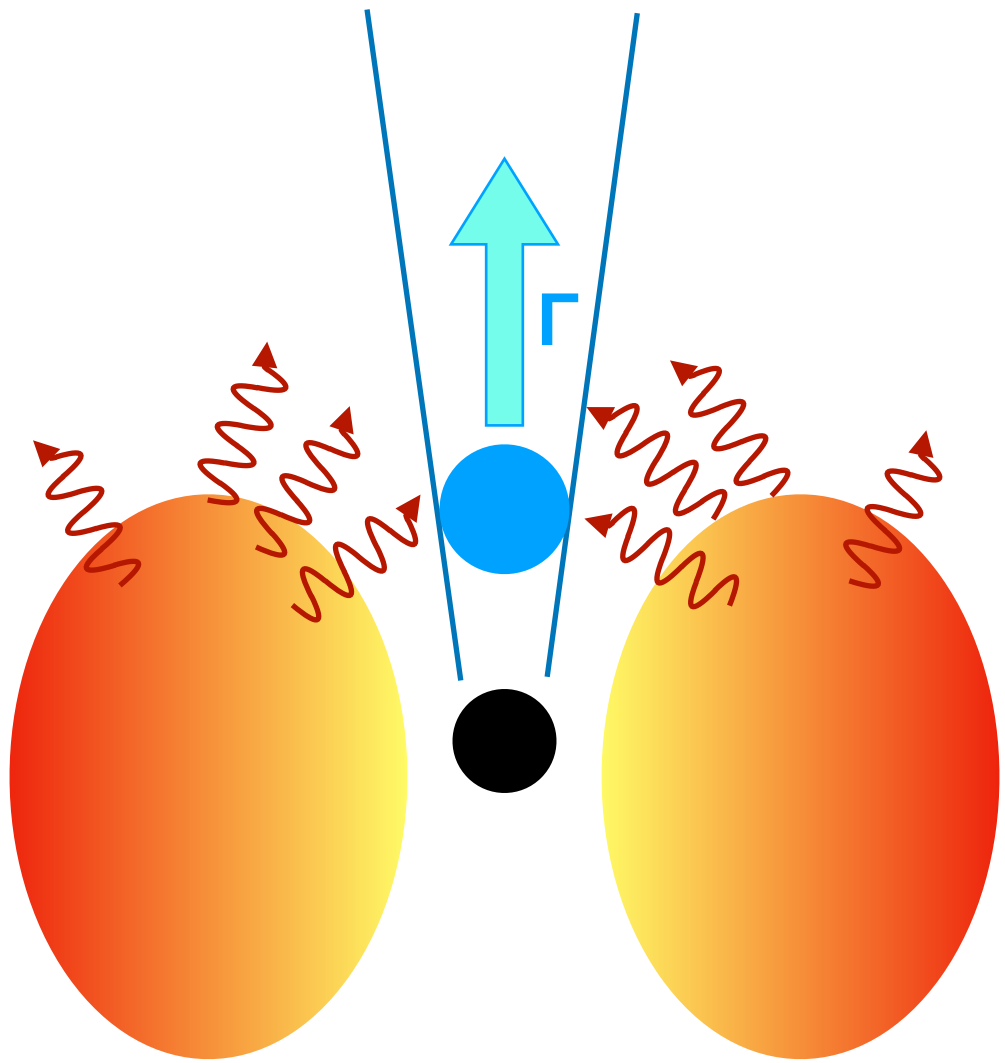


$P_j \approx 4 \times 10^{45} - 10^{46}$ erg s^{-1}

MAGIC Coll. 2018

Numerical model by. W. Bhattacharyya

A role for the accretion flow?



Chiara's talk

Take home messages

The astrophysical setting is relevant! Environment could play an important role

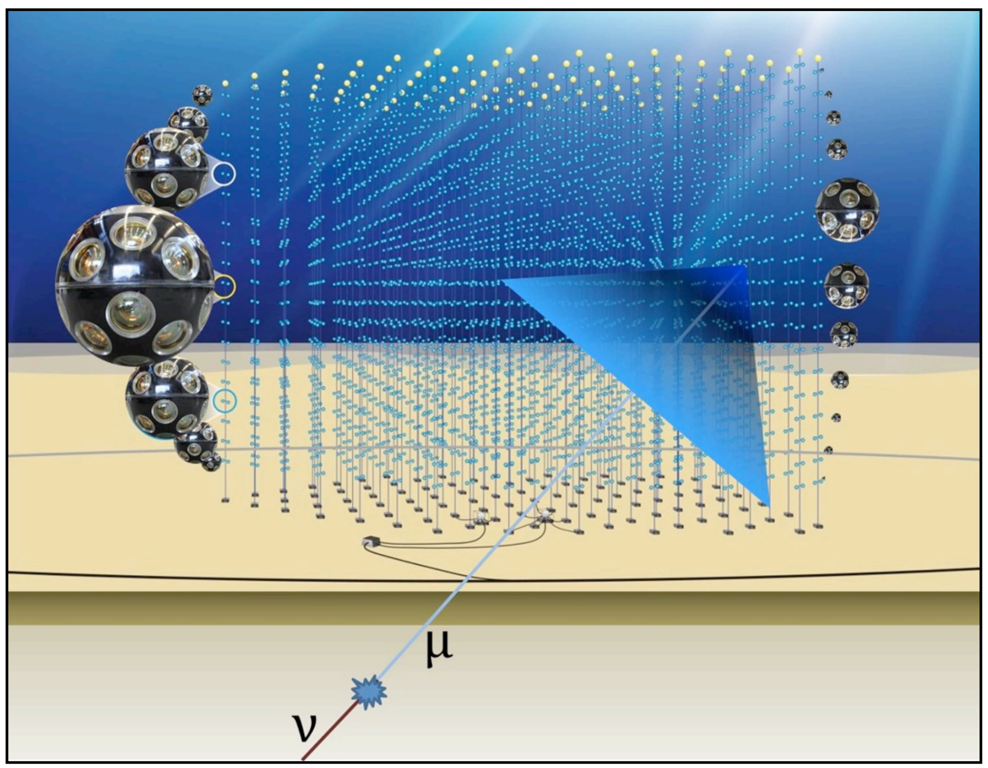
External photons can help to keep the jet power below 10^{47} erg/s

Fits using the structured jet scenario allow us to determine several parameters in a self-consistent way (but several parameters!)

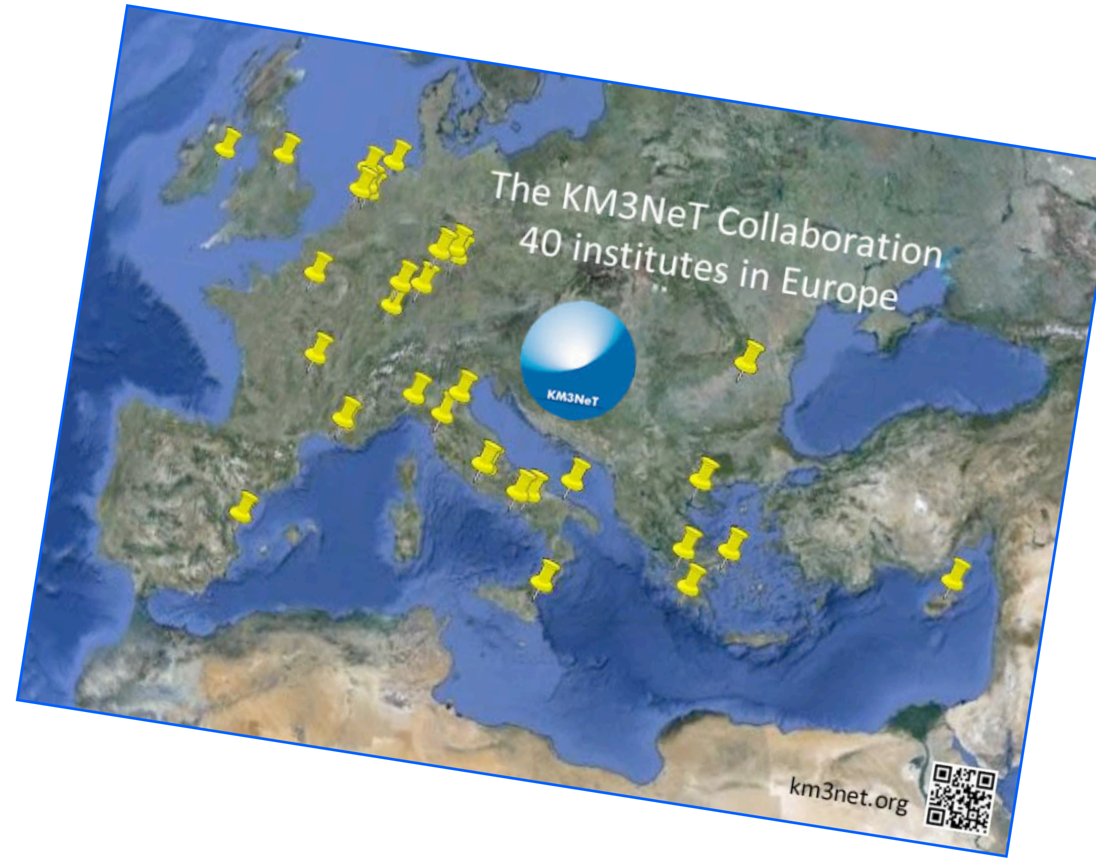
Thank you!

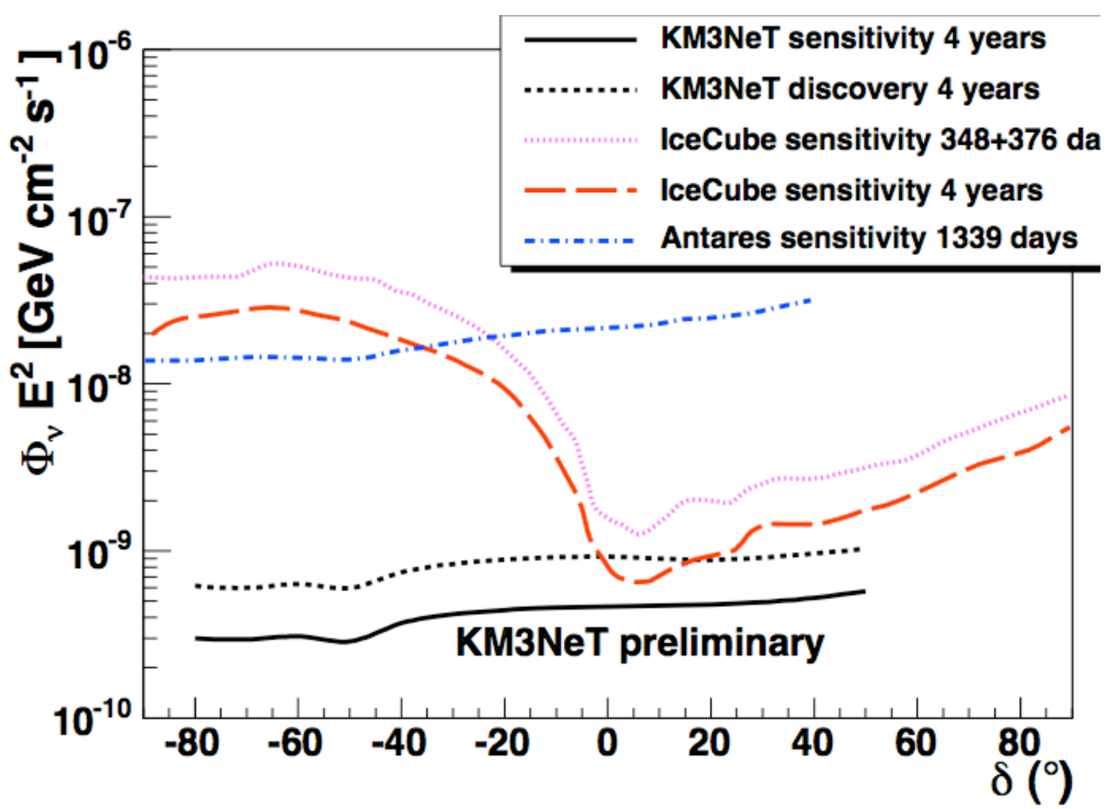
The future

KM3NeT



To be deployed in the Mediterranean Sea





Trovato et al. 2014

Take home message

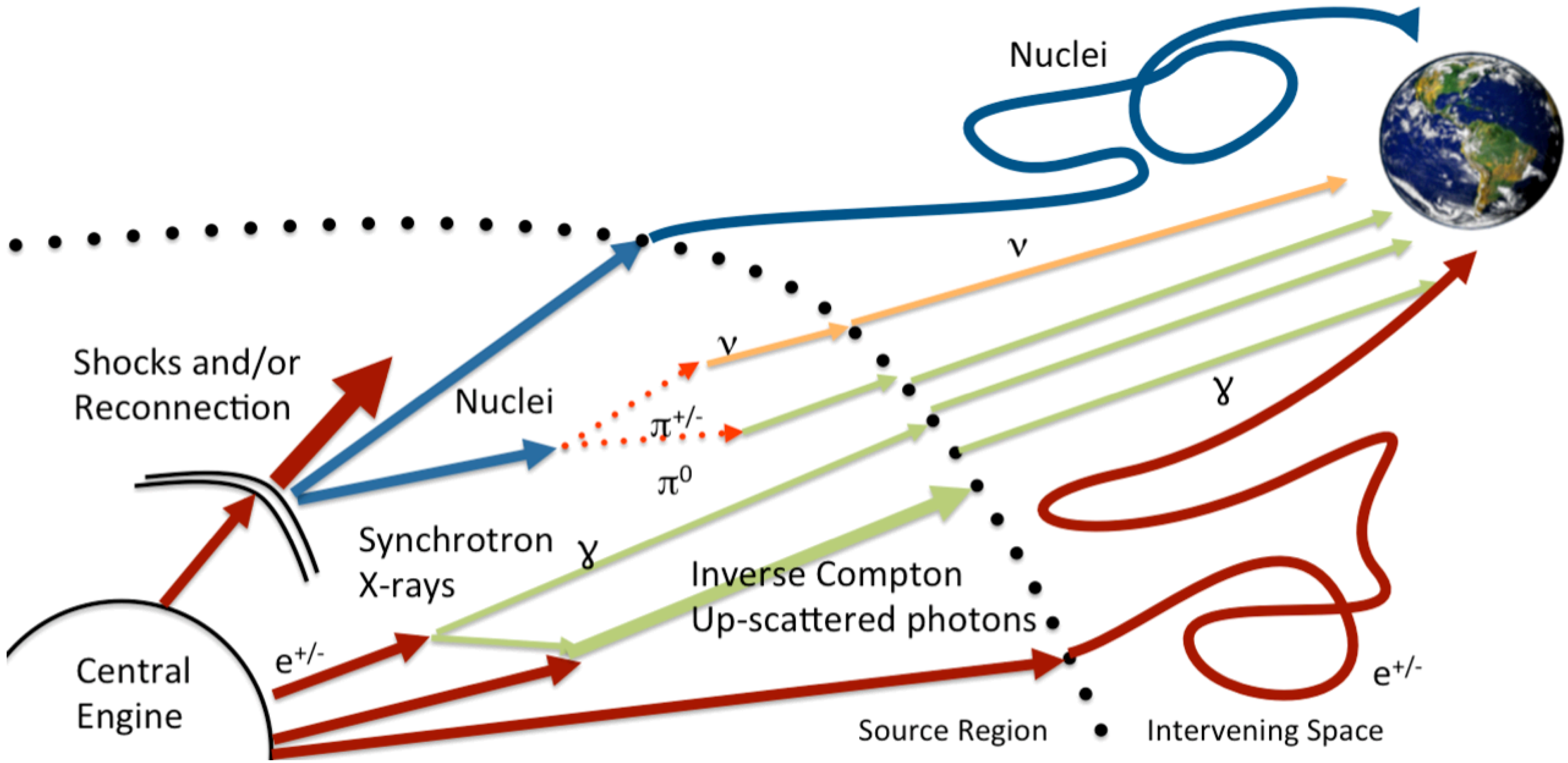
Neutrino provide us an effective probe of acceleration/propagation of particles at the highest energies

Detection of PeV neutrinos by IceCube

Candidate sources: probably a mix?

Blazars? Stay tuned …

HE neutrinos: probes of extreme accelerators

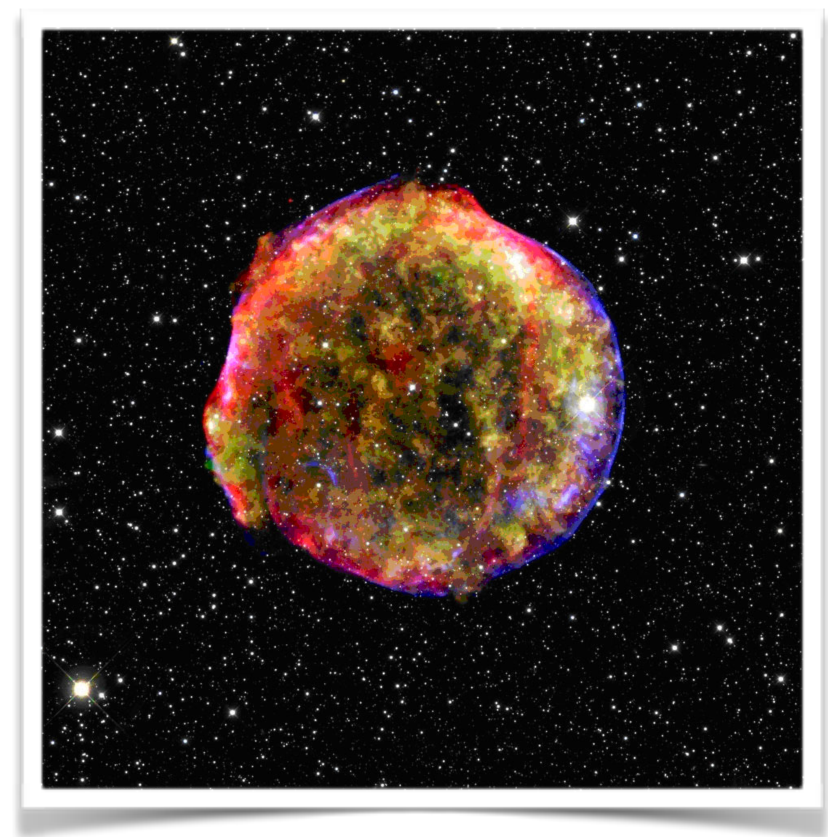


The prime suspects

Tidal disruption events?

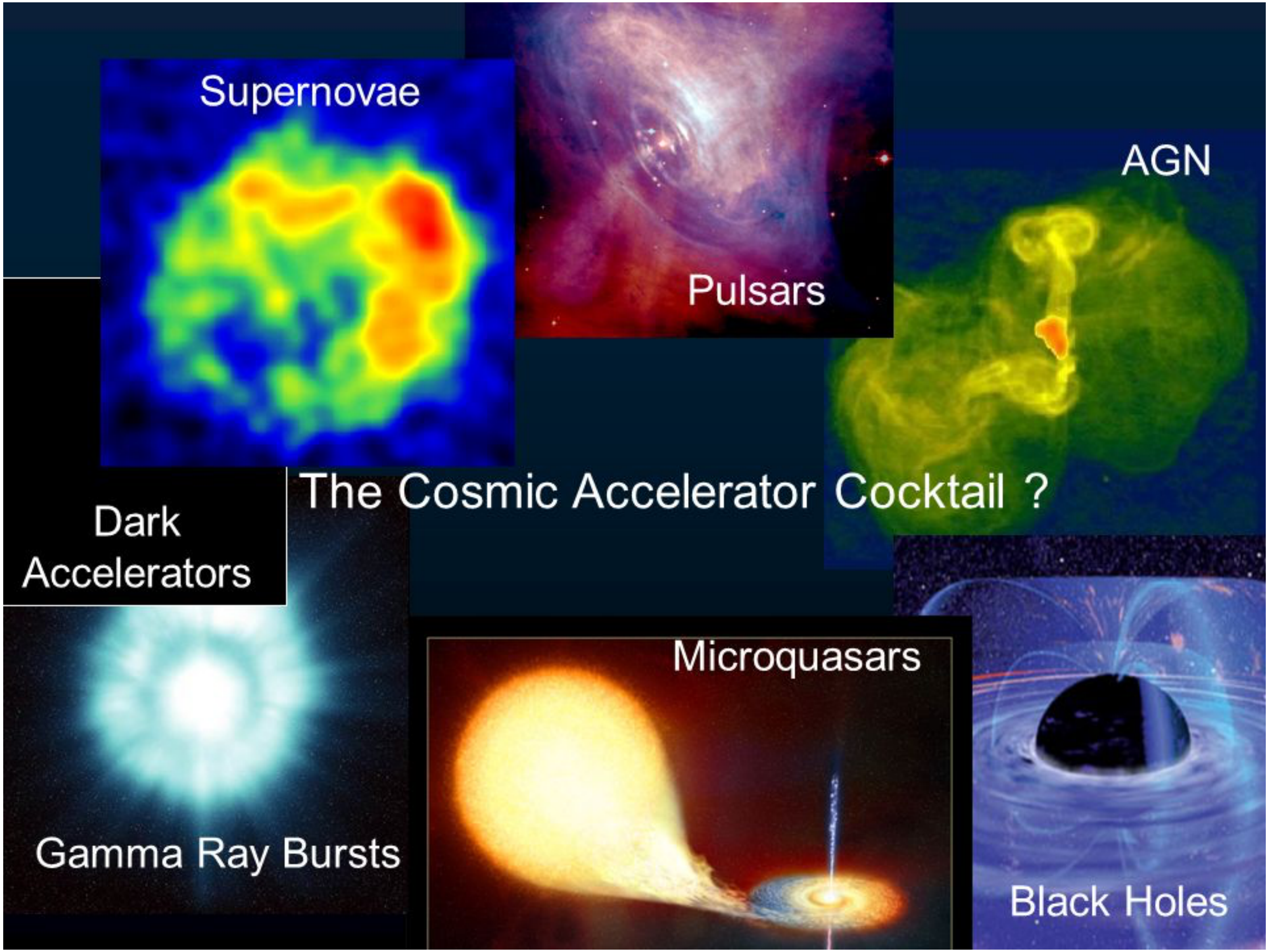
Guepin et al. 2018

SN IIn?



Petropoulou et al. 2017

Potential source(s)



Constraints

$$\phi_\nu \approx \frac{c}{4\pi H_0} \xi_z \rho_0 L_\nu$$

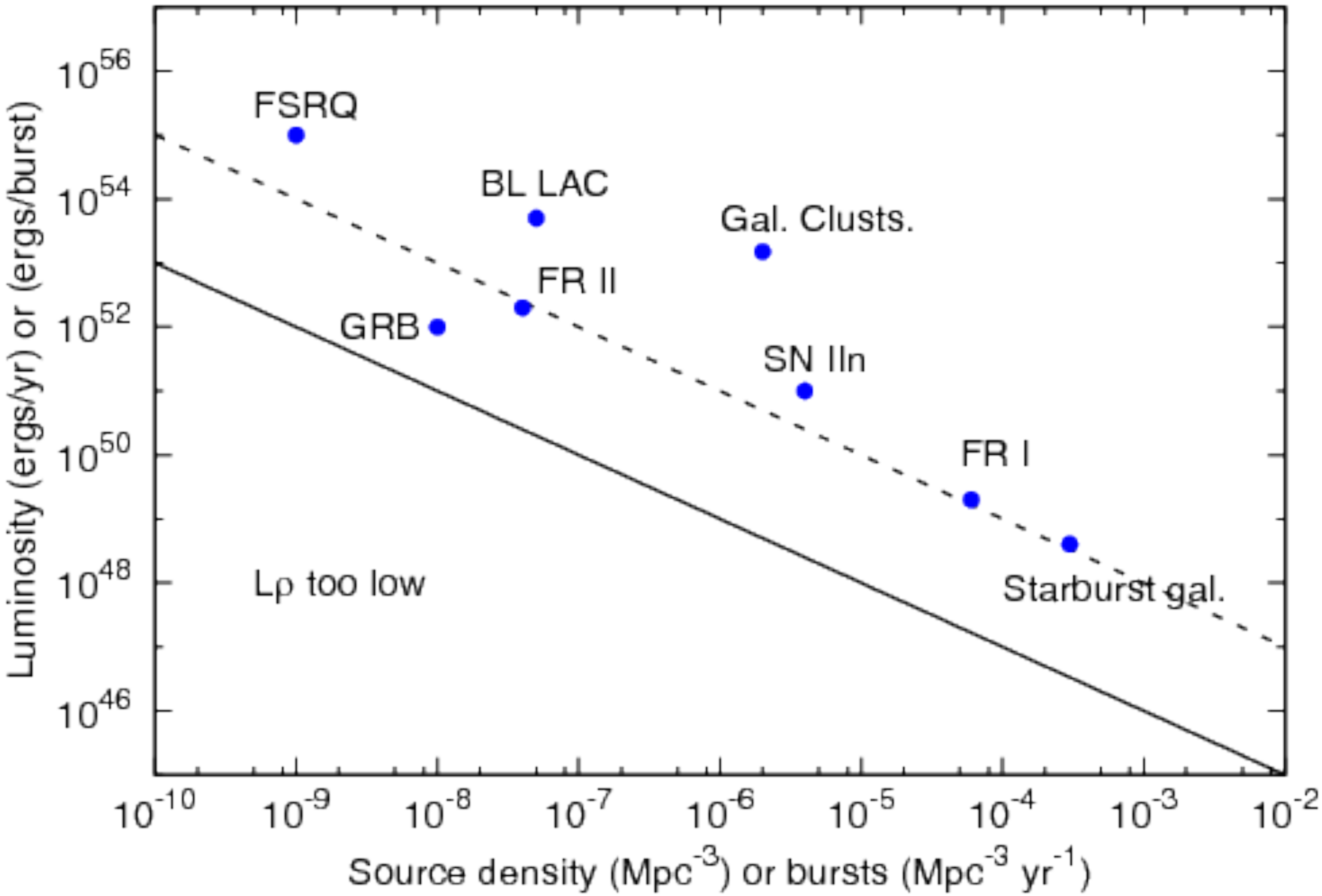
Assuming one population

$$\Rightarrow \quad \rho_0 L_\nu \approx \frac{\phi_\nu 4\pi H_0}{\xi_z c} = const$$

Constraints

Assuming the entire IceCube flux

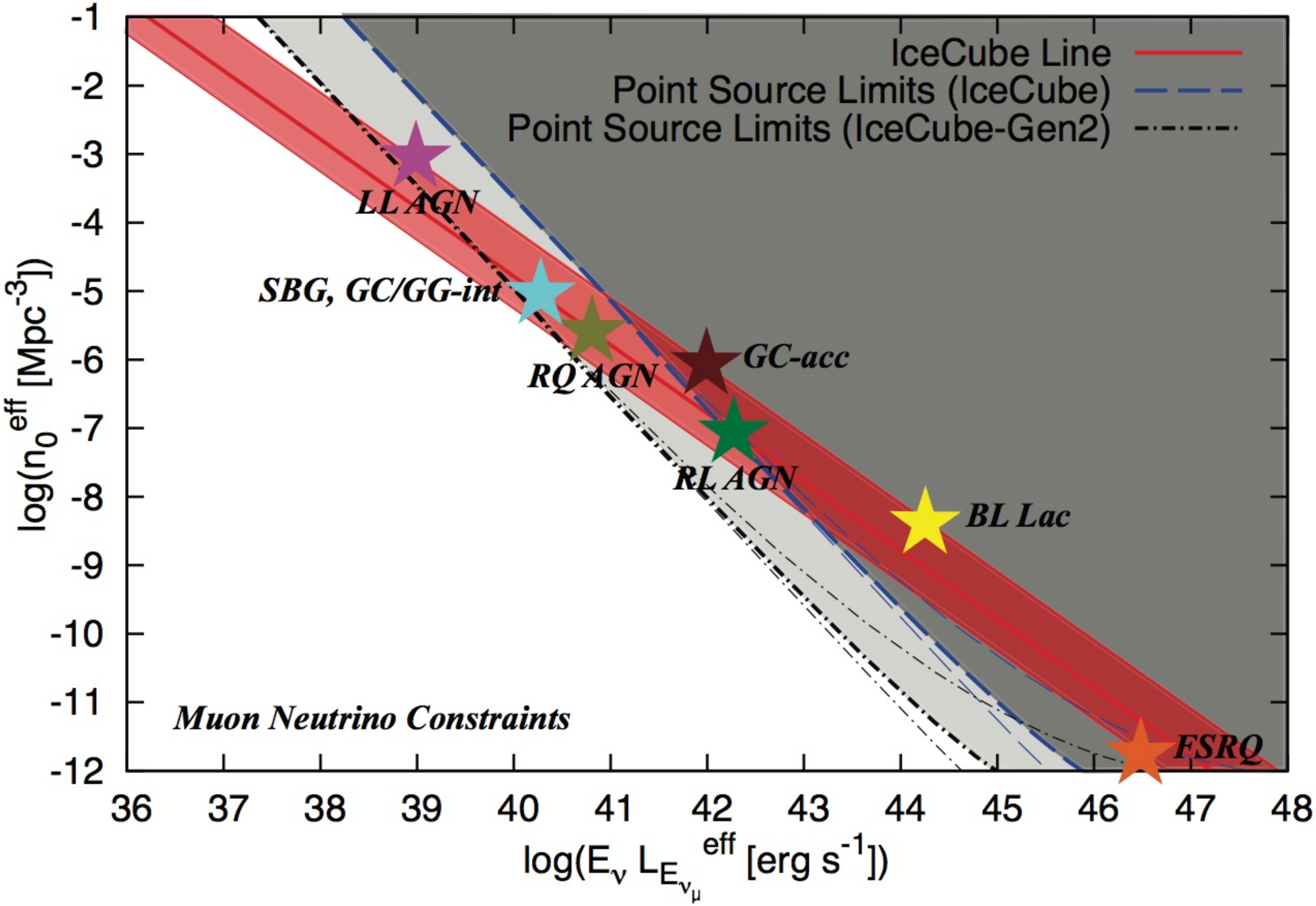
Kowalski 2015



Constraints

Assuming the entire IceCube flux

Murase & Waxman 2016



See also Palladino & Vissani 2017

The prime suspects

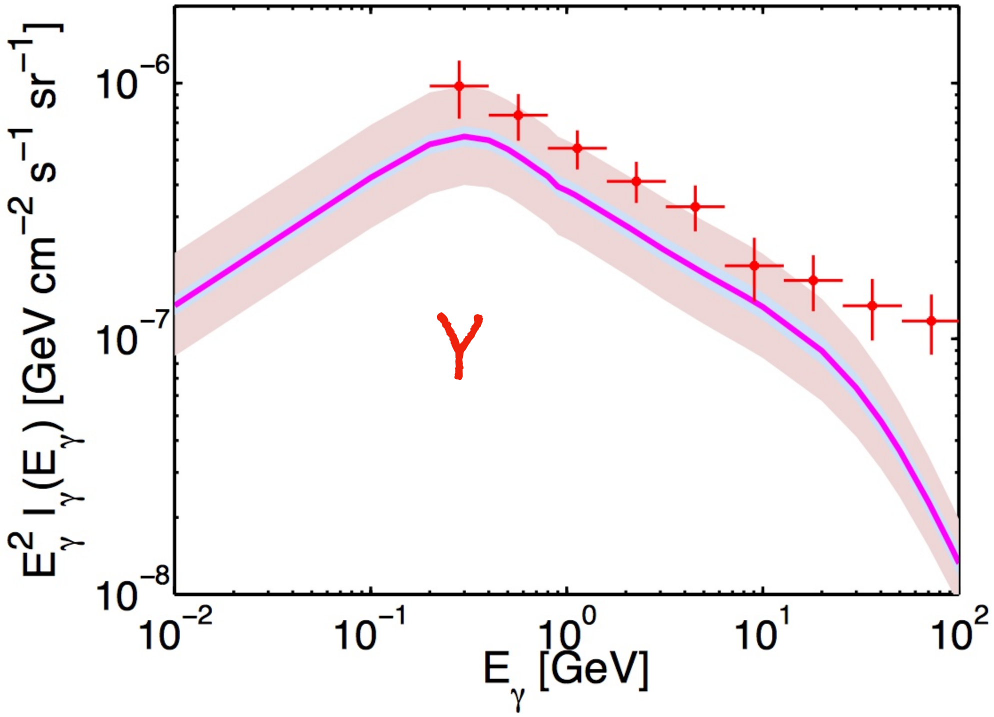
Starburst/Star forming galaxies?

Loeb & Waxman 2006
Tamborra et al. 2014

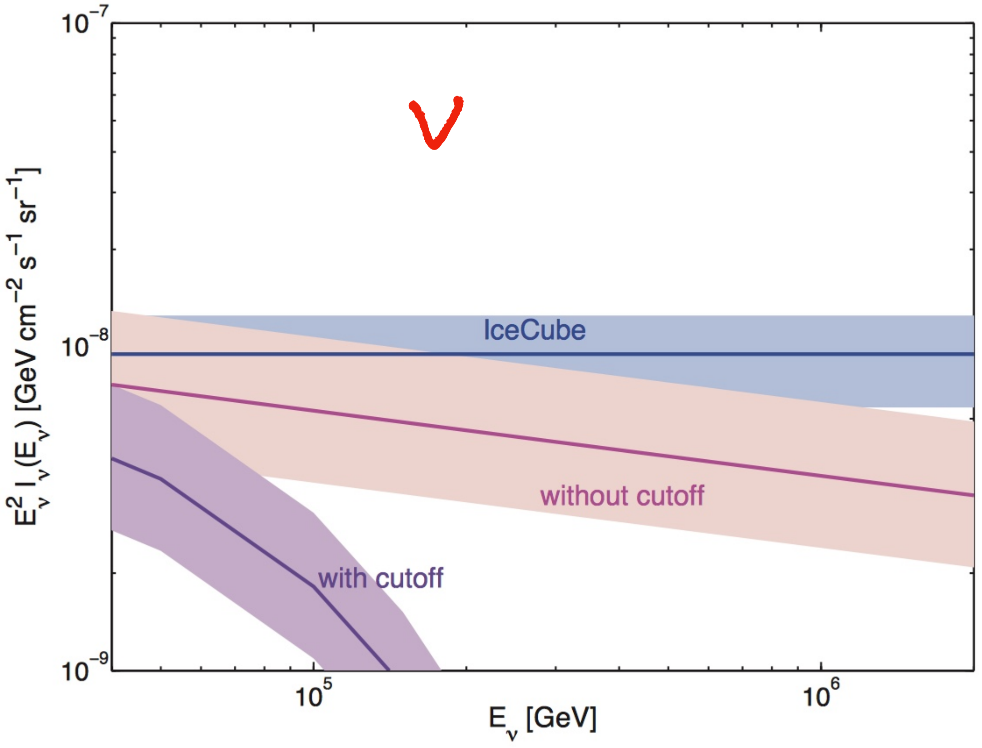
CR accelerated in SNR + dense gas

The prime suspects

Starburst/Star forming galaxies?



Ep>10^16 eV?



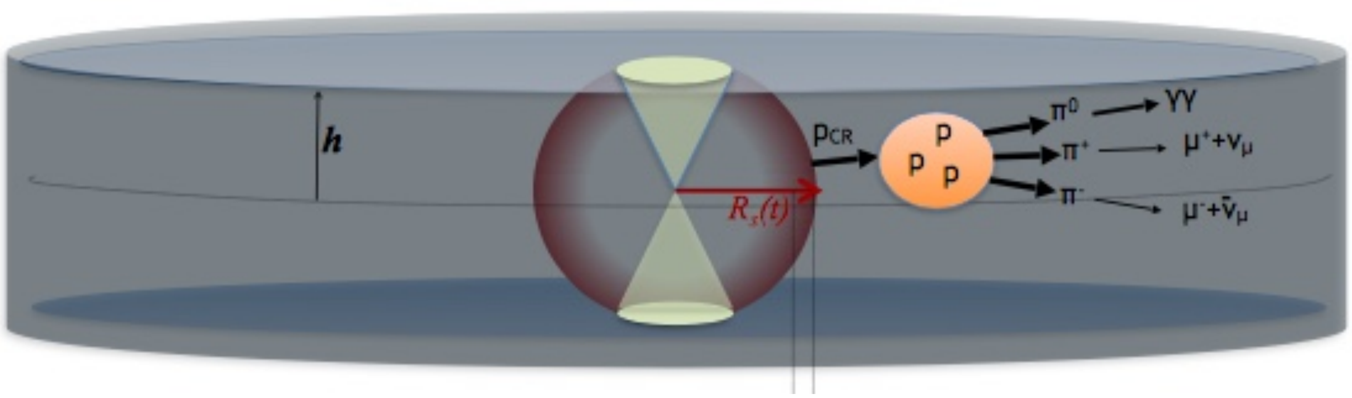
Tamborra et al. 2014

Difficult to obtain a direct association

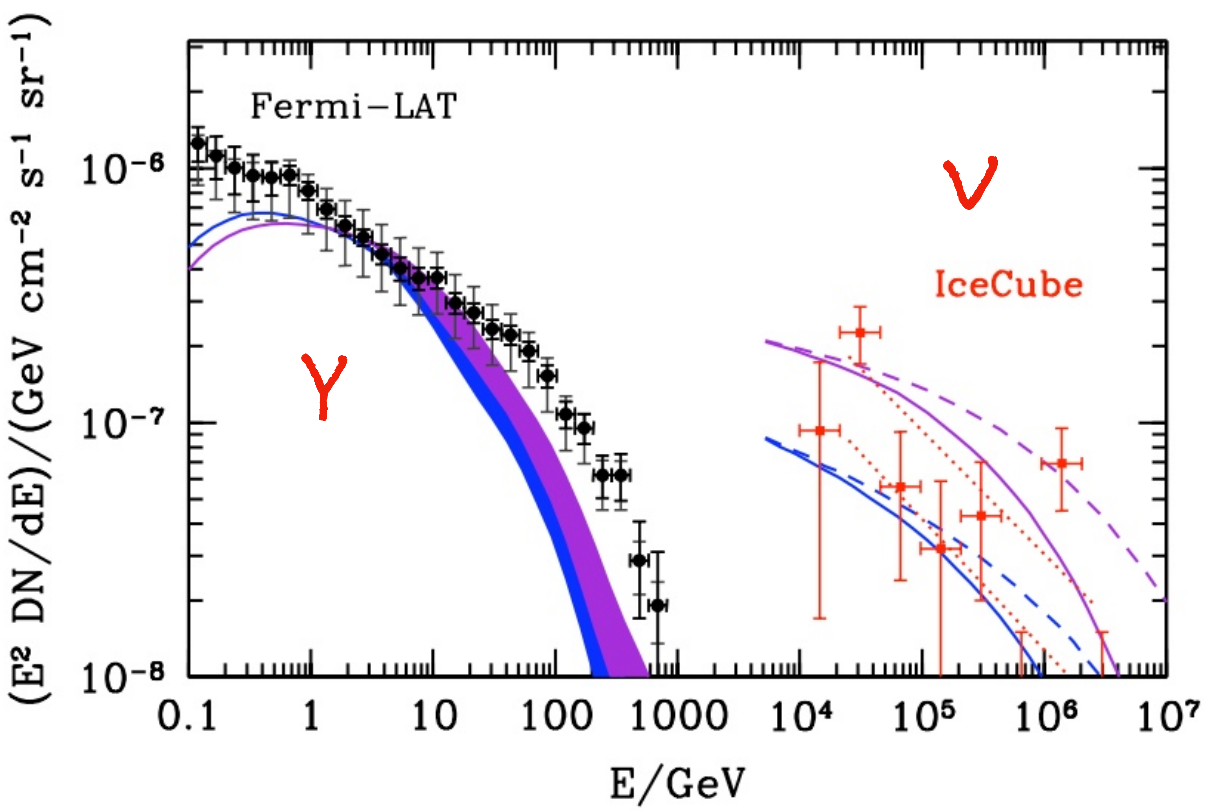
The prime suspects

AGN-driven winds?

Lamastra et al. 2016, 2017



CR accelerated in the shock wind + dense gas

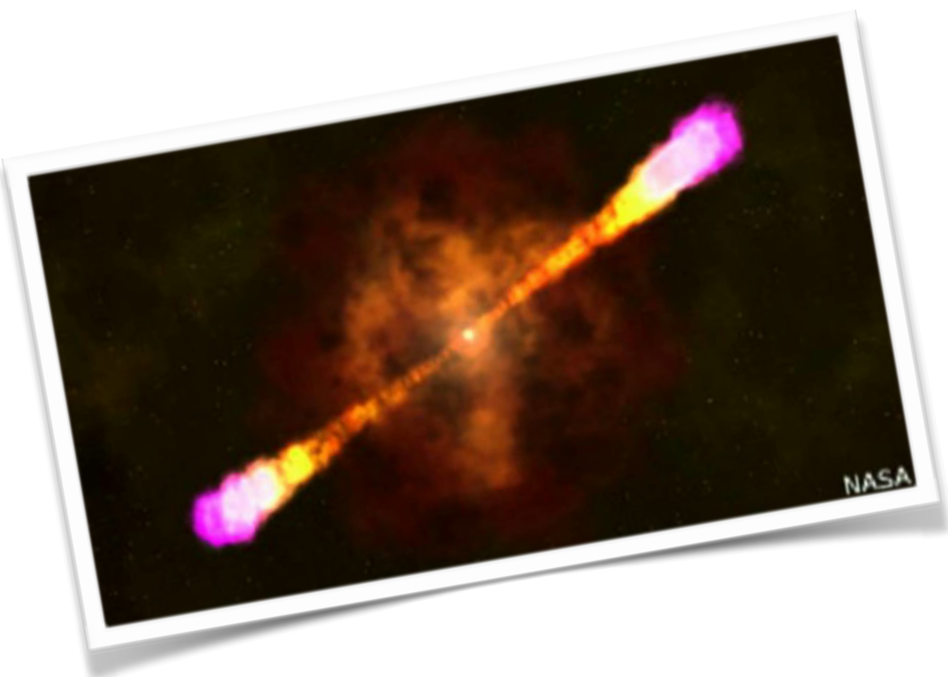


The prime suspects

CR accelerated in shocks + radiation

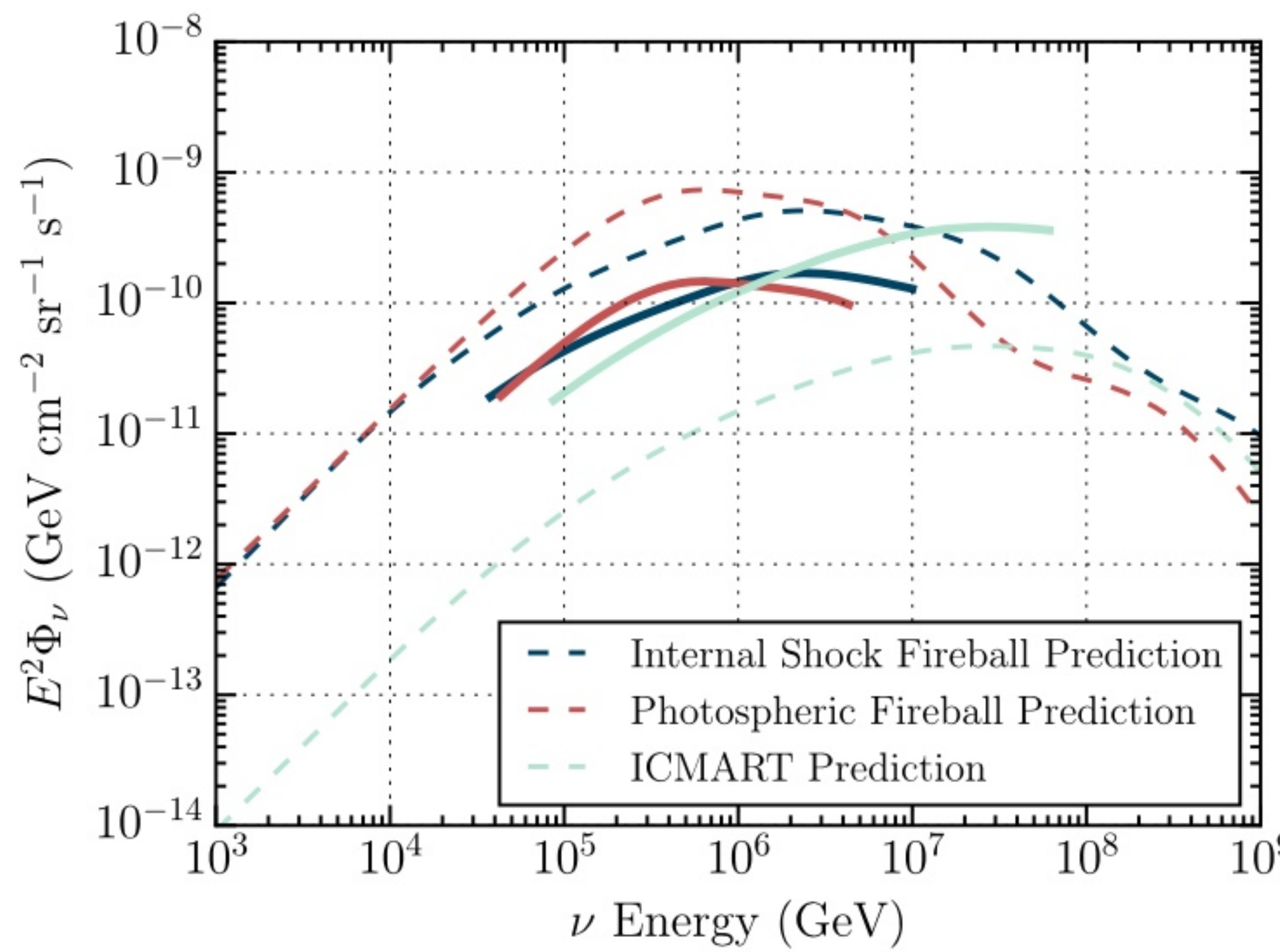
Gamma-ray bursts?

Waxman & Bahcall 1997



Probably no...

Aartsen et al. 2017



The prime suspects

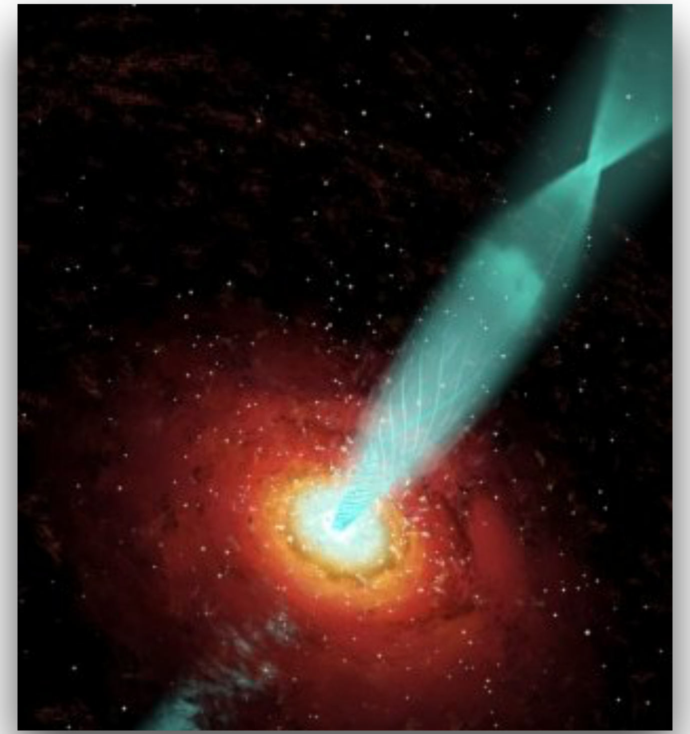
Relativistic jets: radiogalaxies?

CR accelerated in shocks + gas in the jet

Becker-Tijus 2004

CR accelerated in shocks + gas in the host

Tavecchio et al. 2018

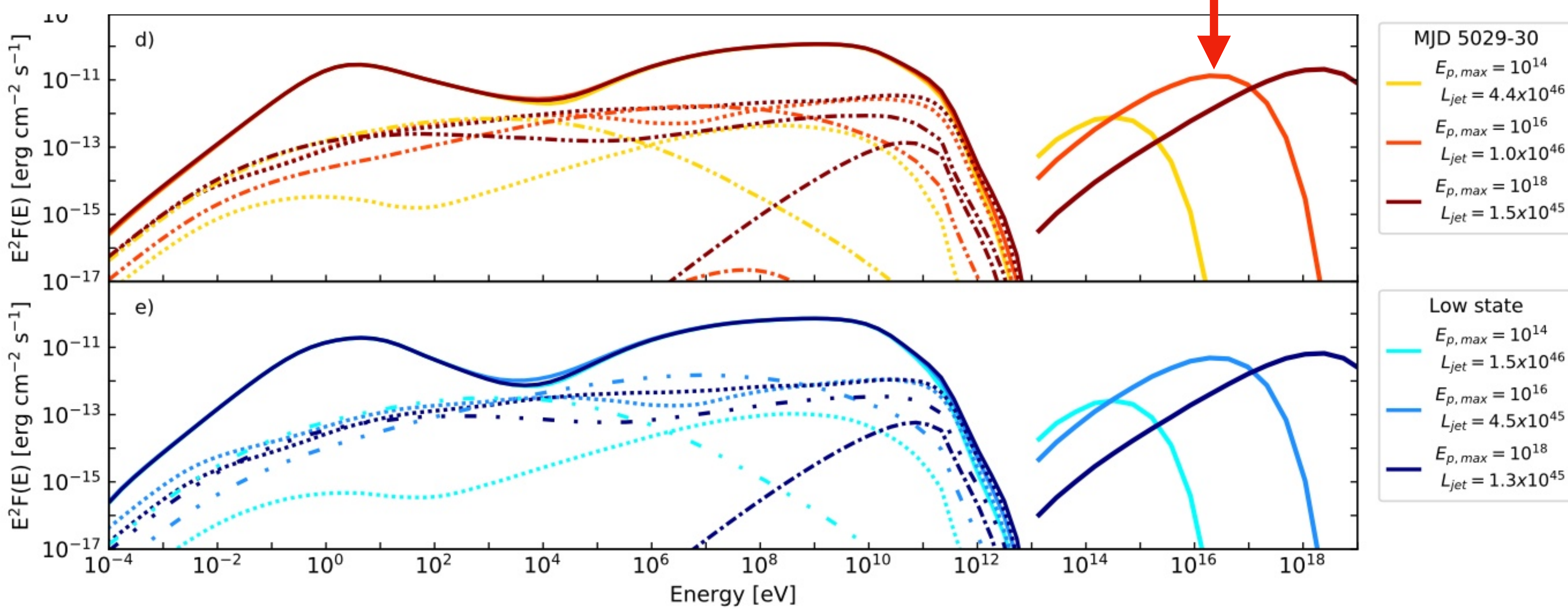


Jet-sheath model

MAGIC Coll. 2018

Effect of maximum proton energy

Constrained by cascade flux in X-rays



Larger Ep —> Lower neutrino rate at 300 TeV

Jet-sheath model

MAGIC Coll. 2018

Table 3. Parameters for the jet-sheath model for $E_{\rm p,max}$=10^{16}.

State	MJD 58029-30	Lower VHE
B [G]	2.6	2.6
$E_{\rm min}$ [eV]	3.2×10^8	2.0×10^8
$E_{\rm br}$ [eV]	7.0×10^8	9.0×10^8
$E_{\rm max}$ [eV]	8×10^{11}	8×10^{11}
n_1	2	2
n_2	3.9	4.4
U_e [erg cm^{-3}]	4.4×10^{-4}	3.6×10^{-4}
U_B [erg cm^{-3}]	0.27	0.27
U_p [erg cm^{-3}]	1.8	0.7
P_e [erg s^{-1}]	2×10^{42}	1.6×10^{42}
P_p [erg s^{-1}]	8×10^{45}	3×10^{45}
P_B [erg s^{-1}]	1.2×10^{45}	1.2×10^{45}

$$P_j \approx 4 \times 10^{45} - 10^{46} \text{ erg s}^{-1}$$