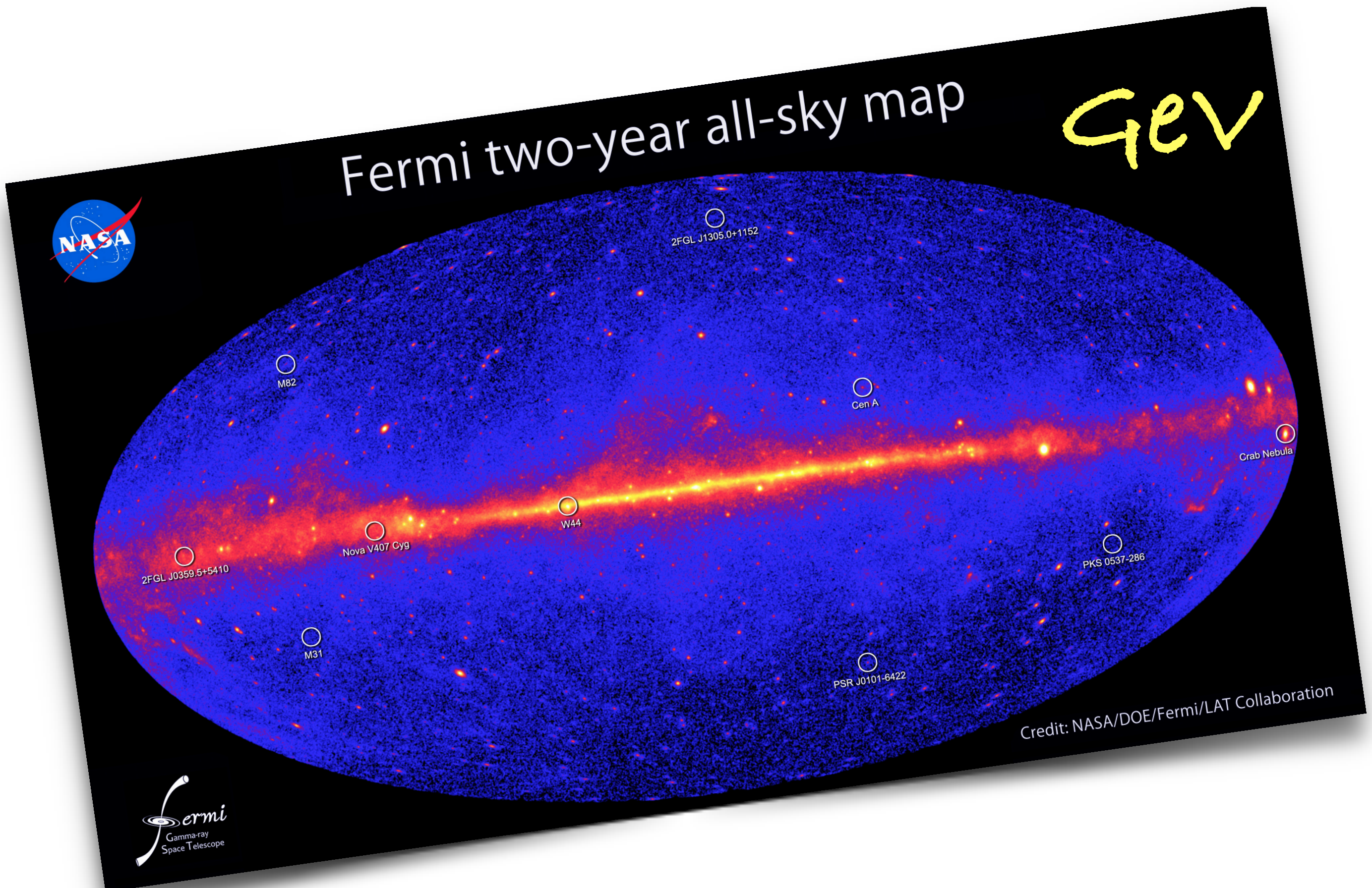
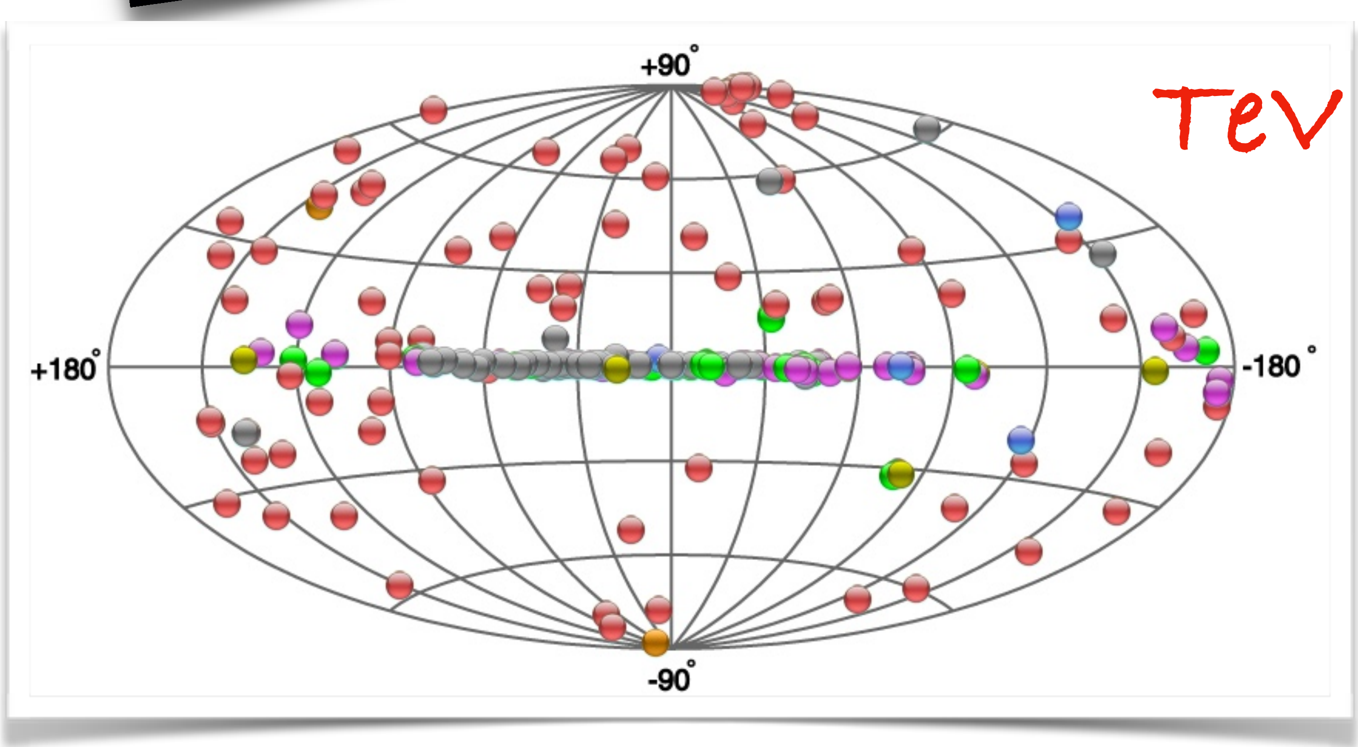
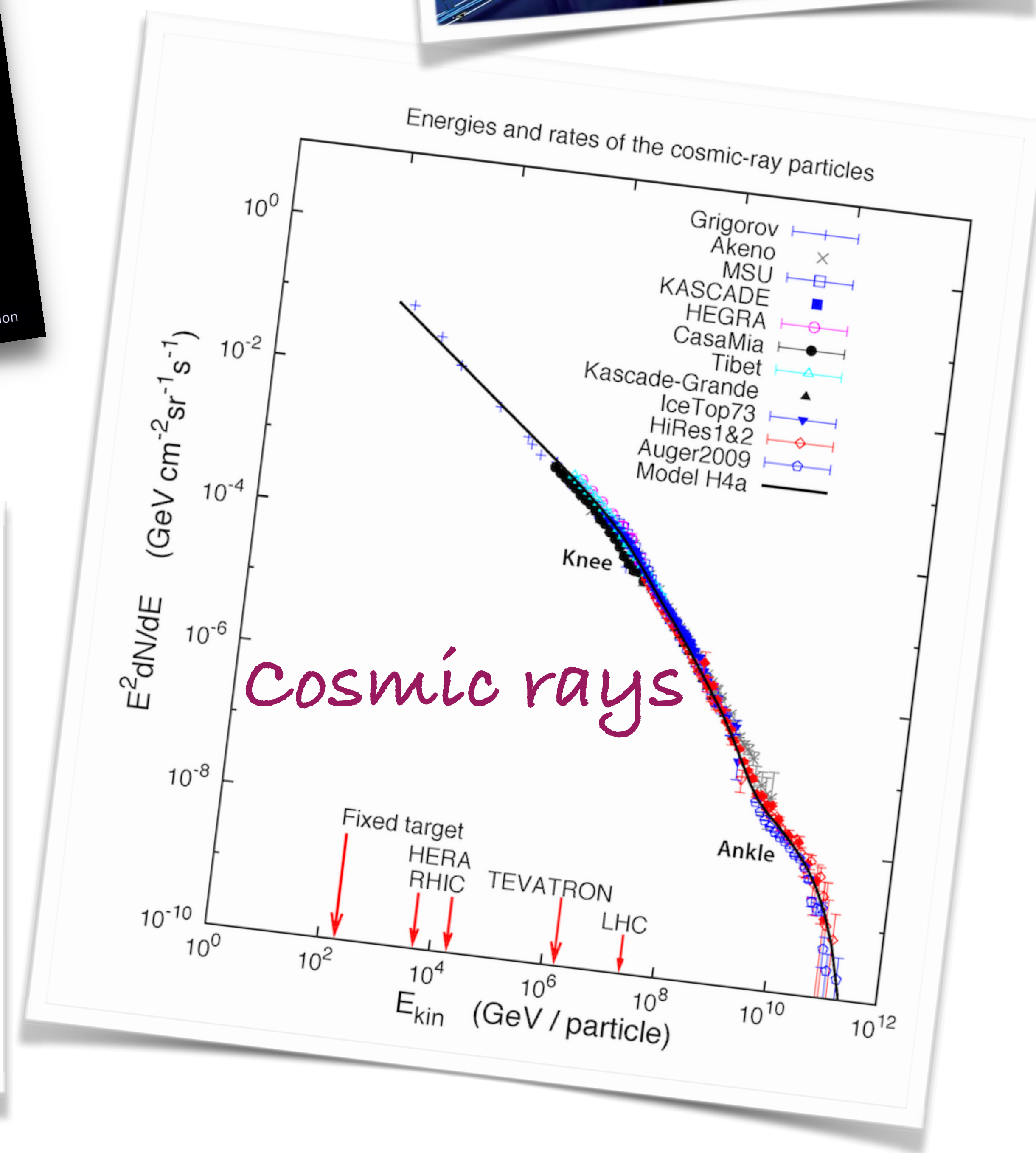
High-energy neutrinos from blazars

Fabrizio Tavecchio
INAF-OAB

Particle accelerators in the sky

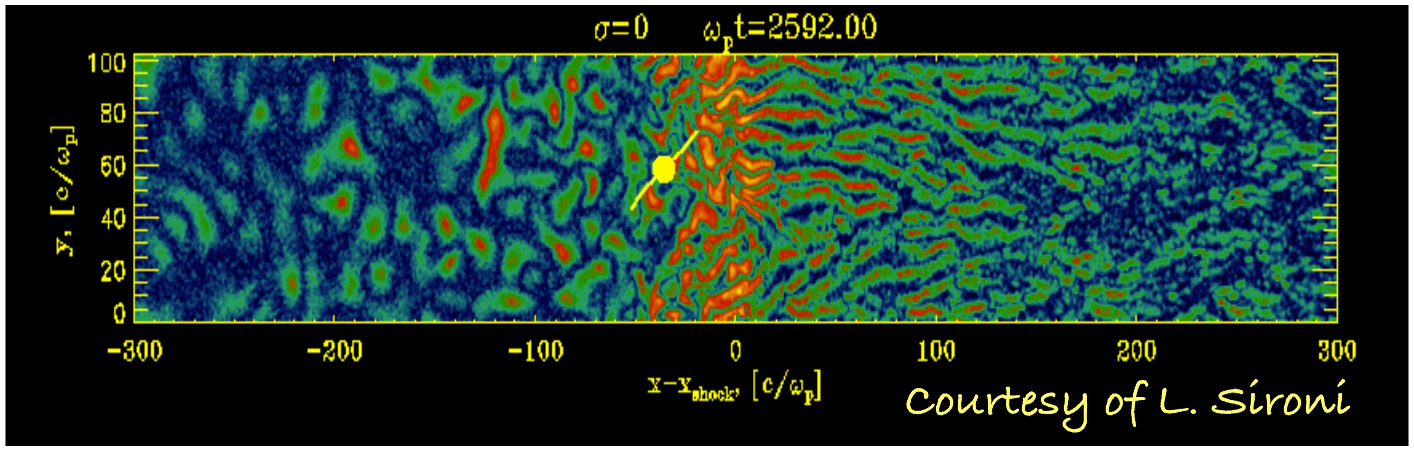






Particle accelerators in the sky

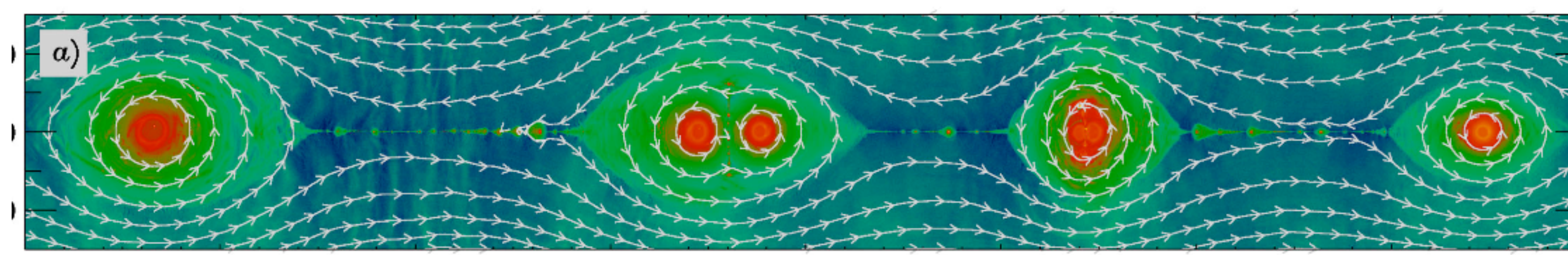
Diffusive shock acceleration (Fermi I)?



SNR, Jets, PWN, GRB
Compact galactic objects

Bell 1978
Blandford & Ostriker 1978

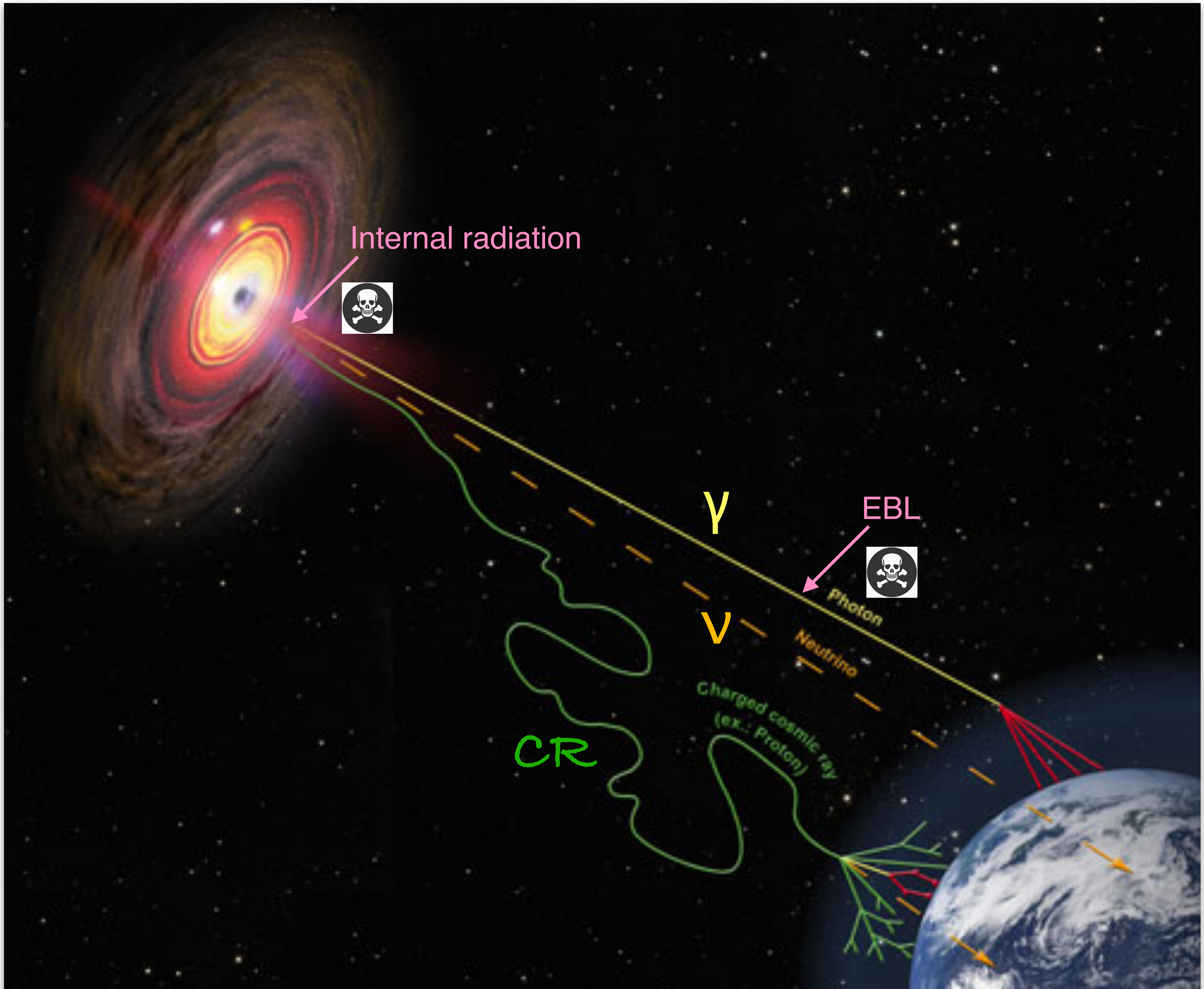
Magnetic reconnection?



Jets, PWN, GRB?

Drenkhan 2002
Giannios 2011
Sironi et al. 2015

Messengers from cosmic accelerators



HE neutrinos: probes of hadronic accelerators

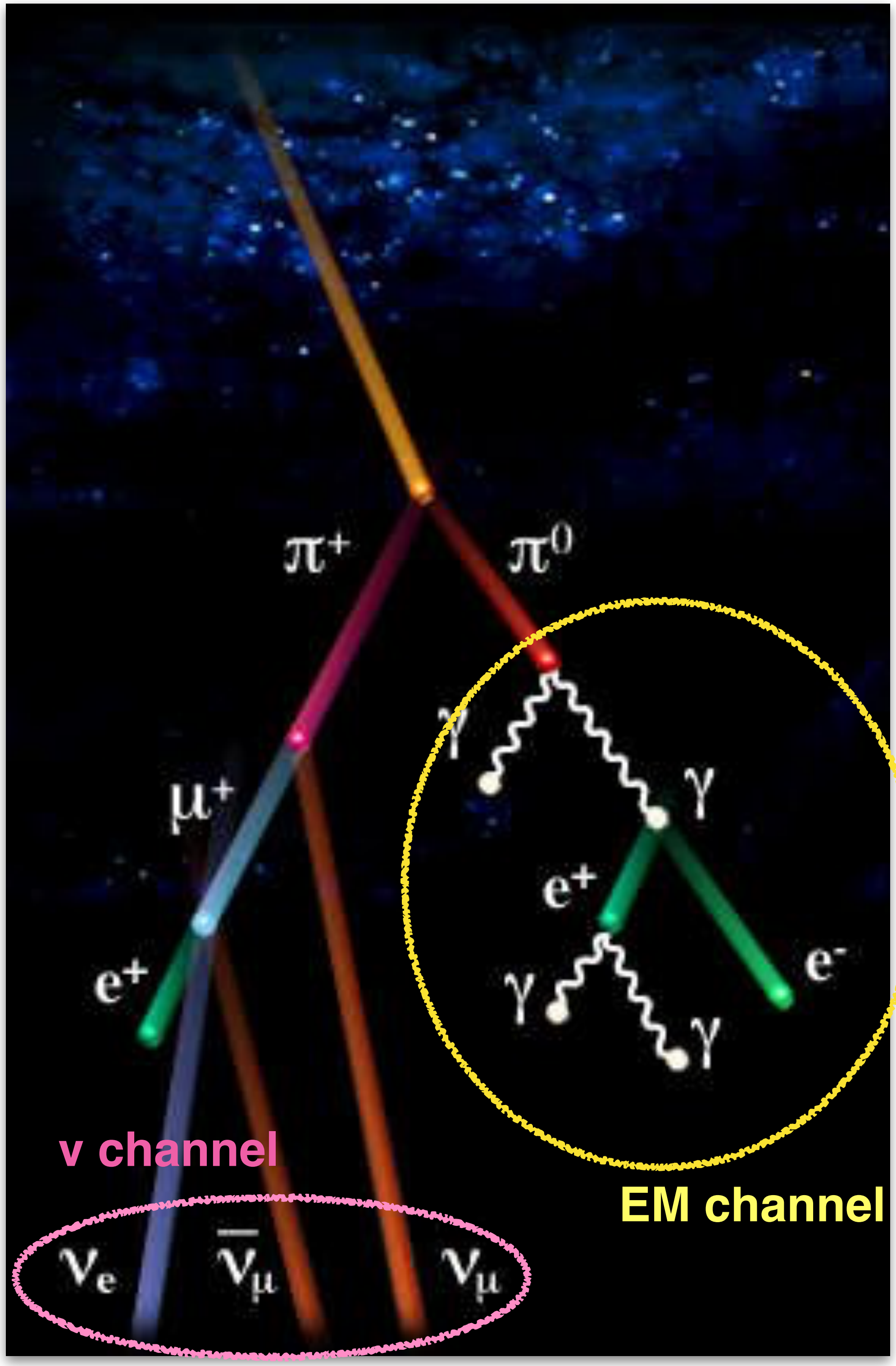
Ingredients:

high-energy protons (nuclei)

+

Targets: matter, photons

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



Astrophysical production in a nutshell

proton-proton (pp)

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

proton-photon (pγ)

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \rightarrow 2\gamma$$

Astrophysical production in a nutshell

proton-photon (pγ)

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

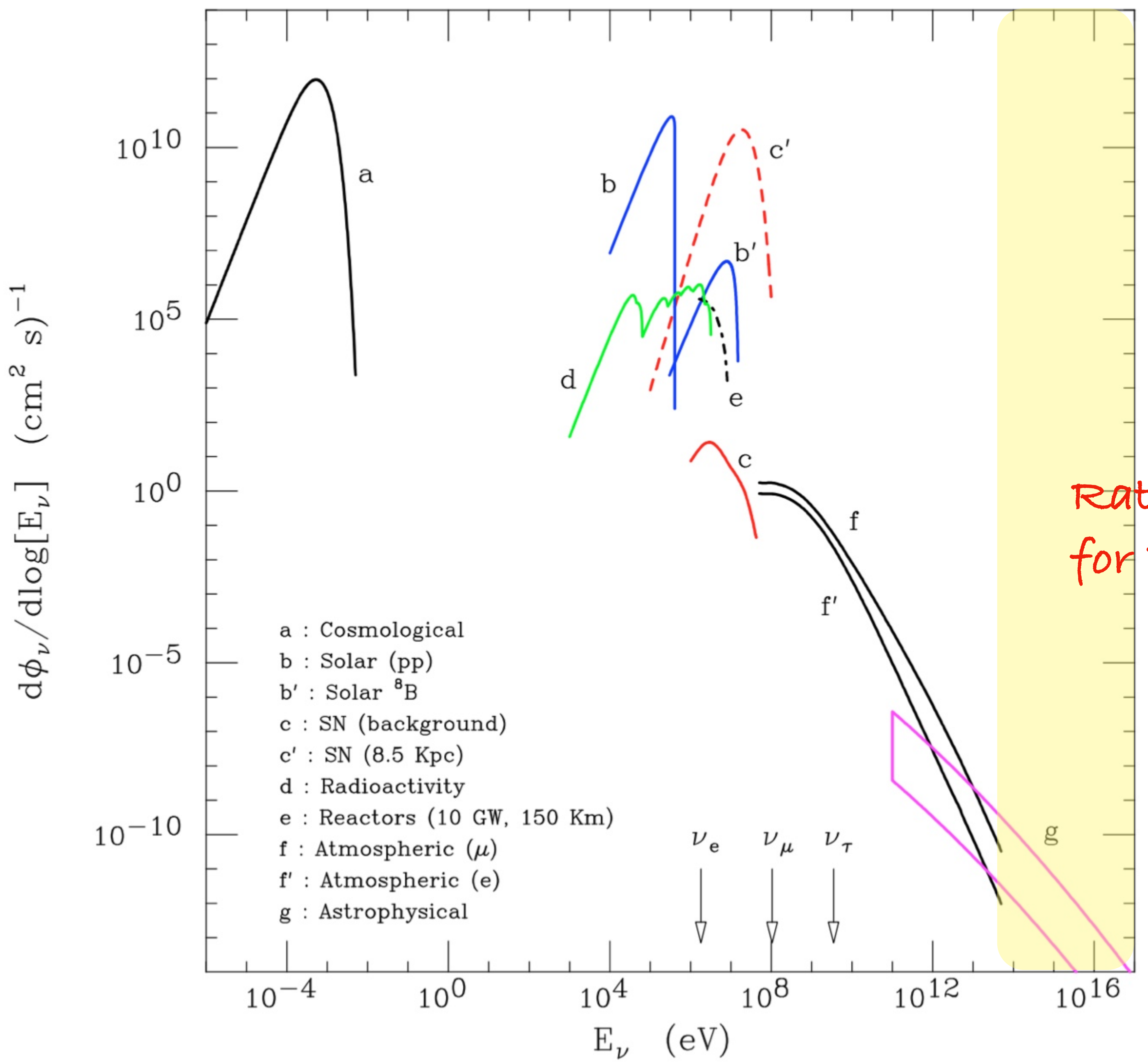
$$p + \gamma \rightarrow p + \pi^0$$

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

Ep~20 Ev

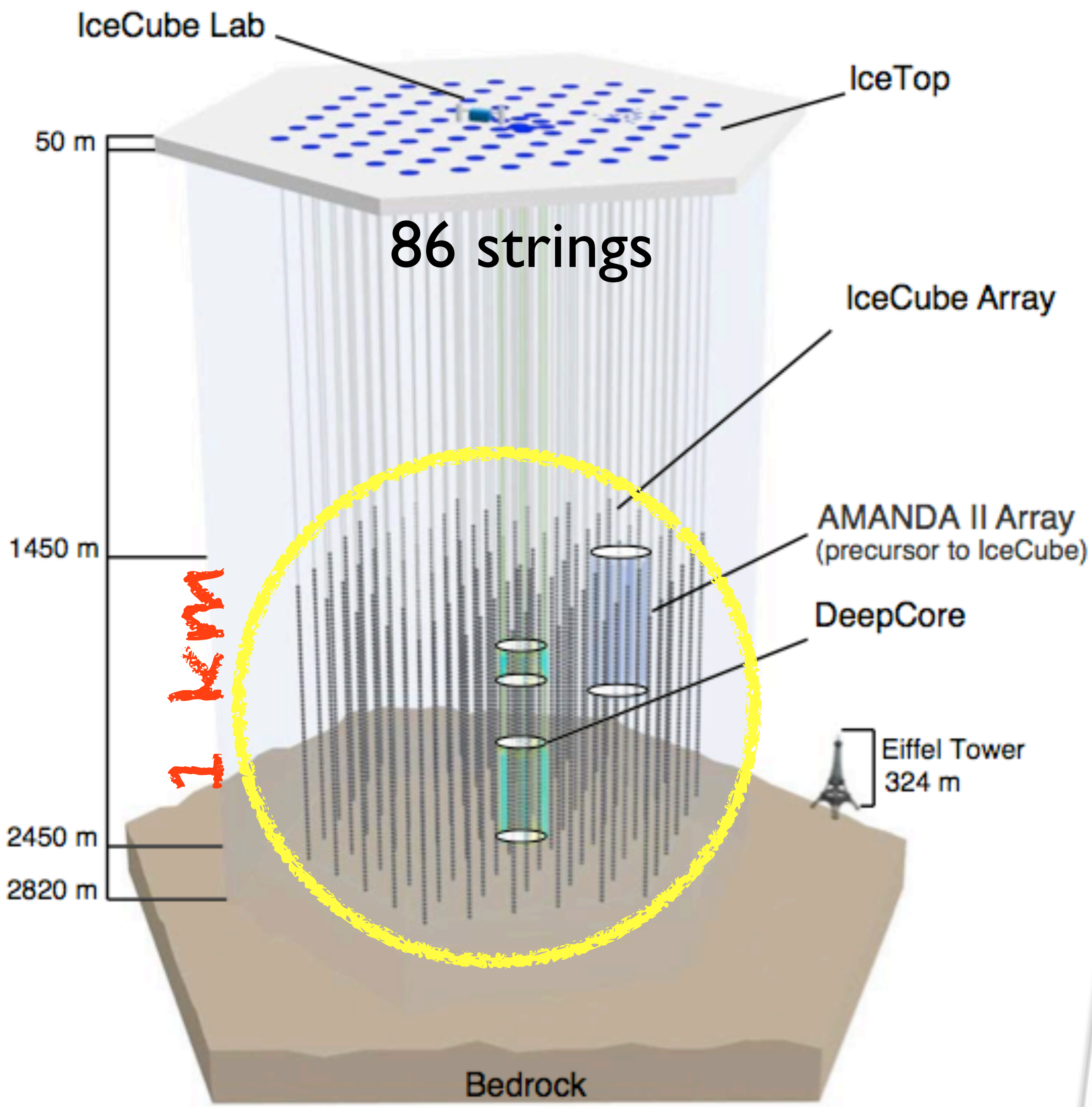
Lγ~Lν

E> 100 TeV



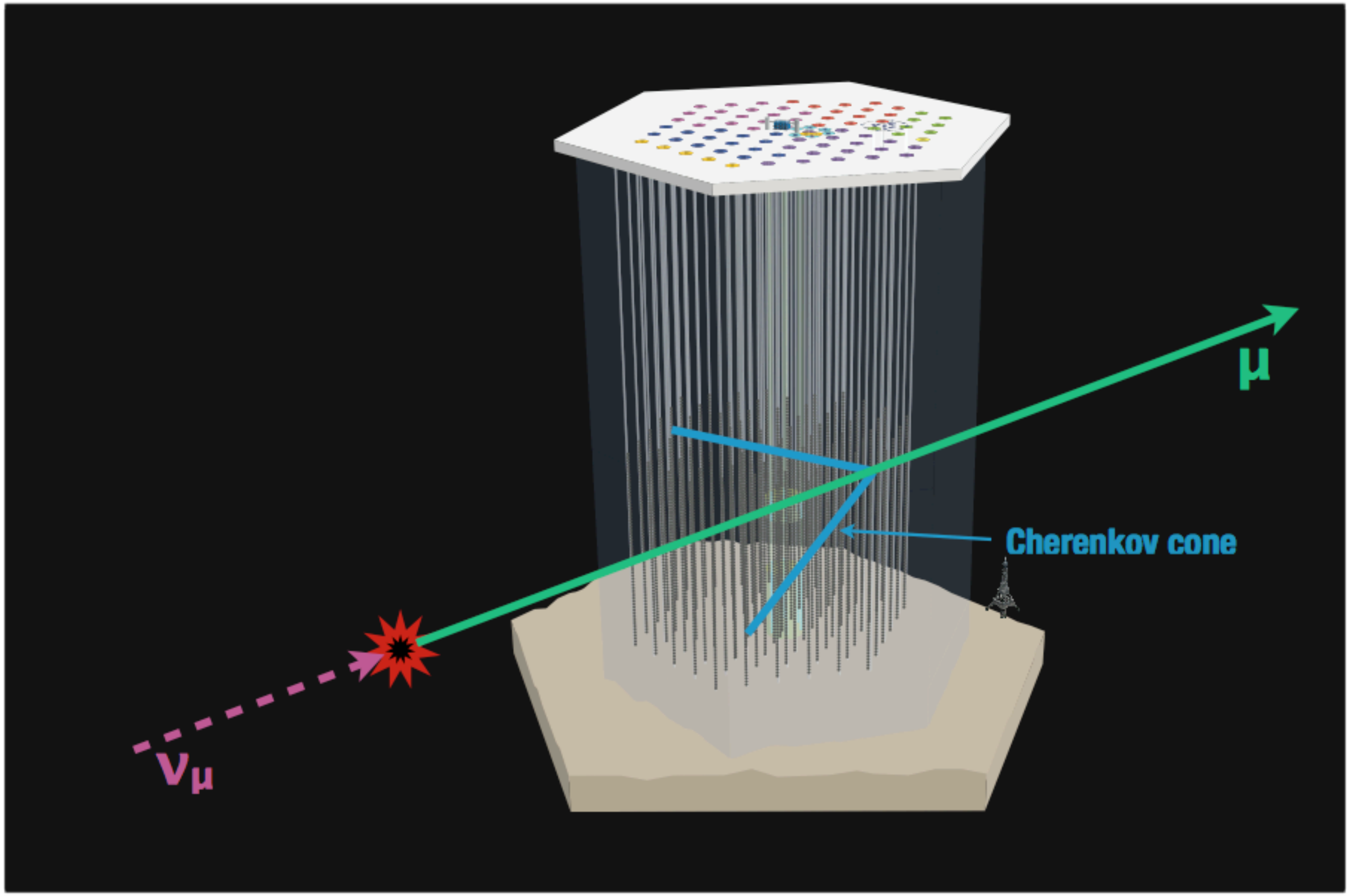
Rate~few tens/y
for V=1km3

IceCube



@ South Pole
(Amundsen-Scott)

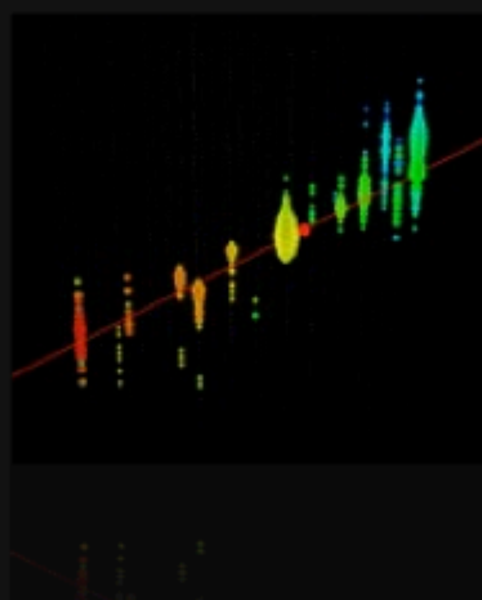
IceCube



IceCube

Kopper 2014

CC Muon Neutrino

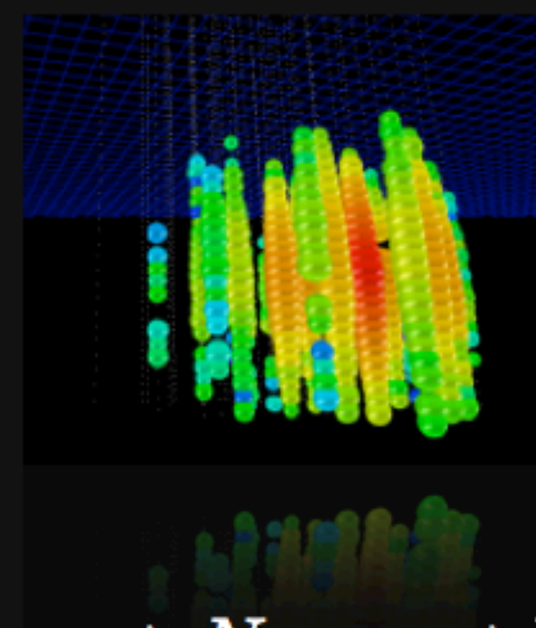


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current / Electron Neutrino



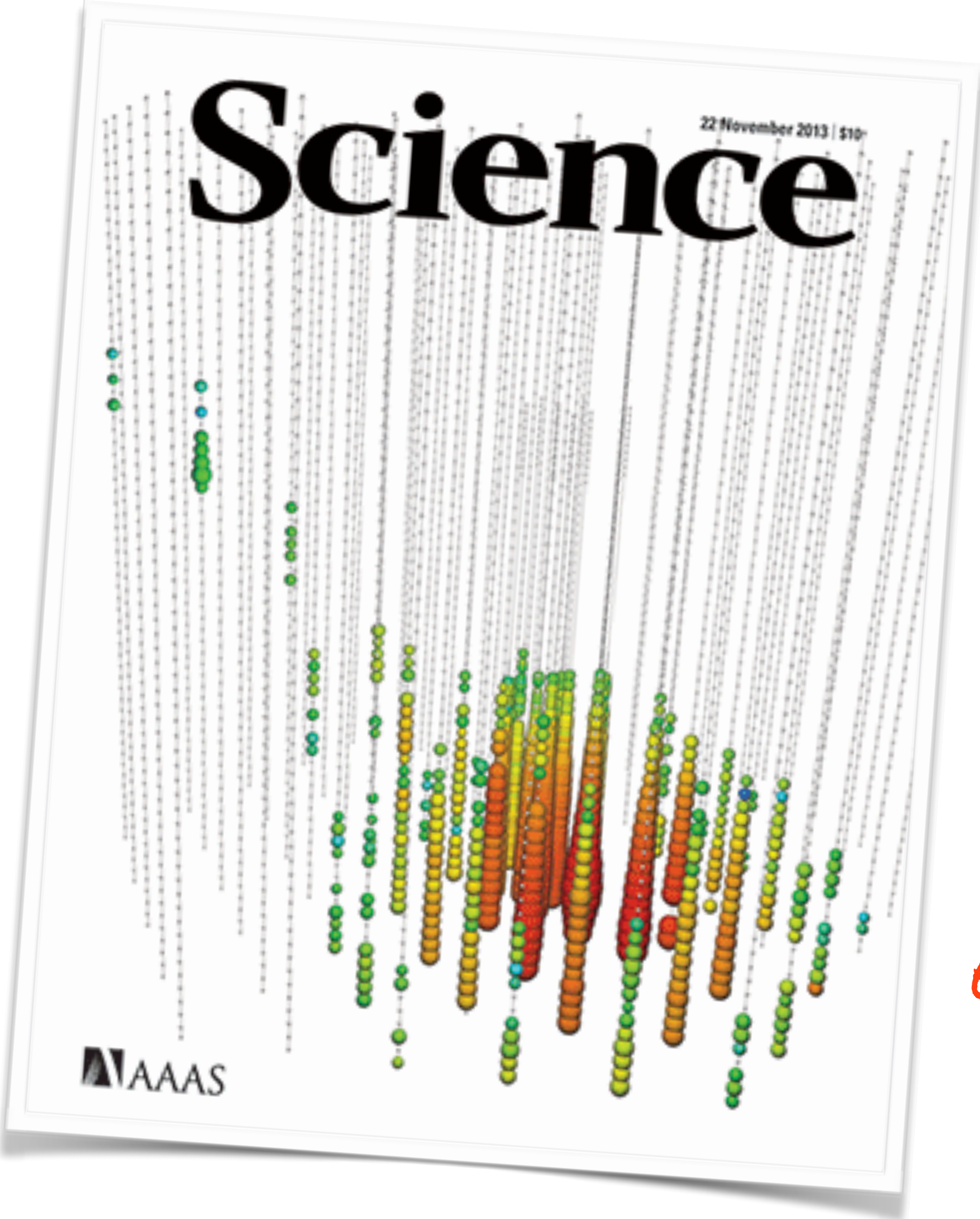
$$\nu_e + N \rightarrow e + X$$

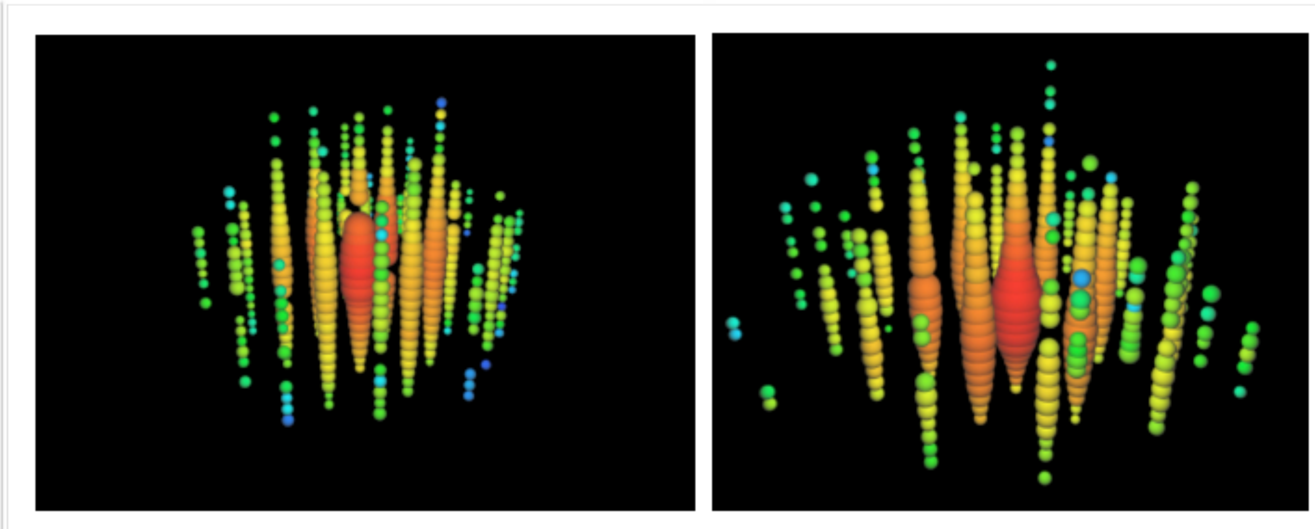
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

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

Discovery of high-energy neutrinos



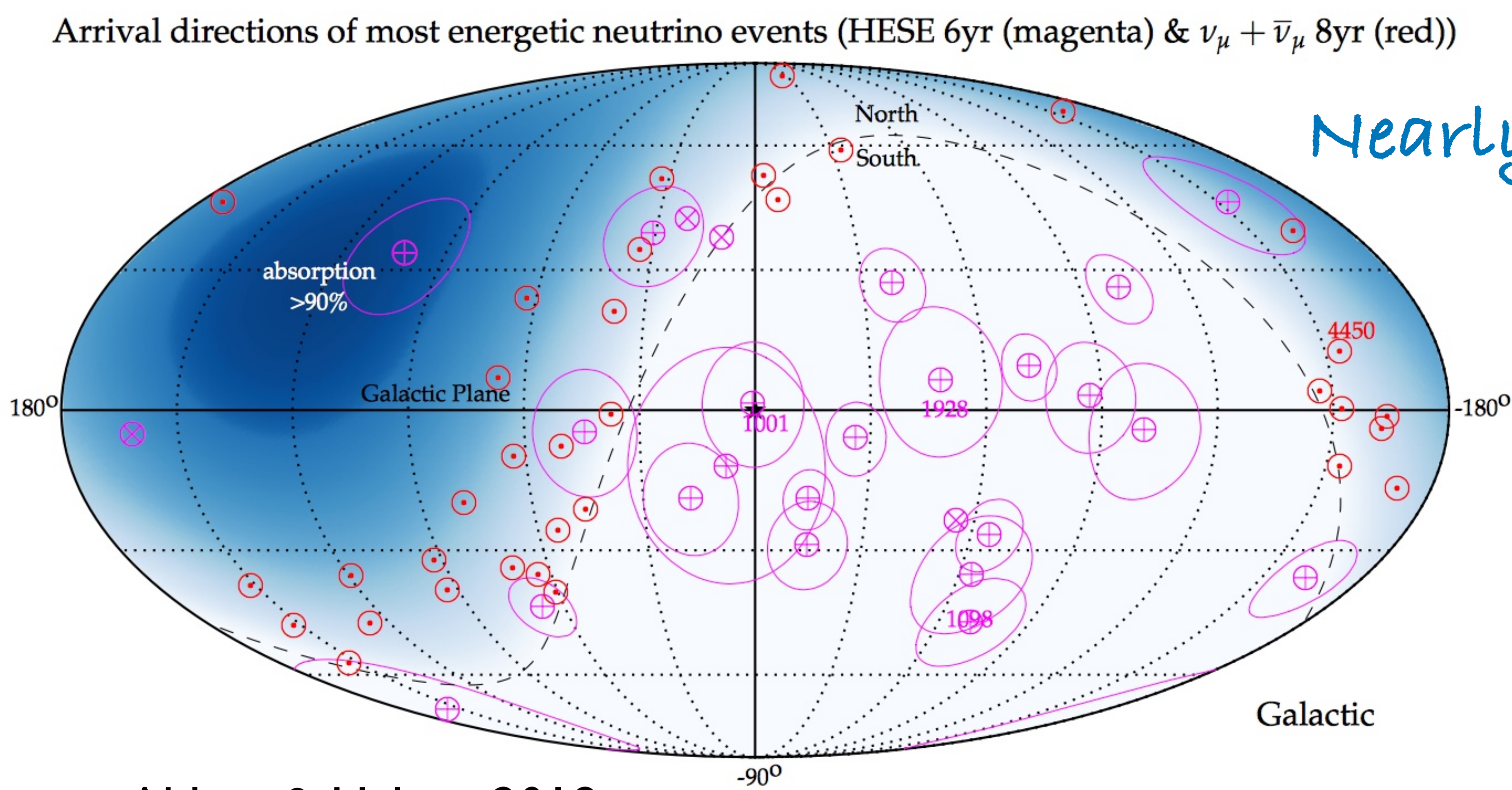


28 events (21 shower)
May 2010-May 2012

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

Abbasi et al. 2013

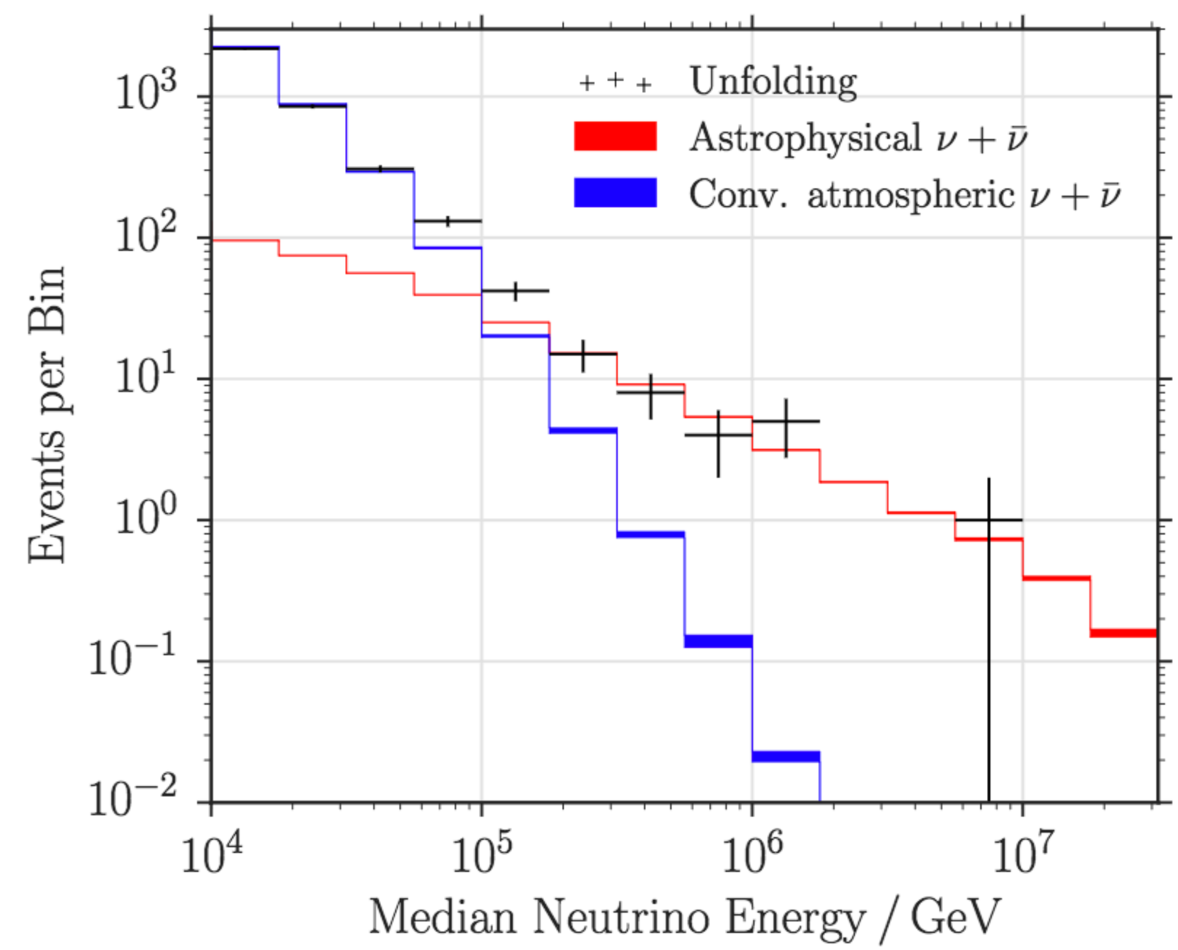
Current status



Nearly isotropic

Ahlers & Halzen 2018

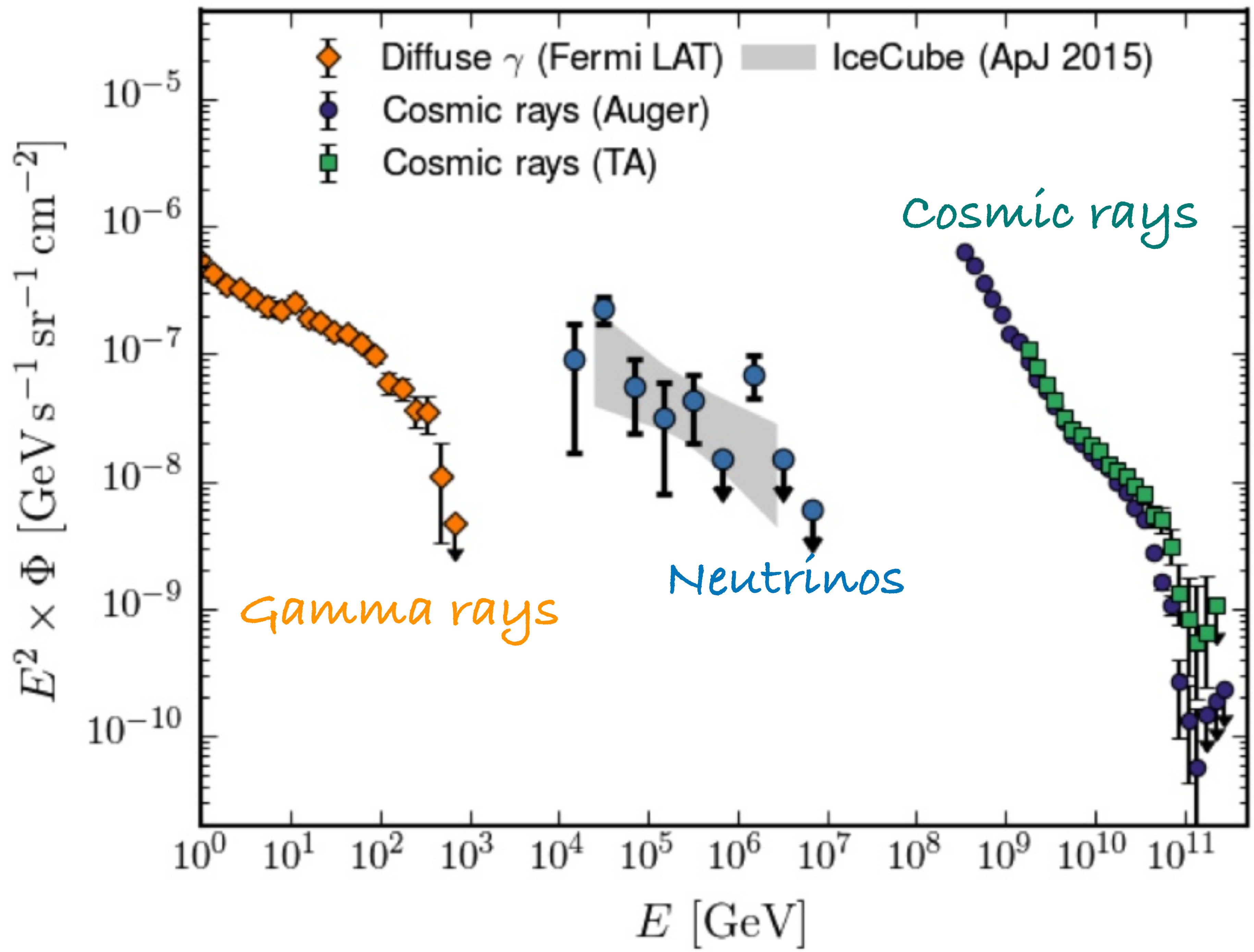
About 80 (tracks) events



Aartsen et al. 2016

Current status

Gaisser 2018



"Multimessenger sky background"

Potential source(s)

Ingredients:

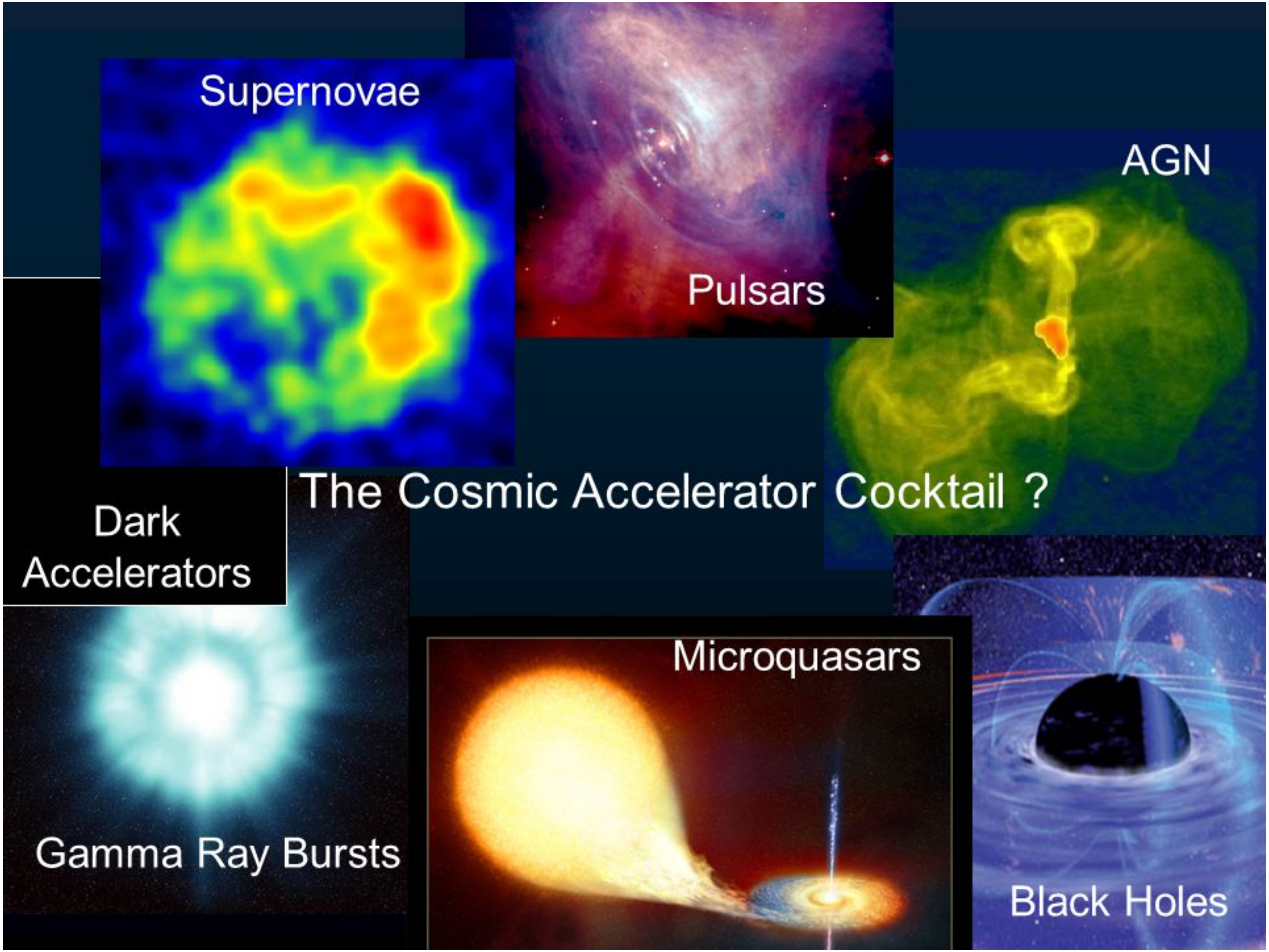
high energy protons (nuclei) → Injected luminosity, spectrum, maximum energy

+

Targets: matter, photons

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

Potential source(s)



Constraints on cosmic populations

Measured

Cosmic density

Averaged luminosity

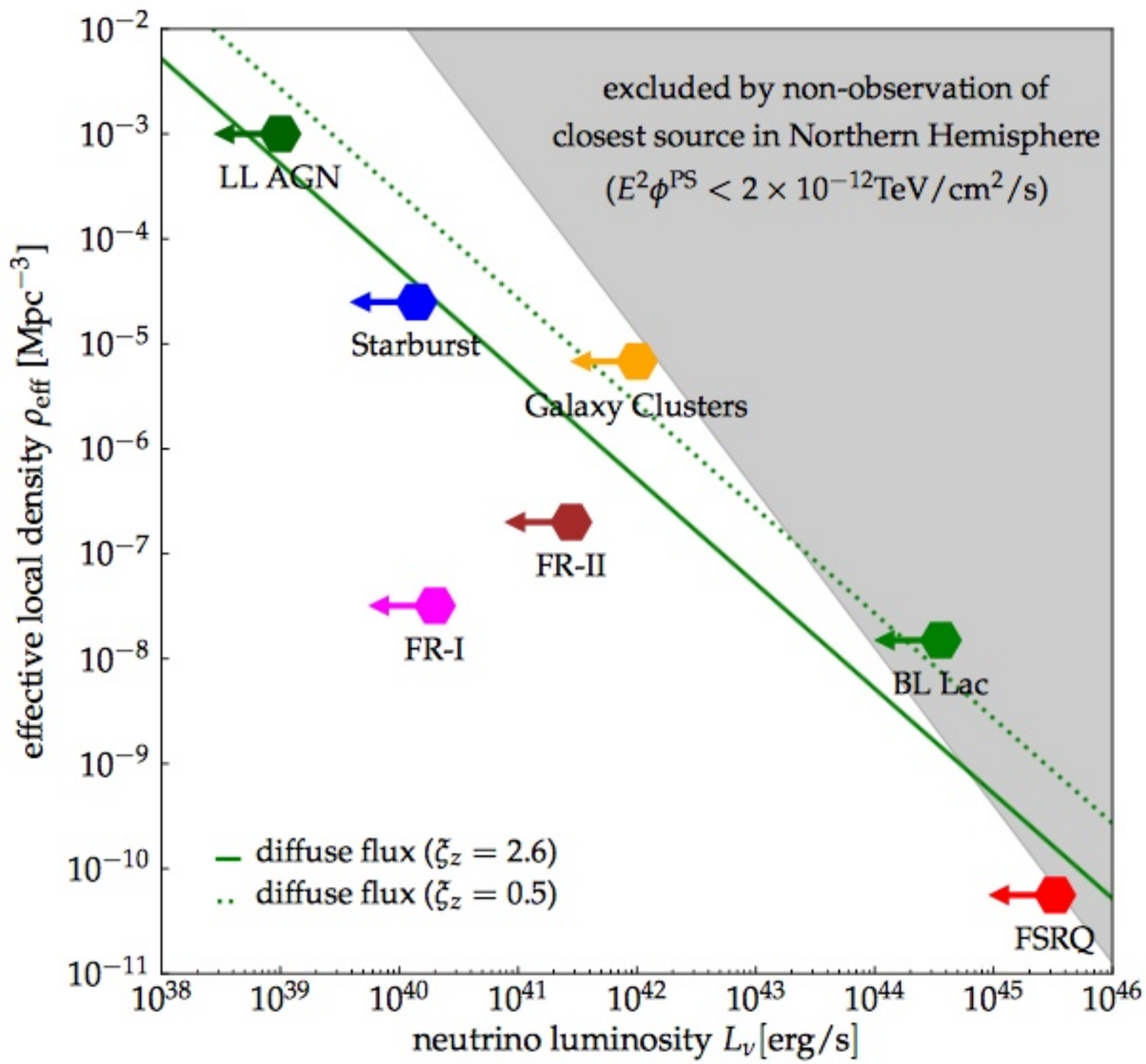
$$\phi_\nu \approx \frac{c}{4\pi H_0}\,\xi_z\,\rho_0 L_\nu$$

Evolution

Assuming a single population

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

Constraints on cosmic populations



Kowalski 2015

Ahlers & Halzen 2018

See also Murase & Waxman 2016
Palladino & Vissani 2017

The prime suspects

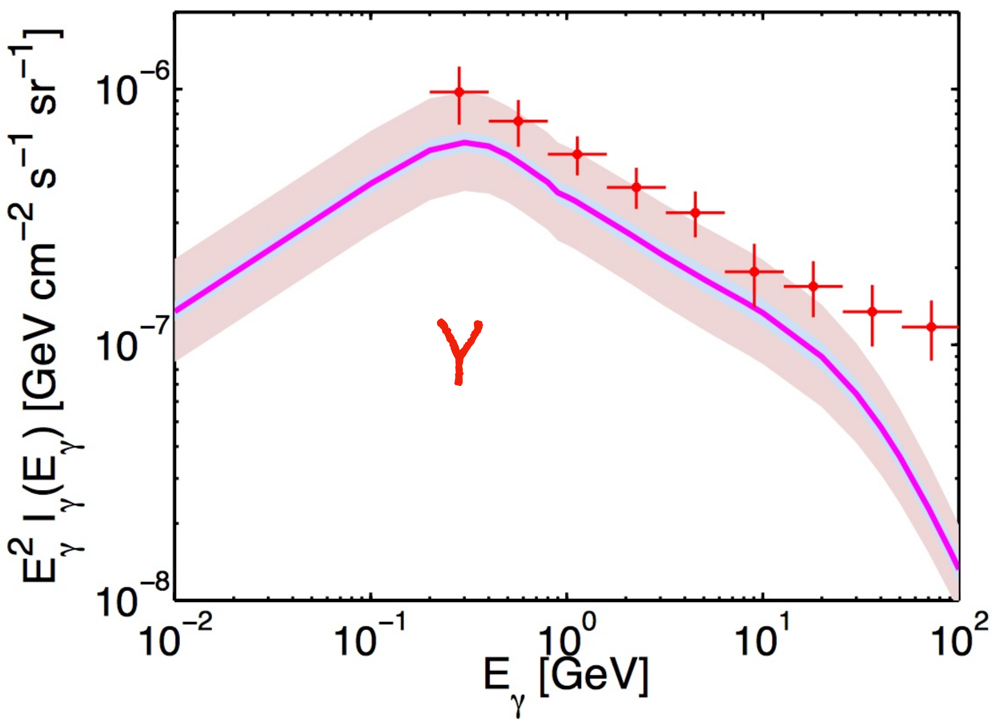
Starburst/Star forming galaxies?

Loeb & Waxman 2006
Tamborra et al. 2014

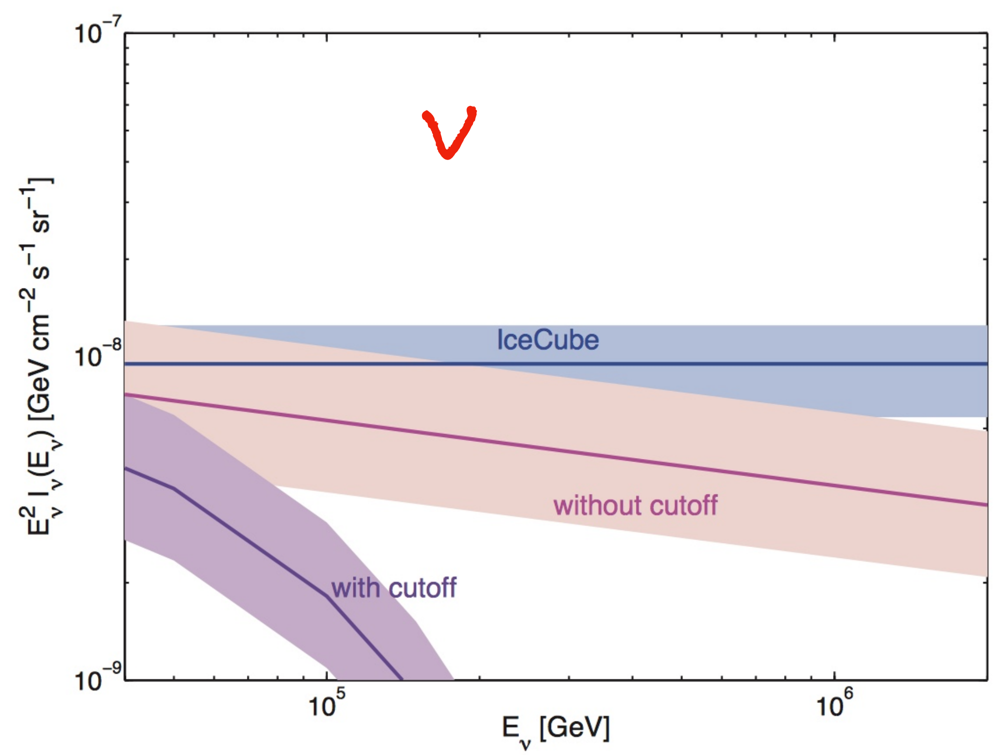
CR accelerated in SNR + dense gas

The prime suspects

Starburst/Star forming galaxies?



Ep>10[16] eV?



Tamborra et al. 2014

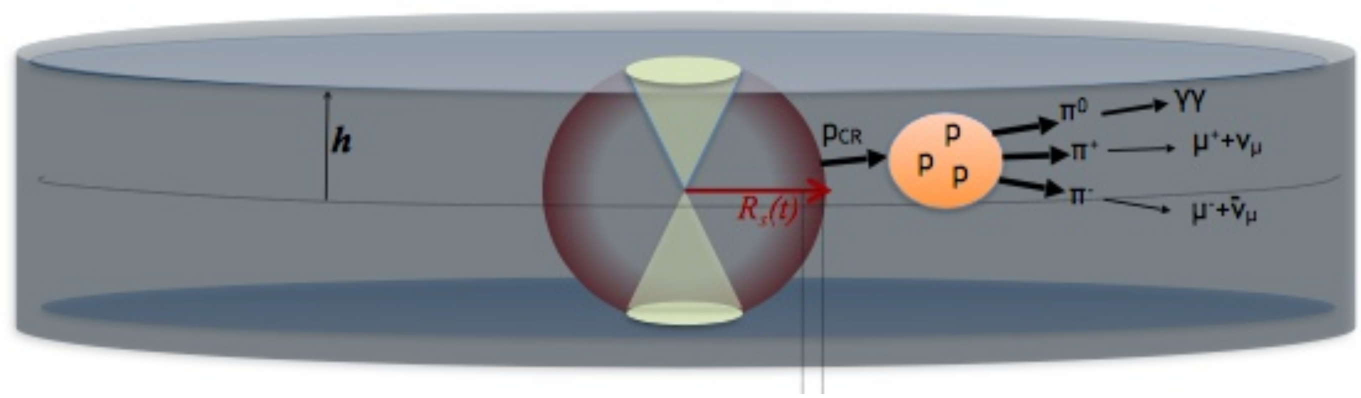
Difficult to obtain a direct association (low fluxes!)

The prime suspects

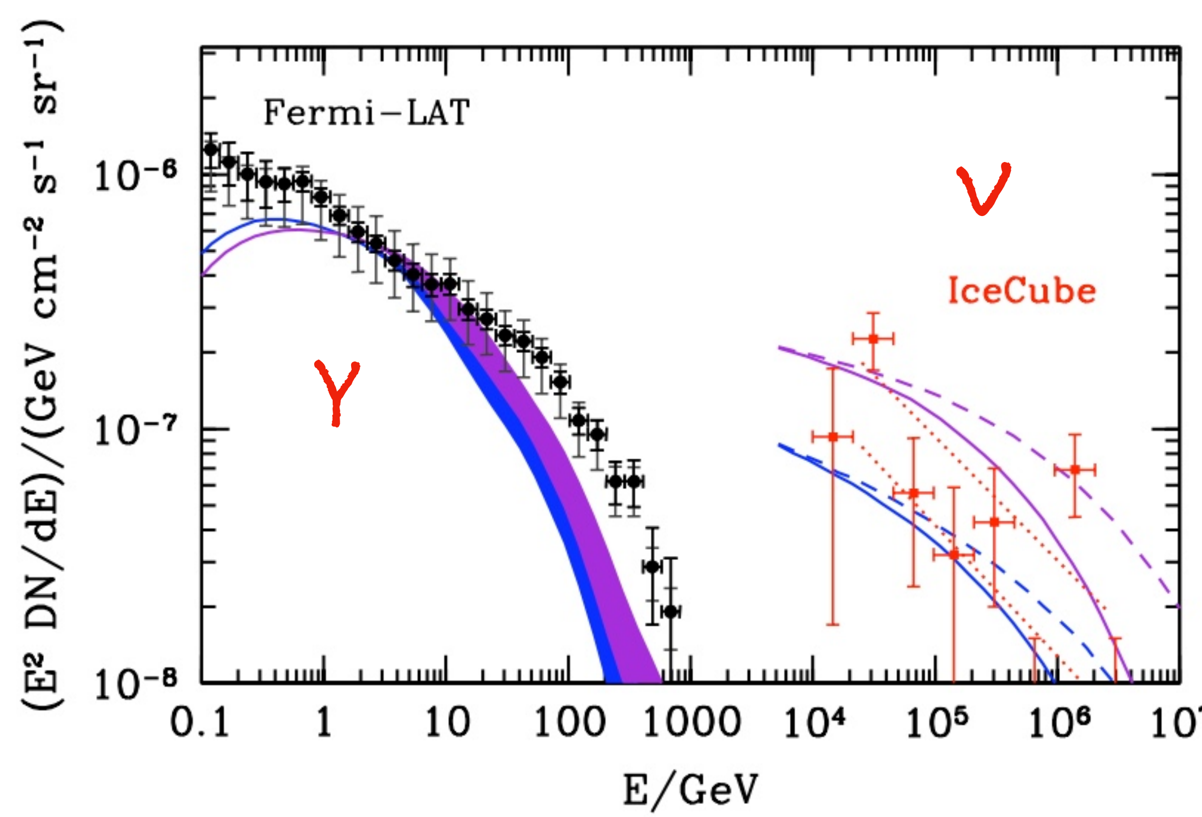
AGN-driven winds/outflows?

Wang & Loeb 2016
Lamastra et al. 2016, 2017

But see Padovani et al. 2018



CR accelerated in the shock wind + dense gas

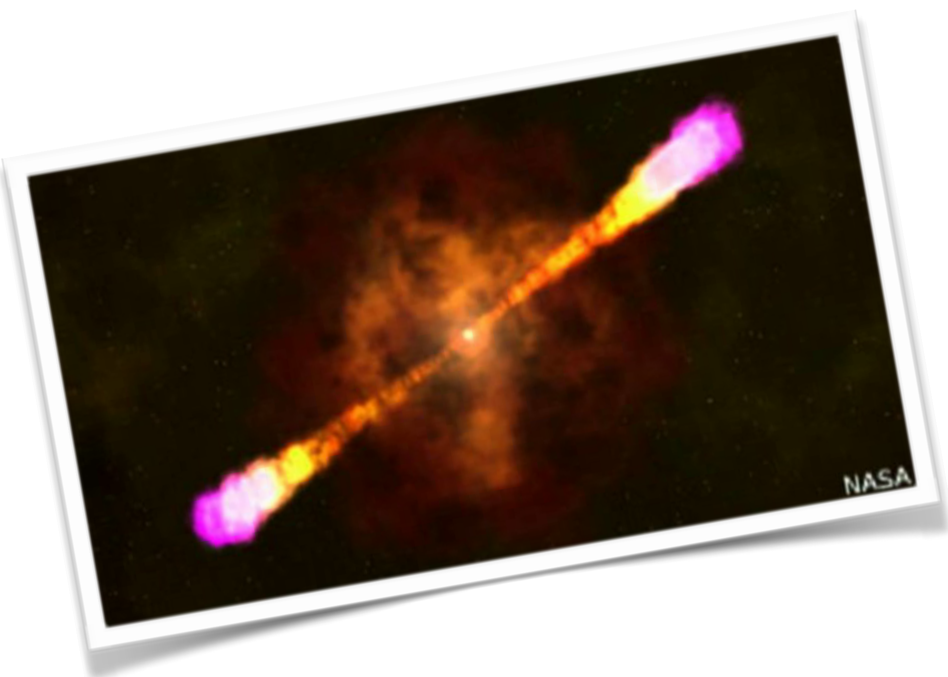


The prime suspects

CR accelerated in shocks + radiation

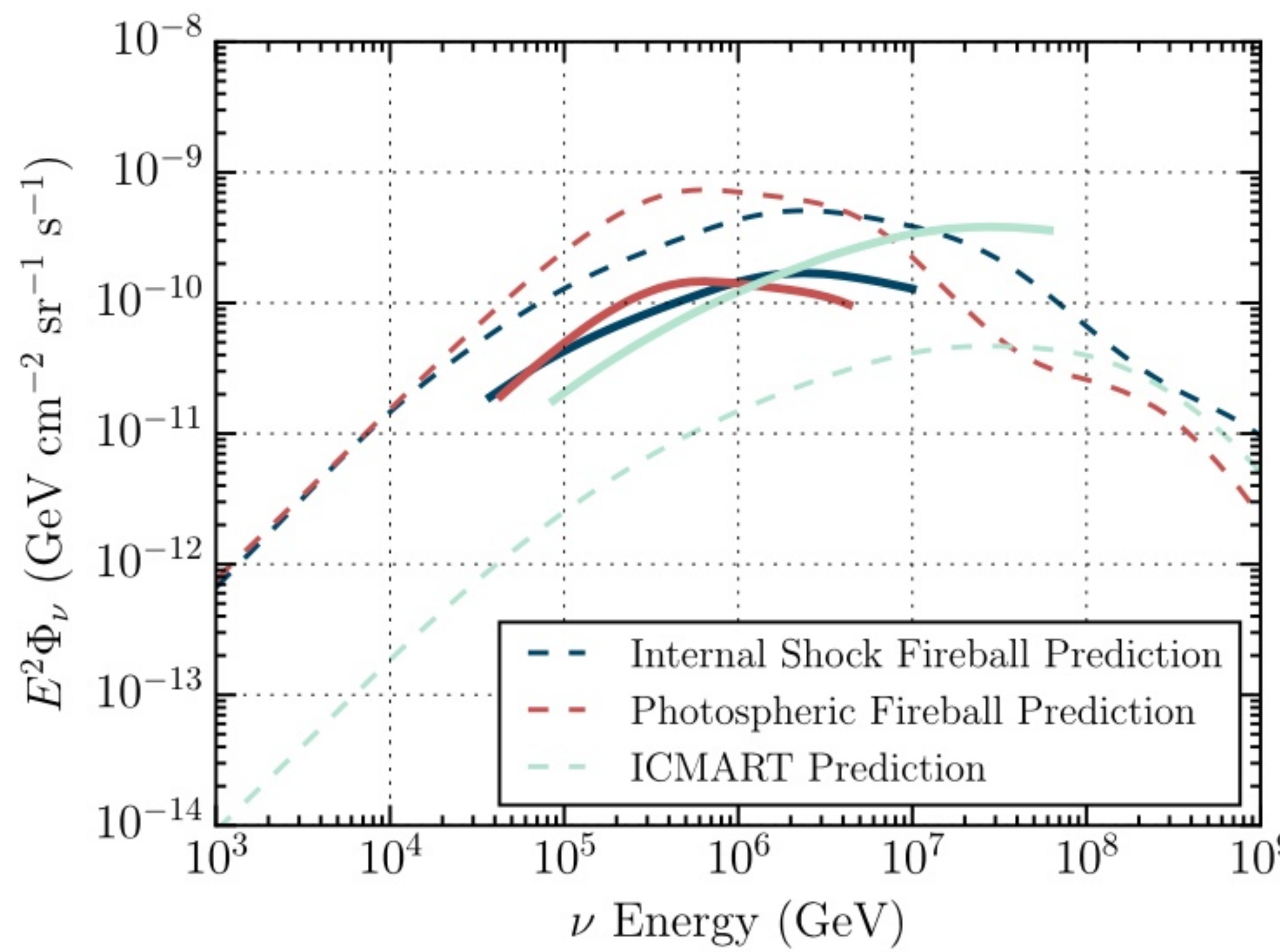
Gamma-ray bursts?

Waxman & Bahcall 1997



Probably no...

Aartsen et al. 2017

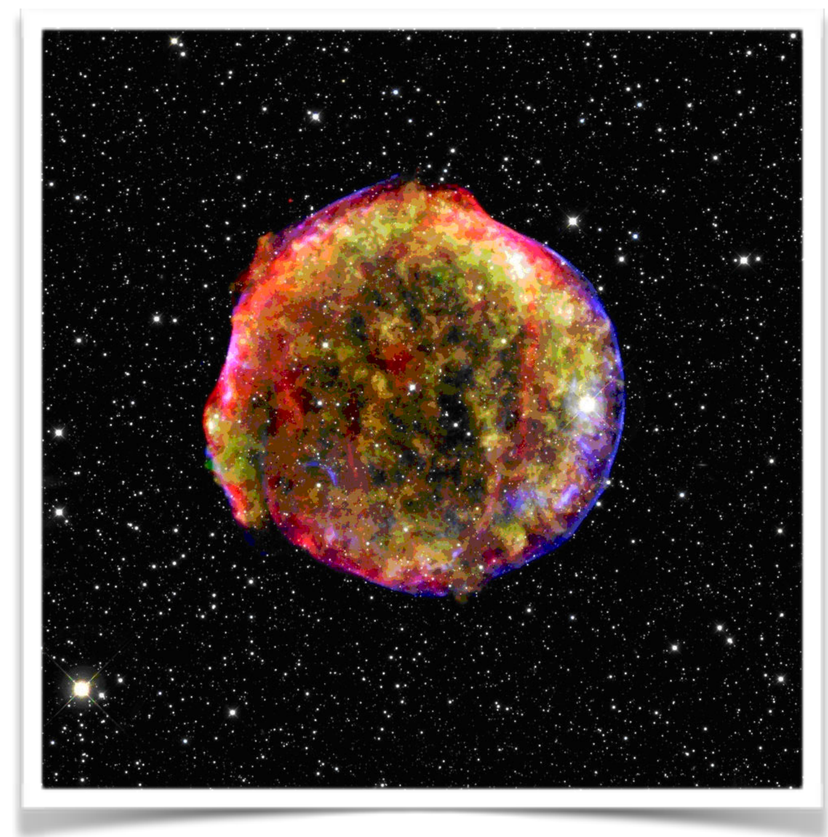


The prime suspects

Tidal disruption events?

Guepin et al. 2018

SN IIn?



Petropoulou et al. 2017

The prime suspects

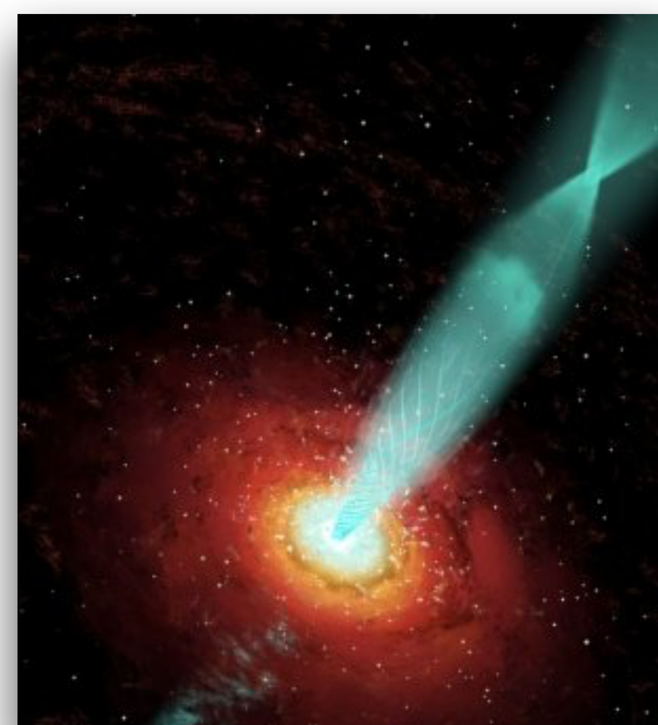
Relativistic jets: radiogalaxies?

CR accelerated in shocks + gas in the jet

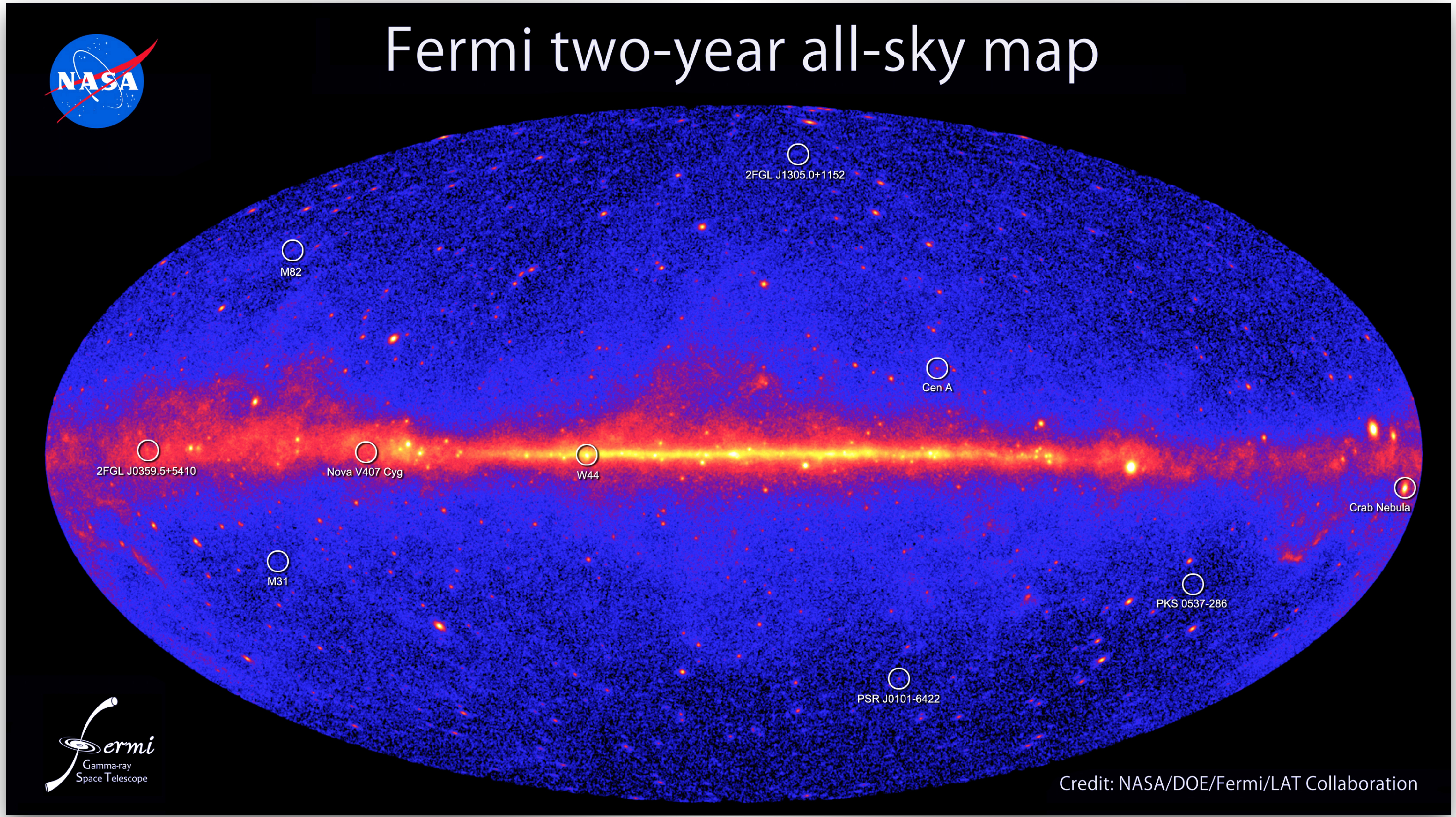
Becker-Tijus 2004

CR accelerated in shocks + gas in the host

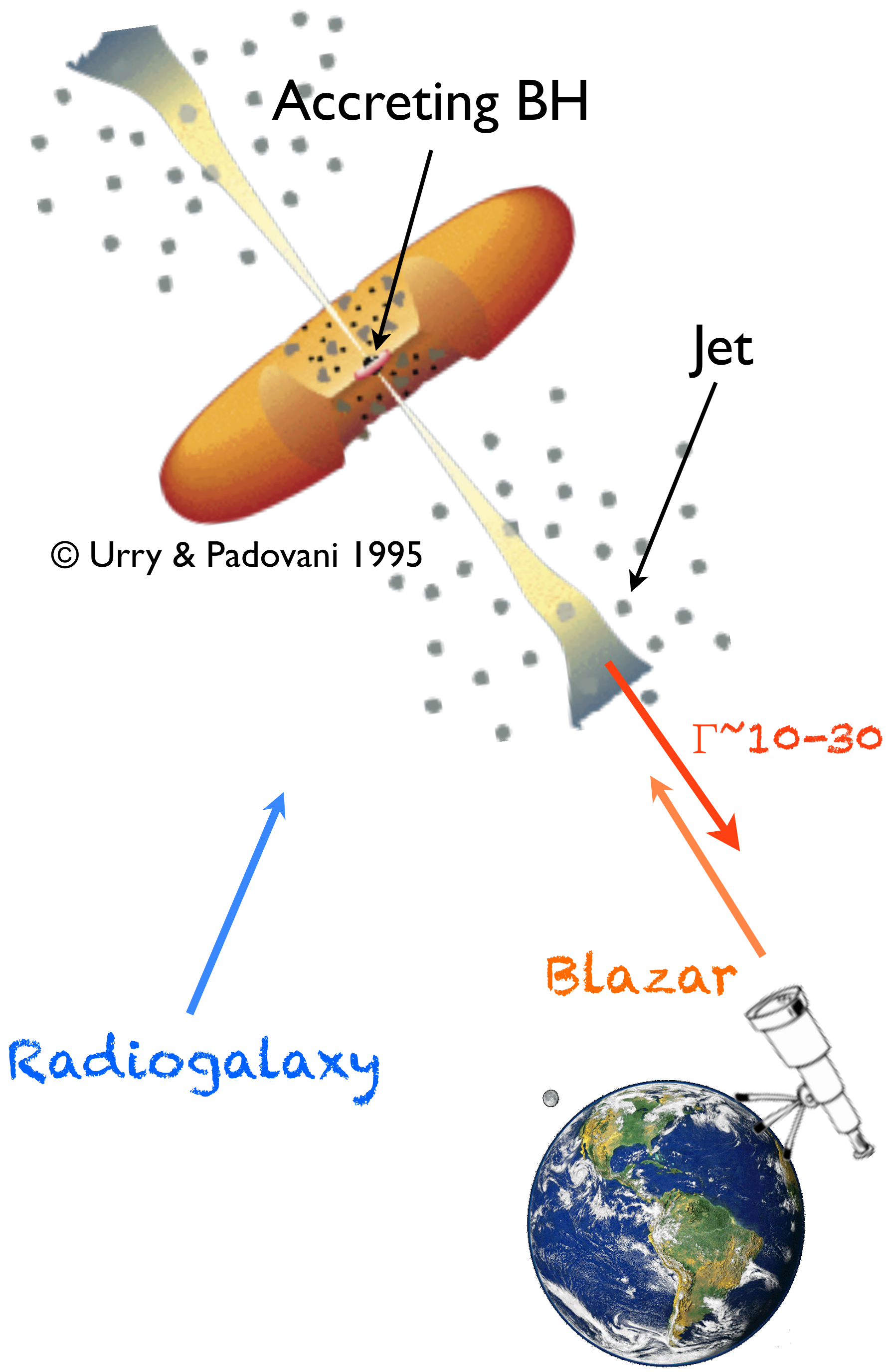
Tavecchio et al. 2018

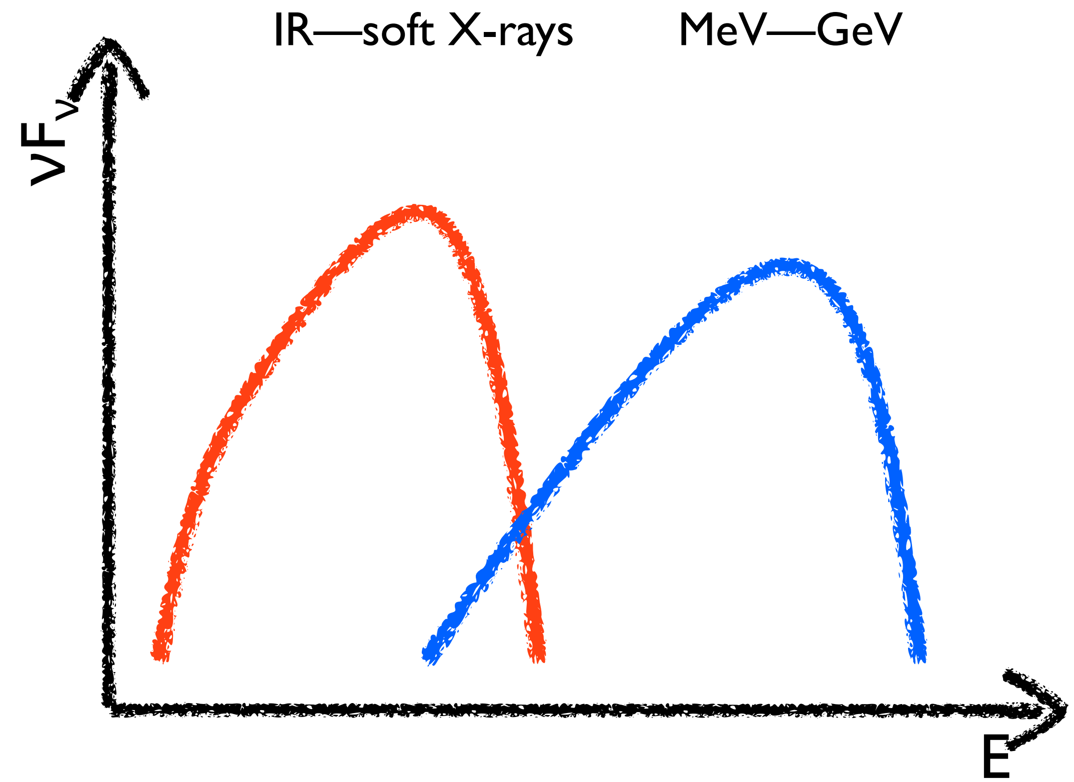


Neutrinos from blazar jets?



Blazars in a nutshell





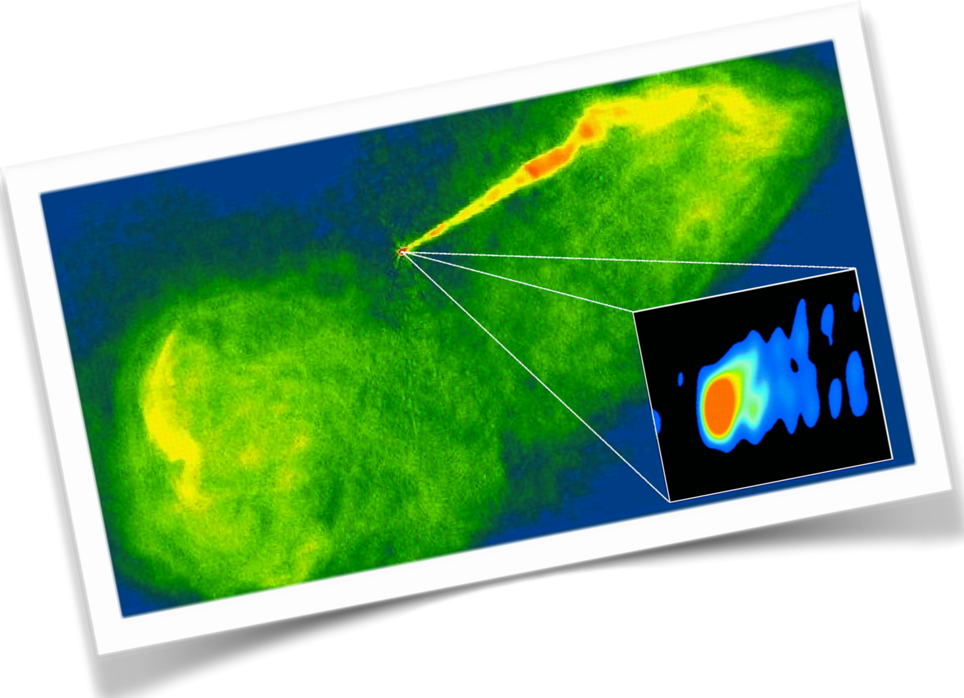
SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

$$L_{\rm obs} = L'\delta^4 \qquad \delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

$$\delta \approx 10 - 20$$

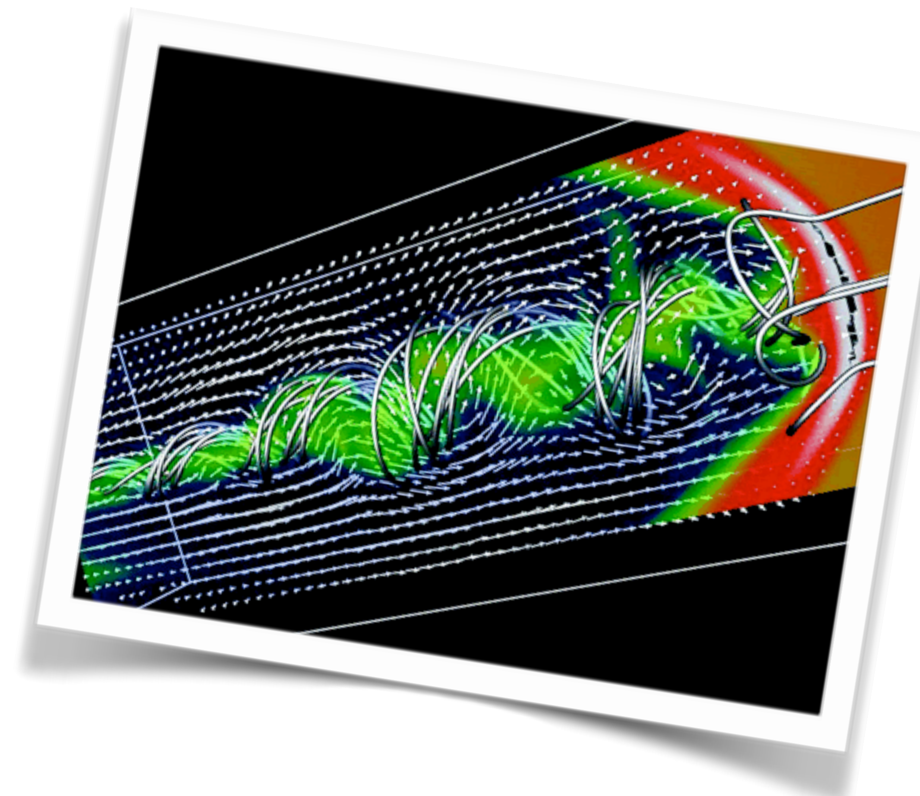
Synchrotron and IC in LEPTONIC models.

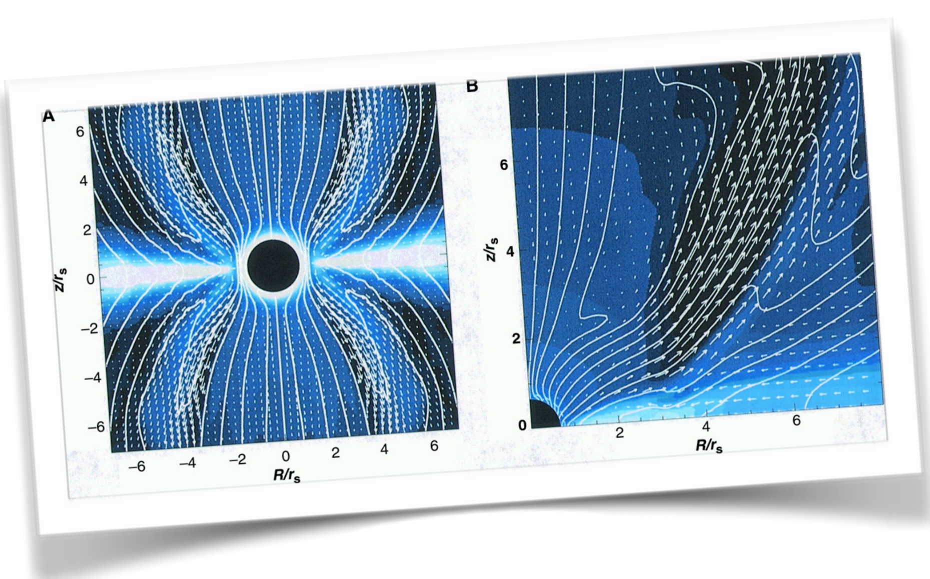
Also HADRONIC scenarios (synchrotron or photo-meson) NEUTRINOS!



Jet speed,
composition,
power

Magnetic fields,
particle acceleration
emission mechanisms





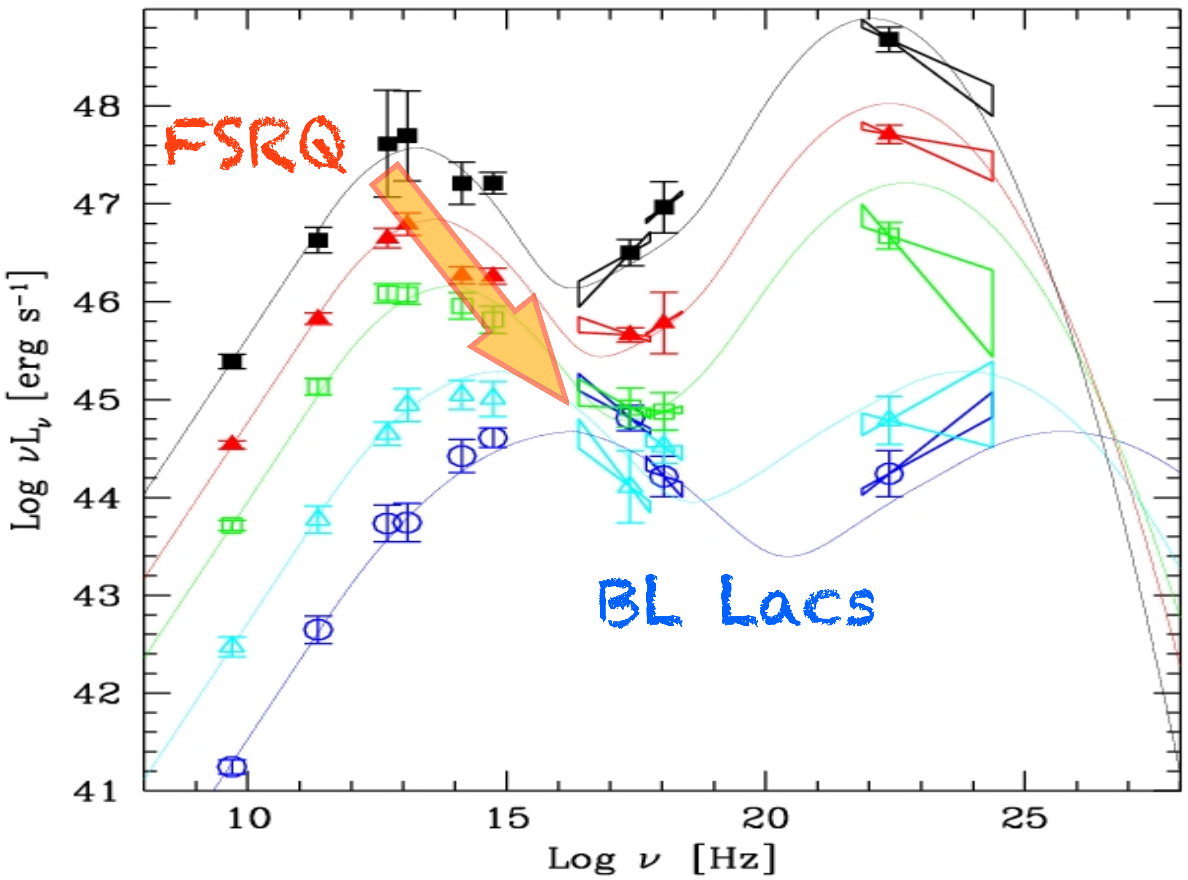
Formation, collimation,
acceleration

Blazars in a nutshell

Blazars occur in two flavors:

FSRQ: high power, thermal optical components (broad lines)

BL Lacs: low power, almost purely non-thermal components



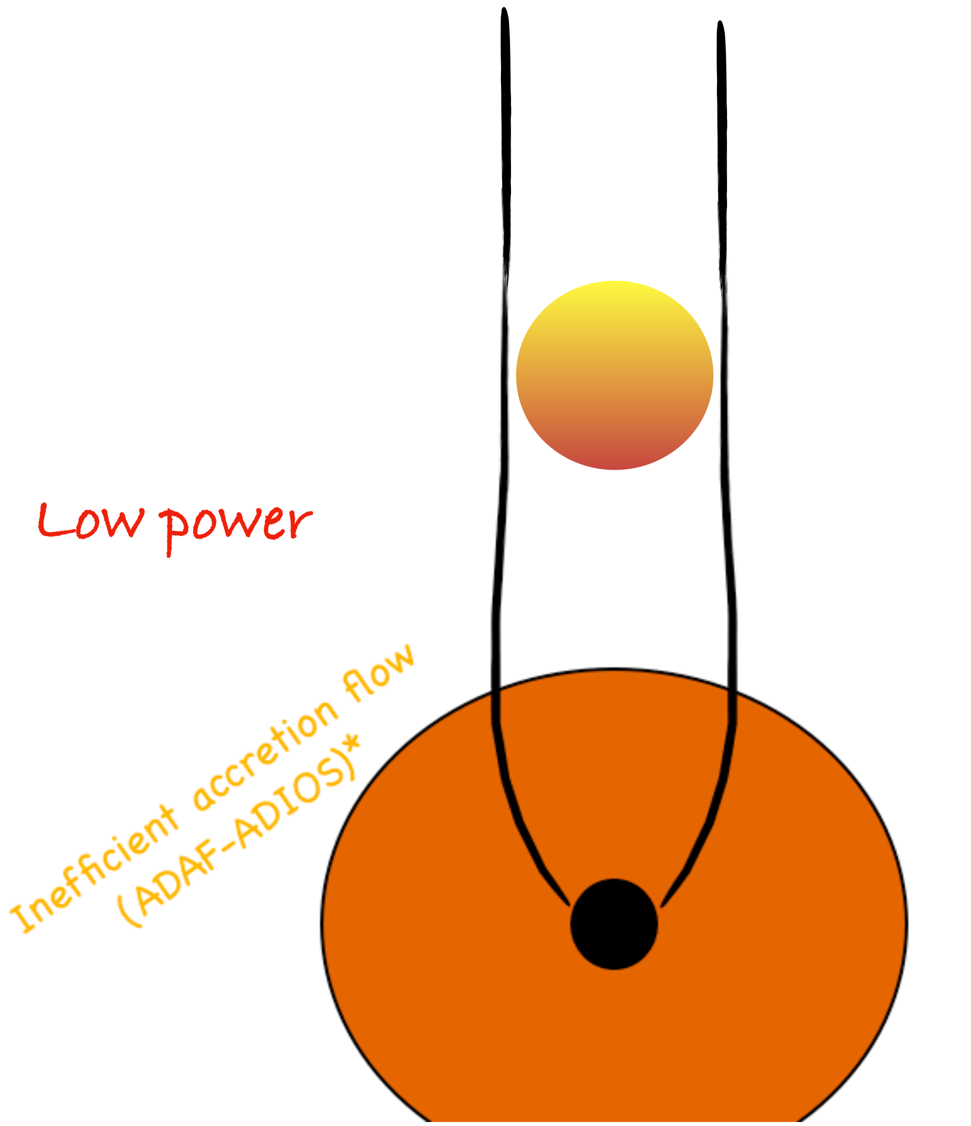
The "blazar sequence"

Fossati et al. 1998
Donato et al. 2002
Ghisellini et al. 2009

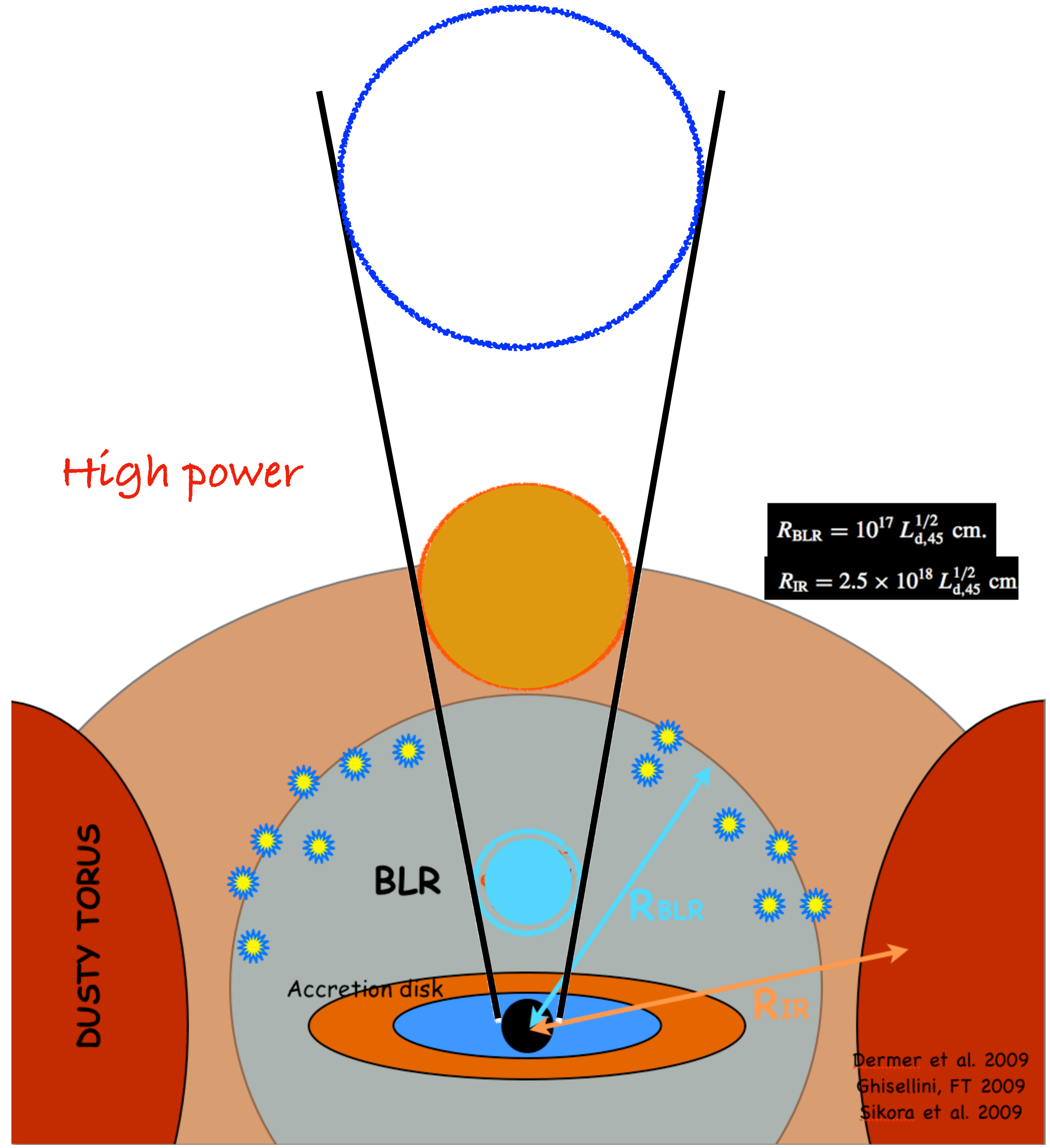
But see several papers by Giommi & Padovani

Blazars in a nutshell

BL Lacs: “naked” jets

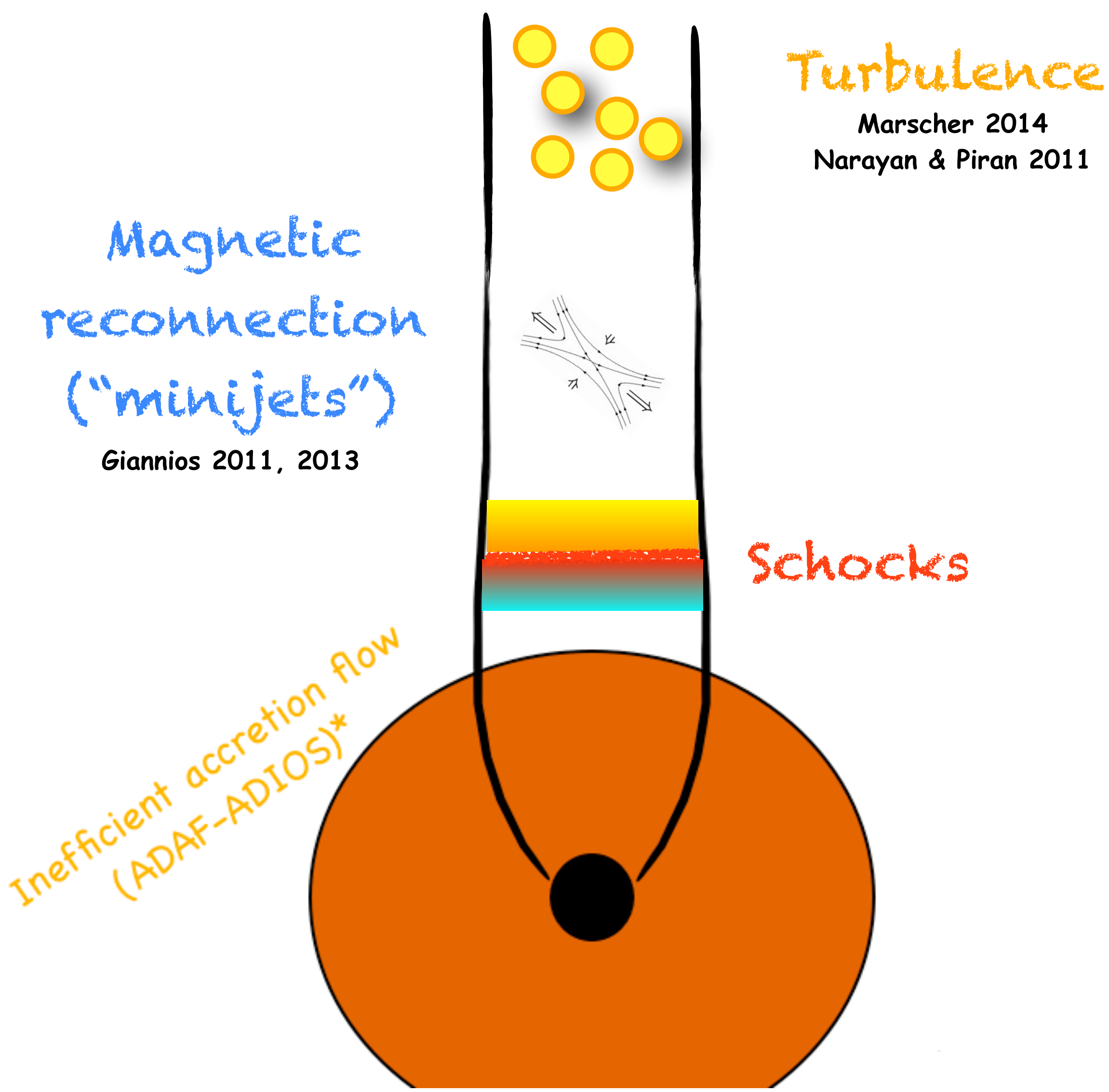


FSRQ: “dressed” jets

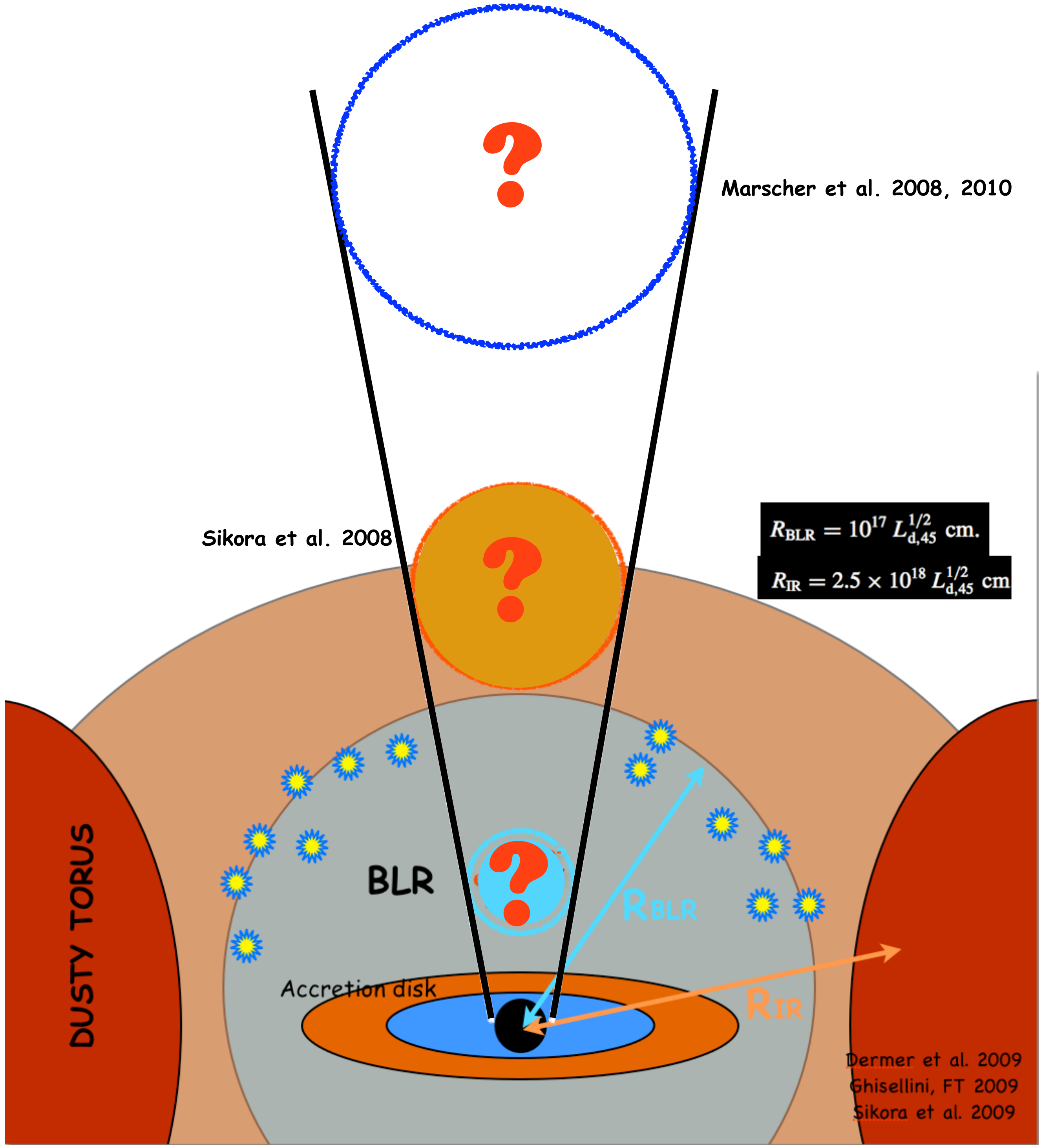


Blazars in a nutshell

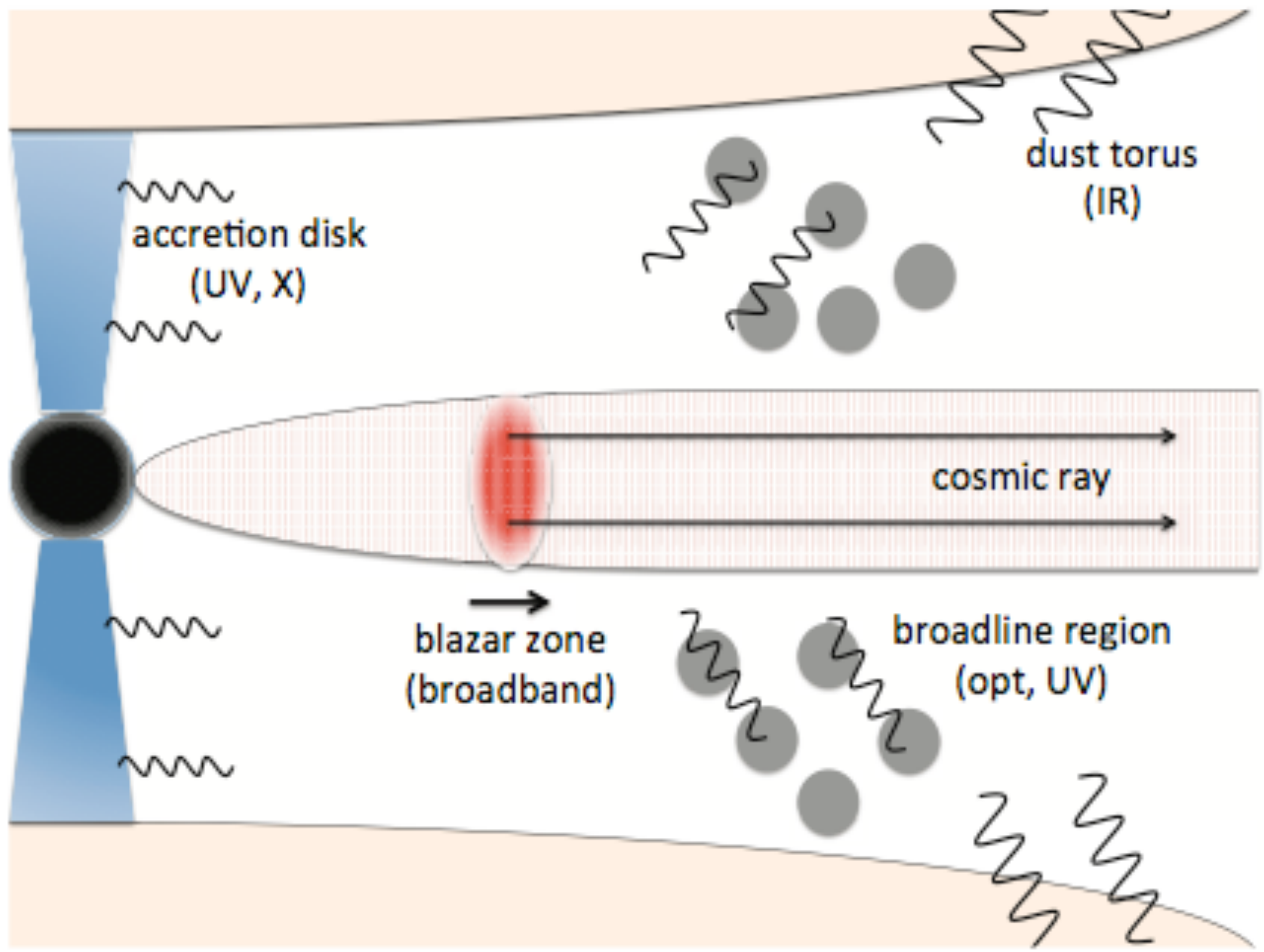
BL Lacs: "naked" jets



FSRQ: "dressed" jets



Neutrino from FSRQ?

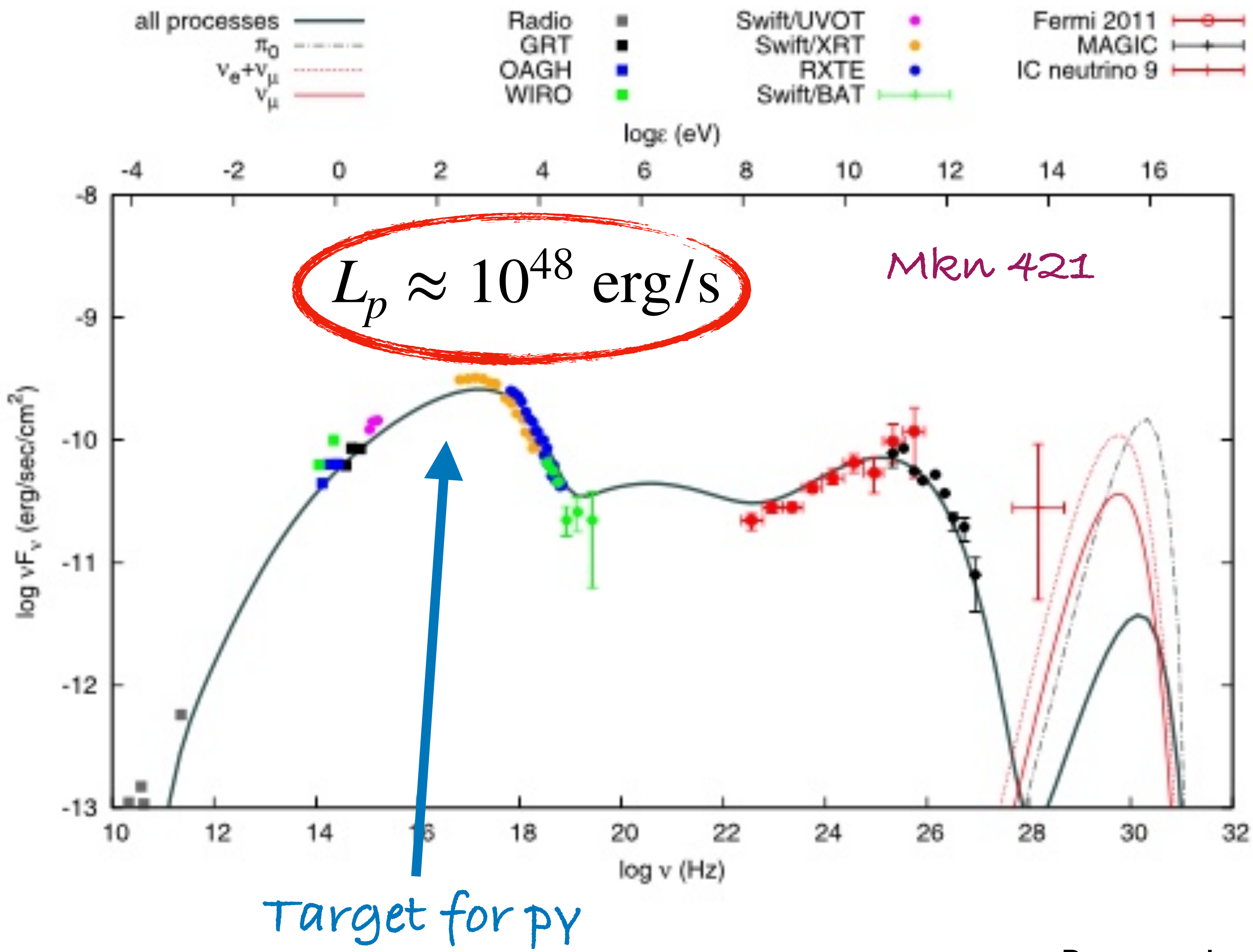


Photomeson production strongly favored

Murase, Inoue & Dermer 2014

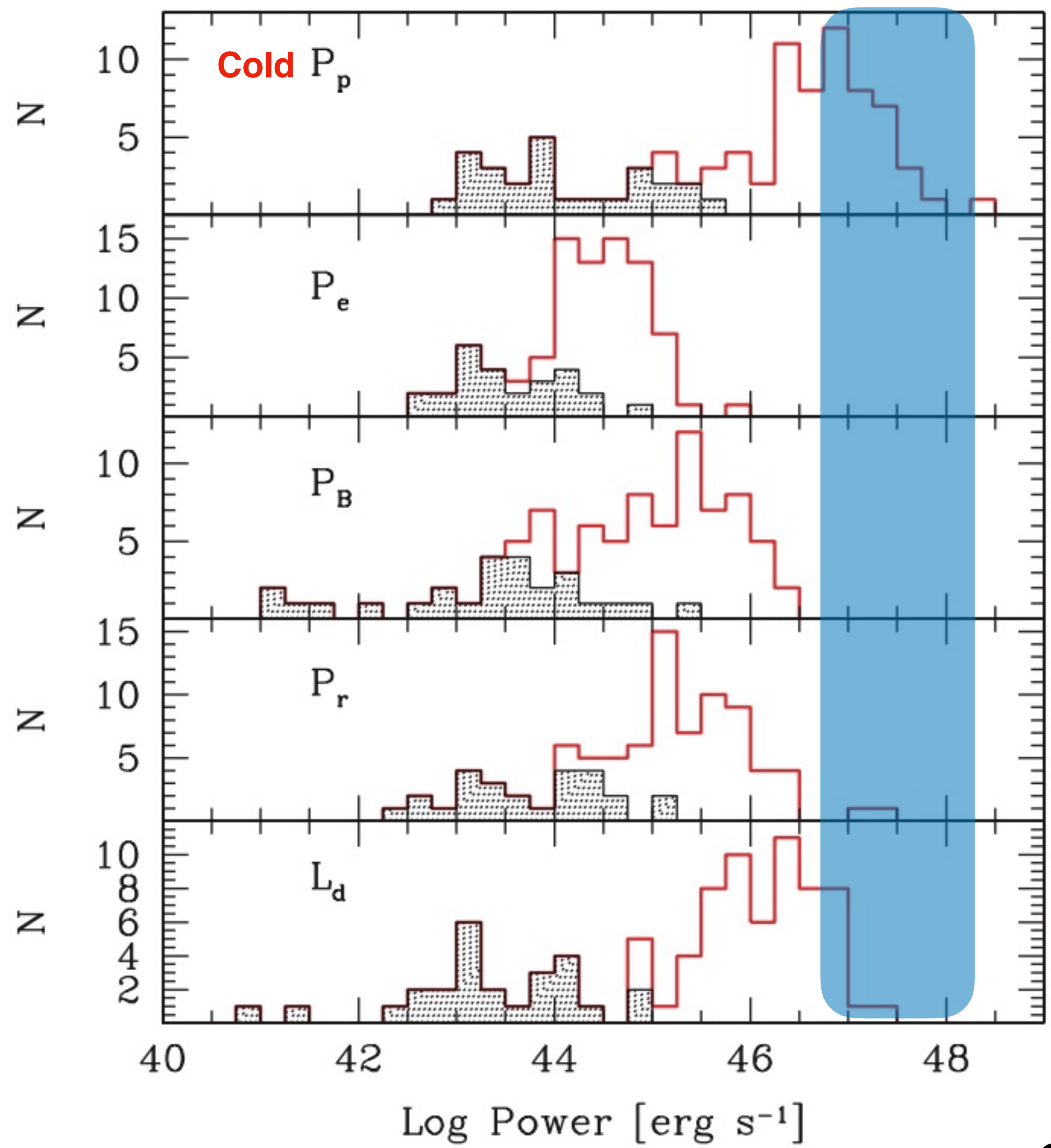
Neutrino from BL Lacs?

One-zone models



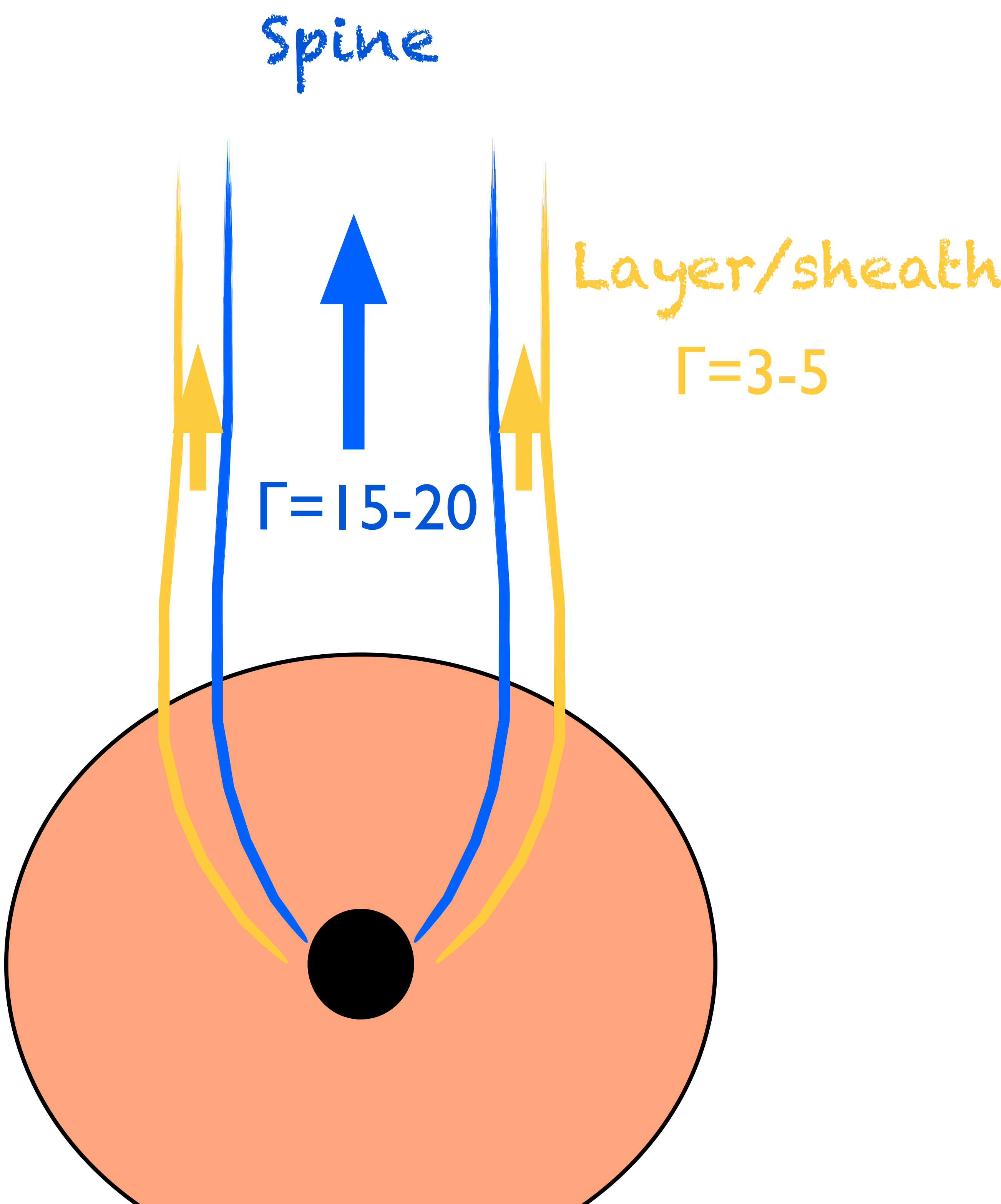
e.g., Petropoulou et al. 2015, 2016

Neutrino from BL Lacs?



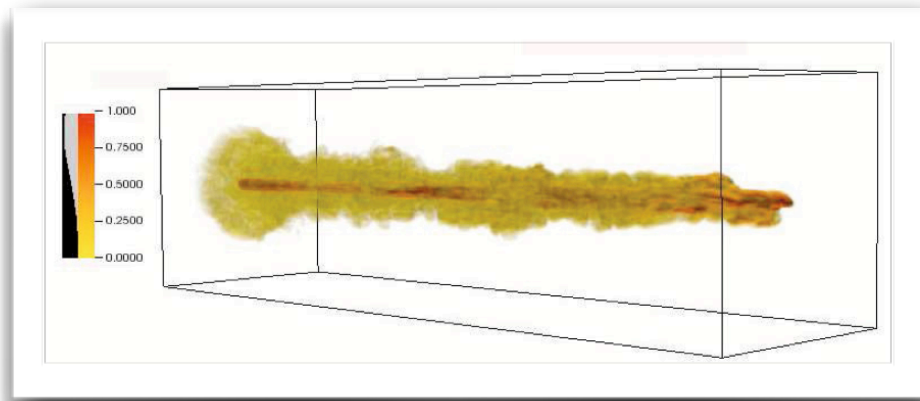
Ghisellini et al. 2010

Structured jets in BL Lacs



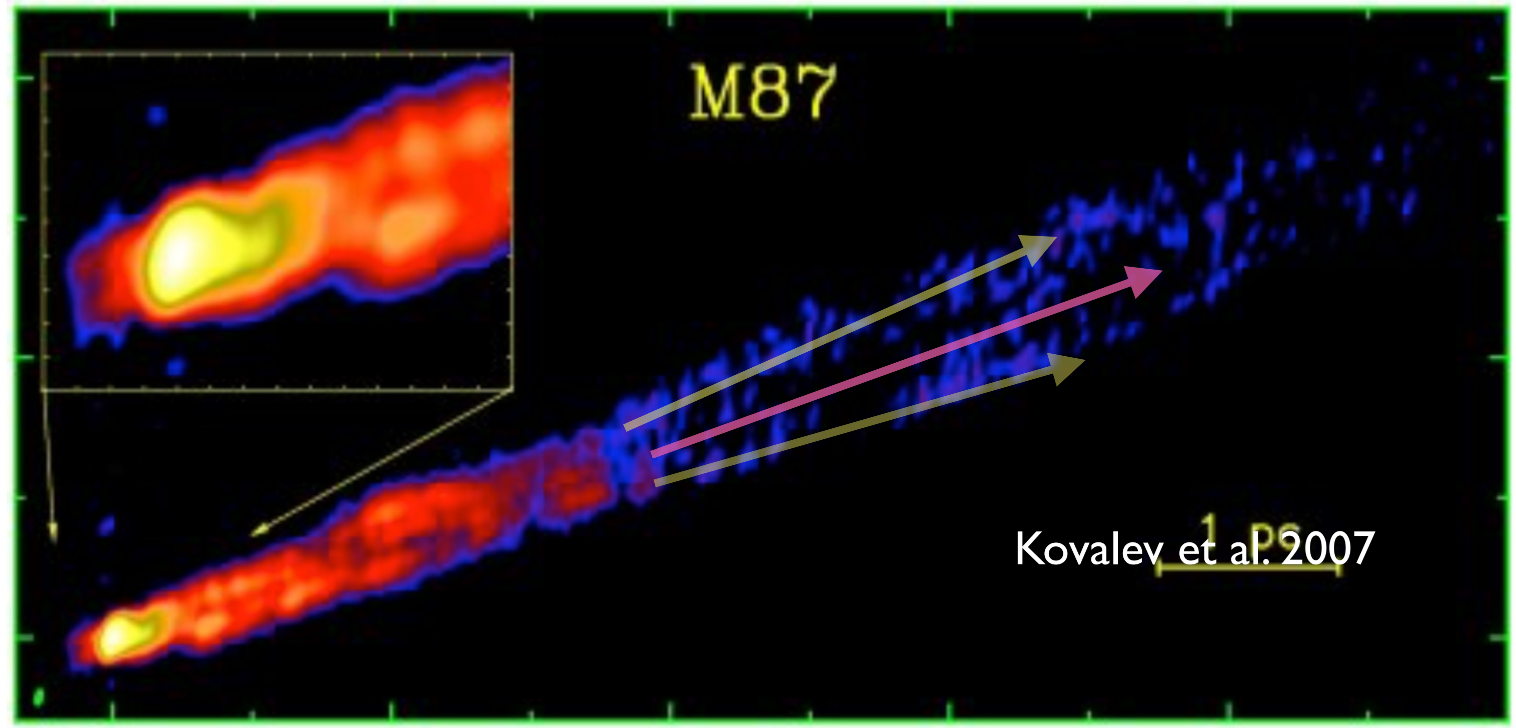
Ghisellini, FT and Chiaberge 2005
Tavecchio & Ghisellini 2008

Structured jets in BL Lacs



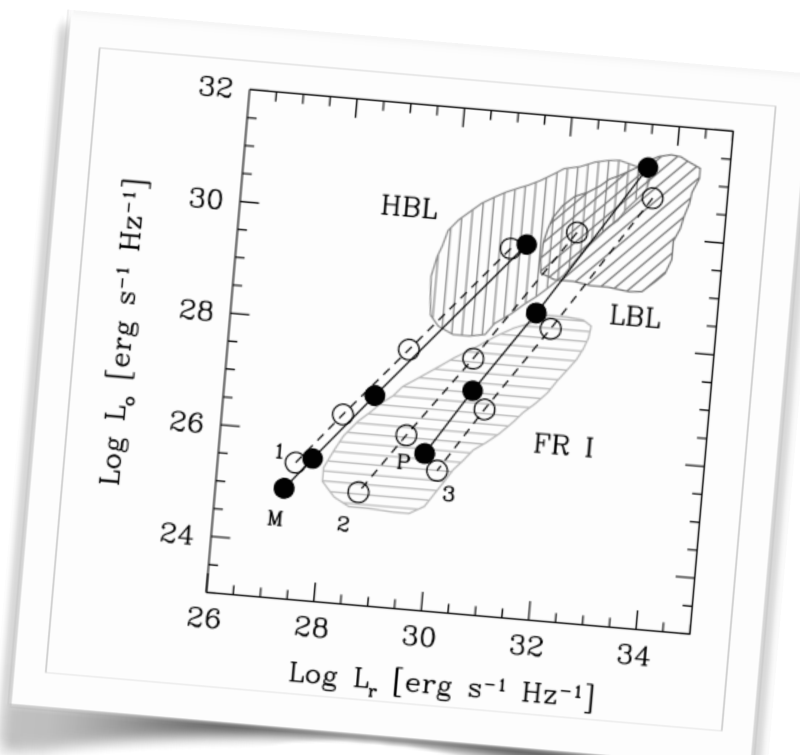
Simulations **predict spine-layer structure**

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**

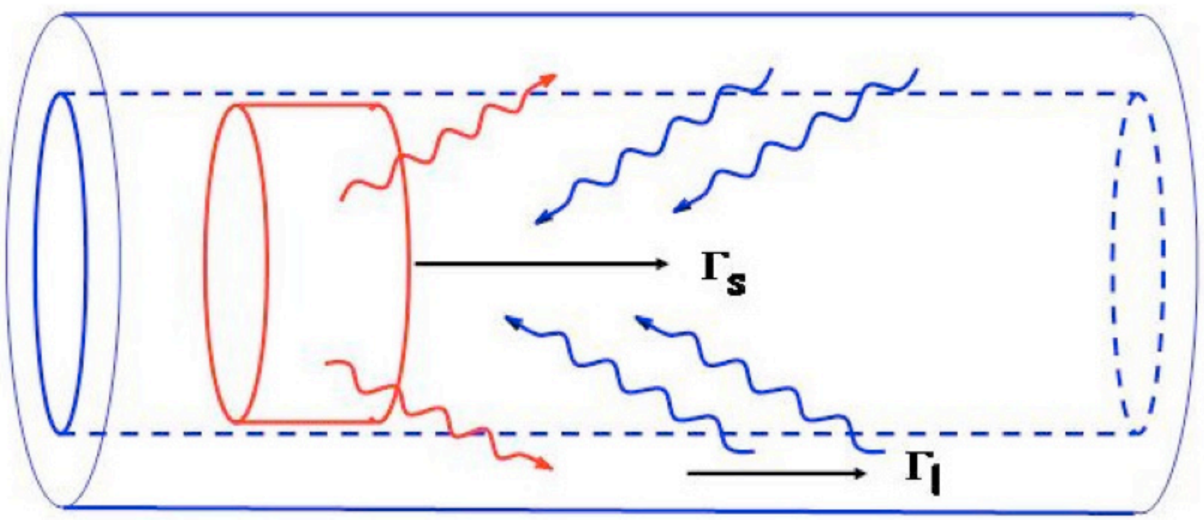
Chiaberge et al. 2000
Meyer et al.
Sbarrato et al. 2014

Similar suggestions for GRBs...

Structured jets in BL Lacs

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

$$U' \simeq U\Gamma^2_{\rm rel}$$

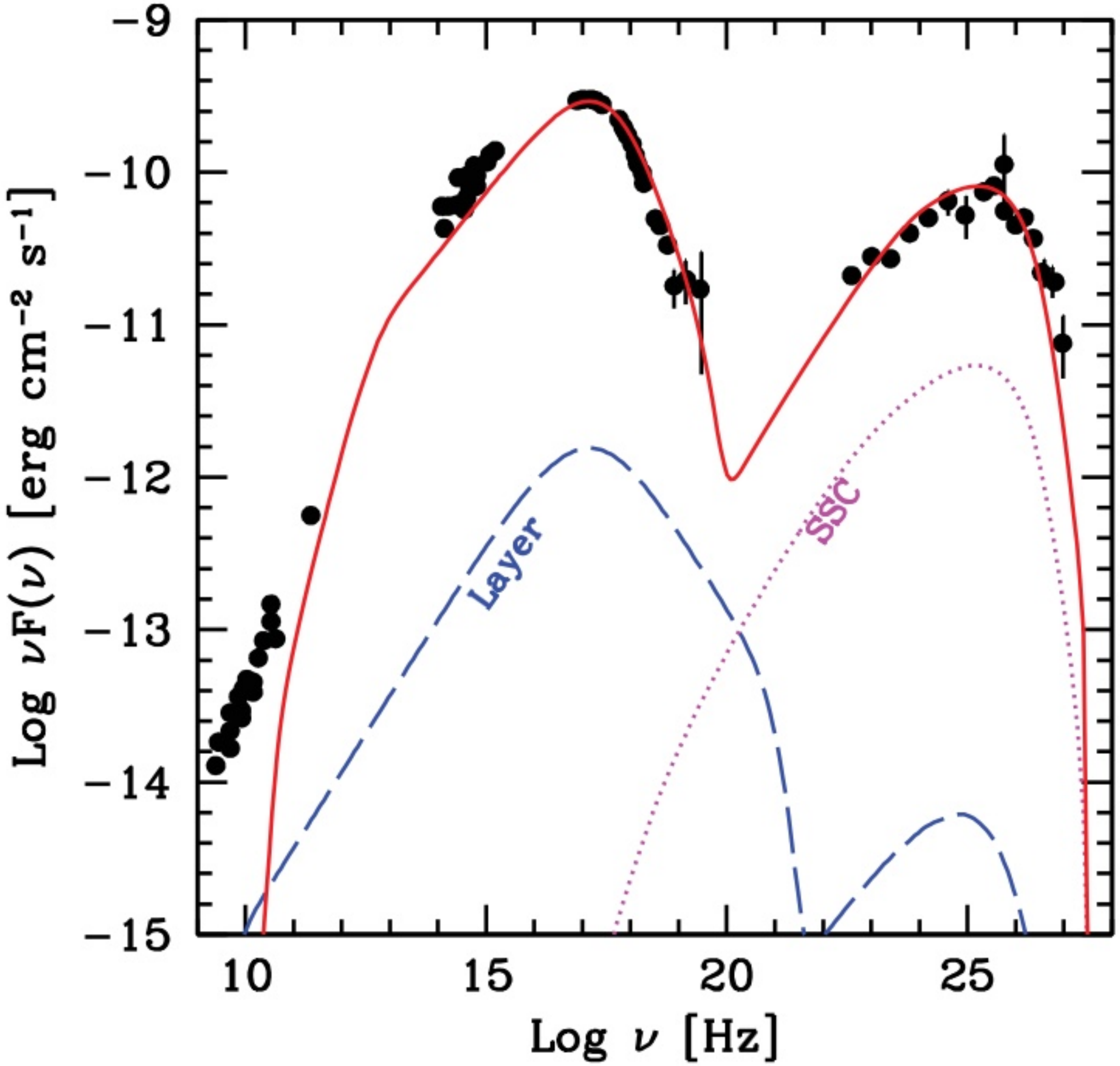


★ The spine "sees" an enhanced u_{rad} coming from the layer

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



Tavecchio & Ghisellini 2016

Structured jets in BL Lacs

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

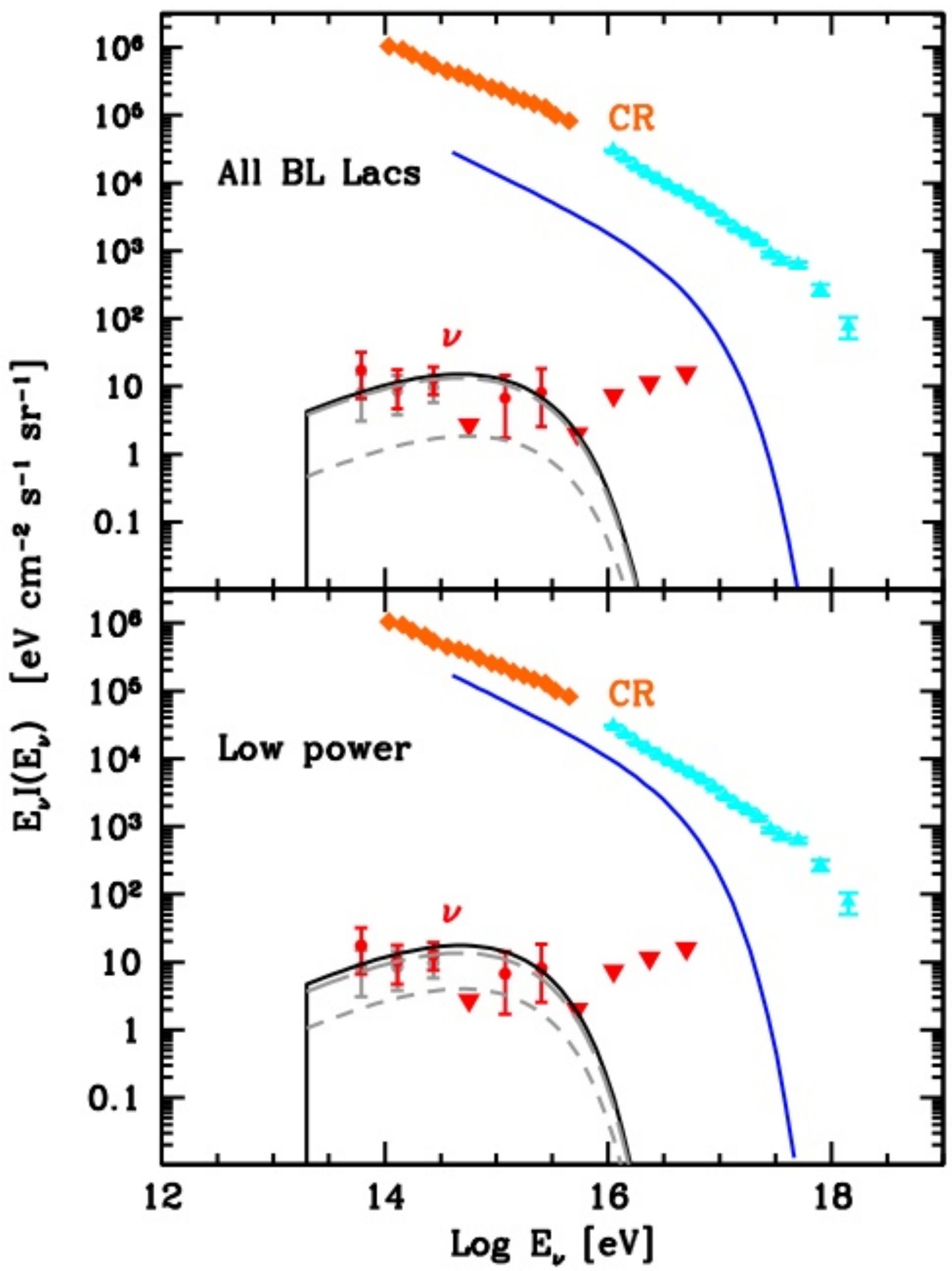
$$f_{p\gamma} \propto n_{soft}$$

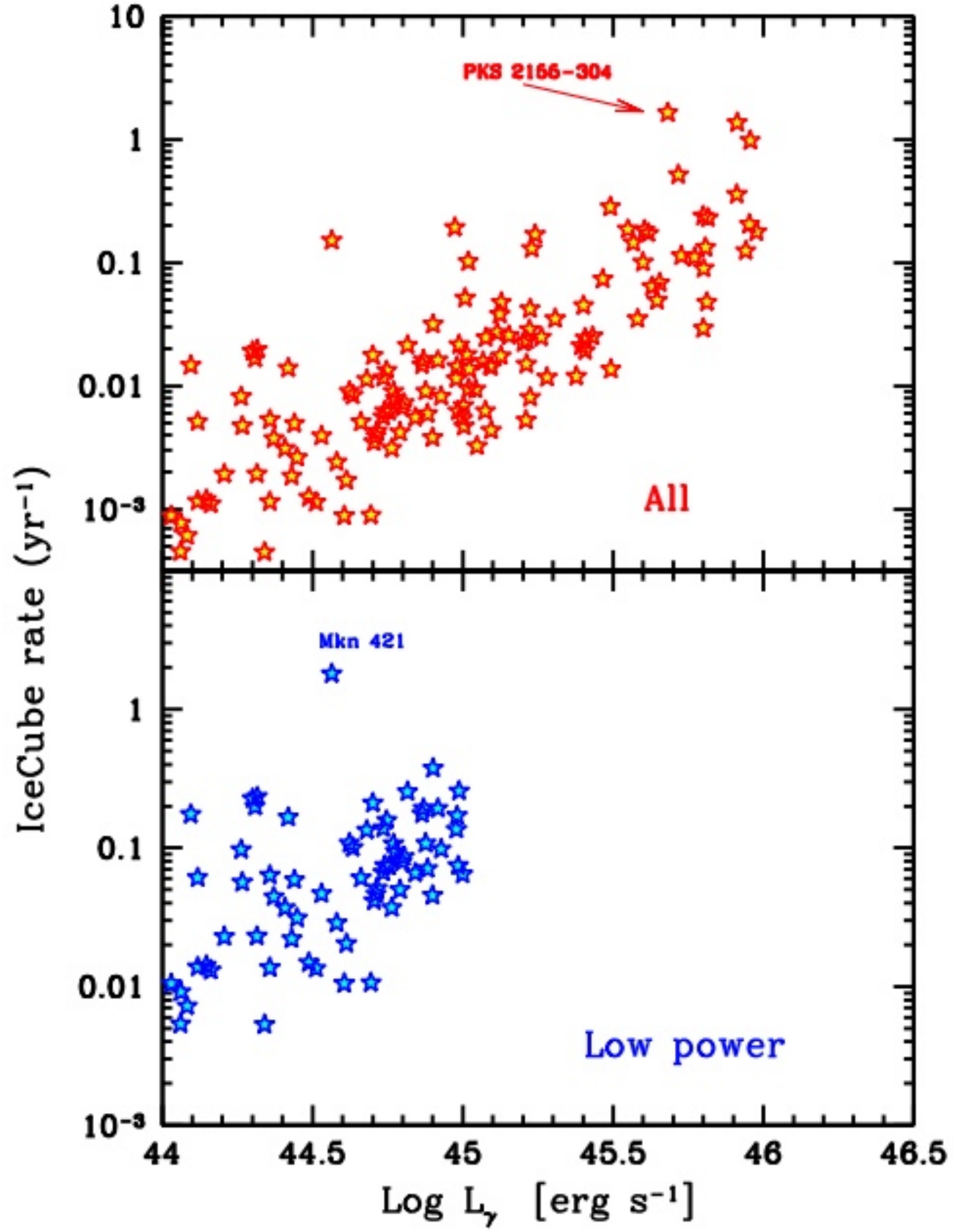
Increased target density

⇒ Reduced proton luminosity

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

Neutrinos from BL Lacs?



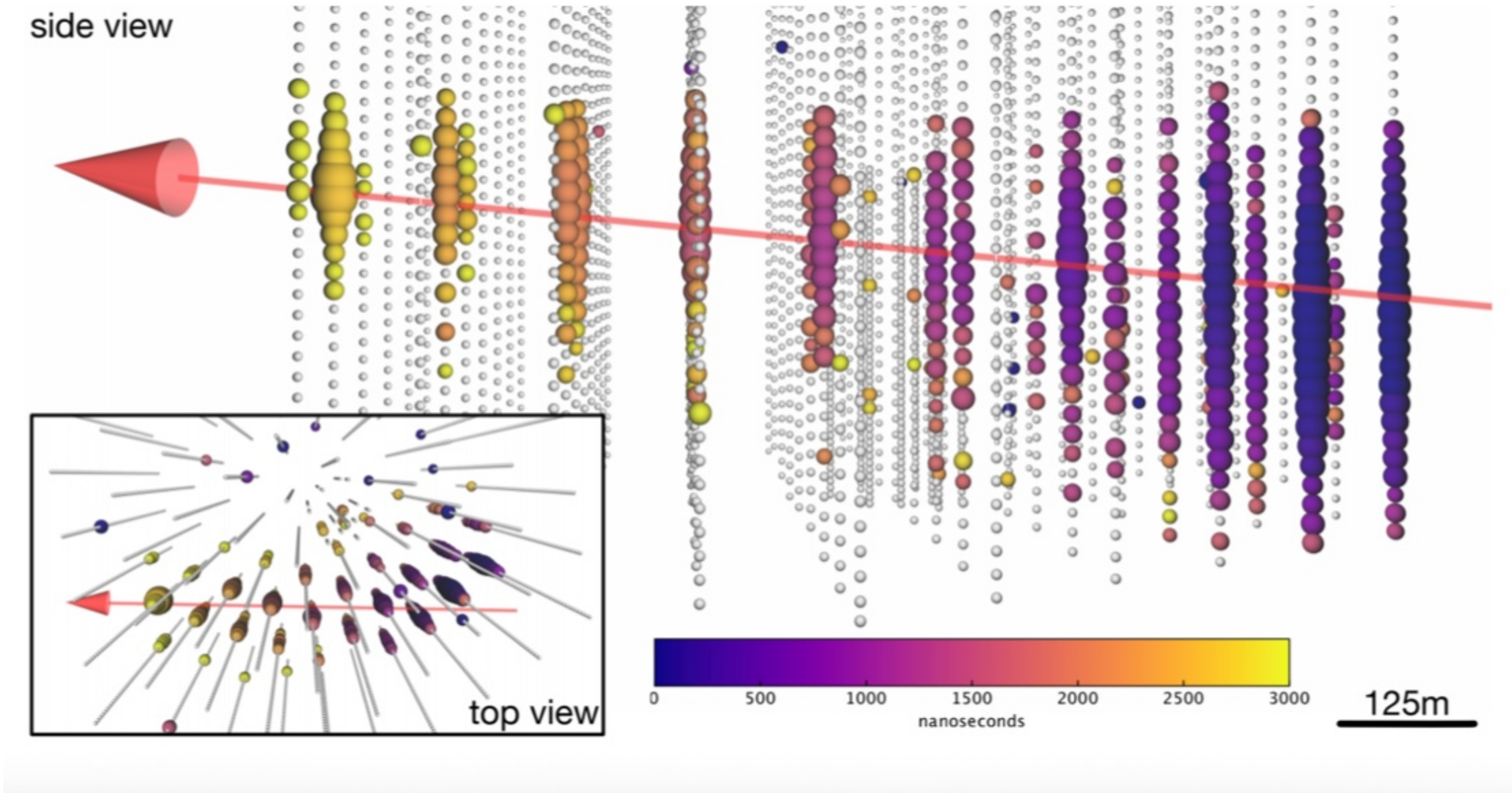


Tavecchio et al. 2014, 2015
Righi FT, Guetta 2017

But see Palladino & Vissani 2017

TXS 0506+056 & IC-170922A

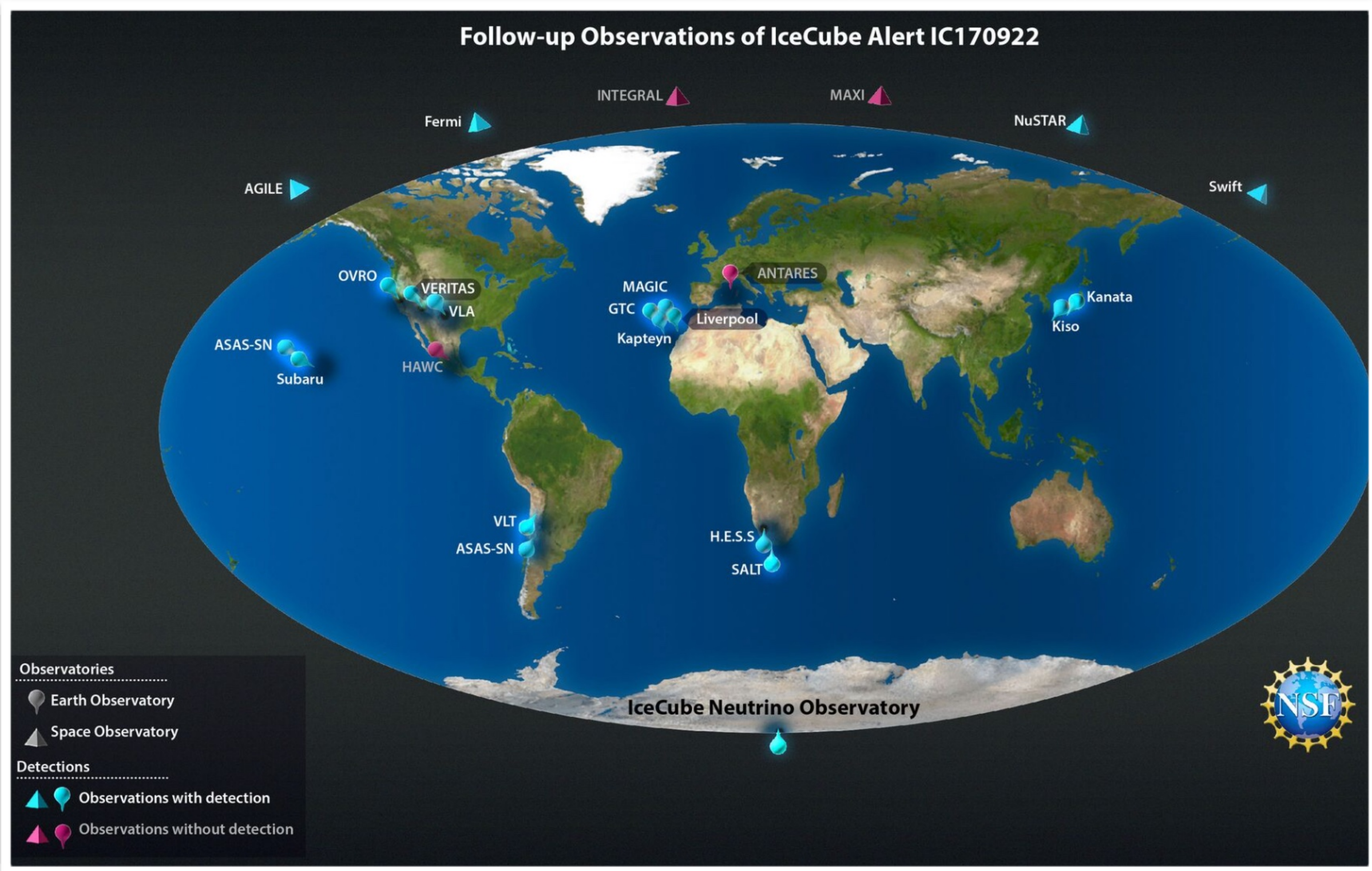
2017 september 22



TXS 0506+056 & IC-170922A

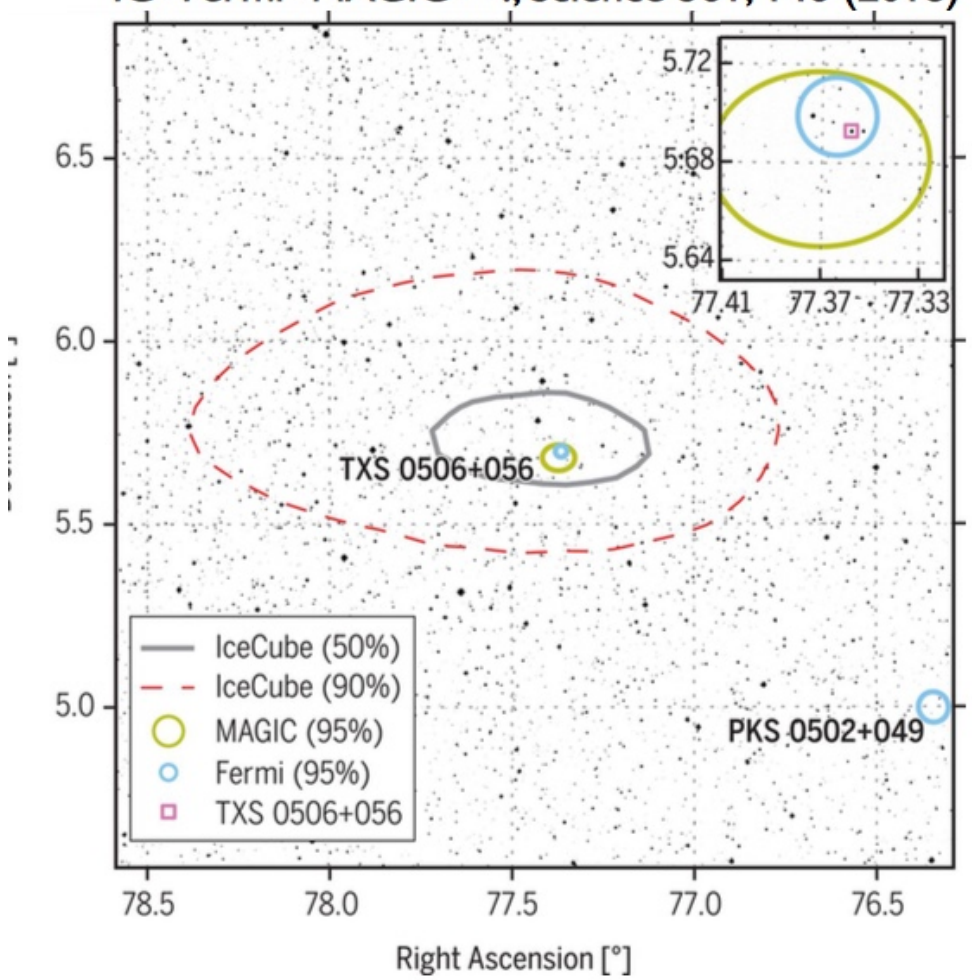
2017 september 22

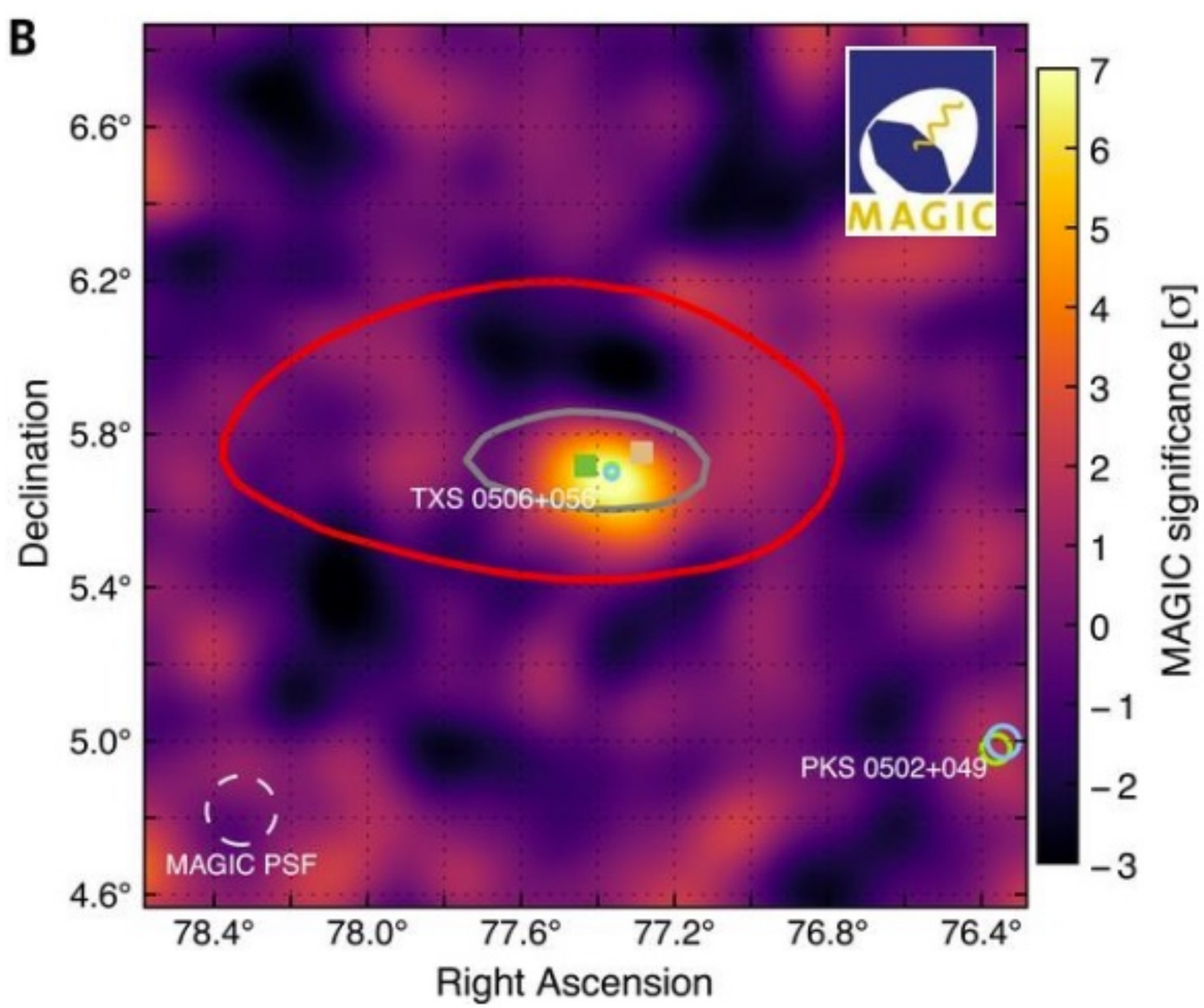
TXS 0506+056 & IC-170922A



TXS 0506+056 & IC-170922A

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





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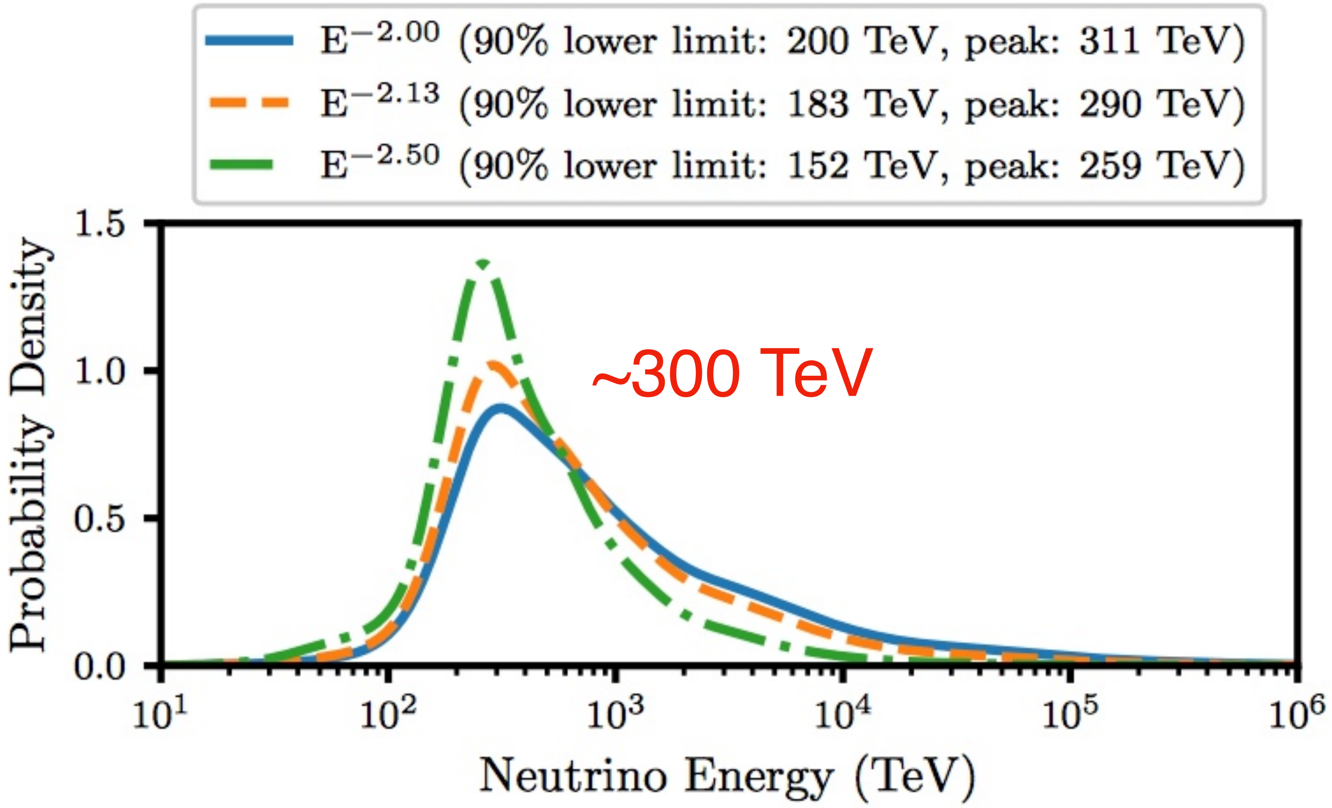
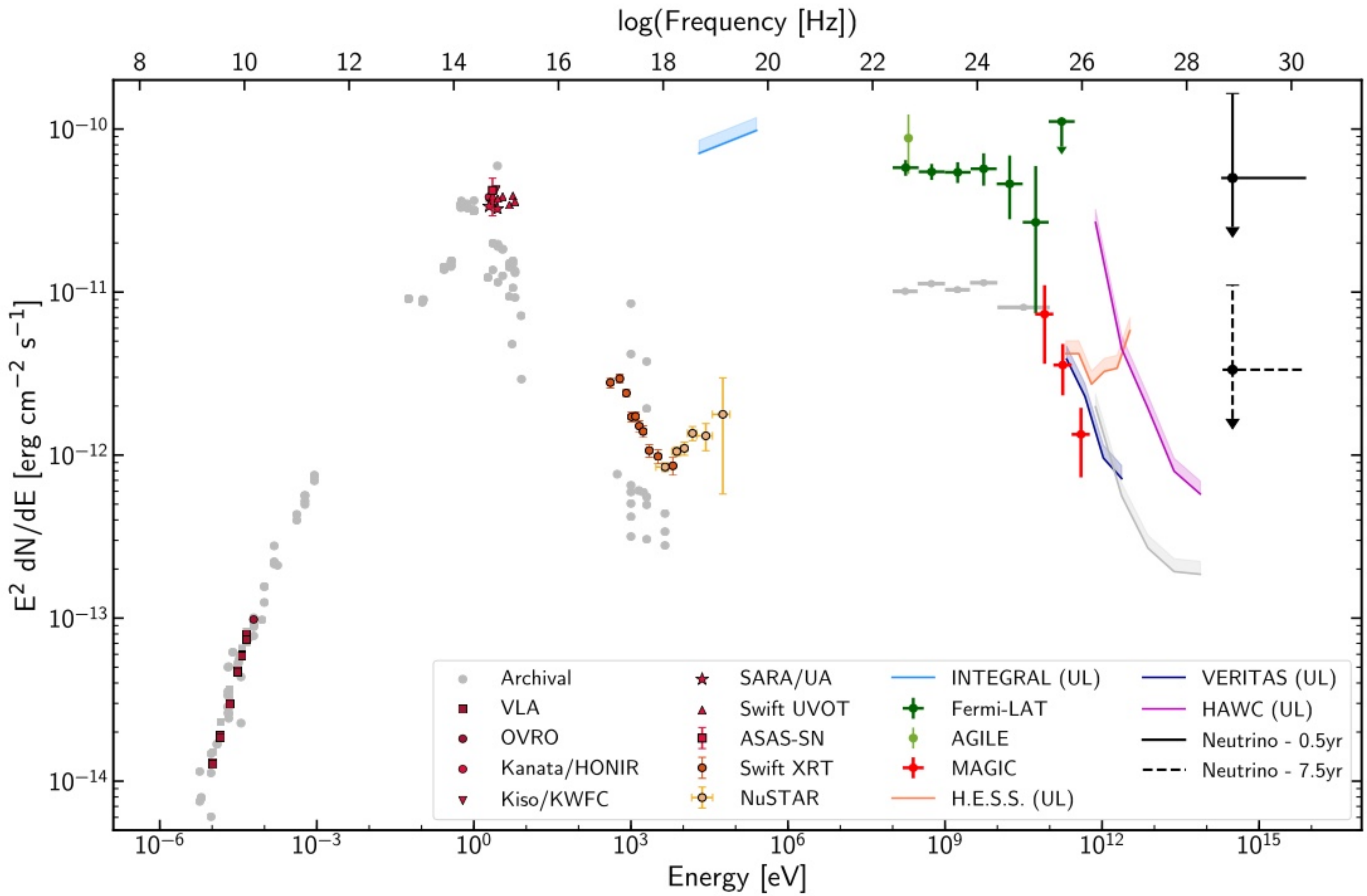
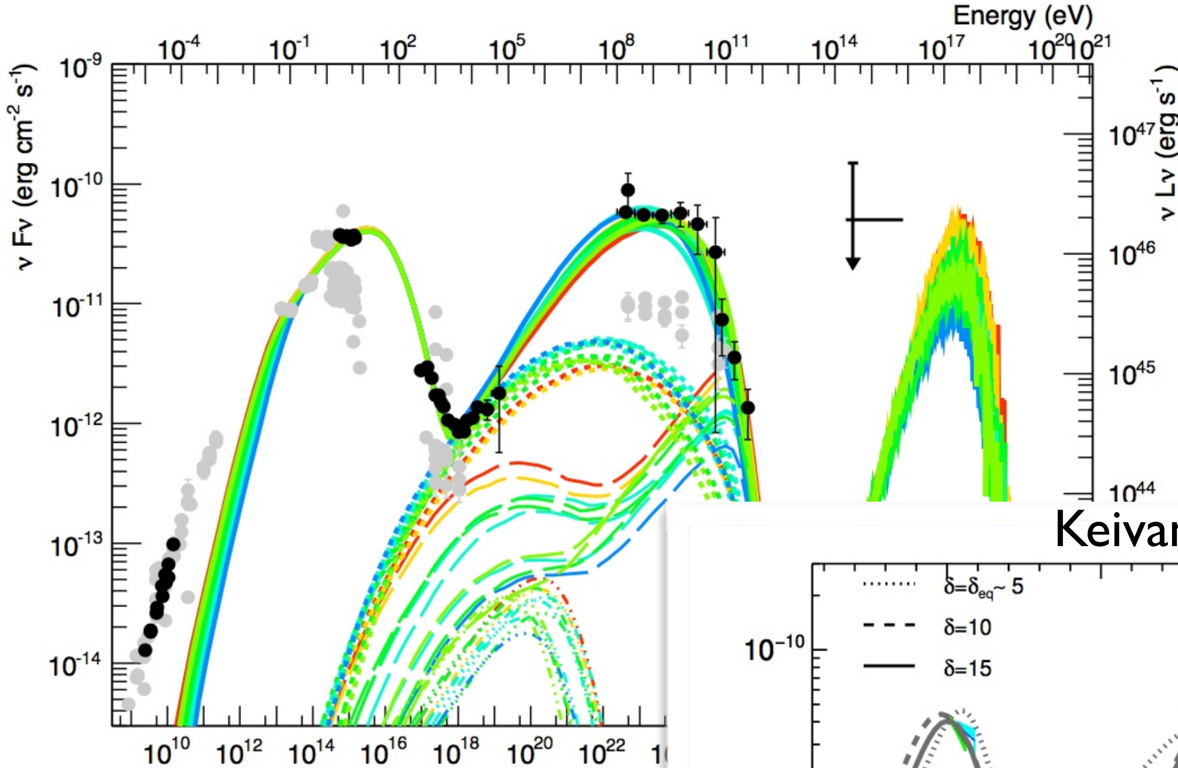


Ep~ 6 PeV (observer frame)

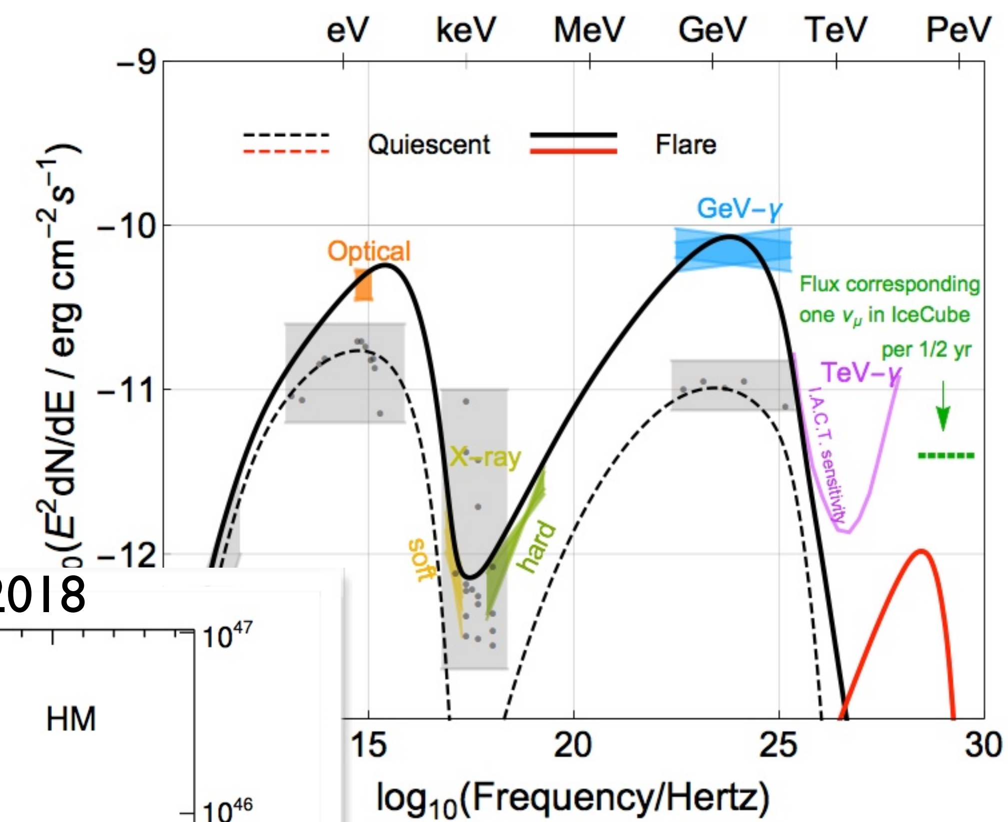
TXS 0506+056 & IC-170922A



A burst of models …

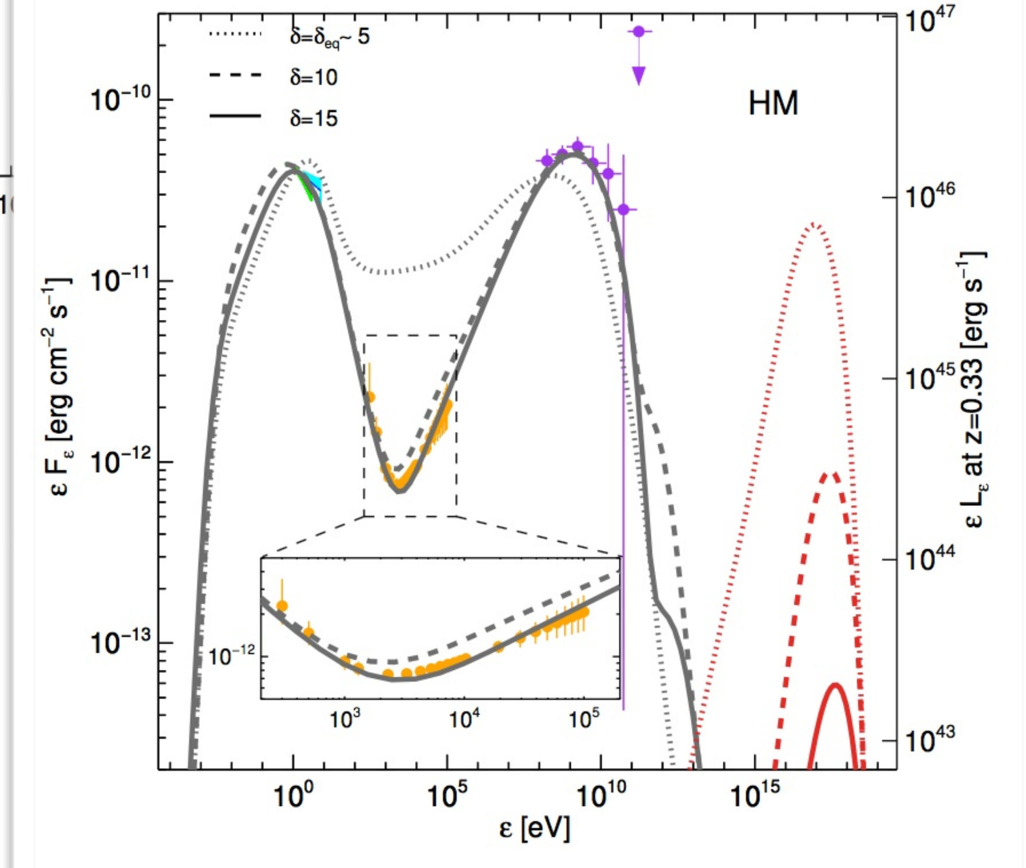


Cerruti et al. 2018



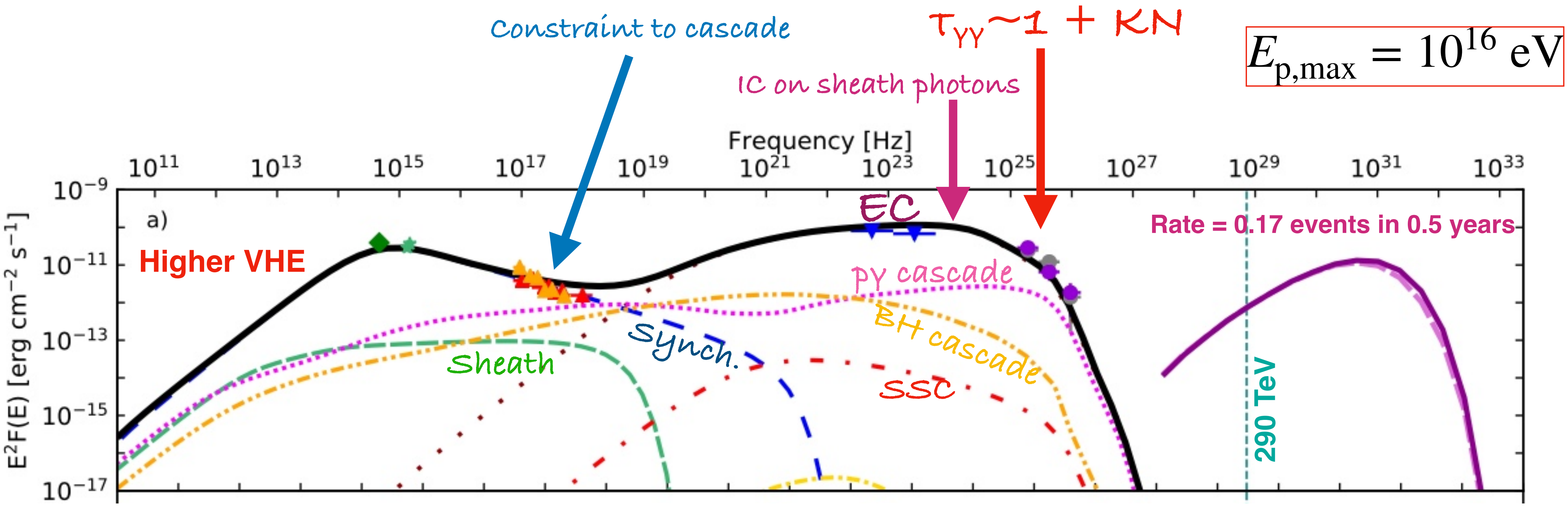
Gao et al. 2018

Keivani et al. 2018



But, again, the jet power is very large!

Jet-sheath model

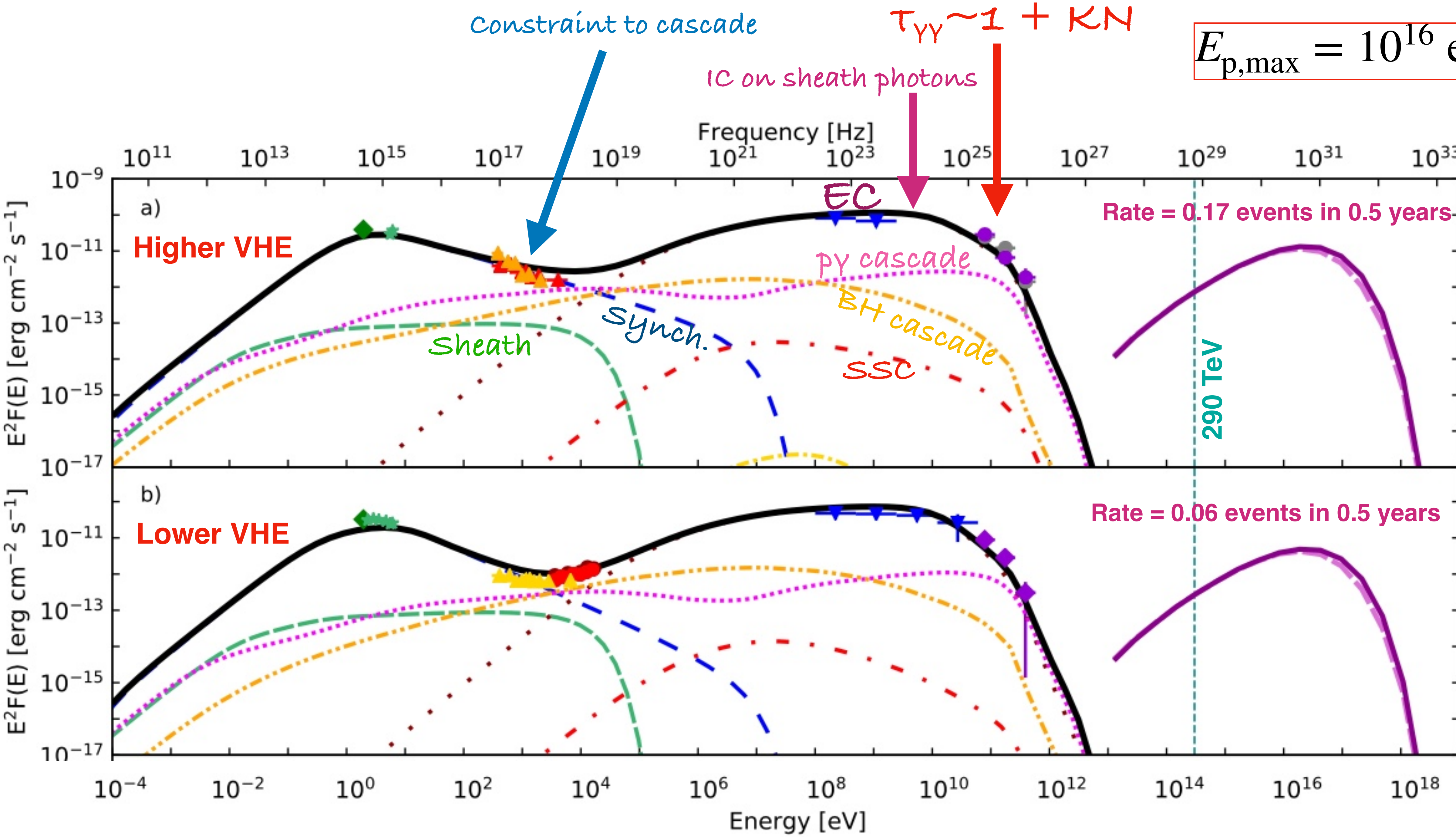


$P_j \approx 4 \times 10^{45} - 10^{46}$ erg s^{-1}

MAGIC Coll. 2018

Numerical model by. W. Bhattacharyya

Jet-sheath model



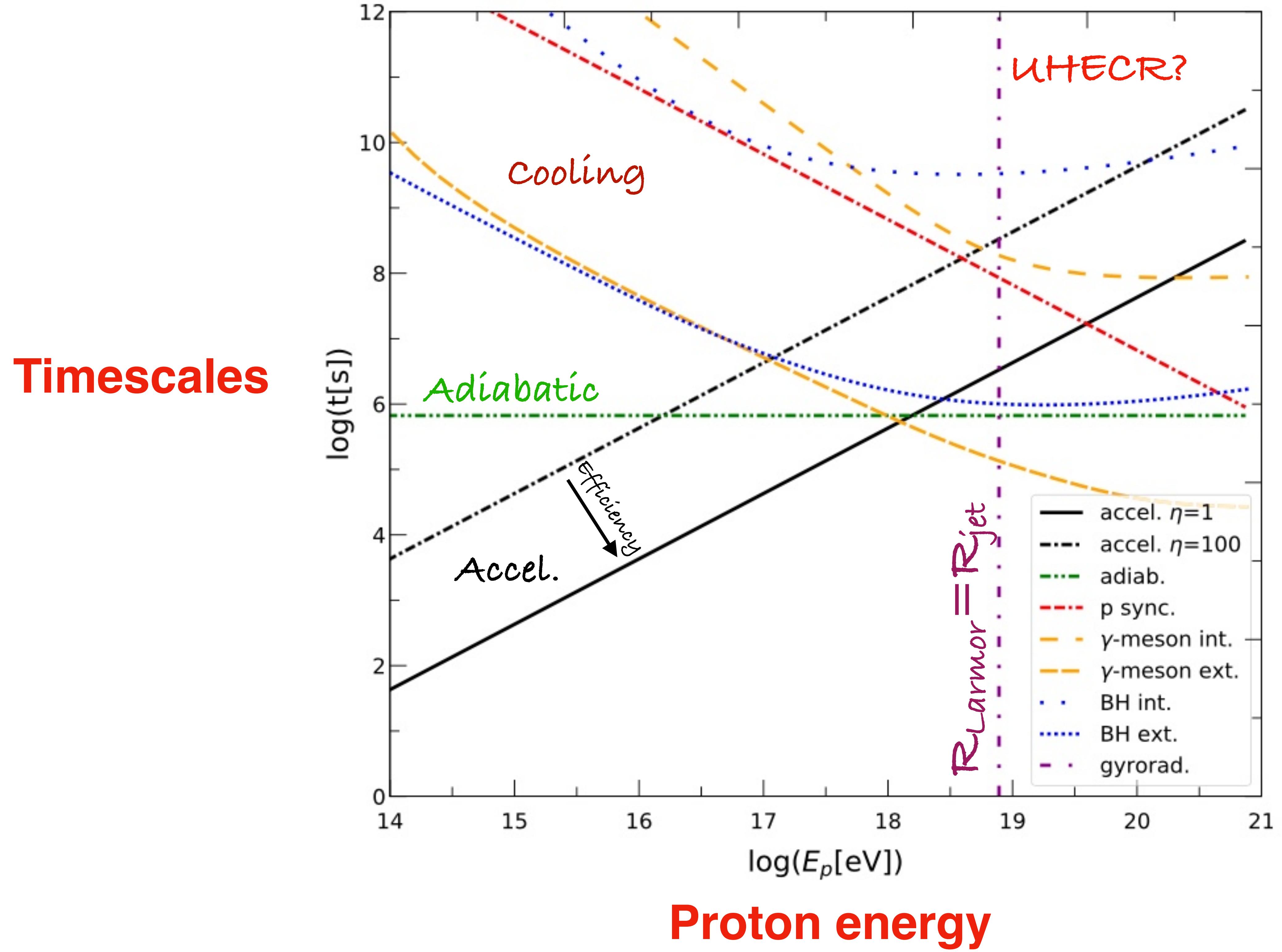
$E_{\rm p,max} = 10^{16}$ eV

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

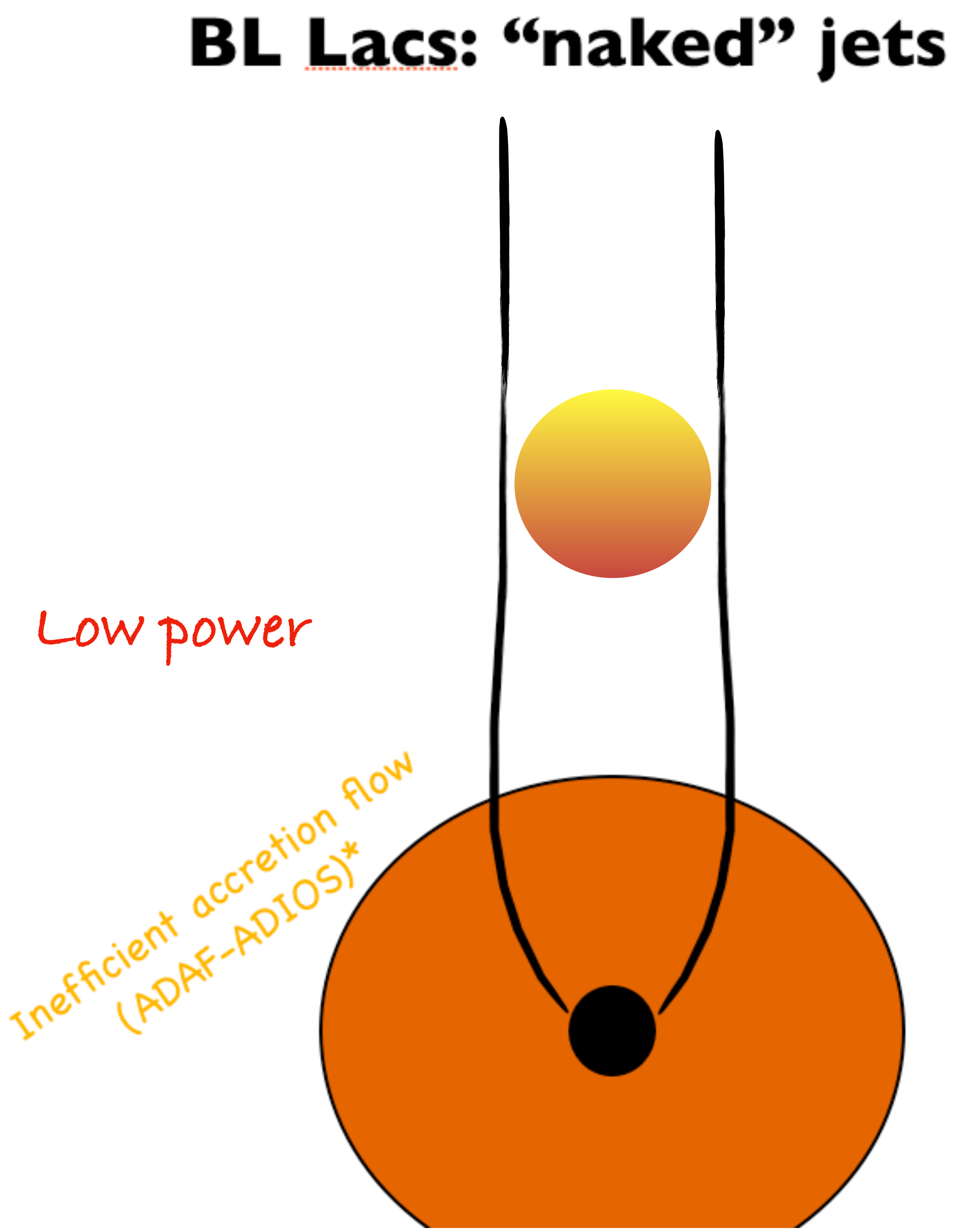
MAGIC Coll. 2018

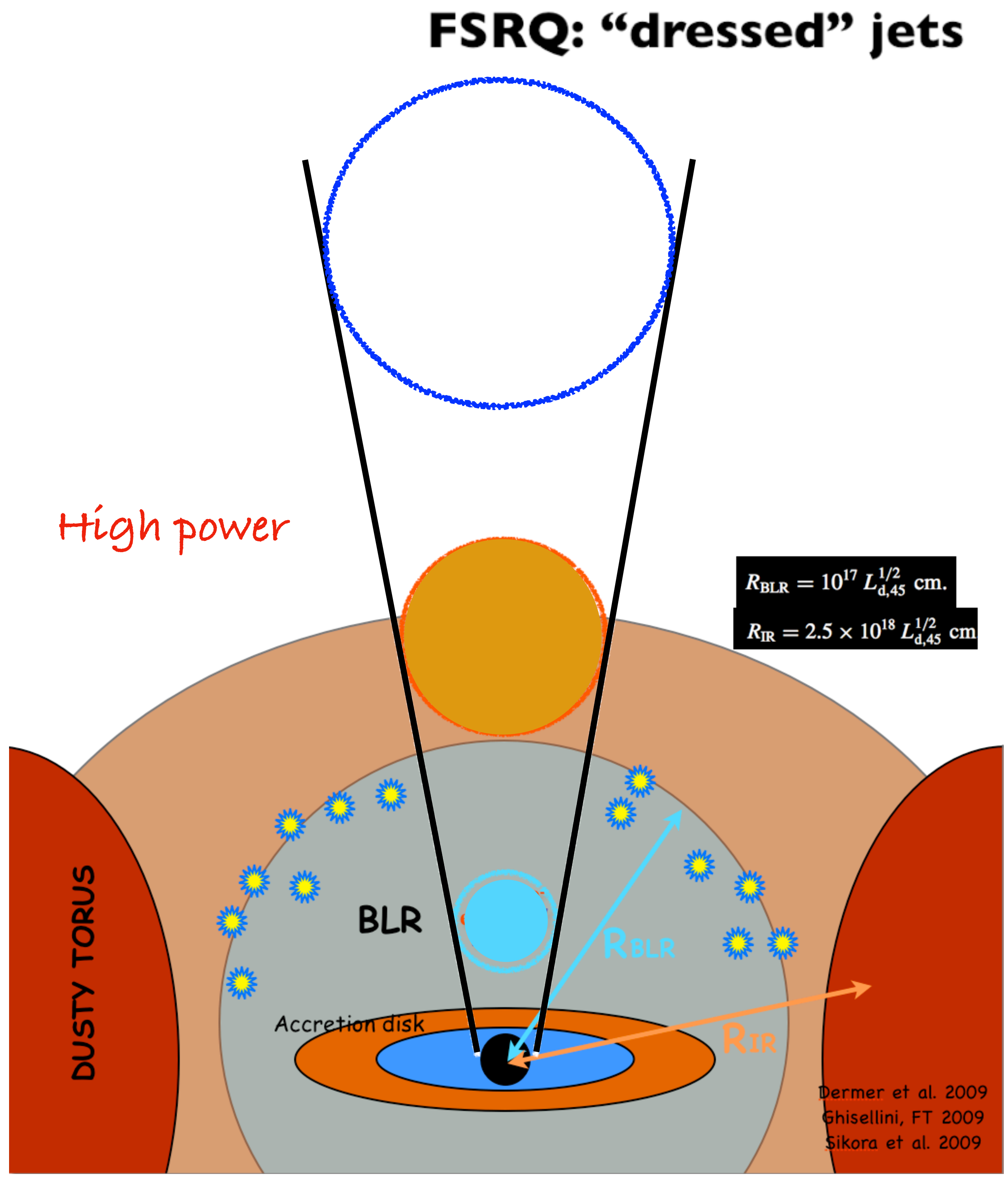
Numerical model by. W. Bhattacharyya

Jet-sheath model



Blazars in a nutshell

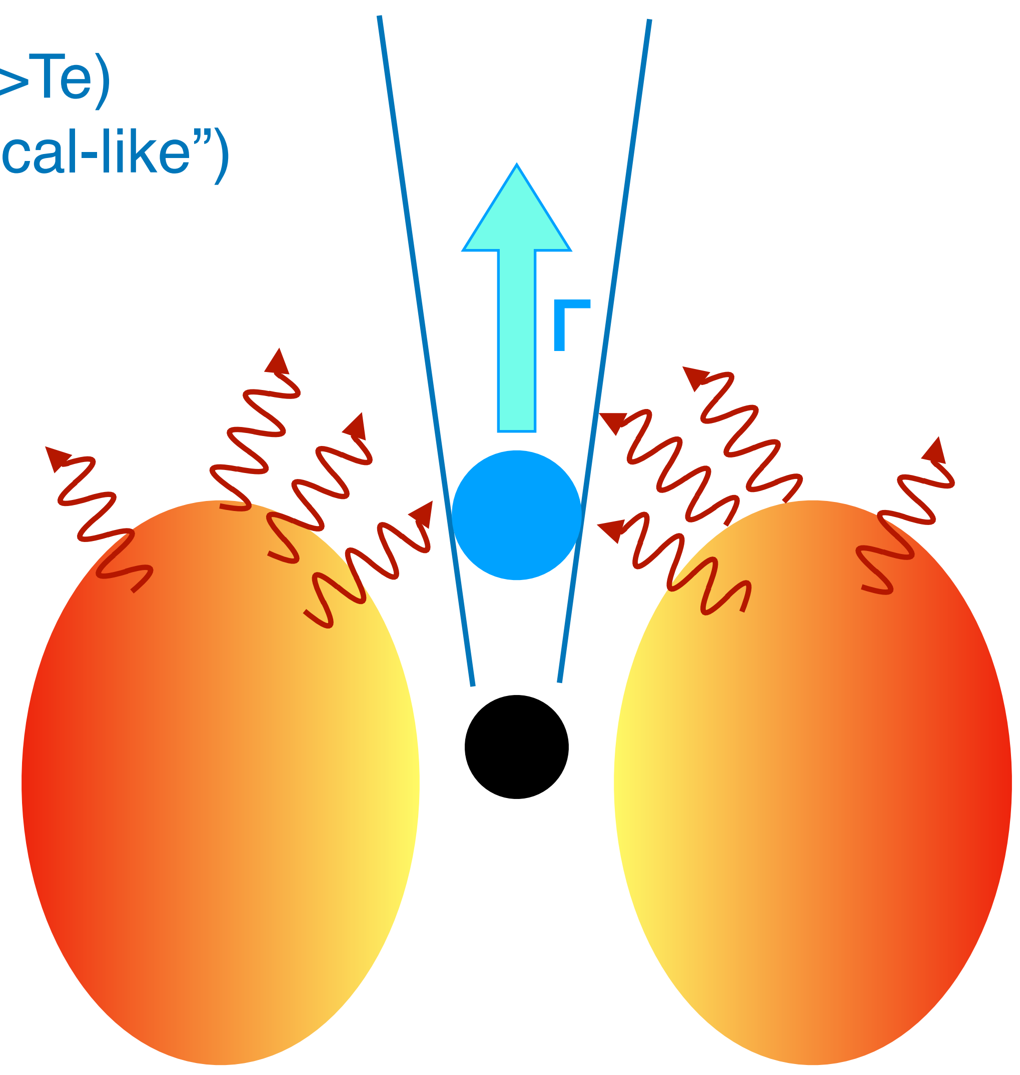




A role for the accretion flow?

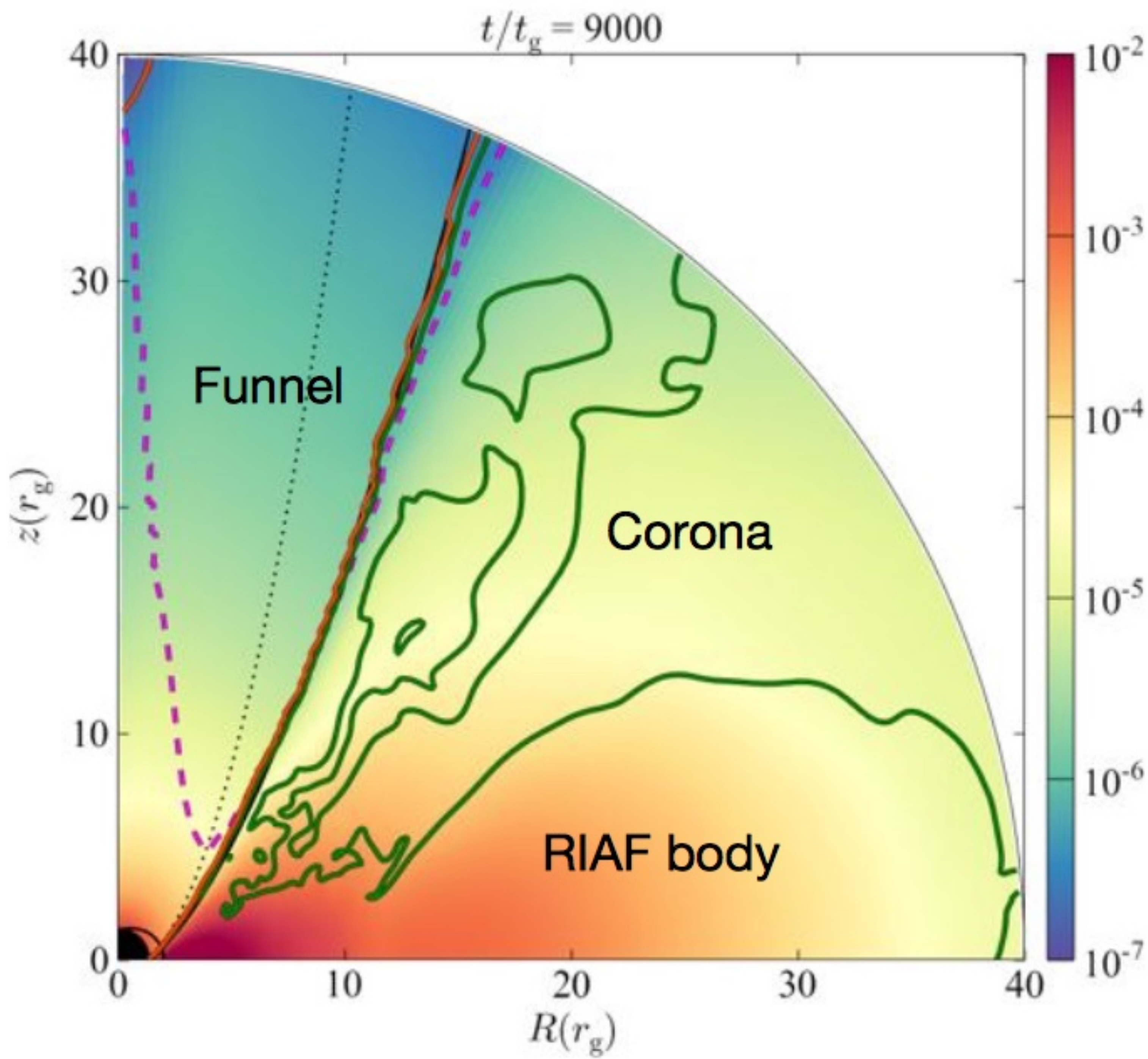
Radiatively Inefficient Accretion Flow (RIAF)
Advection Dominated Accretion Flow (ADAF)

Two-temperature flow (Tp>>Te)
Geometrically thick ("spherical-like")
Optically thin
Outflow?



Ichimaru 1977, Rees et al. 1982, Narayan & Yi 1994, Blandford & Begelman 1999

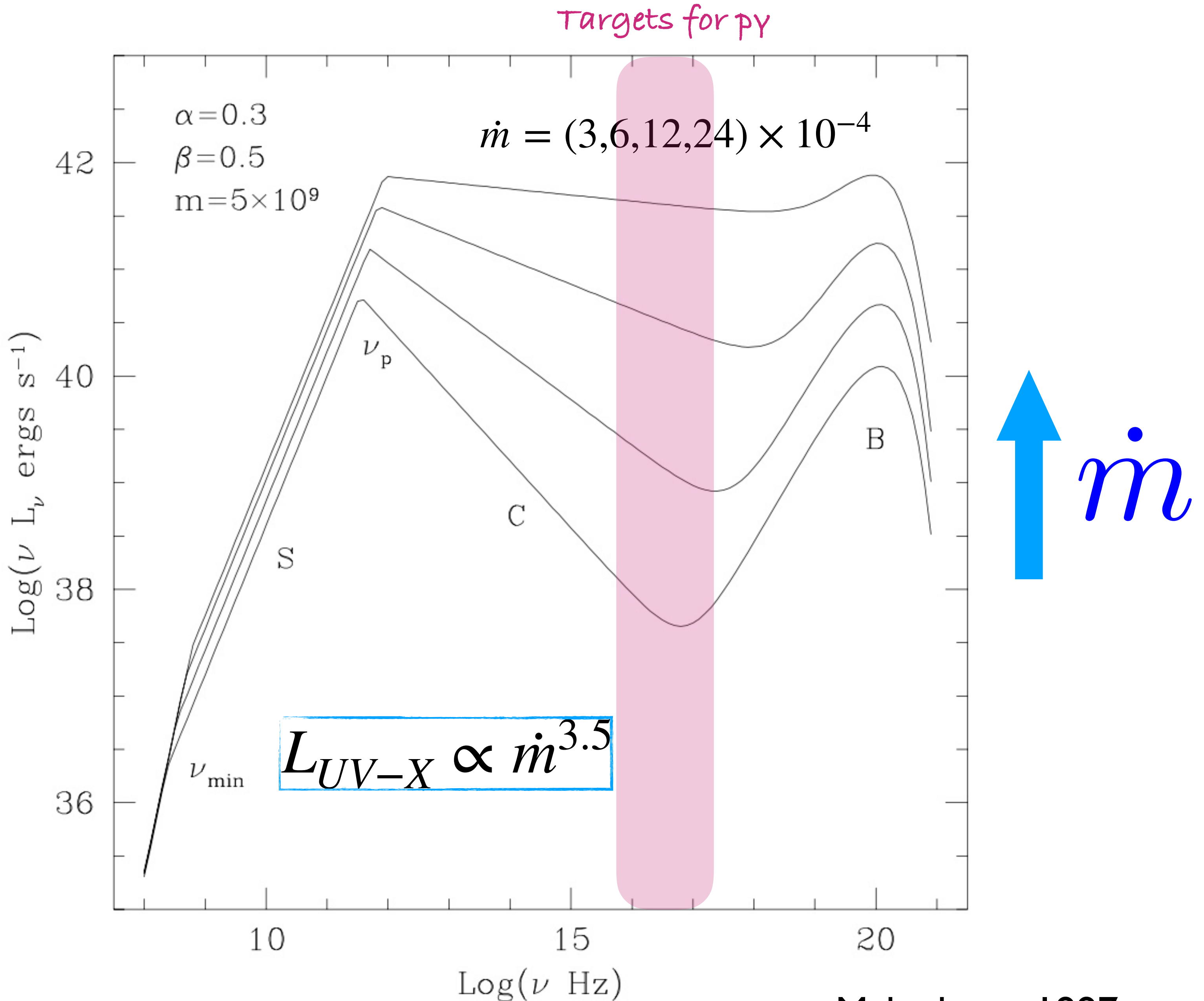
A role for the accretion flow?



Nakamura et al. 2018

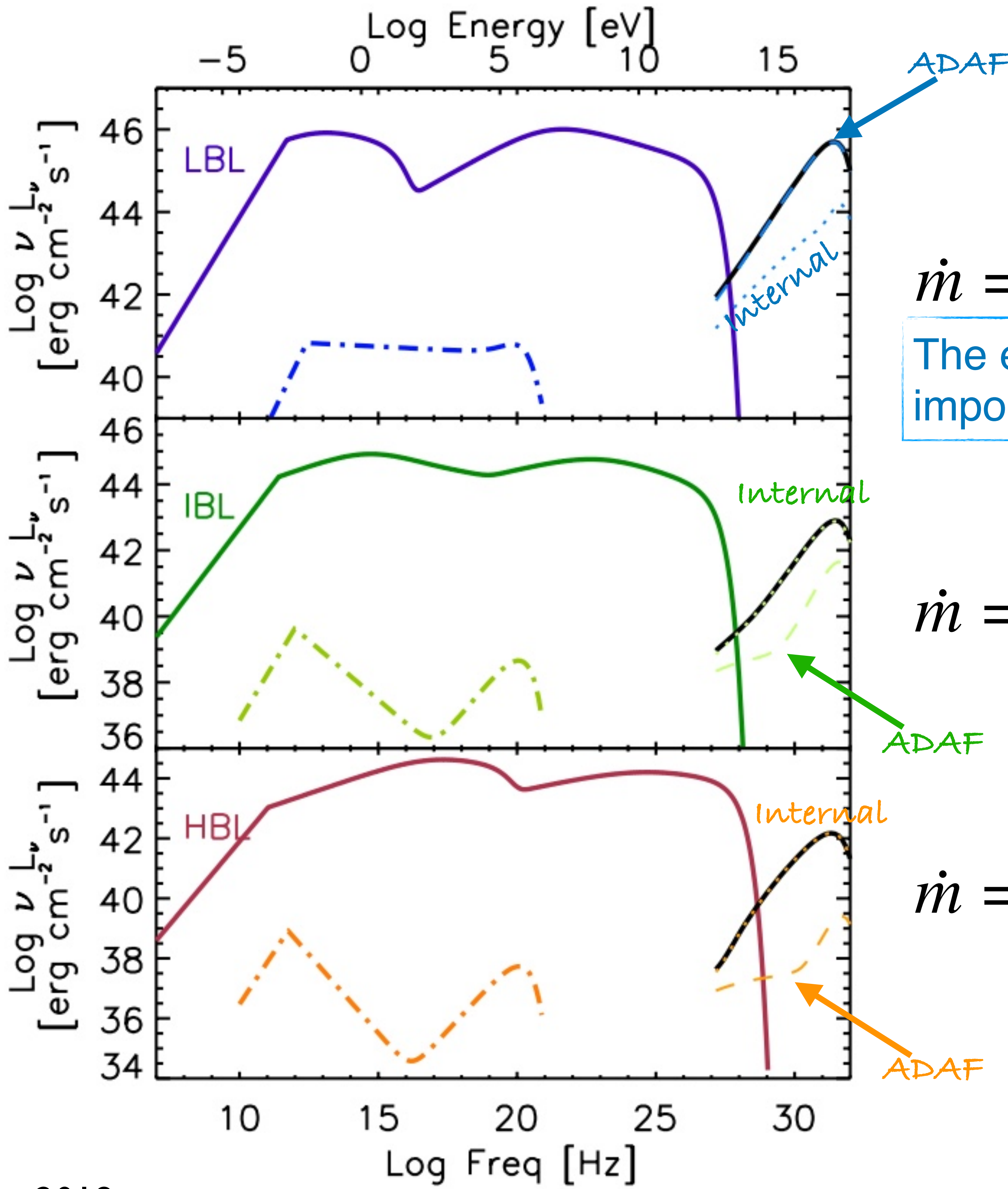
A role for the accretion flow?

Advection dominated accretion flow



Mahadevan 1997

A role for the accretion flow?



$L_p \propto P_{jet}$

$\dot{m} = 10^{-3}$

The external field is important for LBL only

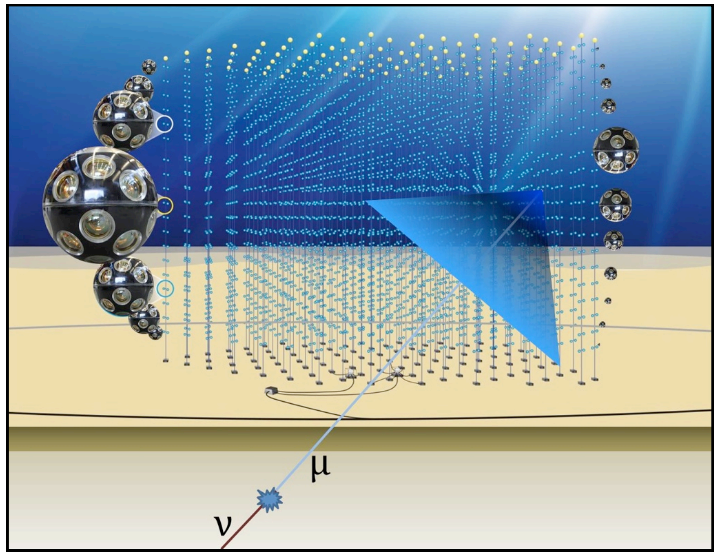
$\dot{m} = 3 \times 10^{-4}$

$\dot{m} = 10^{-4}$

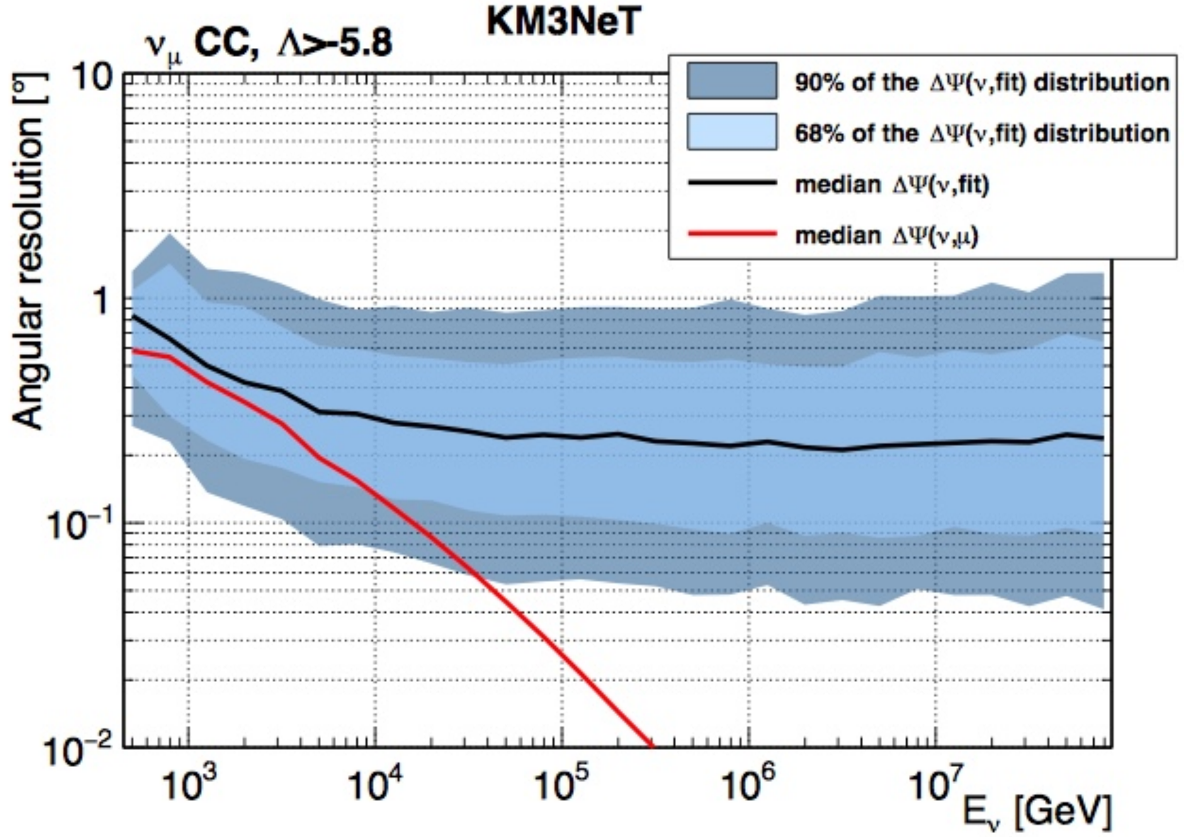
Righi, FT, Inoue 2018

The future

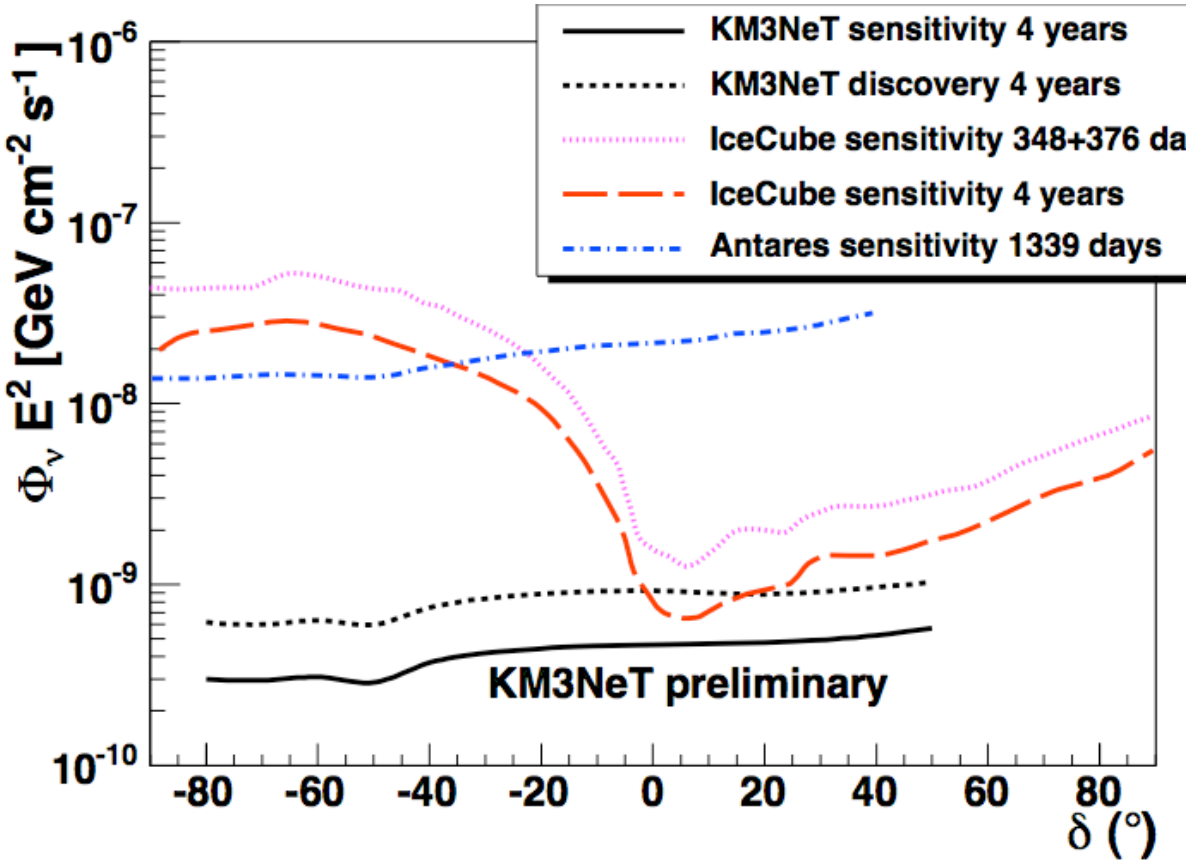
KM3NeT



Under deployment in the Mediterranean Sea



KM3NeT Coll. 2016



Trovato et al. 2014

Take home messages

We are living the dawn of the neutrino astronomy!

Probably several classes of sources contribute to the observed flux

The case of TXS suggests that blazars could provide some contribution

The astrophysical setting is relevant! Environment plays an important role
External photons can help to keep the jet power below 10^{47} erg/s

Thank you!

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 …

Jet-sheath model

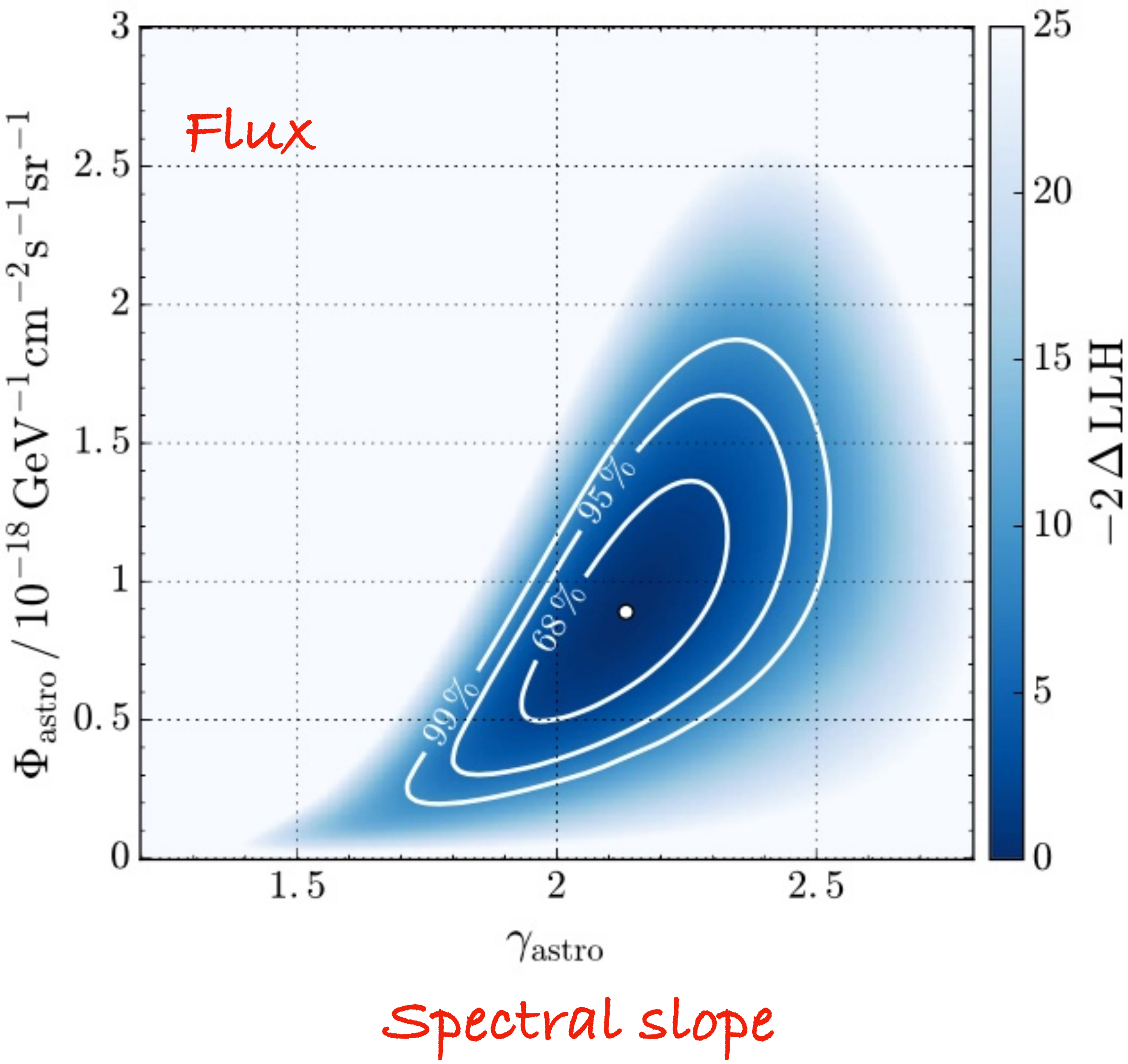
MAGIC Coll. 2018

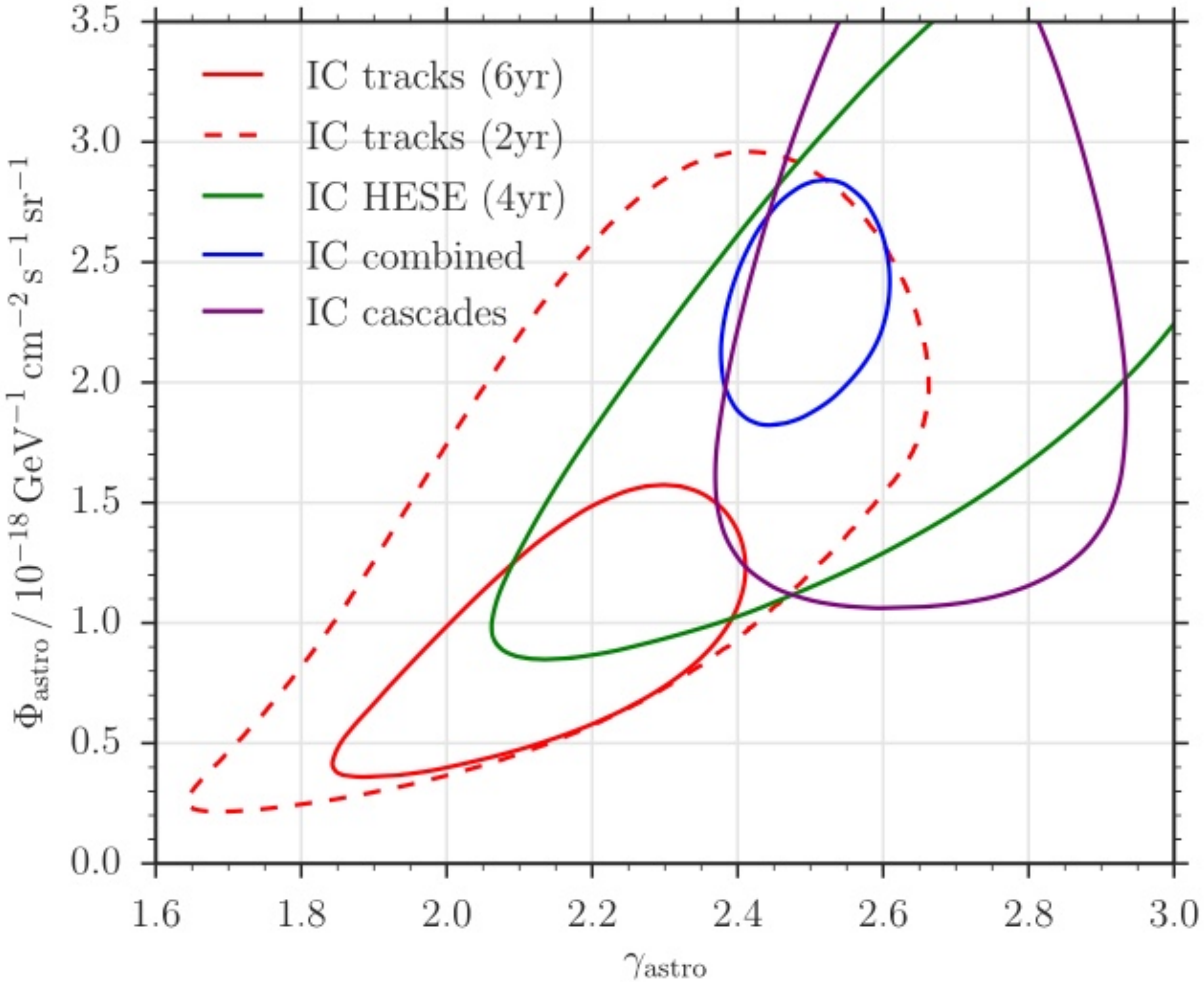
Table 3. Parameters for the jet-sheath model for $E_{\rm p,max}=10^{16}$.

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}

$$P_j \approx 4\times10^{45} - 10^{46}\ \mathrm{erg\,s^{-1}}$$

Current status

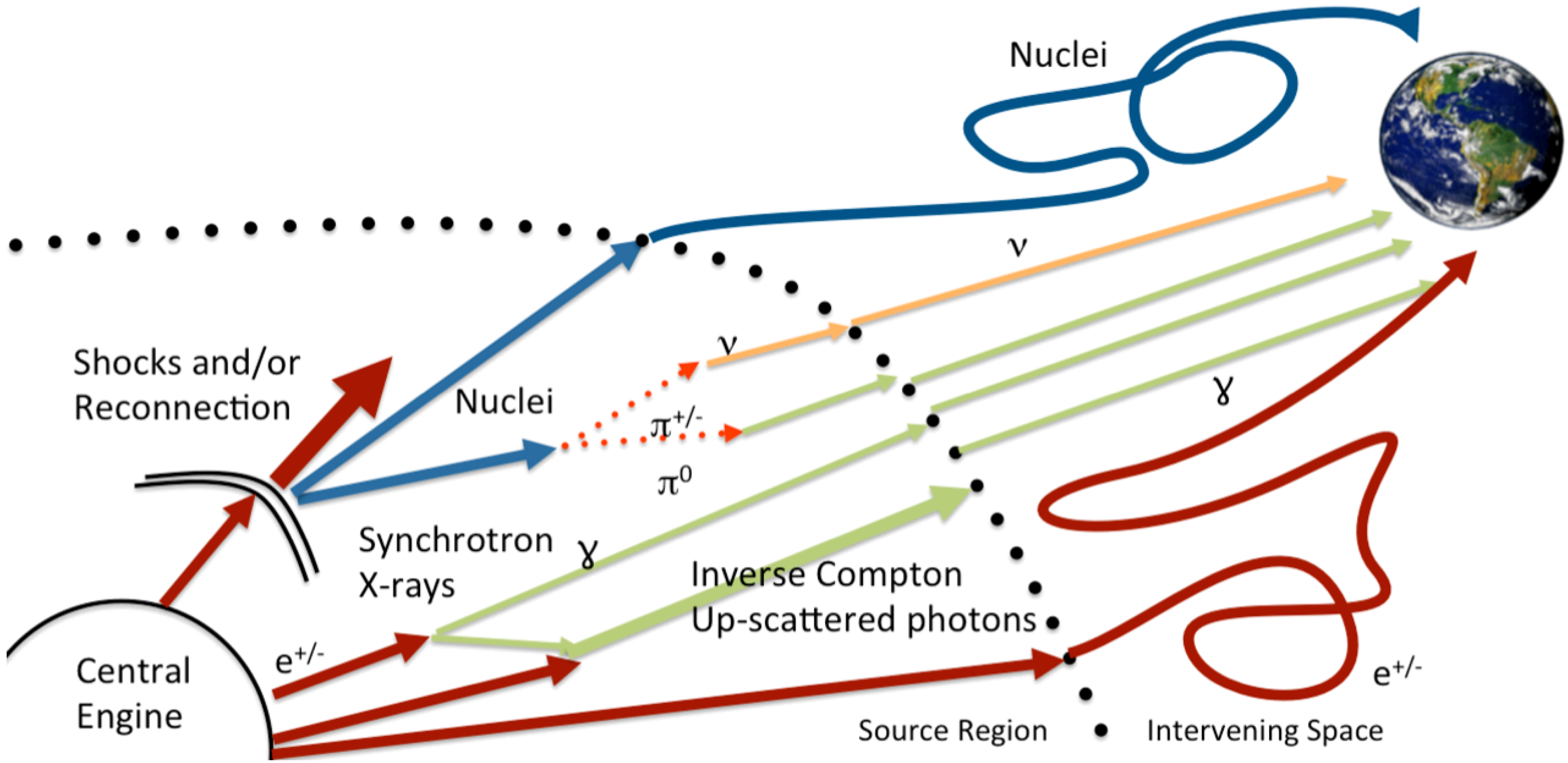




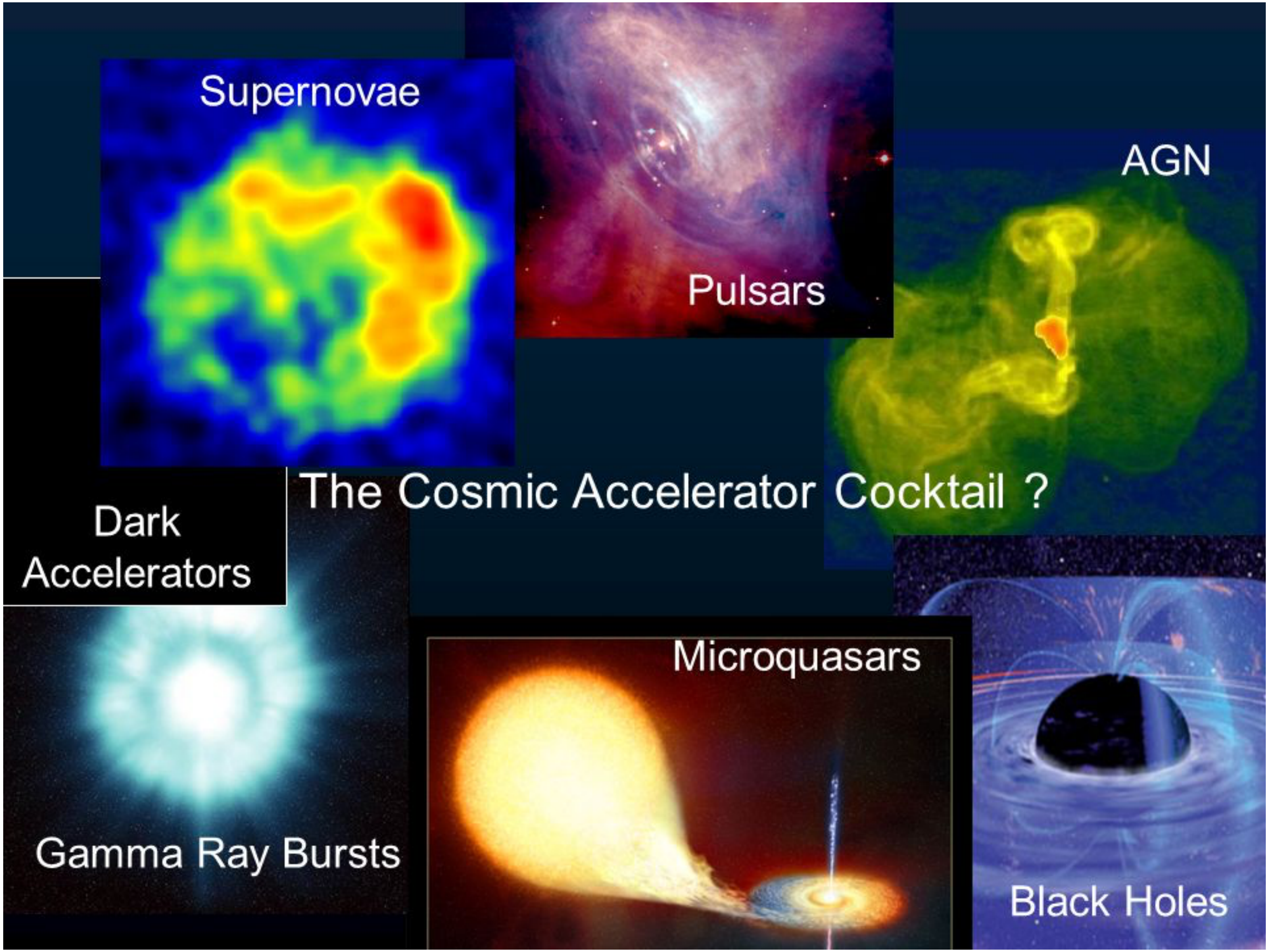
Palladino & Vissani 2016

Aartsen et al. 2016

HE neutrinos: probes of extreme accelerators



Potential source(s)

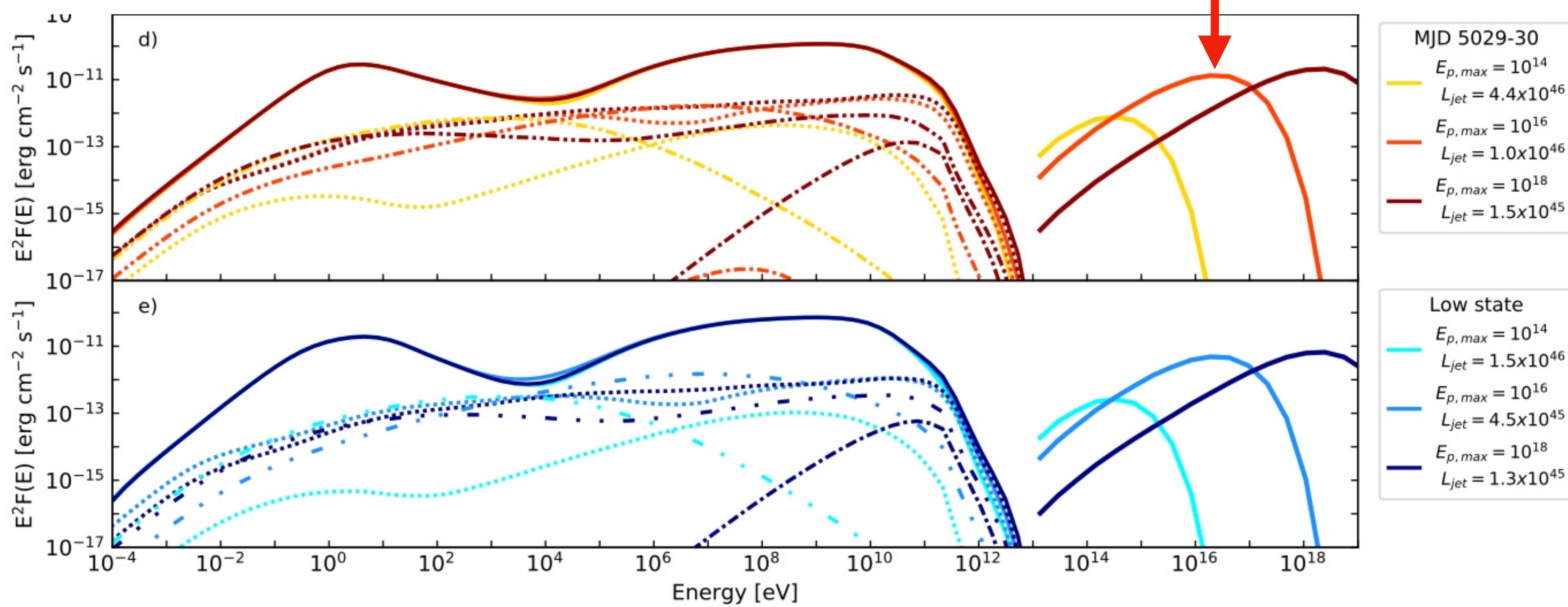


Jet-sheath model

MAGIC Coll. 2018

Effect of maximum proton energy

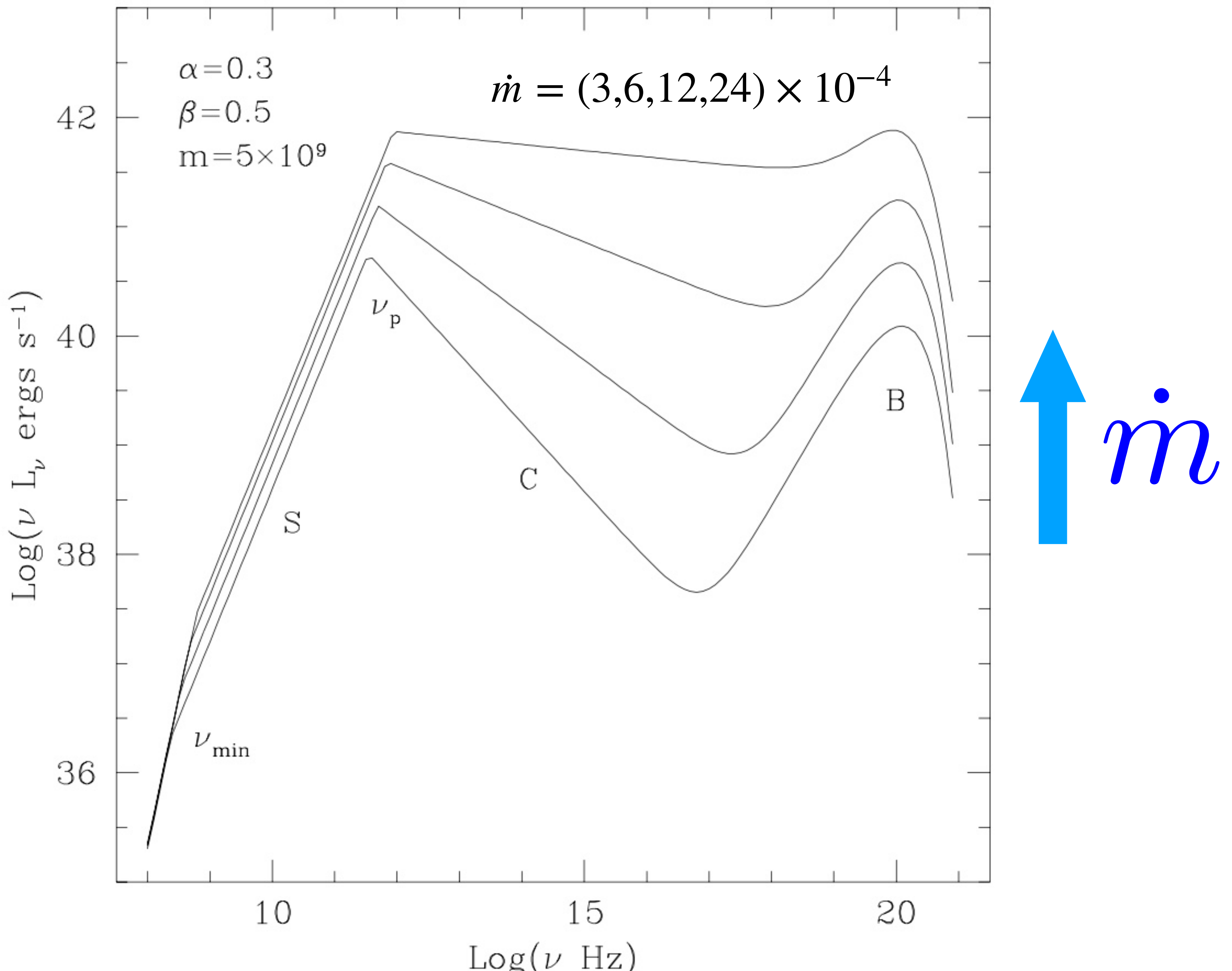
Constrained by cascade flux in X-rays



Larger Ep —> Lower neutrino rate at 300 TeV

A role for the accretion flow?

Advection dominated accretion flow



Mahadevan 1997

Total spectrum!

Any role for the accretion flow?

Low-luminosity AGNs (including BL Lacs and the parent FRI radiogalaxies) are thought to be powered by an accretion flow with quite small accretion rate

e.g., Rees et al. 1982, Yuan et al. 2003, Di Matteo 2003

e.g., Ghisellini et al. 2009, 2011, Meyer 2013 for blazars

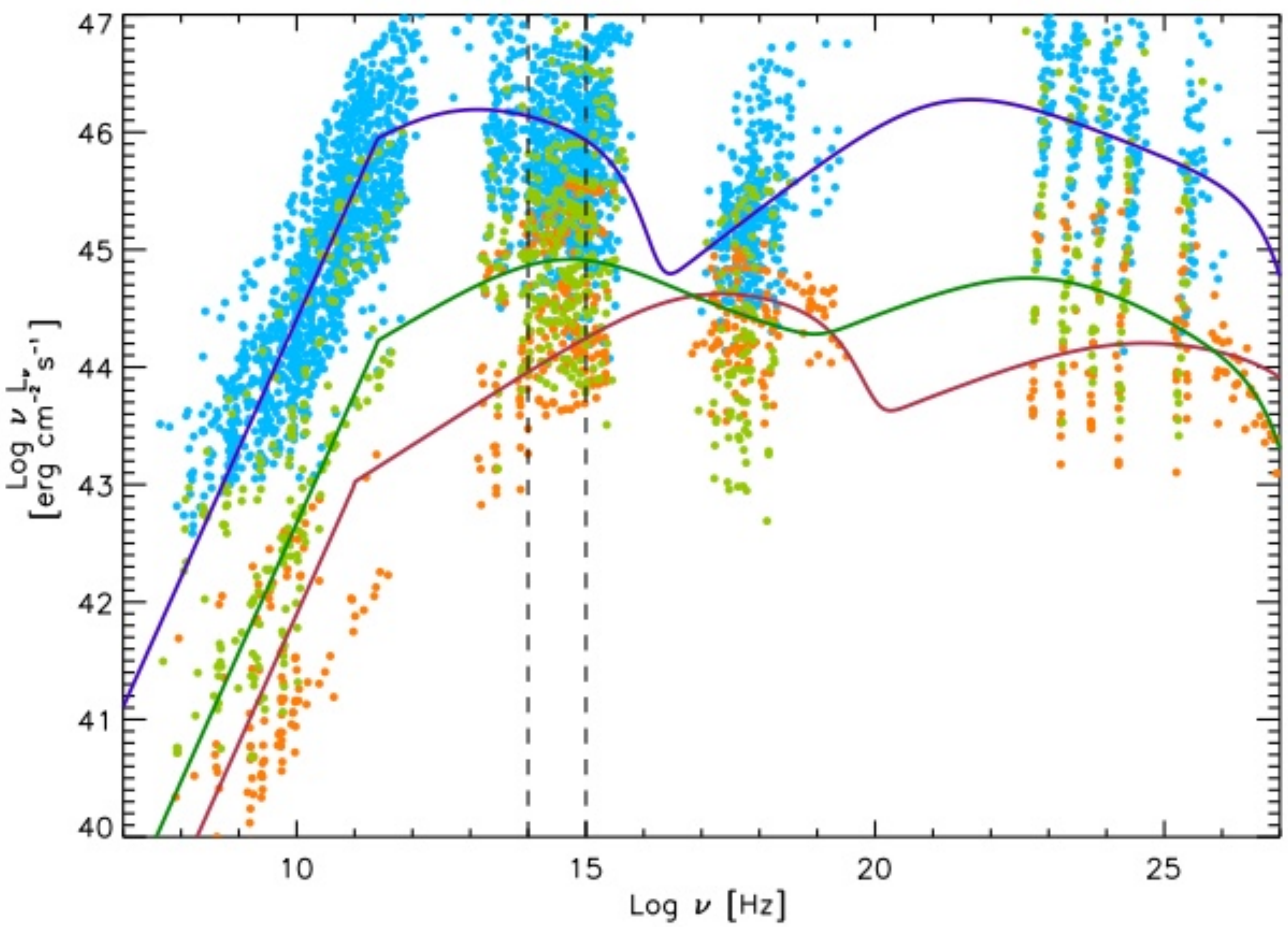
$$\dot{m} < \alpha^2 \approx 10^{-2}$$

Two-temperature flow (Tp>>Te)
Geometrically thick H~R (“spherical-like”)
Optically thin
Outflow?

Ichimaru 1977, Rees et al. 1982, Narayan & Yi 1994, Blandford & Begelman 1999

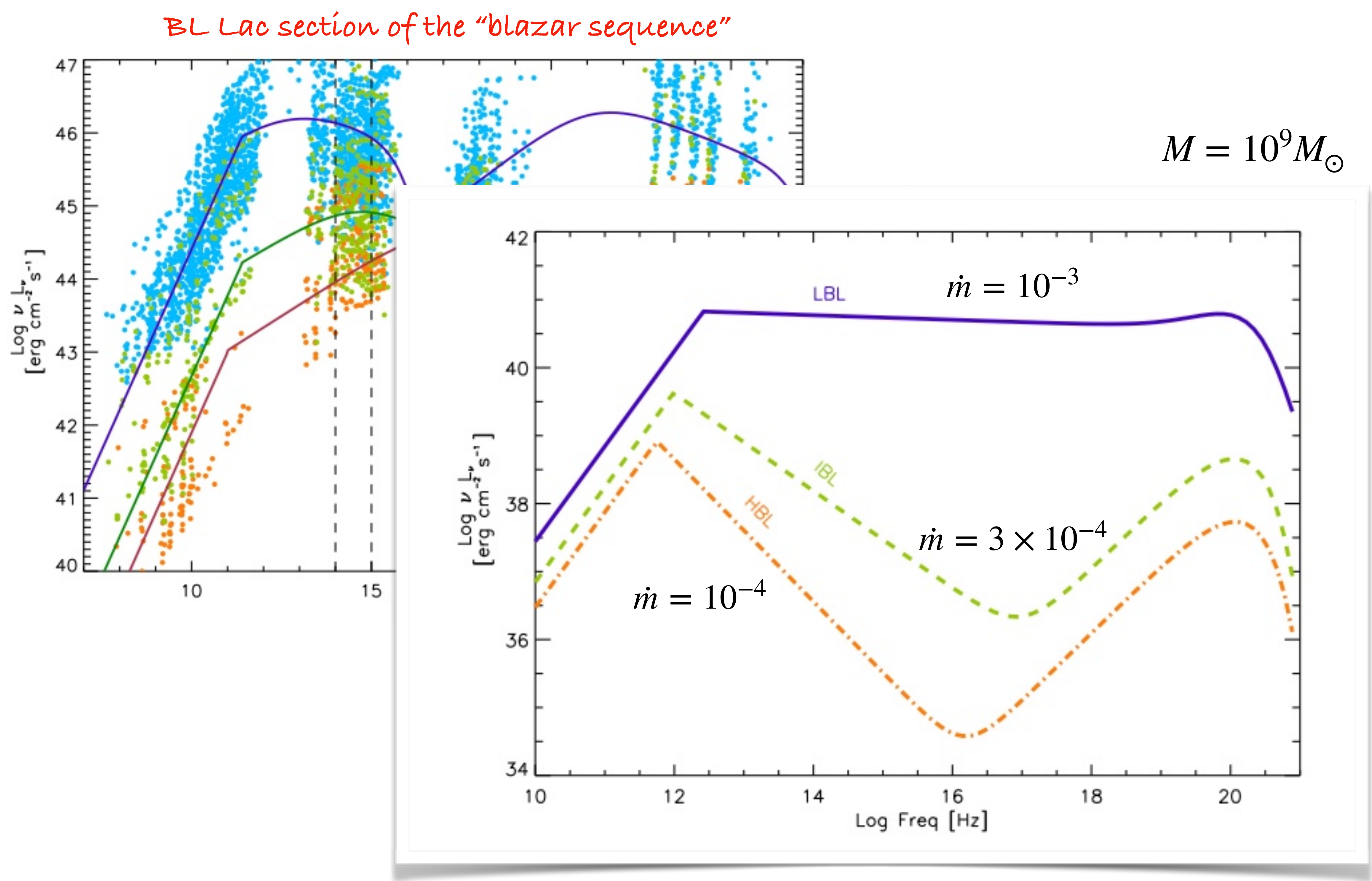
A role for the accretion flow?

BL Lac section of the "blazar sequence"



Righi, FT, Inoue et al. 2018

A role for the accretion flow?



Righi, FT, Inoue et al. 2018

Constraints

Assuming the entire IceCube flux

Kowalski 2015