Multi-messenger fingerprints of distant objects

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OSSERVATORIO ASTRONOMICO DI BRERA

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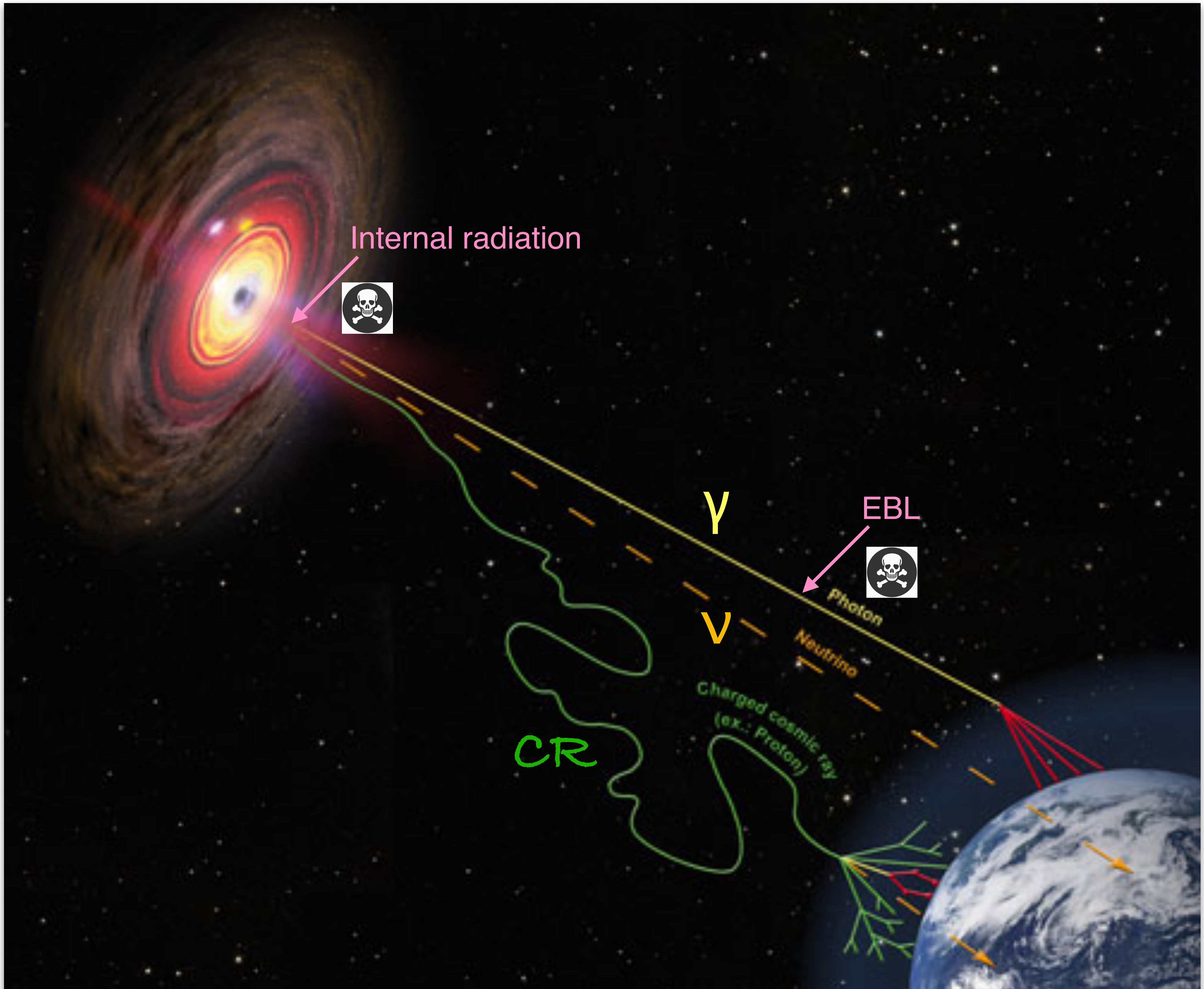
ISTITUTO NAZIONALE DI ASTROFISICA INAF

Messengers from cosmic accelerators



HE ν and γ: probes of hadronic accelerators

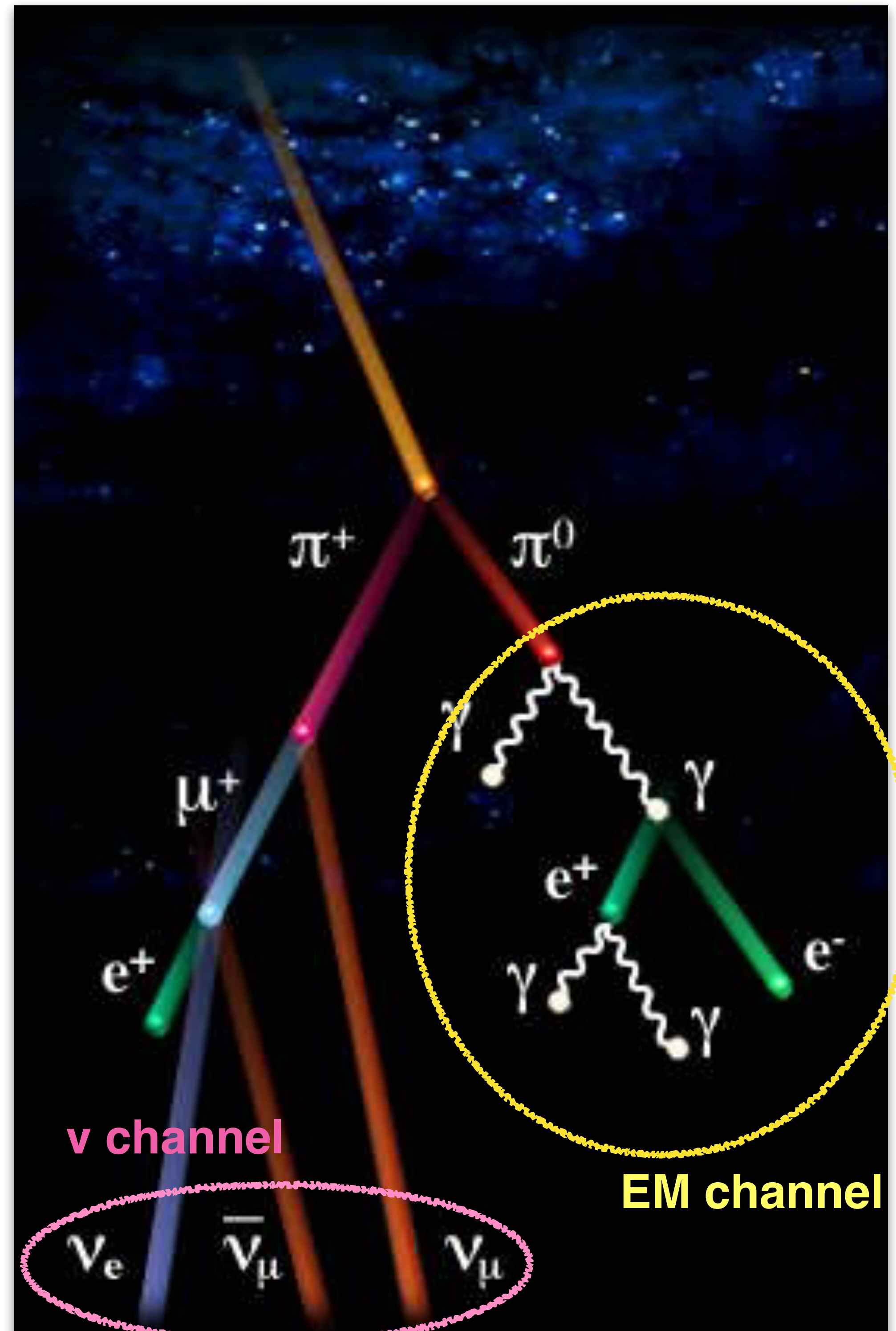
Ingredients:

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)

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

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

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

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

Ep~20 Ev

Lγ~Lν

Potential source(s)

Ingredients:

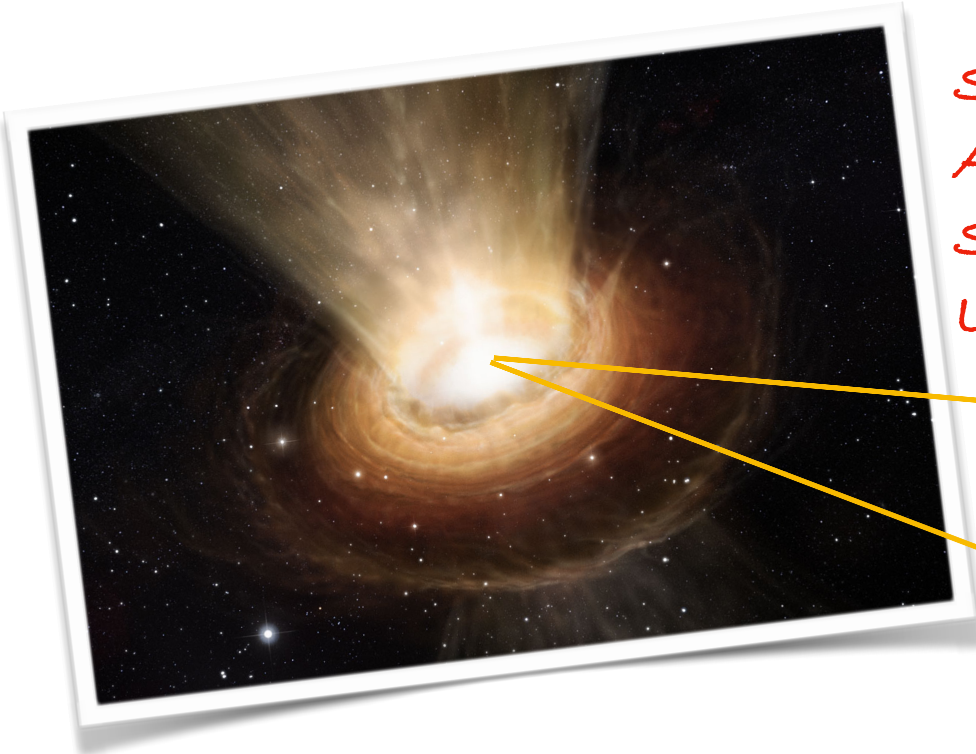
high energy protons (nuclei)

+

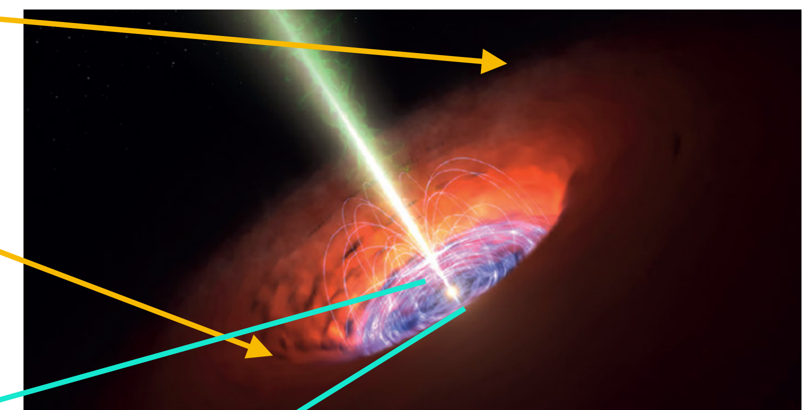
Targets: matter, photons

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

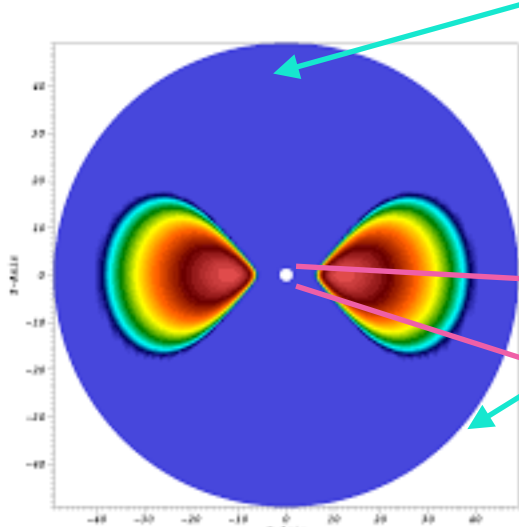
From host galaxies to black holes



Starbursts
AGN winds
Superwinds
Large-scale jets

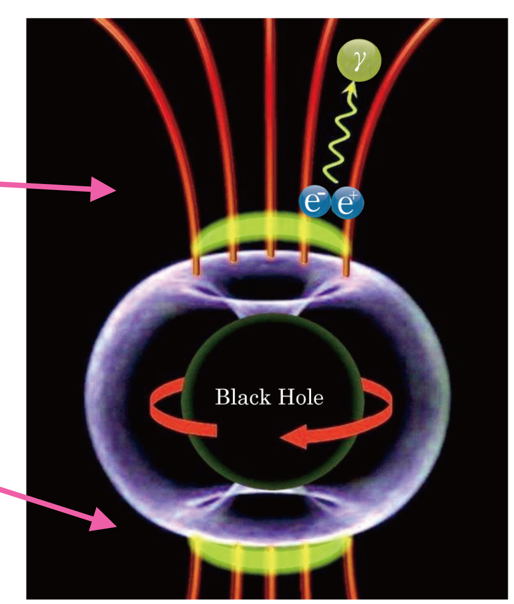


Jets/blazars



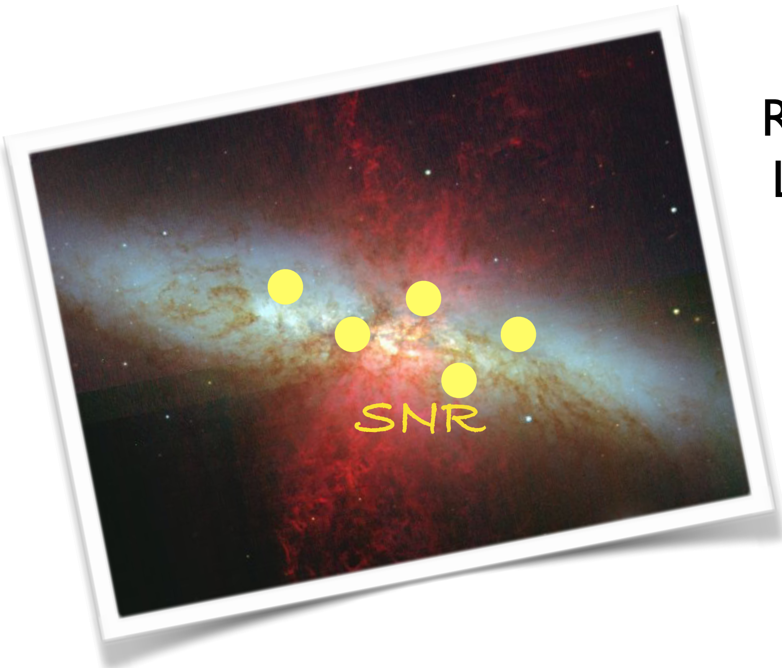
(Inefficient) Accretion flow

BH Magnetosphere



Starburst/Superwinds/AGN winds

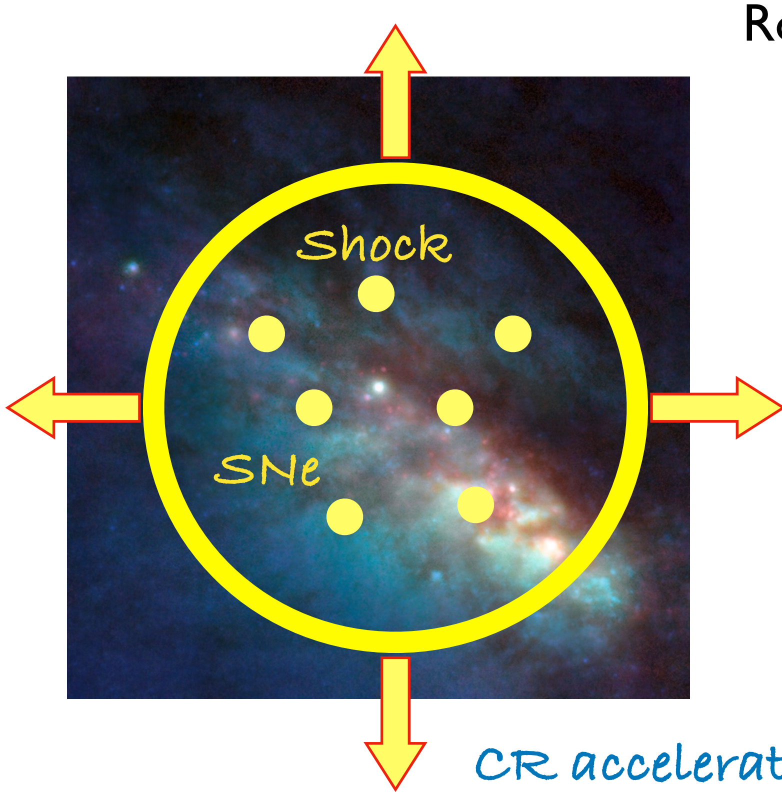
CR accelerated by SNR



Romero & Torres 2003
Loeb & Waxman 2006
Tamborra et al. 2014

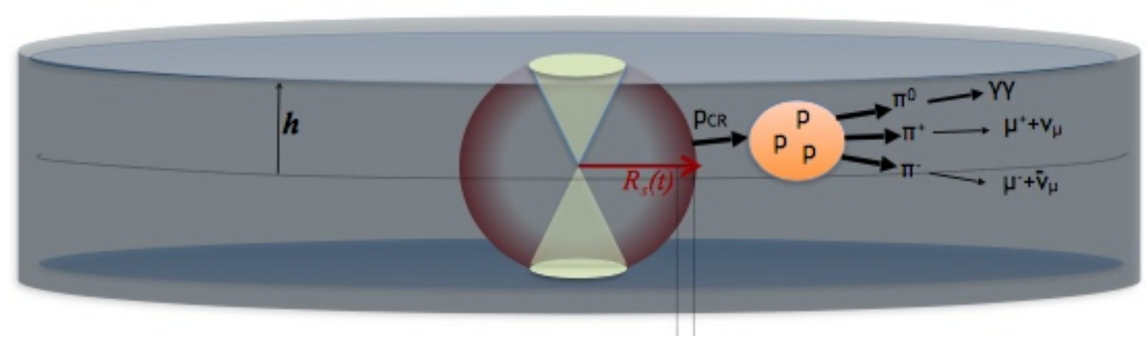
Diffusing CR accelerated in shocks
+
dense gas/dust

Anchordoqui et al. 1999
Romero et al. 2018



CR accelerated by
galactic scale shock

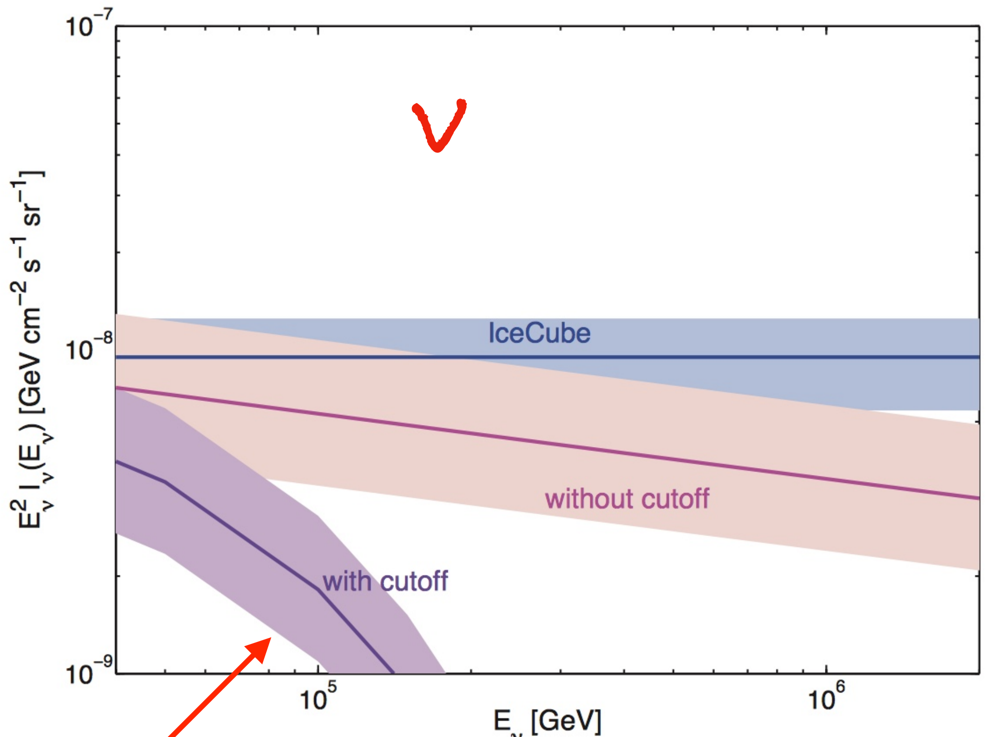
CR accelerated by
AGN-driven shock



Wang & Loeb 2016
Lamastra et al. 2016, 2017
Liu et al. 2018

Starburst/Superwinds/AGN winds

Tamborra et al. 2014



Proton cut off at ~1 PeV

SB/SF

Ep>10^16 eV?

Acceleration? Difficult for standard SNR!
Peculiar Supernovae (e.g. Murase et al. 2013)?
Probably too rare

Diffusion and confinement? See e.g. Peretti et al. 2018

Superwinds/AGN winds

Ep~10^16 eV (but no UHECR)

Possible with diffusive shock acceleration?

Larger energies possible if B-field significantly amplified at shock front

Romero et al. 2018

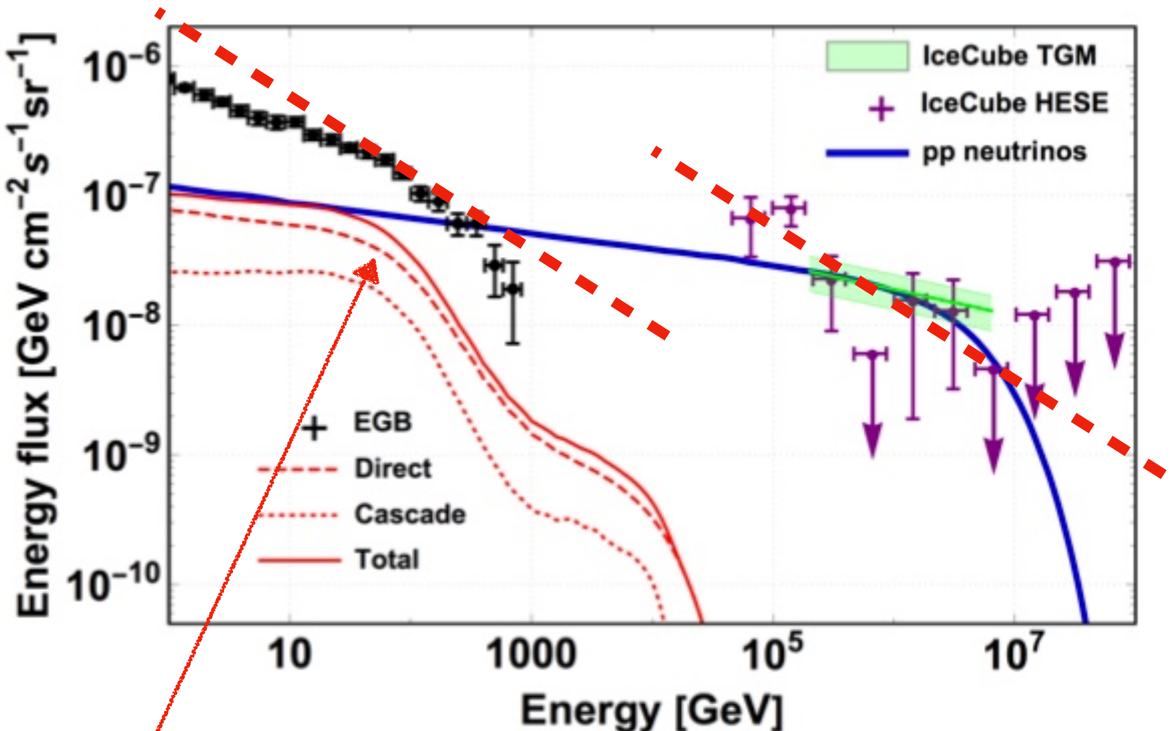
Starburst/Superwinds/AGN winds

Limits to the gamma-ray bkg constrain the CR spectrum to be quite hard, Γ<2.2-2.3

A problem for standard acceleration+diffusion models?
e.g. Milky Way

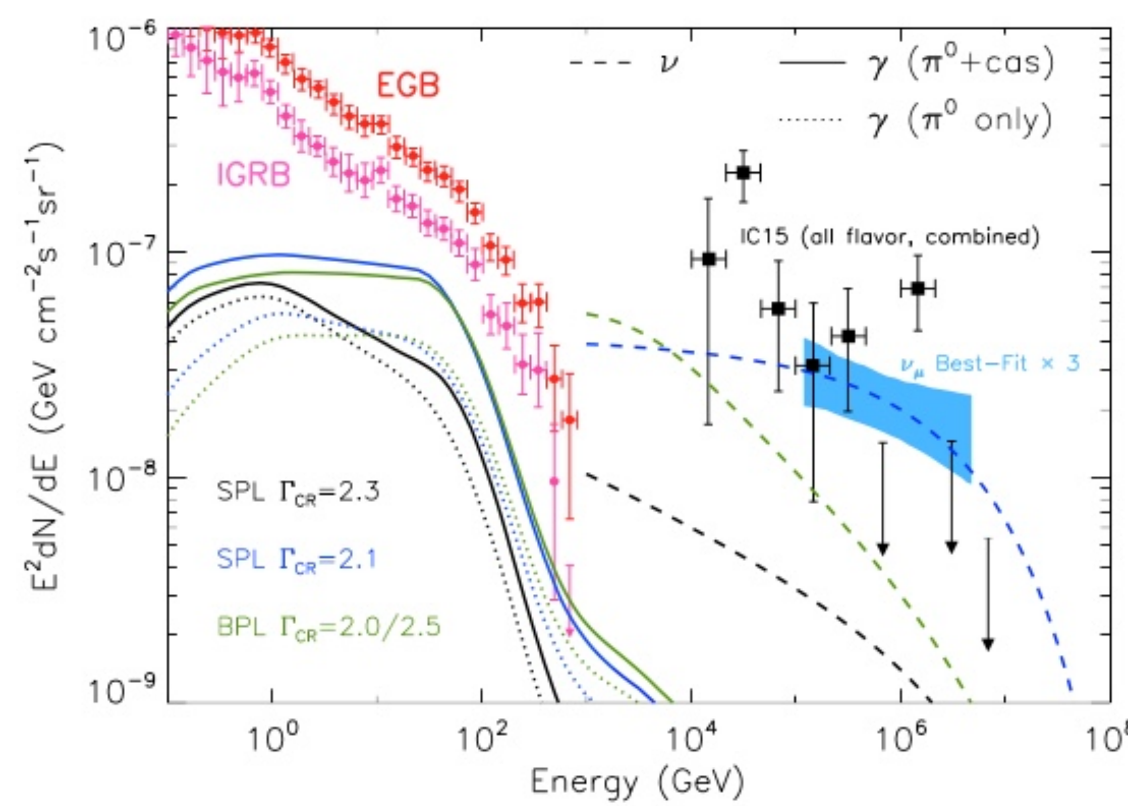
Bechtol et al. 2017
Palladino et al. 2018
Liu et al. 2018

Palladino et al. 2018



Non-blazar contribution: < 20-25%

Liu et al. 2018



Relativistic jets: radiogalaxies?

CR accelerated in shocks + gas in the jet

Becker-Tijus 2004

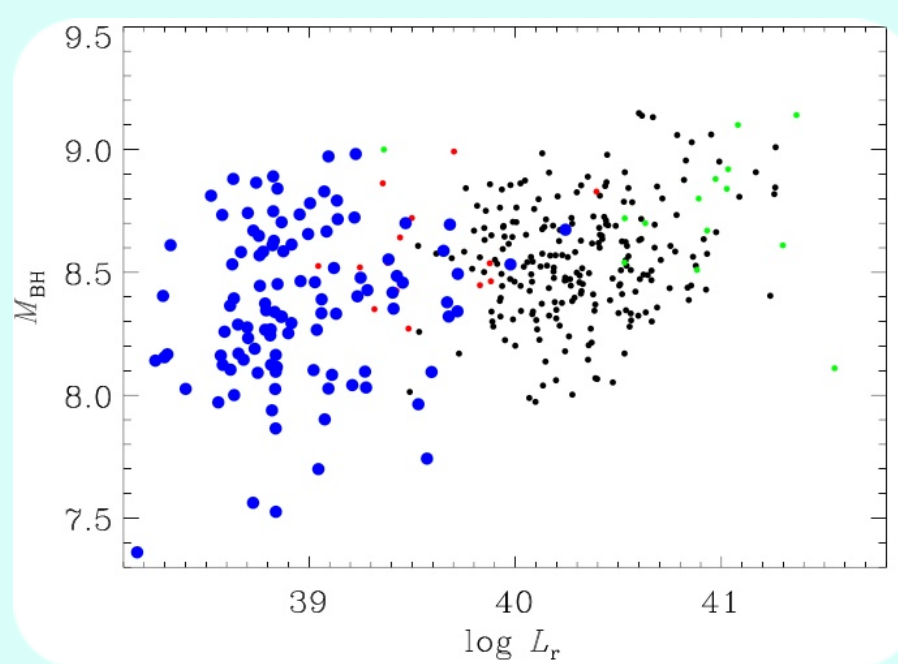
Large jet power!

CR accelerated in shocks + gas in the host

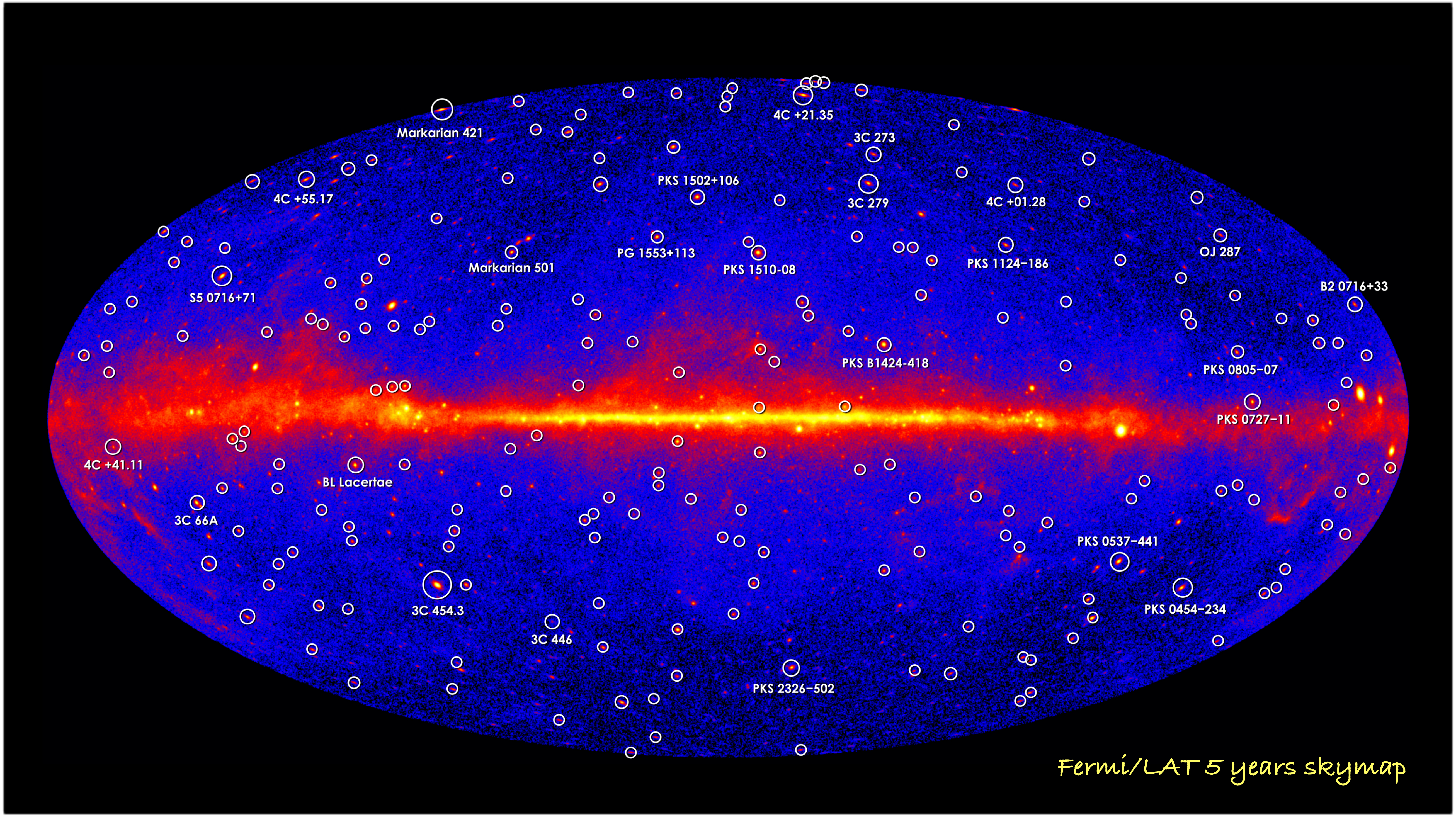
Hooper 2016
Tavecchio et al. 2018

Diffusion in ellipticals?

Recent studies (e.g. Baldi et al. 2018) show that very weak RG (FR0) are very abundant. Possible neutrino emitters? (Tavecchio et al. 2018)



Neutrinos from blazar jets?

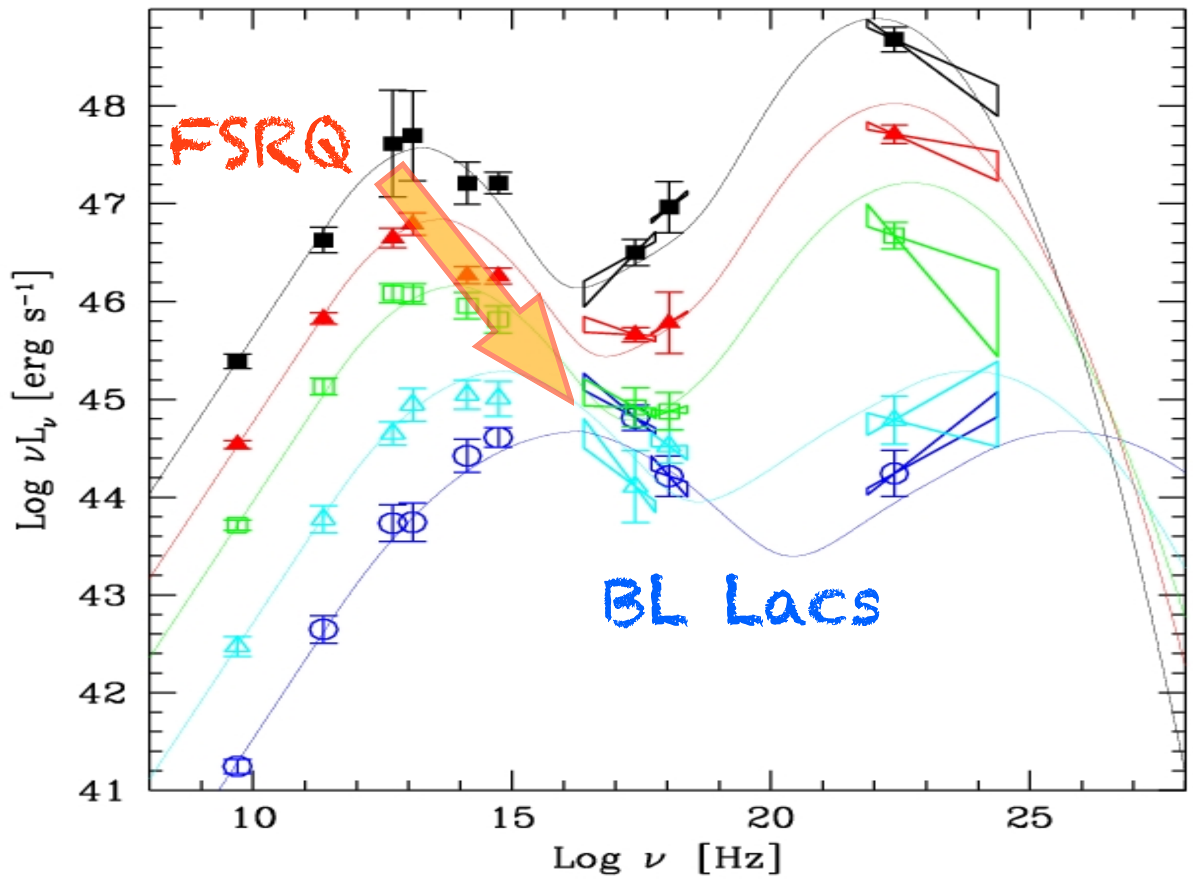


Blazars in a nutshell

Blazars occur in two flavors:

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

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



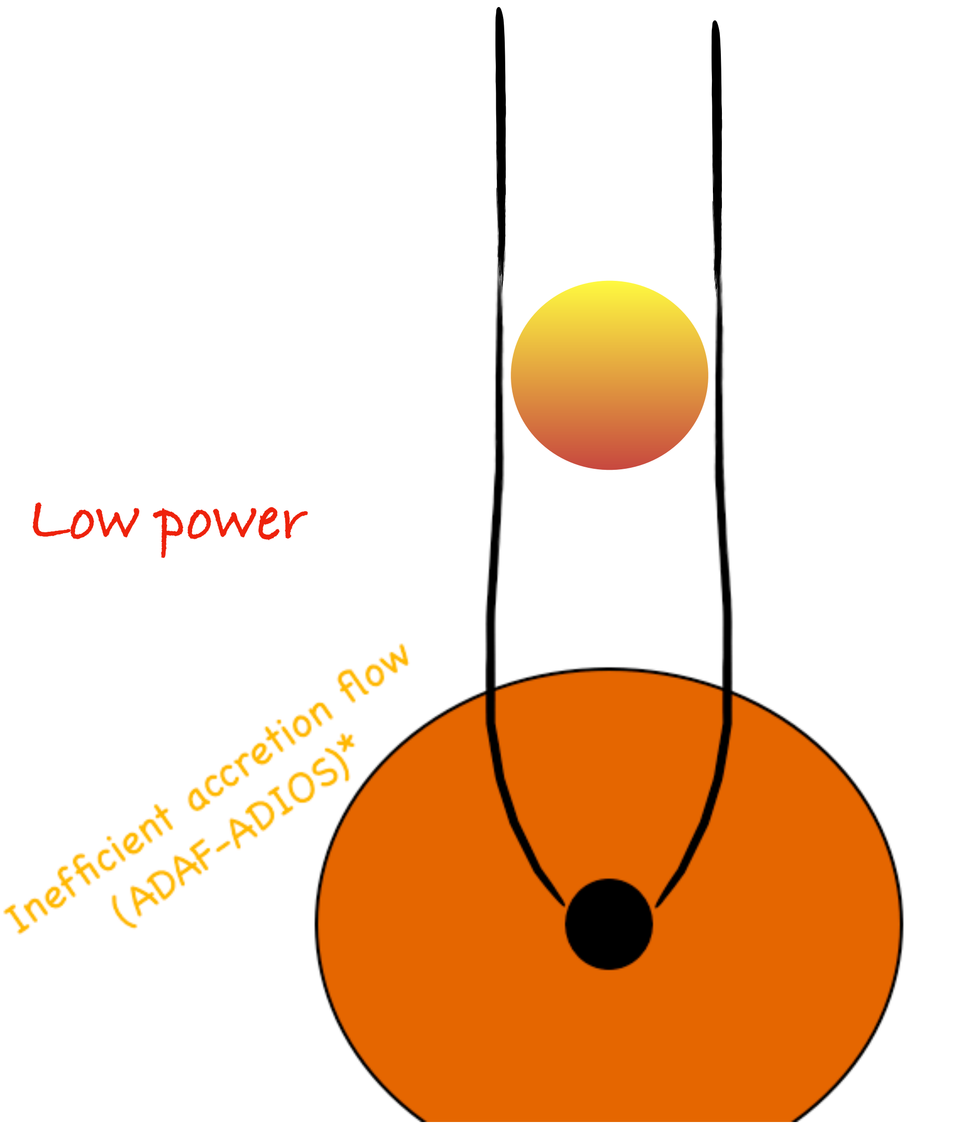
The "blazar sequence"

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

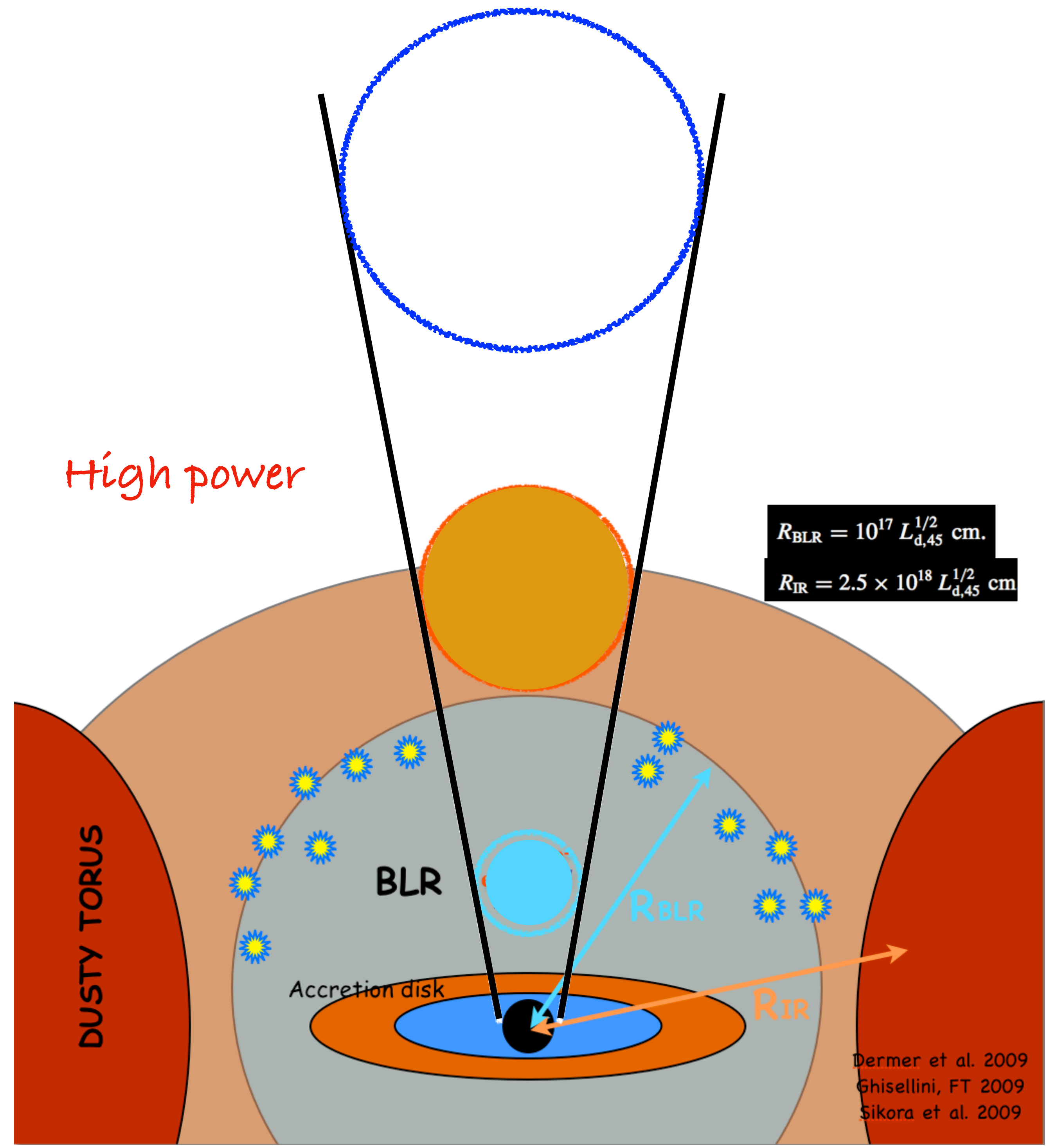
But see several papers by Giommi & Padovani

Blazars in a nutshell

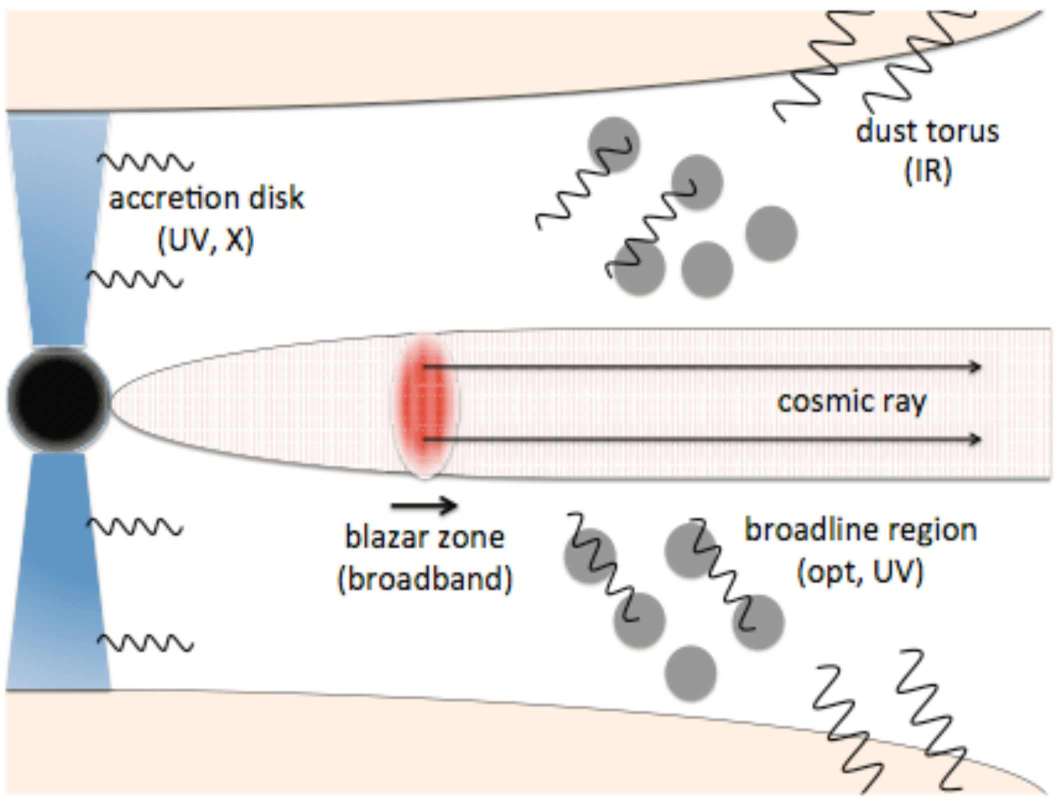
BL Lacs: “naked” jets



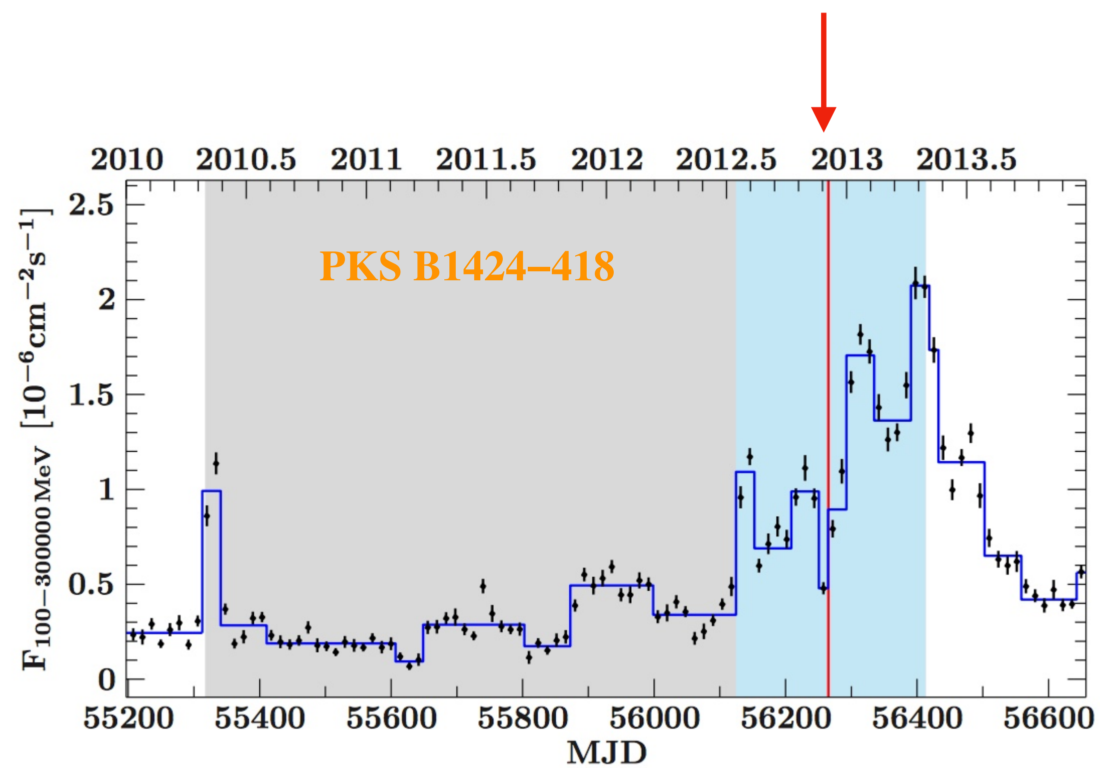
FSRQ: “dressed” jets



Neutrino from FSRQ?



"Big bird"



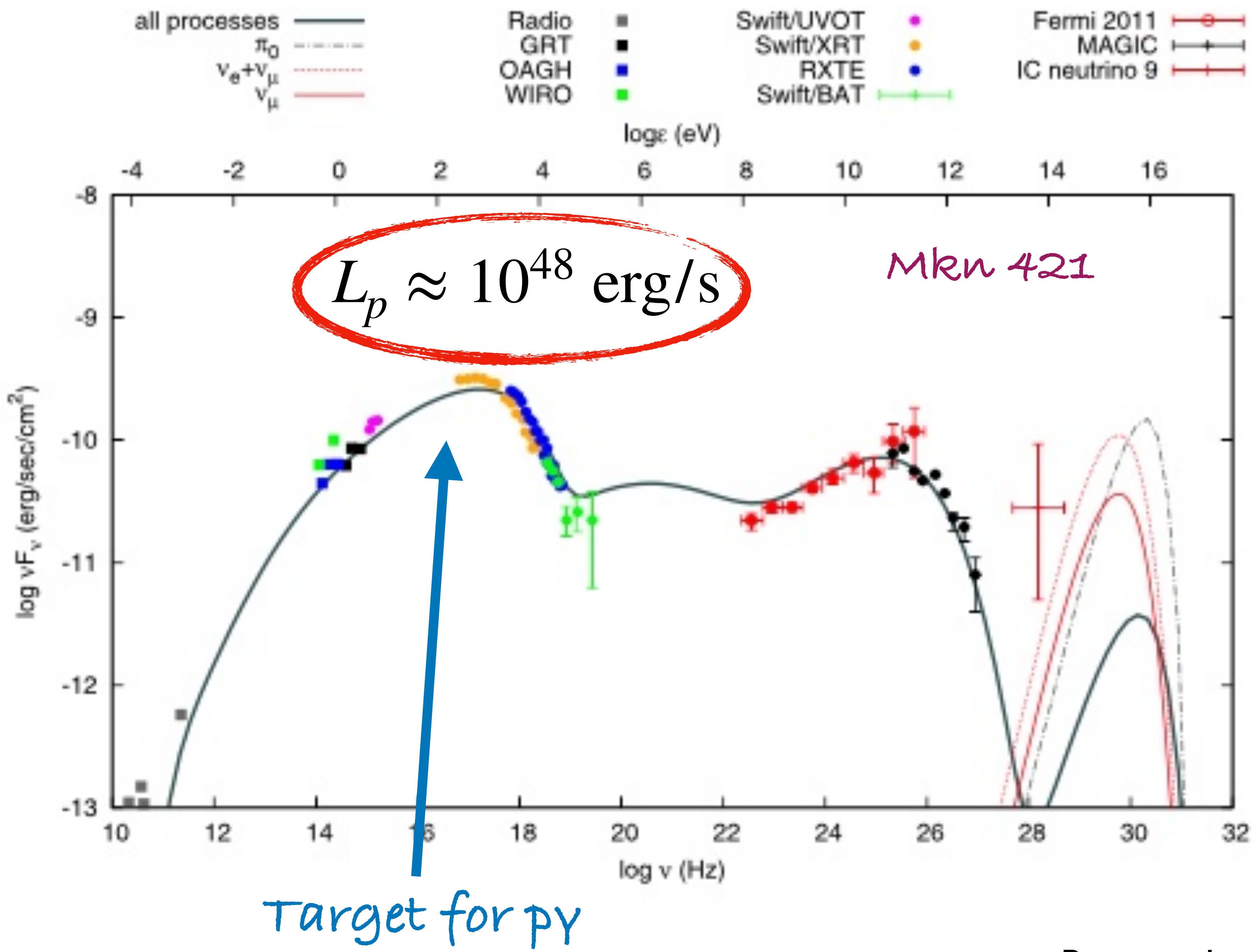
Kadler et al. 2016

Photomeson production strongly favored

Mannheim 1993
Murase, Inoue & Dermer 2014

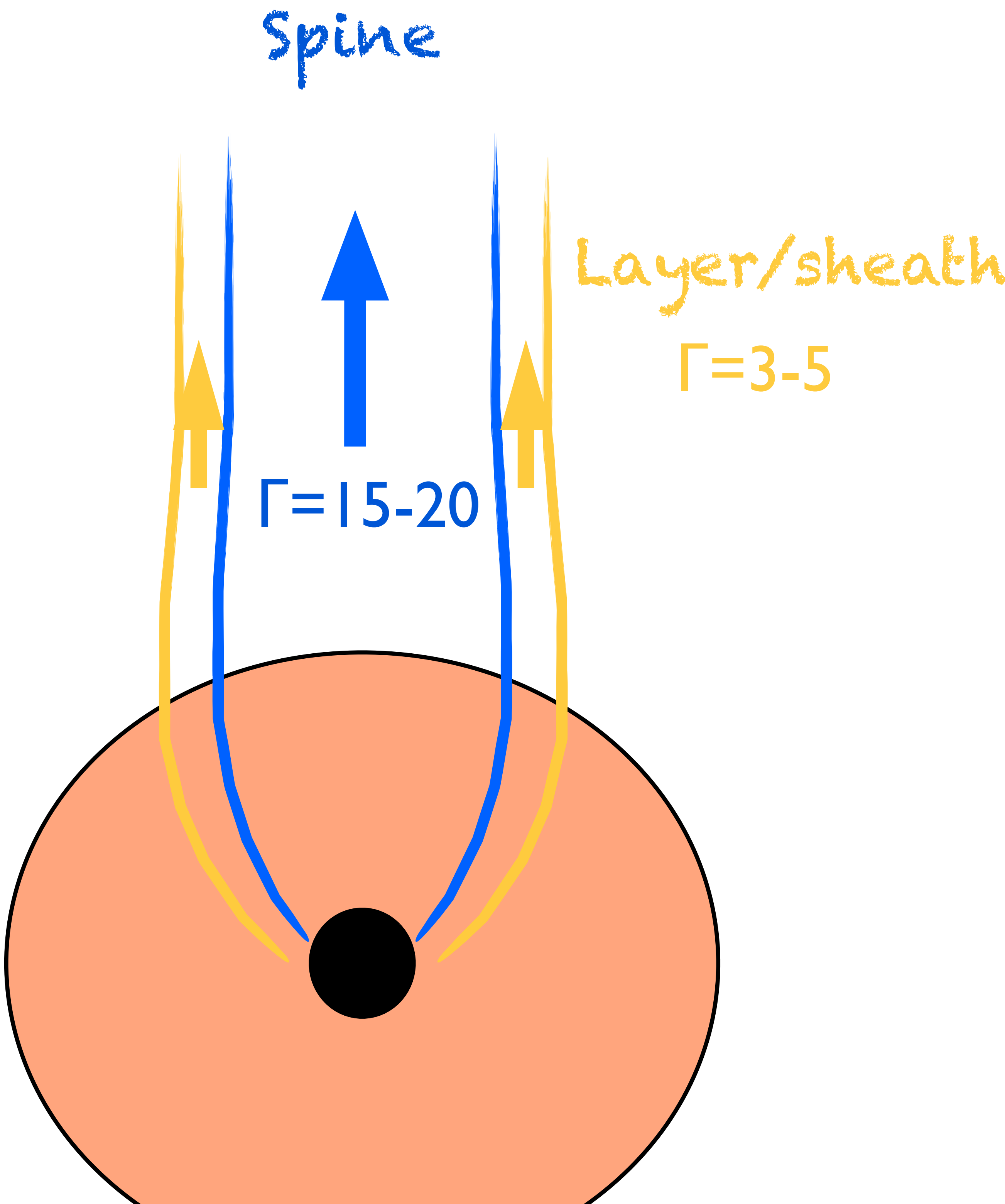
Neutrino from BL Lacs?

One-zone models: inefficient!



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

Structured jets in BL Lacs

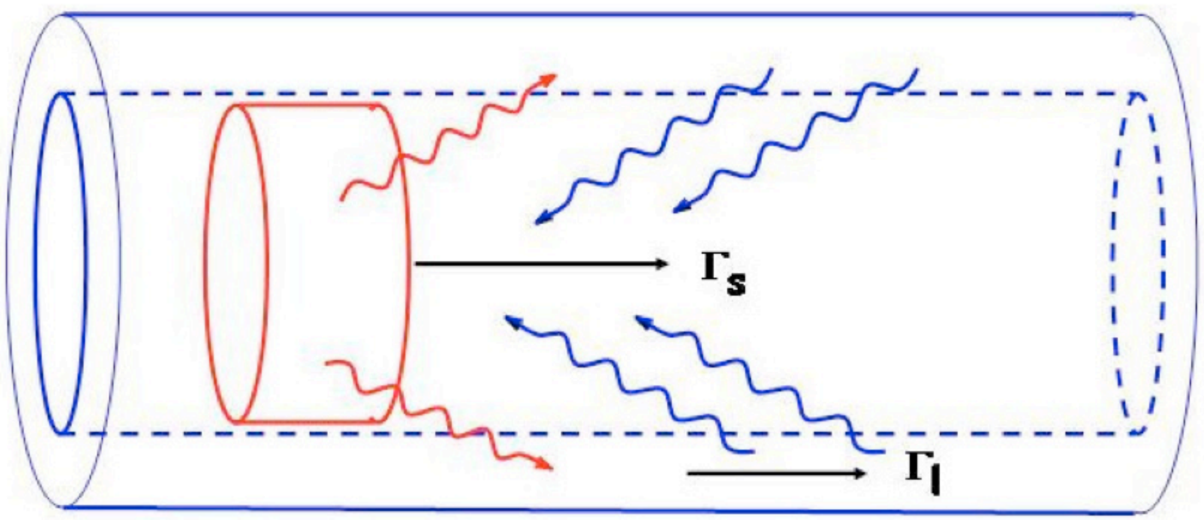


Ghisellini, FT and Chiaberge 2005
Tavecchio & Ghisellini 2008

Structured jets in BL Lacs

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

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



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

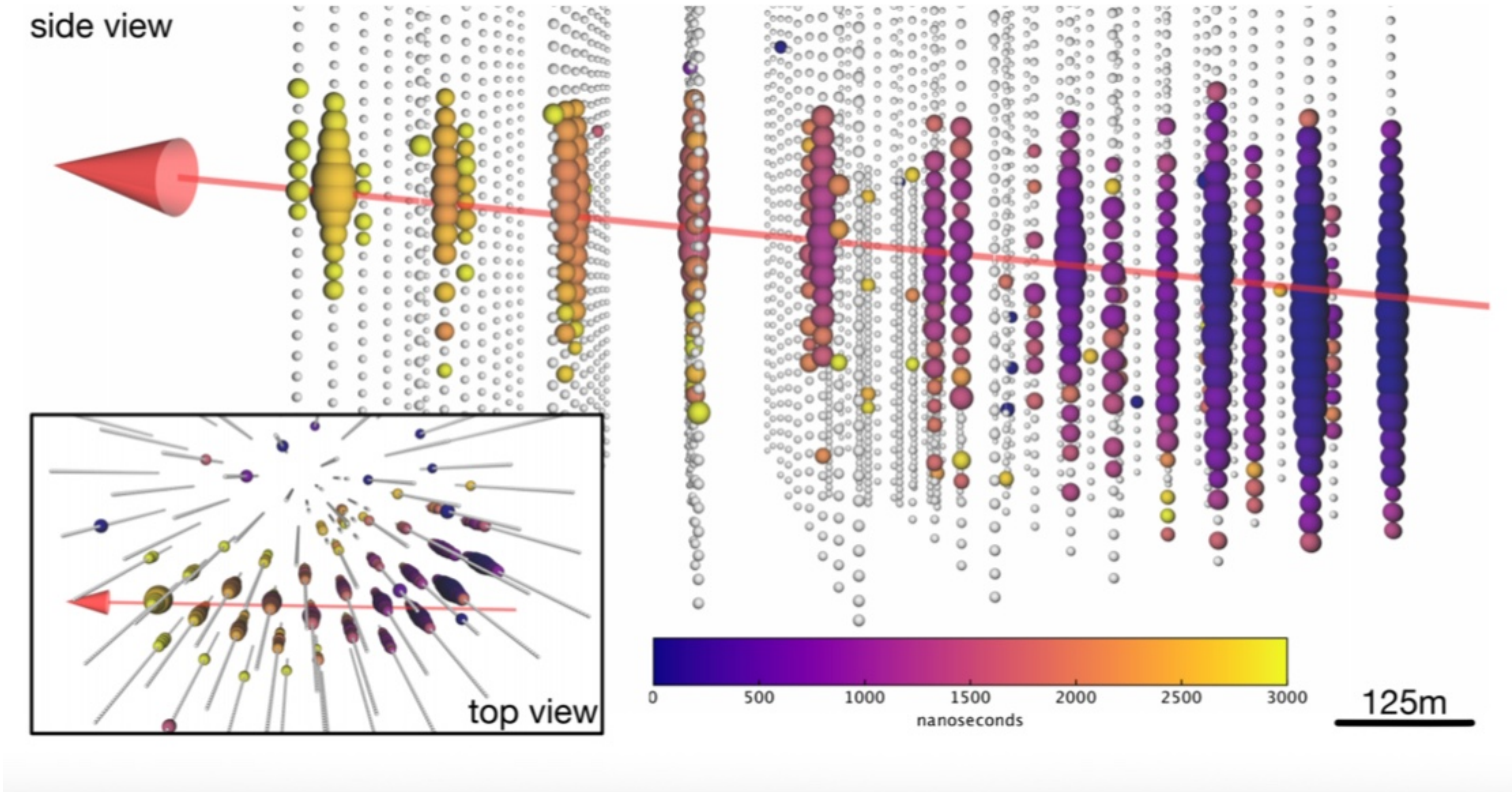
Rates of processes involving soft photons are enhanced w.r.t. to the one-zone model

Both IC and neutrino emission!

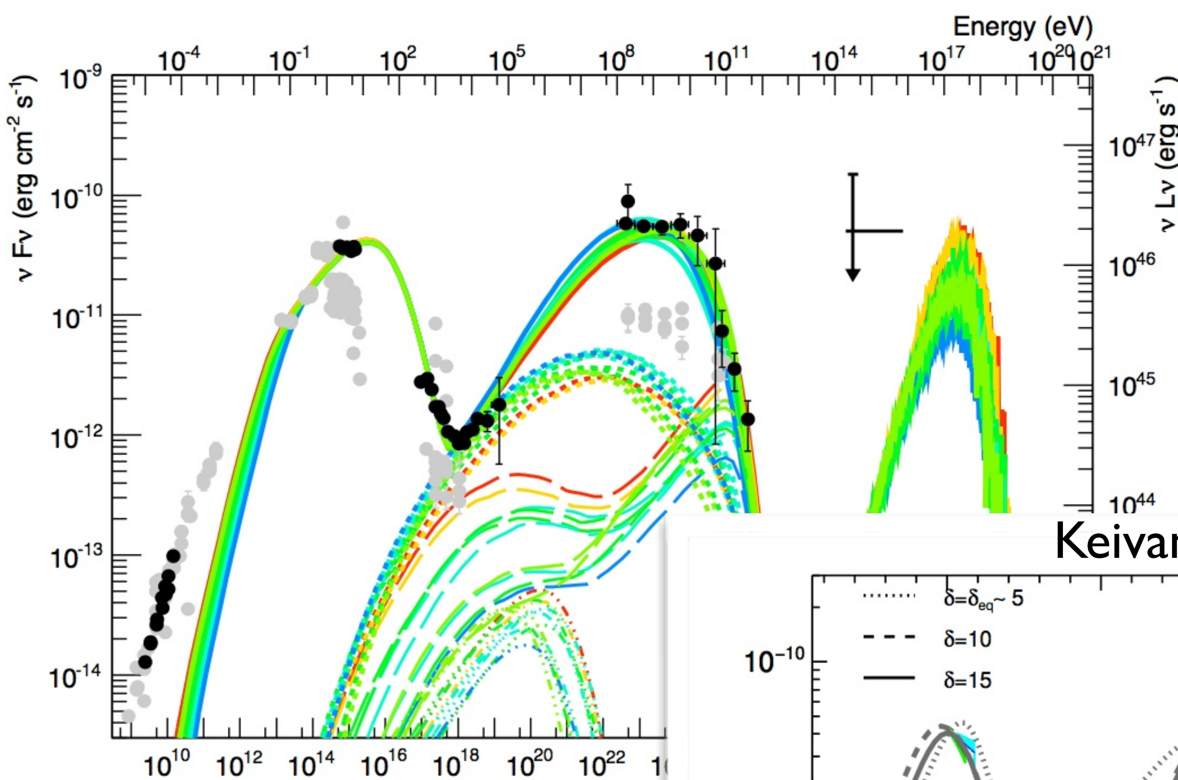
Tavecchio et al. 2014, 2015

TXS 0506+056 & IC-170922A

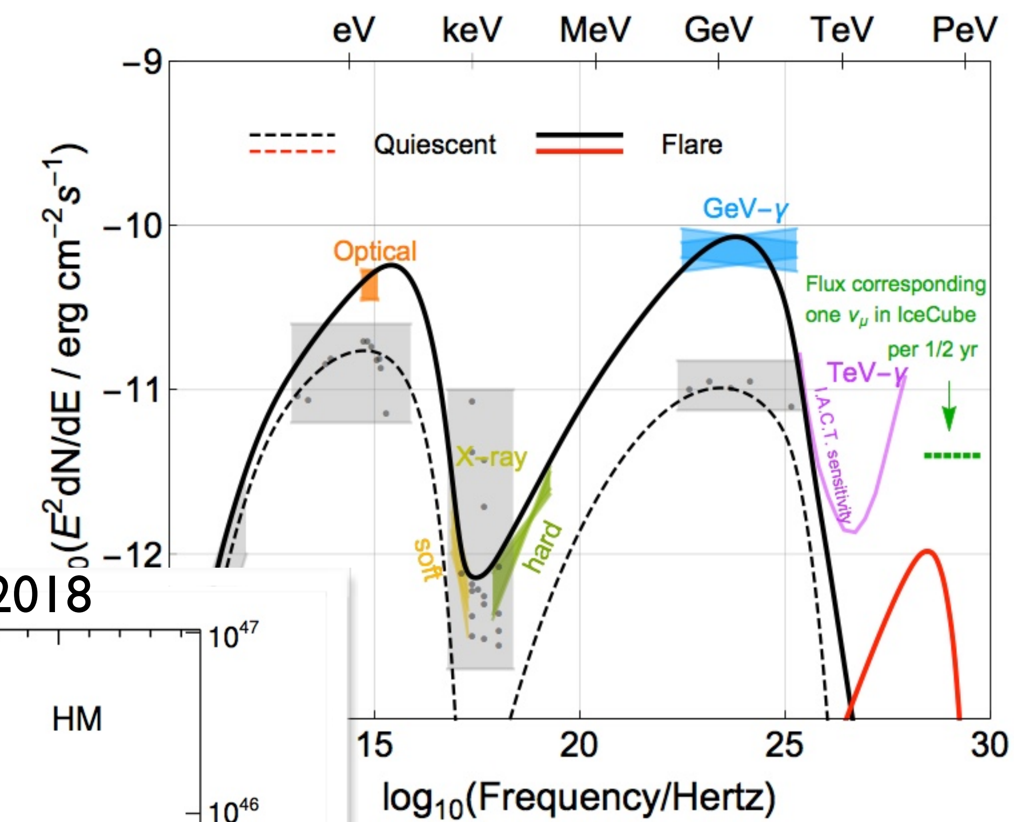
2017 september 22



A burst of (one-zone) models …

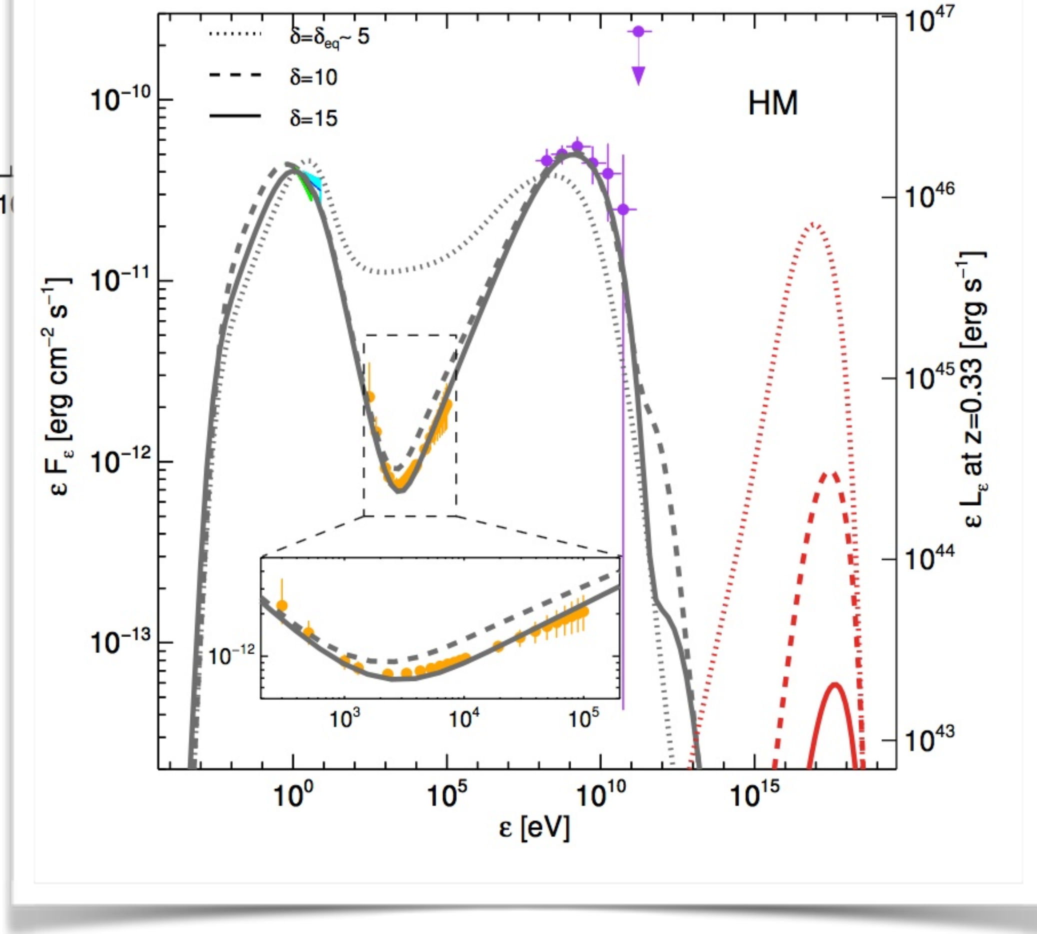


Cerruti et al. 2018



Gao et al. 2018

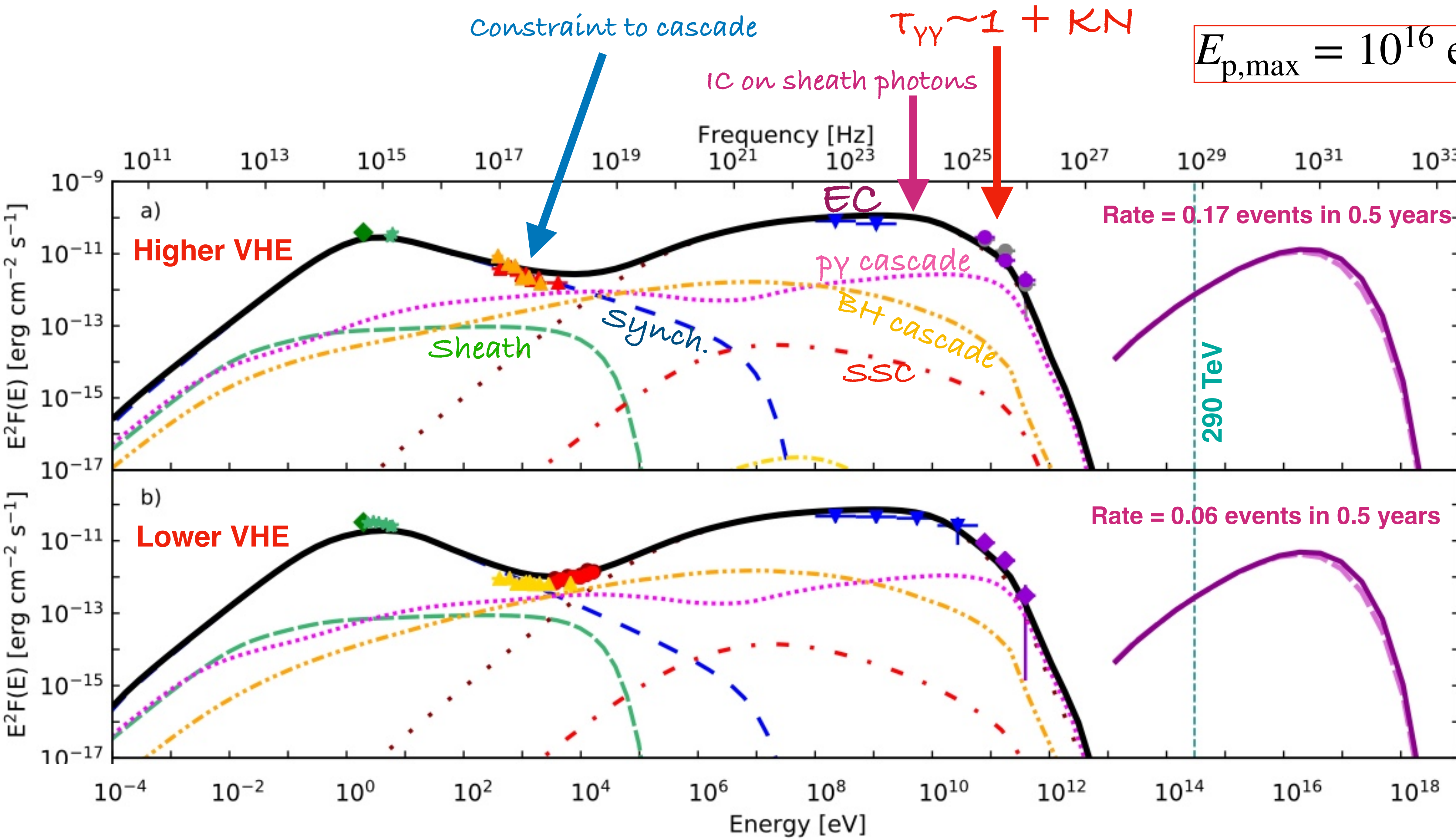
Keivani et al. 2018



But, again, the jet power is very large!

Jet-sheath model

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



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

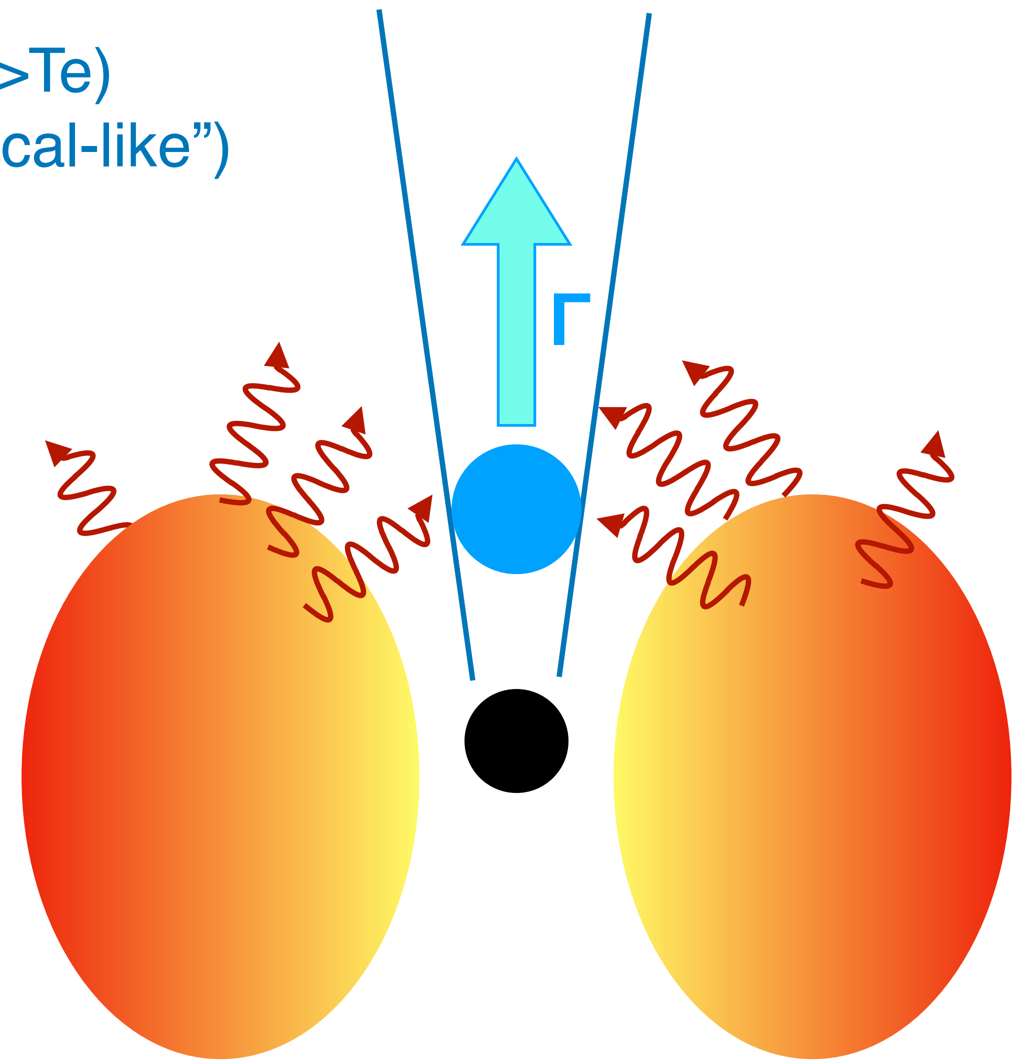
MAGIC Coll. 2018

Numerical model by. W. Bhattacharyya

A role for the accretion flow?

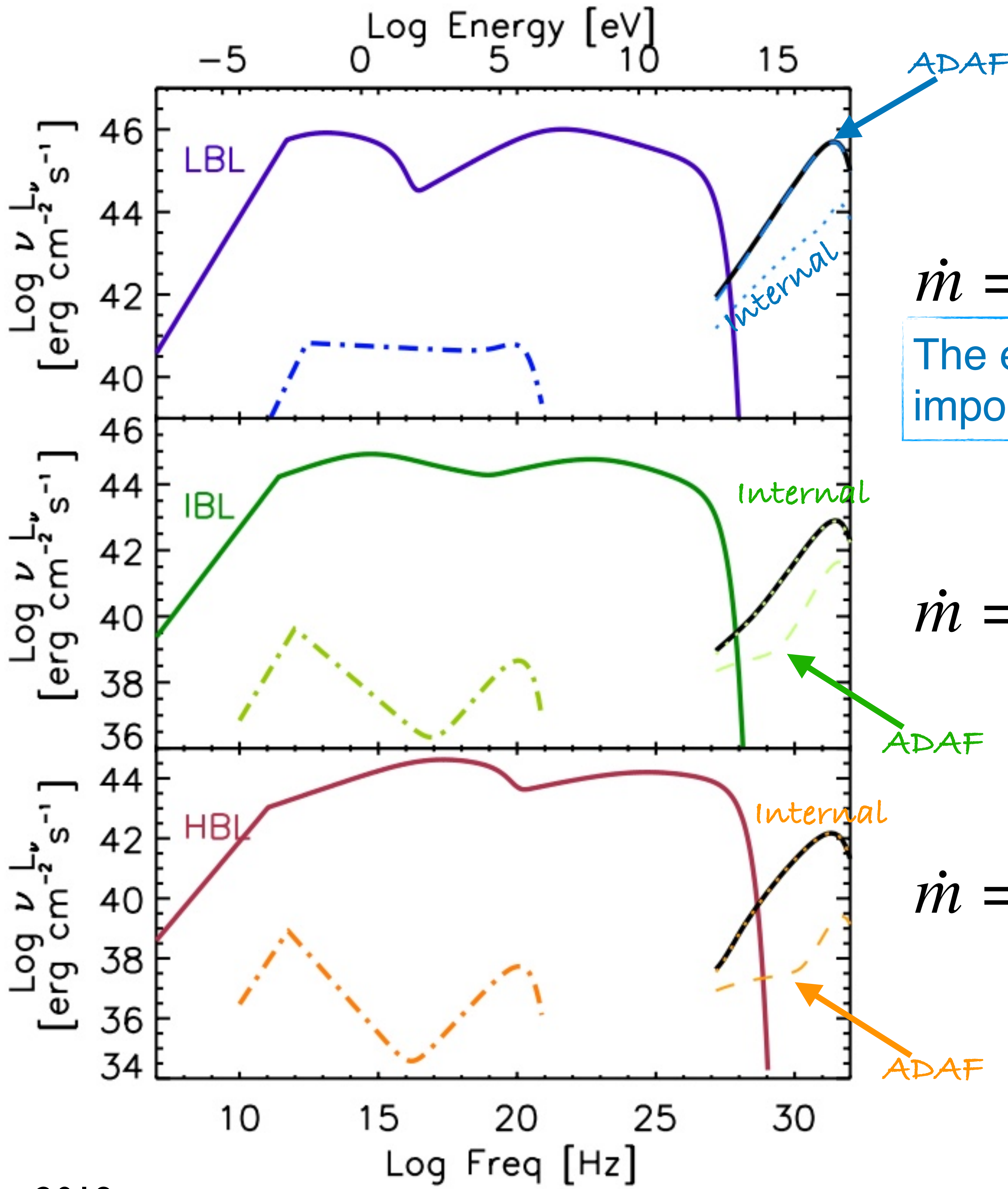
Radiatively Inefficient Accretion Flow (RIAF)
Advection Dominated Accretion Flow (ADAF)

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?



$L_p \propto P_{jet}$

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

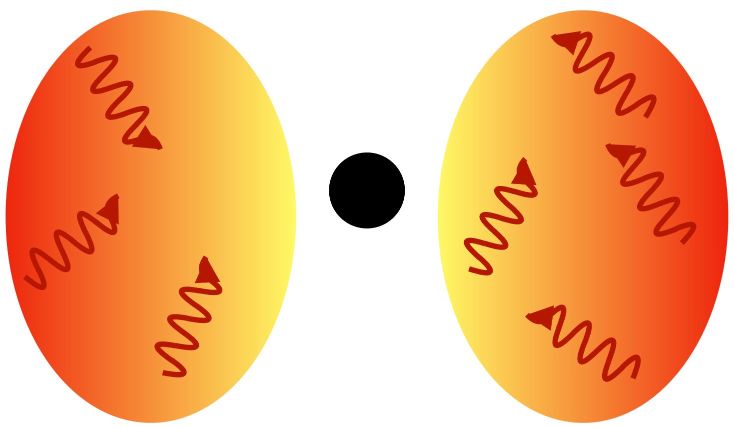
The external field is important for LBL only

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

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

Righi, FT, Inoue 2019

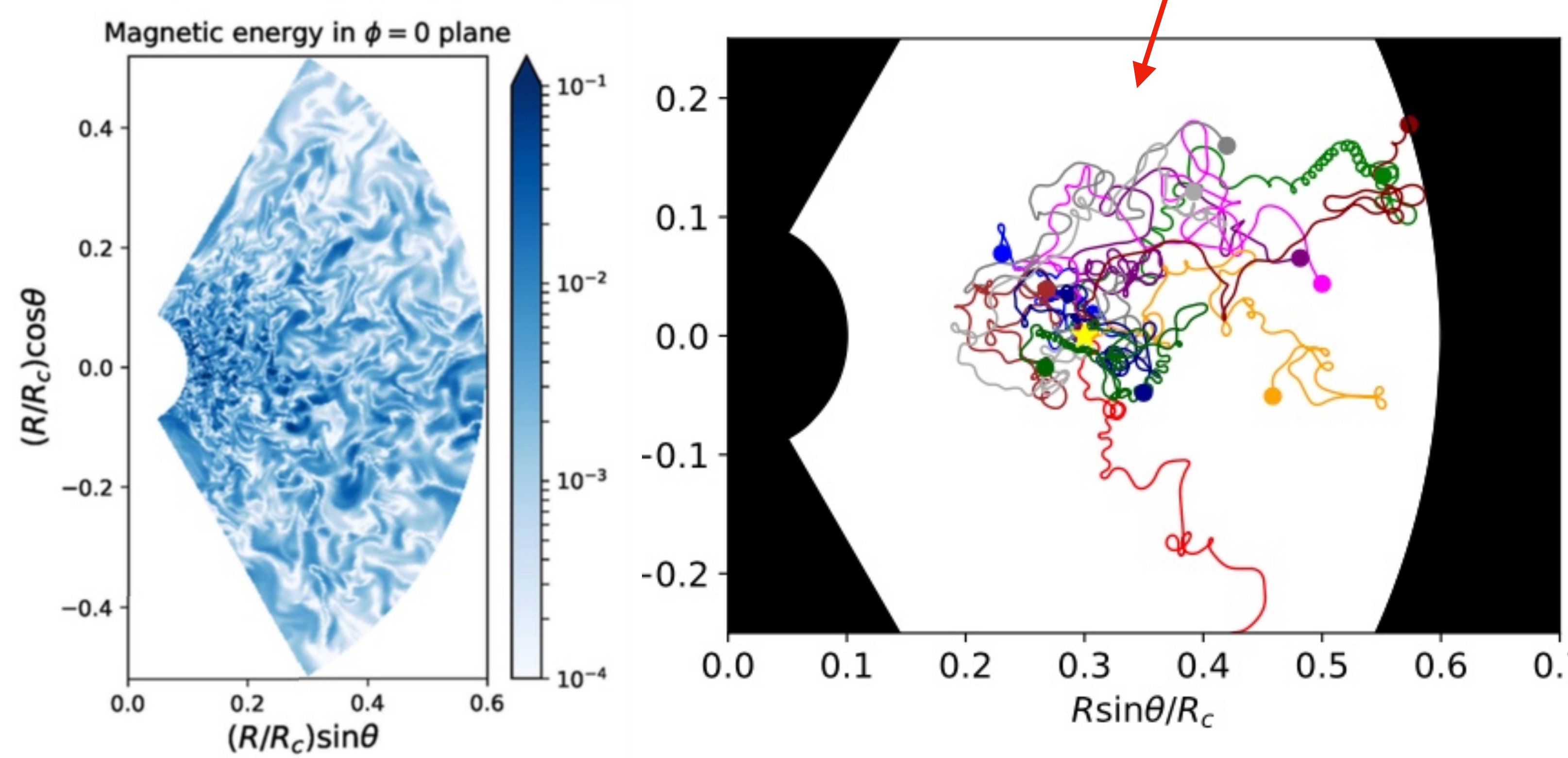
A role for the accretion flow?



Powering **low luminosity AGN**

Kimura et al. 2015; Khiali et al. 2016

Particle accelerated through Fermi II processes
scattering off magnetic turbulence



Protons up to few PeV expected
(no UHECR)

Emission either through pp or pγ

Kimura et al. 2018

Constraints on cosmic populations

Measured

Cosmic density

Effective luminosity

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

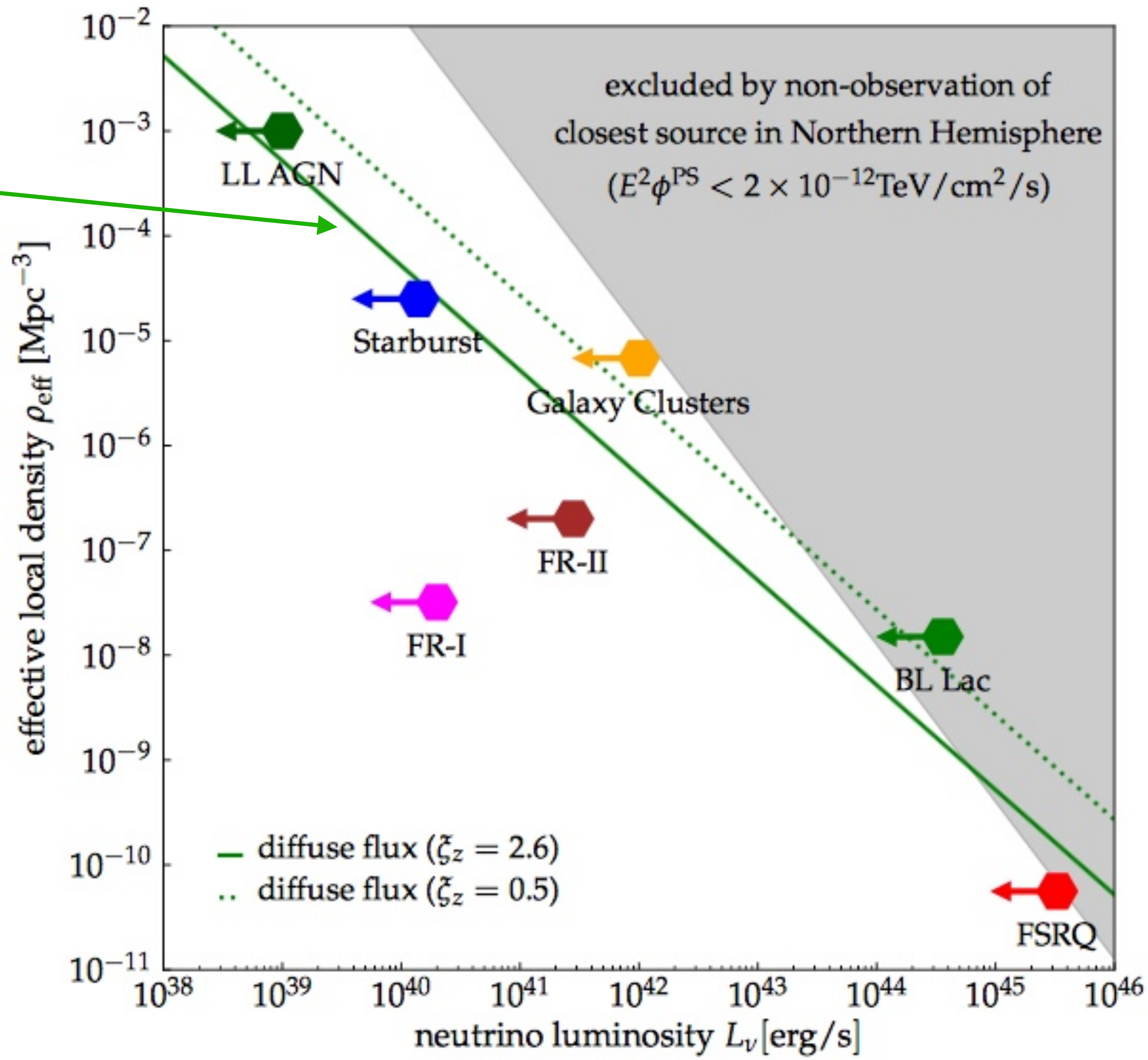
Evolution

Assuming a single population

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

Constraints on cosmic populations

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

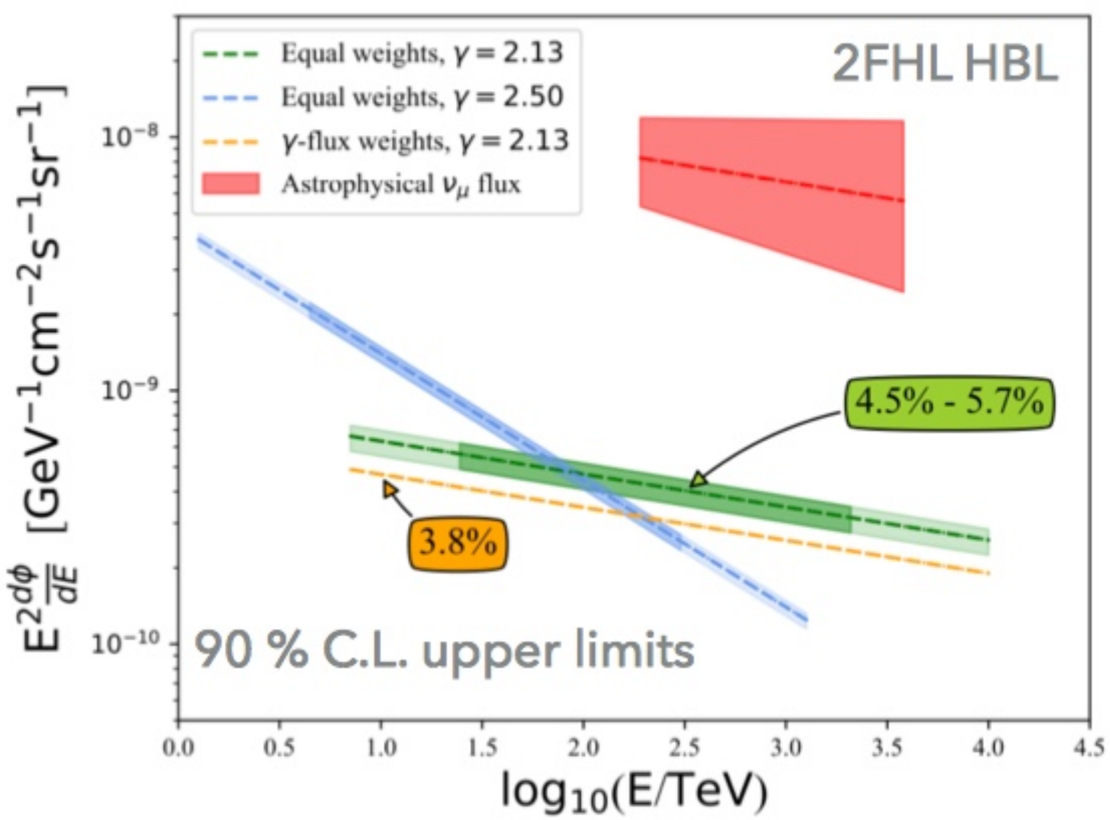


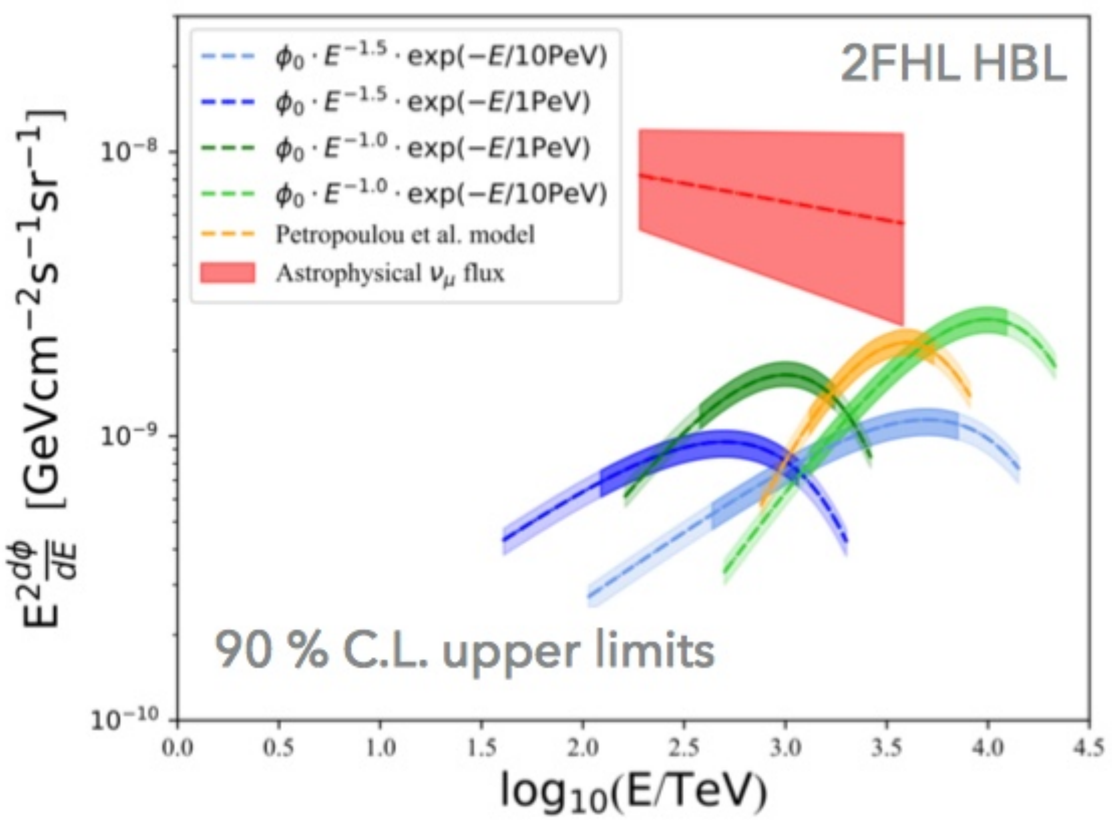
Kowalski 2015
Ahlers & Halzen 2018

See also Murase & Waxman 2016
But see Neronov & Semikoz 2018

Constraints on cosmic populations

Maximum blazar contribution from stacking

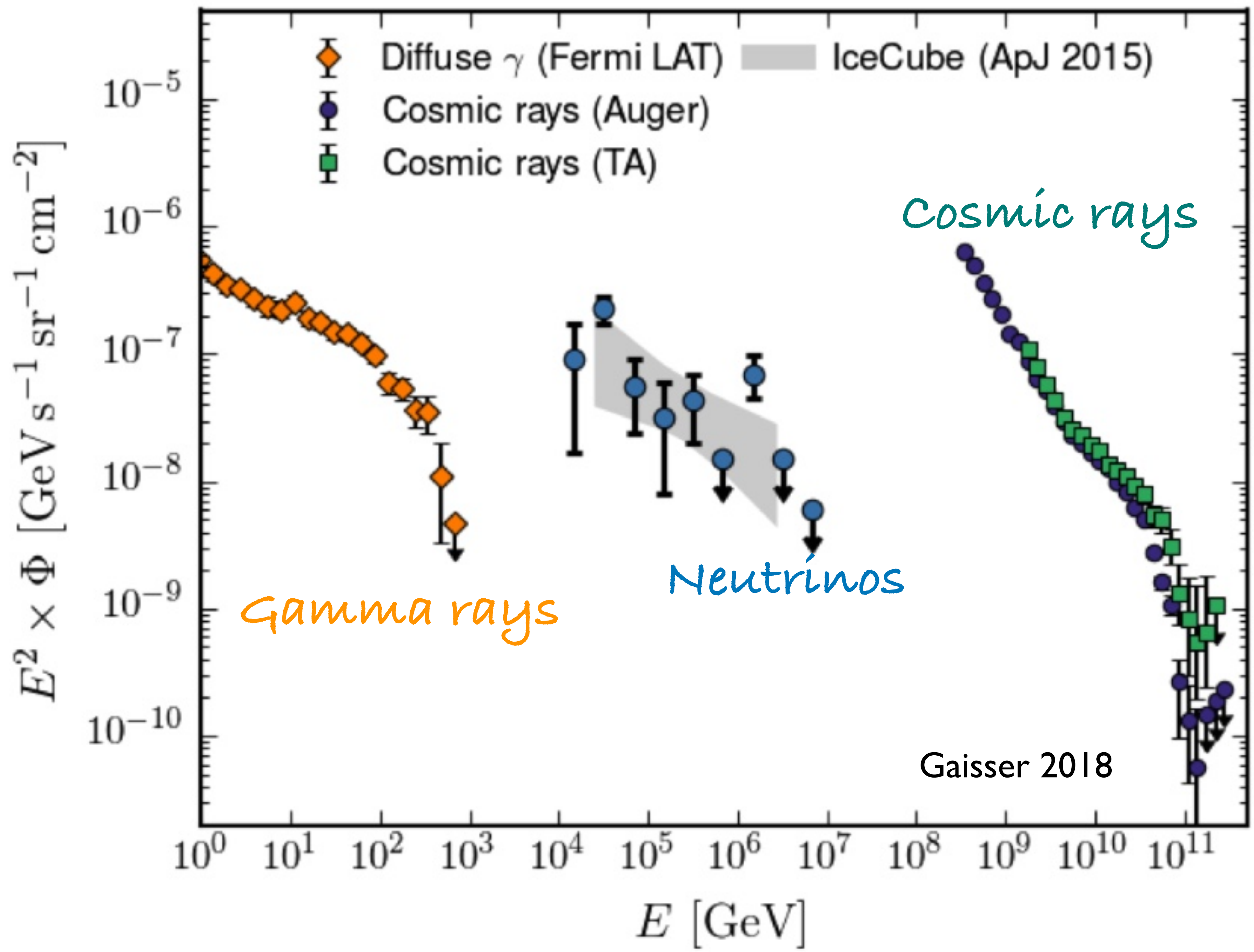




Huber et al. 2017

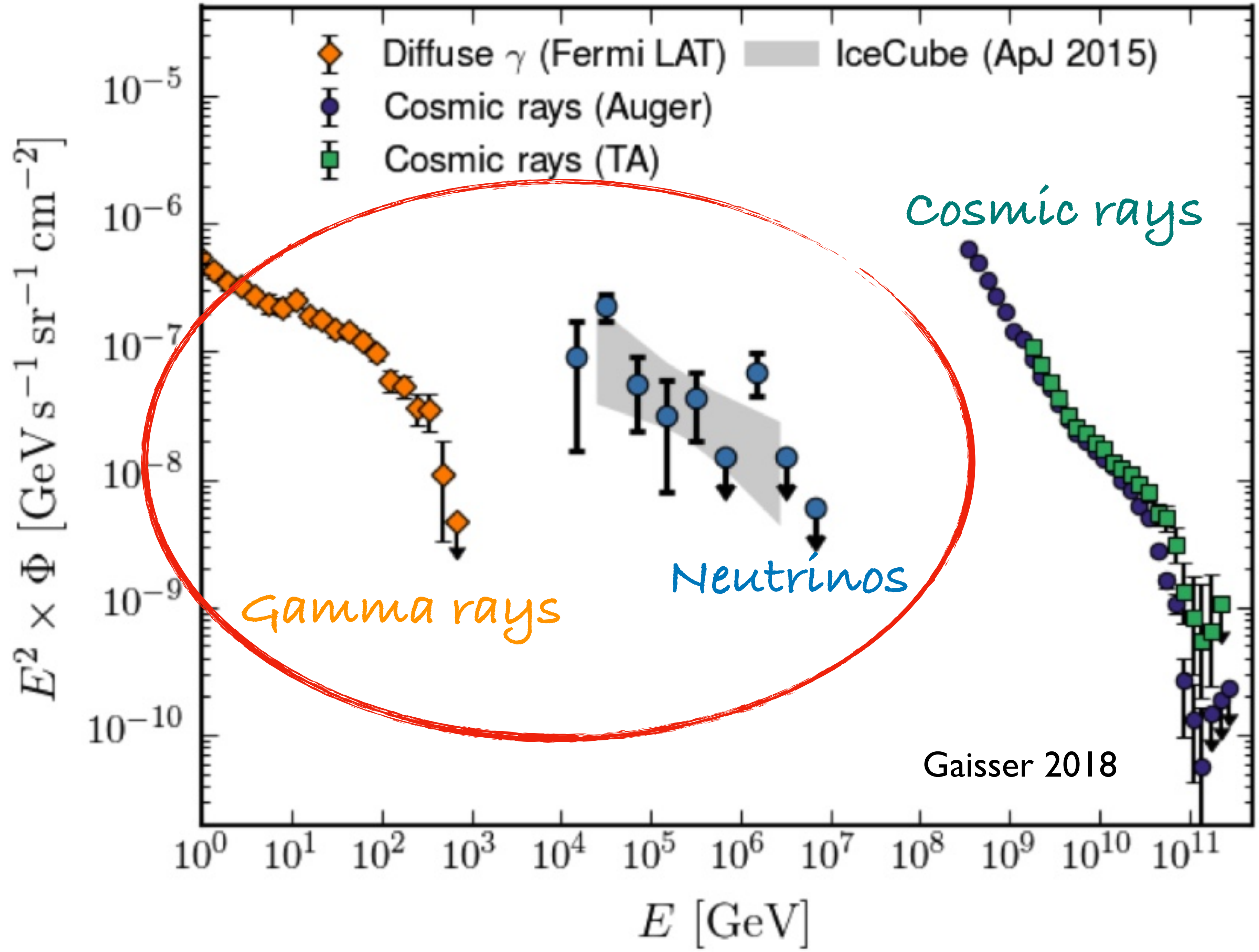
Cumulative MM fluxes

"Multimessenger sky background"



The same source(s)?

Cumulative MM fluxes

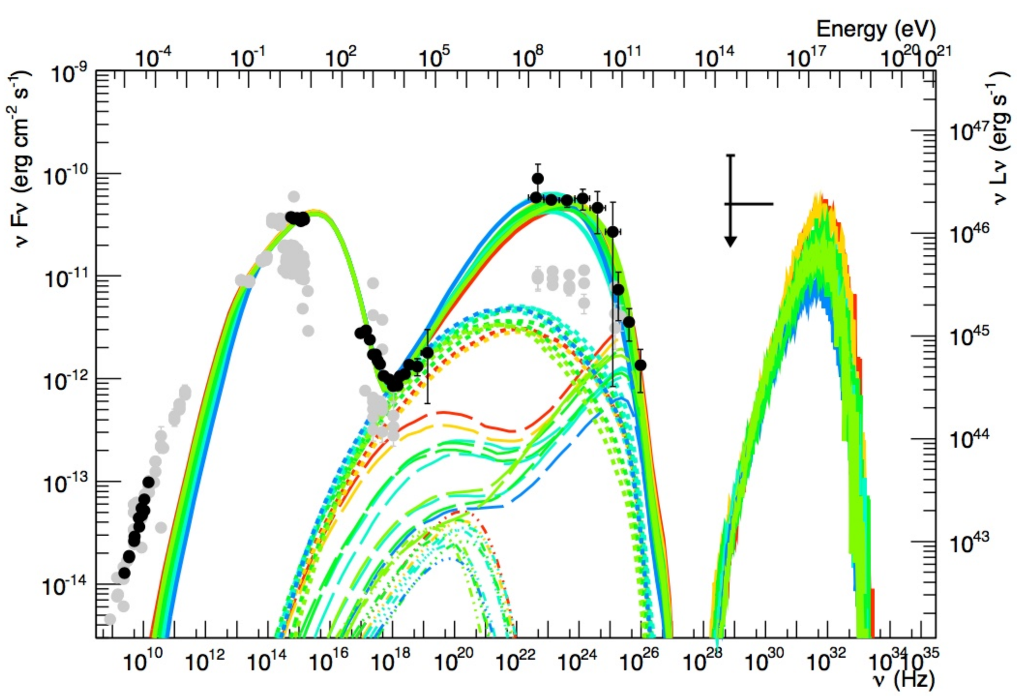


γ-ν connection

Gamma-rays can be **directly** connected to neutrinos for **transparent** sources.
In case of important opacity situation is more complex (cascades etc…).

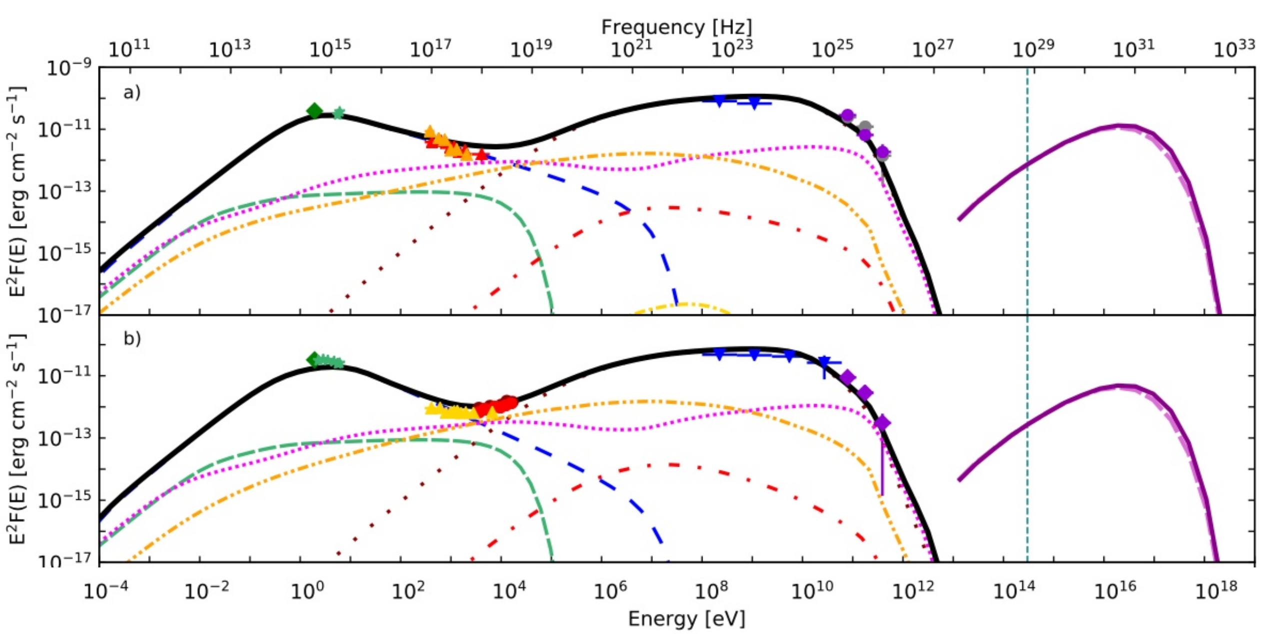
From TXS we know that hadronic gamma-rays are **subdominant** with respect to leptonic emission.
This is probably valid in general for blazars.

Since blazars contribute to ~80% to ExGal BKG, the “hadronic backgorund” is max 20% of the total.

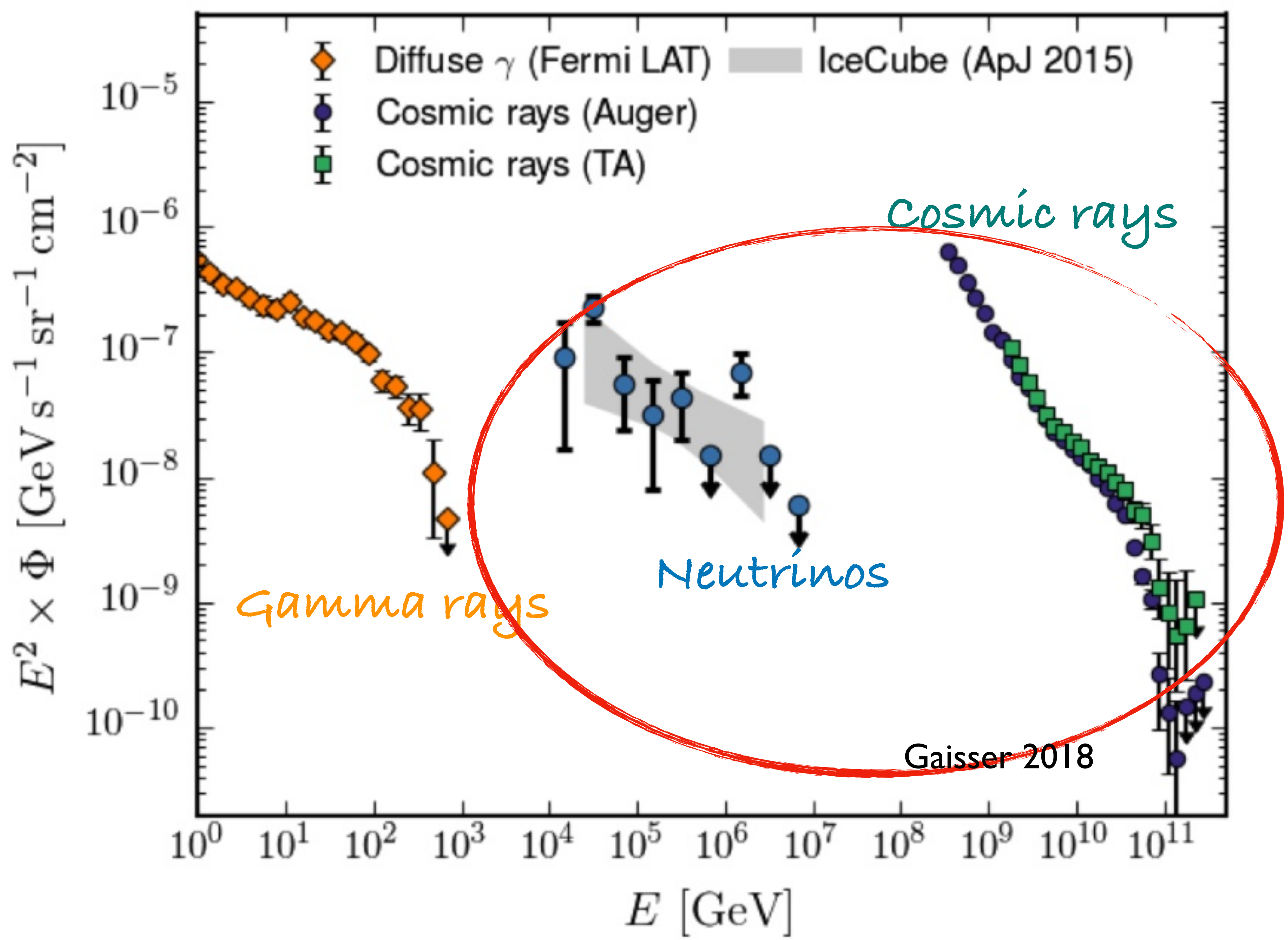


Cerruti et al. 2018

MAGIC Coll. 2018

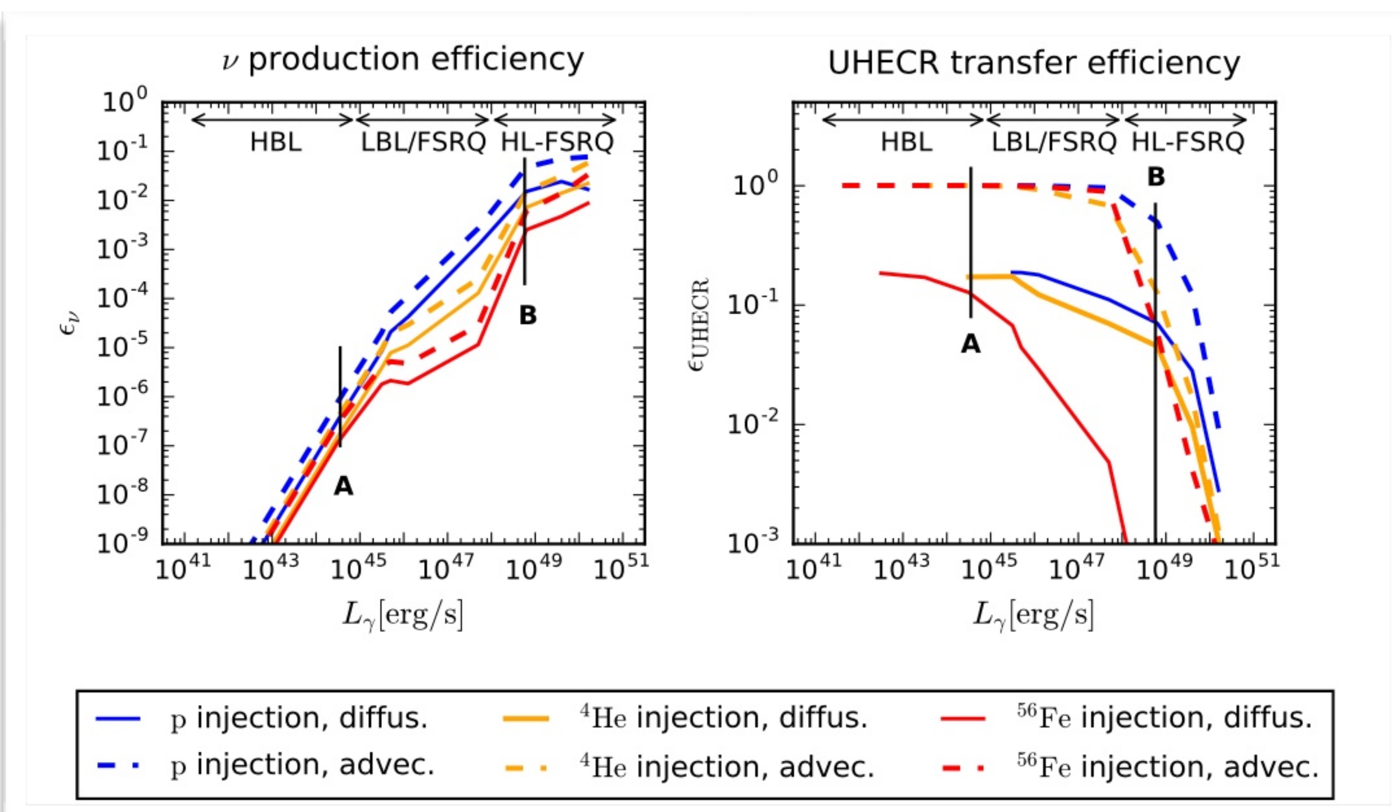


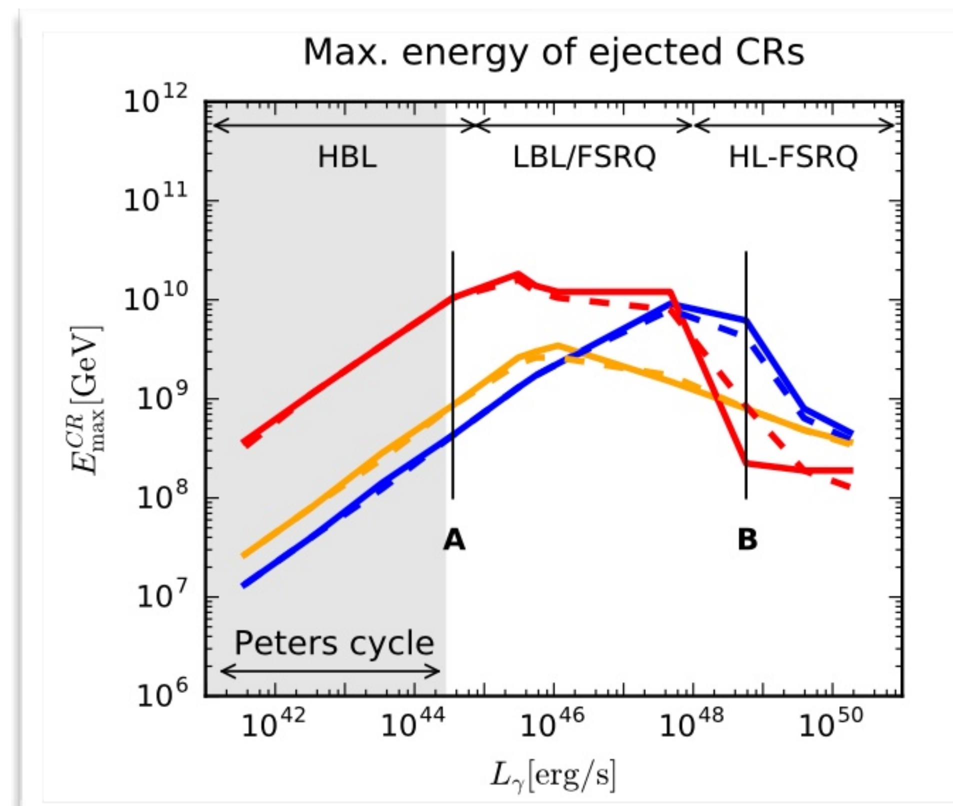
Cumulative MM fluxes



CR-ν connection

	Neutrinos	UHECR
BL Lac: small photopion and photo disintegration efficiency	✗	✓
FSRQ: large photopion and photo disintegration efficiency	✓	✗





Rodrigues et al. 2018

Final thoughts

Several kind of extragalactic sources are good candidates

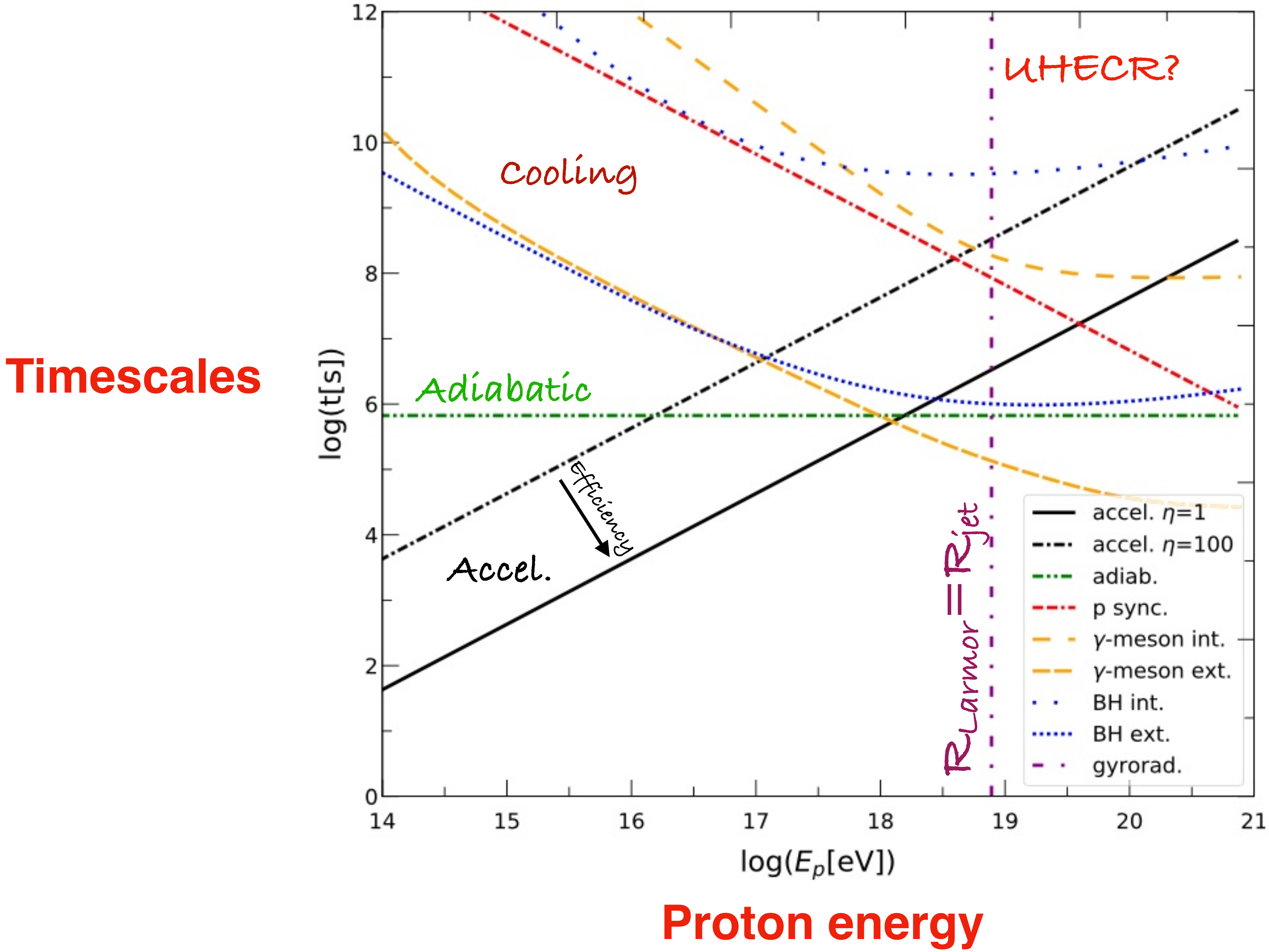
Physics of pp sources are constrained by the gamma-ray BKG. Hard spectra!
Usually “stationary” sources. Difficult to identify (cfr TXS)!

The case of TXS suggests that blazars should provide contribution (how much?)
Their hadronic gamma-ray emission is expected to be subdominant.

Probably we have to find the right “mix” of sources

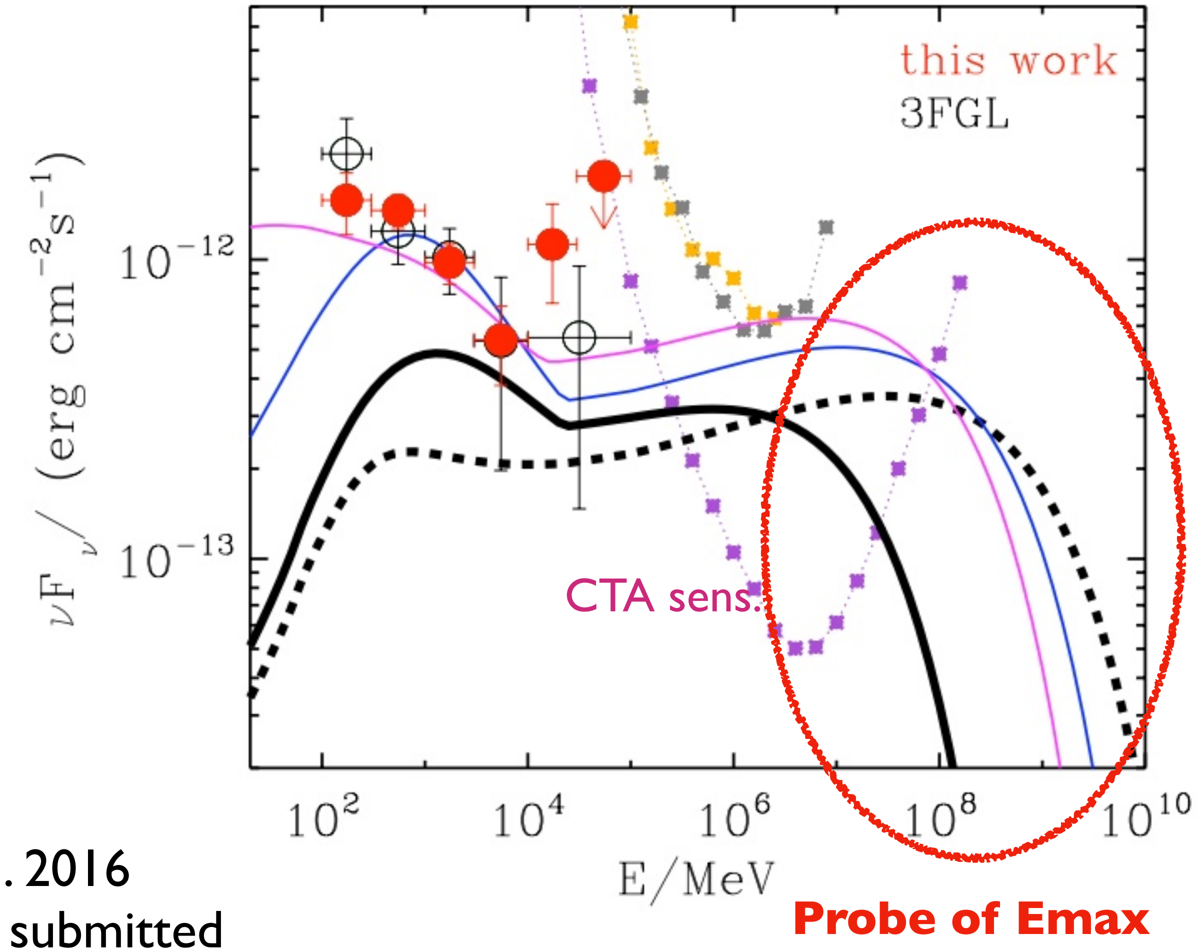
Backup

Jet-sheath model



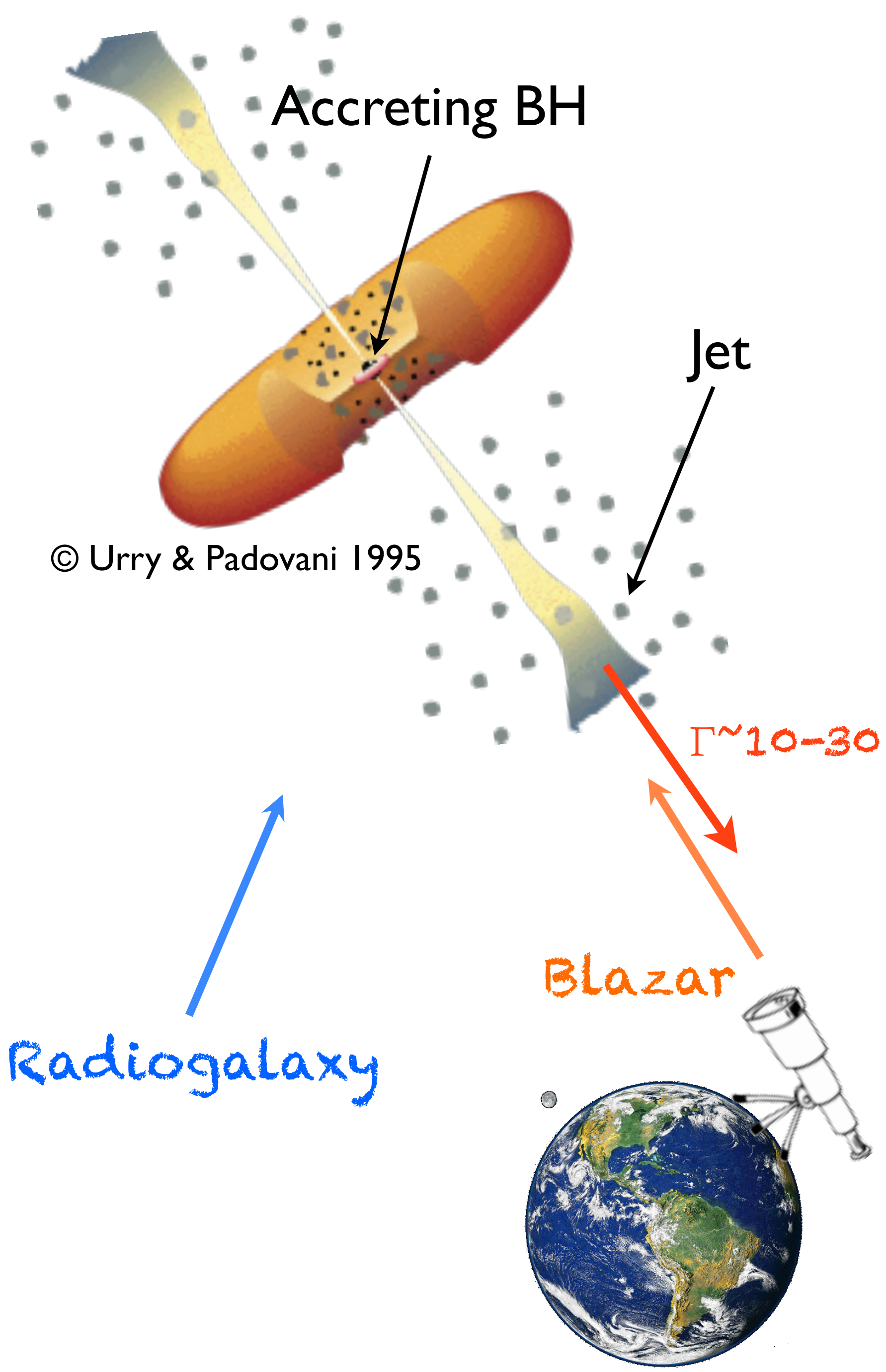
AGN-driven winds

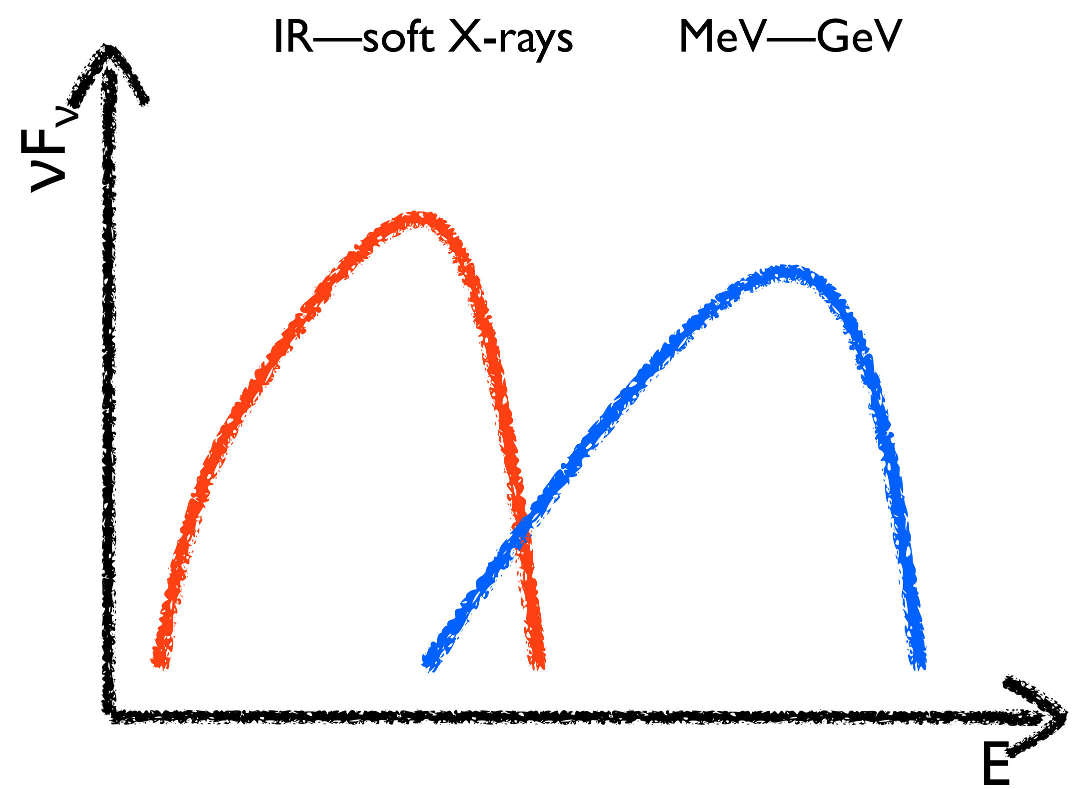
A prototypical case: NGC 1068



Lamastra et al. 2016
Lamastra, FT et al. submitted

Blazars in a nutshell





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

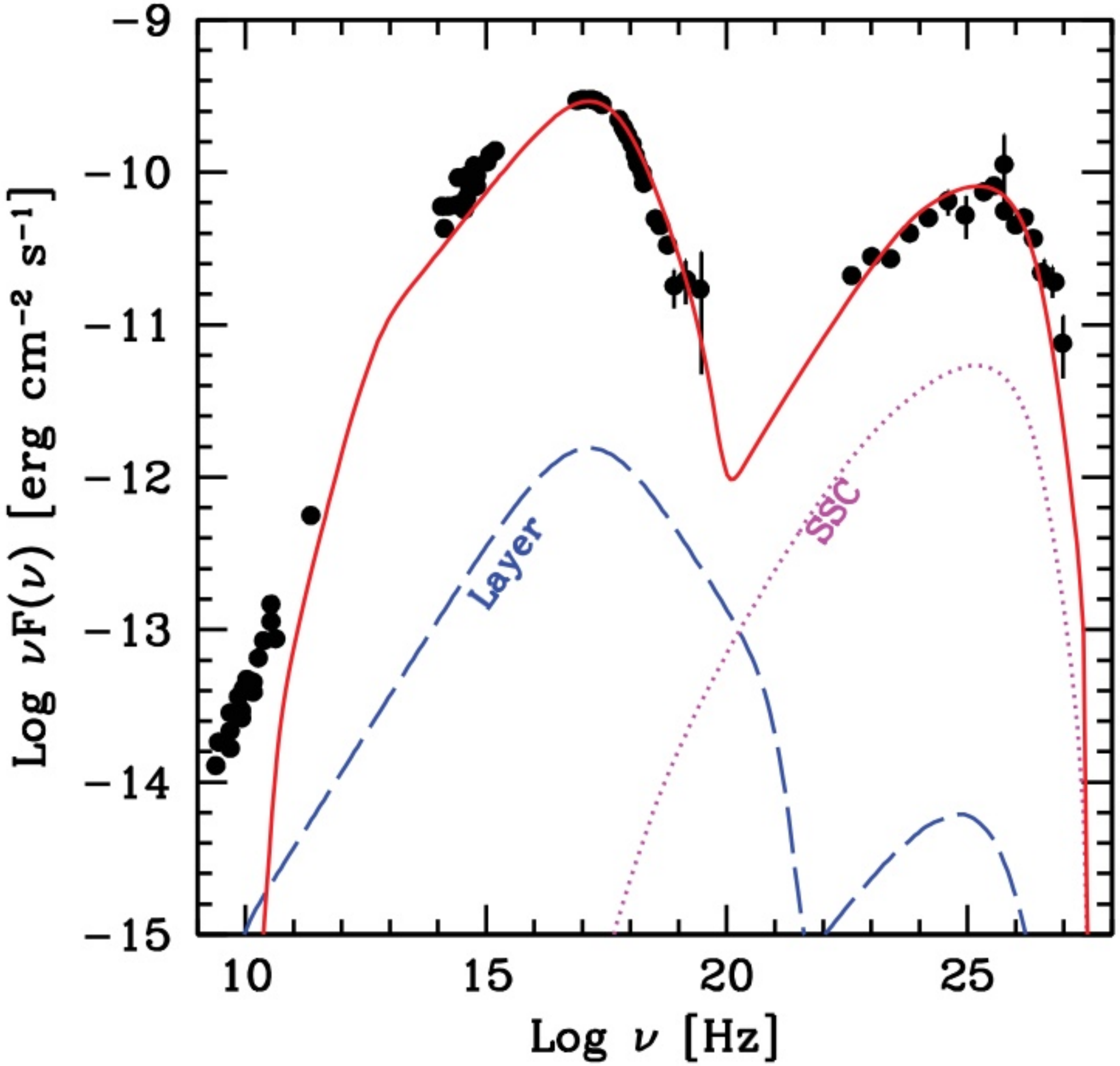
$$L_{\rm obs} = L'\delta^4 \qquad \delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

$$\delta \approx 10 - 20$$

Synchrotron and IC in LEPTONIC models.

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

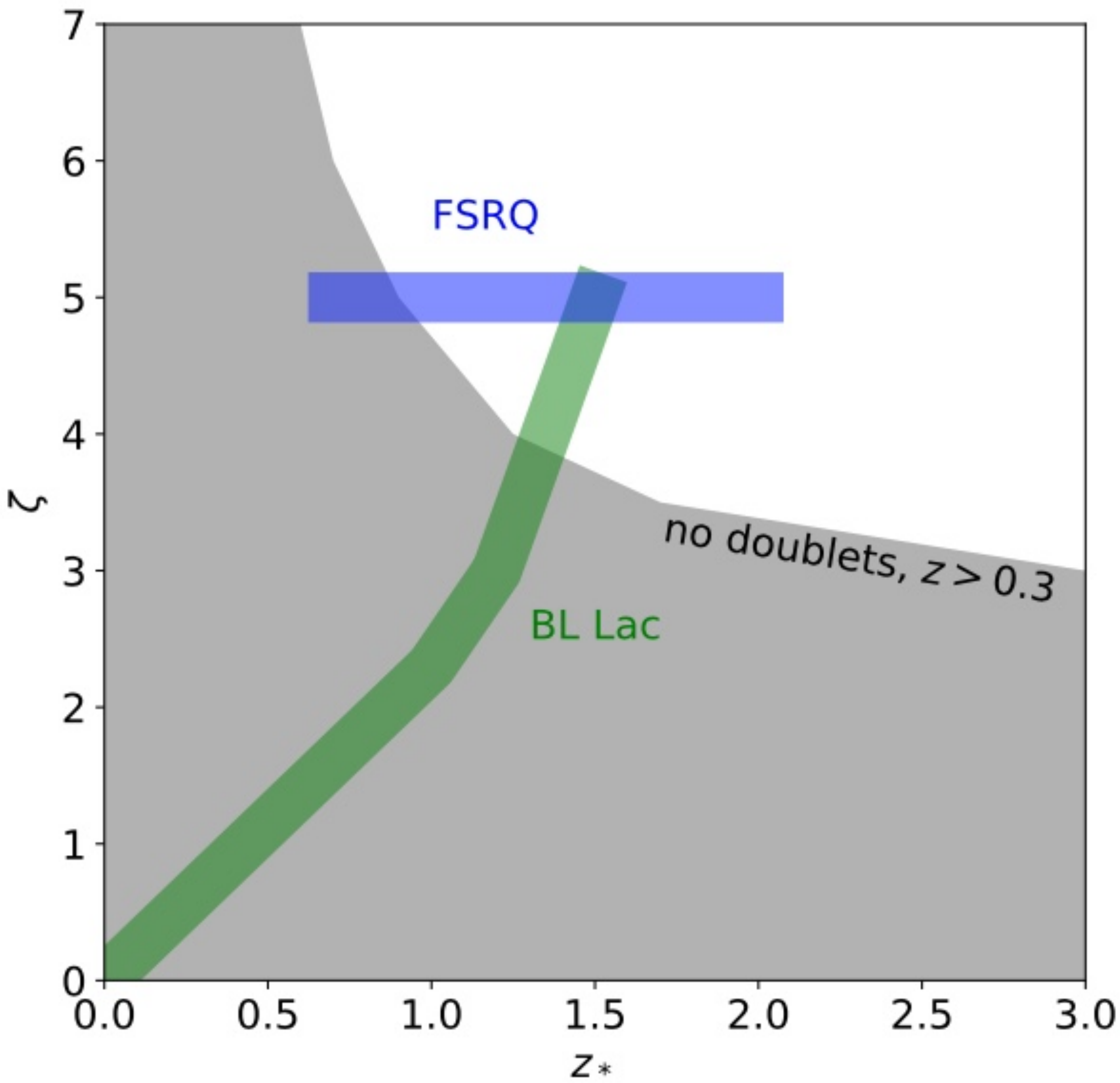
Structured jets in BL Lacs

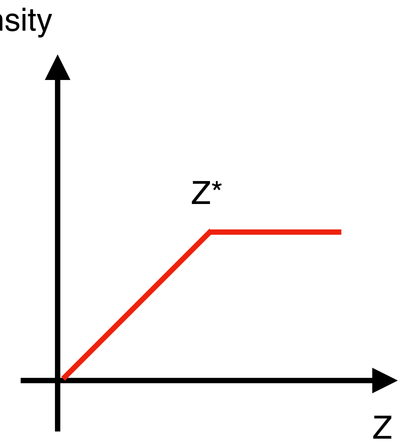


Tavecchio & Ghisellini 2016

Constraints on cosmic populations

Evolution speed





Redshift of the maximum

Neronov & Semikoz 2018

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

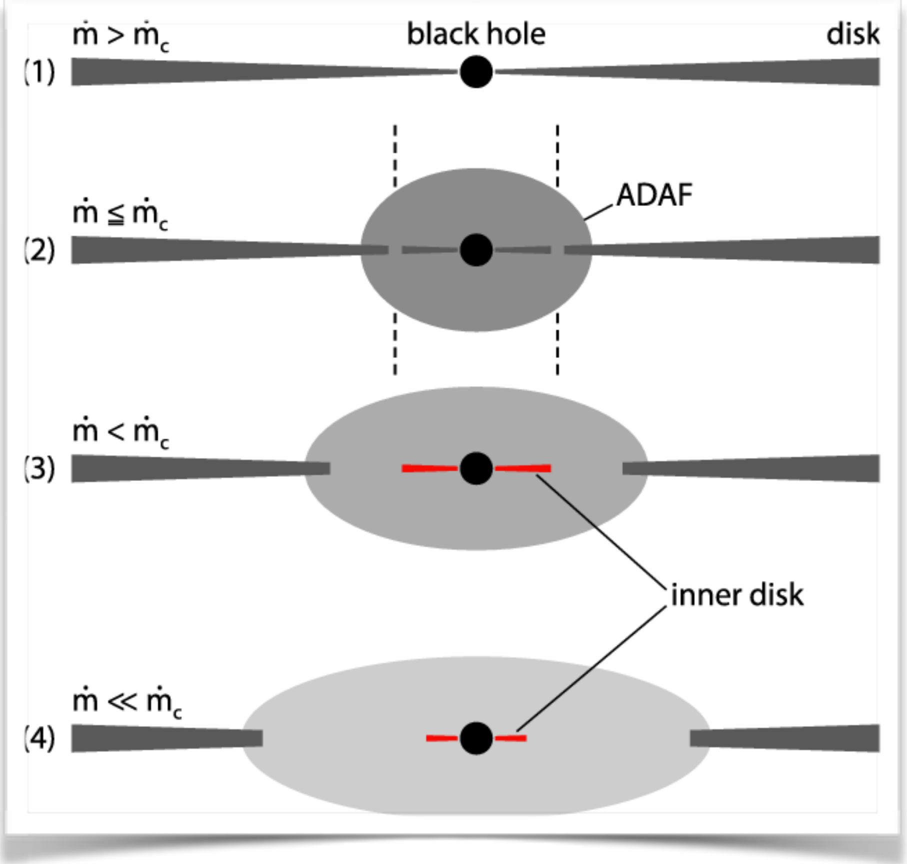
FT et al. 2014, 2015
Righi FT, Guetta 2017

Is TXS a BL Lac?

Padovani et al. 2019

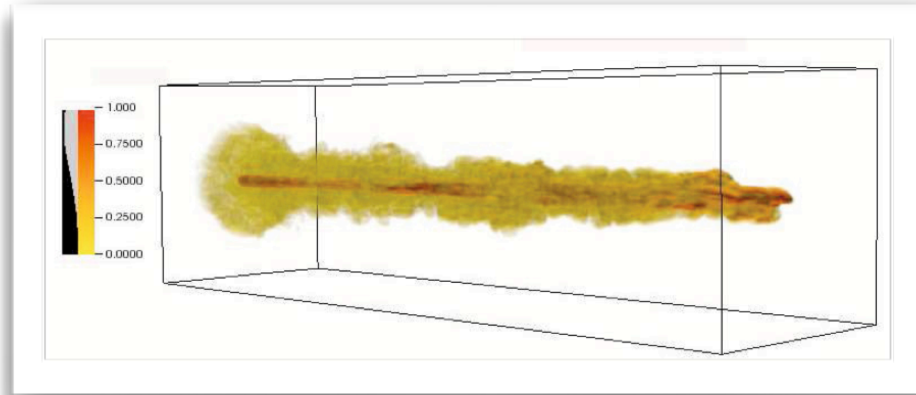
The observed spectrum is consistent with a BLR of limited luminosity
Large radio power

Yes but …



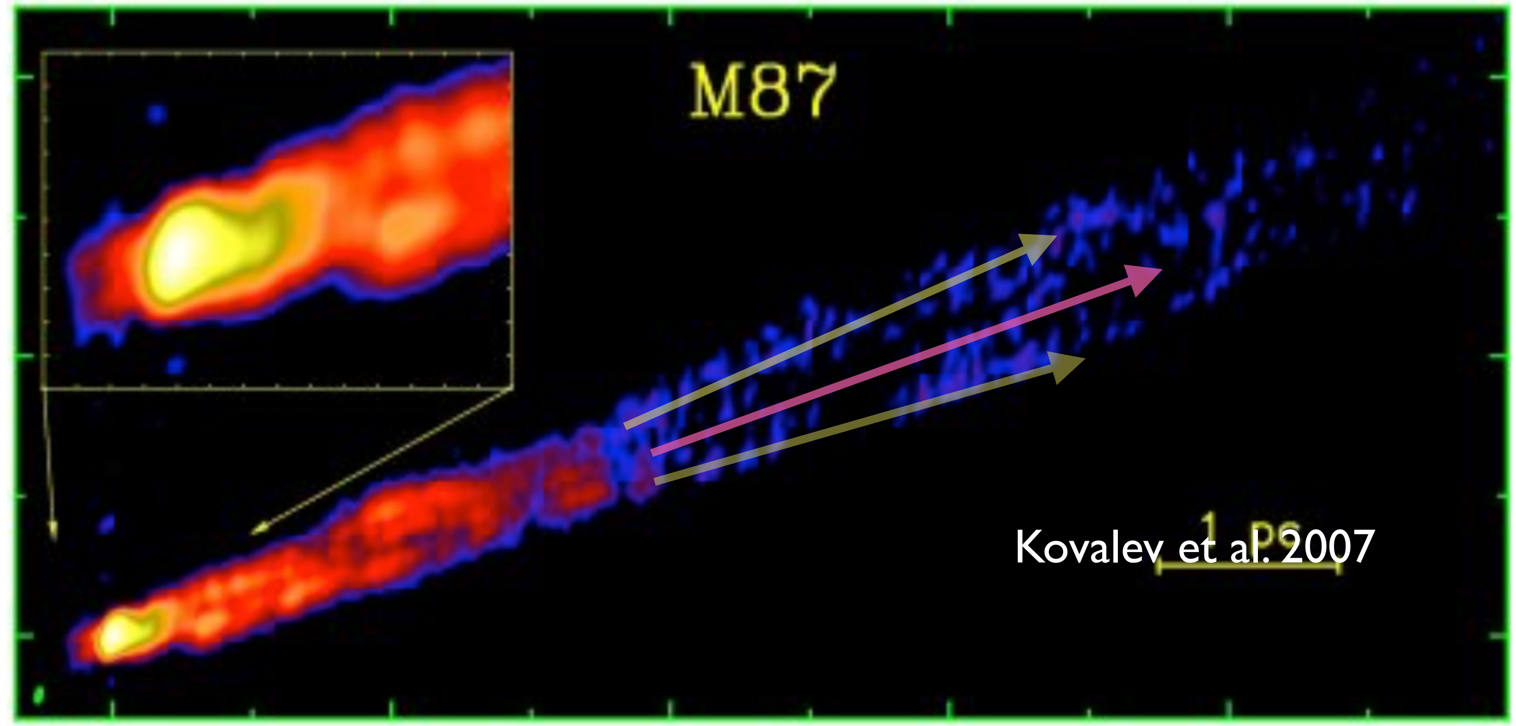
Righi et al. in prep.

Structured jets in BL Lacs



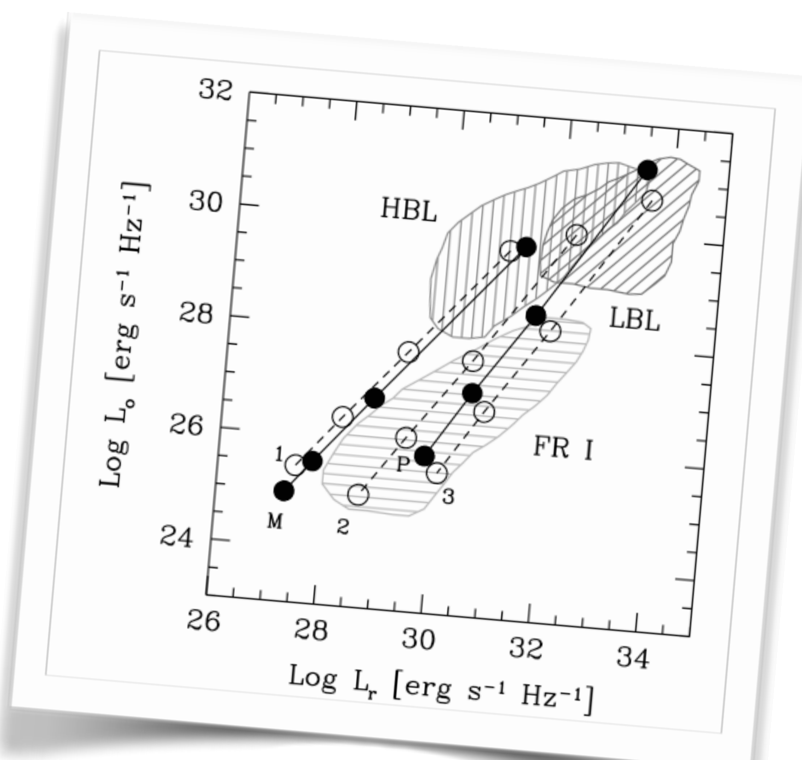
Simulations predict spine-layer structure

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

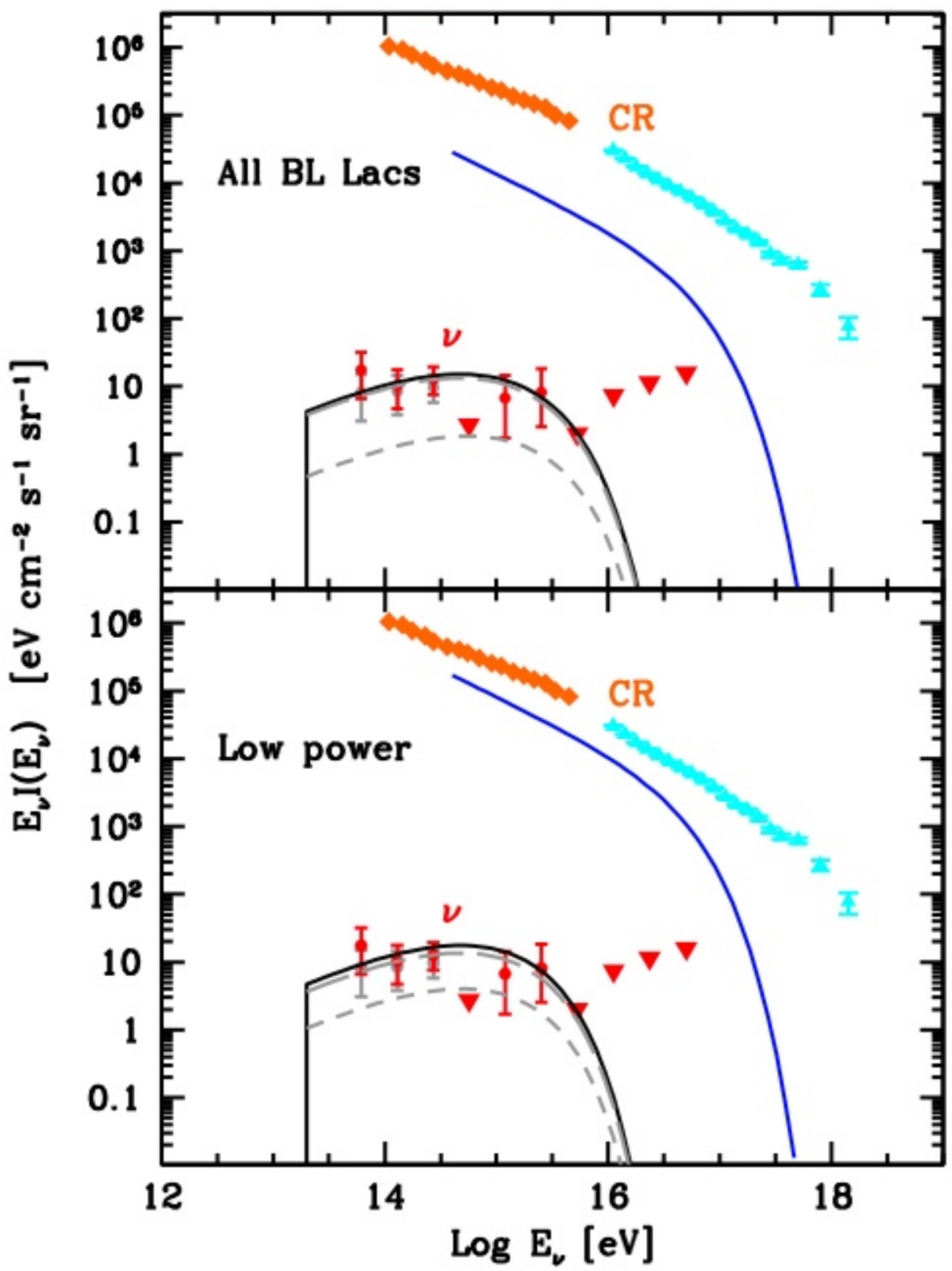


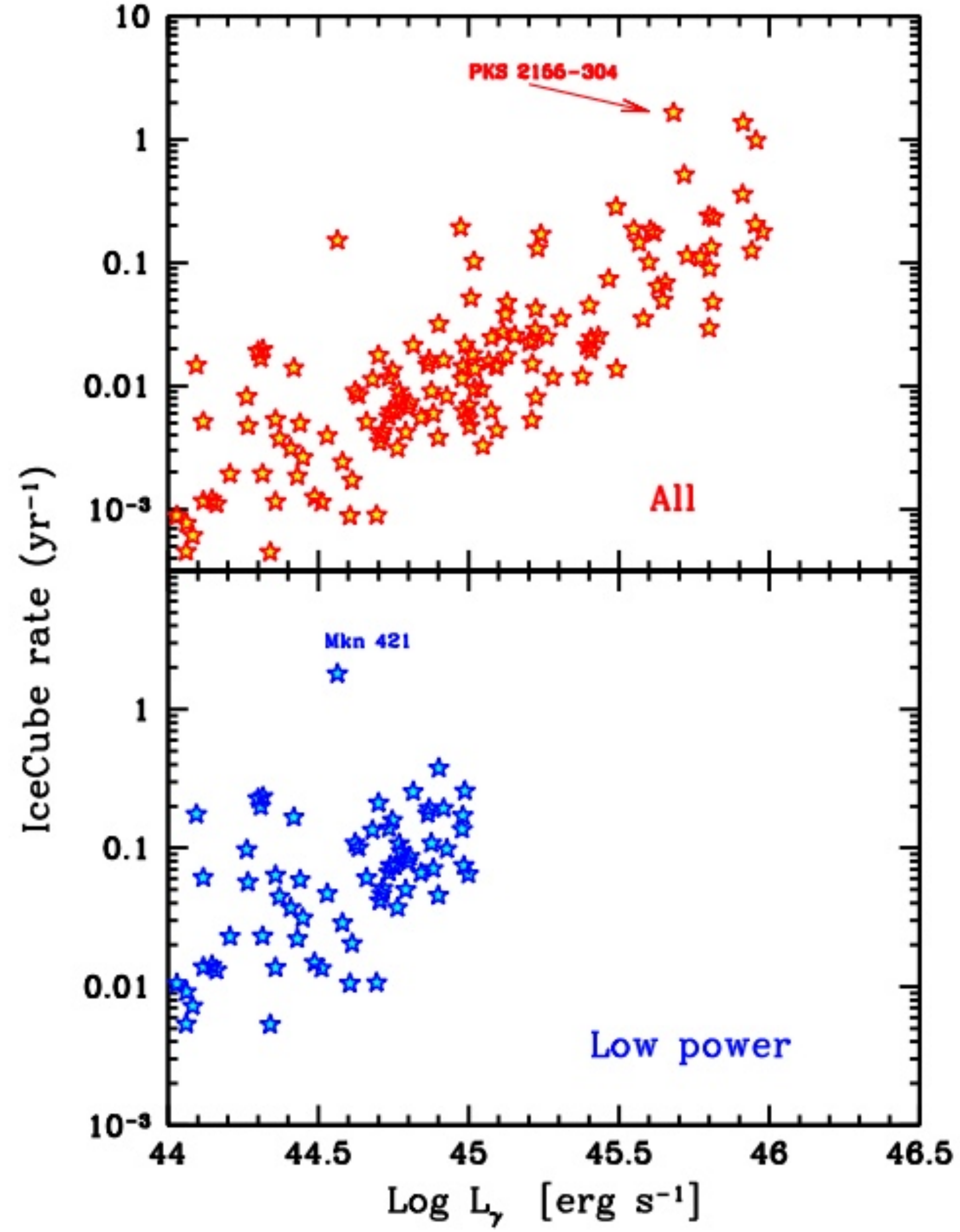
Unification requires velocity structures

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

Similar suggestions for GRBs...

Neutrinos from BL Lacs?

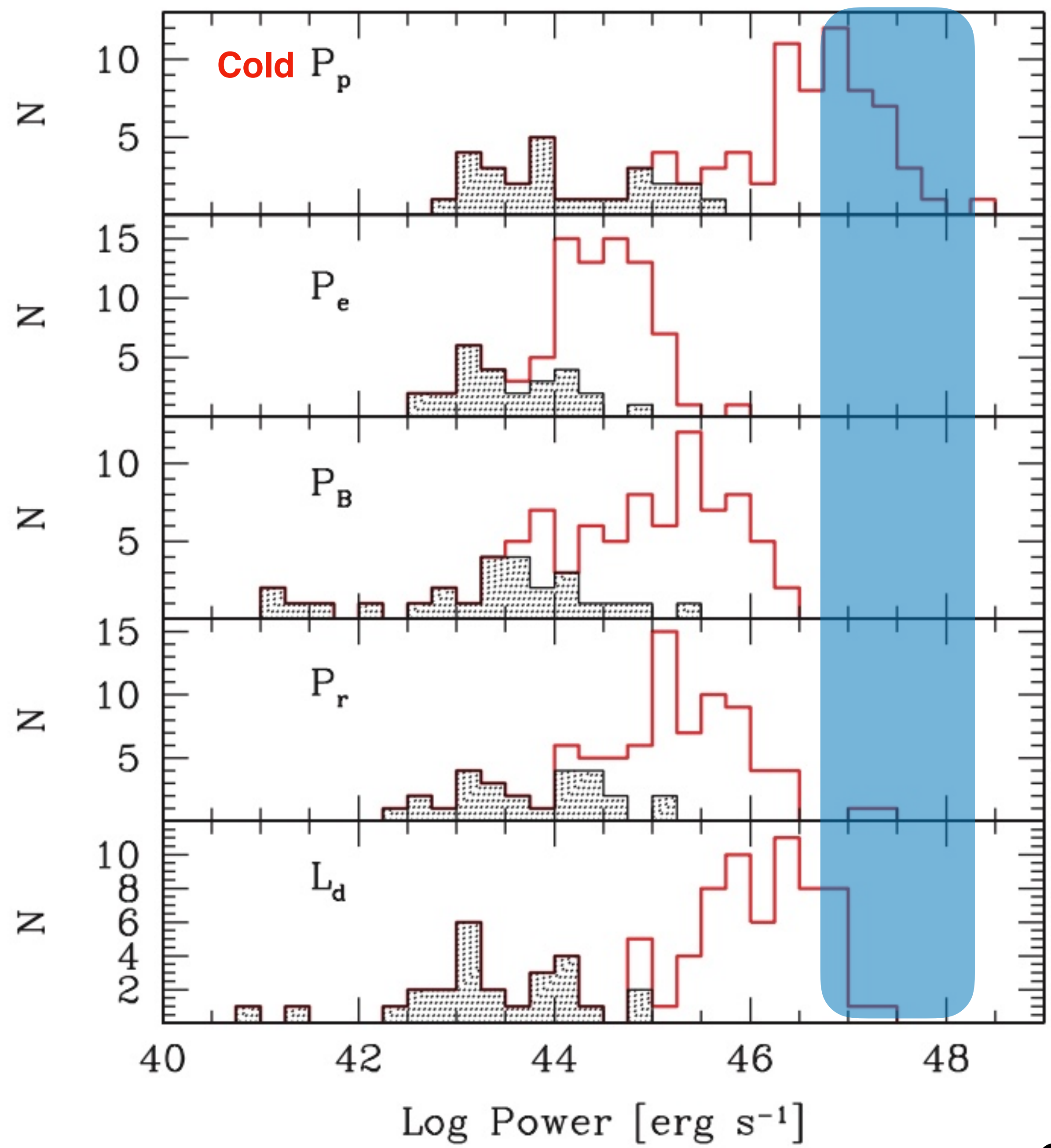




Tavecchio et al. 2014, 2015
Righi FT, Guetta 2017

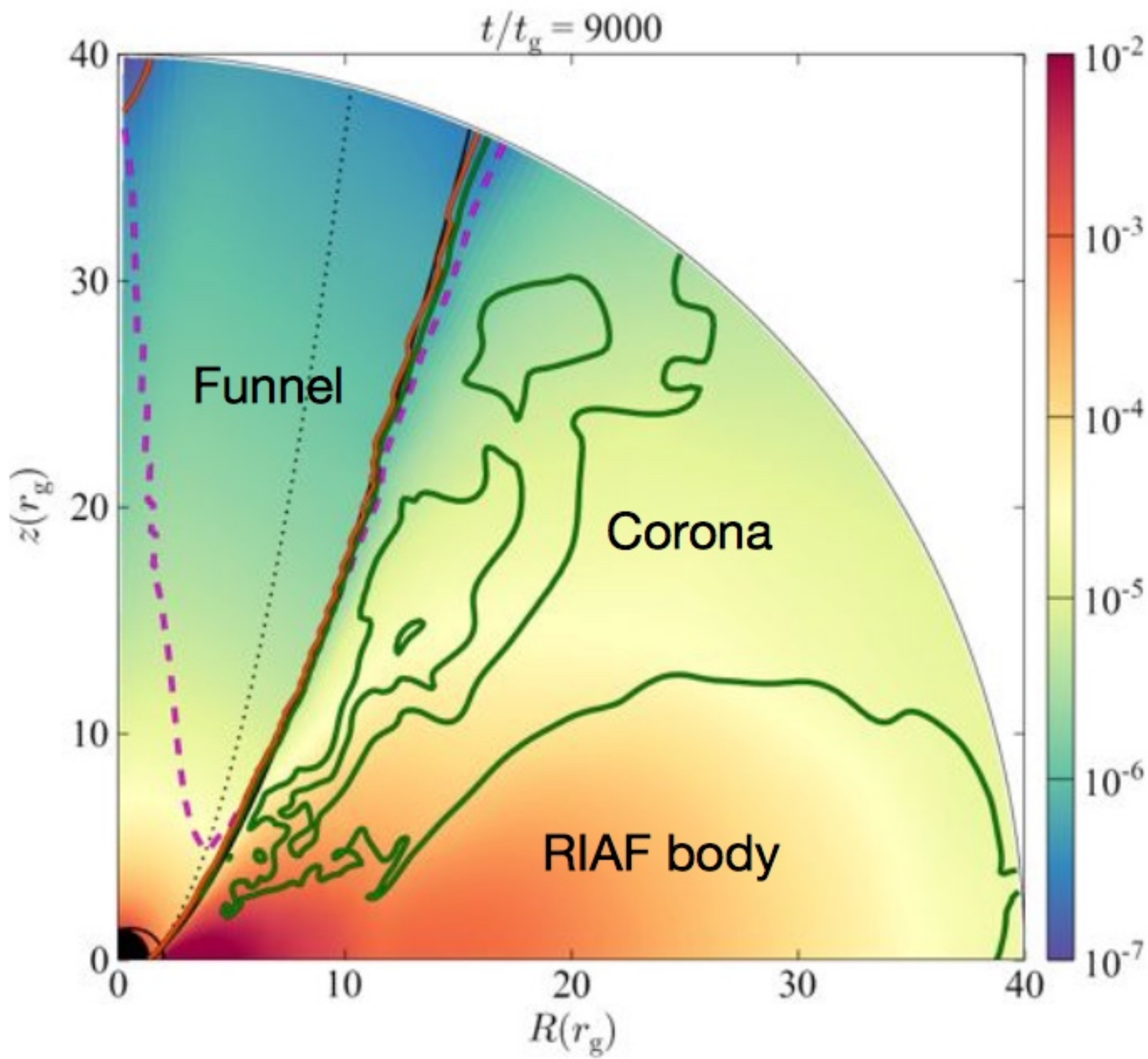
But see Palladino & Vissani 2017

Neutrino from BL Lacs?



Ghisellini et al. 2010

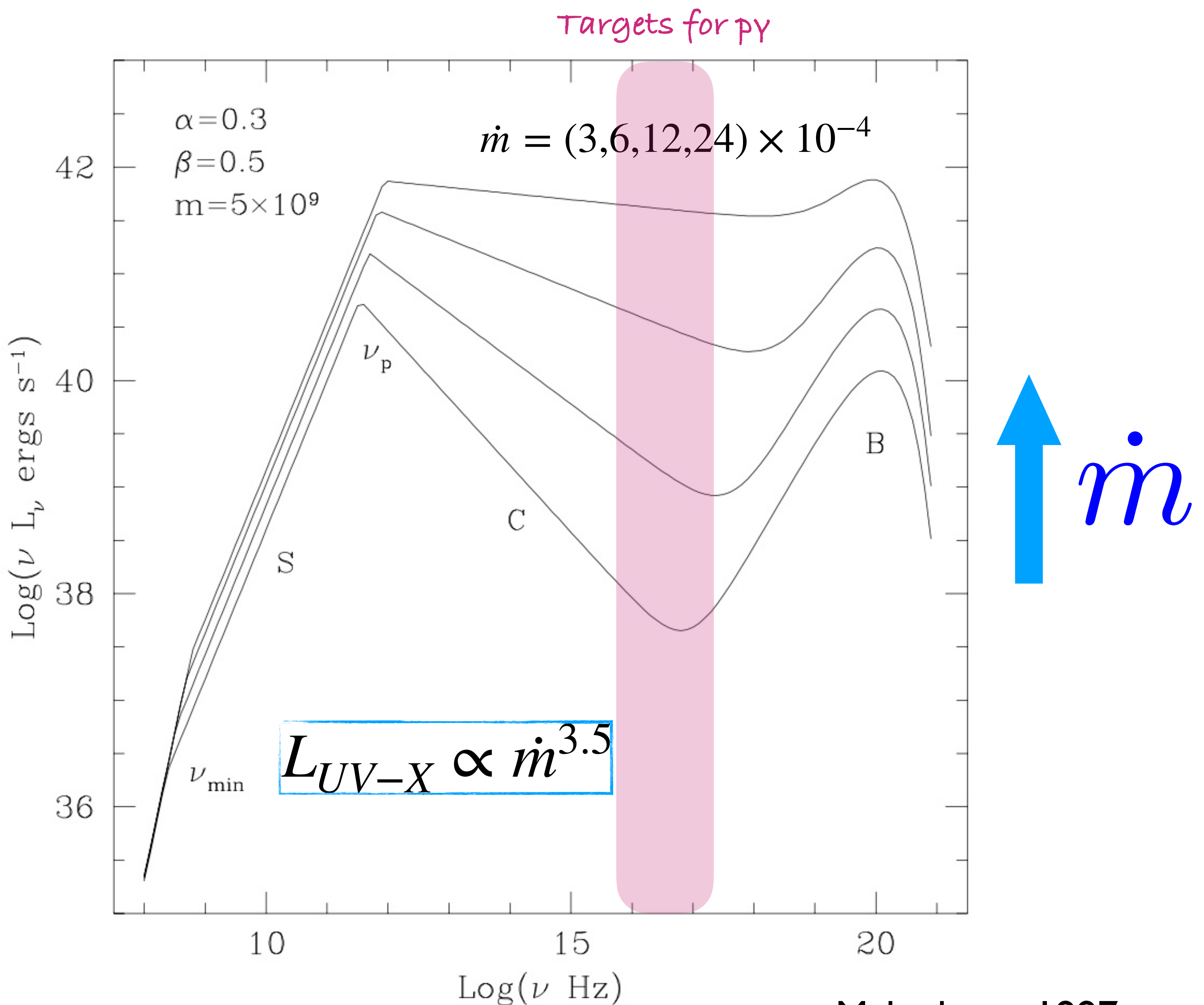
A role for the accretion flow?



Nakamura et al. 2018

A role for the accretion flow?

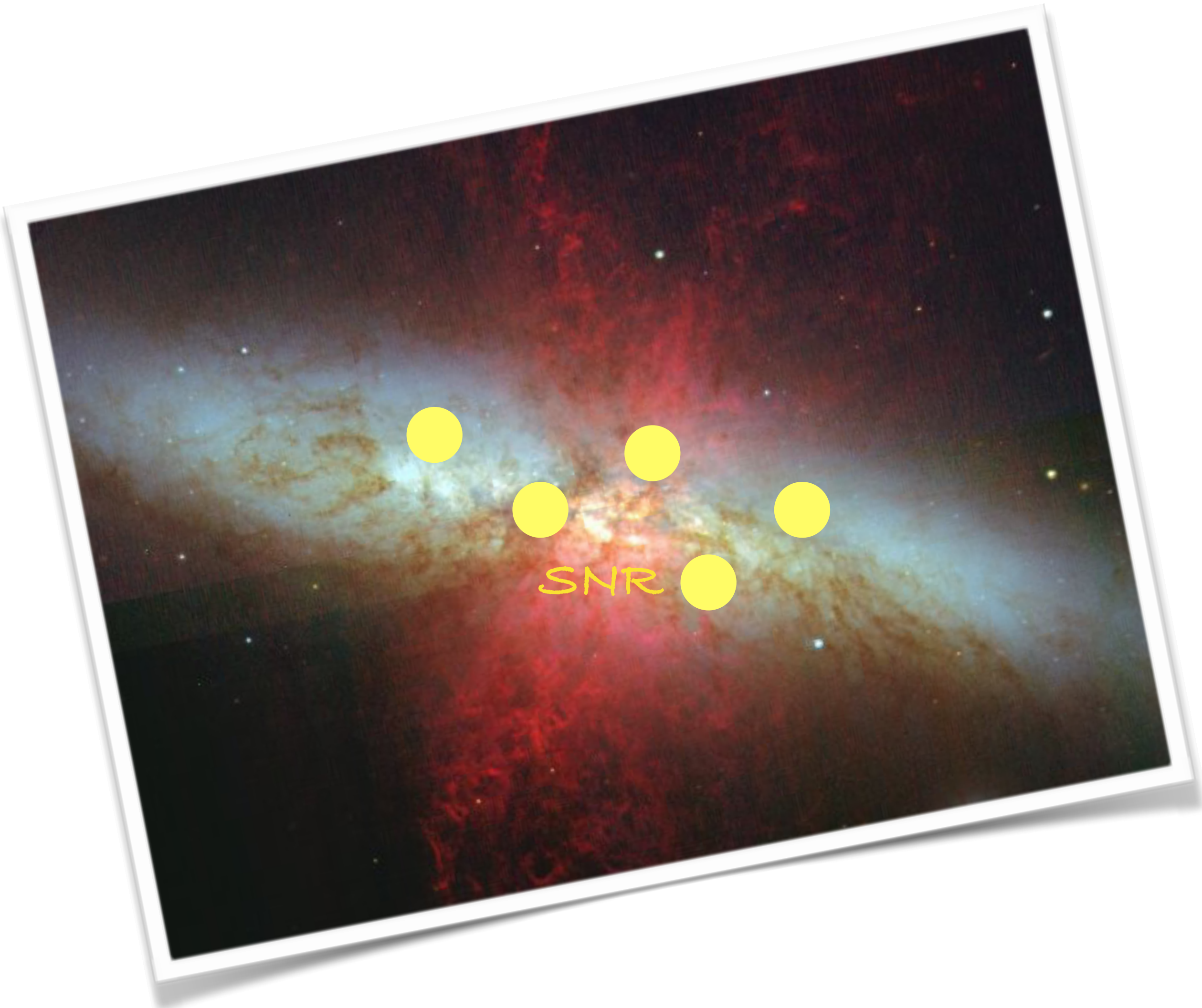
Advection dominated accretion flow



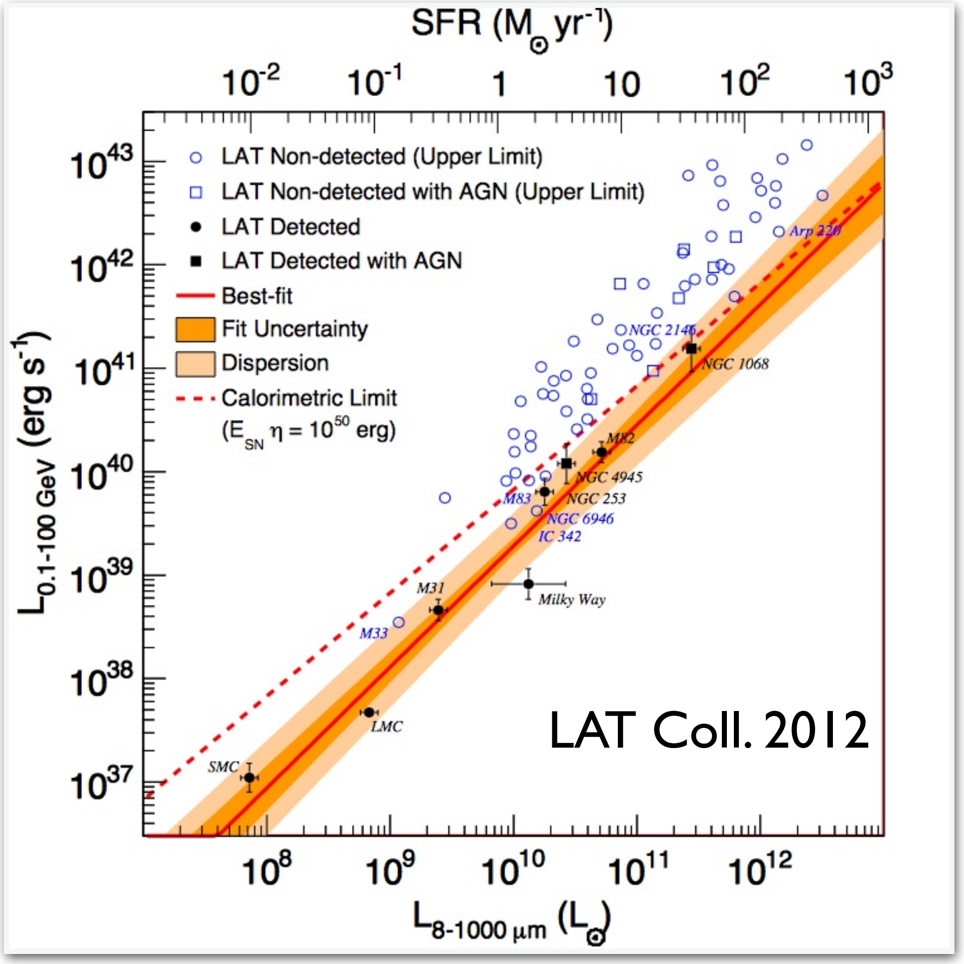
Mahadevan 1997

Starburst/Star forming galaxies?

Romero & Torres 2003
Loeb & Waxman 2006
Tamborra et al. 2014



Diffusing CR accelerated in SNR
+
dense gas/dust



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}

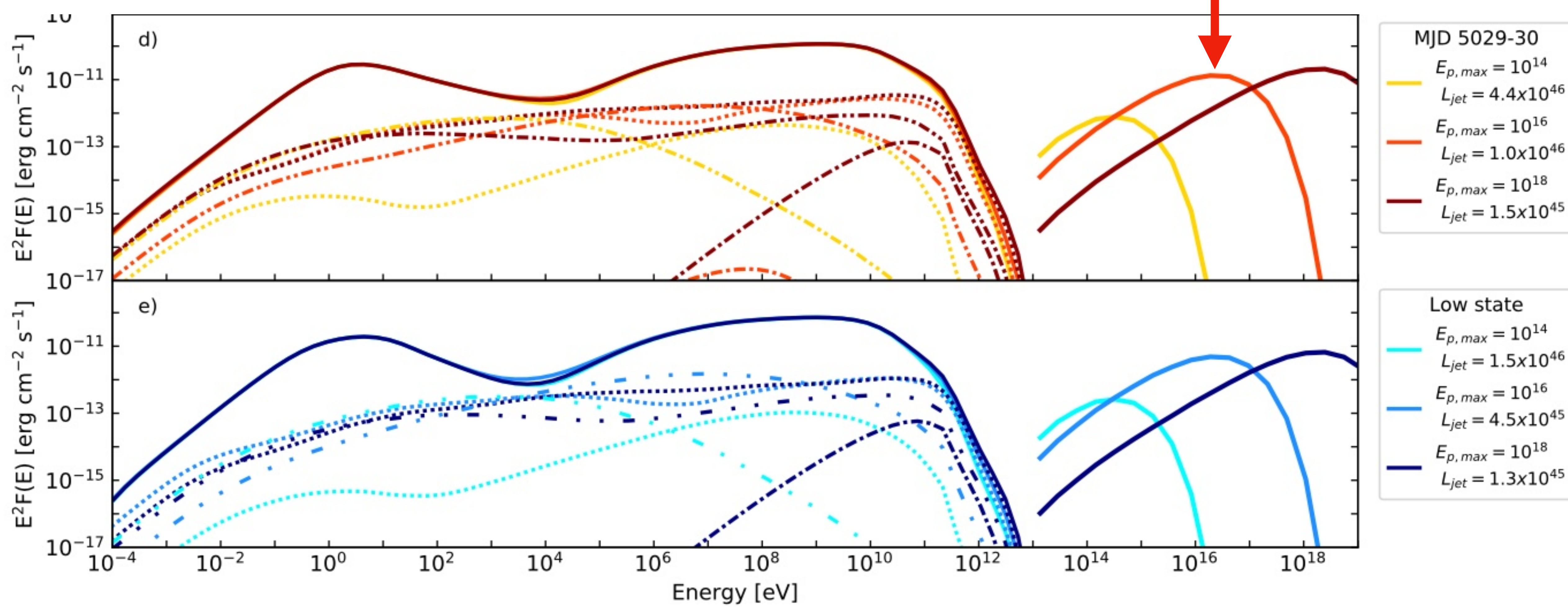
$$P_j \approx 4 \times 10^{45} - 10^{46} \ \mathrm{erg\,s^{-1}}$$

Jet-sheath model

MAGIC Coll. 2018

Effect of maximum proton energy

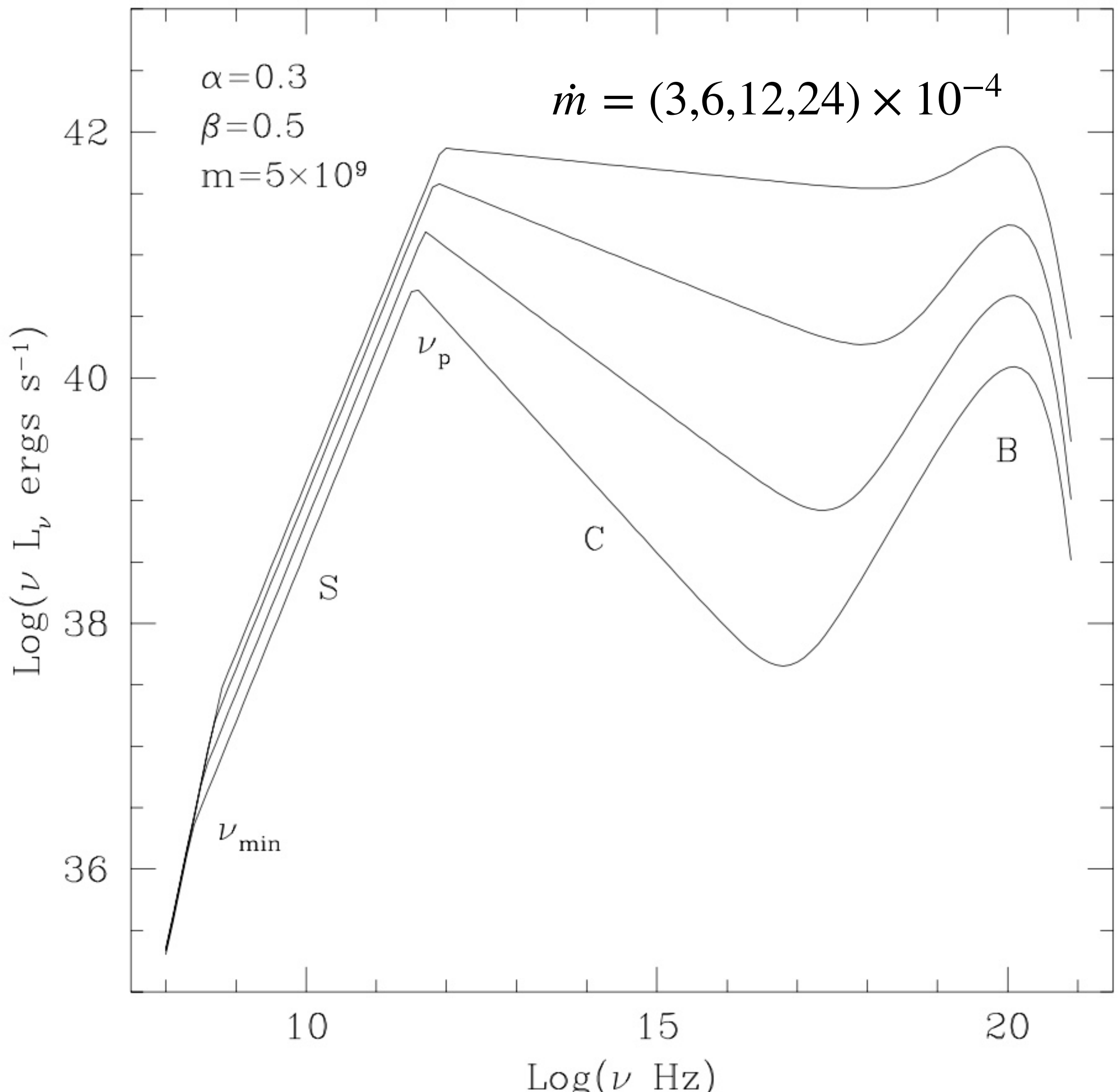
Constrained by cascade flux in X-rays

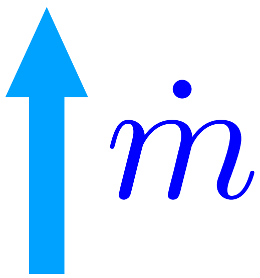


Larger Ep —> Lower neutrino rate at 300 TeV

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

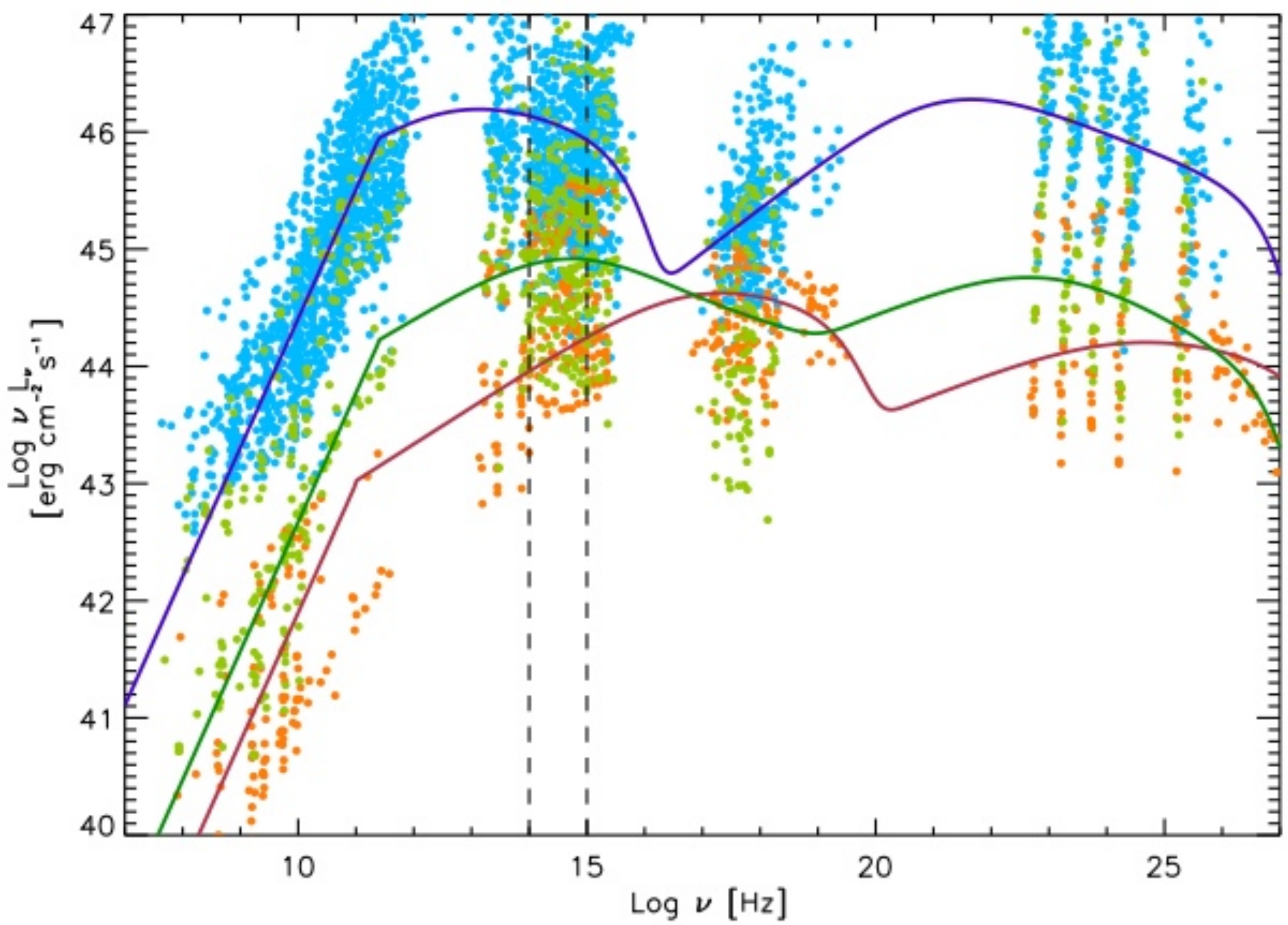
$$\dot{m} < \alpha^2 \approx 10^{-2}$$

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"

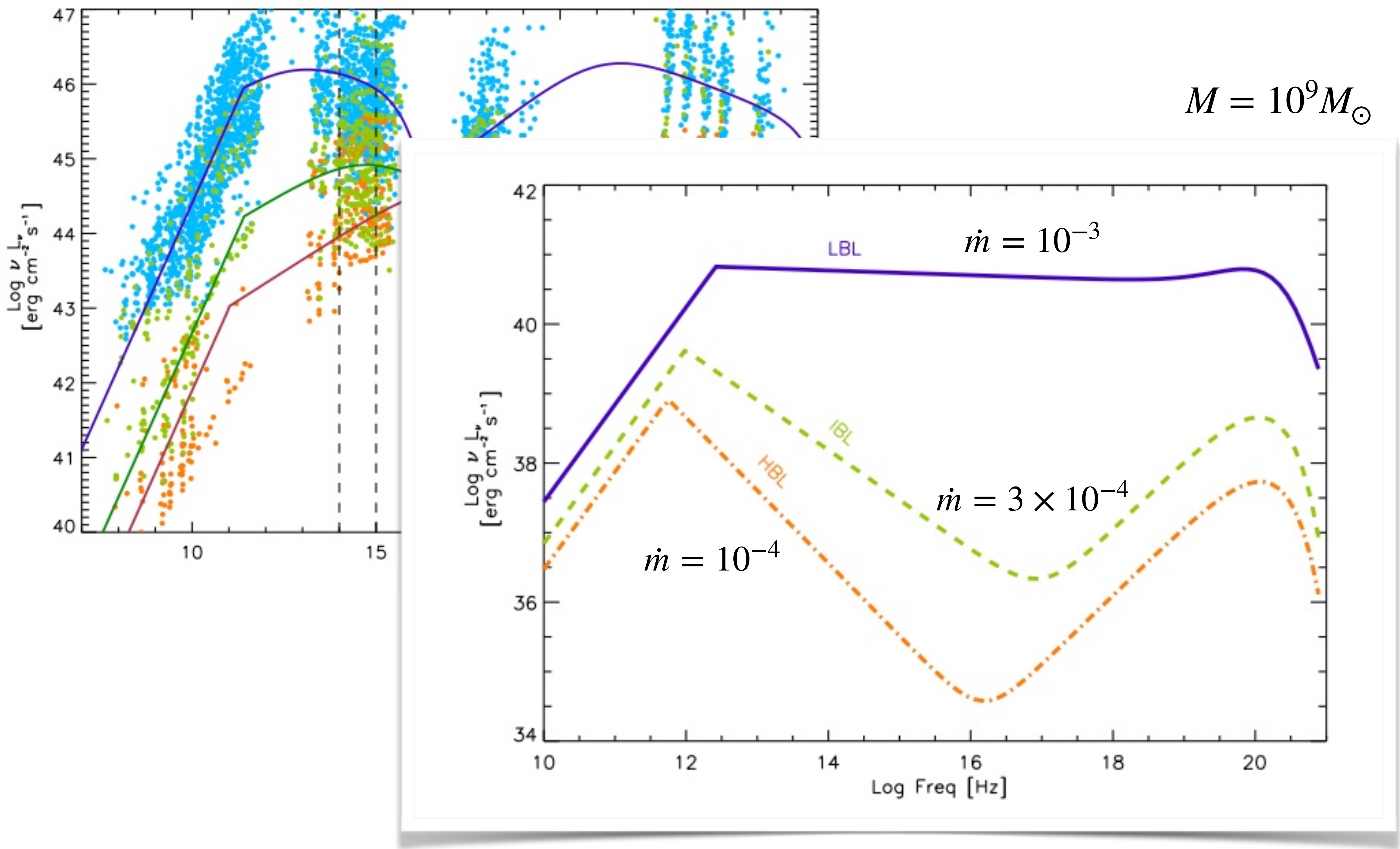


Righi, FT, Inoue et al. 2018

A role for the accretion flow?

BL Lac section of the "blazar sequence"

$M = 10^9 M_\odot$



Righi, FT, Inoue et al. 2018