Gamma-ray emitters and multimessenger signatures of particle acceleration

(A few selected cases)

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Outlook

Introduction

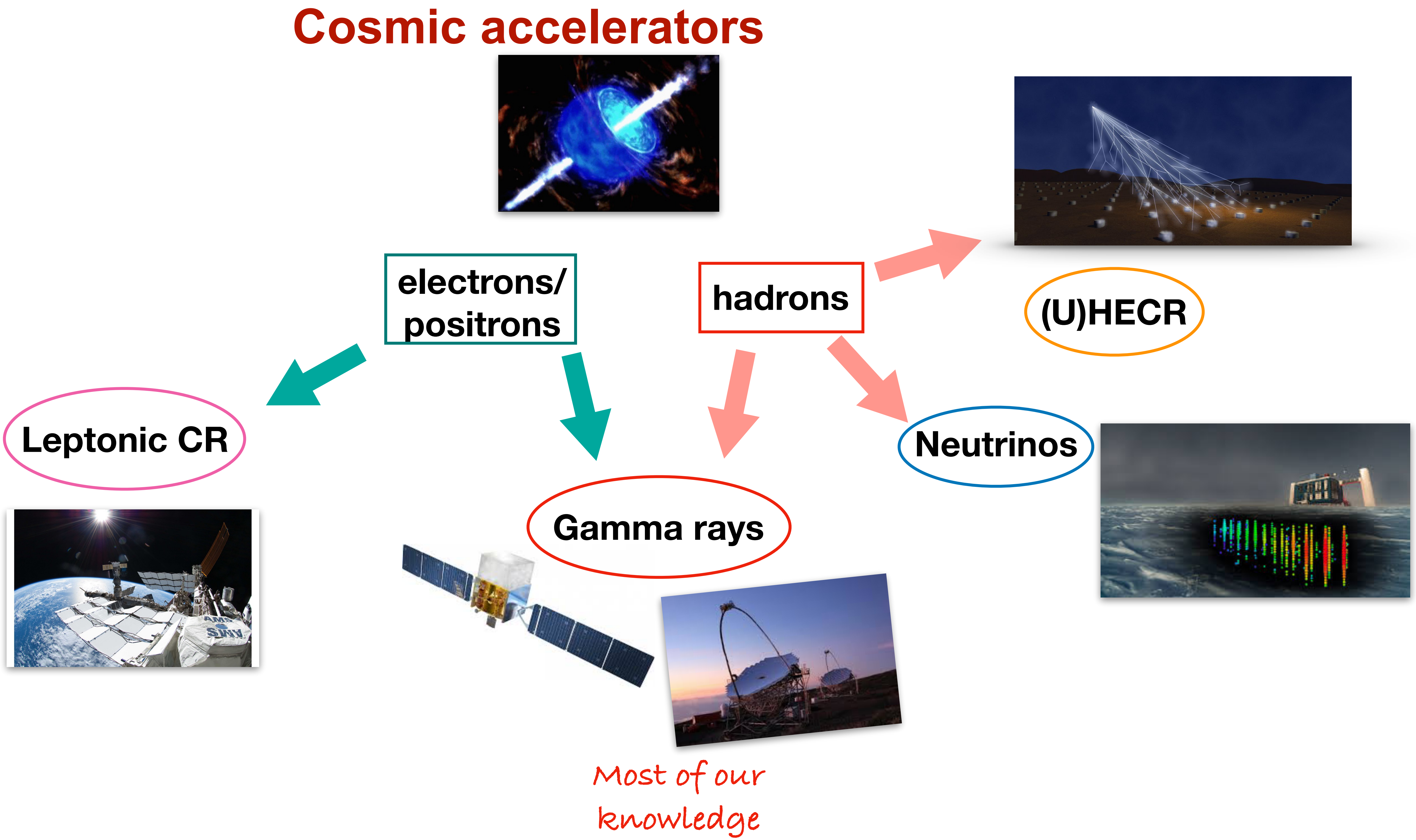
Galactic sources: SNR and PWN

Extragalactic sources: (starbursts), AGN, blazars
<u>The case of TXS 0506+056</u>

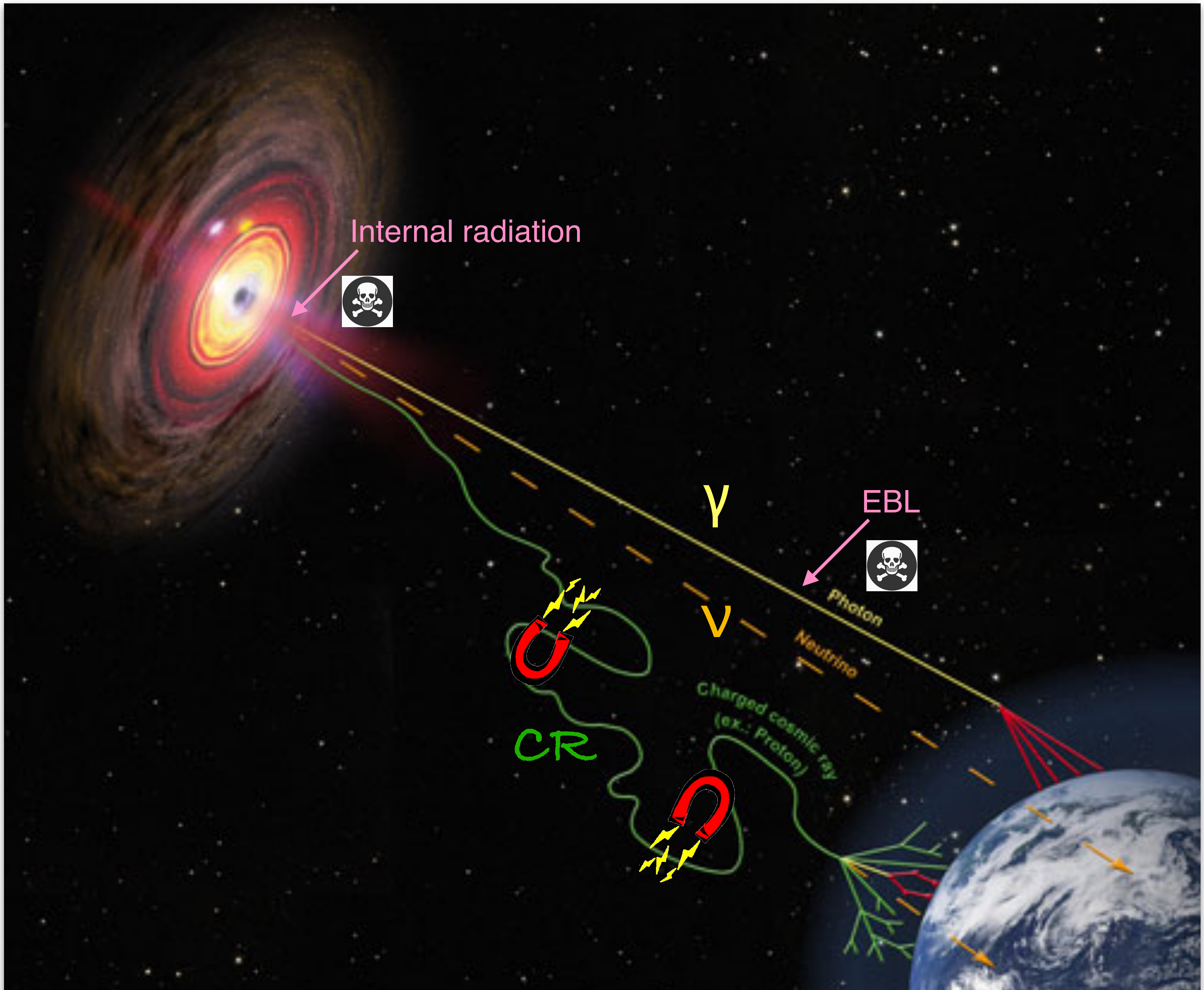
Final considerations

Introduction

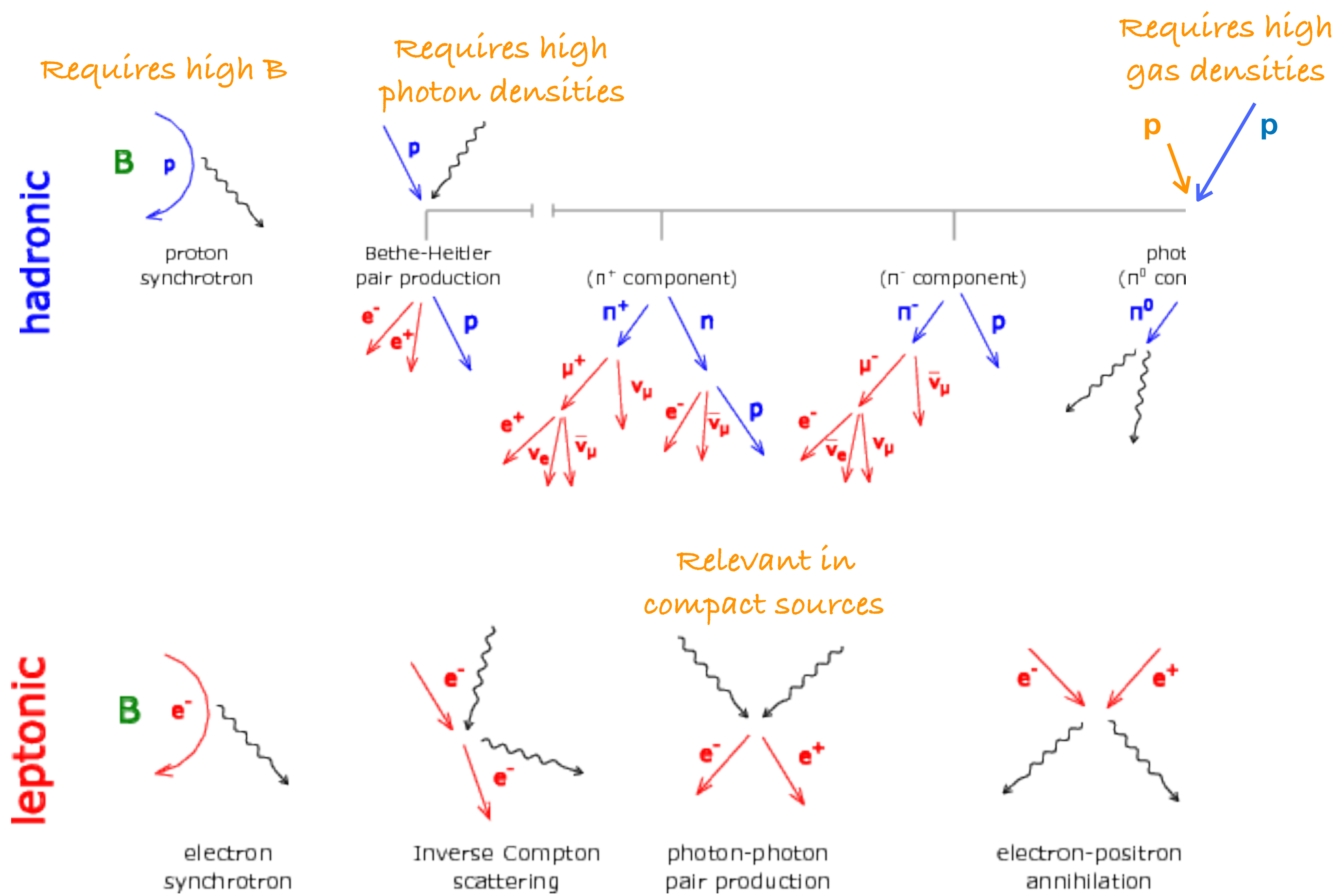
Messengers: a synoptic view



Messengers from cosmic accelerators



Processes in a nutshell



Hadronic processes

proton-proton (pp)

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

Relevant in sources
with large gas density

proton-photon (pγ)

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

Relevant in sources
with large photon density

Hadronic processes

proton-proton (pp)

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

proton-photon (pγ)

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

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

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

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

Opacity could be relevant!

$$\gamma\gamma_{\rm soft} \rightarrow e^\pm$$

Eν~Ep/20
Eγ~Ep/10
Lγ~Lν

Hadronic processes

proton-photon (pγ) $p + \gamma \rightarrow \pi + X$

Eν~Ep/20
Eγ~Ep/10
Lγ~Lν

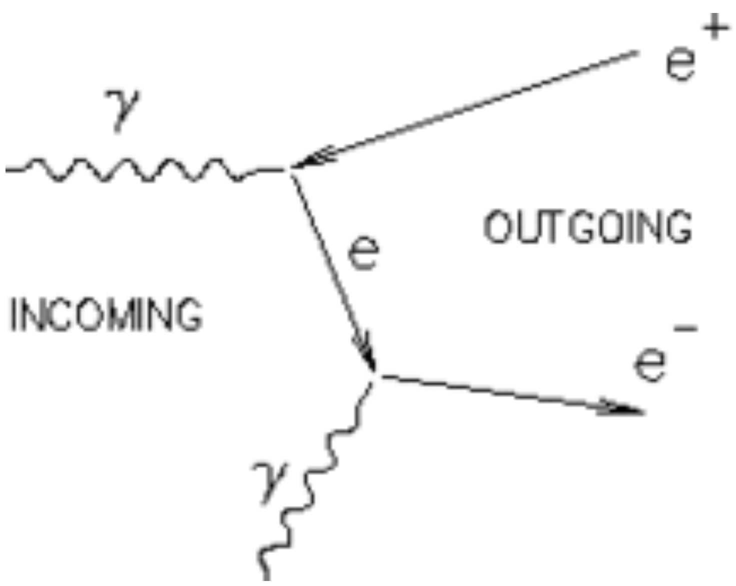
$$E_{\rm th} = \frac{2m_p m_\pi + m_\pi^2}{4\epsilon} \simeq 7 \times 10^{16} \left(\frac{\epsilon}{\rm eV}\right)^{-1} \, {\rm eV}$$

$$E_\nu = 100 \text{ TeV} \rightarrow E_{\rm p} = 2 \times 10^{15} \text{ eV}$$

$$\rightarrow \epsilon \simeq 30 \text{ eV}$$

Opacity

$$\gamma\gamma \rightarrow e^+e^-$$



$$\epsilon_{\rm min} = \frac{m_{\rm e}^2 c^4}{E_\gamma}$$

$$E_\gamma = 10 \text{ GeV}$$

$$\rightarrow \epsilon_{\rm min} = 25 \text{ eV}$$

Opacity

Efficient photomeson reactions require high photon density

Large opacity to gamma rays

The direct link between high-energy gamma-ray emission and neutrinos is (at least partially) lost

$$L_\nu \approx f_{p\gamma} L_p$$

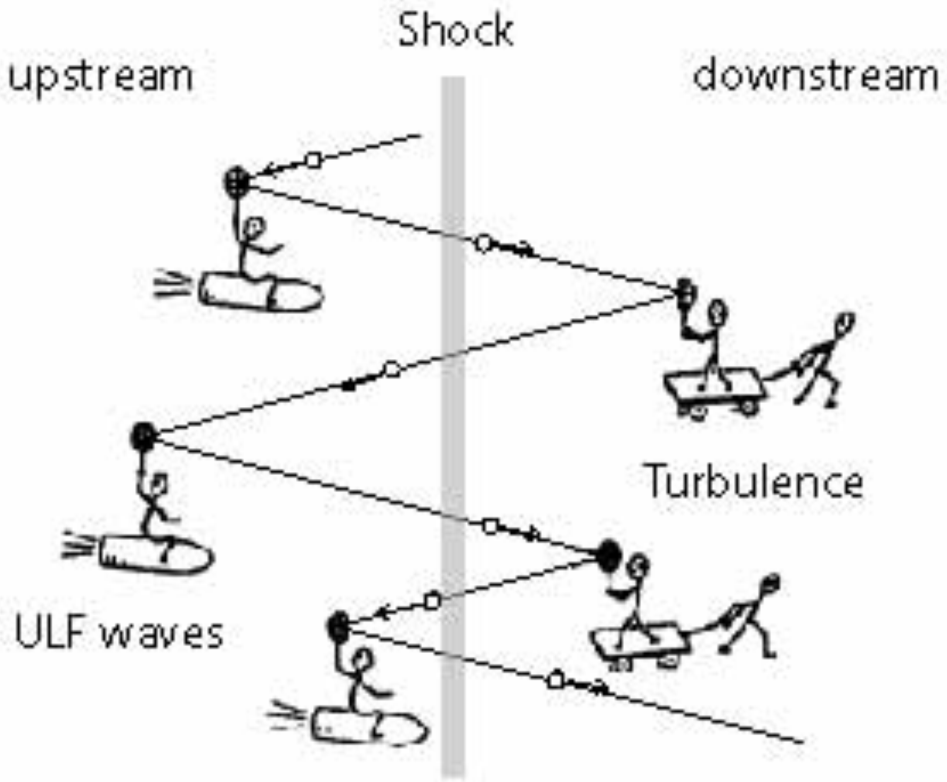
$$f_{p\gamma} \propto n_{soft}$$

$$\tau_{\gamma\gamma}(\varepsilon_\gamma^c) \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_{p\gamma}(\varepsilon_p) \sim 10 \left(\frac{f_{p\gamma}(\varepsilon_p)}{0.01}\right)$$

$$\varepsilon_\gamma^c \approx \frac{2m_e^2c^2}{m_p\bar{\varepsilon}_\Delta}\varepsilon_p \sim \mathrm{GeV}\ \left(\frac{\varepsilon_\nu}{25\ \mathrm{TeV}}\right)$$

Murase et al. 2016

Particle acceleration at shocks

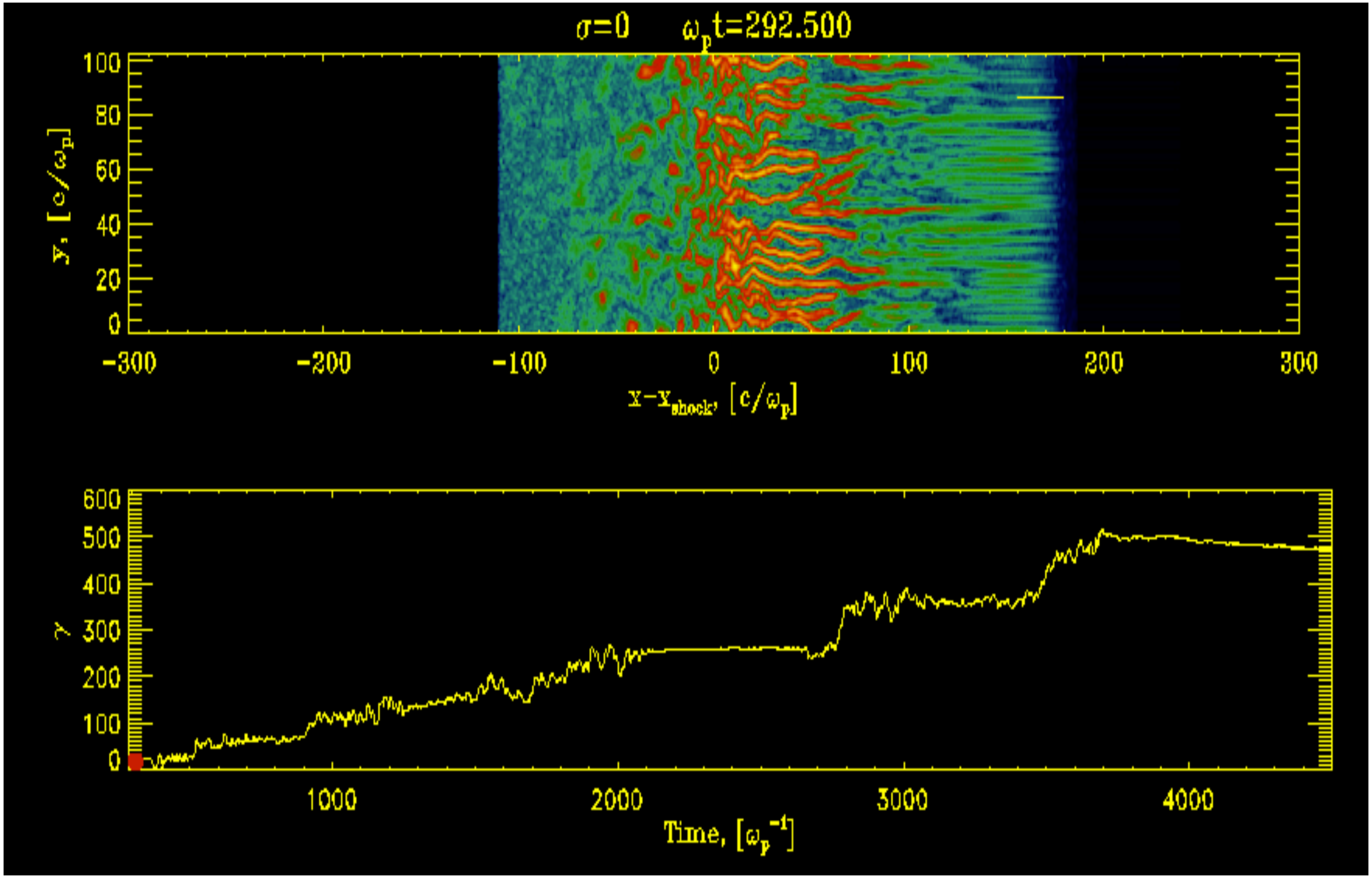


Diffusive acceleration

$$\langle \frac{\Delta E}{E} \rangle = \frac{4}{3} \frac{v_1 - v_2}{c}$$

First order Fermi process

Diffusive shock acceleration

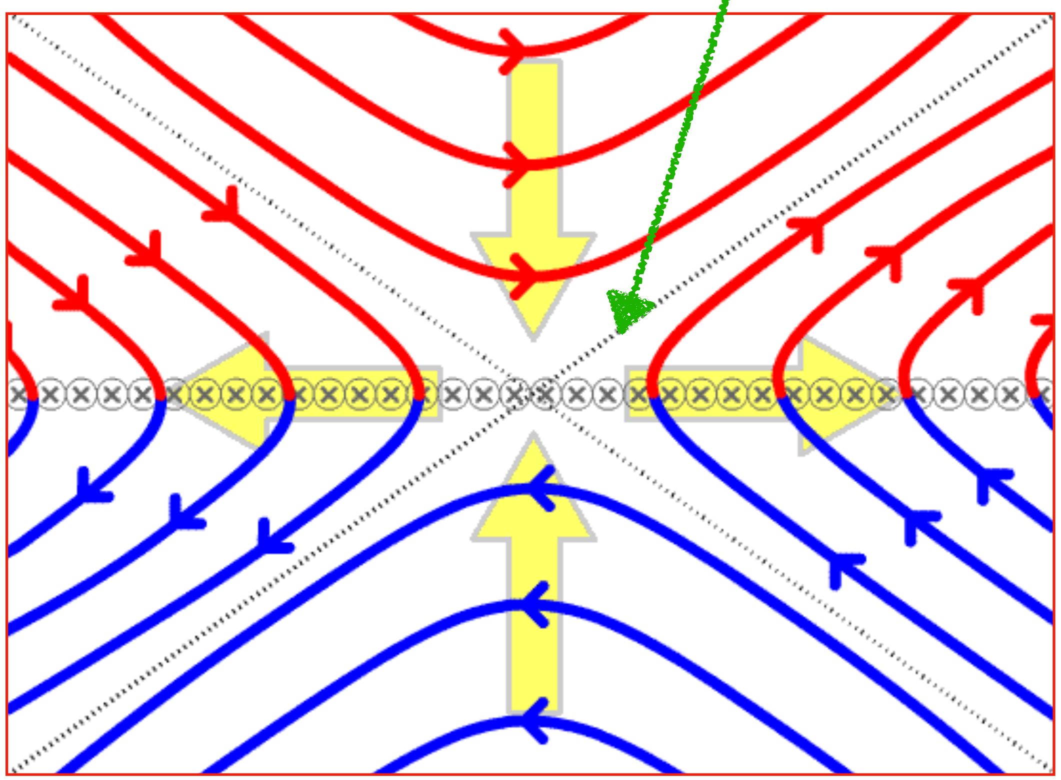


PIC simulation by L. Sironi

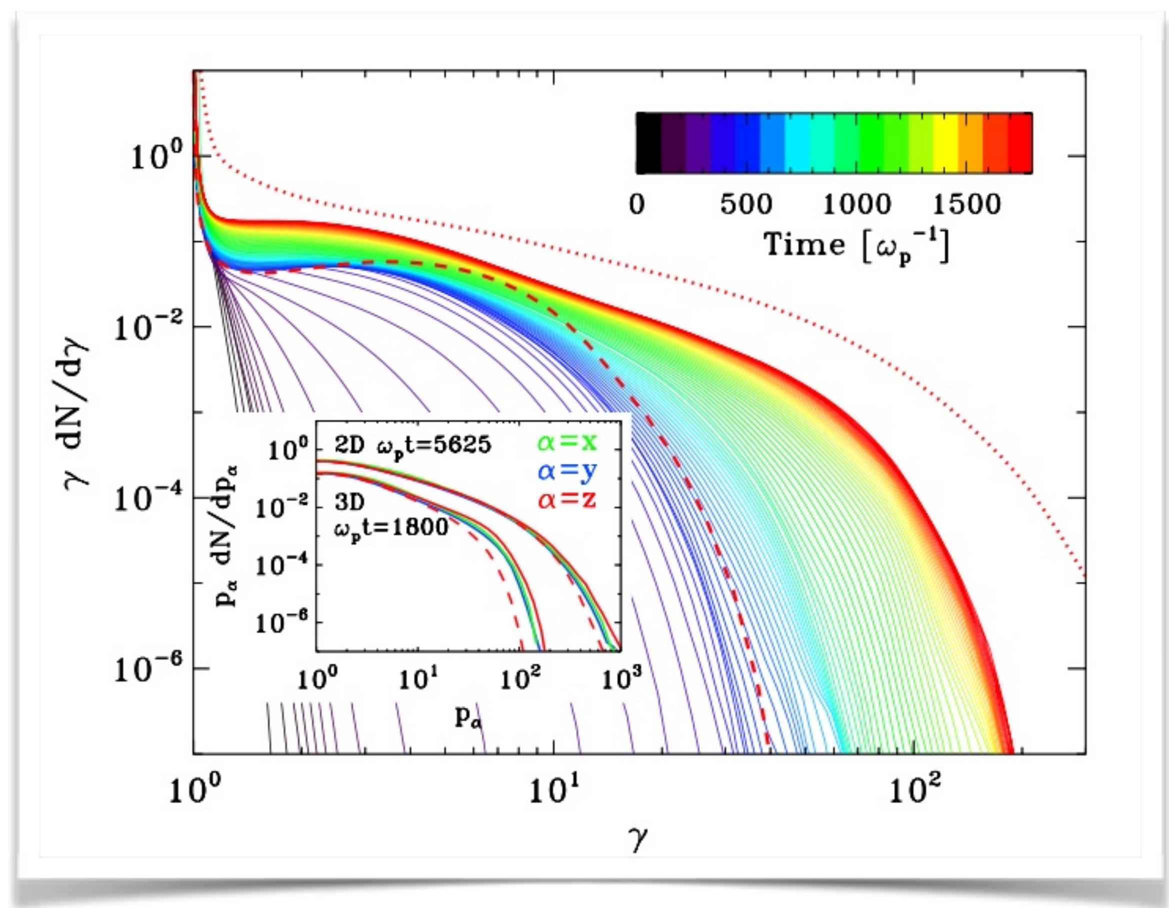
Magnetic reconnection

Change in the topology of the lines
("magnetic field annhilation")

Direct conversion of magnetic
into kinetic/heat energy



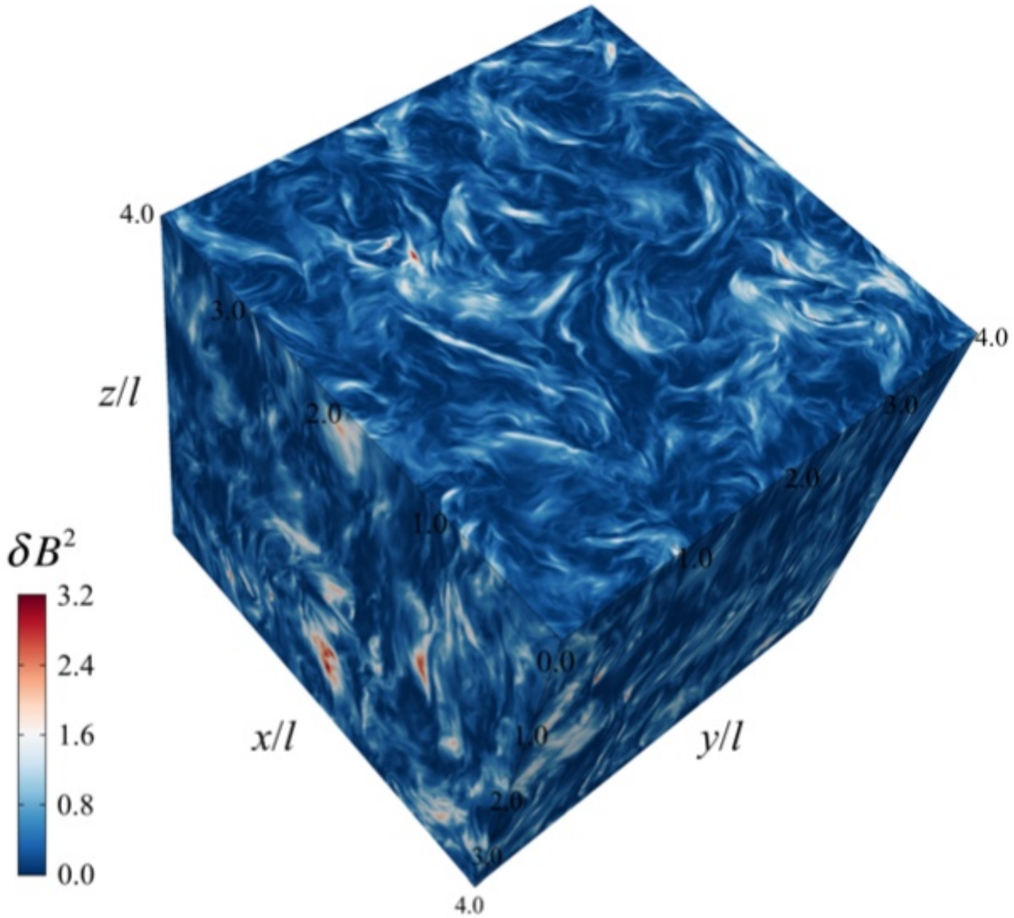
Relativistic particles with
Power law energy
distribution



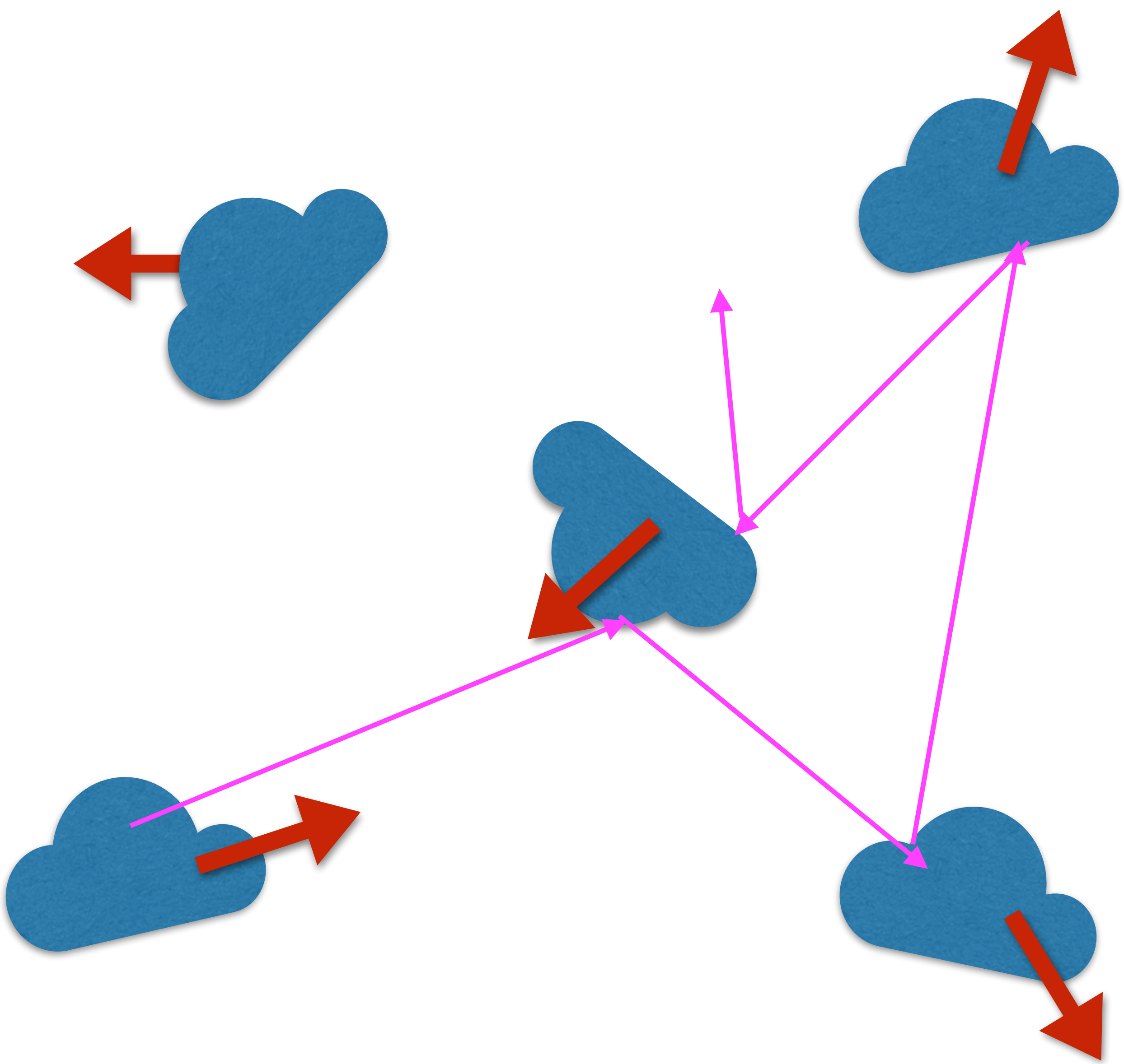
Zenitani & Hoshino 2001

Sironi & Spitkovsky 2014

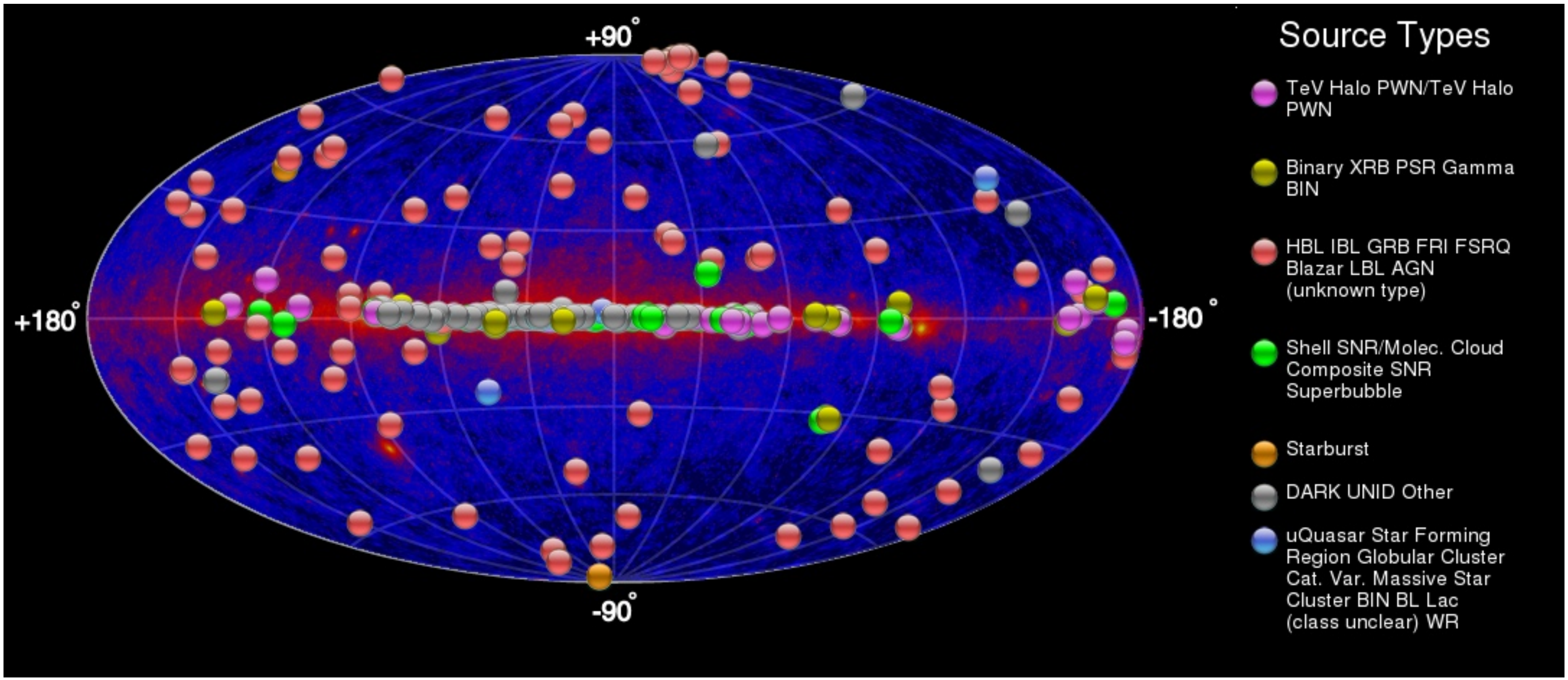
Turbulence



Zhdankin et al. 2019
Comisso & Sironi 2019



Gamma ray emitters: potential MM sources



Gamma ray emitters: potential MM sources

Galactic

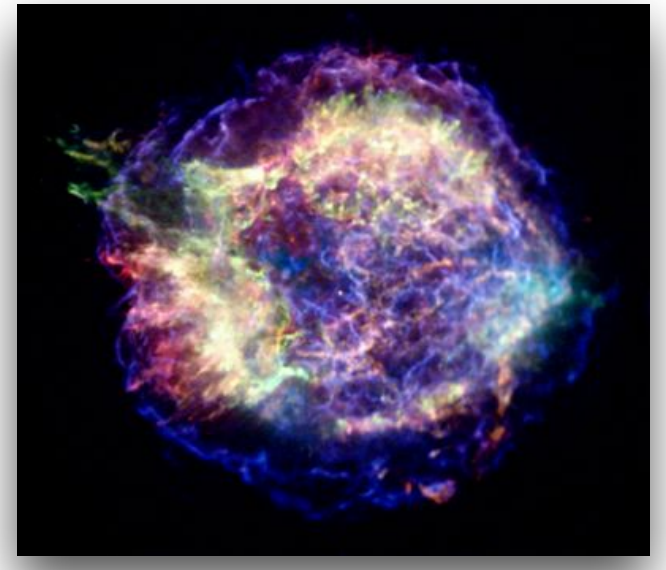
Supernova remnants
Pulsar wind nebulae
Star forming regions
...

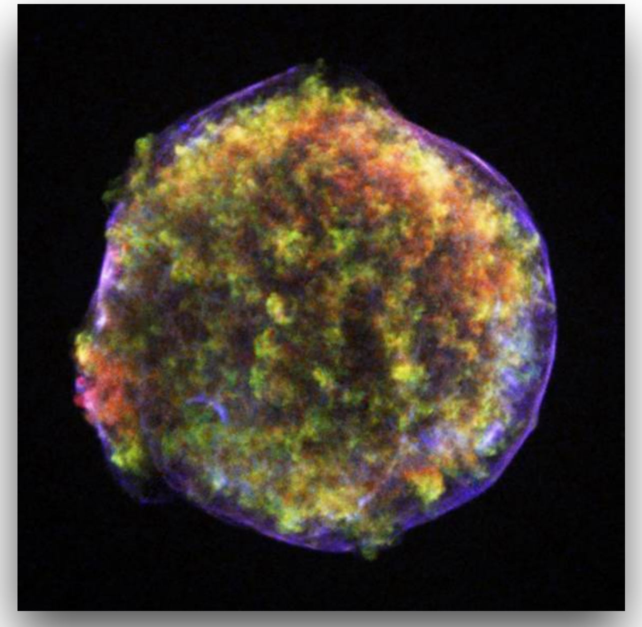
Extra-Galactic

Starburst Galaxies
AGNs
Relativistic jets
...

Galactic sources: SNRs and PWN

Supernova remnants



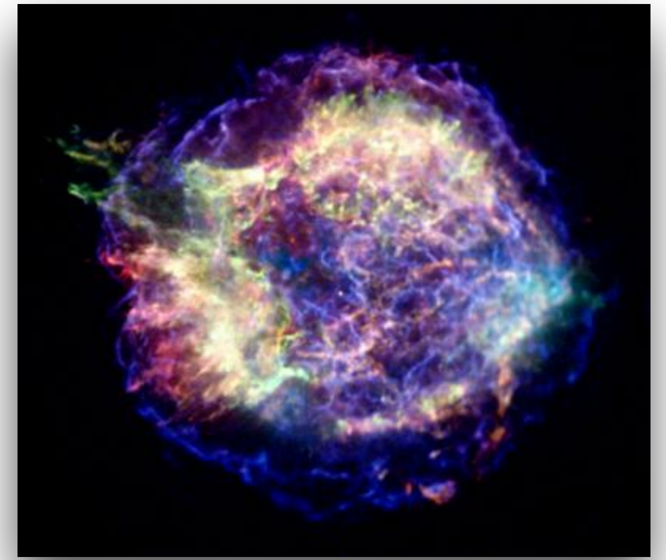


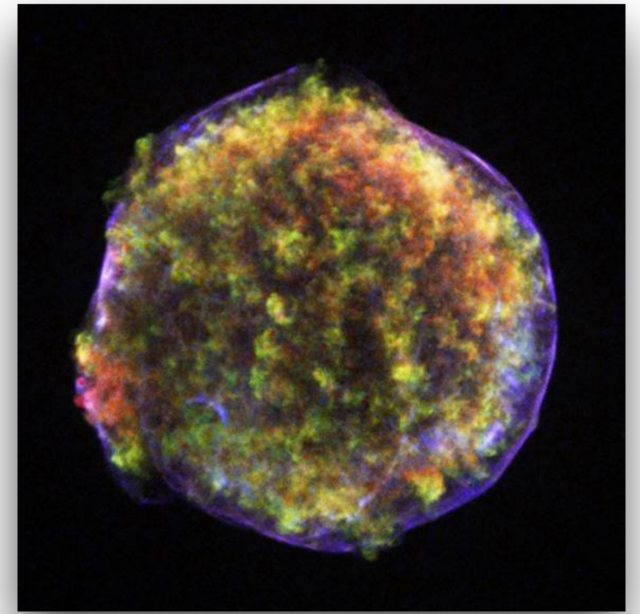
Left-over of SN explosions

Shell-like remnants

Emission dominated by a shock propagating into the ISM

Supernova remnants





FREE EXPANSION VELOCITY: $V_s = \sqrt{\frac{2E_{ej}}{M_{ej}}} = 10^9\ E_{51}^{1/2}\ M_{ej,\Theta}^{-1/2}\ \mathrm{cm/s}$

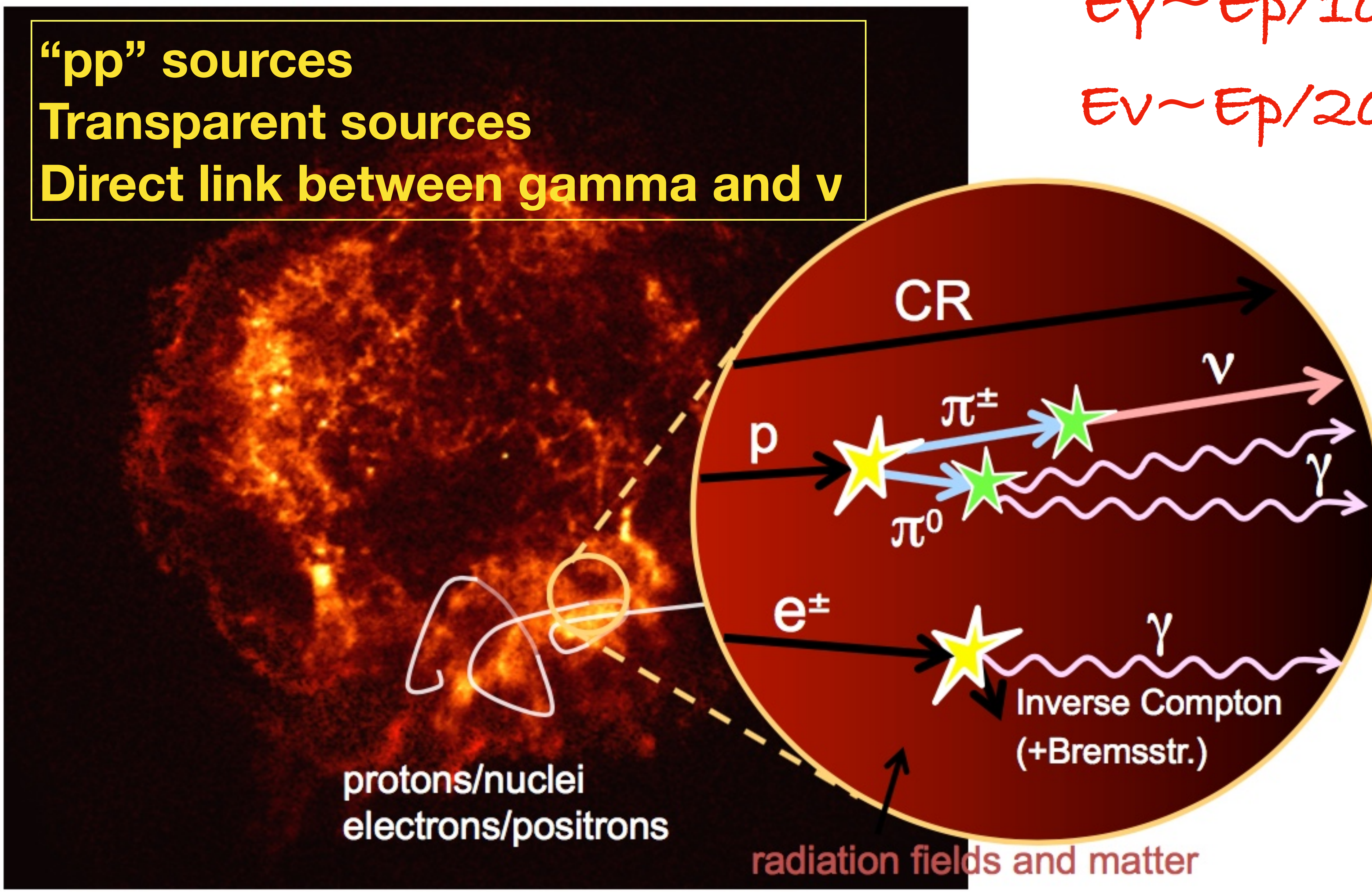
STRONG (COLLISIONLESS) SHOCK WAVE

Expected to provide the bulk of galactic protons up to 10^{15} eV

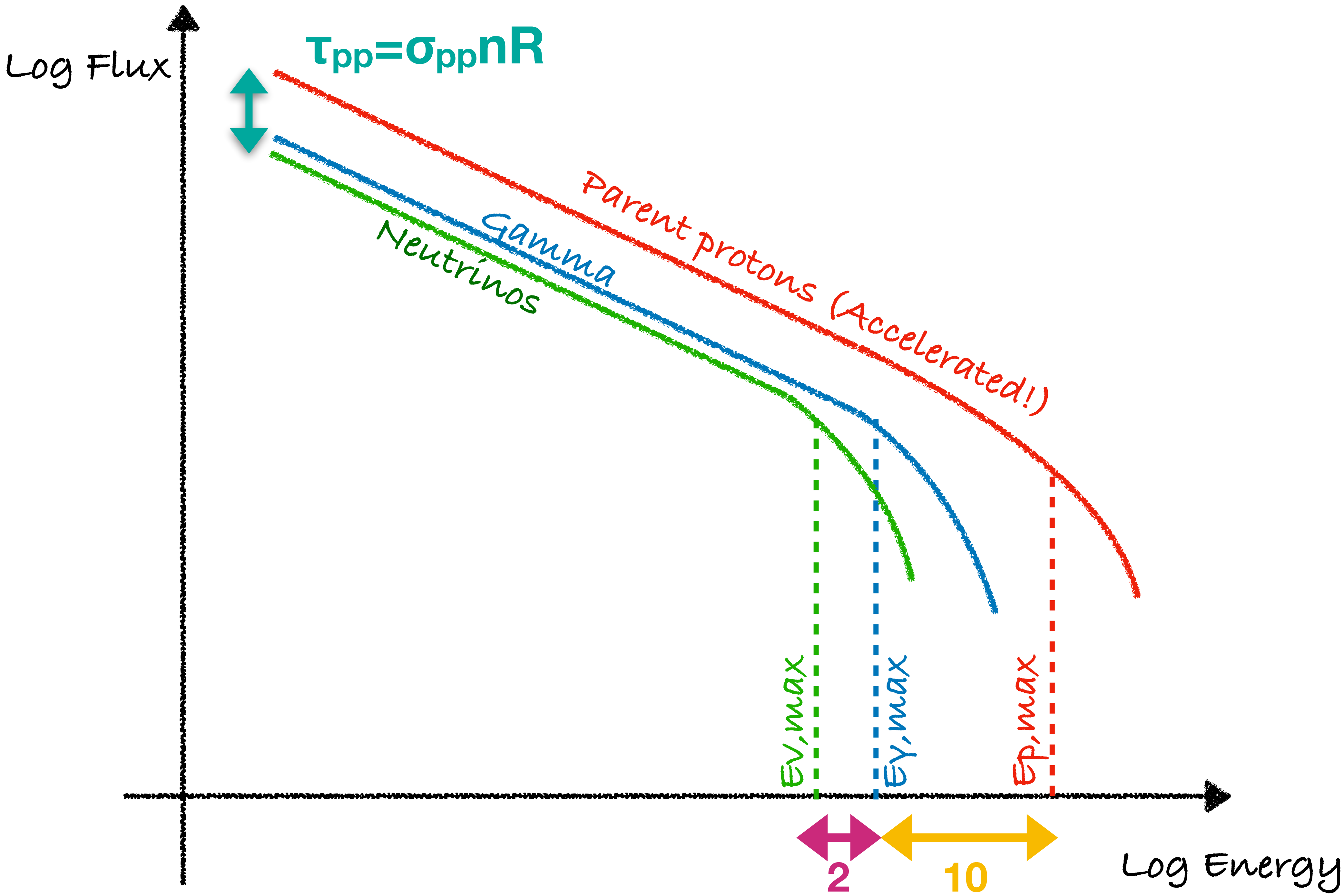
Gamma rays and neutrinos

Eγ~Ep/10

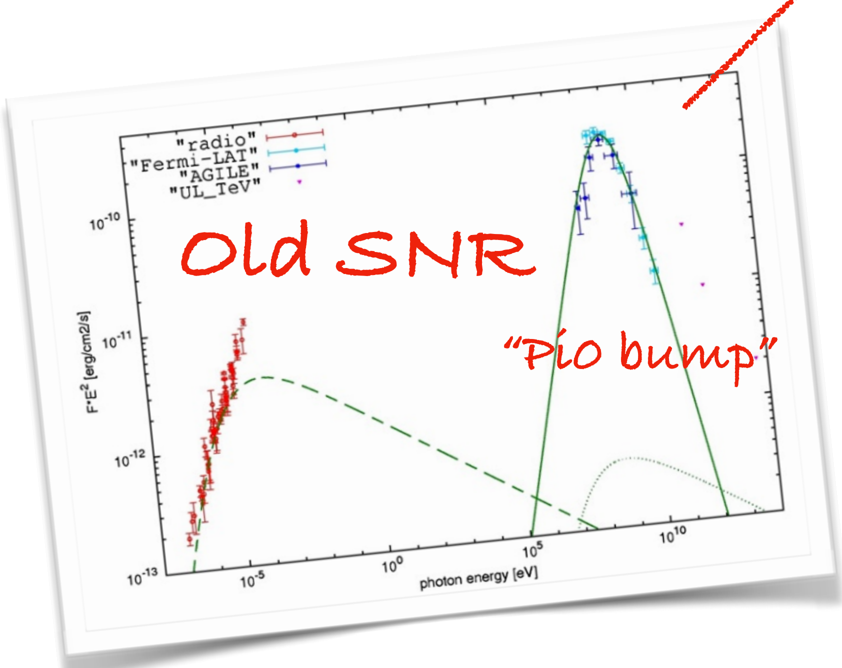
Eν~Ep/20



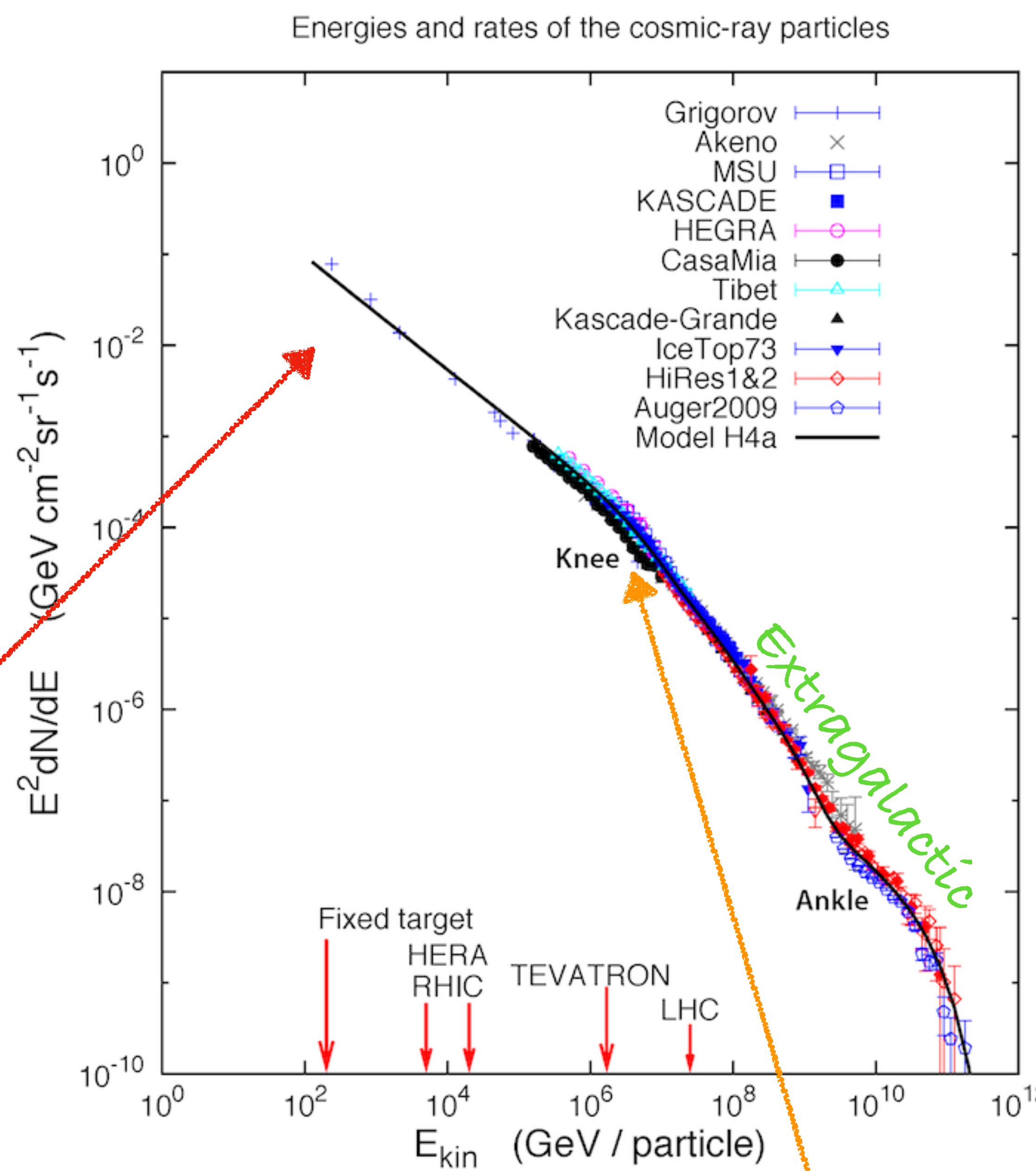
Gamma rays and neutrinos



SNR and cosmic rays



Giuliani et al. 2011

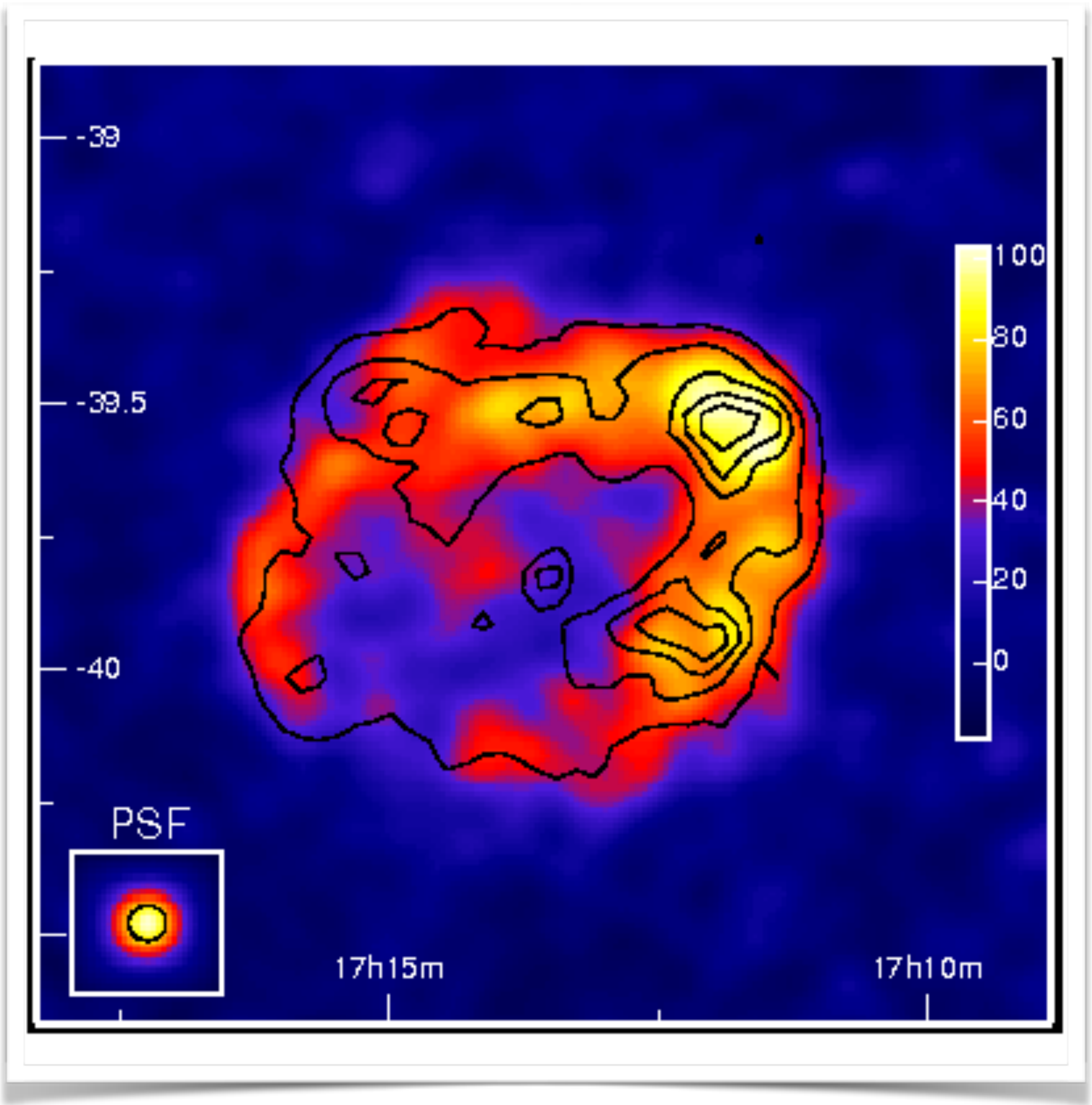


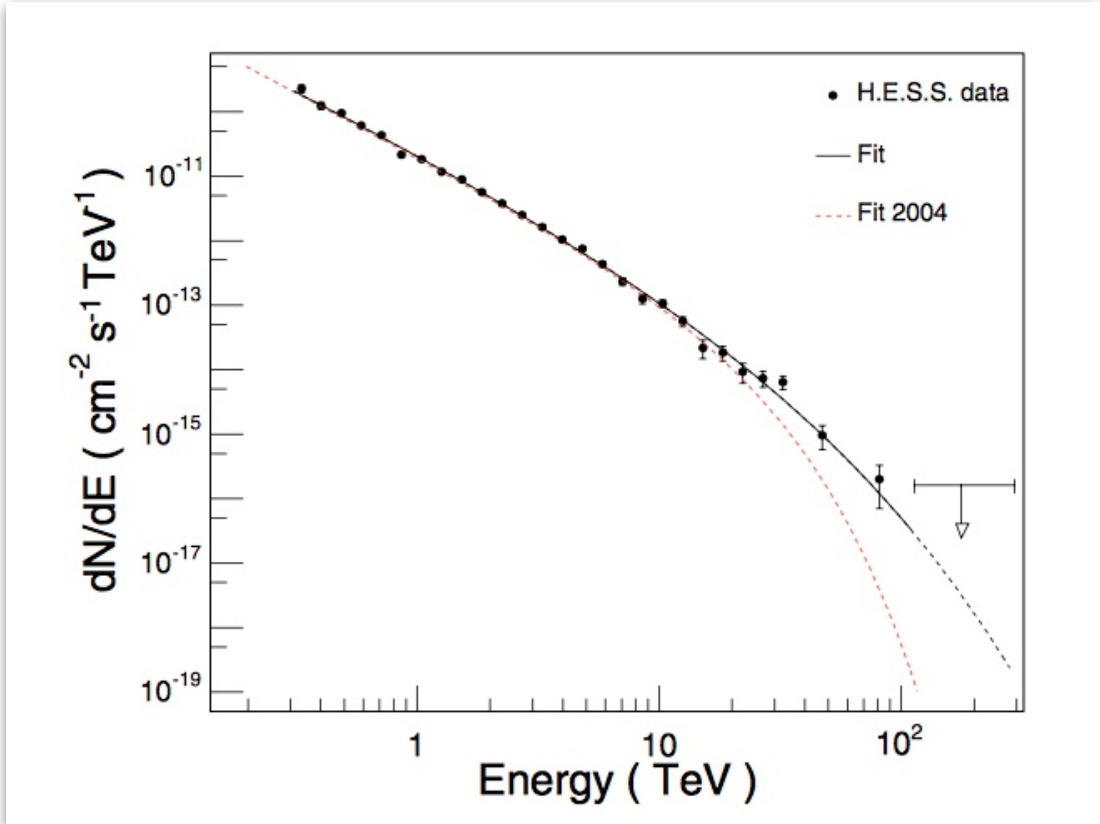
Pevatrons?

Age <1000 y or even 100 y

A case study

RXJ1713.7-3946

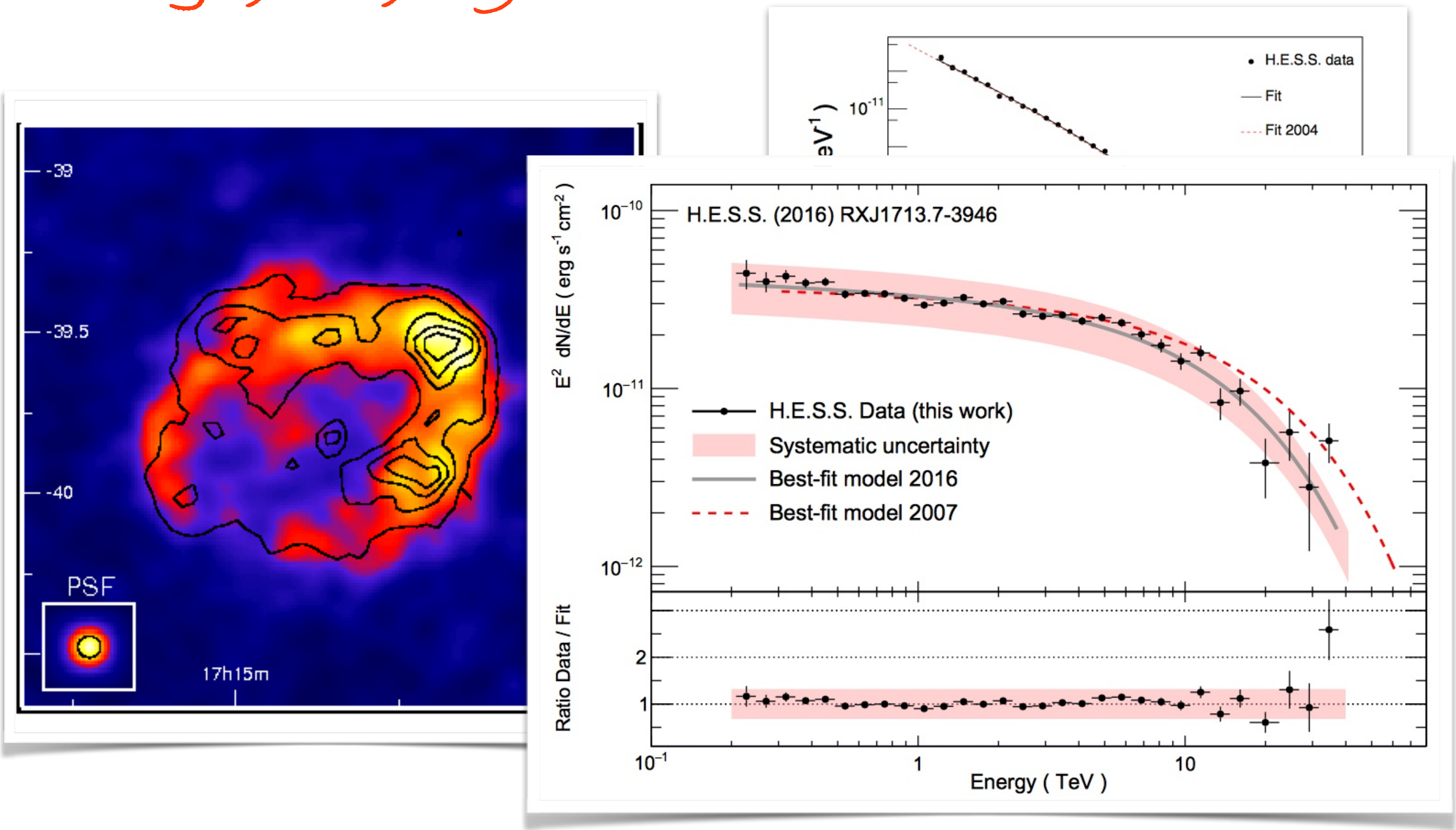




HESS Coll. 2007,2018

A case study

RXJ1713.7-3946



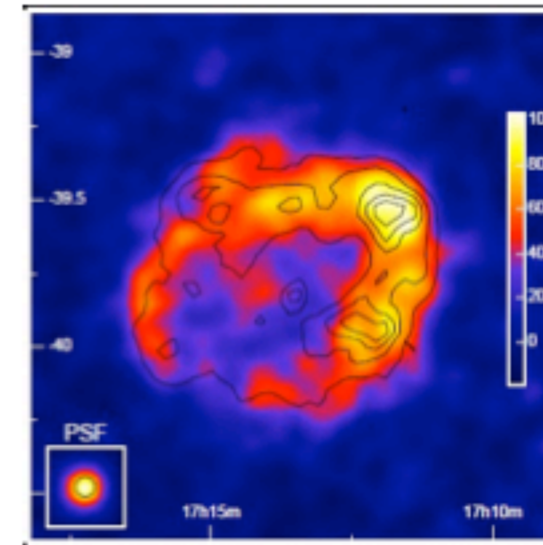
HESS Coll. 2007,2018

A case study

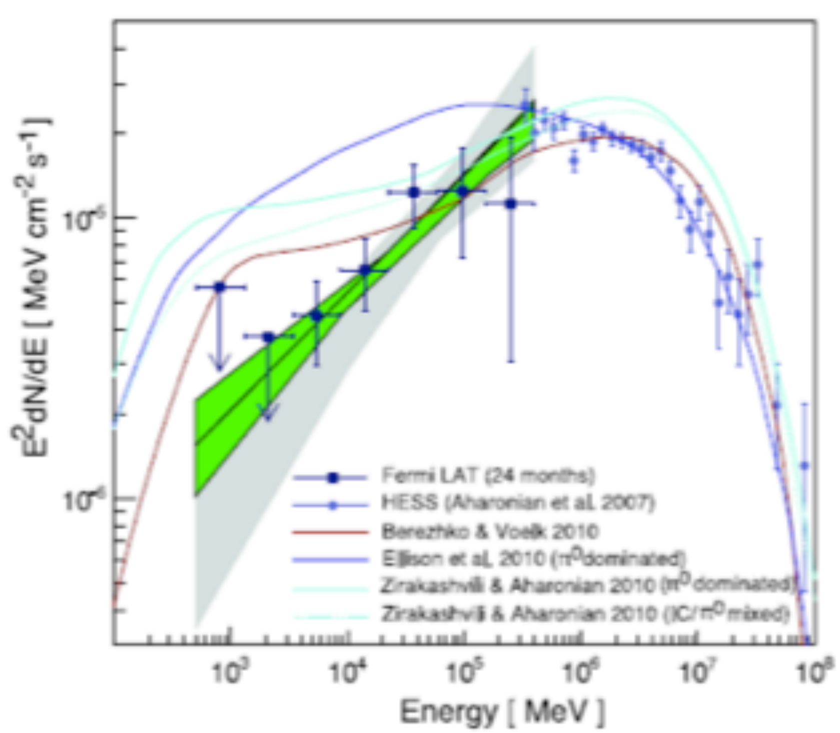
The remnant **RX J1713.7-3946** has been considered the most promising candidate to prove the existence of accelerated hadrons

FermiLAT data seem to favor a probable leptonic origin

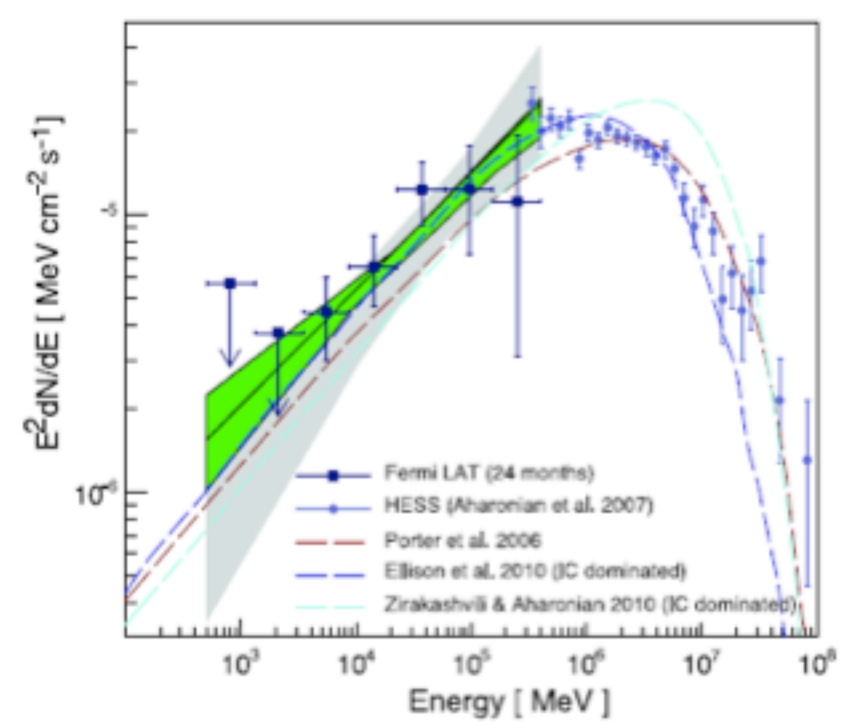
BUT... Need a IR background 30 > Gal. average



Hadronic model(s): π⁰ →γγ

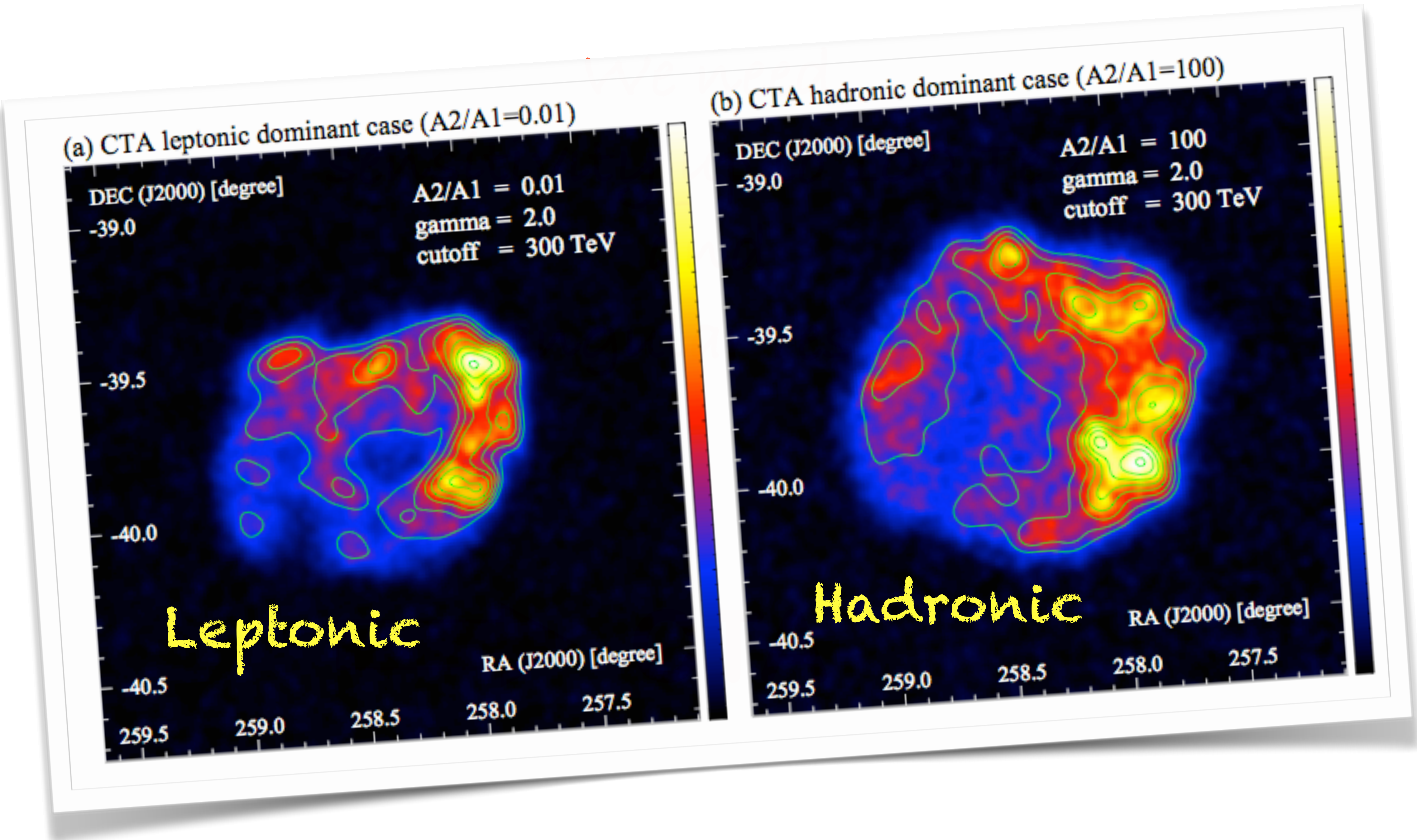


Leptonic model(s): inverse Compton scattering



A case study

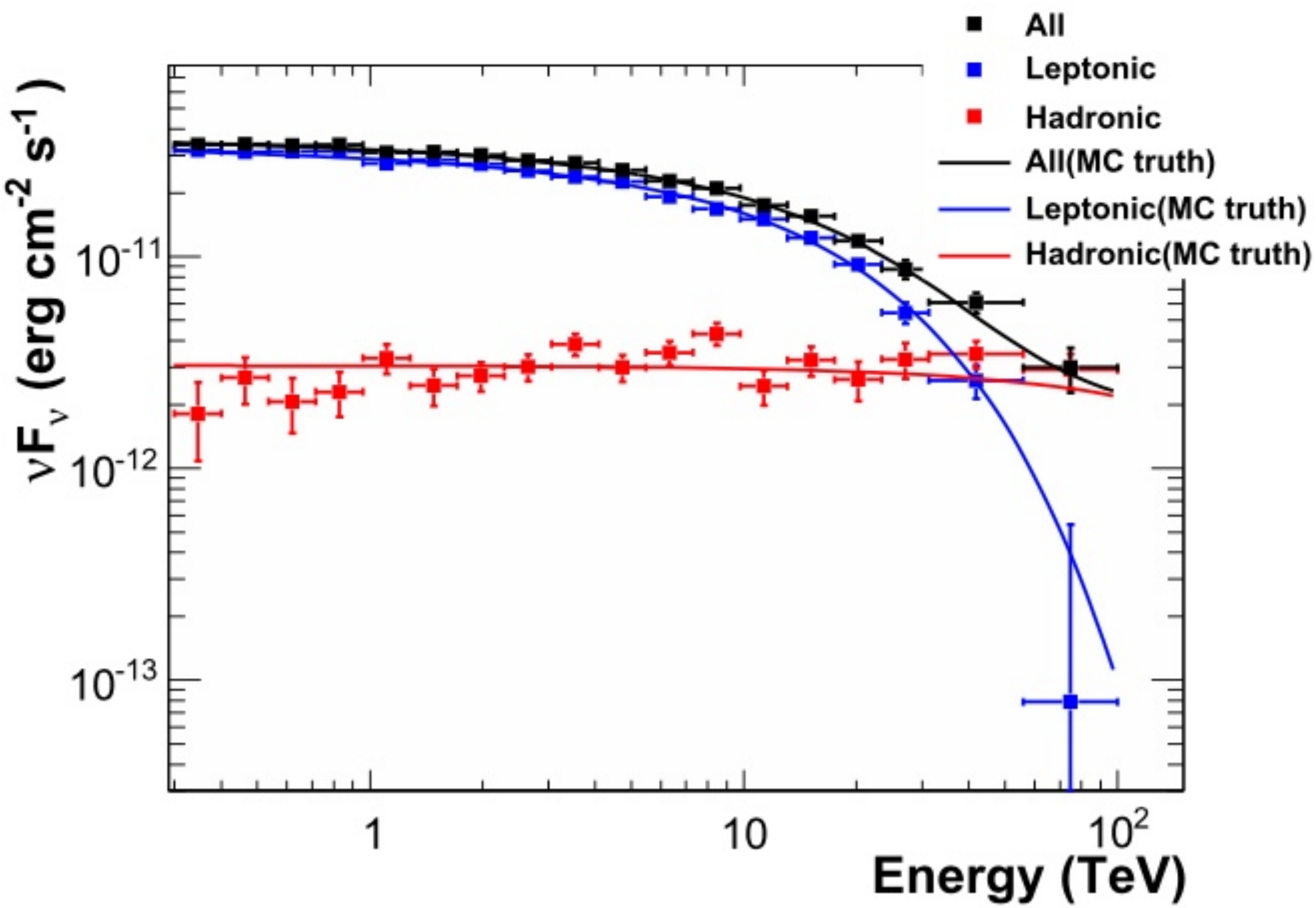
The CTA view



CTA Coll., 2017

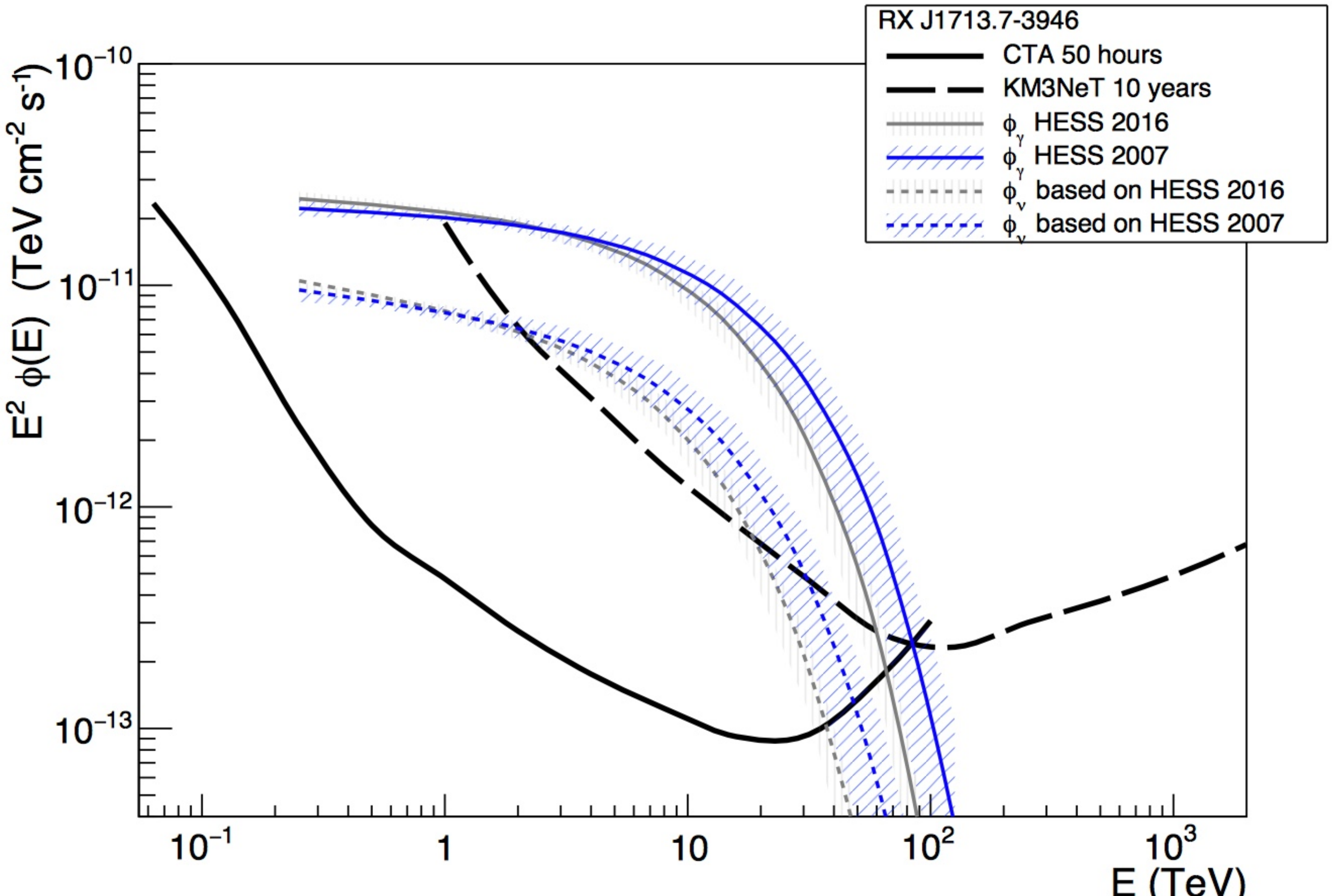
Gamma rays

RX J1713.7-3946



CTA Coll., 2017

Neutrinos: the hadronic smoking gun



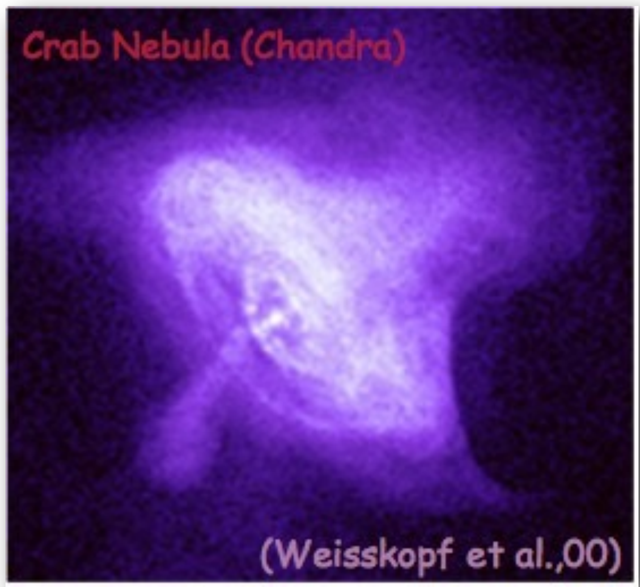
Reliable prediction of neutrino spectra requires good gamma-ray data above 10 TeV

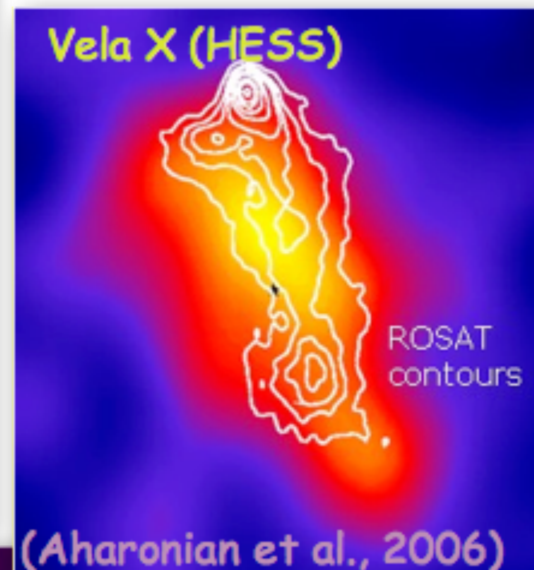
Ambrogi et al. 2018

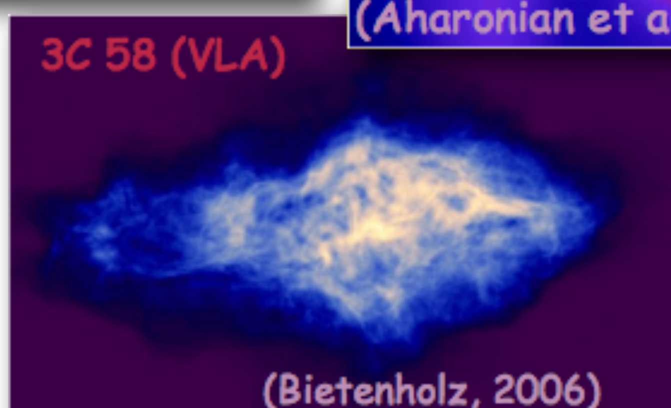
Pulsar Wind Nebulae

Pulsar-driven (plerion) SNR

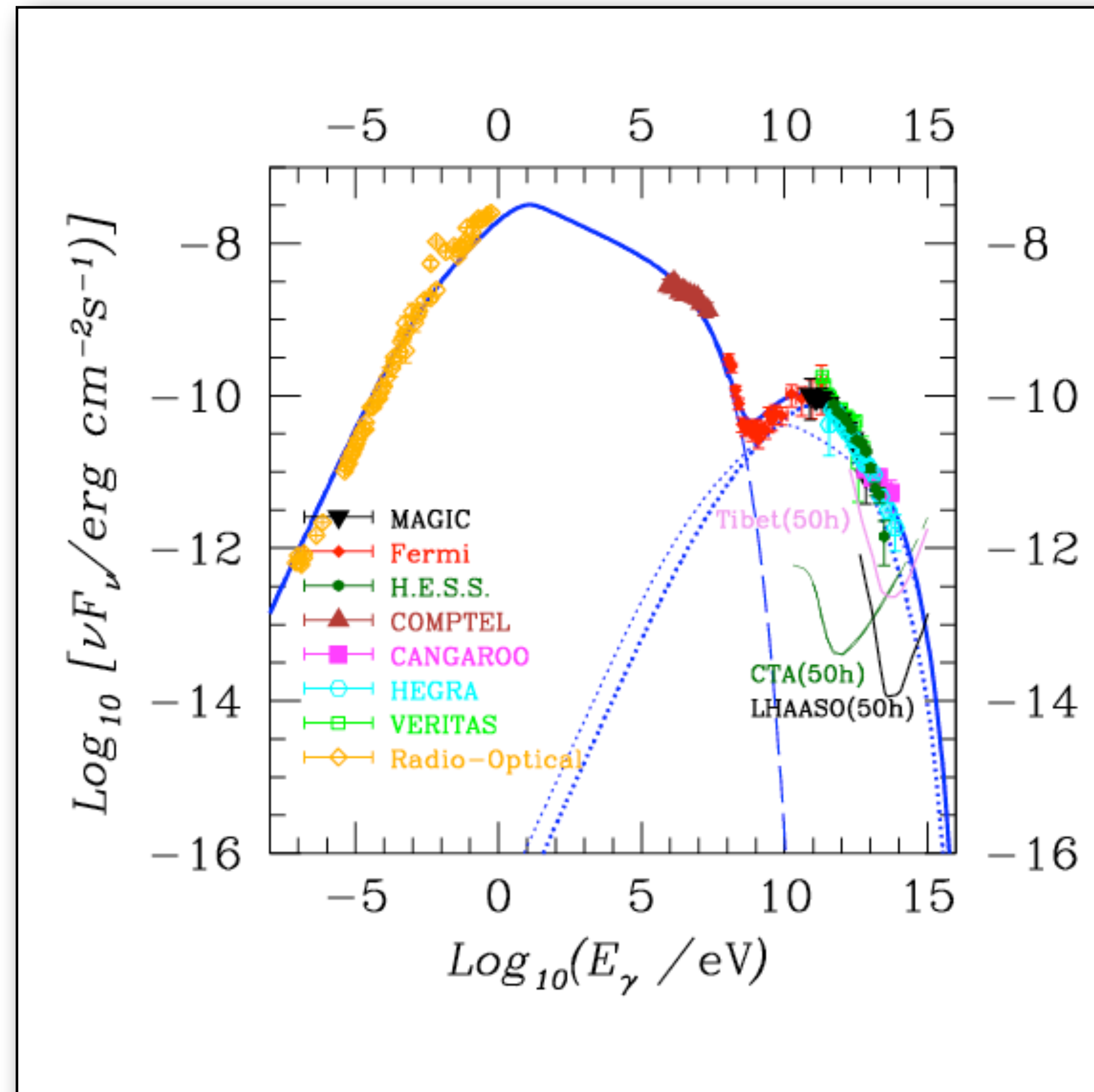
The majority of LAT and CT galactic sources





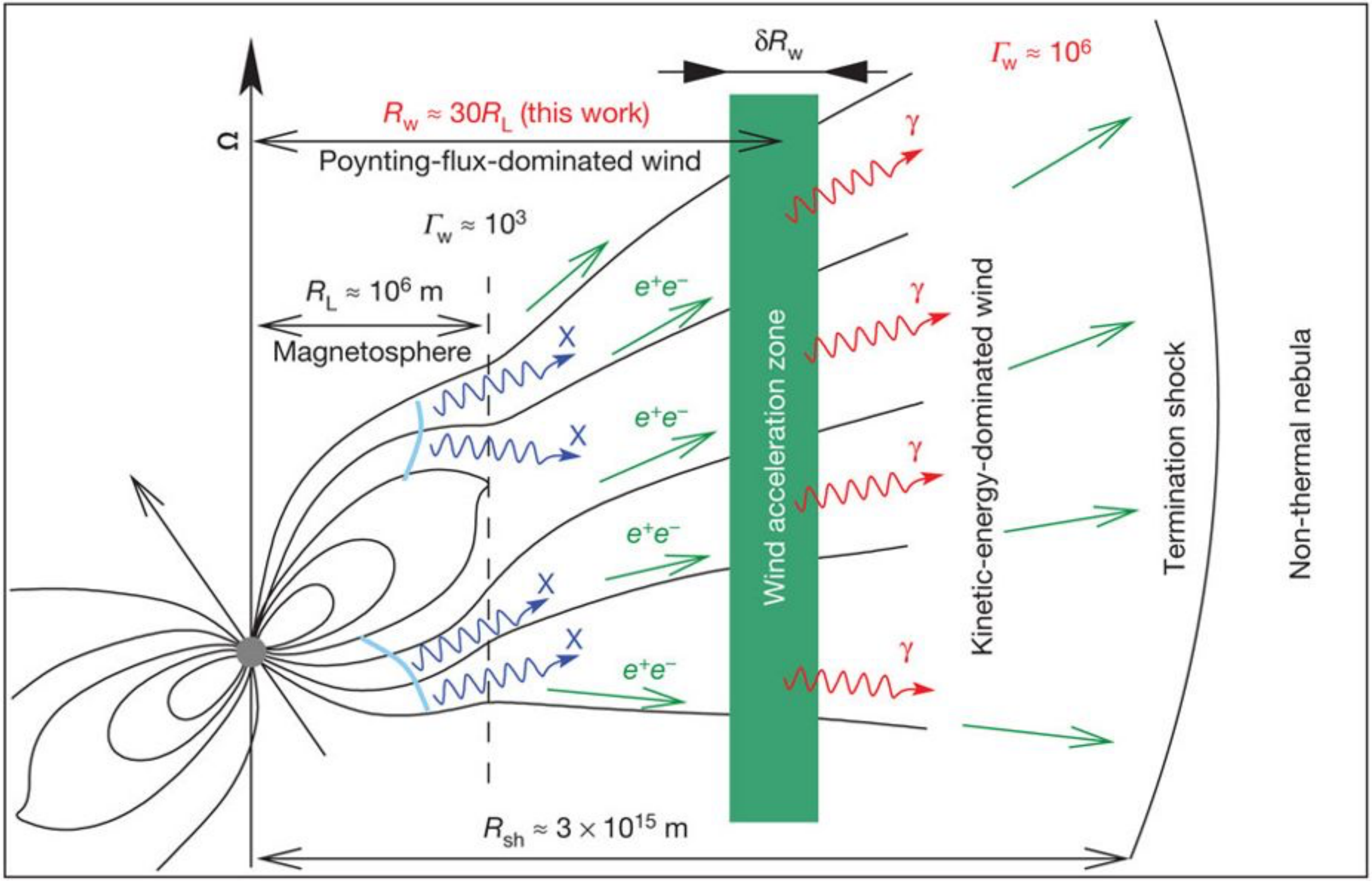


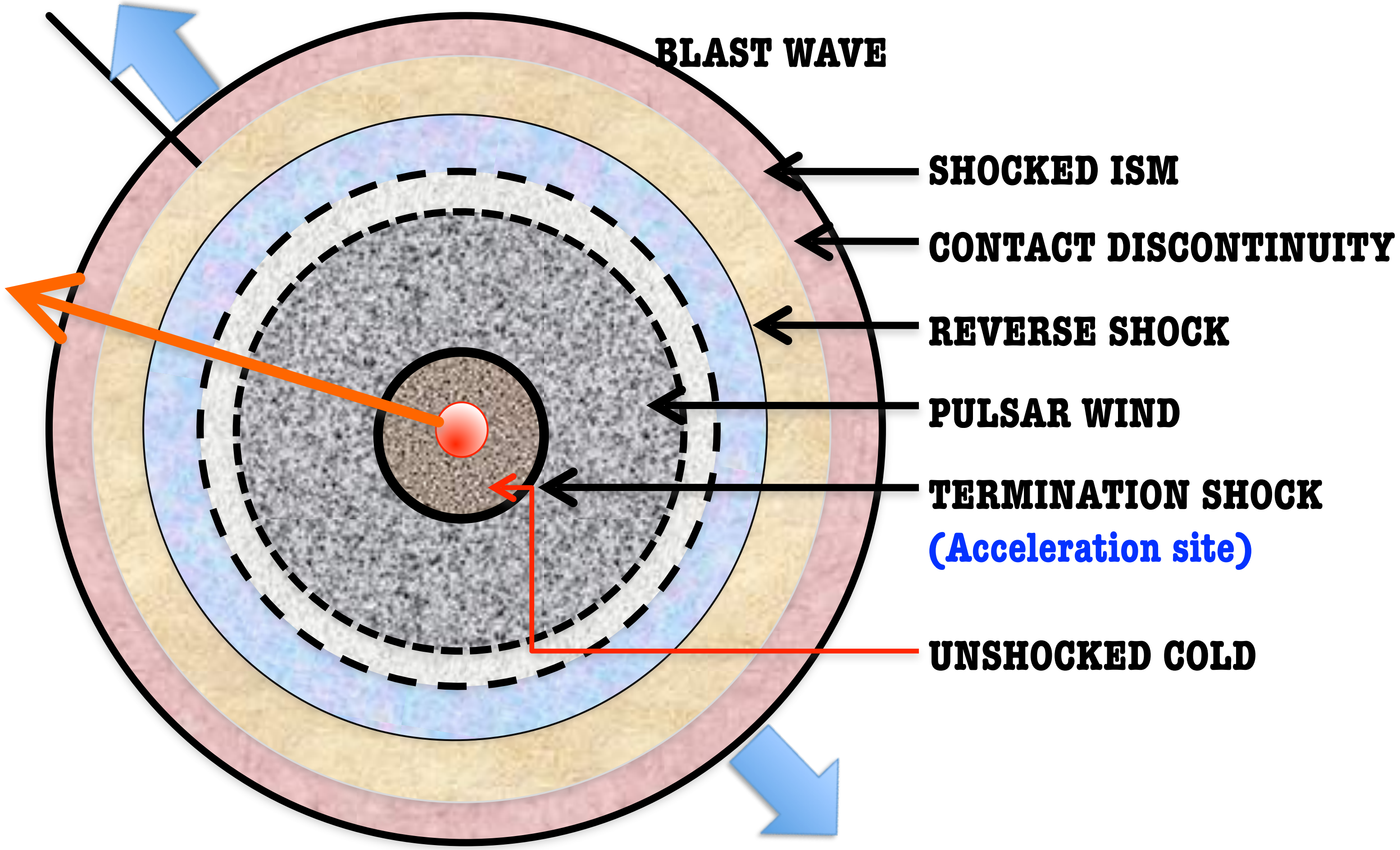
Crab Nebula

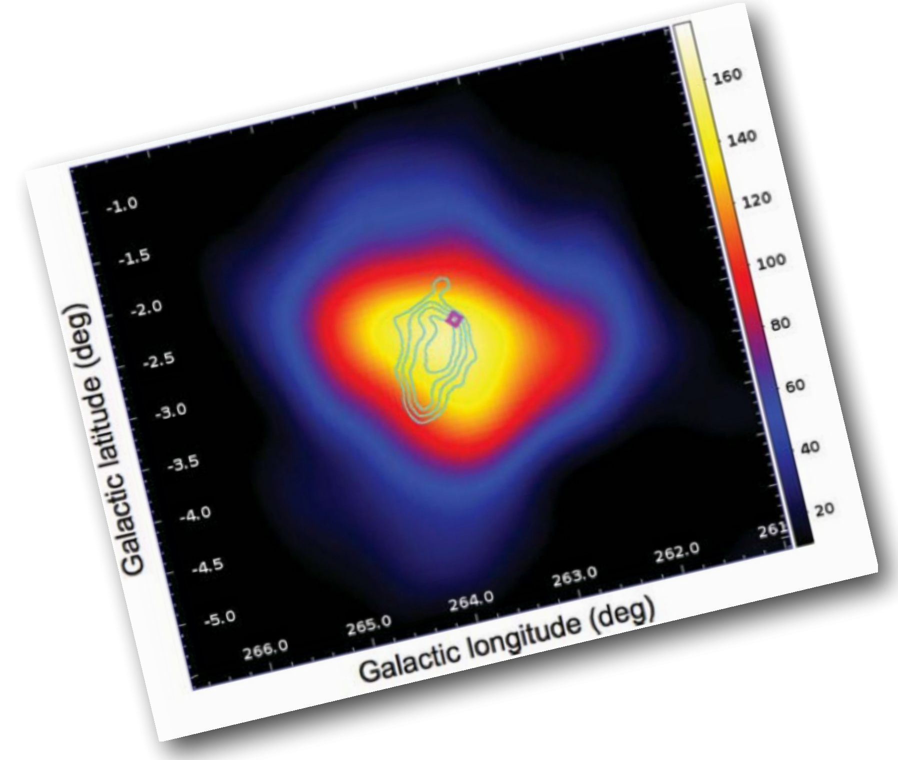


MW and variable (Crab!) sources

Pulsar Wind Nebulae







Fundamental open issues:

- Origin of Crab-like flares (reconnection?)

- Particle acceleration in PWN (shock? reconnection?) - Problem of particle acceleration at relativistic shocks: B is very large!

- Transformation of B energy into kinetic energy of the wind

- Connection with positrons in cosmic rays?

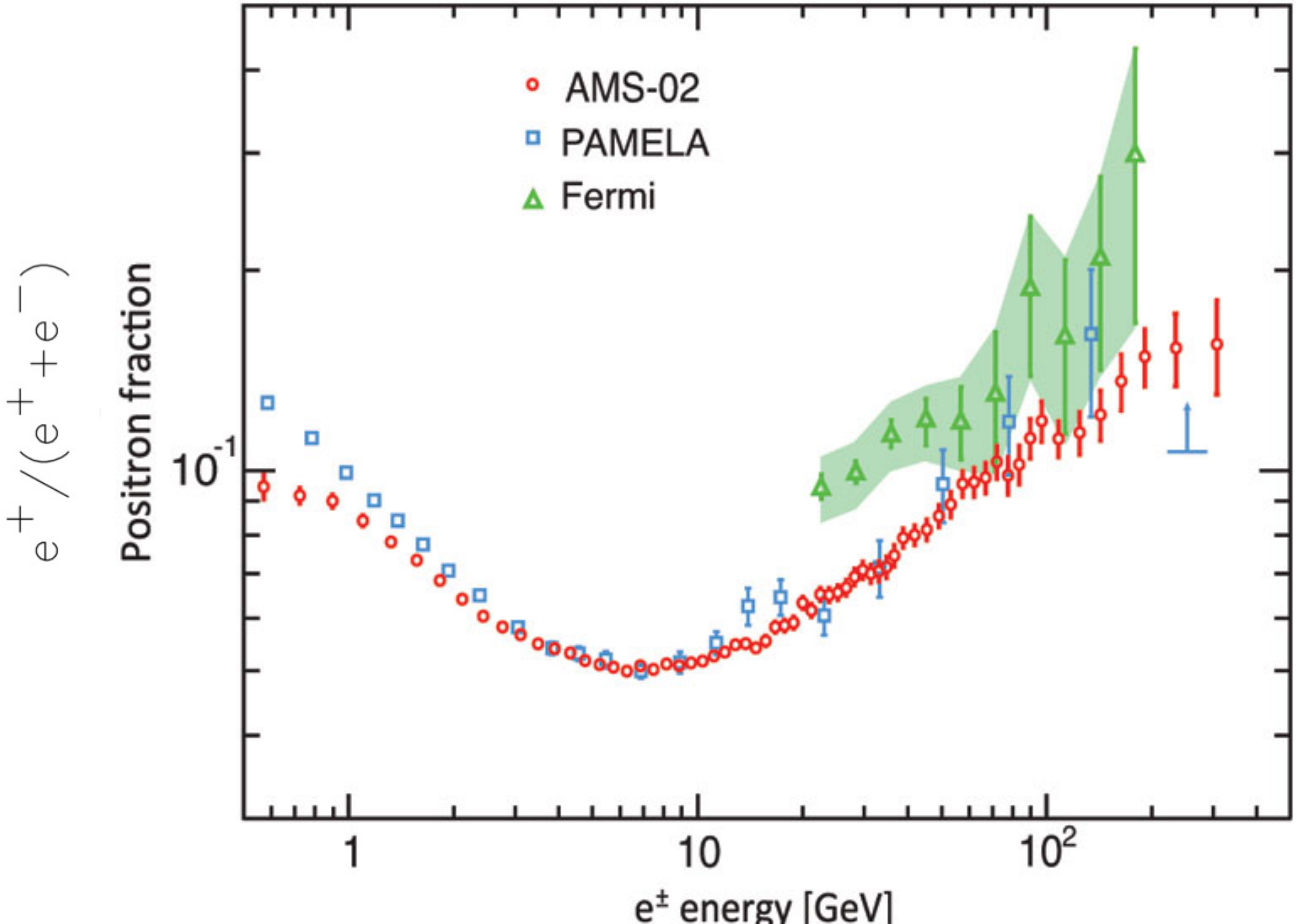
Neutrinos from PWN?

Idea: part of the gamma-rays are of hadronic (pp) origin
(this would solve problems with the powerful IC)

Present data cannot esclude that the
<u>entire</u> gamma-ray emission is hadronic

Bednarek 2003
Amato et al. 2003
Di Palma et al. 2017

Positron excess from PWN?



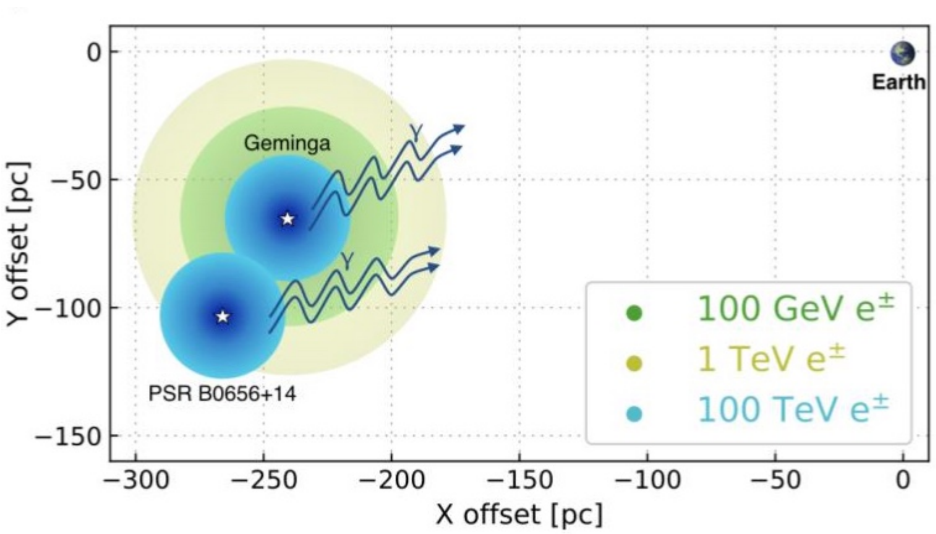
Evidence of dark matter?

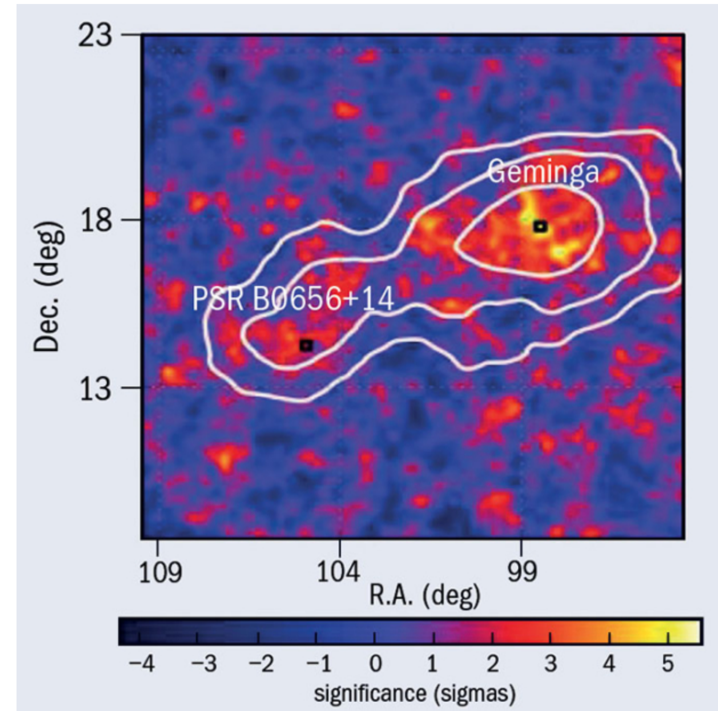
Positron excess from PWN?

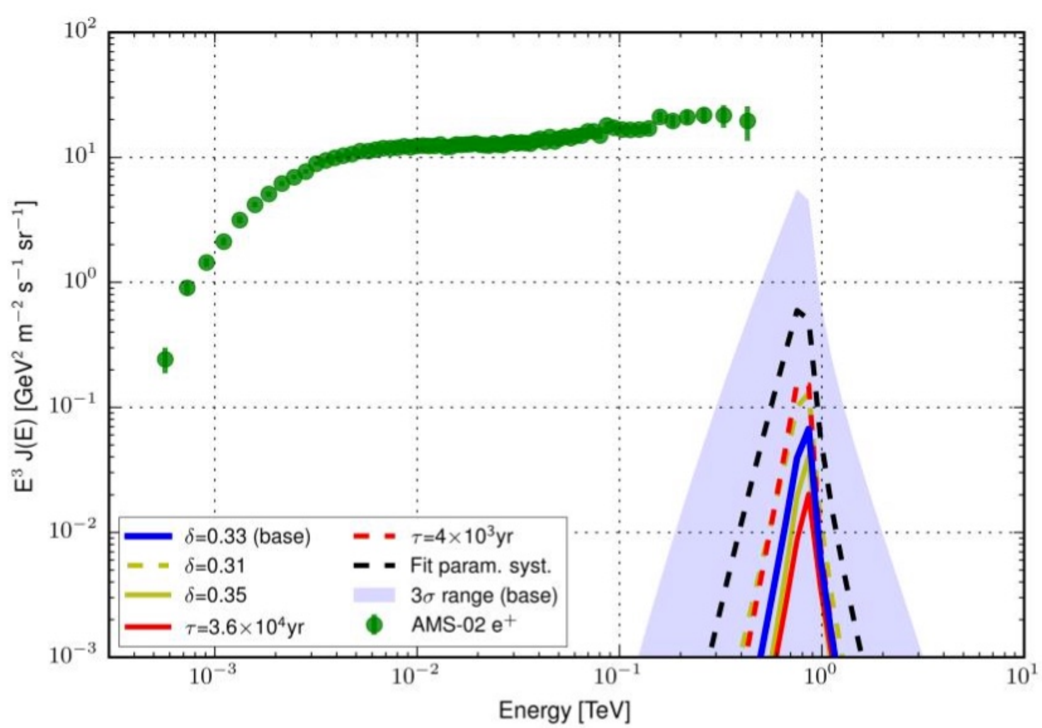
Difficult …

The diffusion of particles in the IGM is quite slower than usually assumed.

HAWC Coll. 2017







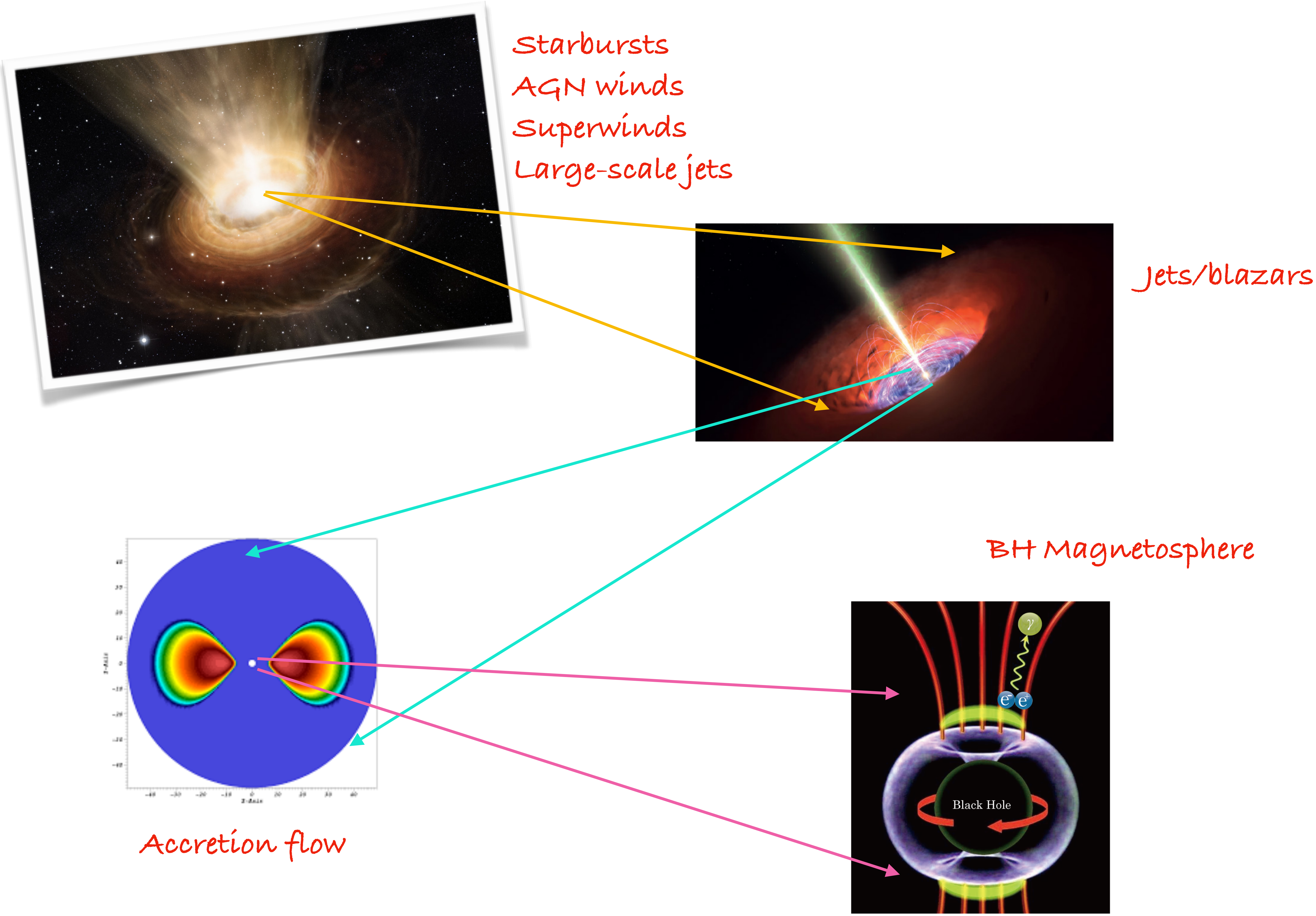
But see:

Cholis et al. 2018
Amato 2018
Di Mauro et al. 2019
Fang et al. 2019
…

Sum of the galactic pulsar population still consistent

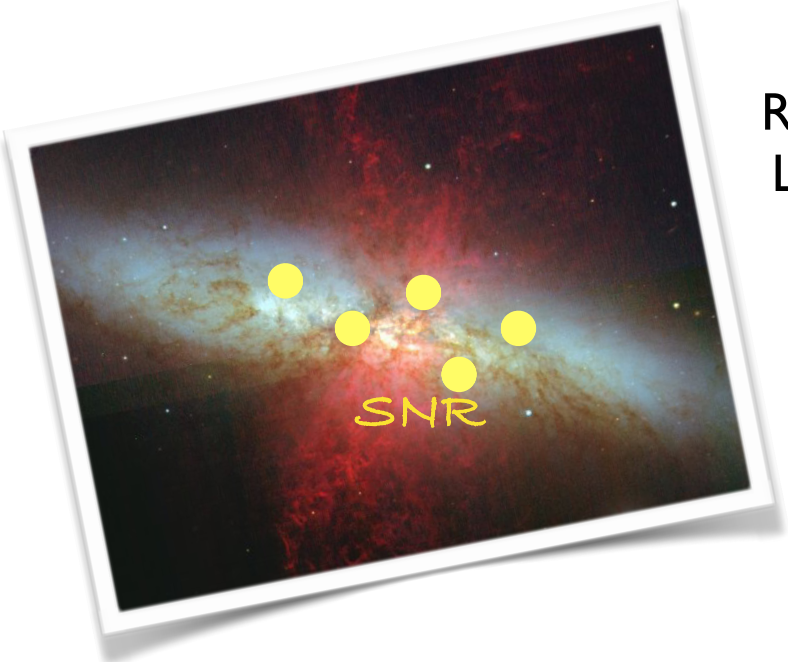
Extragalactic sources: AGNs & blazars

From galaxies to central black holes



Starburst/Superwinds/AGN winds

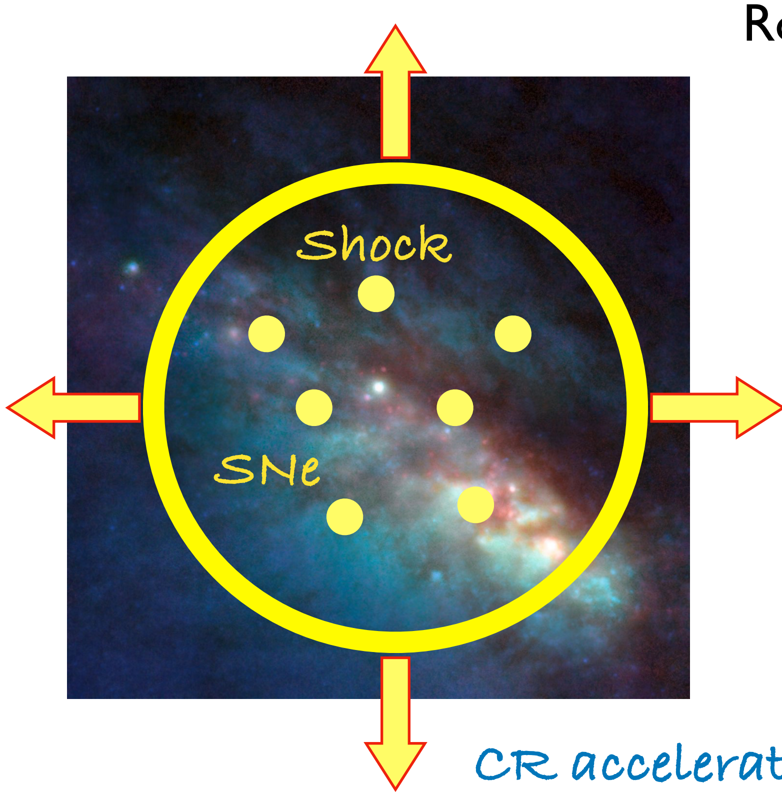
CR accelerated by SNR



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

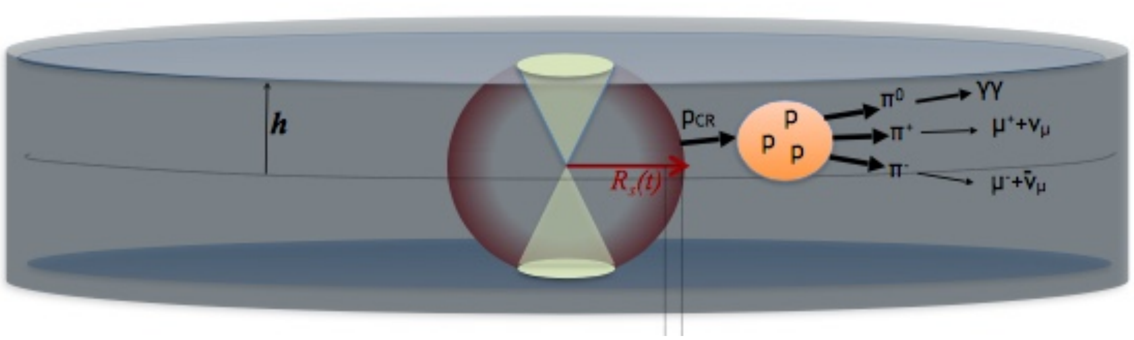
Diffusing CR accelerated in shocks
+
dense gas/dust

Anchordoqui et al. 1999
Romero et al. 2018



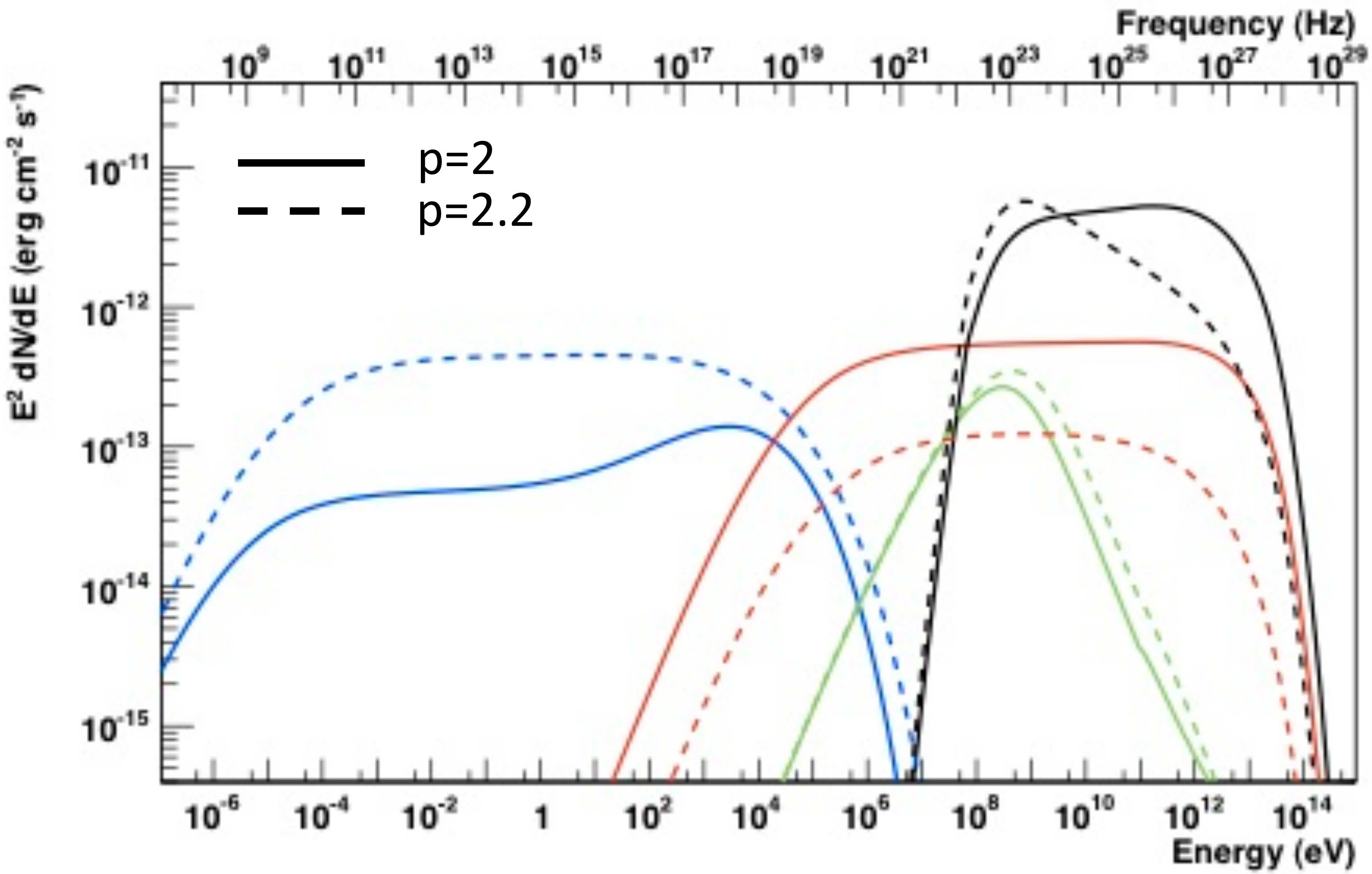
CR accelerated by galactic scale shock

CR accelerated by AGN-driven shock



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

Gamma-ray emission

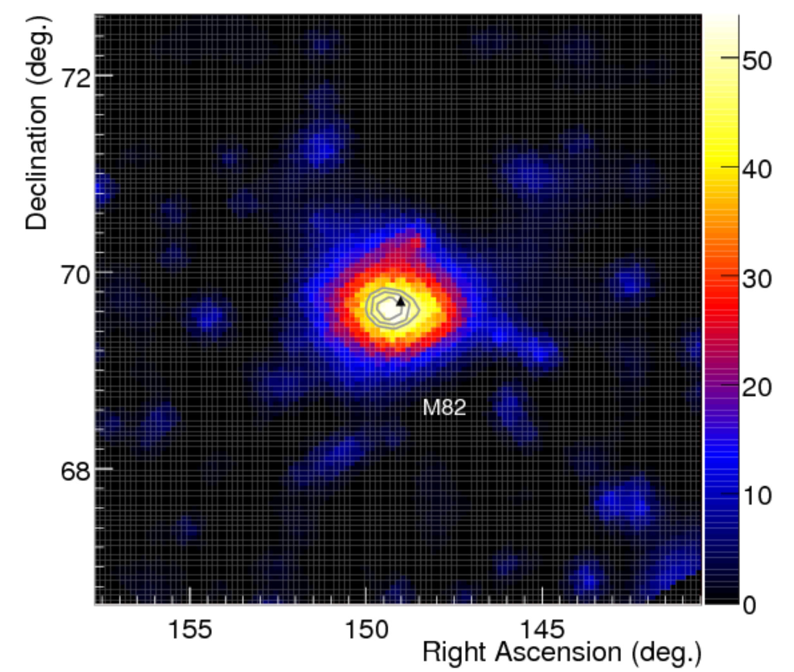


Ohm & Hinton 2012

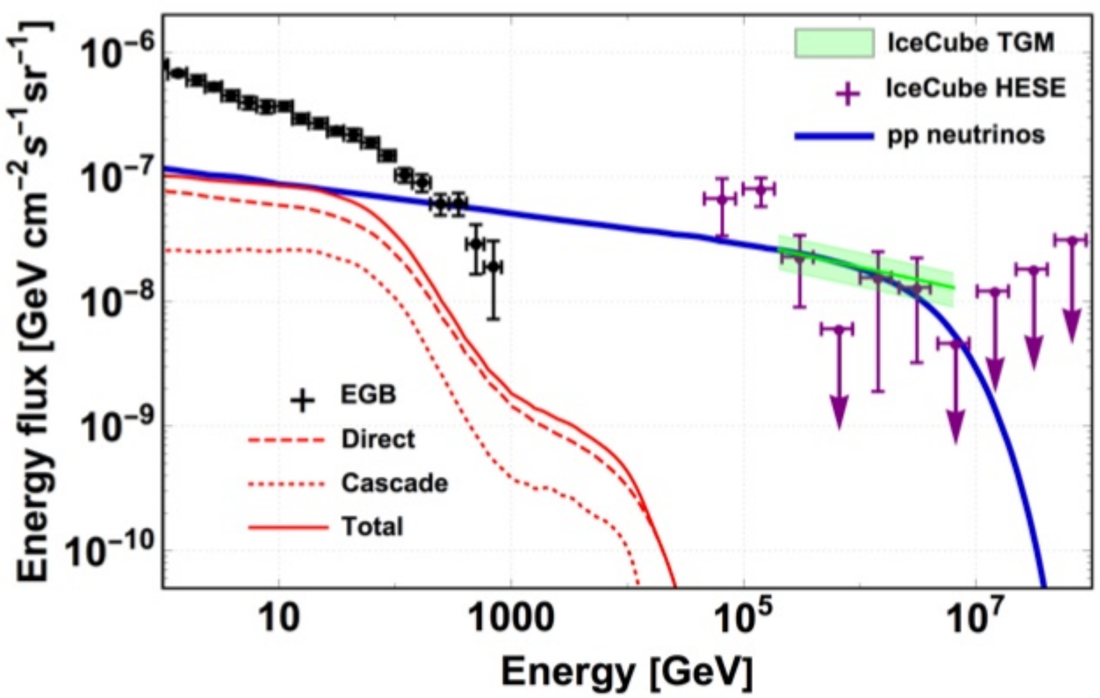
Starbursts: MM sources?

LAT coll. 2010

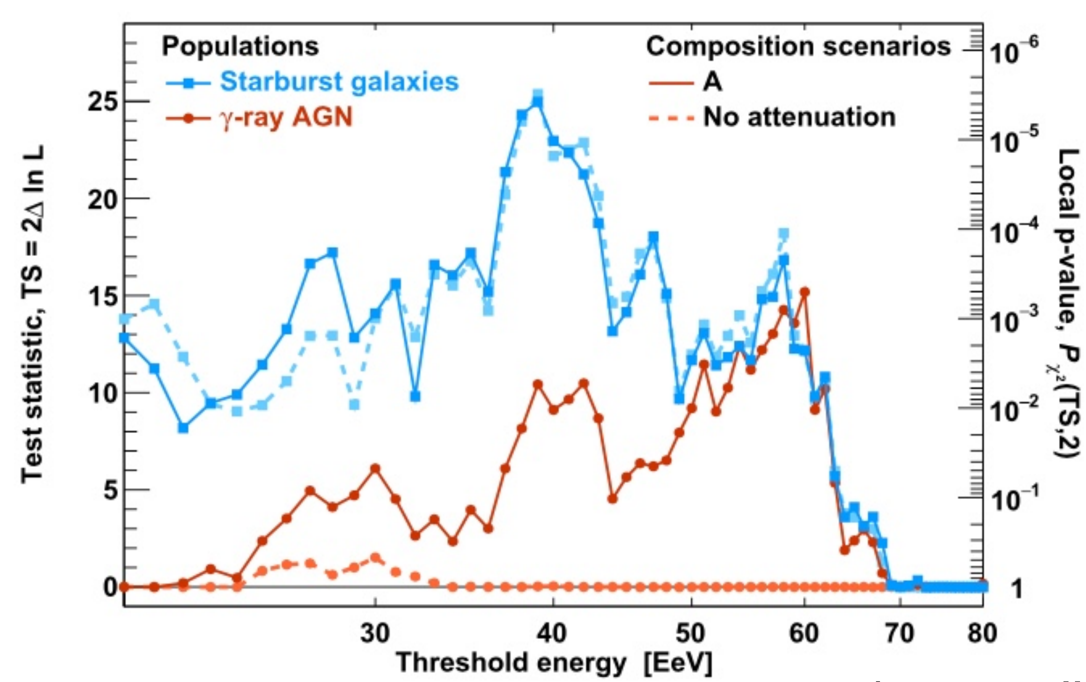
Gamma



Palladino et al. 2019



UHECR



Neutrinos

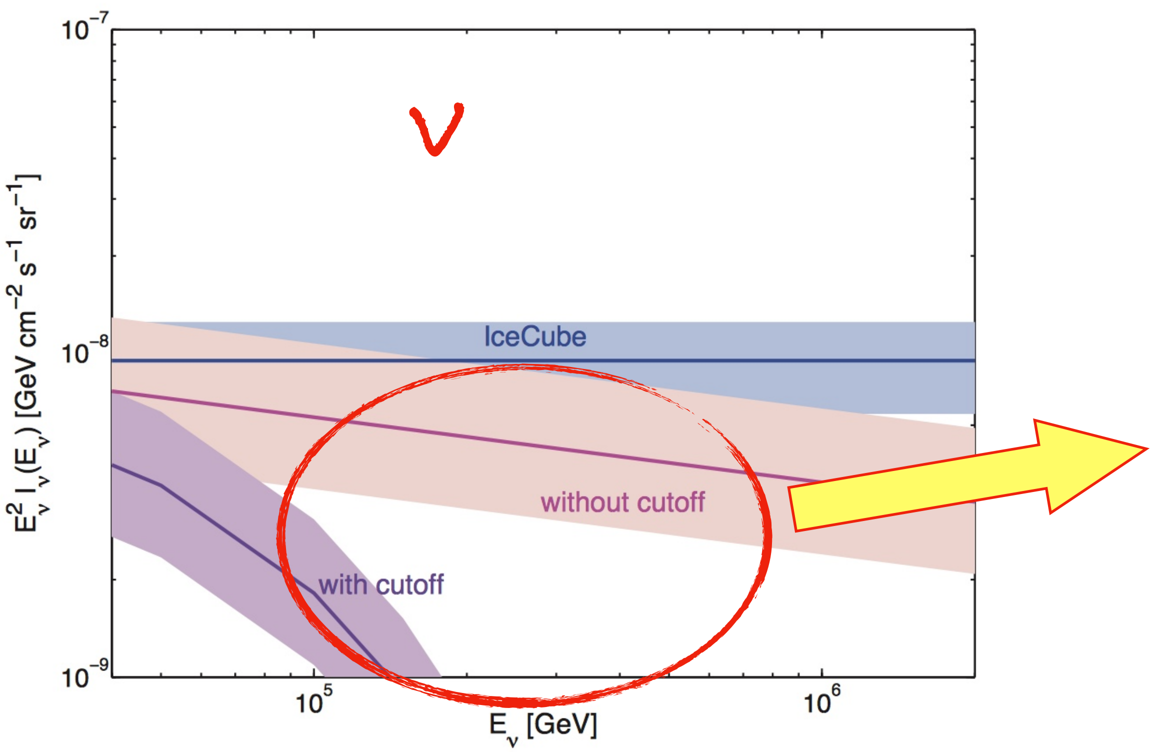
e.g. Waxman & Loeb 2006
Tamborra et al. 2014
and many others

Possible overproduction of the gamma-ray bkg?

Auger coll. 2018

Magnetic deflection not included!

Starbursts: MM sources?



Tamborra et al. 2014

$E_p > 10^{16}$ eV?

Peculiar Supernovae (e.g. Murase et al. 2013)? Probably too rare
Diffusion and confinement? See e.g. Peretti et al. 2018

Difficult to obtain a direct association (low fluxes!)

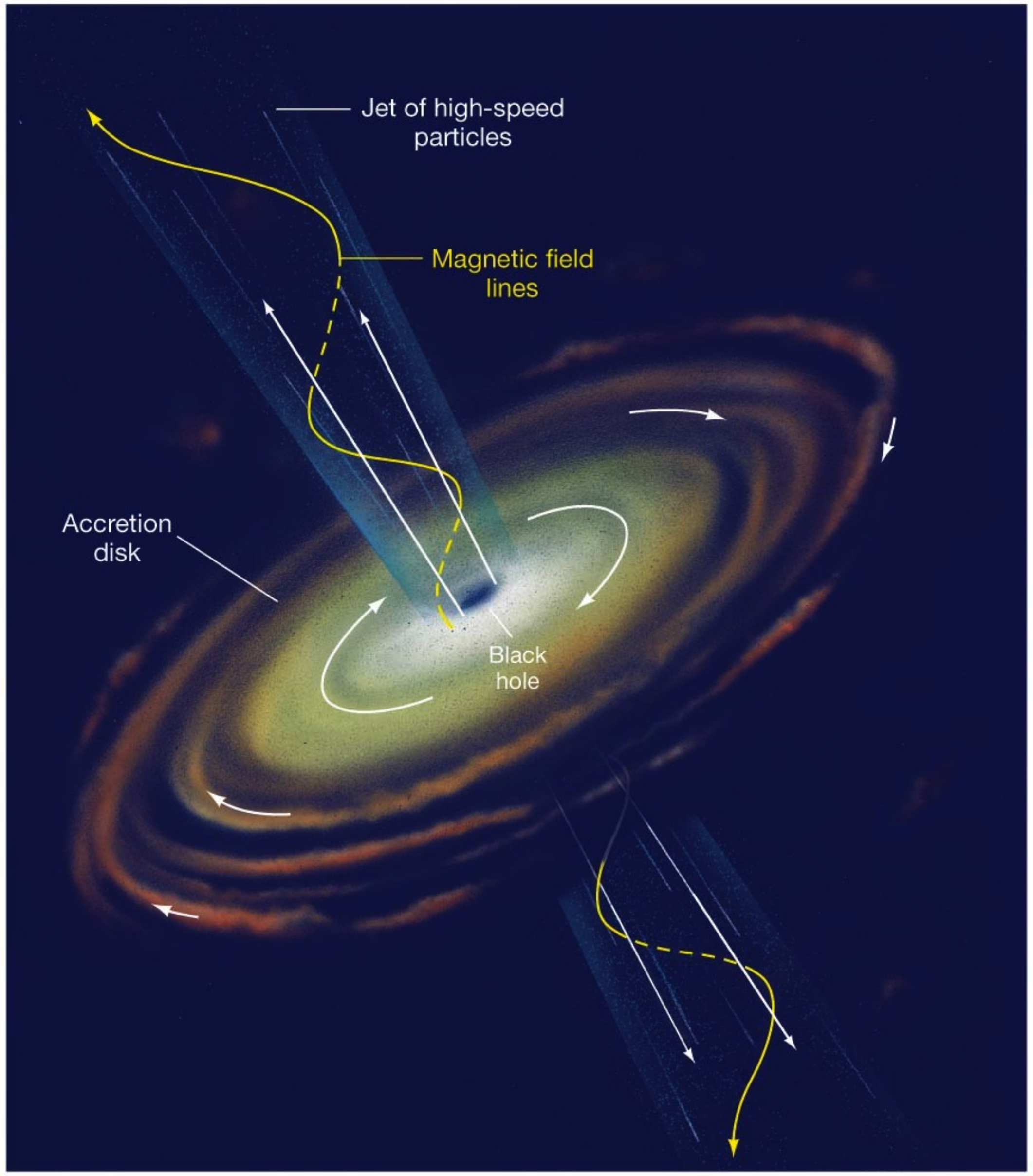
But see Lunardini et al. 2019: <10% to the total flux

Active galactic nuclei

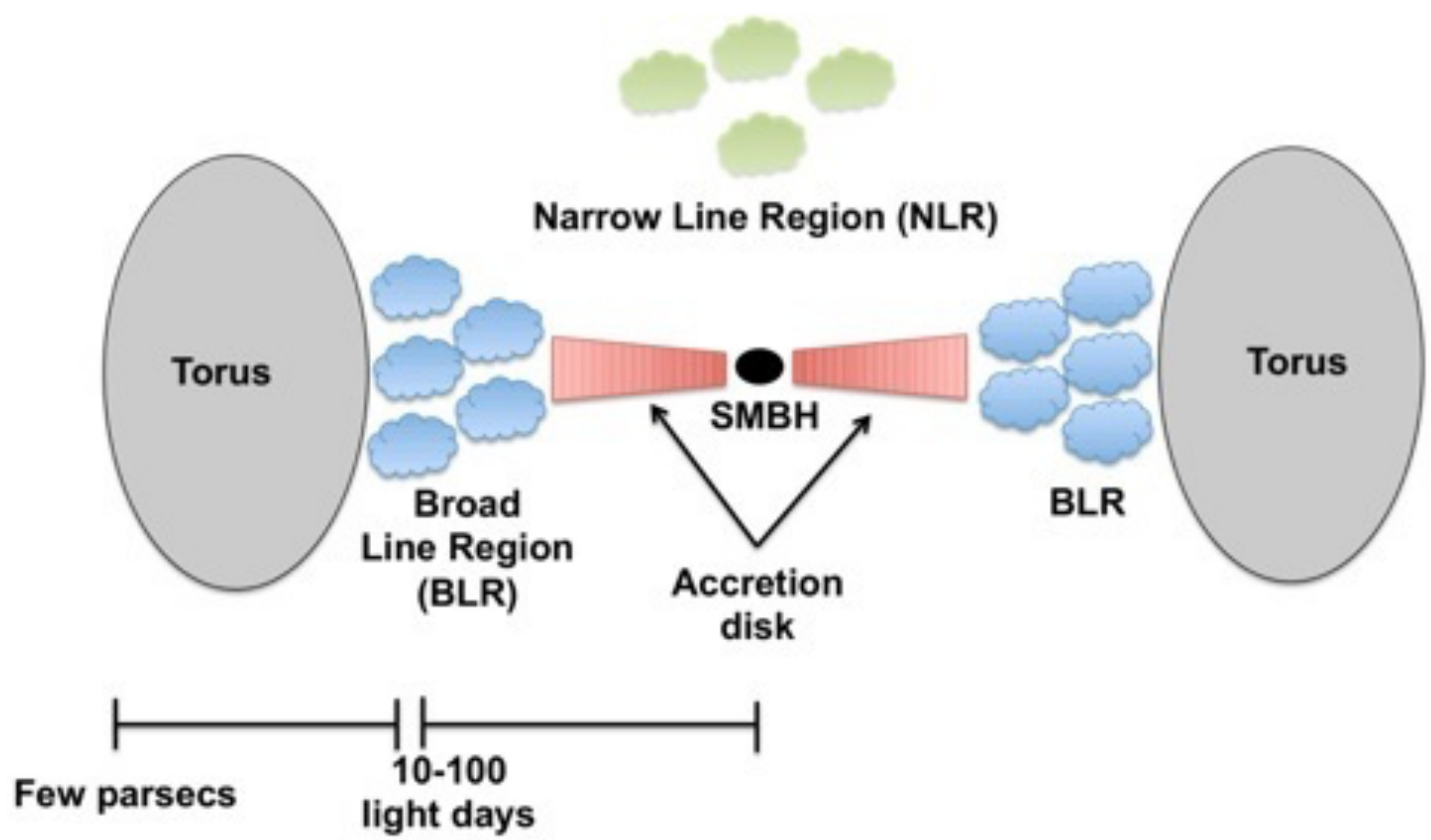
Most powerful sources in the Universe (up to 10^{48} erg/s).
Energy is generated by conversion of gravitational energy of the infalling material onto SMBH ($M_{BH}=10^6$-10^9 $M_\odot$) into radiation and outflows.

Non-jetted AGN:
- Bulk of the AGN population
- Wider angle winds with velocities from a few thousands km/s up to mildly relativistic values.
- Electromagnetic emission dominated by thermal emission in the UV-optical band produced by the accretion disk around SMBH

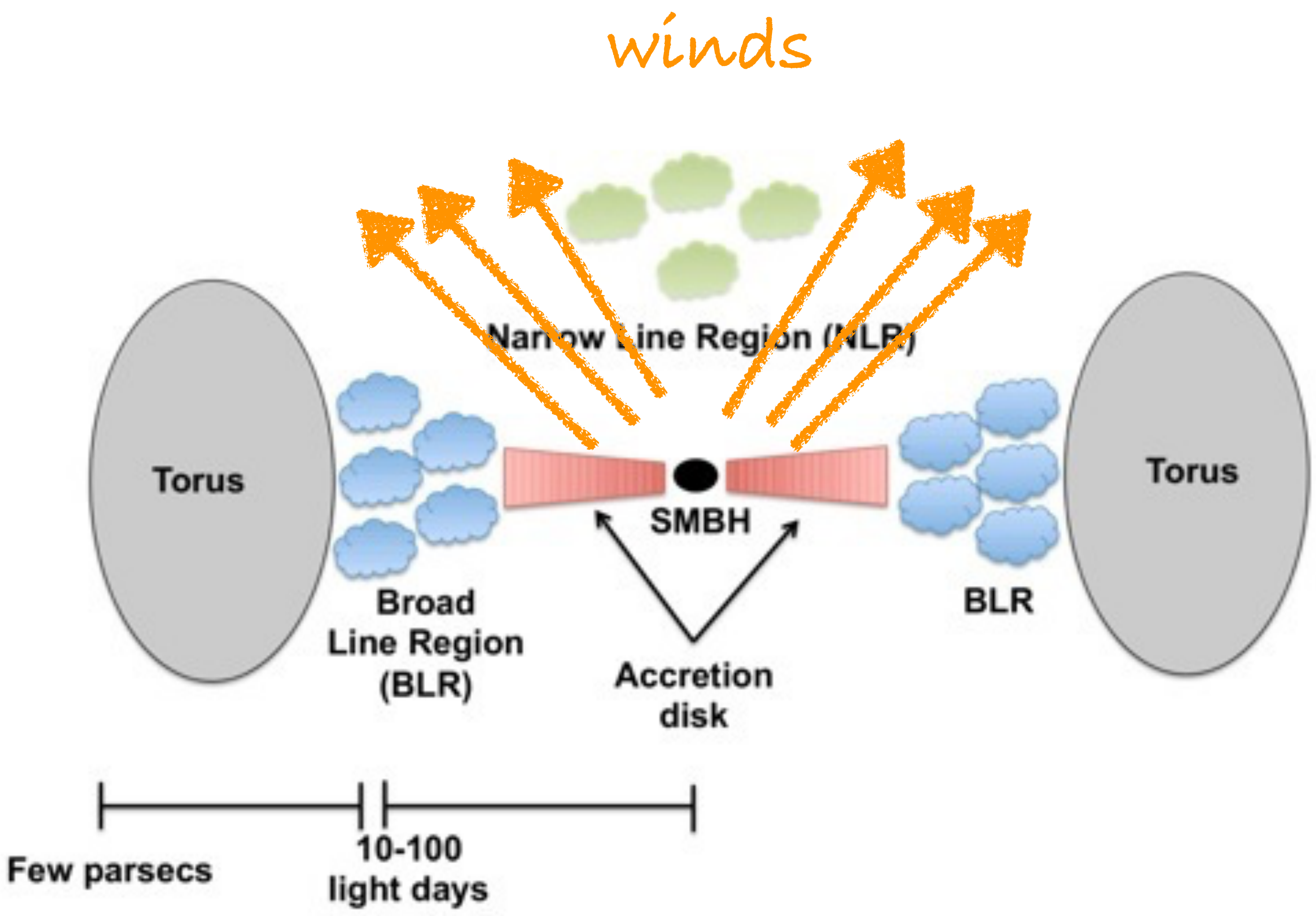
Jetted AGN:
- ~10% of the AGN population
- Highly collimated relativistic outflows
- Electromagnetic emission dominated by jet non-thermal emission in the radio and gamma-ray band



Active galactic nuclei

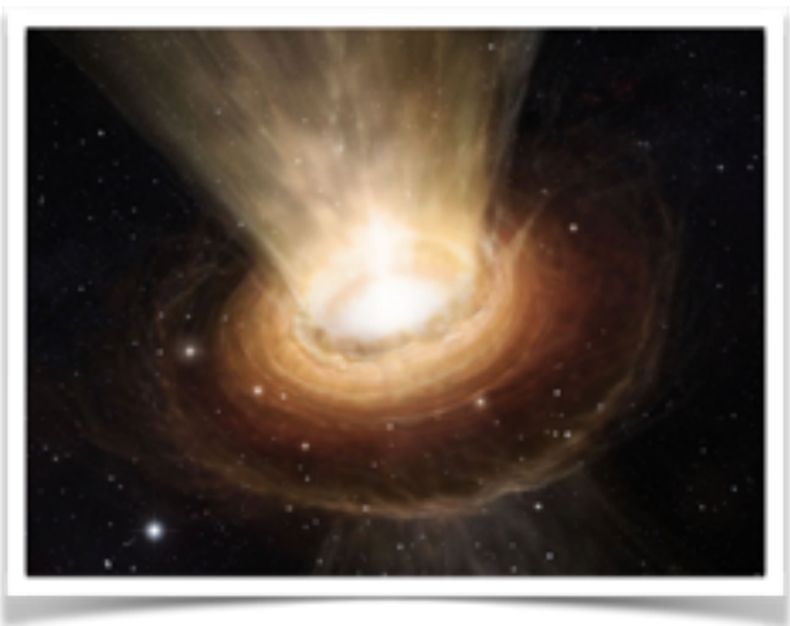


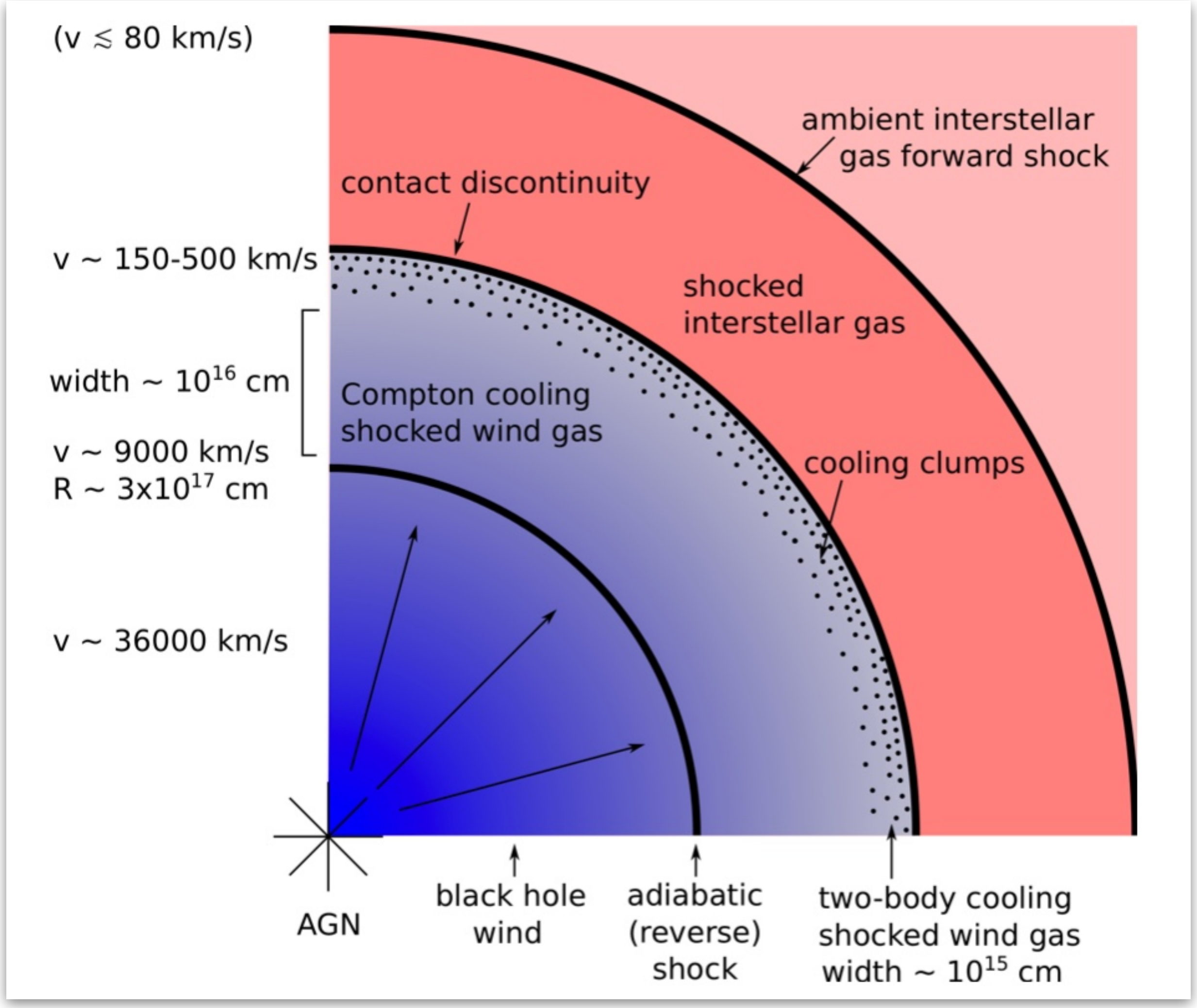
Active galactic nuclei



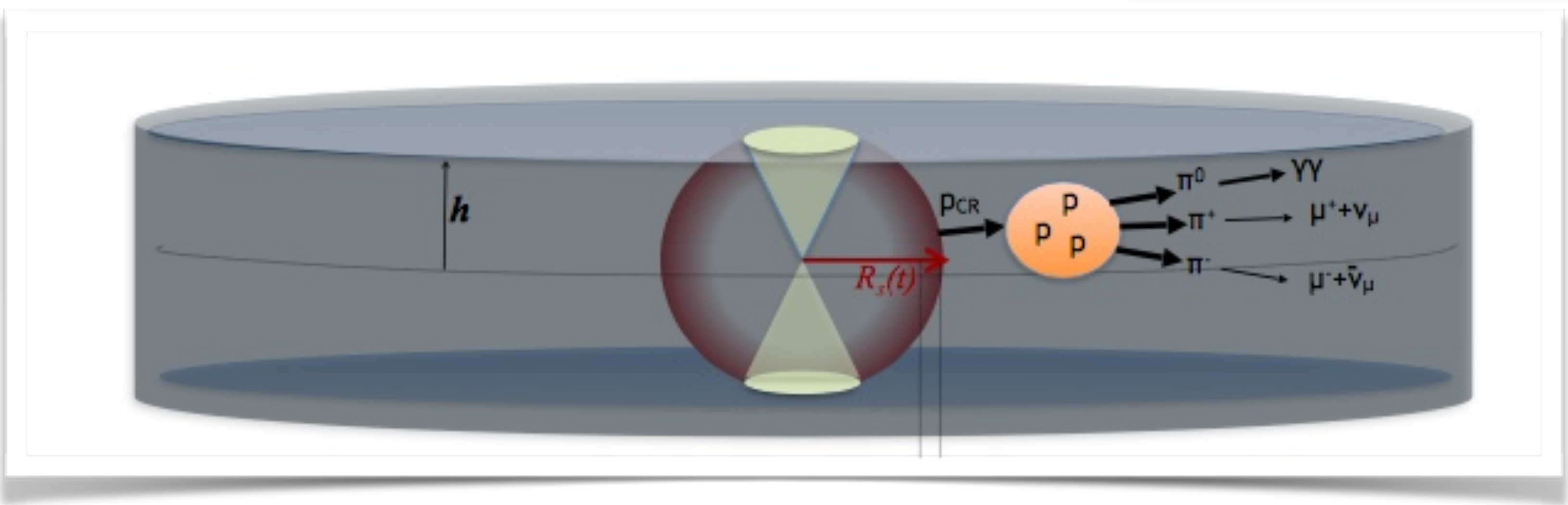
AGN-driven shocks

Widespread evidence for
outflows at different scales



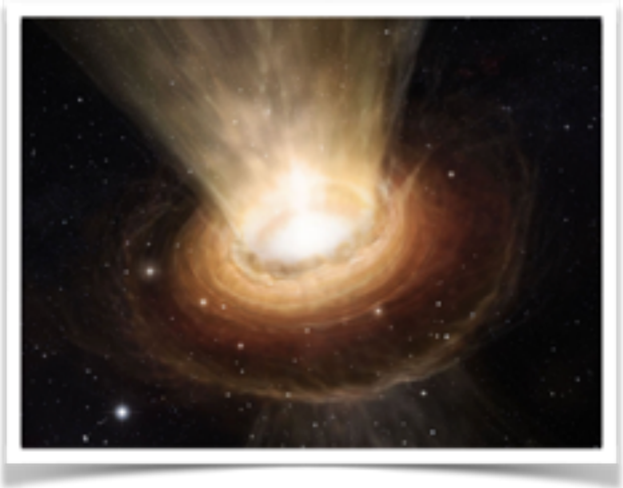


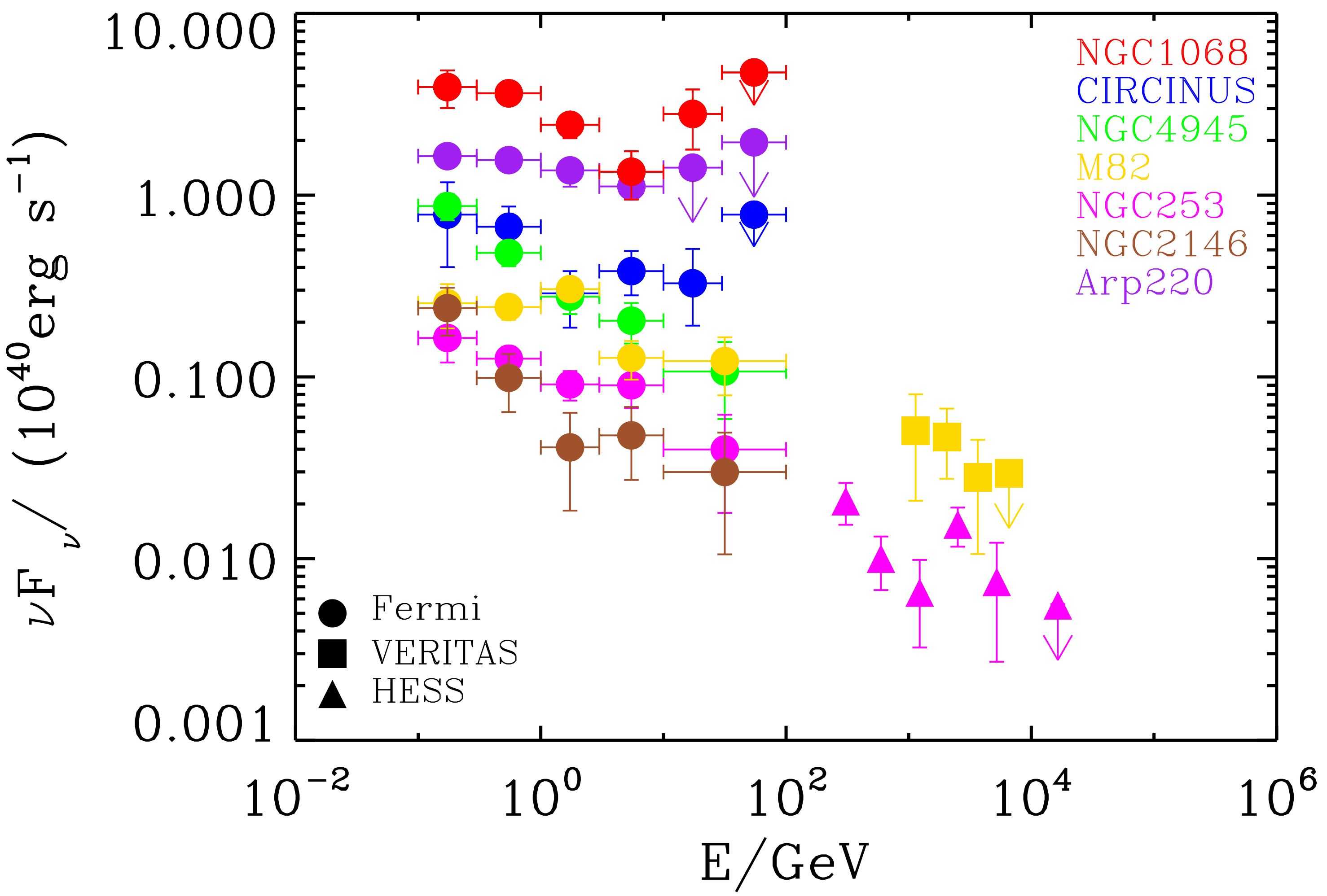
King & Pounds 2015



Lamastra et al. 2016, 2017

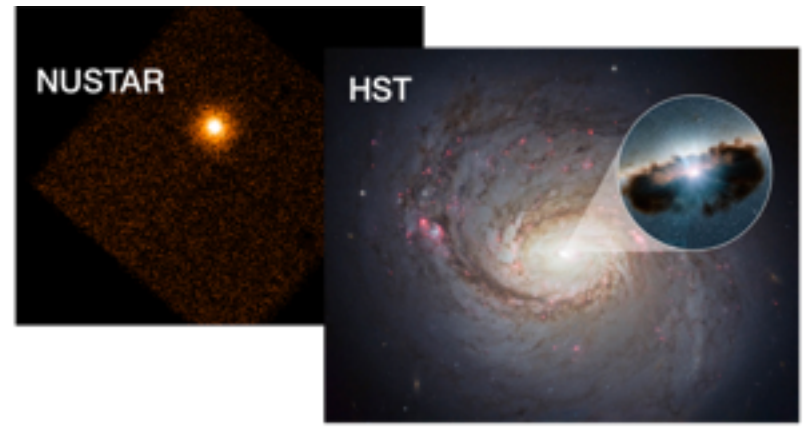
Sturbursts and AGNs



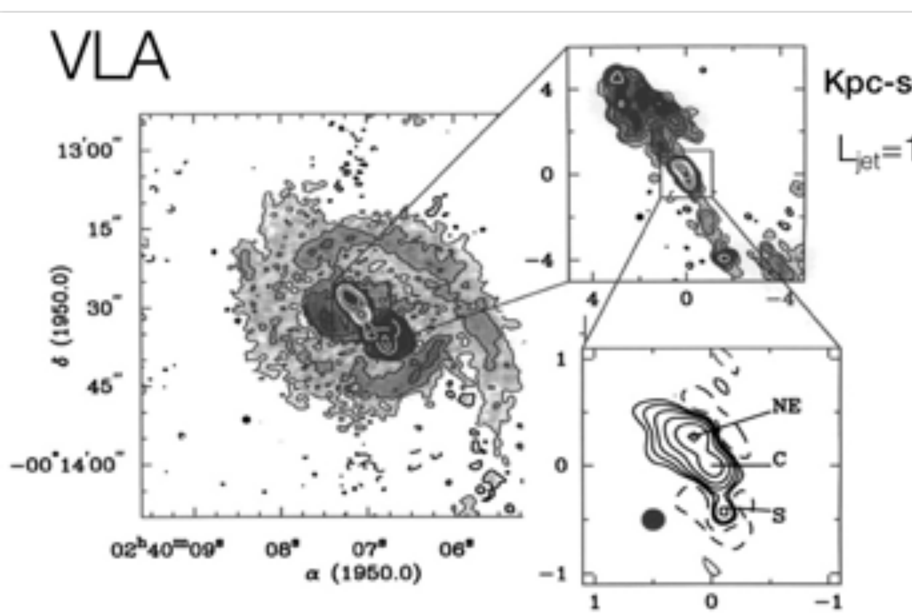


Akermann et al. 2012

NGC 1068



- distance D=14.4 Mpc
- composite starburst/AGN galaxy ($M_{BH} \approx 10^7 M_\odot$)
- Luminous infrared galaxy $L_{IR}=2.8 \times 10^{11} L_\odot$
- High luminosity ($L_{AGN}=10^{44}-10^{45}$ erg/s) high obscured ($N_H > 10^{24}$ cm^{-2}) AGN



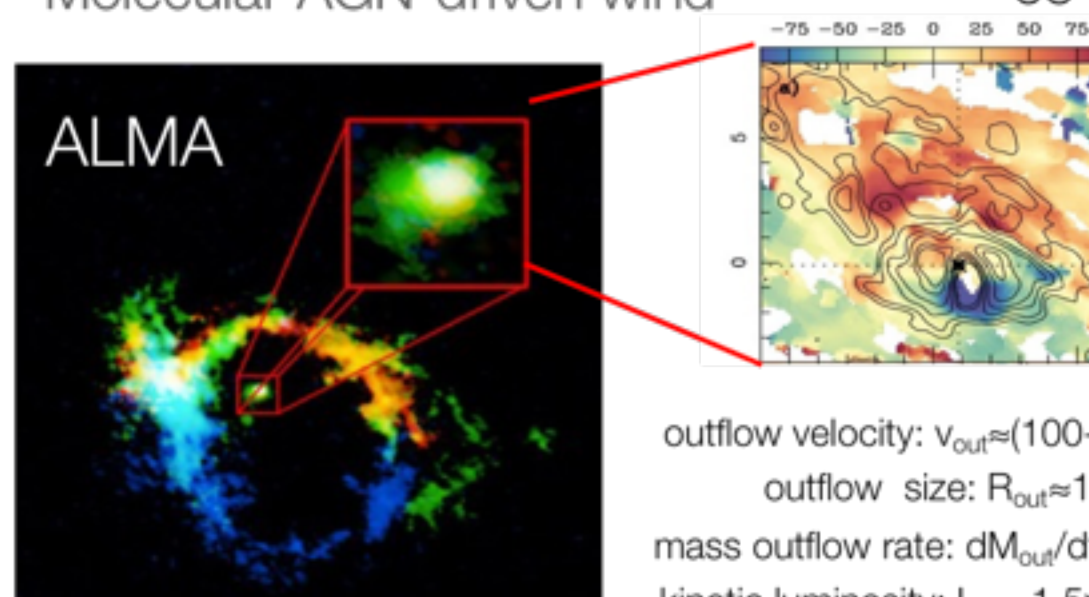
Kpc-scale radio jet

$L_{jet}=10^{43}$ erg/s

100 pc-scale radio jet

- Molecular AGN-driven wind

CO velocity map

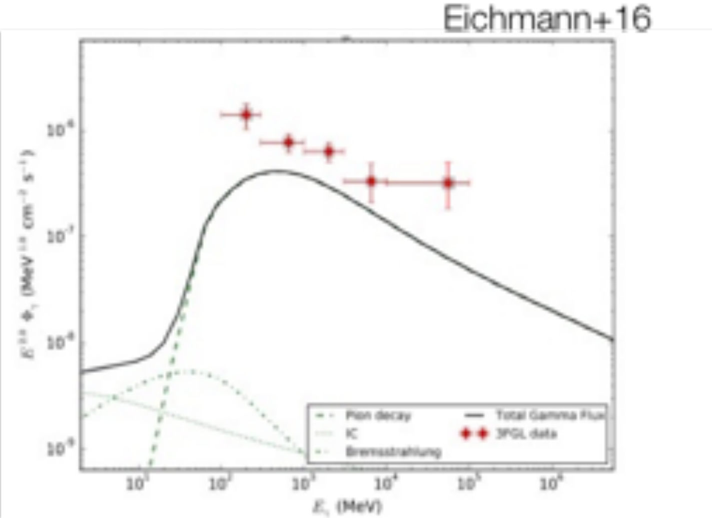


outflow velocity: $v_{out} \approx (100-200)$ km/s
outflow size: $R_{out} \approx 100$ pc
mass outflow rate: $dM_{out}/dt \approx 10^8 M_\odot$/yr
kinetic luminosity: $L_{kin} \approx 1.5 \times 10^{42}$ erg/s

Models for NGC 1068

Starburst model

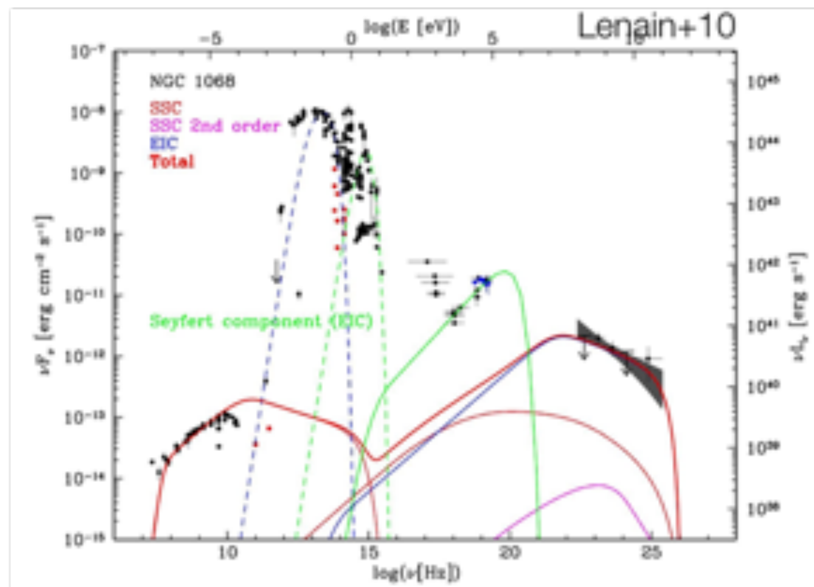
Eichmann+16



Physical parameters	NGC 1068
q_0^e [10^{-18} cm^{-3} s^{-1}]	32
q_0^p [10^{-20} cm^{-3} s^{-1}]	20
α	2.35 ± 0.025
γ_B	$10^{4 \pm 0.3}$
B [μG]	1000 ± 109
N_r [cm^{-3}]	139^{+19}_{-13}
v_{adv} [10^7 cm s^{-1}]	1 ± 1.3
l_c [10^{16} cm]	0.1 ± 0.25

AGN jet model

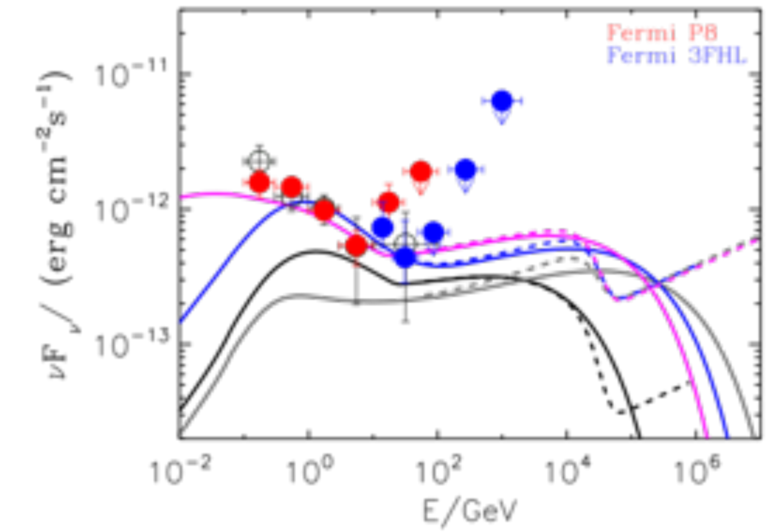
Lenain+10



Source	Component[a]	δ_b	B (G)	r_b (cm)	T (K)	τL_{nuc} (erg s^{-1})	R (cm)	K (cm^{-3})	n_1	n_2	γ_{break}	γ_{max}
NGC 1068	1	1.2	10^{-4}	2.0×10^{19}	130–520	1.5×10^{42}	2.2×10^{20}	12.5	2.2	3.3	10^4	10^6

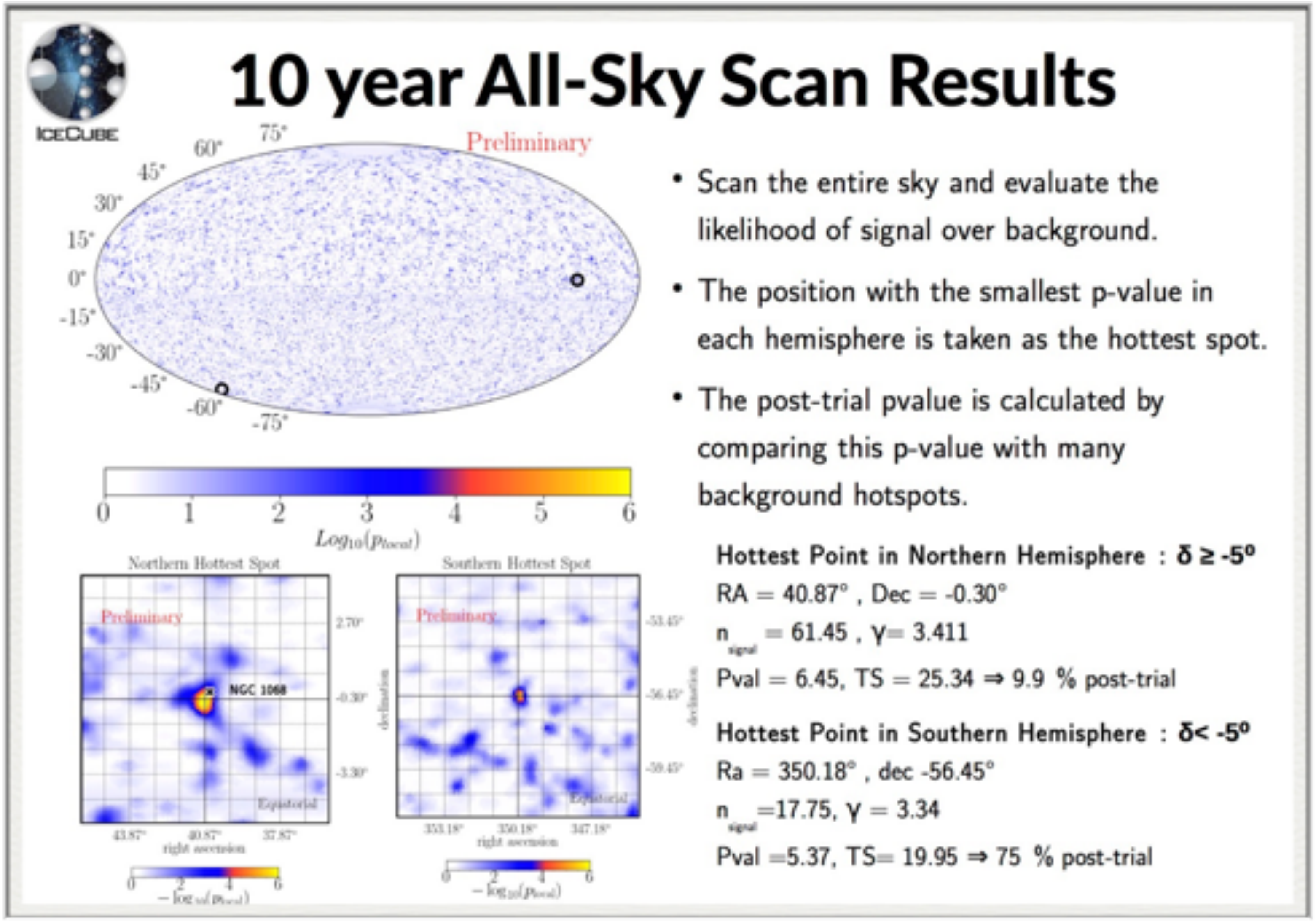
AGN wind model

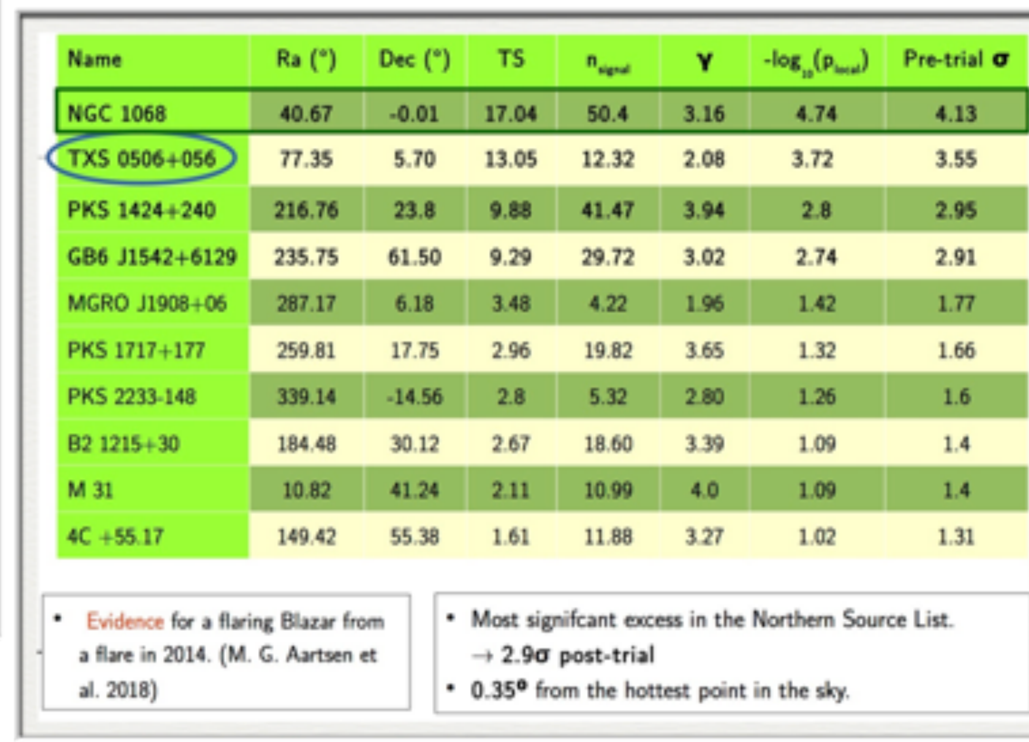
Lamastra+16,+19



Model	L_{kin}/L_{AGN}	n_H (cm^{-3})	F_{cal}	B (G)	η_p	η_e
W1	3×10^{-3}	10^4	1	3×10^{-5}	0.2	0.02
W2	3×10^{-3}	10^4	1	2×10^{-3}	0.2	0.02
W3	7×10^{-4}	120	0.5	25×10^{-5}	0.5	0.4
W4	3×10^{-3}	10^4	1	60×10^{-5}	0.3	0.1

Neutrinos from NGC 1068?





Name	Ra (°)	Dec (°)	TS	n_{signal}	γ	$-\log_{10}(p_{local})$	Pre-trial σ
NGC 1068	40.67	-0.01	17.04	50.4	3.16	4.74	4.13
TXS 0506+056	77.35	5.70	13.05	12.32	2.08	3.72	3.55
PKS 1424+240	216.76	23.8	9.88	41.47	3.94	2.8	2.95
GB6 J1542+6129	235.75	61.50	9.29	29.72	3.02	2.74	2.91
MGRO J1908+06	287.17	6.18	3.48	4.22	1.96	1.42	1.77
PKS 1717+177	259.81	17.75	2.96	19.82	3.65	1.32	1.66
PKS 2233-148	339.14	-14.56	2.8	5.32	2.80	1.26	1.6
B2 1215+30	184.48	30.12	2.67	18.60	3.39	1.09	1.4
M 31	10.82	41.24	2.11	10.99	4.0	1.09	1.4
4C +55.17	149.42	55.38	1.61	11.88	3.27	1.02	1.31

- Evidence for a flaring Blazar from a flare in 2014. (M. G. Aartsen et al. 2018)

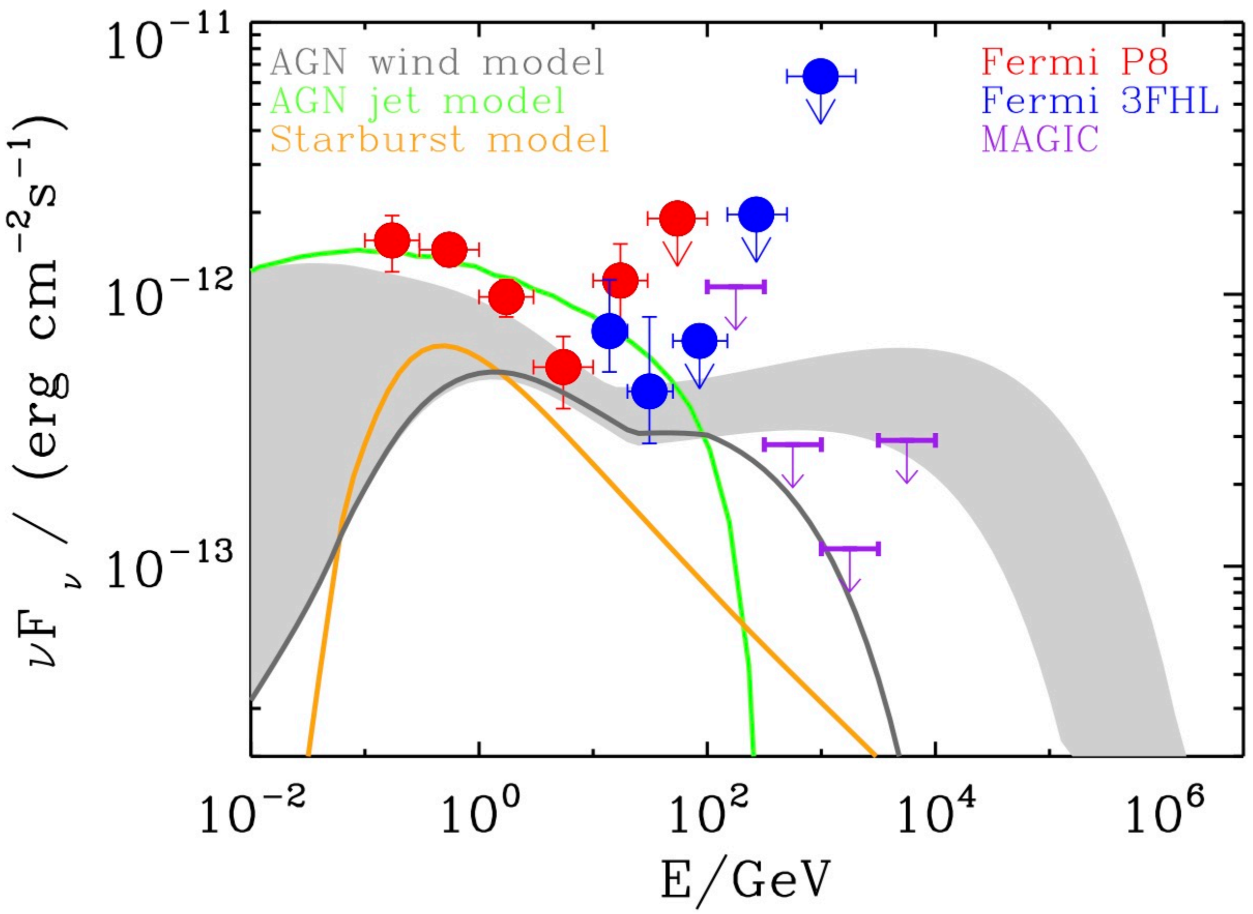
- Most signifcant excess in the Northern Source List.
  → 2.9σ post-trial
- 0.35° from the hottest point in the sky.

Credits:
Tessa Carver (Workshop on Neutrino Telescopes)
Francis Halzen (CTA 1st Science Symposium)

Constraints from gamma rays

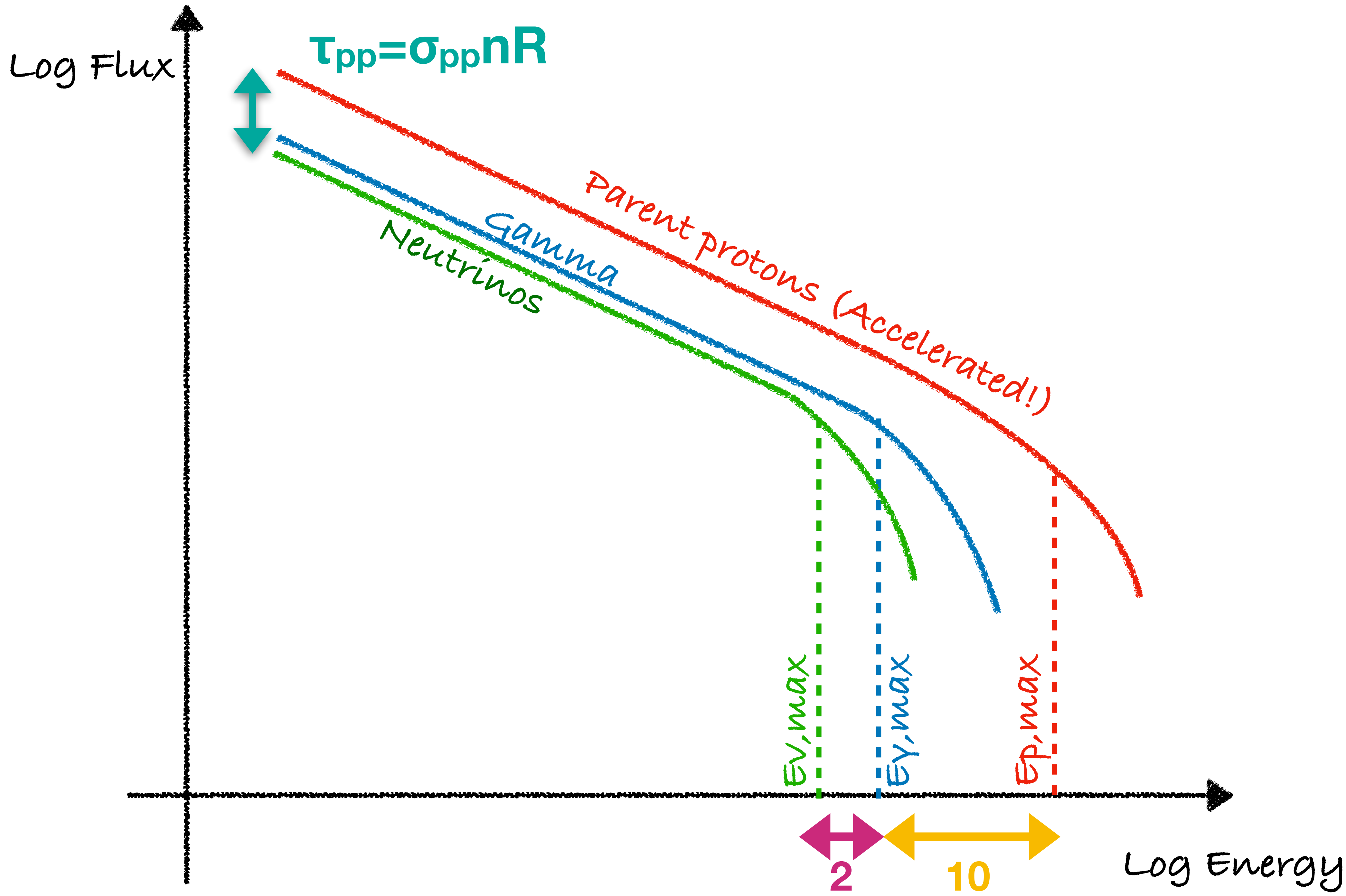
- The MAGIC telescopes observed NGC 1068 from January 2016 to January 2019 for a total of 125 hours

- Constraints on the hadron-nuclear emission of the models (both AGN-wind and SB) (no contraints on leptonic jet model)

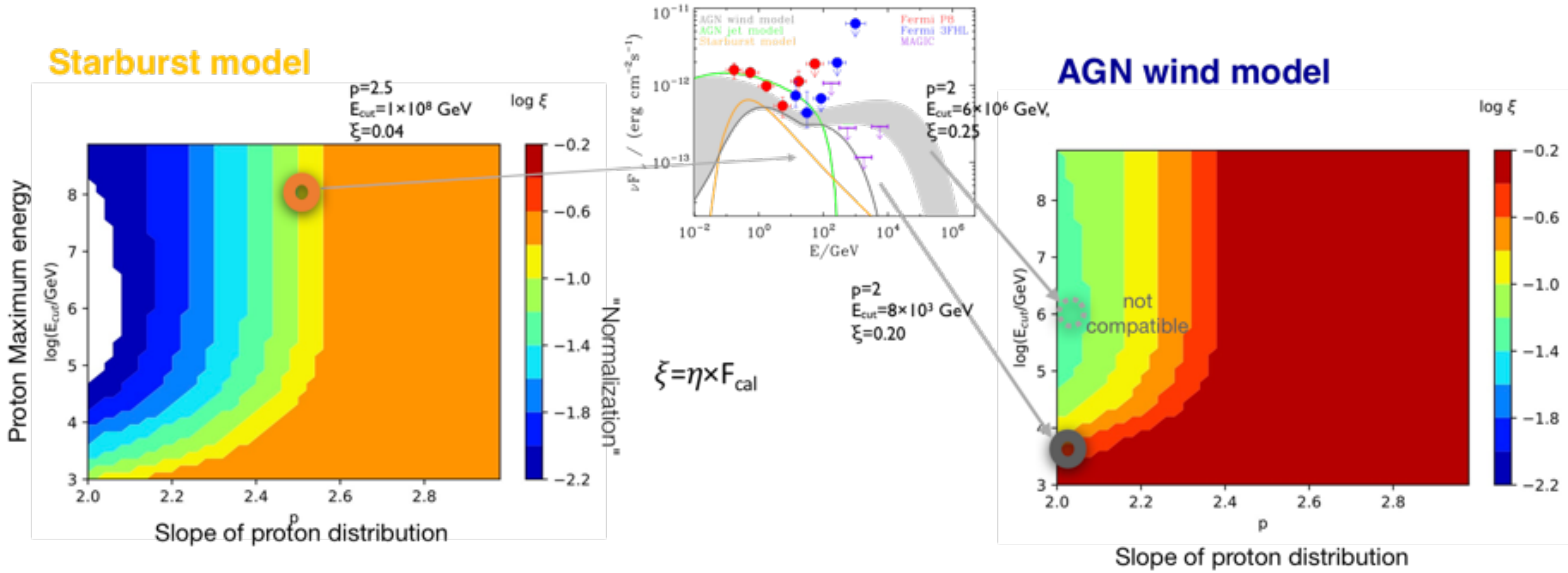


MAGIC Coll. 2019

Gamma rays and neutrinos



Constraints from gamma rays



Diffusive shock acceleration

$$N_p(E) = A_p E^{-p} \exp\left[-\left(\frac{E}{E_{max,p}}\right)\right]$$

$$\epsilon_p^{max} \approx (3/20)(V_w/c)eB_wR \simeq 21\ \mathrm{PeV}\ \epsilon_{B,-2}^{1/2} L_{w,44}^{1/2} (V_w/1000\ \mathrm{km\ s^{-1}})^{1/2}$$

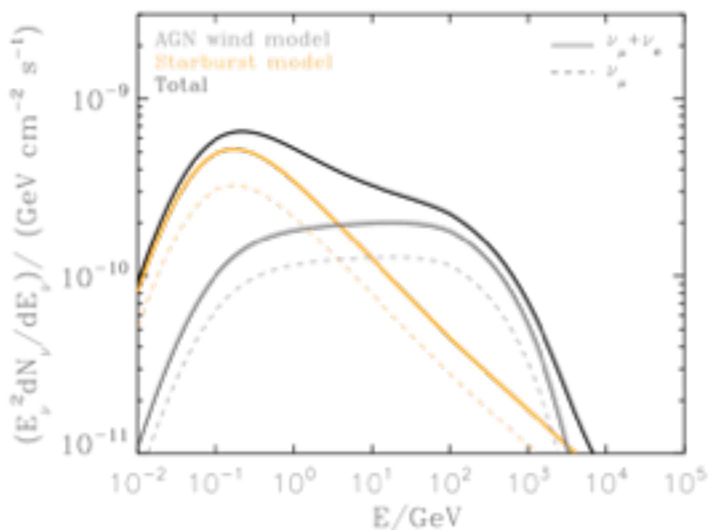
$\xi = \eta \times F_{cal}$

- η: acceleration efficiency
- F_{cal}: calorimetric fraction

Typically:
$\eta = (0.1\text{-}0.3)$
Fcal $= 0.3\text{-}0.6$

Constraints from gamma rays

Emitted ν spectrum



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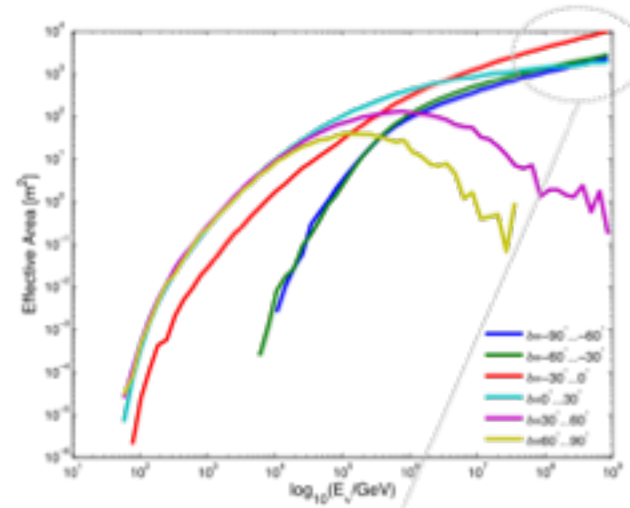
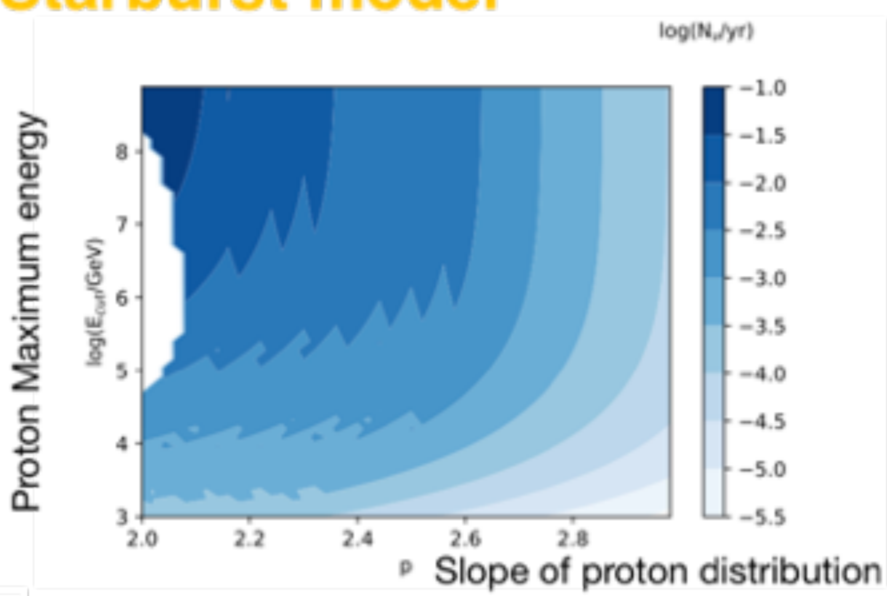


IceCube Eff. Area

Starburst model



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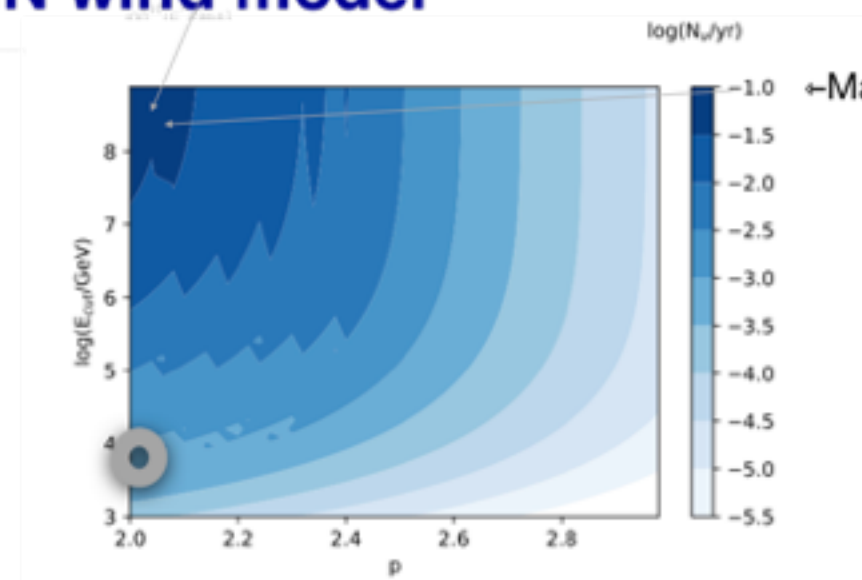
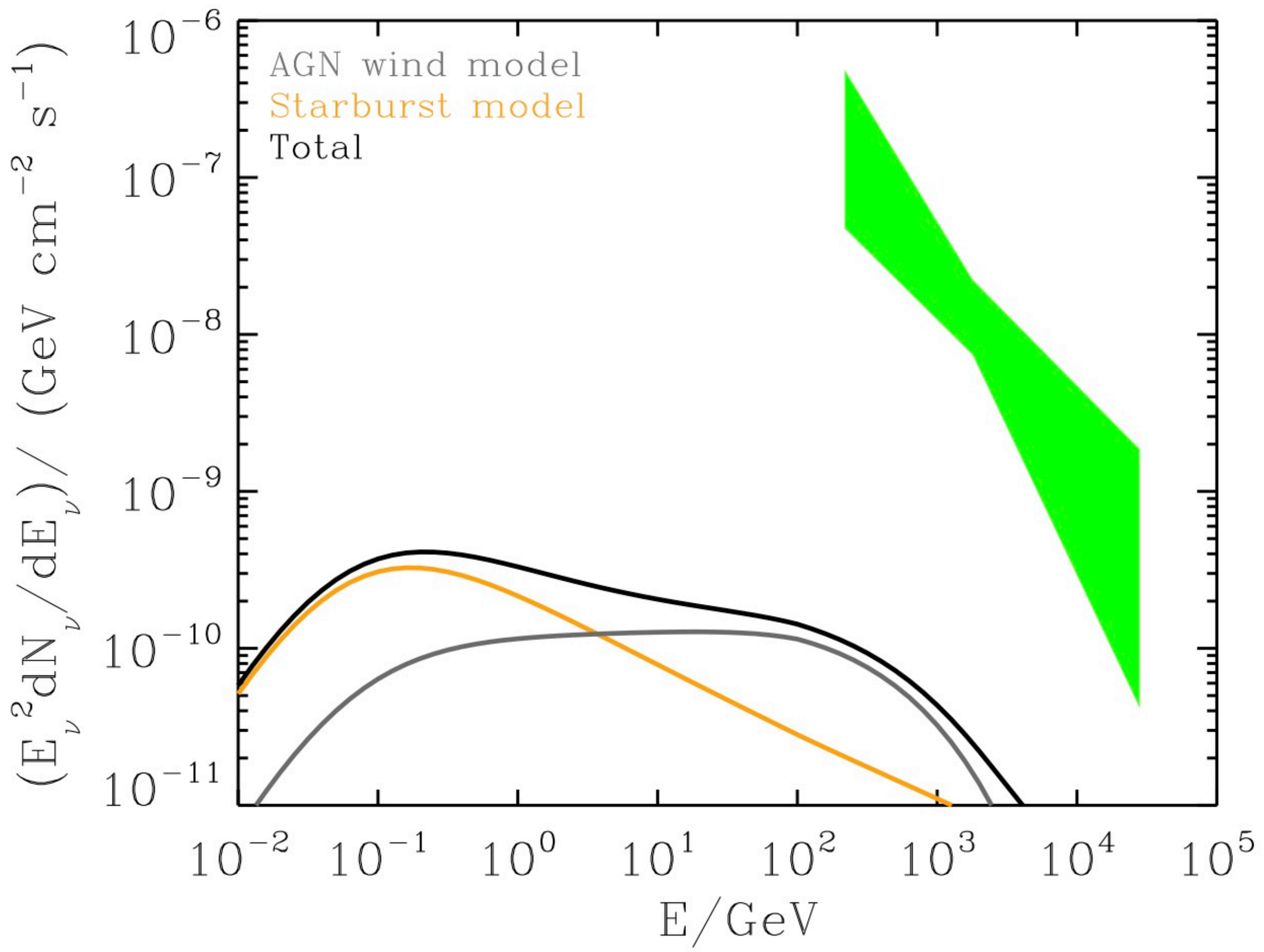
Expected ν-rate

AGN wind model

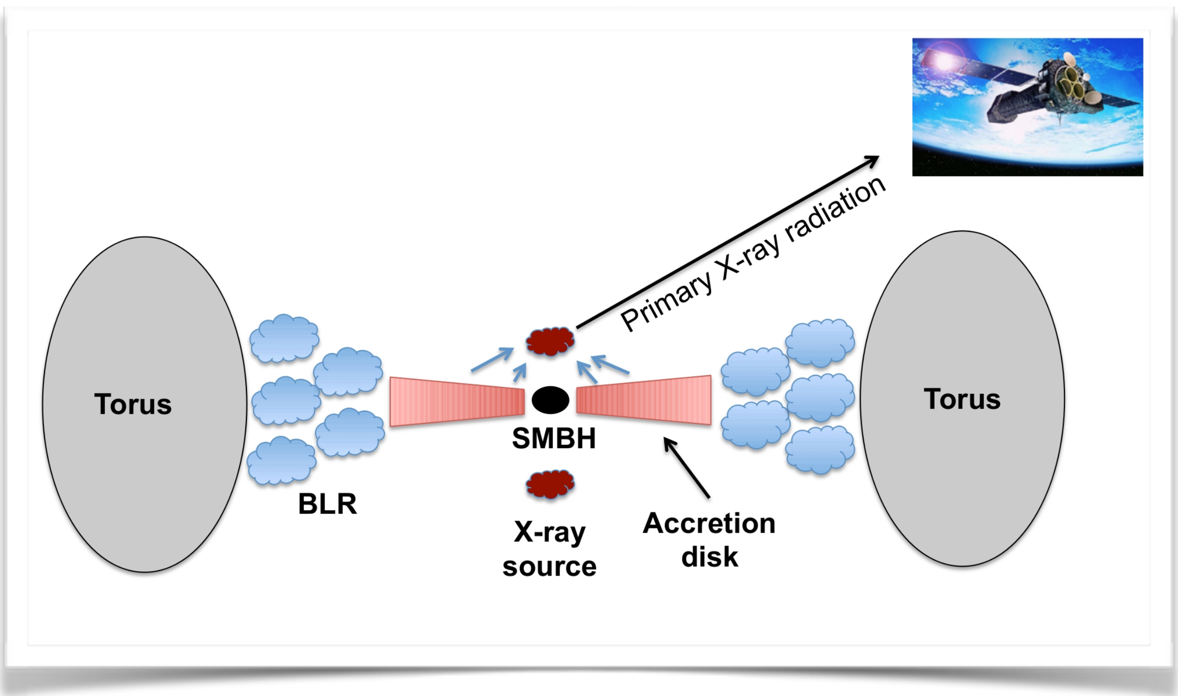


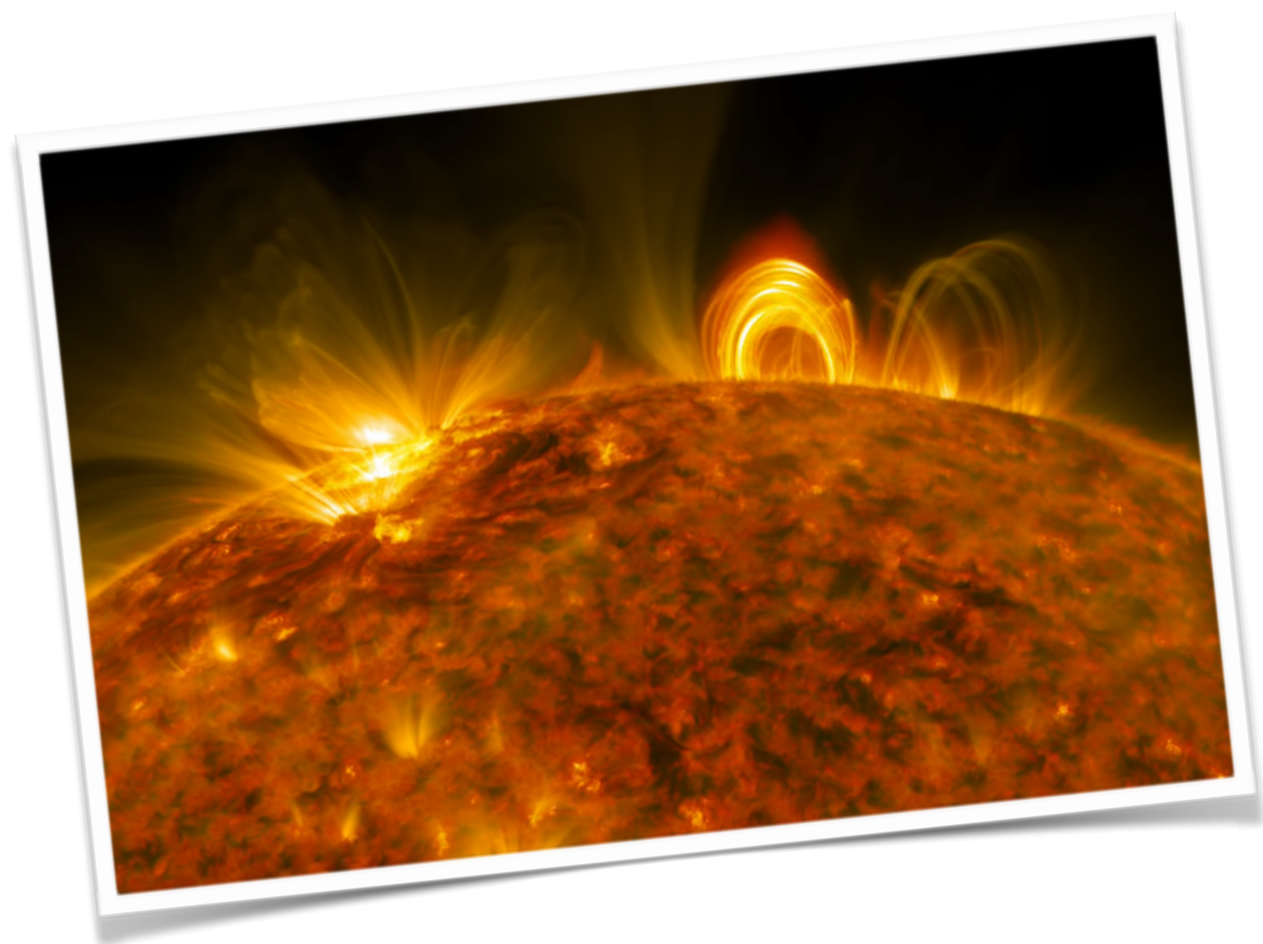
Constraints from gamma rays

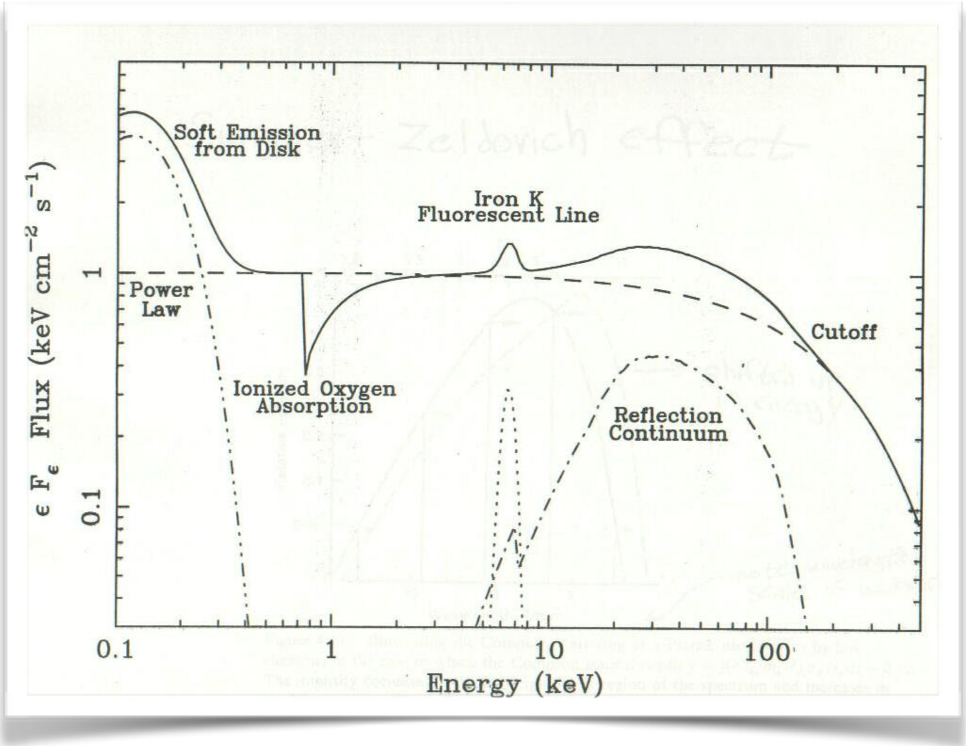


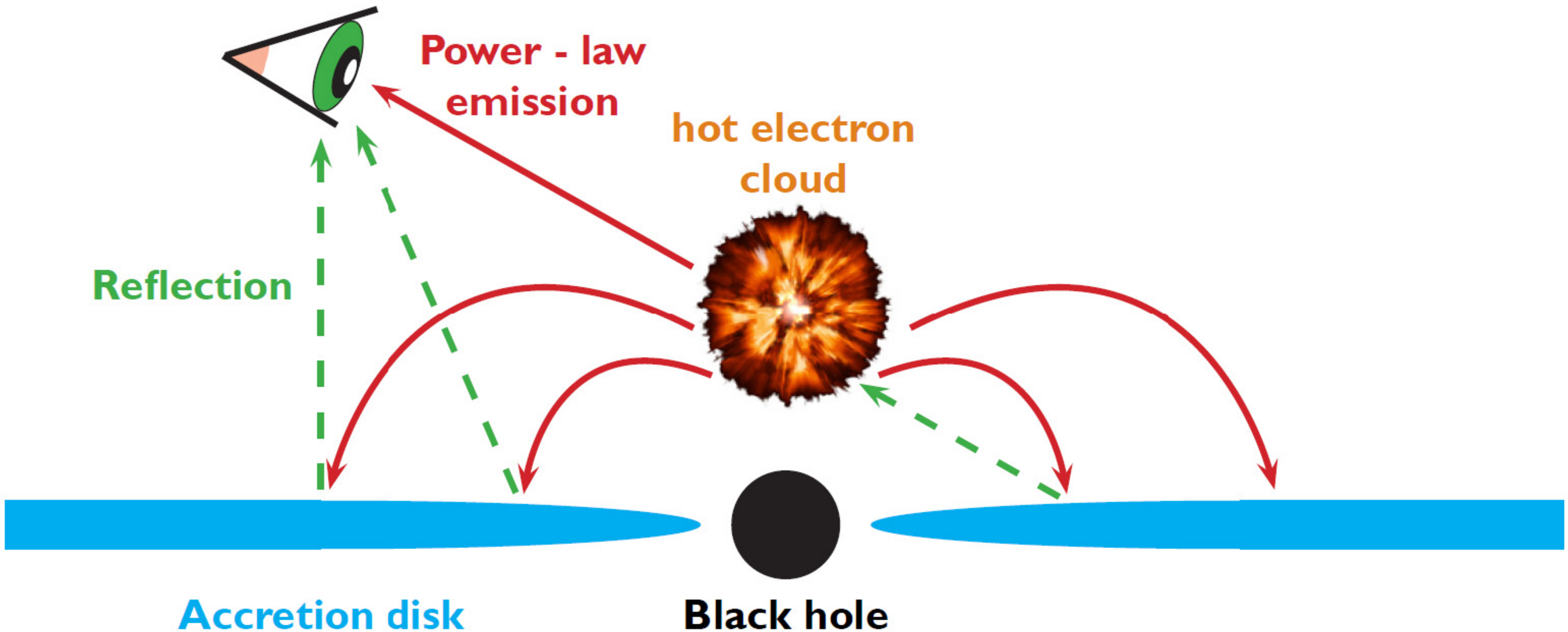
MAGIC Coll. 2019

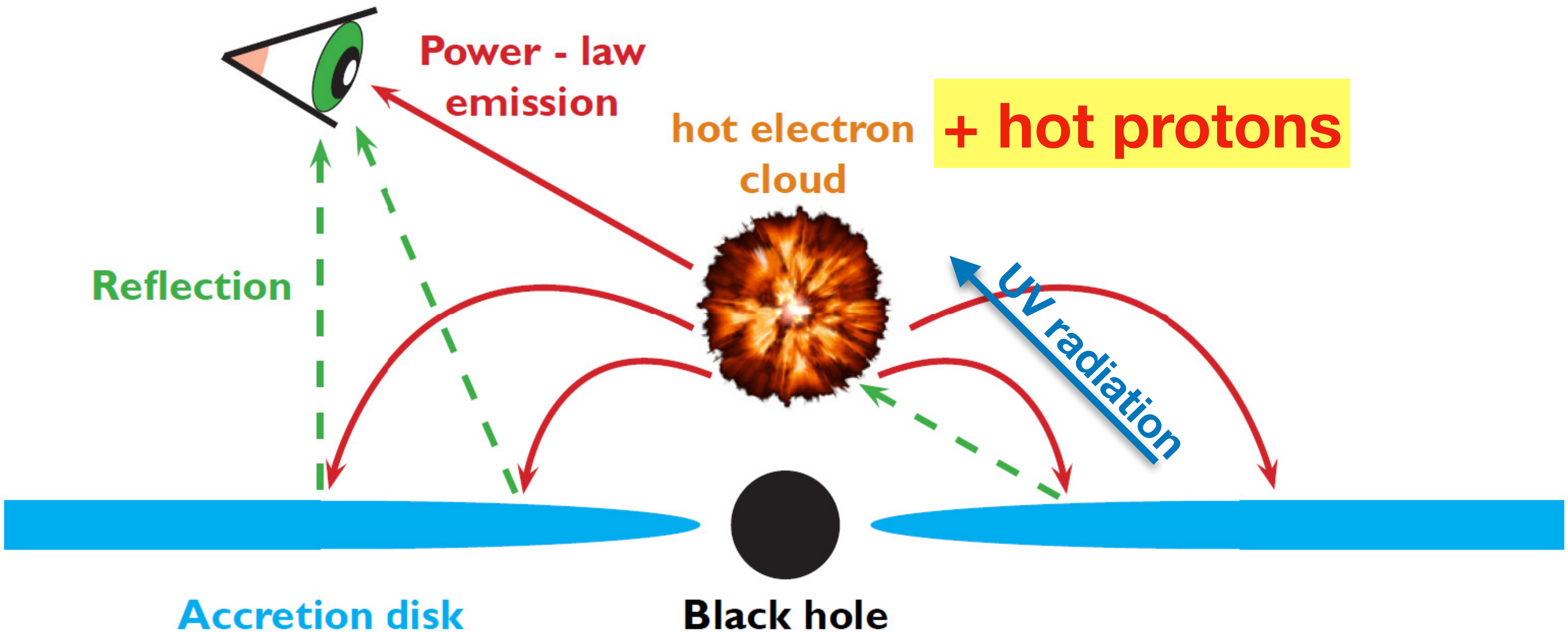
Emission from the nucleus?





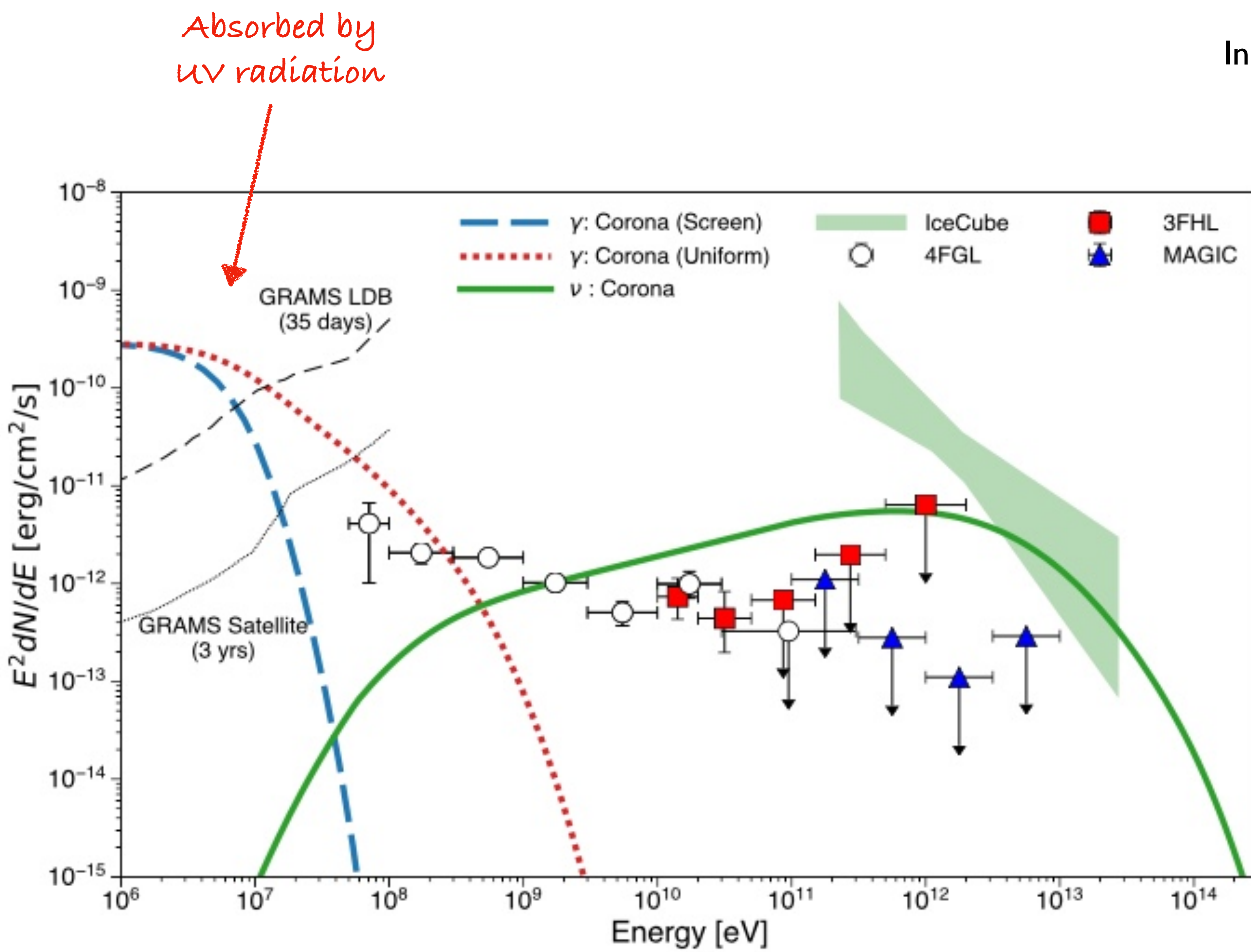

Soft Emission from Disk
Iron K Fluorescent Line
Power Law
Cutoff
Ionized Oxygen Absorption
Reflection Continuum
ϵF_ϵ Flux (keV cm^{-2} s^{-1})
Energy (keV)
0.1
1
10
100


Power - law emission
hot electron cloud
Reflection
Accretion disk
Black hole


Power - law
emission
hot electron
cloud
+ hot protons
Reflection
UV radiation
Accretion disk
Black hole

Emission from the nucleus?

Inoue et al. 2019



Active galactic nuclei

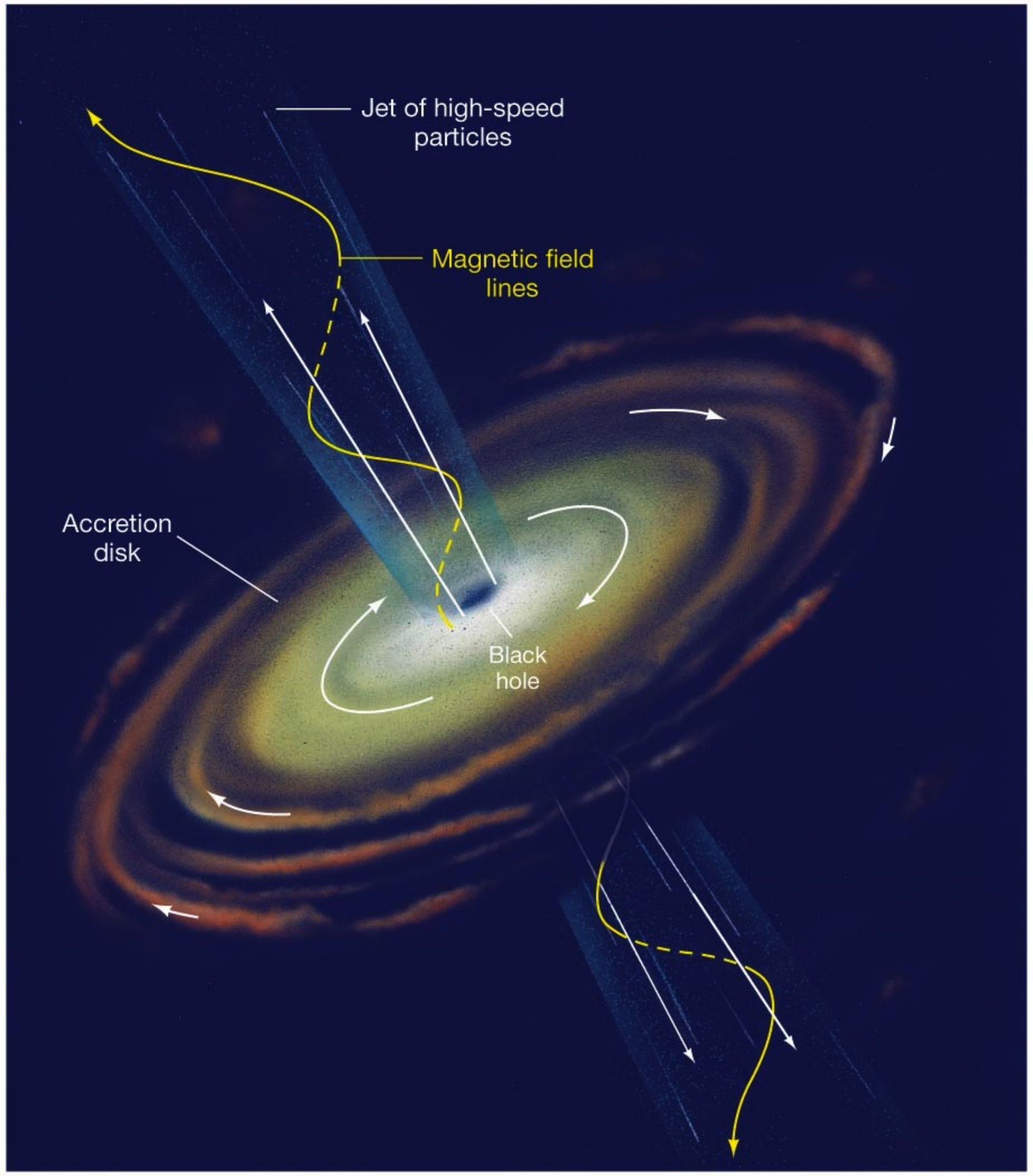
Most powerful sources in the Universe (up to 10^{48} erg/s).
Energy is generated by conversion of gravitational energy of the infalling material onto SMBH ($M_{BH}=10^6$-10^9 $M_{\odot}$) into radiation and outflows.

Non-jetted AGN:

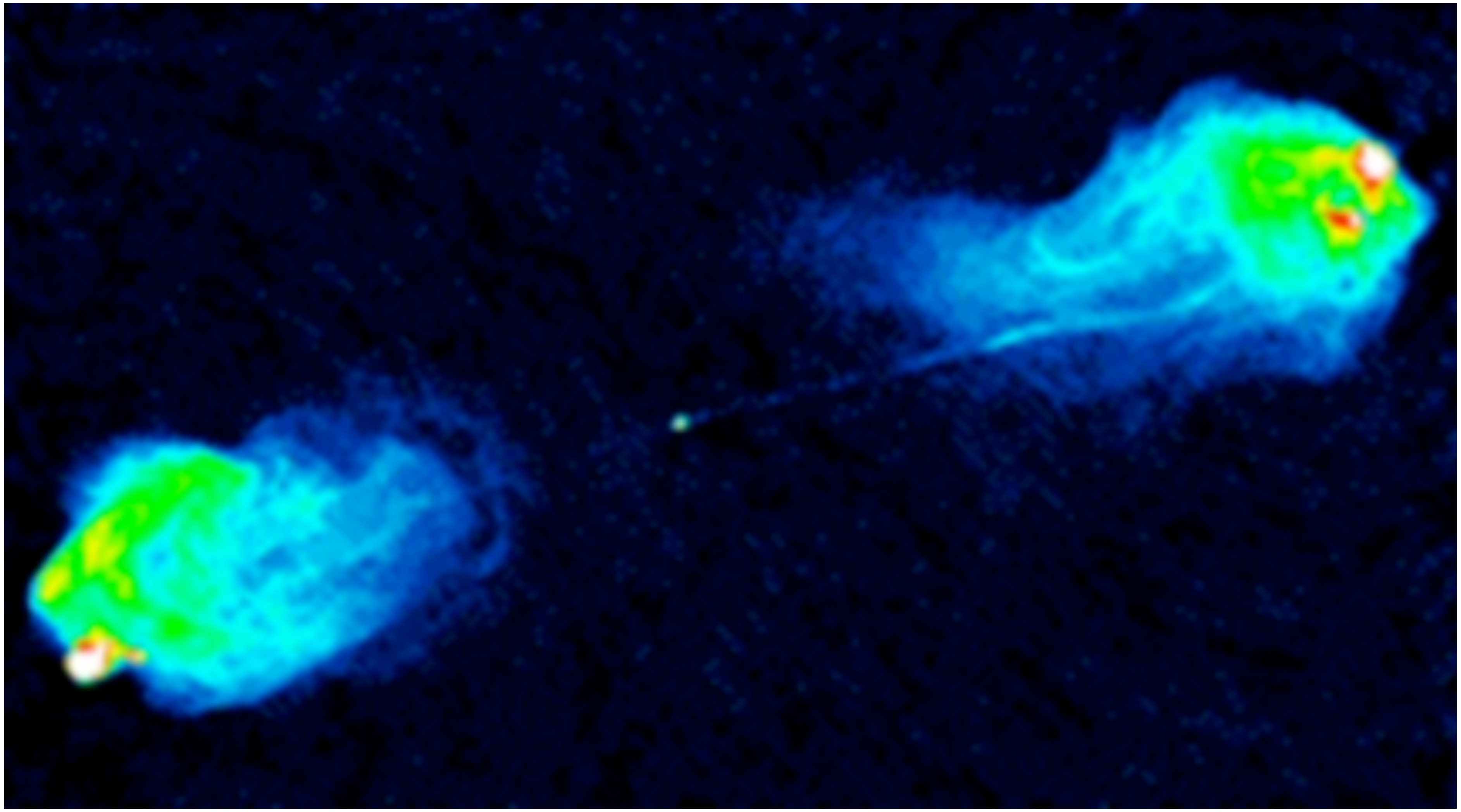
- Bulk of the AGN population
- Wider angle winds with velocities from a few thousands km/s up to mildly relativistic values.
- Electromagnetic emission dominated by thermal emission in the UV-optical band produced by the accretion disk around SMBH

Jetted AGN:

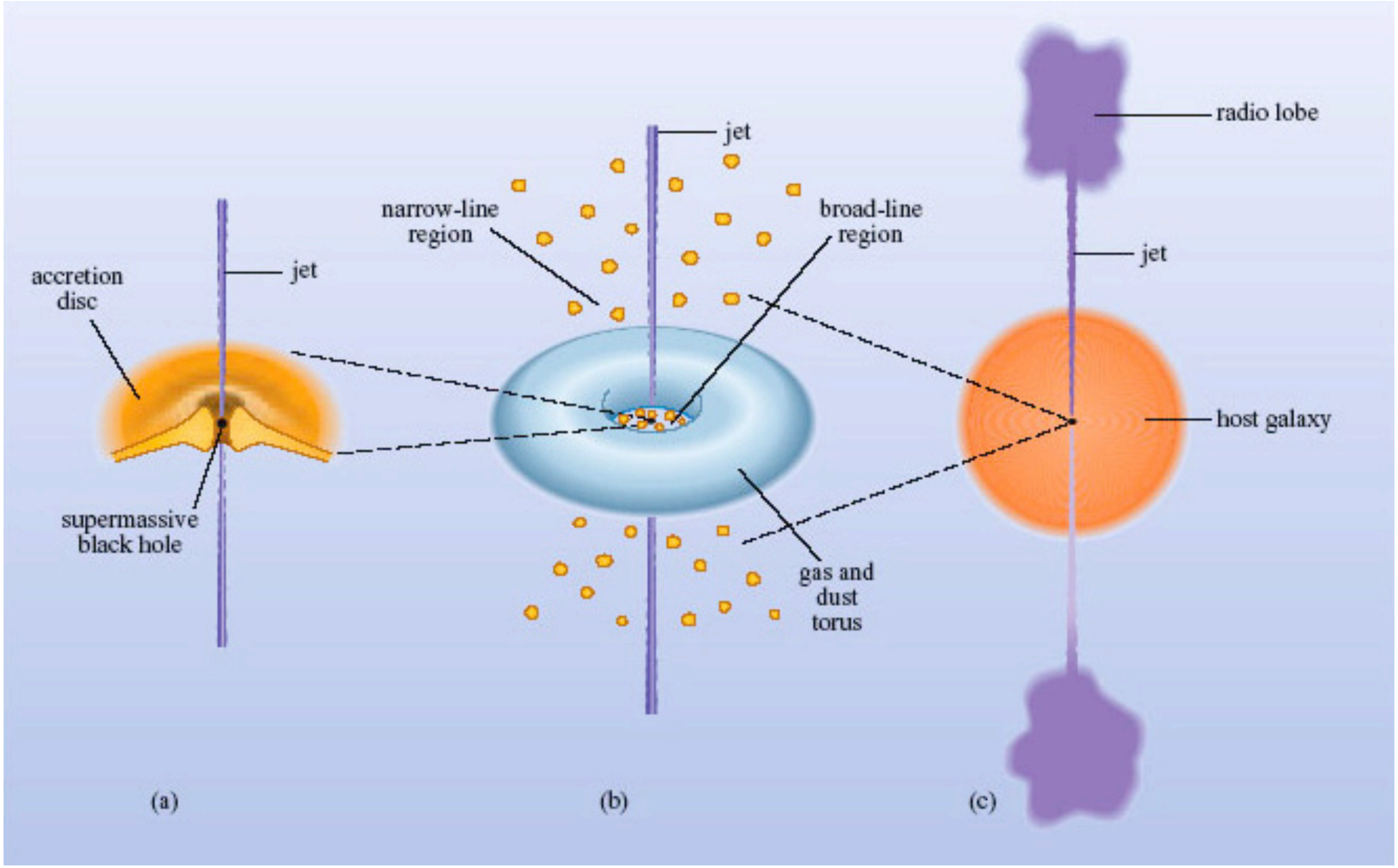
- ~10% of the AGN population
- Highly collimated relativistic outflows
- Electromagnetic emission dominated by jet non-thermal emission in the radio and gamma-ray band



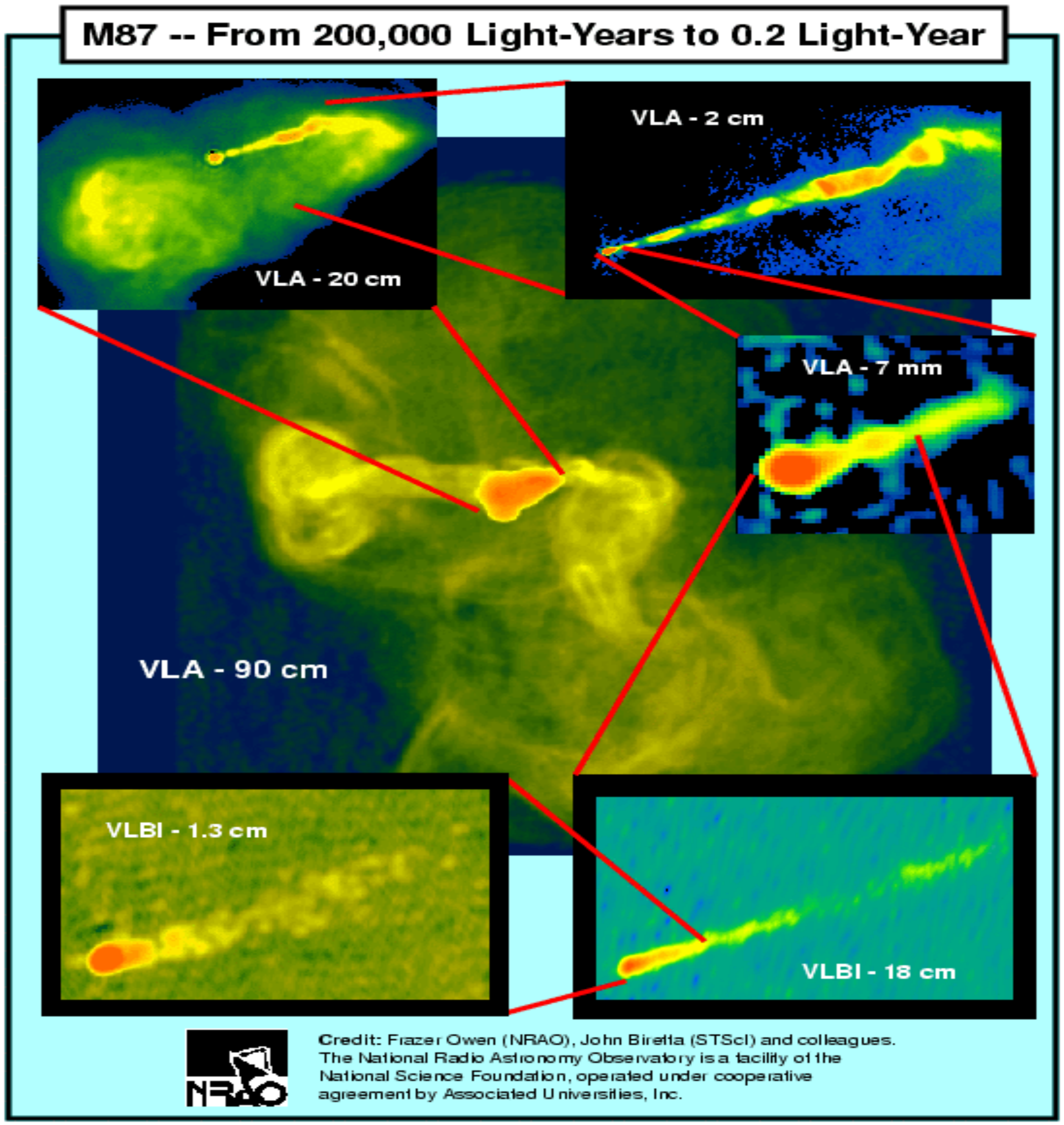
Relativistic jets



Relativistic jets

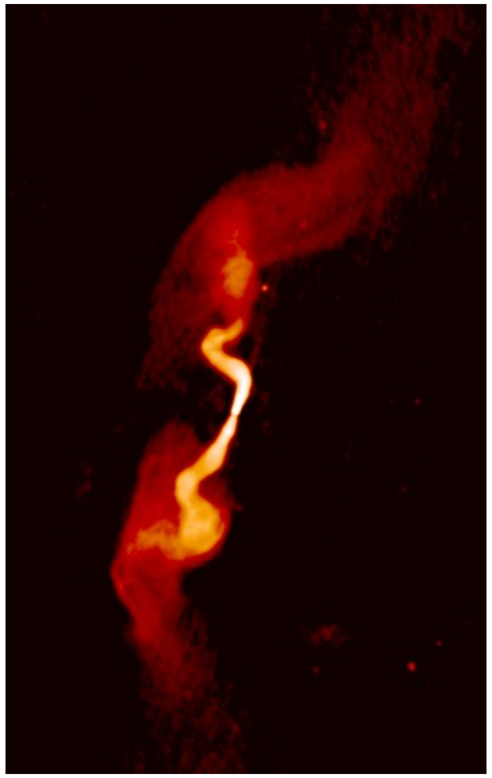


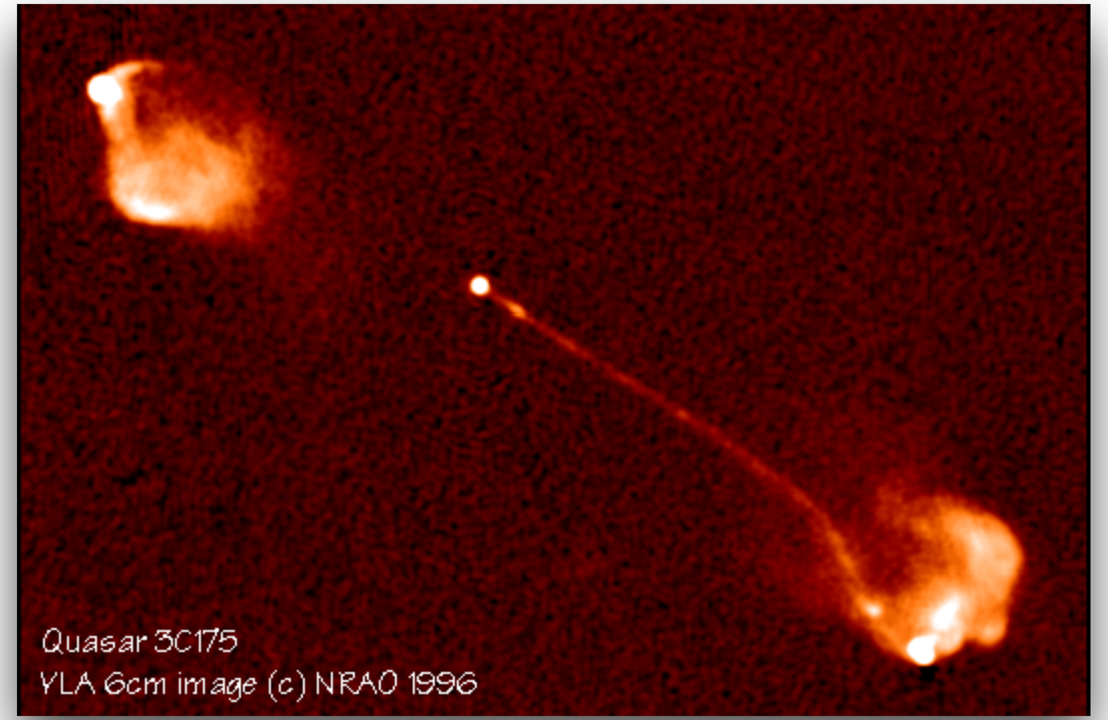
Relativistic jets



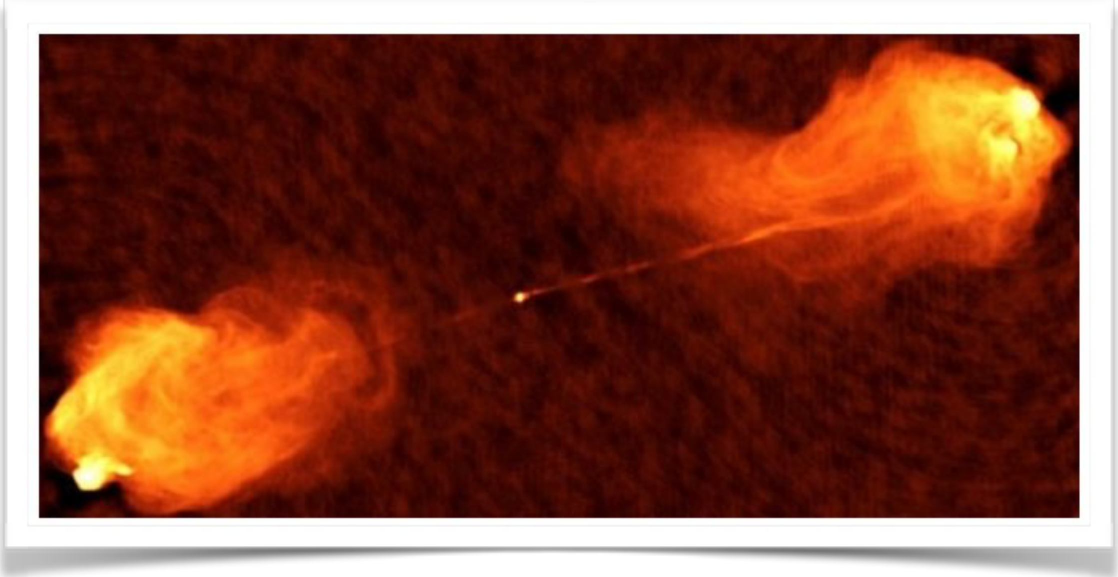
Relativistic jets

FR I

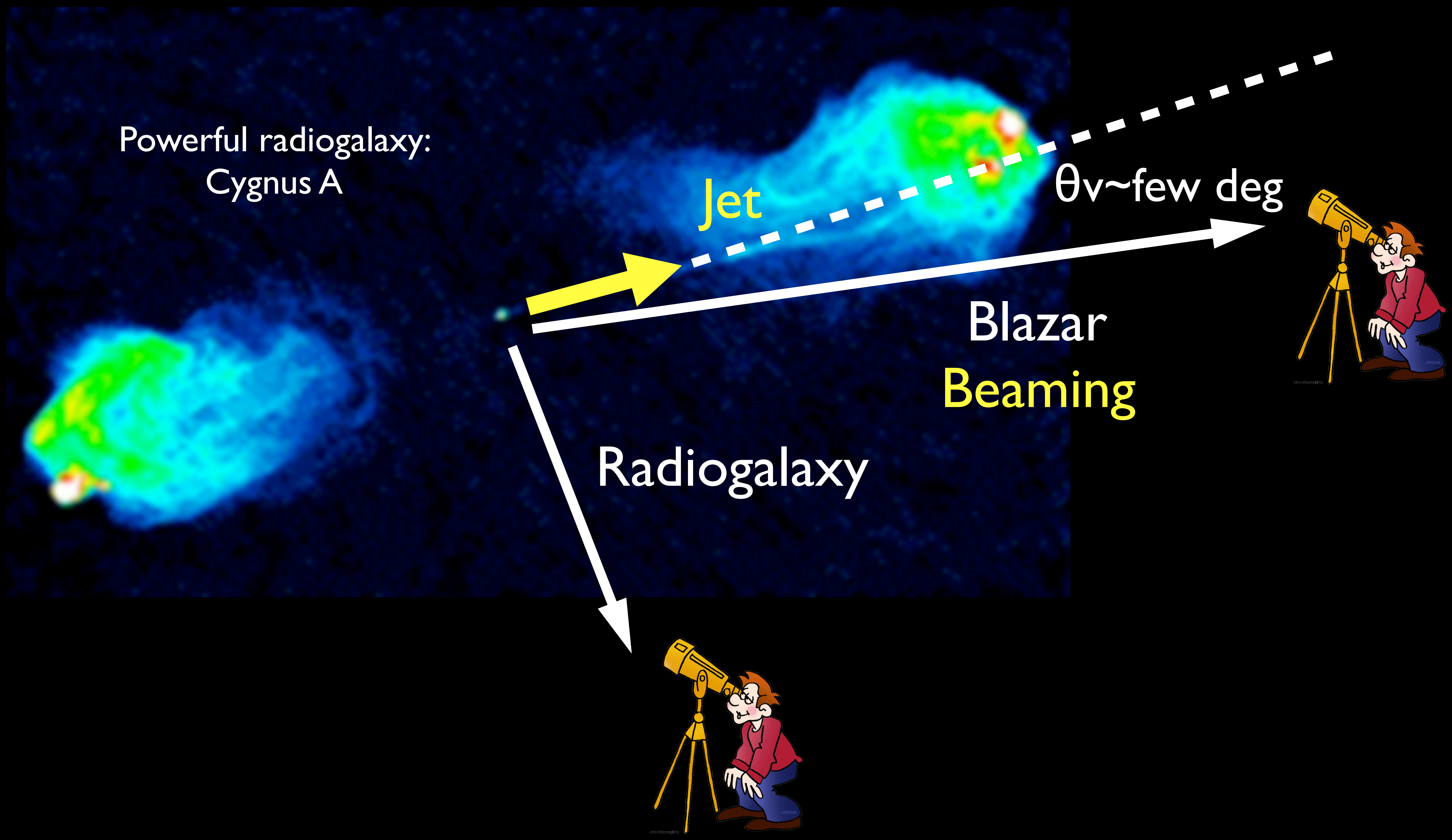




FR II

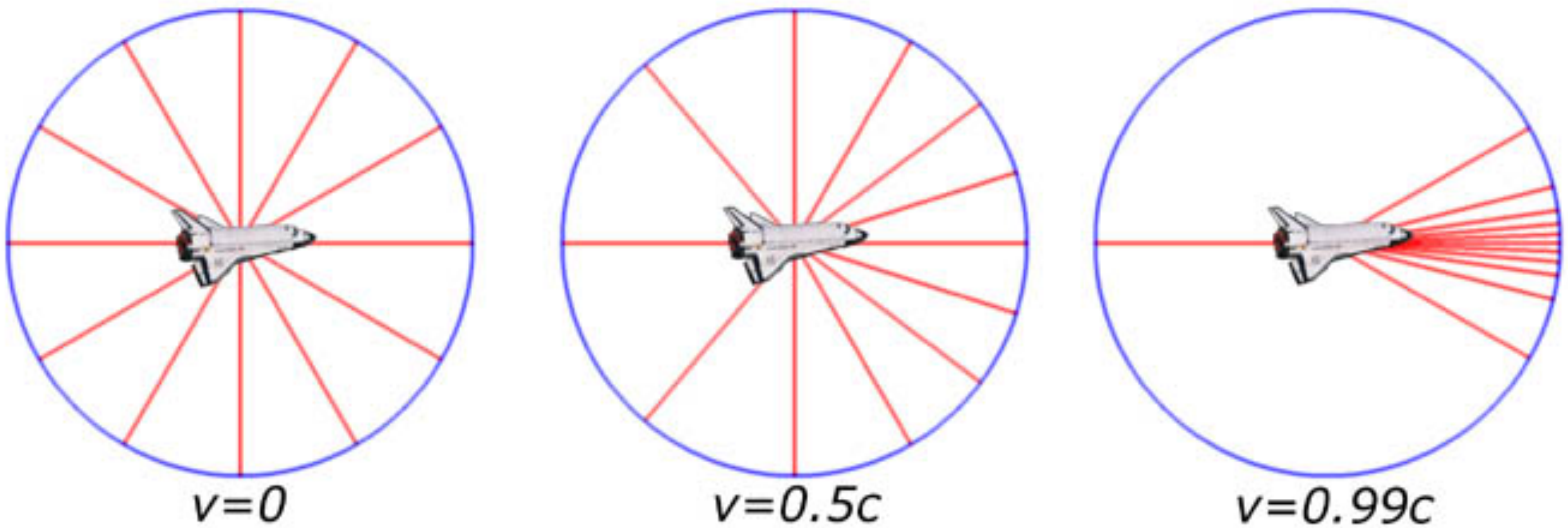


Blazars: relativistic jets pointing at us



(Special) relativity at work

Doppler beaming

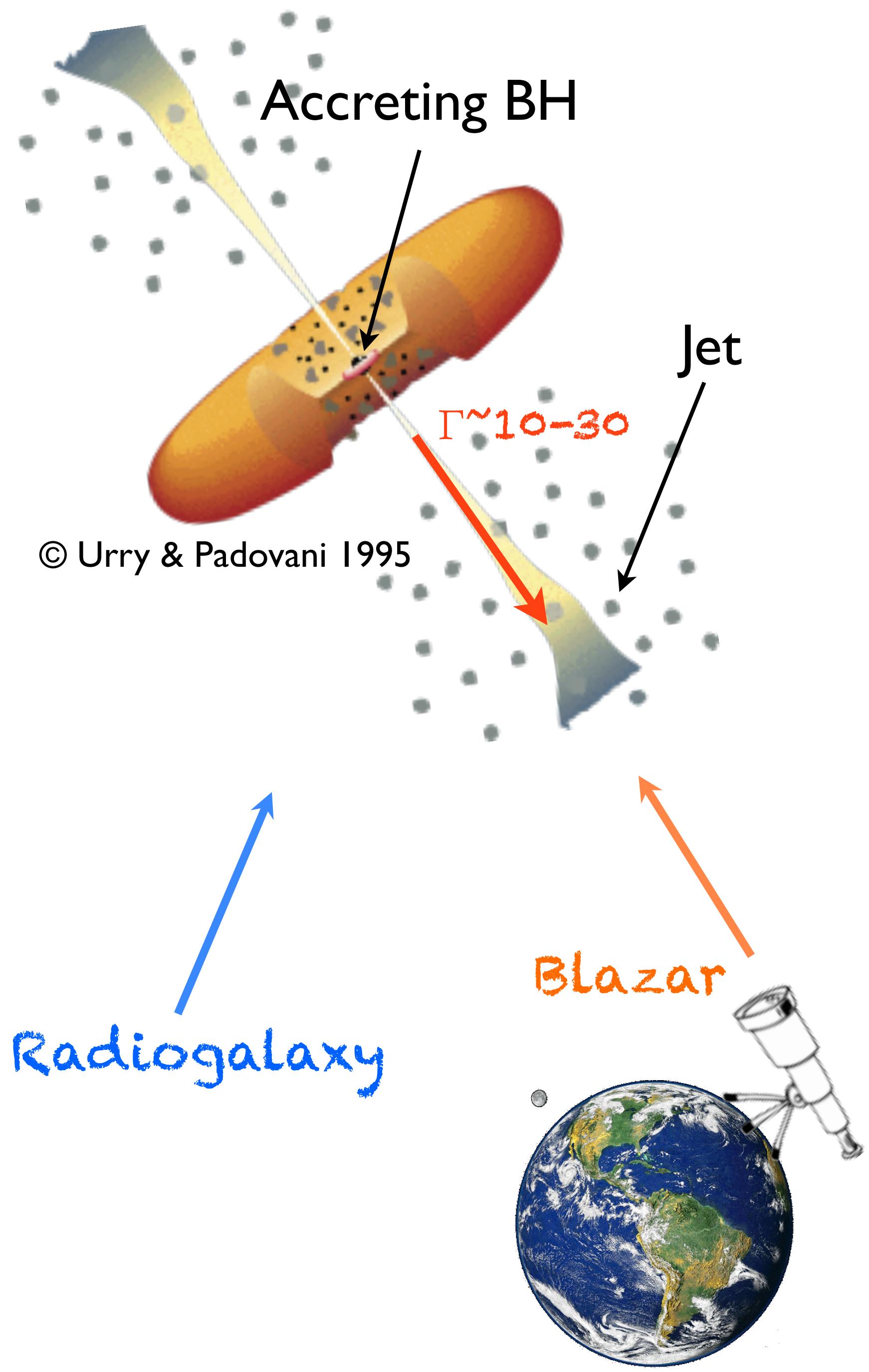


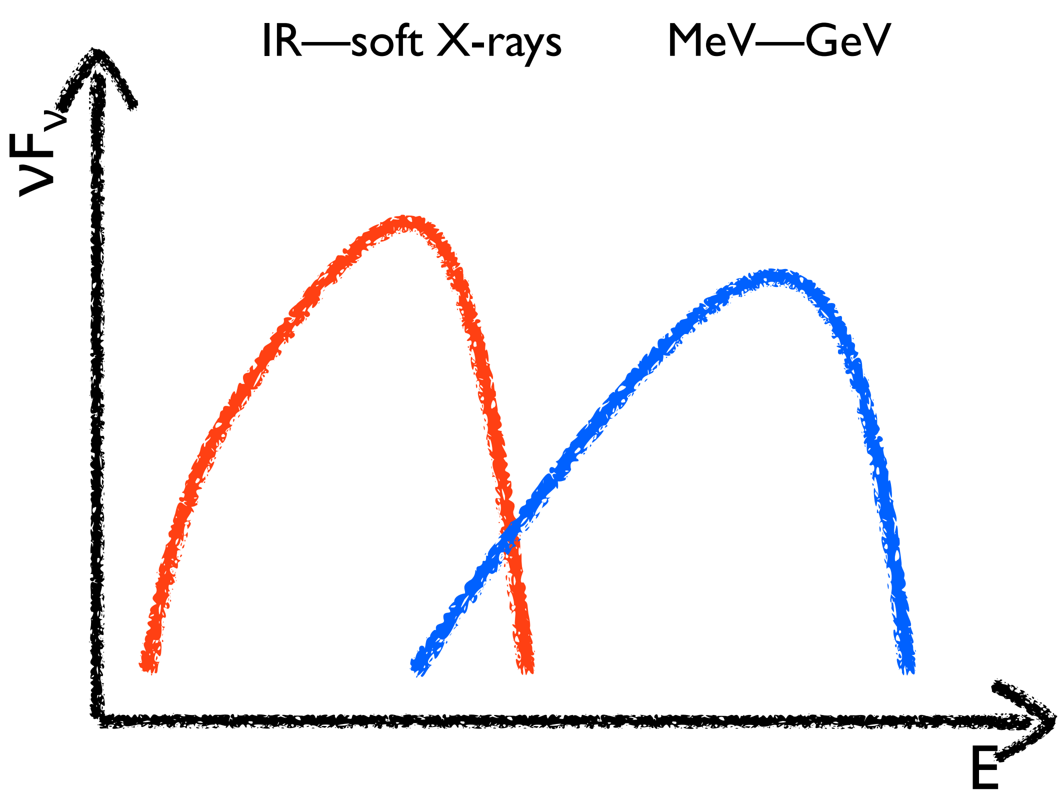
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

Amplification	$L_{\rm obs} = L'\delta^4$
Blueshift	$\nu_{obs} = \nu'\delta$
Shortening of timescales	$t_{\rm obs} = t'/\delta$

$$\delta \approx 10 - 20$$

Blazars in a nutshell

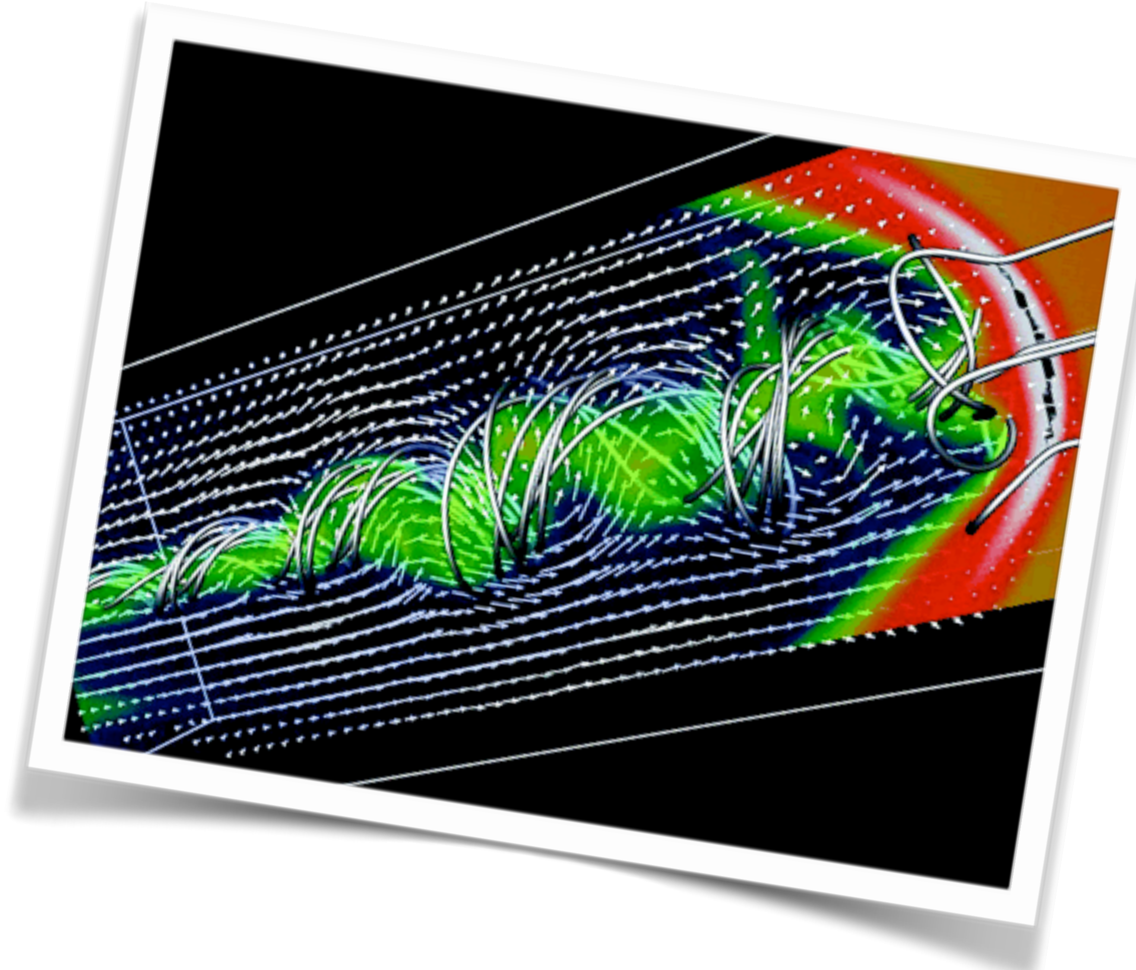




SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

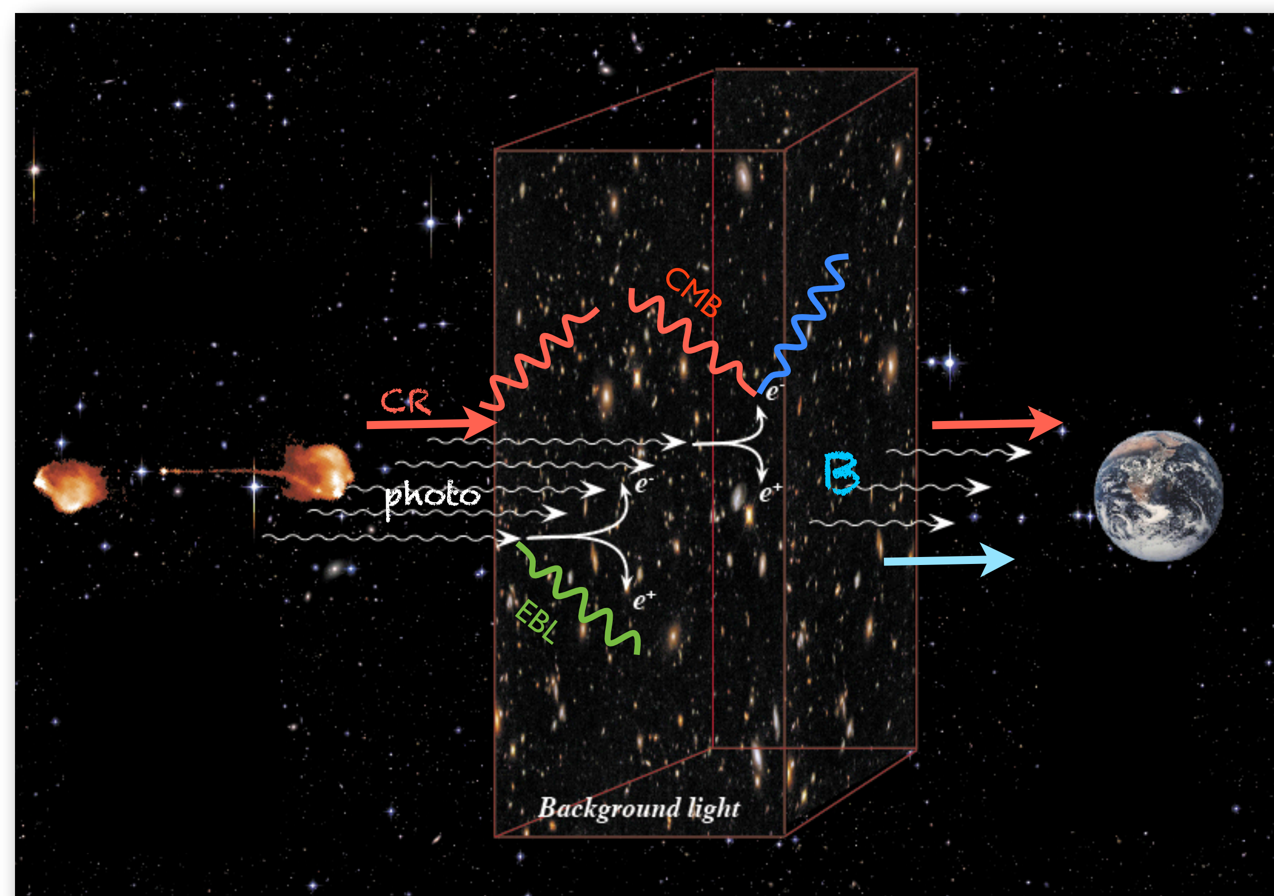
Jet physics

Particle acceleration
Plasma and B-field physics
Reconnection vs shock
Hadronic vs leptonic emission
Location of emission region
...



Propagation effects

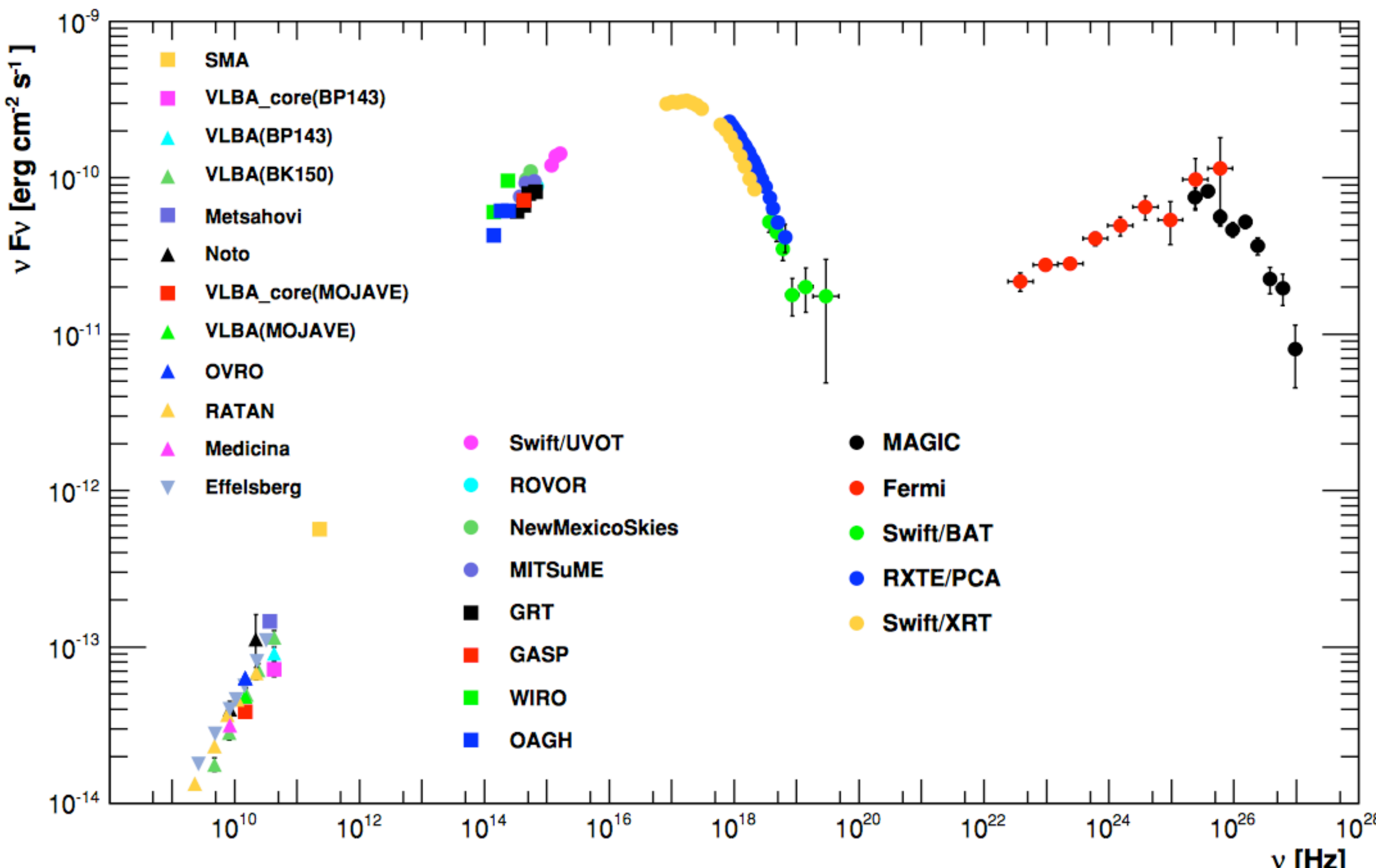
Extragalactic background light
Intergalactic magnetic field
Hadronic beams
LIV and ALPs-induced effects and other anomalies



The spectral energy distribution

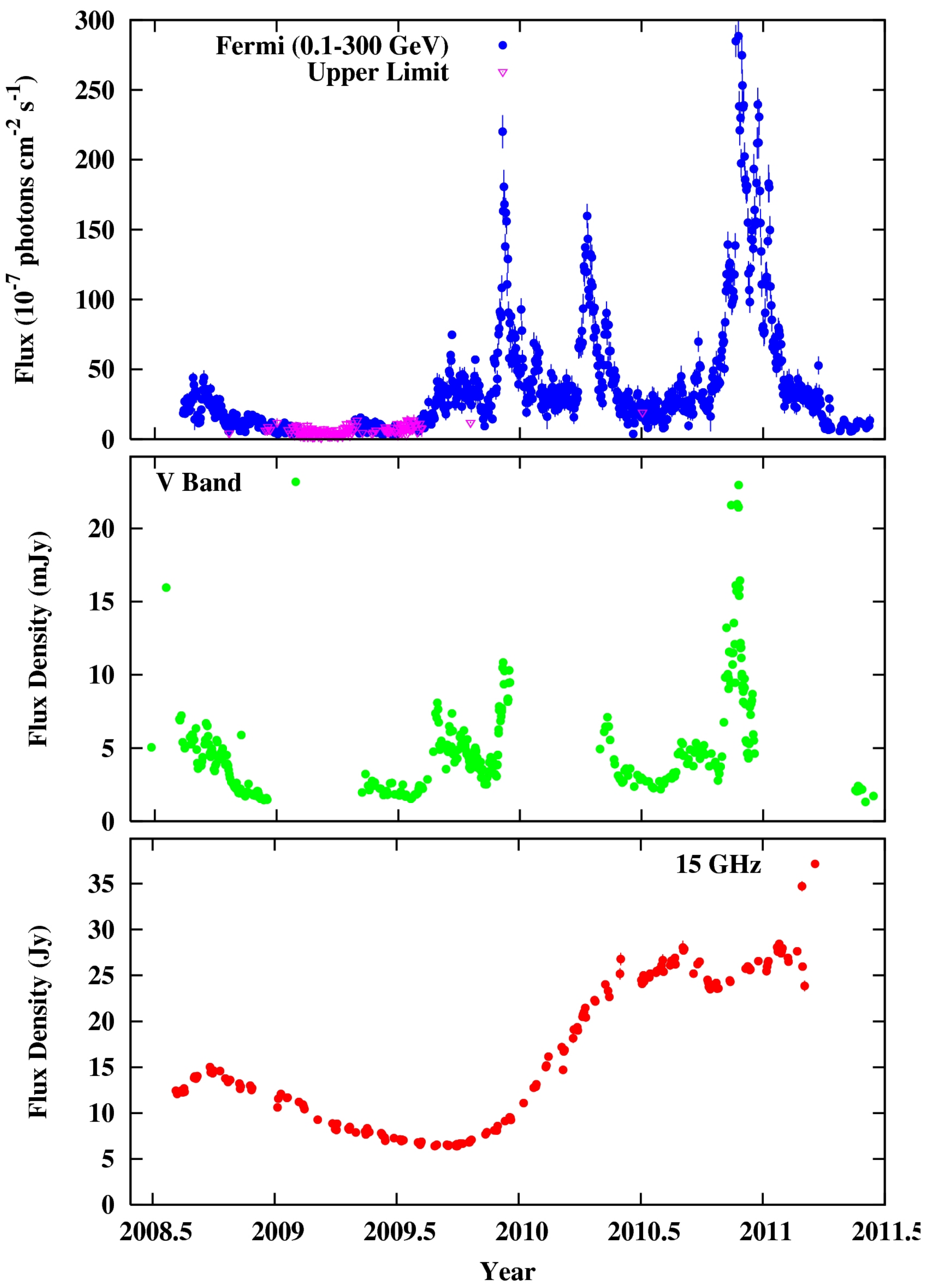
Extended over the whole EM spectrum
Extremely variable

Important observational effort



Abdo et al. 2011

Variability



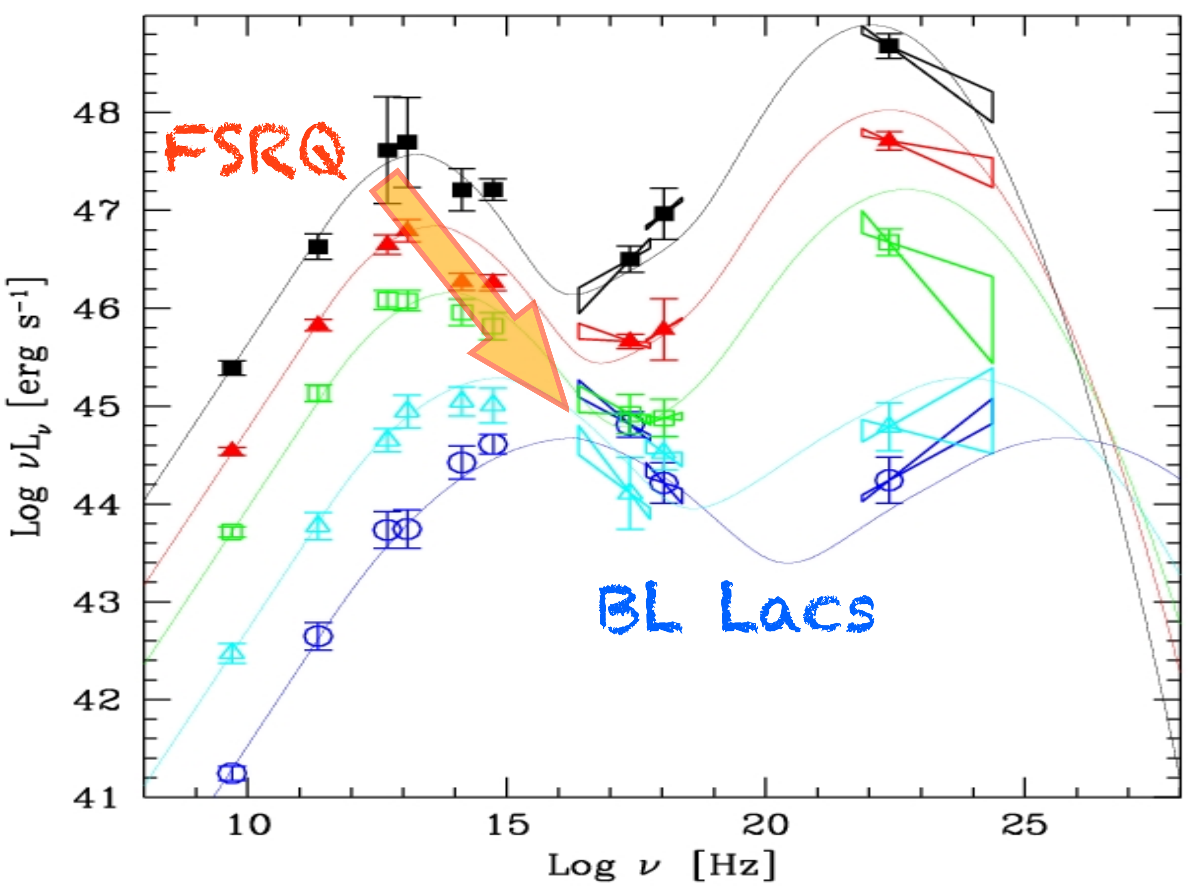
Variability

Blazars: basic phenomenology

Blazars occur in two flavors:

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

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

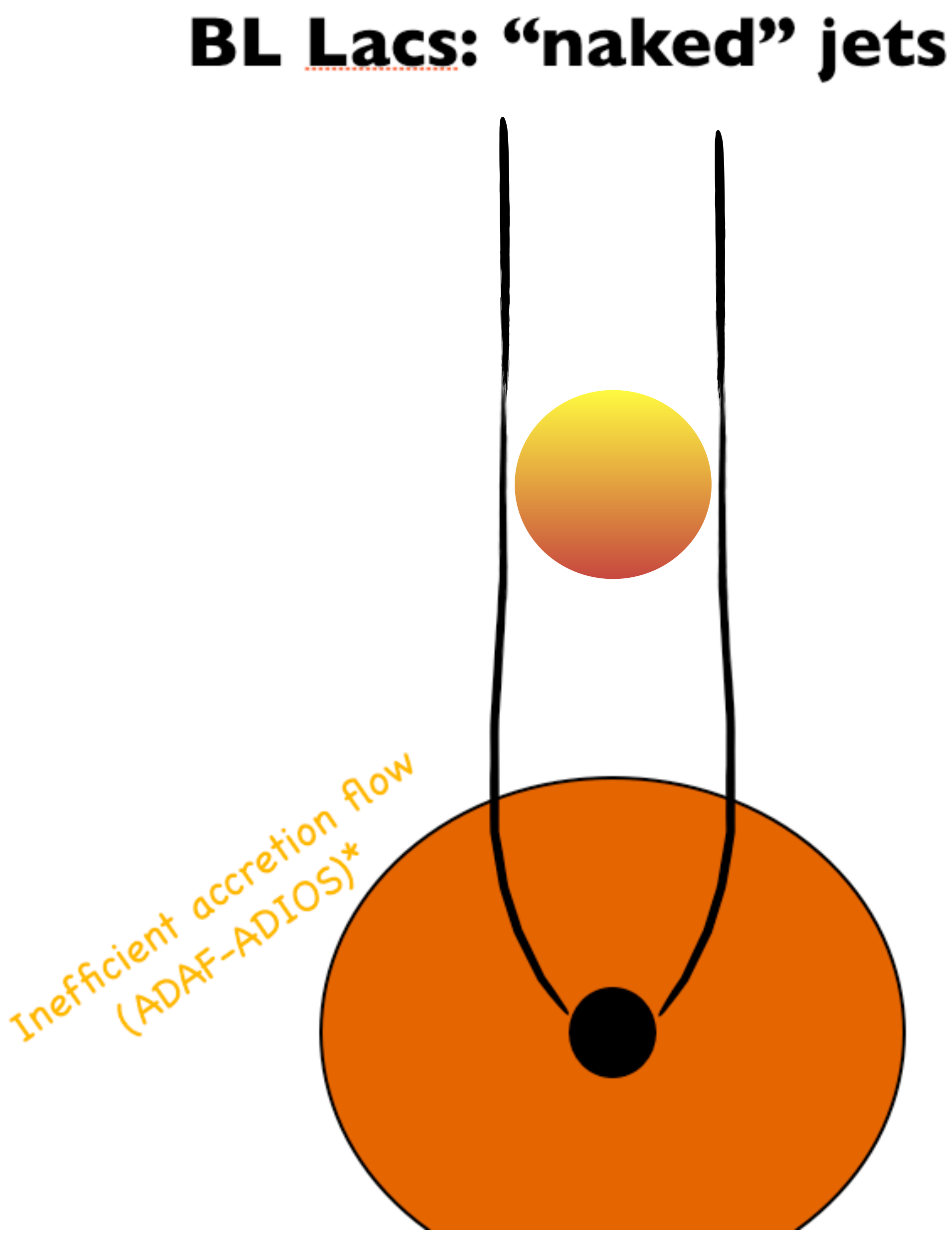


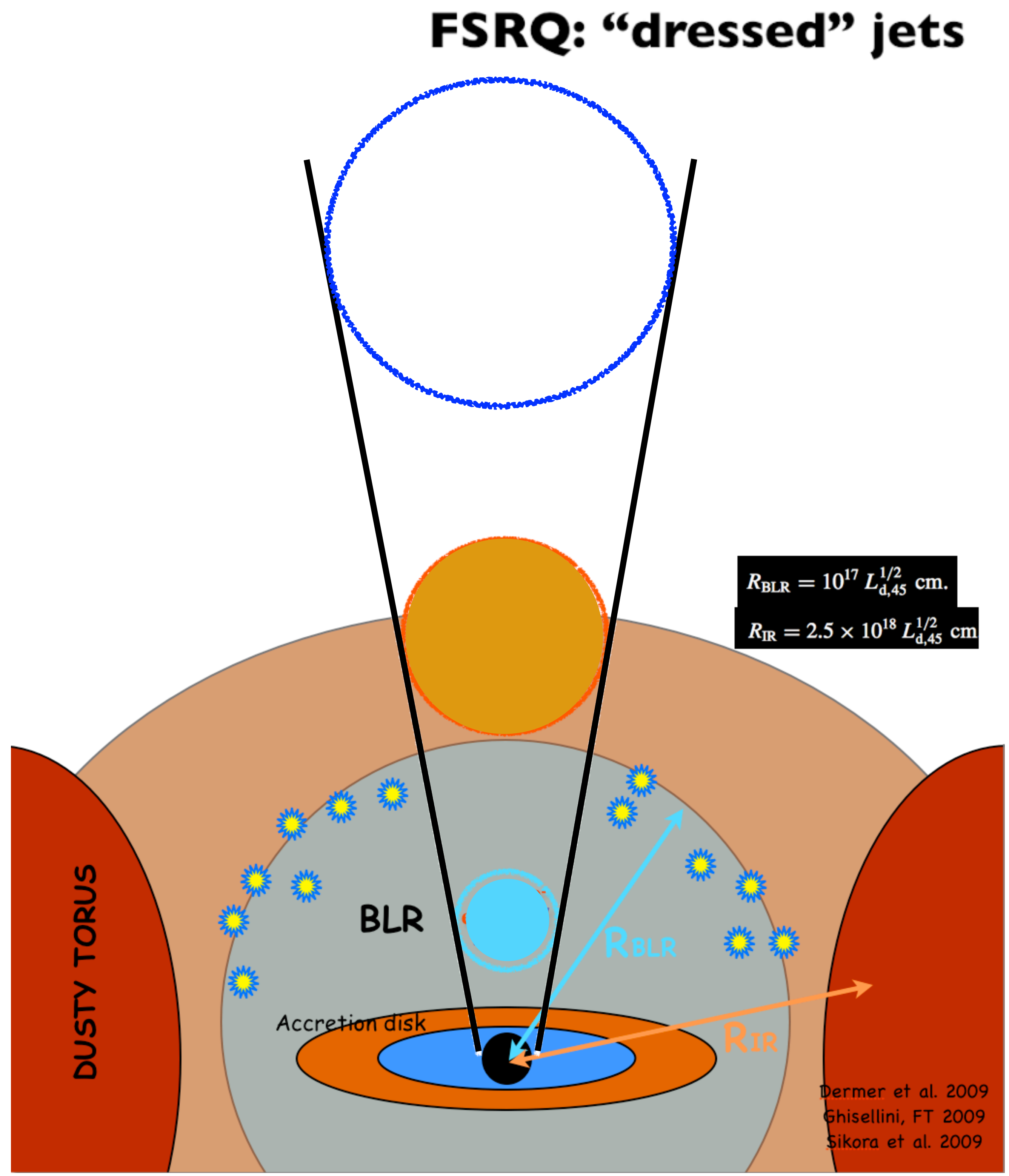
The "blazar sequence"

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

But see several papers by Giommi & Padovani

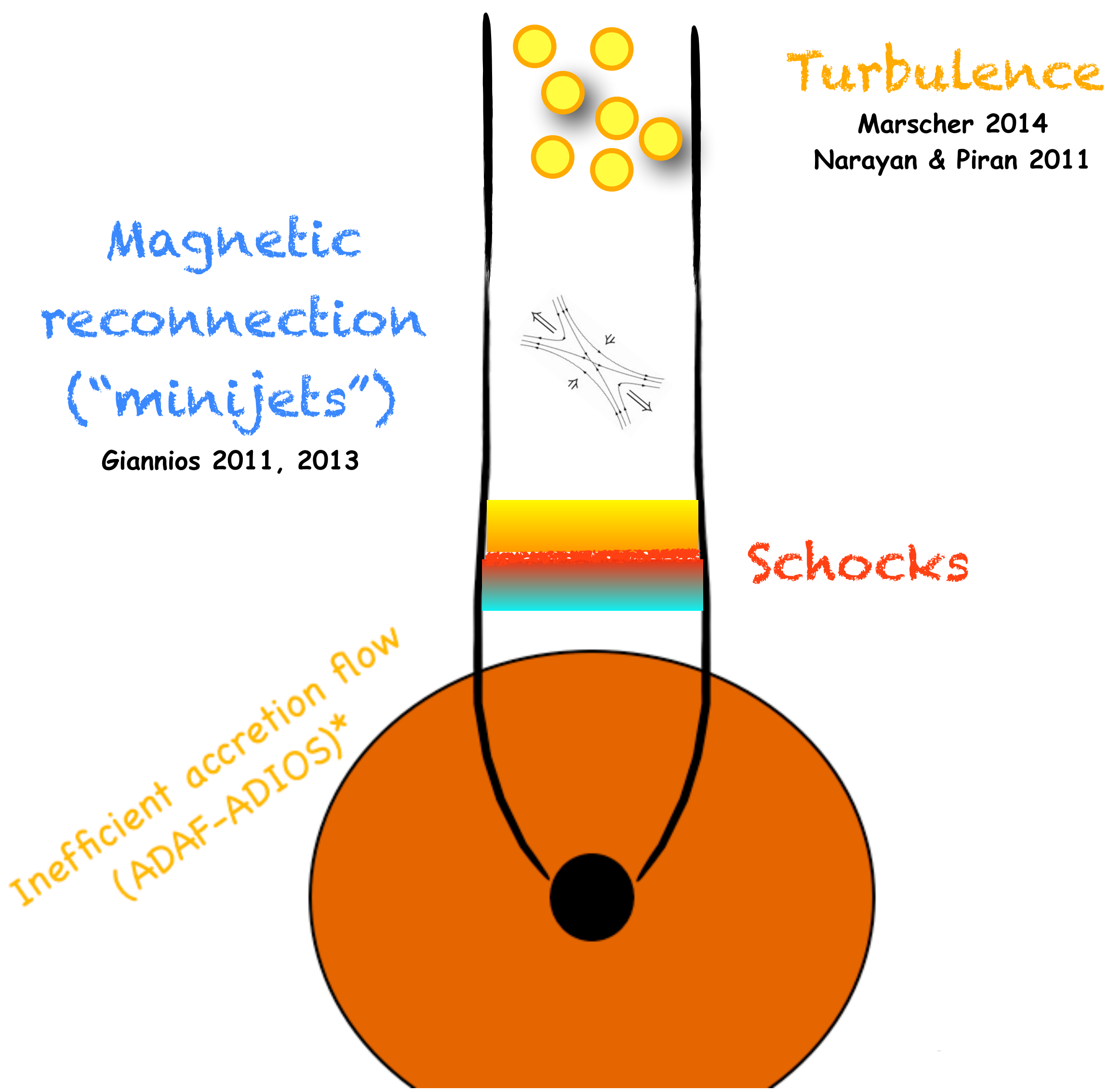
Blazars in a nutshell



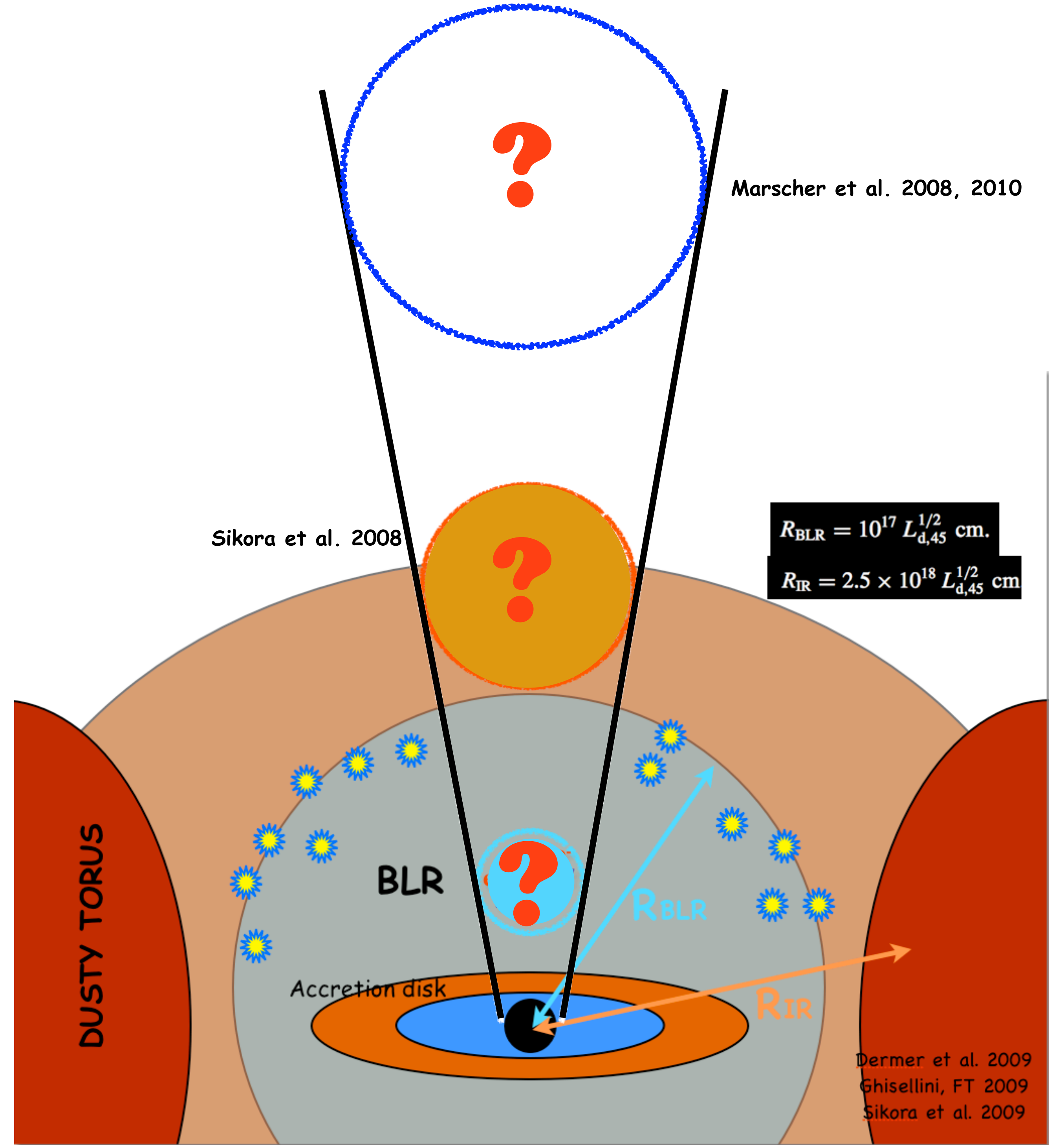


Blazars in a nutshell

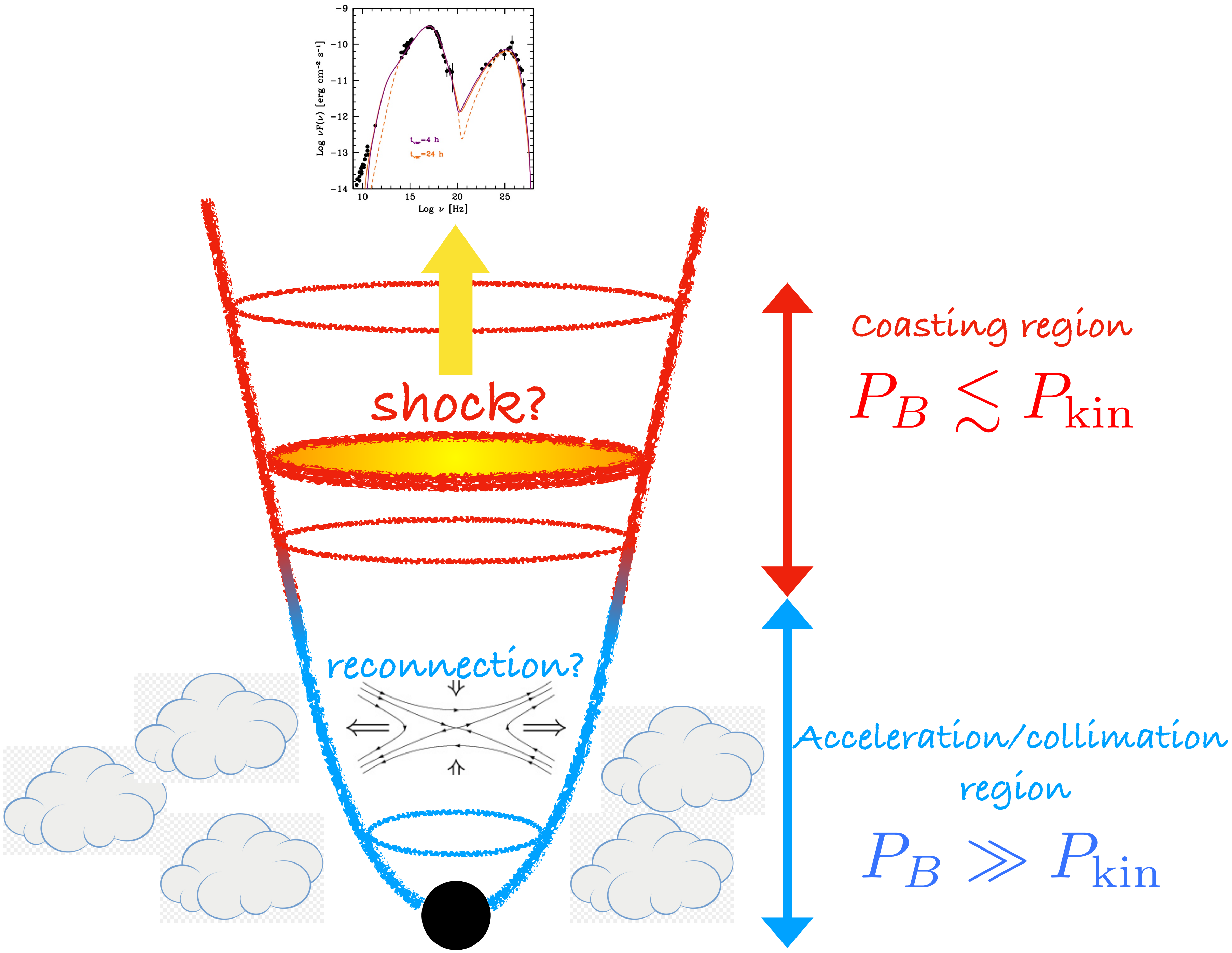
BL Lacs: “naked” jets



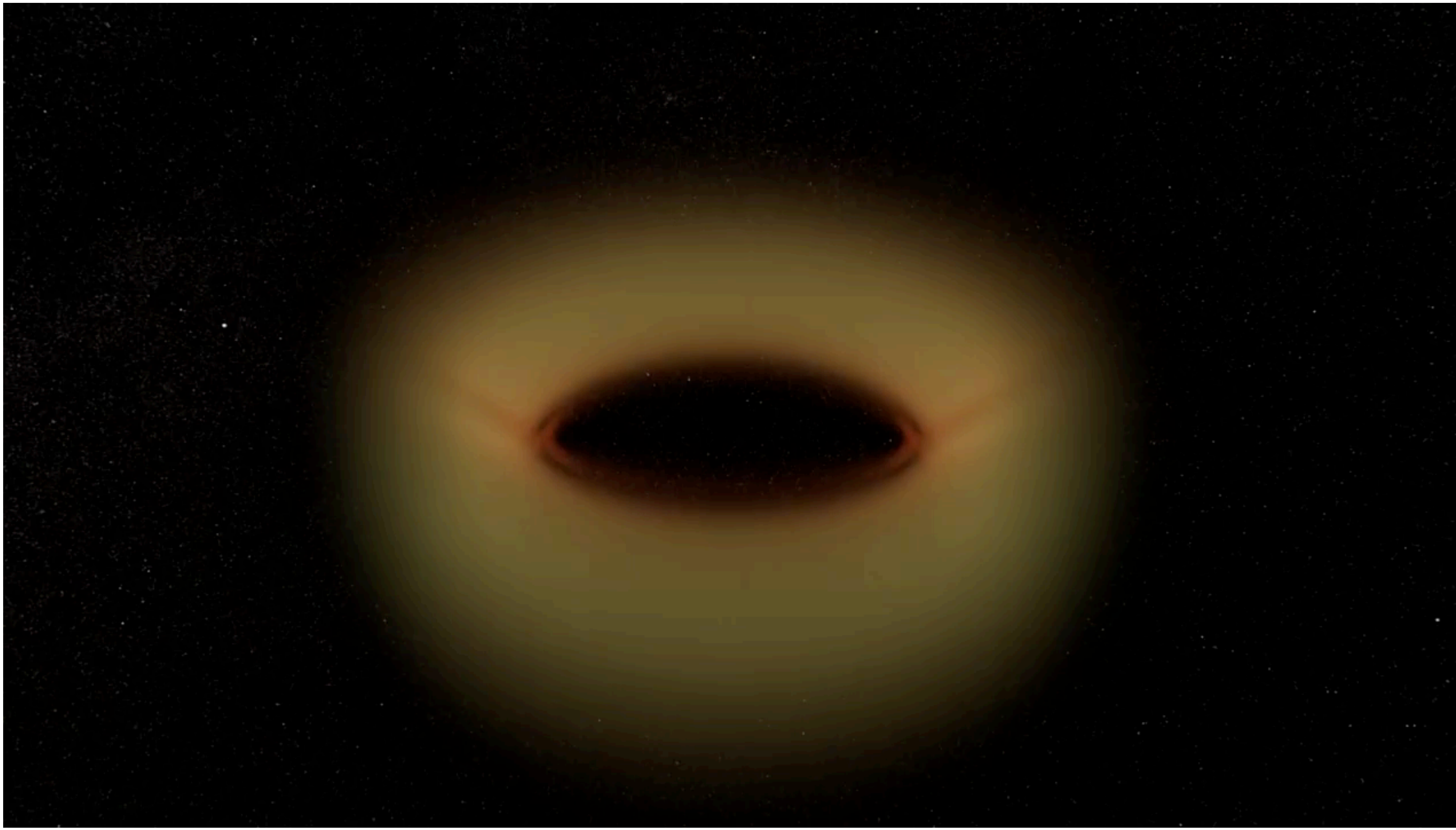
FSRQ: “dressed” jets



The full problem



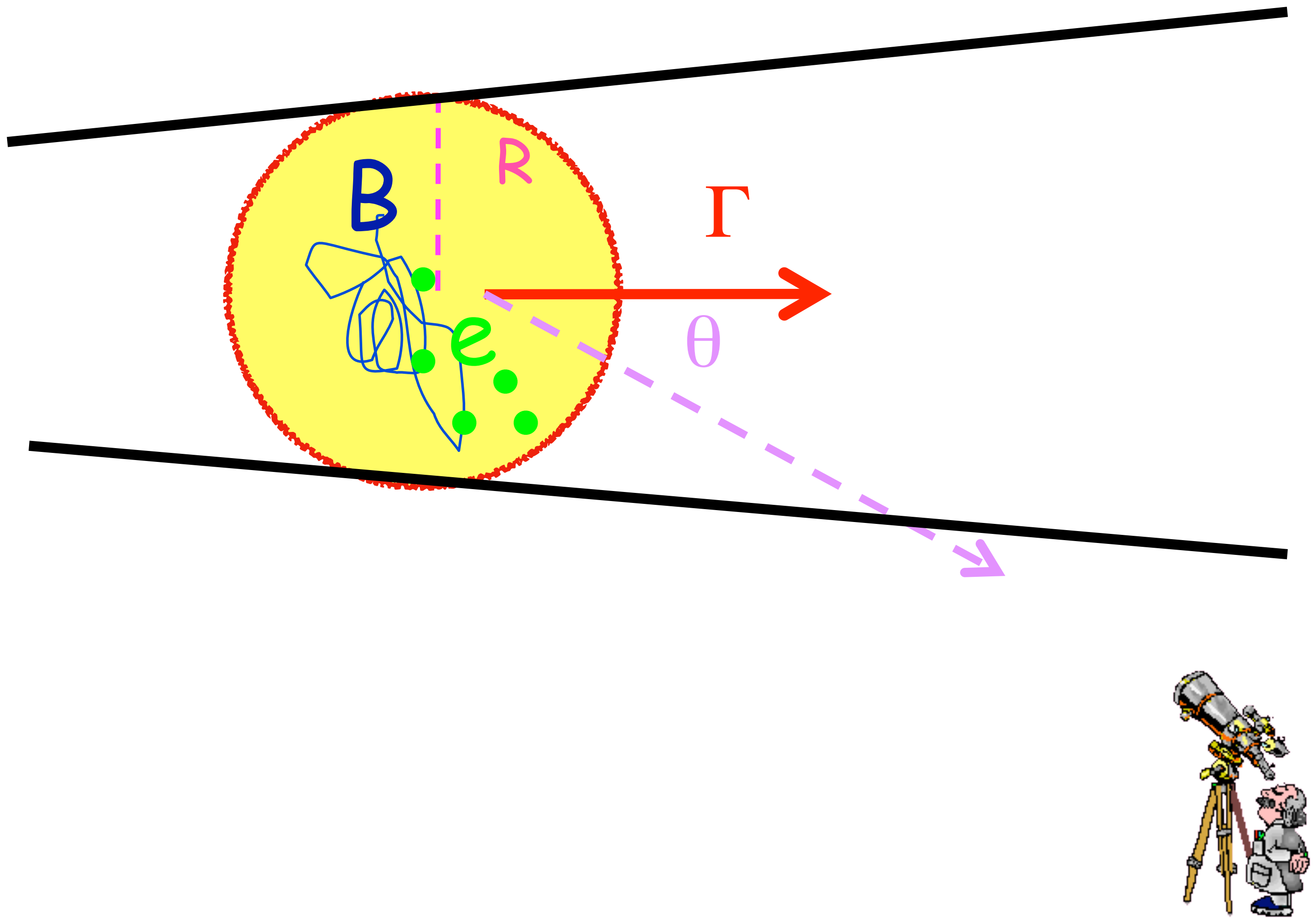
The full problem



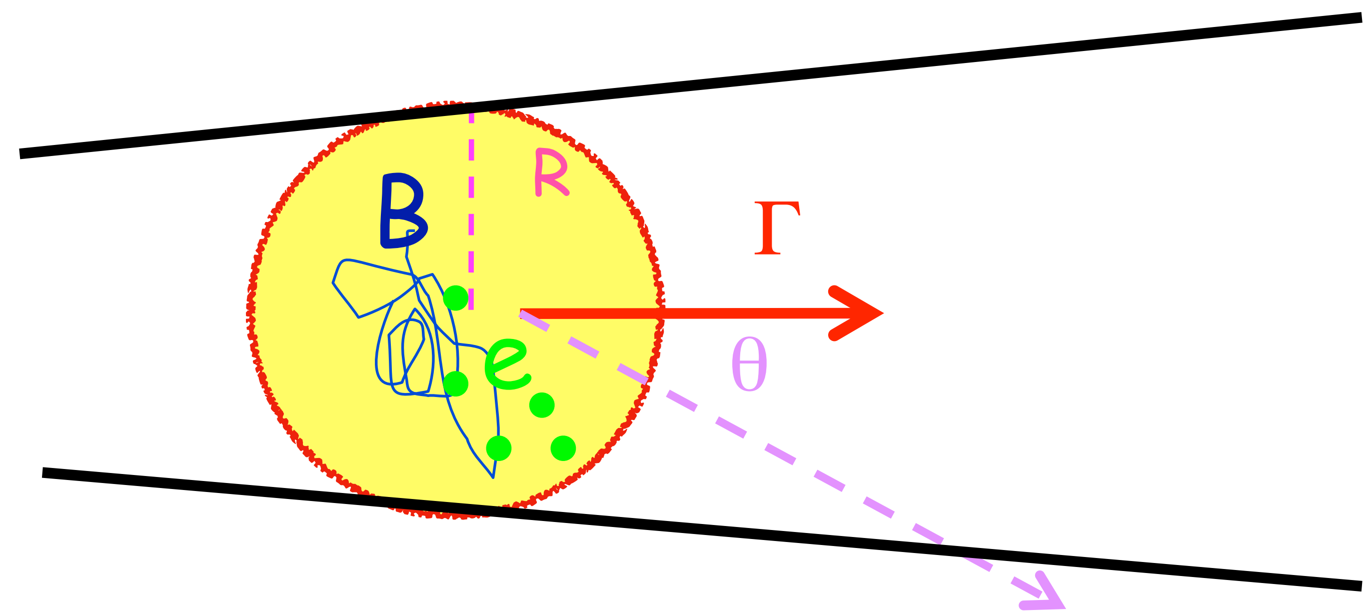
McKinney, Tchekhovskoy, and Blandford 2012

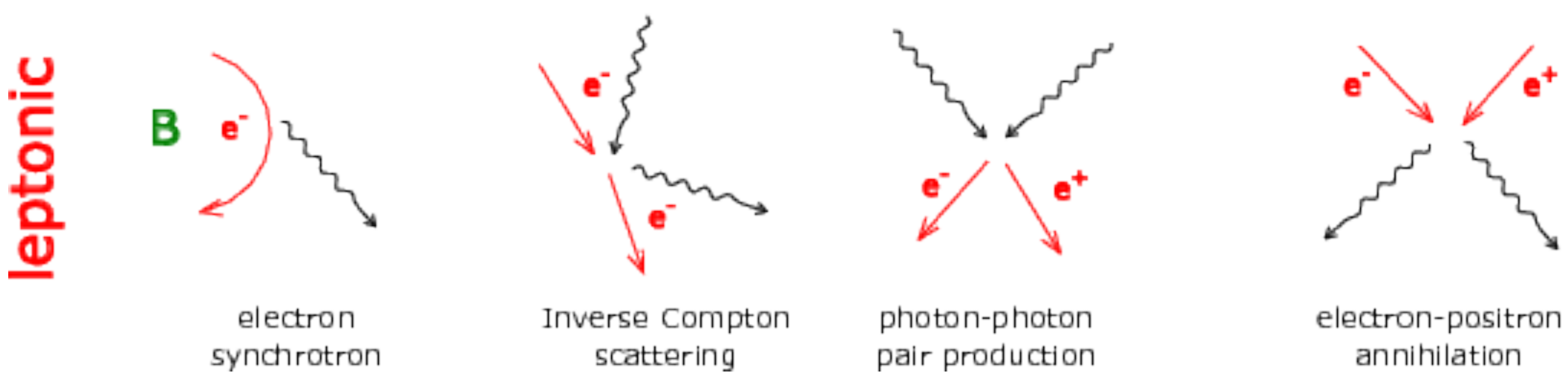
A more modest model

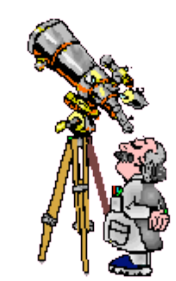
"One zone"



A more modest model

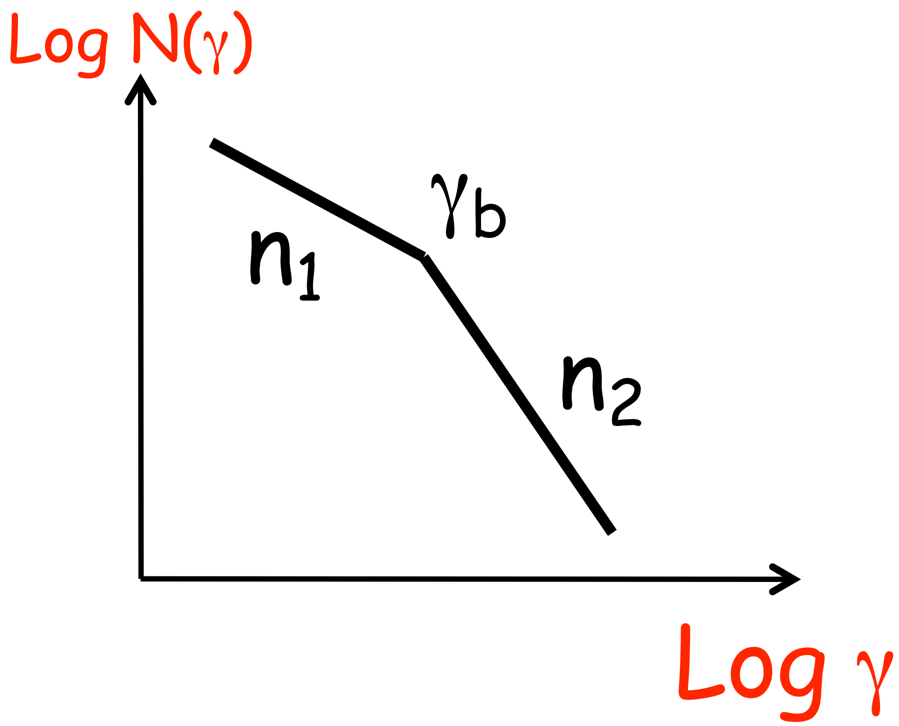


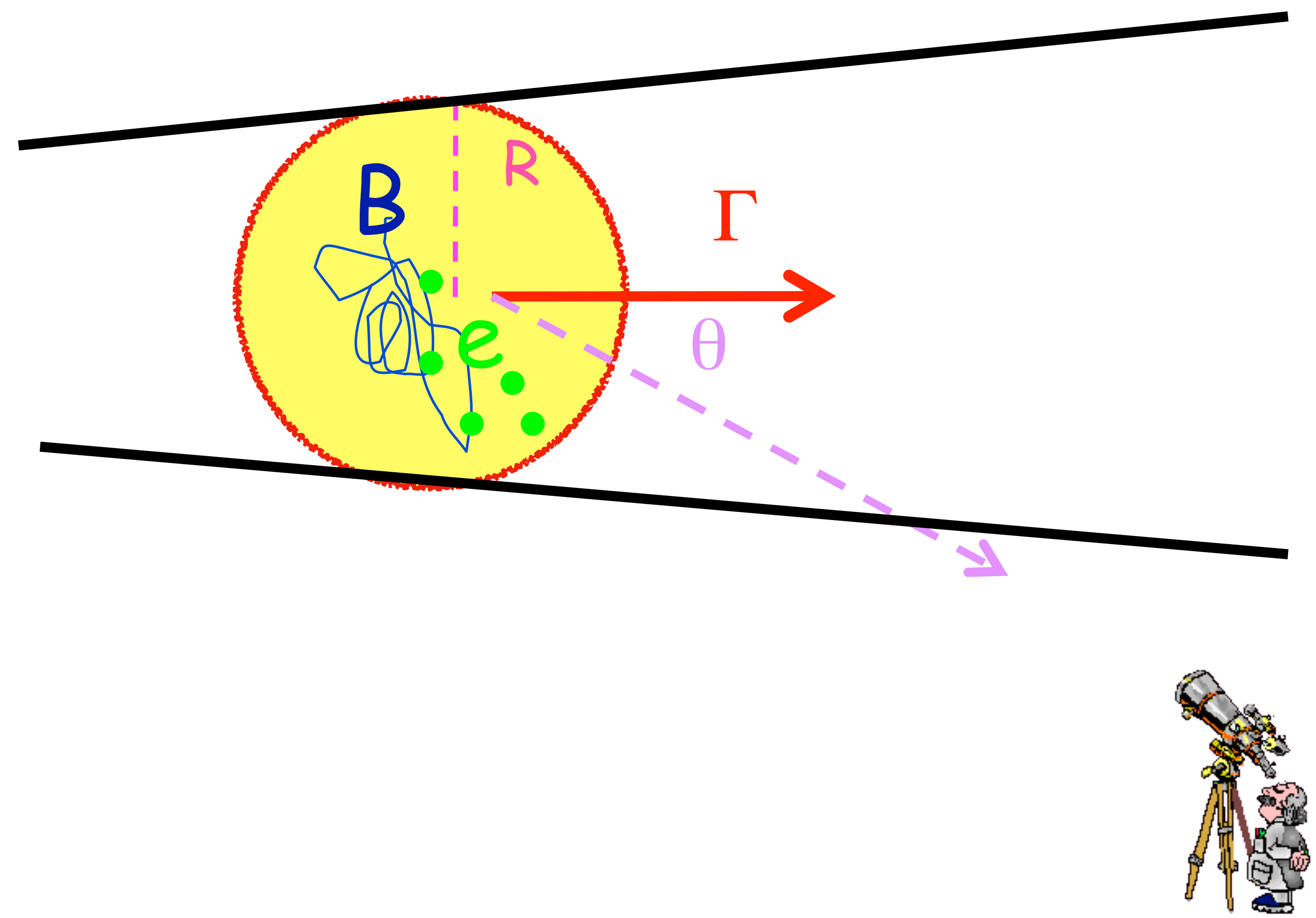




Hadron not important for the emission (but not for energetics!)

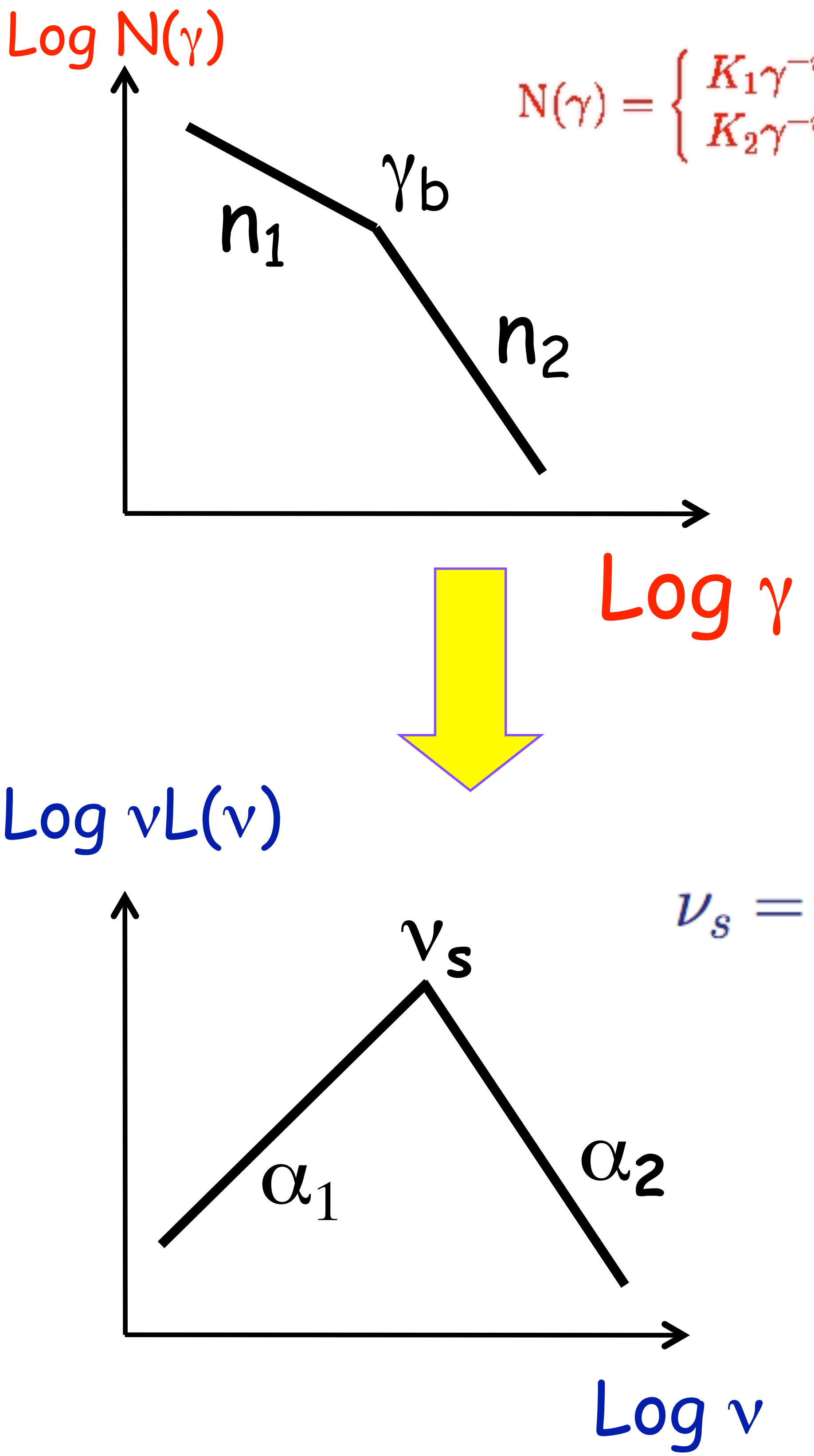
A more modest model - 1



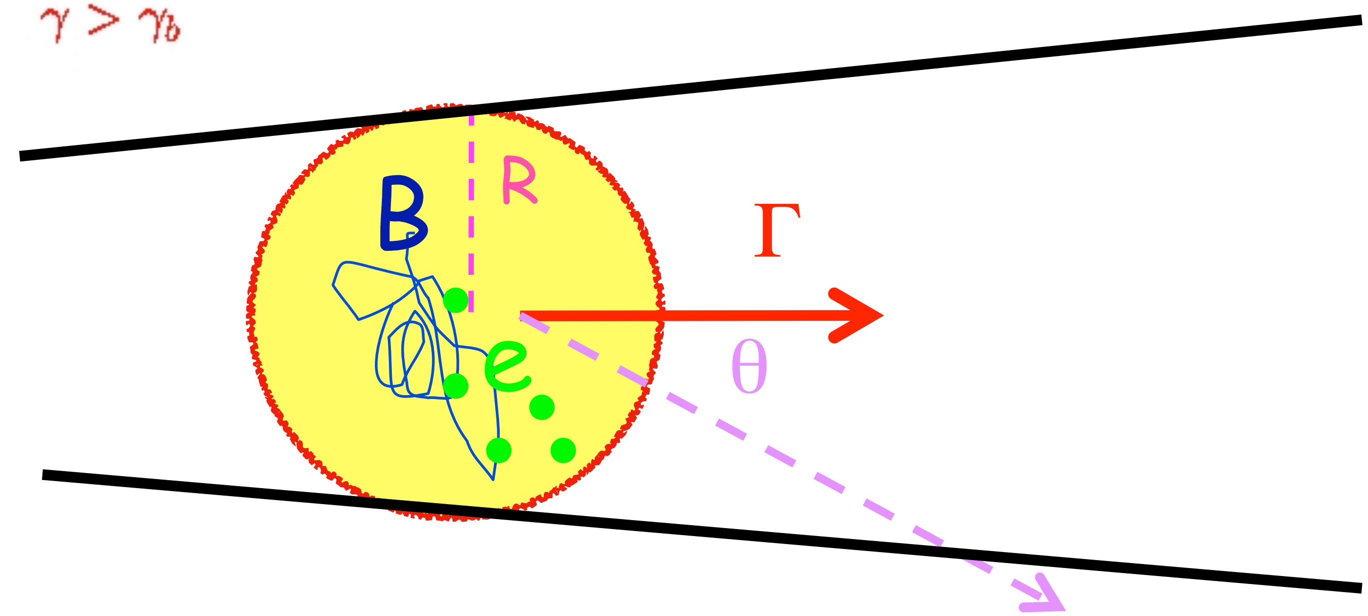


$$N(\gamma) = \begin{cases} K_1 \gamma^{-n_1} & \gamma < \gamma_b \\ K_2 \gamma^{-n_2} & \gamma > \gamma_b \end{cases}$$

A more modest model - 1

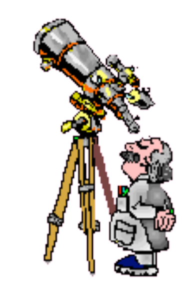


$$N(\gamma) = \begin{cases} K_1\gamma^{-n_1} & \gamma < \gamma_b \\ K_2\gamma^{-n_2} & \gamma > \gamma_b \end{cases}$$

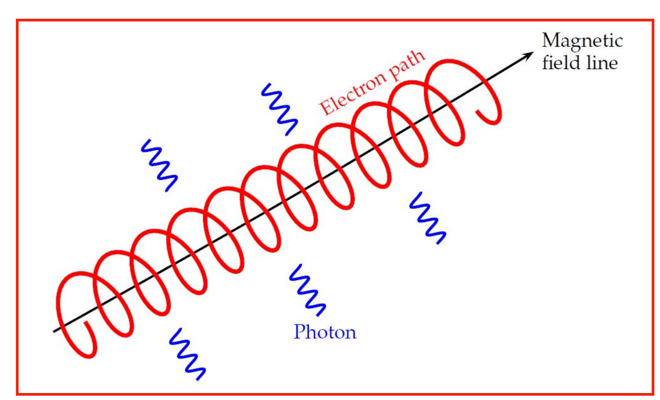


$$\nu_s = 3 \times 10^6 B\gamma_b^2\delta$$

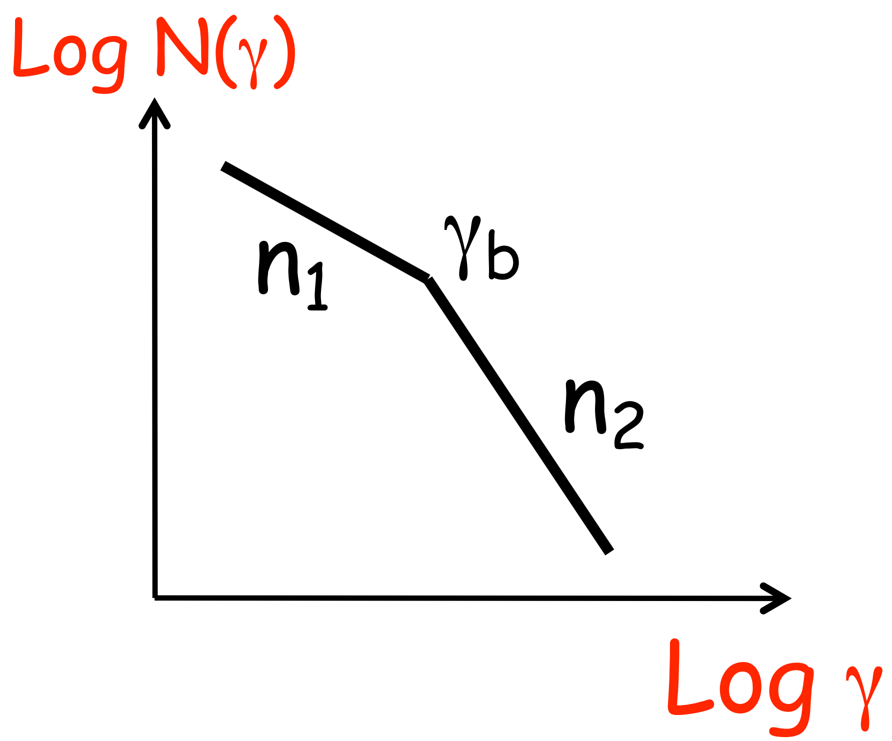
$$\alpha_i = \frac{n_i - 1}{2}$$



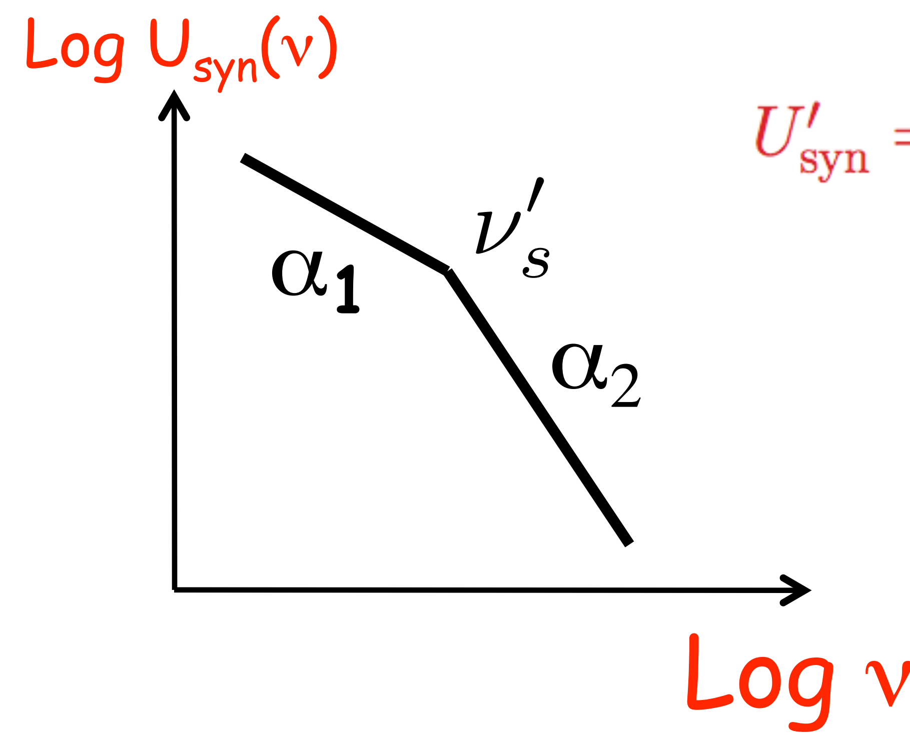
Synchrotron emission



A more modest model - 1

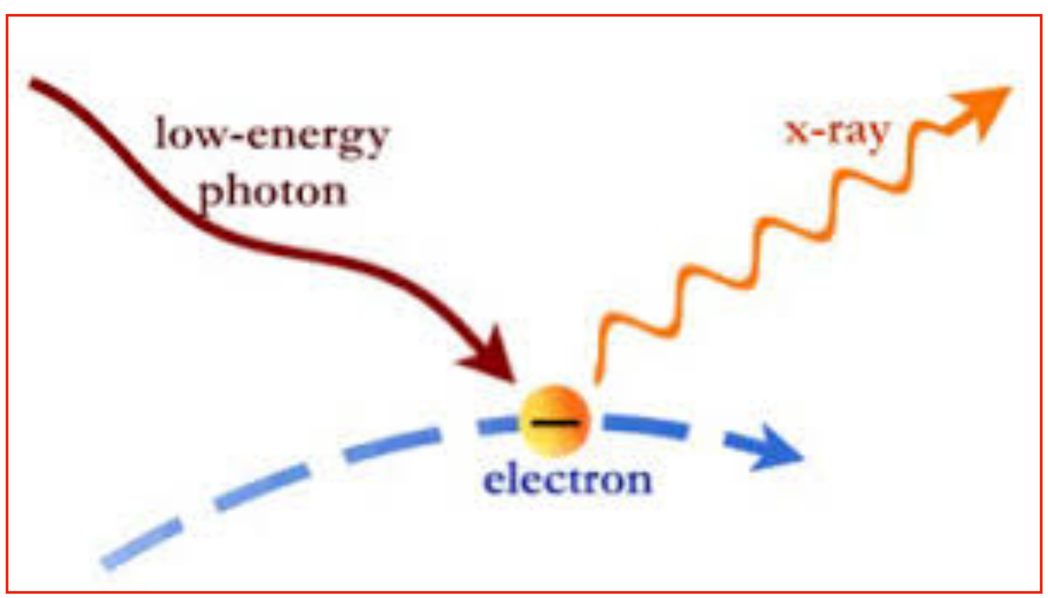


+

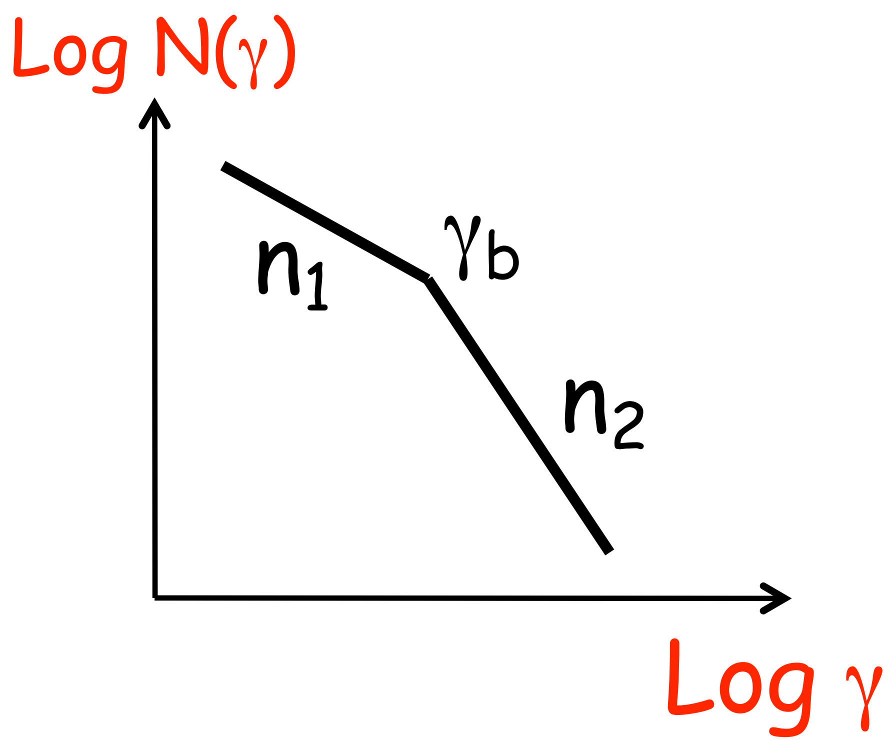


$$U'_{\rm syn} = \frac{\nu_s L(\nu_s)}{4\pi R^2 c \delta^4}$$

Inverse Compton



A more modest model - 1



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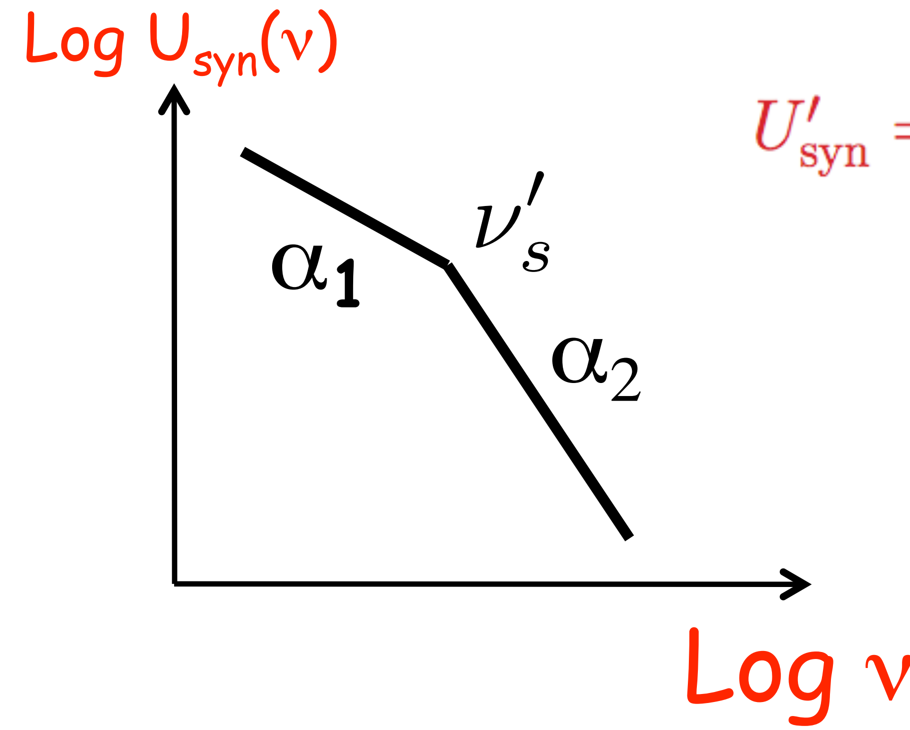
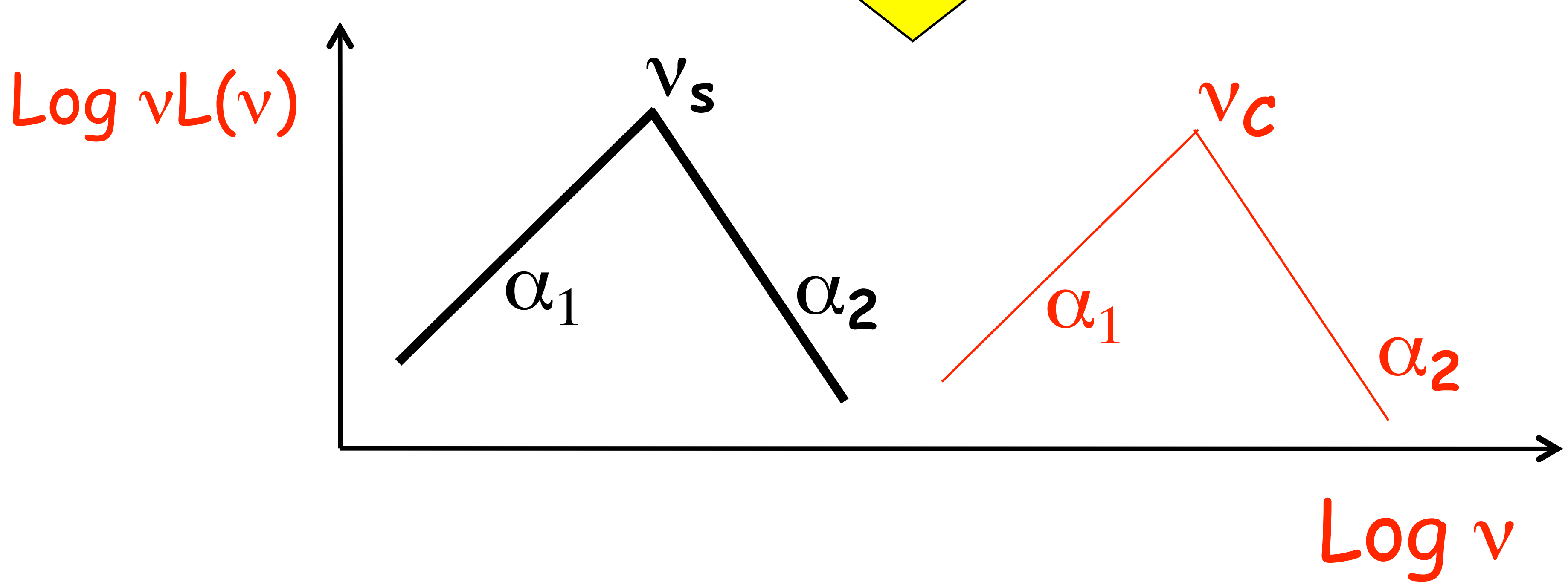


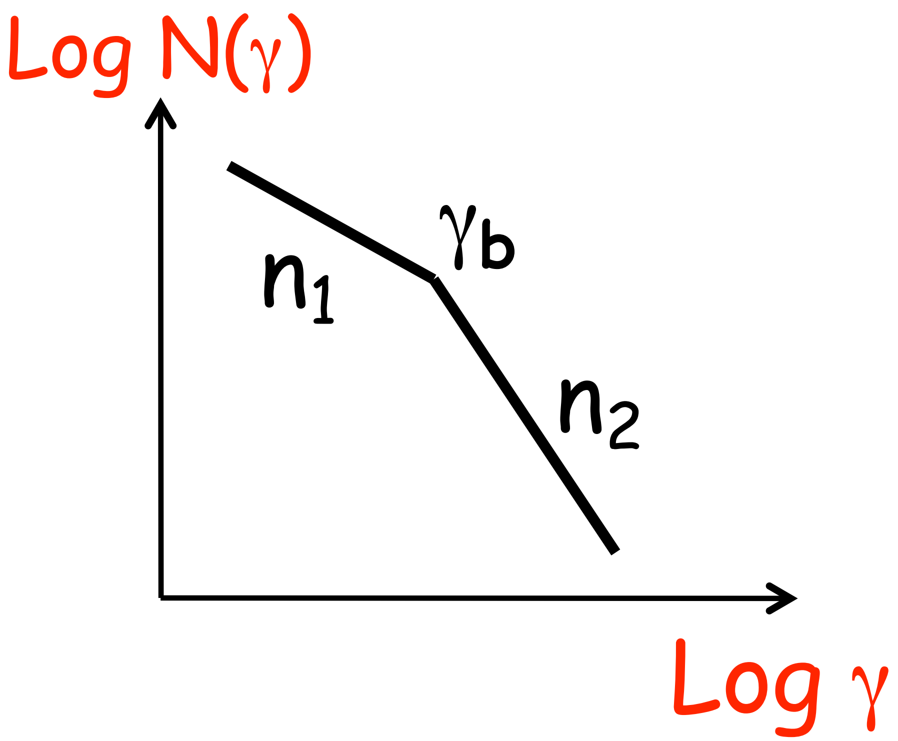
$$U'_{\rm syn} = \frac{\nu_s L(\nu_s)}{4\pi R^2 c \delta^4}$$

$$\nu_c = \nu'_s \gamma_b^2 \delta \quad \nu'_s = \nu_s/\delta$$

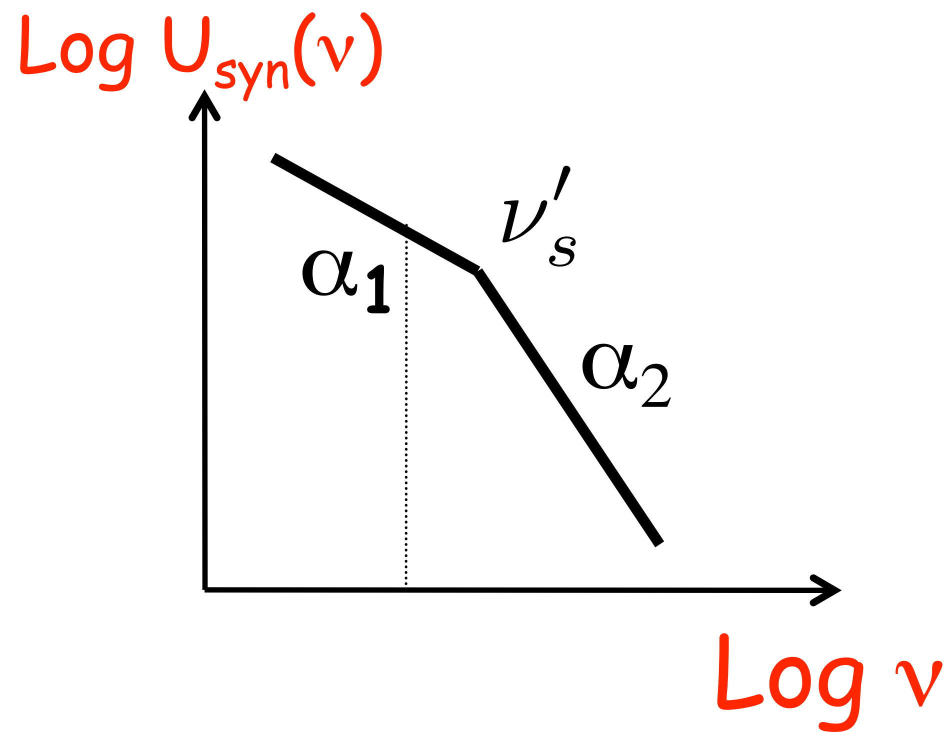


$$\frac{\nu_c L(\nu_c)}{\nu_s L(\nu_s)} = \frac{U'_{\rm syn}}{U_B}$$

A more modest model - 1

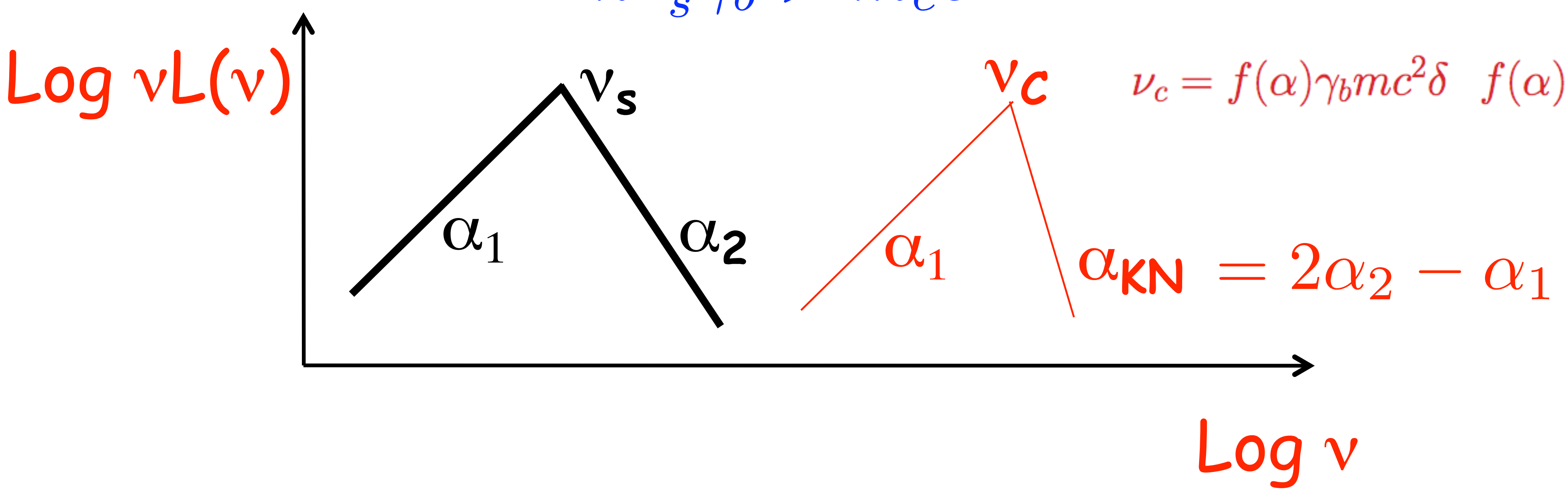


+



"Klein-Nishina regime"

$$h\nu'_s\gamma_b > m_e c^2$$



$$\nu_c = f(\alpha)\gamma_b m c^2 \delta \quad f(\alpha) \simeq 0.1 - 0.2$$

In principle, in this simple version of the Synchrotron-Self Compton (SSC) model, all parameters can be constrained by quantities available from observations:

7 free parameters

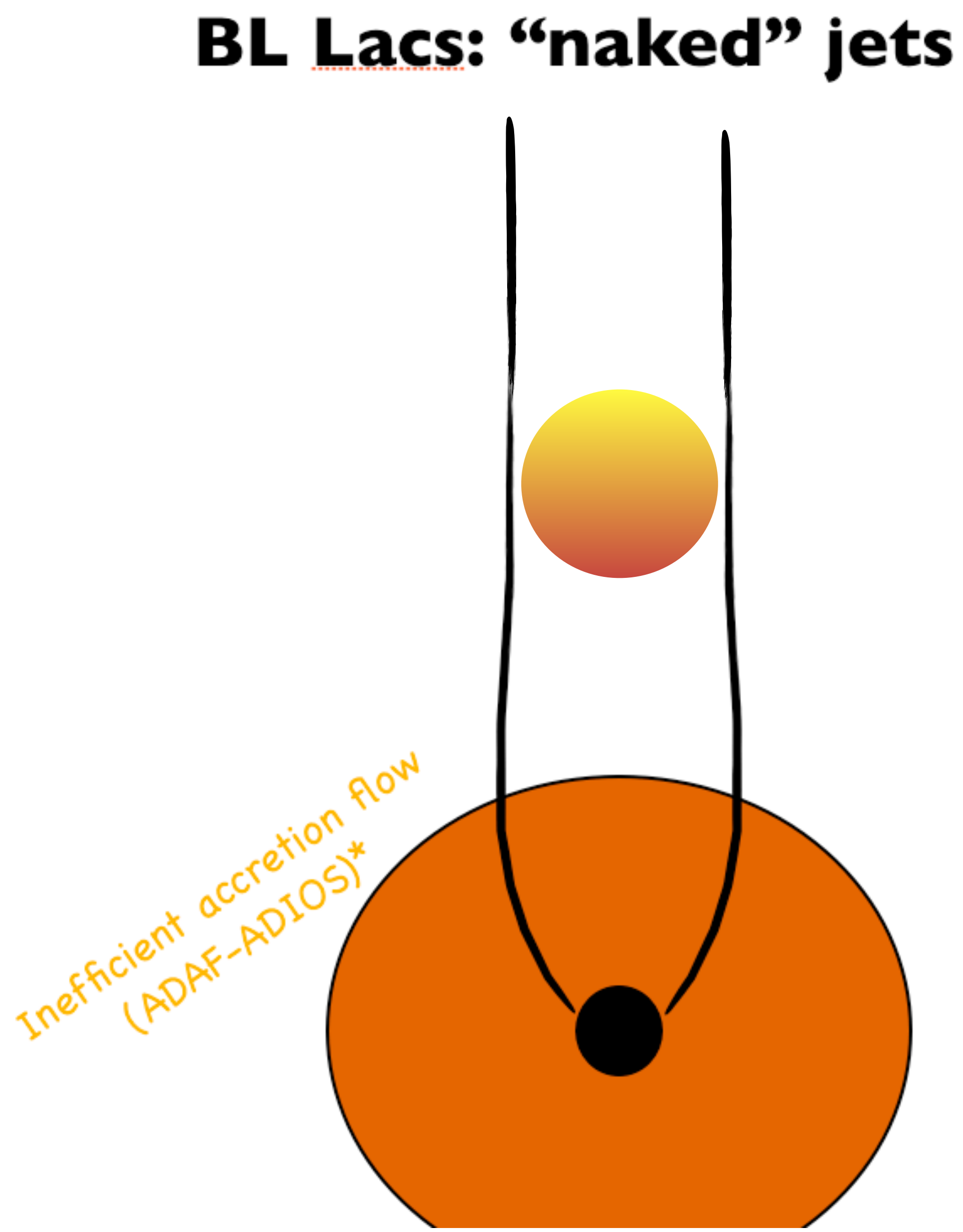
R B N_o γ_b n_1 n_2 δ

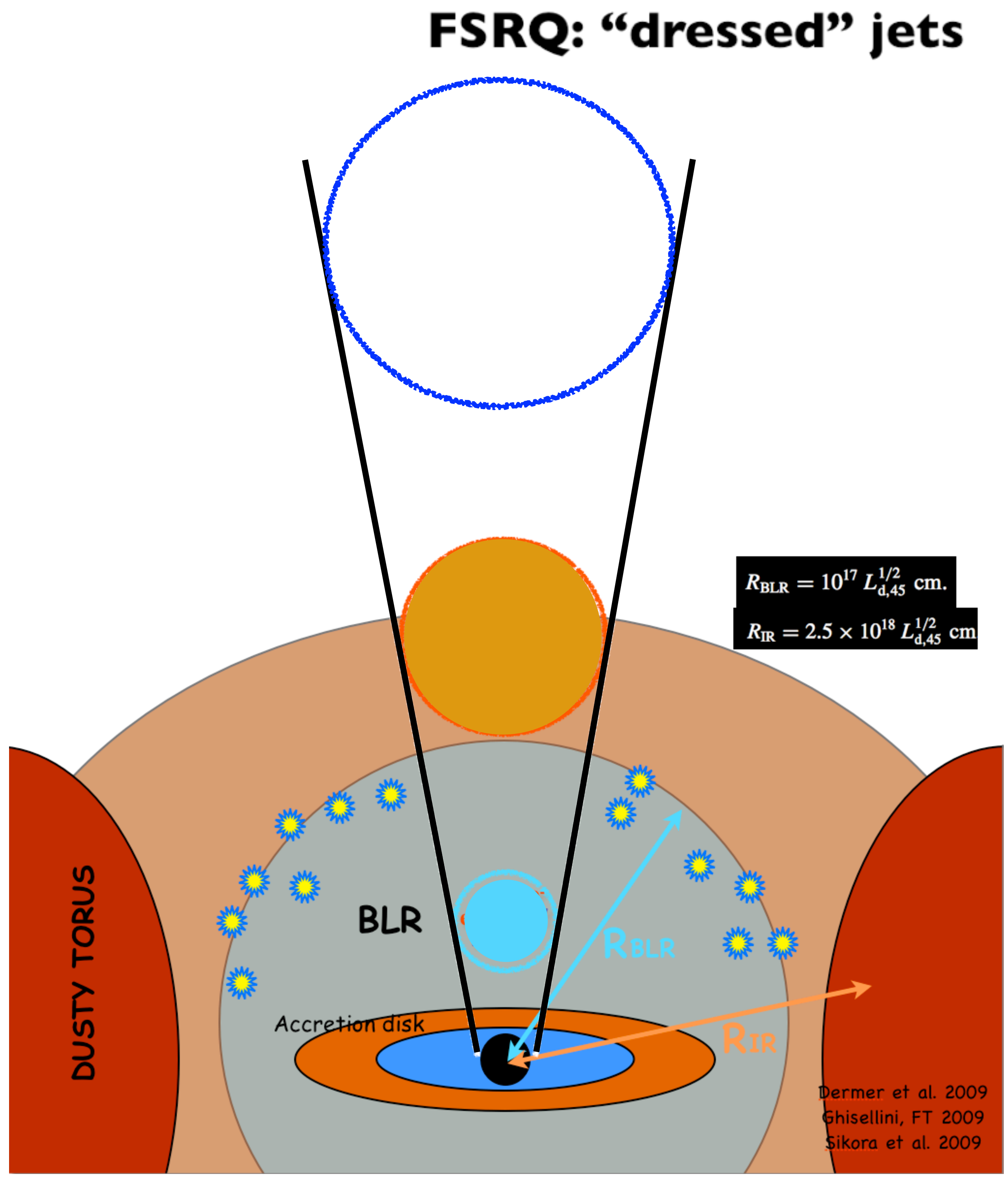
7 observational quantities

ν_s L_s ν_C L_C t_{var} α_1 α_2

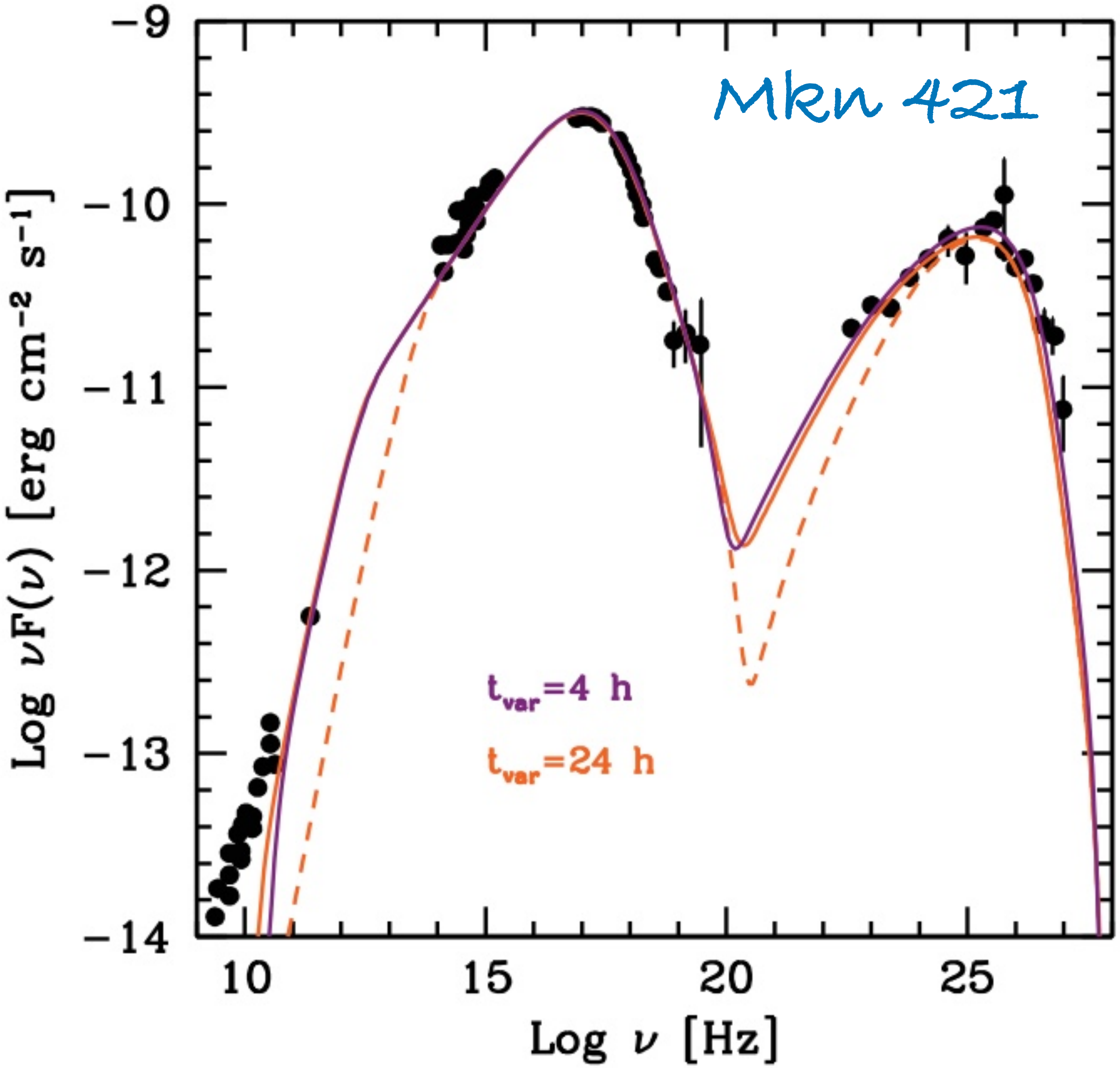
Tavecchio, Maraschi & Ghisellini 1998

Blazars in a nutshell



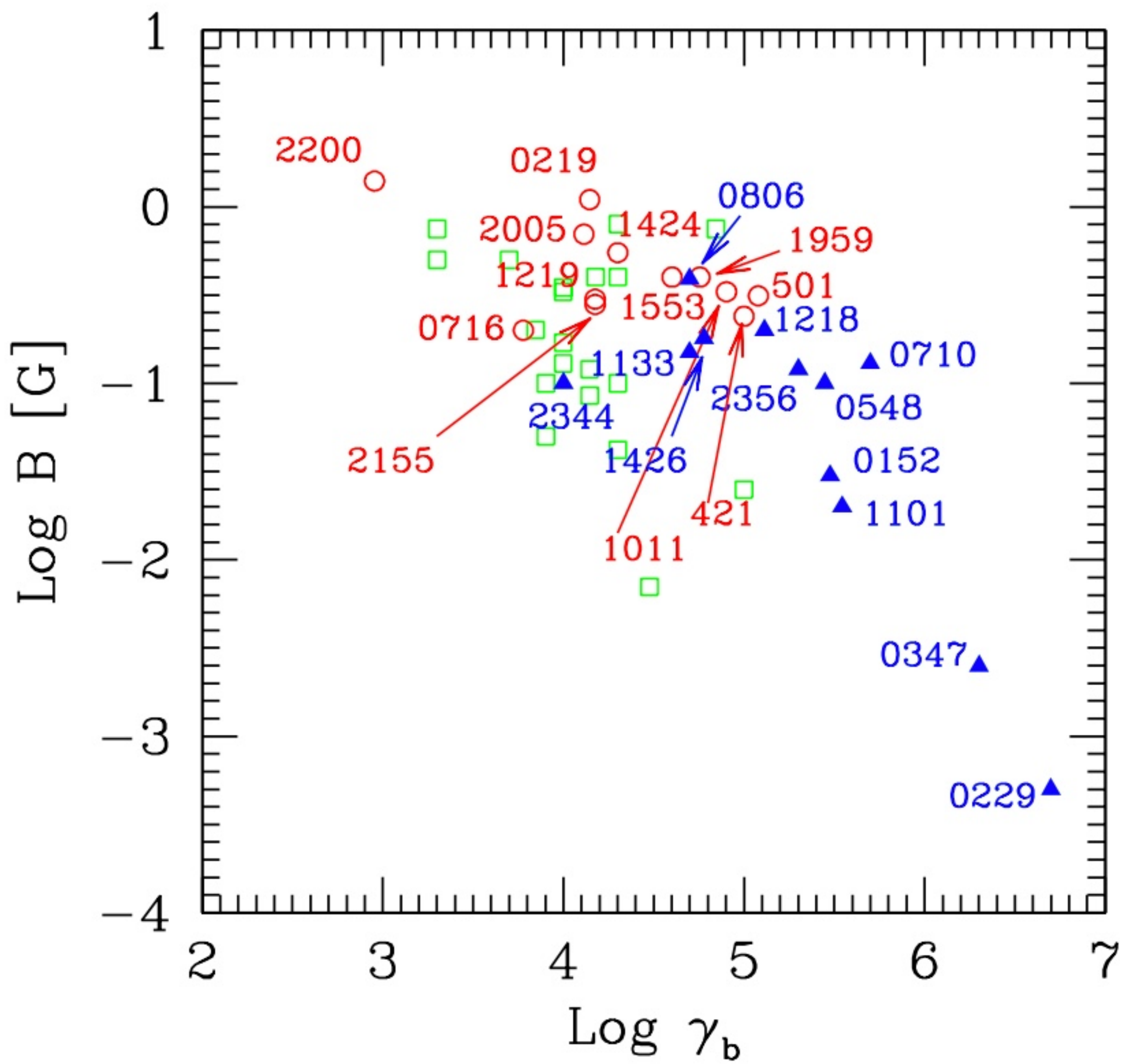


Application: BL Lacs



Tavecchio and Ghisellini 2016

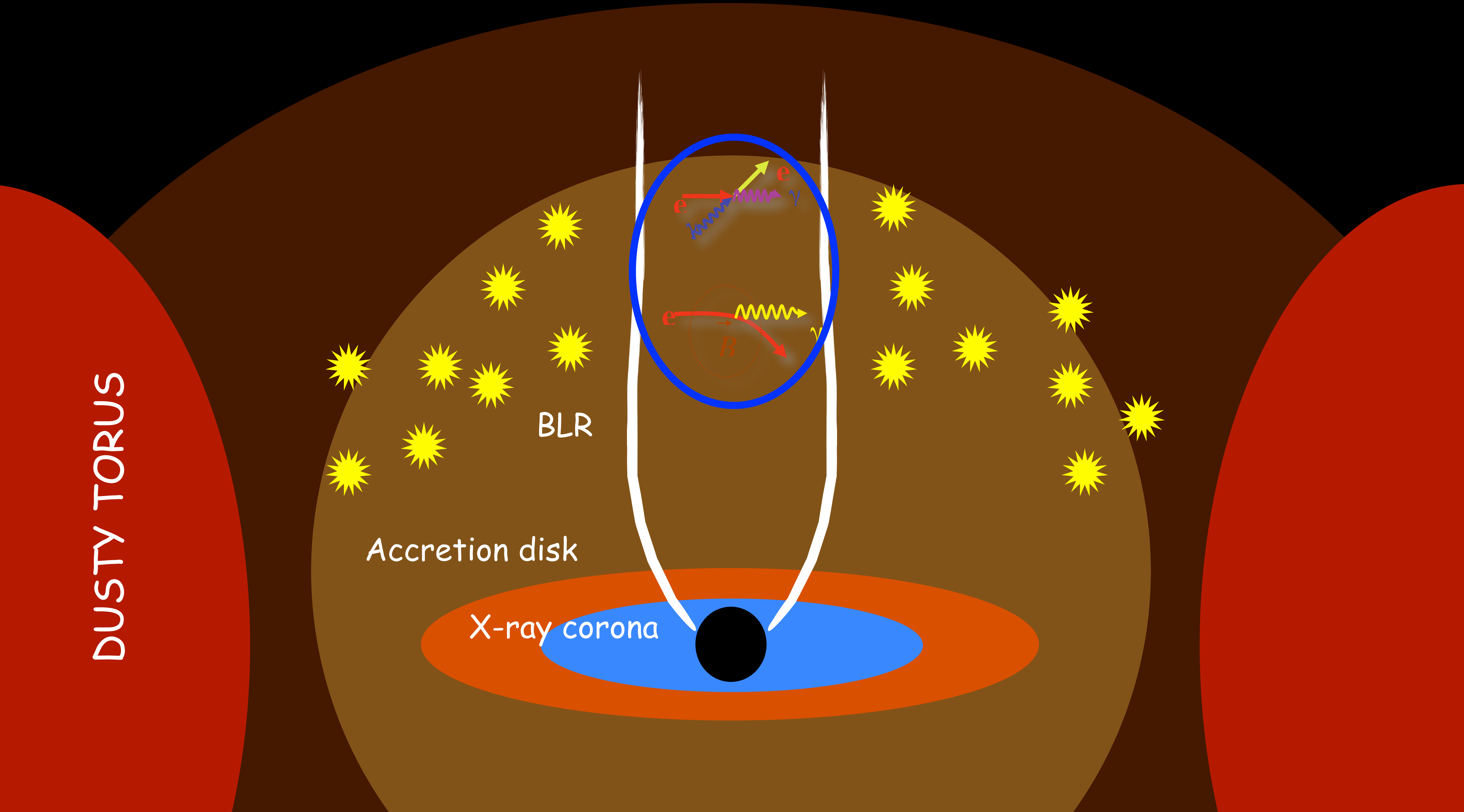
Model (1)	γ_{min} (2)	γ_b (3)	γ_{max} (4)	n_1 (5)	n_2 (6)	B (7)	K (8)	R (9)	δ (10)
1	500	1.7×10^5	2×10^6	2.2	4.8	0.075	1.3×10^4	1	25
2	700	2.5×10^5	4×10^6	2.2	4.8	0.06	3.2×10^3	3.6	14



Tavecchio et al. 2010

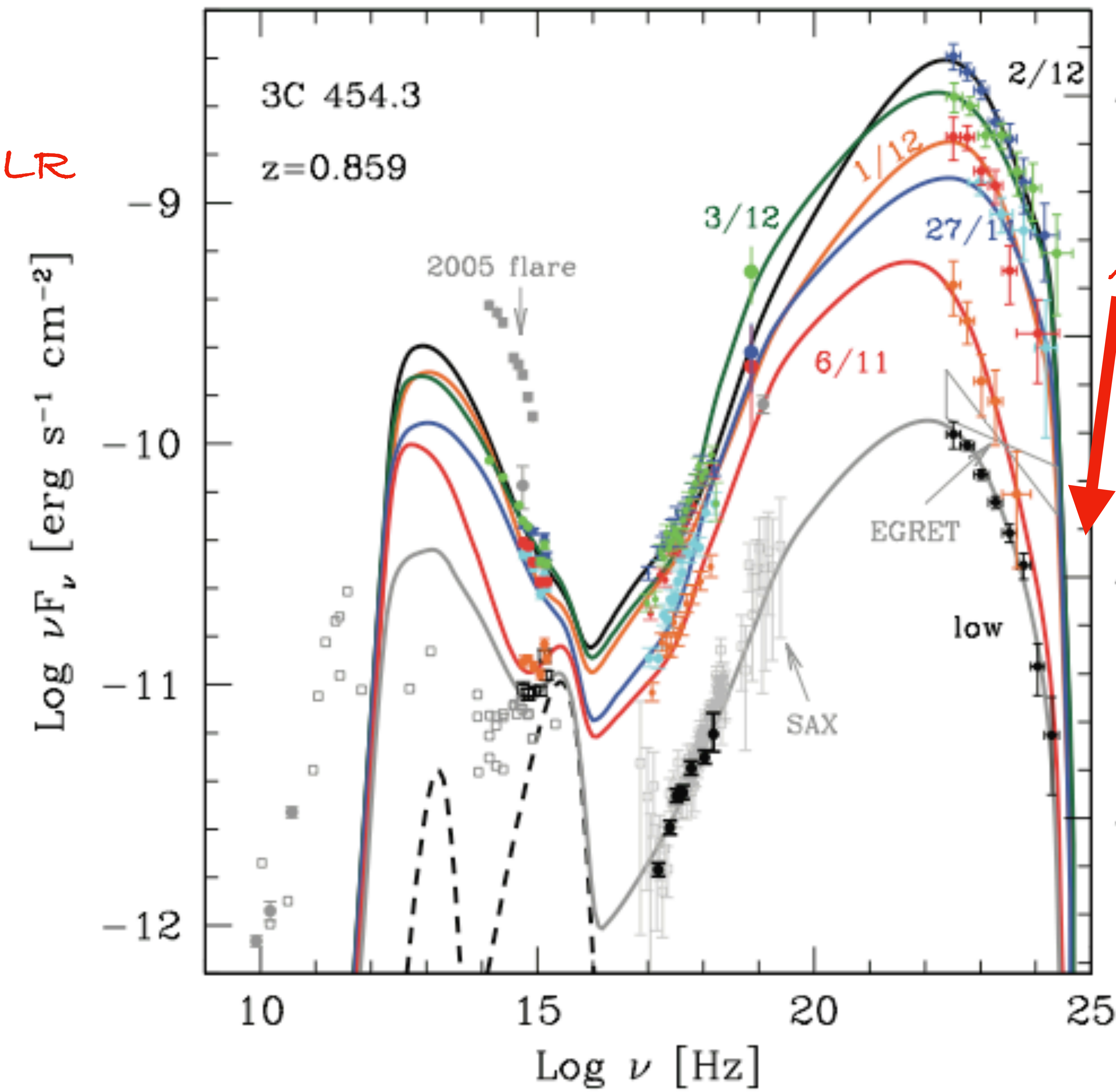
FSRQs: the "canonical" scenario

Dermer et al. 2009
Ghisellini, FT 2009
Sikora et al. 2009



4C454.3

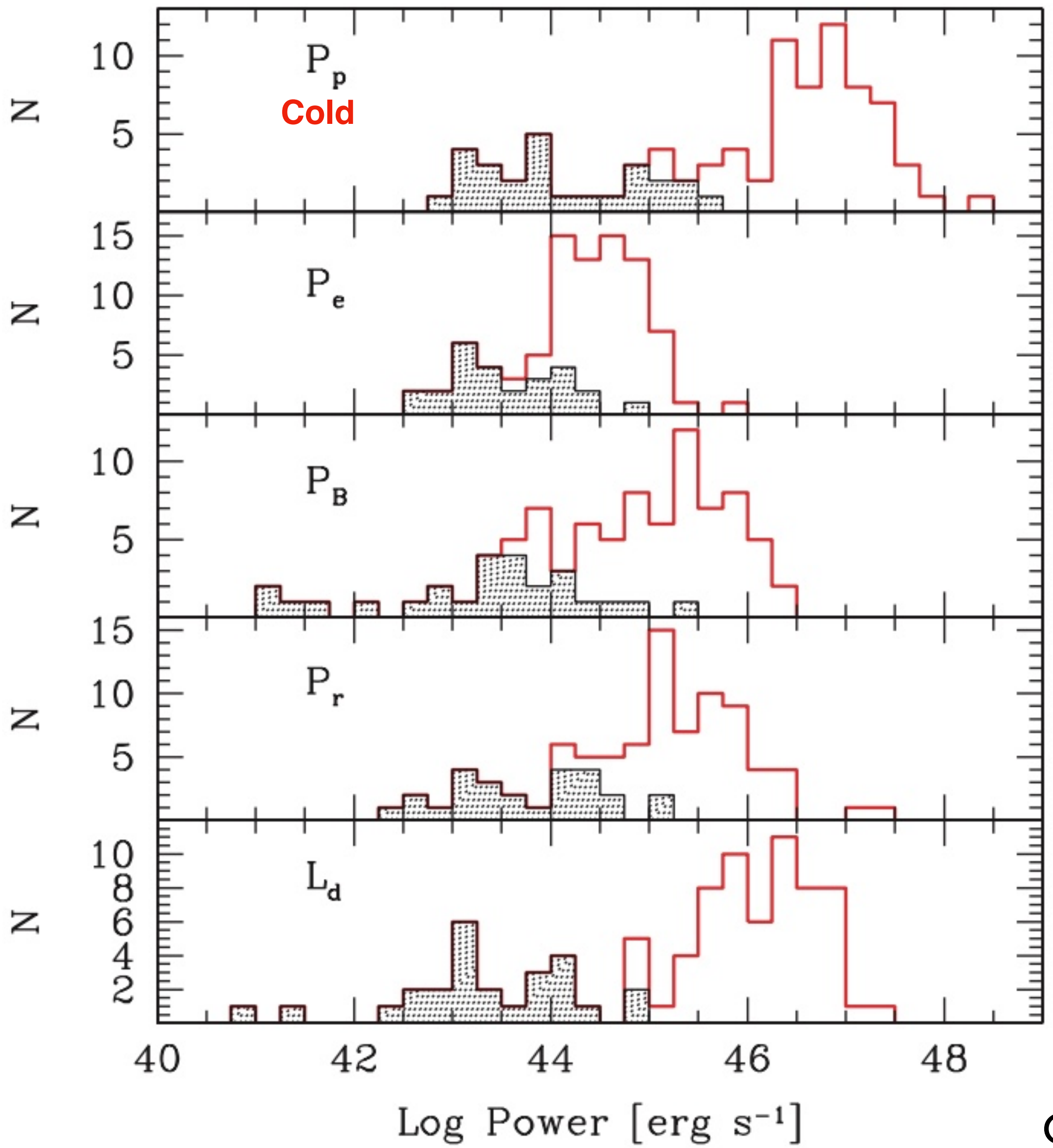
Within the BLR



Absorption (20 GeV)

Bonnoli et al. 2011

Jet powers



Ghisellini et al. 2010

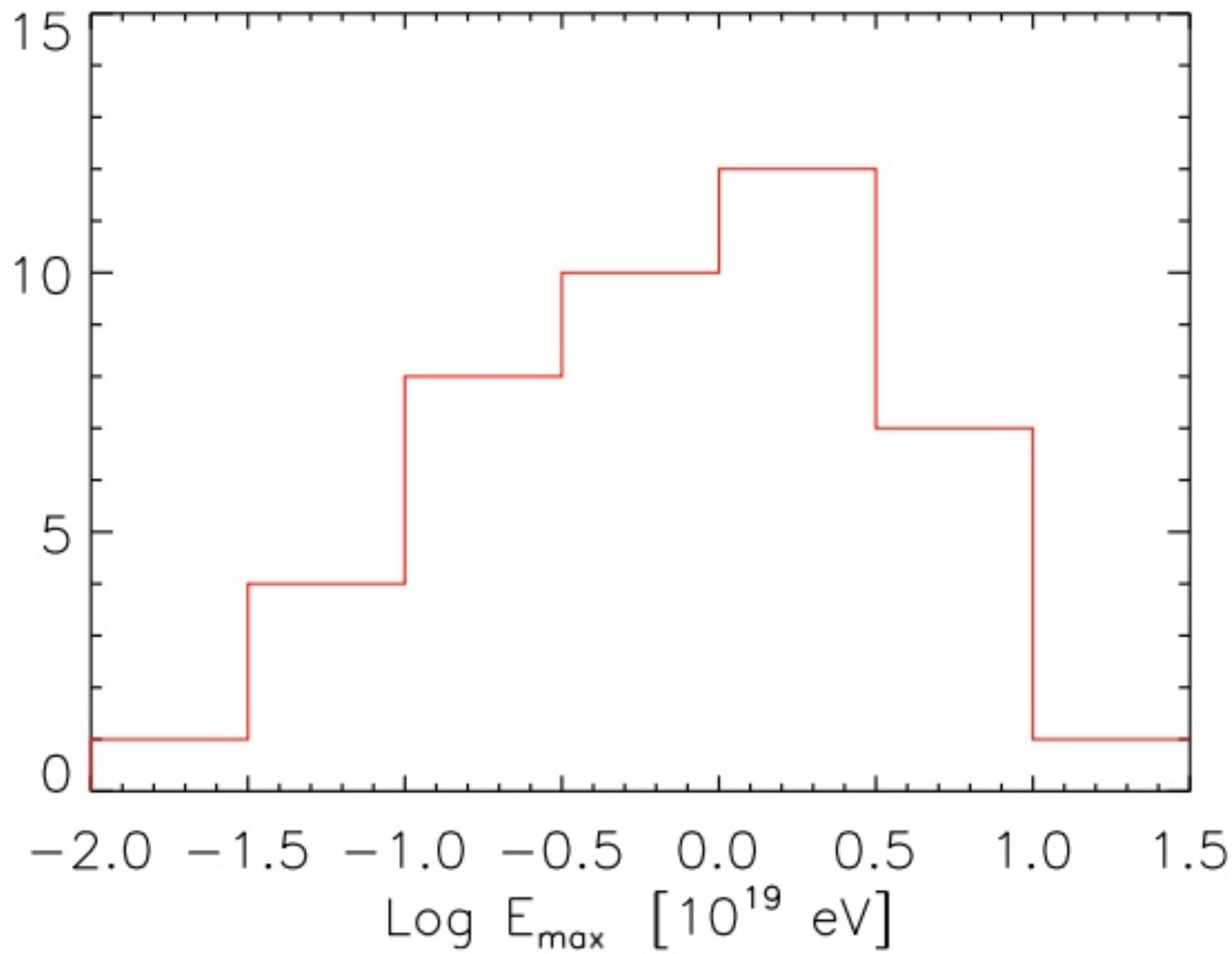
Leptons or hadrons?

Hadrons could be accelerated to very-high and ultra-high energy

Jets offer ideal conditions (B, radius,power)

→ UHECR
Neutrinos

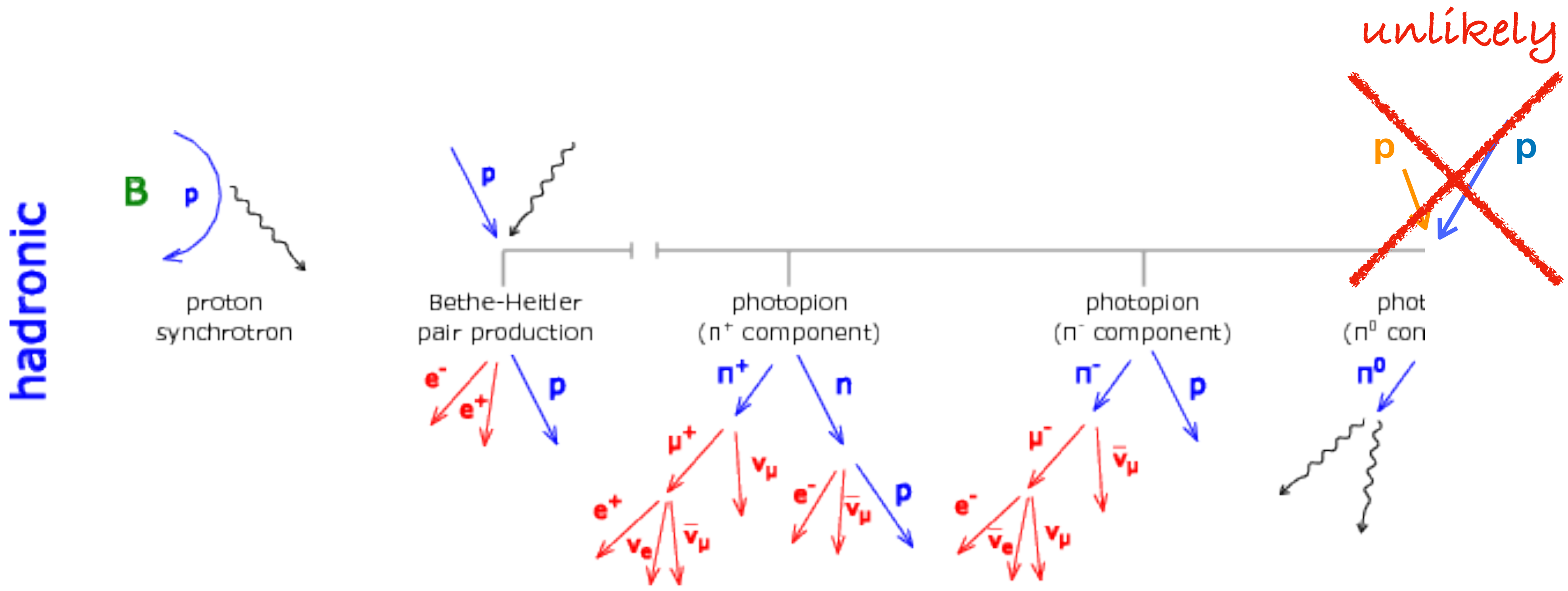
Maximum proton energy



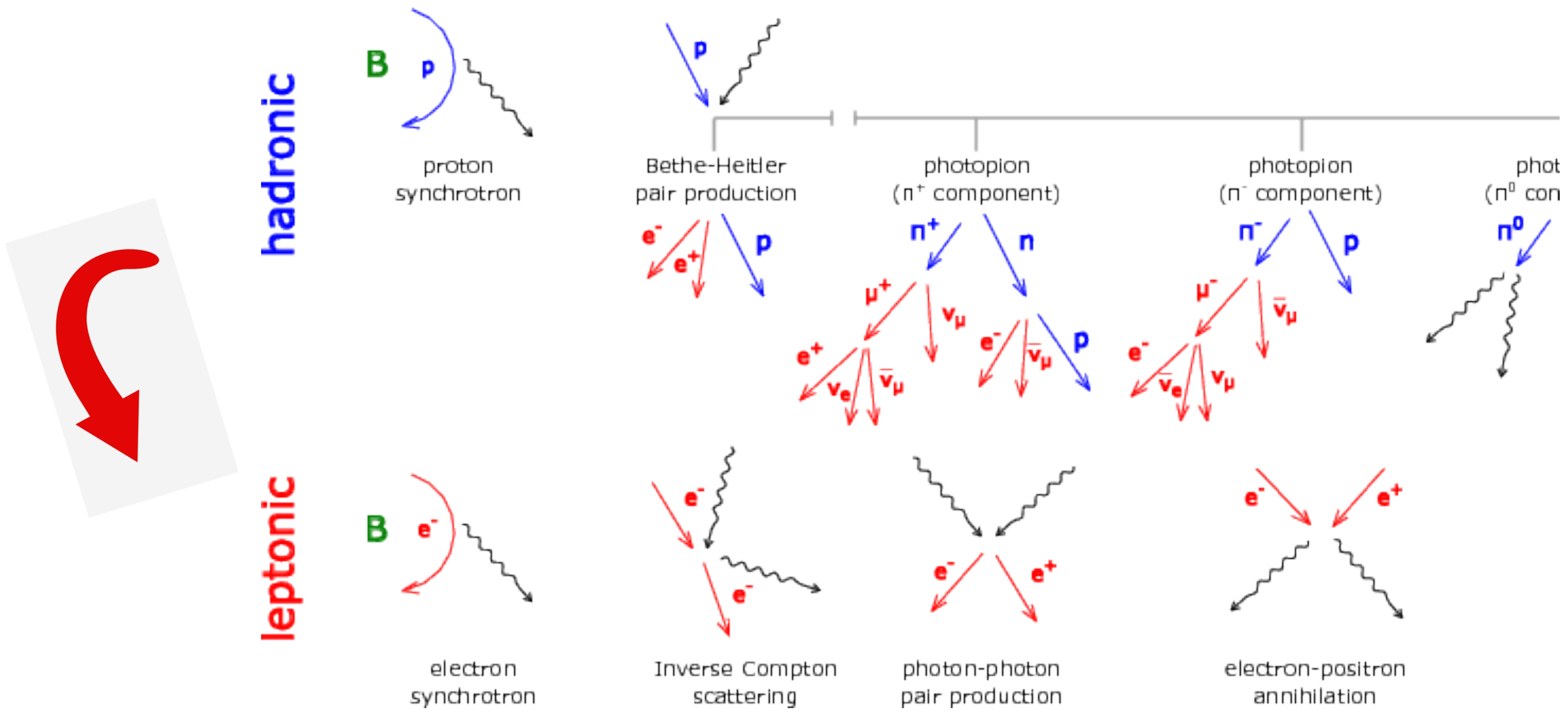
Z=1
Obs. frame

Hillas criterium

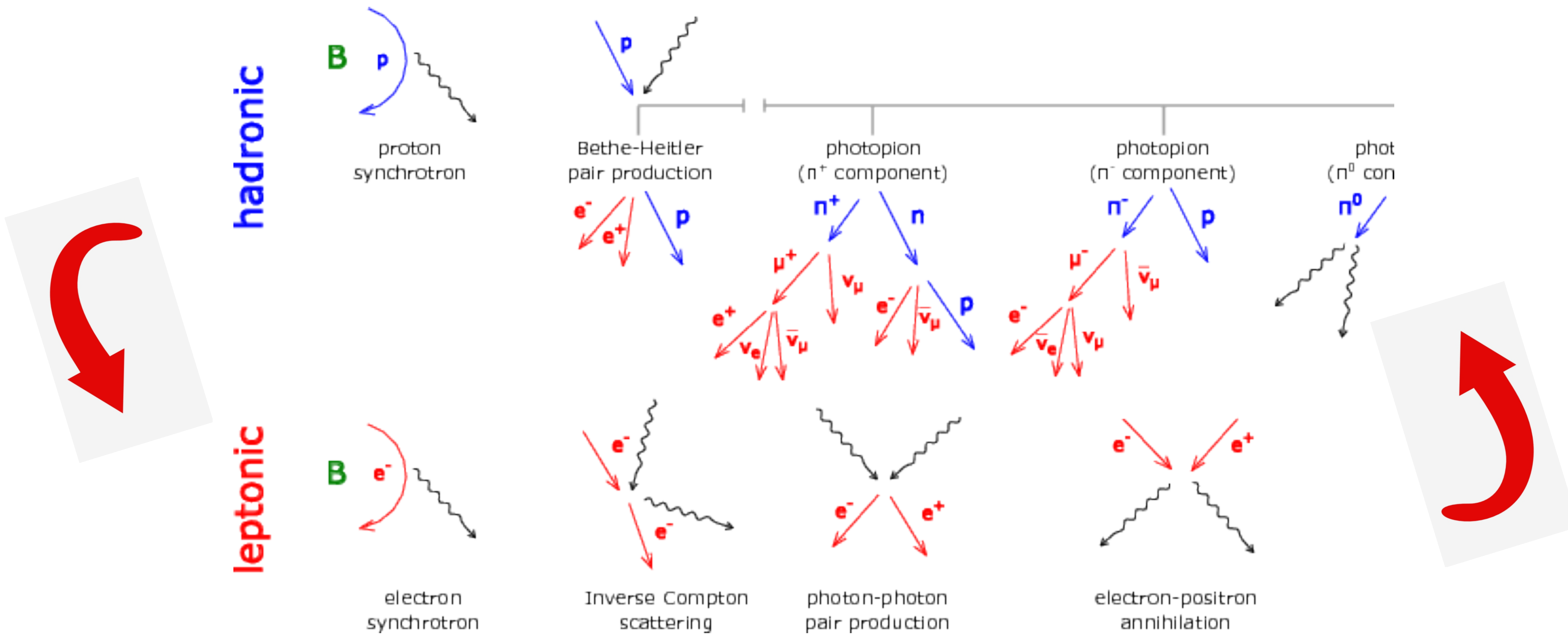
$$E_{Z,\max} = 7 \times 10^{20}\,\mathrm{eV} \left(\frac{Z}{26}\right) \left(\frac{B}{0.35\,\mathrm{G}}\right)$$



hadronic
B
p
proton synchrotron
p
Bethe-Heitler pair production
e^-
e^+
p
photopion (π^+ component)
π^+
n
μ^+
ν_μ
e^+
ν_e
$\bar{\nu}_\mu$
e^-
$\bar{\nu}_\mu$
p
photopion (π^- component)
π^-
p
μ^-
$\bar{\nu}_\mu$
e^-
$\bar{\nu}_e$
ν_μ
phot
(π^0 con
π^0
unlikely
p
p



hadronic
leptonic
B
p
proton synchrotron
Bethe-Heitler pair production
photopion (π⁺ component)
photopion (π⁻ component)
phot (π⁰ con
e⁻
e⁺
n
π⁺
π⁻
π⁰
μ⁺
μ⁻
electron synchrotron
Inverse Compton scattering
photon-photon pair production
electron-positron annihilation



hadronic
leptonic
B
p
proton
synchrotron
p
Bethe-Heitler
pair production
photopion
(π⁺ component)
photopion
(π⁻ component)
phot
(π⁰ con
e⁻
e⁺
p
π⁺
n
μ⁺
ν_μ
e⁺
ν_e
ν̄_μ
e⁻
ν̄_μ
p
π⁻
p
μ⁻
ν̄_μ
e⁻
ν̄_e
ν_μ
π⁰
B
e⁻
electron
synchrotron
e⁻
e⁻
Inverse Compton
scattering
e⁻
e⁺
photon-photon
pair production
e⁻
e⁺
electron-positron
annihilation

Opacity

Efficient photomeson reactions requires high photon density

↓

Large opacity to gamma rays

↓

The direct link between high-energy gamma-ray emission and neutrinos is (at least partially) lost

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

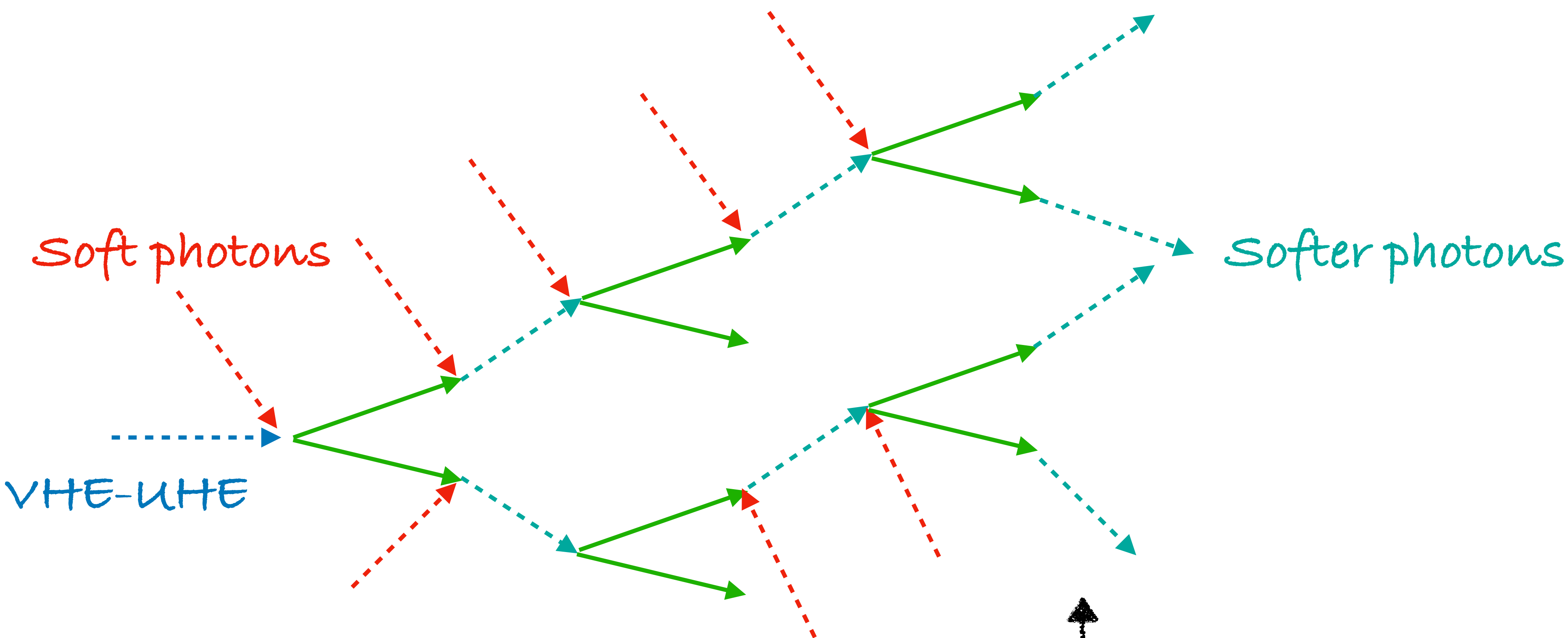
$$f_{p\gamma} \propto n_{soft}$$

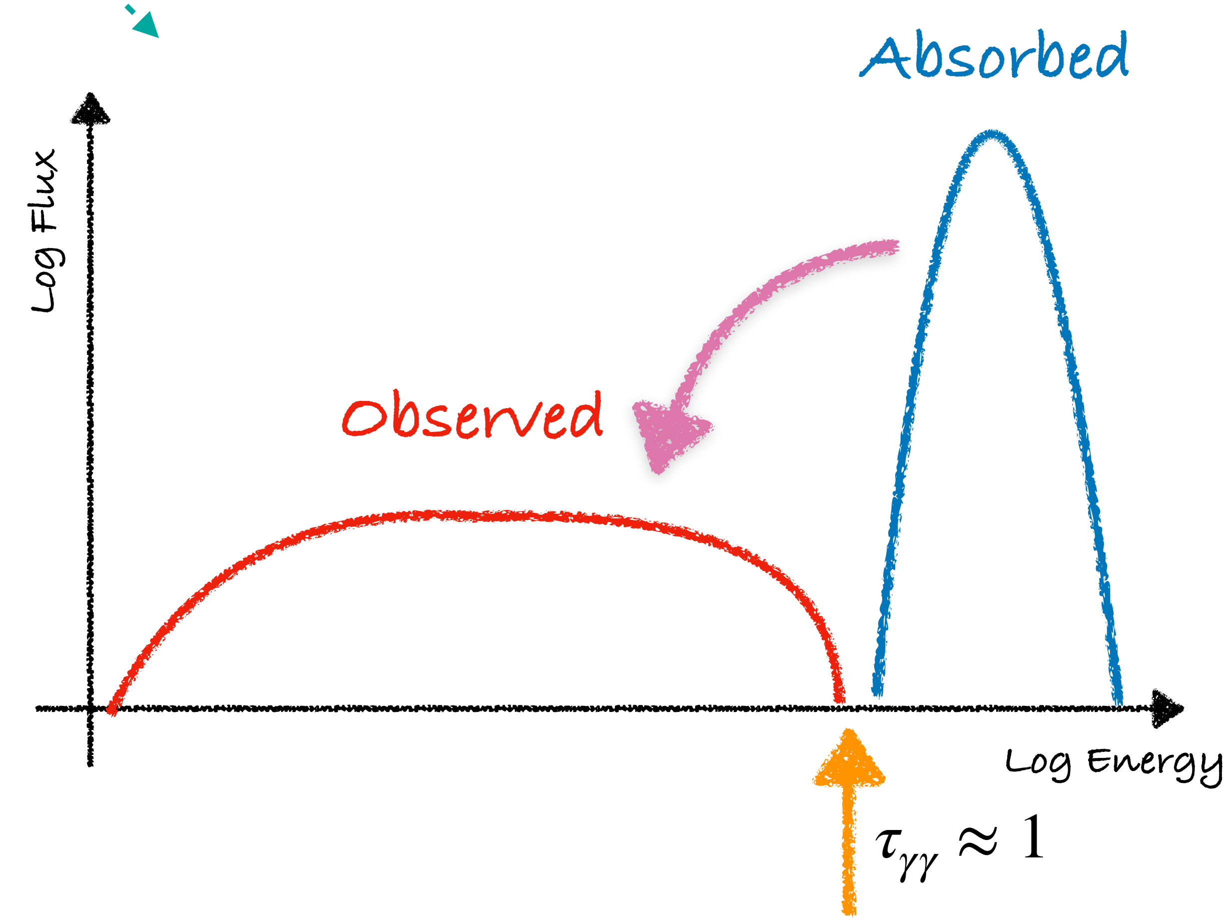
$$\tau_{\gamma\gamma}(\varepsilon_\gamma^c) \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_{p\gamma}(\varepsilon_p) \sim 10 \left(\frac{f_{p\gamma}(\varepsilon_p)}{0.01}\right)$$

$$\varepsilon_\gamma^c \approx \frac{2m_e^2c^2}{m_p\bar{\varepsilon}_\Delta}\varepsilon_p \sim \mathrm{GeV}\ \left(\frac{\varepsilon_\nu}{25\ \mathrm{TeV}}\right)$$

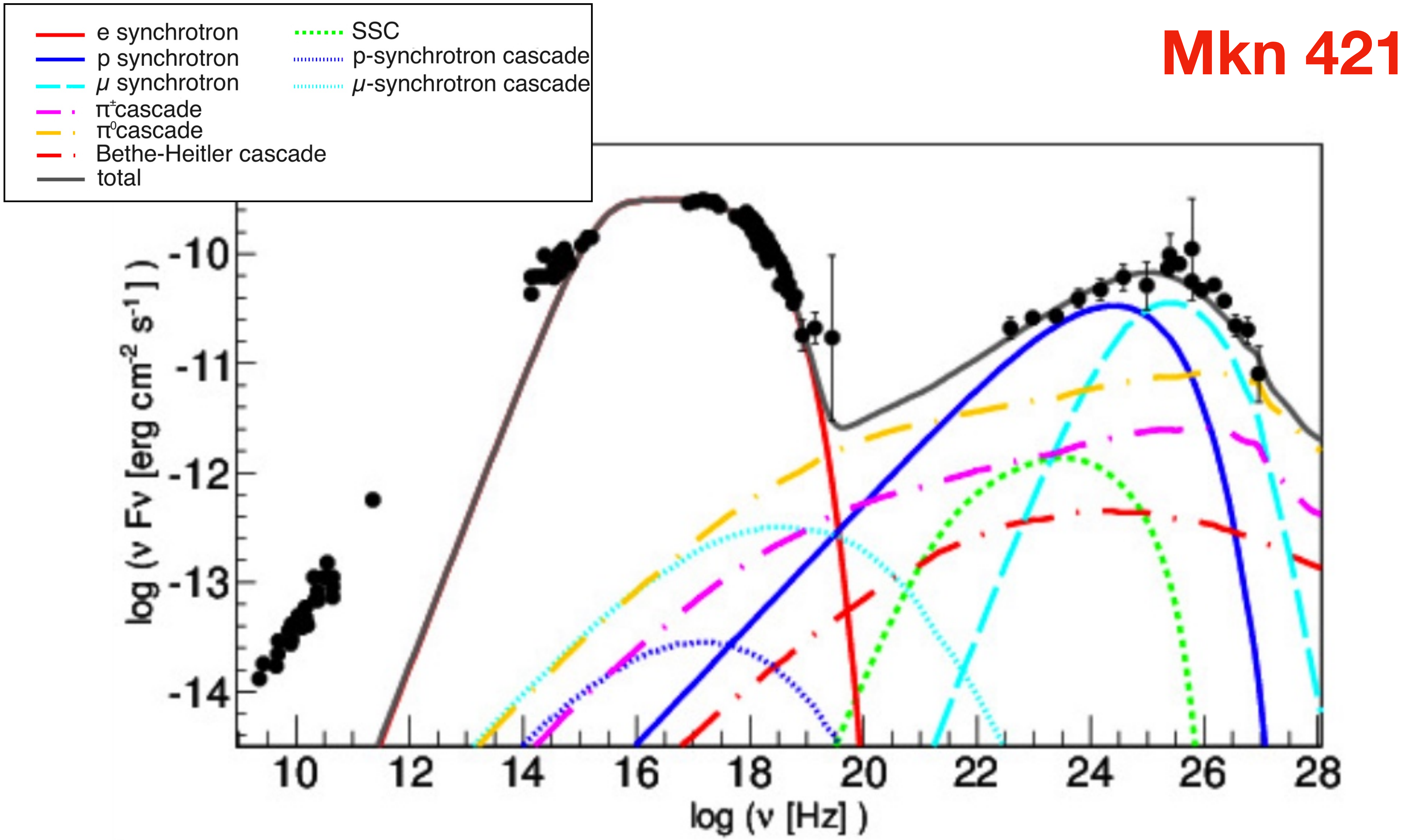
Murase et al. 2016

Cascades


Soft photons
Softer photons
VHE-UHE

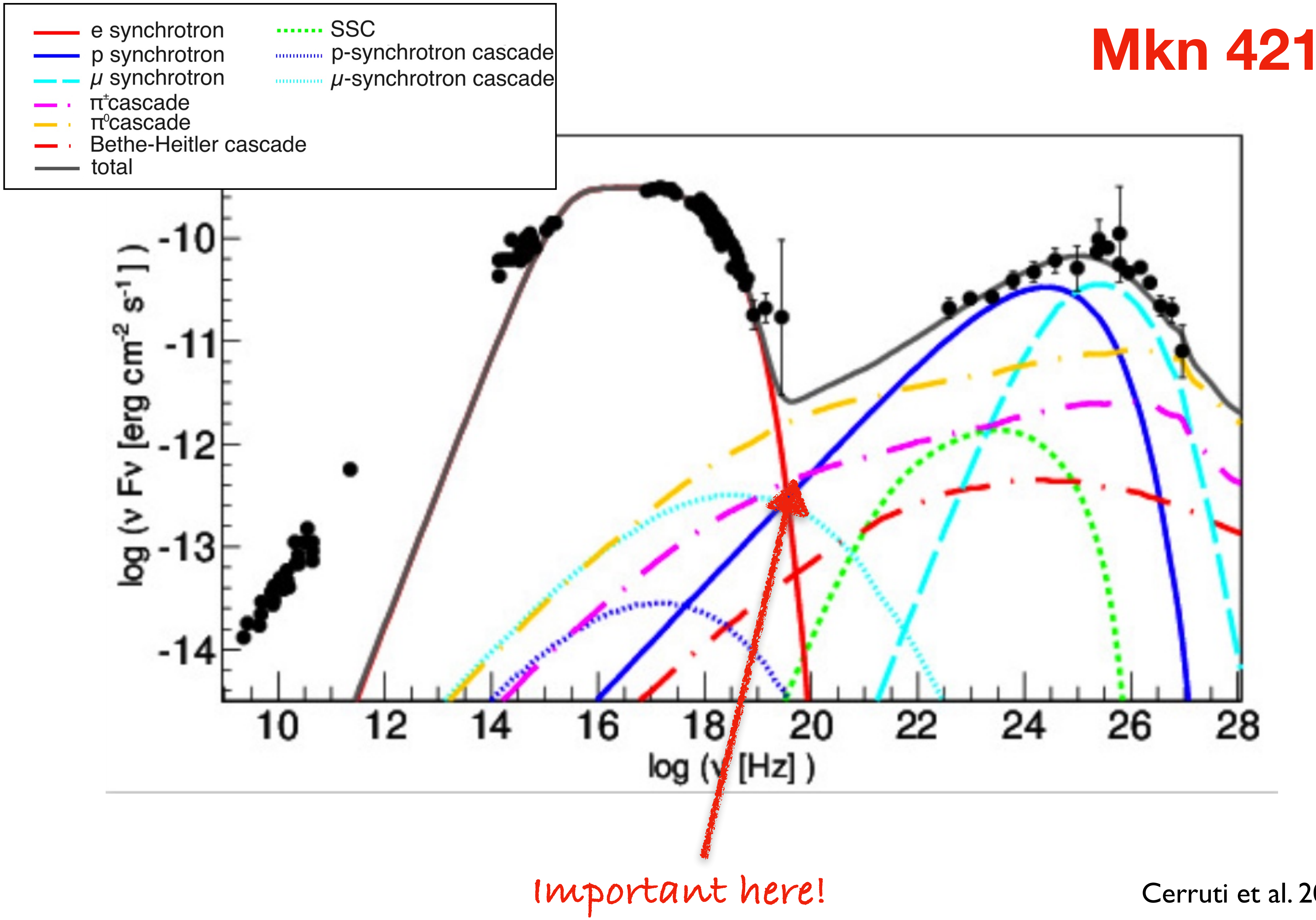

Absorbed
Log Flux
Observed
Log Energy
$\tau_{\gamma\gamma} \approx 1$

Lepto-hadronic models



Cerruti et al. 2015

Lepto-hadronic models

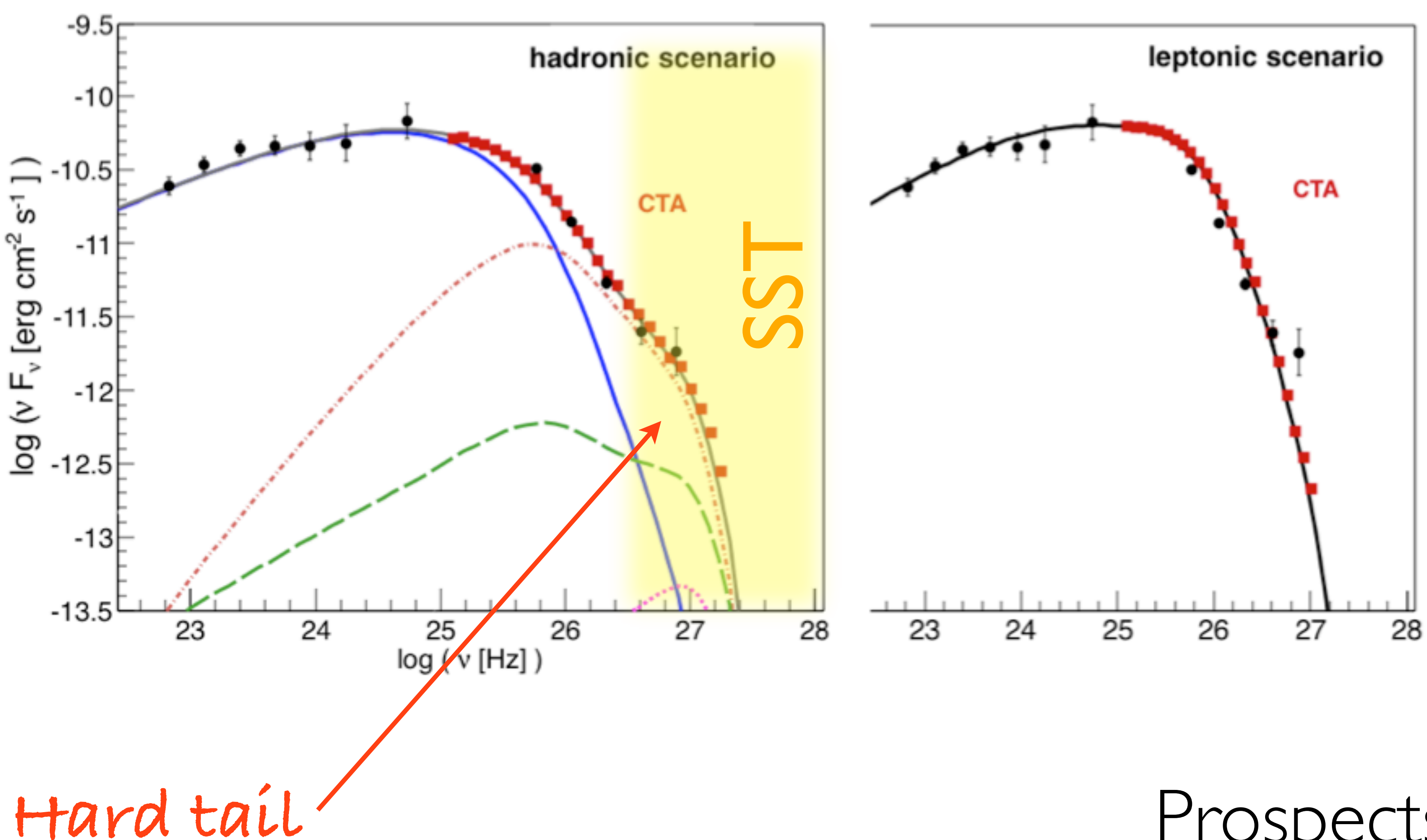


Cerruti et al. 2015

Lepto-hadronic models

Zech et al. 2017

PKS 2155-304

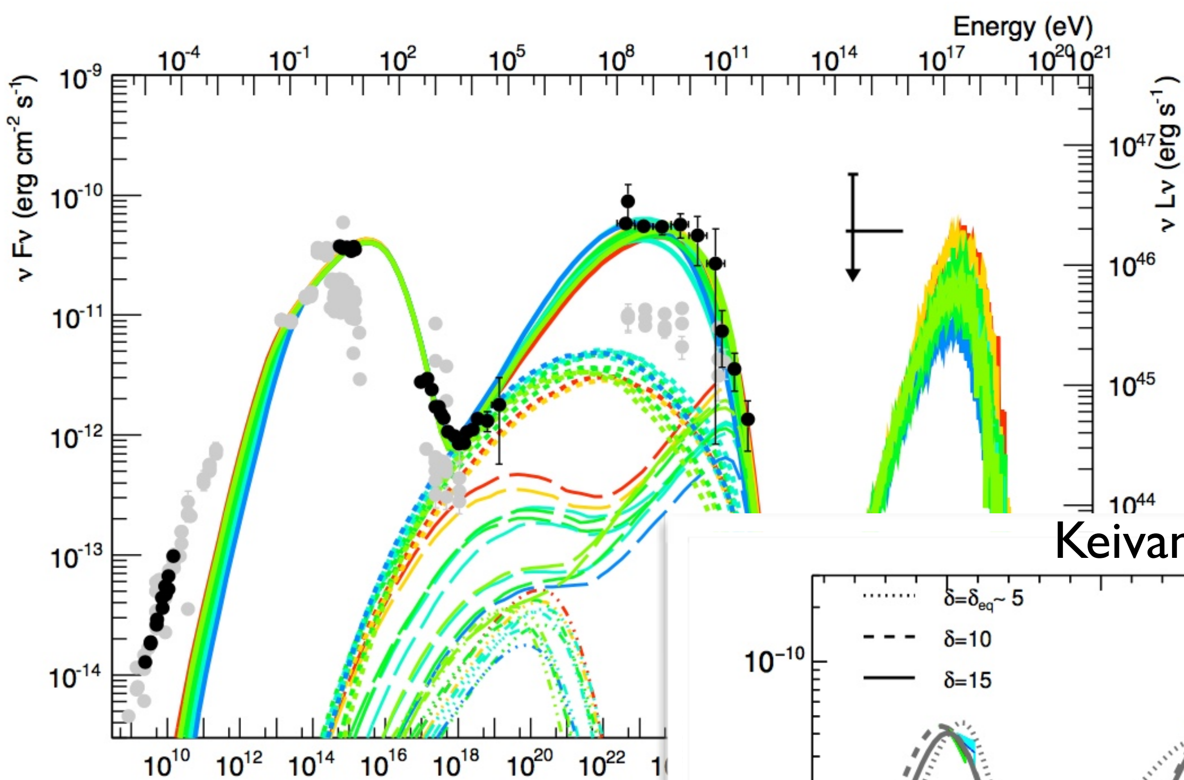


Prospects for CTA

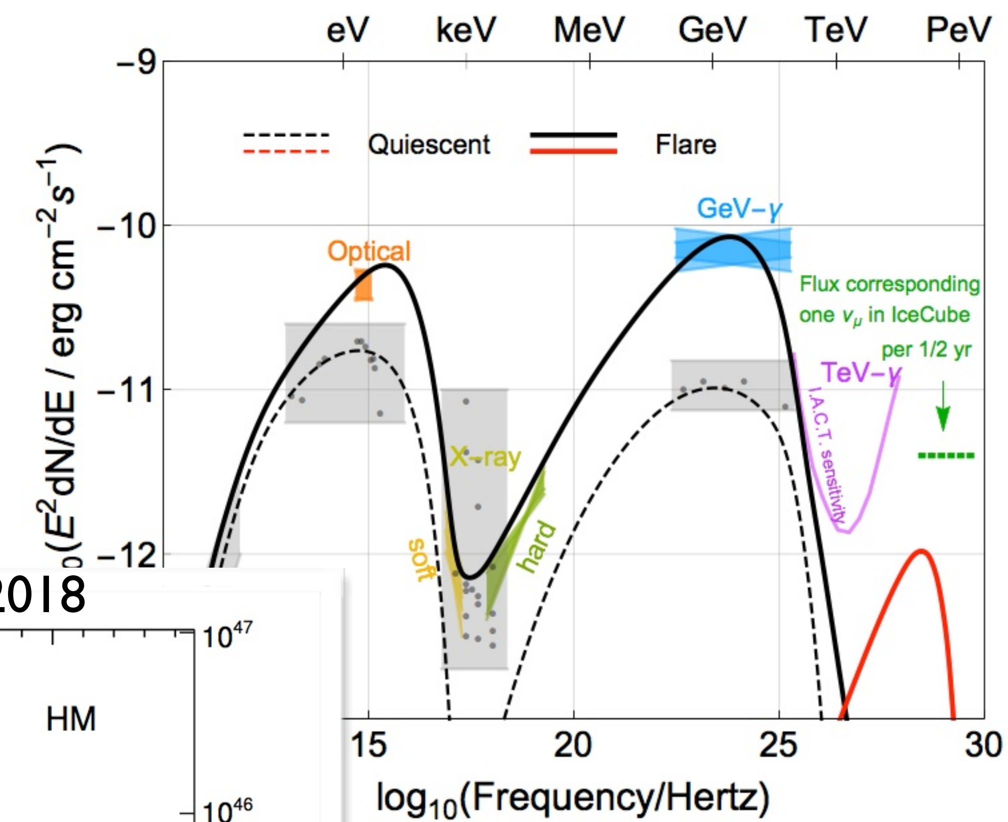
TXS 0506+056 & IC-170922A

2017 september 22

A burst of (one-zone) models …

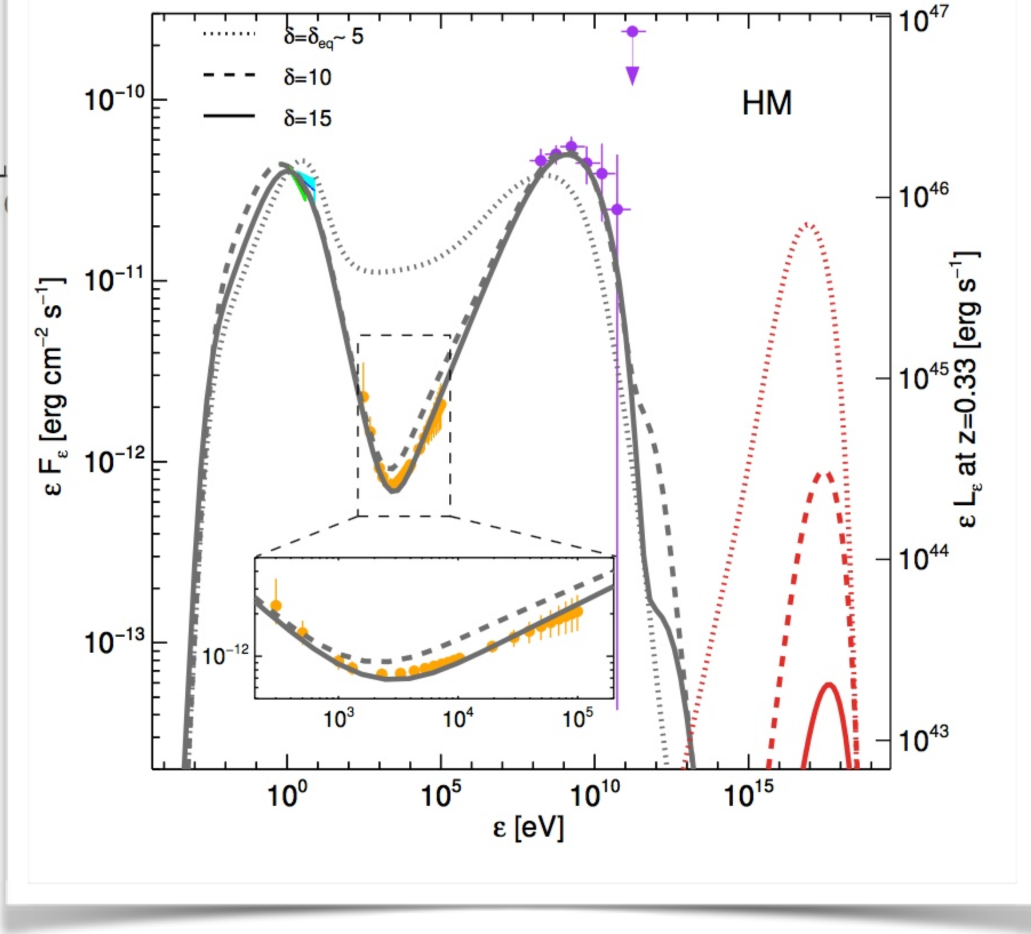


Cerruti et al. 2018



Gao et al. 2018

Keivani et al. 2018



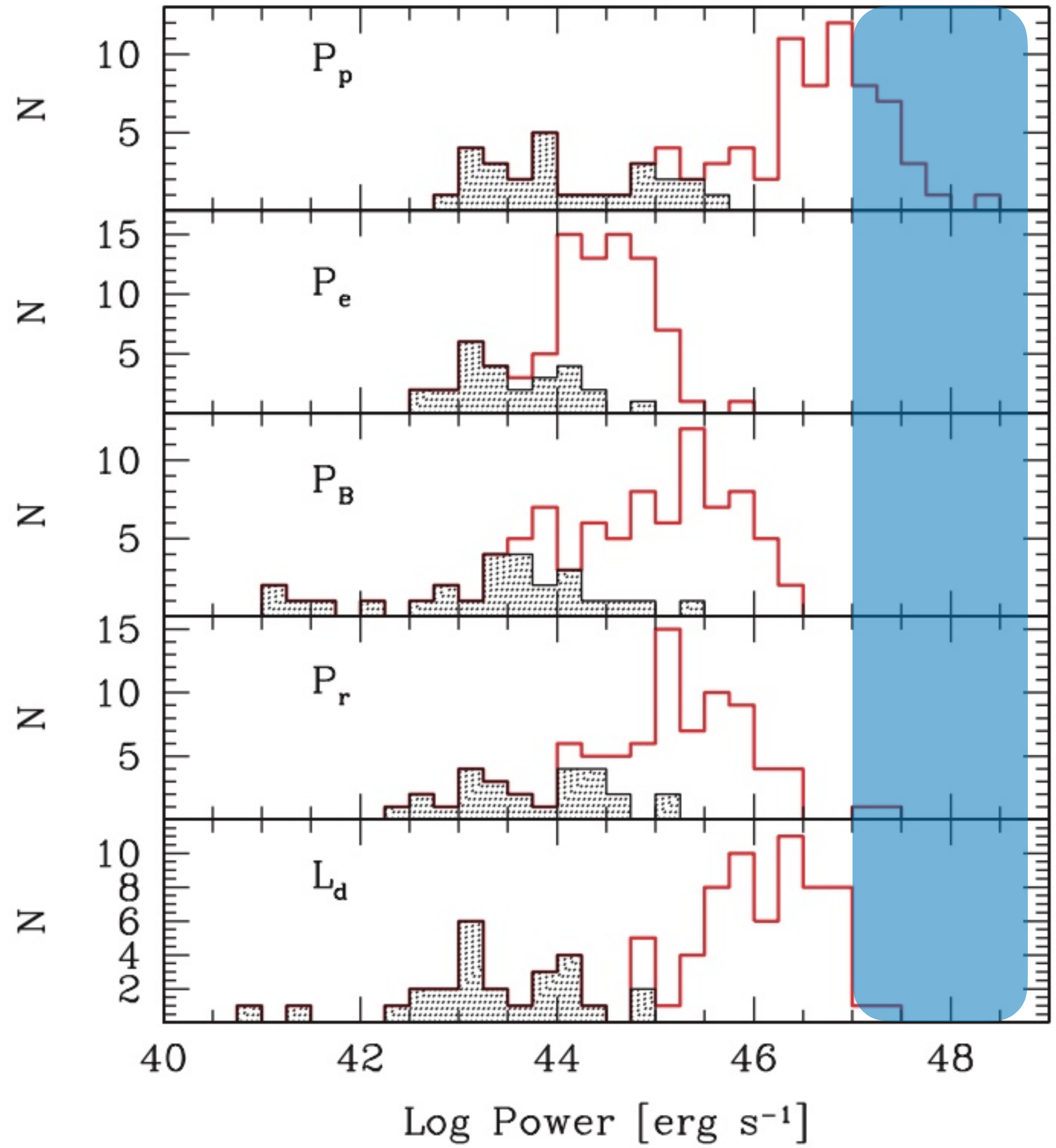
But the required jet power is very large!

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

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

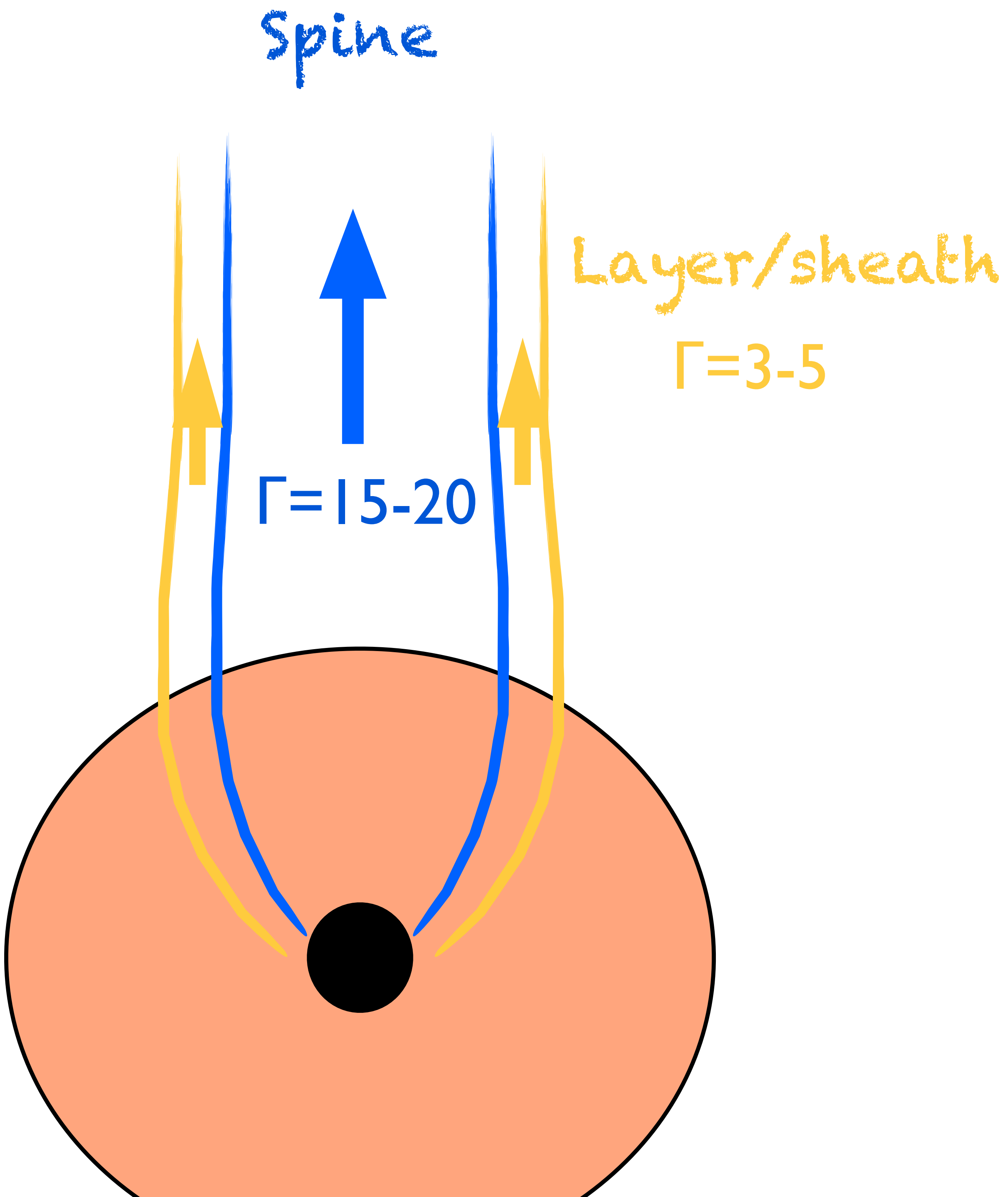
Low target density

Large proton luminosity



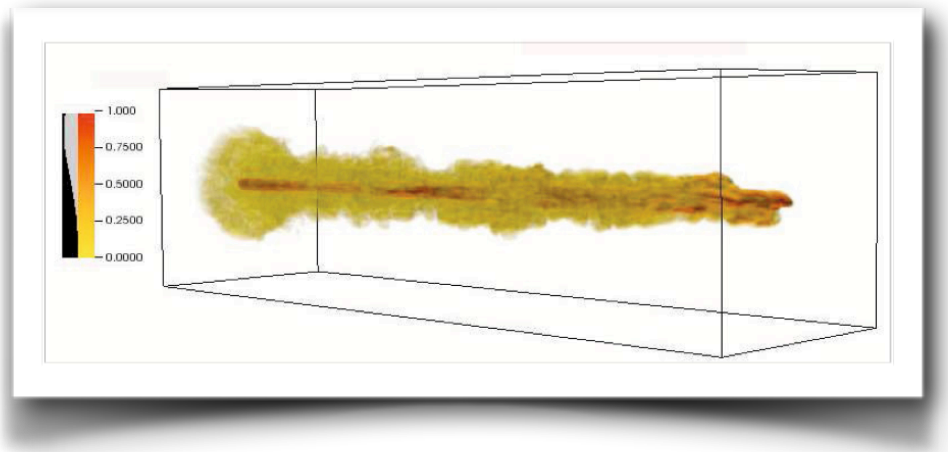
Ghisellini et al. 2010

Structured jets in BL Lacs



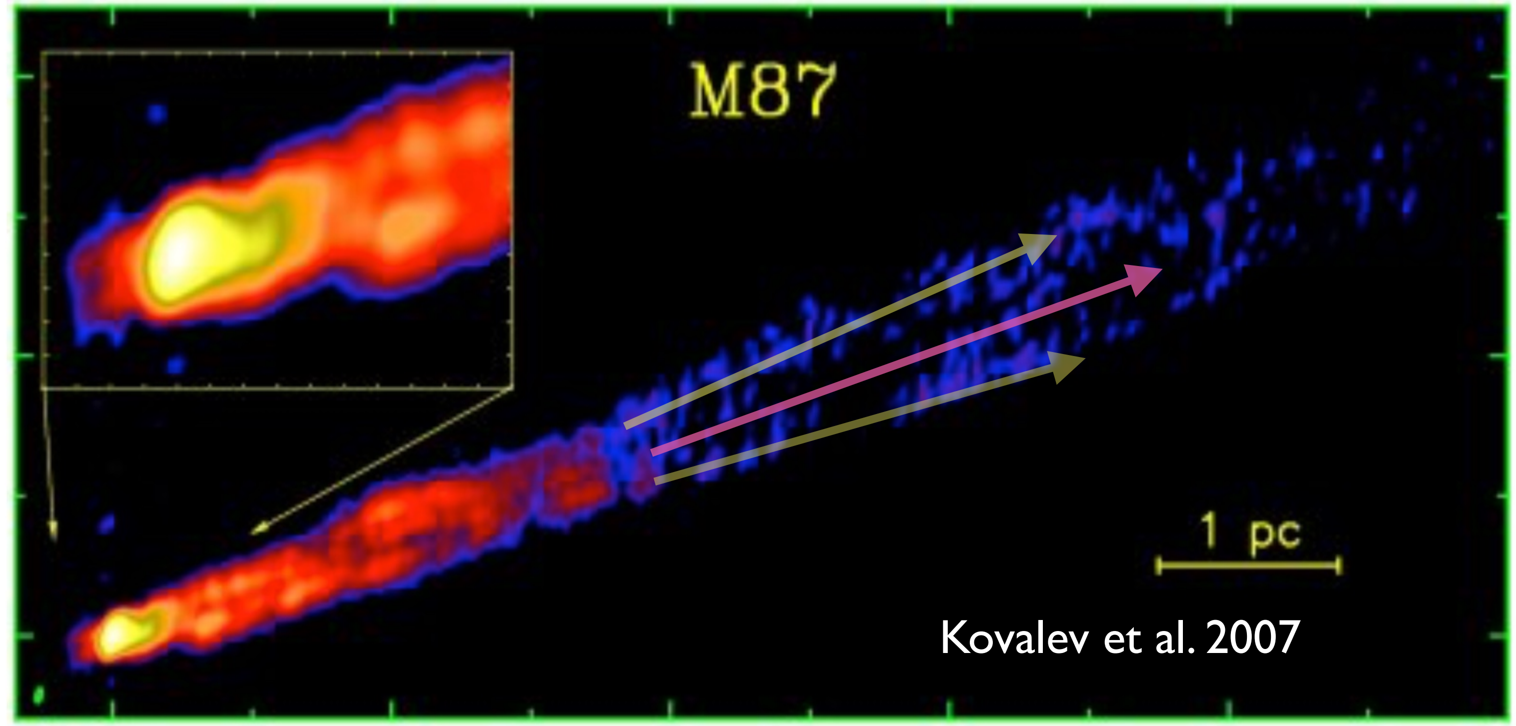
Ghisellini, FT and Chiaberge 2005
Tavecchio & Ghisellini 2008

Structured jets in BL Lacs



Simulations predict spine-layer structure

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

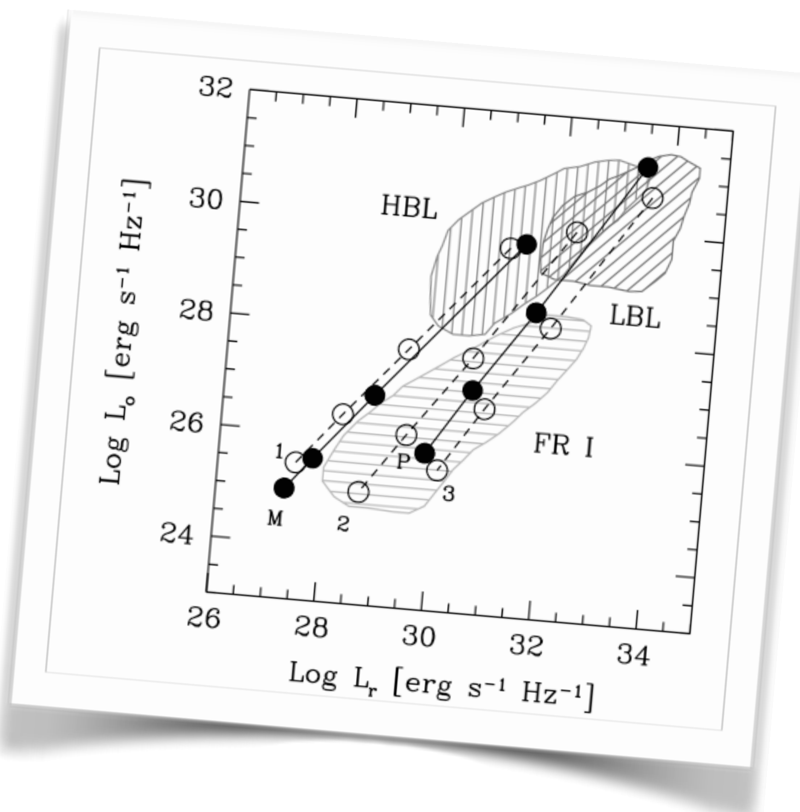


Limb brightening
Mkn 501, Mkn 421, M87, NGC 1275

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

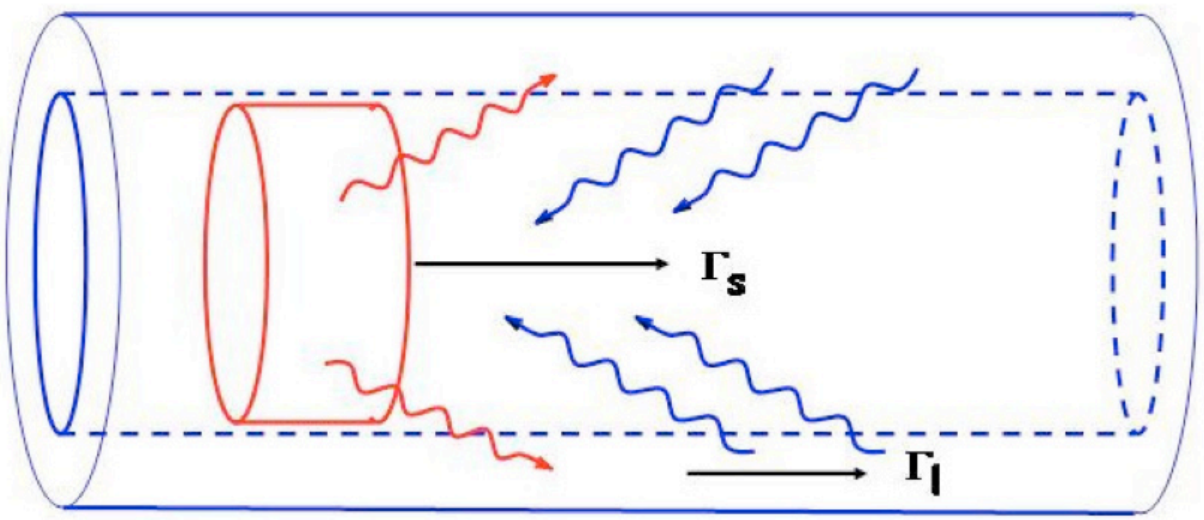


Similar suggestions for GRBs...

Structured jets in BL Lacs

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

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

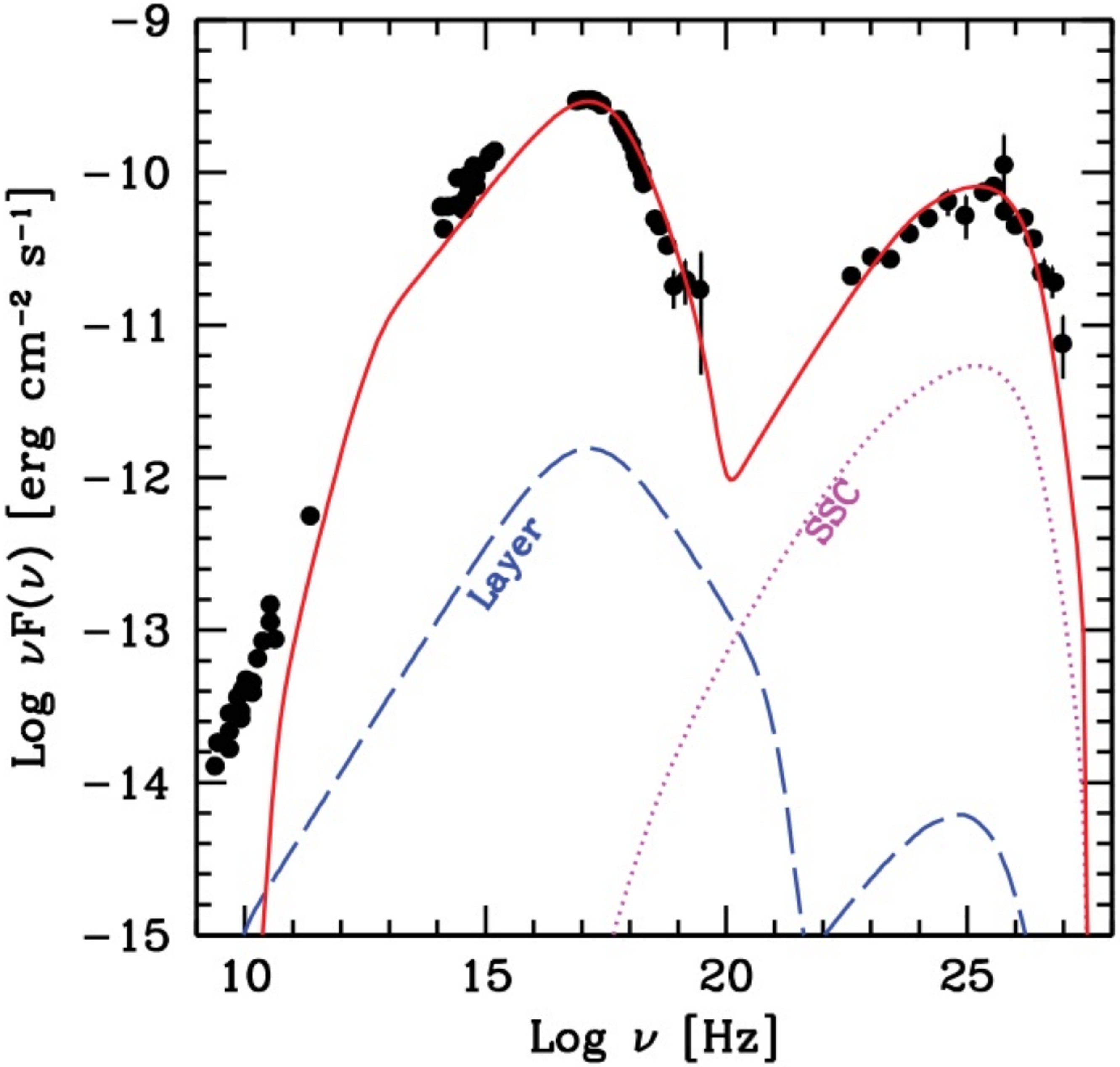


★ The spine "sees" an enhanced U_{rad} coming from the layer

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

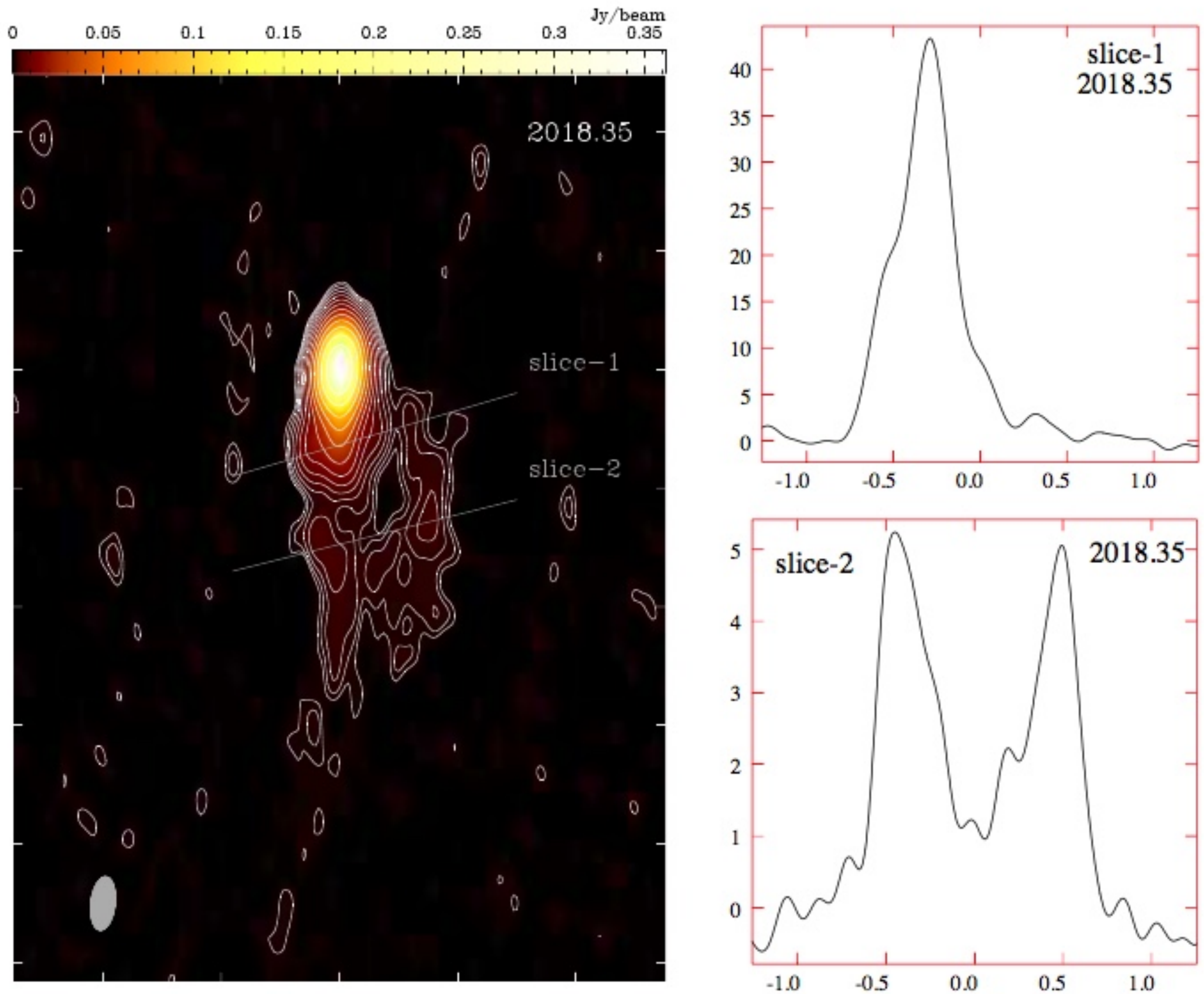
Application: BL Lacs

Mkn 421



Tavecchio and Ghisellini 2016

A structured jet in TXS!



Ros et al. 2019

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

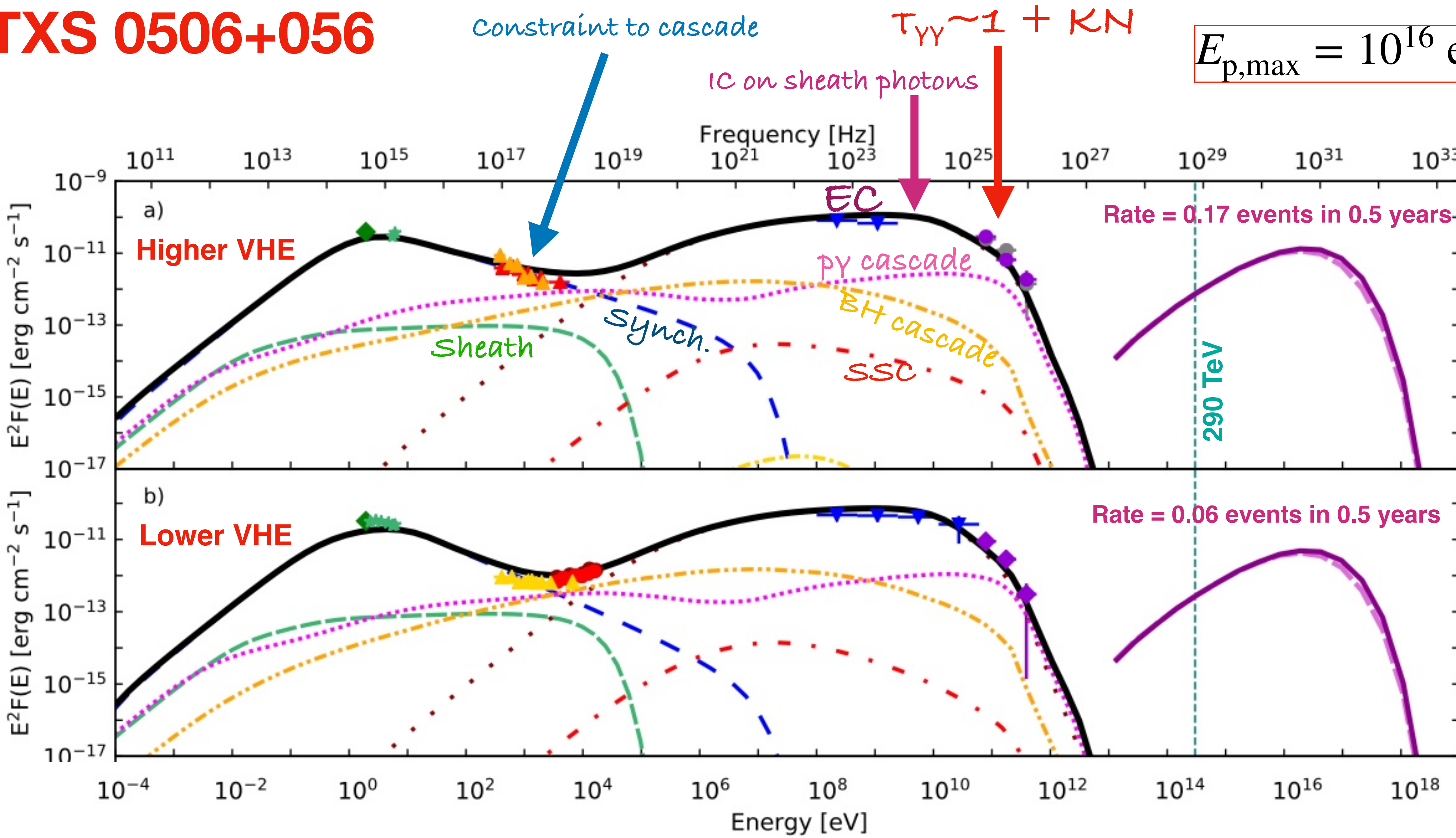
⇒ Reduced proton luminosity

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

Jet-sheath model

TXS 0506+056

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



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

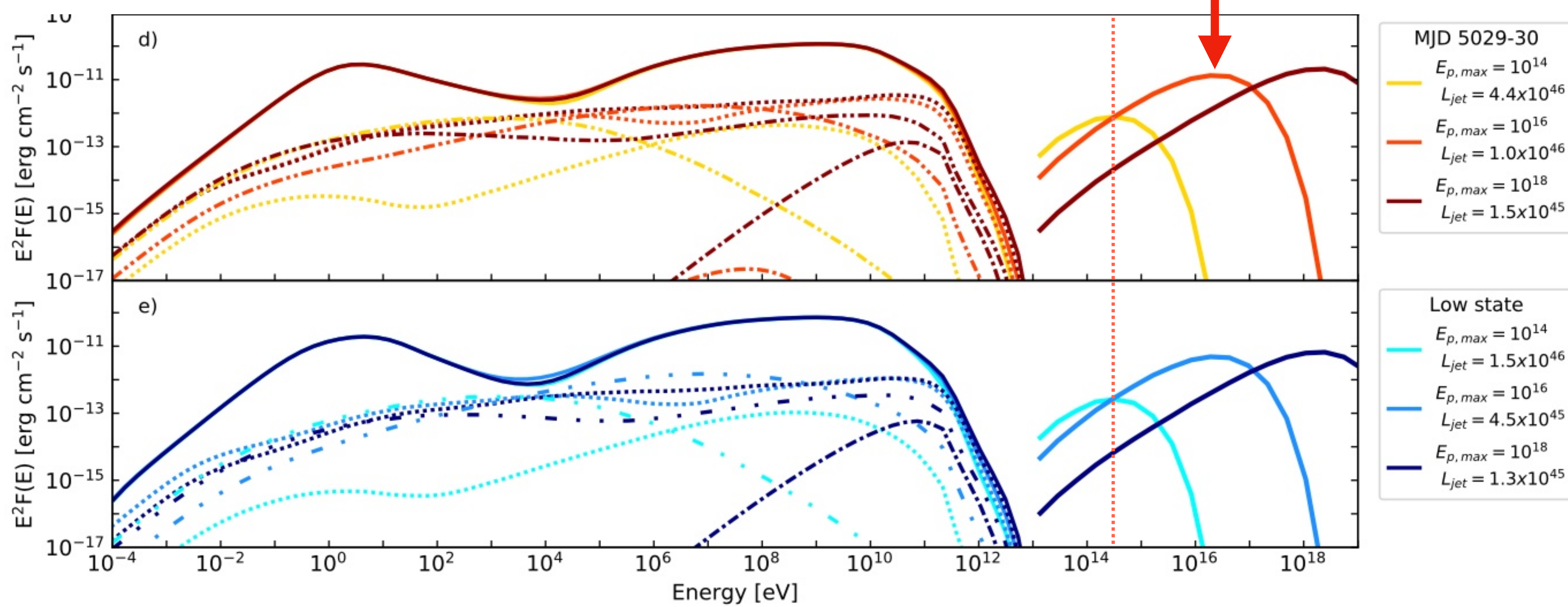
MAGIC Coll. 2018

Jet-sheath model

MAGIC Coll. 2018

Effect of maximum proton energy

Constrained by cascade flux in X-rays

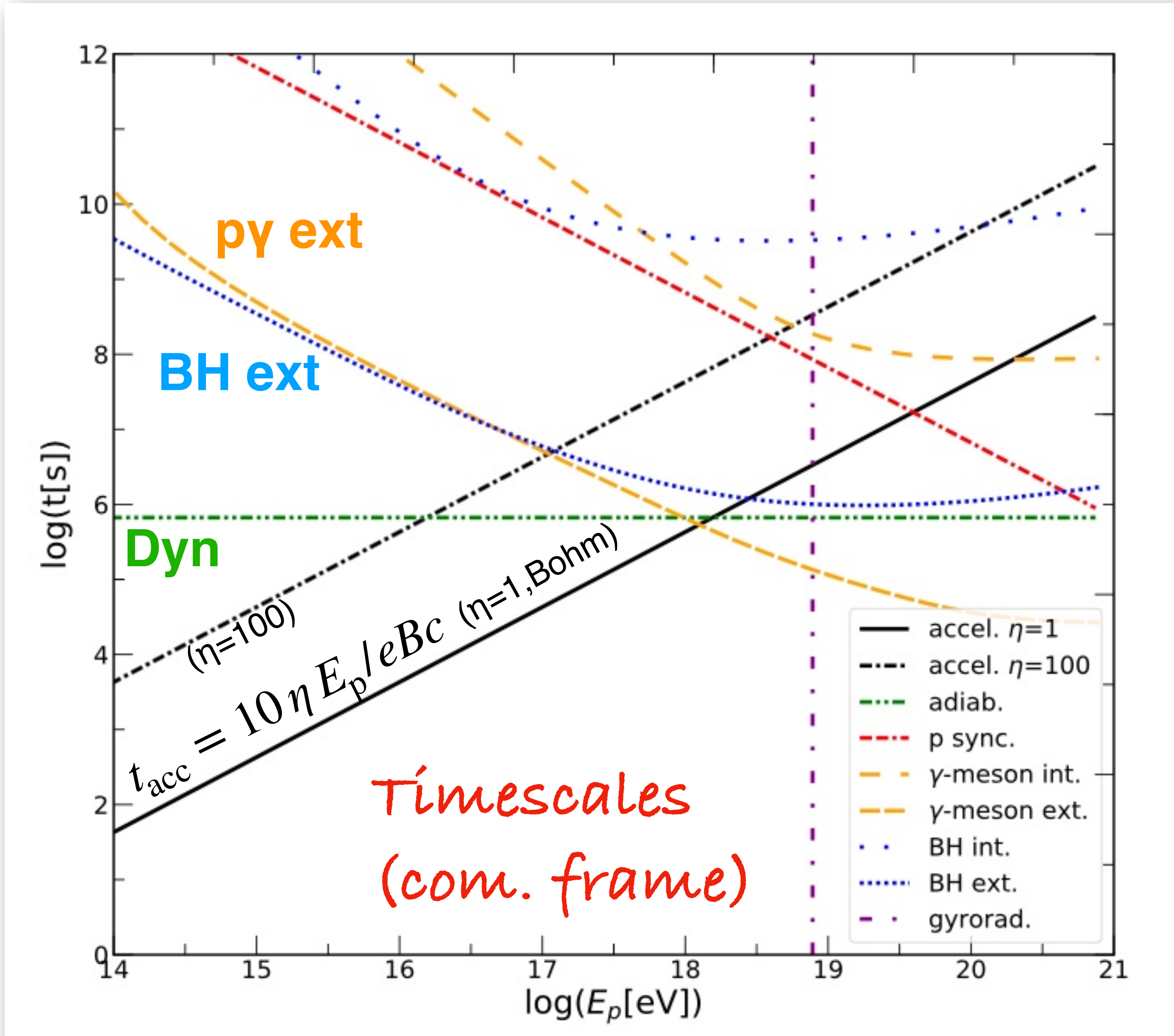


Larger Ep —> Lower neutrino rate at 300 TeV

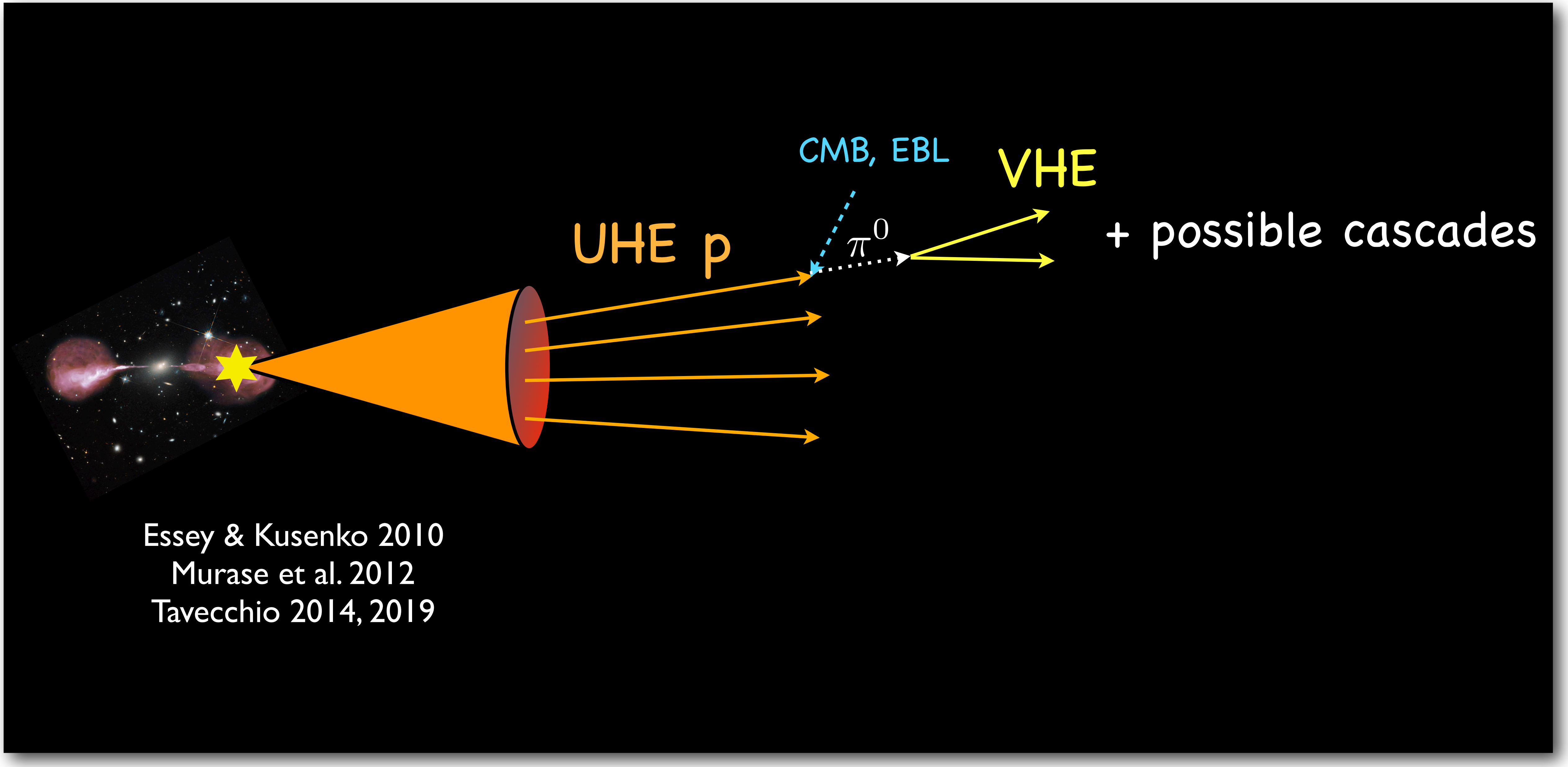
—> Upper limit to Ep,max

Jet-sheath model

MAGIC Coll. 2018



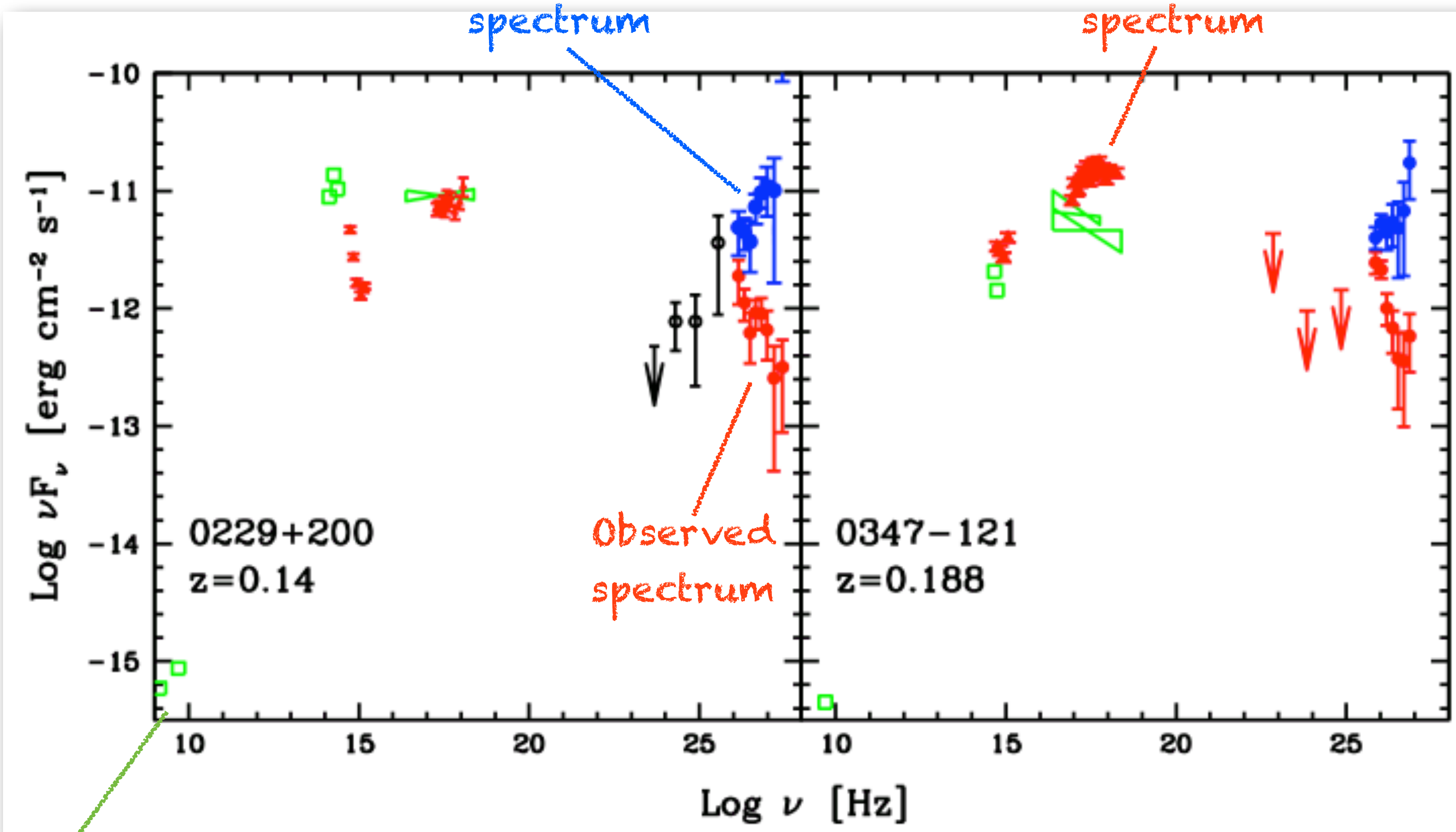
Hadron beams?



Scenario for "extreme Bl Lacs"

Extreme BL Lacs

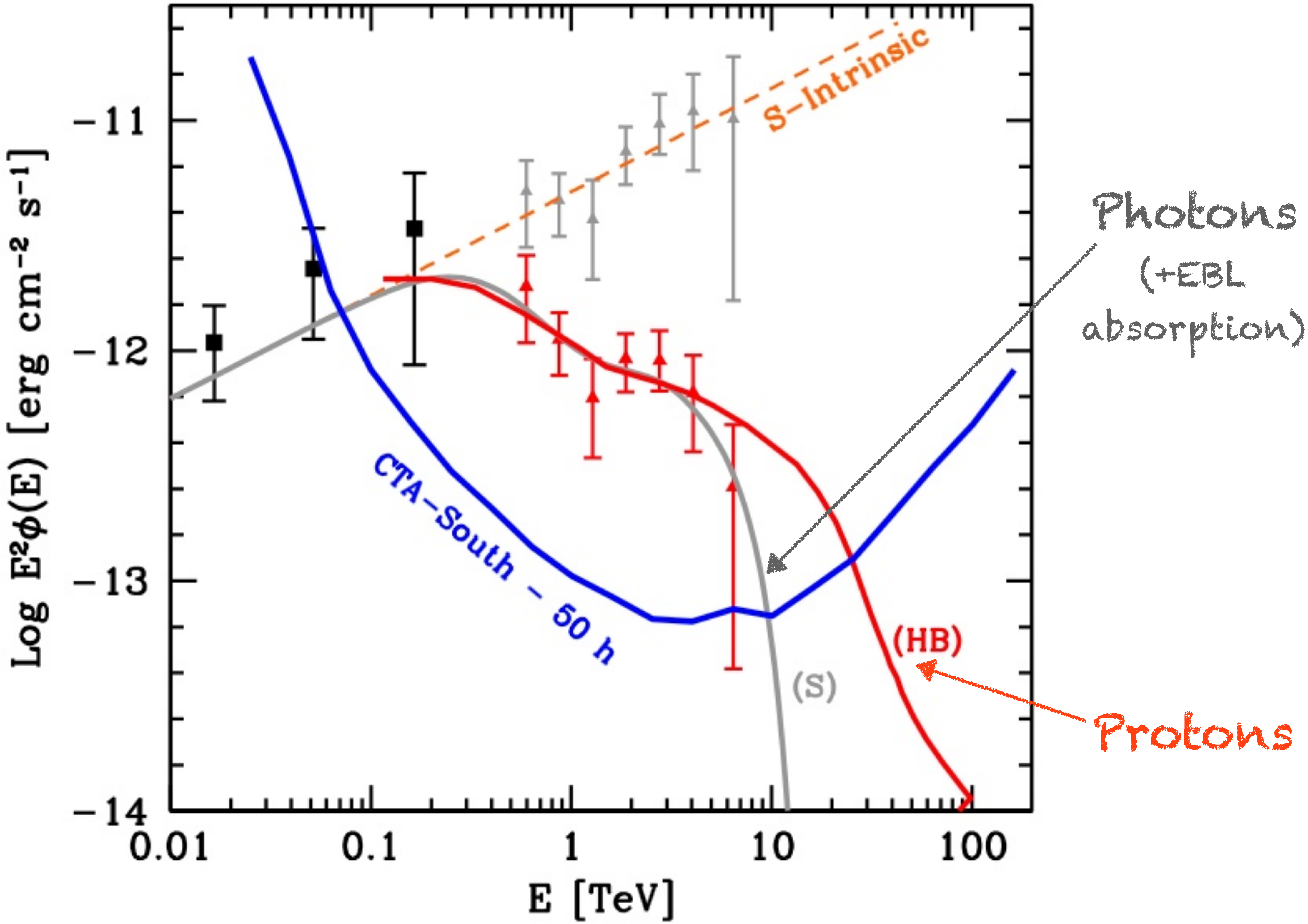
after Costamante et al. 2001



Bonnoli et al. 2015

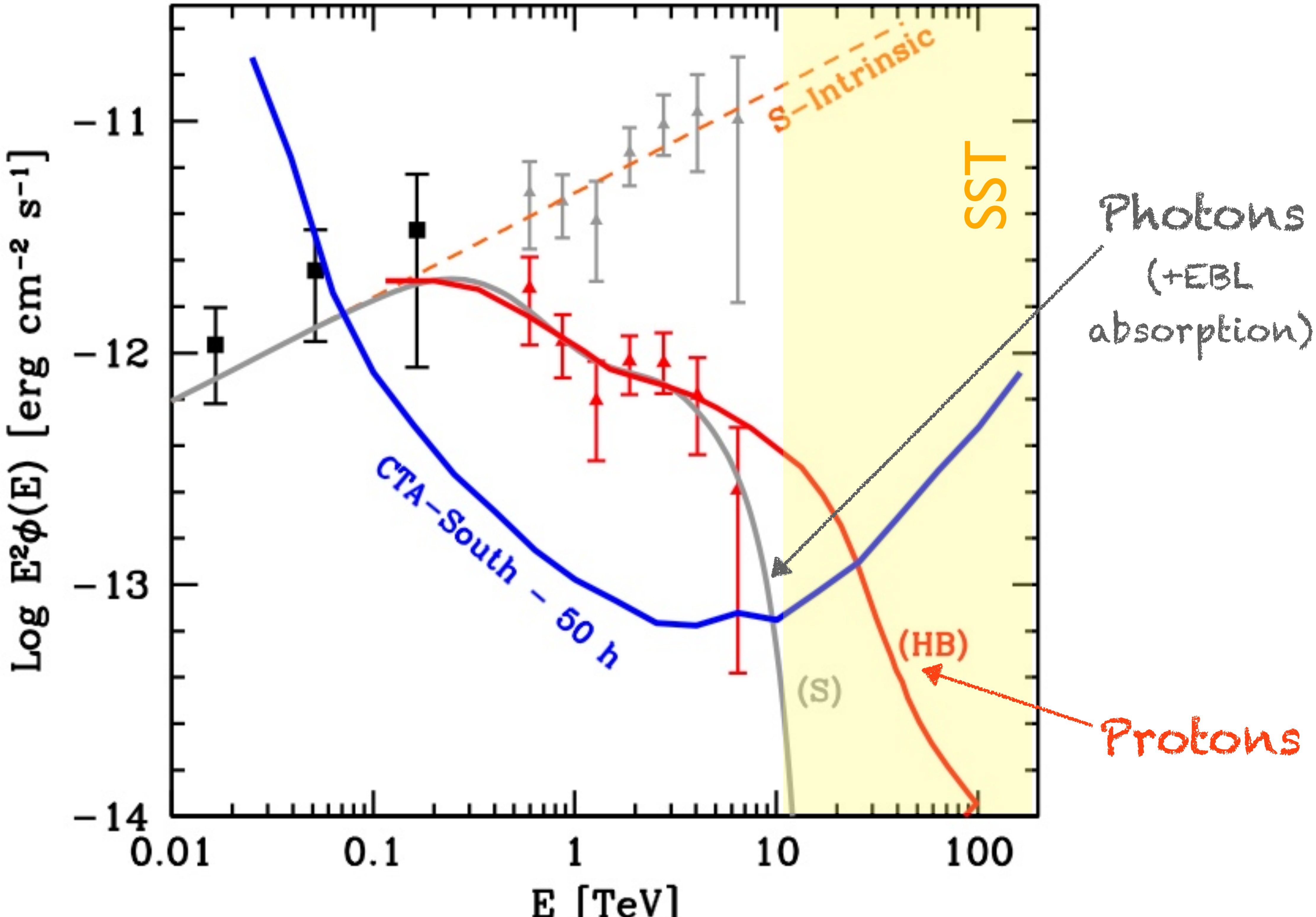
Hadron beams?

Tavecchio et al. 2019



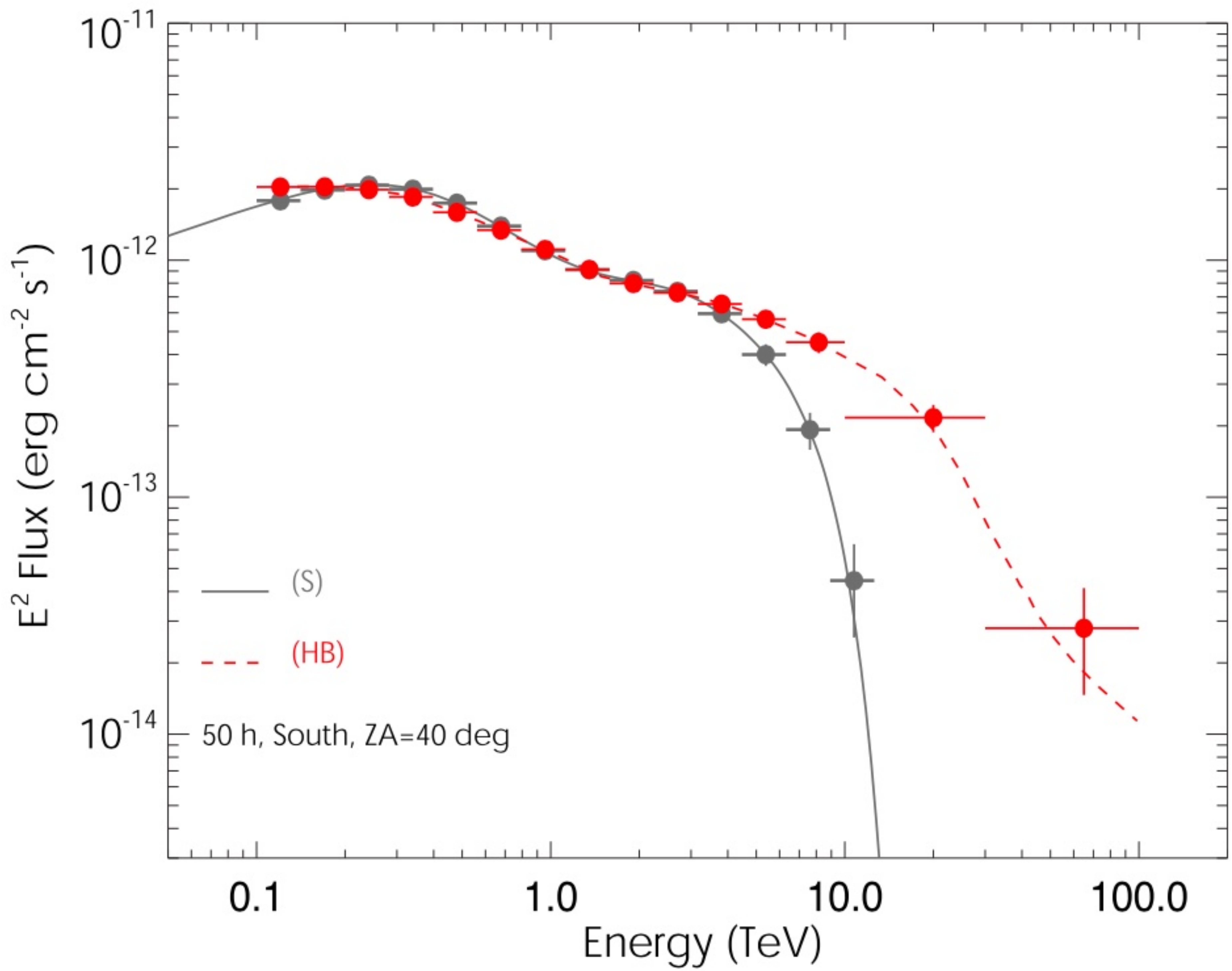
Hadron beams?

Tavecchio et al. 2019

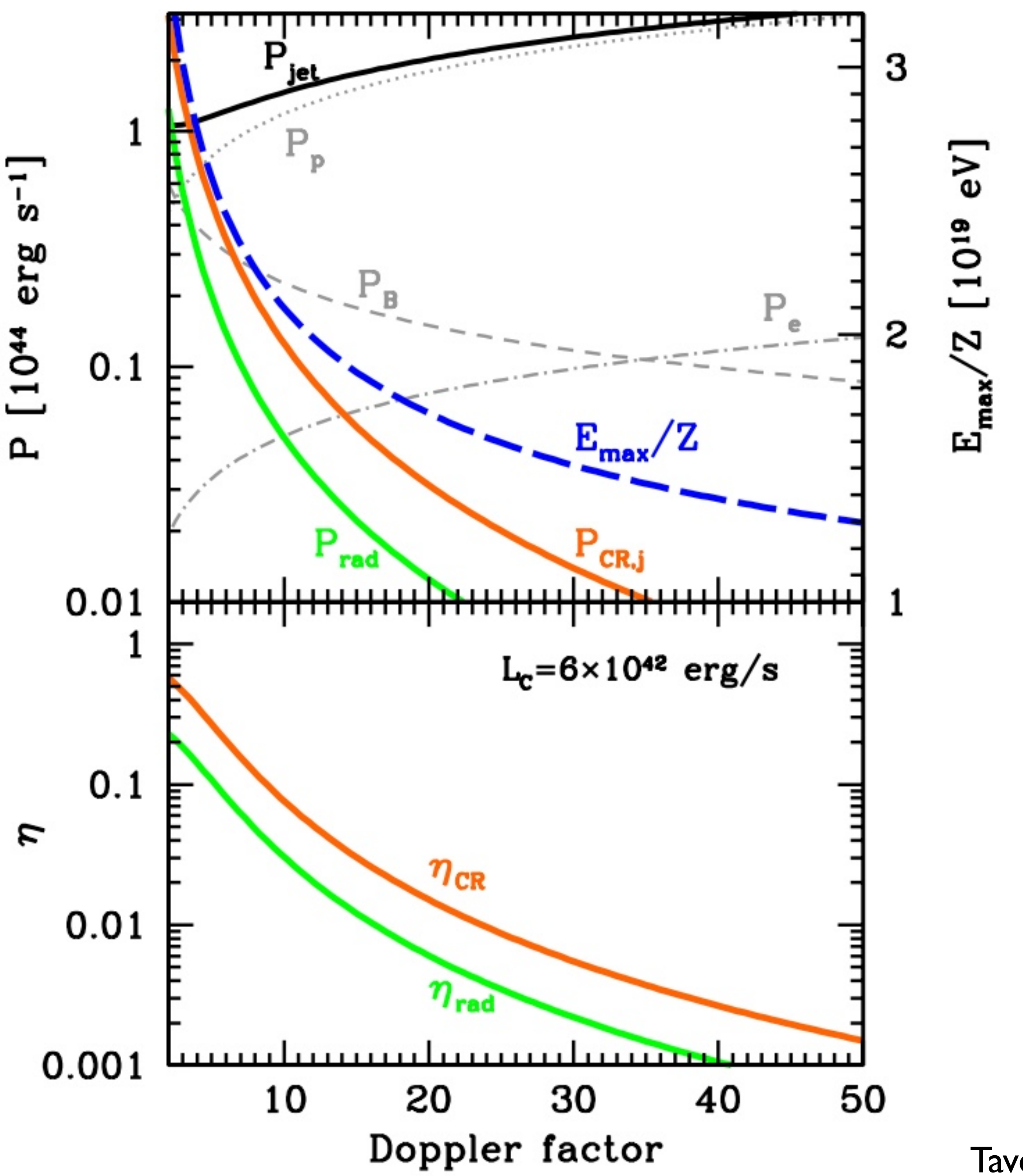


Hadron beams?

Tavecchio et al. 2019

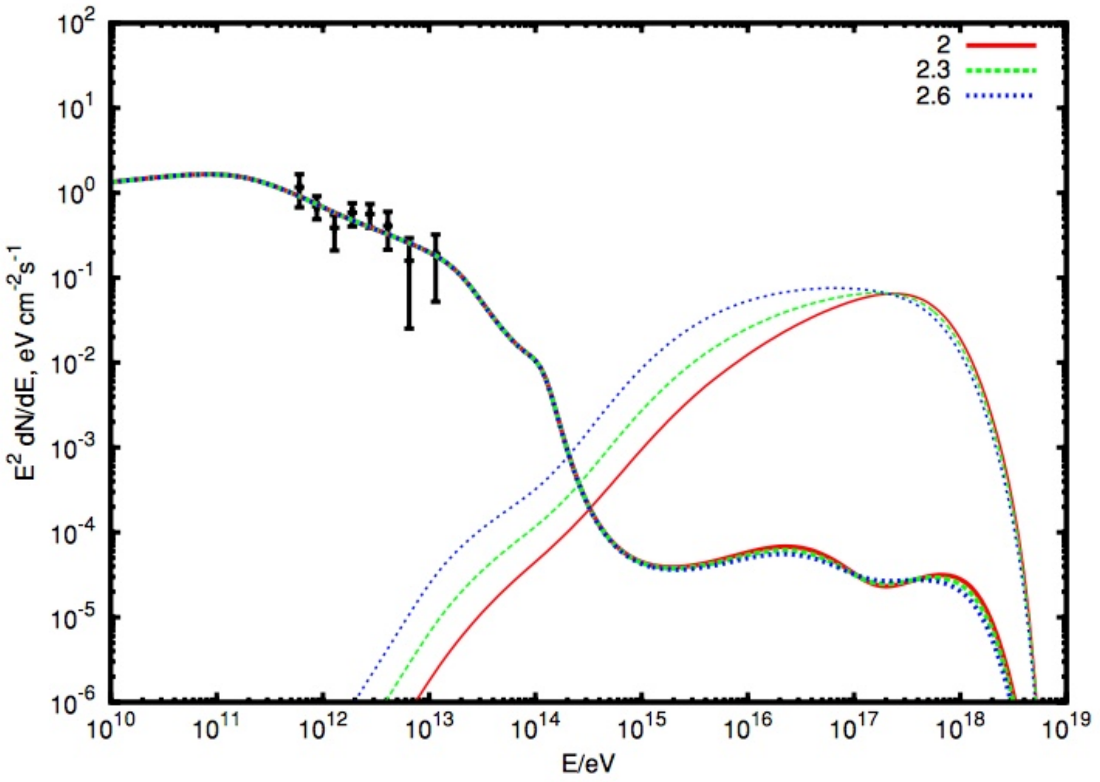


Extreme BL Lacs



Tavecchio 2014

Neutrinos from hadron beams?

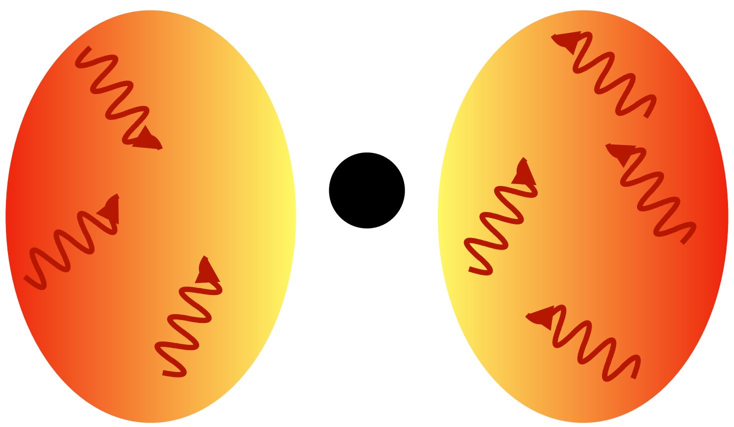


Essey et al. 2011

Difficult to detect single sources

Murase et al. 2012

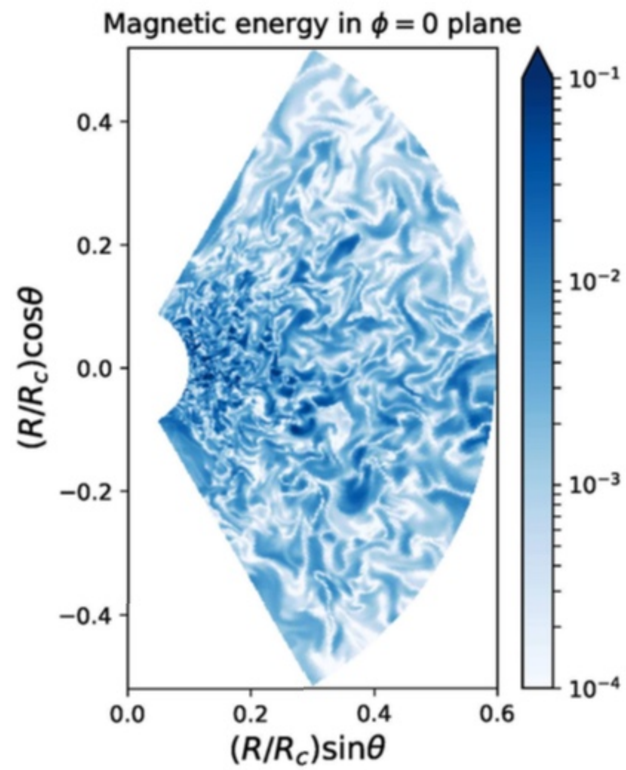
A role for the accretion flow?

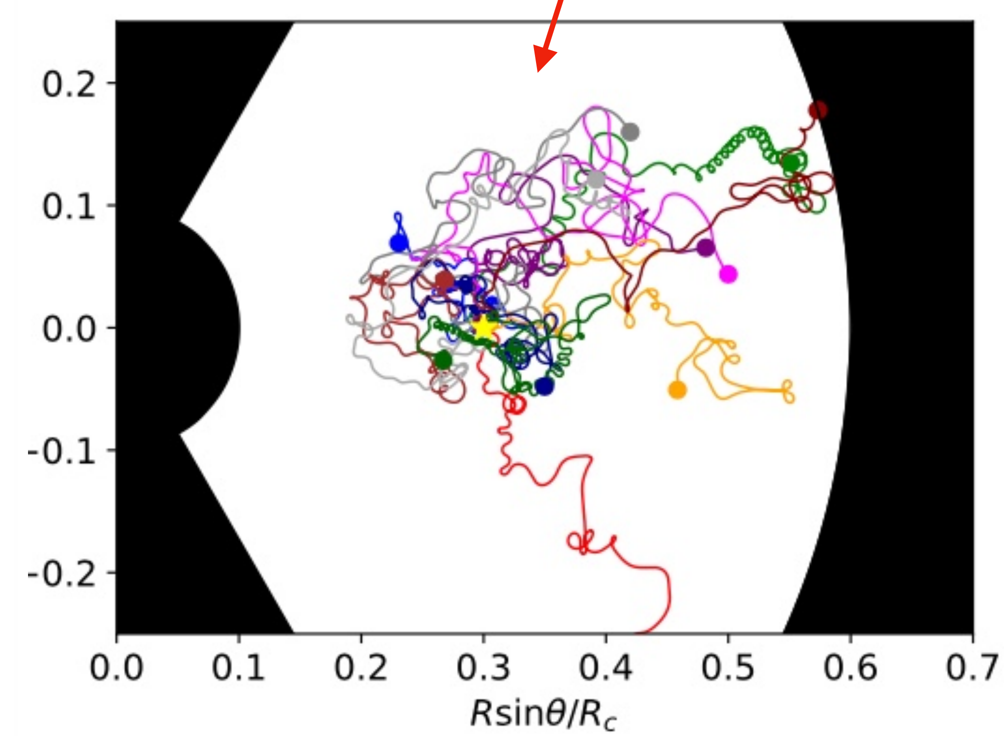


Powering **low luminosity AGN**

Kimura et al. 2015; Khiali et al. 2016

Particle accelerated through Fermi II processes
scattering off magnetic turbulence



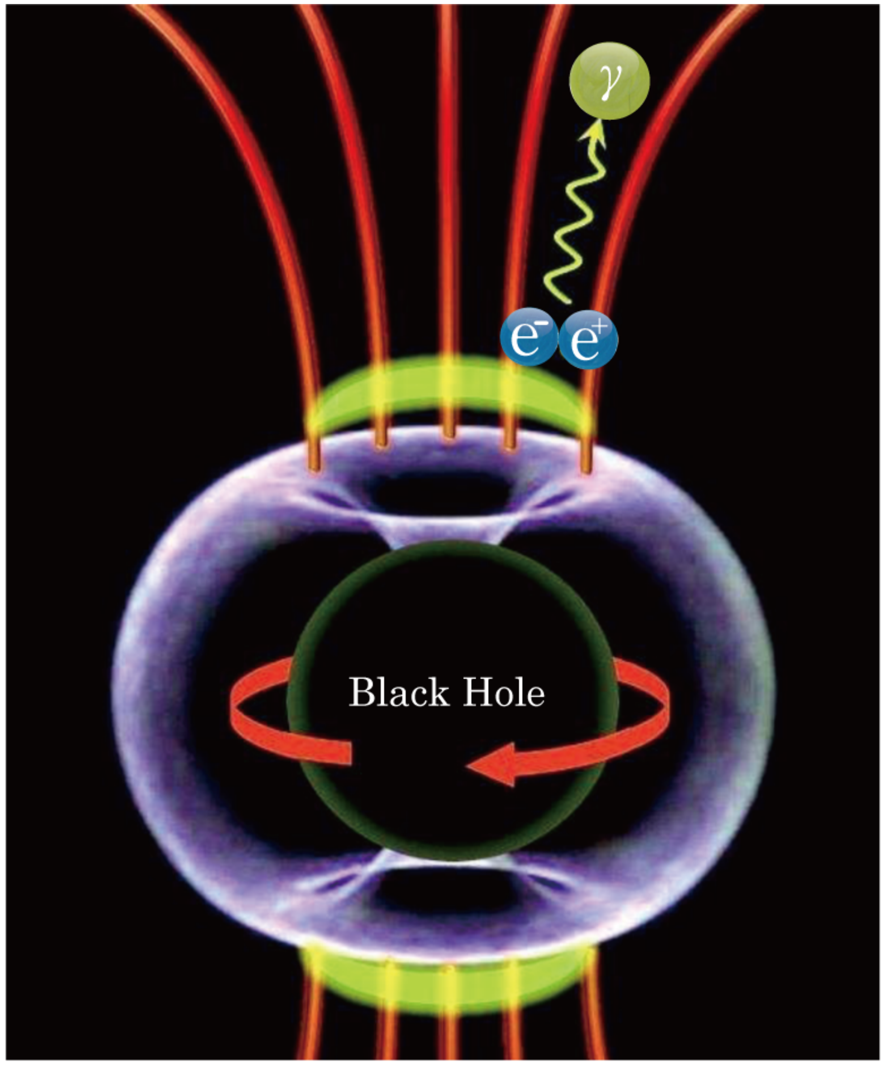


Protons up to few PeV expected
(no UHECR)

Emission either through pp or pγ

Kimura et al. 2018

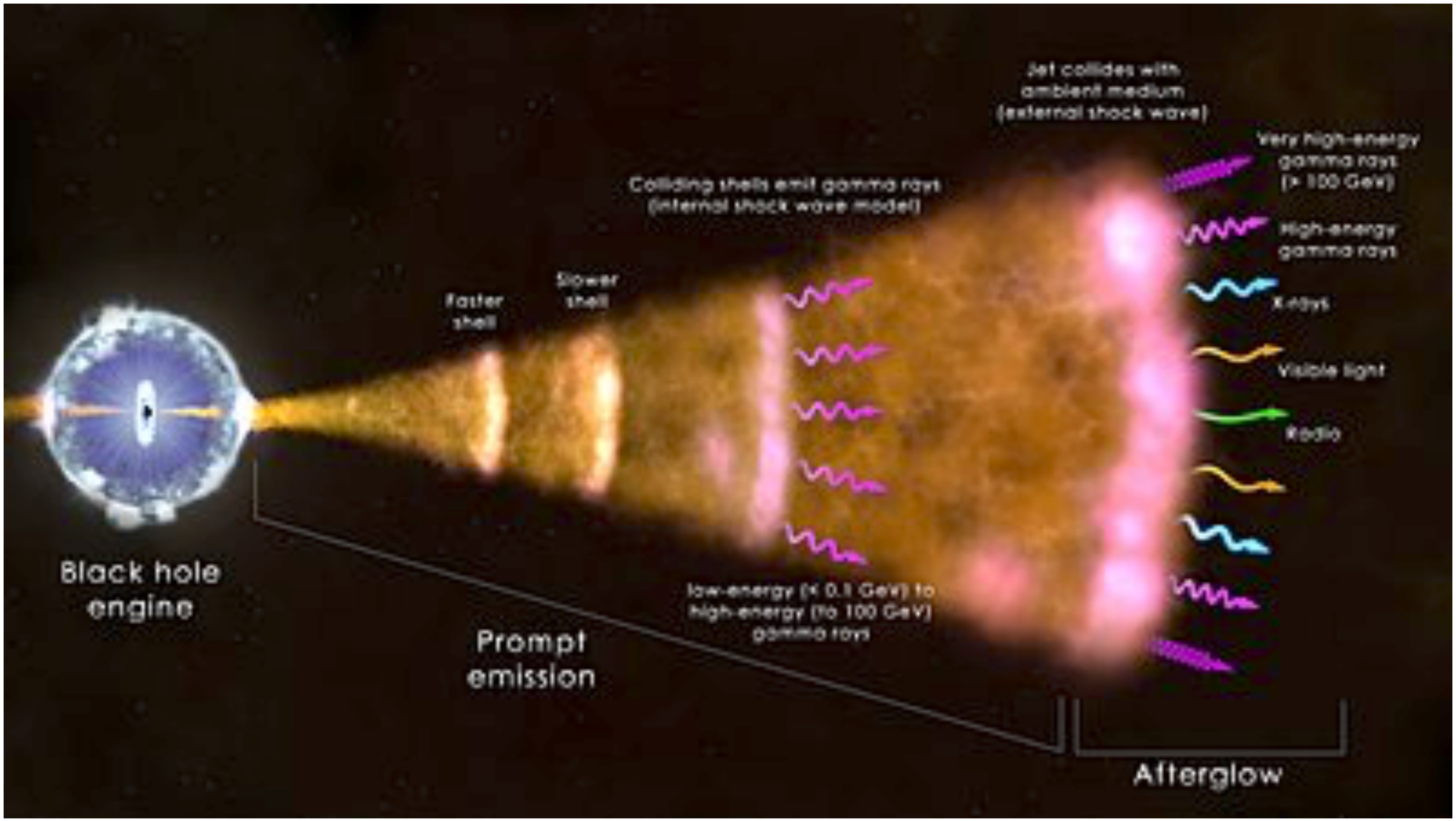
A role for the magnetosphere?



High energy particles can
be accelerated by direct
electric fields in gaps or centrifugally

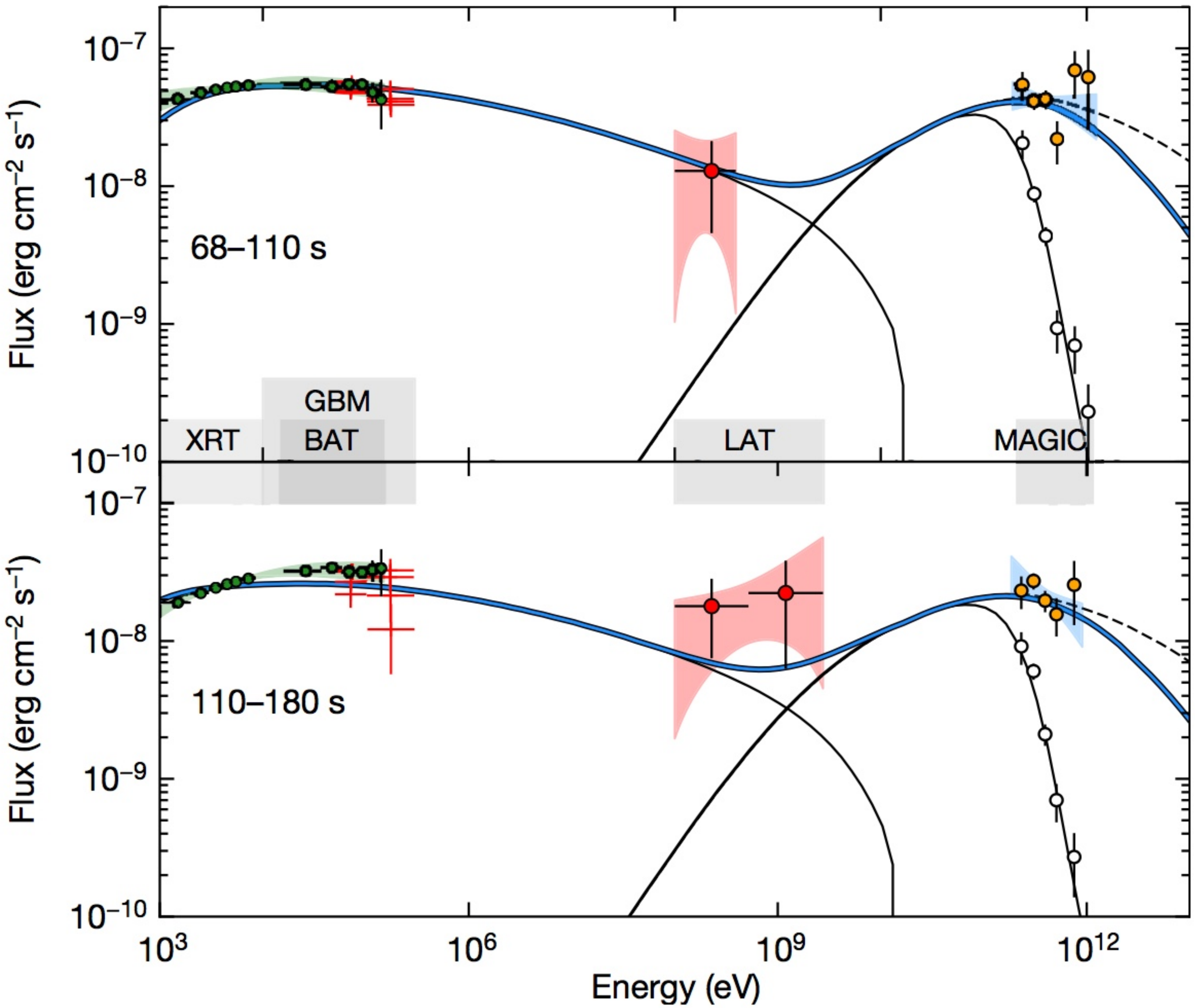
e.g. Rieger 2011

Gamma-ray bursts



Gamma-ray bursts

SSC



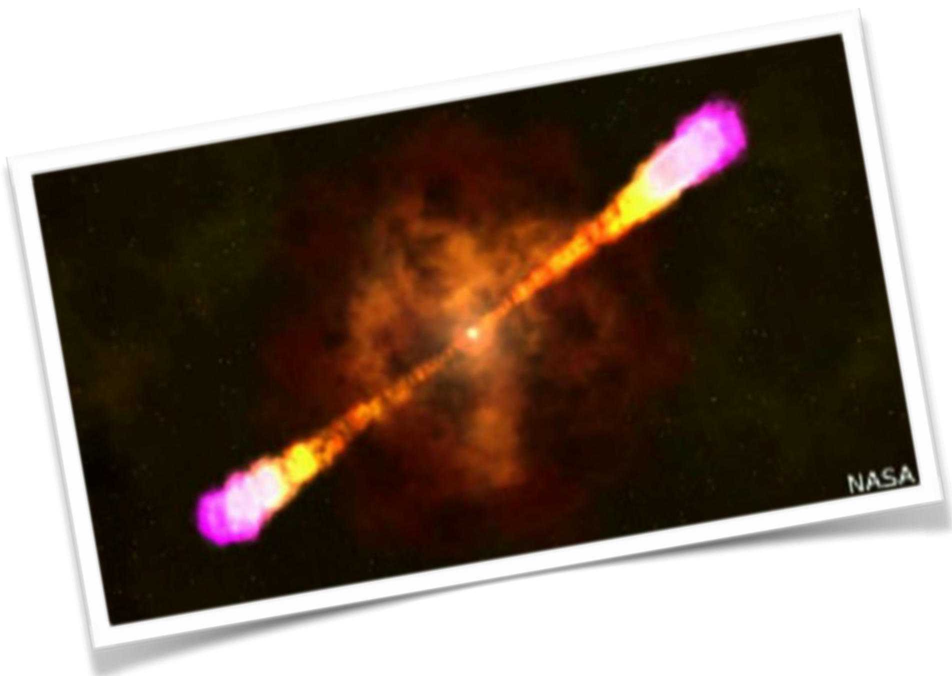
MAGIC Coll. 2019

Gamma-ray bursts

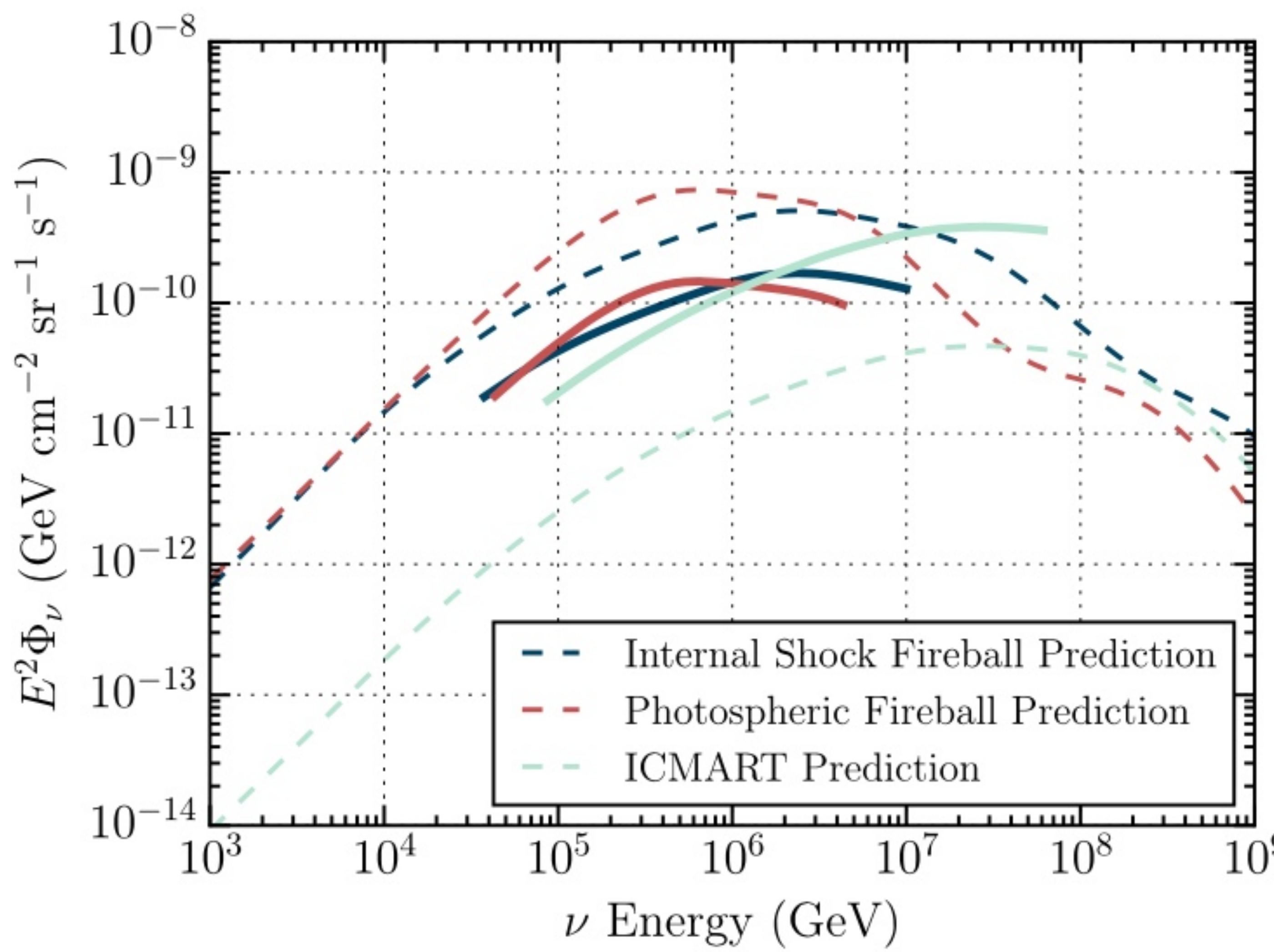
CR accelerated in shocks + radiation ($p\gamma$)

Probably no...

Waxman & Bahcall 1997
And many others…

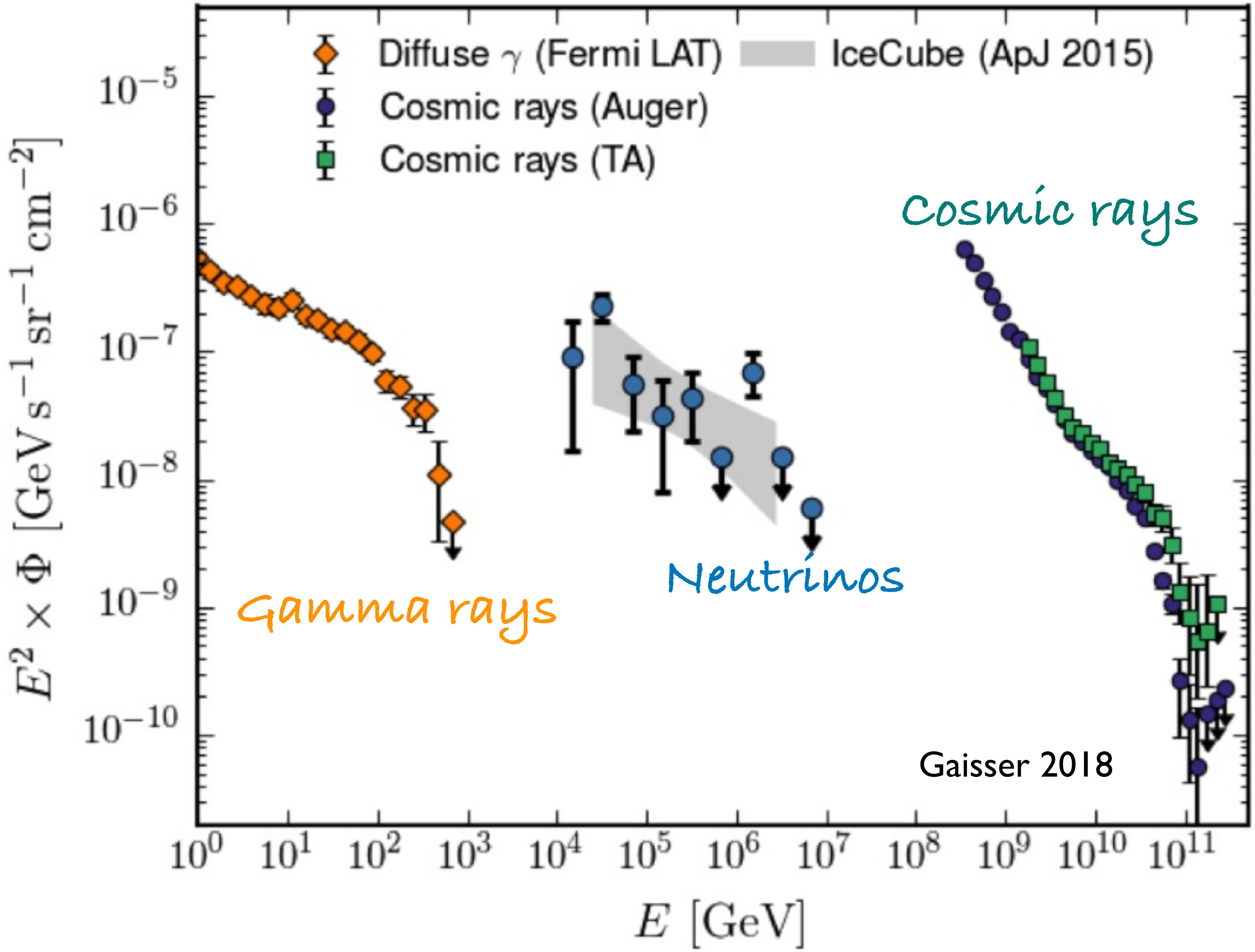


Aartsen et al. 2017



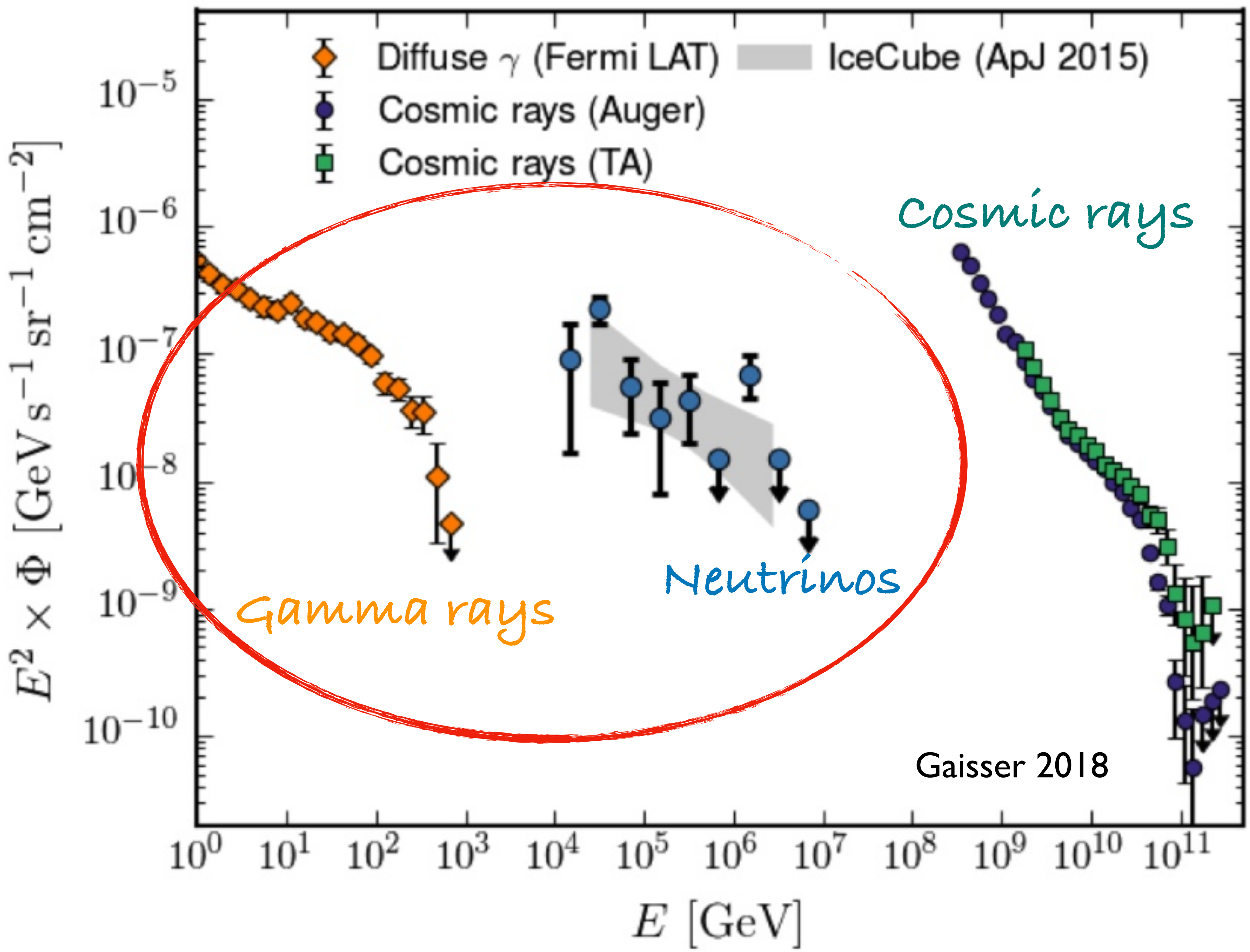
Cumulative MM fluxes

"Multimessenger sky background"



The same source(s)?

Cumulative MM fluxes

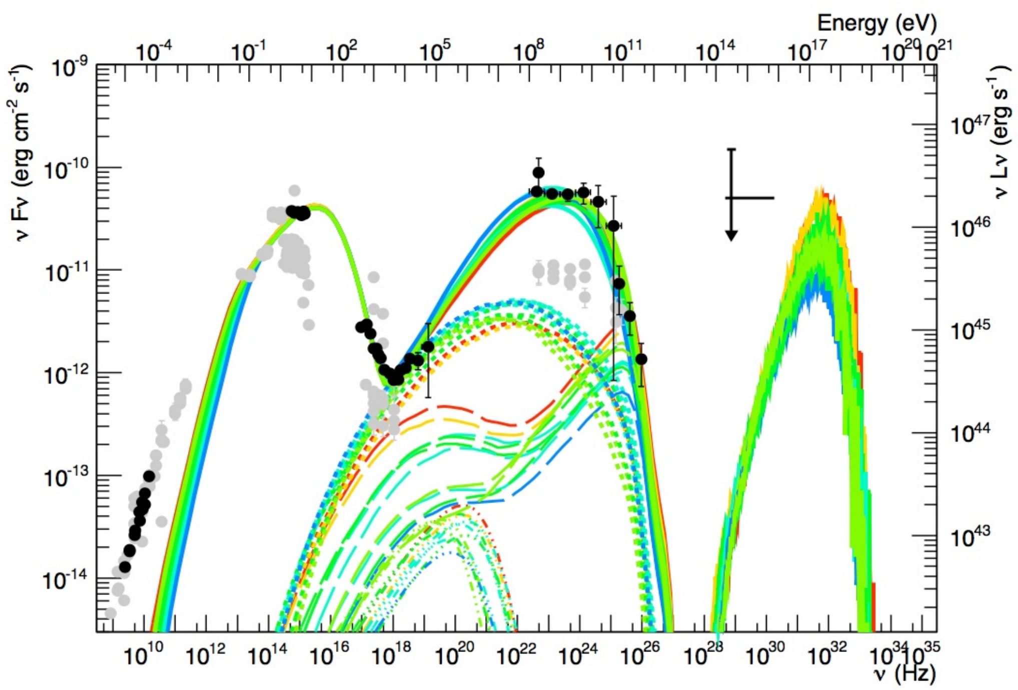


γ-ν connection

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

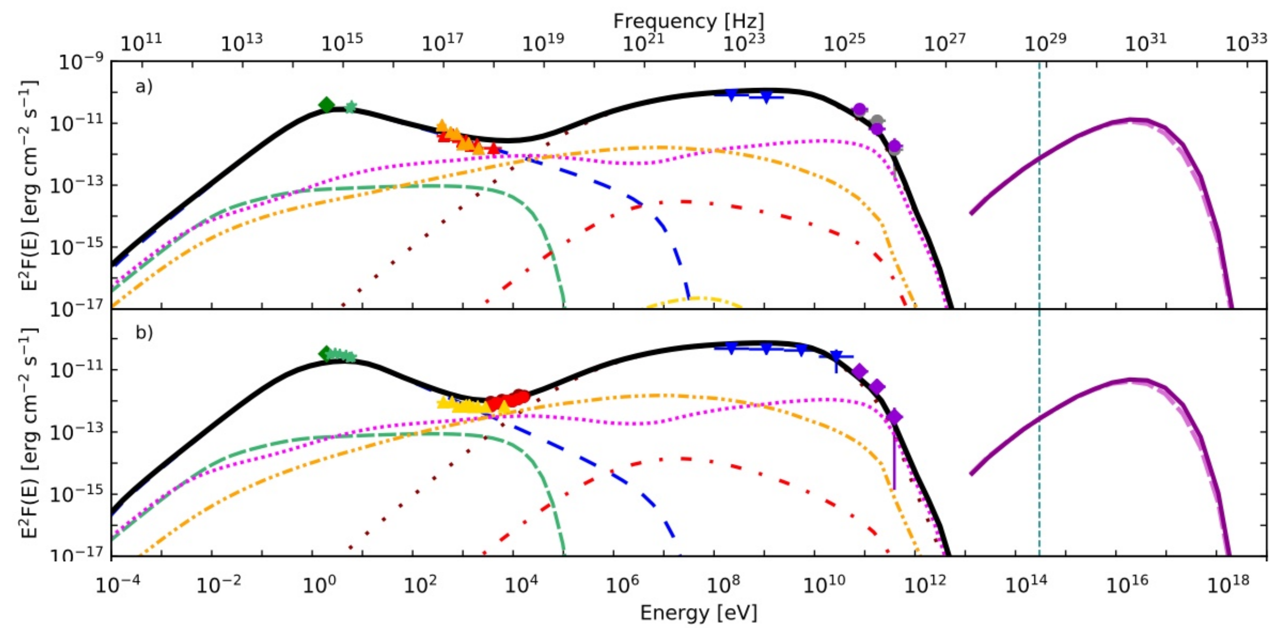
From TXS we know that hadronic gamma-rays are **subdominant** with respect to leptonic emission.
This is probably valid in general for blazars.

Since blazars contribute to ~80% to ExGal BKG, the "hadronic background" is max 20% of the total.

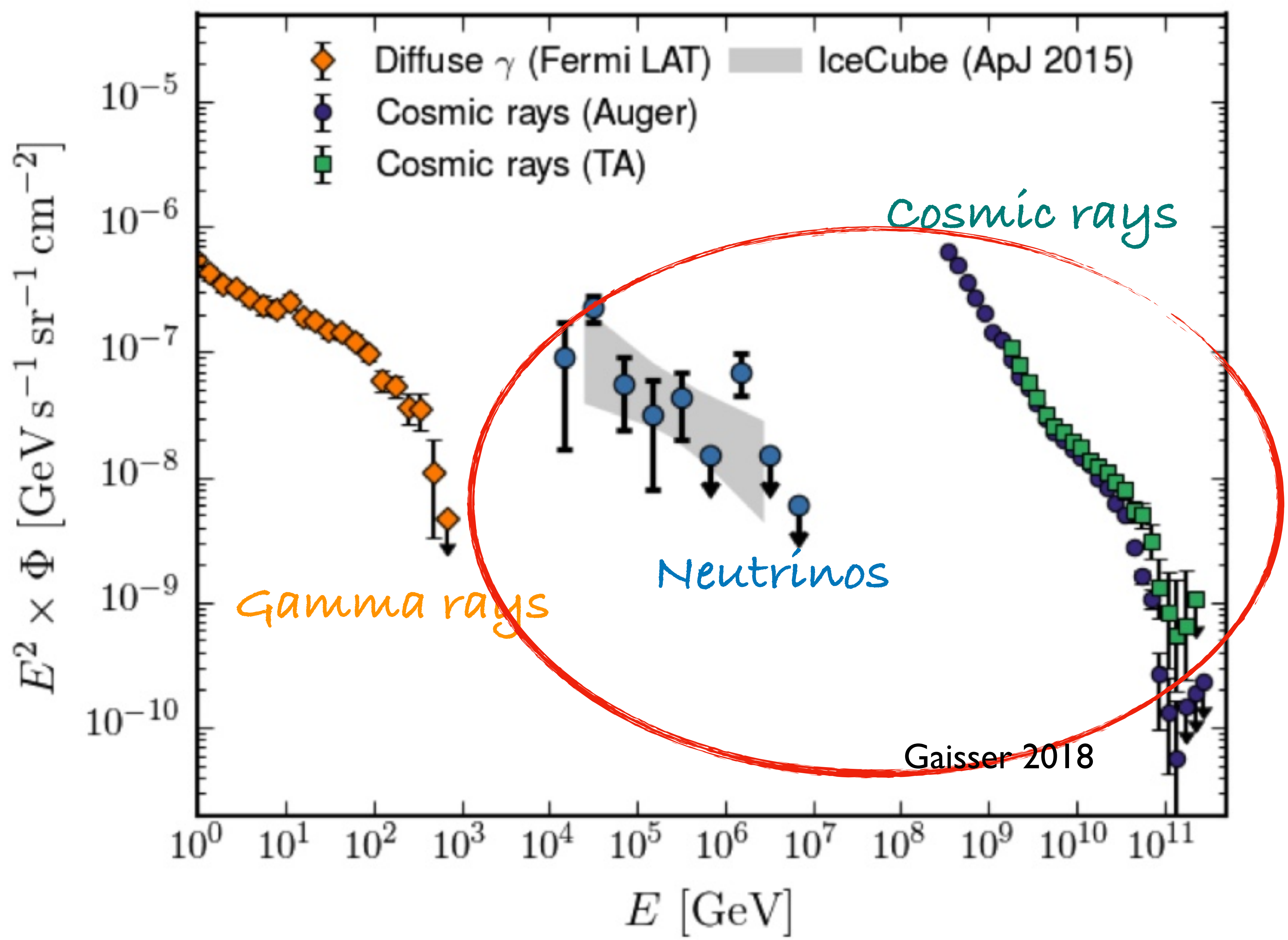


Cerruti et al. 2018

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	✓	✗

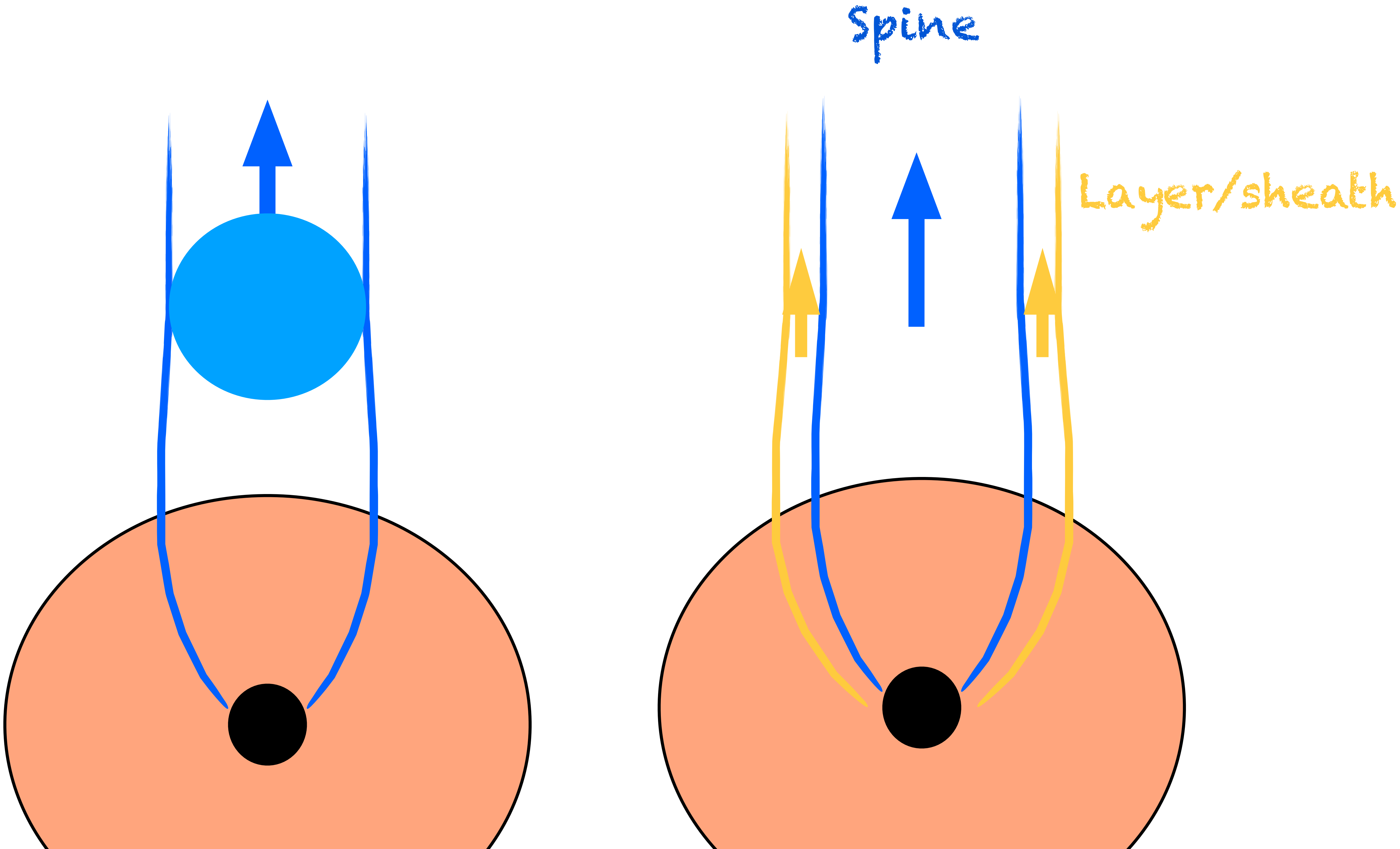
Rodrigues et al. 2018
Tavecchio et al. 2019

Radiation energy density

A key parameter for several MM processes:

Inverse Compton, absorption	γ-rays
photomeson reactions	ν
destruction of heavy nuclei	UHECR

Two scenarios

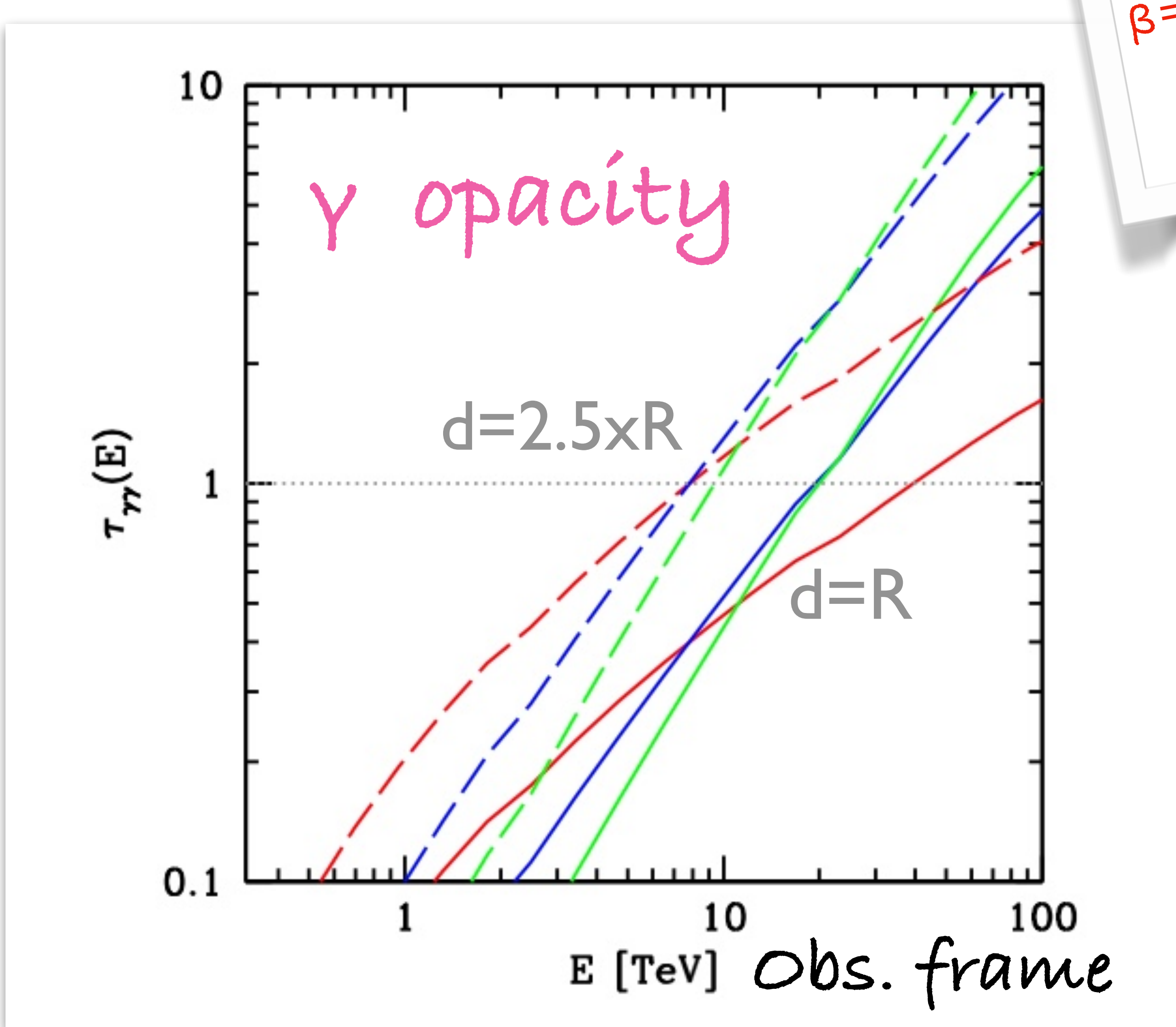


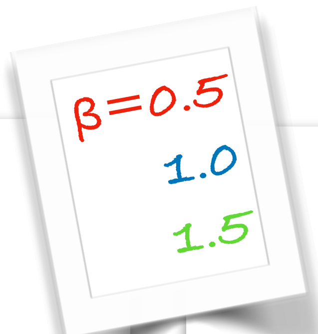
Maximum radiation energy density

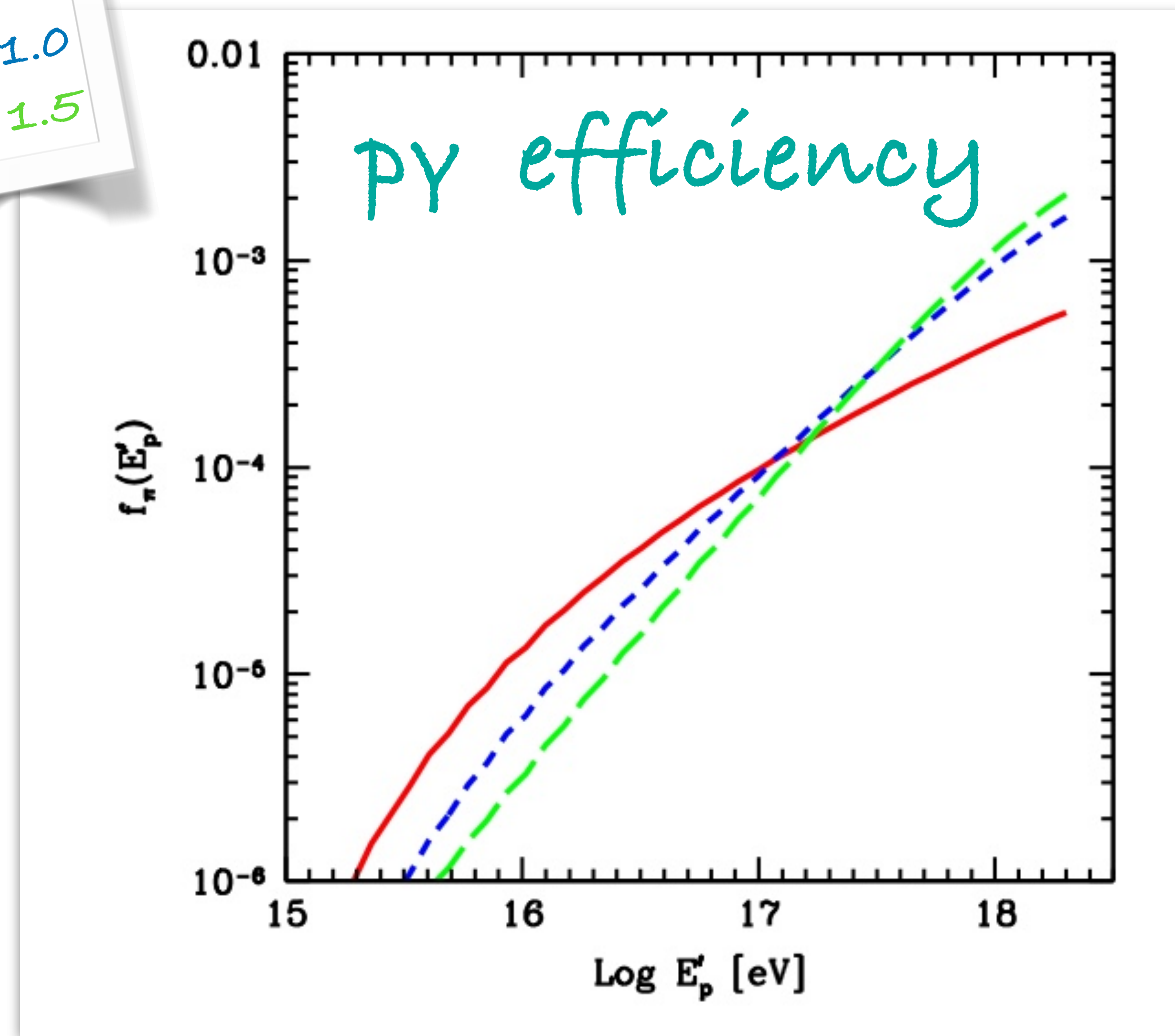
$$U_{\rm rad} = 10 \times U_{SSC}$$

$$\tau_{\gamma\gamma}(E') = \frac{\sigma_{\rm T}}{5} d\, n'_{\rm rad}(\epsilon')\epsilon'$$

$$f_\pi(E'_{\rm p}) = t'_{\rm dyn}/t'_{p\gamma}(E'_{\rm p})$$

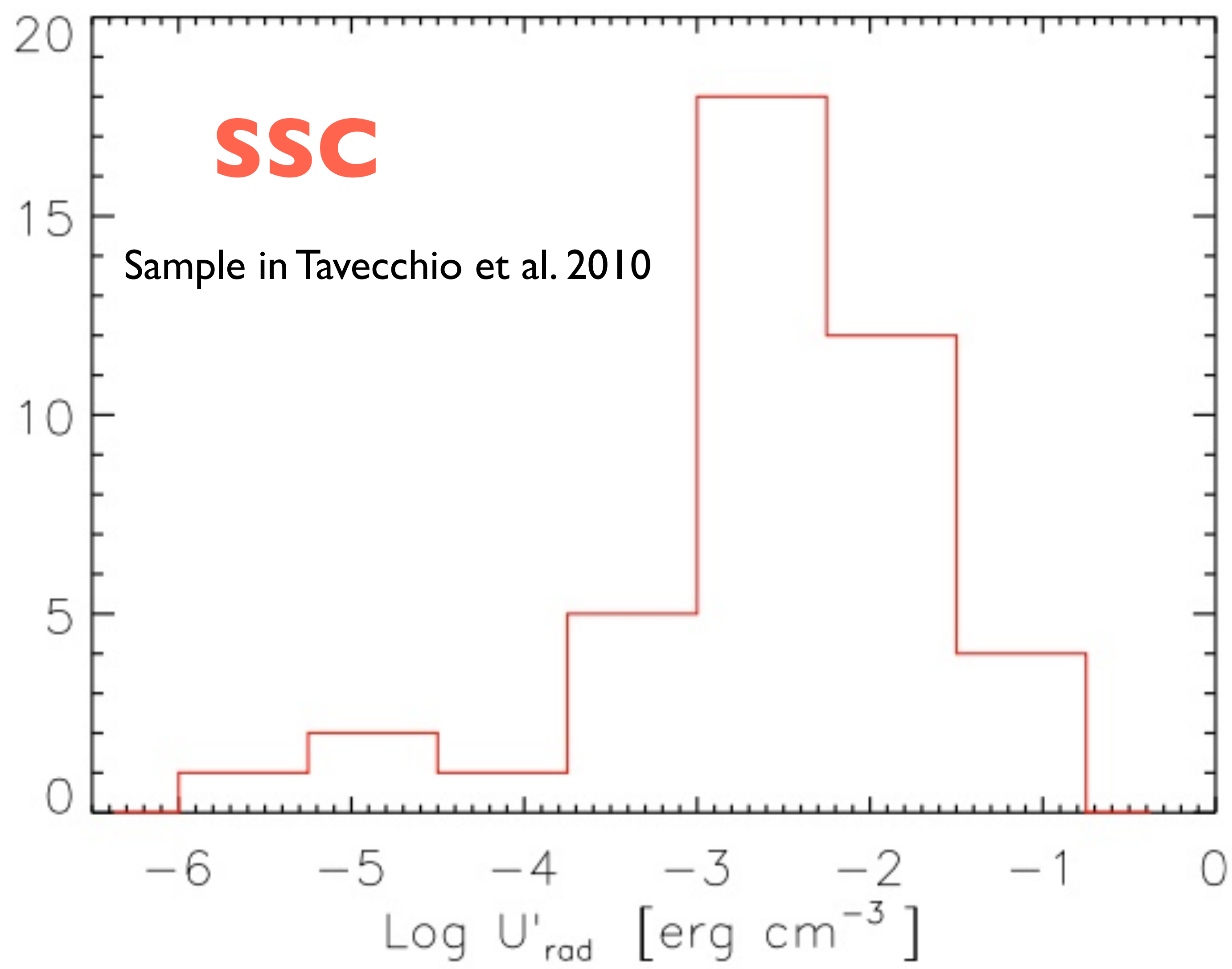






Tavecchio, Oikonomou, Righi 2019

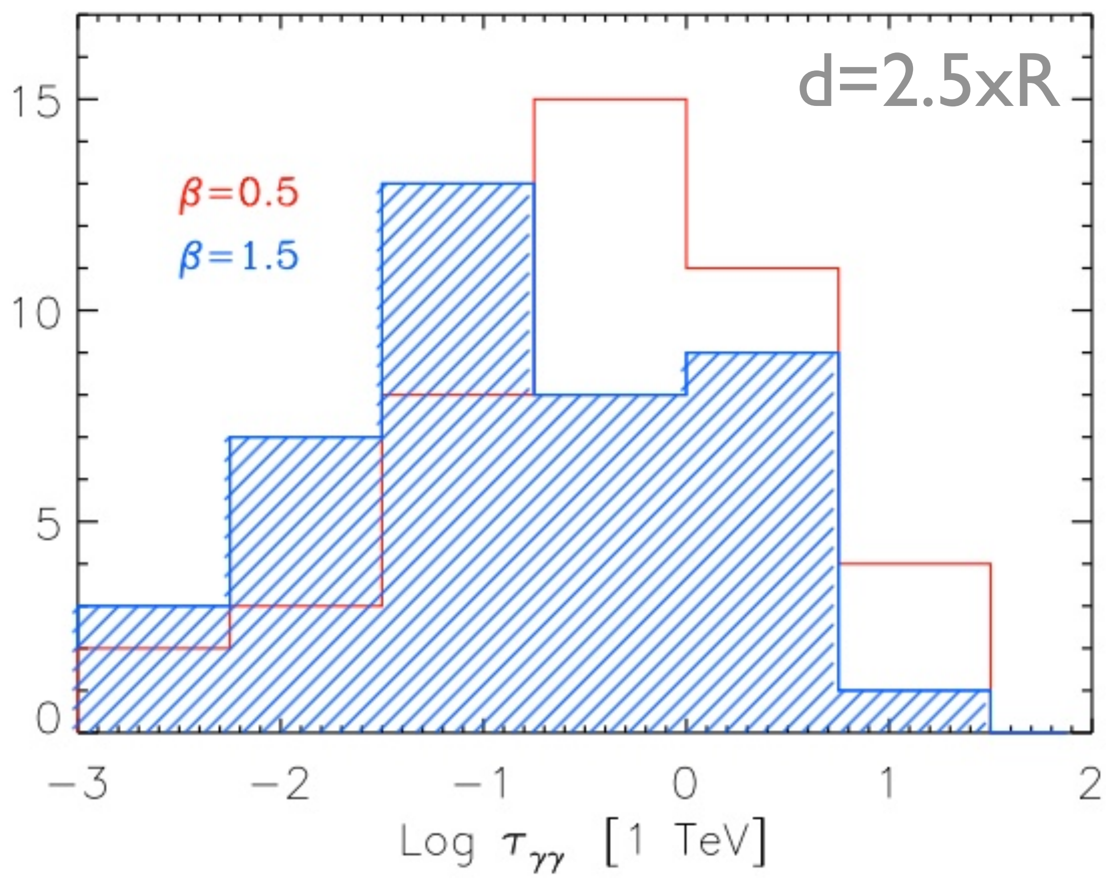
BL Lac population



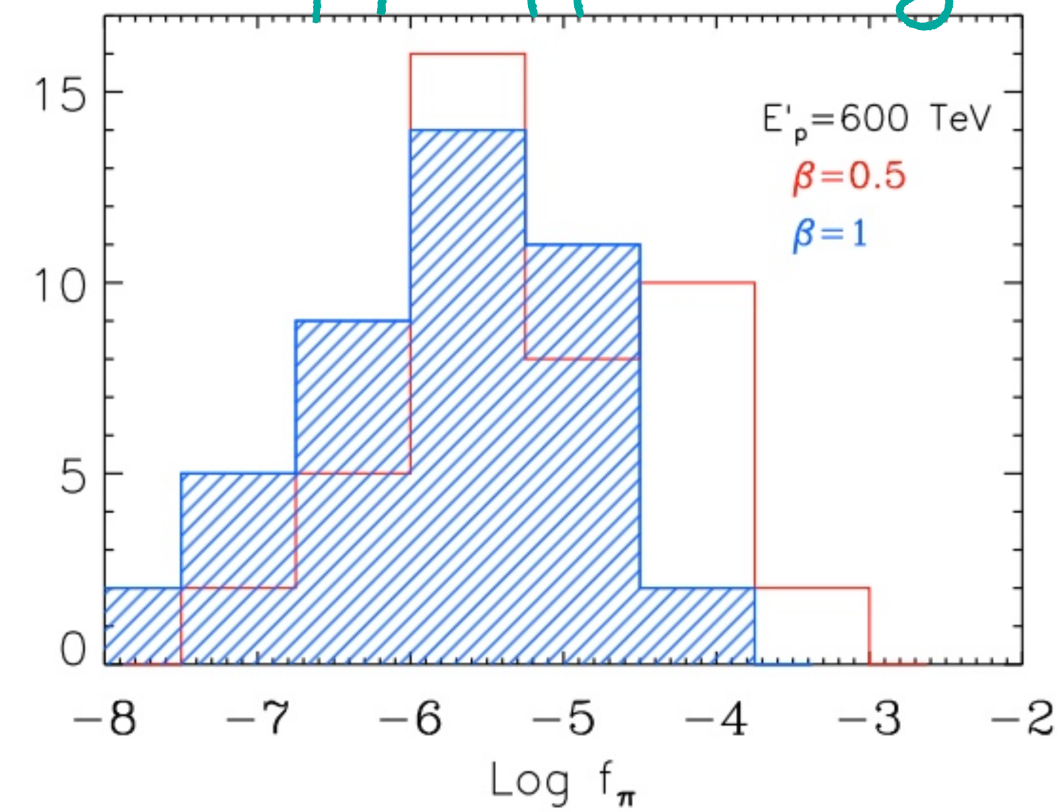
BL Lac population

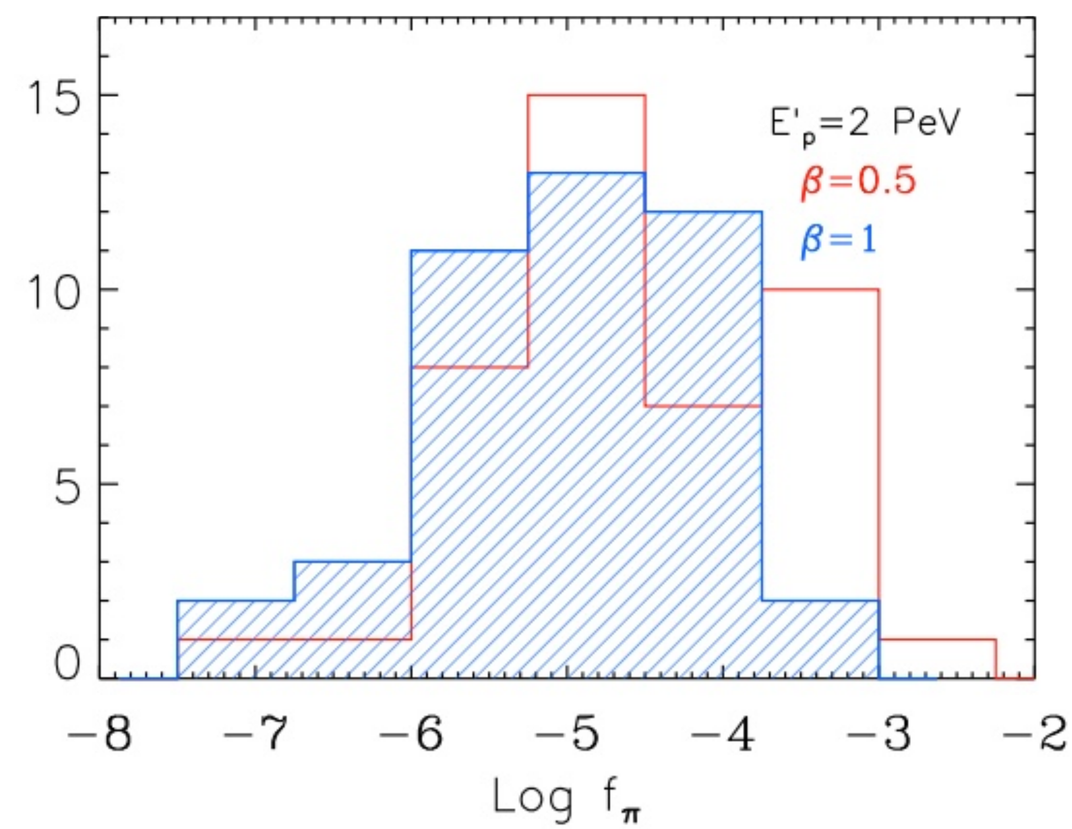
$$U_{\rm rad} = 10 \times U_{SSC}$$

γ opacity

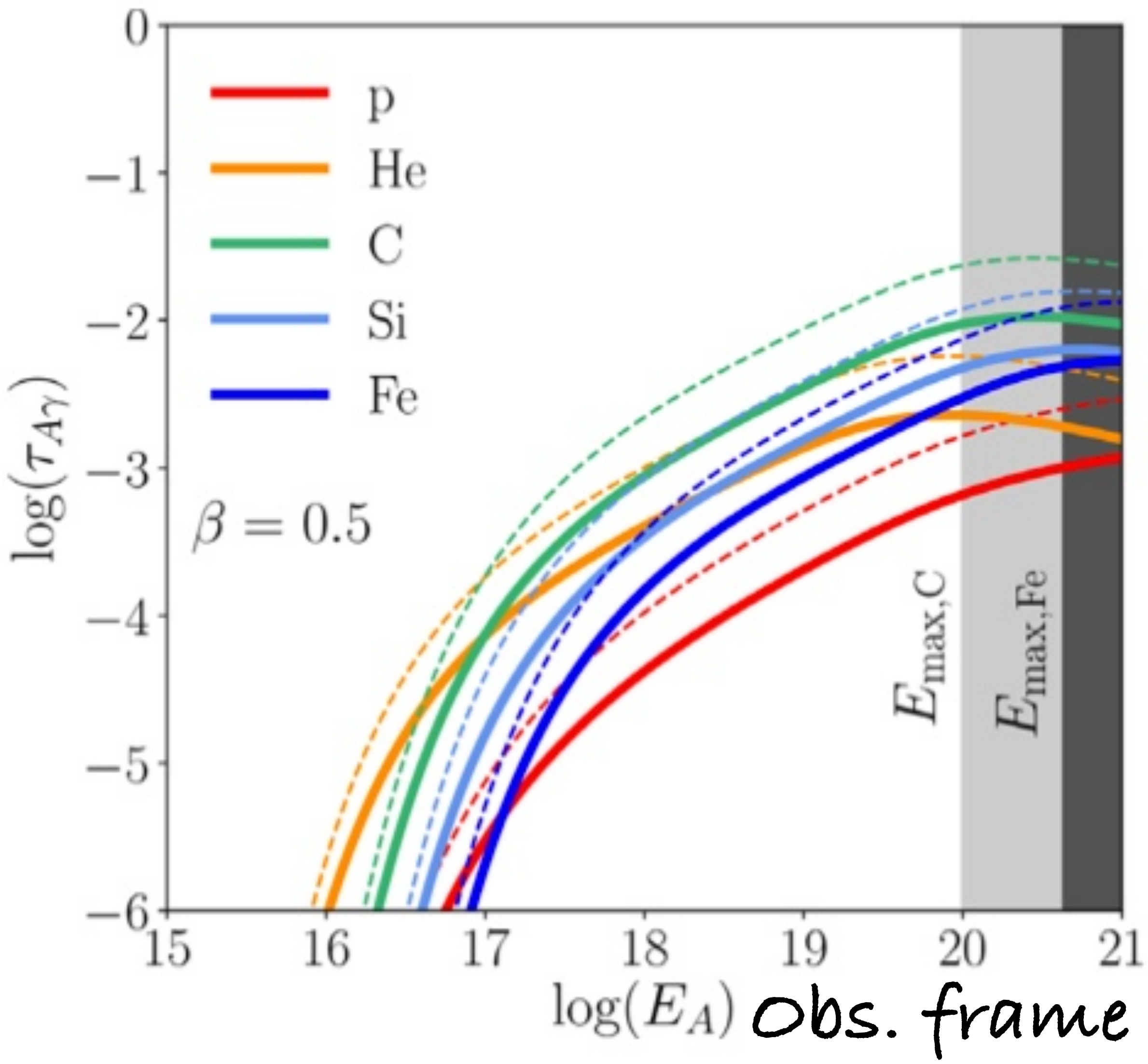


pγ efficiency





Photodisintegration of nuclei

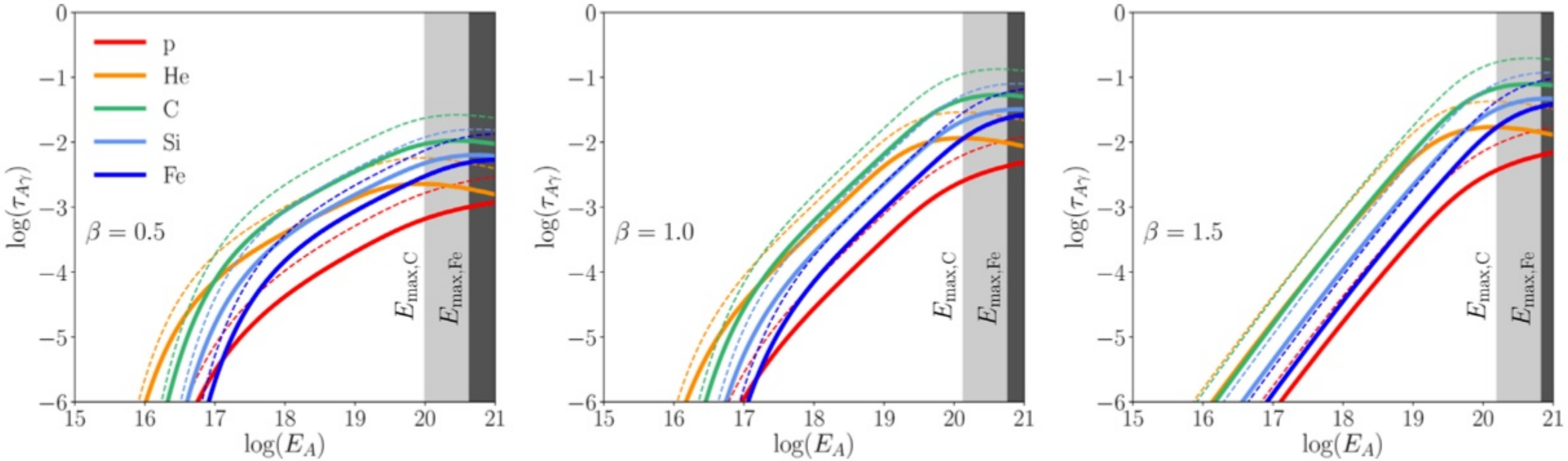


Mkn 421

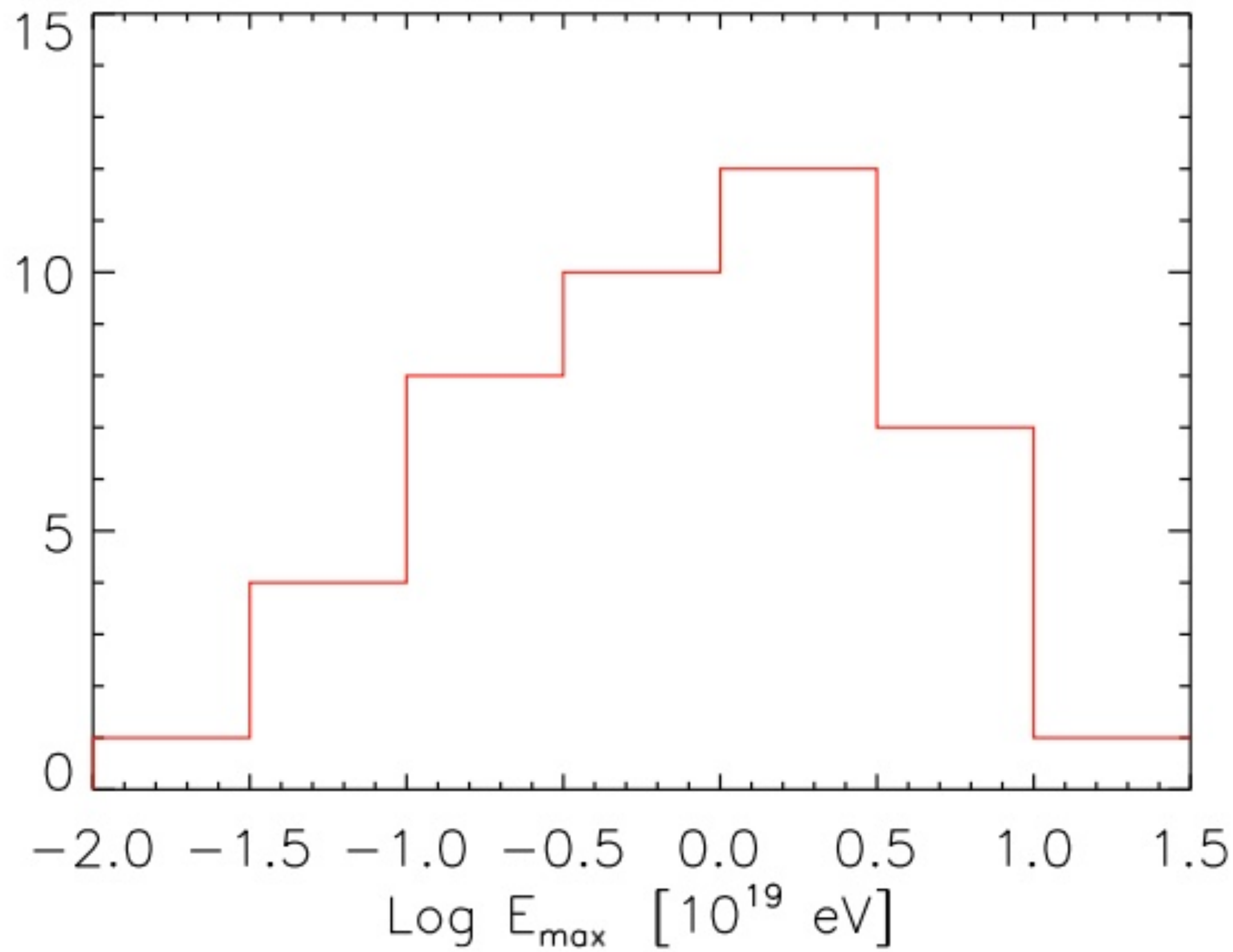
$$U_{\rm rad} = 10 \times U_{SSC}$$

$$E_{Z,\max} = 7 \times 10^{20}\,\text{eV}\left(\frac{Z}{26}\right)\left(\frac{B}{0.35\,\text{G}}\right)$$

Photodisintegration of nuclei



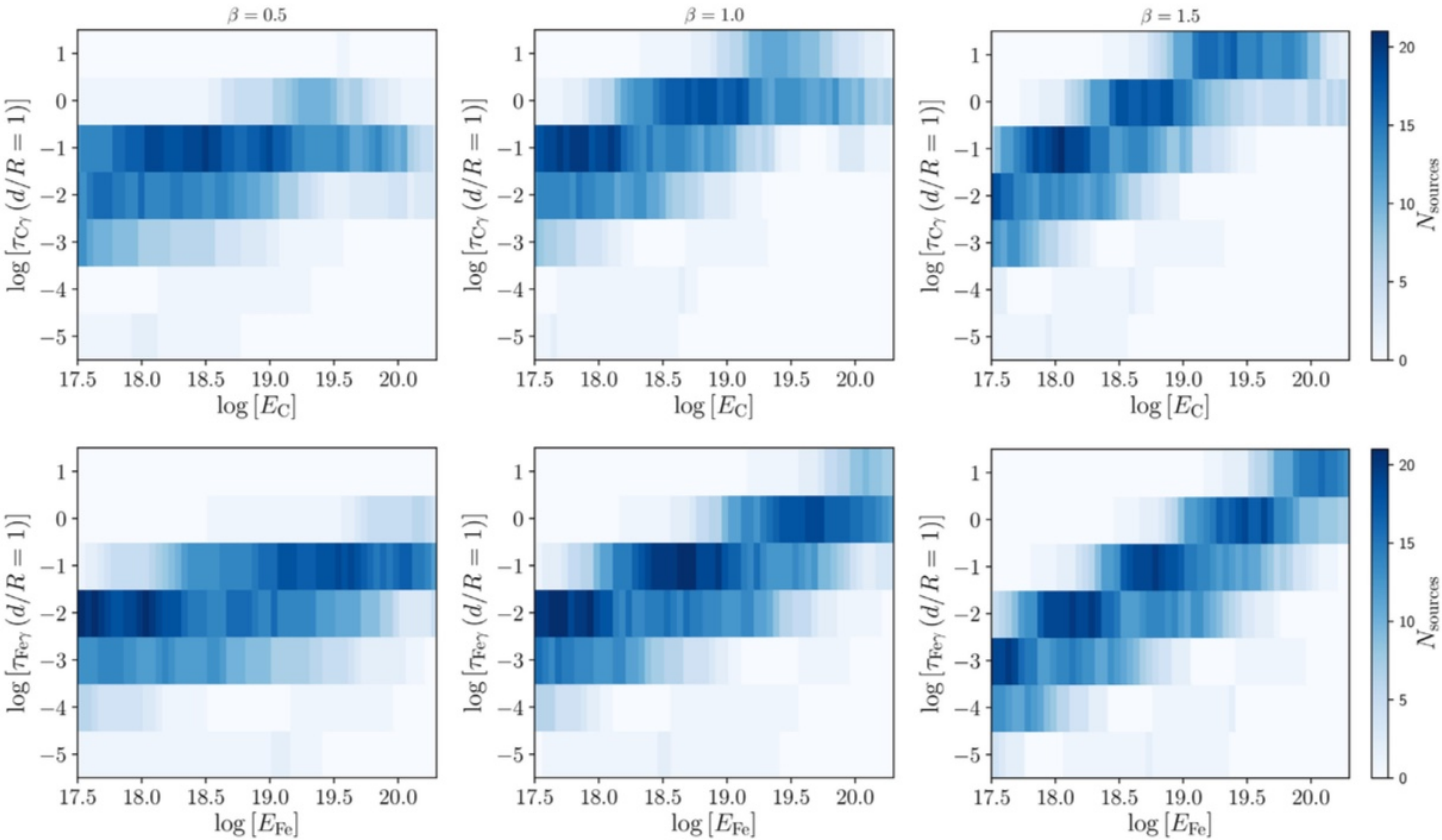
UHECR: BL Lac population



Z=1
Obs. frame

$$E_{Z,\max} = 7 \times 10^{20}\,\mathrm{eV} \left(\frac{Z}{26}\right) \left(\frac{B}{0.35\,\mathrm{G}}\right)$$

UHECR: BL Lac population



d=R

Gamma-ray opacity: small up to 10-20 TeV ☺

photomeson reactions: low efficiency ☹

destruction of heavy nuclei: not very effective ☺

Final thoughts

Strong synergy between theory/models and observations

The astrophysical conditions of sources must be considered!

Important to compile smart lists/catalogues of candidates (trials)