



Active Galactic Nuclei

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Outlook

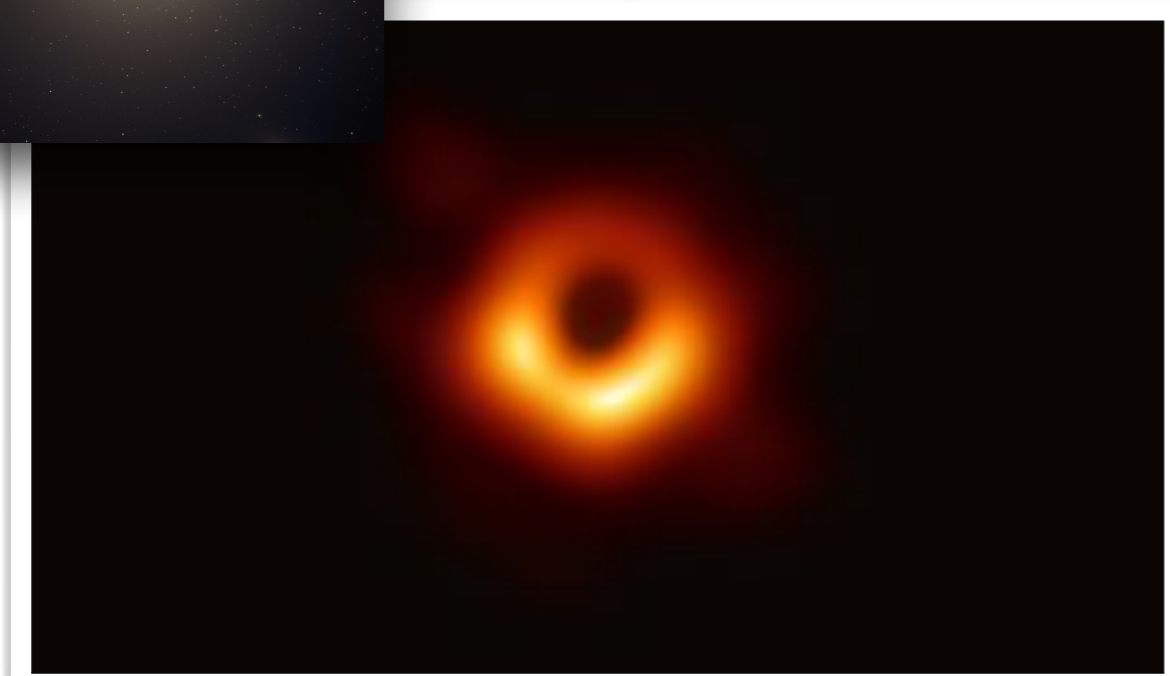
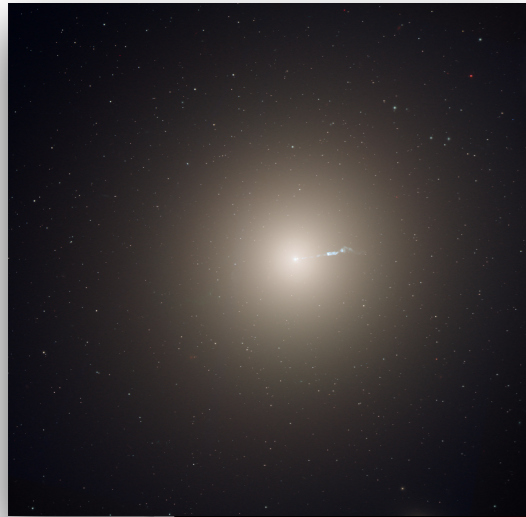
SMBH in galaxies, AGNs

AGNs with jets

Blazars: cosmic accelerators

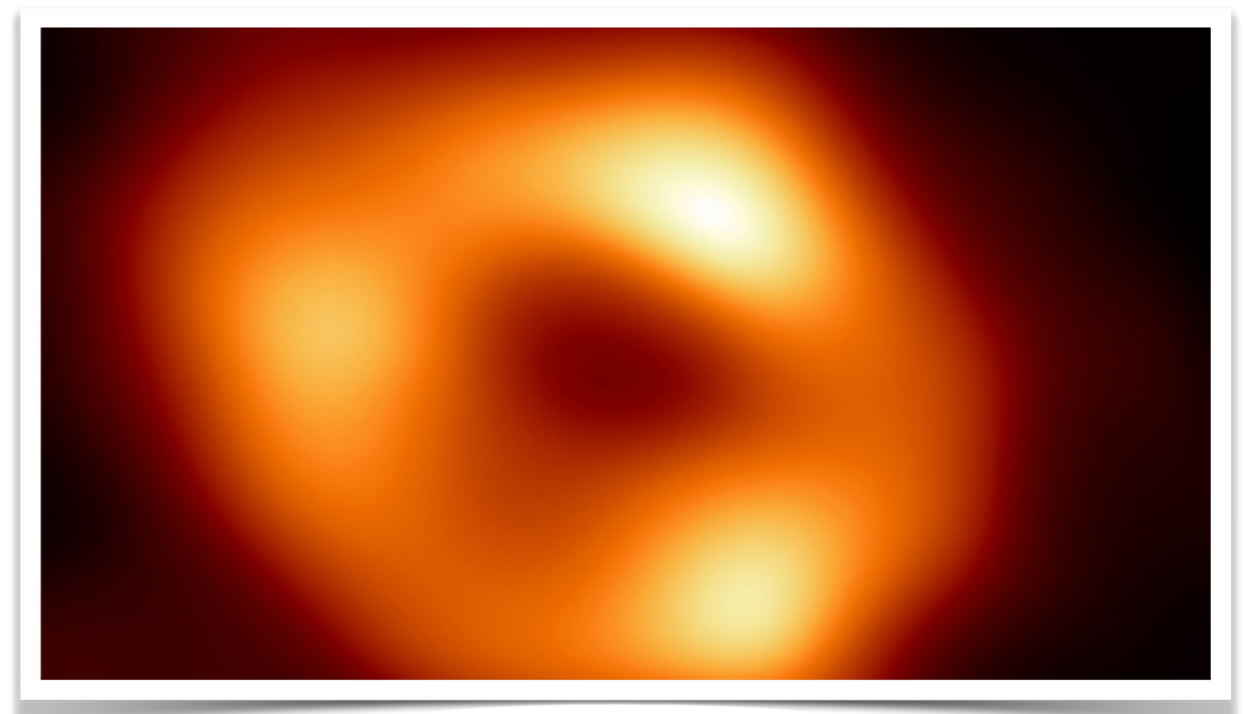
Active Galactic Nuclei

Every galaxy harbors a supermassive BH in its center



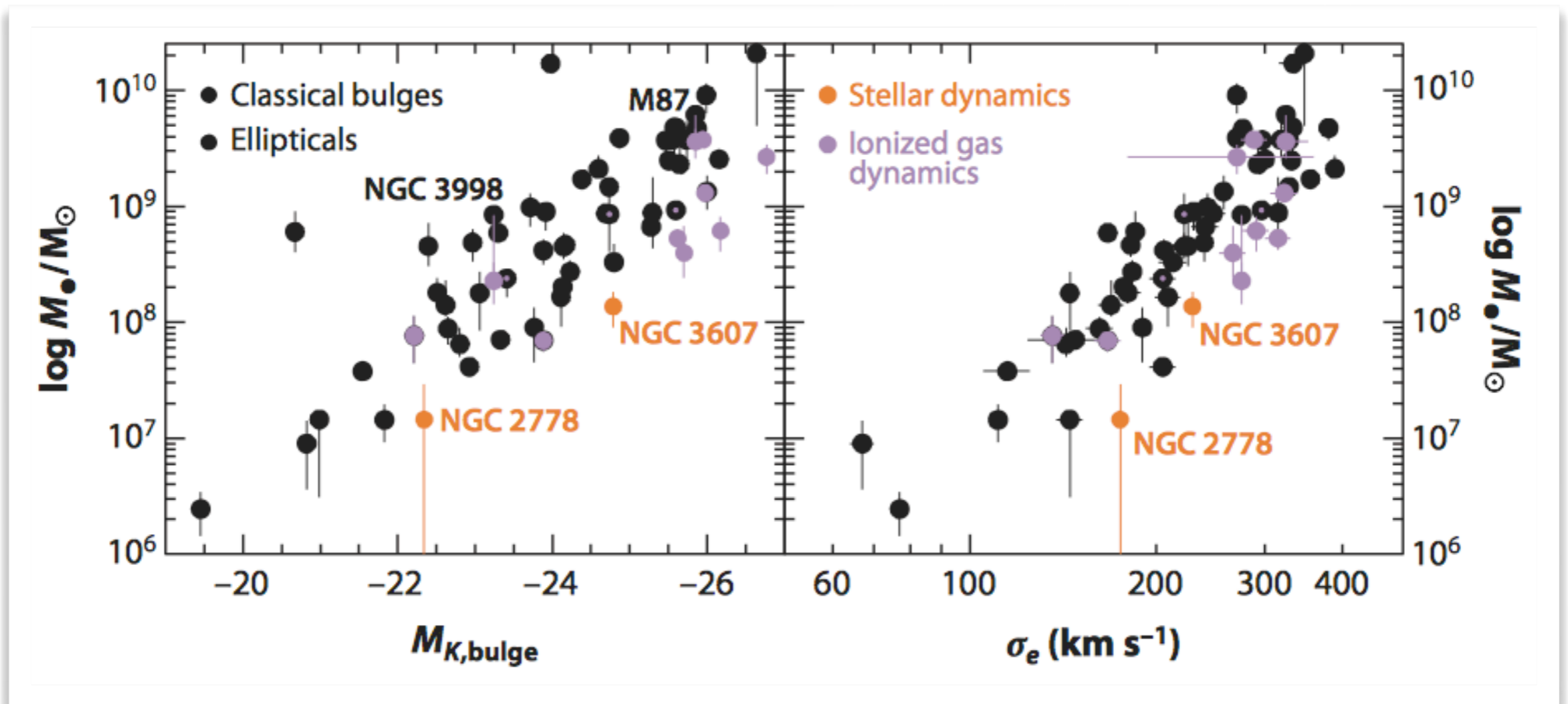
M87 - $6.5e9 M_{\text{sun}}$

MW - $4e6 M_{\text{sun}}$



Event Horizon Telescope images

Active Galactic Nuclei

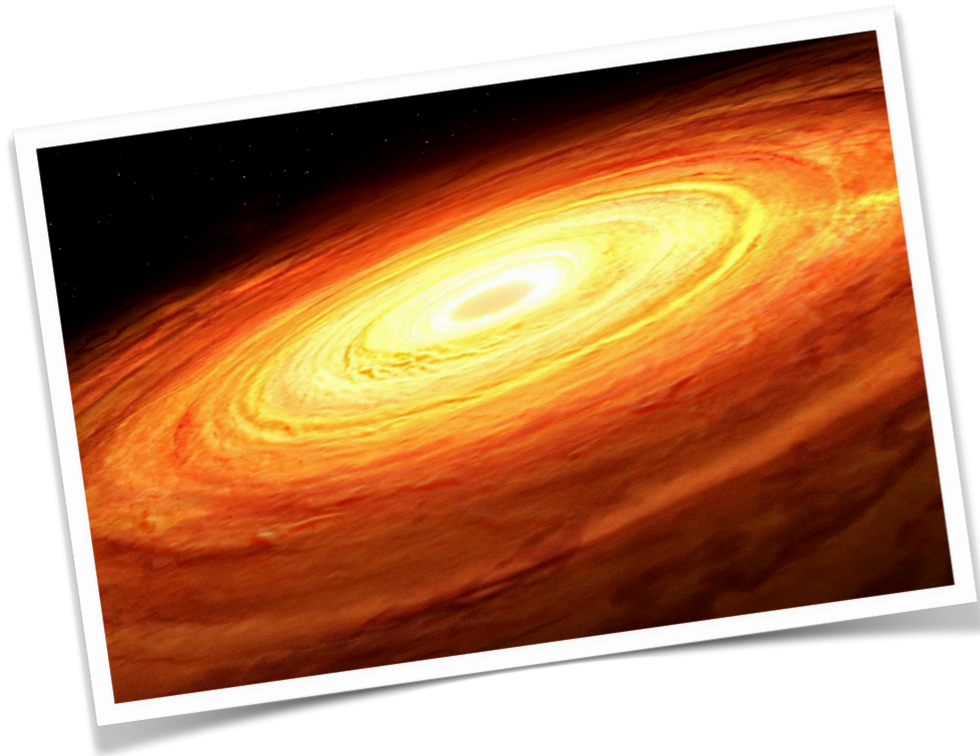


SMBH-galaxy coevolution
Feedback?

Kormendy & Ho 2013

Active Galactic Nuclei

In about 1% of the galaxies the BH is active (AGN)



Very bright **galactic nuclei** in nearby galaxies

High excitation **emission** lines

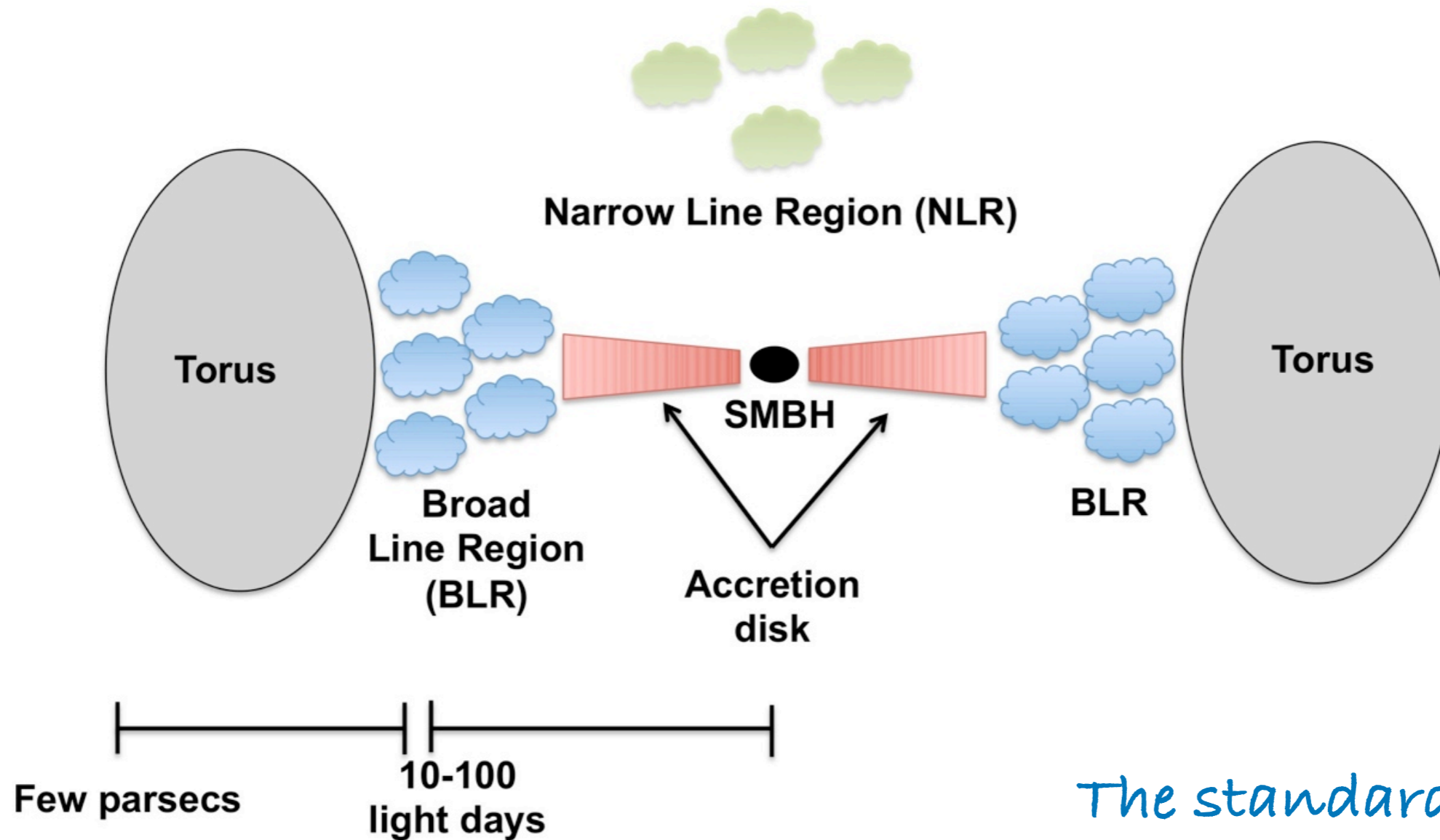
Very bright, distant (**cosmological**) sources

Non-thermal (radio, X rays, gamma rays) emission

...

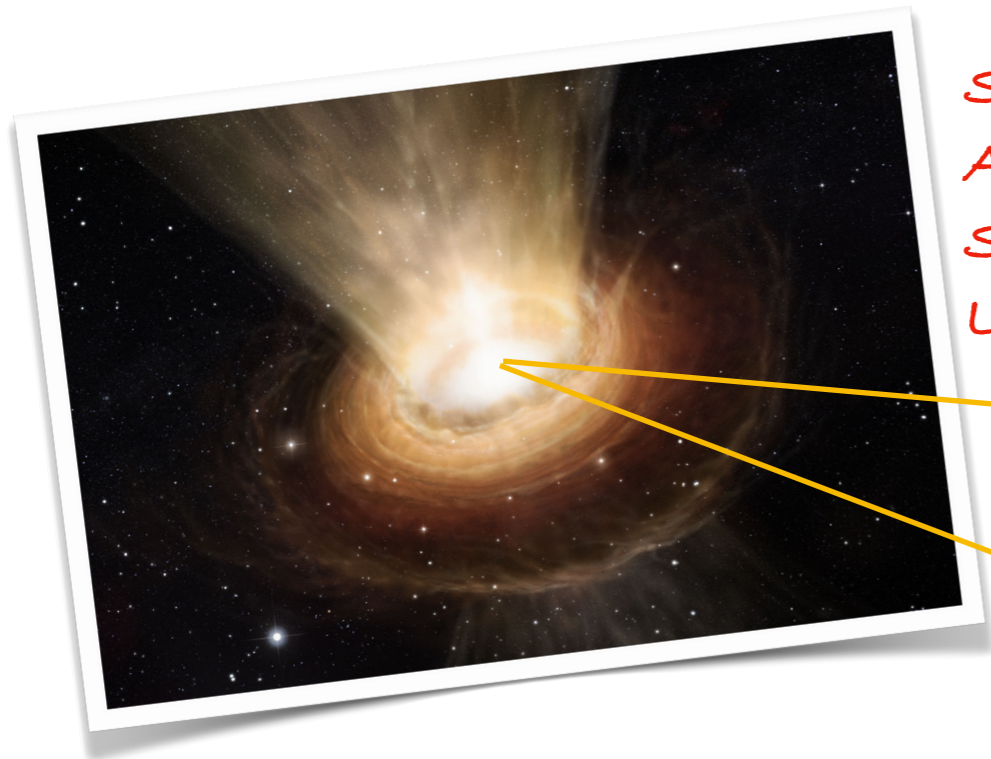
AGNs are ultimately powered by the gravitational energy lost by matter falling into the SMBH

Active Galactic Nuclei

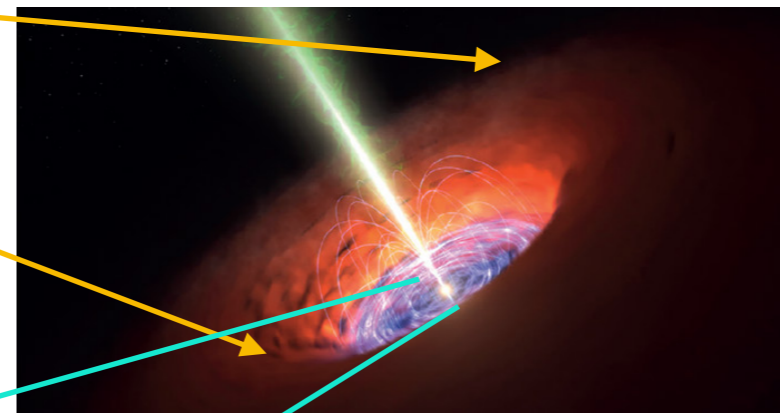


*The standard picture
(unification scheme)*

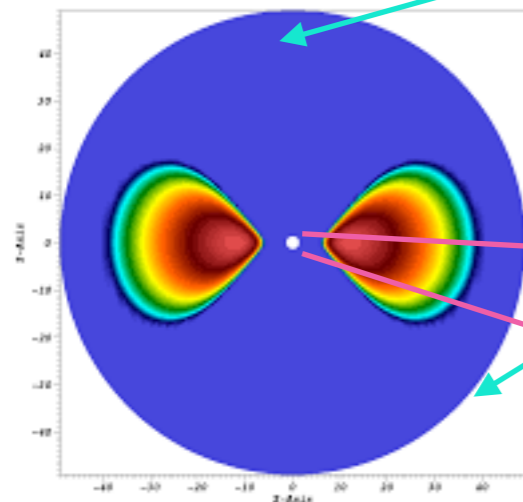
From galaxies to central black holes



Starbursts
AGN winds
Superwinds
Large-scale jets

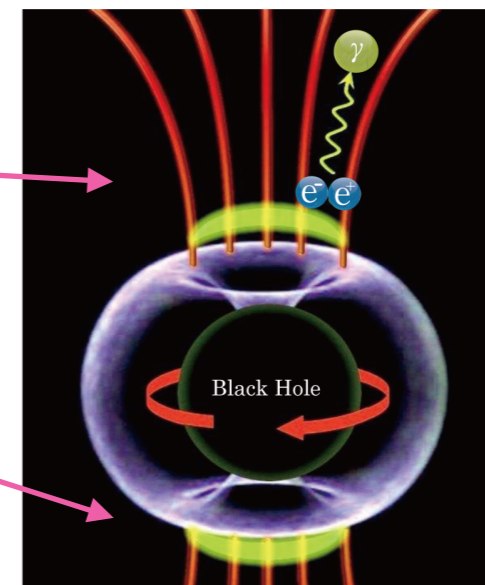


Jets/blazars



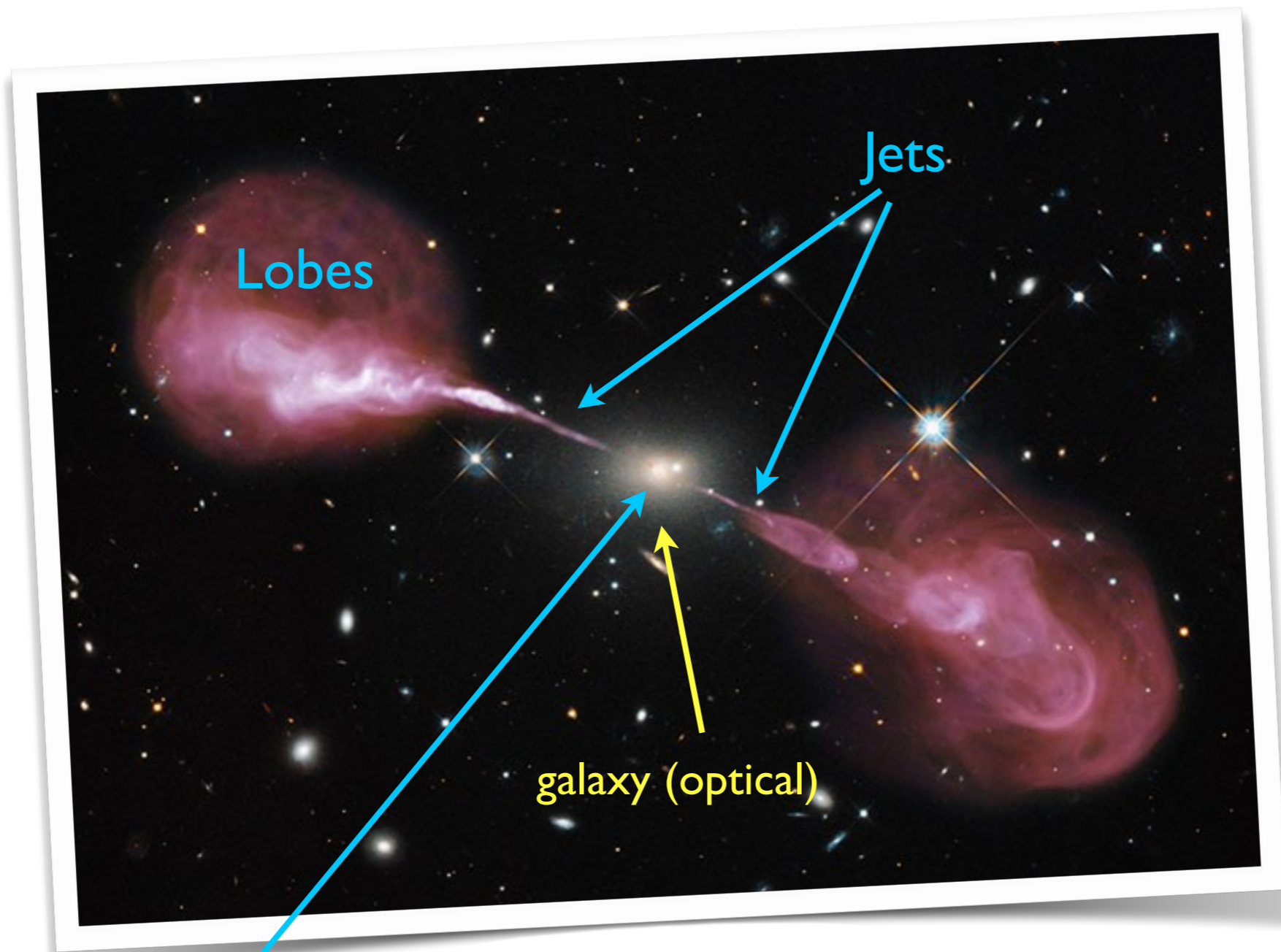
Accretion flow

BH Magnetosphere



Relativistic jets in AGNs

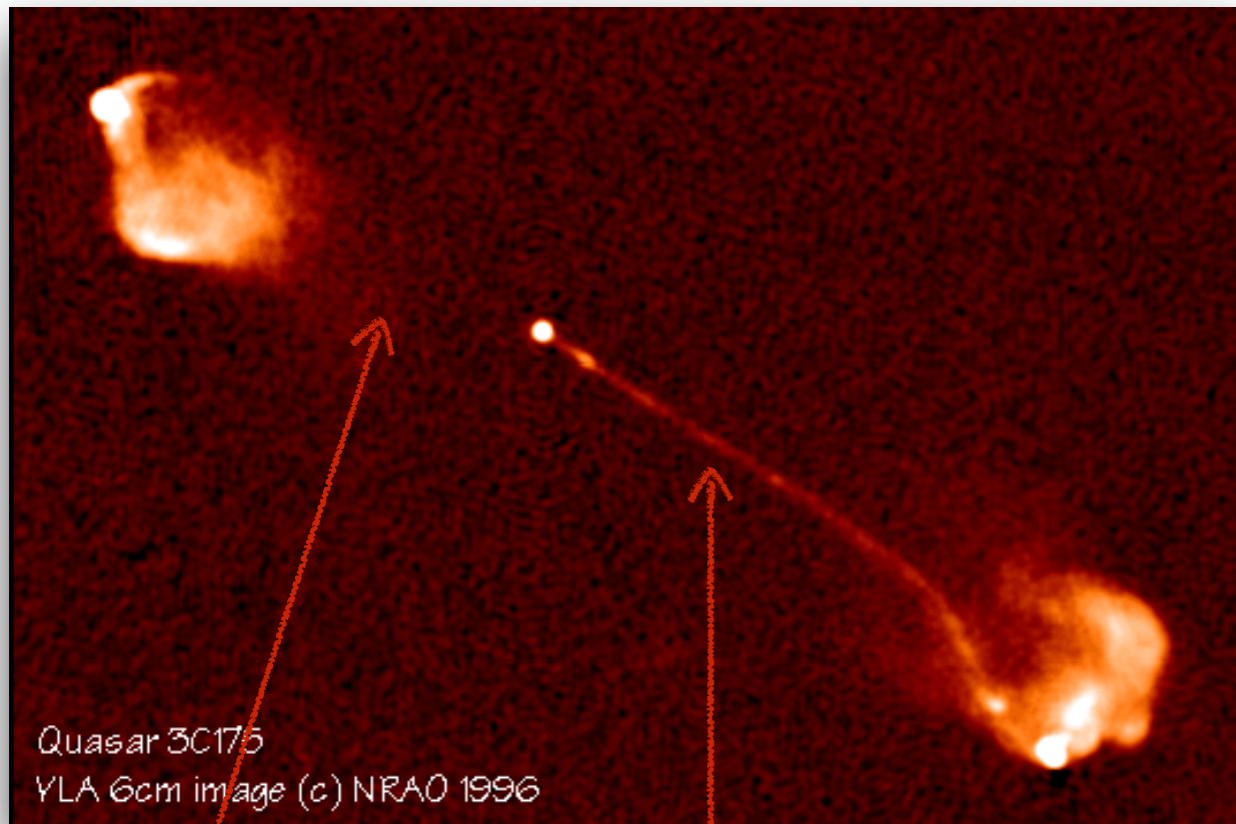
About 10% of AGN are radio loud: relativistic JETS



Central engine (BH)

Relativistic jets in AGNs

Jet asymmetries



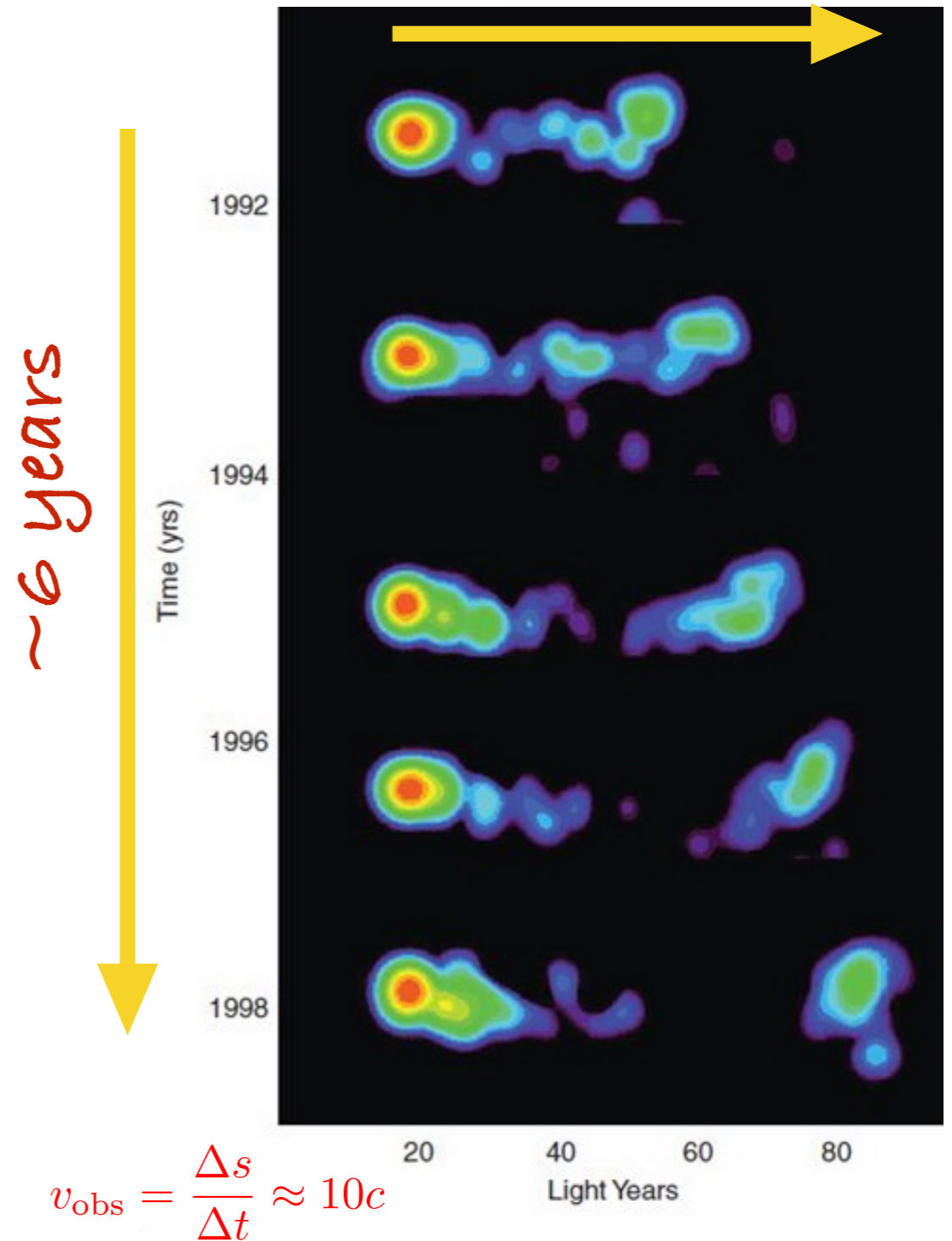
Counterjet

Jet

Evidences for bulk relativistic motion
($\Gamma \sim 10$)

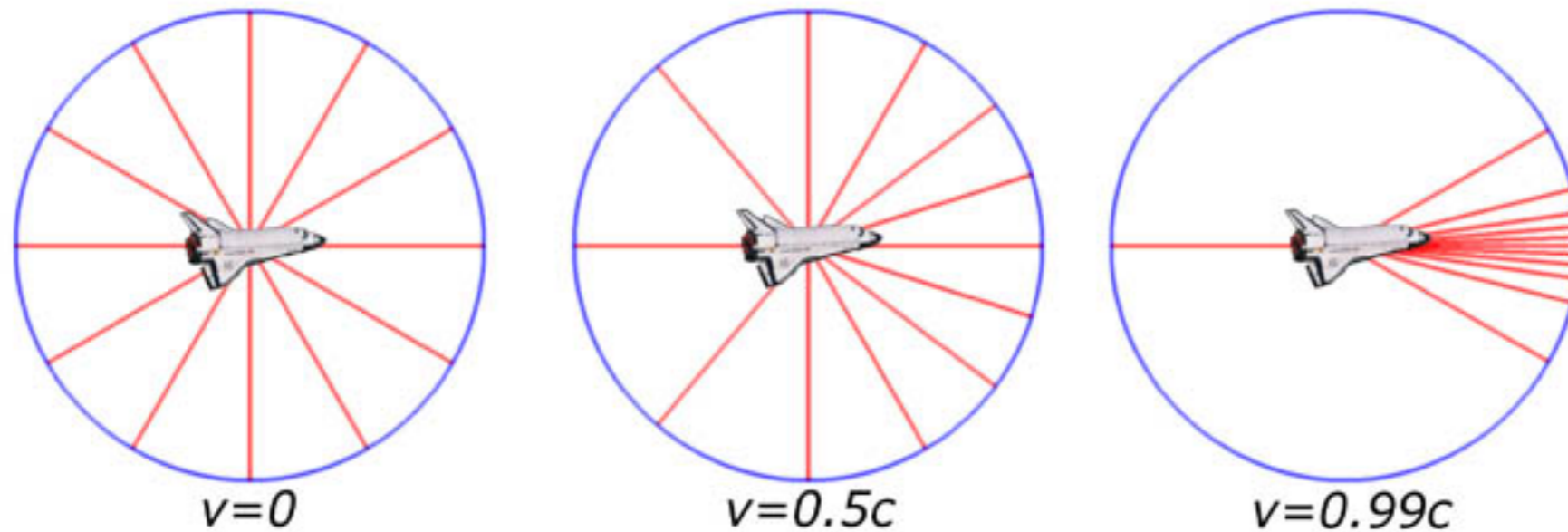
Superluminal motion

~60 light years



(Special) relativity at work

Doppler beaming



$v=0$

$v=0.5c$

$v=0.99c$

$$\delta = \frac{1}{\Gamma(1 - \beta \cos \theta_v)}$$

Amplification $L_{\text{obs}} = L' \delta^4$

Blueshift $\nu_{\text{obs}} = \nu' \delta$

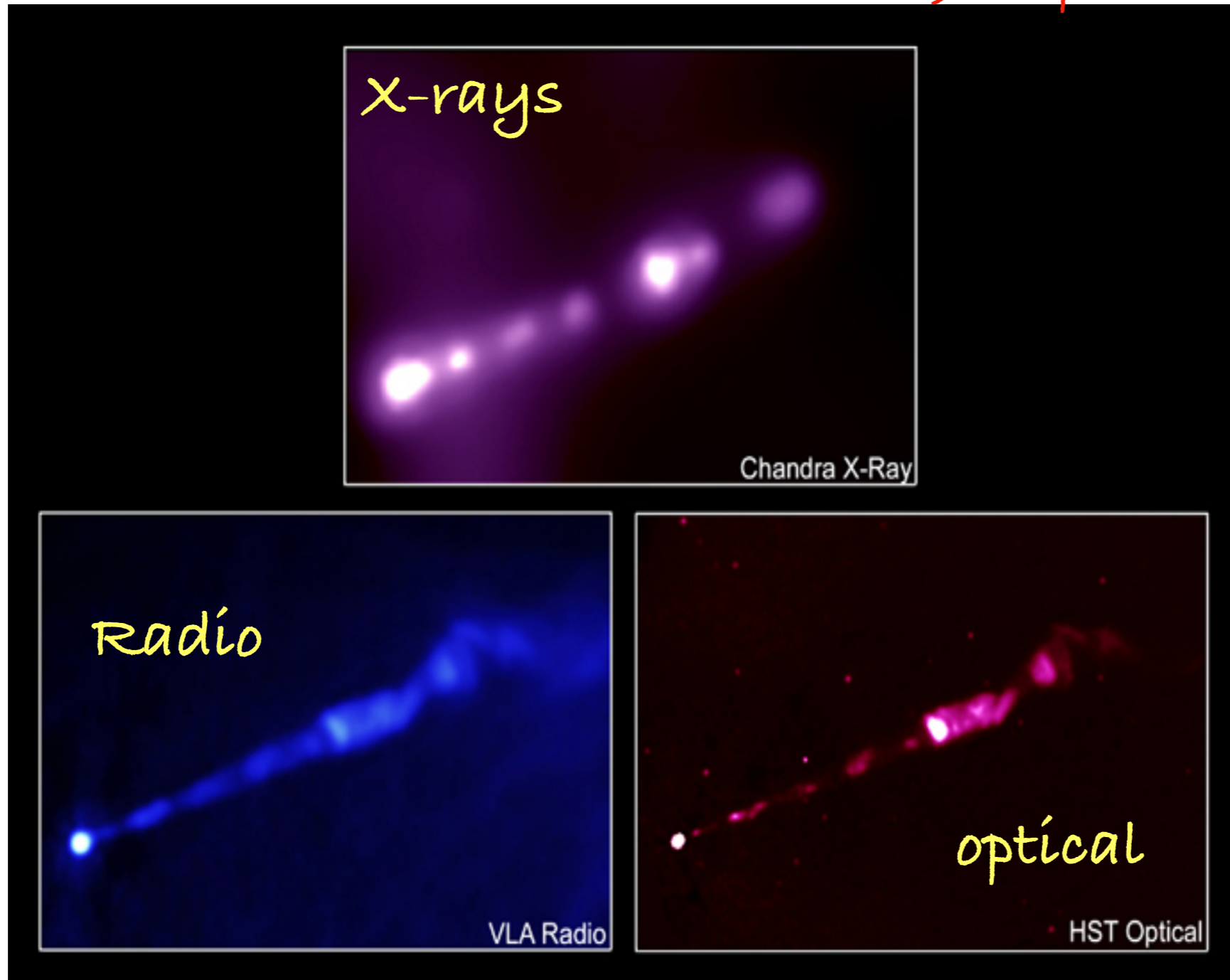
Shortening
of timescales $t_{\text{obs}} = t' / \delta$

$$\delta \approx 10 - 20$$

Relativistic jets in AGNs

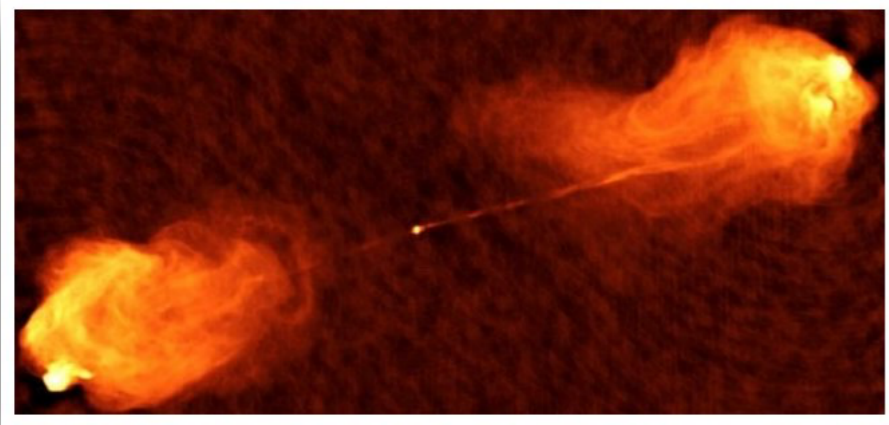
Multi λ structures

M87@kpc scale



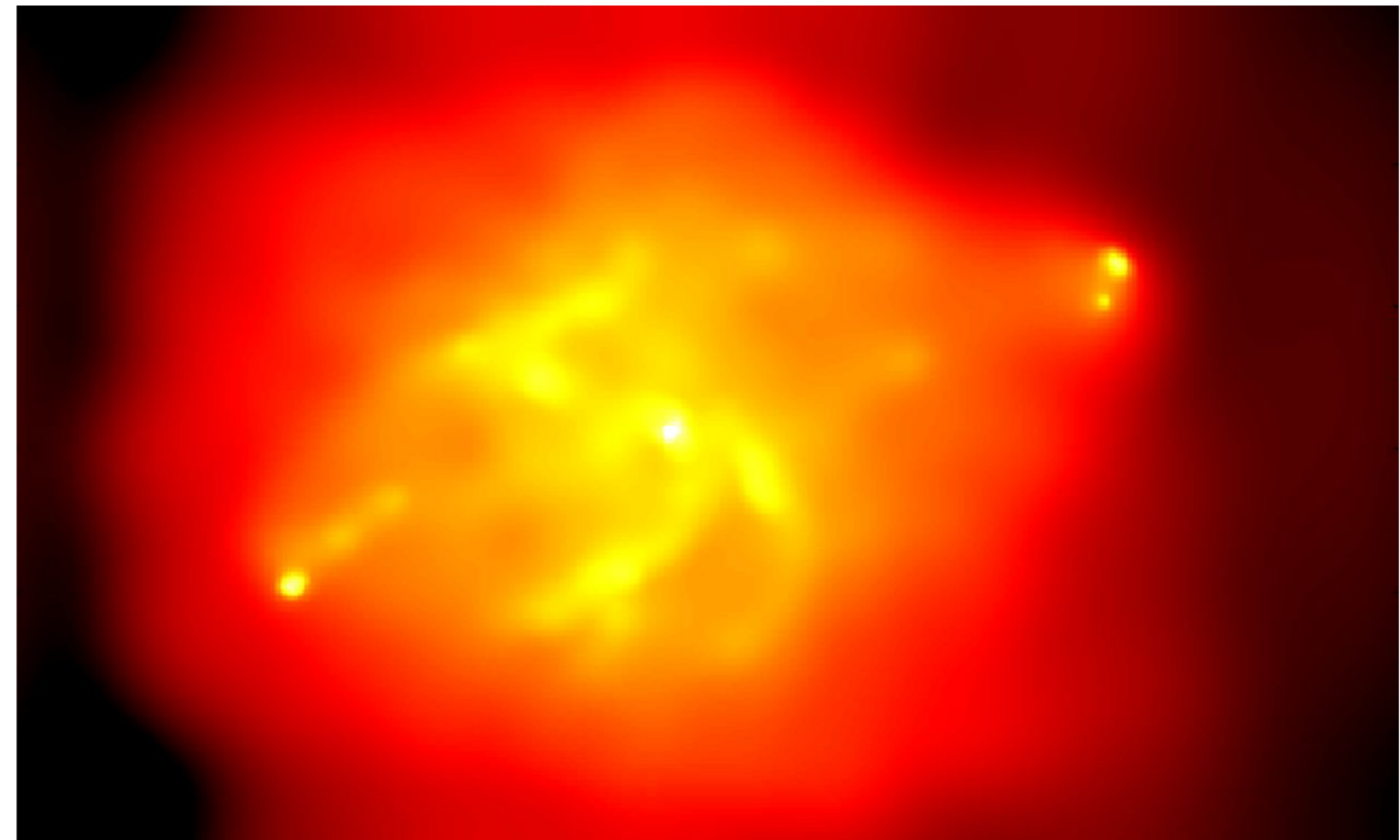
Relativistic jets in AGNs

Radio

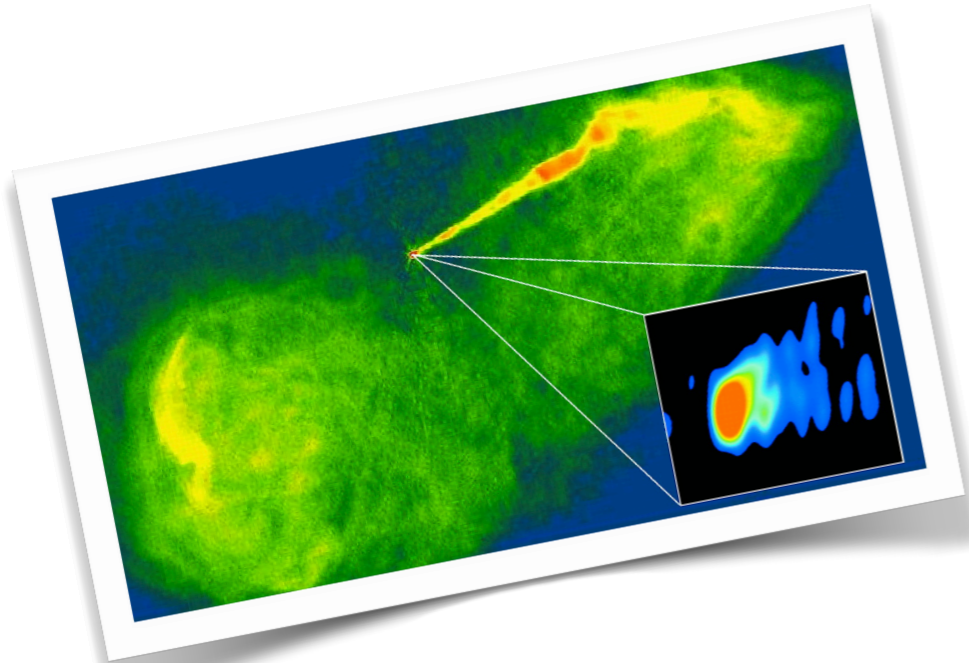


Strong impact on the environment

X-rays

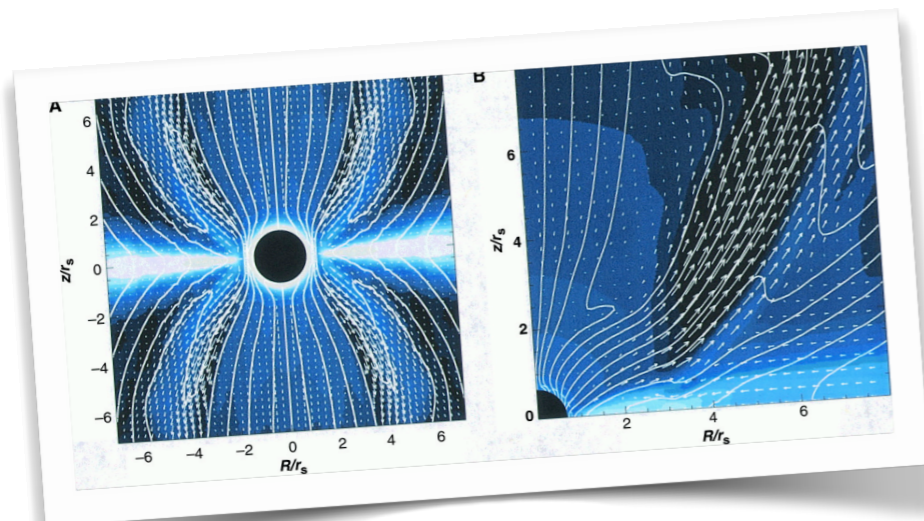
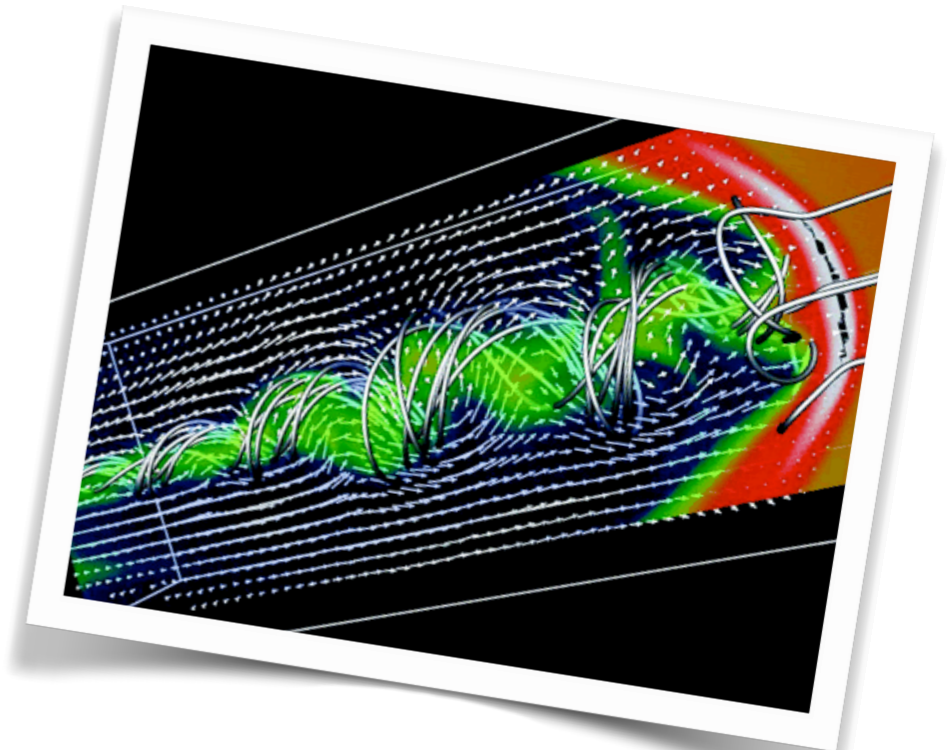


Basic astrophysical issues



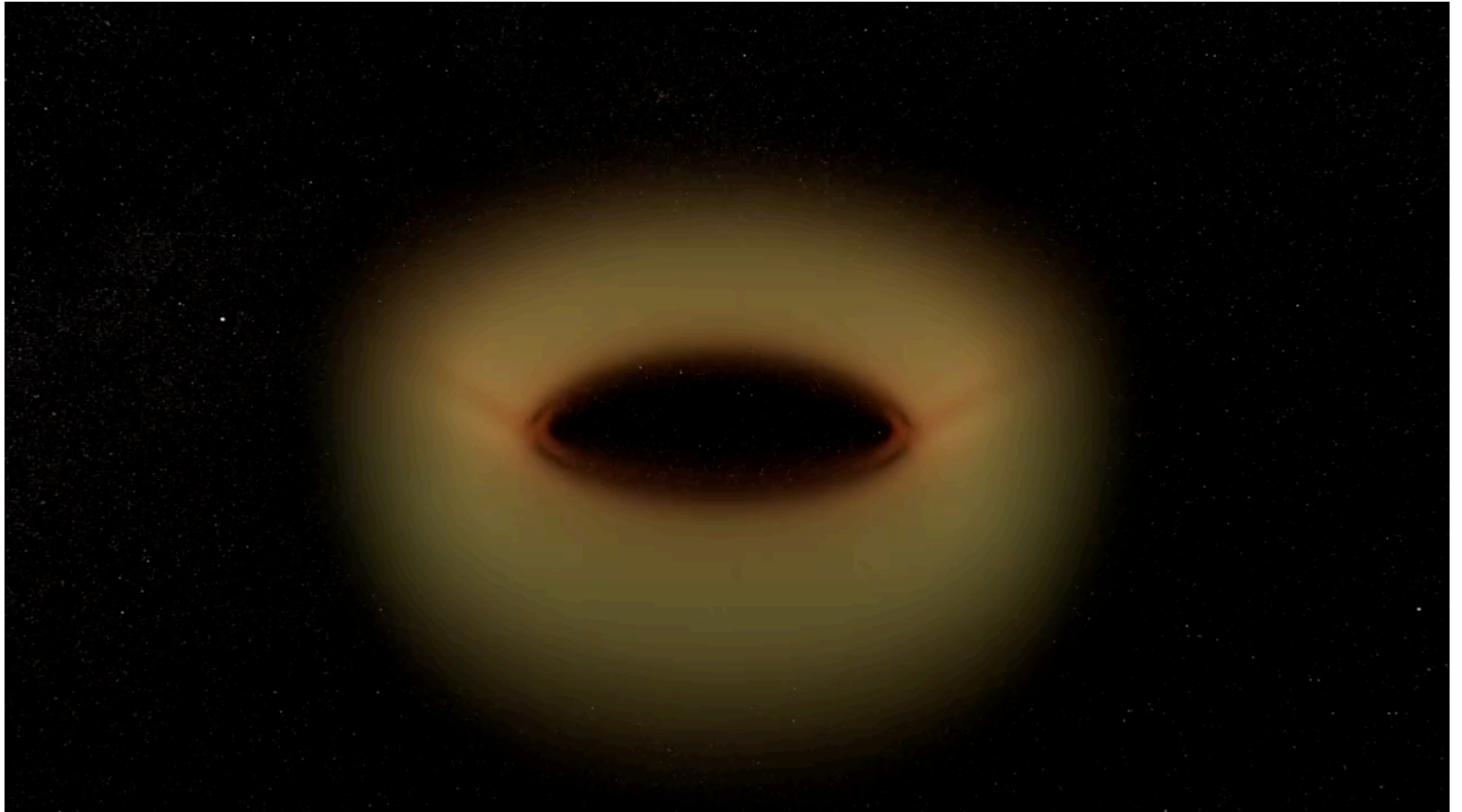
Jet speed,
composition,
power

Magnetic fields,
particle acceleration
emission mechanisms



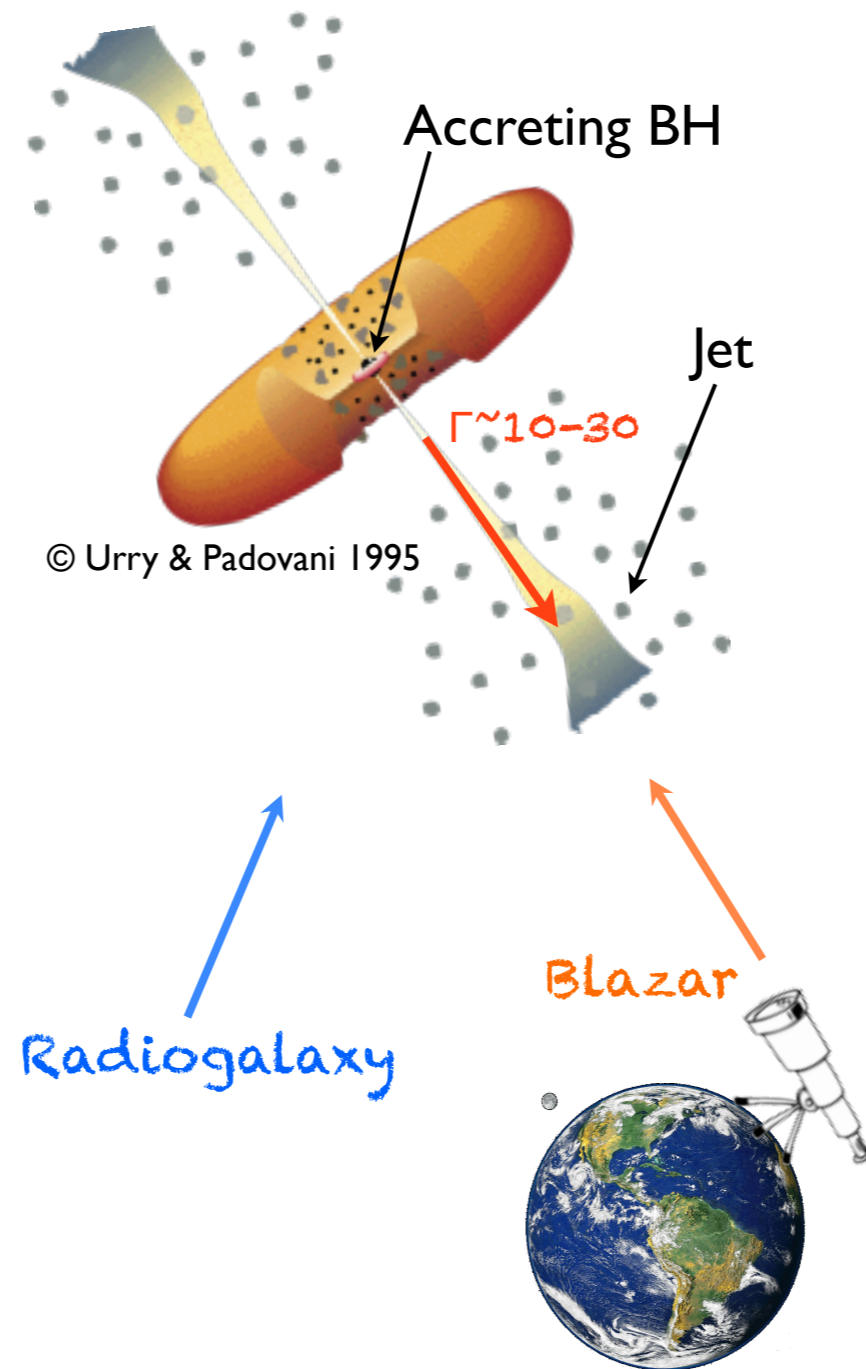
Formation, collimation,
acceleration

The central engine



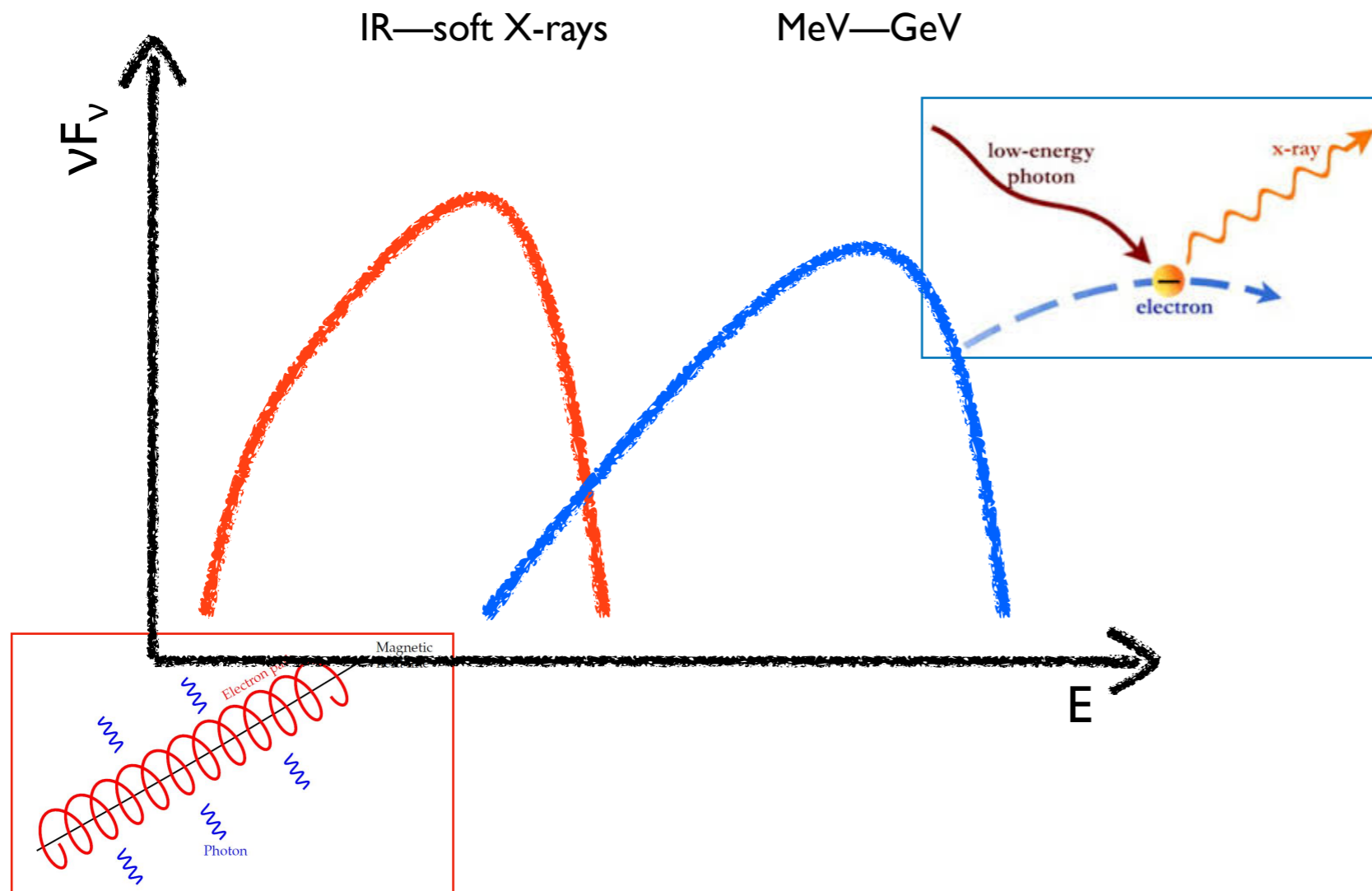
GRMHD simulation by McKinney, Tchekhovskoy, and Blandford 2012

Blazars: pointed jets



- Compact radio core
- Extreme variability
- High polarization
- Superluminal motion with extreme apparent speeds
- Emission from radio to gamma rays

Blazars: pointed jets

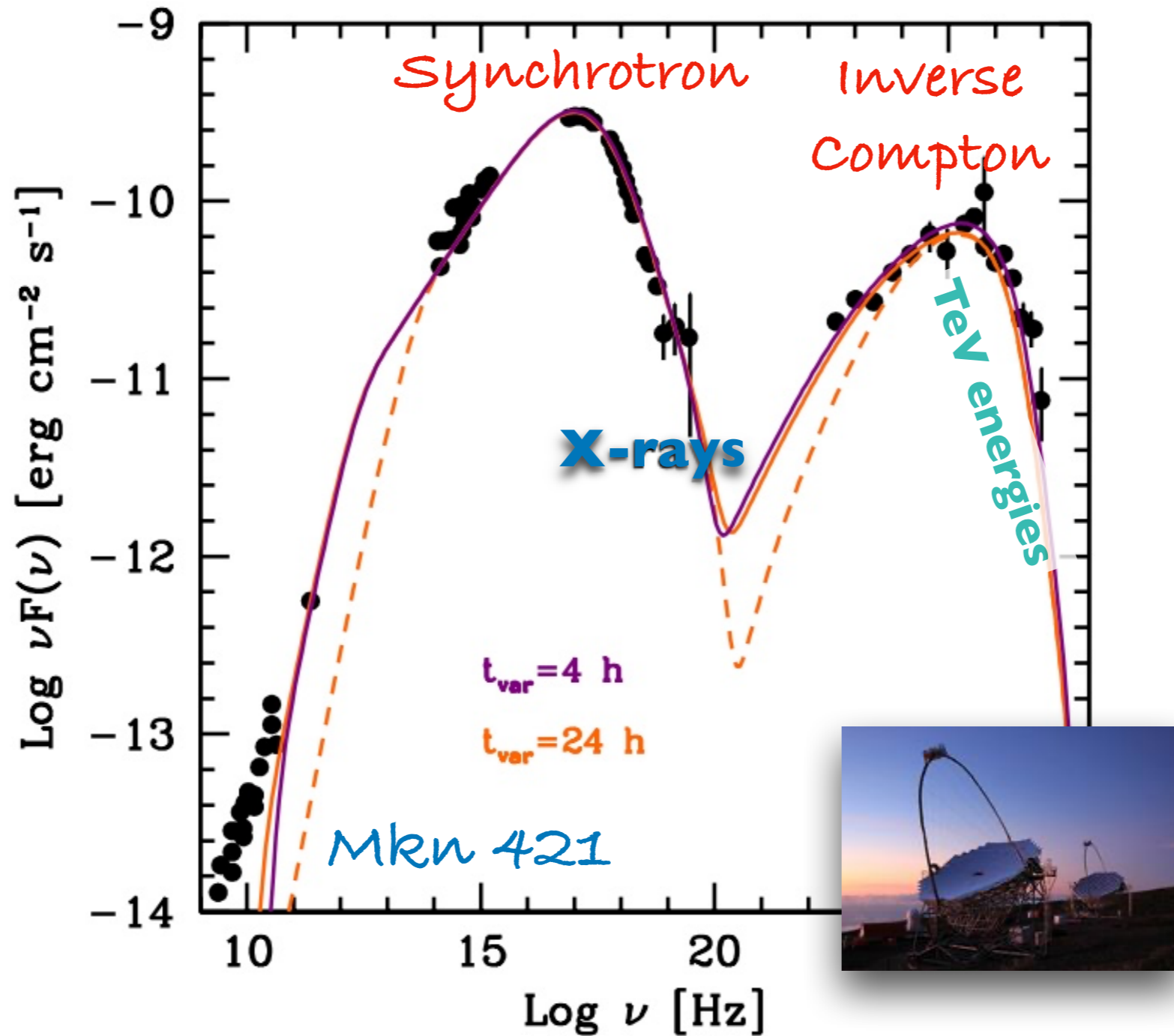


SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

Synchrotron and IC in LEPTONIC models.

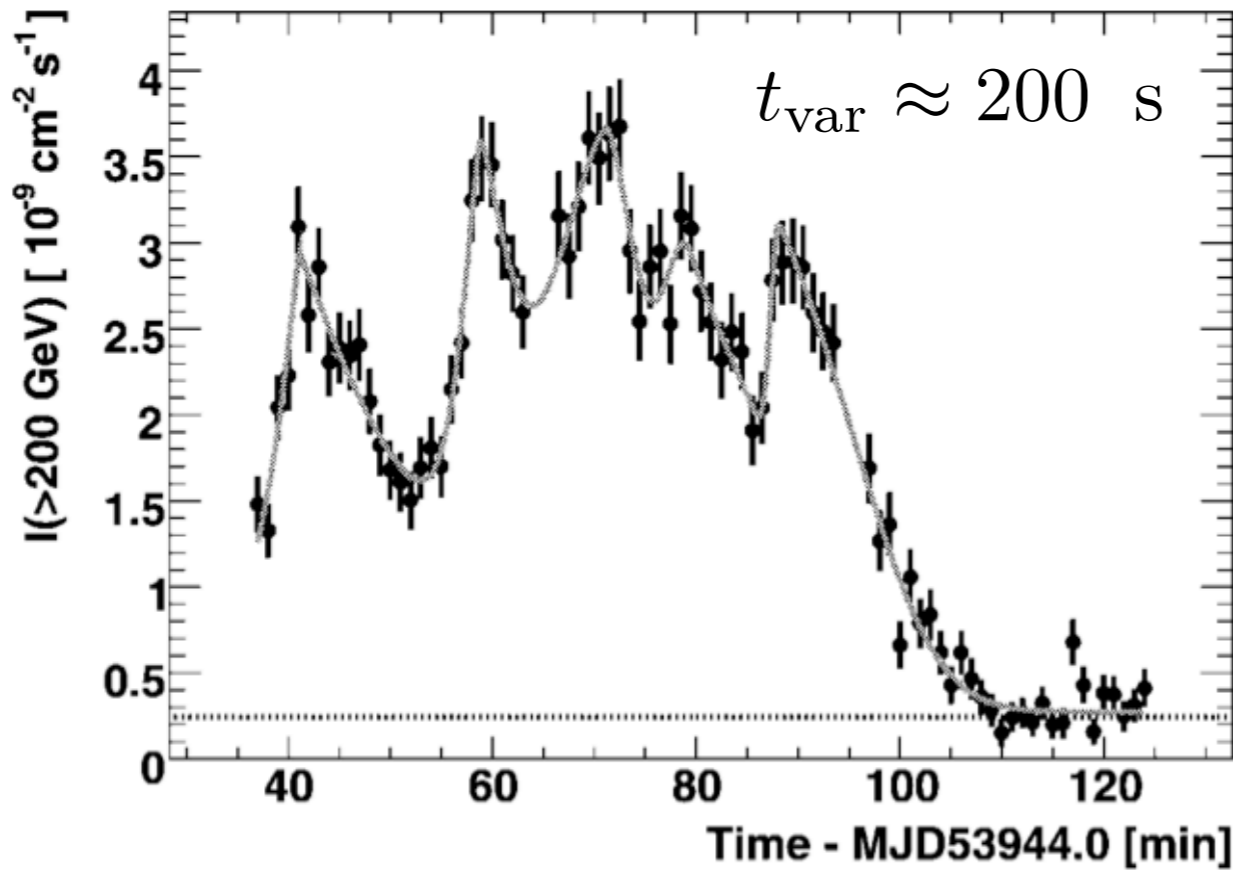
Multifrequency sources

The bulk of extragalactic gamma-ray (GeV-TeV) sources



Variability

PKS 2155-304@TeV



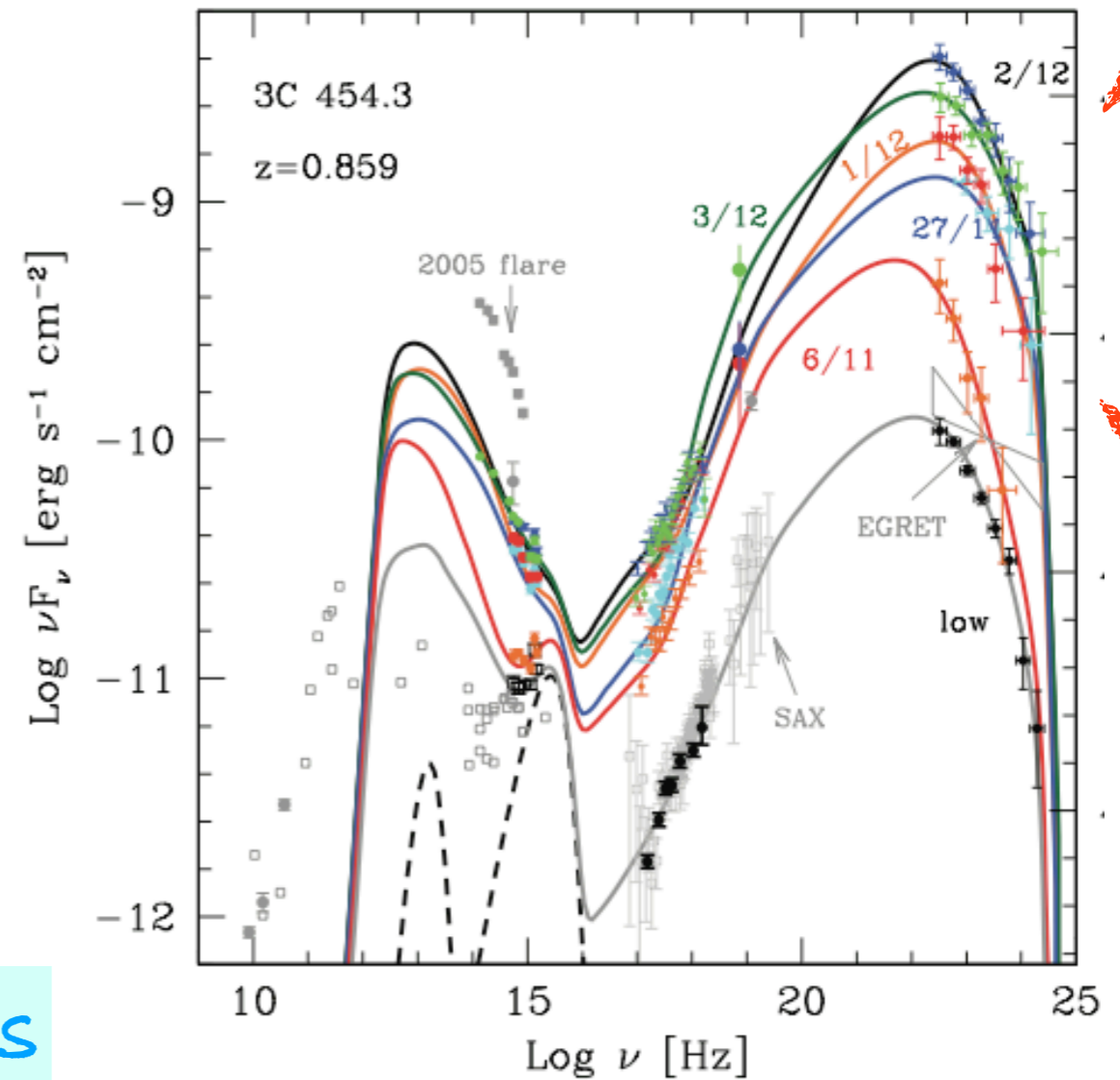
Aharonian et al. 2007

Short time-scales

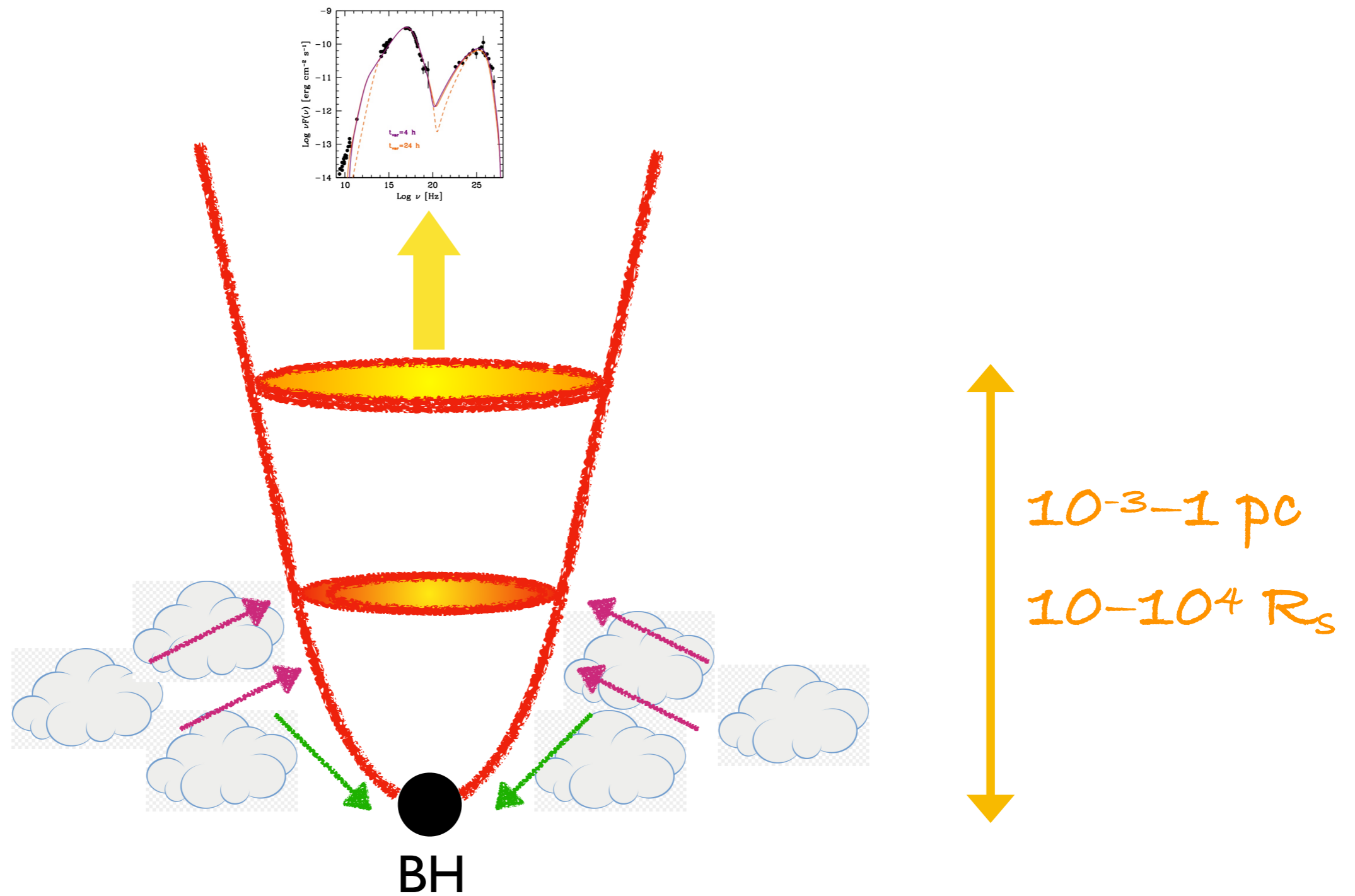
Small spatial scales
Close to the BH

Large amplitudes

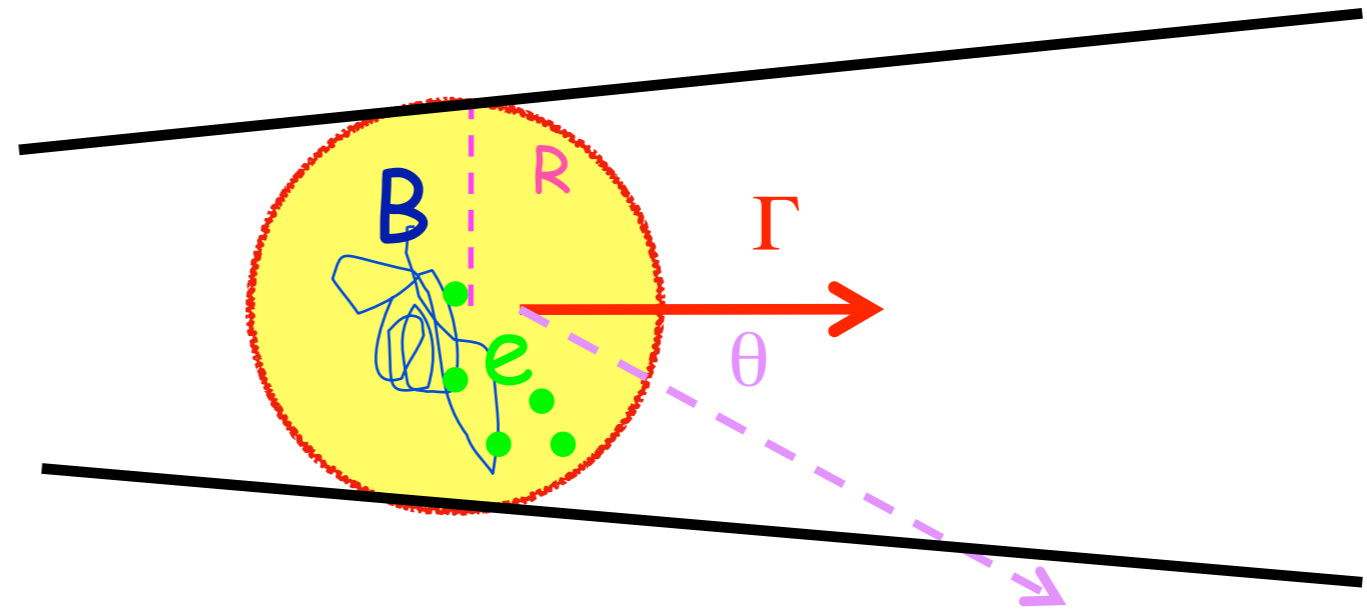
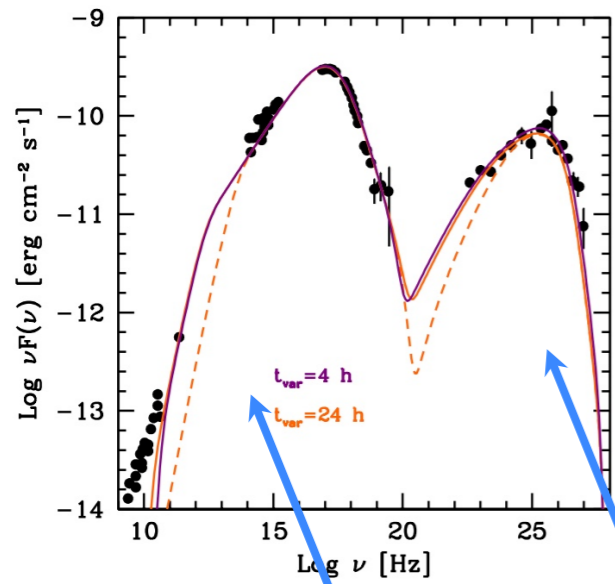
Bonnoli et al. 2011



Blazars: the interpretative framework



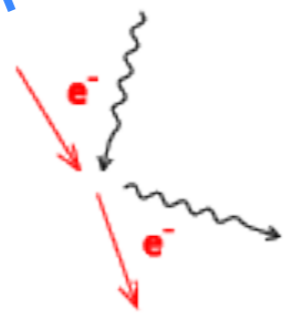
Blazars: the interpretative framework



leptonic

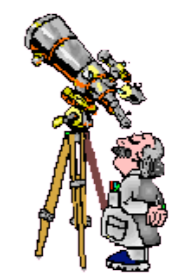


electron synchrotron



Inverse Compton scattering

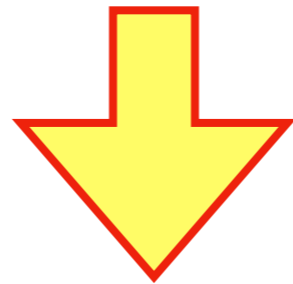
Electrons with energies up few TeV



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

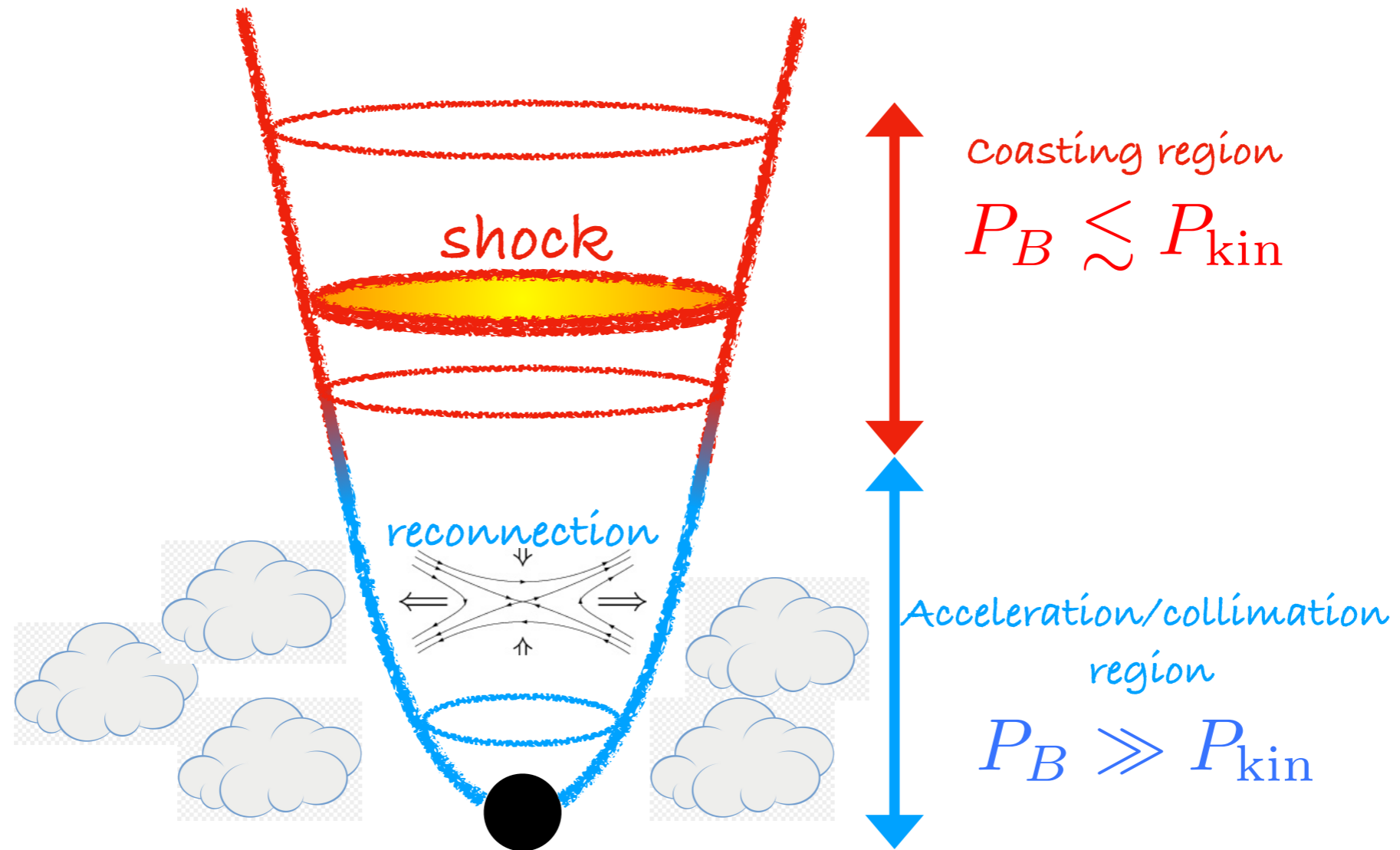
Energizing the particles

Despite the huge adiabatic (expansion) and radiative losses emission by highly energetic particles is detected at large distances.



Dissipation and acceleration mechanism(s)?

Energizing the particles



Contopoulos 1994
Komissarov et al. 2009
Tchekhovskoy et al. 2009

Energizing the particles

Magnetic field \rightarrow kinetic \rightarrow shocks \rightarrow particles

Dissipation

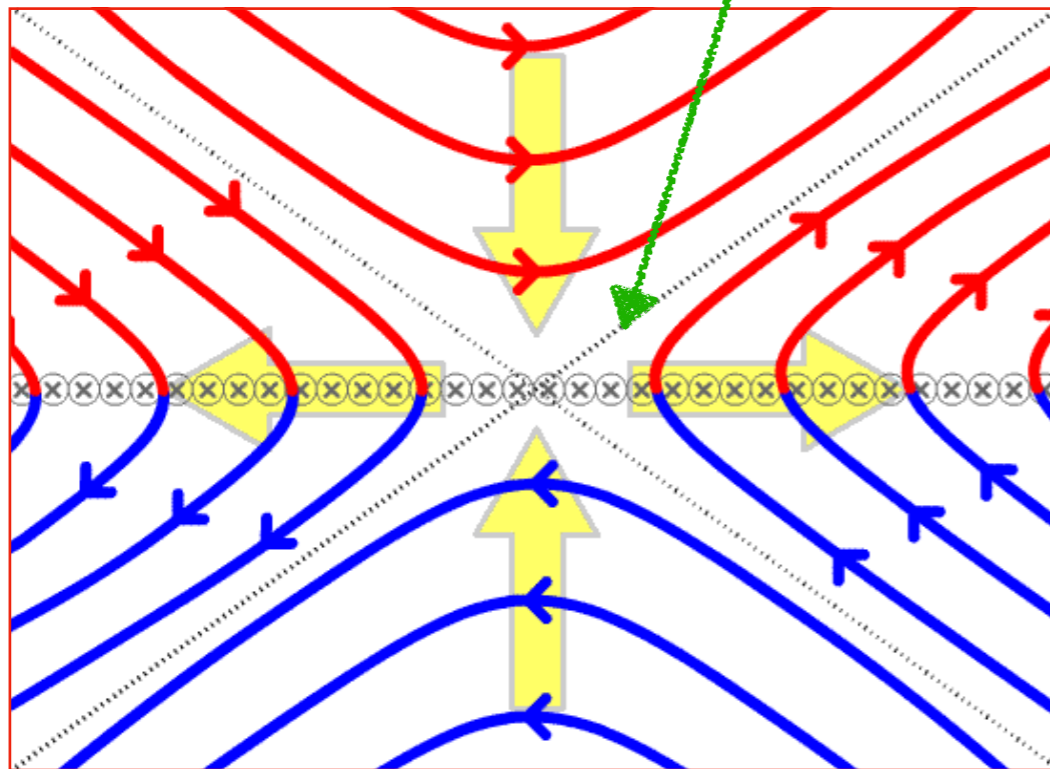
Magnetic field \rightarrow reconnection \rightarrow particles



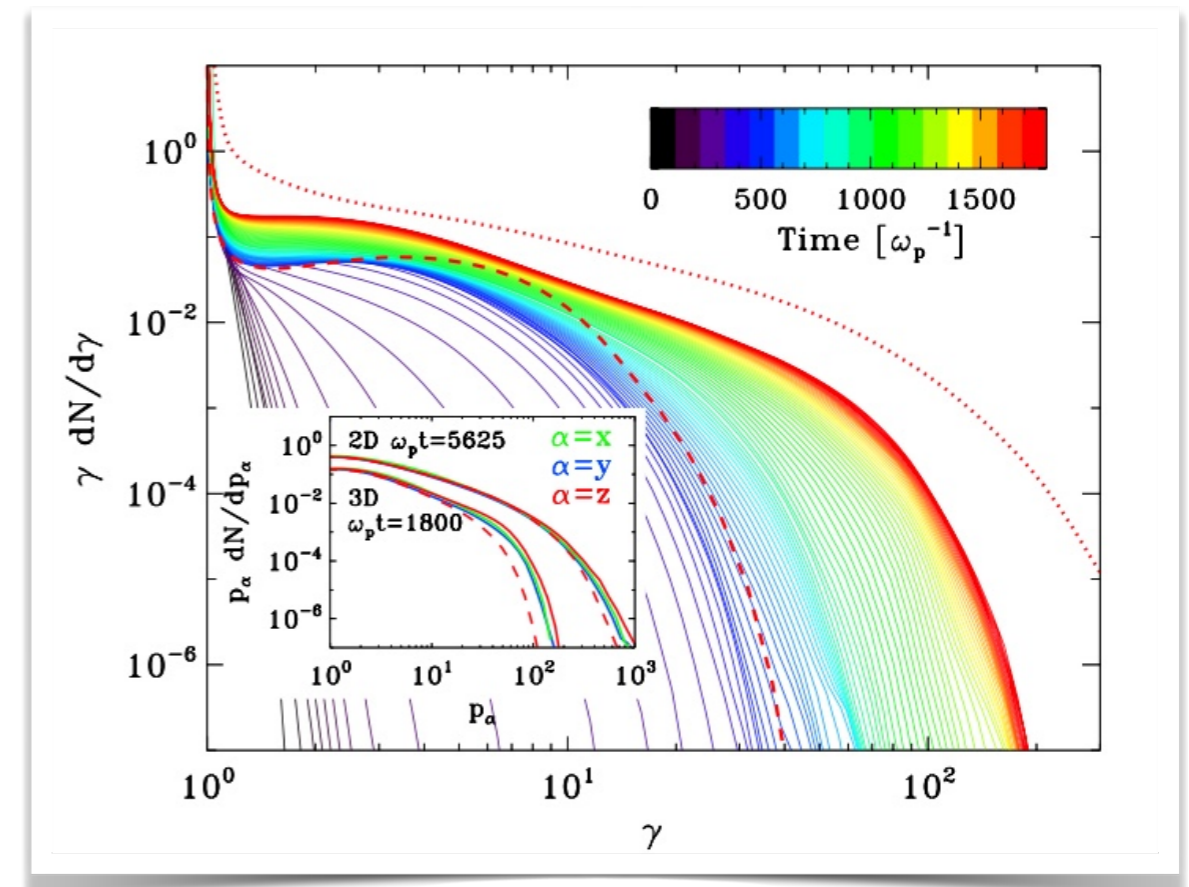
Magnetic reconnection?

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

Direct conversion of magnetic
into kinetic/heat energy



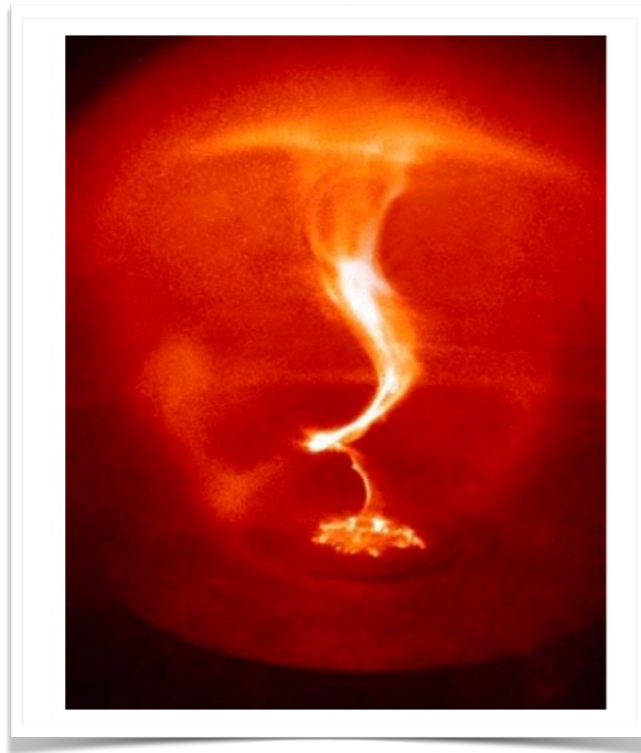
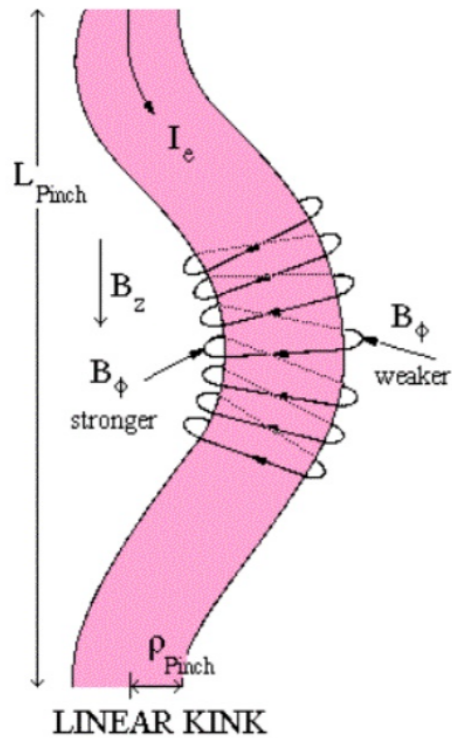
Relativistic particles with
Power law energy
distribution



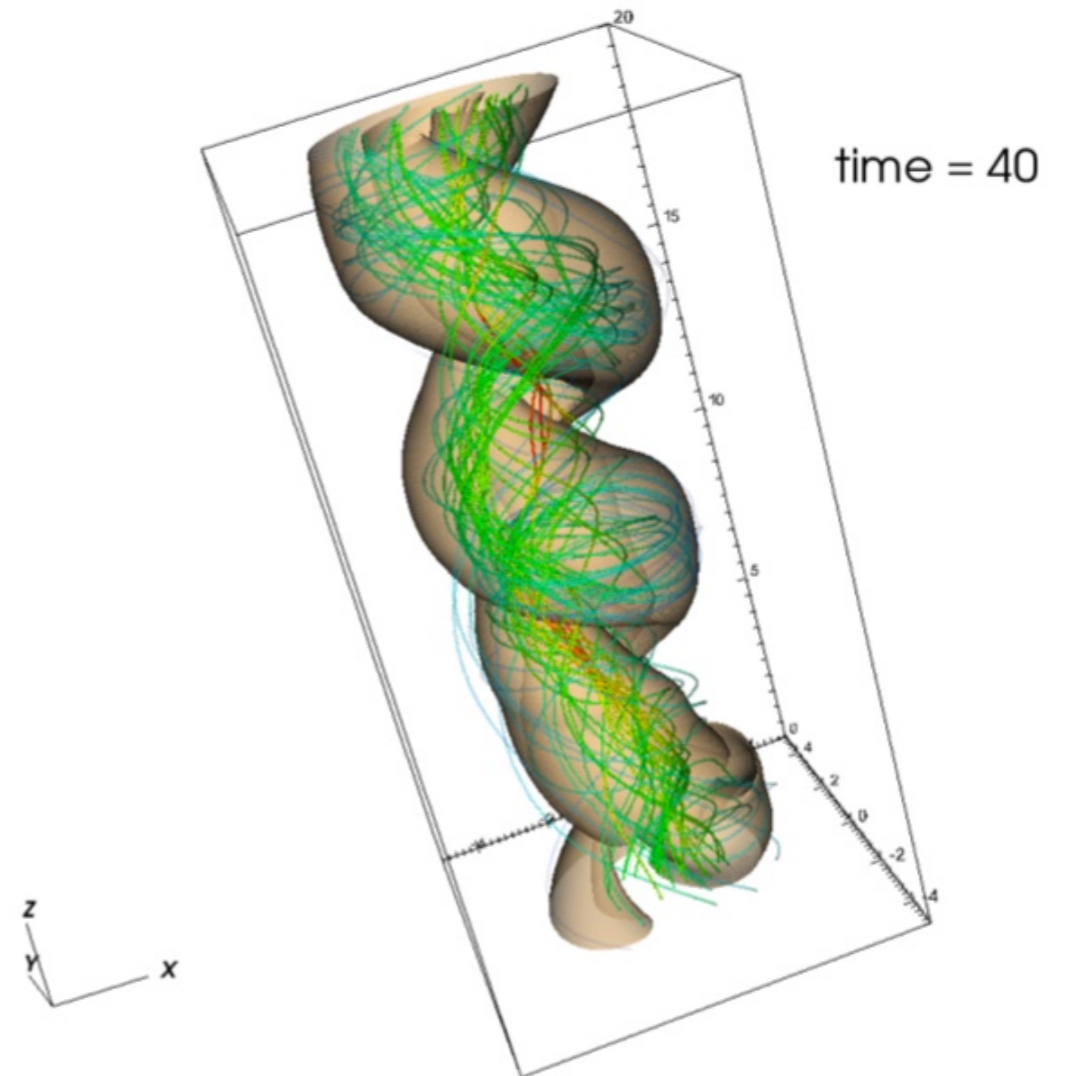
Zenitani & Hoshino 2001

Sironi & Spitkovsky 2014

Magnetic reconnection from jet (kink) instabilities?

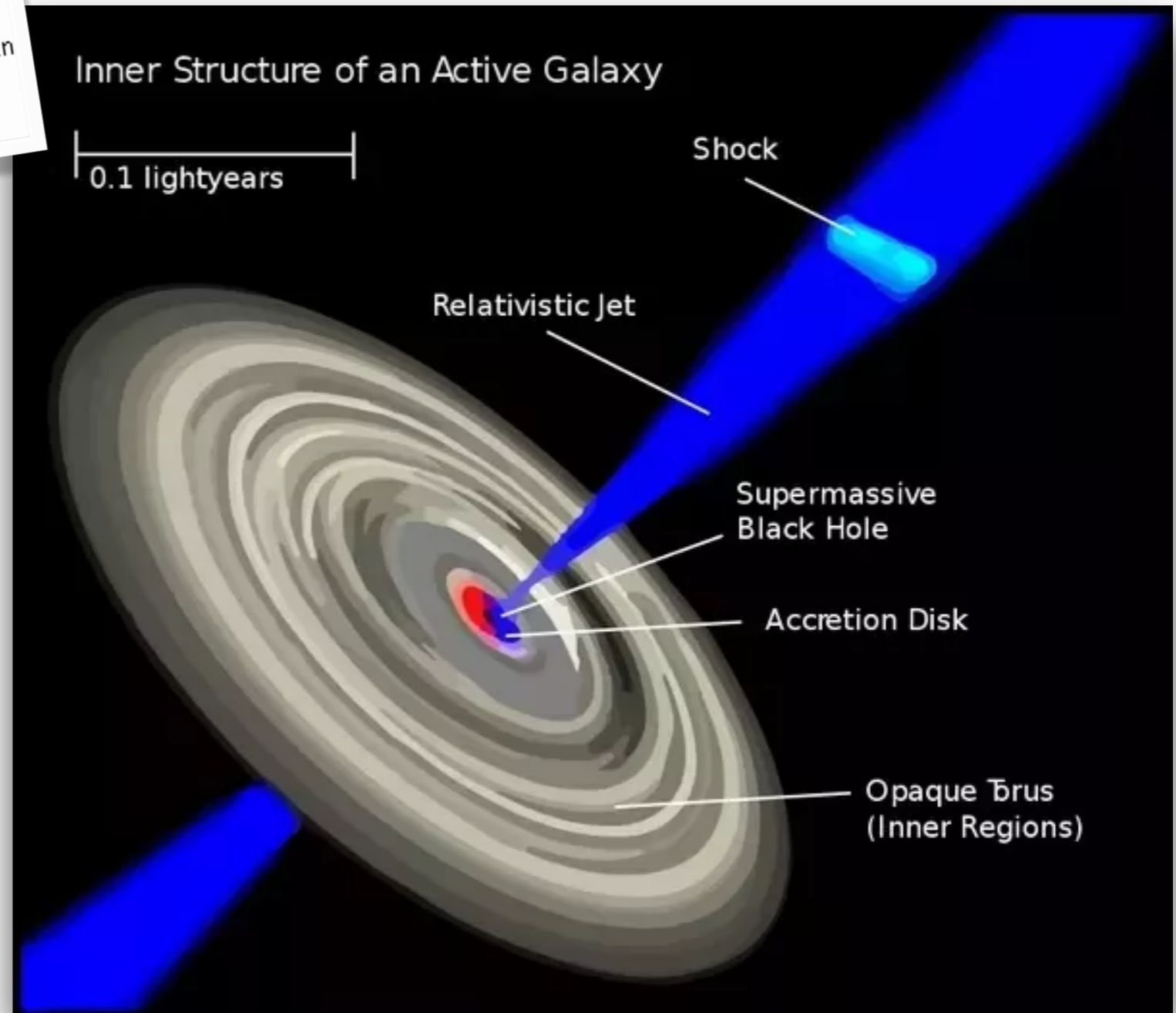
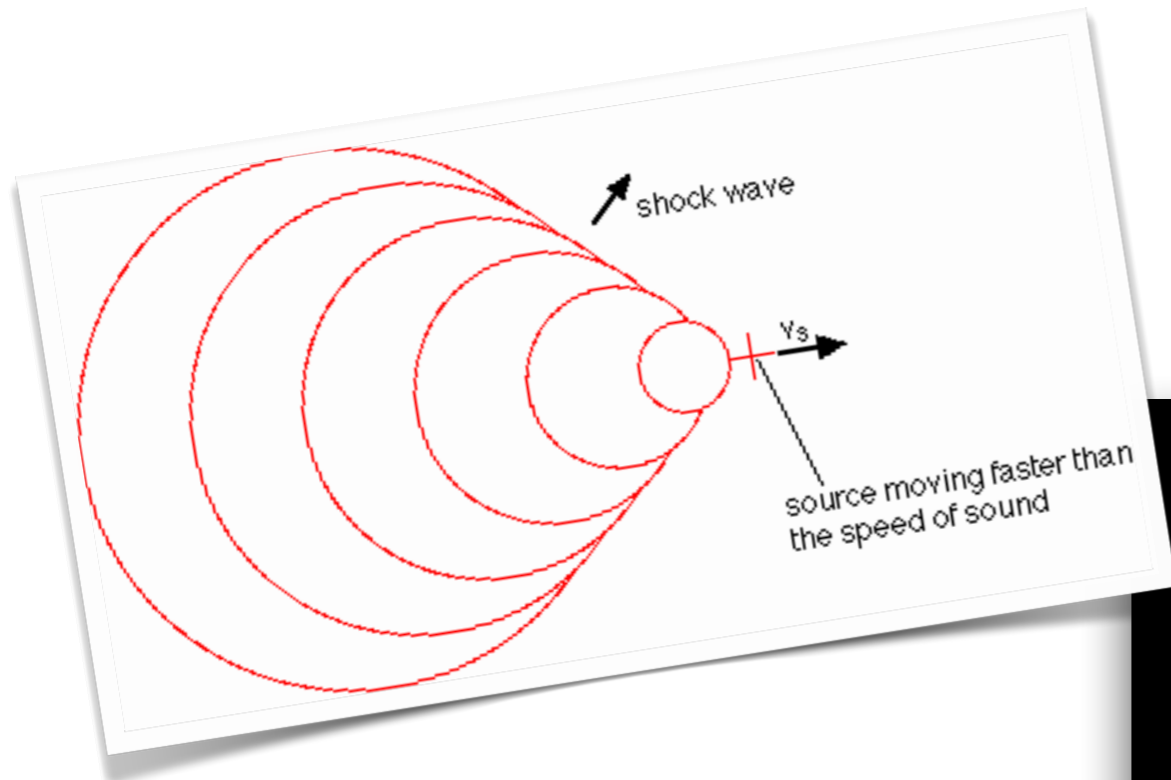


Instability in the lab

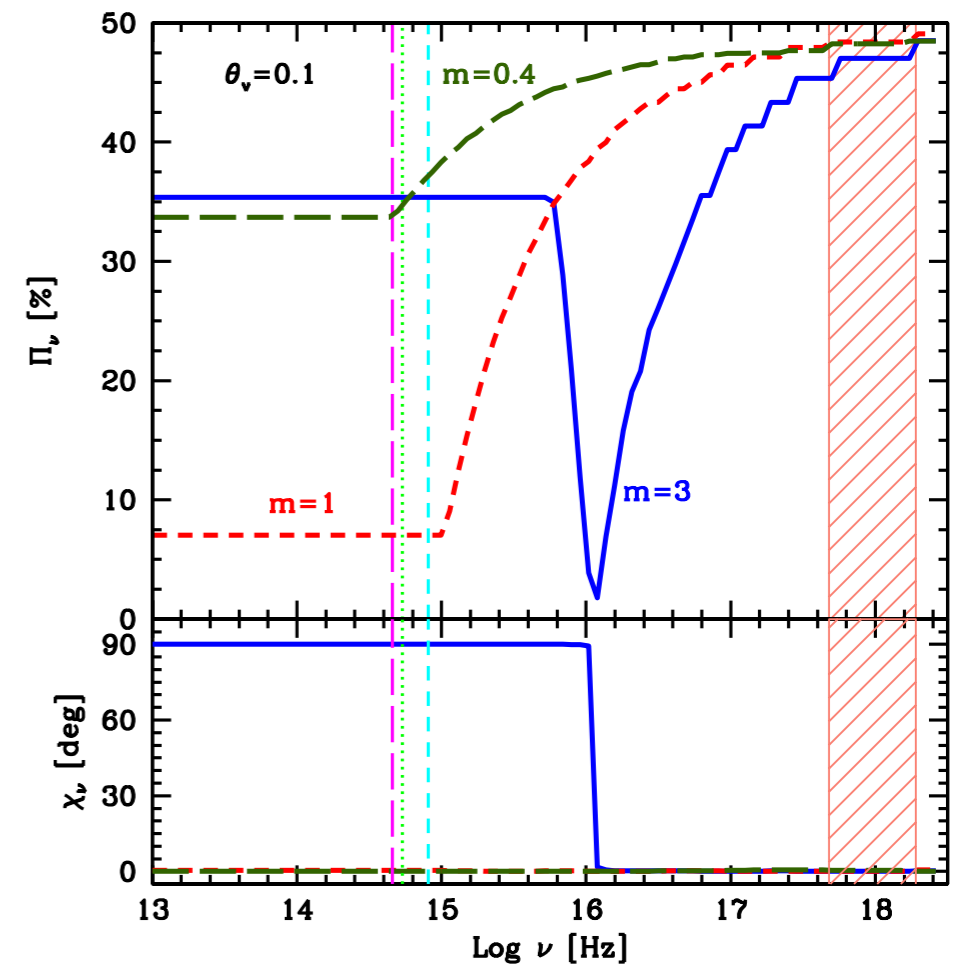
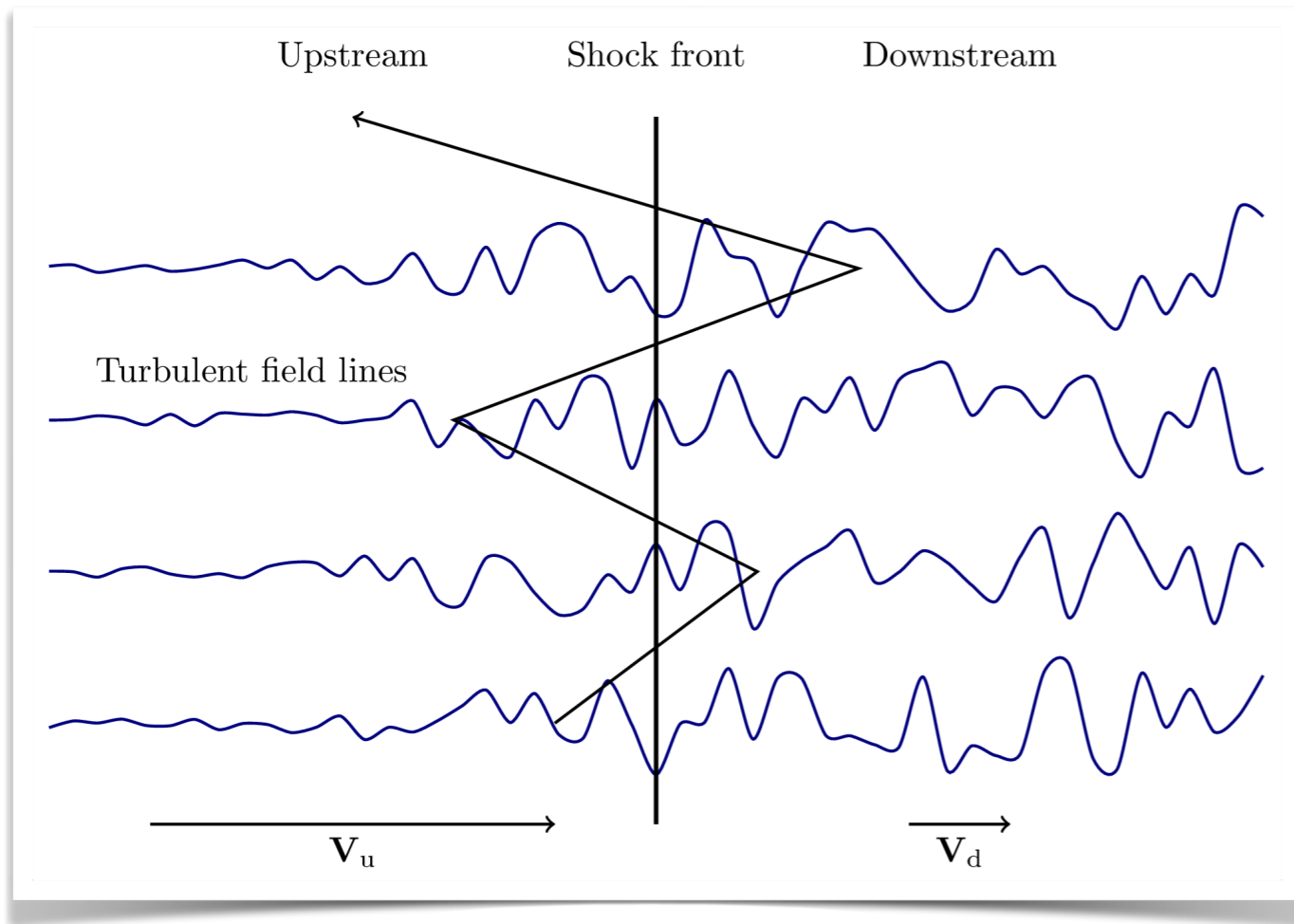


e.g. Begelman 1998, Barniol-Duran 2017

Particle acceleration at shocks



Particle acceleration at shocks

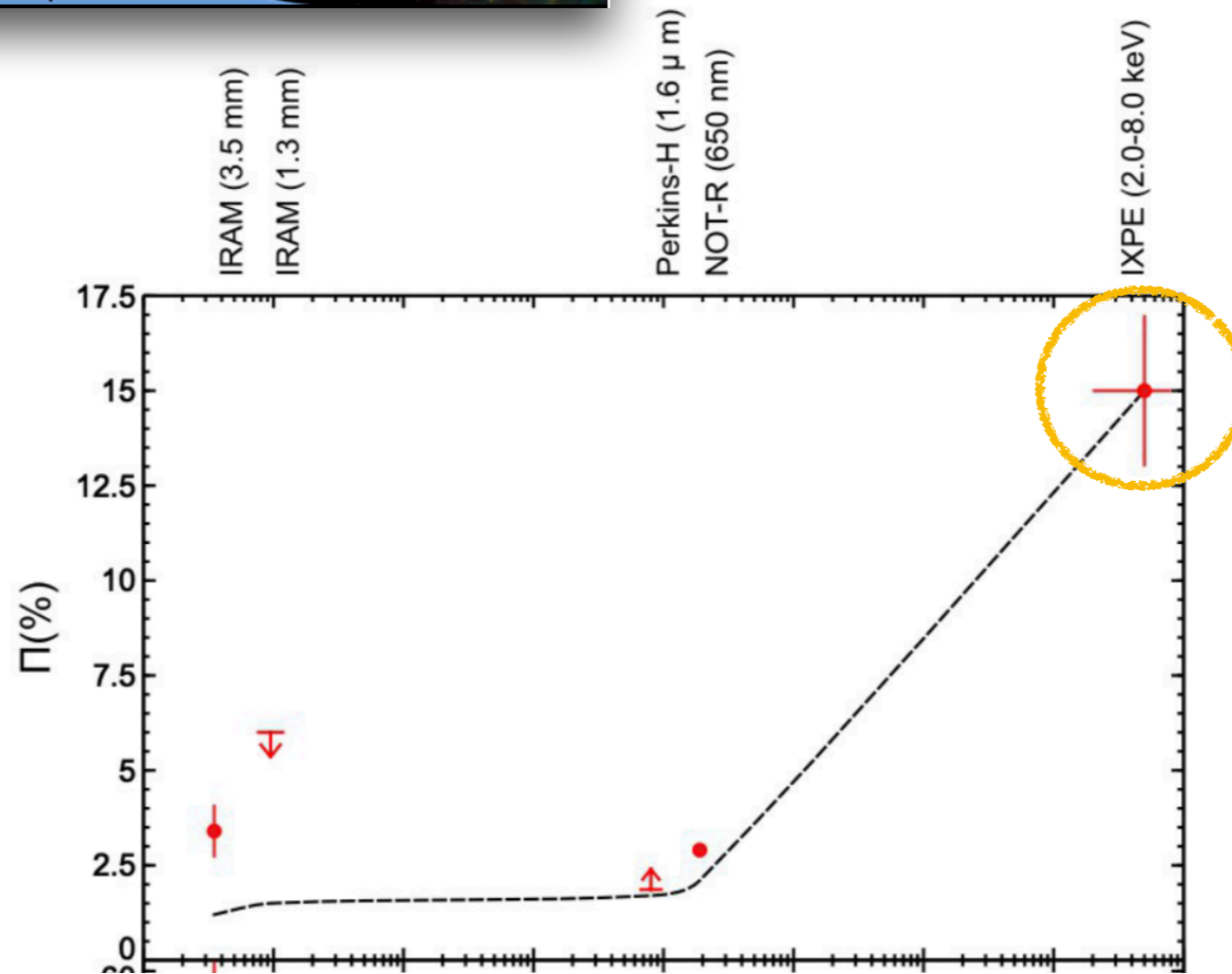


Efficient acceleration requires (self-produced) magnetic fields close to the front

Signature: high polarization in X-rays, lower at low frequency
Tavecchio et al. 2018, 2020

First hints from IXPE

Di Gesu (+Tavecchio) et al. 2022

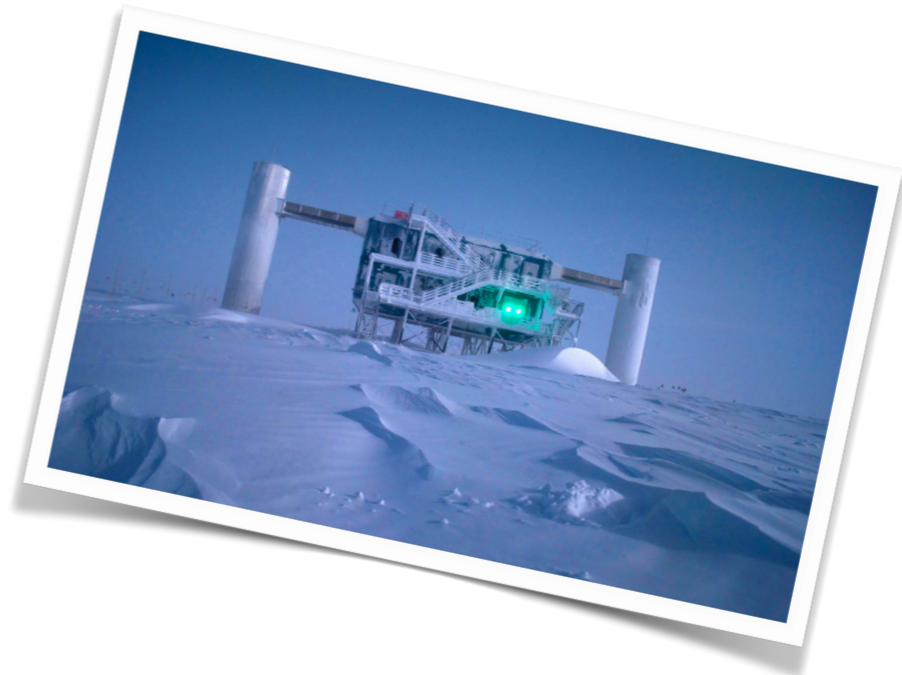
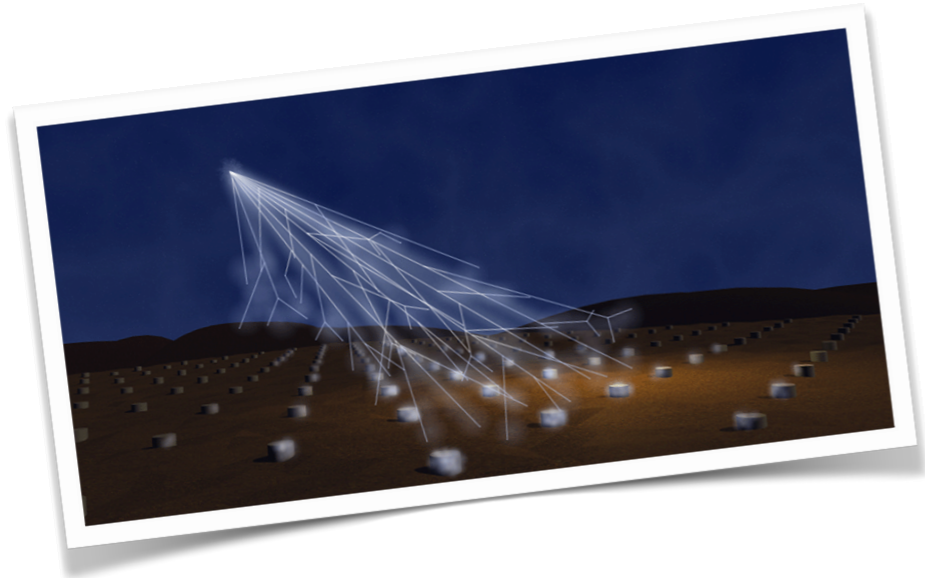


First IXPE observation of Mkn 421 in April 2022

Similar results for Mkn 501 (Liodakis et al. 2022)

Shock acceleration?
Detailed modeling in progress

Leptons or hadrons?



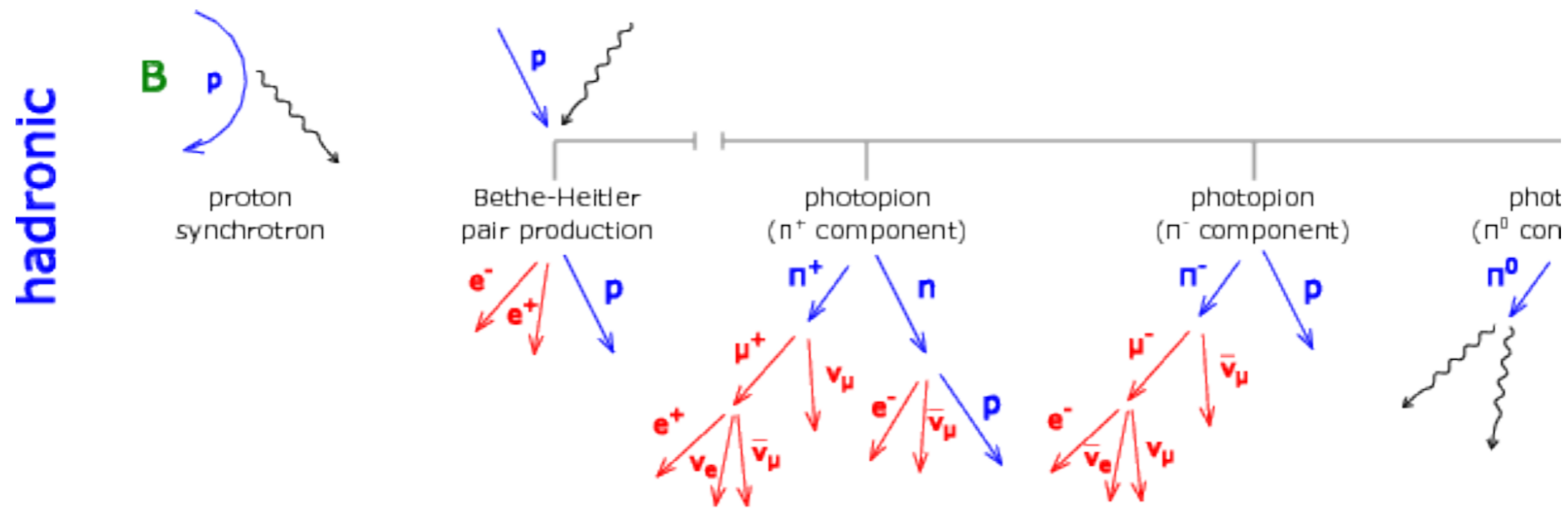
UHECR
IceCube Neutrinos



Hadrons are accelerated to very-high and ultra-high energy somewhere in the extragalactic space

Jets offer ideal conditions (B, radius, power)

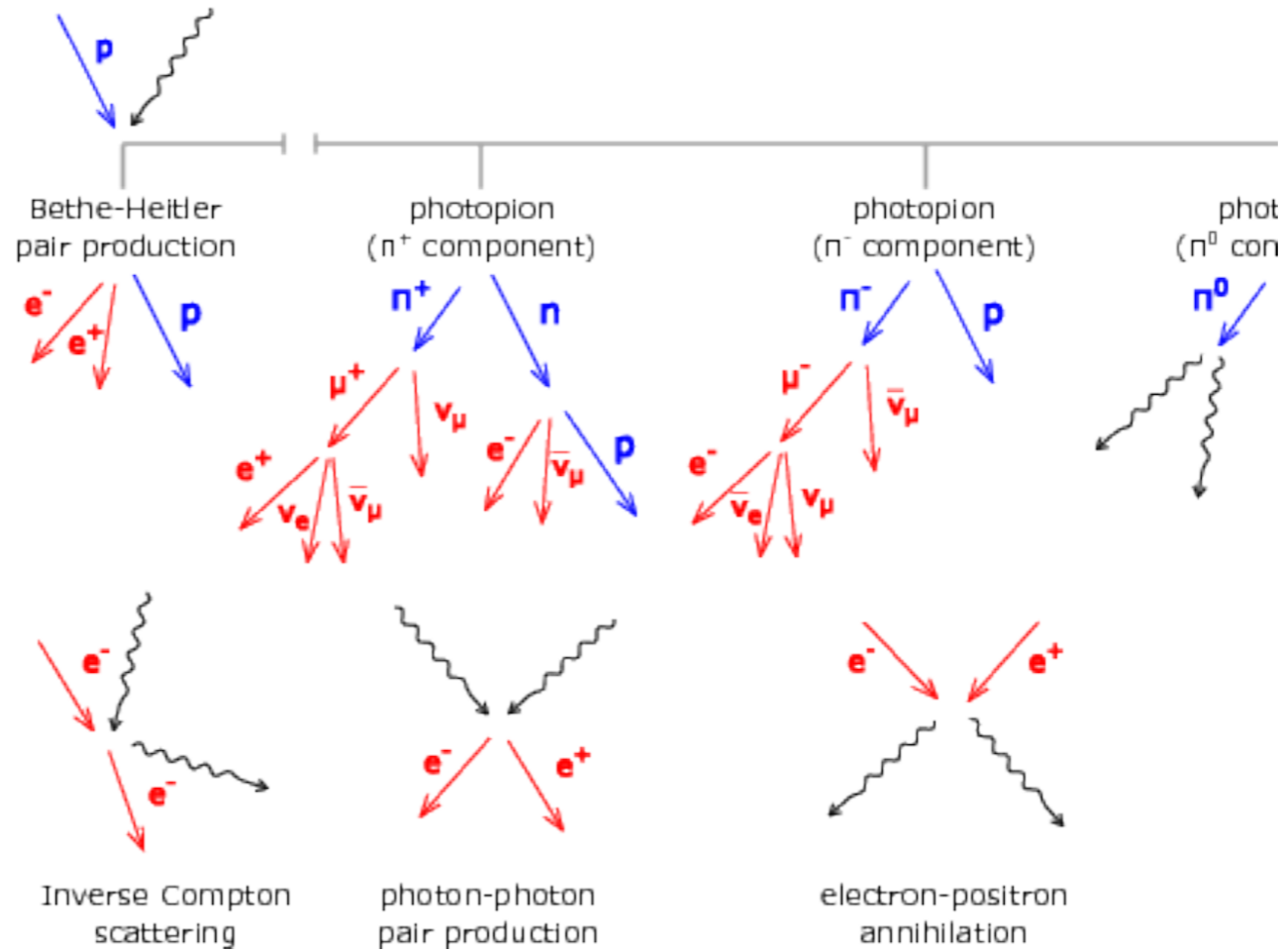
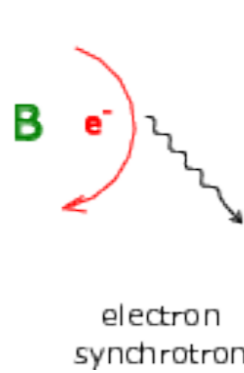
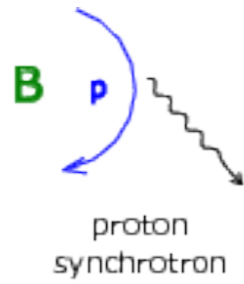
Leptons or hadrons?



Leptons or hadrons?

hadronic

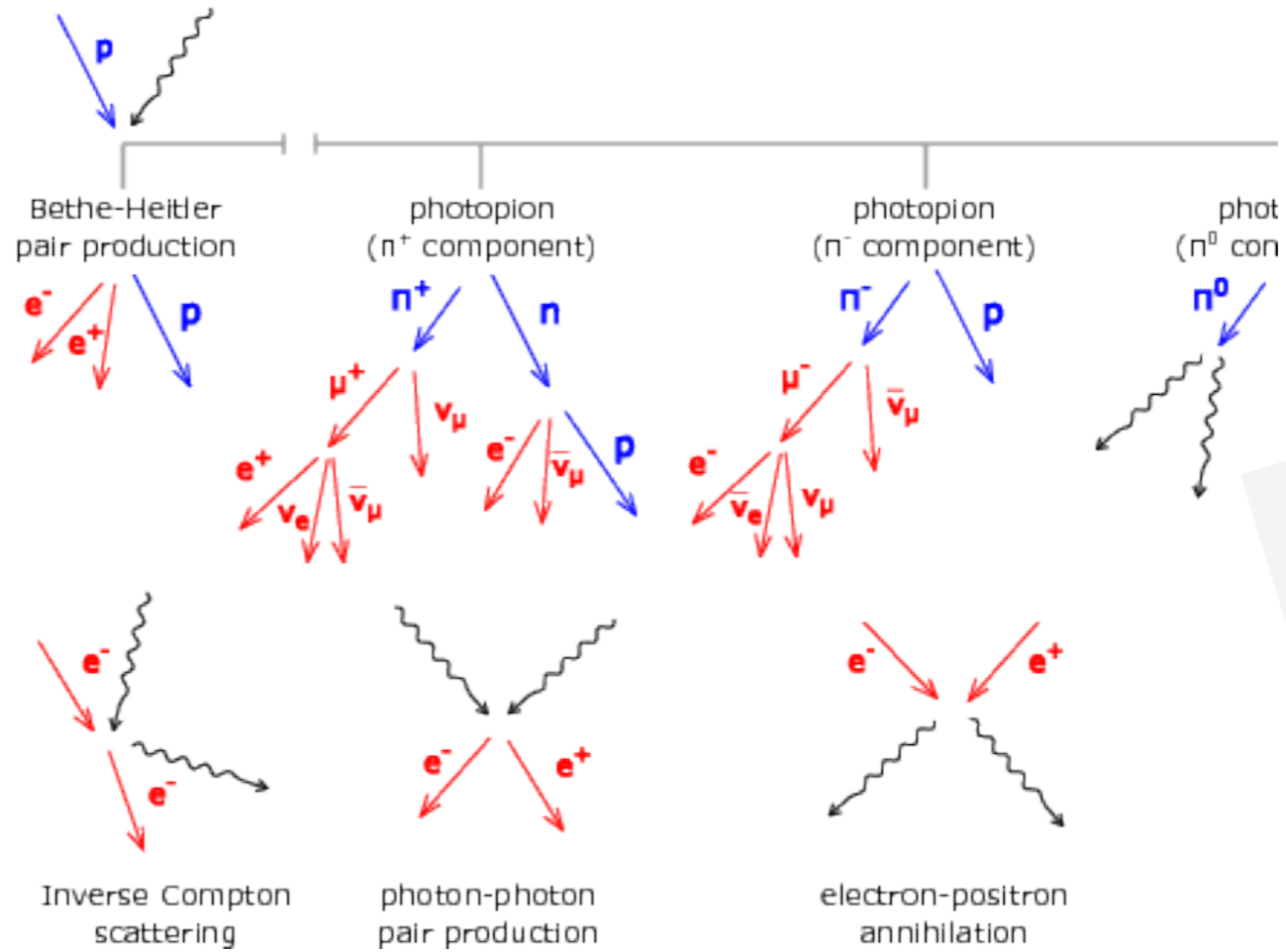
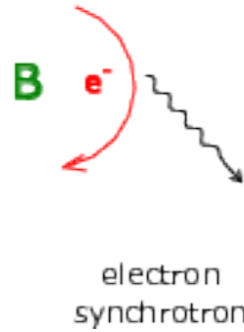
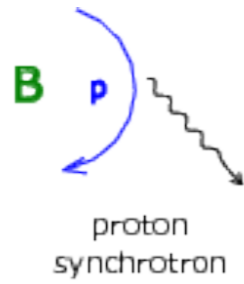
leptonic



Leptons or hadrons?

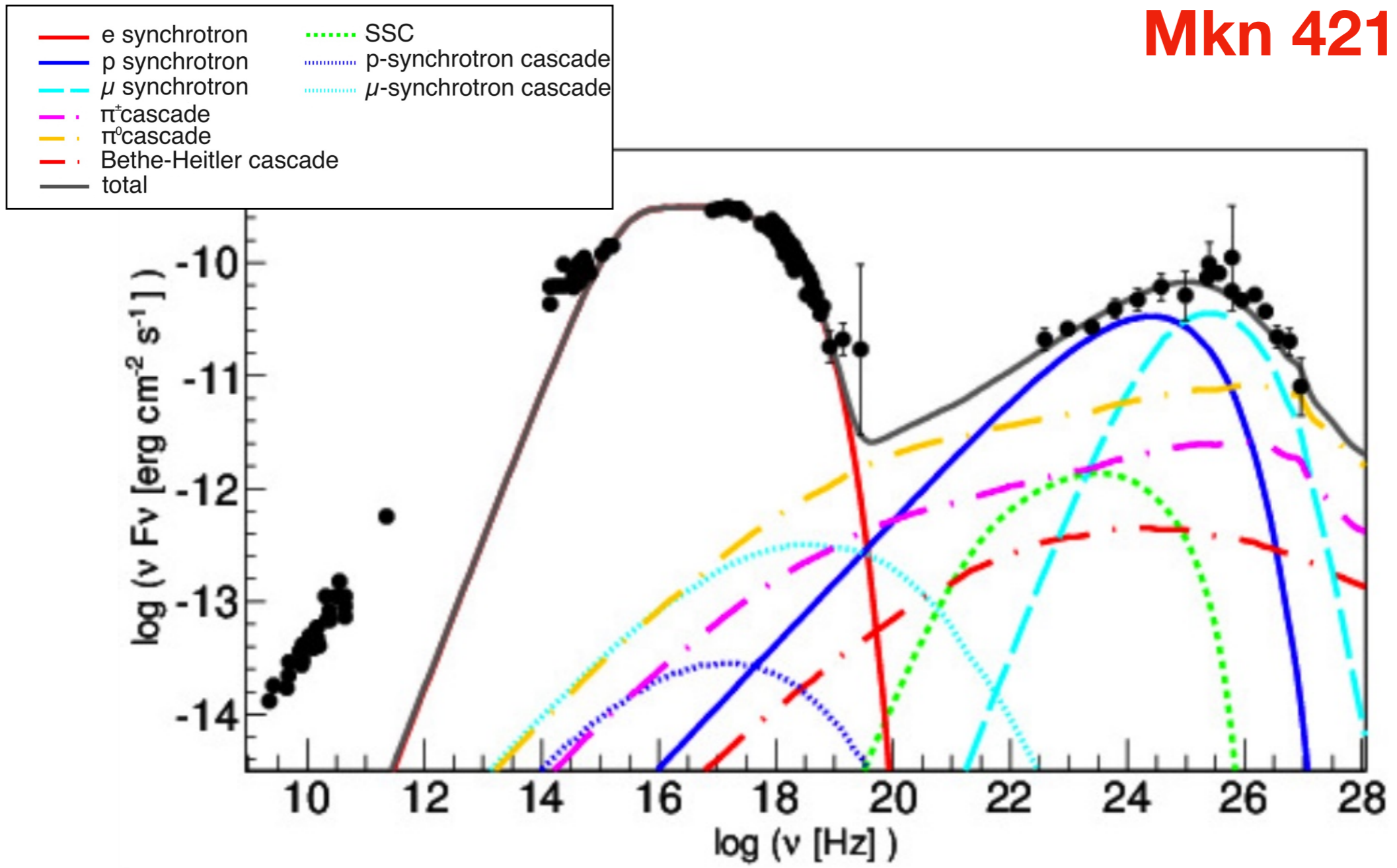
hadronic

leptonic



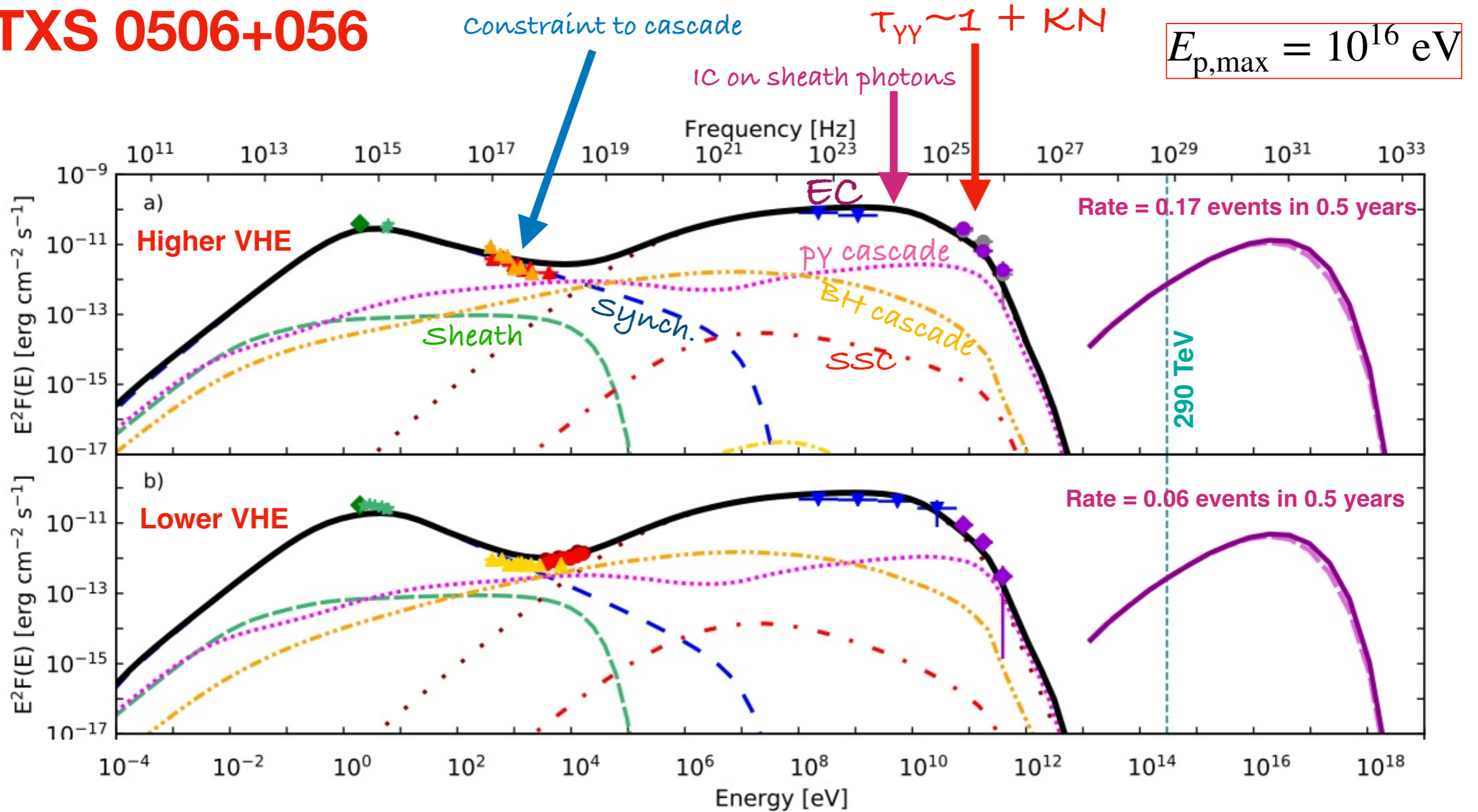
Lepto-hadronic models

Mkn 421



Lepto-hadronic models

TXS 0506+056



Potentially associated with IC 170922A

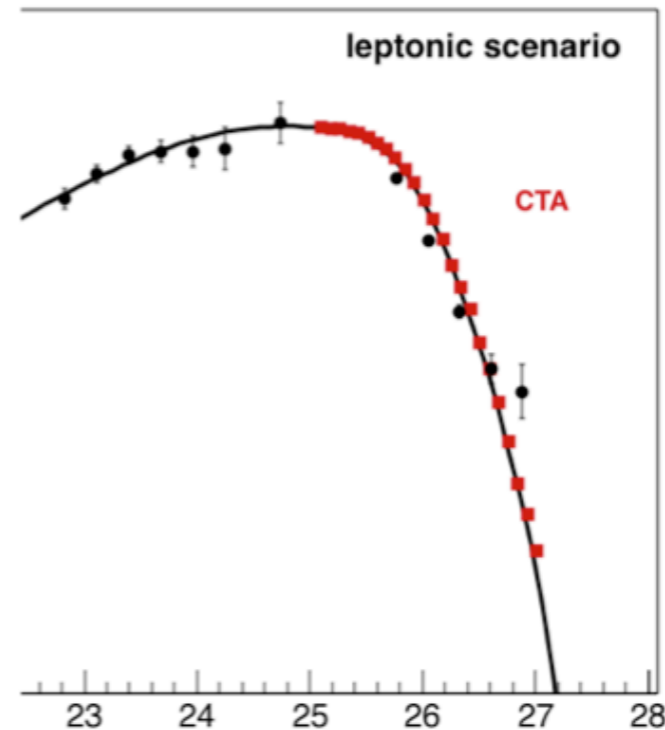
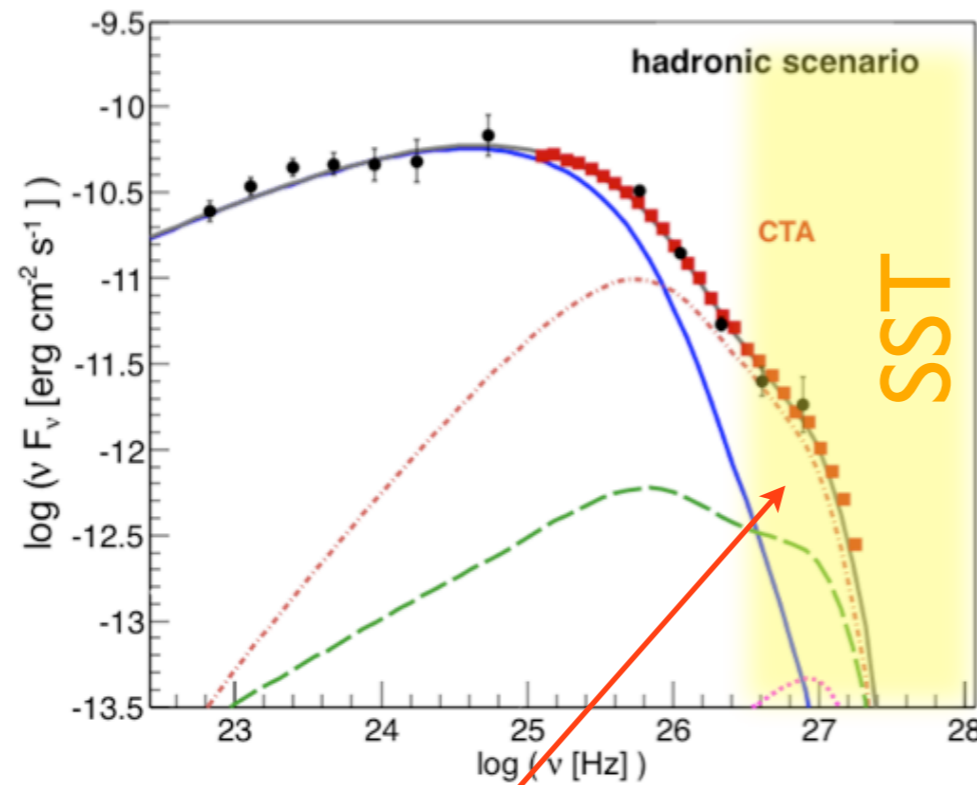
MAGIC Coll. 2018

Lepto-hadronic models

Prospects for CTA

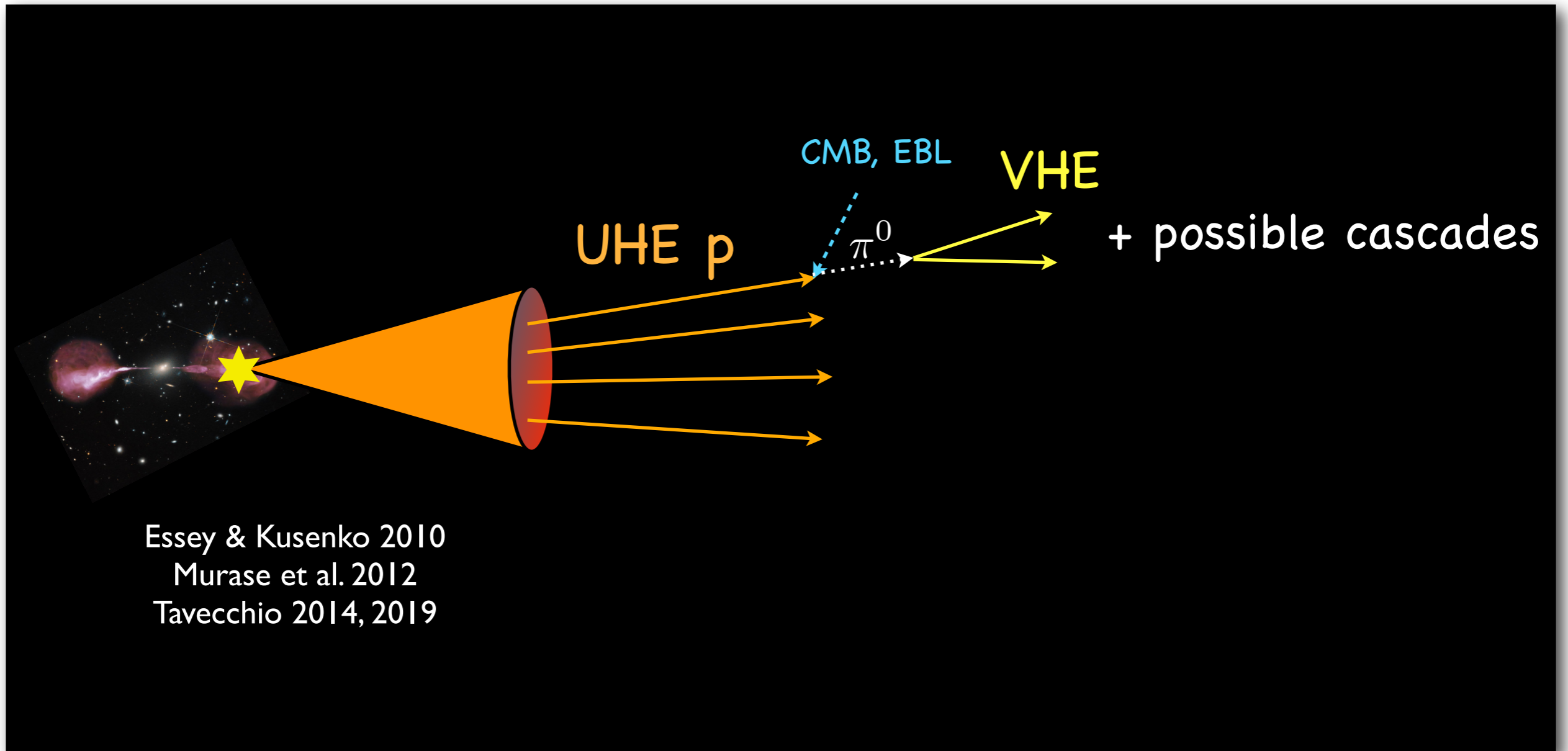


PKS 2155-304



Hard tail

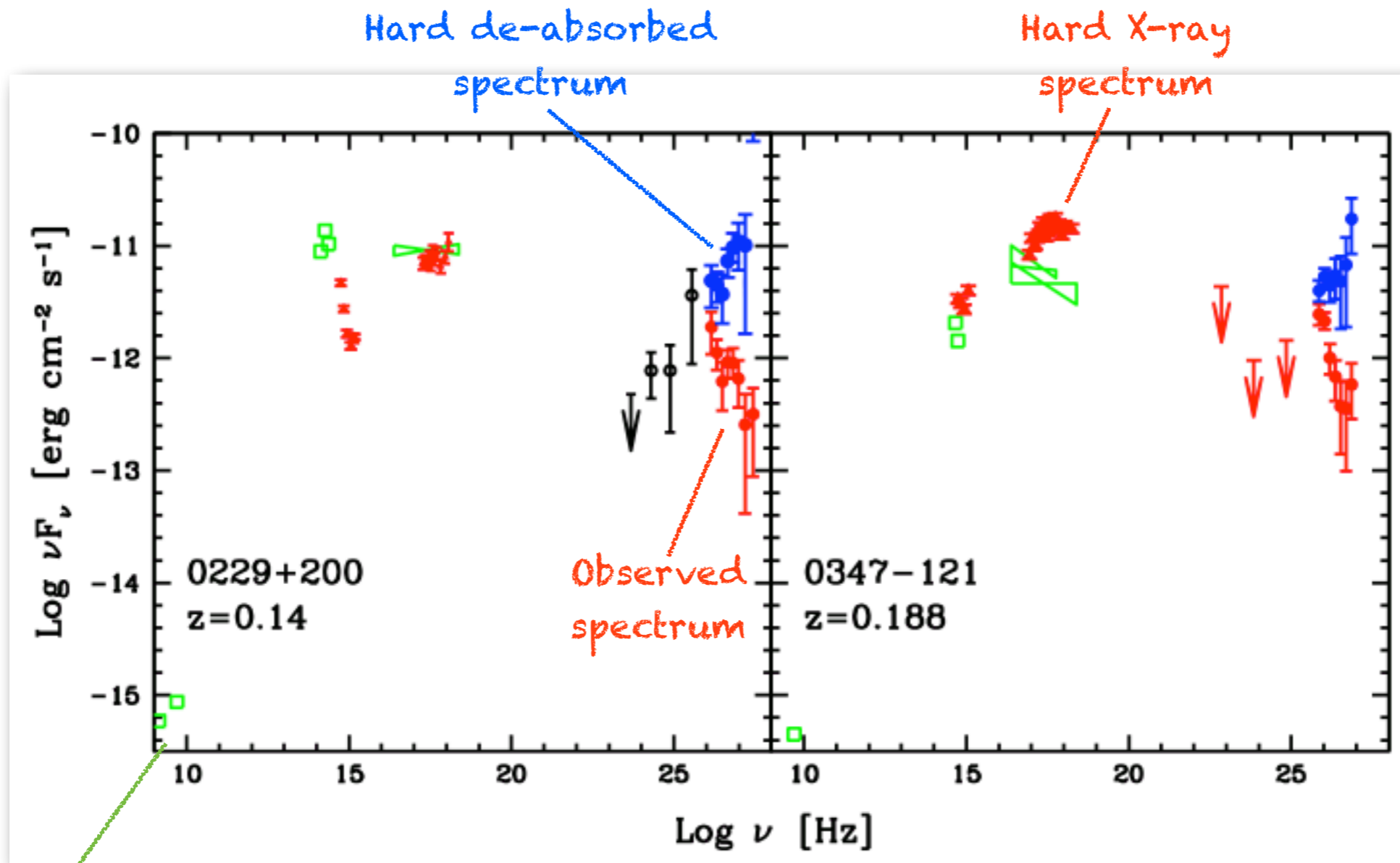
Hadron beams?



Scenario for "extreme BL Lacs"

Extreme BL Lacs

after Costamante et al. 2001

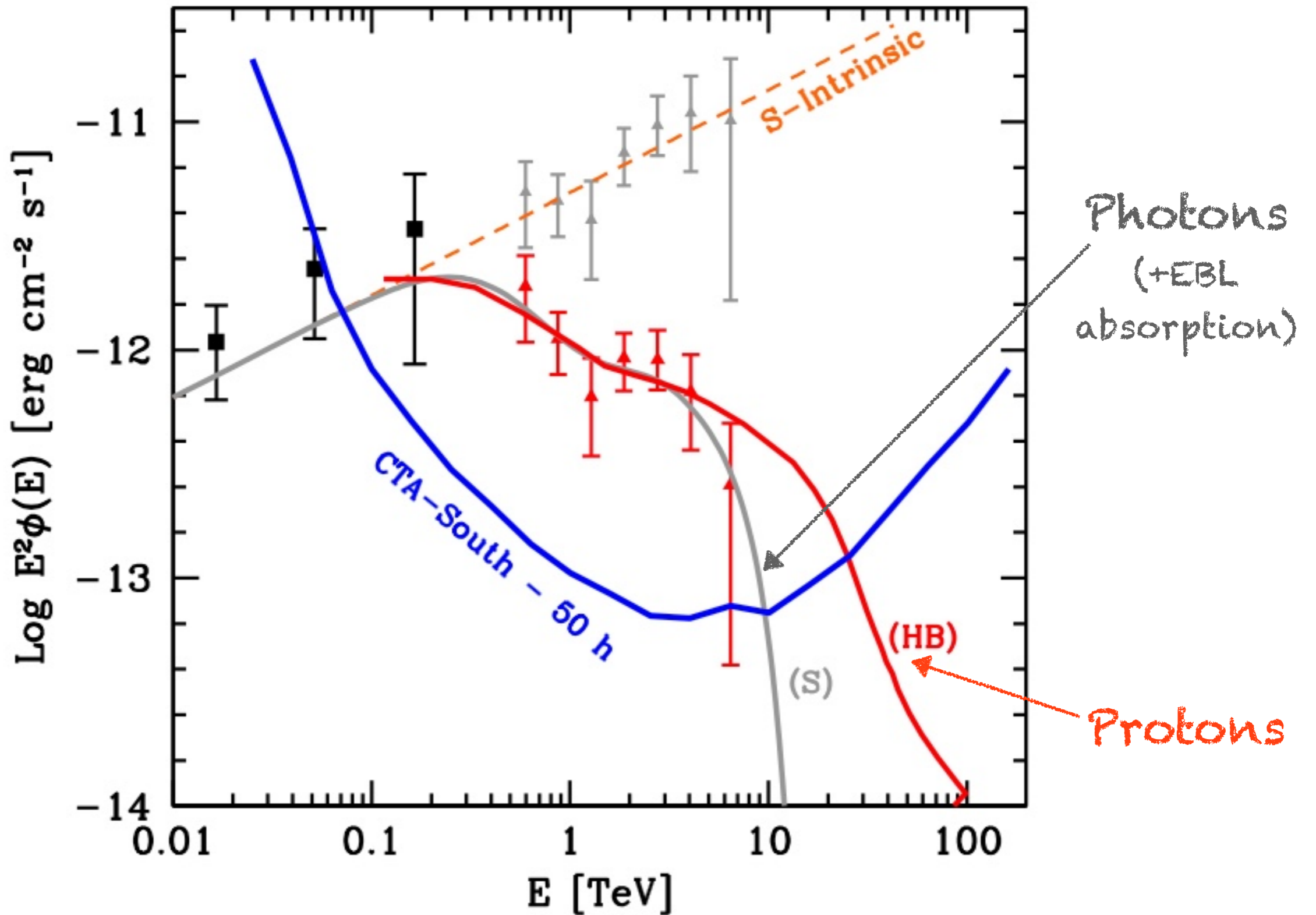


Small radio flux

Bonnoli et al. 2015

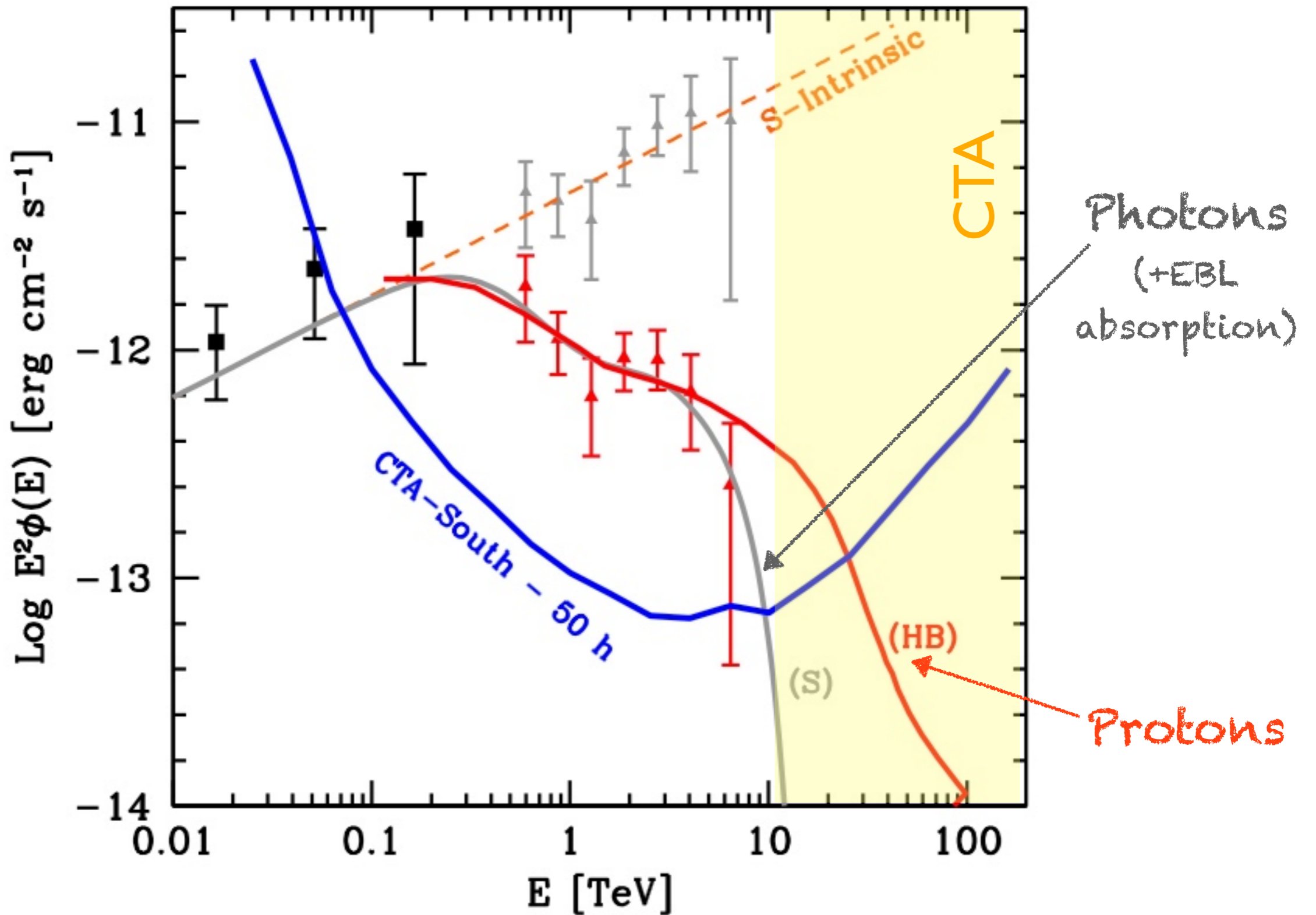
Hadron beams?

Tavecchio et al. 2019



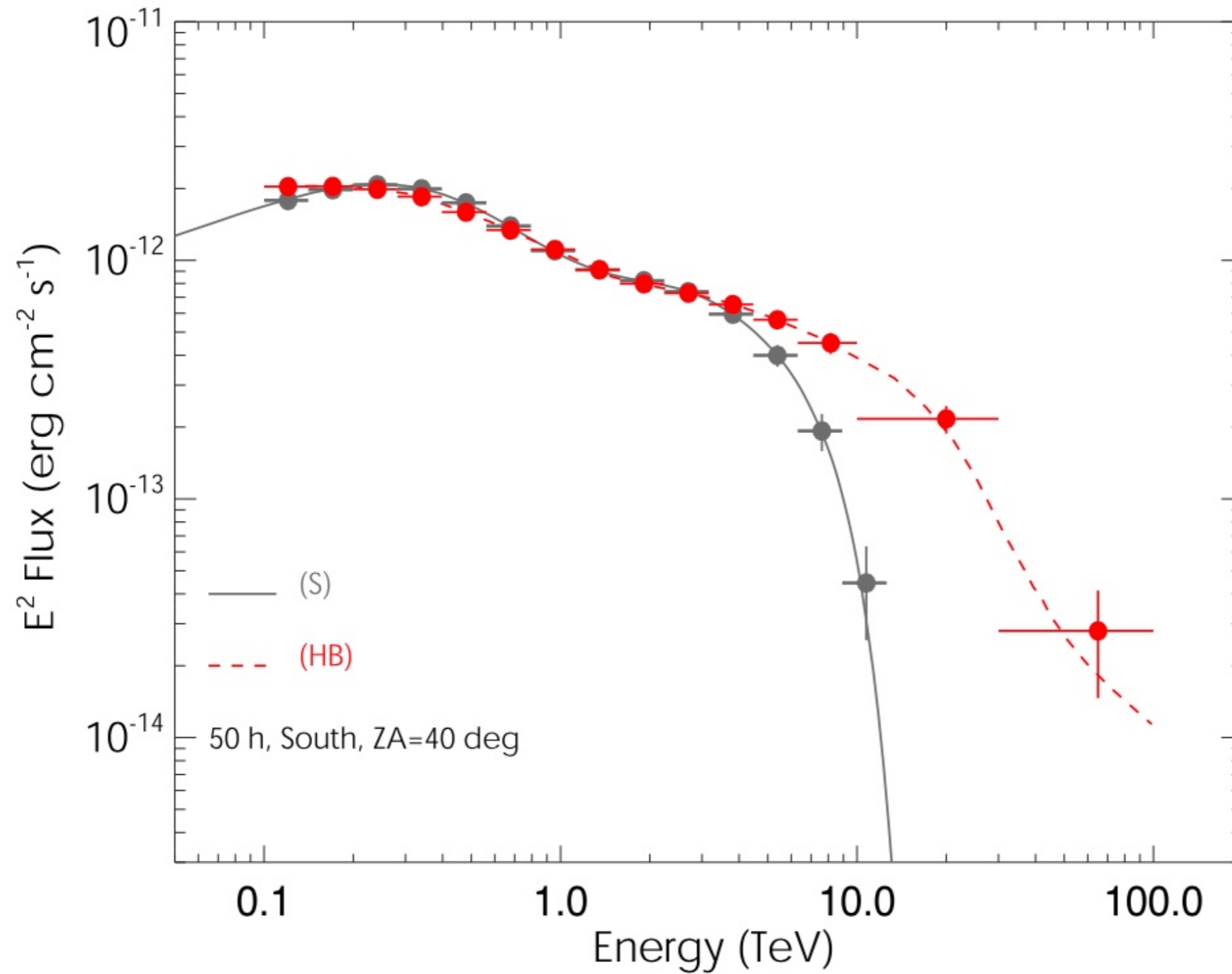
Hadron beams?

Tavecchio et al. 2019

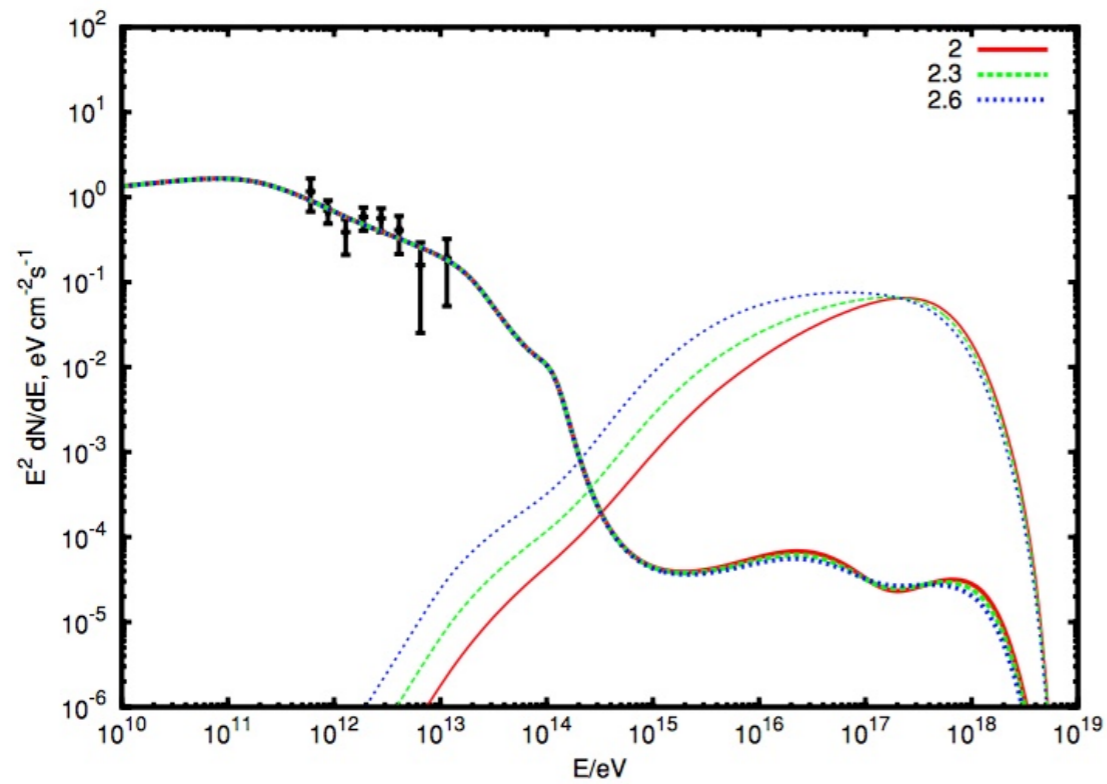


Hadron beams?

Tavecchio et al. 2019



Neutrinos from hadron beams?

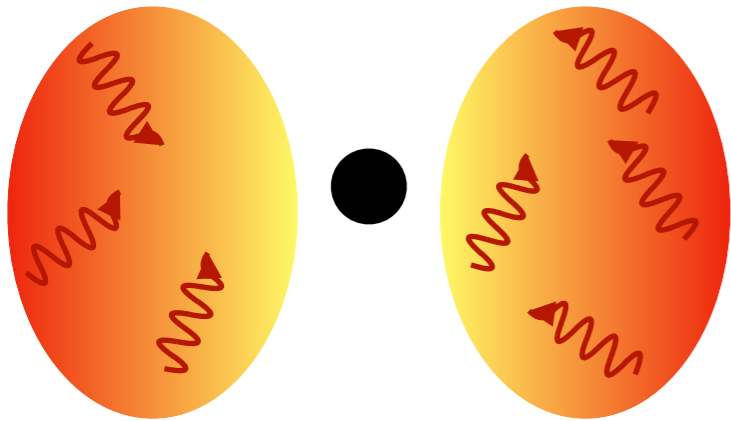


Essey et al. 2011

Difficult to detect single sources

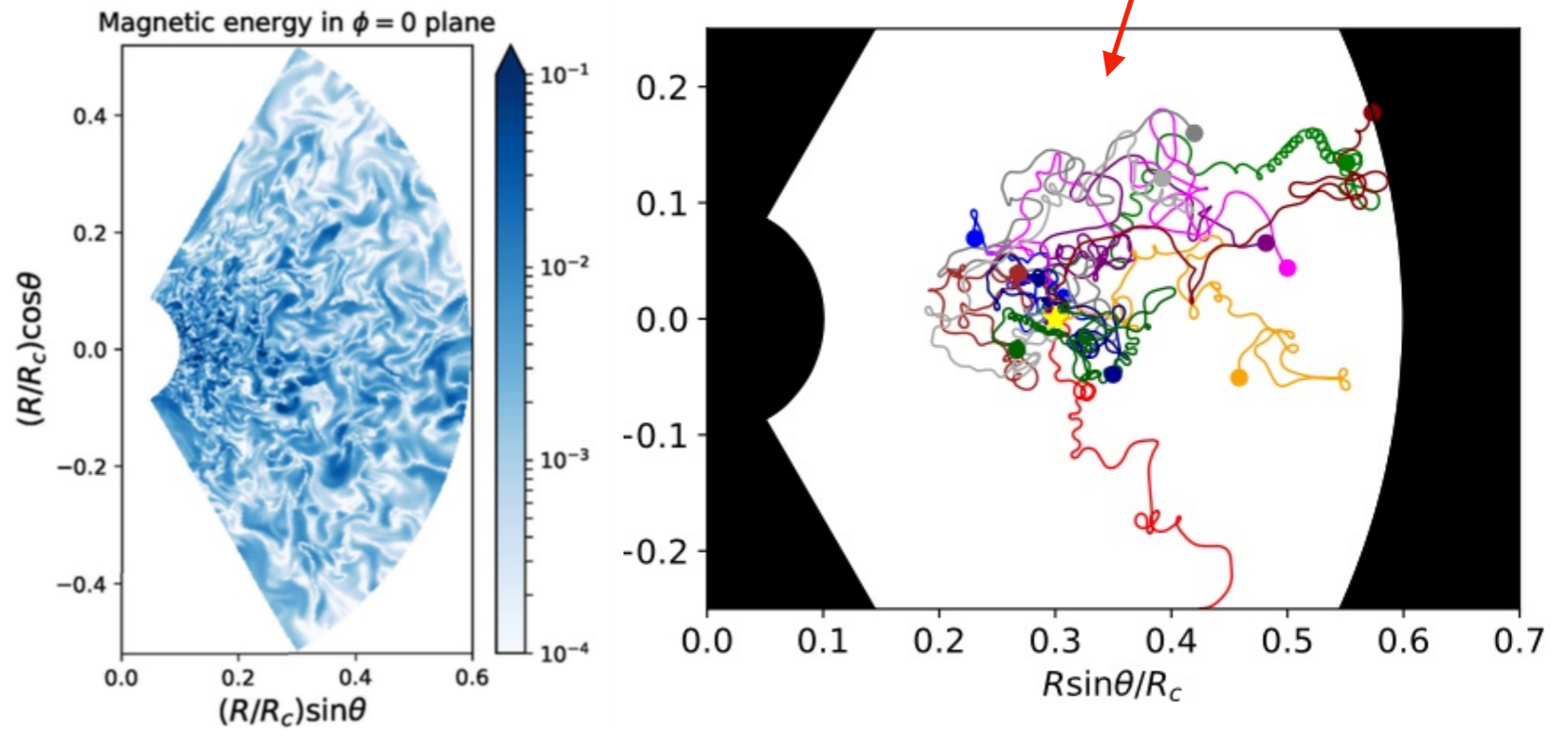
Murase et al. 2012

A role for the accretion flow?



Powering **low luminosity AGN**

Kimura et al. 2015; Khiali et al. 2016

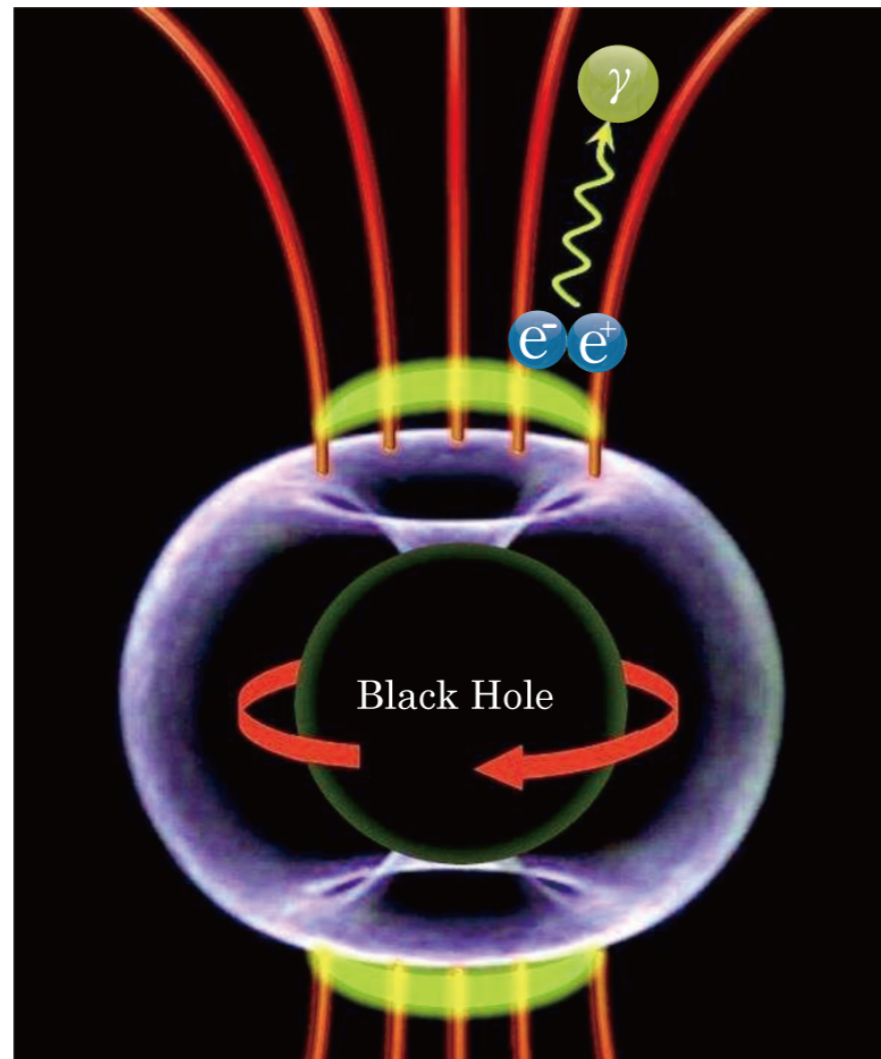


Protons up to few PeV expected
(no UHECR)

Emission either through pp or py

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

Final thoughts

Active Galactic Nuclei interesting after more than 50 years

Potential MM role (neutrinos, UHECR)

Waiting for new HE facilities...

A space-themed background featuring a large, bright starburst in the center, with streaks of light radiating outwards. The text "THANK YOU!" is written in a bold, black, sans-serif font across the middle of the image. The background is filled with numerous small, distant stars and a few larger, brighter stars with diffraction spikes.

THANK YOU!