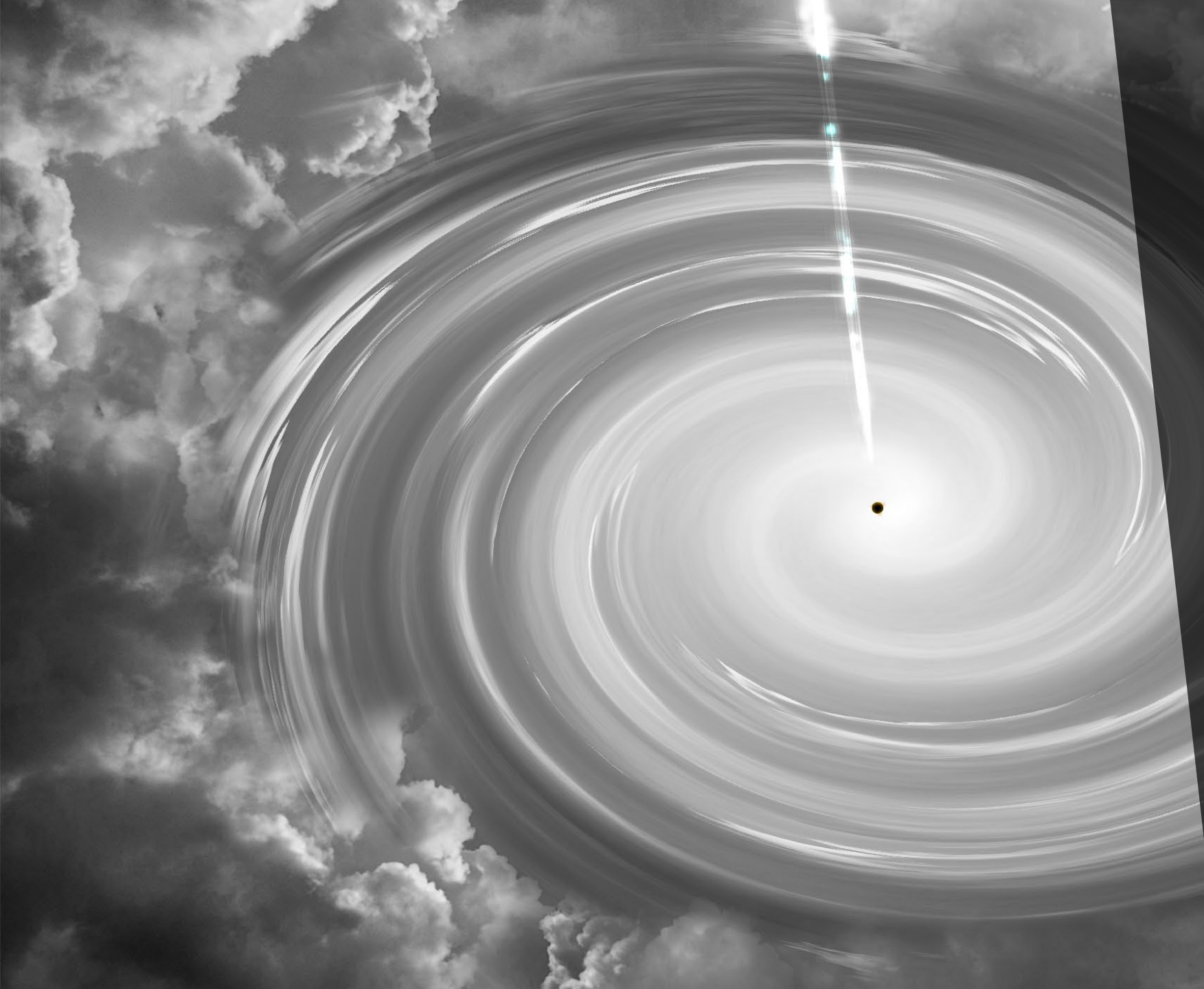


Blazar Jets Through Cosmic Time

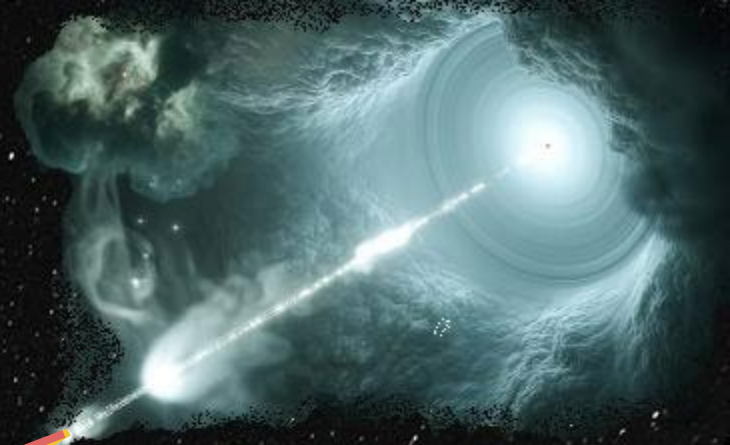
Tracing the Evolution of the Universe's Powerhouses

Presented by:
Lea Marcotulli

Illuminating the Active Universe, 17th Sept. 2026

Lea Marcotulli | lea.marcotulli@desy.de







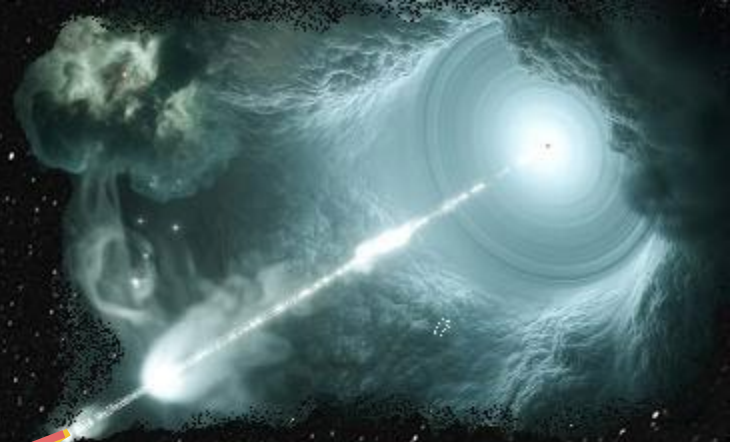
Blazars

AGN with jets pointed at Earth

(viewing angle, $\theta_V \leq 5^\circ - 10^\circ$)

Lea Marcotulli | lea.marcotulli@desy.de



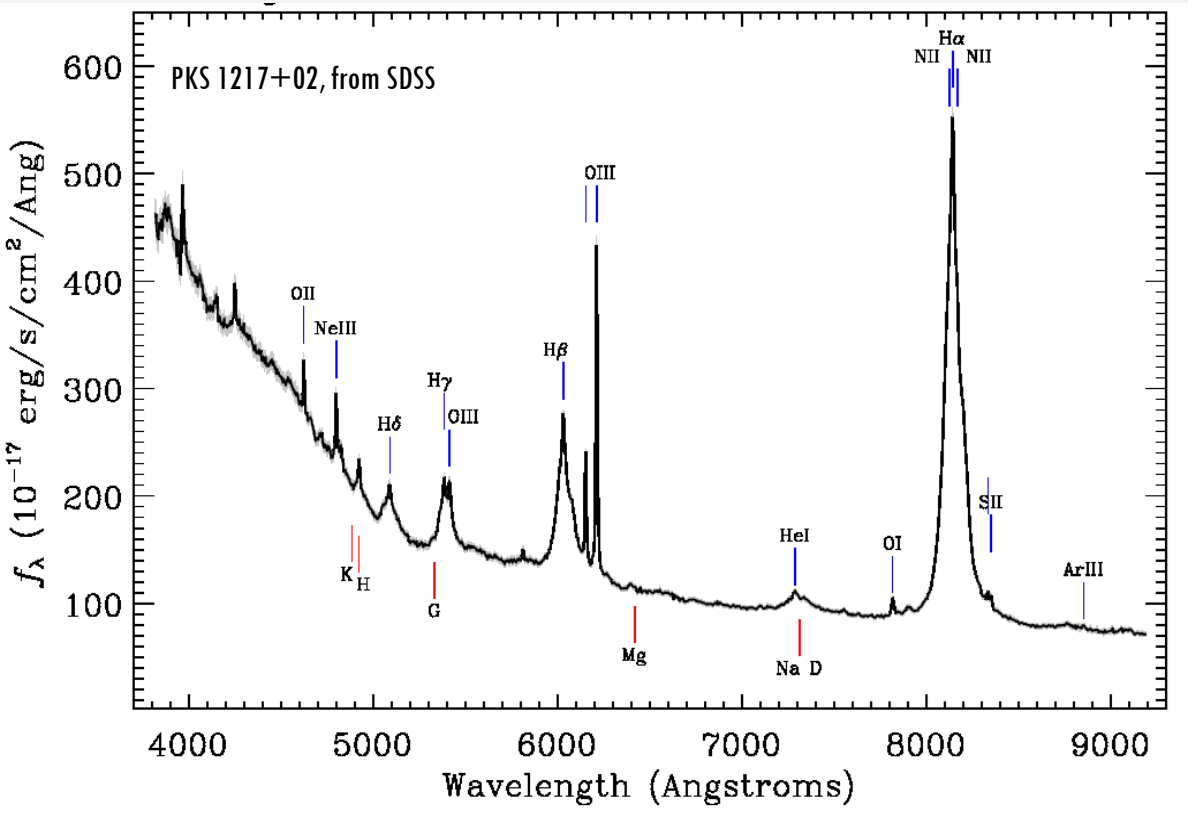


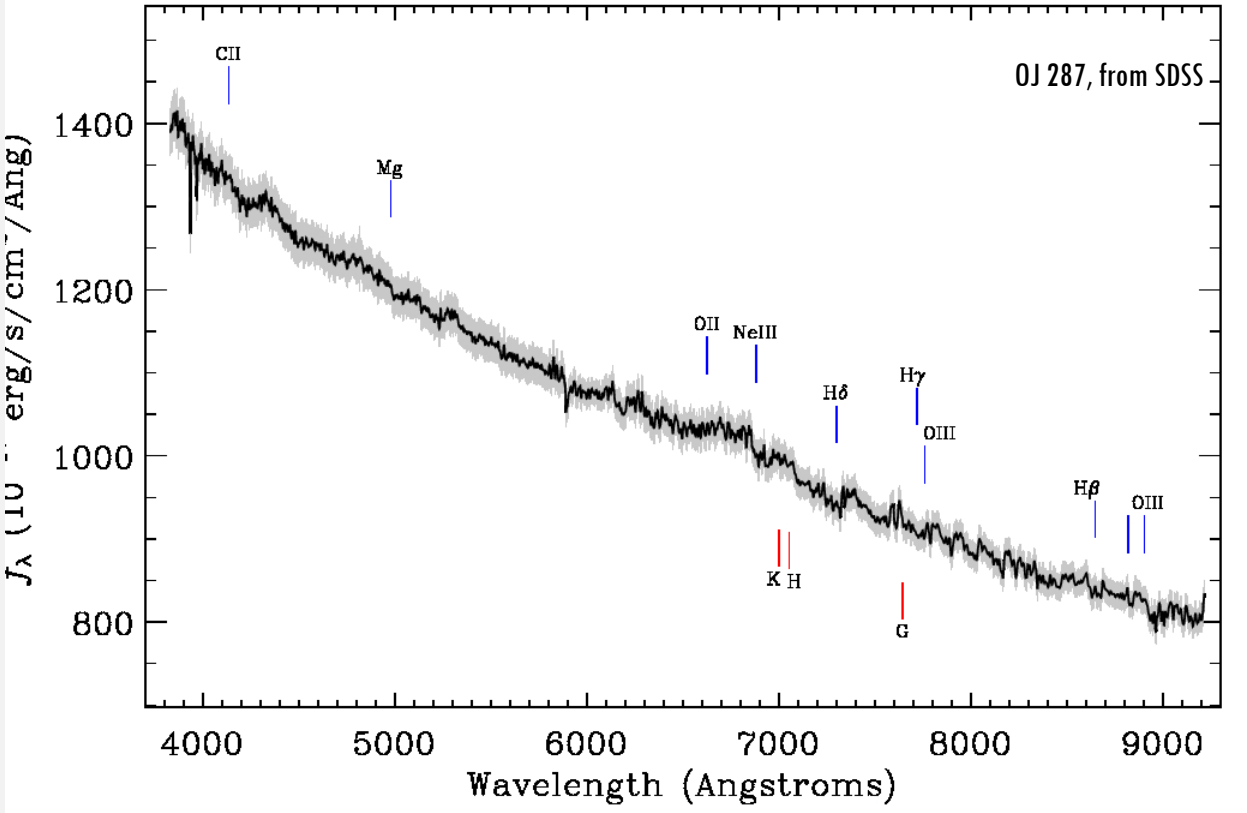


Blazars

AGN with jets pointed at Earth

(viewing angle, $\theta_V \leq 5^\circ - 10^\circ$)





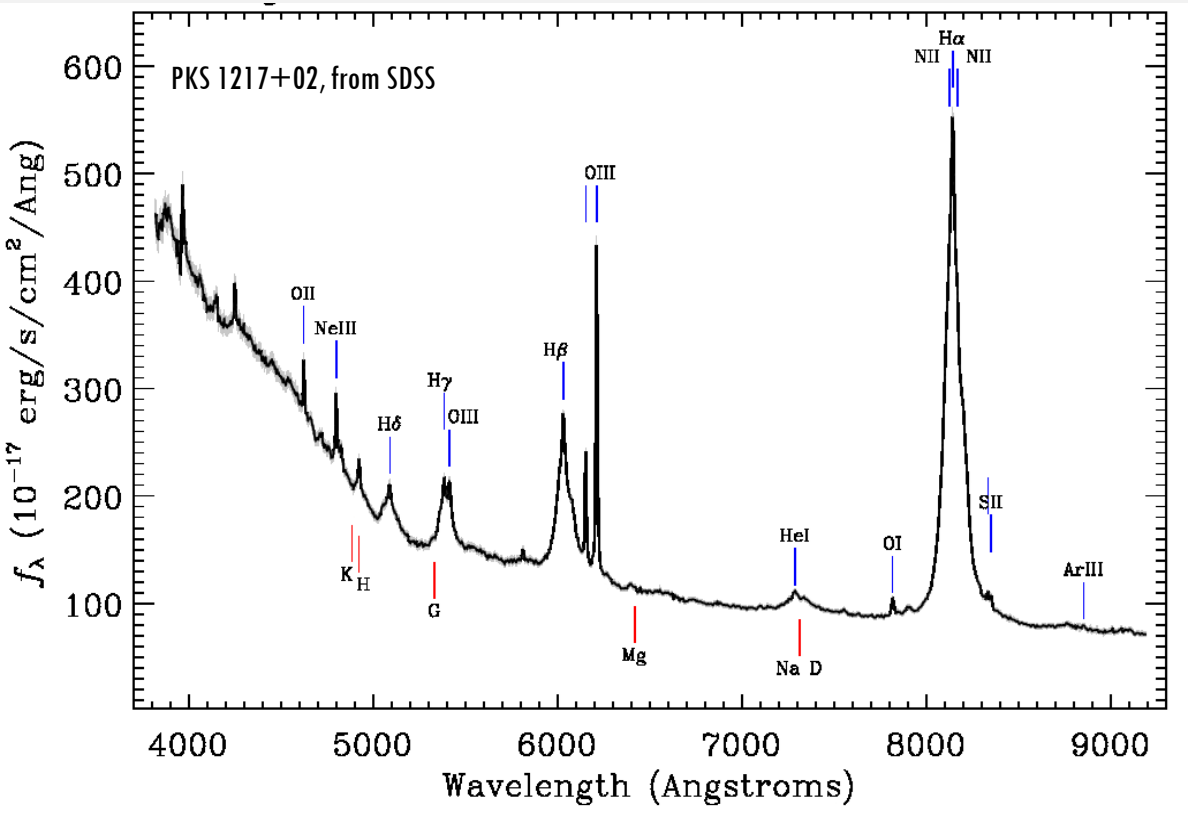
Flat Spectrum Radio Quasars (FSRQ)

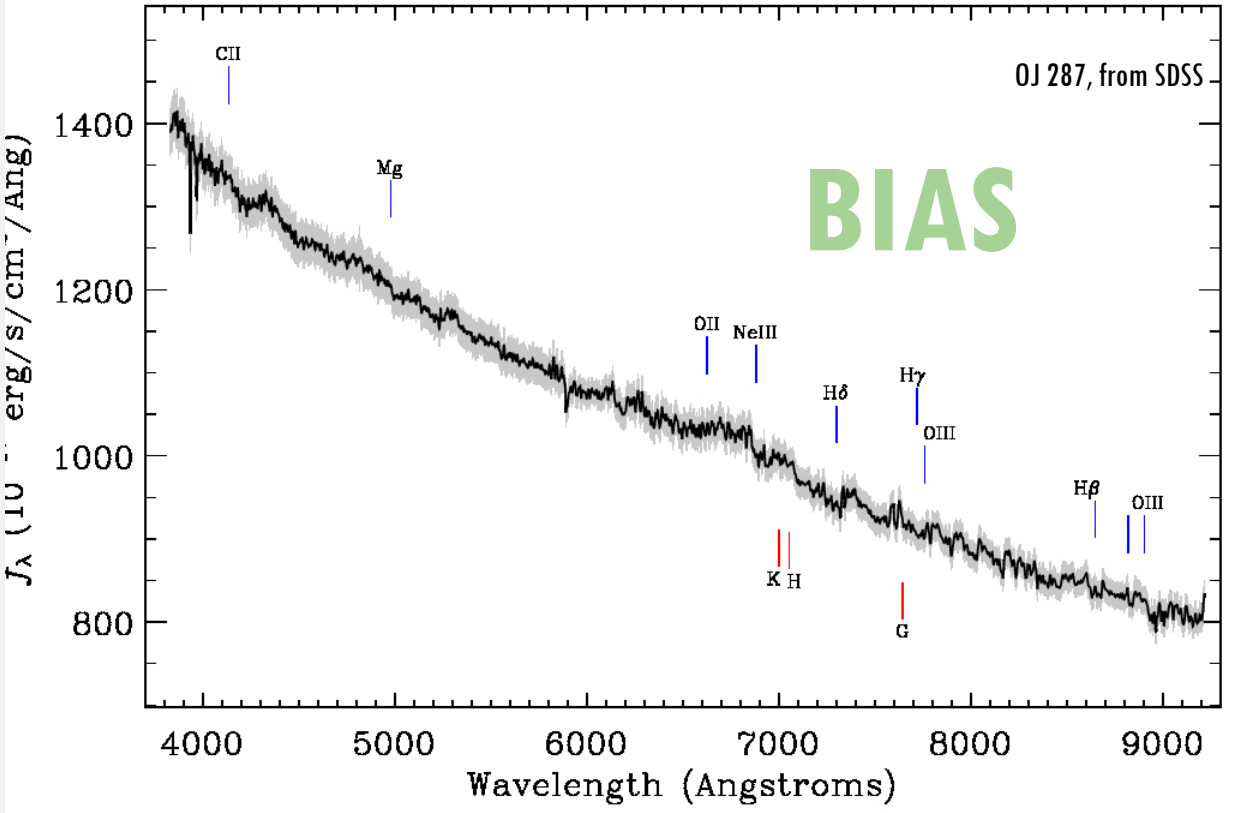
Presence of broad emission lines in the optical spectrum

BL Lacertae Objects (BL Lacs)

Absence of broad emission lines in the optical spectrum

BLAZARS





Flat Spectrum Radio Quasars (FSRQ)

Presence of broad emission lines in the optical spectrum

- Redshift → luminosity
- BH masses & accretion disk luminosity

BLAZARS

BL Lacertae Objects (BL Lacs)

Absence of broad emission lines in the optical spectrum

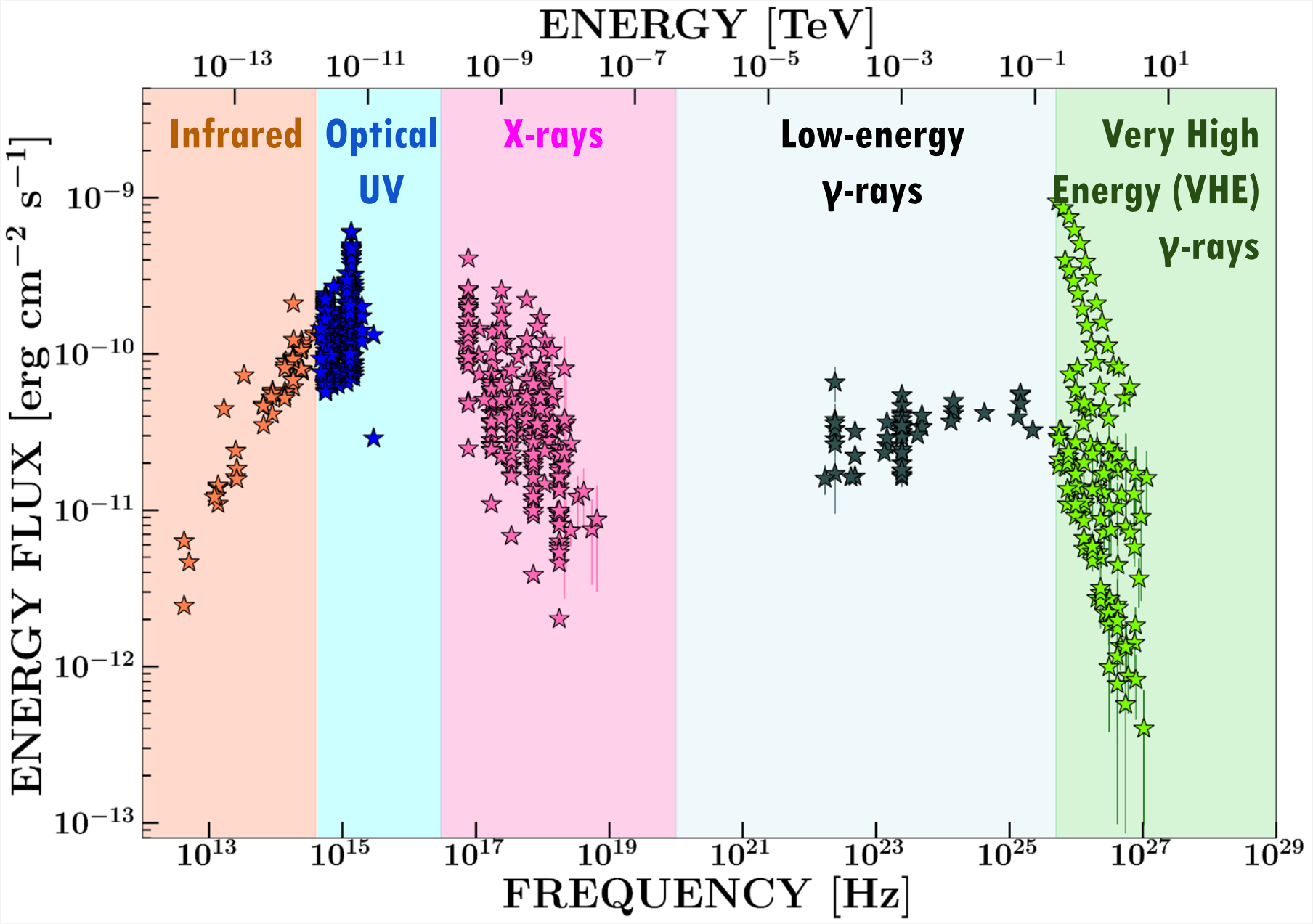
- Redshift [difficult] → luminosity?
- BH masses & accretion disk luminosity ? [can only be inferred by modelling/scaling relations]

What do blazar jets look like?

Lea Marcotulli | lea.marcotulli@desy.de

Blazar jet emission: multiwavelength & highly variable

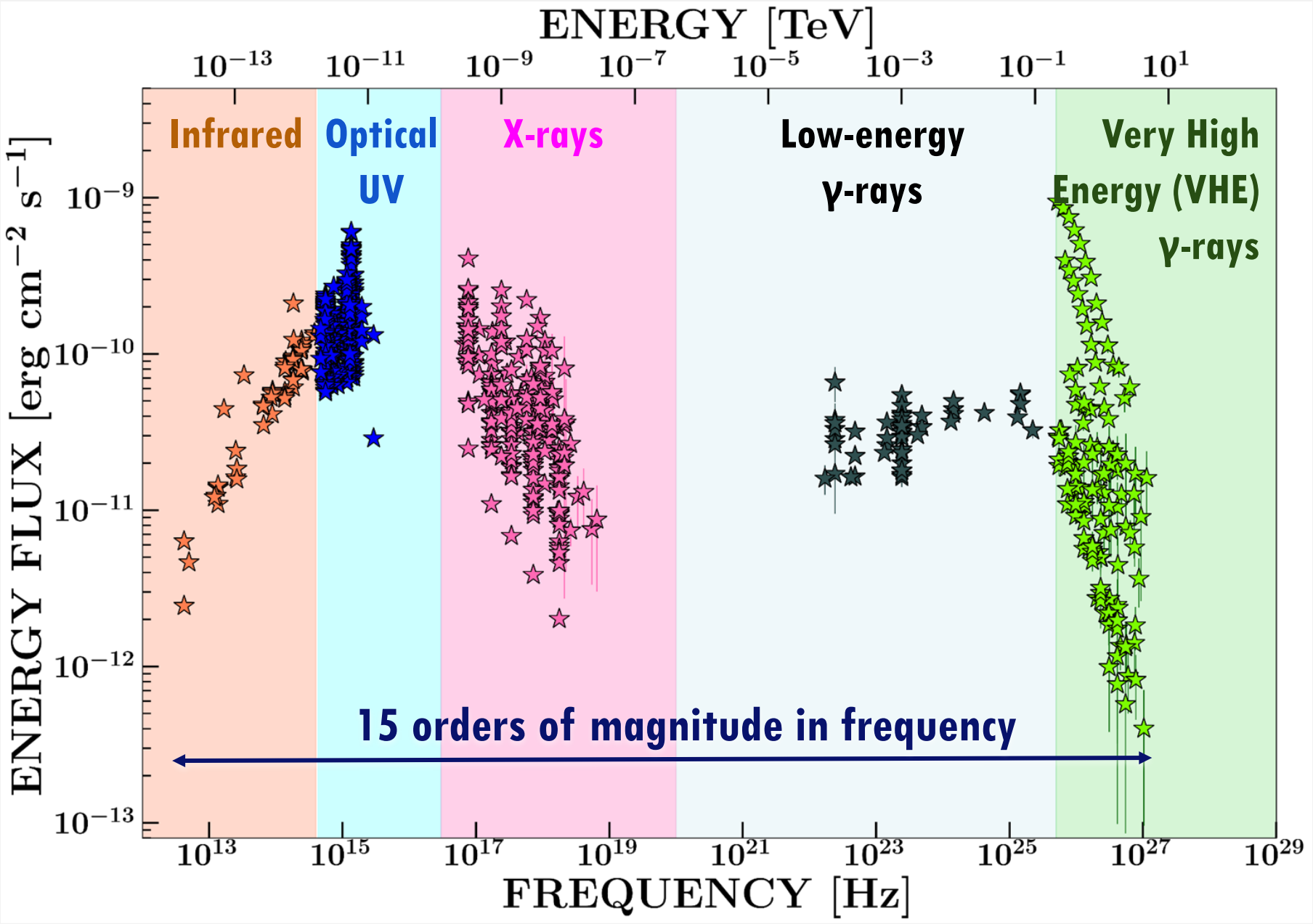
Typical picture of a blazar monitored for **several years** at **all accessible wavelengths**



Adapted from Marcotulli+24

Blazar jet emission: multiwavelength & highly variable

Typical picture of a blazar monitored for **several years** at **all accessible wavelengths**

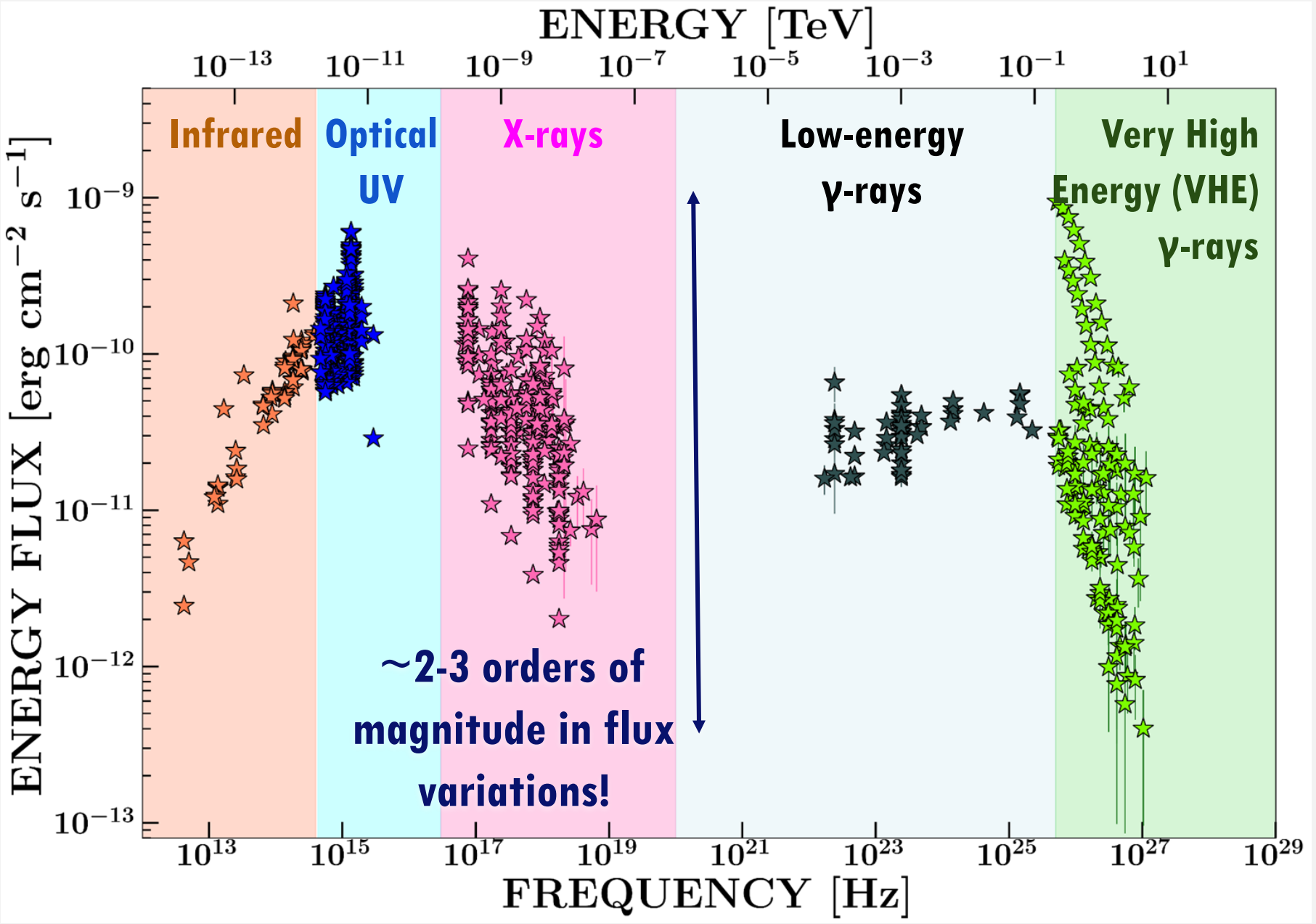


BIAS

Adapted from Marcotulli+24

Blazar jet emission: multiwavelength & highly variable

Typical picture of a blazar monitored for **several years** at **all accessible wavelengths**



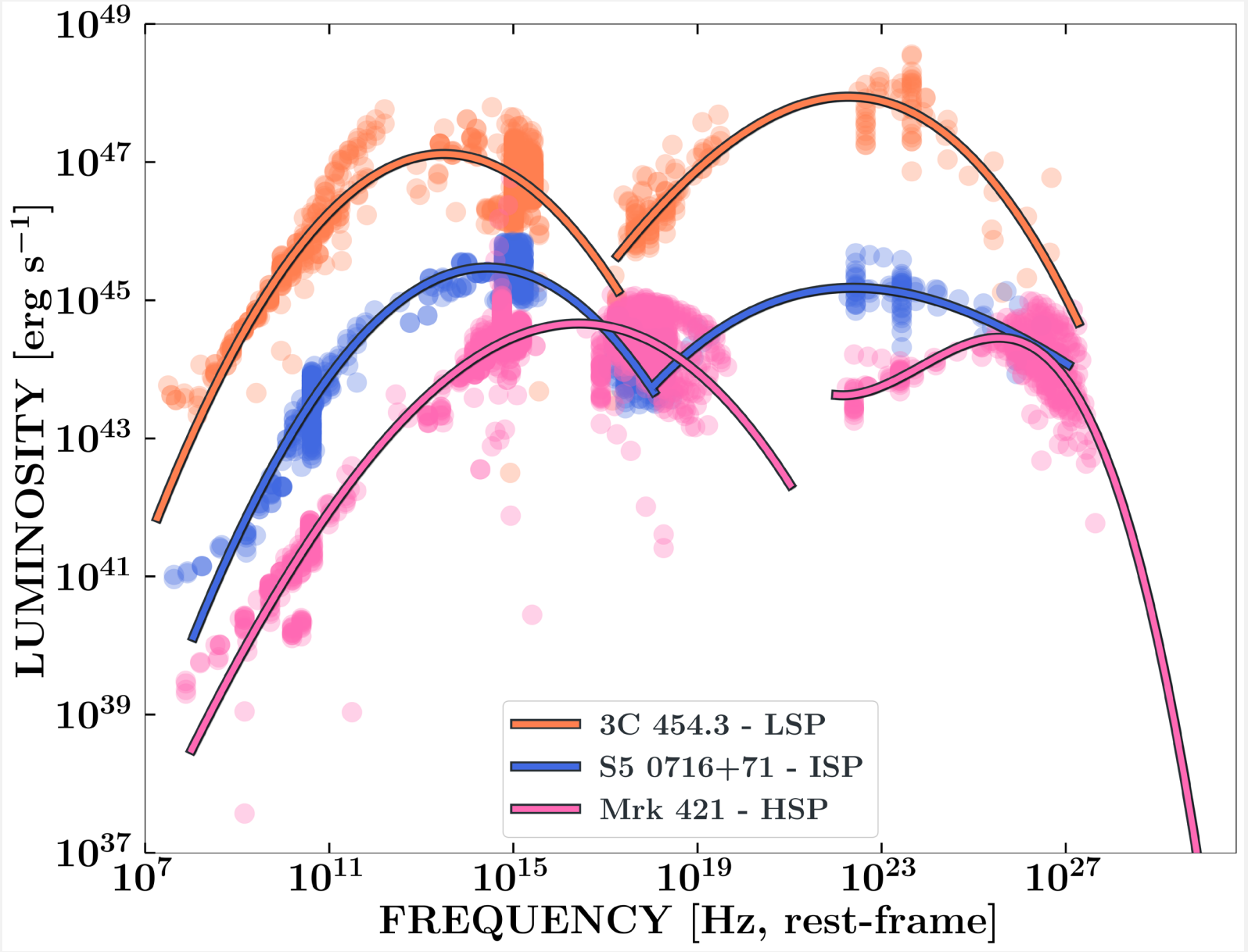
BIAS

Adapted from Marcotulli+24

Blazars as a population

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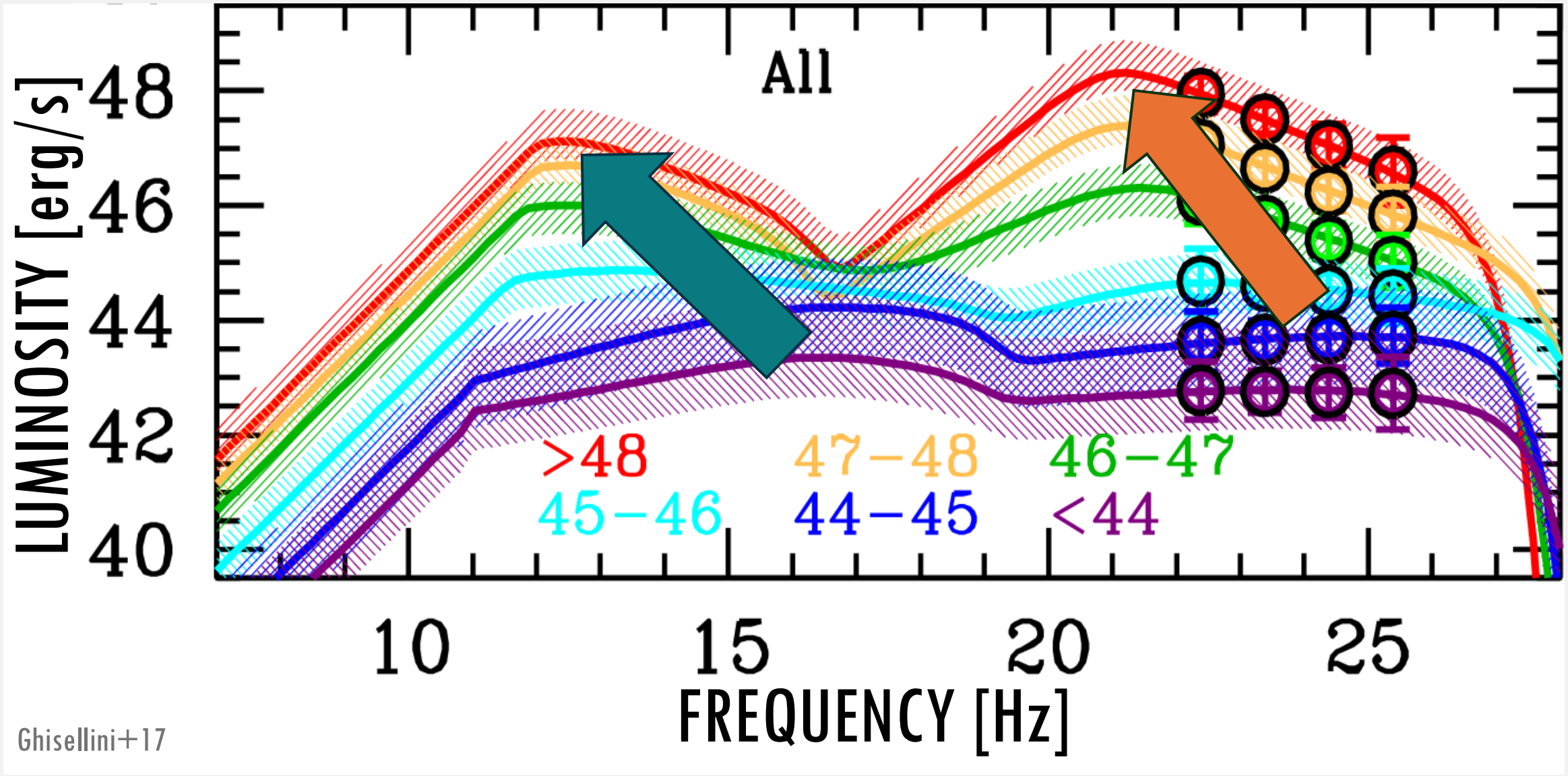
Blazar types and their SED evolution



Data taken from the SED builder

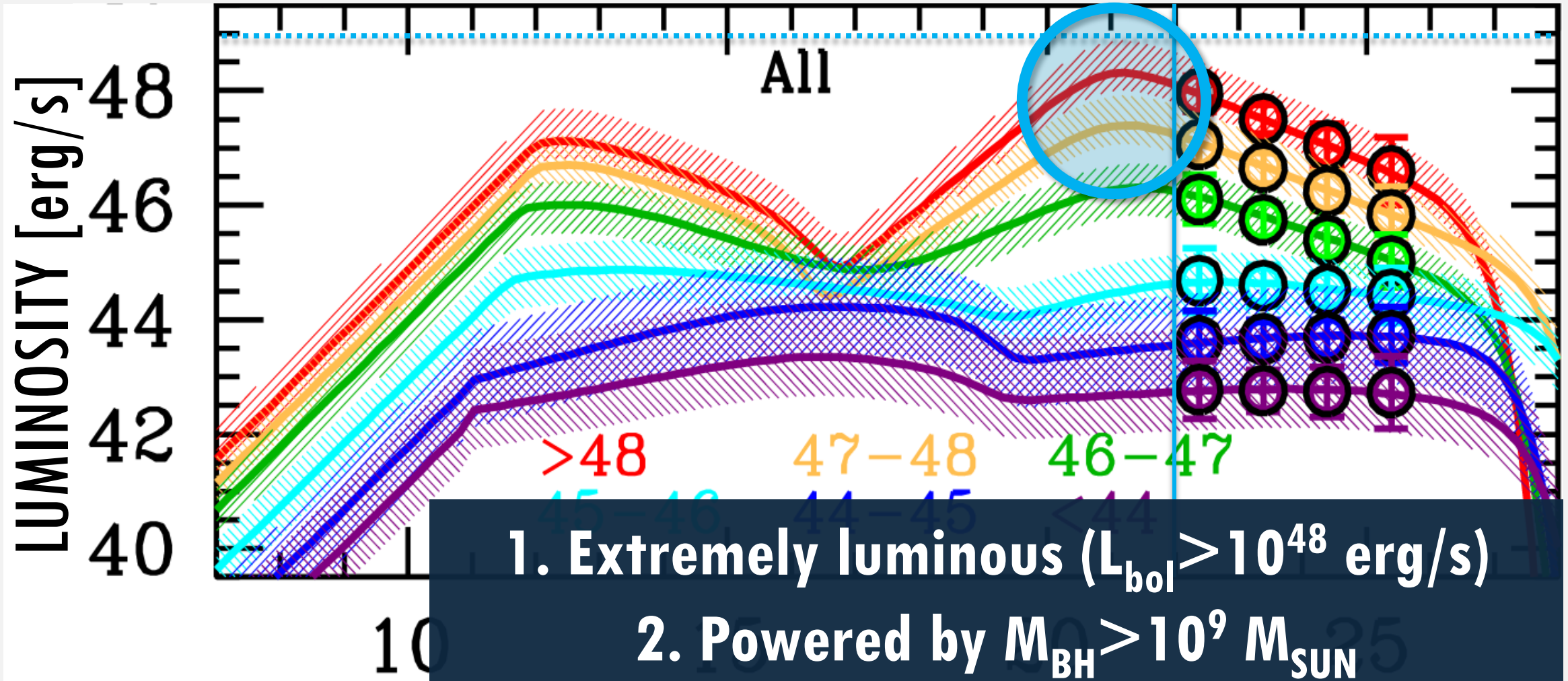
Padovani & Giommi +95
Abdo+10

Blazar types and their SED evolution



Ghisellini+17

MeV peaked blazars

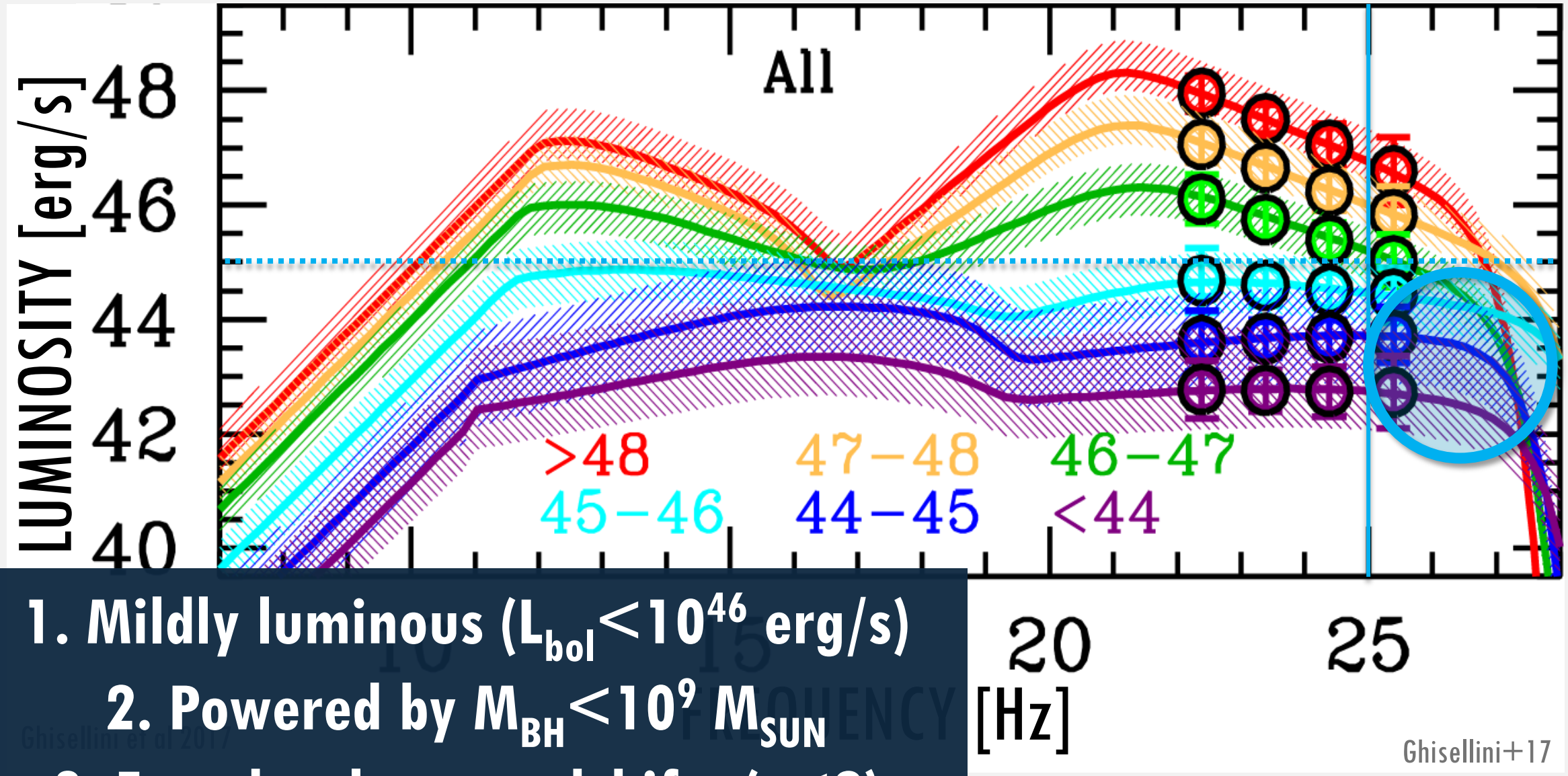


Ghisellini+17

1. Extremely luminous ($L_{bol}>10^{48}$ erg/s)
2. Powered by $M_{BH}>10^{9}$ M_{SUN}
3. Found at the highest redshifts (z>4)

GeV peaked blazars

100 GeV

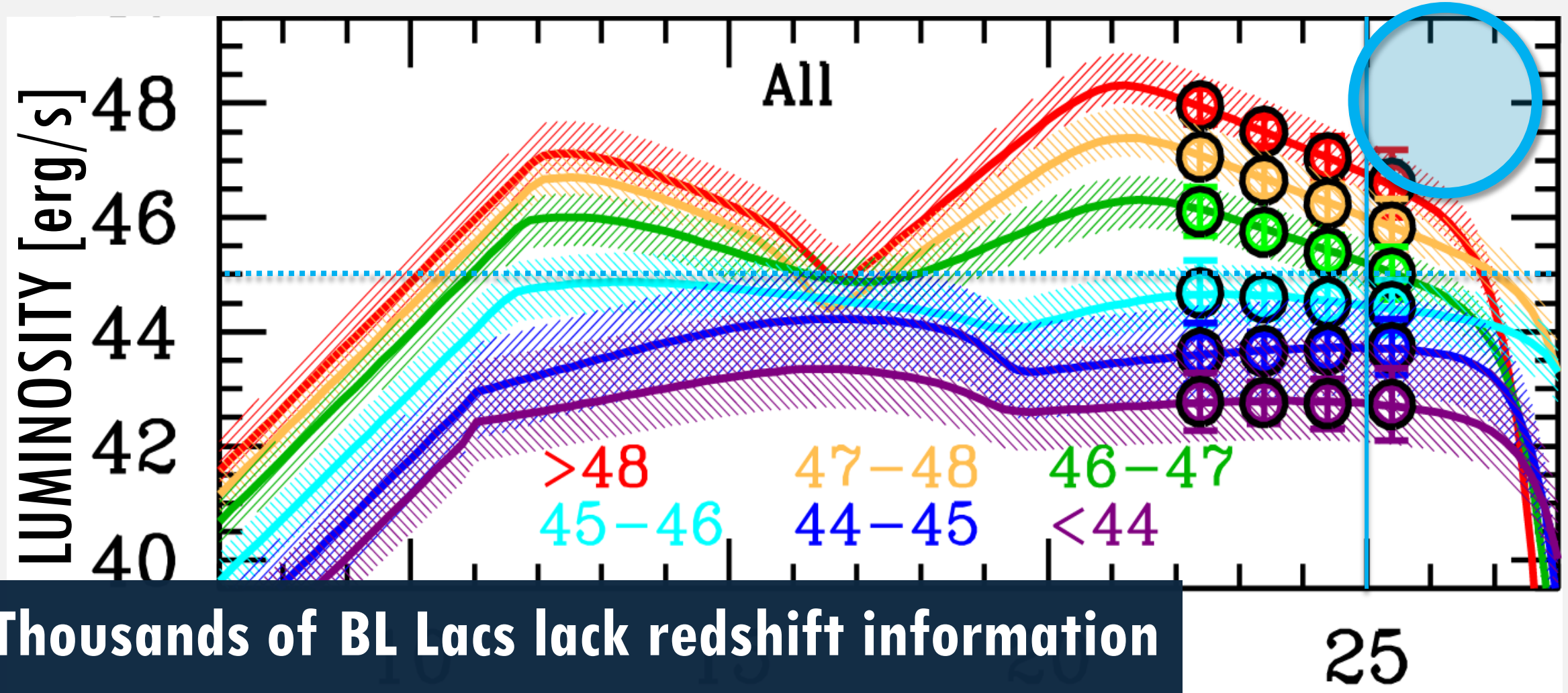


1. Mildly luminous ($L_{bol}<10^{46}$ erg/s)
2. Powered by $M_{BH}<10^{9}$ M_{SUN}
3. Found at lower redshifts (z<2)

GeV peaked blazars

BIAS

100 GeV



Ghisellini+17

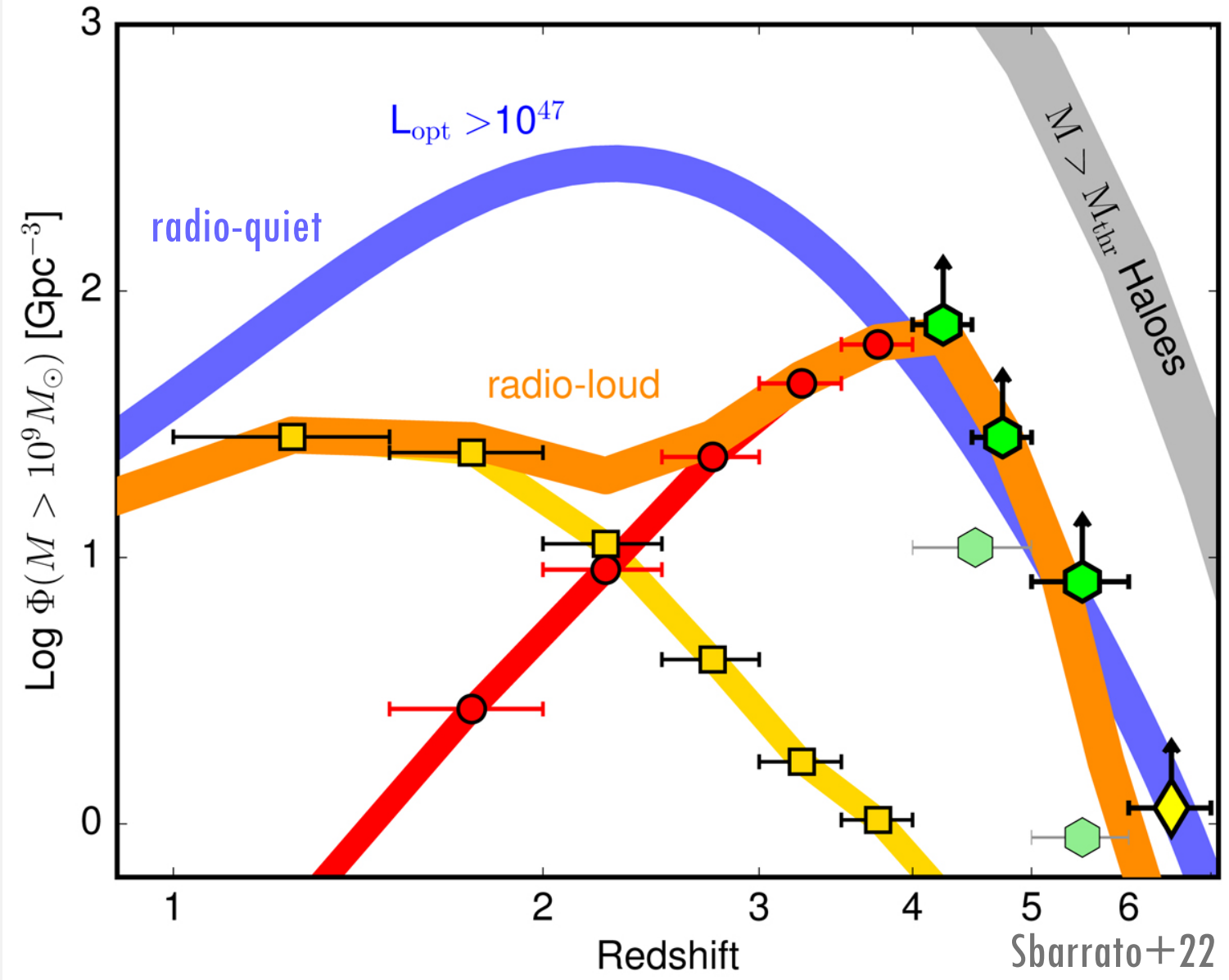
Thousands of BL Lacs lack redshift information

Maybe we are just missing the so-called "masquerading" BL Lacs

e.g. Giommi+11, Padovani+12; Rajagopal+2020; Rajguru+2024

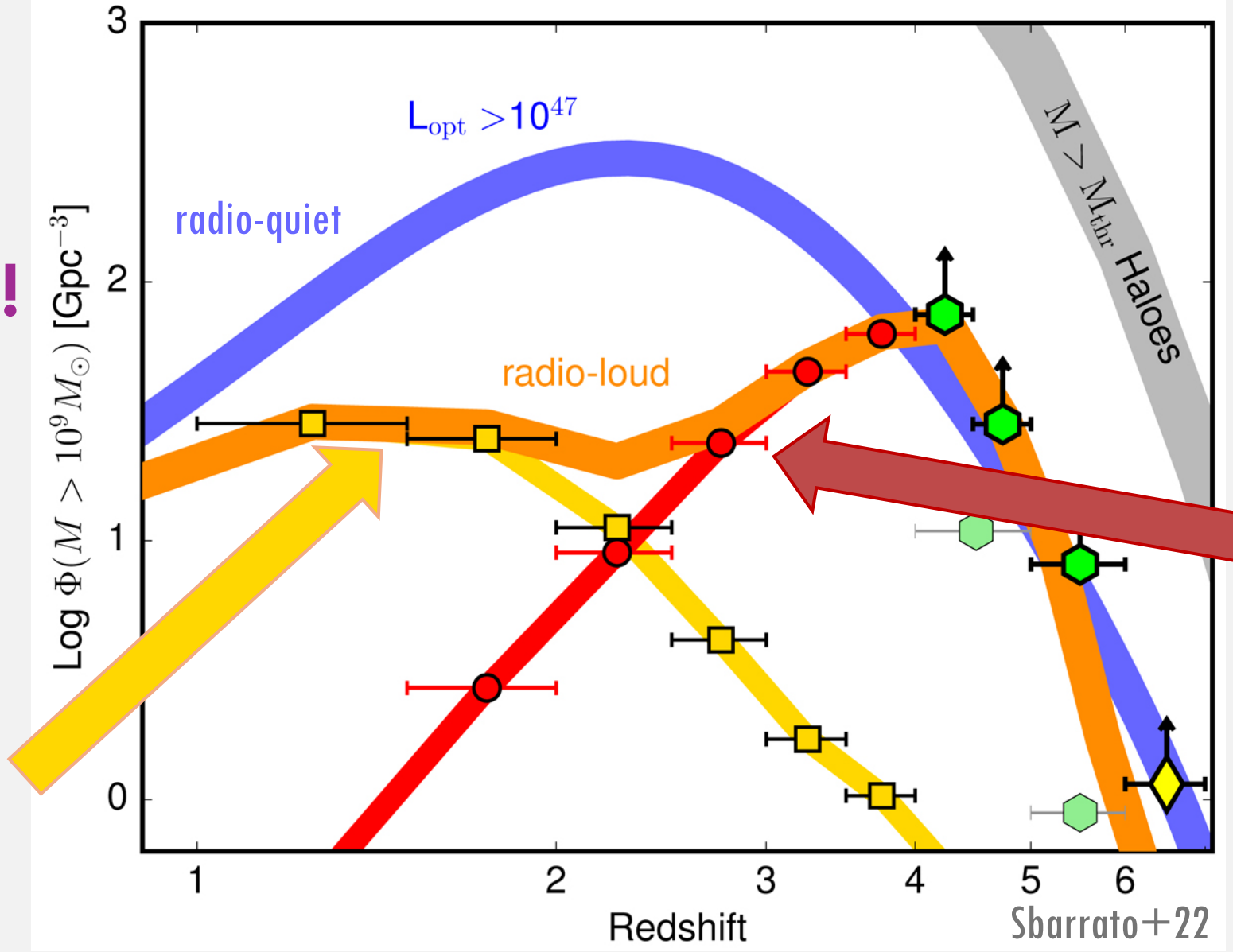
Blazar jets and supermassive black hole evolution

Blazar jets and supermassive black hole evolution



Blazar jets and supermassive black hole evolution

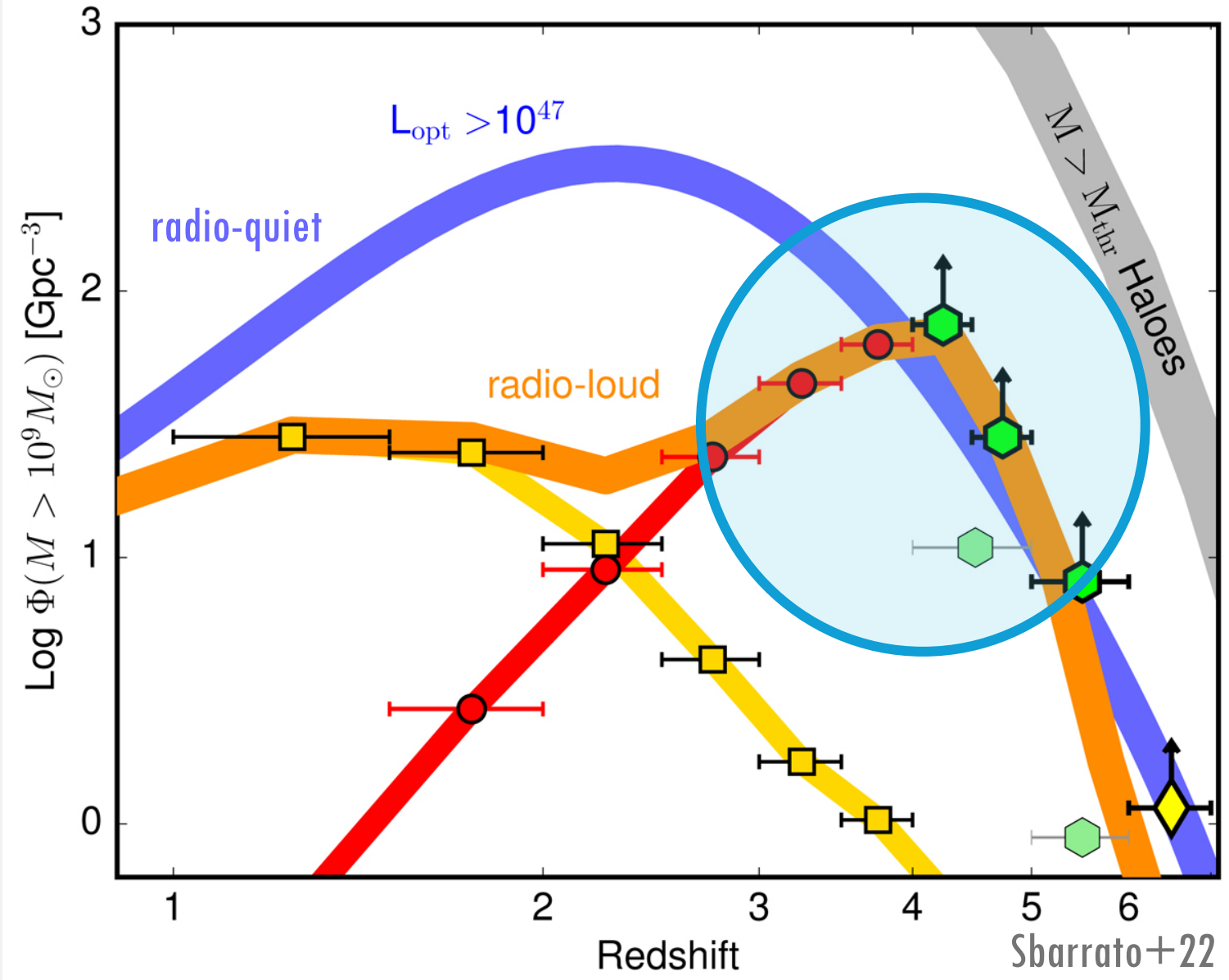
$2\Gamma^2$ correction!



γ-ray detected blazars

X-ray detected blazars

Blazar jets and supermassive black hole evolution



Peak of the evolution at 'cosmic brunch'

Wilkins+24

Blazar jets and supermassive black hole evolution

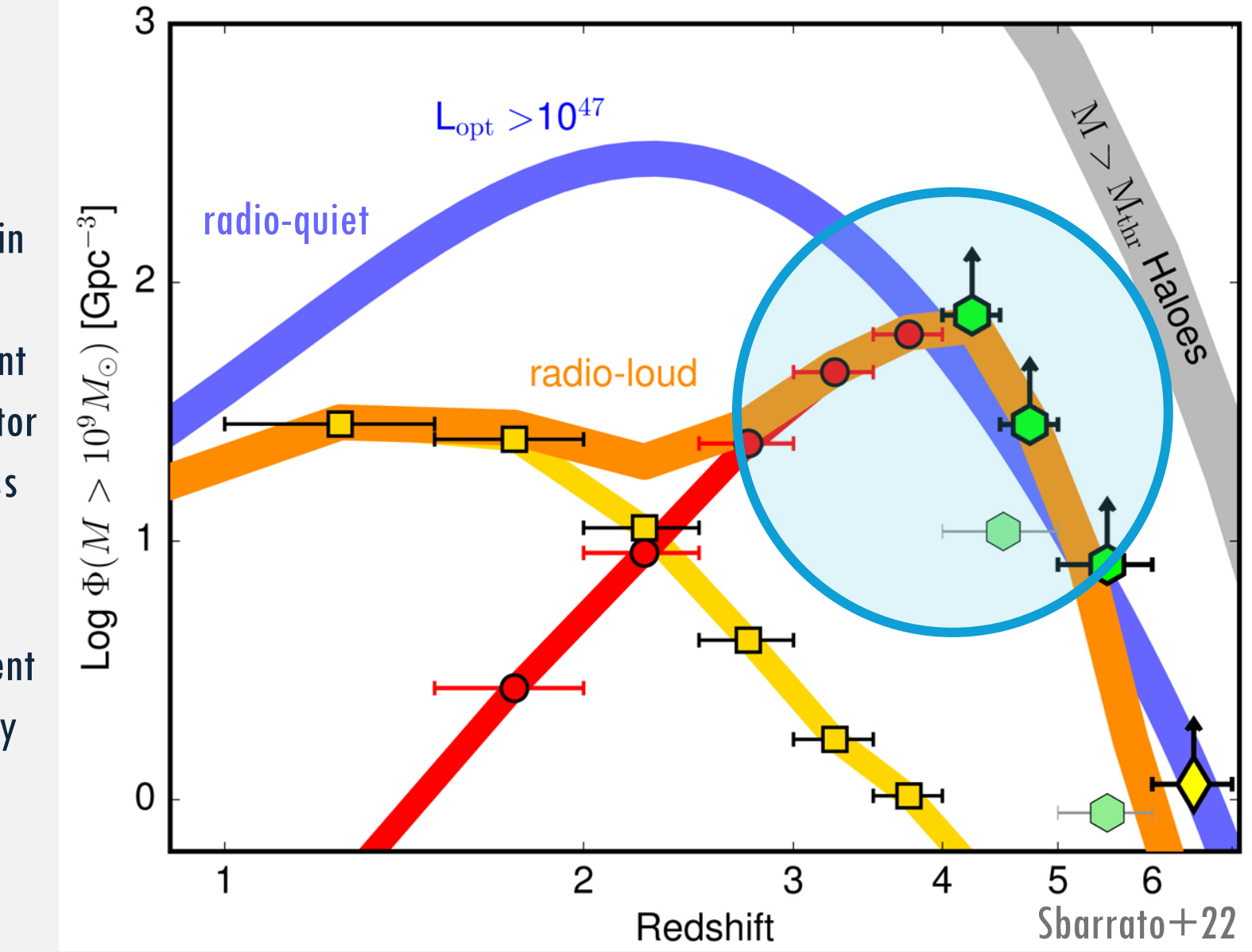
Caveats

1. Number of sources detected per redshift bin

2. Reliable measurement of the bulk Lorentz factor (Γ) and black hole mass (M_{BH})

3. Accurate measurement of the blazar luminosity function

BIAS



Peak of the evolution at 'cosmic brunch'

Wilkins+24

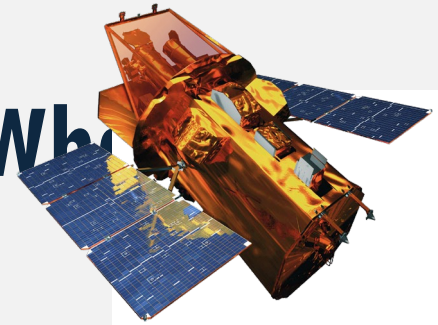
The Evolution of Blazar Jets

Lea Marcotulli | lea.marcotulli@desy.de

What do we need

1. Clean sample (i.e. blazars with measured redshift and flux)

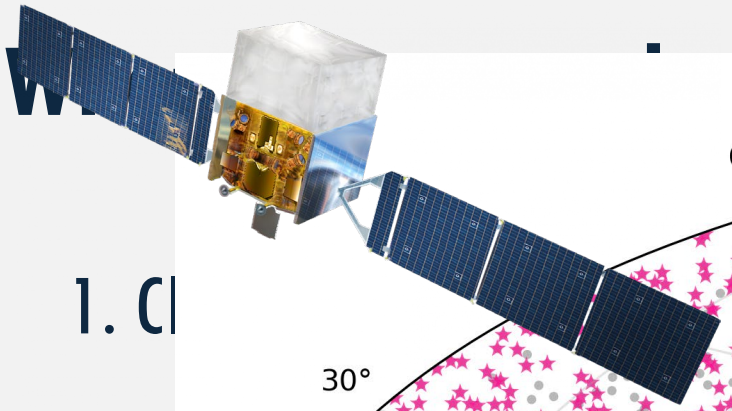




Wh

1.

BAT-105 all sky source map, 14-195 keV using ~9 years of data, Oh et al. 2018



1. Cl

Fermi-LAT FL8Y all sky map, 100 MeV – 1TeV ~8 years of data

What do we need

1. Clean sample (i.e. blazars with measured redshift and flux)
2. **Set of cuts to minimize uncertainties**



What do we need



1. Clean sample (i.e. blazars with measured redshift and flux)
2. Set of cuts to minimize uncertainties
3. **Account for survey biases**

Eddington Bias

If a source is near the detection threshold of the instrument, it is more likely to detect it with a flux

$F_{obs} = F_{true} + \Delta F$

Malmquist Bias

A flux limited sample overrepresents intrinsically luminous sources

Variability Bias

Sources are more likely to be detected in a flaring state

Spectral-selection Bias

Hard/bright sources are easier to detect

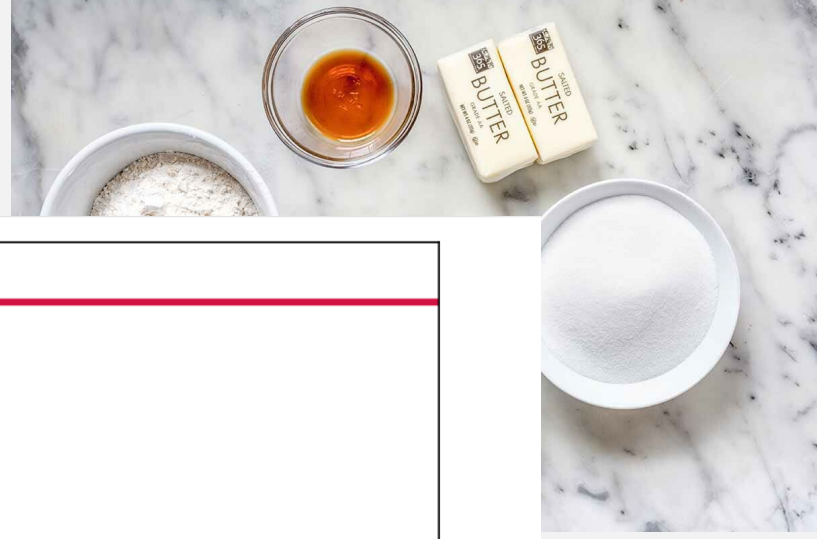
What do we need

1. Cle
2. Set
3. Ac



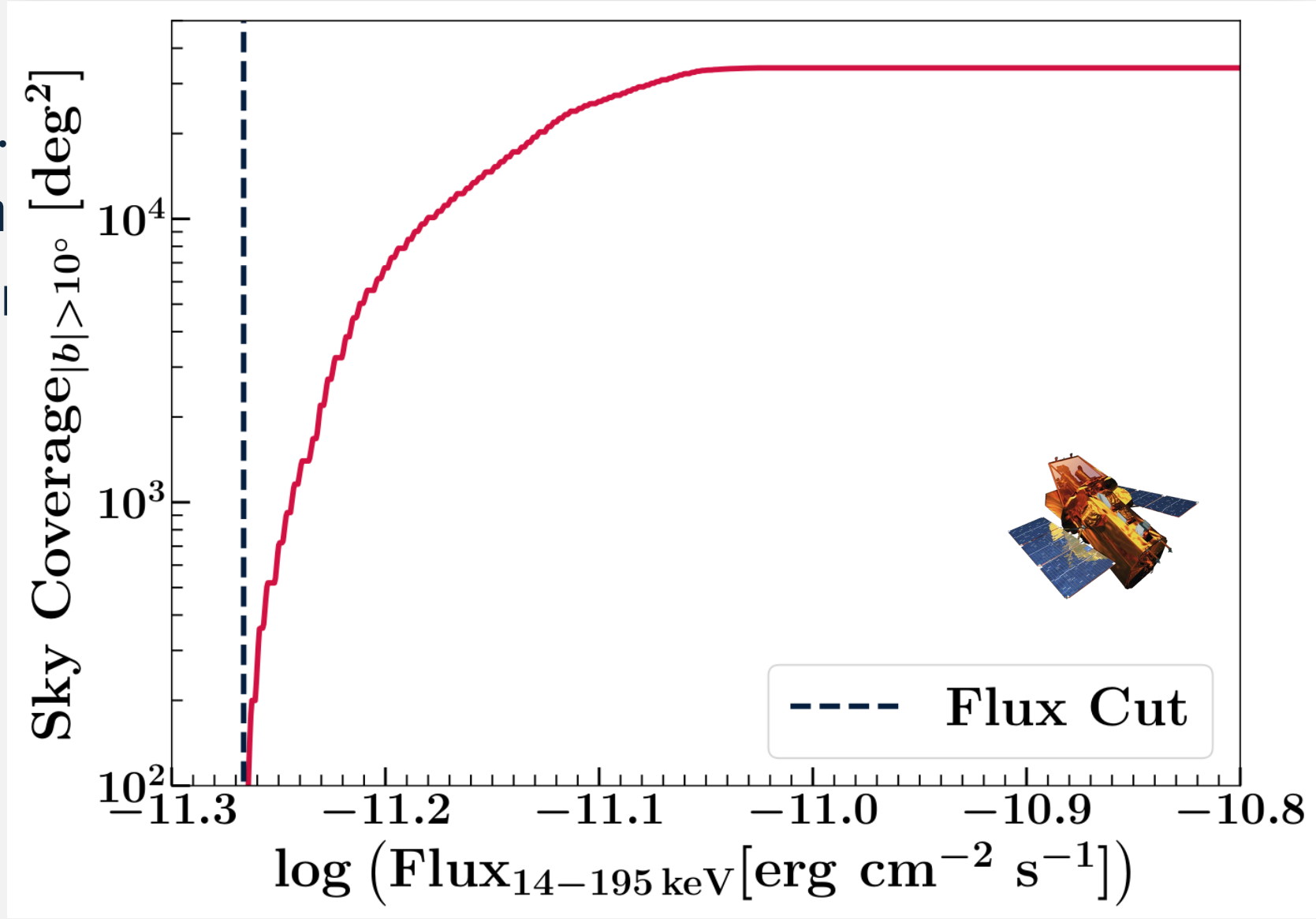
Exposure Bias

What do we need



1. Clean sample (i.e.
2. Set of cuts to min
3. **Account for su**

Sky Coverage



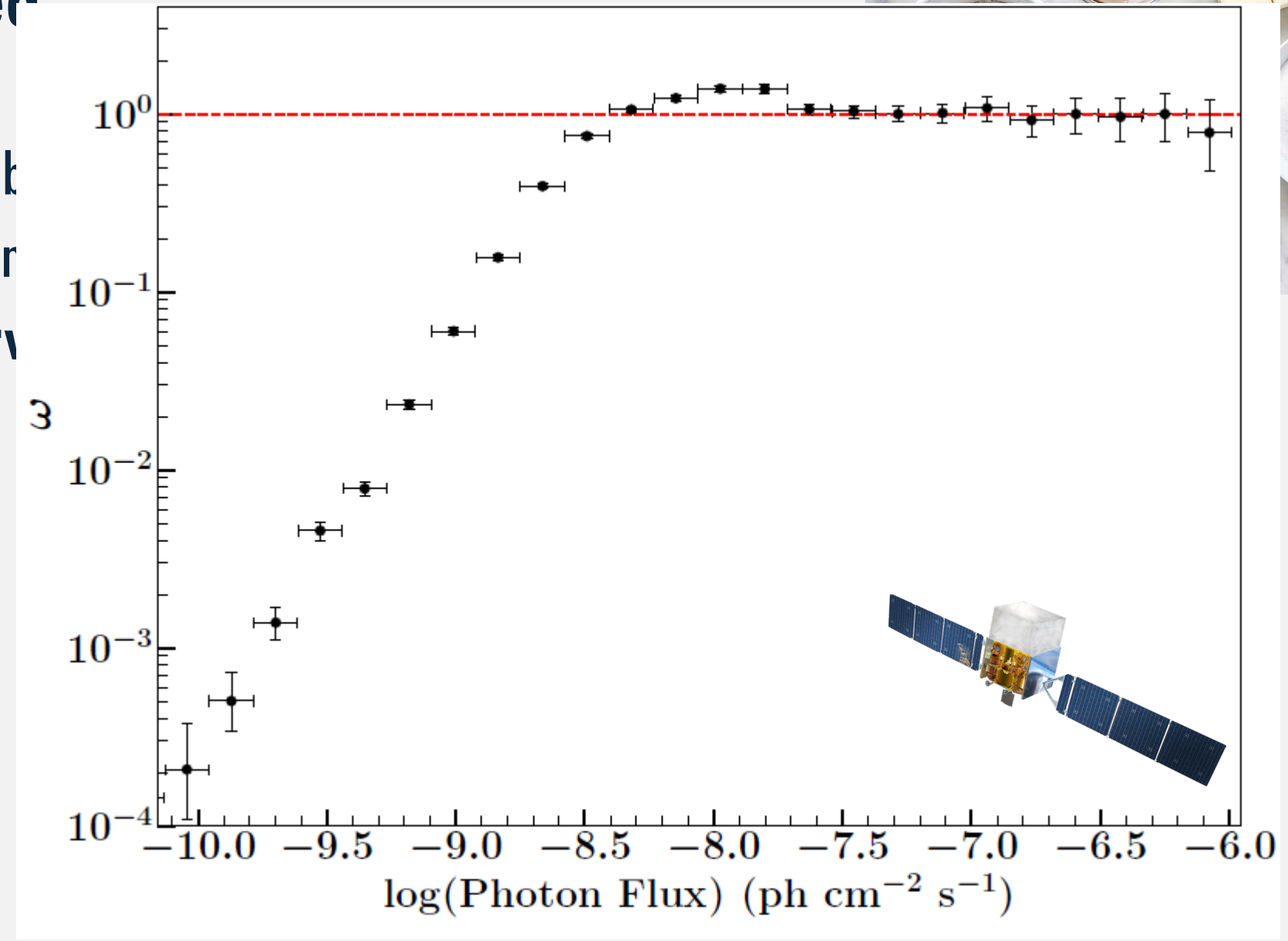
Marcotulli+22

What do we need

1. Clean sample (i.e. b
2. Set of cuts to minir
3. **Account for surv**

Detection Efficiency





Marcotulli+20

What do we need

4. X-ray luminosity function models (Ajello et al. 2009/2012/2014)

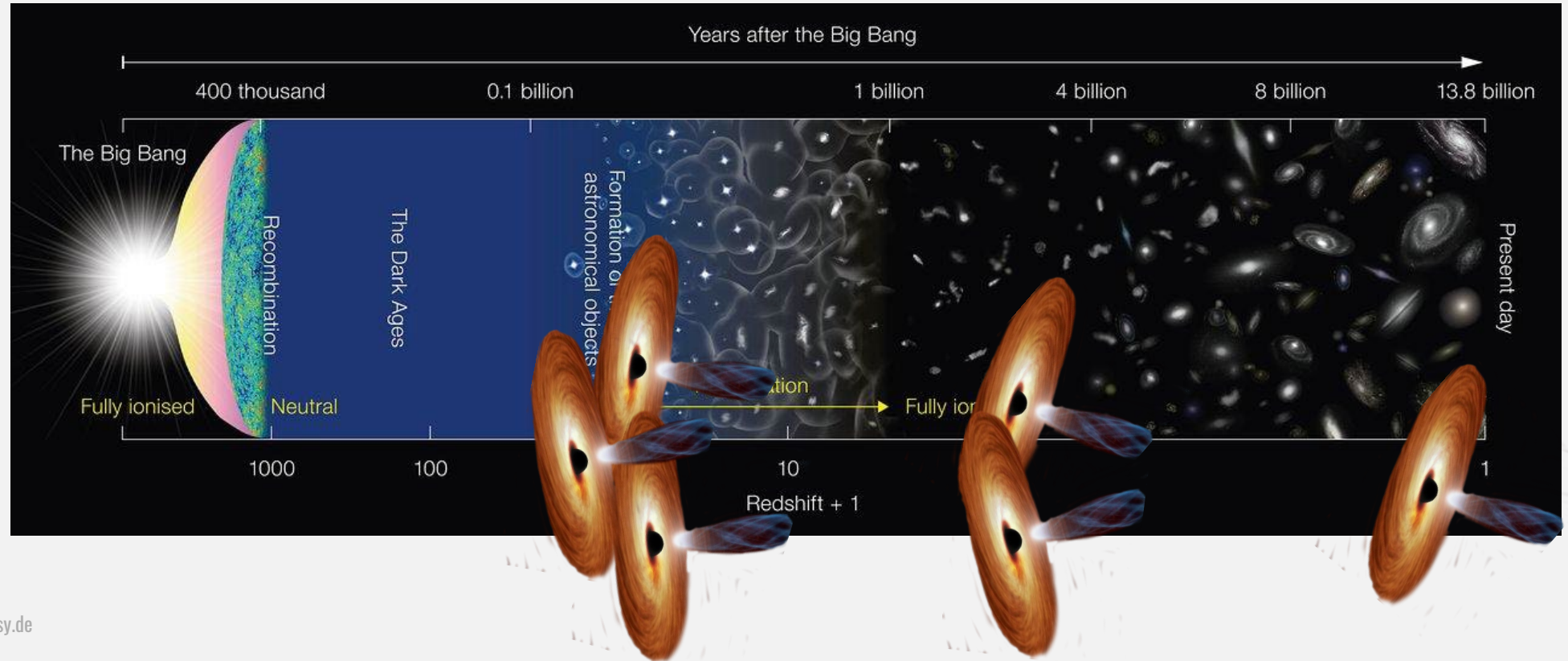


What do we need



4. X-ray luminosity function models (Ajello et al. 2009/2012/2014)

⟶ Pure Density Evolution (PDE)

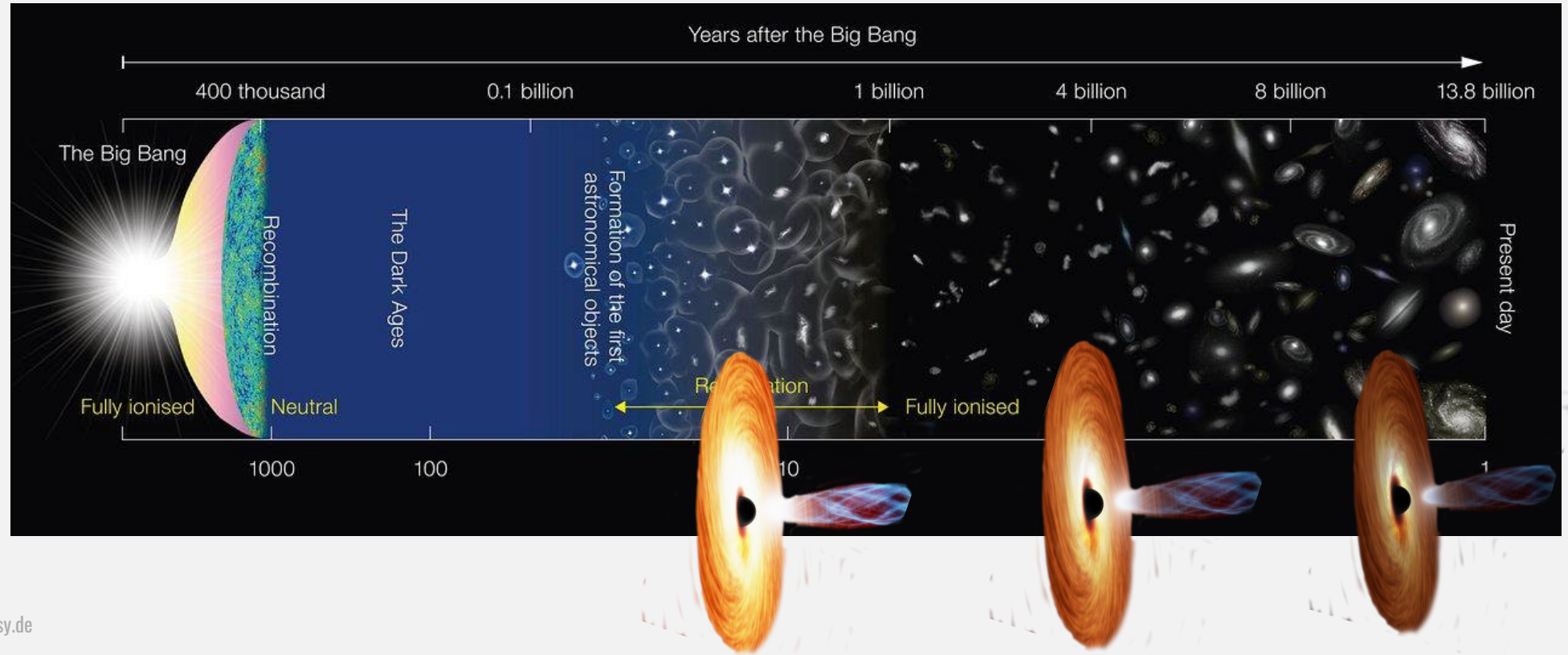


What do we need



4. X-ray luminosity function models (Ajello et al. 2009/2012/2014)

⟶ Pure Luminosity Evolution (PLE)

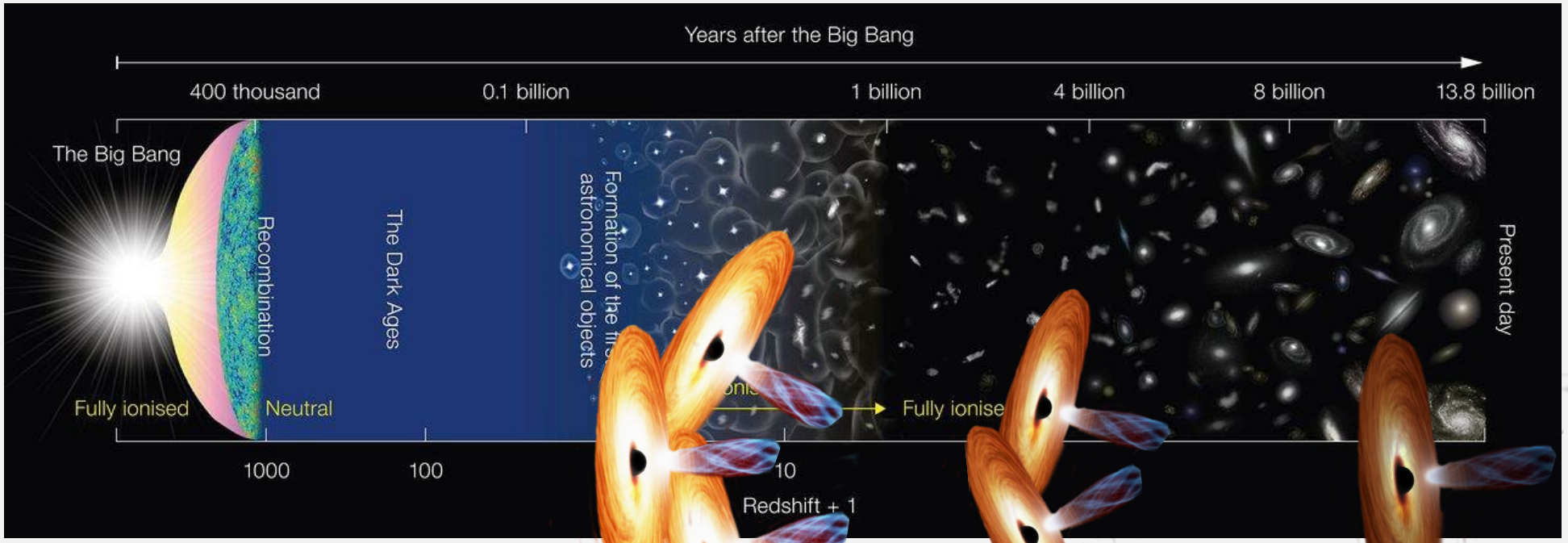


What do we need

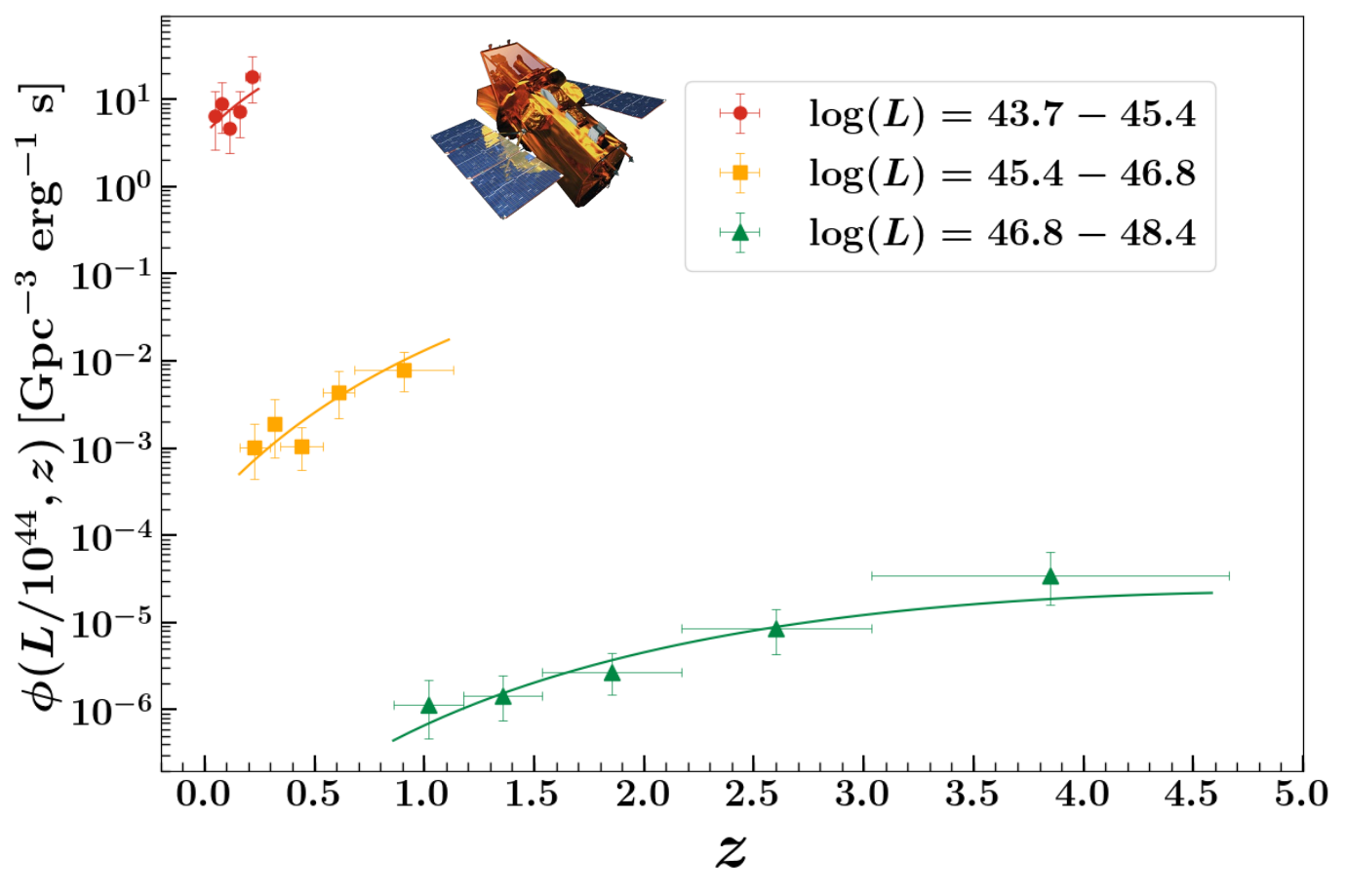


4. X-ray luminosity function models (Ajello et al. 2009/2012/2014)

⟶ Luminosity-Density Dependent Evolution (LDDE)

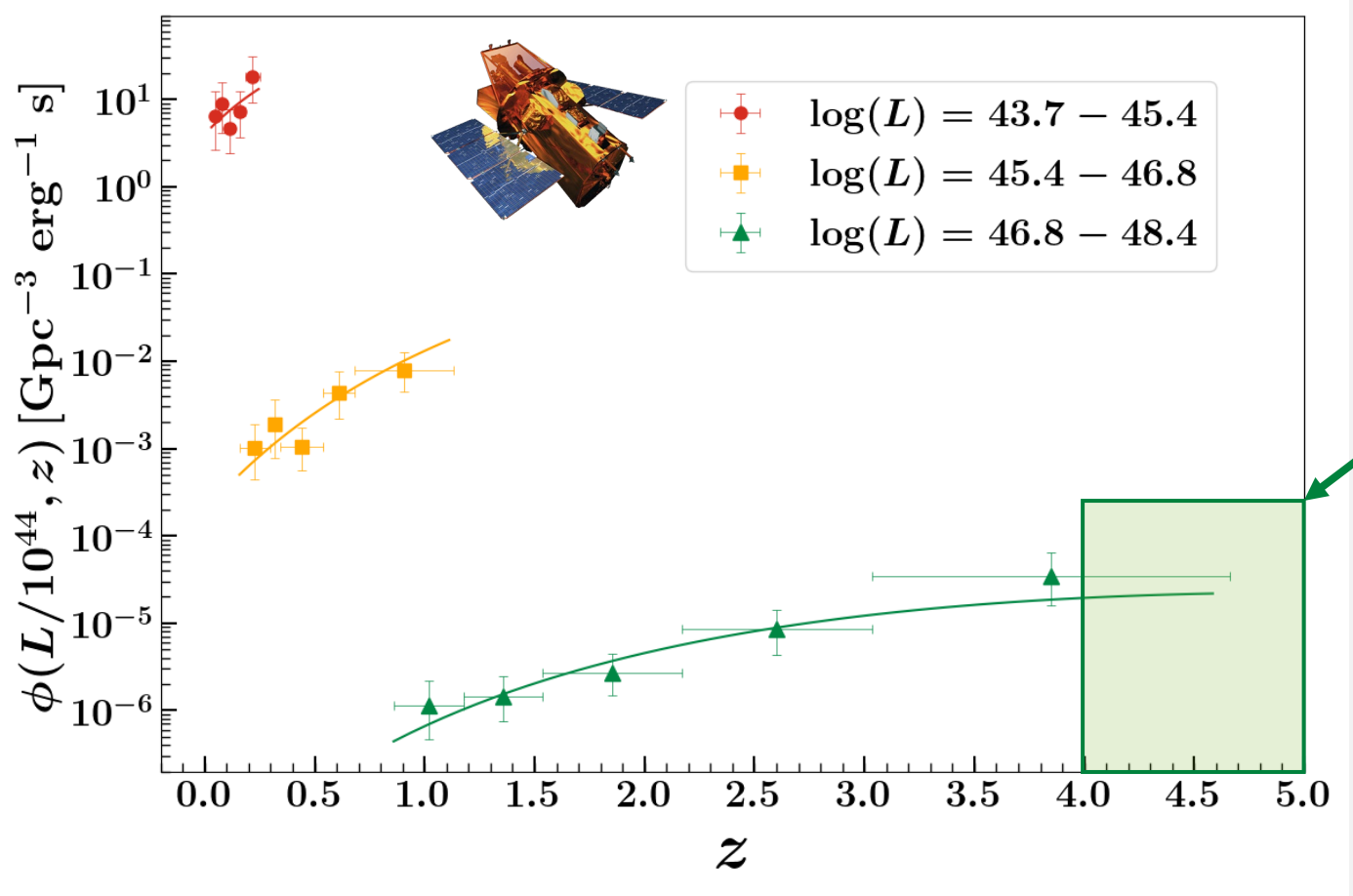


Most up to date hard X-ray luminosity function of FSRQs jets



Marcotulli+22, Ajello+09

Most up to date hard X-ray luminosity function of FSRQs jets



Marcotulli+22, Ajello+09

X-ray FSRQs evolve positively

The peak of the evolution of the most luminous X-ray blazars is confirmed at z=4.3

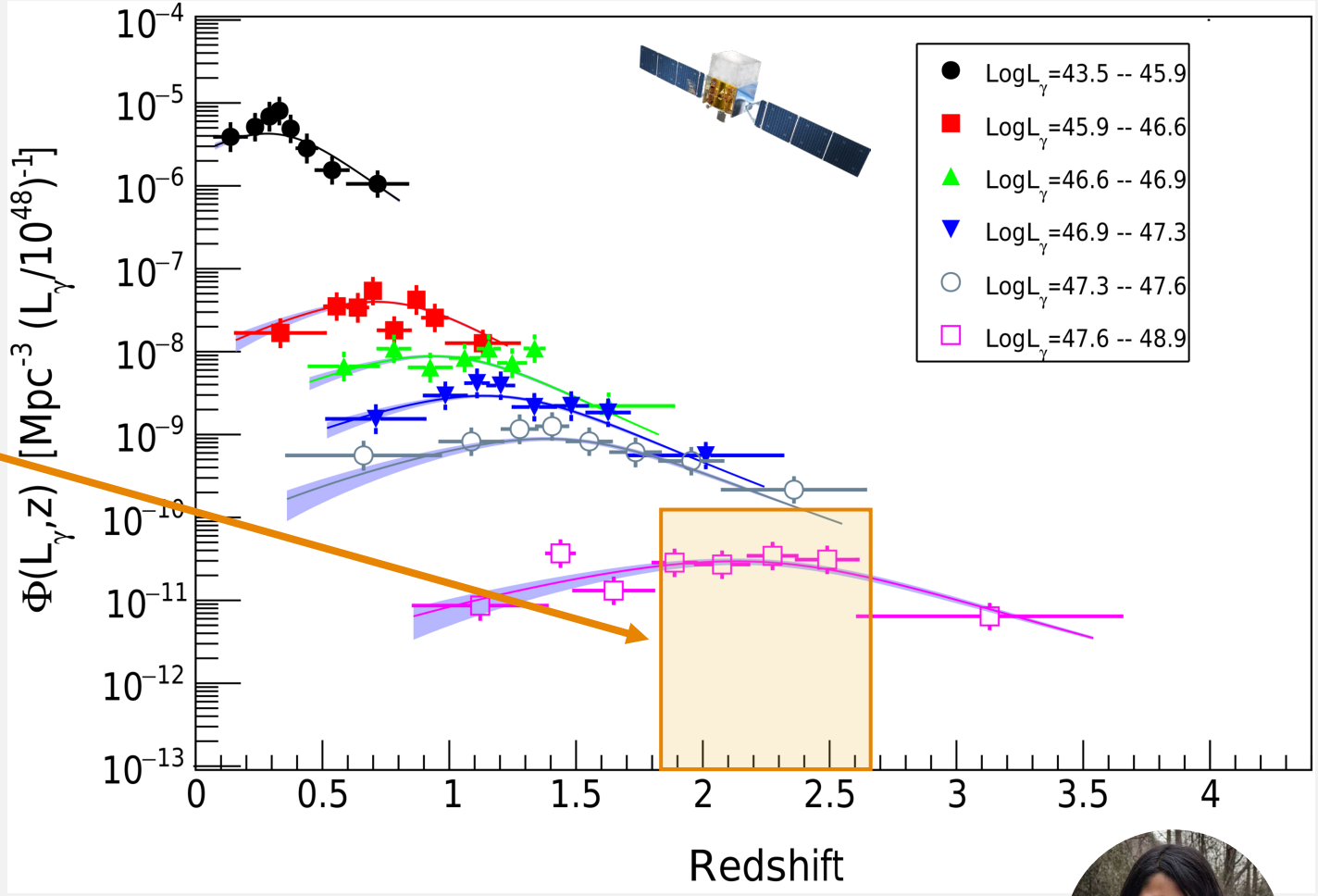
It is yet not possible to determine the type of evolution

Most up to date γ-ray luminosity function of FSRQs jets

Gamma-ray FSRQs evolve positively

The peak of the evolution of the most luminous gamma-ray blazars is at z∼2

They follow a luminosity-dependent evolution





Rajguru+25

Marcotulli+20, Ajello+12

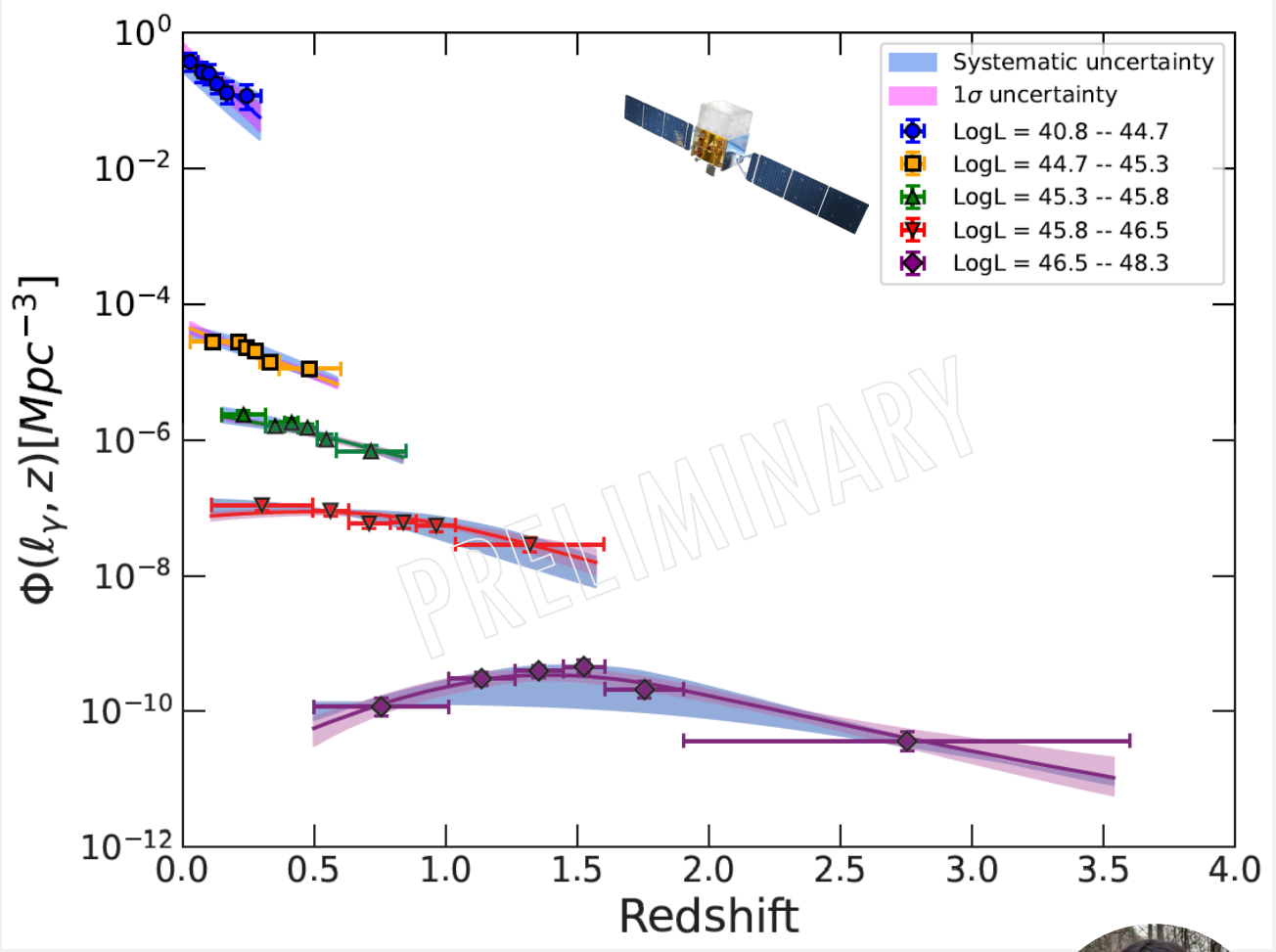
Most up to date γ-ray luminosity function of BL Lacs jets

SAMPLE: 1035 objects
Missing redshift bias accounted for.

Gamma-ray BL Lacs evolve:

1. Negatively for $L < 10^{46}$ erg/s
2. Positively for $L > 10^{46}$ erg/s

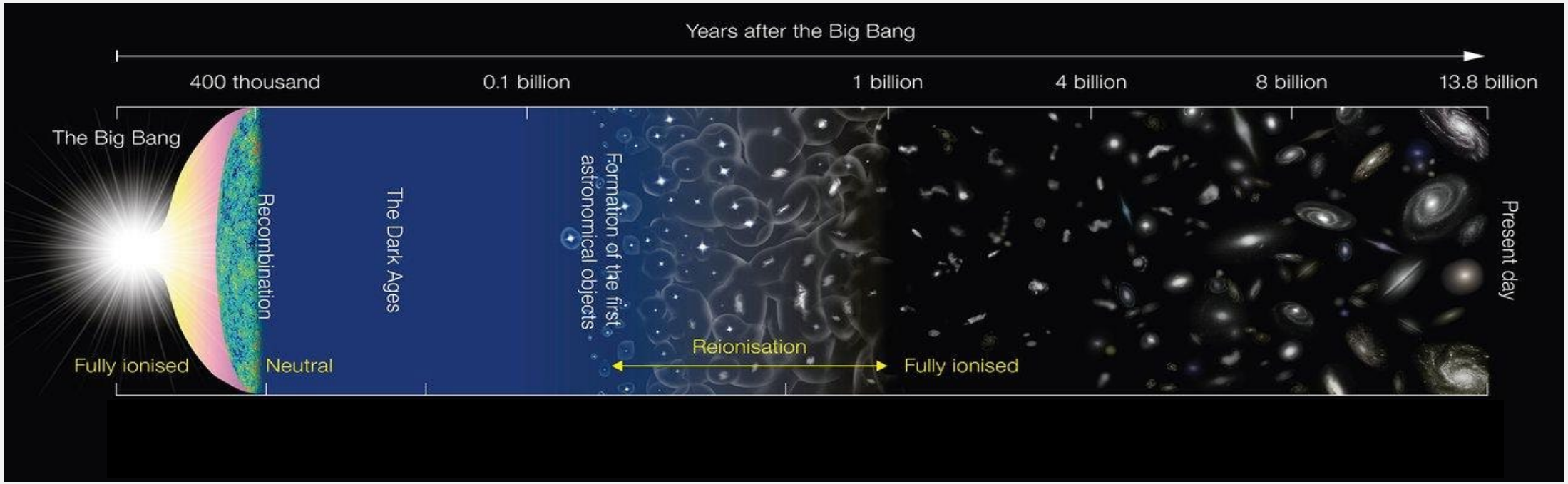
Confirm that BL Lacs and FSRQs seem to show similar evolution in their number densities
→ contamination from masquerading BLLacs



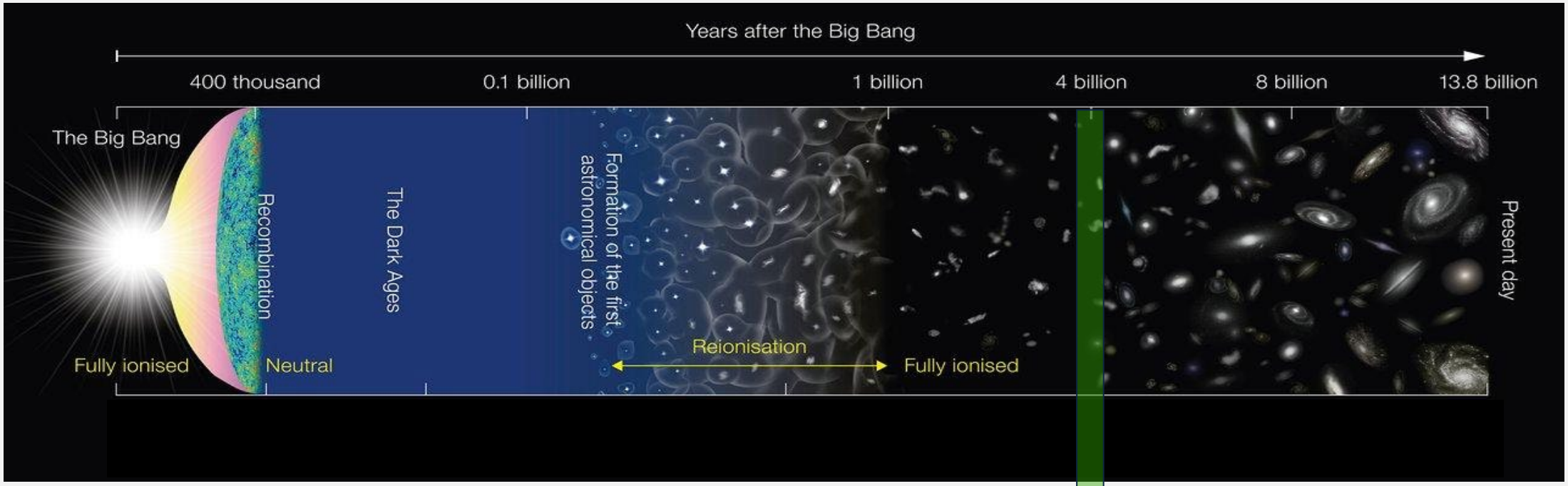
Rajguru+26 (under review),
Ajello+14



Timeline of the universe



Timeline of the universe



"Cosmic Noon"

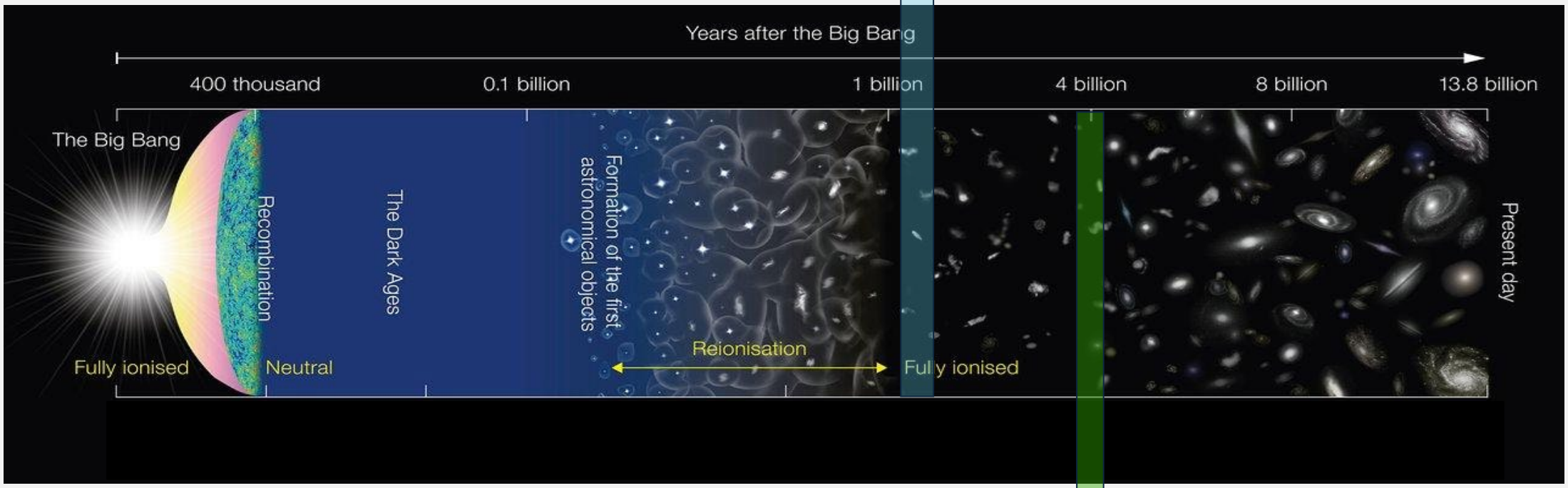
Point in time when we find the majority of stars, galaxies, AGN & γ-ray blazar jets

Timeline of the universe

Marcotulli+20, +22
see also, Sbarrato+15,+22,+26; Cao+17; Caccianiga+19; Ighina+19; An & Romani 20; Belladitta+22; Hammerich+25; and many more

"Cosmic Brunch"

Point in time when we find the majority of X-ray blazars jets tracing the most massive black holes in the universe



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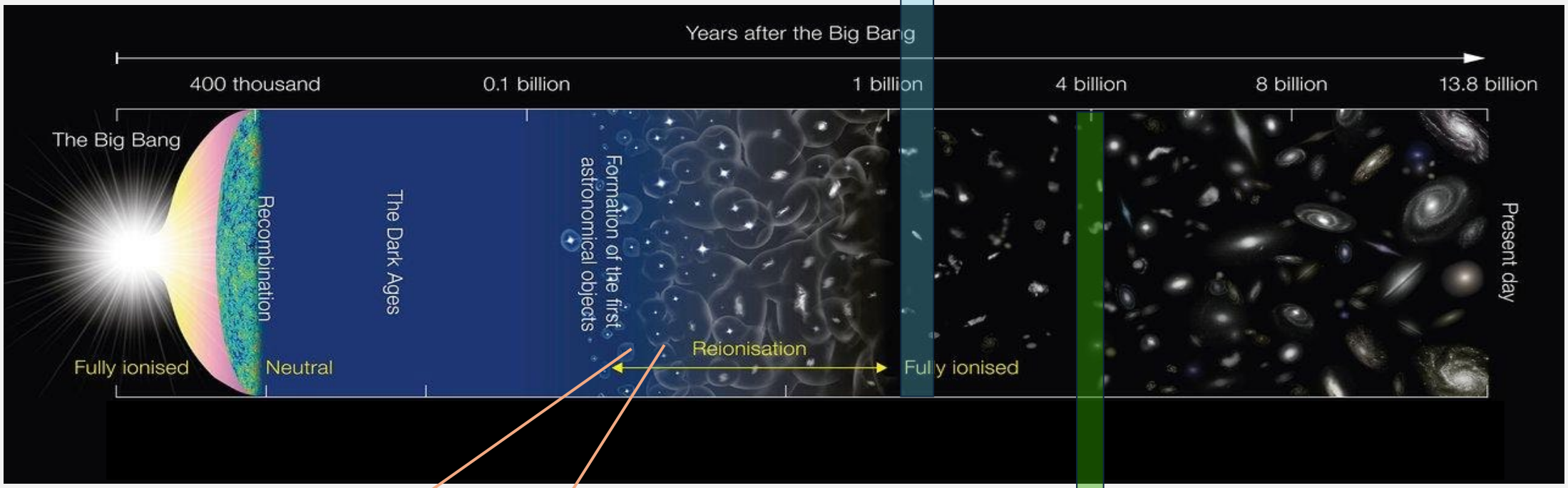
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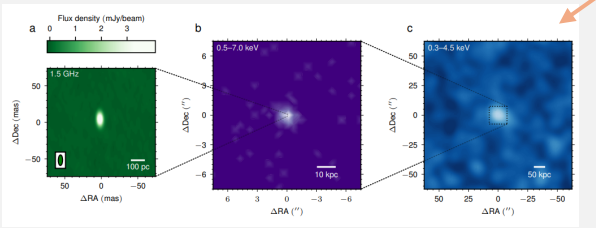
Marcotulli+20, +22
see also, Sbarrato+15,+22,+26; Cao+17; Caccianiga+19; Ighina+19; An & Romani 20; Belladitta+22; Hammerich+25; and many more

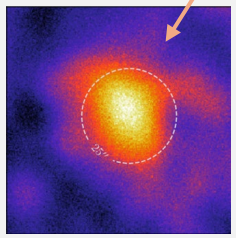
"Cosmic Brunch"

Point in time when we find the majority of X-ray blazars jets tracing the most massive black holes in the universe



Banados+24, VLASS J041009.05-013919.88 at z = 7





z=6.19
CFHQS J142952+544717
NuSTAR image
[Marcotulli+25]

"Cosmic Noon"

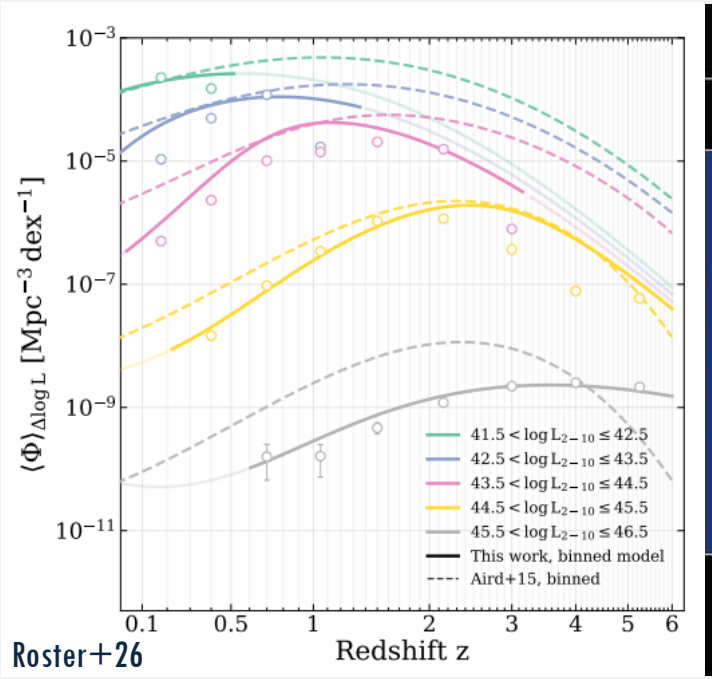
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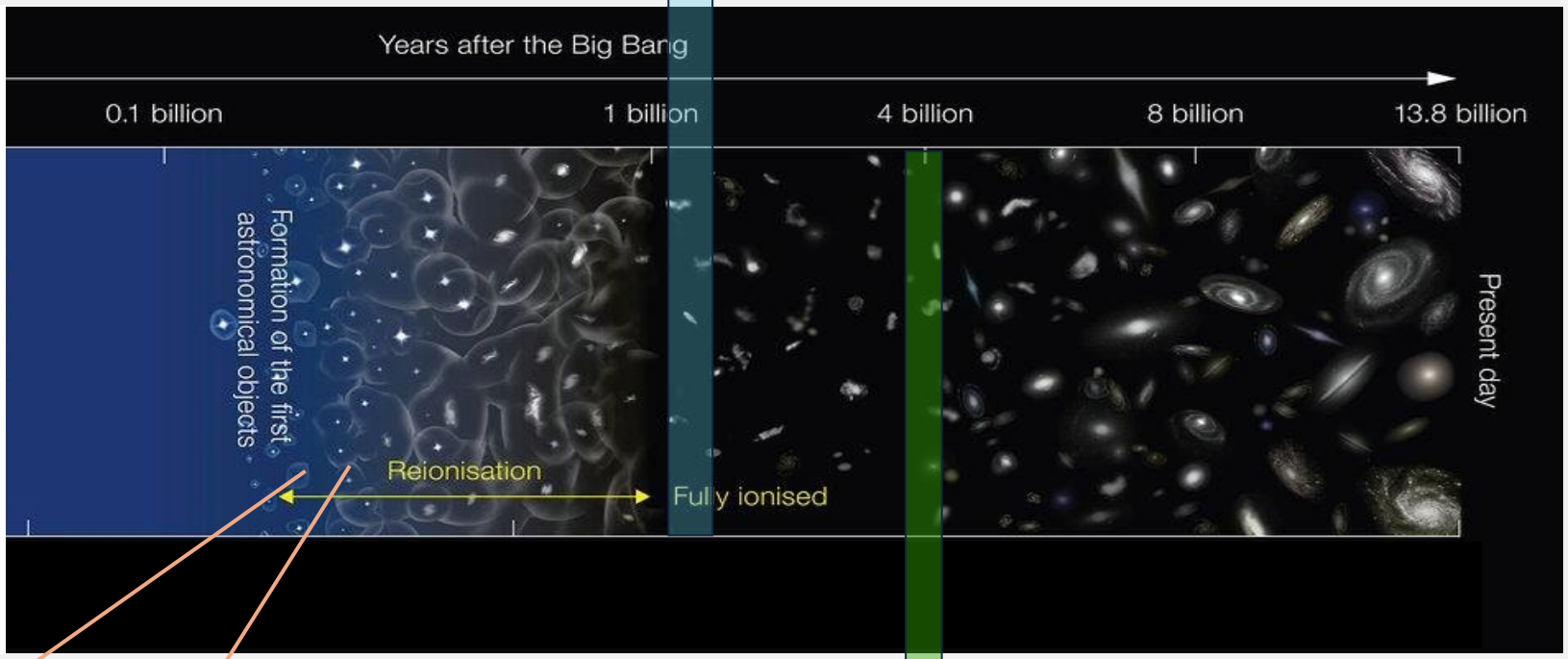
Marcotulli+20, +22
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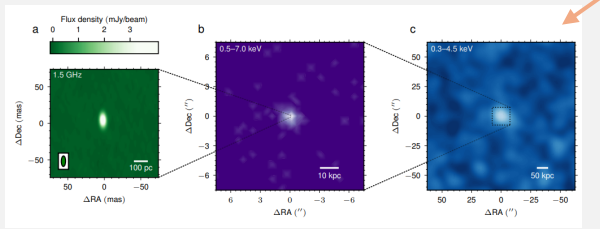
Point in time when we find the majority of X-ray blazars jets tracing the most massive black holes in the universe

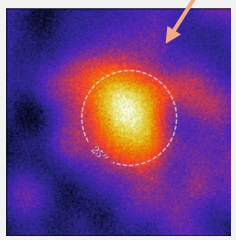


Roster+26



Banados+24, VLASS J041009.05-013919.88 at z = 7





z=6.19
CFHQS J142952+544717
NuSTAR image
[Marcotulli+25]

"Cosmic Noon"

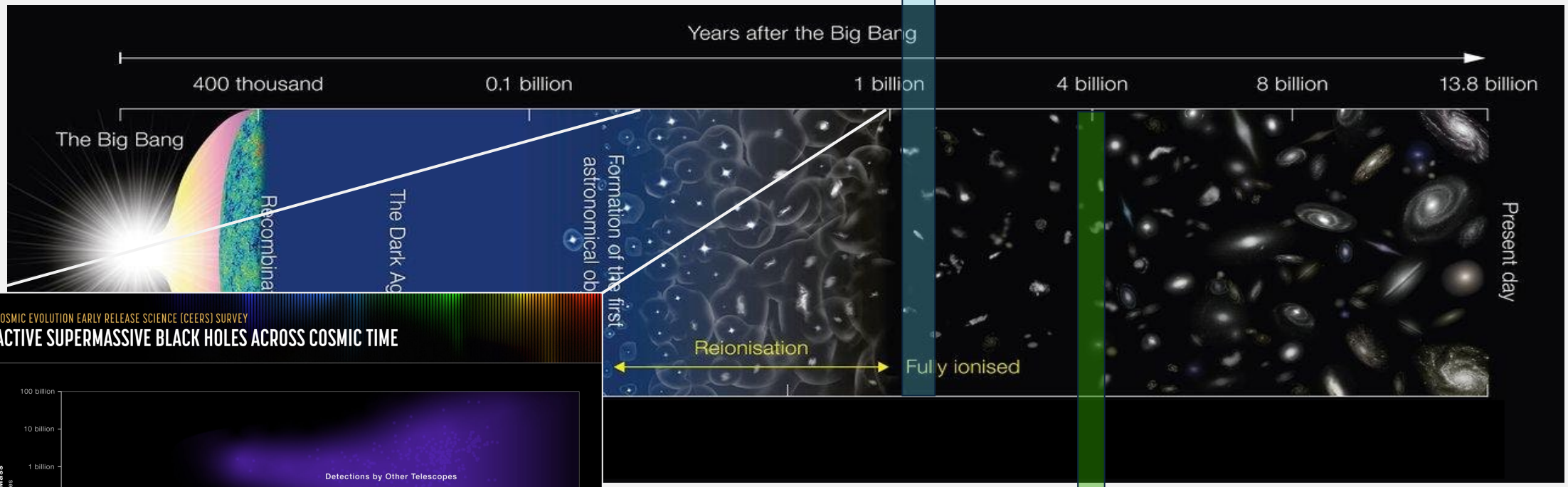
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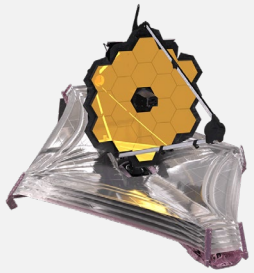
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Point in time when we find the majority of X-ray blazars jets tracing the most massive black holes in the universe





"Cosmic Noon"

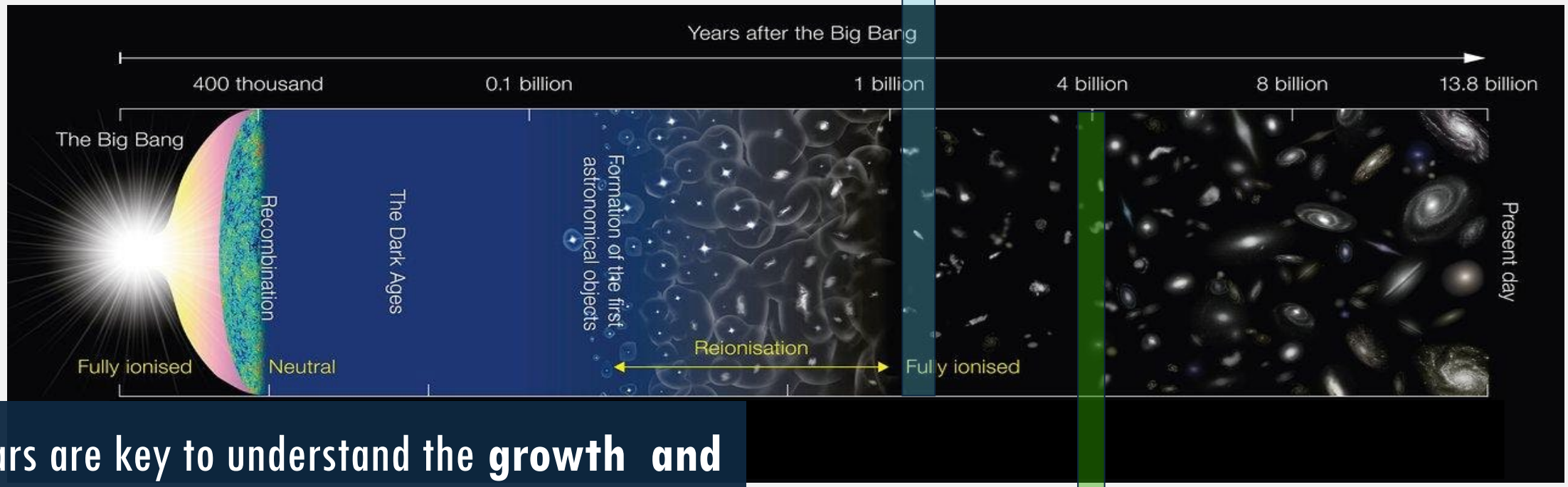
Point in time when we find the majority of stars, galaxies, AGN & γ-ray blazar jets

Timeline of the universe

Marcotulli+20, +22
see also, Sbarrato+15,+22,+26; Cao+17; Caccianiga+19; Ighina+19; An & Romani 20; Belladitta+22; Hammerich+25; and many more

"Cosmic Brunch"

Point in time when we find the majority of X-ray blazars jets tracing the most massive black holes in the universe



Blazars are key to understand the **growth and evolution of supermassive black holes through cosmic times**

"Cosmic Noon"

Point in time when we find the majority of stars, galaxies, AGN & γ-ray blazar jets

Beaming Effects and the Blazar Parent Population

Lea Marcotulli | lea.marcotulli@desy.de

Jet Distribution

Urry & Shafer (1984)

Jet Distribution

Few important relations

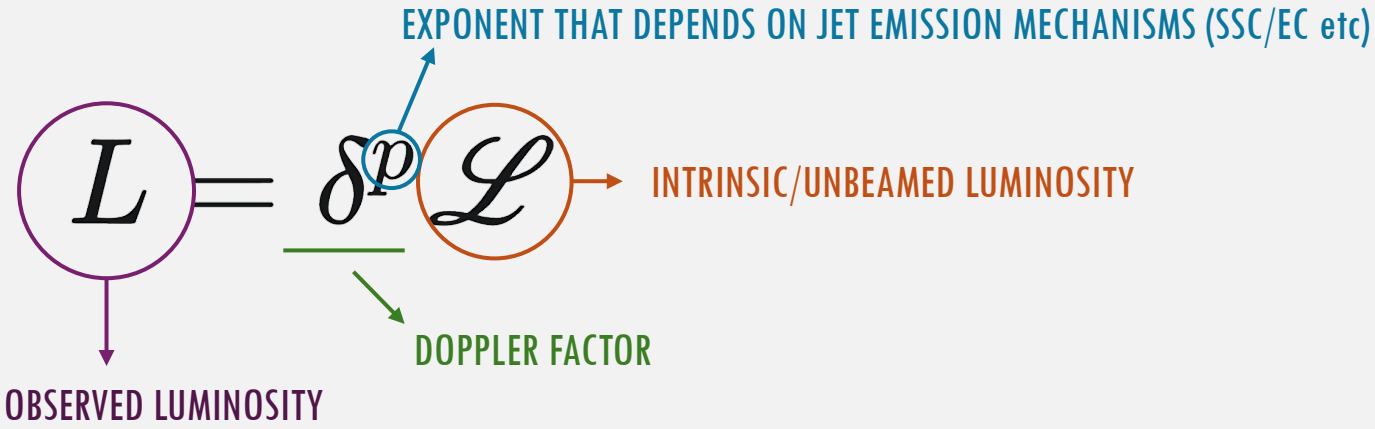
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$$L = \delta^p \mathscr{L}$$

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Few important relations

$$L = \delta^p \mathscr{L}$$

Assume a power law for simplicity

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

INTRINSIC LUMINOSITY FUNCTION
OF UNBEAMED JETS

Jet Distribution

Few important relations

Urry & Shafer (1984)

$$L = \delta^p \mathscr{L}$$

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

ASSUME JETS VIEWING ANGLES ARE RANDOMLY ORIENTED IN THE SKY

$$P(\theta) \propto \sin\theta_V$$

Urry & Shafer (1984)

Jet Distribution

Few important relations

$$L = \delta^p \mathscr{L}$$

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

$$P(\theta) \propto \sin\theta_V$$

ASSUME JETS HAVE THE SAME Γ

$$\boxed{P(\Gamma) \propto \delta(\Gamma - \Gamma_0)}$$

Jet Distribution

Few important relations

Urry & Shafer (1984)

$$L = \delta^p \mathscr{L}$$

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

$$P(\theta) \propto \sin\theta_V$$

$$P(\Gamma) \propto \delta(\Gamma - \Gamma_0)$$

$$\boxed{P(\delta)}$$

PROBABILITY DISTRIBUTION OF DOPPLER FACTORS

Urry & Shafer (1984)

Jet Distribution

Few important relations

$$L = \delta^{p} \mathscr{L}$$

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

$$P(\theta) \propto \sin\theta_V$$

$$P(\Gamma) \propto \delta(\Gamma - \Gamma_0)$$

$$P(\delta)$$

$$P(L|\delta) \propto L^{-(p+1)/p}$$

PROBABILITY DISTRIBUTION OF OBSERVING A CERTAIN LUMINOSITY GIVEN A DOPPLER FACTOR

Urry & Shafer (1984)

Jet Distribution

Few important relations

$$L = \delta^{p} \mathscr{L}$$

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

$$P(\theta) \propto \sin\theta_V$$

$$P(\Gamma) \propto \delta(\Gamma - \Gamma_0)$$

$$\downarrow$$

$$P(\delta)$$

$$P(L|\delta) \propto L^{-(p+1)/p}$$

$$\boxed{\phi(L)}$$

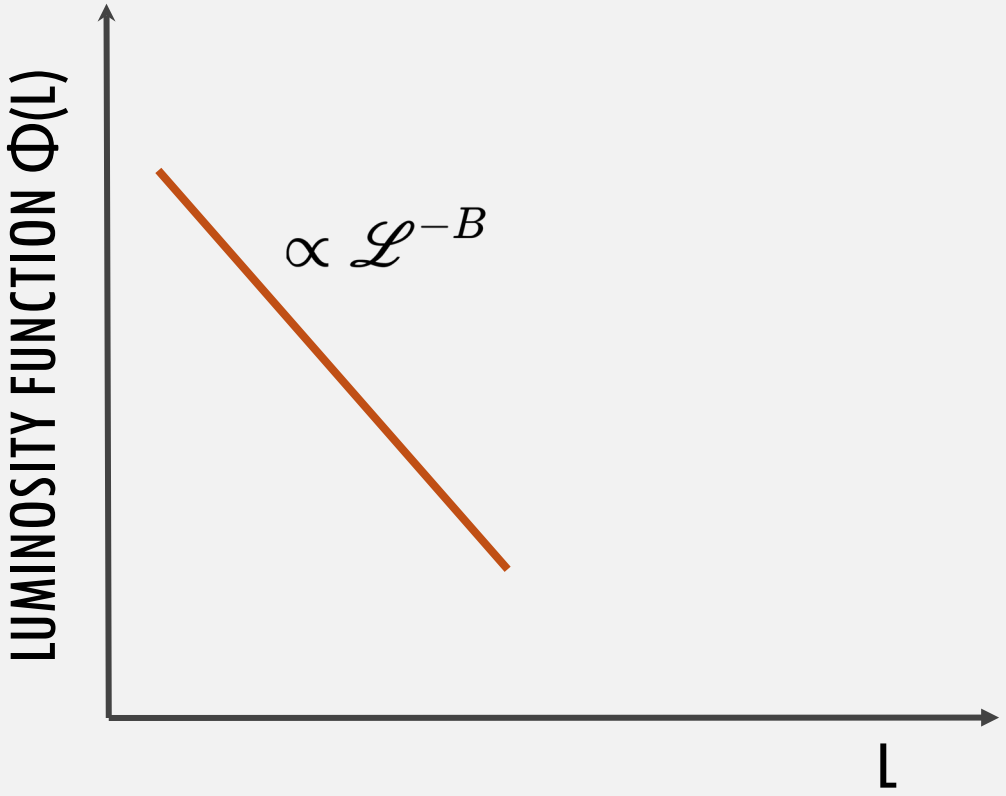
OBSERVED BEAMED JETS LUMINOSITY FUNCTION

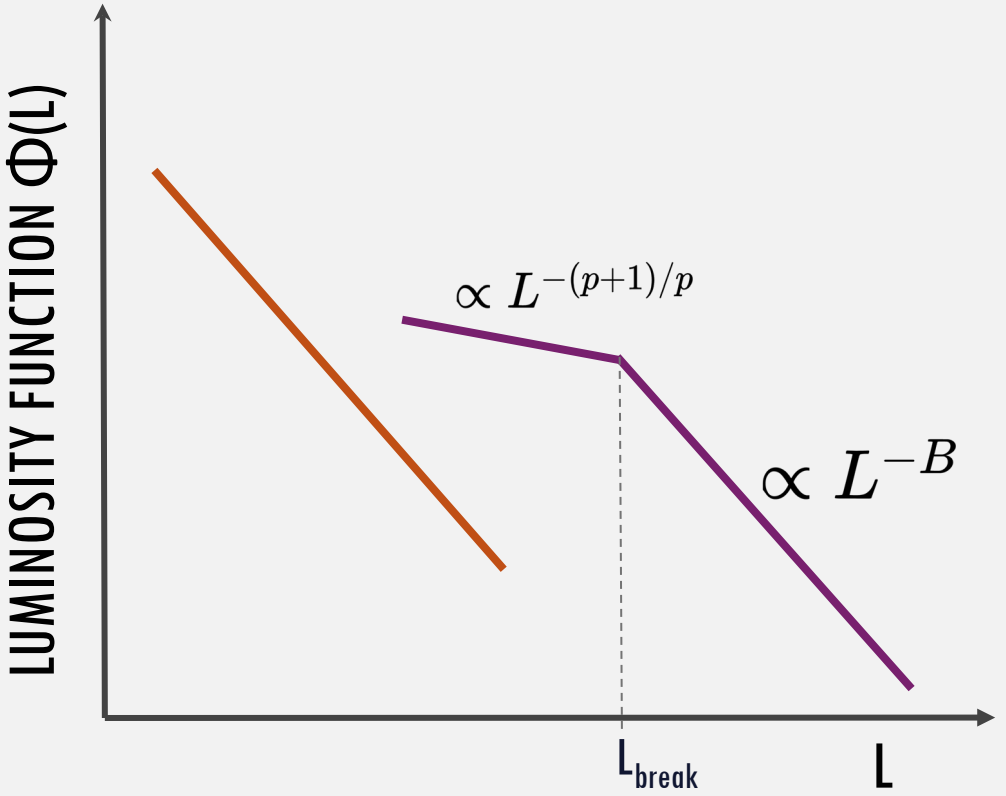
Jet Distribution

Urry & Shafer (1984)

$$\phi(\mathscr{L}) = k_1 \mathscr{L}^{-B}$$

$$\phi(L) = \begin{cases} \propto L^{-(p+1)/p}, & L < L_{\text{break}} \\ \propto L^{-B}, & L > L_{\text{break}} \end{cases}$$



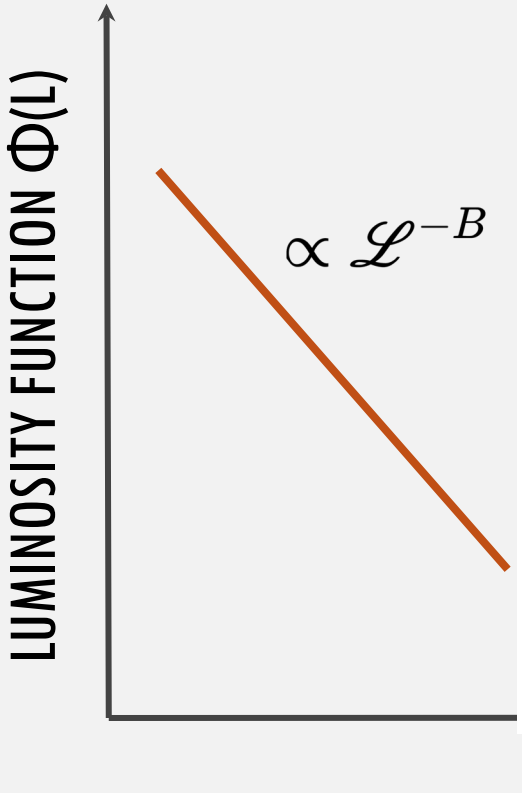


Jet Distribution

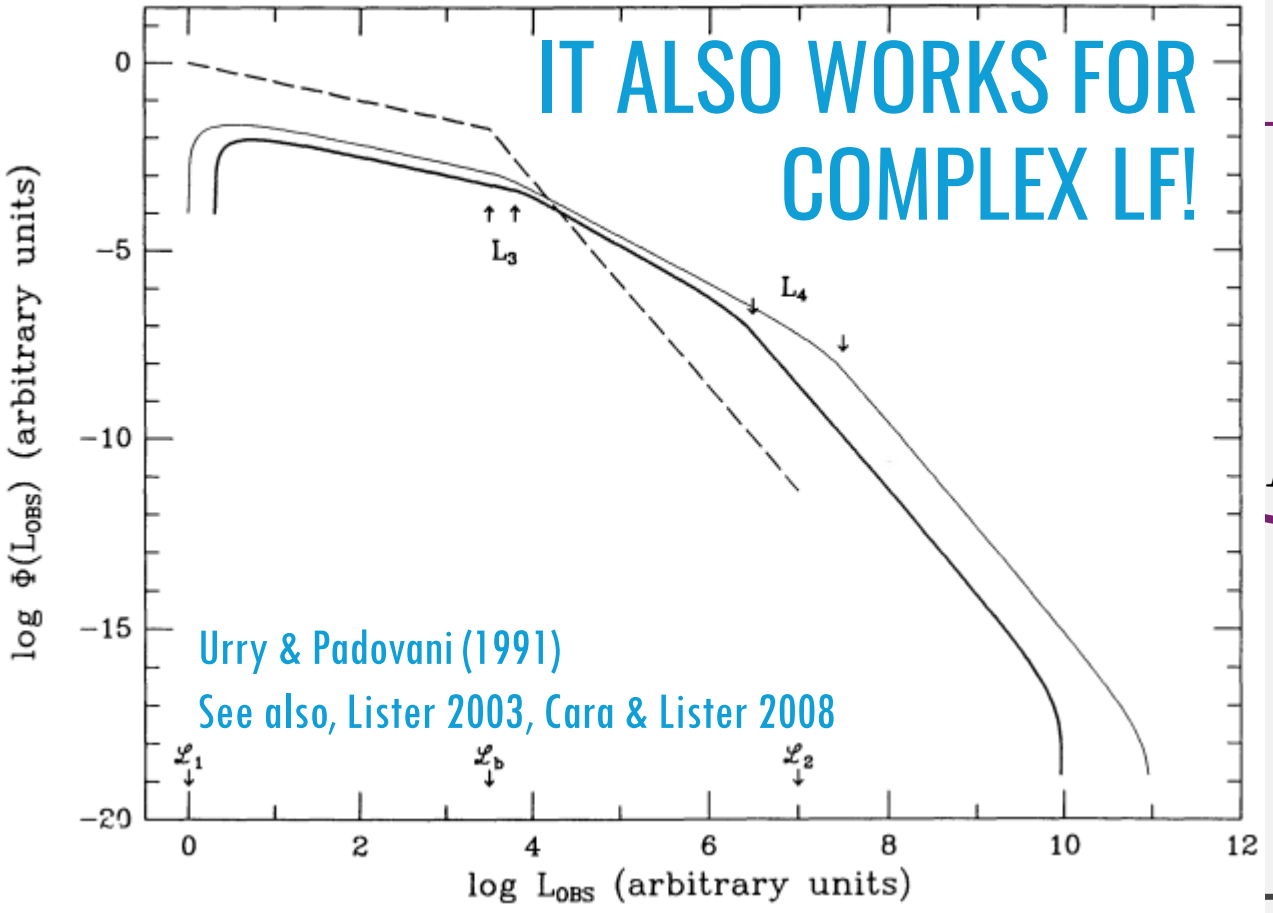
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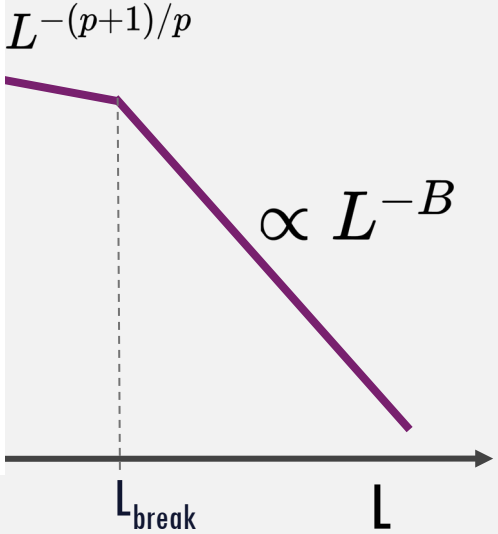


IT ALSO WORKS FOR COMPLEX LF!



Urry & Padovani (1991)

See also, Lister 2003, Cara & Lister 2008

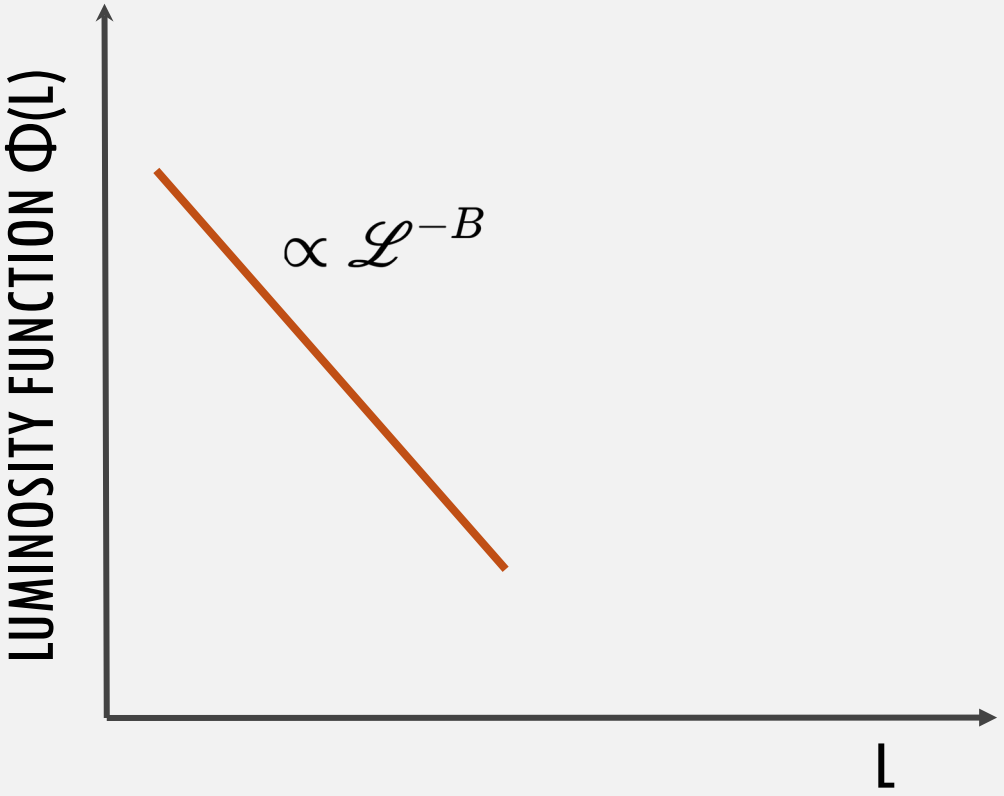


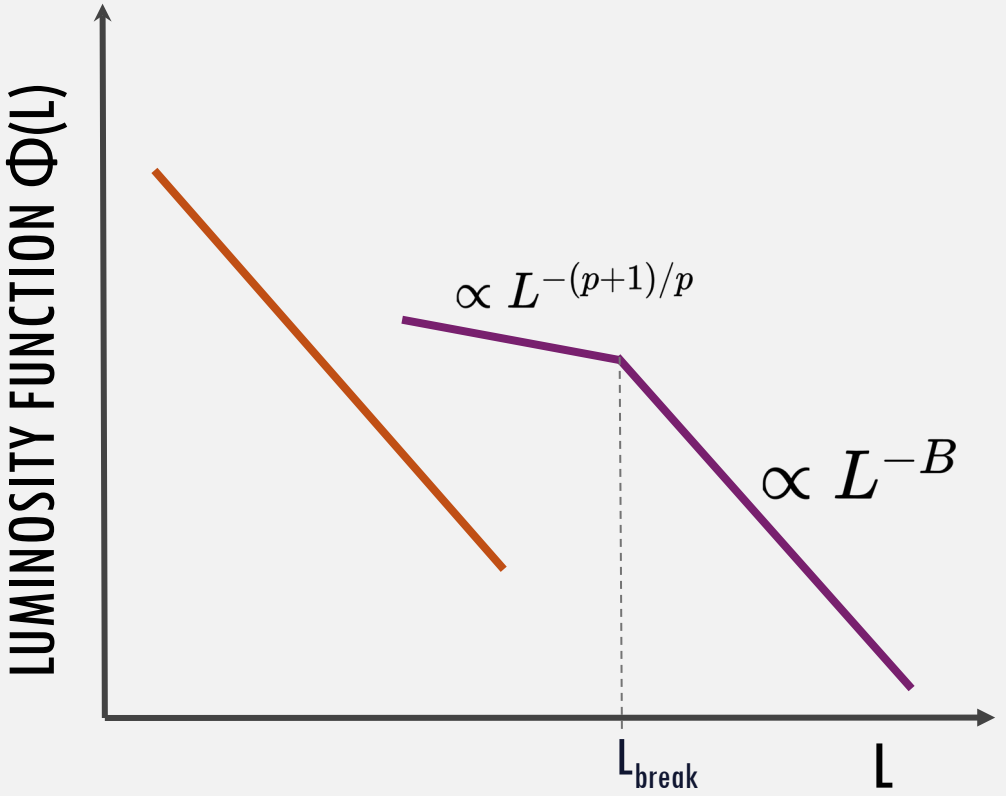
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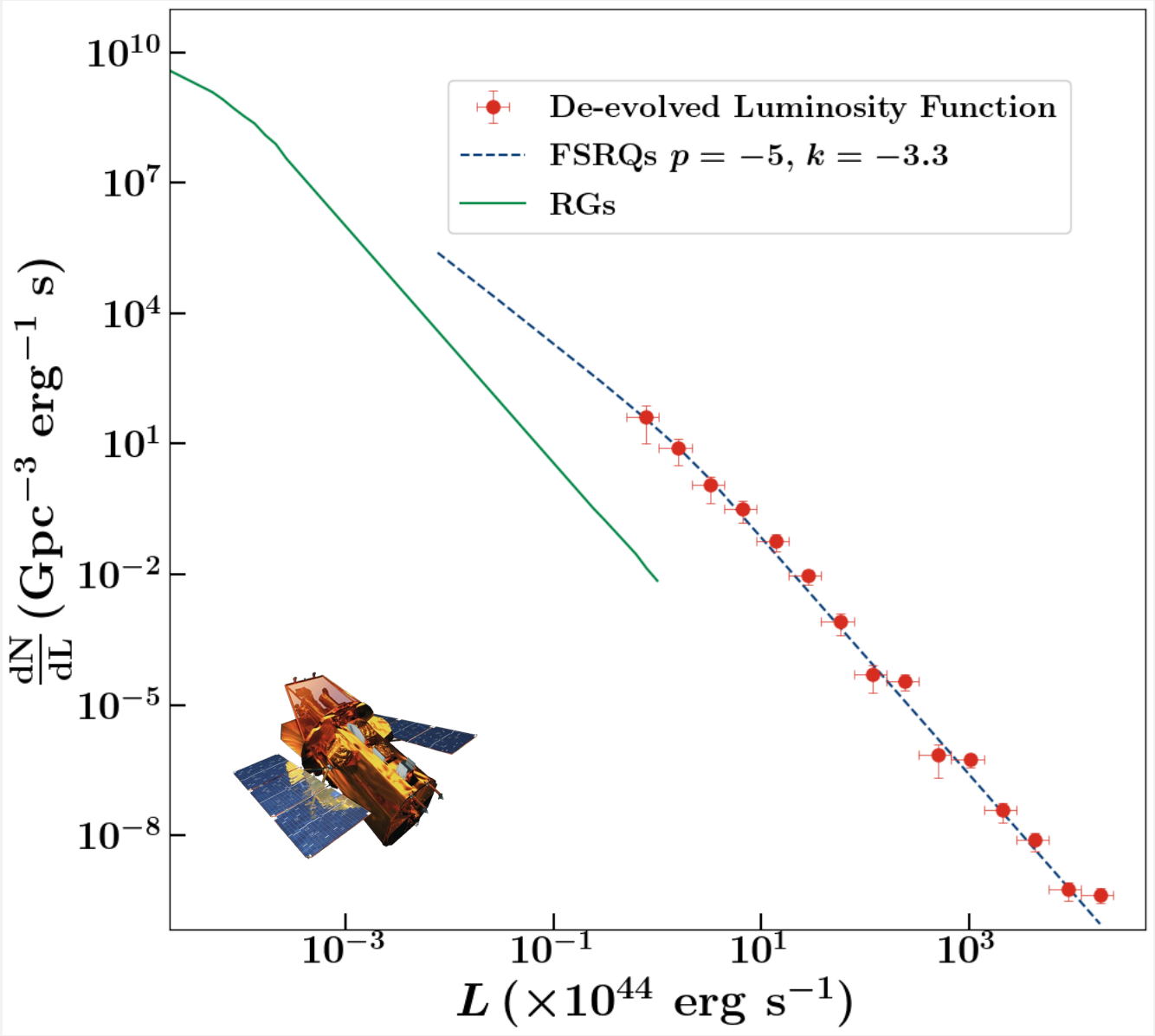
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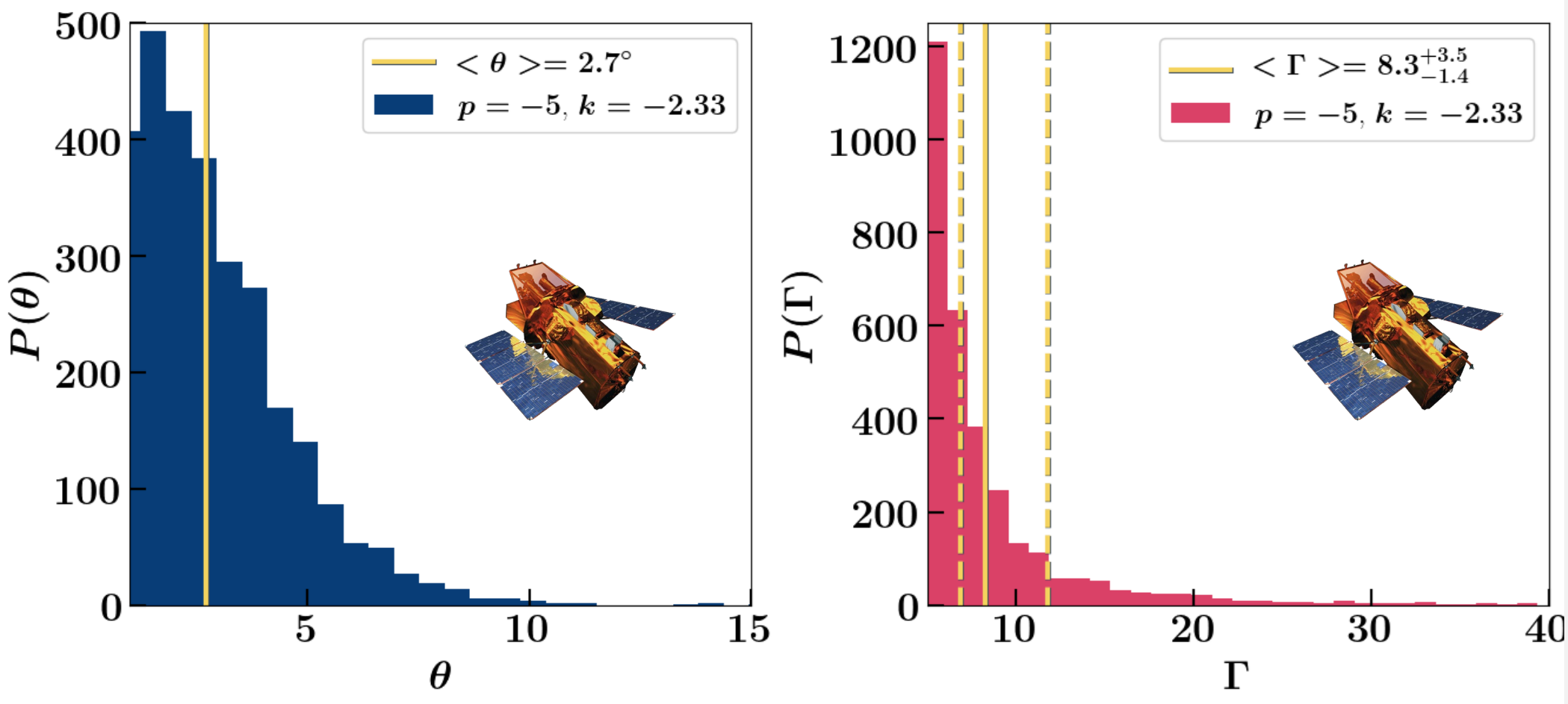
Beaming Fit



Marcotulli+22

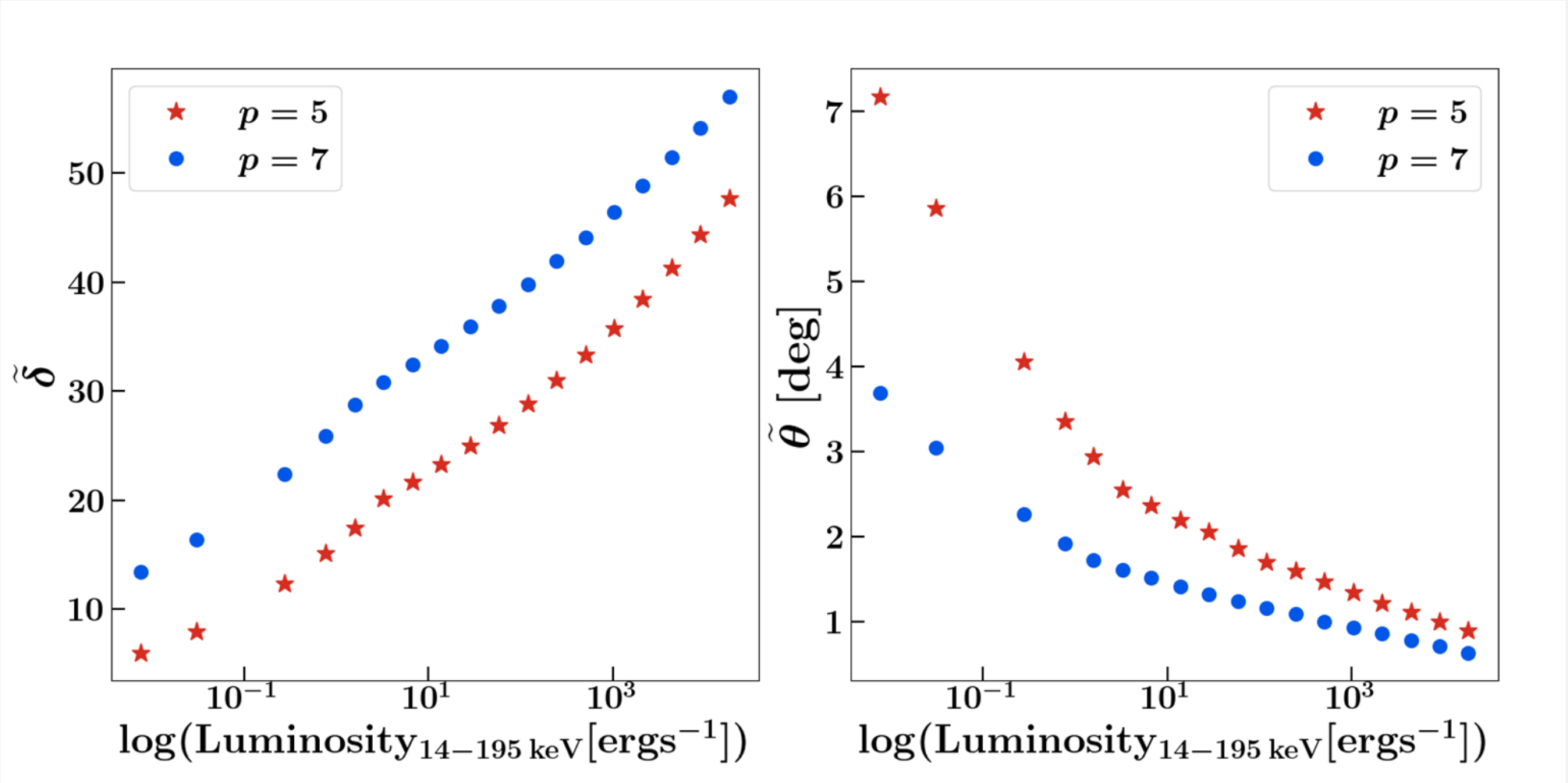
Jet Distribution

$2\Gamma^2$ correction!



Marcotulli+22

Strong Selection Effects



Marcotulli+22

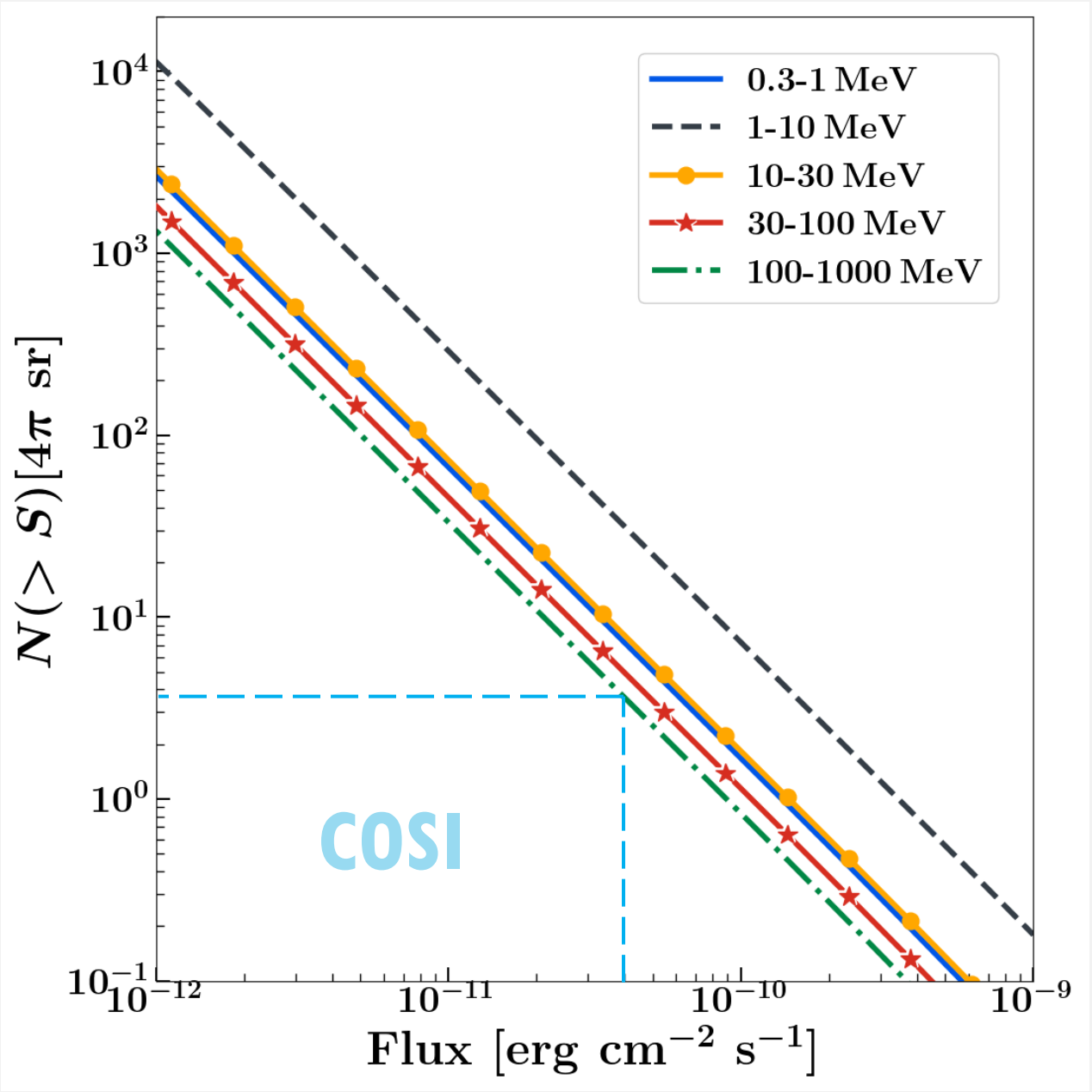
Future Prospects

Lea Marcotulli | lea.marcotulli@desy.de

Prediction for MeV missions

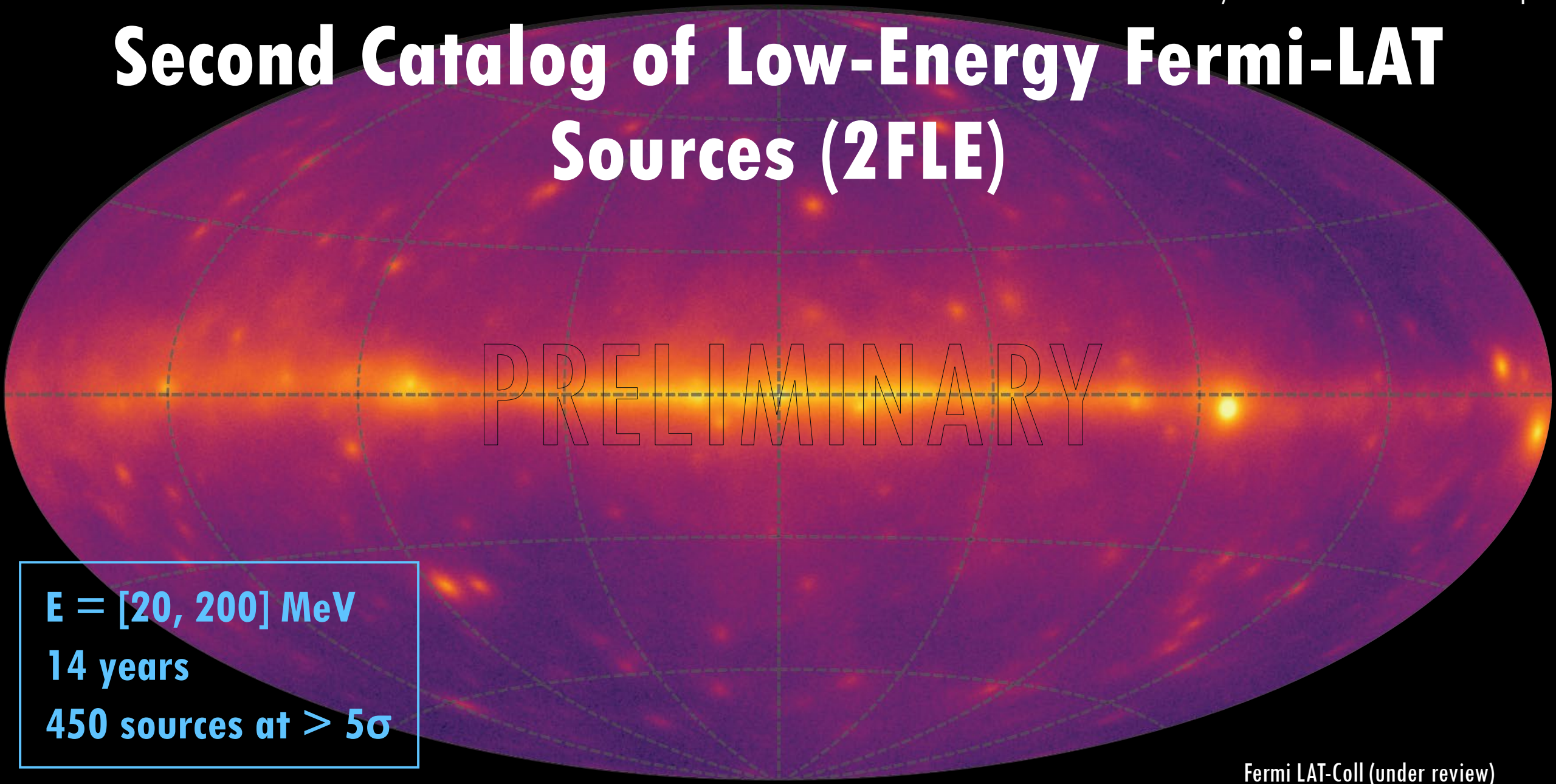
MISSION	Sensitivity	N(>S) [4π sr]	Timeline
Fermi - LAT	$>2\times10^{-12}$ erg cm^{-2} s^{-1} (20-200 MeV in 10 years)	~1000	Operational since 2008
COSI	$>4\times10^{-11}$ erg cm^{-2} s^{-1} (0.2-5 MeV in 2 years)	~40	Launch in 2027!!
AMEGO-X	$>1.6\times10^{-11}$ erg cm^{-2} s^{-1} (1-10 MeV in 3 year)	~130	Future NASA MIDEX calls
ASTROGAM	$>5\times10^{-12}$ erg cm^{-2} s^{-1} (1-10 MeV in 1 year)	~832	Future ESA mission calls

Marcotulli+22



All-sky 20-200 MeV Fermi-LAT counts map

Second Catalog of Low-Energy Fermi-LAT Sources (2FLE)



E = [20, 200] MeV
14 years
450 sources at > 5σ

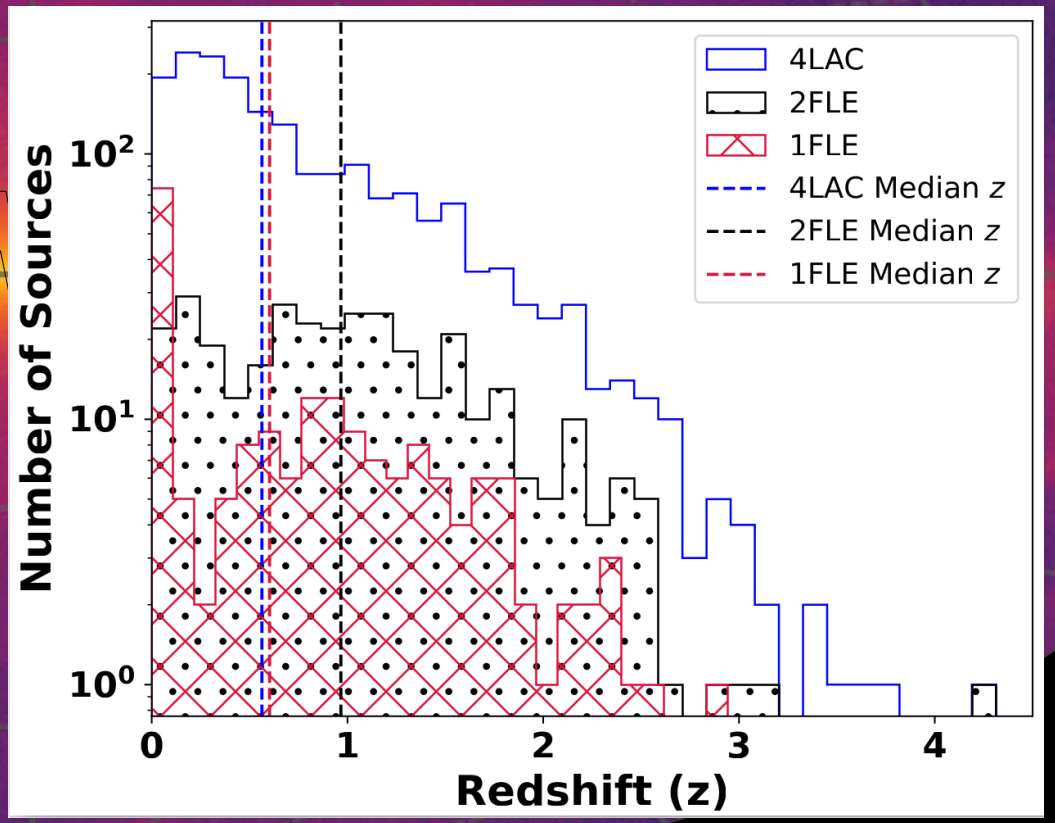
Fermi LAT-Coll (under review)

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All-sky 20-200 MeV Fermi-LAT counts map

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PRELIM

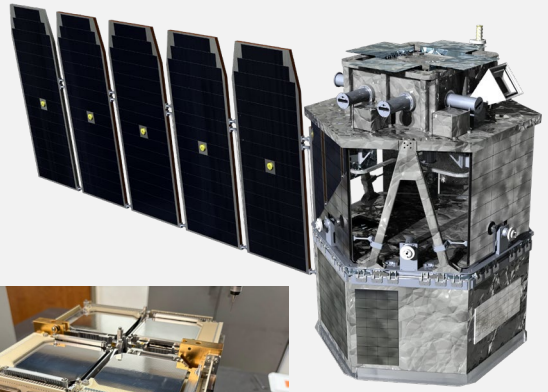


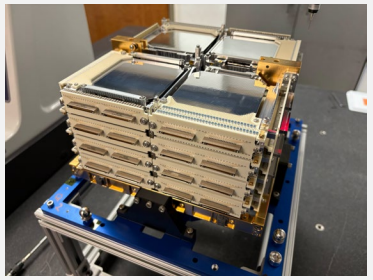
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New High-Energy missions on the Horizon





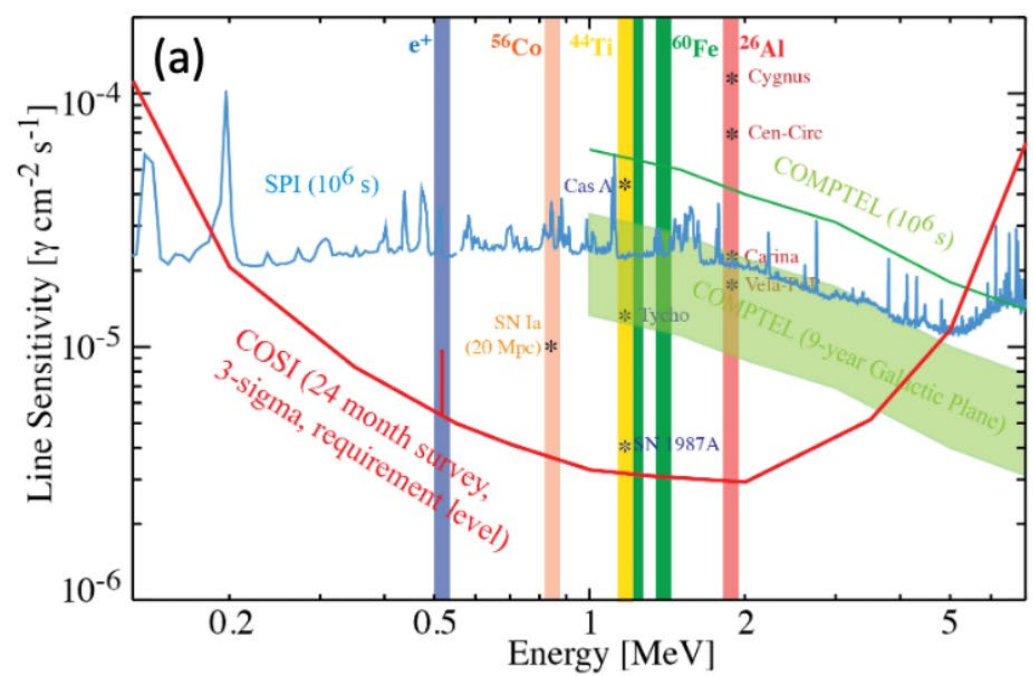
COSI detectors, credit: John Tomsick

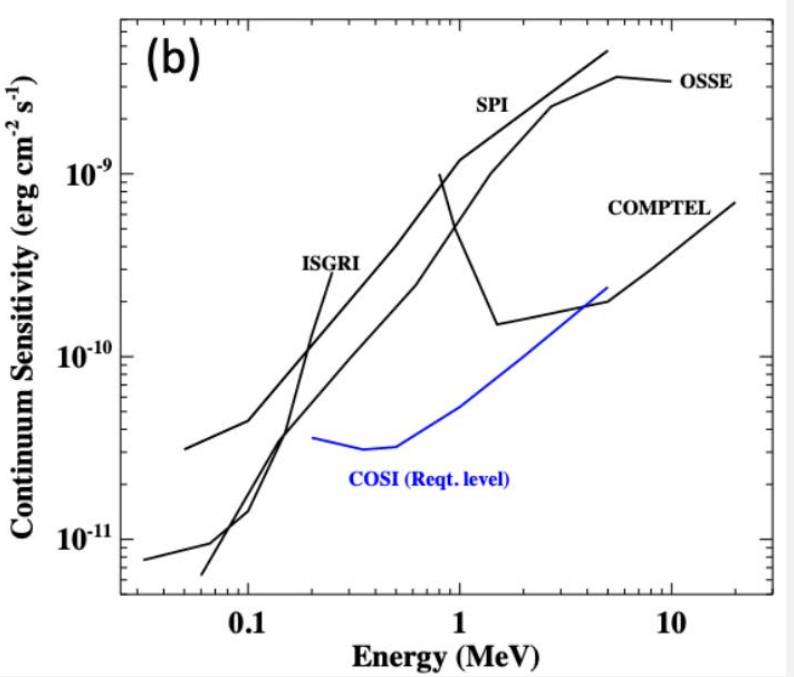
Compton Spectrometer and Imager **(COSI)**

E = 0.2 - 5 MeV

Launch 2027

Optimized to **detect MeV lines**, but has **continuum sensitivity and polarization** capabilities



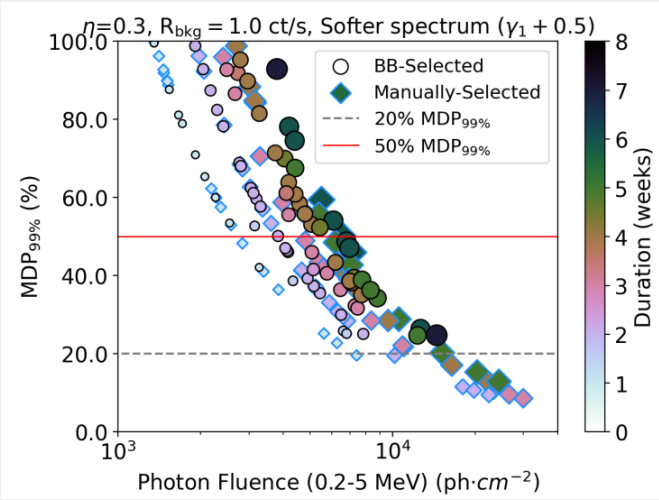


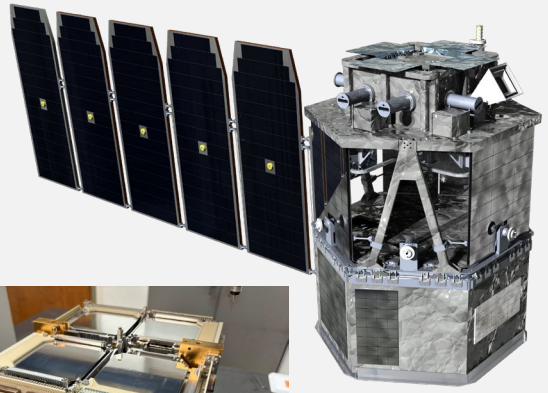
Tomsick+23

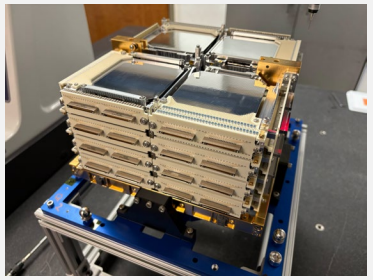
New High-Energy missions on the Horizon

Latiolais+26

Predictions for MPD in blazar flares







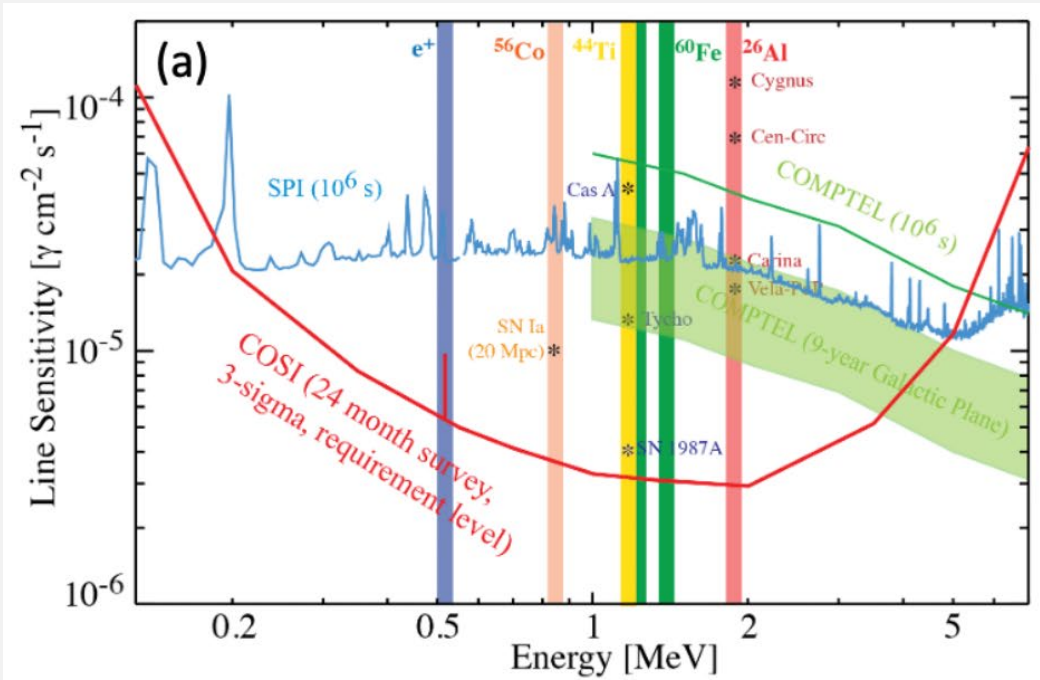
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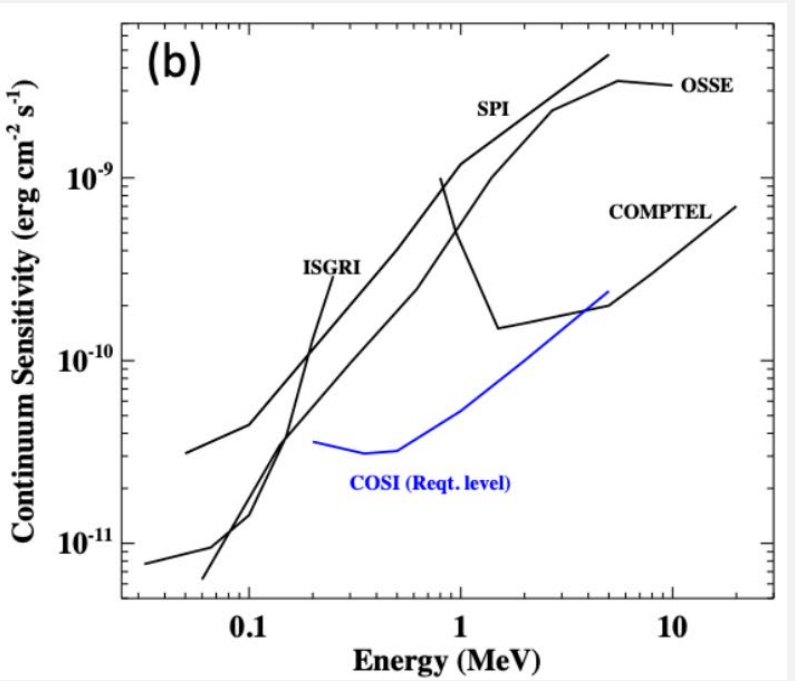
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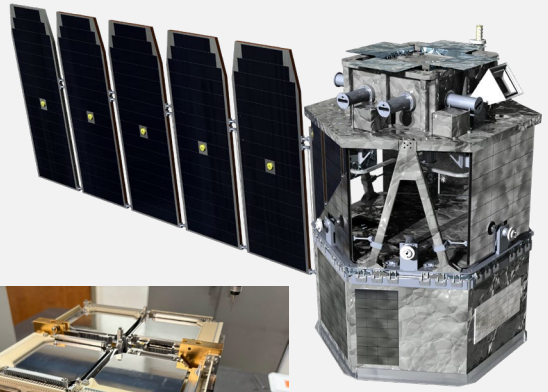


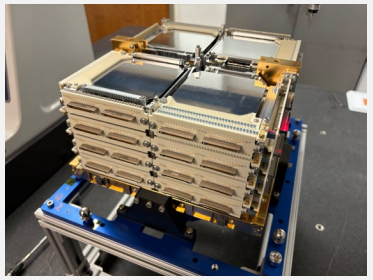
Tomsick+23

Parshad Patel - AGN Coronae with COSI



New High-Energy missions on the Horizon





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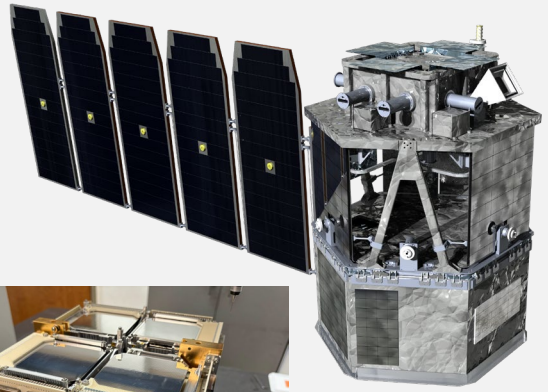
Cherenkov Telescope Array Observatory (CTAO)

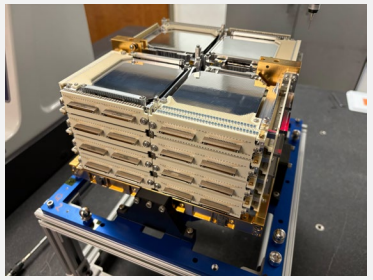
E = 30 GeV to 300 TeV

4 LSTs in northern site almost ready!



New High-Energy missions on the Horizon





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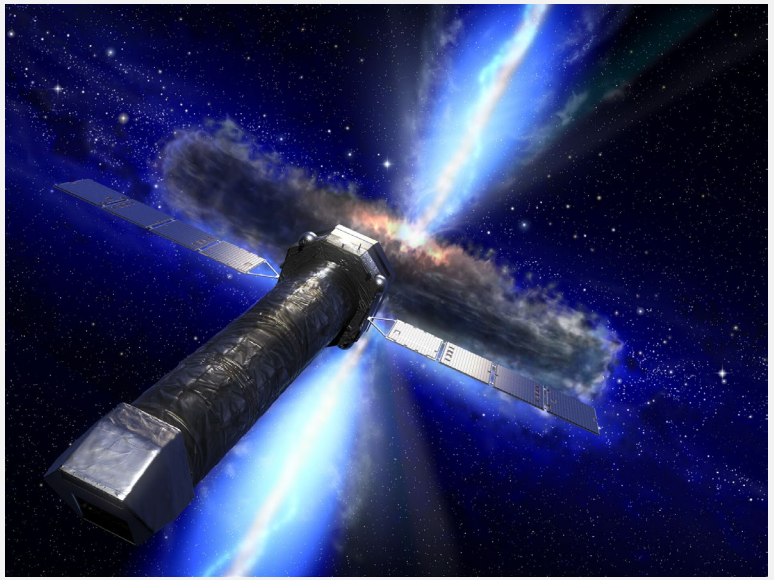


Cherenkov Telescope Array Observatory (CTAO)

E = 30 GeV to 300 TeV

4 LSTs in northern site almost ready!





NewAthena

E = 0.2-10 keV

Launch est. 2037

Take home points

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WHAT DRIVES THIS DIFFERENCES?

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- Blazar jets are key to **follow the supermassive black hole evolution** into the dawn of cosmic time
- Beaming effects allow us to trace back the **parent population of jetted AGN** and overall beaming properties
- High-energy missions (both **current and future**) will be necessary to continue the quests for these cosmic monsters

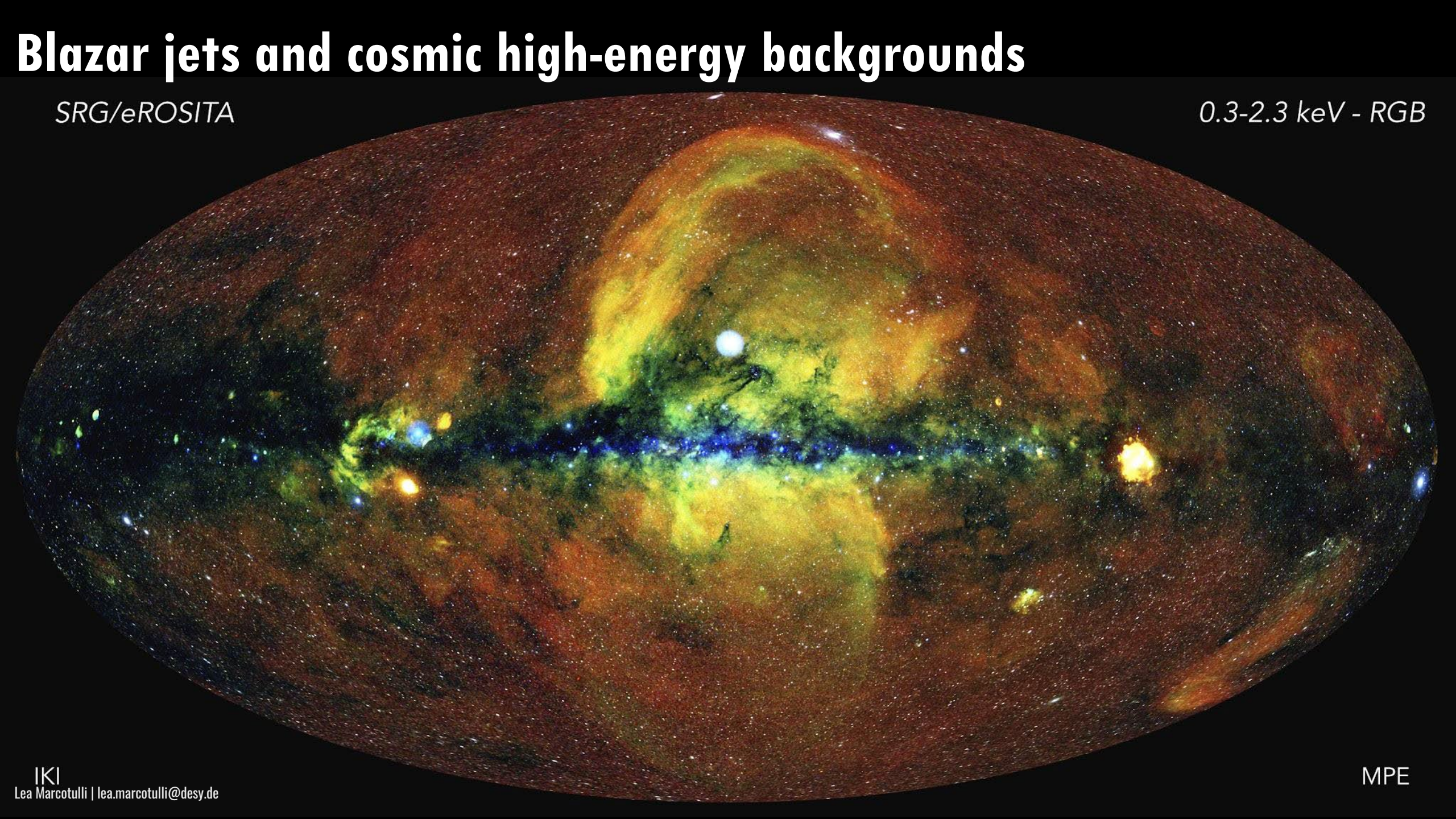
EXTRA SLIDES

Blazar jets and cosmic high-energy backgrounds

Integrated emission of all RESOLVED and UNRESOLVED sources + diffuse processes (DM annihilation?)

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Blazar jets and cosmic high-energy backgrounds

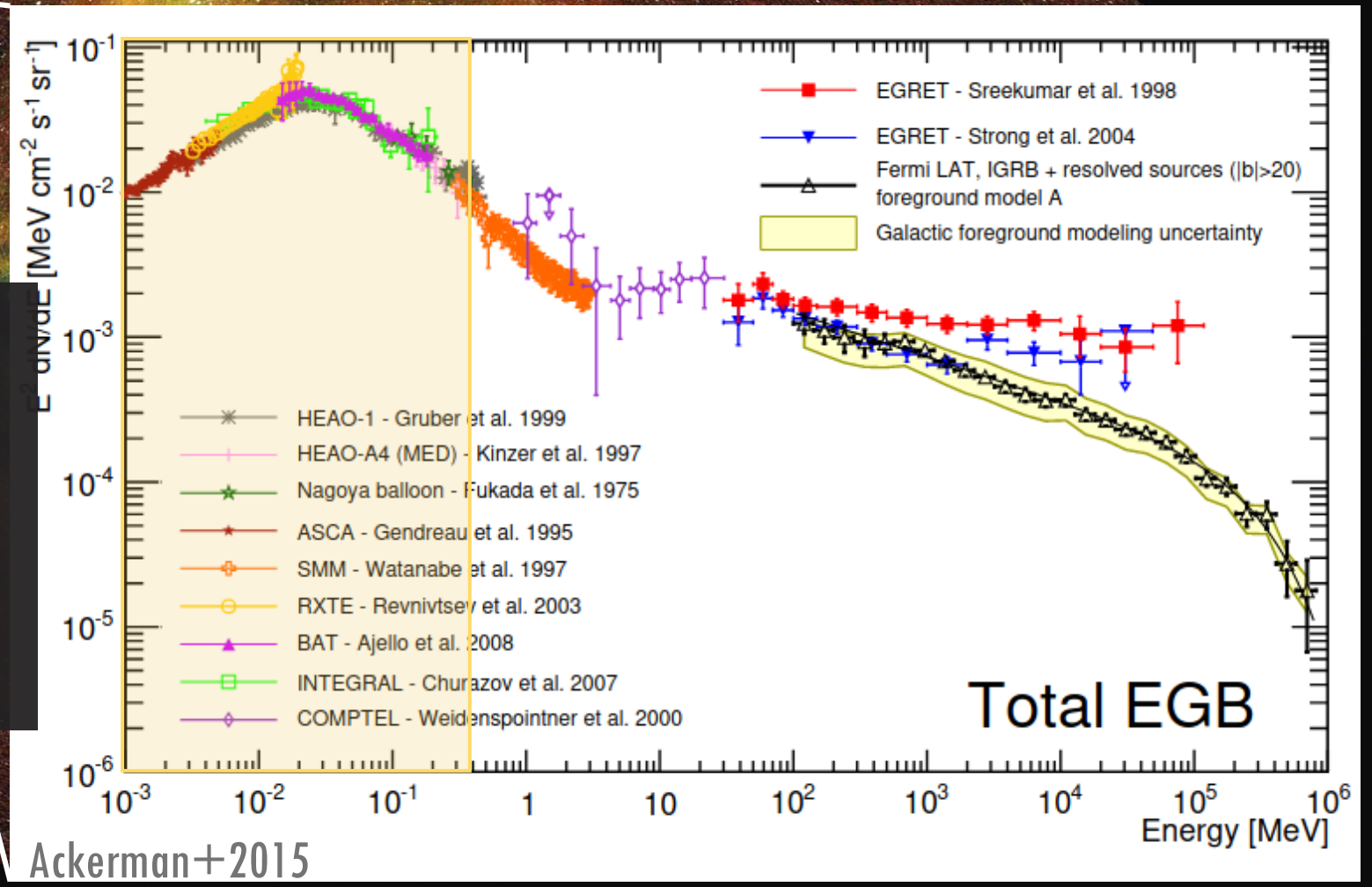


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Blazar jets and cosmic high-energy backgrounds

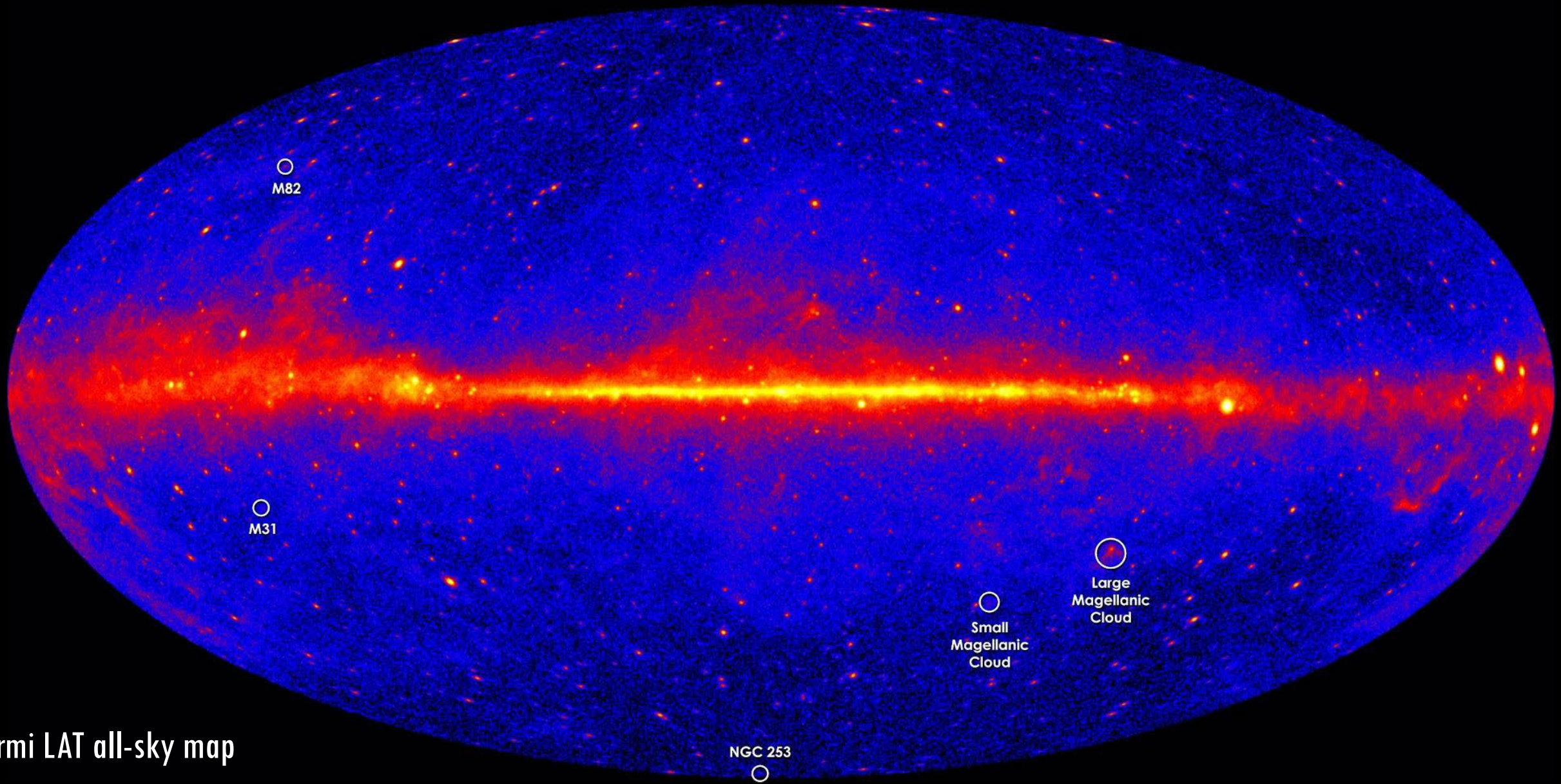
SRG/eROSITA *0.3-2.3 keV - RGB*

Blazars account for ~5-10 % of the CXB above 14 keV and could make up 100% of the MeV background



IKI
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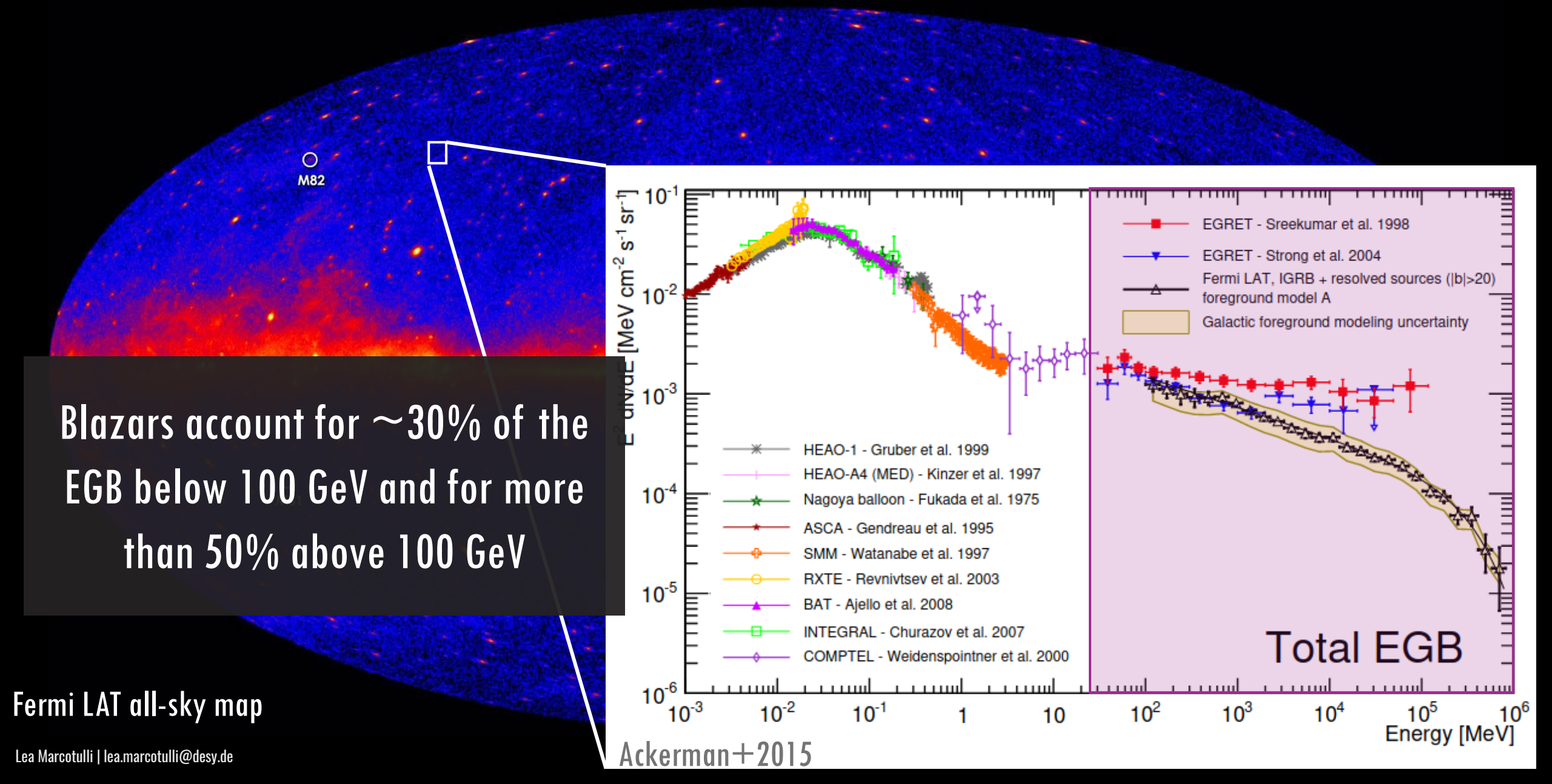
Blazar jets and cosmic high-energy backgrounds



Fermi LAT all-sky map

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Blazar jets and cosmic high-energy backgrounds



Blazars account for ~30% of the EGB below 100 GeV and for more than 50% above 100 GeV

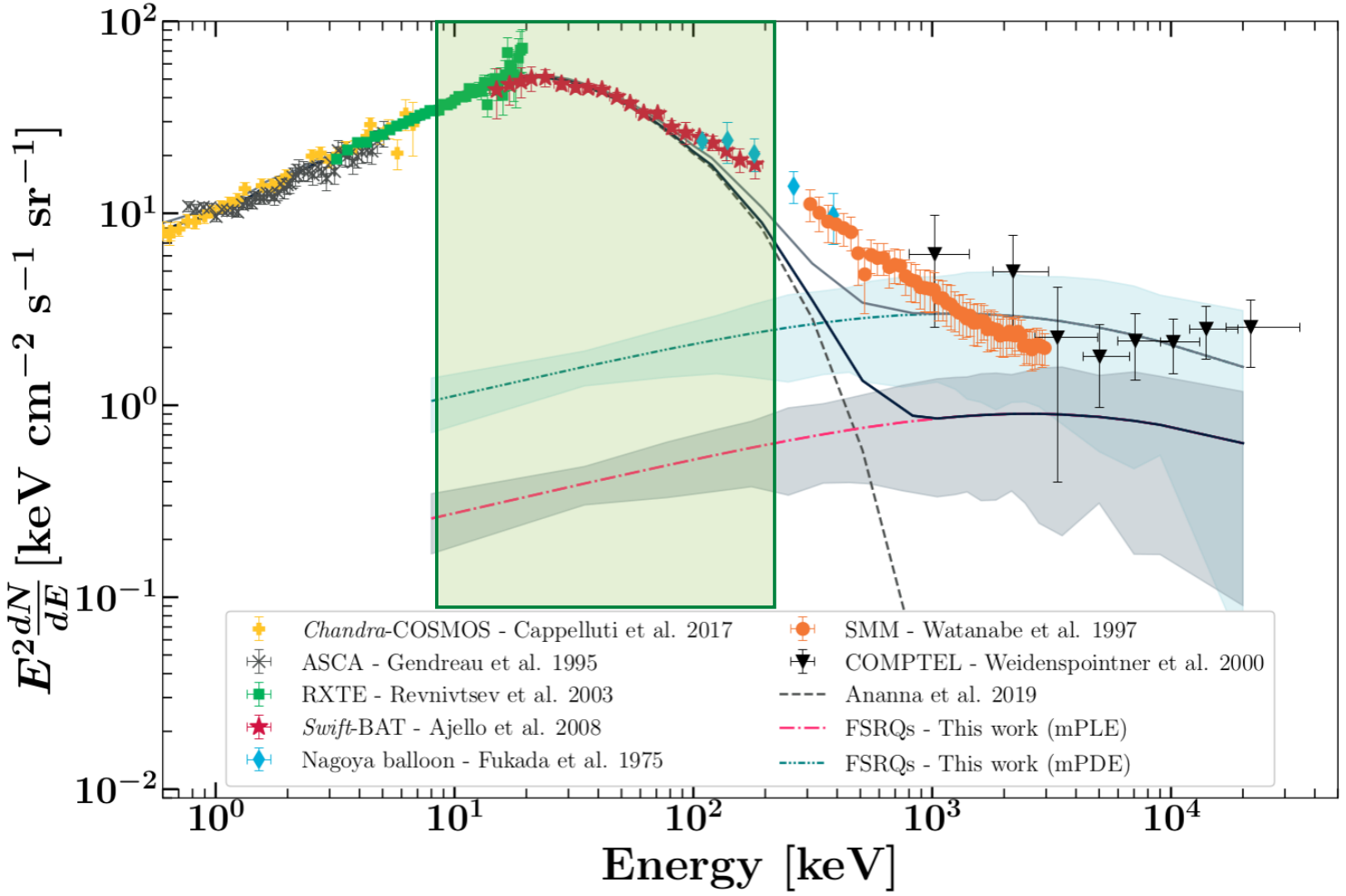
Fermi LAT all-sky map

Ackerman+2015

Lea Marcotulli | lea.marcotulli@desy.de

Contribution of blazar jets to the high-energy background

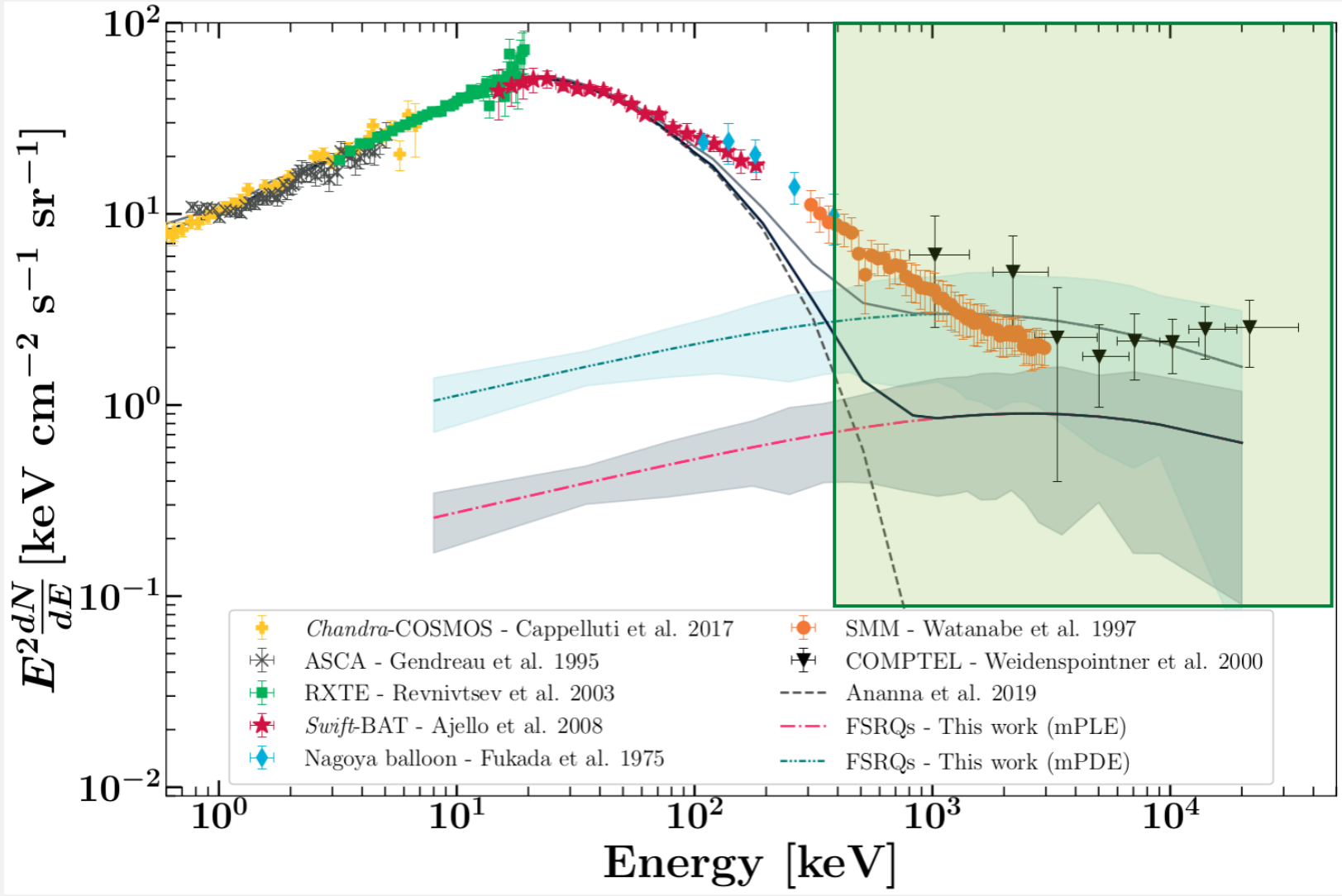
Between 2-9% of the cosmic X-ray background >10 keV



Ajello+09, Marcotulli+22

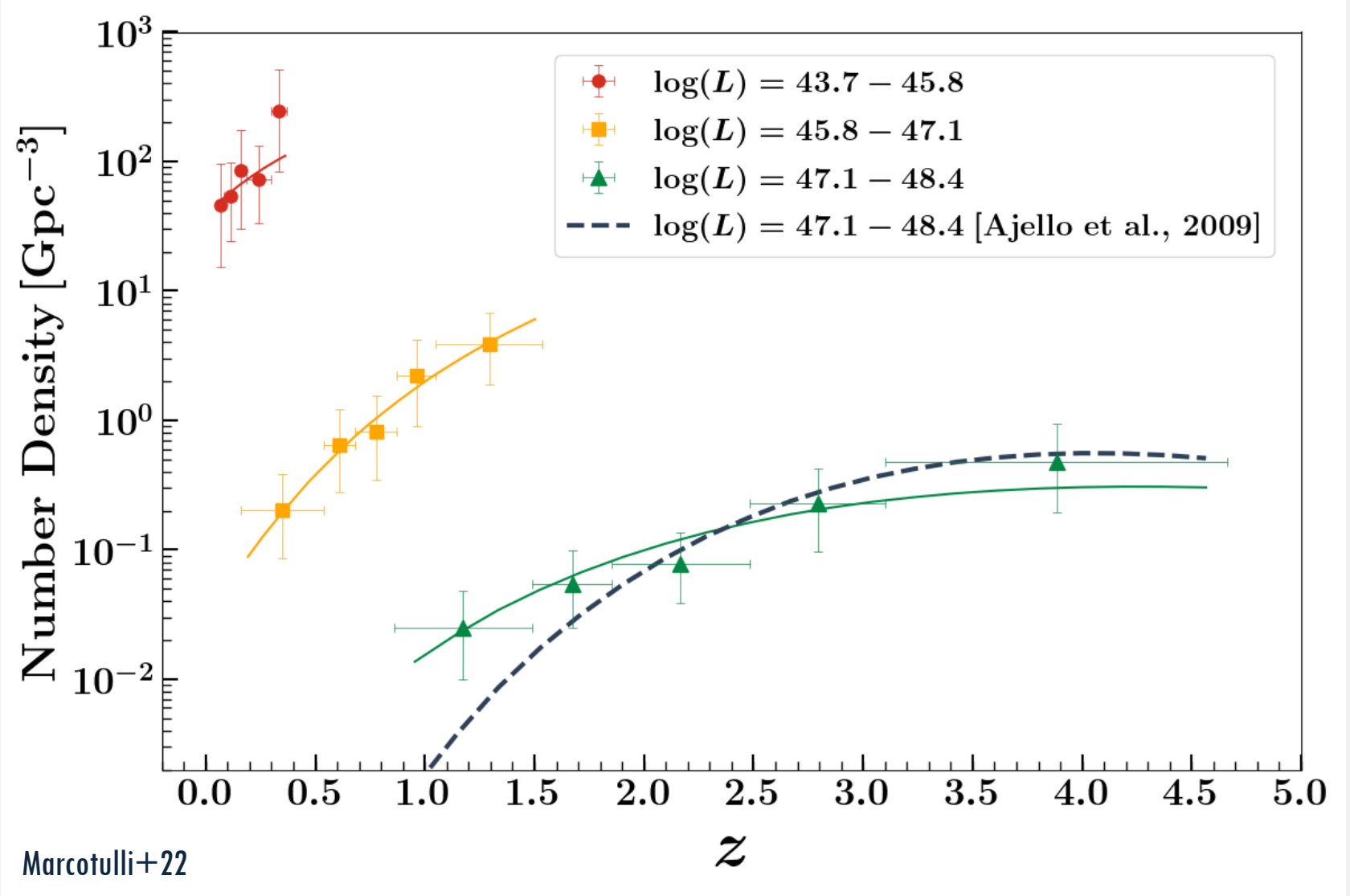
Contribution of blazar jets to the high-energy background

Between 70-100% of the cosmic MeV background!



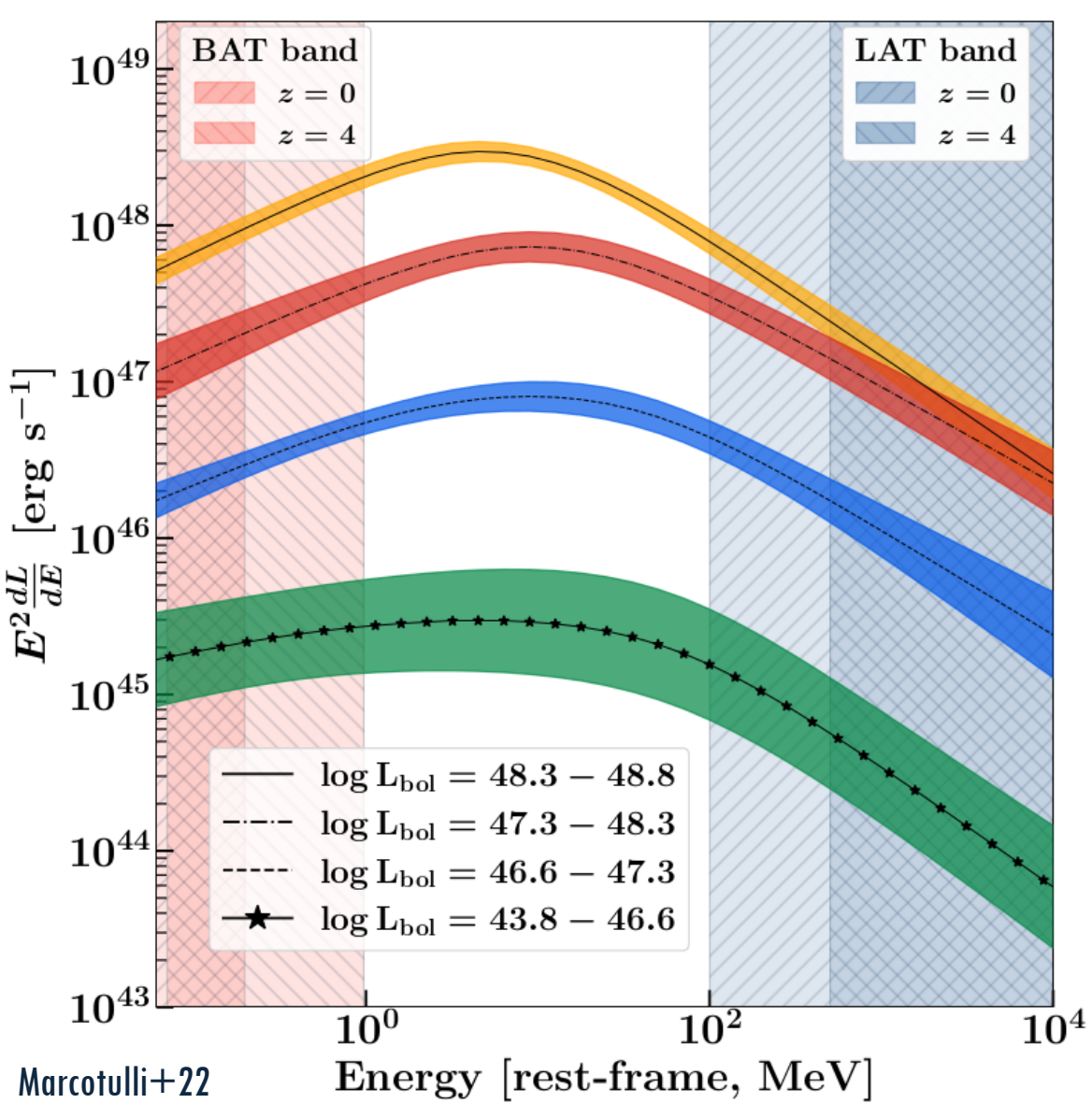
Ajello+09, Marcotulli+22

Number densities



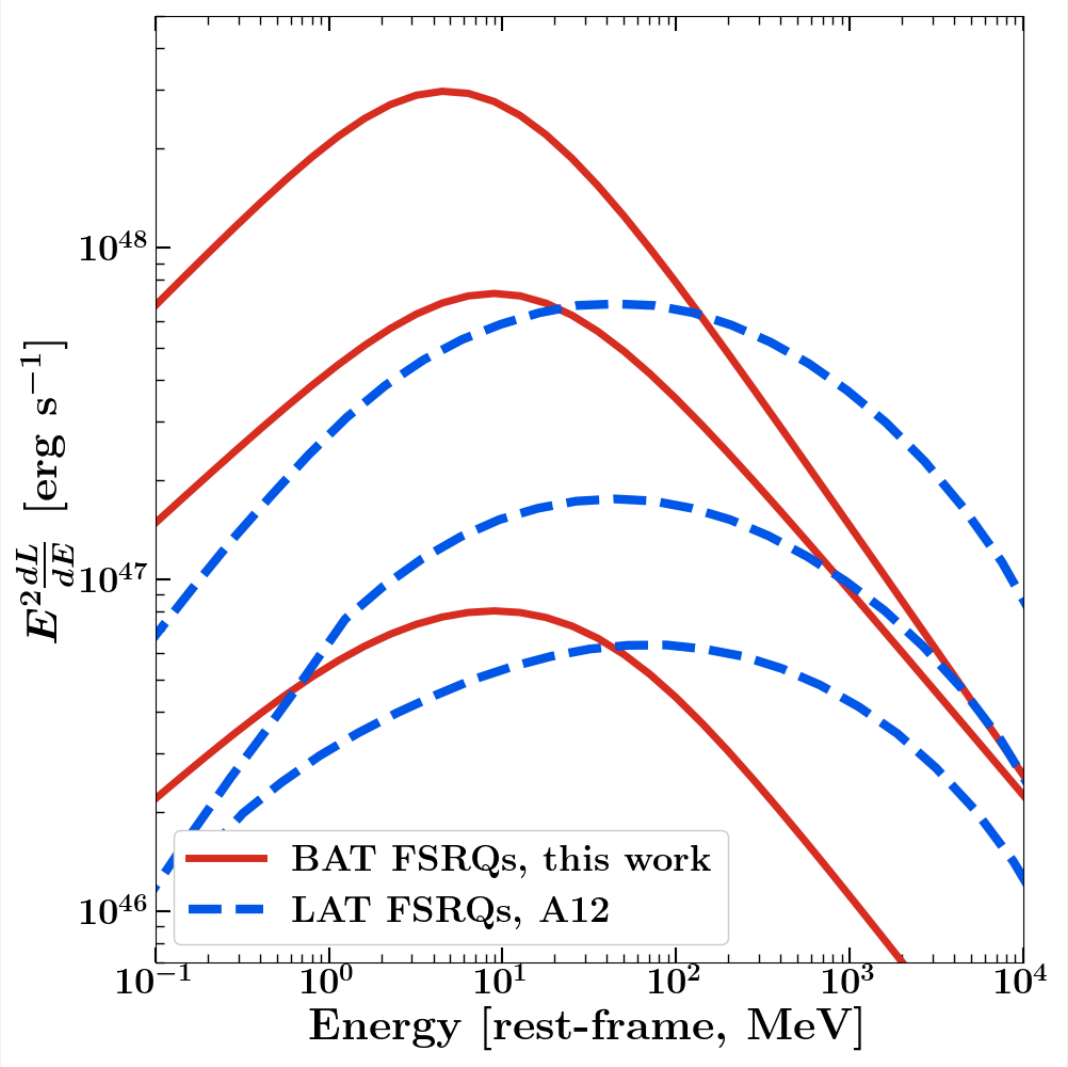
Marcotulli+22

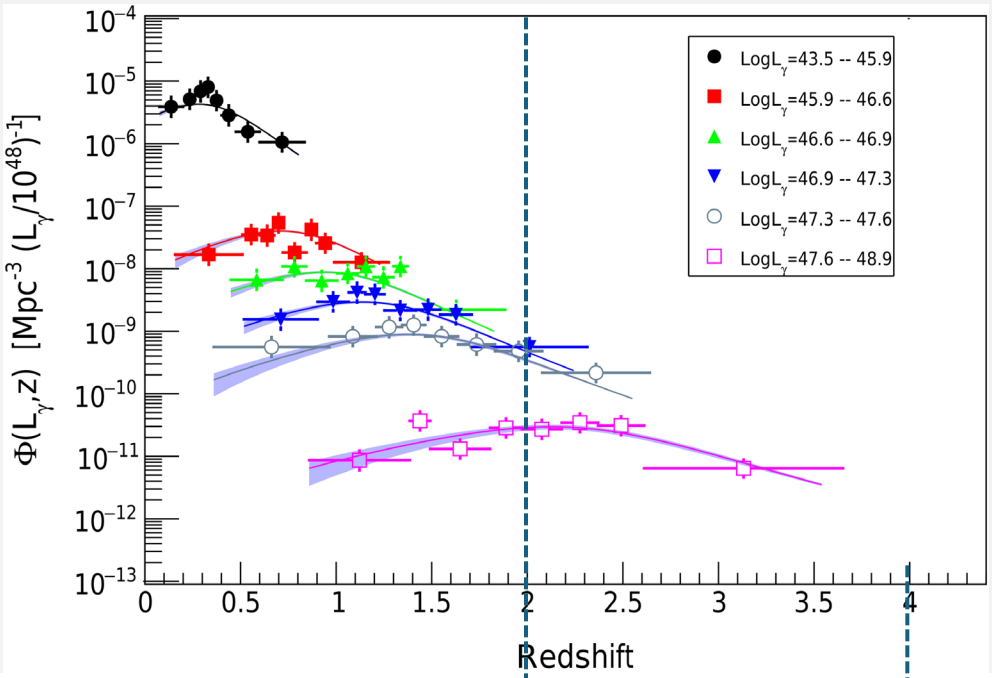
Average SED

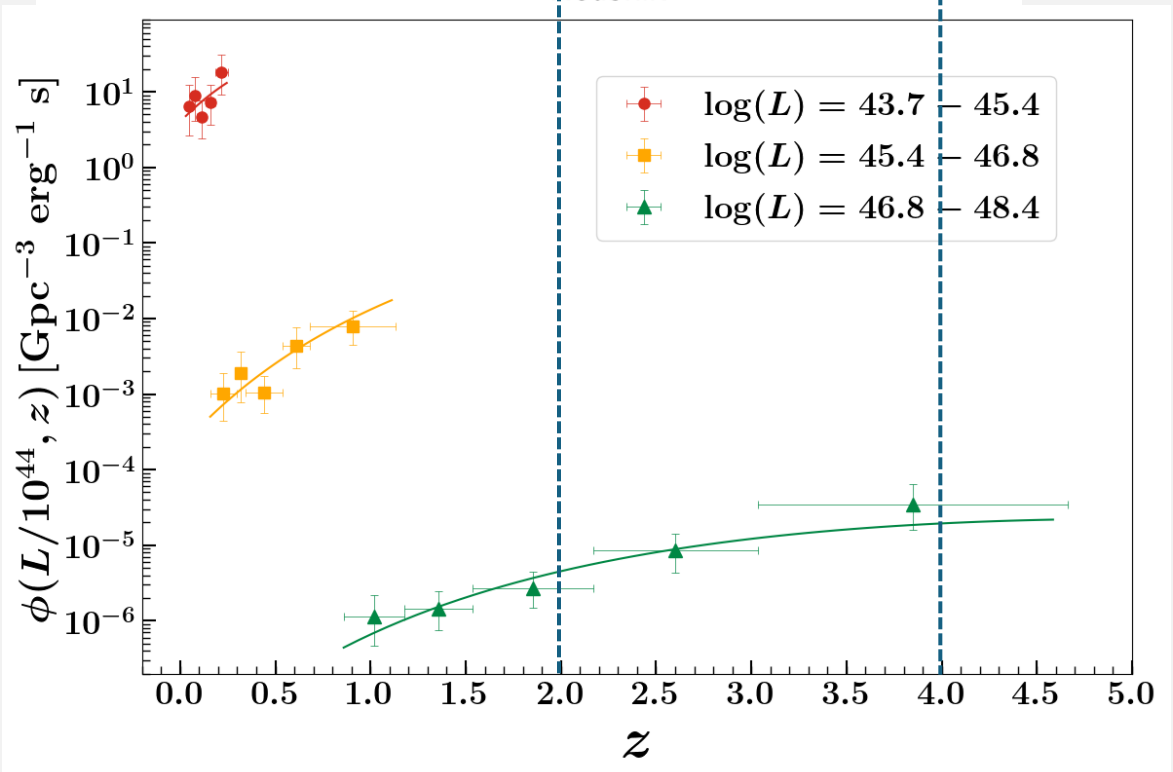


Marcotulli+22

Hard X-ray vs. γ-ray FSRQs







Ajello+12, Marcotulli+22, Rajguru+25