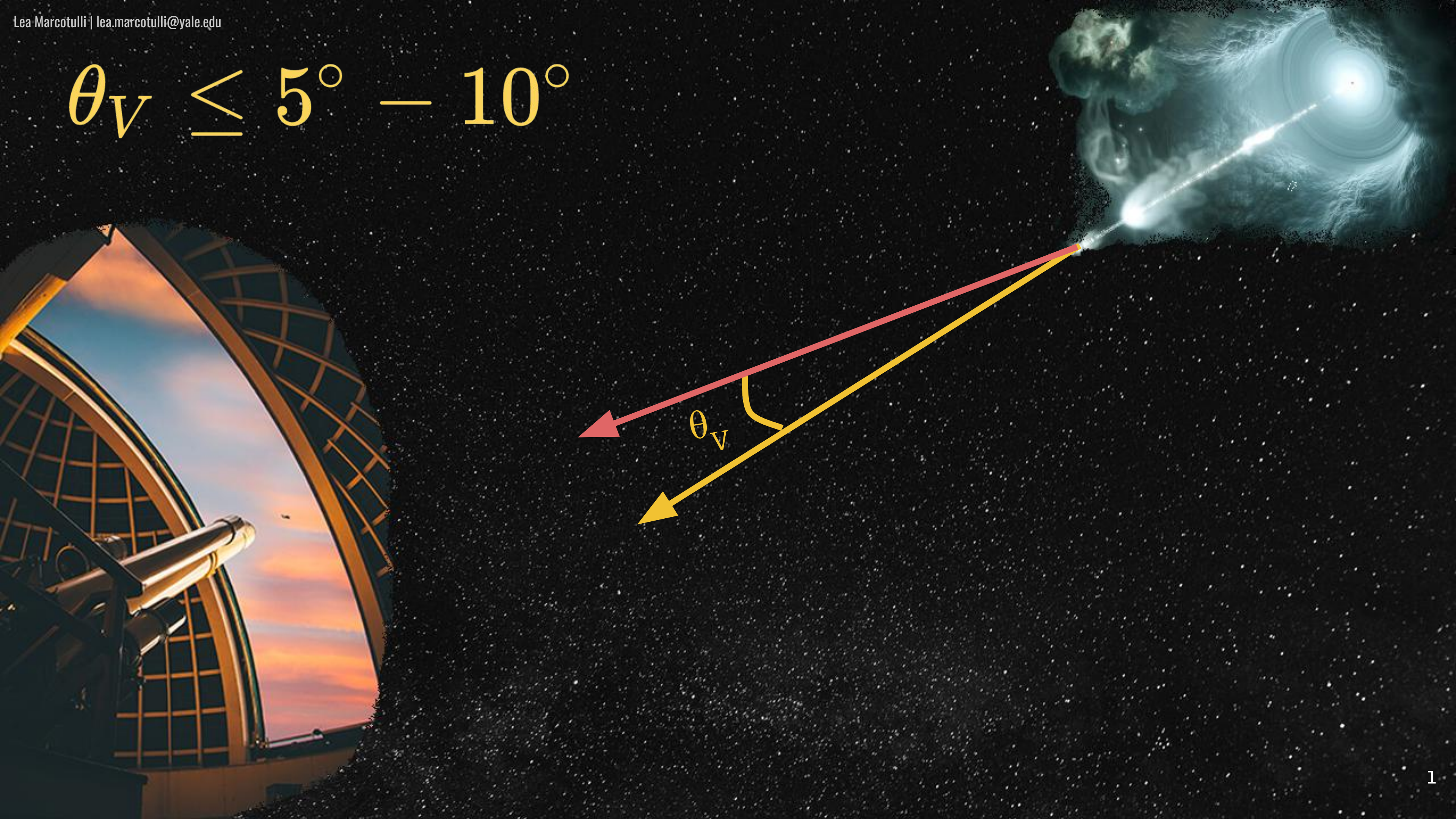
Image credits: https://blenderartist.org

The most powerful persistent jets through cosmic time

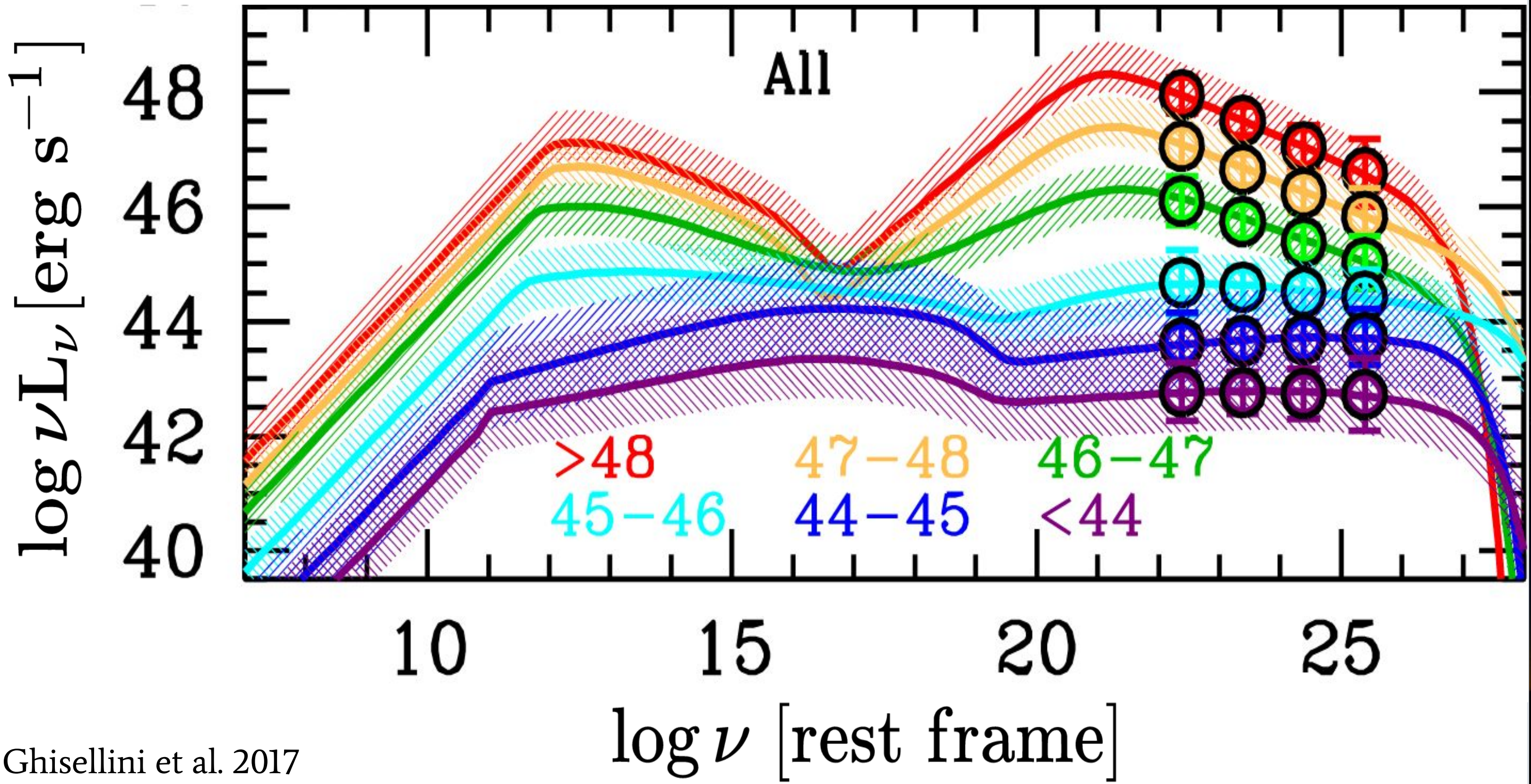
DESY, Berlin
June 23rd, 2023

Presented by: Lea Marcotulli
lea.marcotulli@yale.edu

$$\theta_V \leq 5^\circ - 10^\circ$$

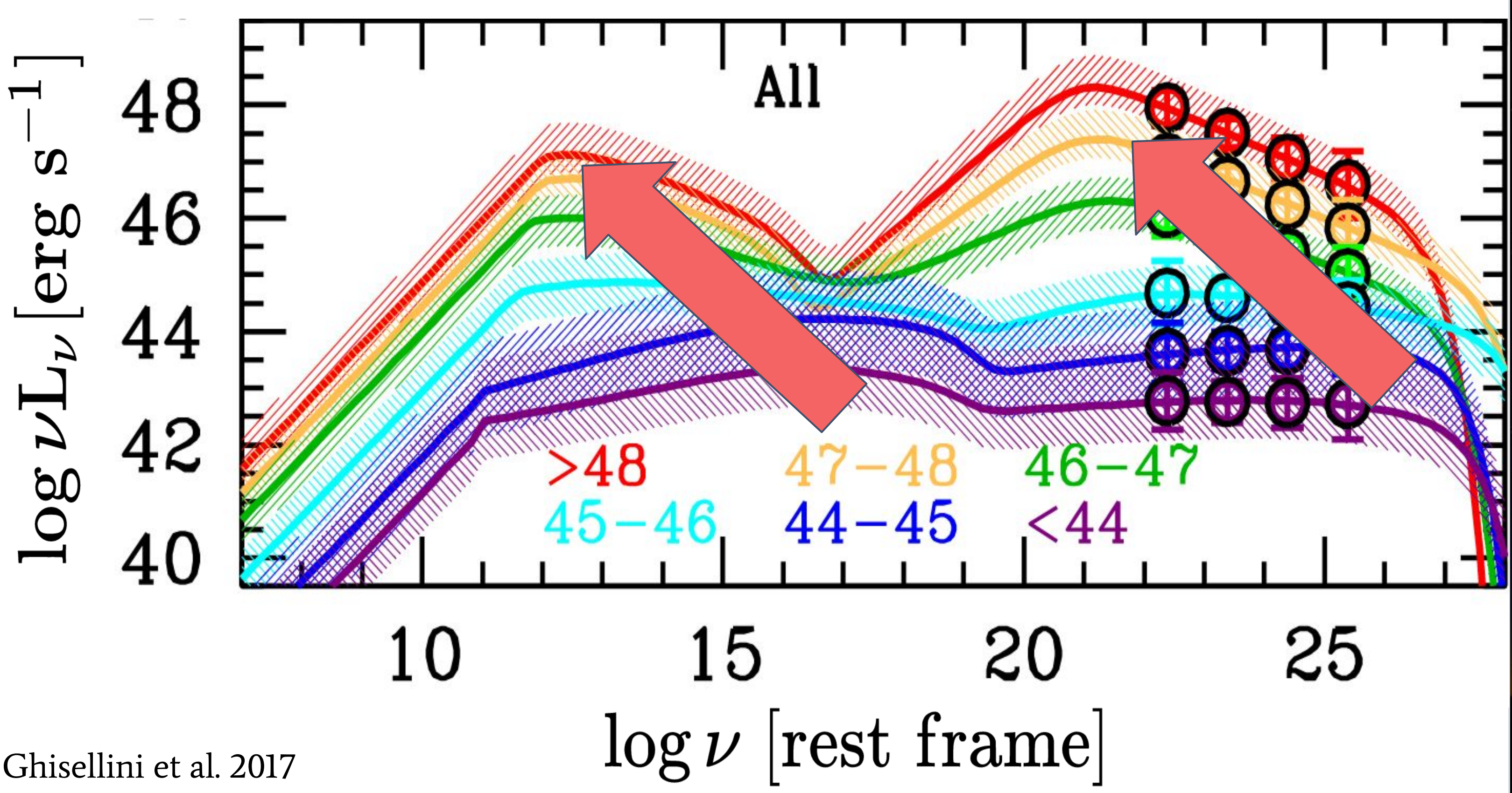


Blazar population



Ghisellini et al. 2017

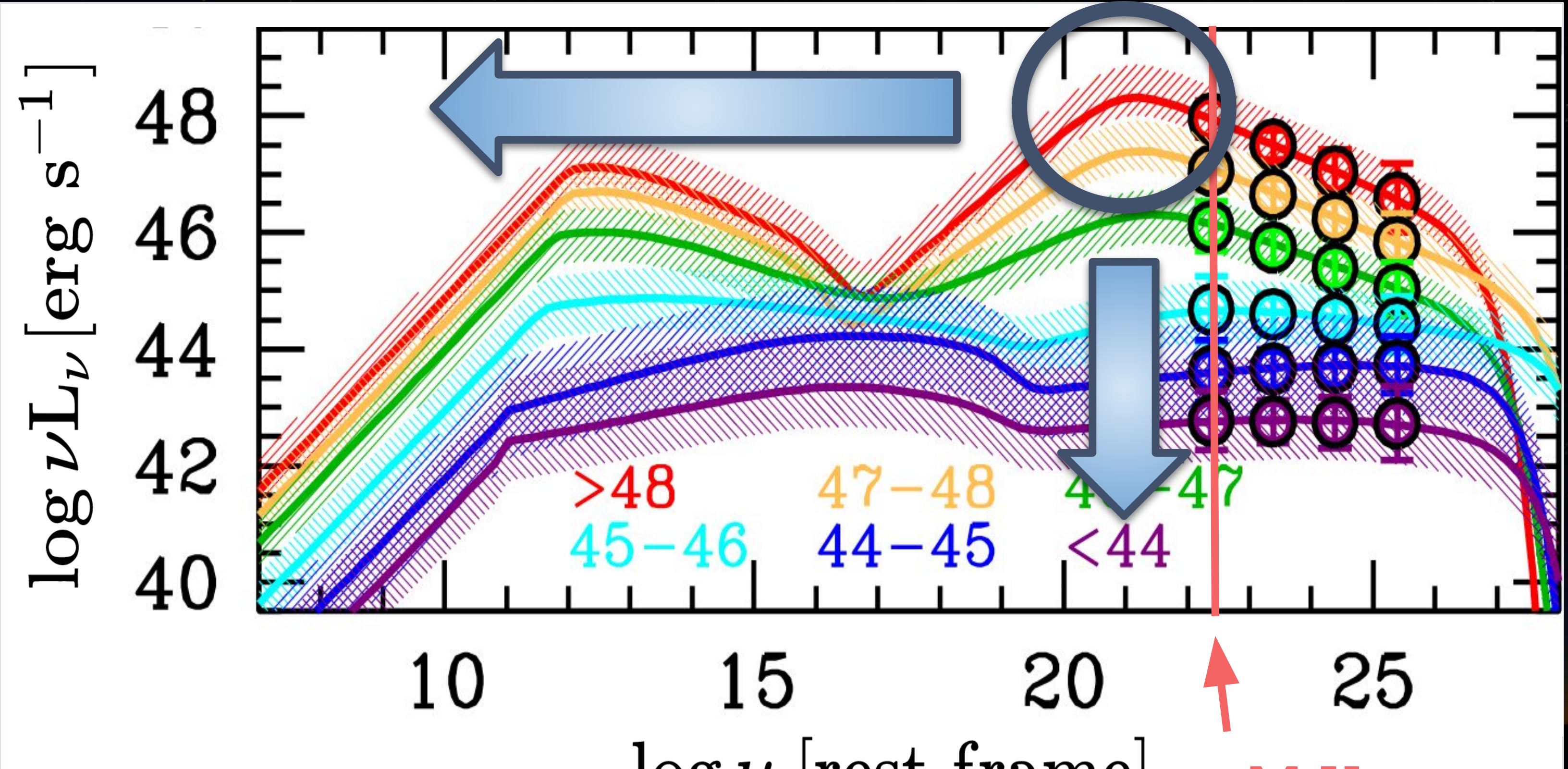
Blazar population



Ghisellini et al. 2017

Lea Marcotulli | lea.marcotulli@yale.edu

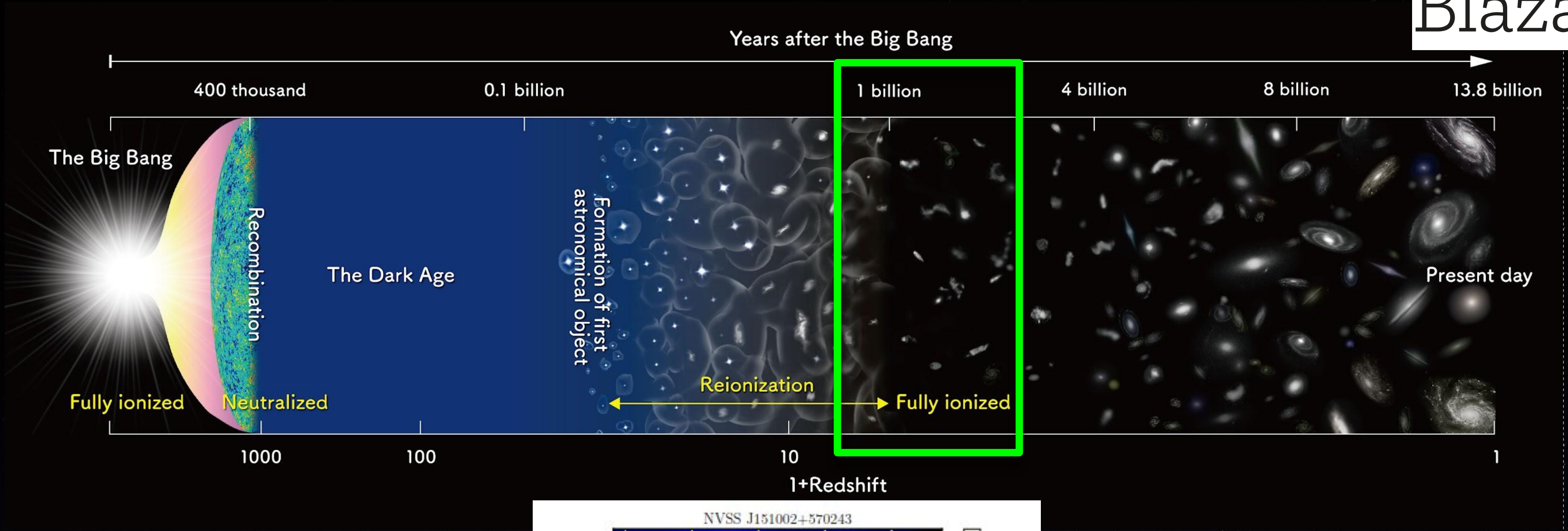
Blazar population



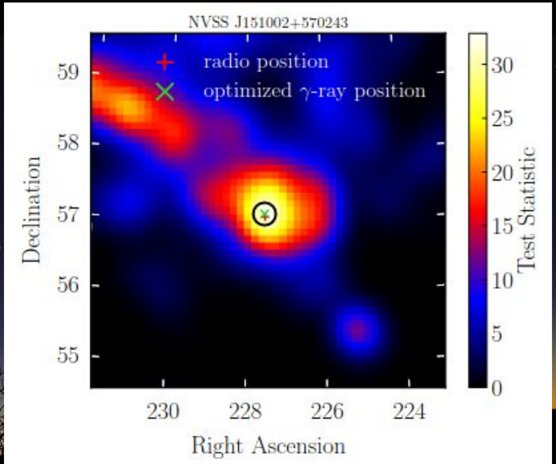
Ghisellini et al. 2017

Lea Marcotulli | lea.marcotulli@yale.edu

Blazars



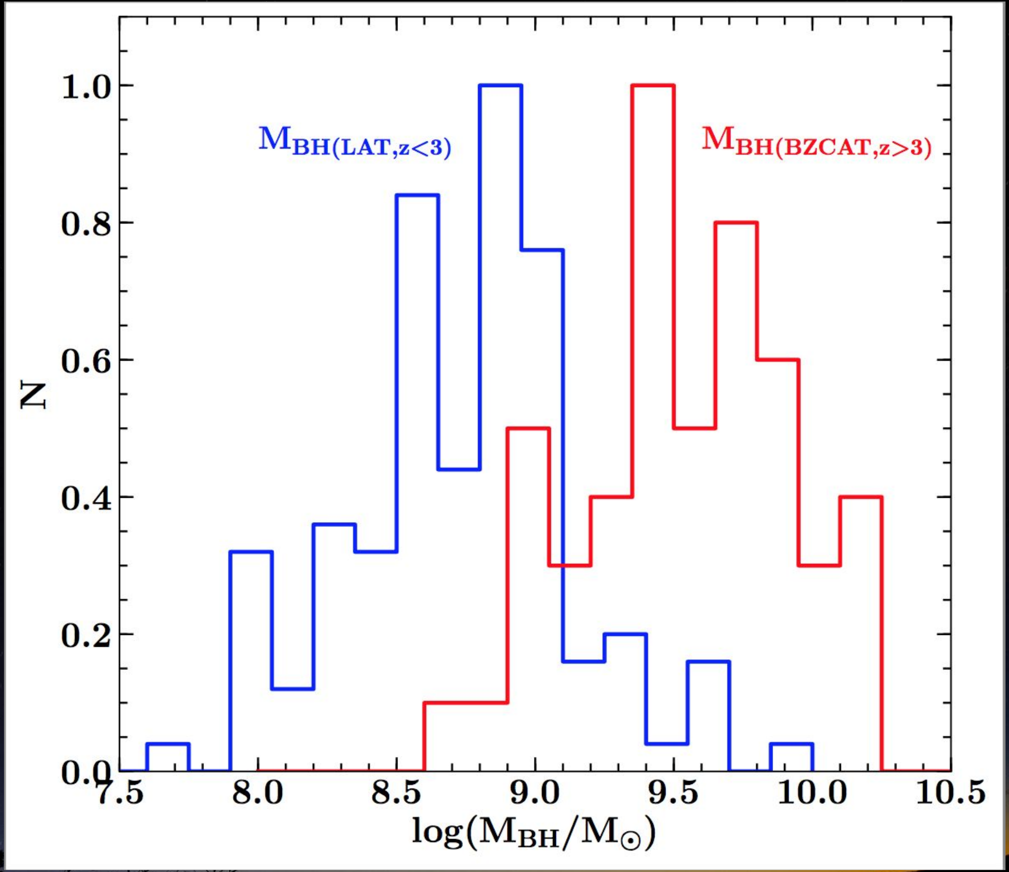
E.g. Sbarrato et al. 2015; An & Romani 2018; Marcotulli et al. 2020



Ackermann et al. 2017

z = 4.3

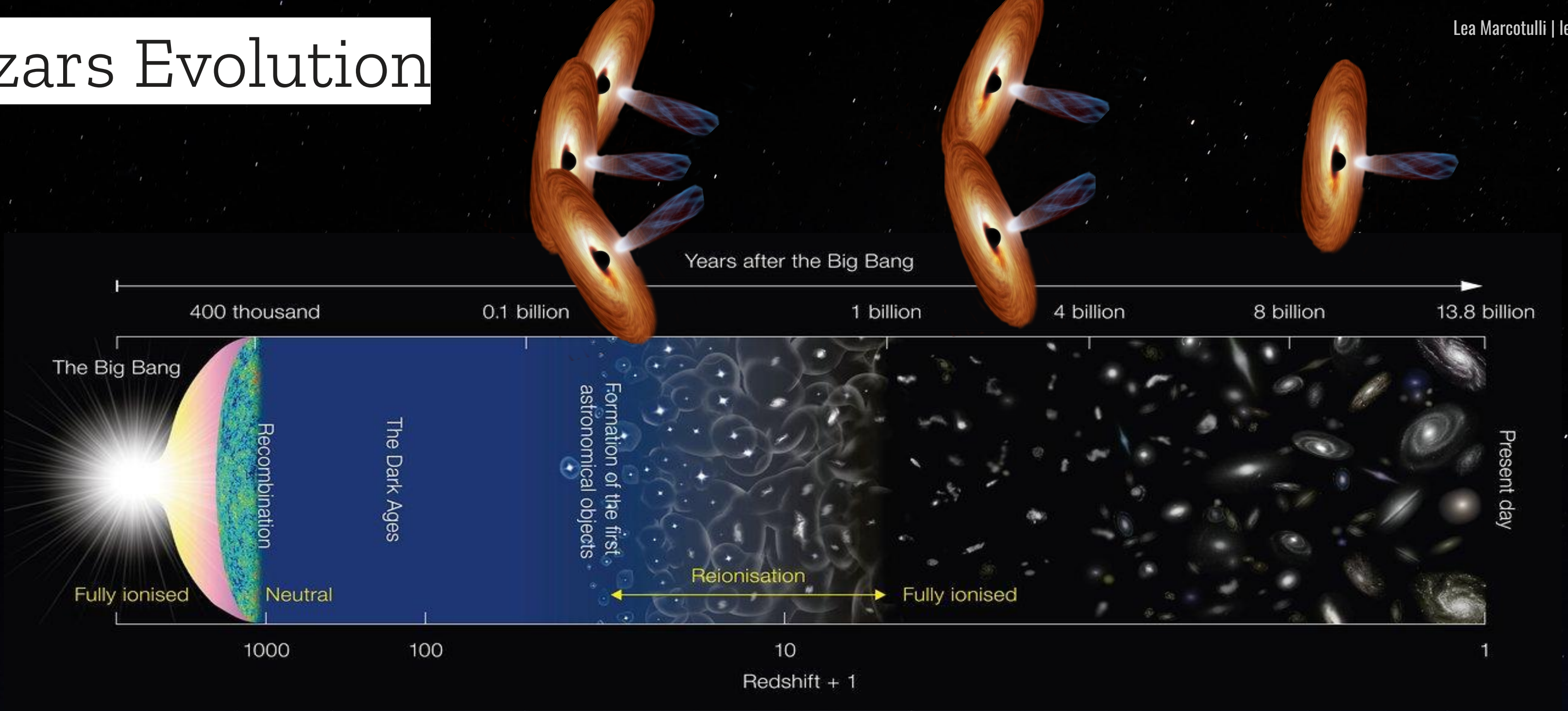
Blazars



Credit: Paliya V.
see Paliya, Marcotulli+ 2017

Blazars Evolution

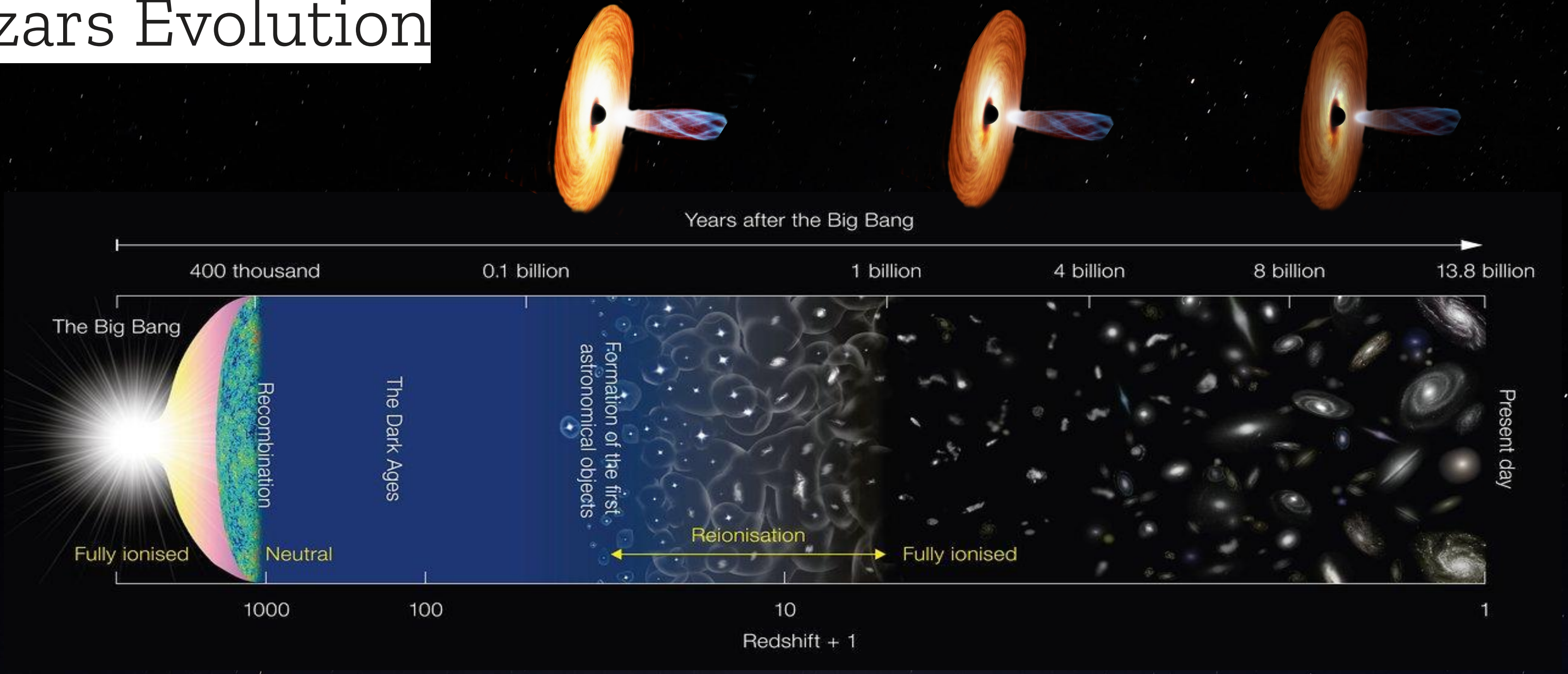
Lea Marcotulli | lea.marcotulli@yale.edu



→ **Pure Density Evolution (PDE)**

Lea Marcotulli | lea.marcotulli@yale.edu

Blazars Evolution

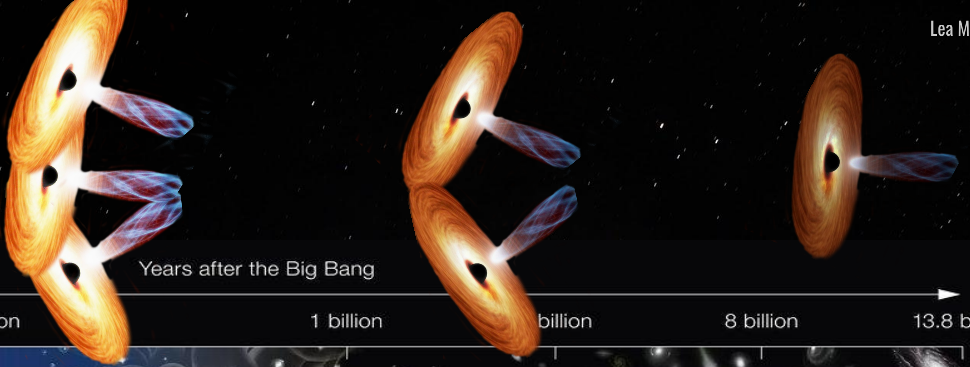


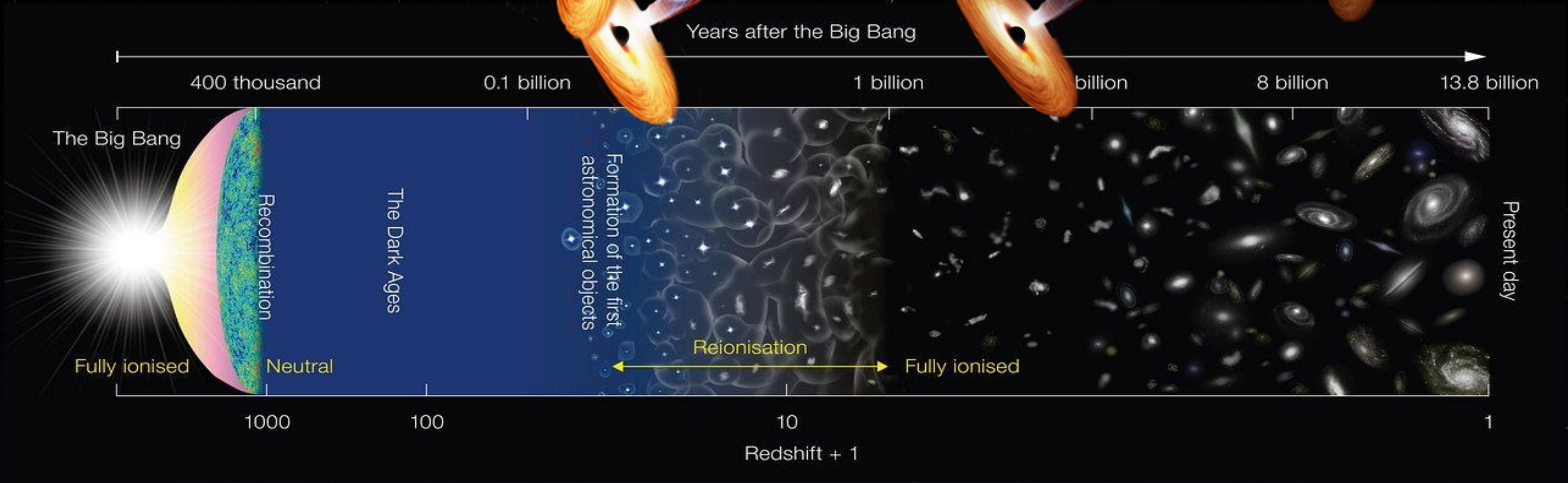
→ **Pure Density Evolution (PDE)**

→ **Pure Luminosity Evolution (PLE)**

Blazars Evolution

Lea Marcotulli | lea.marcotulli@yale.edu



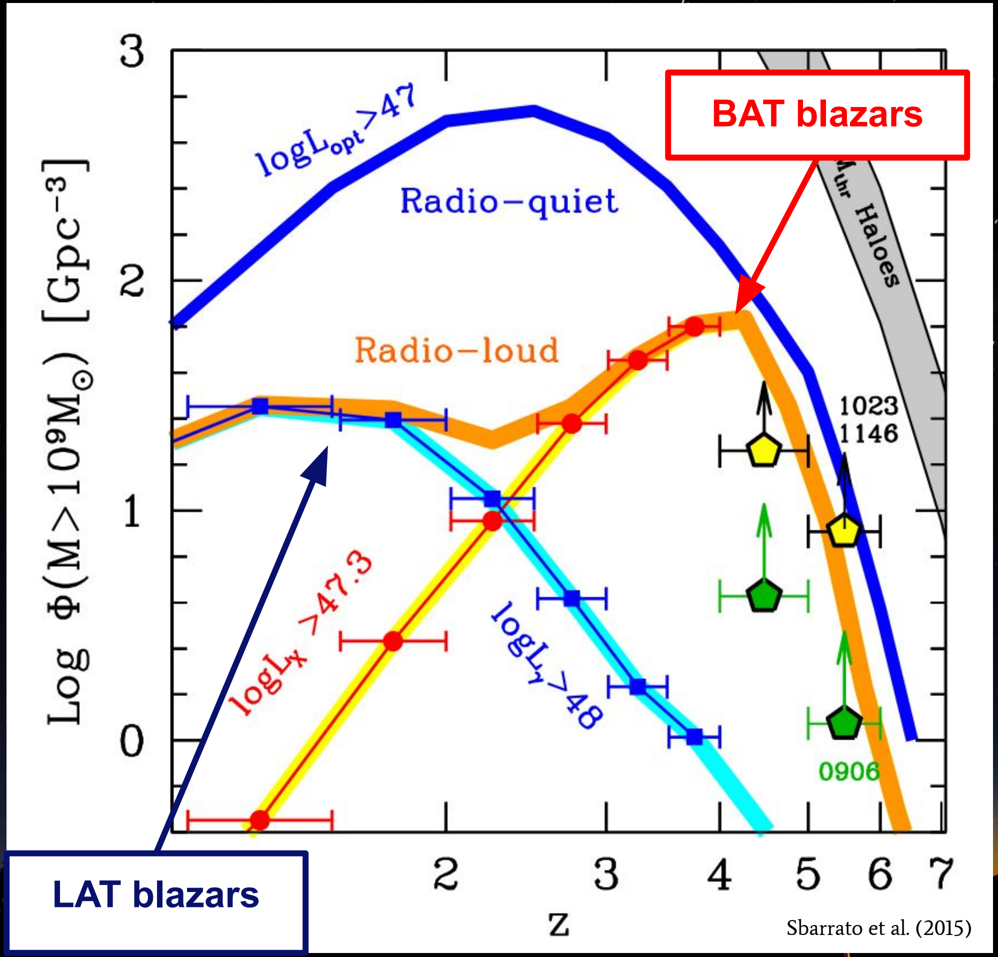


→ **Pure Density Evolution (PDE)**

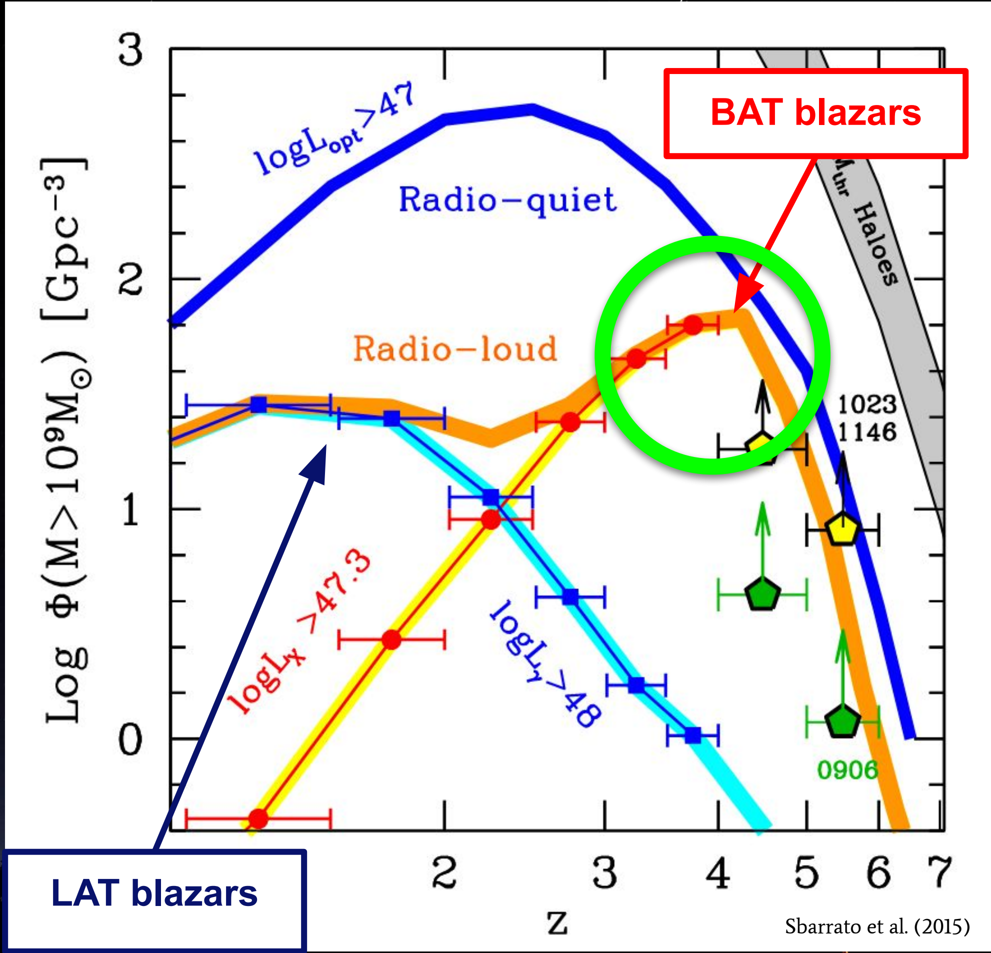
→ **Pure Luminosity Evolution (PLE)**

→ **Luminosity-Density Dependent Evolution (LDDE)**

Blazars and SMBH Evolution



Blazars and SMBH Evolution



Sbarrato et al. (2015)

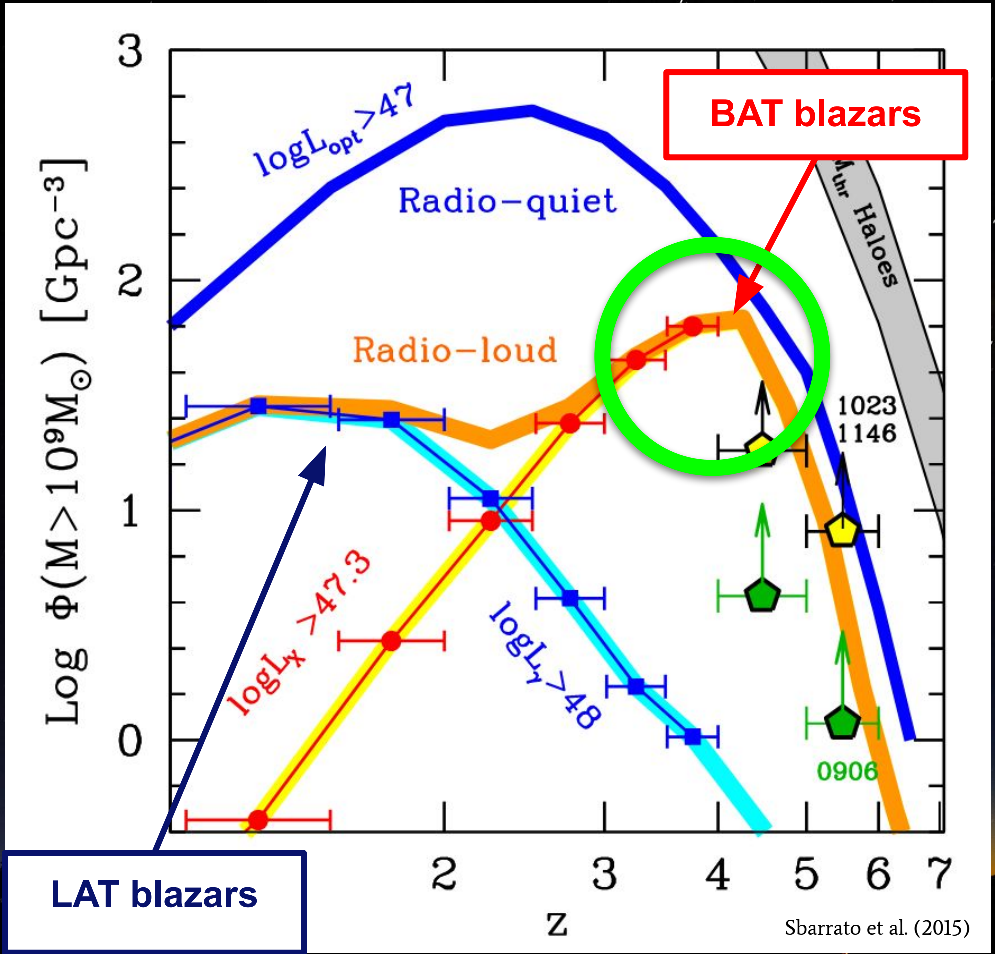
JETS

SMBH GROWTH

Blazars and SMBH Evolution

$2\Gamma^2$

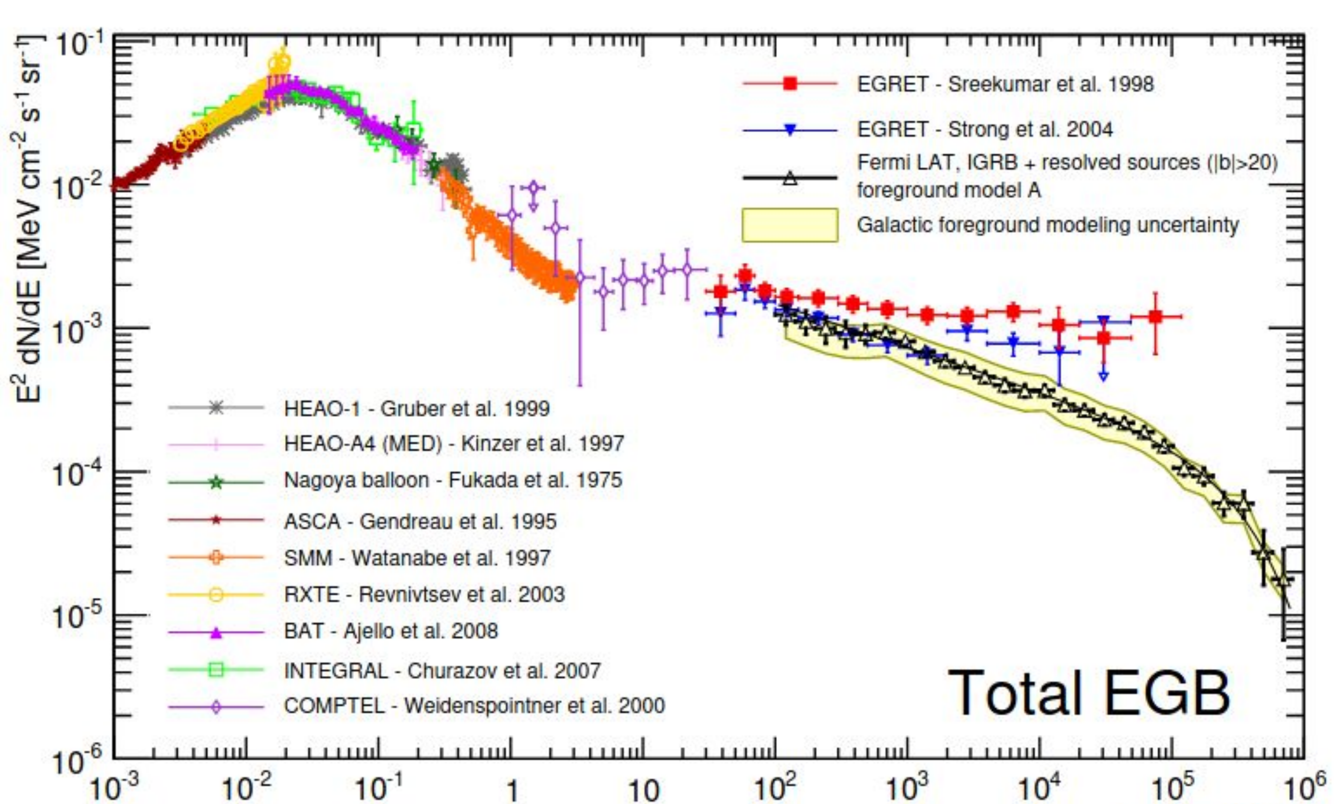
CORRECTION!



JETS

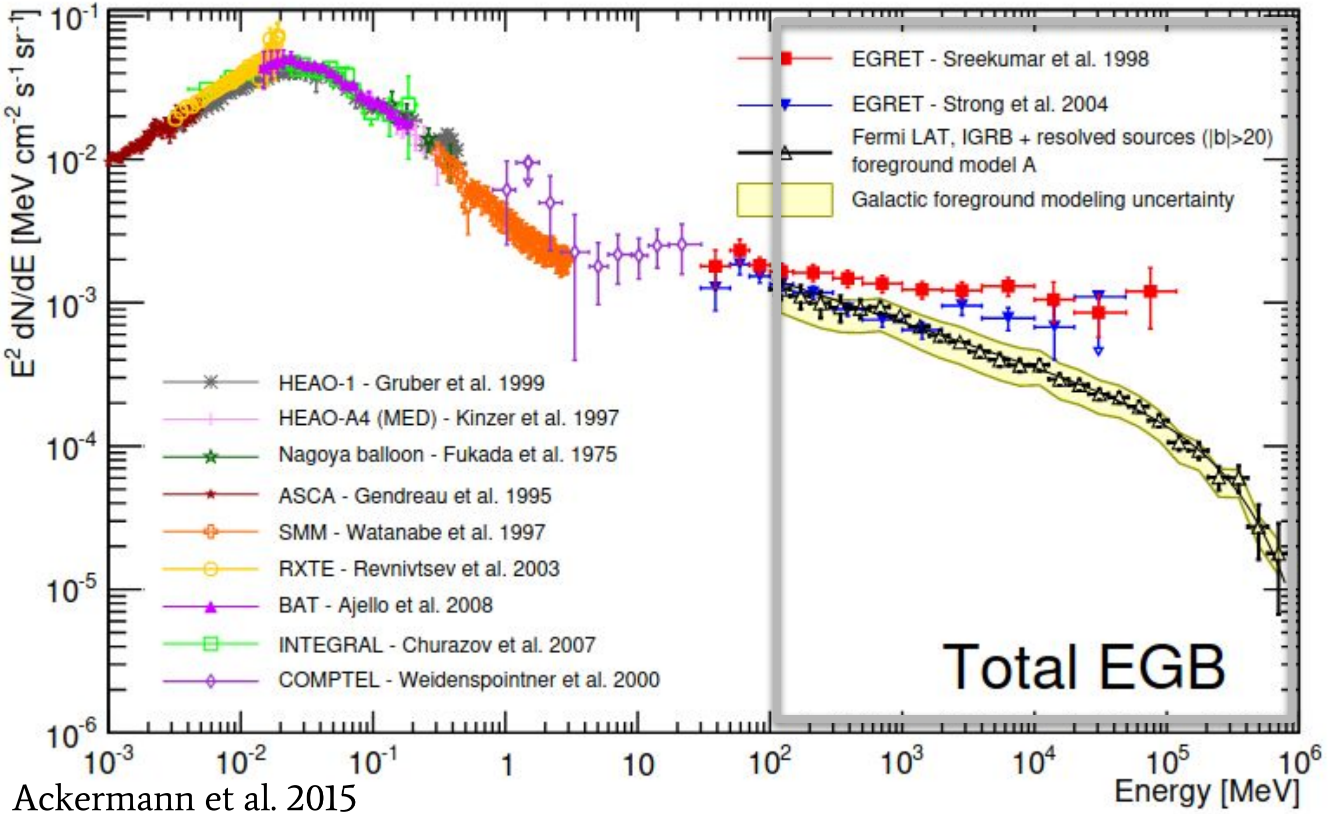
SMBH GROWTH

The Cosmic High-Energy Background



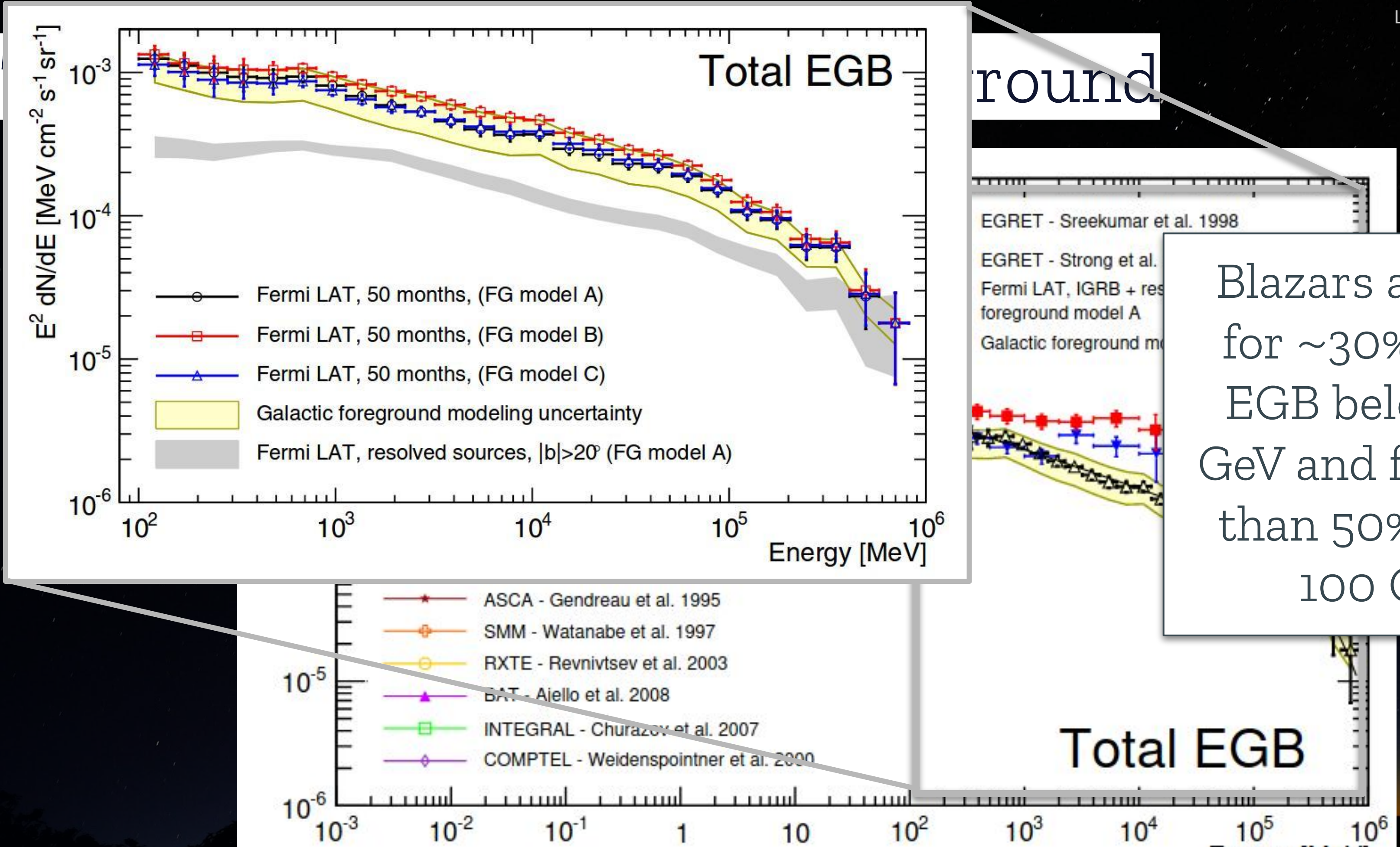
Ackermann et al. 2015

The Cosmic High-Energy Background



Ackermann et al. 2015

...round

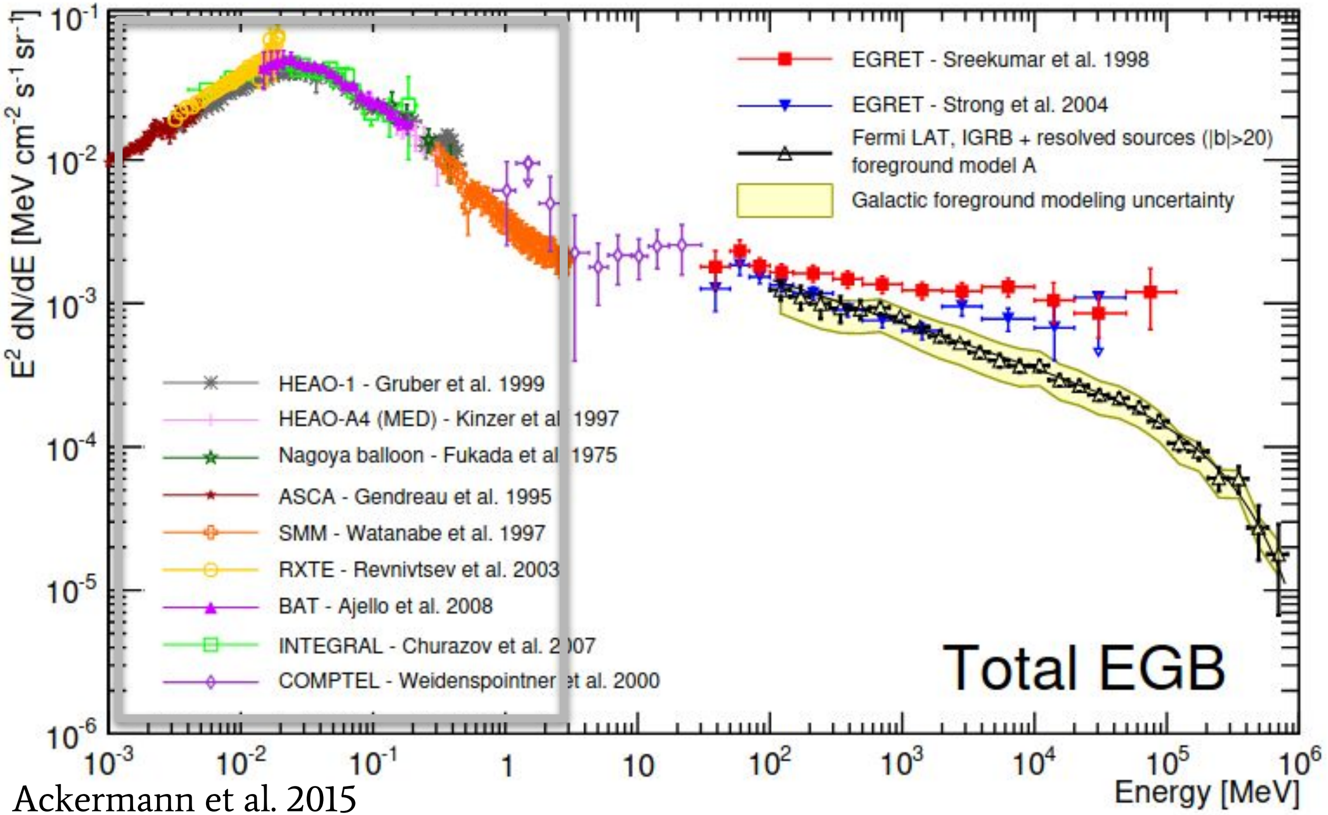


Ackermann et al. 2015

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

Lea Marcotulli | lea.marcotulli@yale.edu

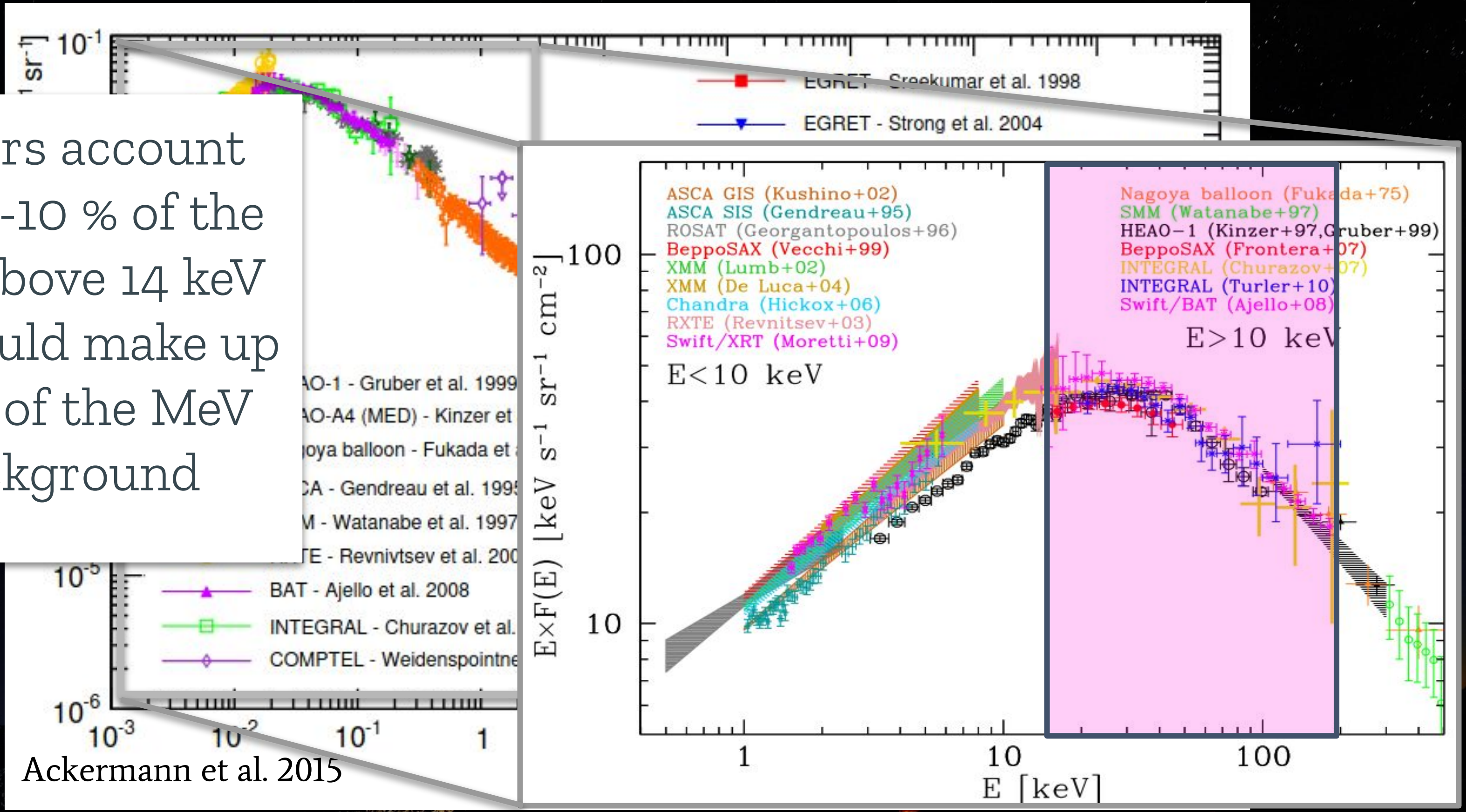
The Cosmic High-Energy Background



Ackermann et al. 2015

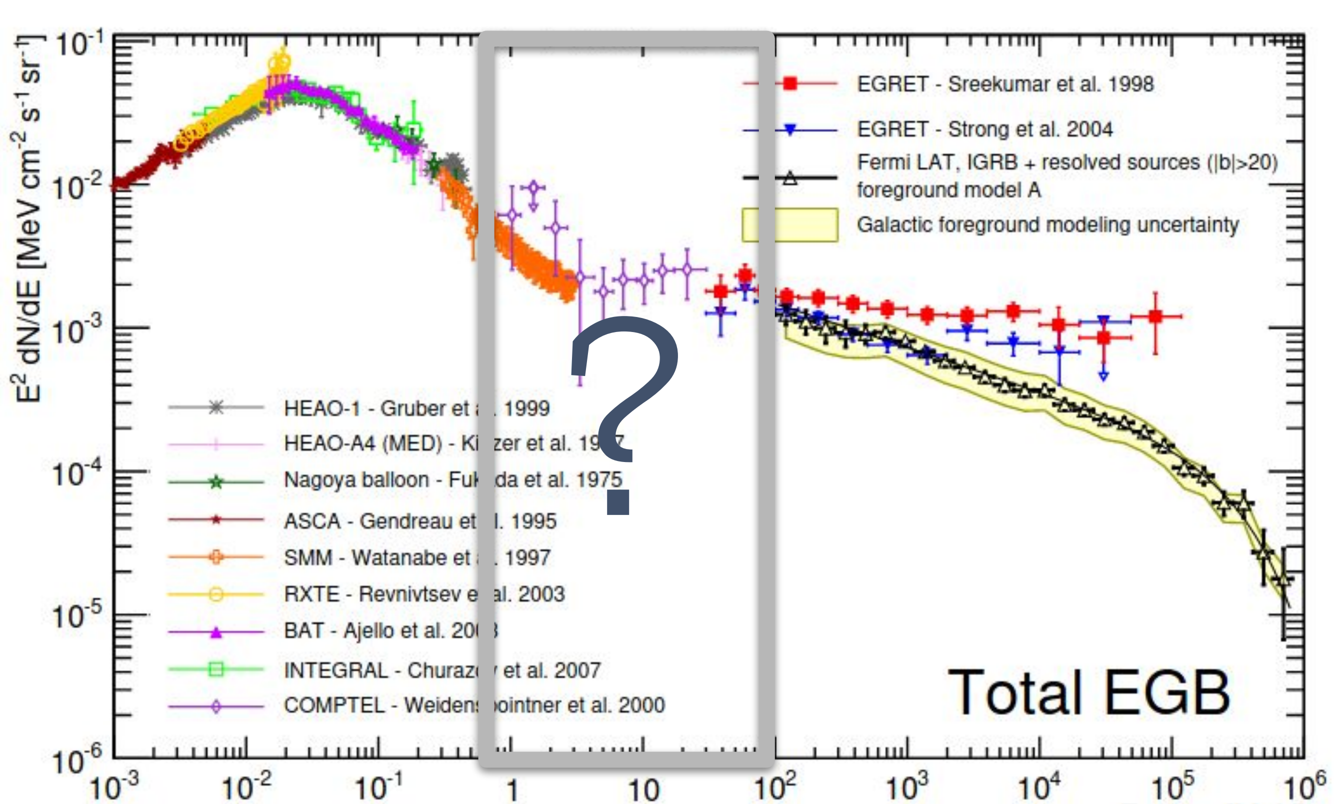
The Cosmic High-Energy Background

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



Ackermann et al. 2015

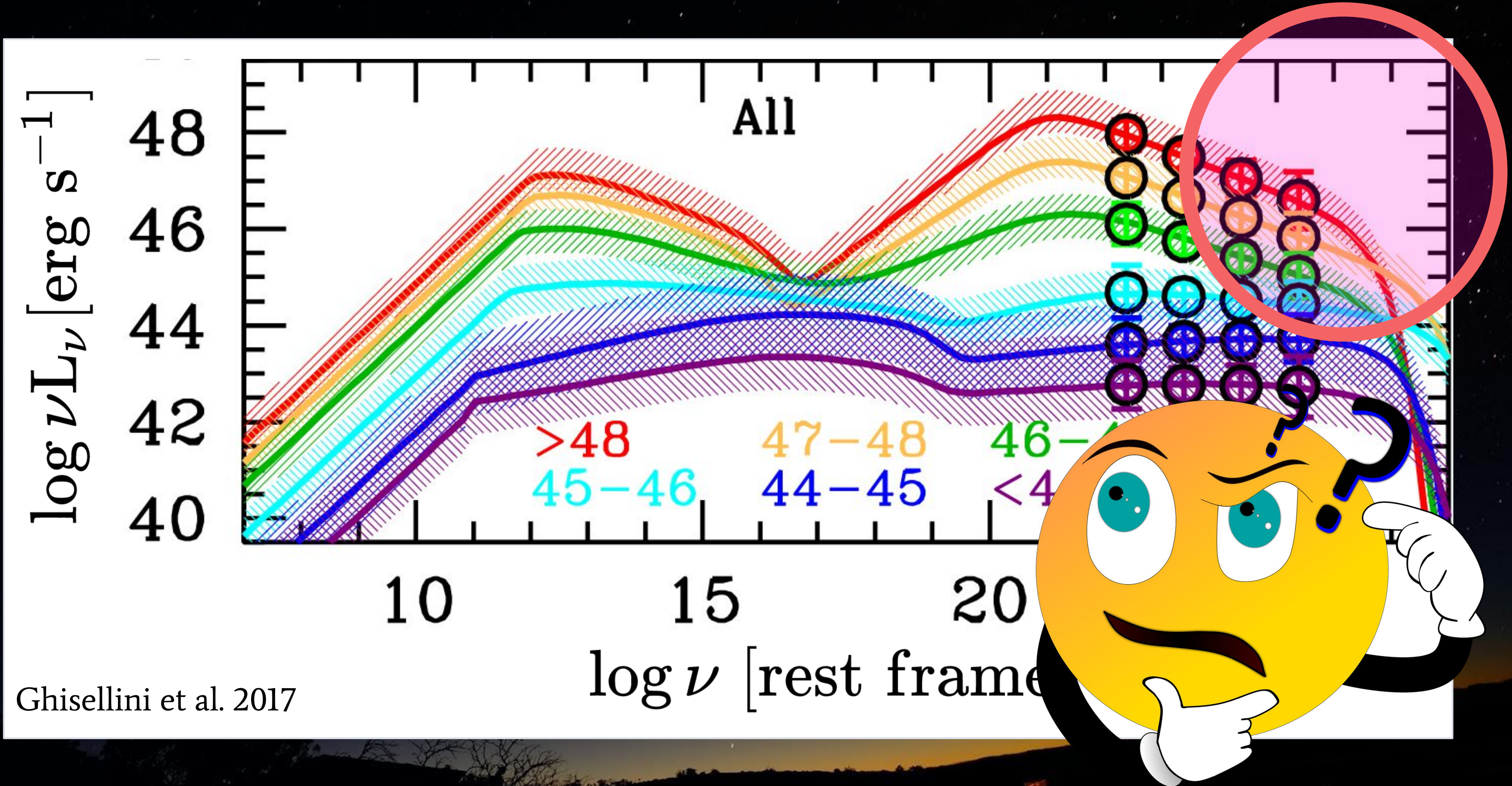
The Cosmic High-Energy Background



Ackermann et al. 2015

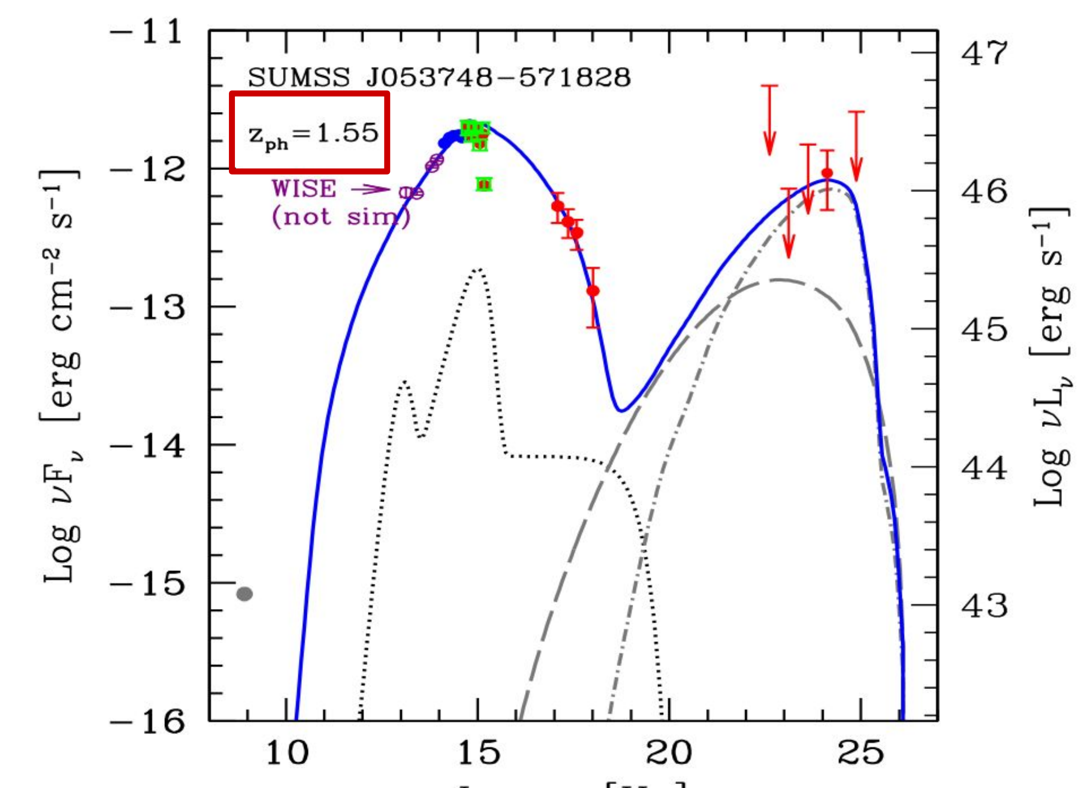
see e.g. Ghisellini+98,17, Meyer+11
but also Giommi+12

Blazar sequence: a selection effect?



Ghisellini et al. 2017

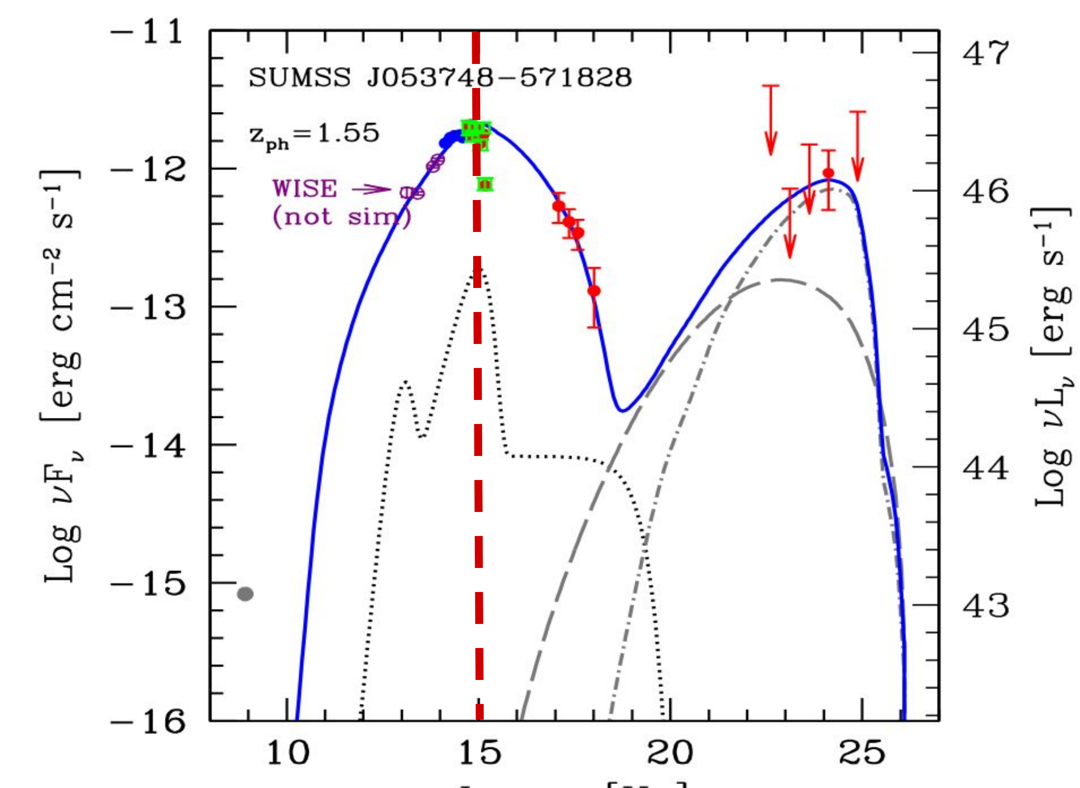
Blue FSRQs or high-luminosity BL Lacs?



Ghisellini et al. 2012

1. **z>1**
2. $\nu_{synch,peak}$ >10^{15} Hz
3. High synchrotron luminosity (>10^{46} erg s^{-1})
4. High radio power (>10^{26} WHz^{-1})

Blue FSRQs or high-luminosity BL Lacs?

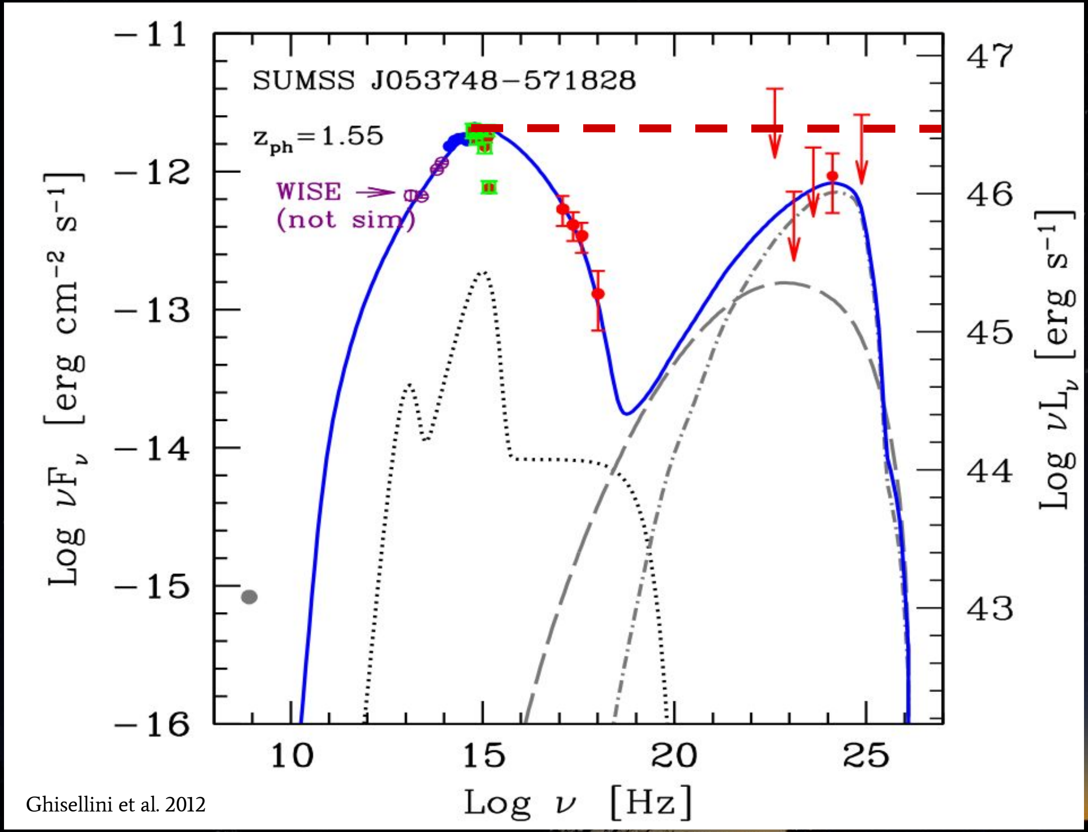


Ghisellini et al. 2012

1. z>1
2. **$\nu_{synch,peak}$ >10^{15} Hz**
3. High synchrotron luminosity (>10^{46} erg s^{-1})
4. High radio power (>10^{26} WHz^{-1})

Lea Marcotulli | lea.marcotulli@yale.edu

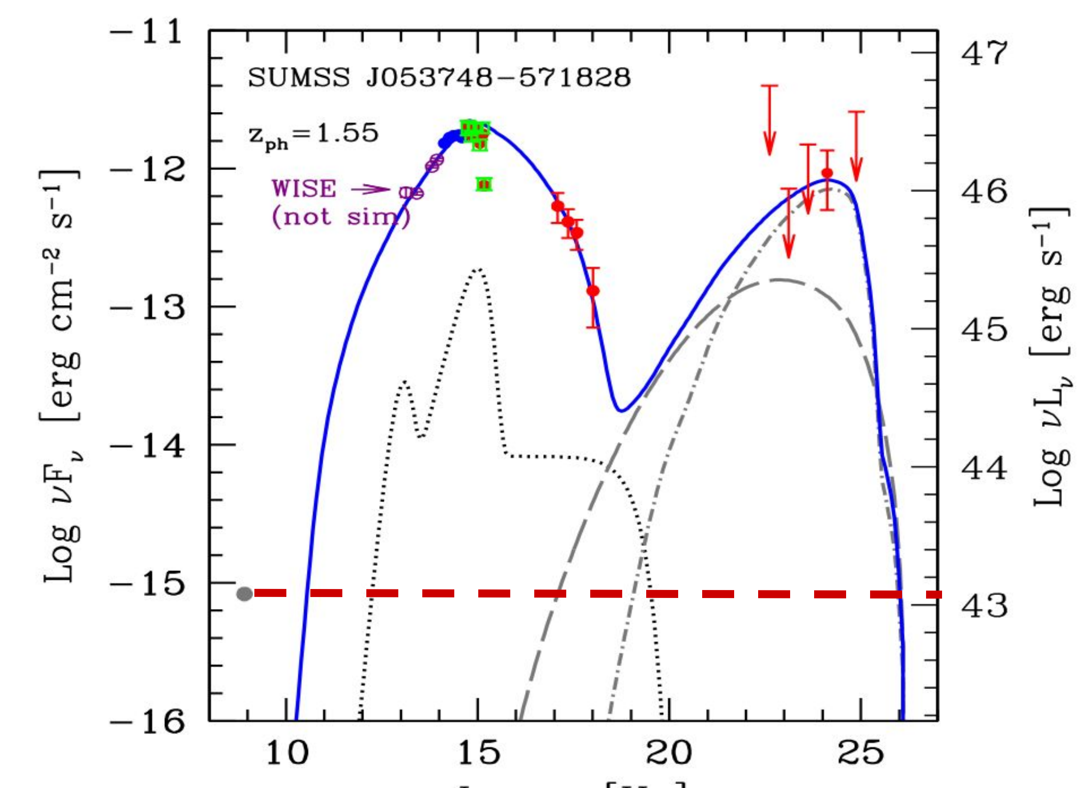
Blue FSRQs or high-luminosity BL Lacs?



Ghisellini et al. 2012

1. z>1
2. $\nu_{synch,peak}$ >10^{15} Hz
3. **High synchrotron luminosity (>10^{46} erg s^{-1})**
4. High radio power (>10^{26} WHz^{-1})

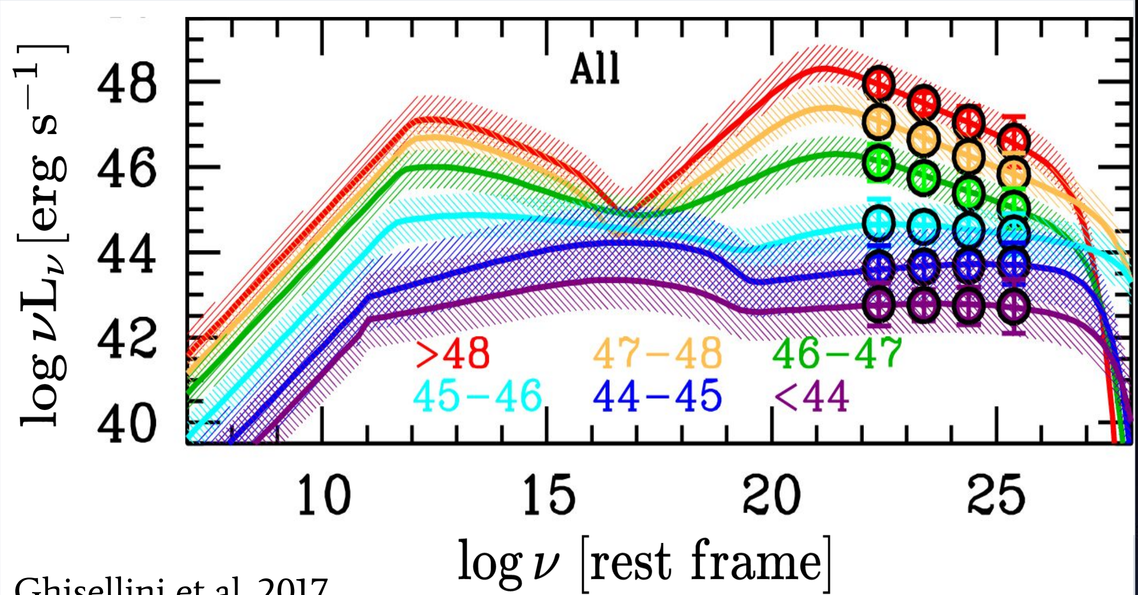
Blue FSRQs or high-luminosity BL Lacs?



Ghisellini et al. 2012

1. z>1
2. $\nu_{synch,peak}$ >10^{15} Hz
3. High synchrotron luminosity (>10^{46} erg s^{-1})
4. **High radio power (>10^{26} WHz^{-1})**

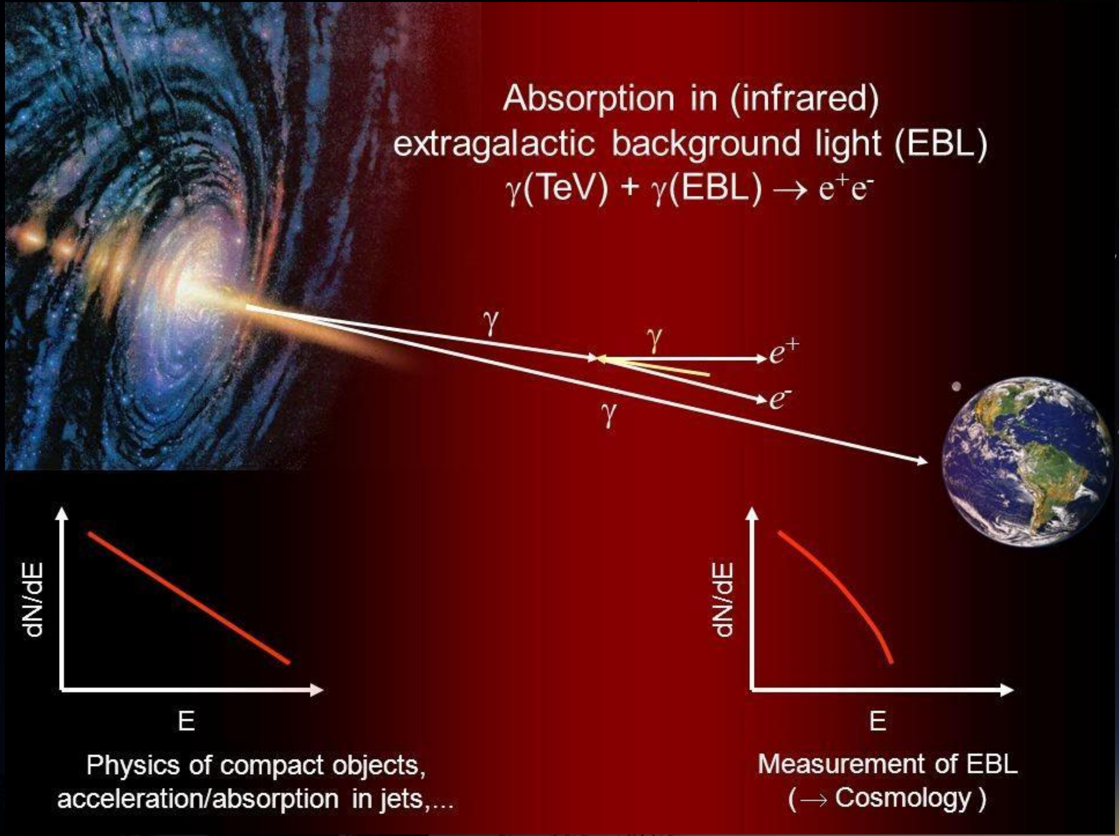
Importance



Ghisellini et al. 2017

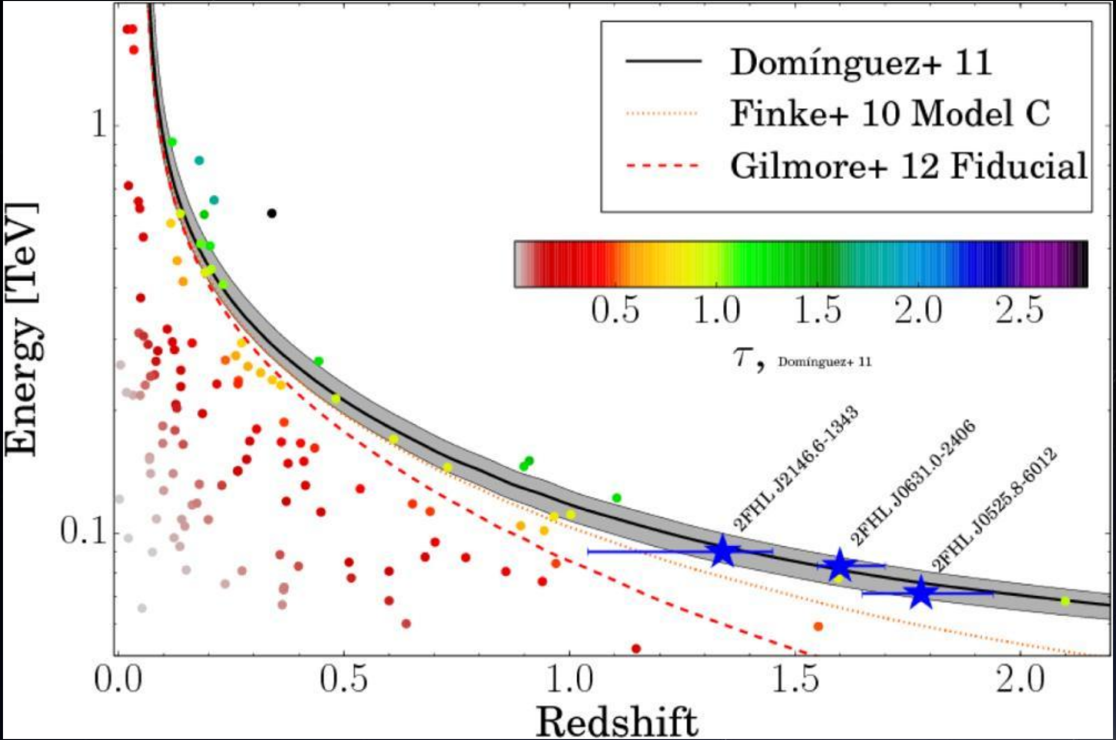
- Constraints on blazars evolution and possible selection effects

Importance



- Constraints on blazars evolution and possible selection effects
- Extragalactic Background Light (EBL) studies (E>10 GeV)

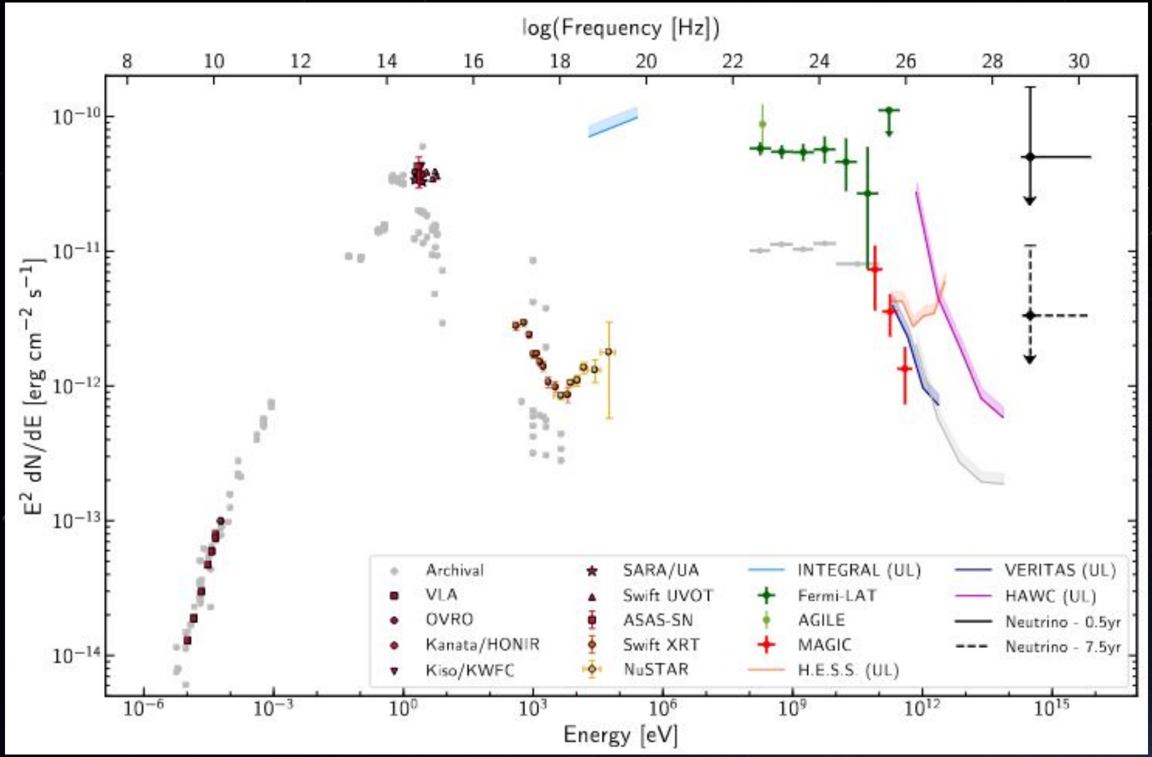
Importance



Kaur et. al 2017

- Constraints on blazars evolution and possible selection effects
- Extragalactic Background Light (EBL) studies (E>10 GeV)

Importance

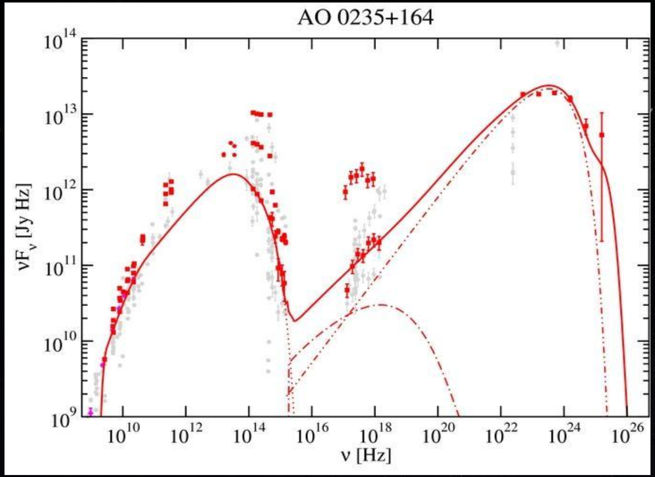


- Constraints on blazars evolution and possible selection effects
- Extragalactic Background Light (EBL) studies (E>10 GeV)
- Neutrino emitters

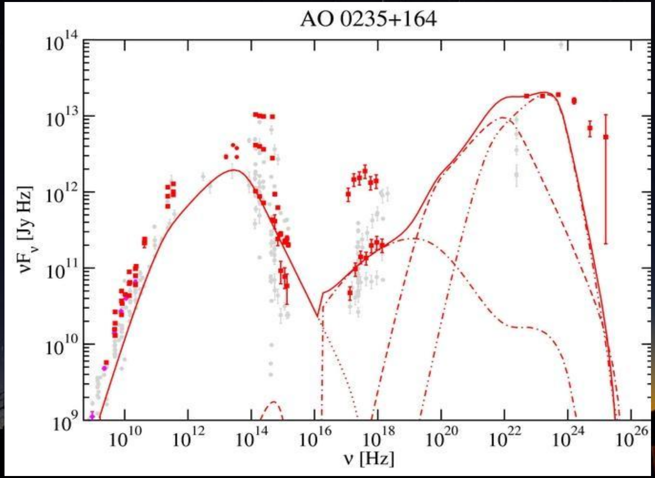
IceCube Coll. 2018, Padovani+ 2019, Petroupoulou+2020

Hadronic vs. Leptonic models

LEPTONIC



HADRONIC

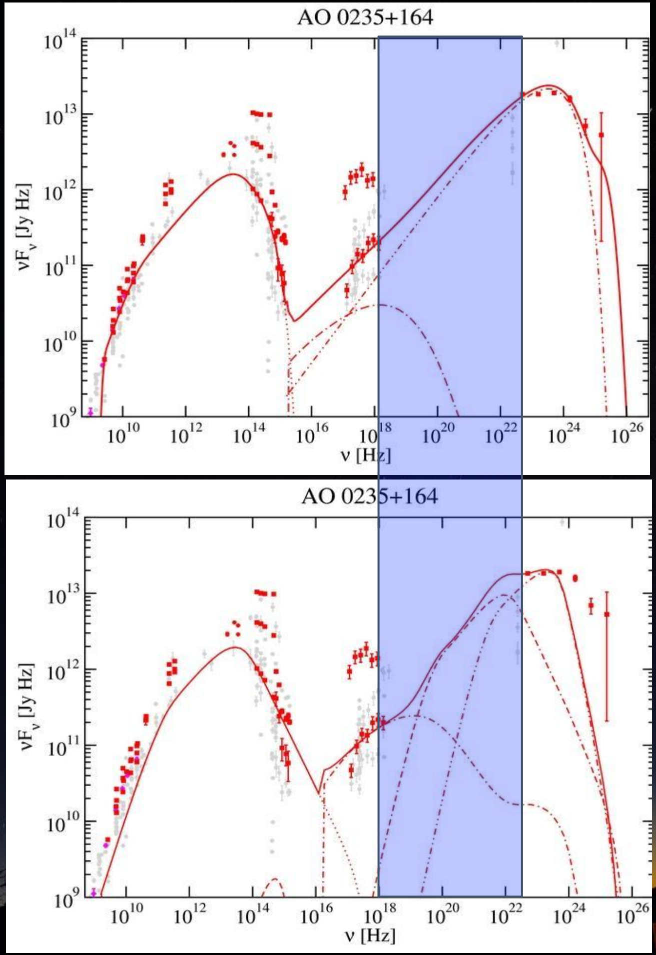


Böttcher et al. 2013

Hadronic vs. Leptonic models

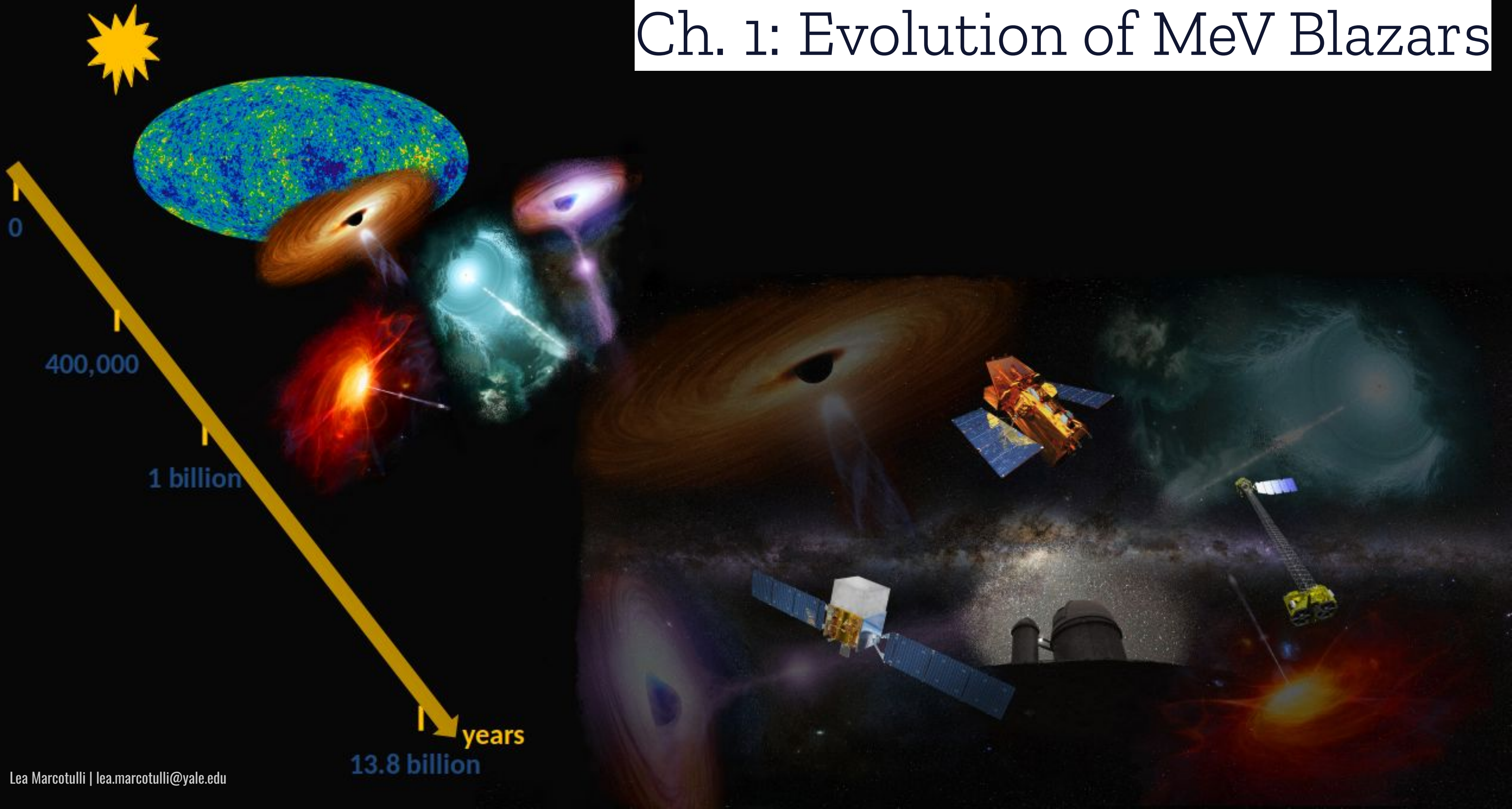
LEPTONIC

HADRONIC



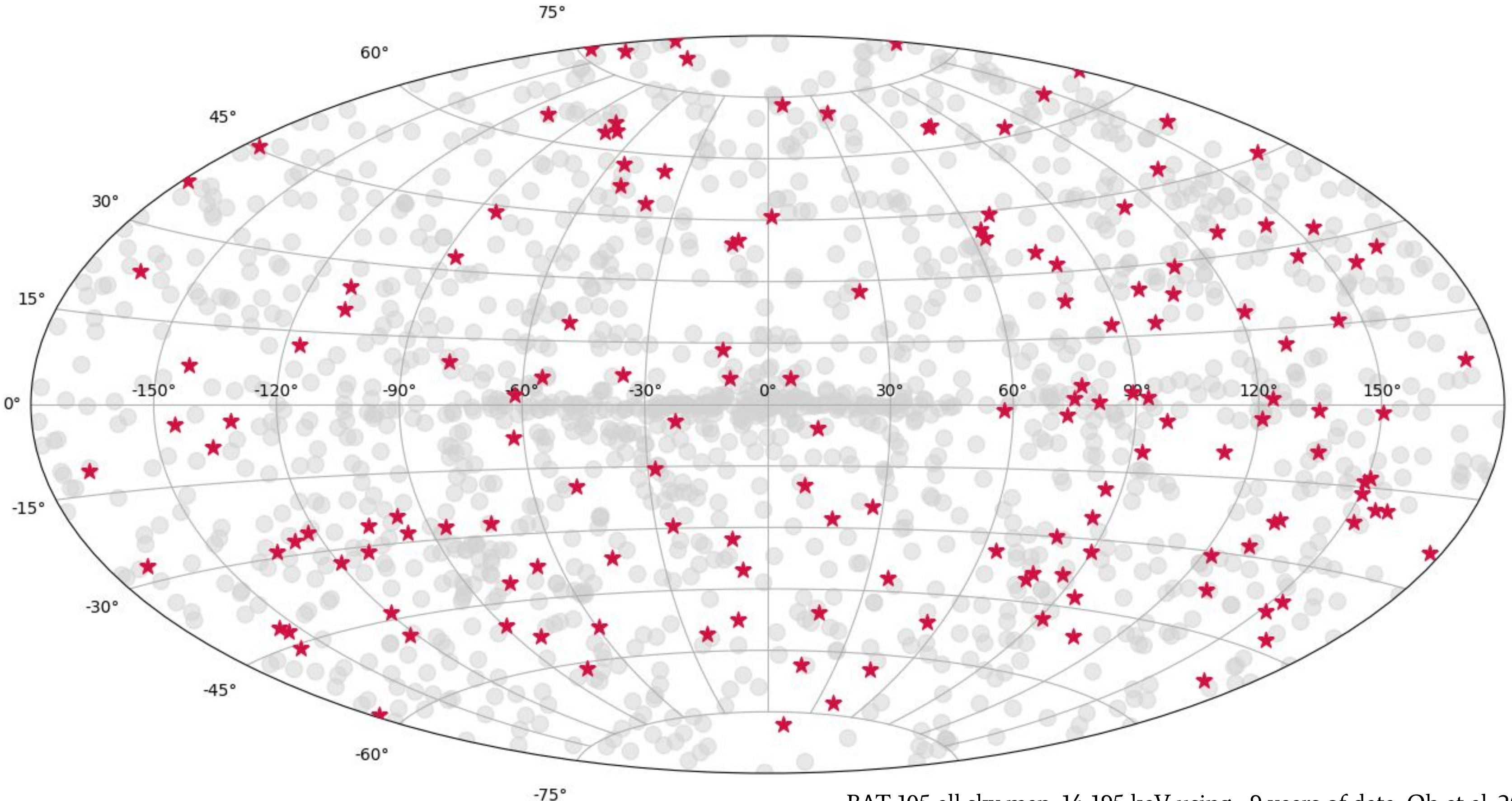
Böttcher et al. 2013

Ch. 1: Evolution of MeV Blazars



What do we need

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



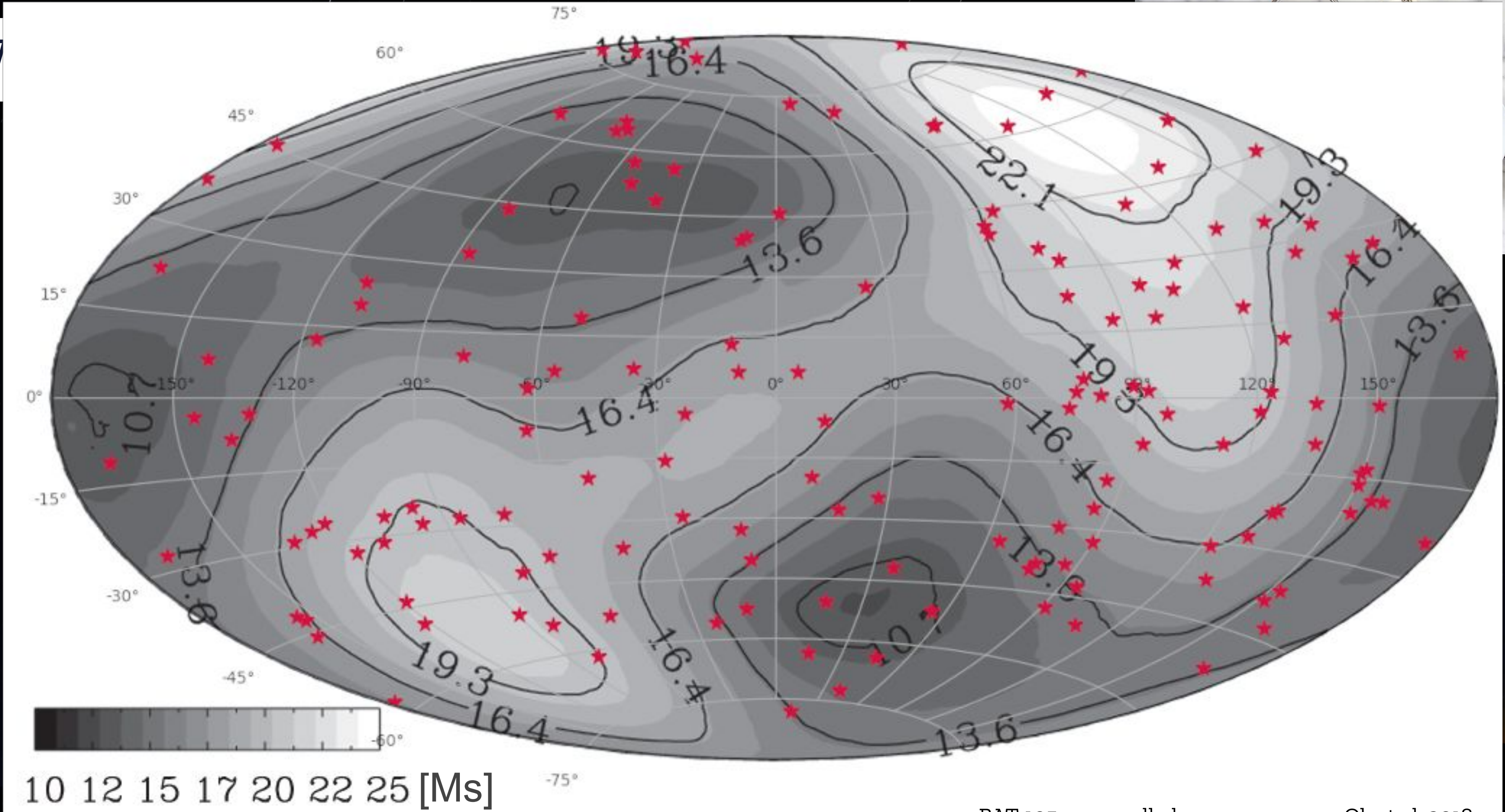
BAT-105 all sky map, 14-195 keV using ~9 years of data, Oh et al. 2018

What do we need

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

W

1.
2.
3.

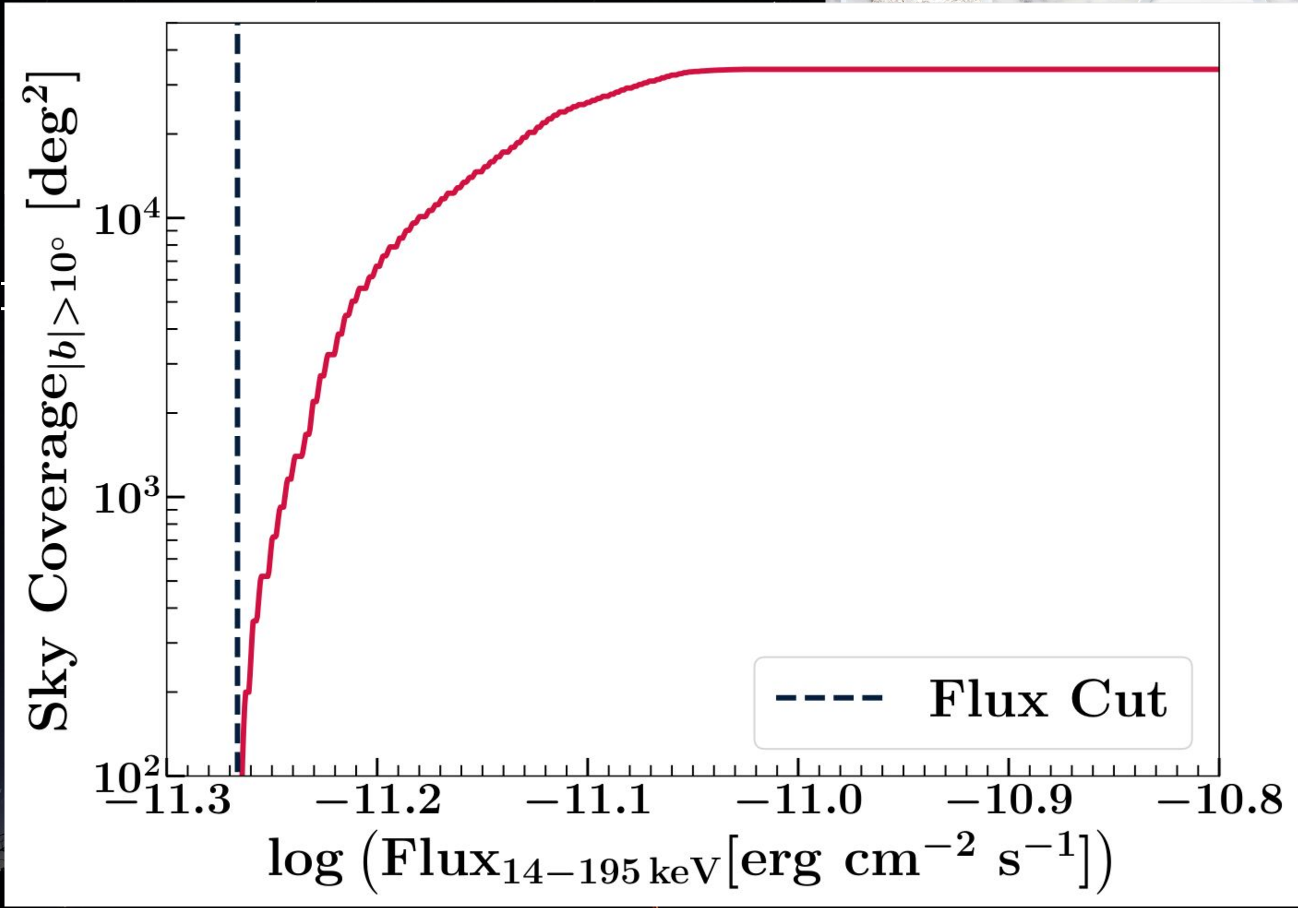


BAT-105 survey all-sky exposure map, Oh et al. 2018

What do we need

Marcotulli et al., 2022

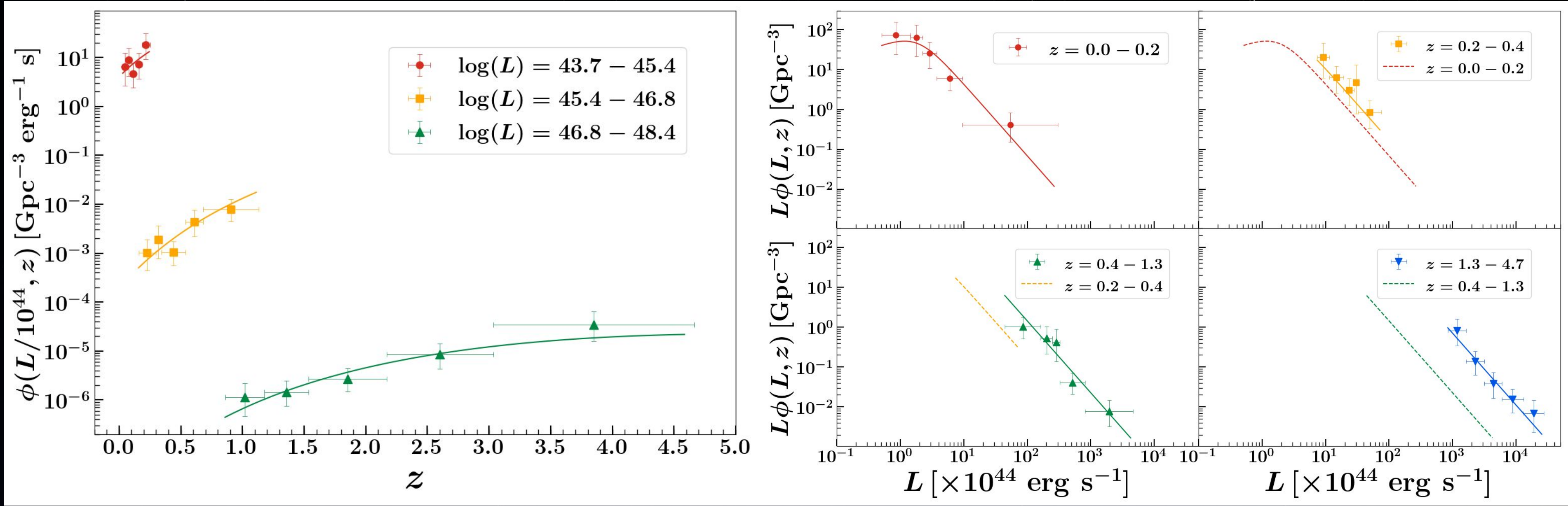
1. Clean sample (i.e.
2. Set of cuts to mini
3. **Sky coverage**



What do we need

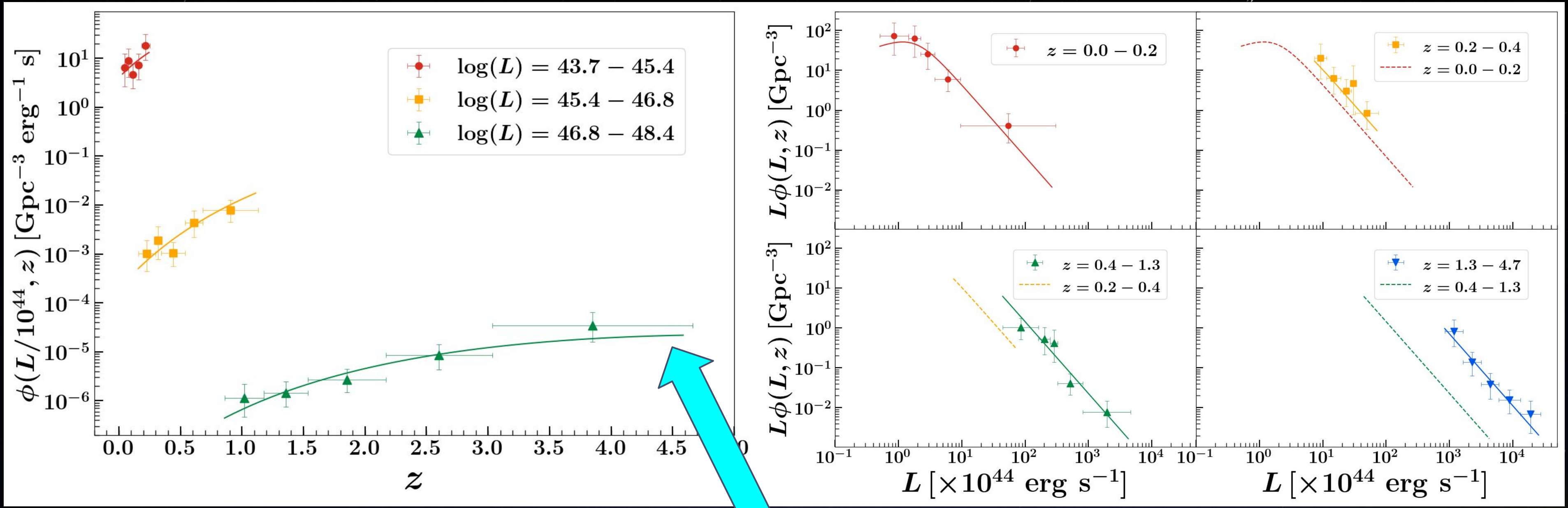
1. Clean sample (i.e. blazars with measured redshift and flux)
2. Set of cuts to minimize uncertainties
3. Sky coverage
4. **X-ray luminosity function models (Ajello et al. 2009/2012/2014)**
   → Pure Density Evolution (PDE)
   → Pure Luminosity Evolution (PLE)
   → Luminosity-Density Dependent Evolution (LDDE)

Best-fit XLF PDE/PLE



Marcotulli et al., 2022

Best-fit XLF PDE/PLE

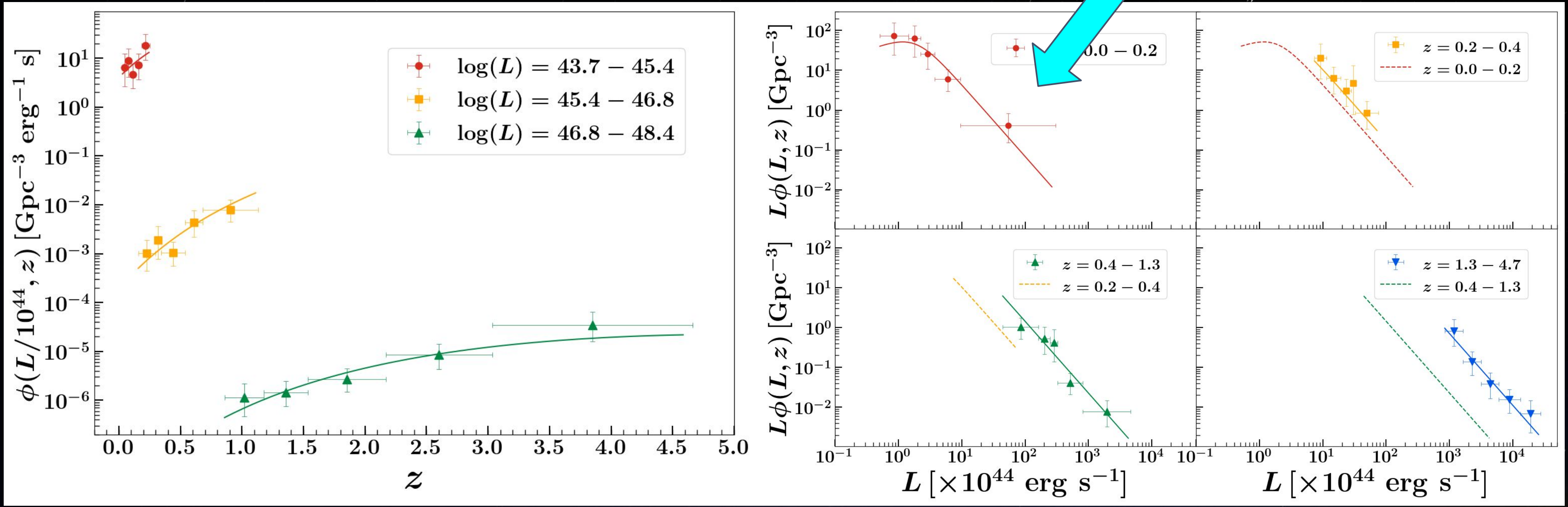


Evolution peak @ z=4.3

Marcotulli et al., 2022

Best-fit XLF PDE/PLE

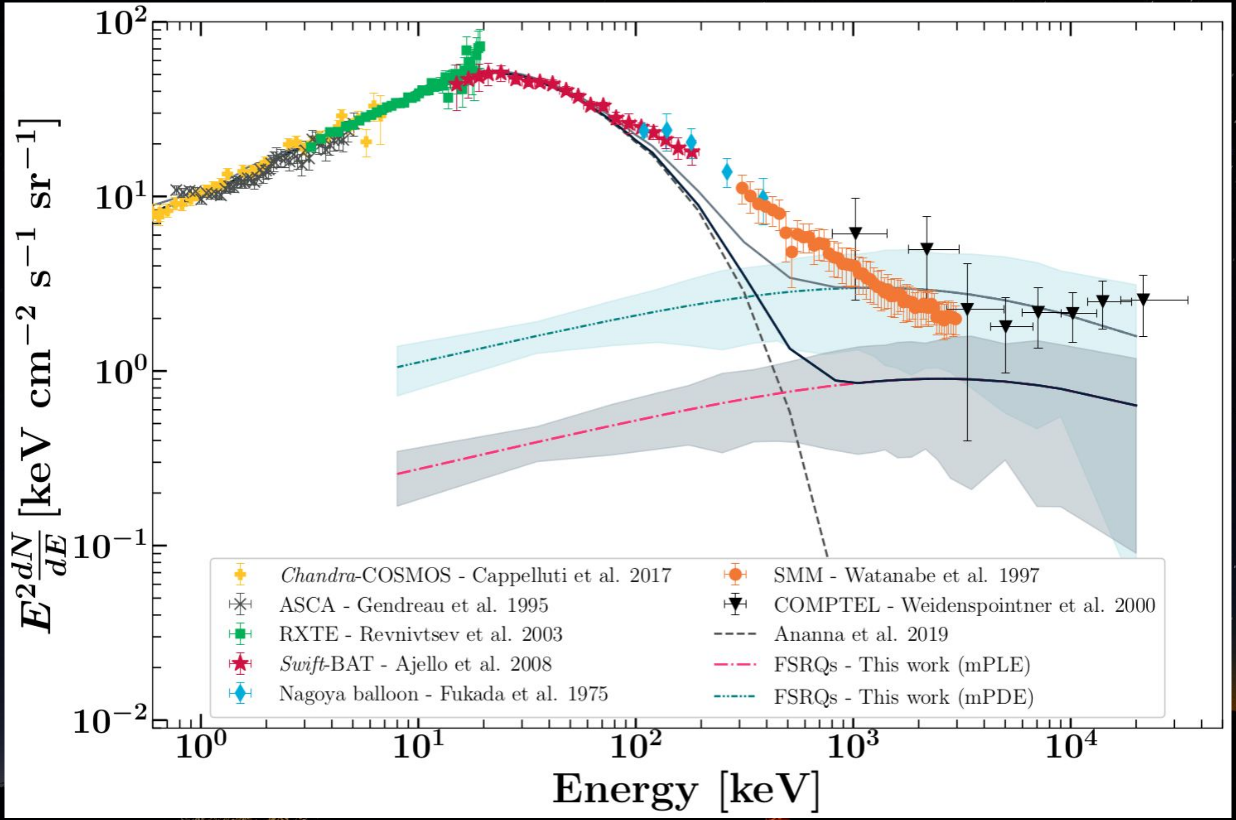
It's a power law!



Marcotulli et al., 2022

CXB Contribution of FSQRs

~9% for PDE
~2% for PLE

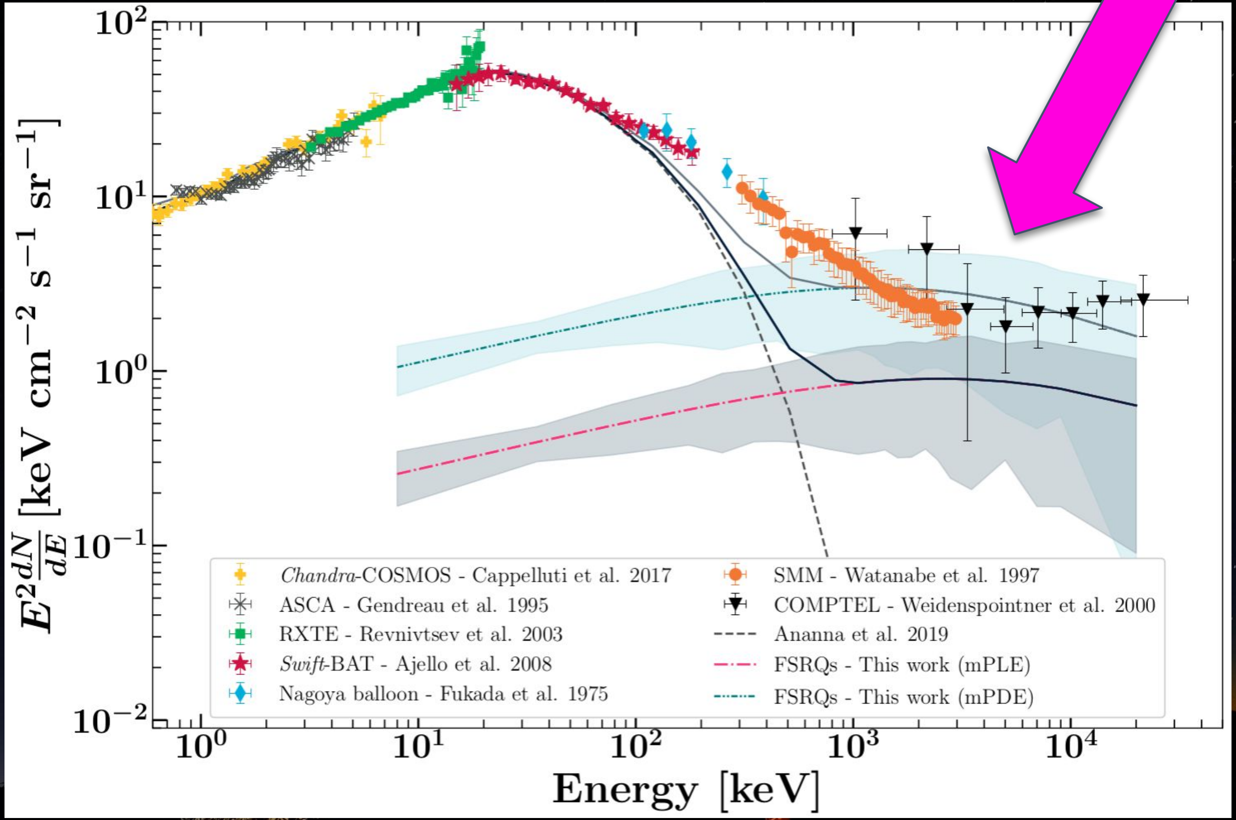


Marcotulli et al., 2022

CXB Contribution of FSQRs

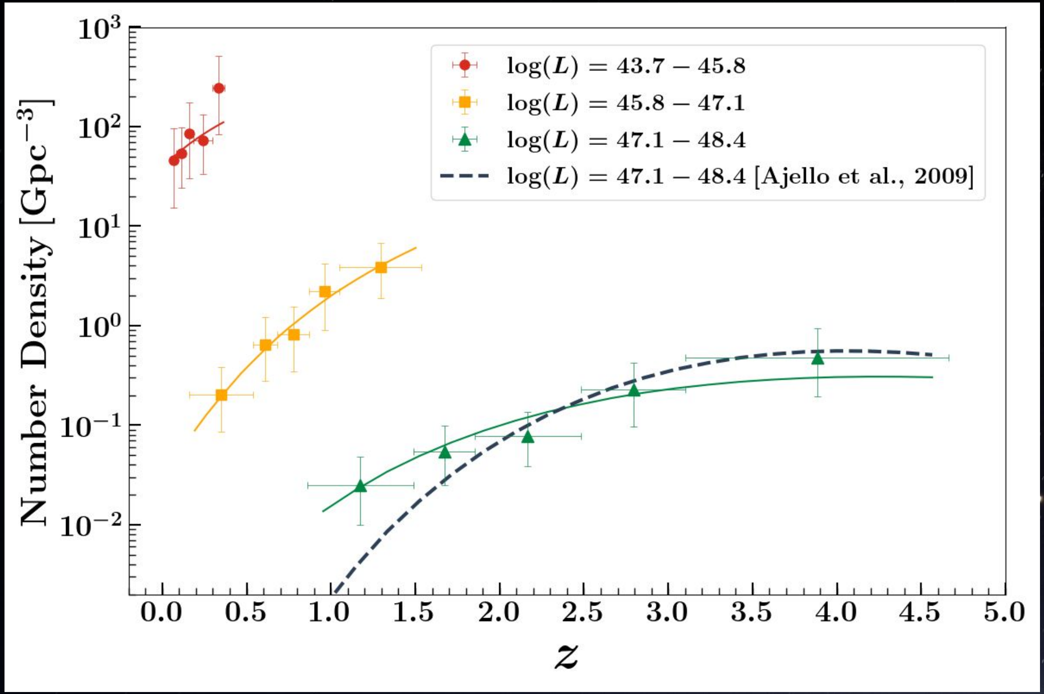
~70-100% of the MeV background

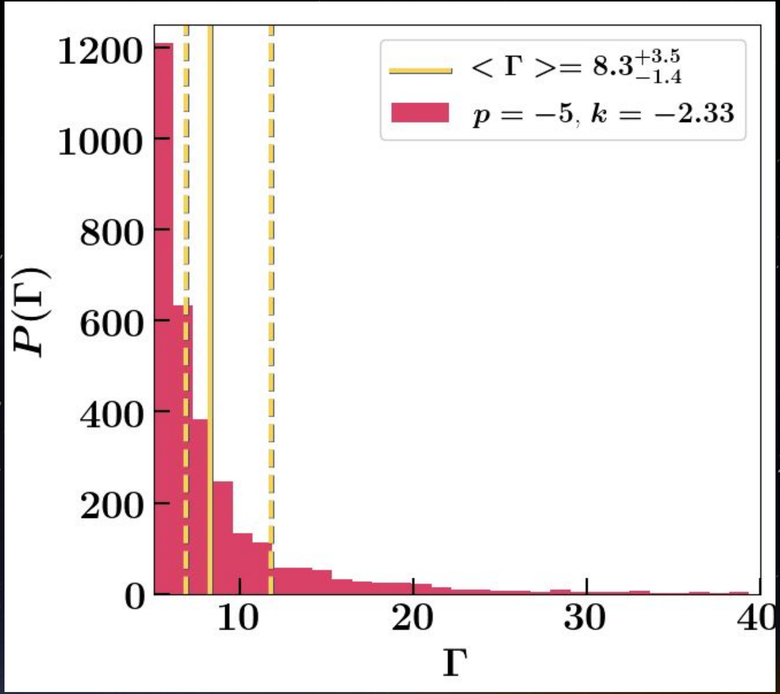
~9% for PDE
~2% for PLE



Marcotulli et al., 2022

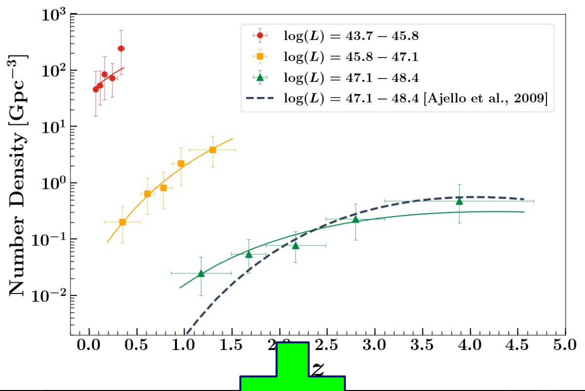
Number densities & Γ distribution

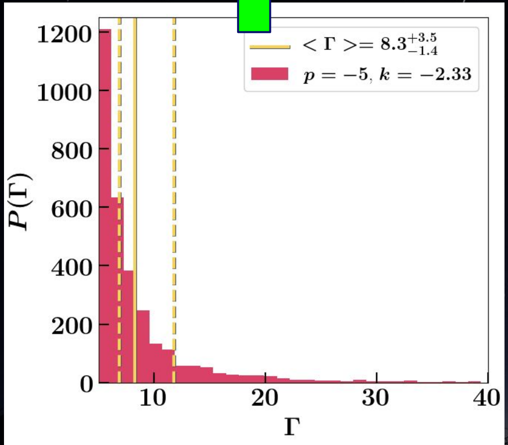


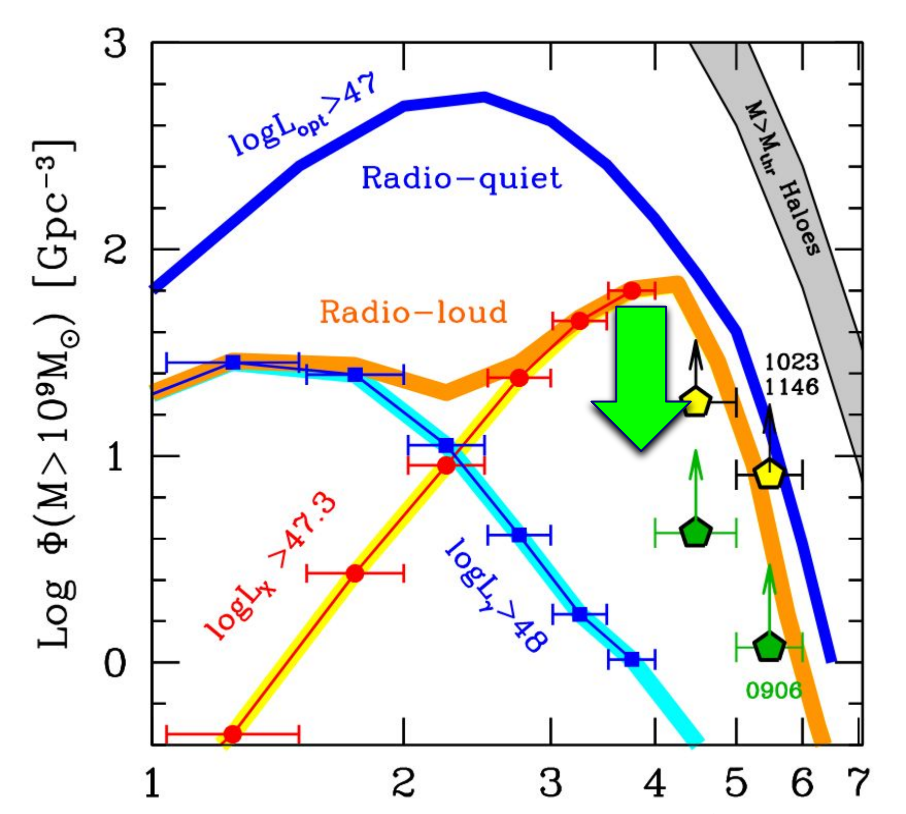


Marcotulli et al., 2022

SMBH space densities



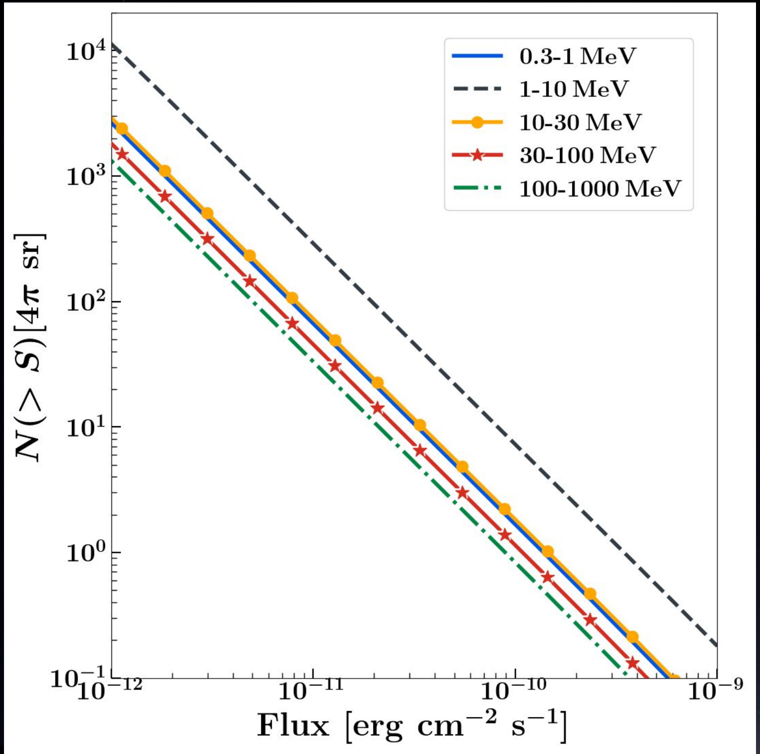




Sbarrato et al. (2015)

Marcotulli et al., 2022, see Sbarrato+2022

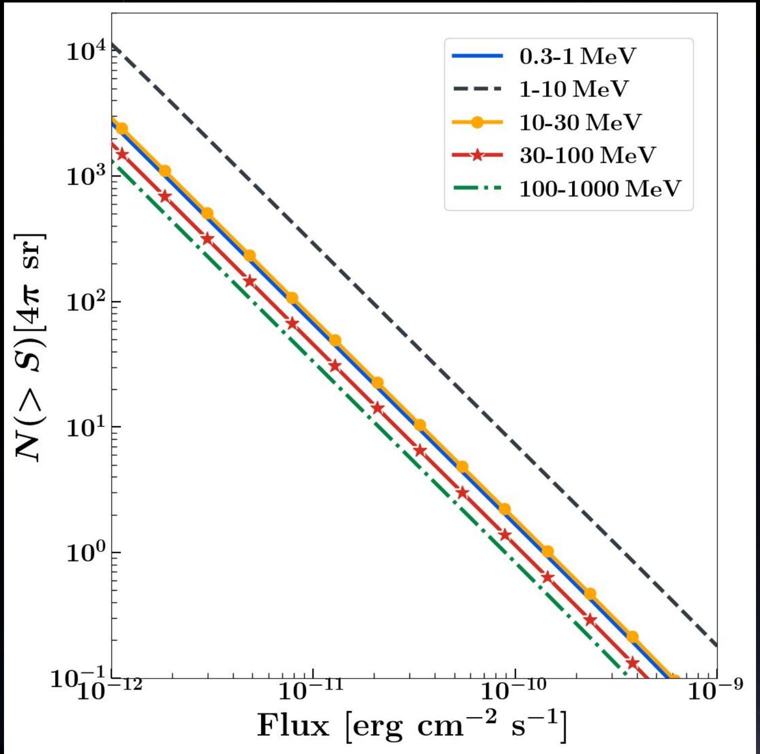
Predictions for MeV missions

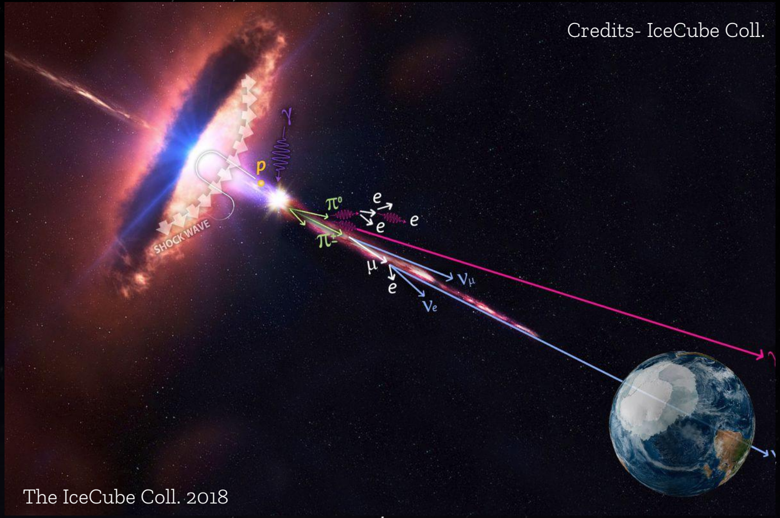


MISSION	Sensitivity	N(>S) [4π sr]	Timeline
Fermi - LAT	>2x10^{-12} erg cm^{-2} s^{-1} (20-200 MeV in 10 years)	~1000	Operational since 2008
COSI	>4x10^{-12} erg cm^{-2} s^{-1} (0.2-5 MeV in 2 years)	~40	Launch expected in 2027
AMEGO-X	>1.6x10^{-11} erg cm^{-2} s^{-1} (1-10 MeV in 3 year)	~130	Future NASA MIDEX calls (launch ~2030)
ASTROGAM	>5x10^{-12} erg cm^{-2} s^{-1} (1-10 MeV in 1 year)	~832	Future ESA mission calls

Marcotulli et al., 2022

Neutrino prediction

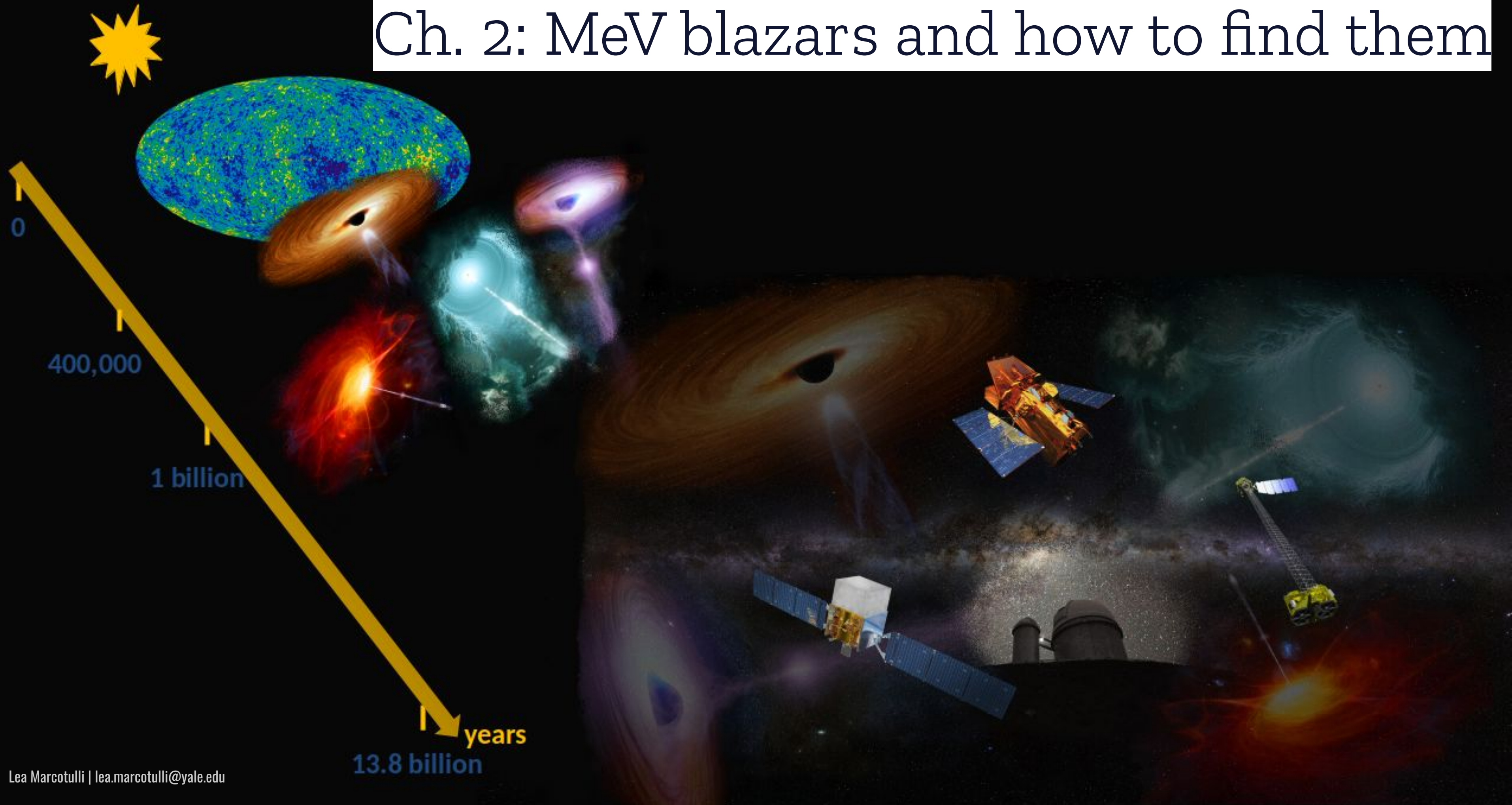




MISSION	Number of coincident neutrinos
COSI	2^{+1}_{-1}
AMEGO-X	4^{+1}_{-1}
ASTROGAM	5^{+1}_{-1}
LOX	11^{+1}_{-2}

Marcotulli et al., 2022

Ch. 2: MeV blazars and how to find them

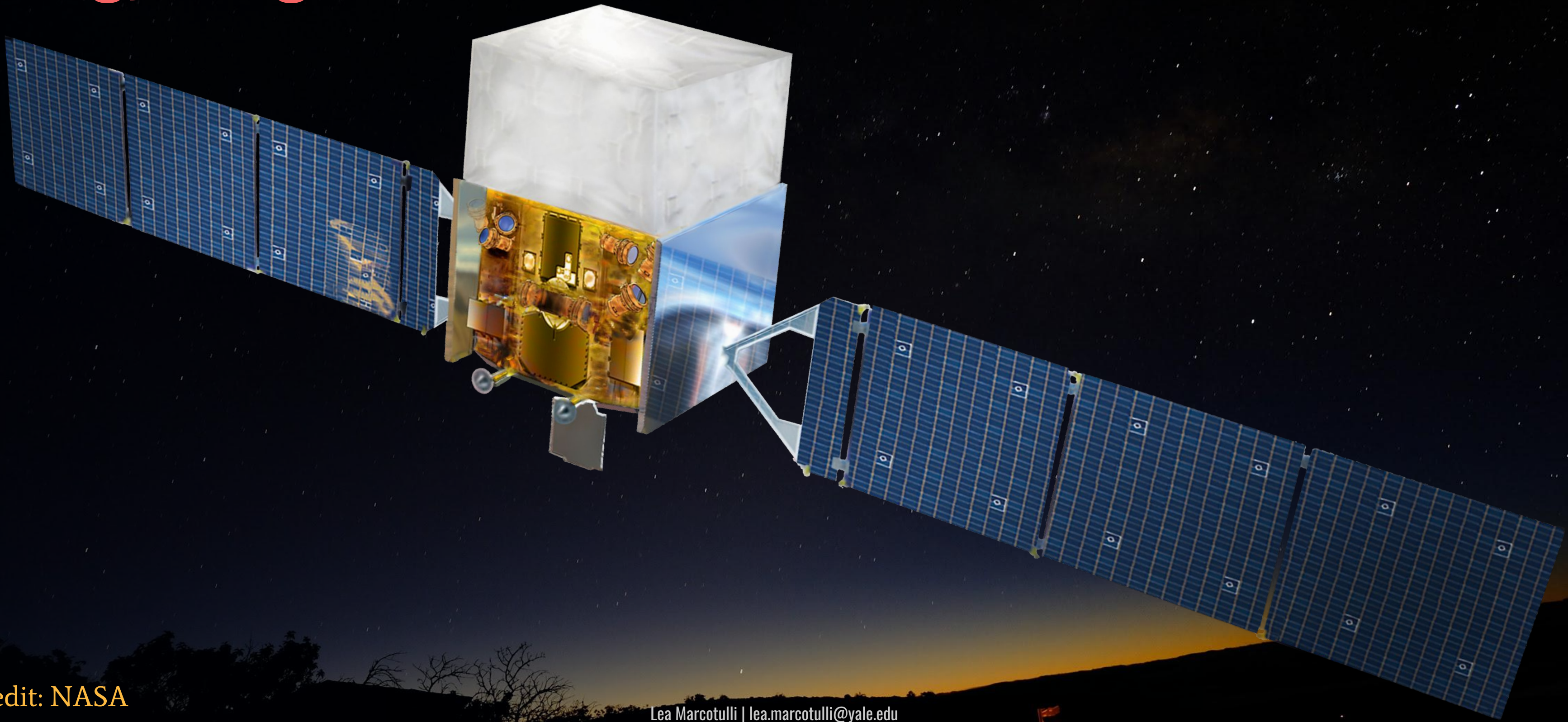


The Strategy

MeV blazars are hard to detect despite being bright!

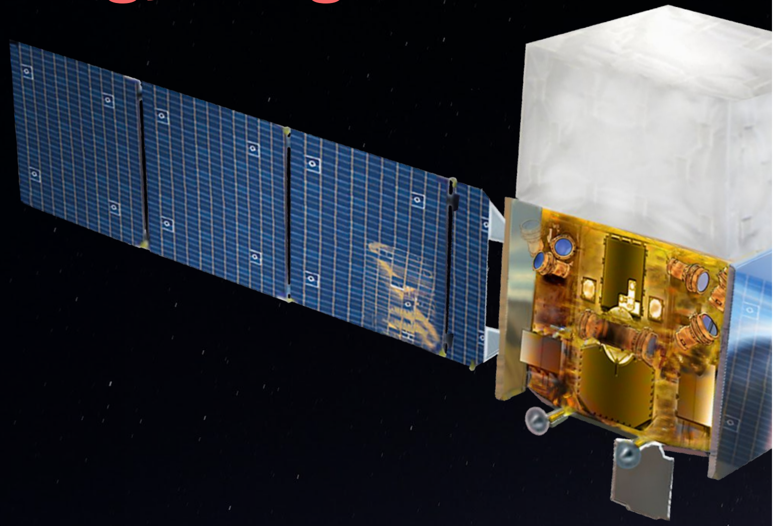
Fermi-Large Area Telescope (LAT)
Energy range: 50 MeV-2 TeV

The Strategy



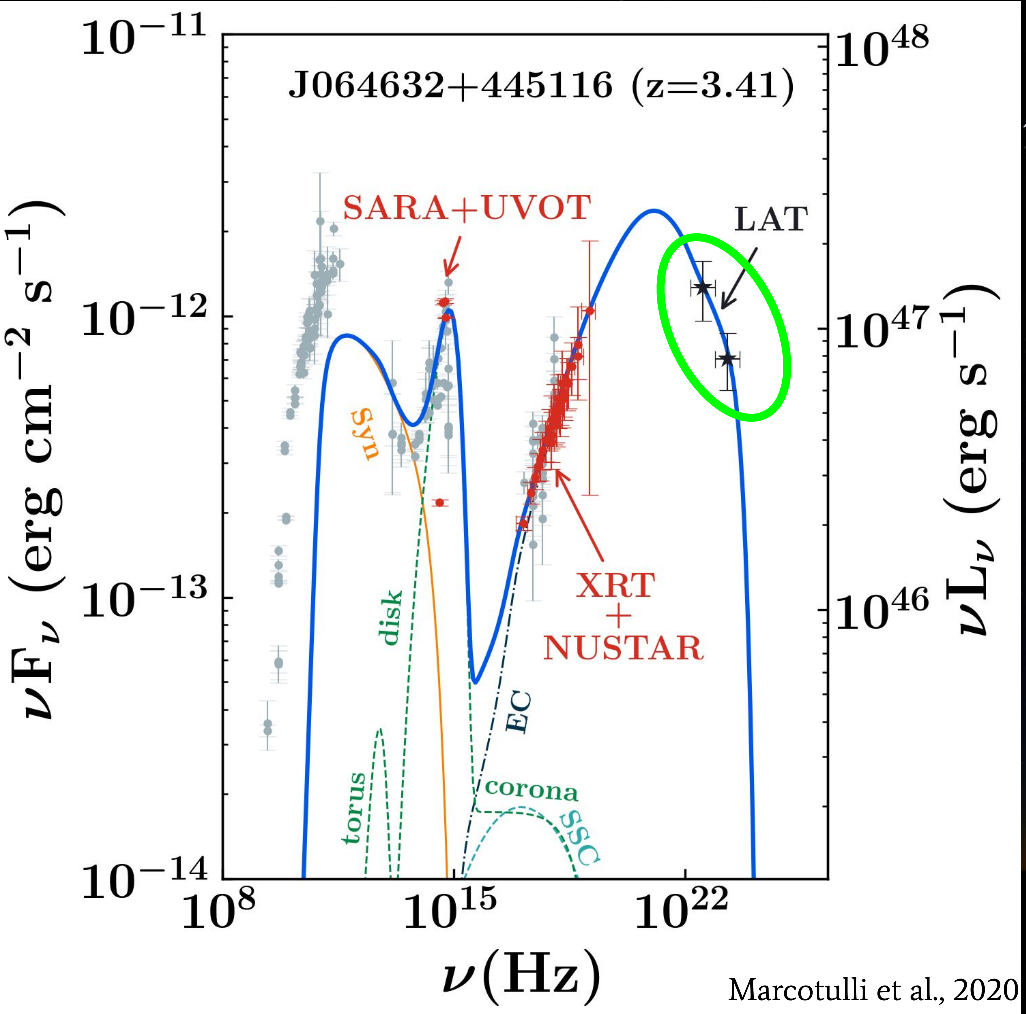
Credit: NASA

Fermi-Large Area Telesco
Energy range: 50 MeV-2



Credit: NASA

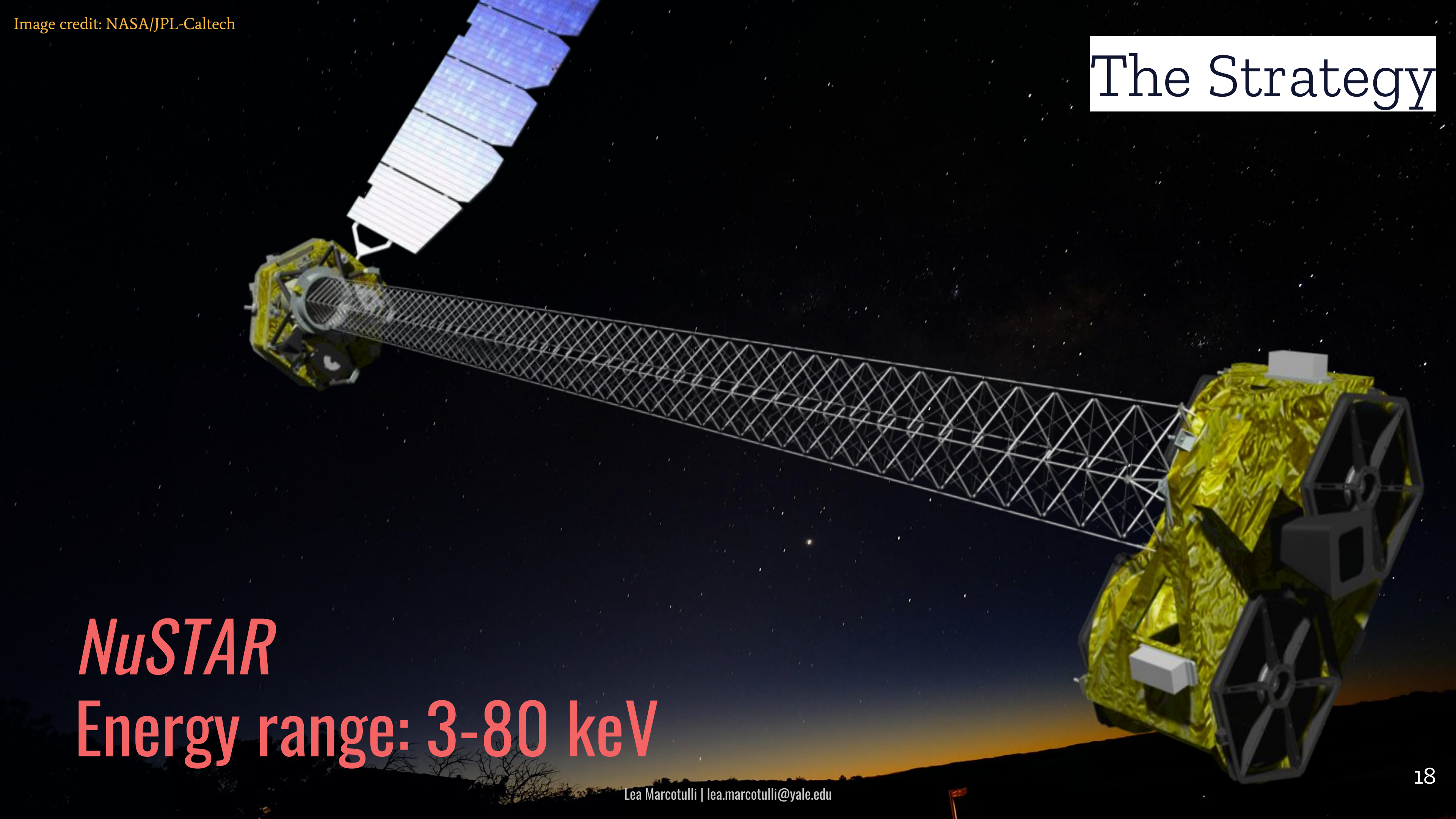
Lea Ma



Marcotulli et al., 2020

The Strategy

Image credit: NASA/JPL-Caltech

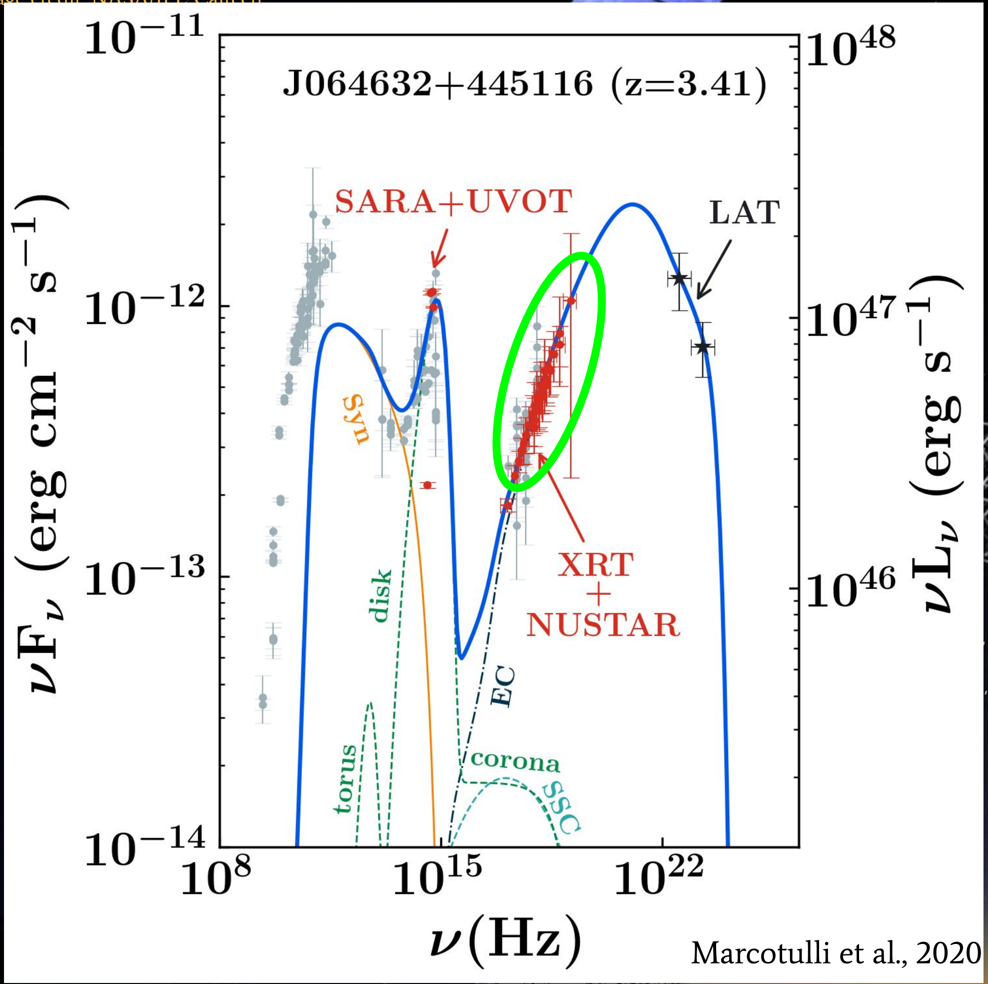


NuSTAR

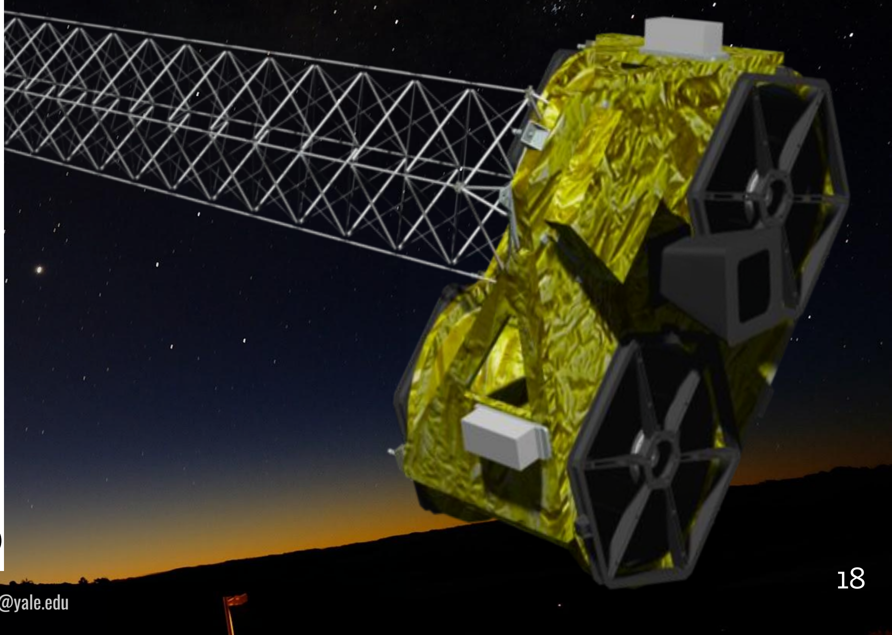
Energy range: 3-80 keV

Image credit: NASA/JPL-Caltech

The Strategy



Marcotulli et al., 2020



Swift X-ray Telescope (XRT)
Energy range: 0.3-10 keV

The Strategy


Image credit: NASA/GSFC/Spectrum Astro.

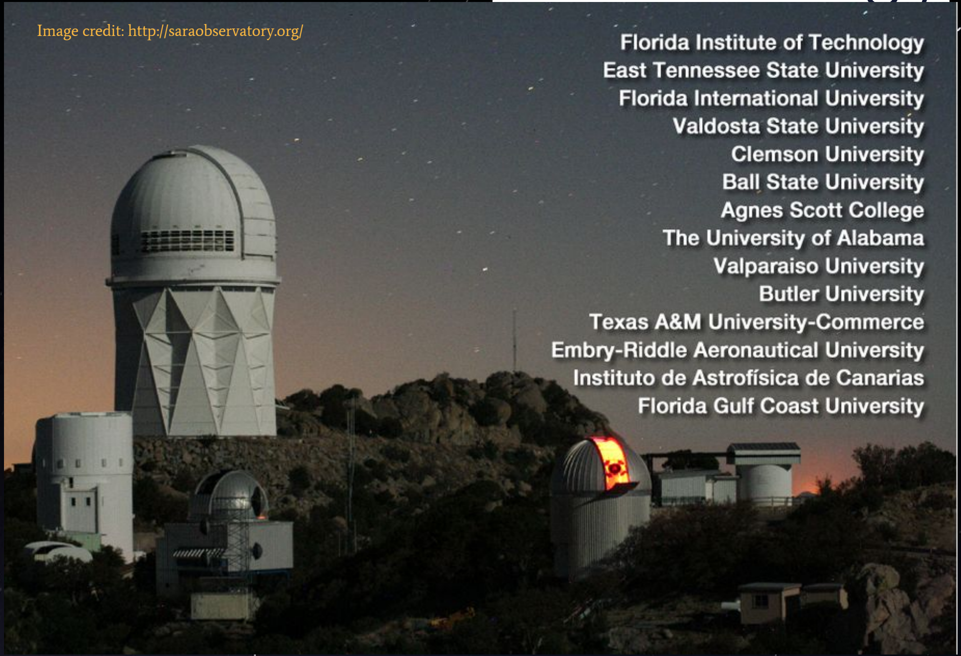
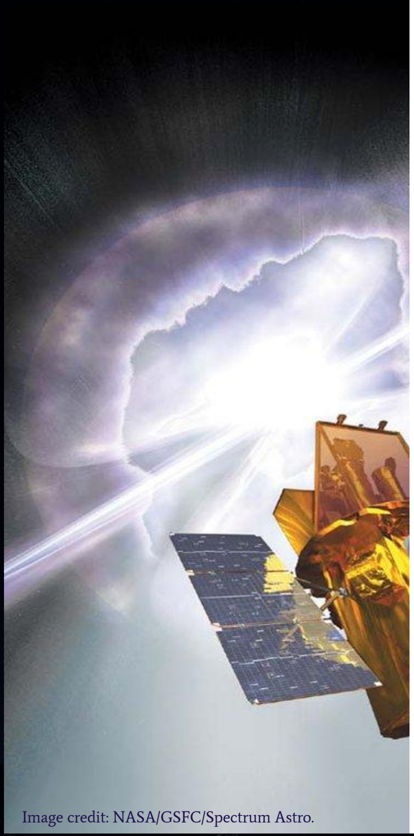


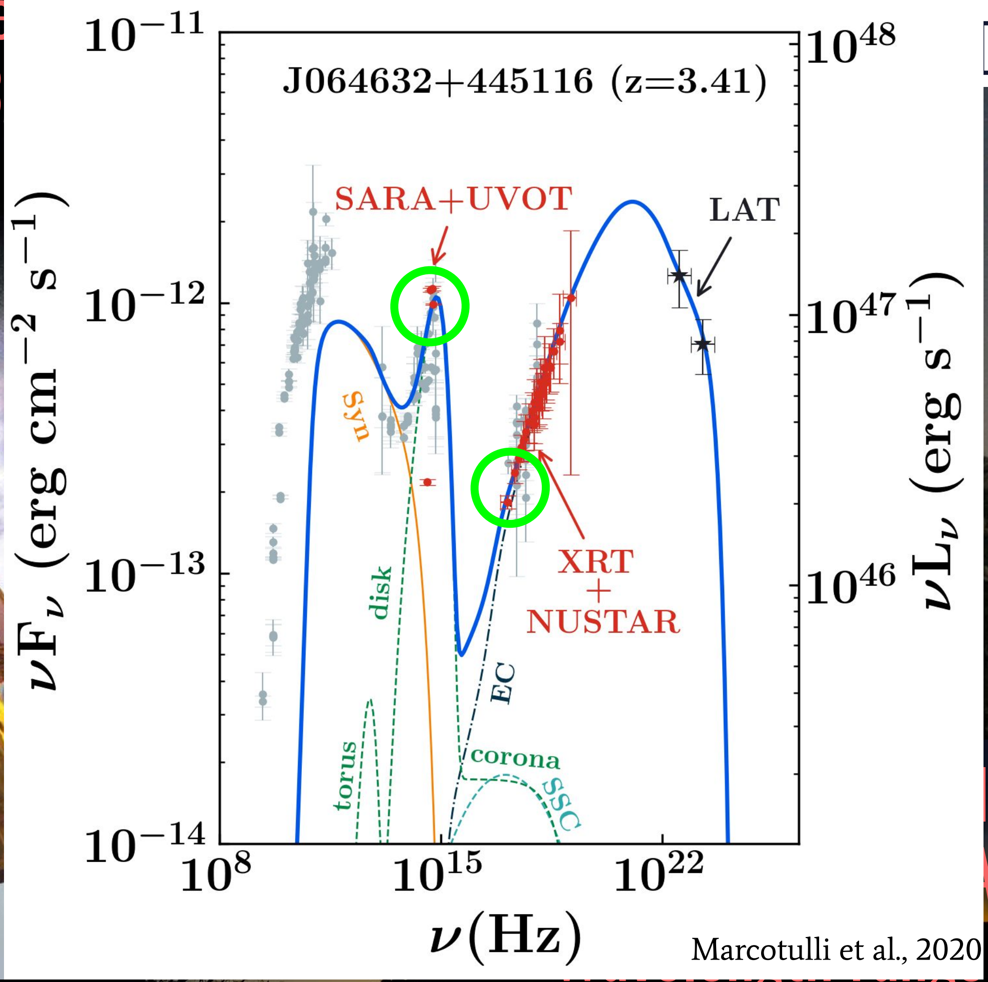
Image credit: http://saraobservatory.org/

Florida Institute of Technology
East Tennessee State University
Florida International University
Valdosta State University
Clemson University
Ball State University
Agnes Scott College
The University of Alabama
Valparaiso University
Butler University
Texas A&M University-Commerce
Embry-Riddle Aeronautical University
Instituto de Astrofísica de Canarias
Florida Gulf Coast University

Swift Optical and UV Telescope (UVOT)
& SARA Telescopes
Wavelength range: 9000-1700 Å

Swift X-ray Tele
Energy range: 3





Marcotulli et al., 2020

The Strategy

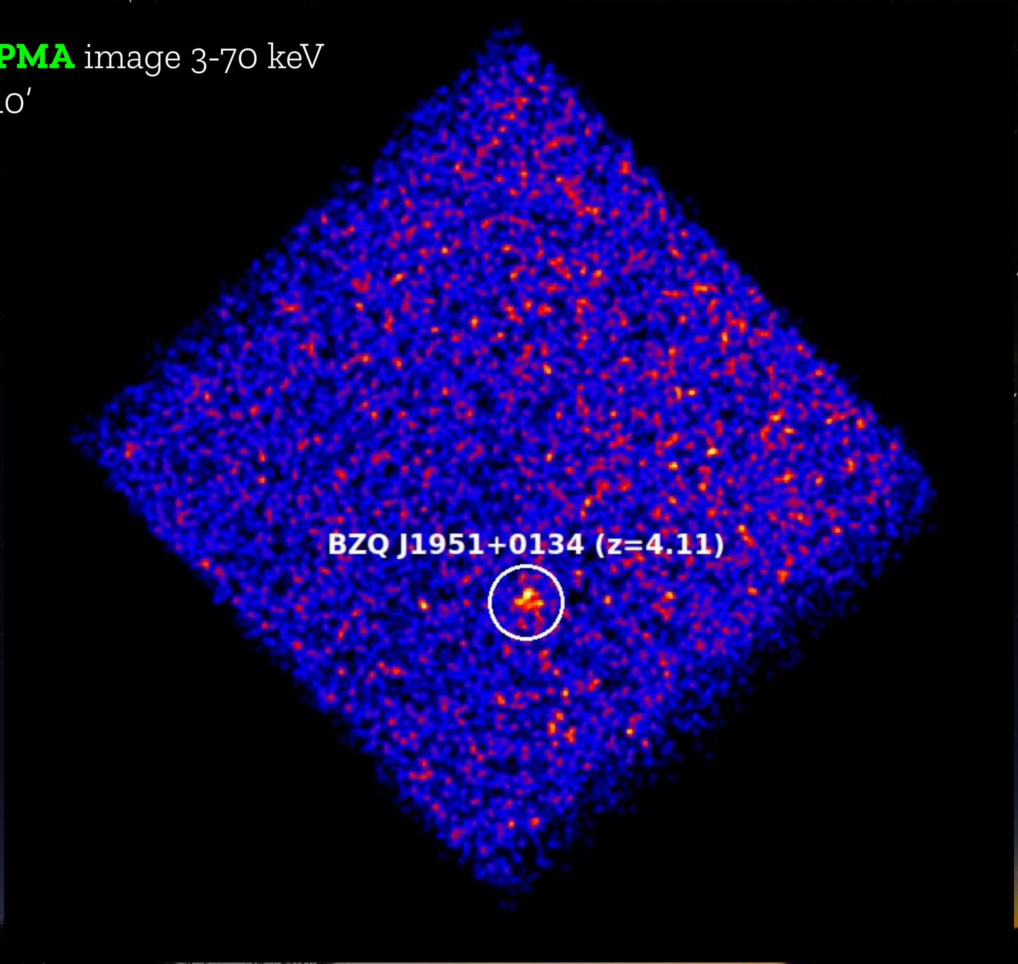
lescope (UVOT)
ARA Telescopes
: 9000-1700 Å

Beyond z=4


75°
60°
30°
15°
0°
-15°
-30°
-45°
-60°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
Florida Institute of Technology
East Tennessee State University
Florida International University
Valdosta State University
Clemson University
Ball State University
Agnes Scott College
The University of Alabama
Valparaiso University
Butler University
Texas A&M University-Commerce
Embry-Riddle Aeronautical University
Instituto de Astrofísica de Canarias
Florida Gulf Coast University

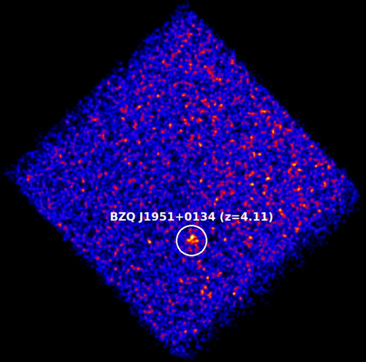
Beyond z=4

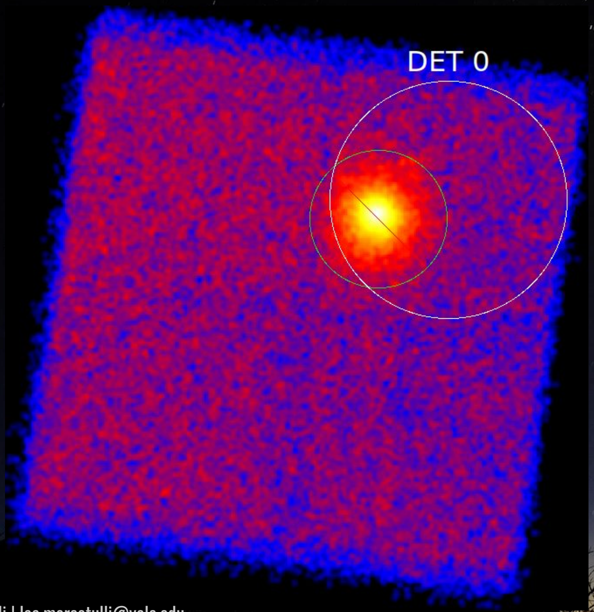
NuSTAR **FPMA** image 3-70 keV
FoV = 10′x10′

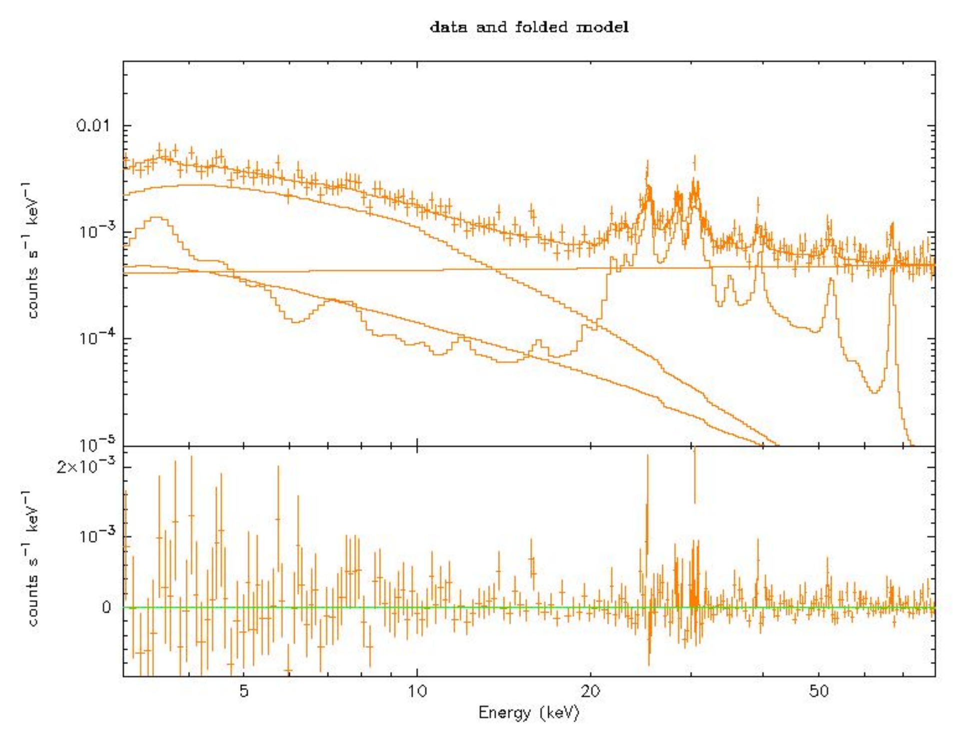


NuSTAR Background

Wik+2014

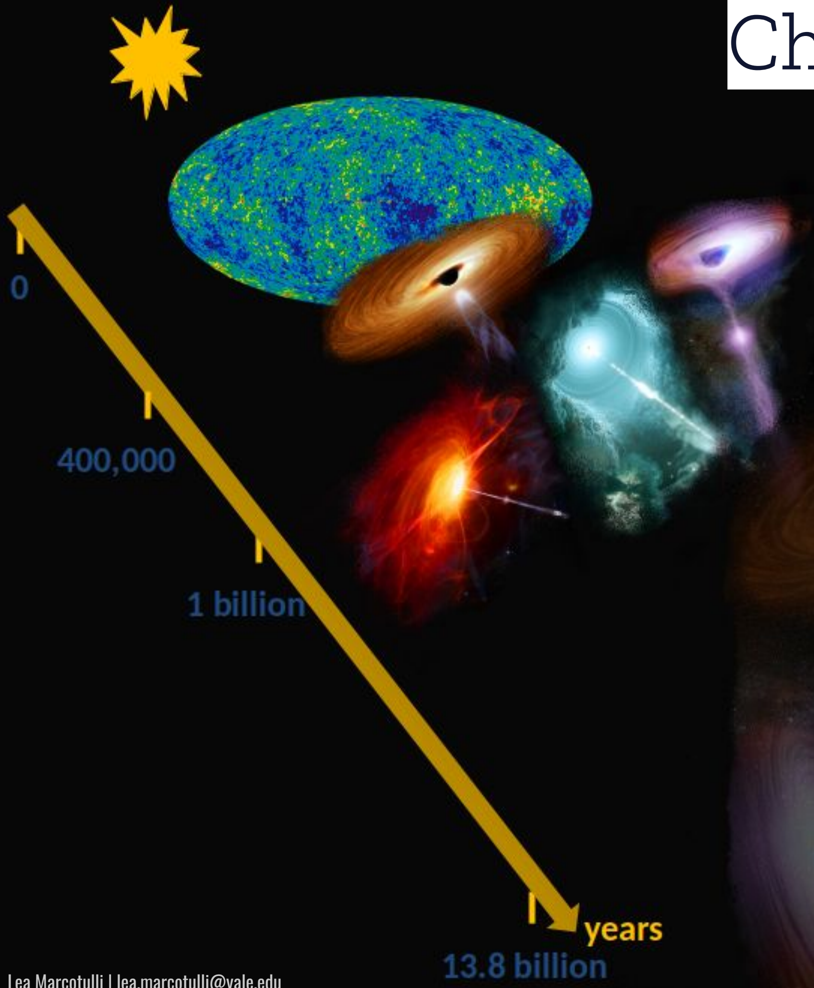


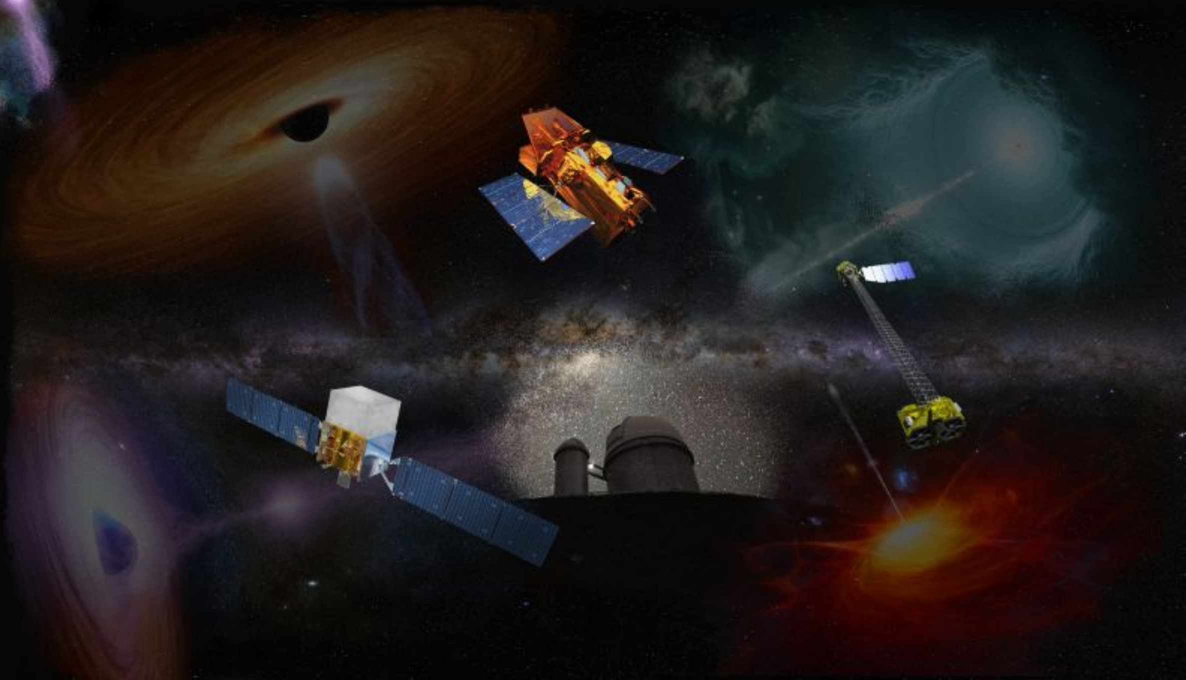


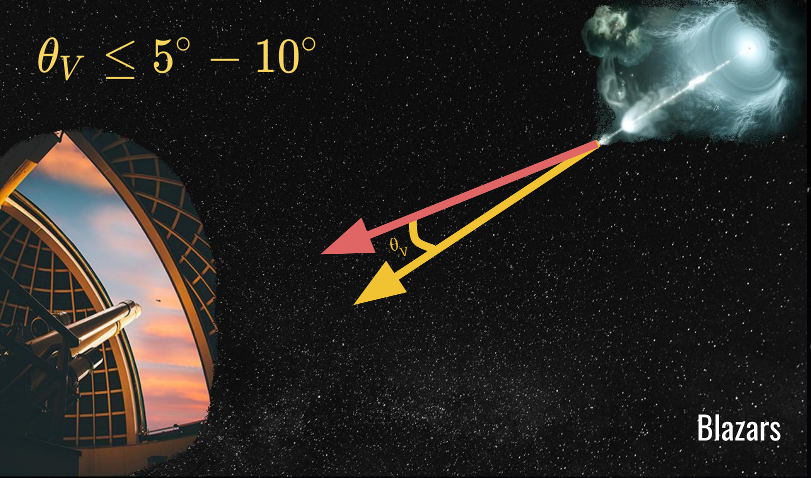


WORK IN PROGRESS

Ch. 3: The future for MeV science



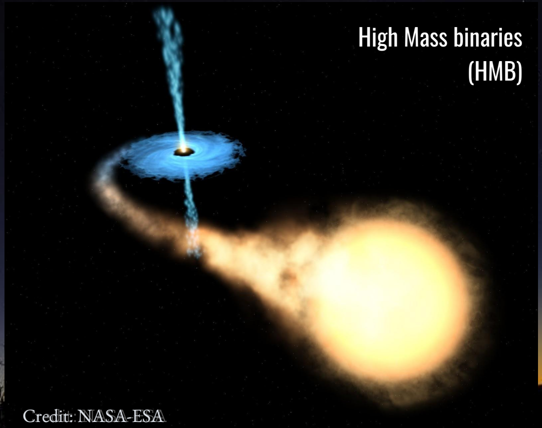



$\theta_V \leq 5^\circ - 10^\circ$
θ_V
Blazars


Pulsars
Credit: Hubble

The MeV sky

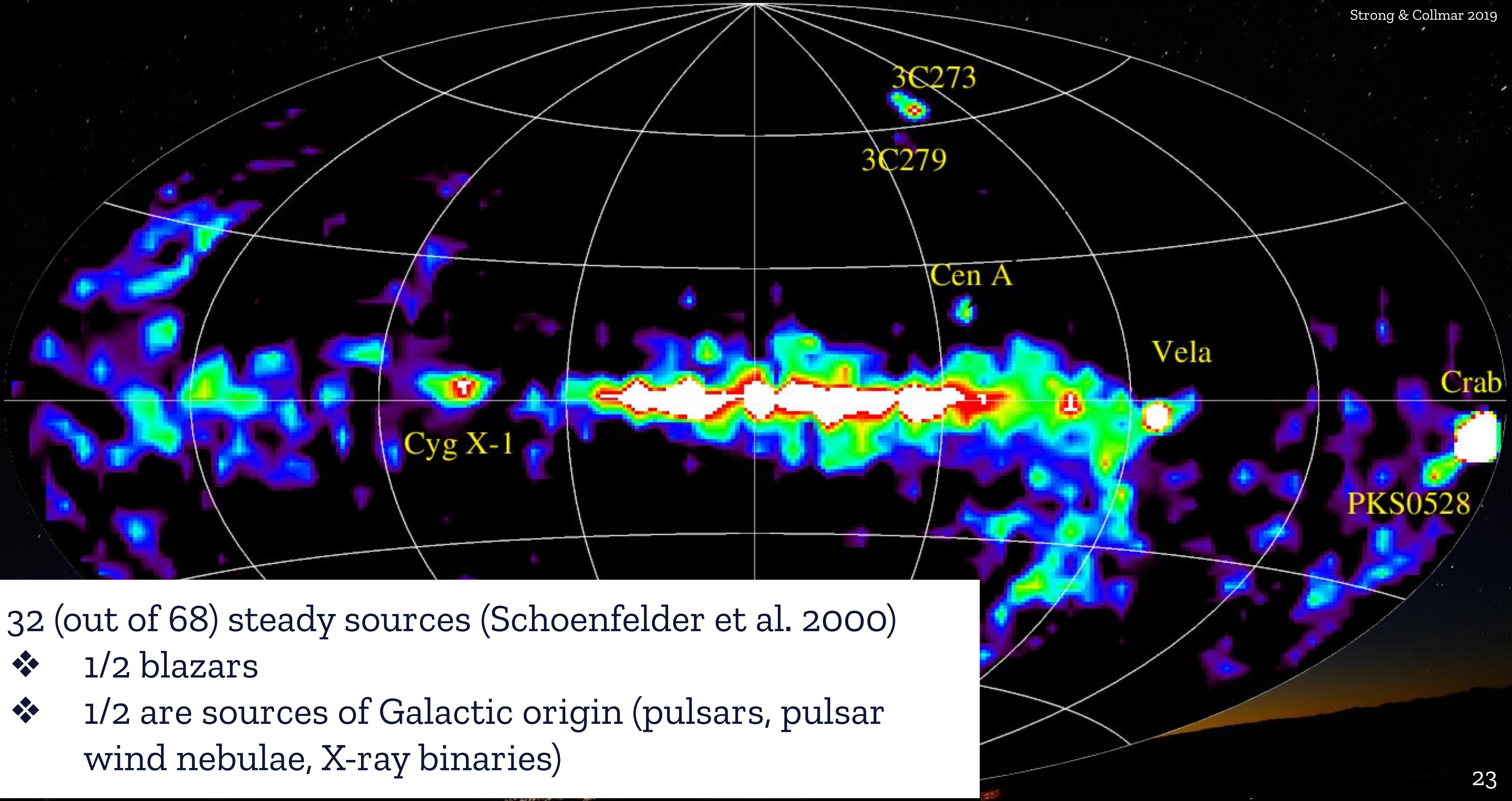

Supernova Remnants
(SNRs)
Credit: Hubble


High Mass binaries
(HMB)
Credit: NASA-ESA

?

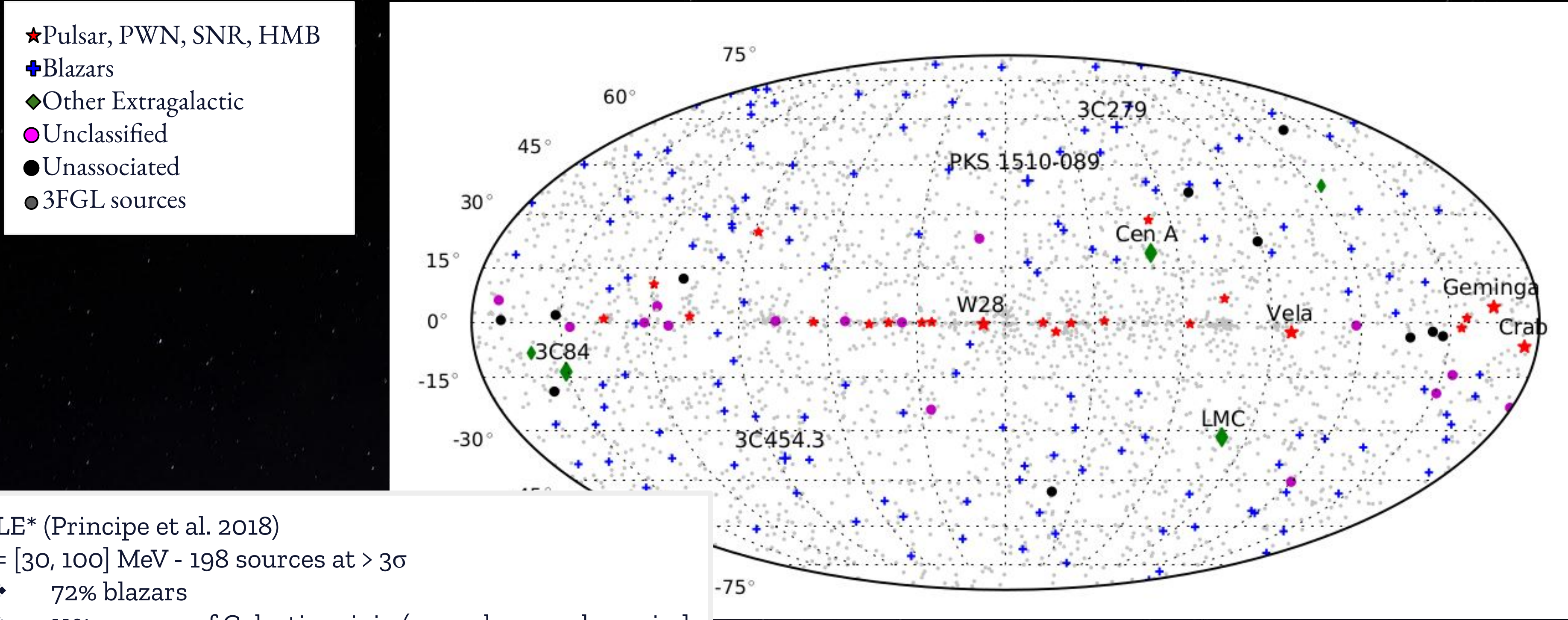
All-sky 1-30 MeV COMPTEL intensity map; Credit: COMPTEL Collaboration

Strong & Collmar 2019



32 (out of 68) steady sources (Schoenfelder et al. 2000)

- ❖ 1/2 blazars
- ❖ 1/2 are sources of Galactic origin (pulsars, pulsar wind nebulae, X-ray binaries)



1FLE all-sky map, Principe et al. 2018

1FLE* (Principe et al. 2018)

E = [30, 100] MeV - 198 sources at > 3σ

- 72% blazars
- 11% sources of Galactic origin (e.g. pulsars, pulsar wind nebulae, high mass binaries)
- 3% other AGN type
- 9% unclassified
- 5% unassociated with the 3FGL

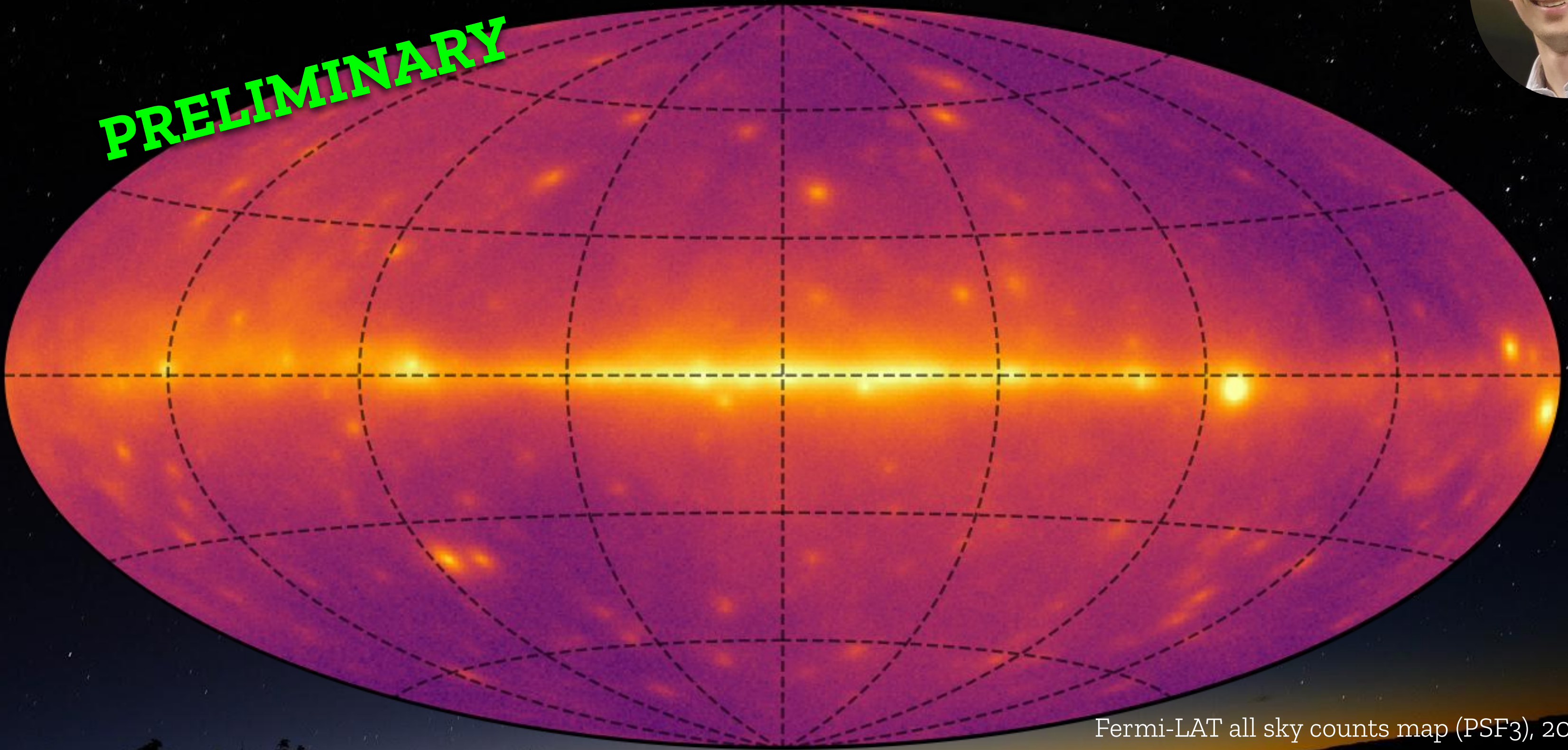
* 8 years data

**wavelet detection algorithm

***no diffuse emission model used

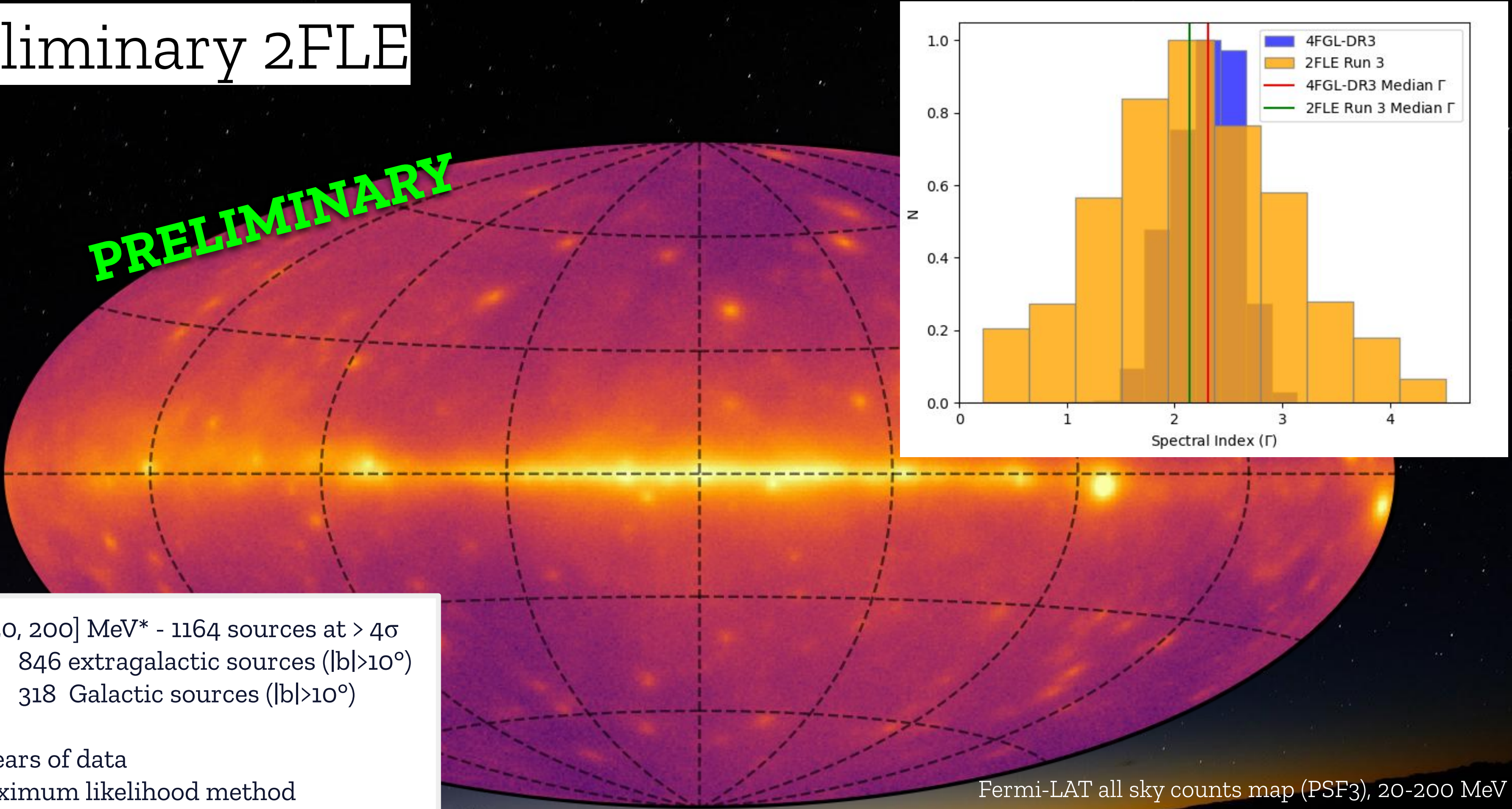
Preliminary 2FLE

Joffre S., **Marcotulli L.** et al. in prep



Fermi-LAT all sky counts map (PSF3), 20-200 MeV

Preliminary 2FLE



E = [20, 200] MeV* - 1164 sources at > 4σ

- ❖ 846 extragalactic sources (|b|>10°)
- ❖ 318 Galactic sources (|b|>10°)

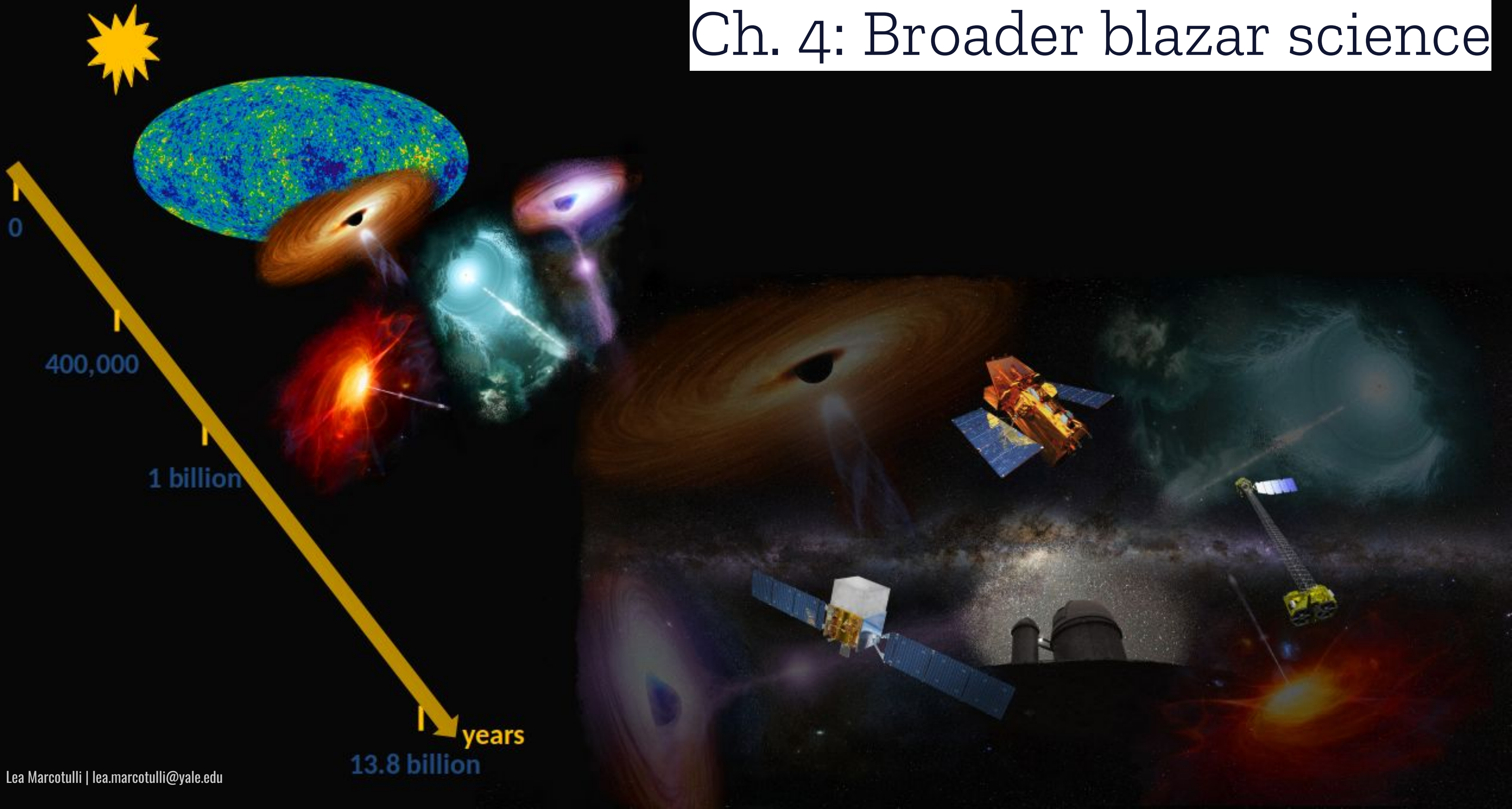
*14 years of data
**maximum likelihood method
***galactic diffuse+isotropic models

Fermi-LAT all sky counts map (PSF3), 20-200 MeV

The Compton Spectrometer and Imager (COSI)

E = 0.2-5 MeV
https://cosi.ssl.berkeley.edu/

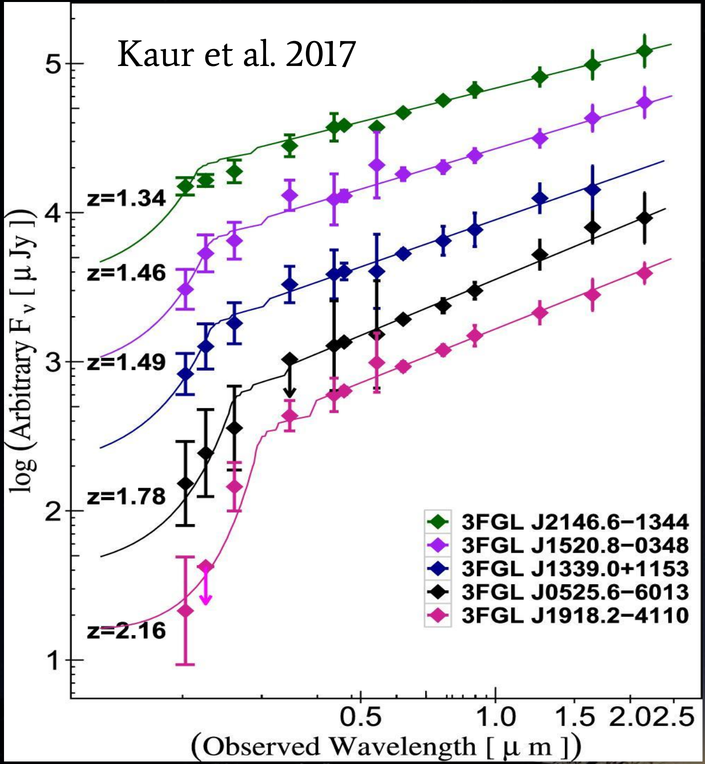
Ch. 4: Broader blazar science



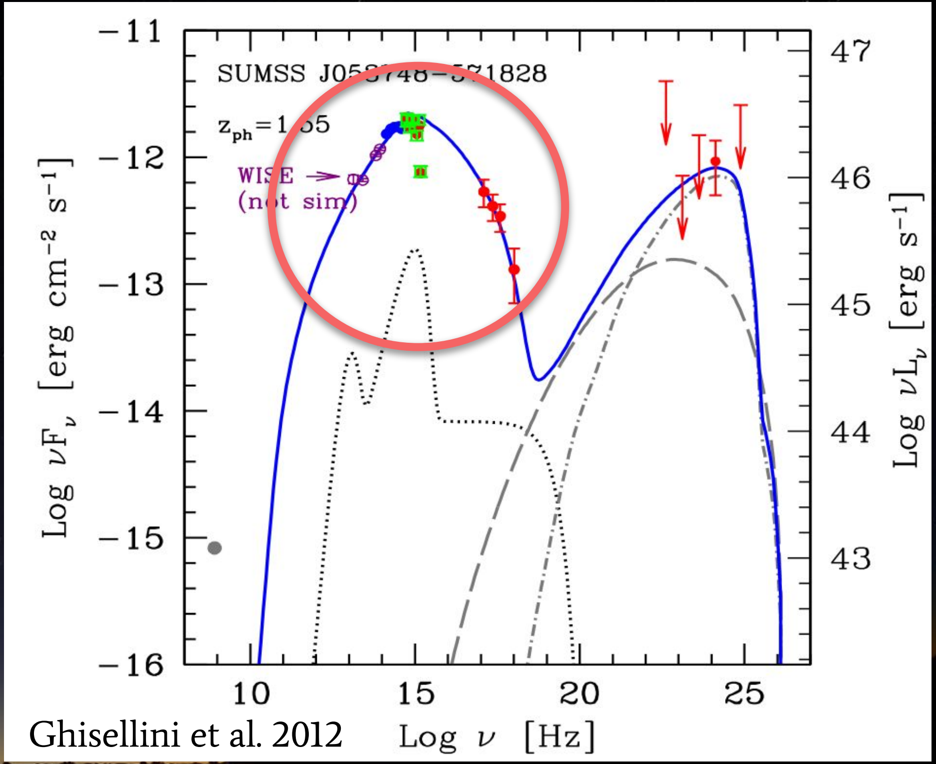
Lea Marcotulli | lea.marcotulli@yale.edu

Blazar sequence: a selection effect?

Photometric redshift



SED modeling

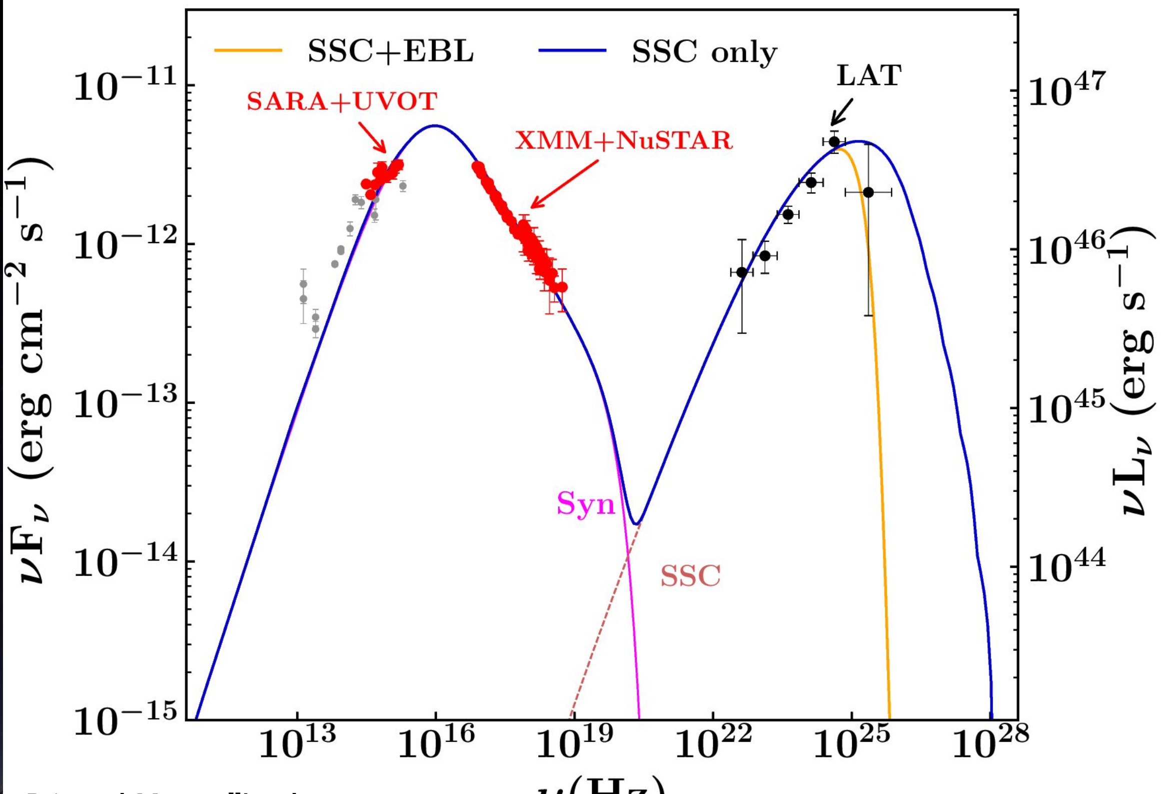


Blazar sequence: a selection effect?

3FGL J2146.5-1344

1. z=1.34
2. L_γ = 6 x 10^{46} erg s^{-1}
3. L_X>5x10^{46} erg s^{-1}
4. $P_{1.4GHZ}$=2.59 × 10^{26} WHz^{-1}

From modeling, both BL Lac and FSRQ scenario work well

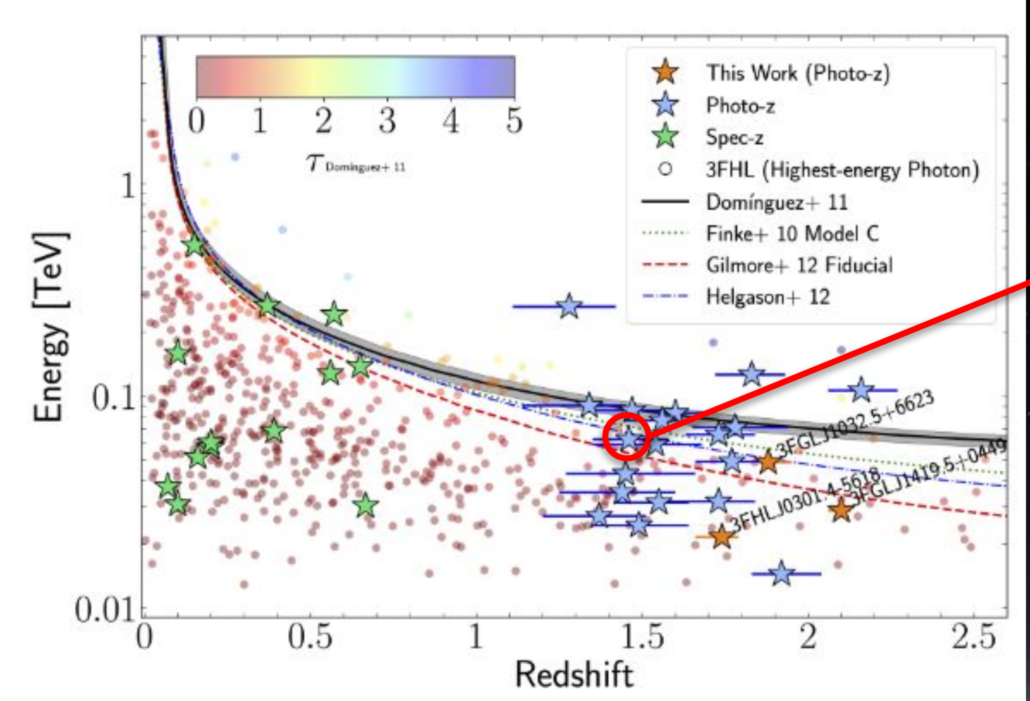


Rajagopal, **Marcotulli** et al. 2021

Work by Dr. Meenakshi Rajagopal

Need to find more sources!!!

Sheng et al. 2022



SARA & XMM + NuSTAR follow-up of 3FGL J1520.8-0348

$z=1.46$, ν_{peak}~10^{15} Hz

→ SED modeling

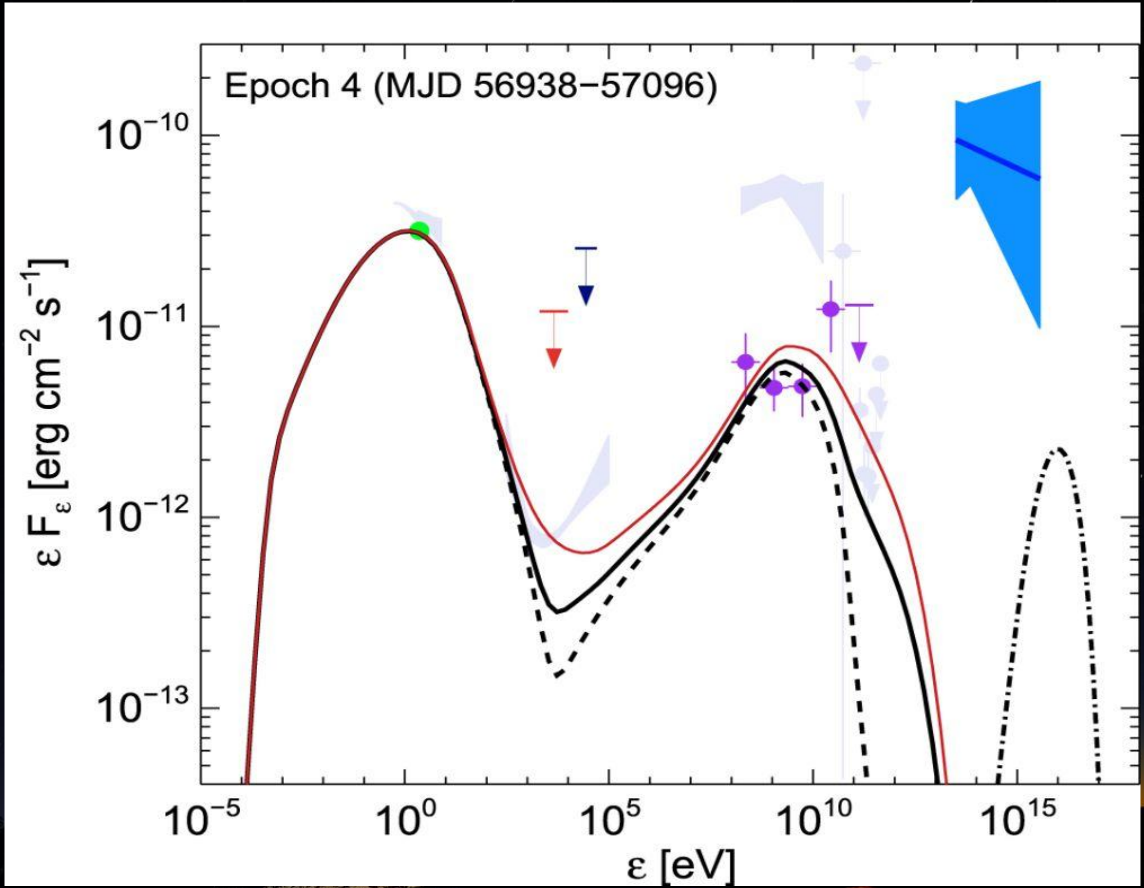
Work by **Garima Rajguru**

See 3FHL campaign: Kaur et al. 2017; Kaur et al. 2019; Marchesi et al. 2018; Desai et al. 2019; Rajagopal et al. 2021; Rajagopal, **Marcotulli** et al. 2022; Sheng et al. 2022

Lea Marcotulli | lea.marcotulli@yale.edu

Hadronic vs. Leptonic models

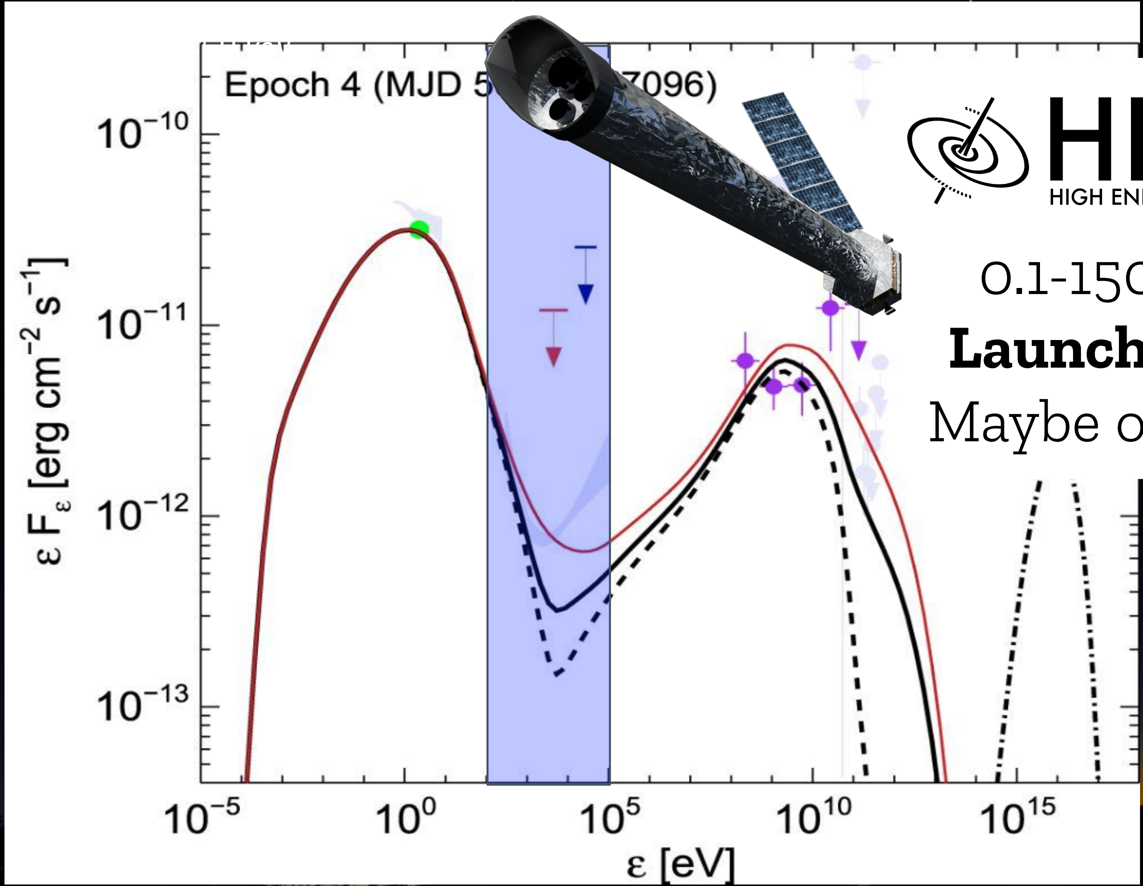
TXS 0506+056 (lepto-hadronic model, 2014 neutrino flare)



Petropoulou+2020

Hadronic vs. Leptonic models

TXS 0506+056 (lepto-hadronic model, 2014 neutrino flare)



Petropoulou+2020

HEX-P
HIGH ENERGY X-RAY PROBE

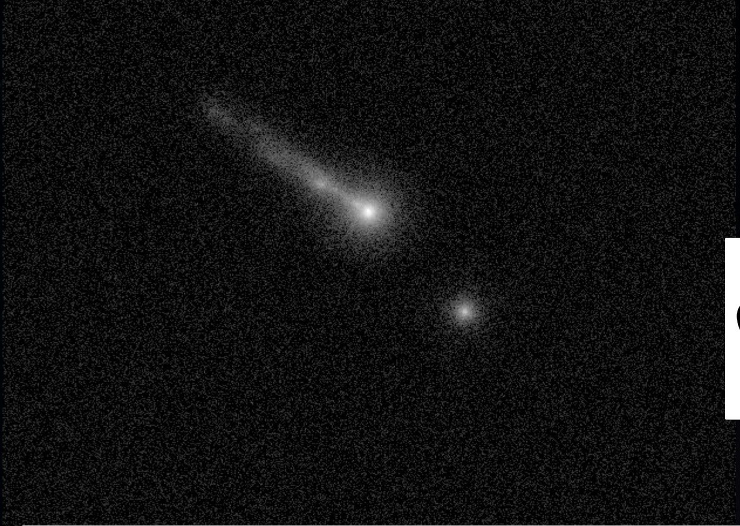
0.1-150 keV

Launch date:

Maybe one day

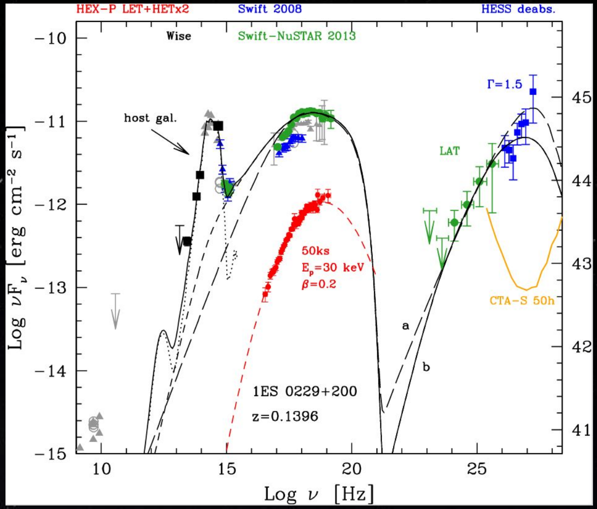
Lea Marcotulli | lea.marcotulli@yale.edu

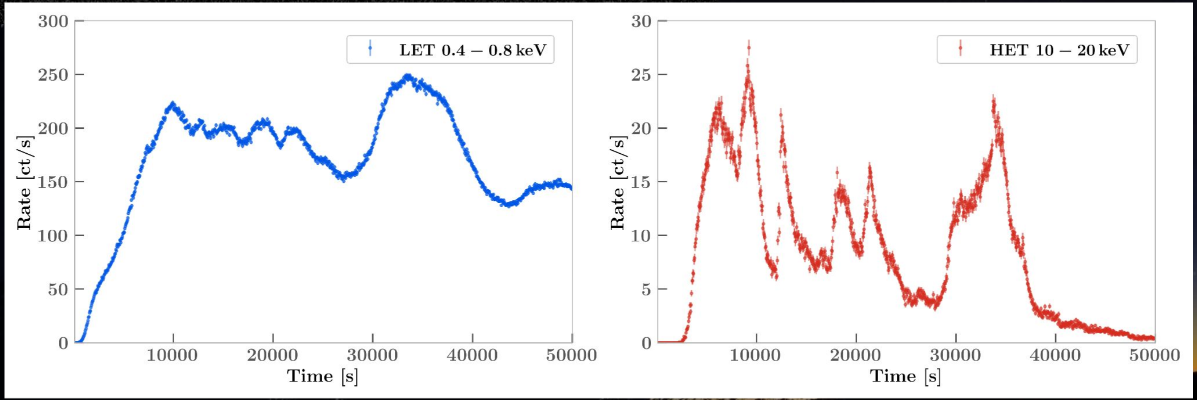
Cen A 20-50 keV with HEX-P
FoV 13'x13'

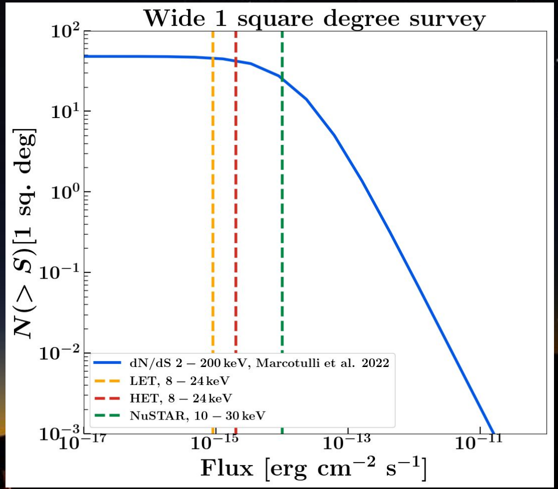


Marcotulli et al. in prep

HEX-P
HIGH ENERGY X-RAY PROBE

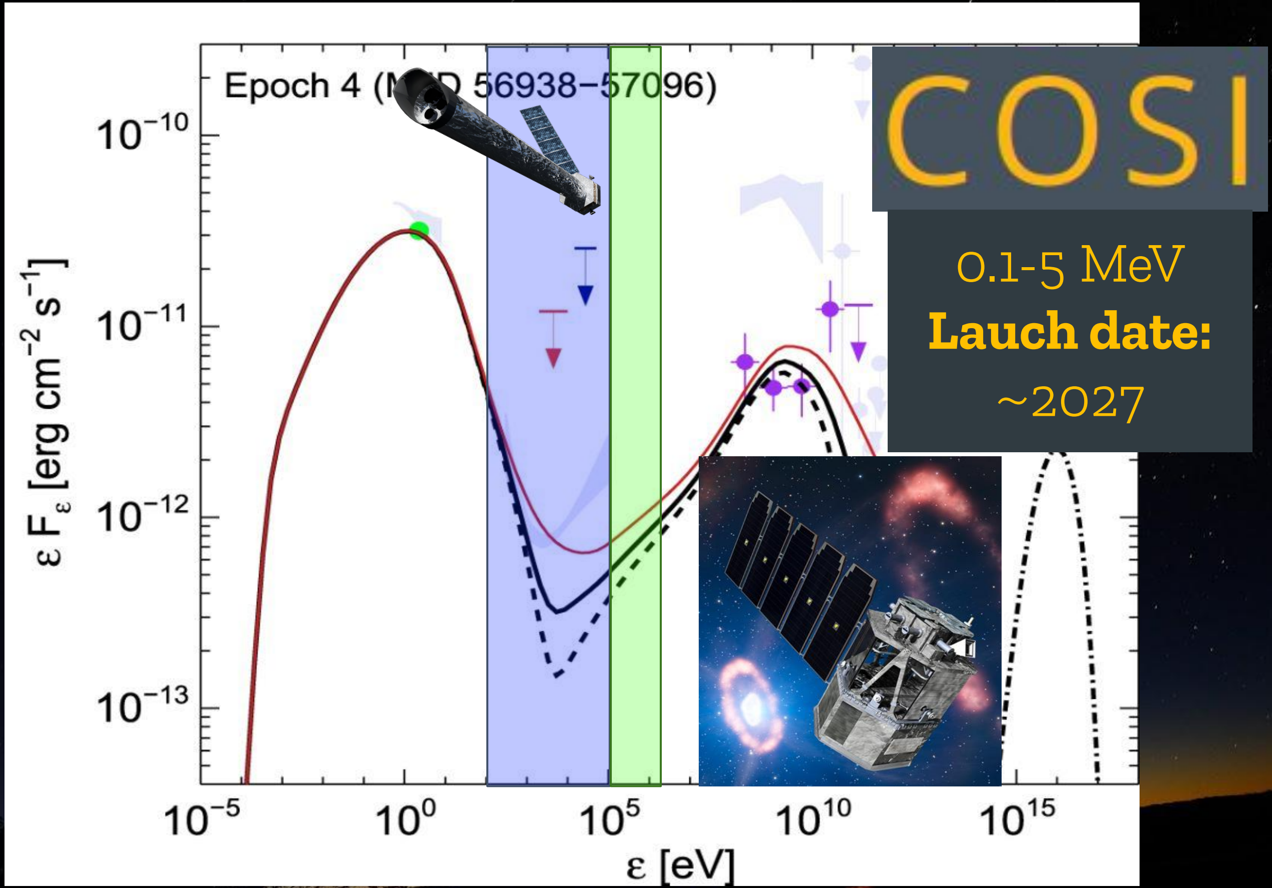






Hadronic vs. Leptonic models

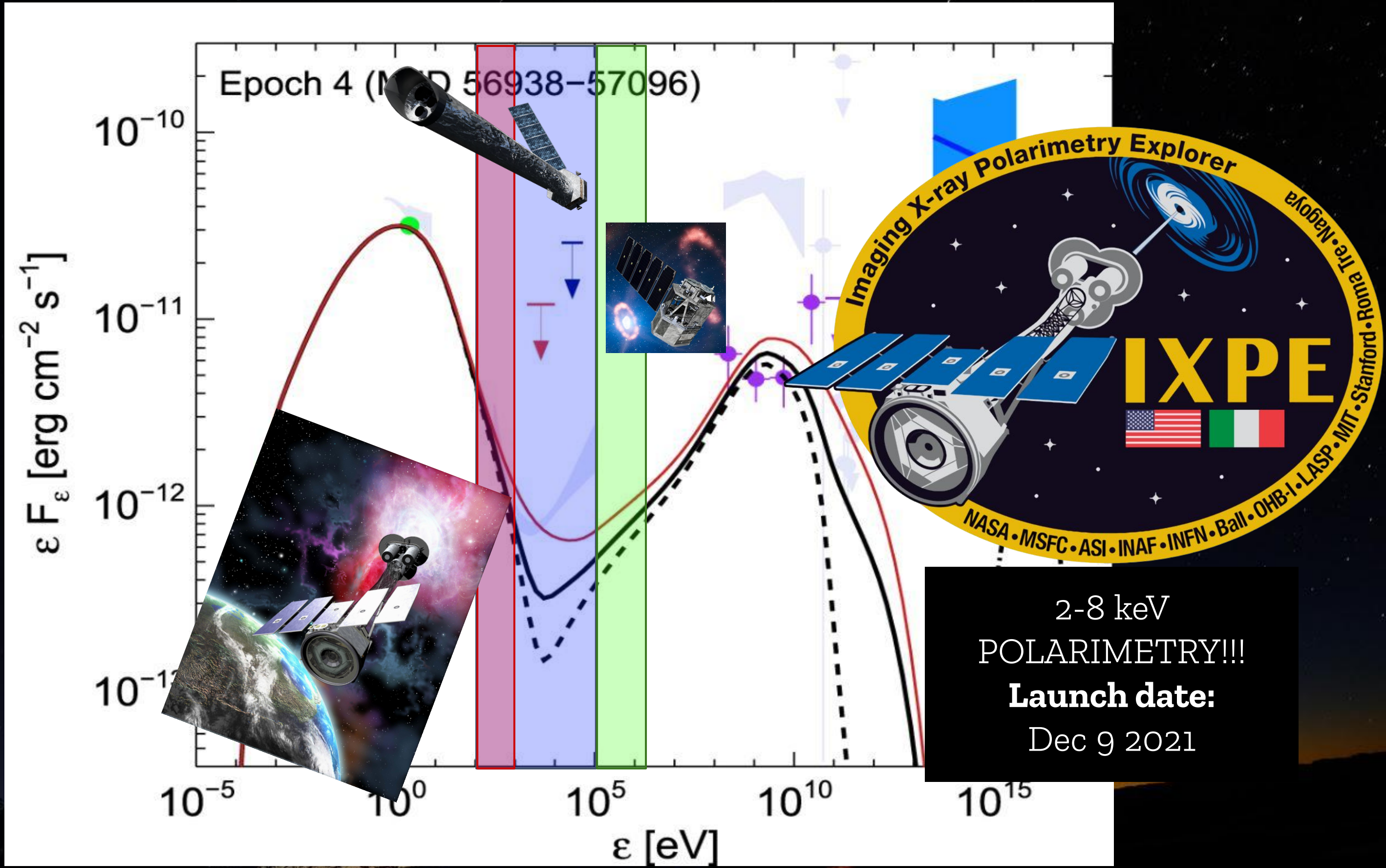
TXS 0506+056 (lepto-hadronic model, 2014 neutrino flare)



Petropoulou+2020

Hadronic vs. Leptonic models

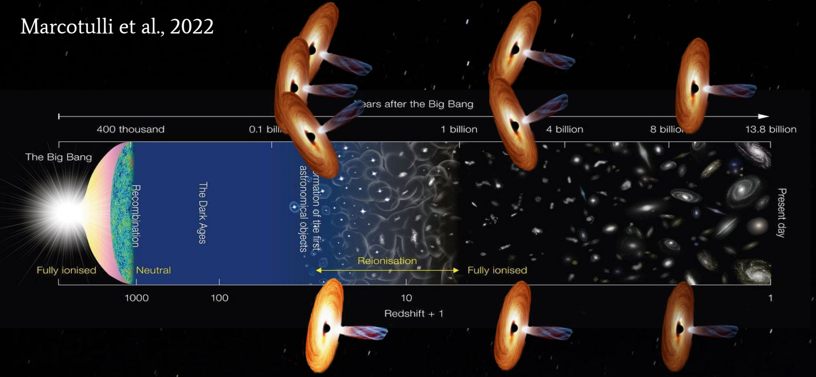
TXS 0506+056 (lepto-hadronic model, 2014 neutrino flare)

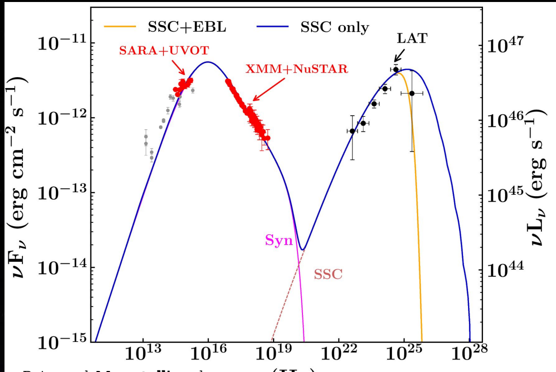


Petropoulou+2020

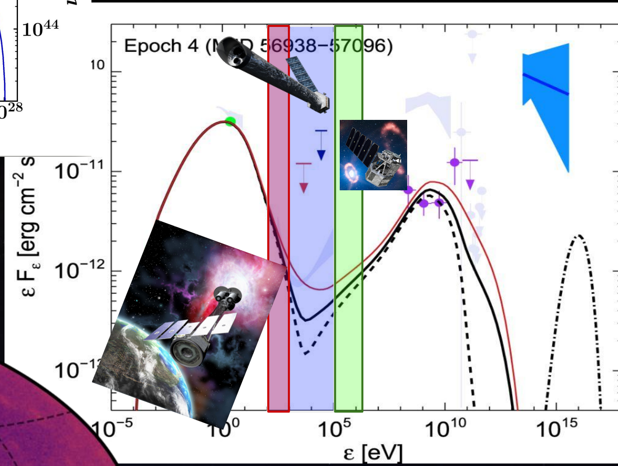
2-8 keV POLARIMETRY!!!
Launch date:
Dec 9 2021

Marcotulli et al., 2022

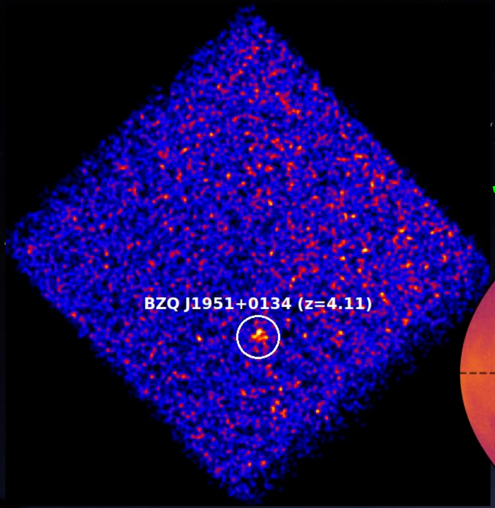




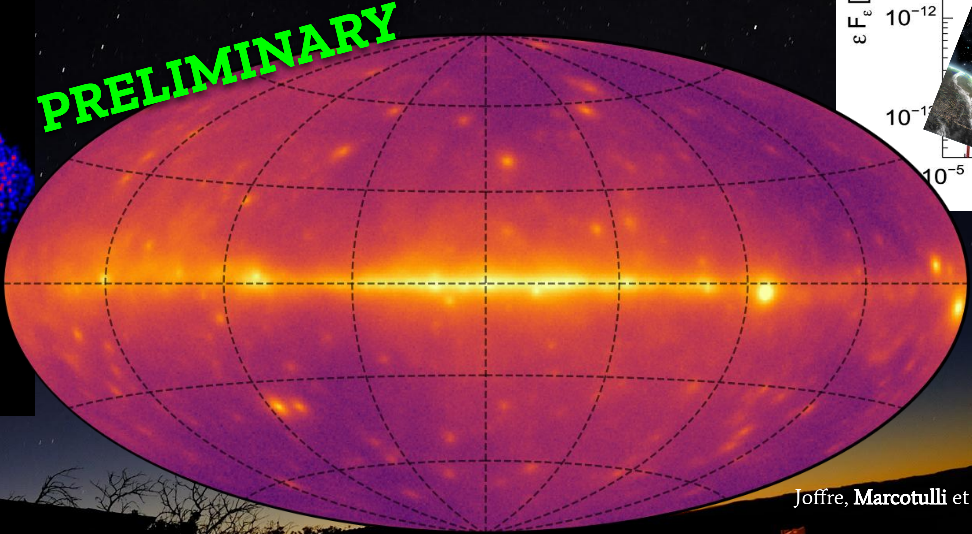
Rajagopal, **Marcotulli** et al. 2021



Marcotulli et al., in prep.



Marcotulli et al., in prep.



Joffre, **Marcotulli** et al., in prep.