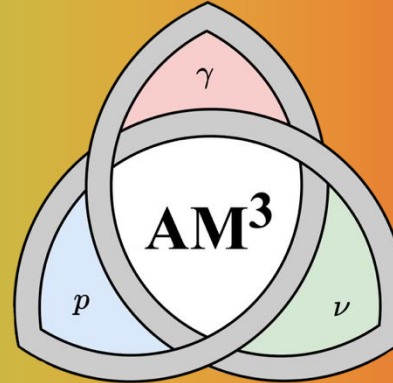




News from AM³ and M87 TeV flare modelling

Marc Klinger-Plaisier, Sera Markoff, Ruby Duncan, and the AM³ folks

MuMeNTA Athens, 03-03-2026

<https://maklinger.github.io/> - m.klinger@uva.nl



UNIVERSITEIT VAN AMSTERDAM



ANTON PANNEKOEK
INSTITUUT

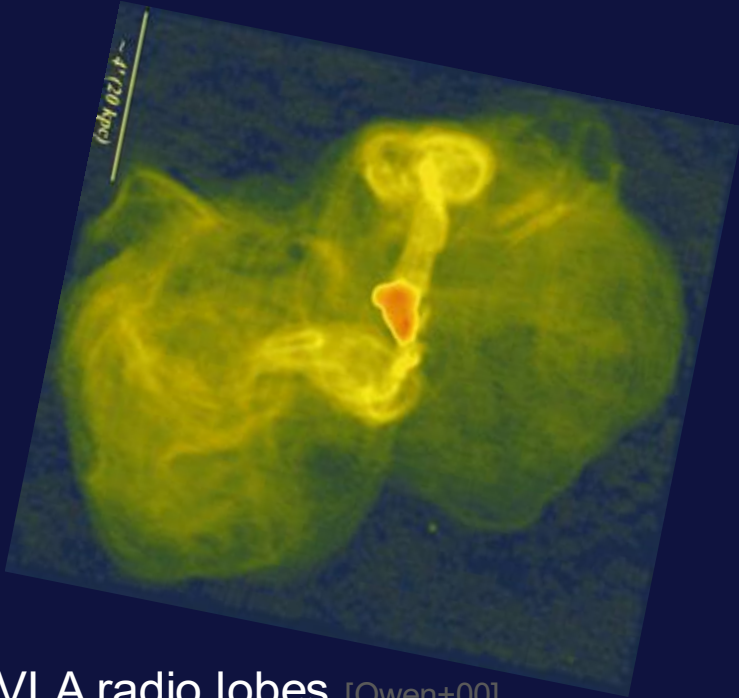
What makes M87 special?

1) M87 is close and heavy

$\sim 16\text{Mpc}$

$\sim 10^9 M_{\odot}$

moon for scale



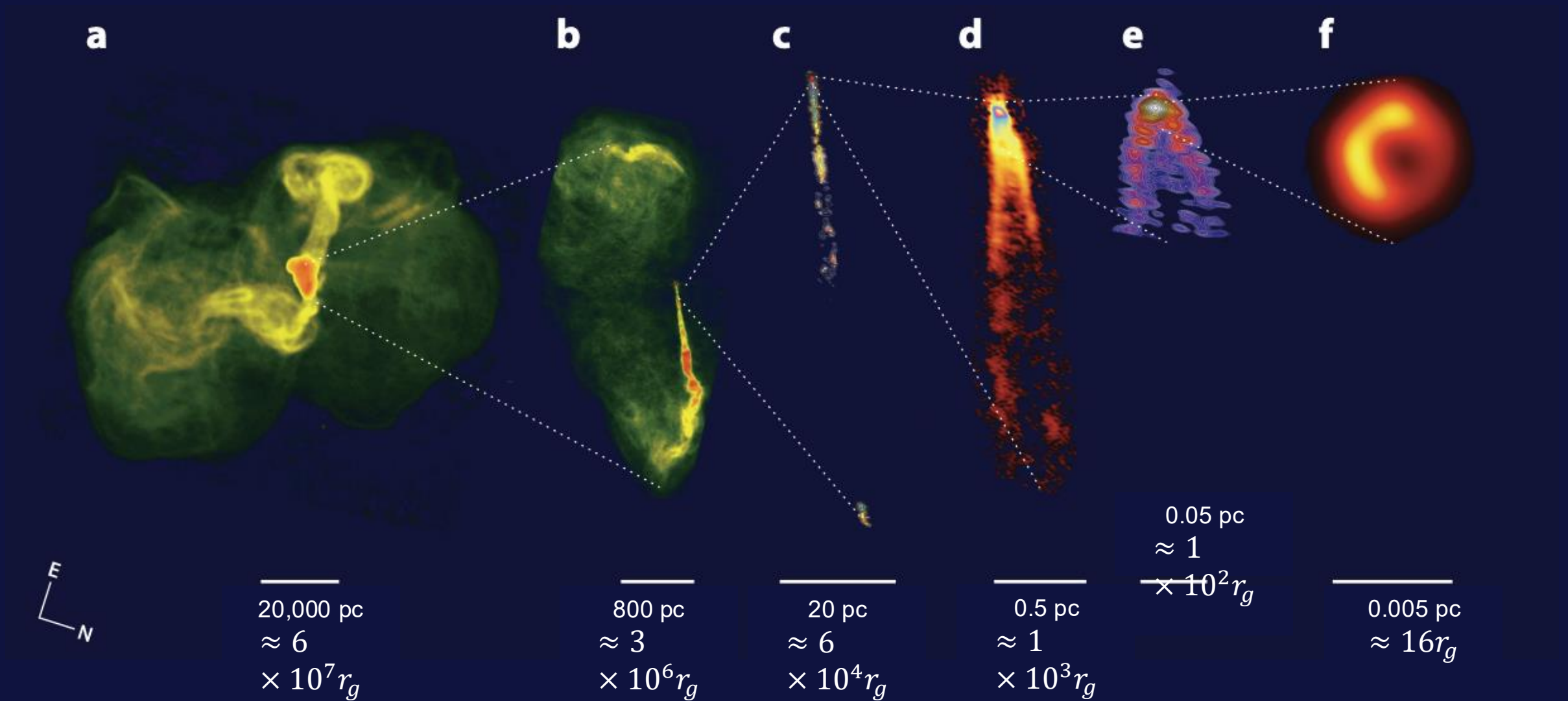
VLA radio lobes [Owen+00]

$4' \approx 0.067^\circ \approx 20\text{kpc} \approx 6 \times 10^7 r_g$

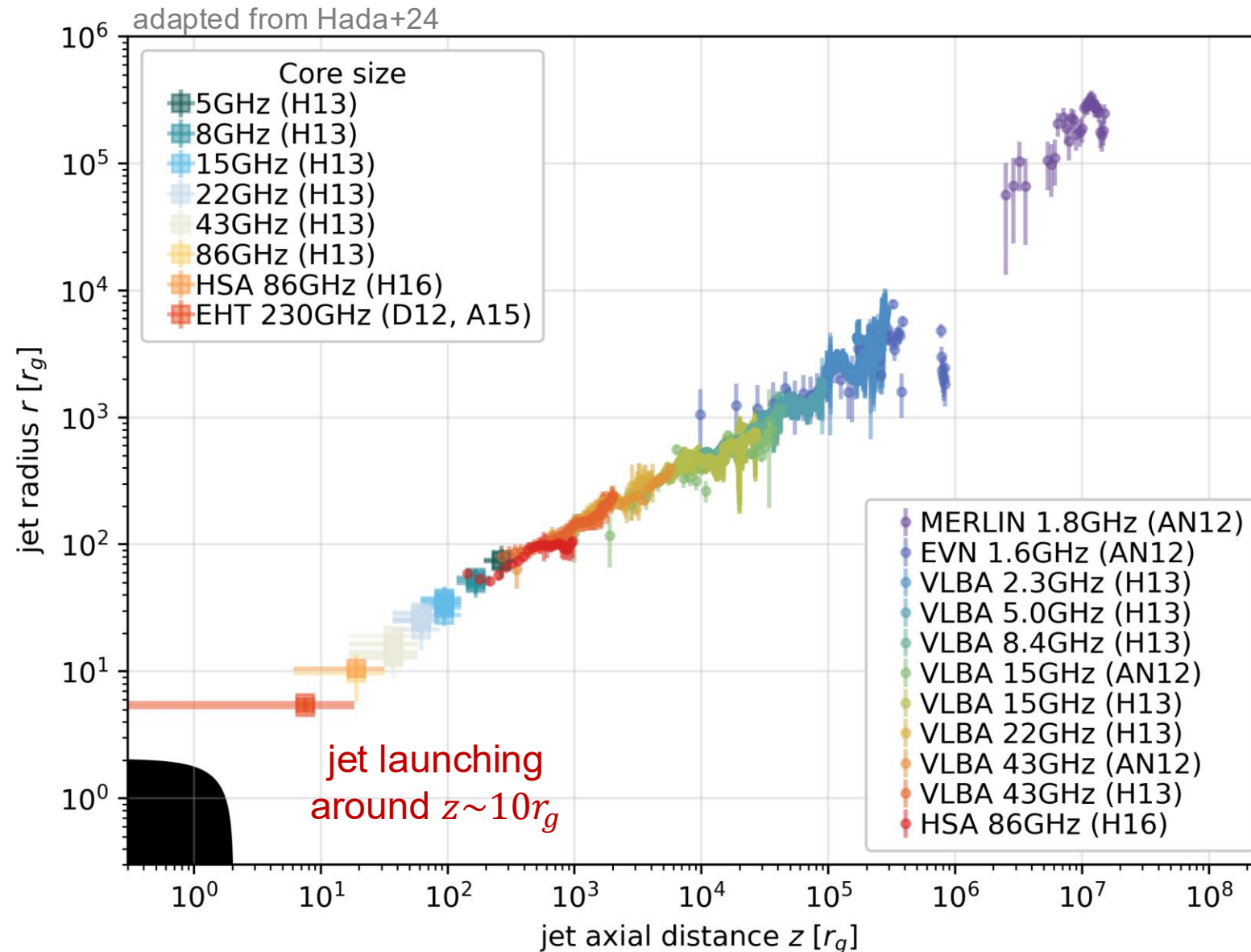
→ big on the sky!



→ We can resolve a jet from $10^7 - 10r_g$ (unique!)

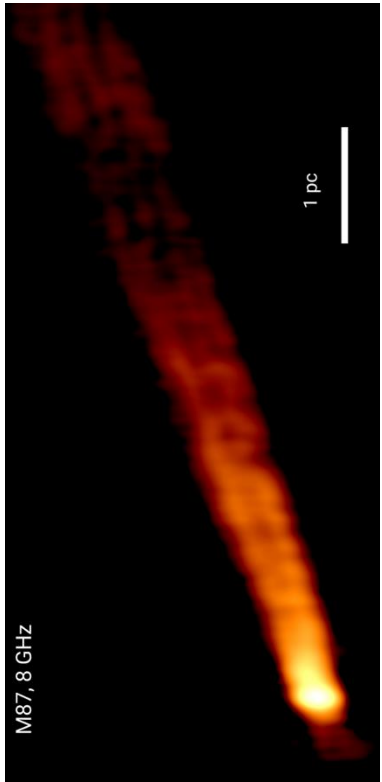


Jet collimation

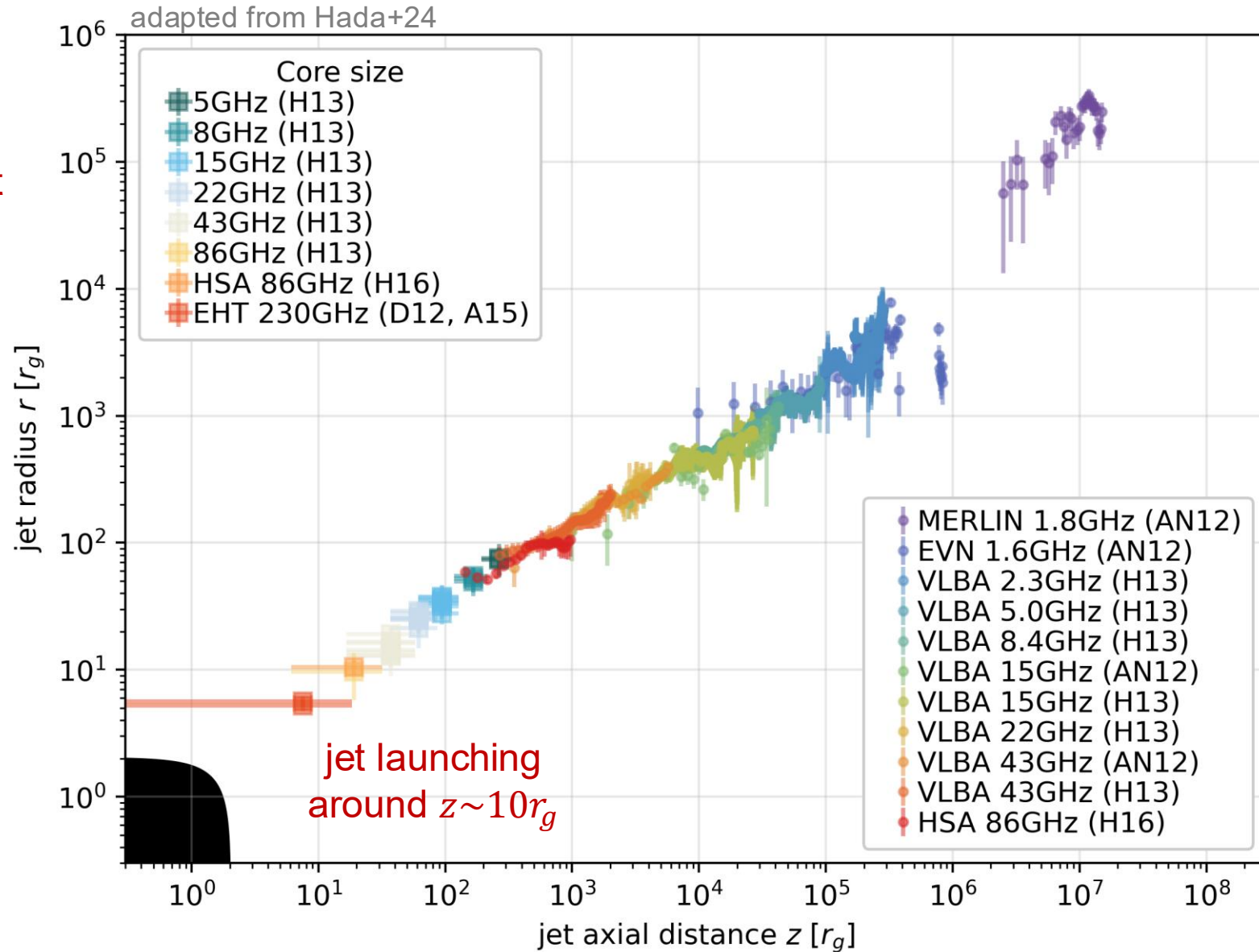


Jet collimation

≈ smooth inner jet

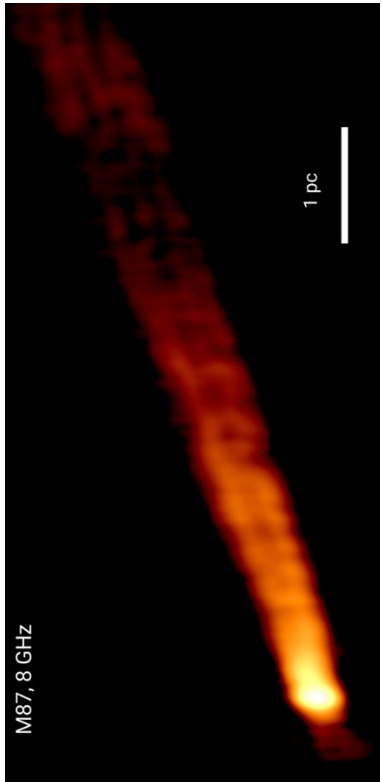


Nikonov+23

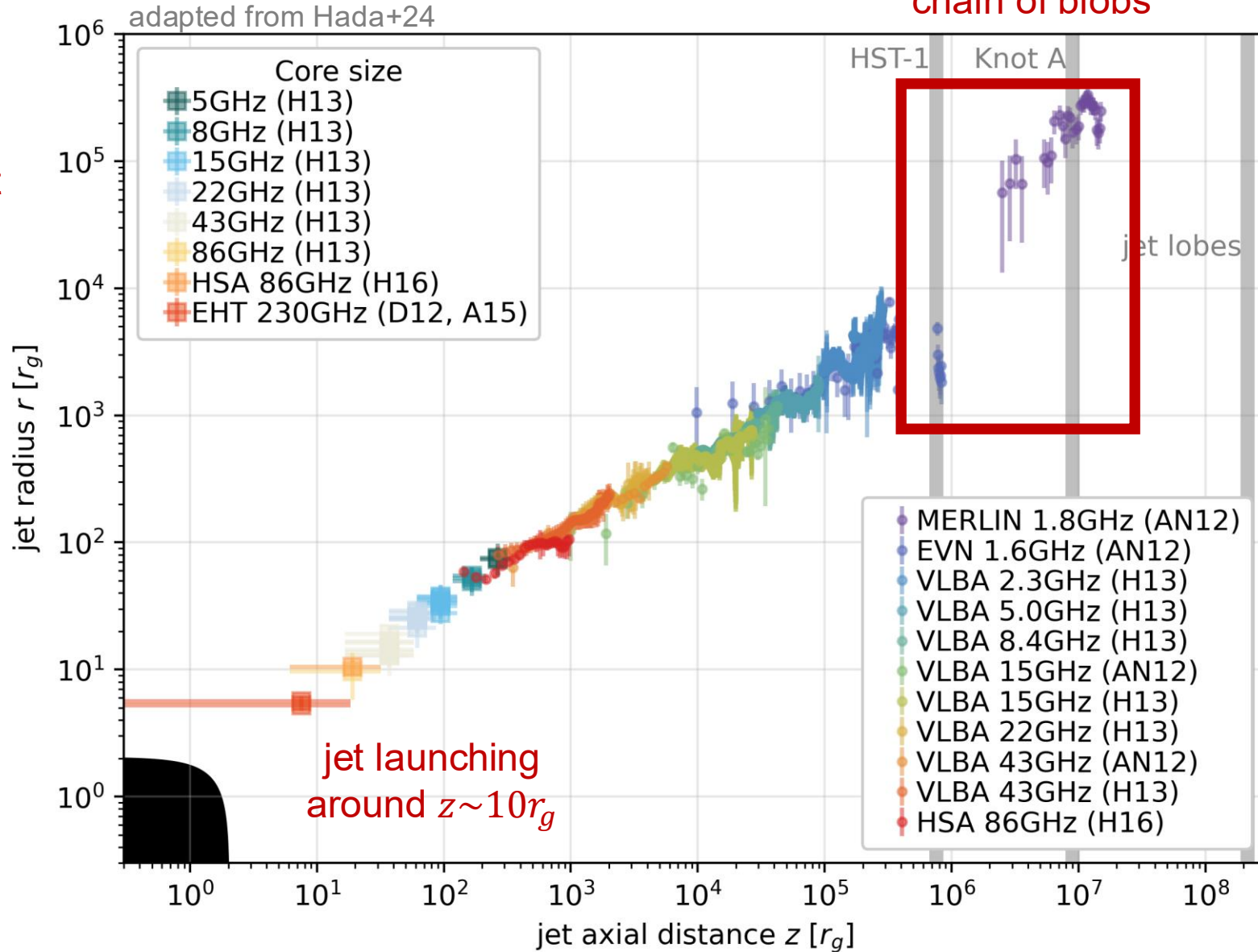


Jet collimation

≈ smooth inner jet



Nikonov+23



Perlman+01

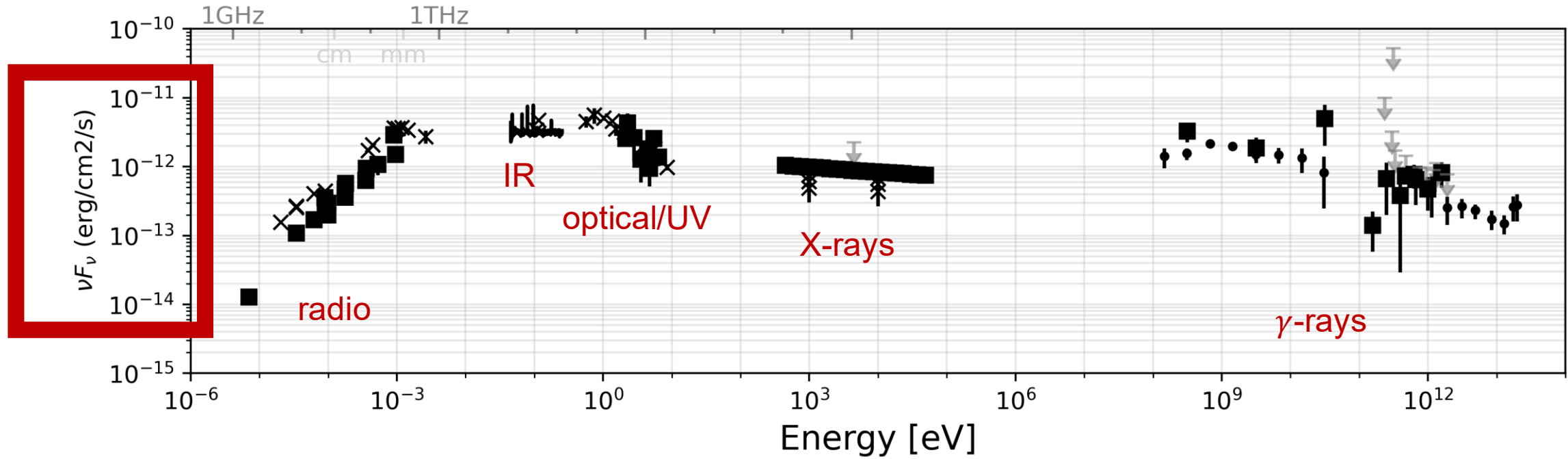
HST image

knot A

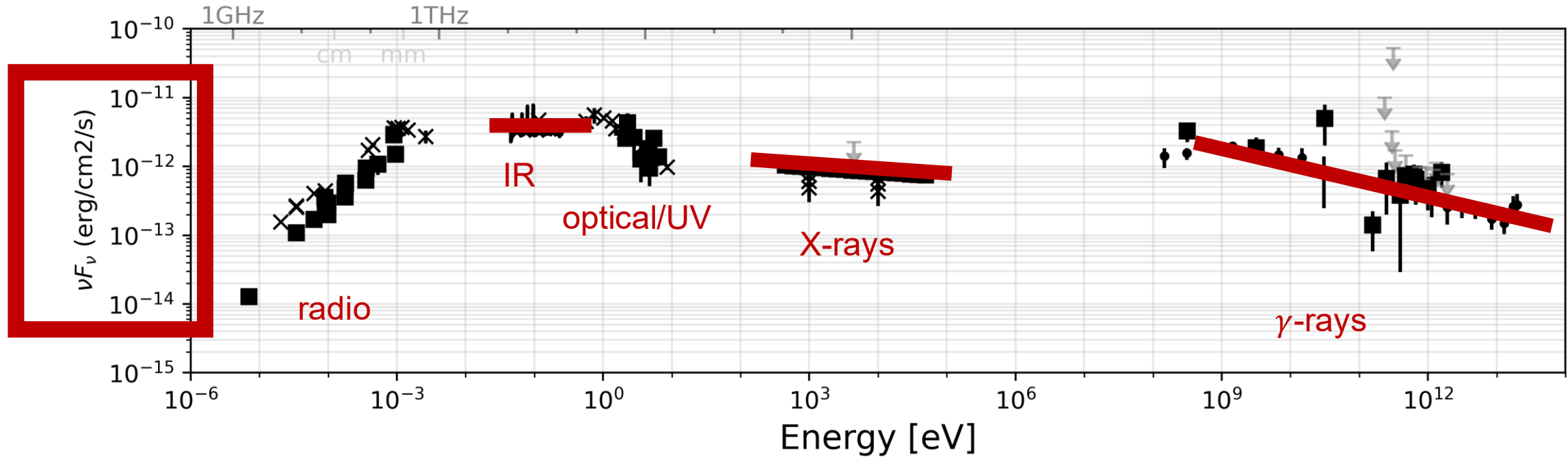
HST-1

core

2) M87 is rather bright from radio to TeV



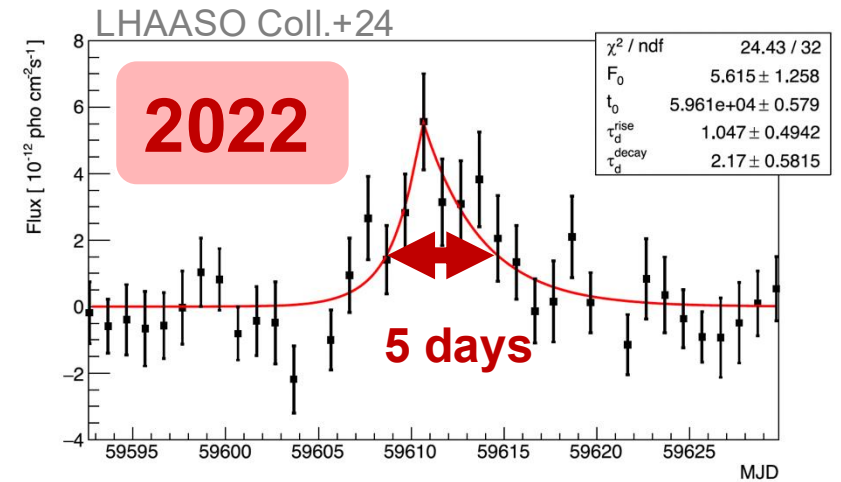
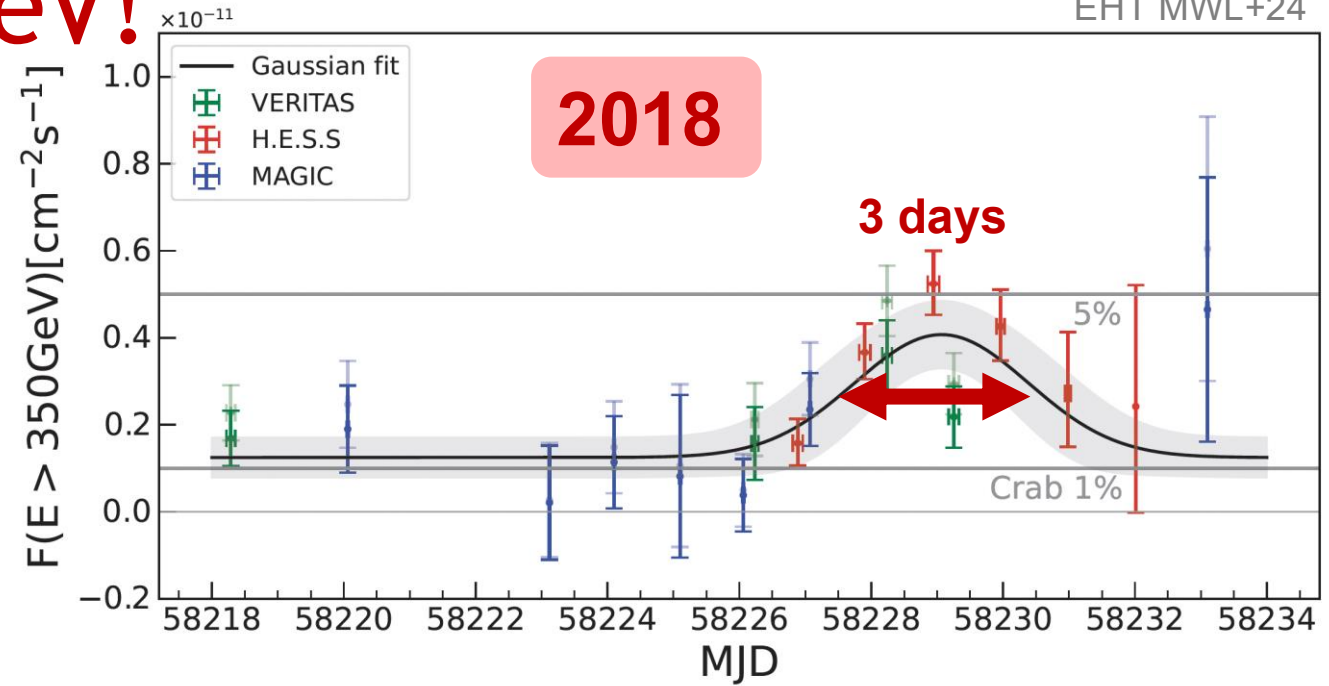
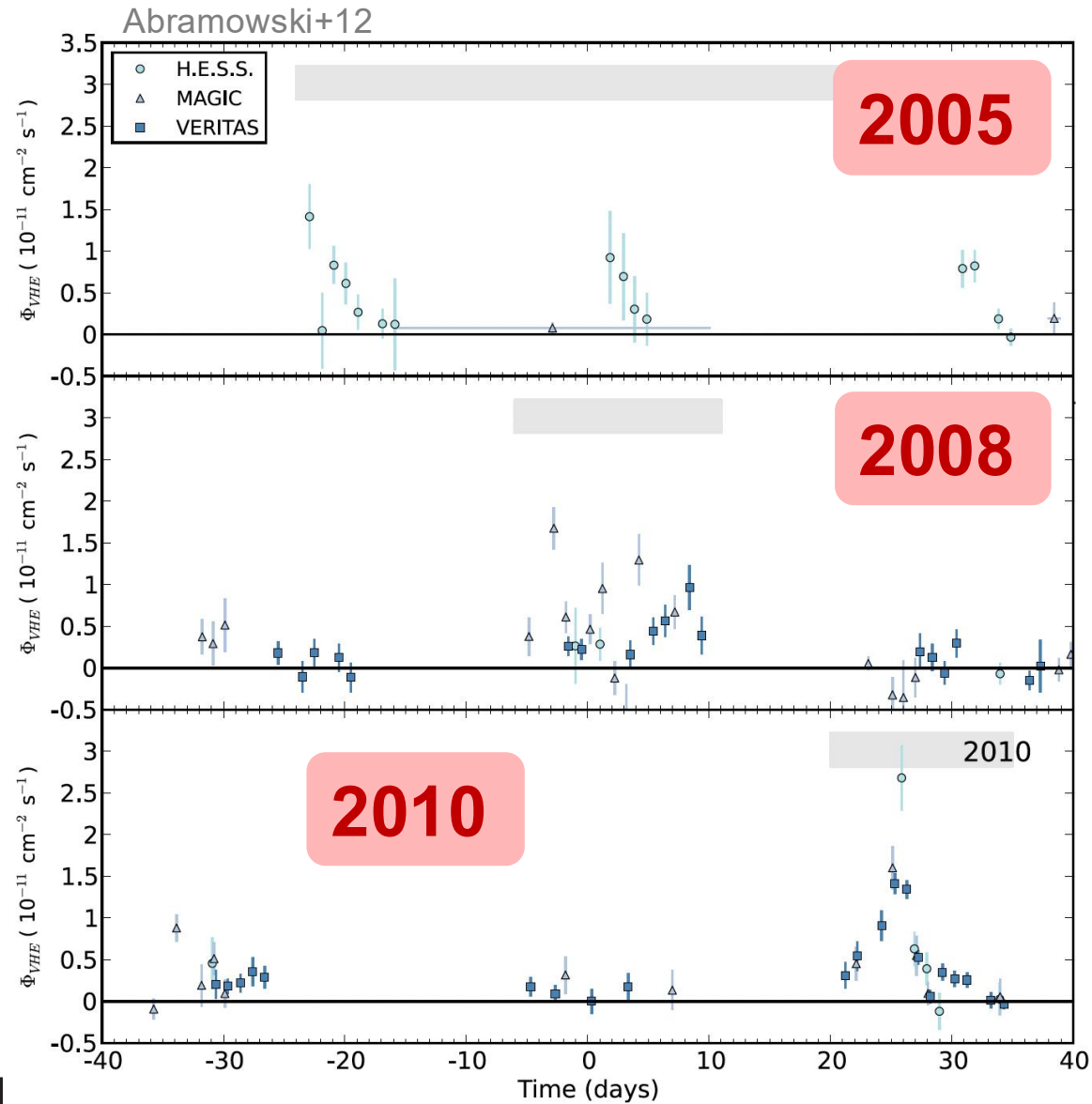
2) M87 is rather bright from radio to TeV



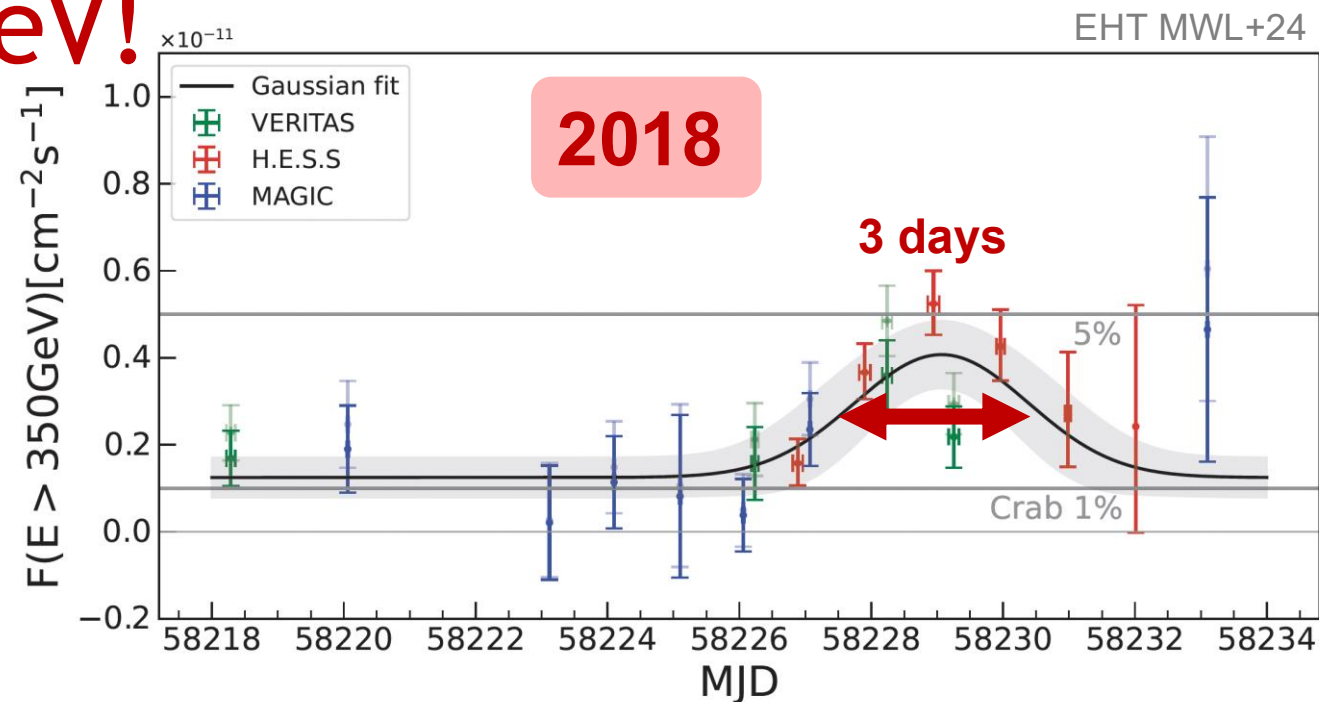
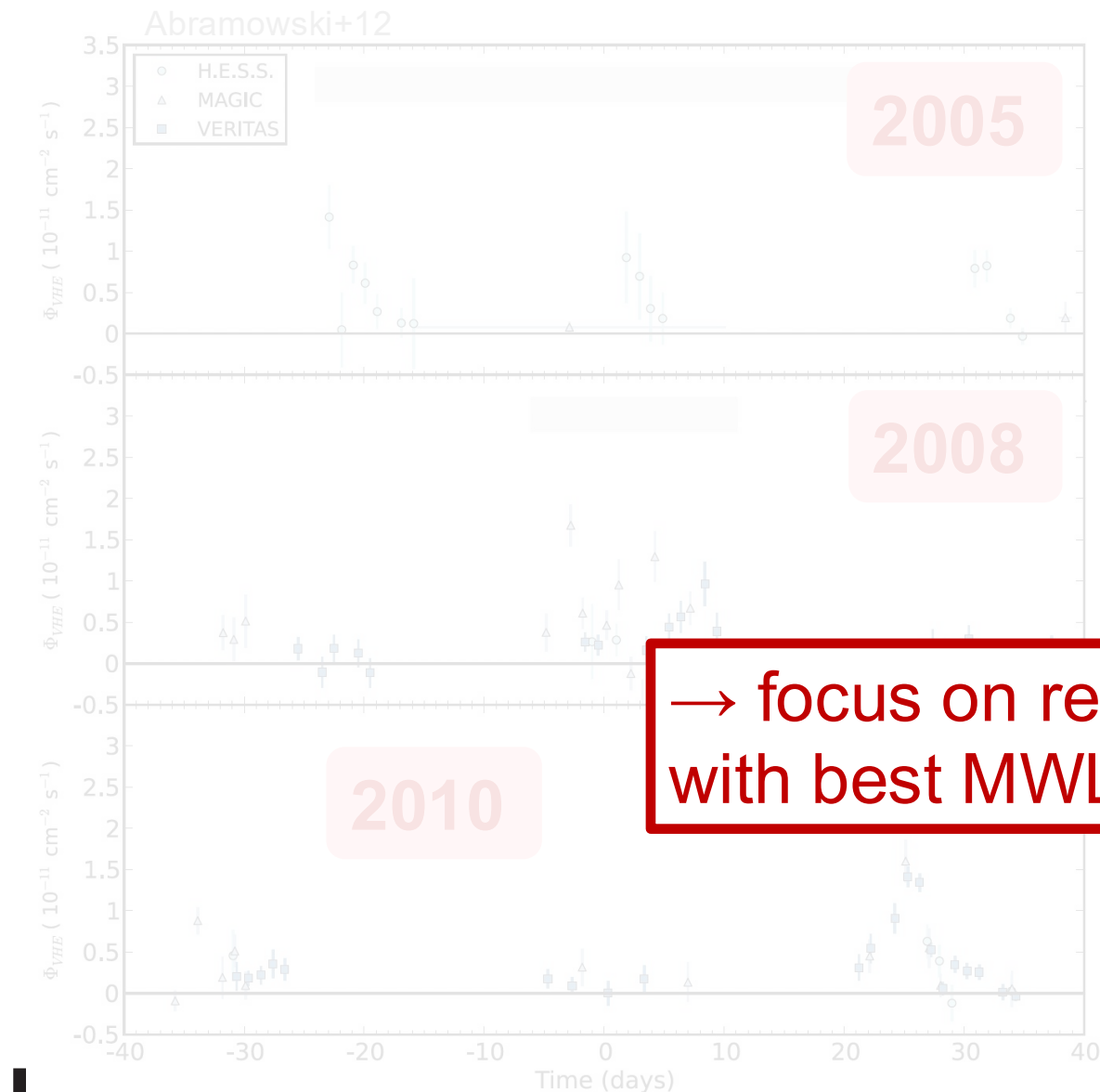
broadband, power-lawish spectra
→ jet = non-thermal particle accelerator!

3) M87 keeps flaring at TeV!

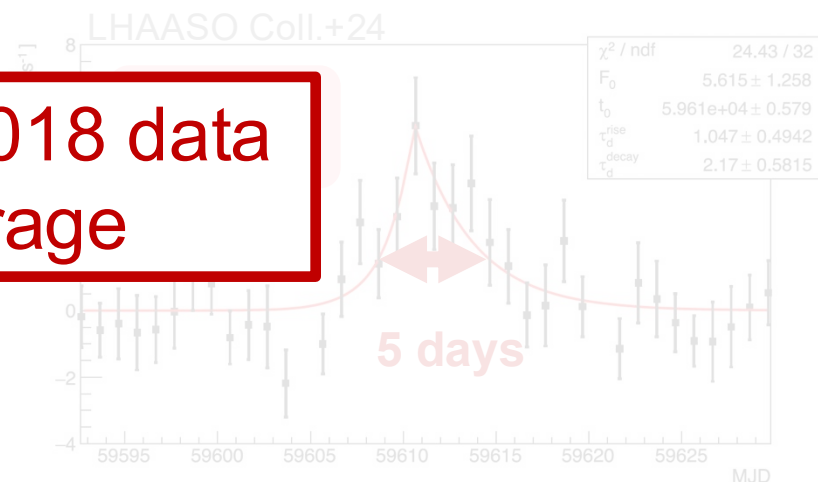
EHT MWL+24



3) M87 keeps flaring at TeV!



→ focus on recent 2018 data with best MWL coverage



Where do these TeV flares come from?

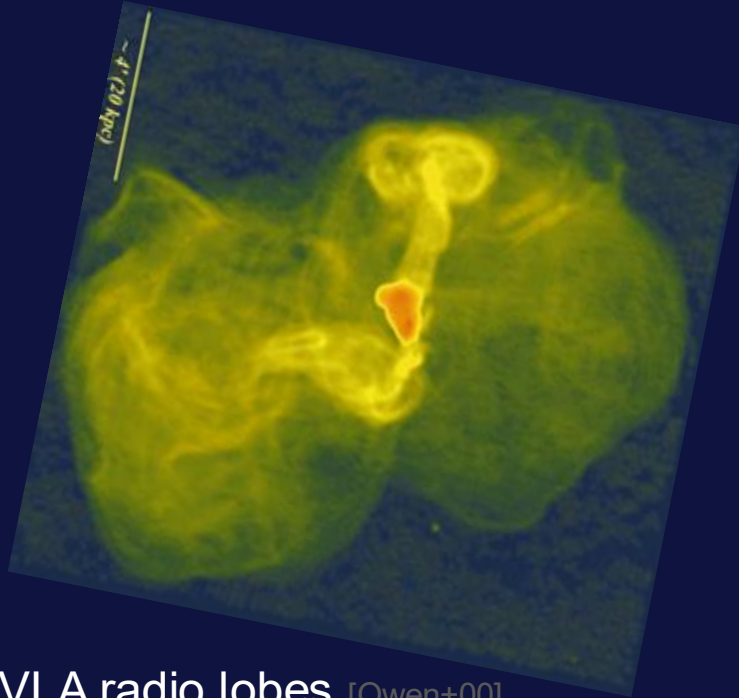
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let's assume they are produced in the jet

× angular resolution at TeV energies

TeV angular resolution?

moon for scale



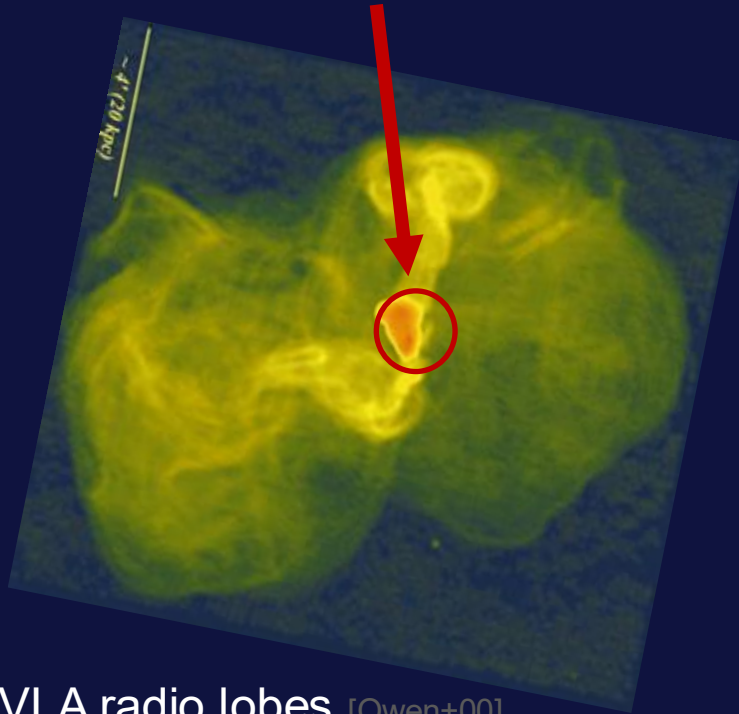
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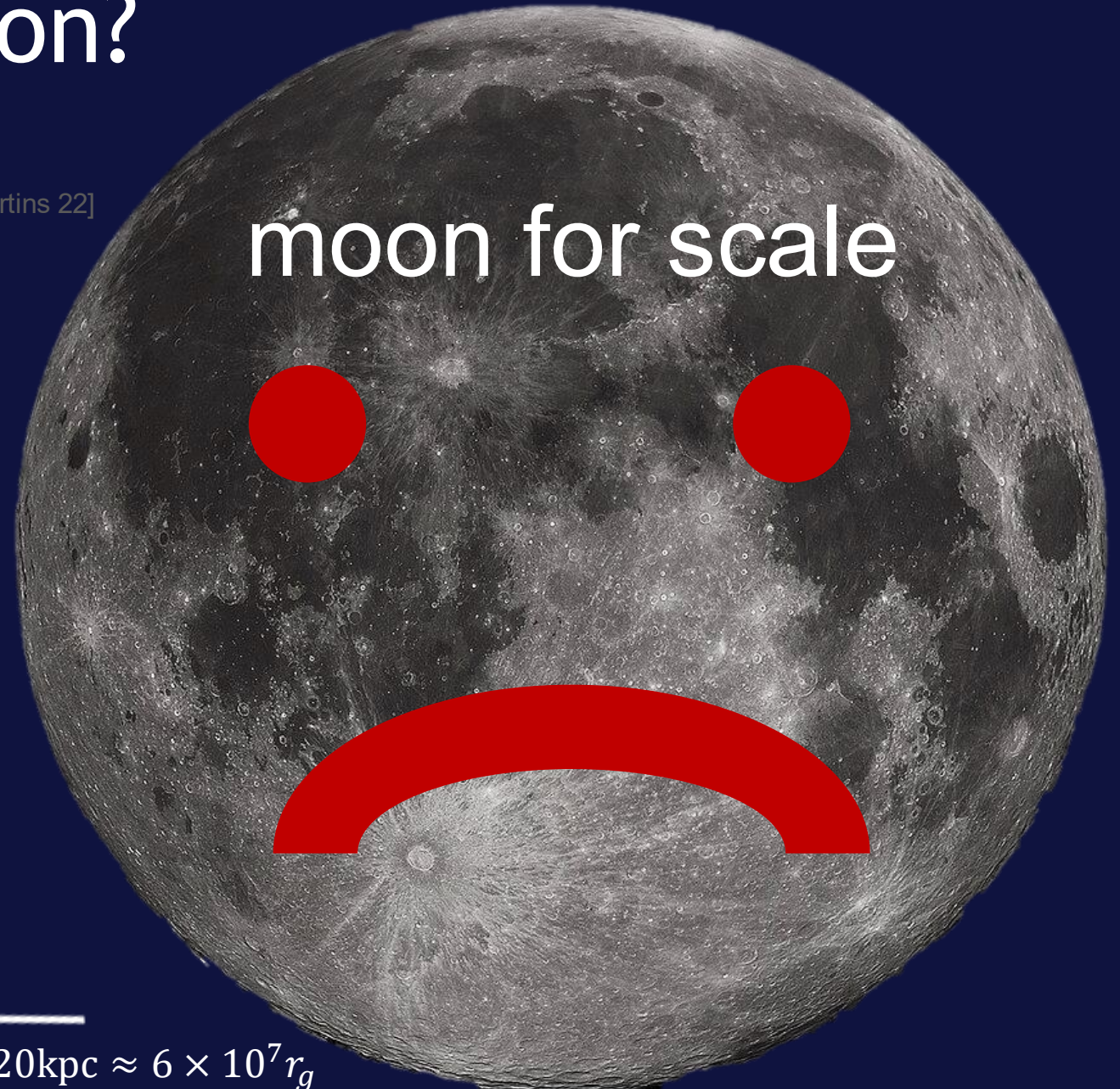
TeV angular resolution?

H.E.S.S. TeV angular resolution [Thesis Barbosa Martins 22]



VLA radio lobes [Owen+00]

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× variability on few days: causality?

→ **only size** of emission region: $\Delta R < \delta c \Delta t_{em} \approx 8 r_g \delta \left(\frac{\Delta t_{em}}{3 \text{ days}} \right)$

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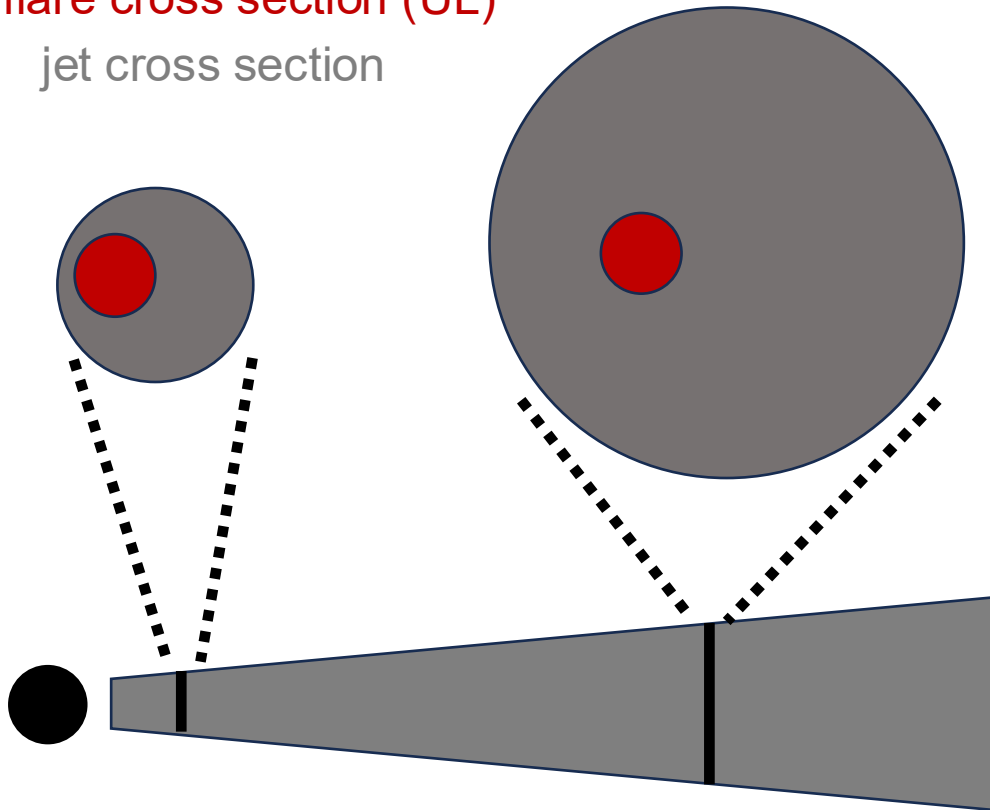
 - **only size** of emission region: $\Delta R < \delta c \Delta t_{em} \approx 8 r_g \delta \left(\frac{\Delta t_{em}}{3 \text{ days}} \right)$

- × fixed flare region size, growing jet: too much power in small jet section?

Jet power concentration?

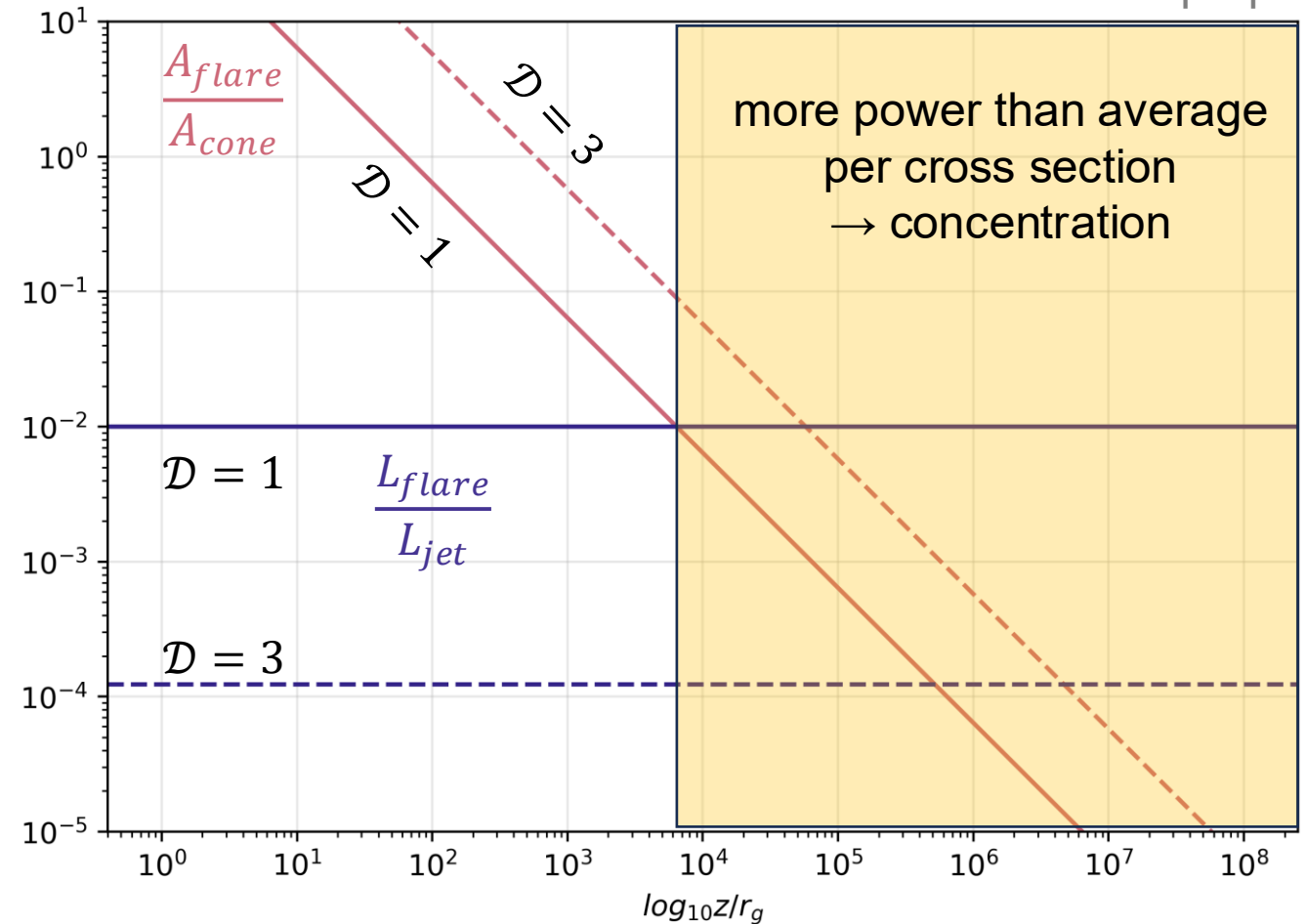
flare cross section (UL)

jet cross section



→ although lots of assumptions!

MKP+ in prep.



$$A_{flare} \approx \pi \Delta R^2 \mathcal{D}^2, A_{cone} \approx \pi r_g z, L_{jet} \approx 10^{43} \frac{erg}{s}, L_{flare} \approx 10^{41} \frac{erg}{s} \mathcal{D}^{-4}$$

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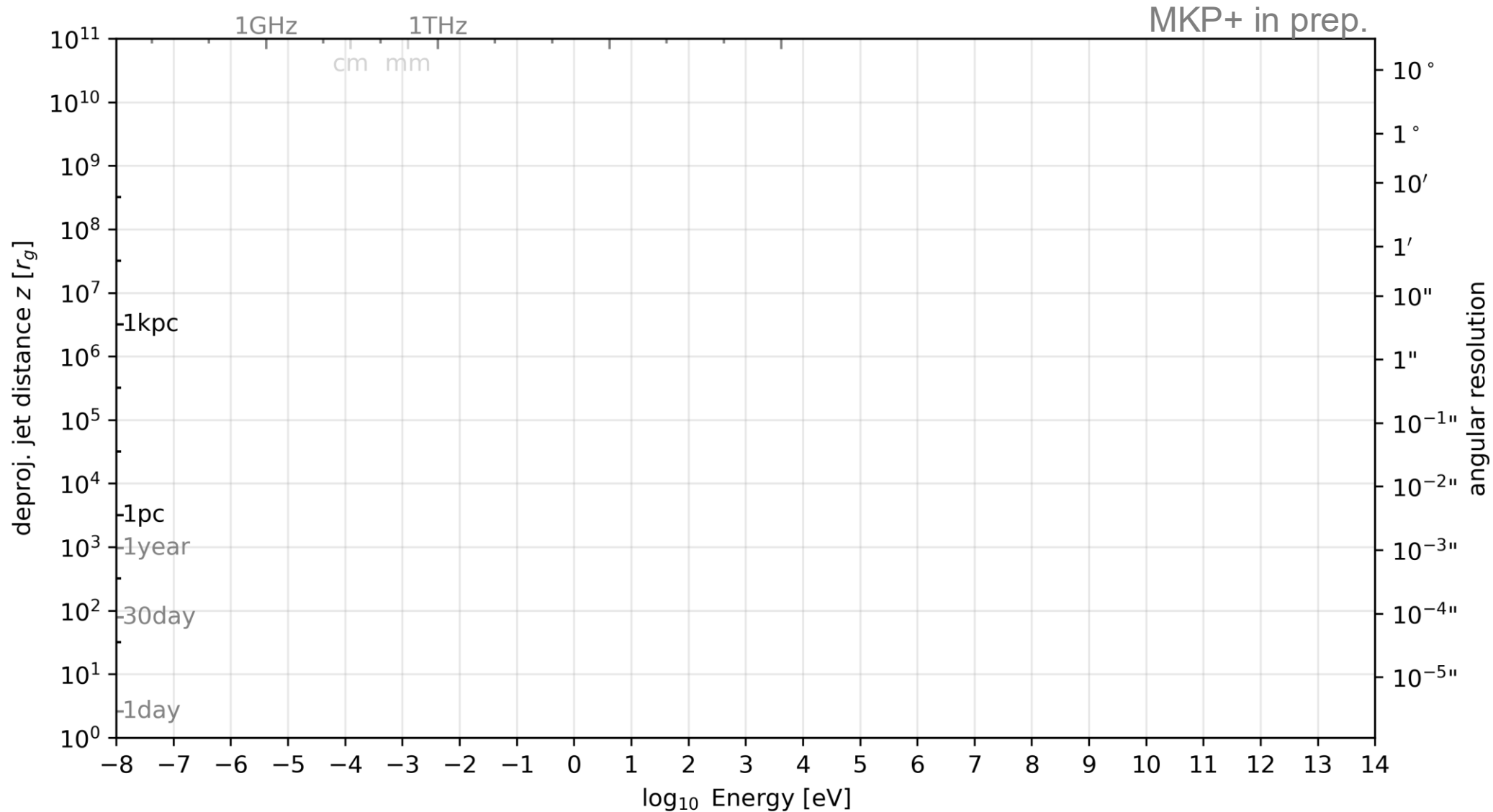
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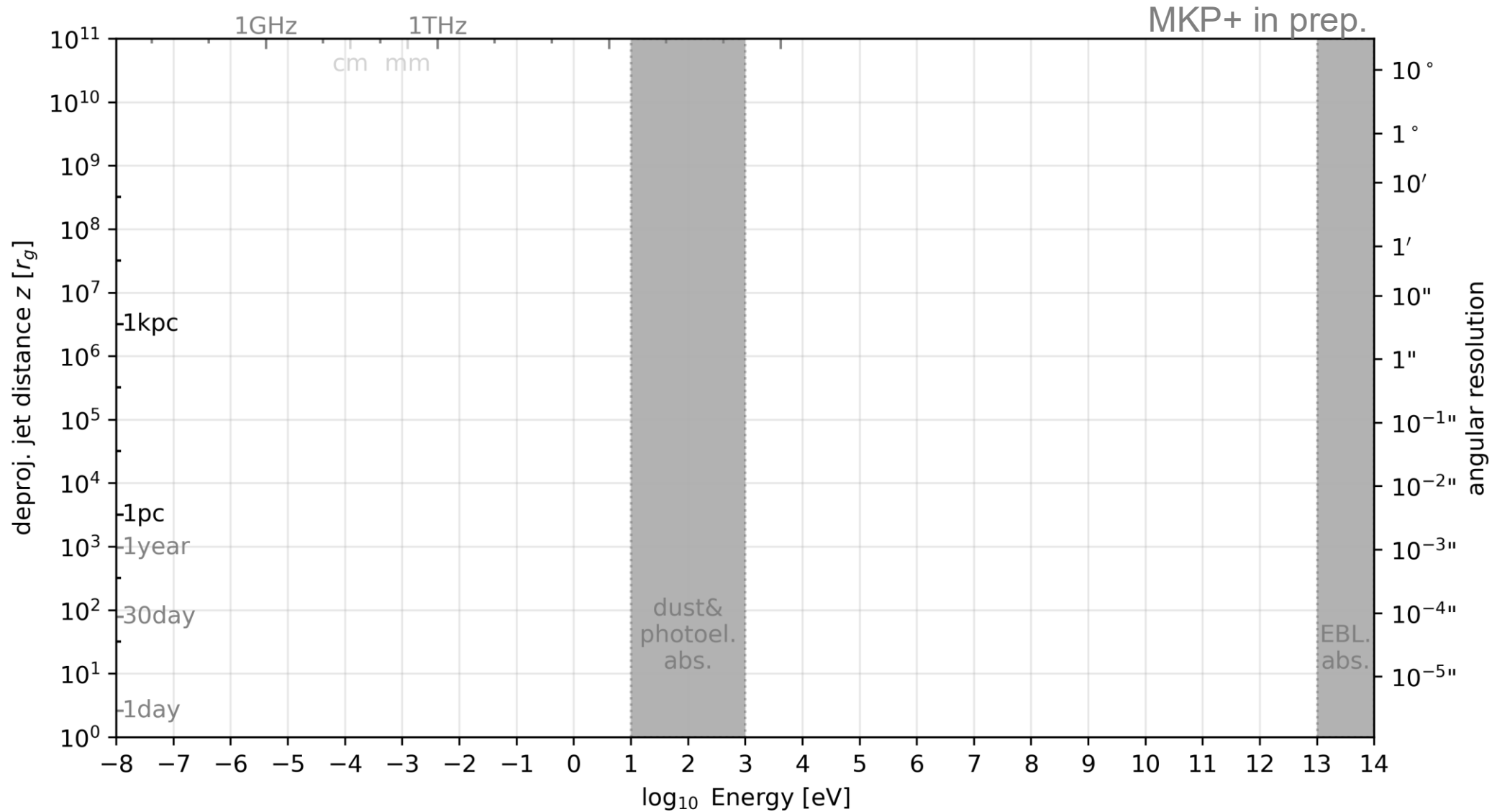
 - not really limiting/constraining

- × multiwavelength picture?

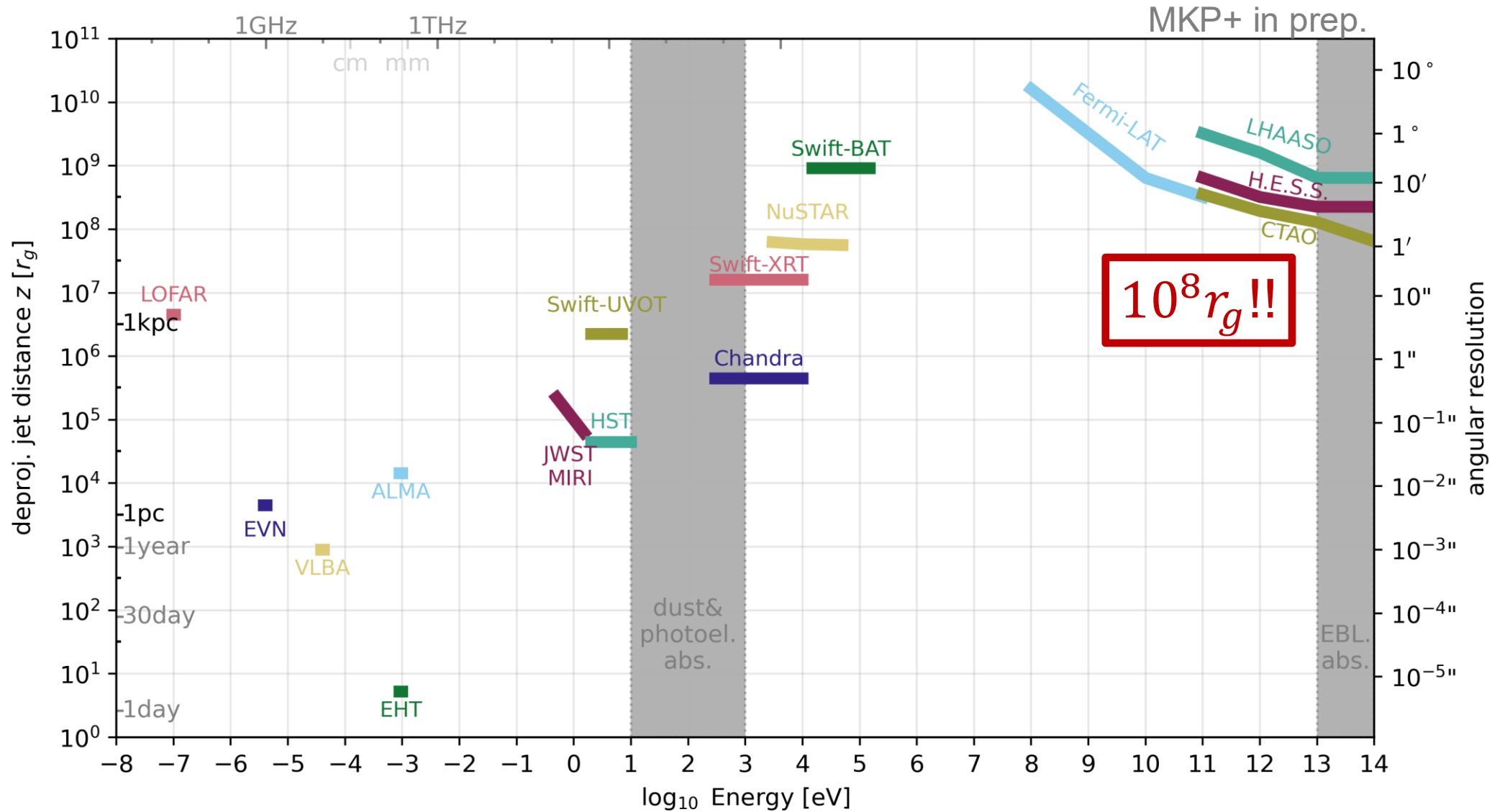
MWL angular resolution



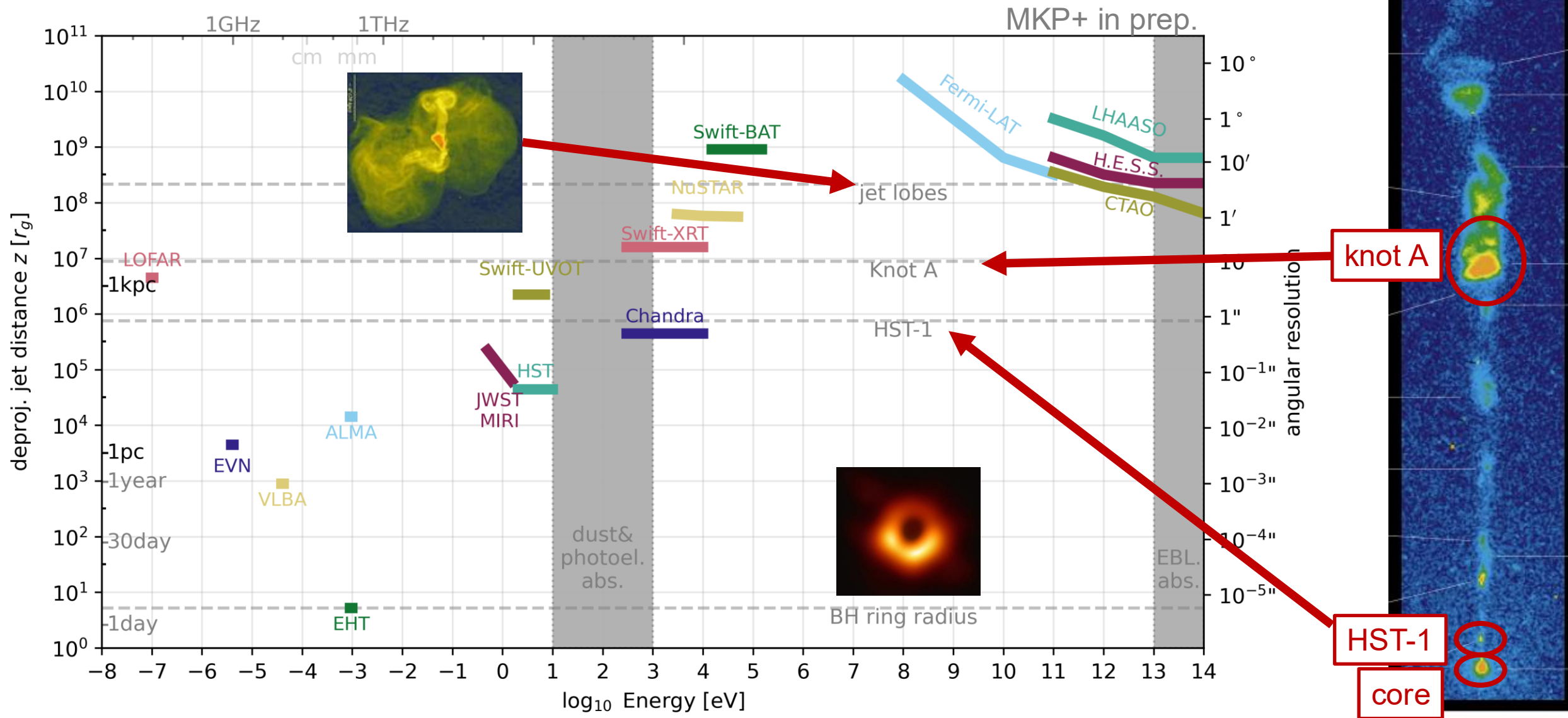
MWL angular resolution



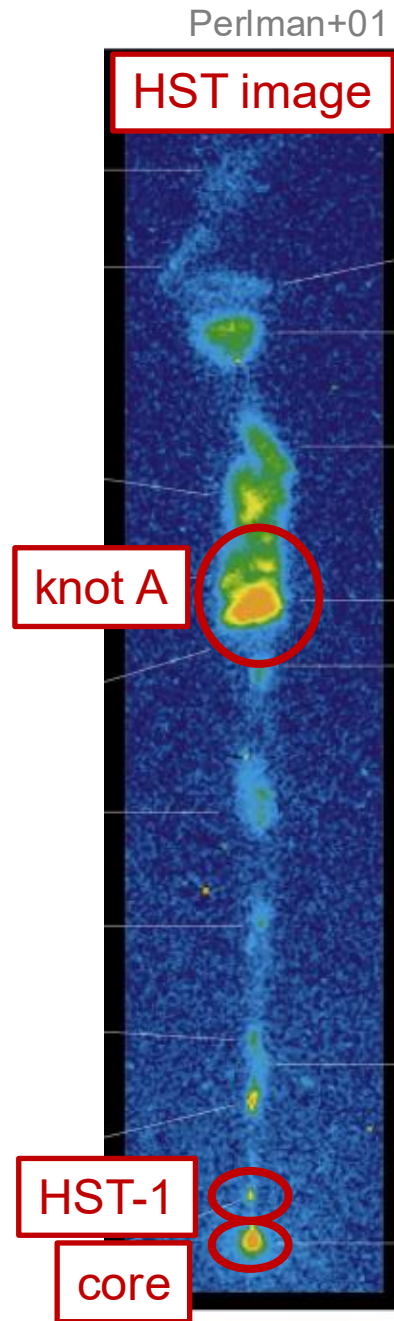
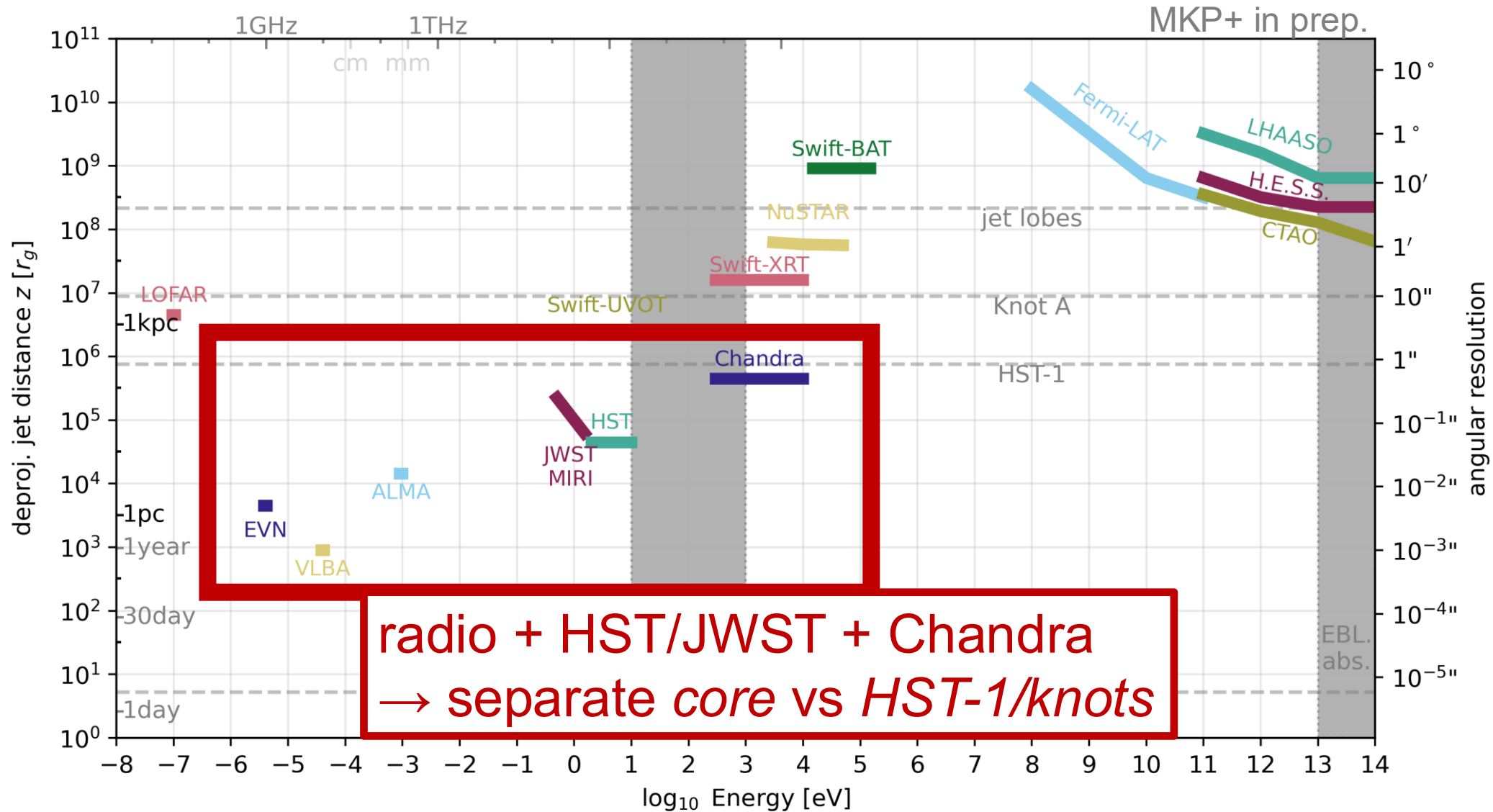
MWL angular resolution



MWL angular resolution

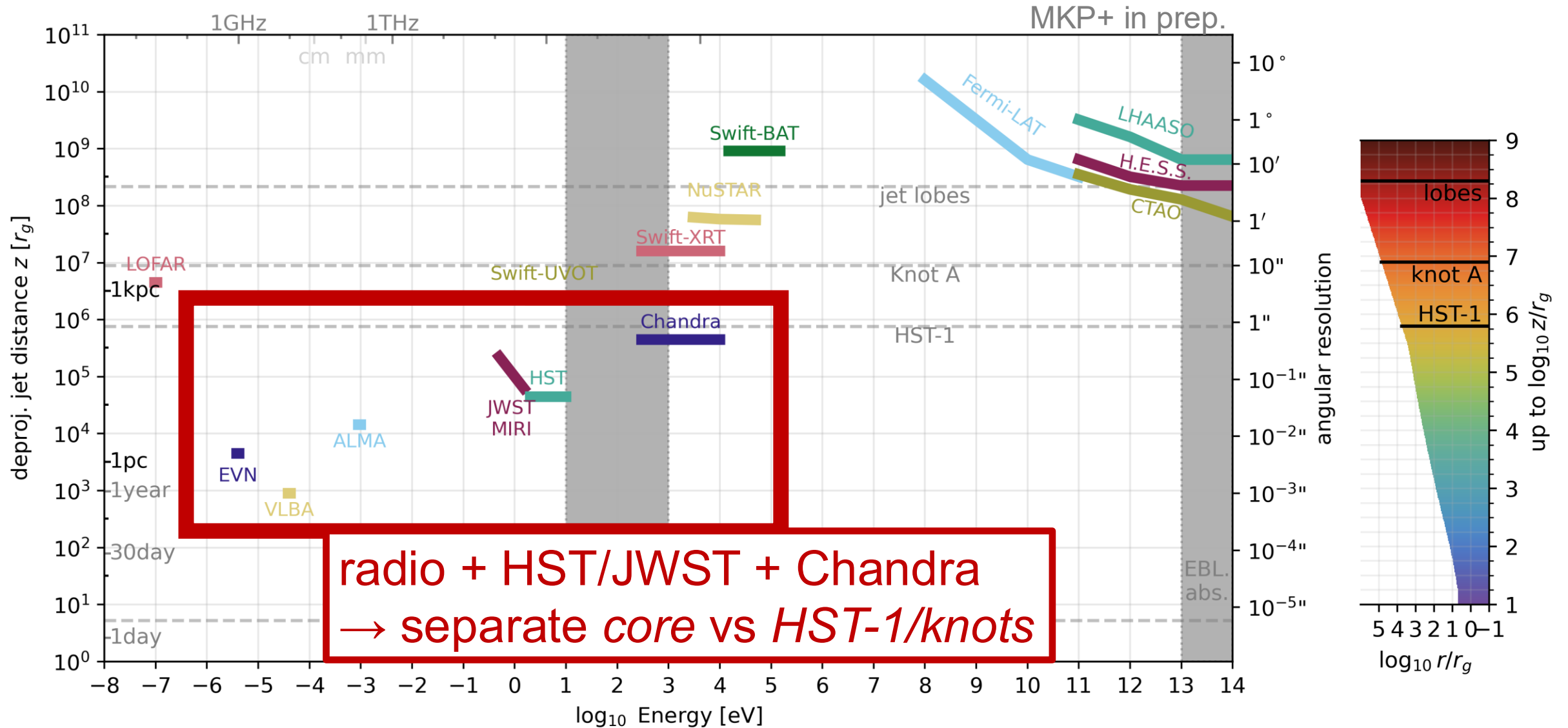


MWL angular resolution

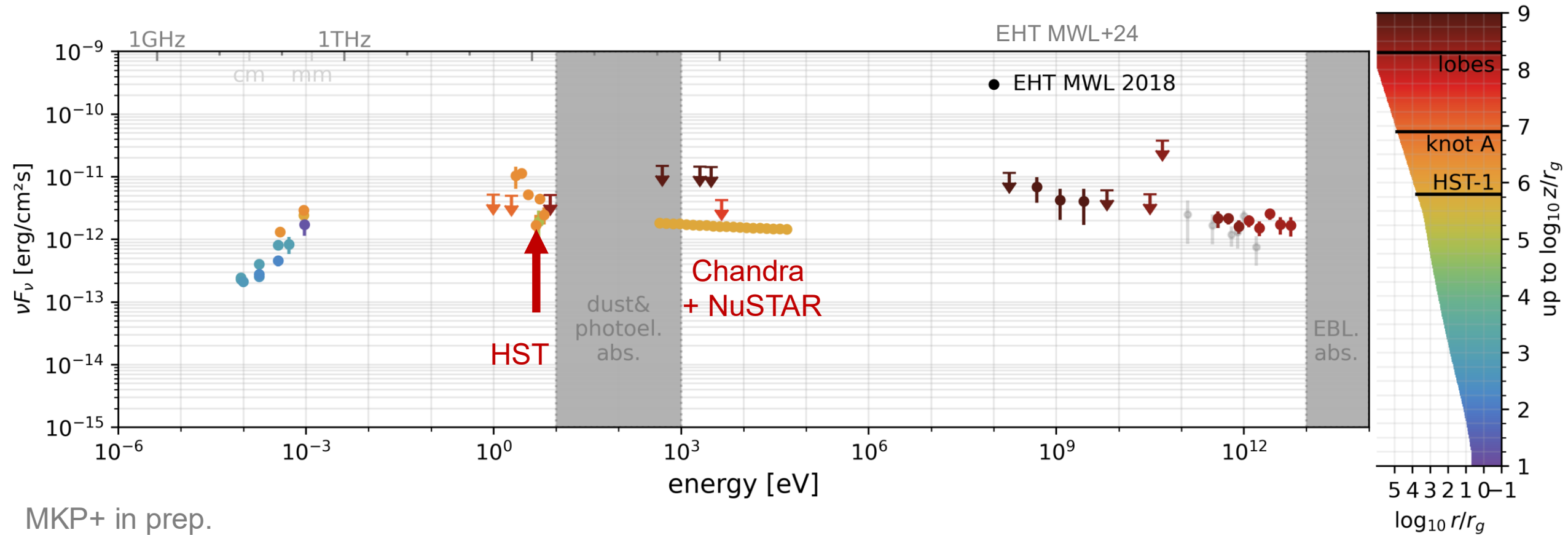


Perlman+01

MWL angular resolution

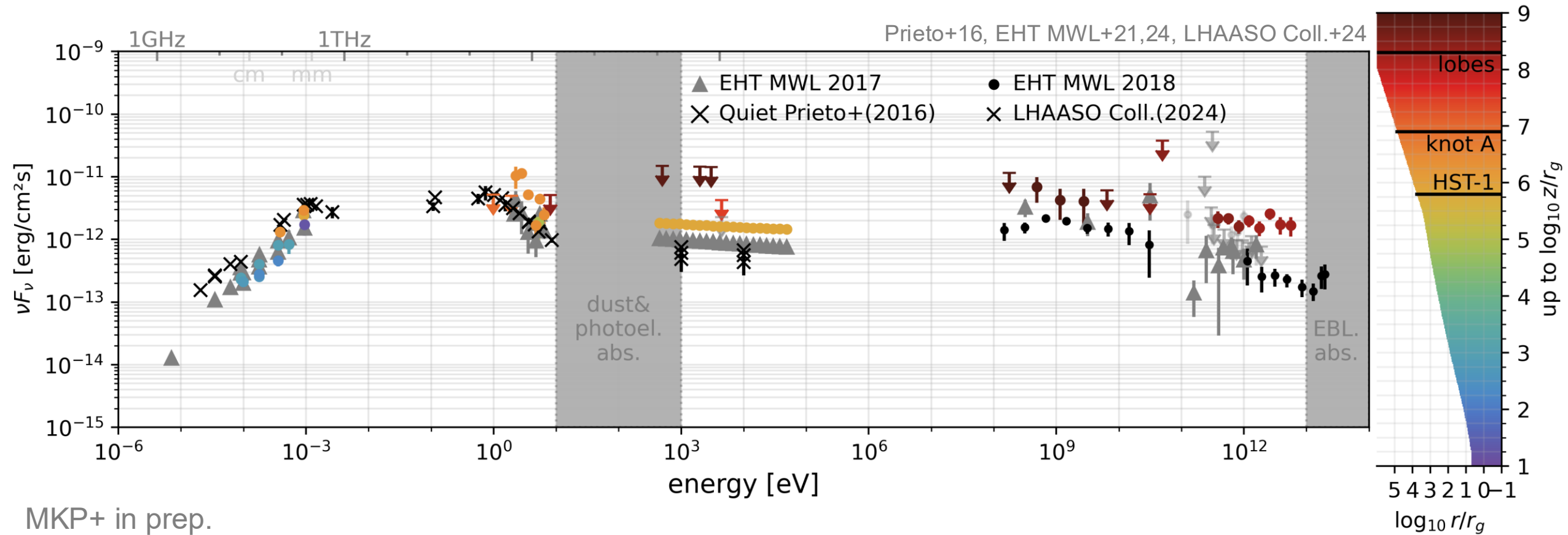


MWL spectrum during 2018 flare



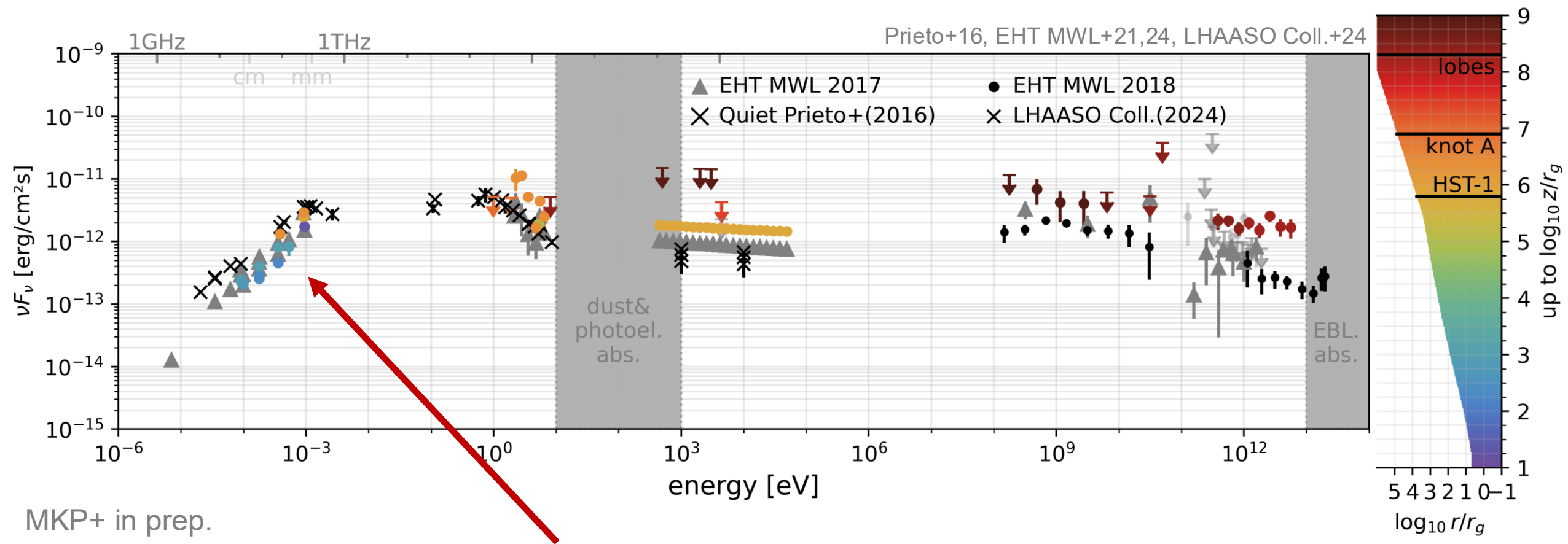
MKP+ in prep.

MWL spectrum during 2018 flare vs quiet



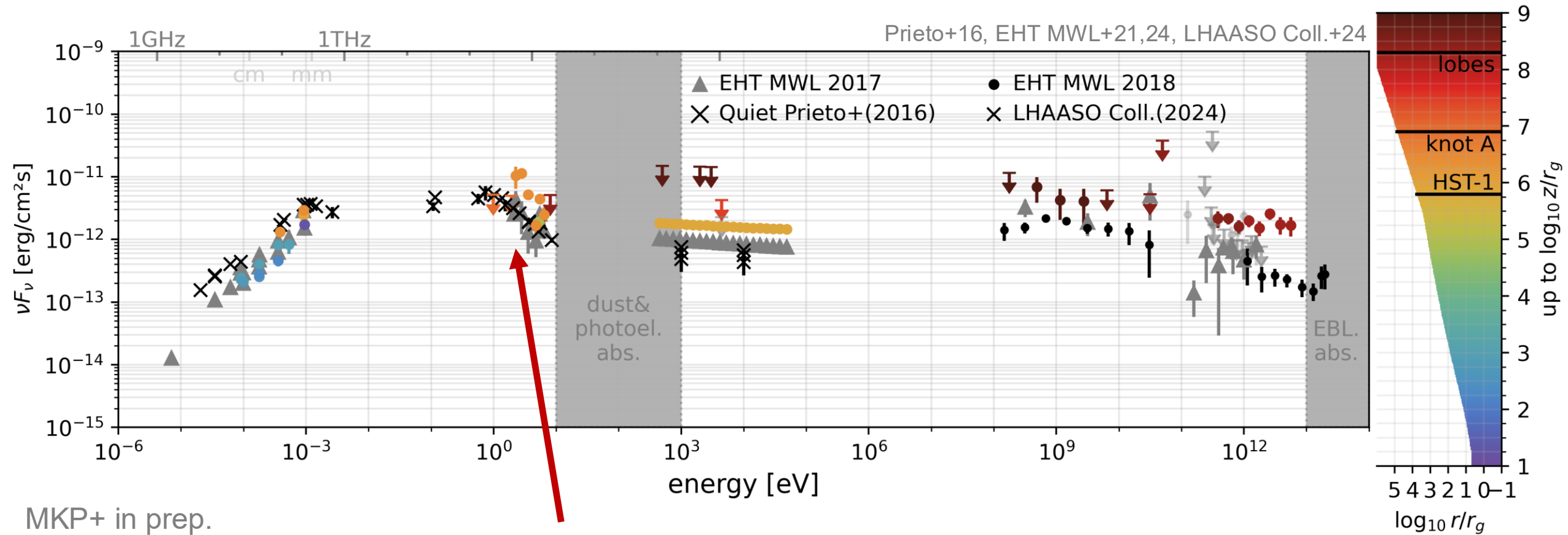
MKP+ in prep.

MWL spectrum during 2018 flare



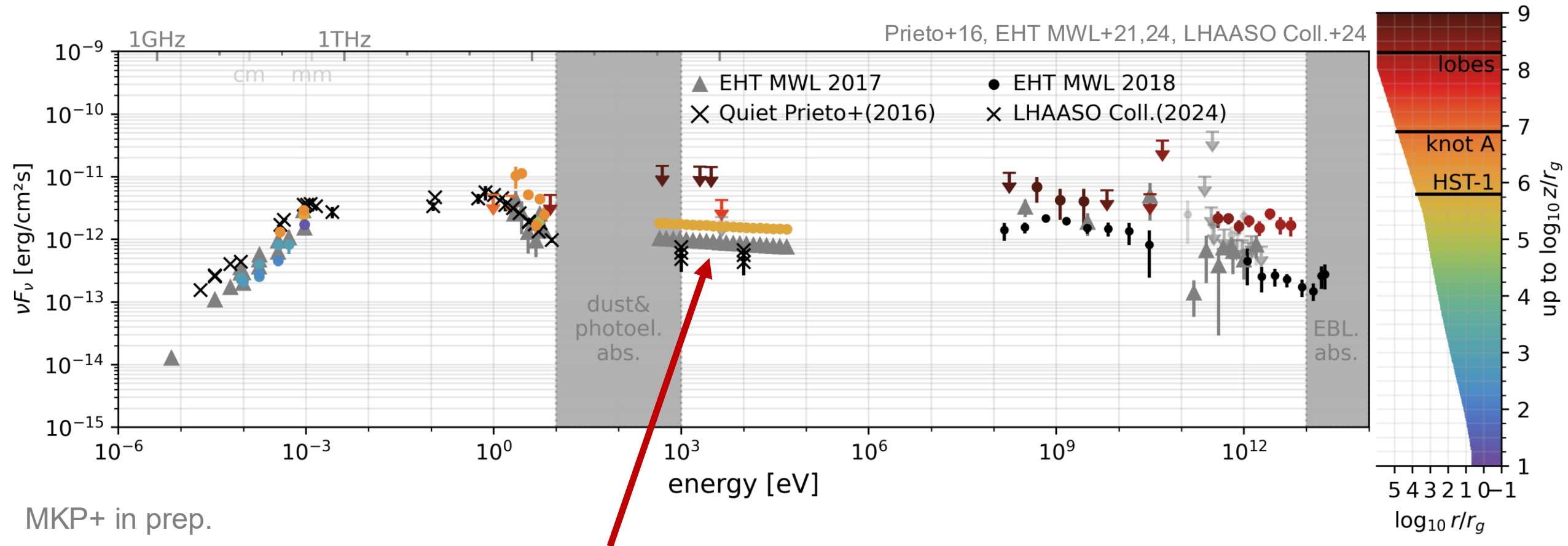
radio: quiet, if not slightly lower

MWL spectrum during 2018 flare



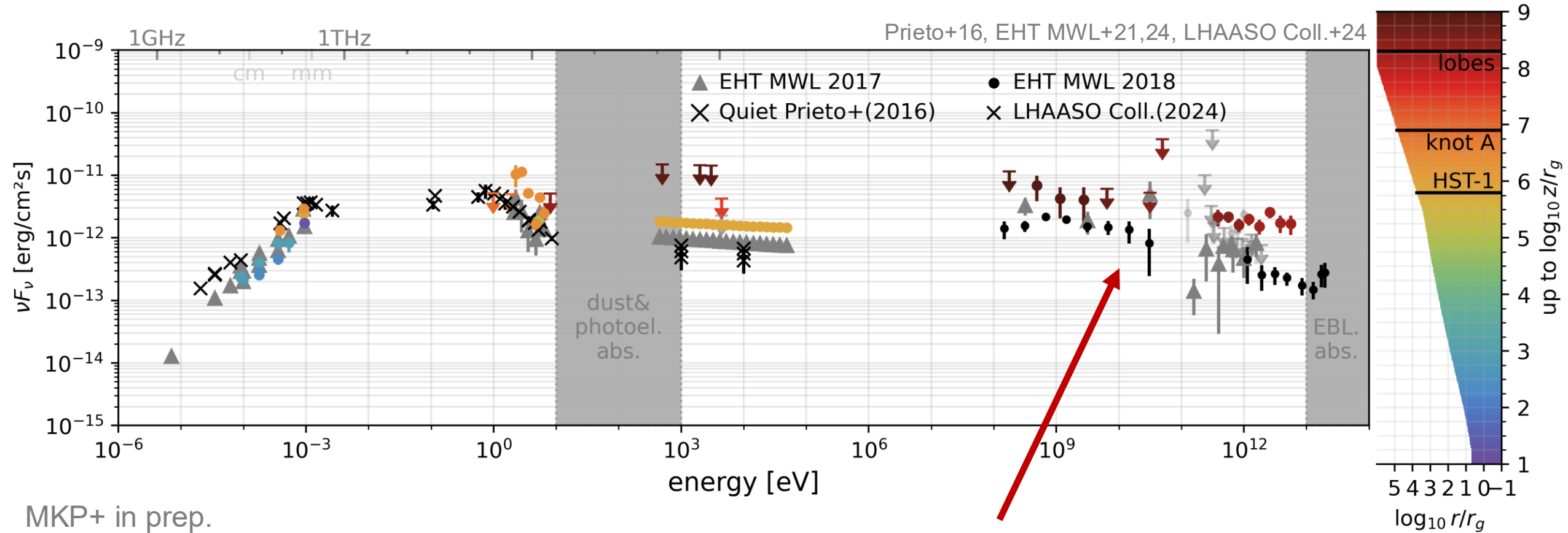
optical/UV: larger aperture, star light contamination from bulge

MWL spectrum during 2018 flare



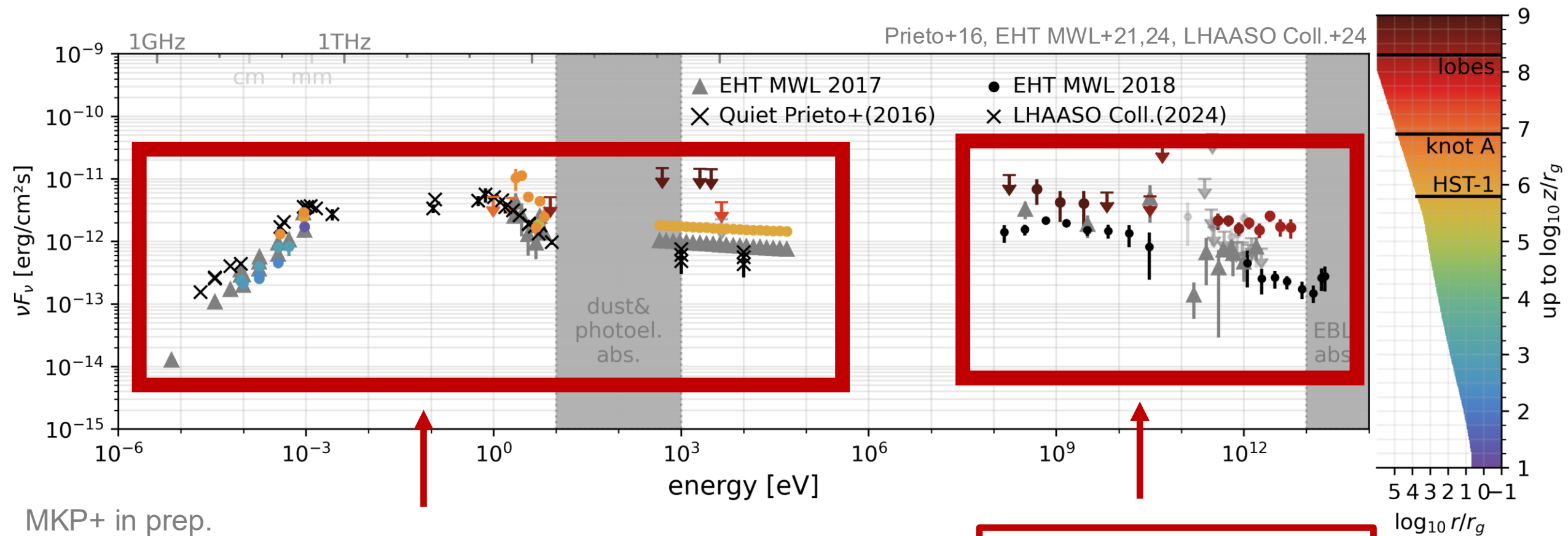
X-ray flux increase x3, but over ~months

MWL spectrum during 2018 flare



GeV-TeV γ -ray flux increase x3 over ~3 days

MWL spectrum during 2018 flare



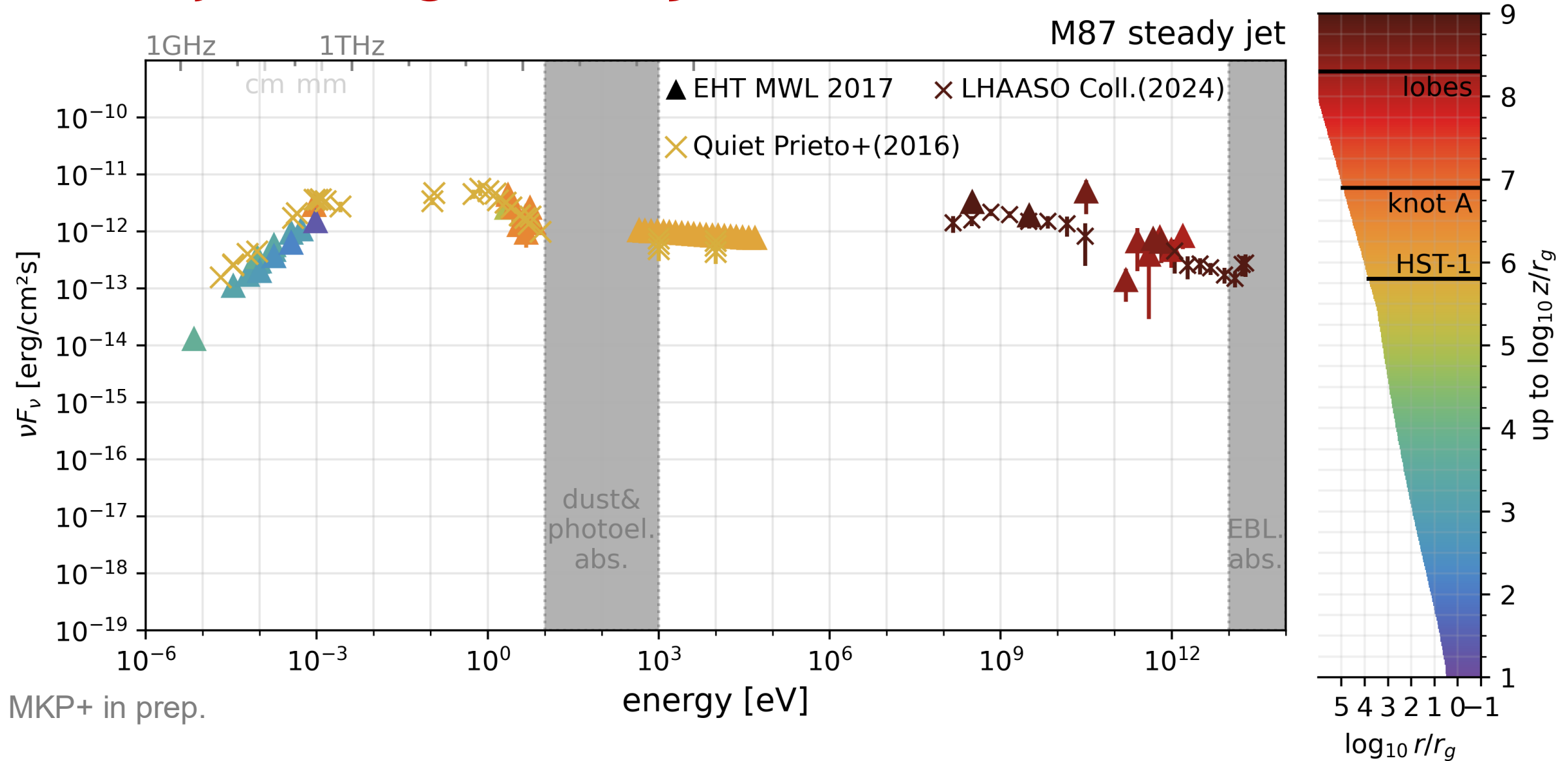
1) “steady” background jet

2) dominated by flaring blob on top

1) Steady background jet

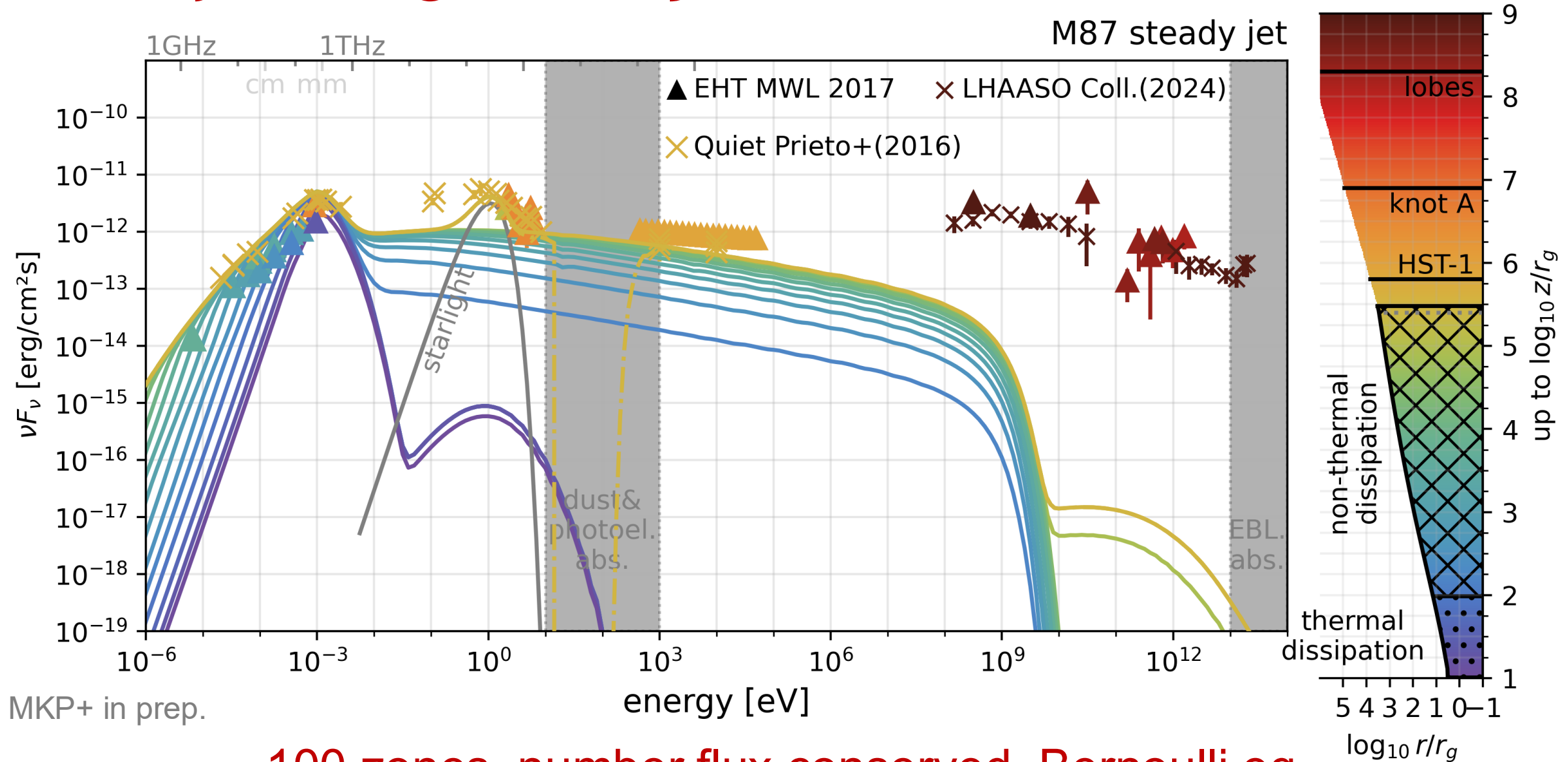
- radio–X-ray using BHJet model/code from Lucchini+19,22
- Blandford&Königl79, Falcke&Biermann95, Markoff+++
- <https://github.com/antonpannekoek/BHJet>
- updated, more user-friendly version coming soon..

Steady background jet



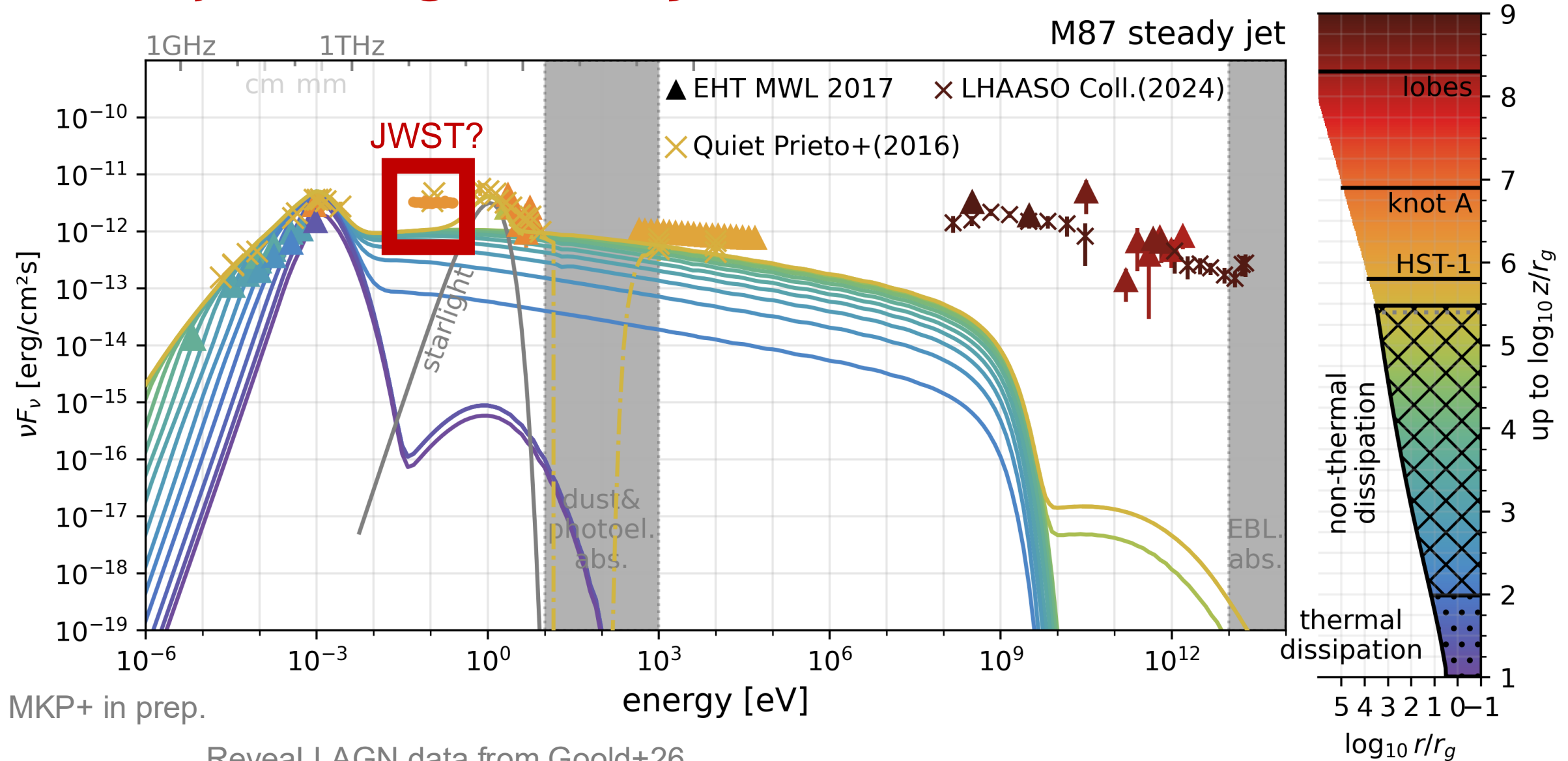
MKP+ in prep.

Steady background jet

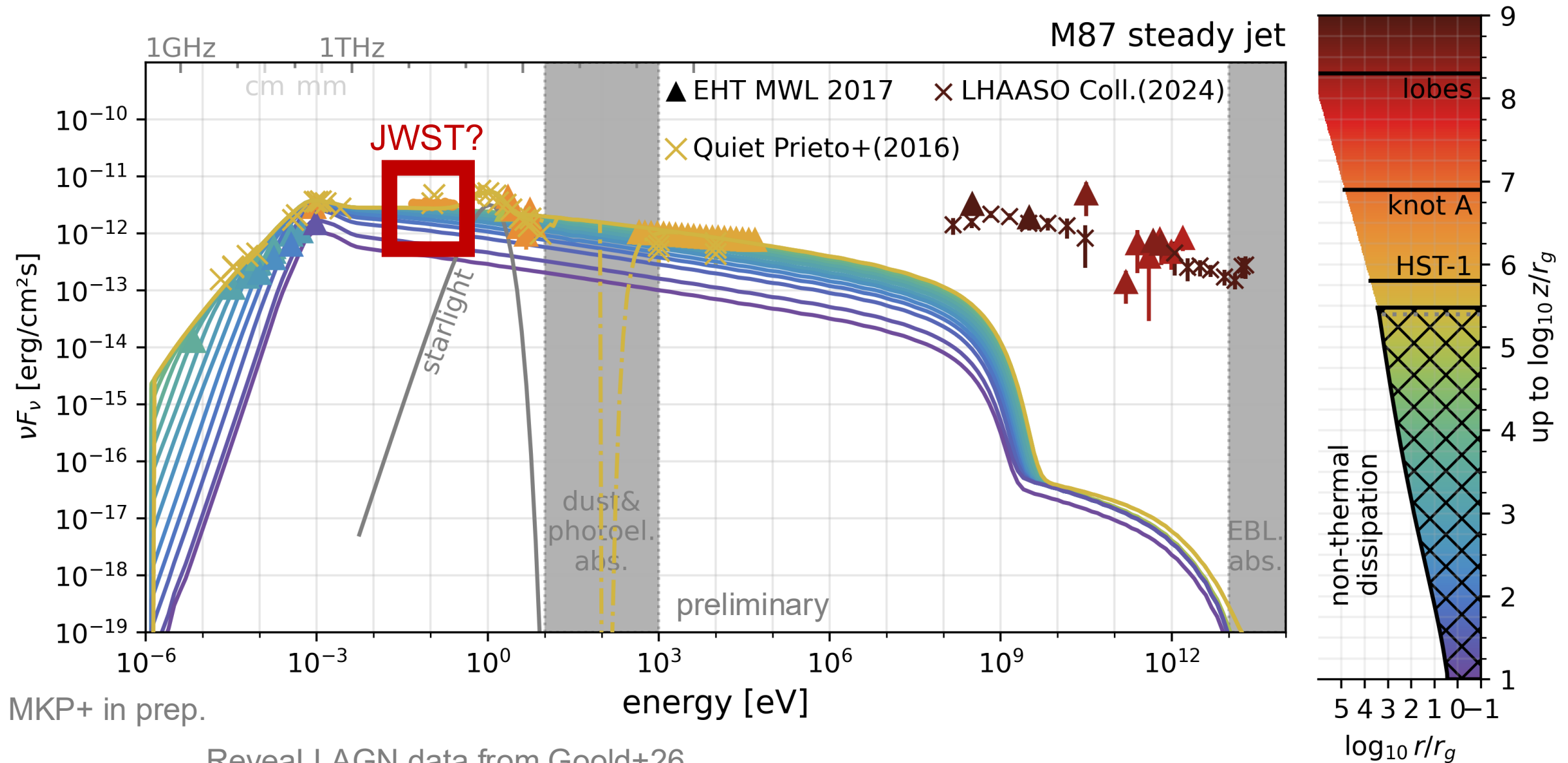


100 zones, number flux conserved, Bernoulli eq.

Steady background jet



Steady background jet - non-thermal to the base?

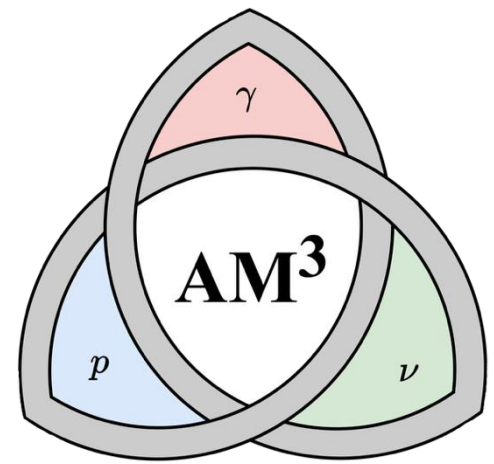


2) The flaring blob on top with AM³

AM³?

- = astrophysical multi-messenger modelling
- × solve transport equations - time dependent!
- × for protons, electrons, photons
+ pions, muons, neutrinos
- × Syn, IC, pair-prod., $p\gamma$, pp , Bethe-Heitler, decays,...
- × speed optimized (steady state in ~ 10 s)
- × component tracking
- × written in C++, interface to python
- × public including documentation!

<https://am3.readthedocs.io/en/latest/>
contact-am3@desy.de

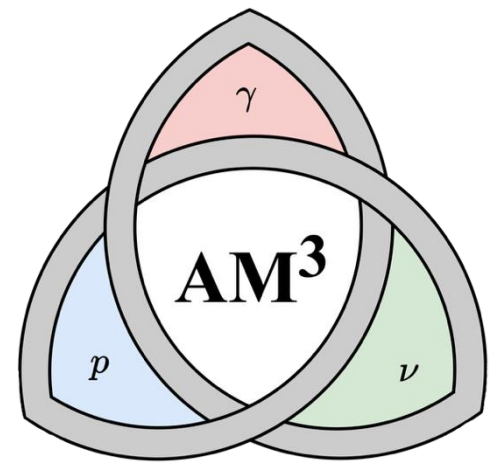


<https://gitlab.desy.de/am3/am3>

→ Klinger et al. ApJS 275 4 (2024)

News from AM³

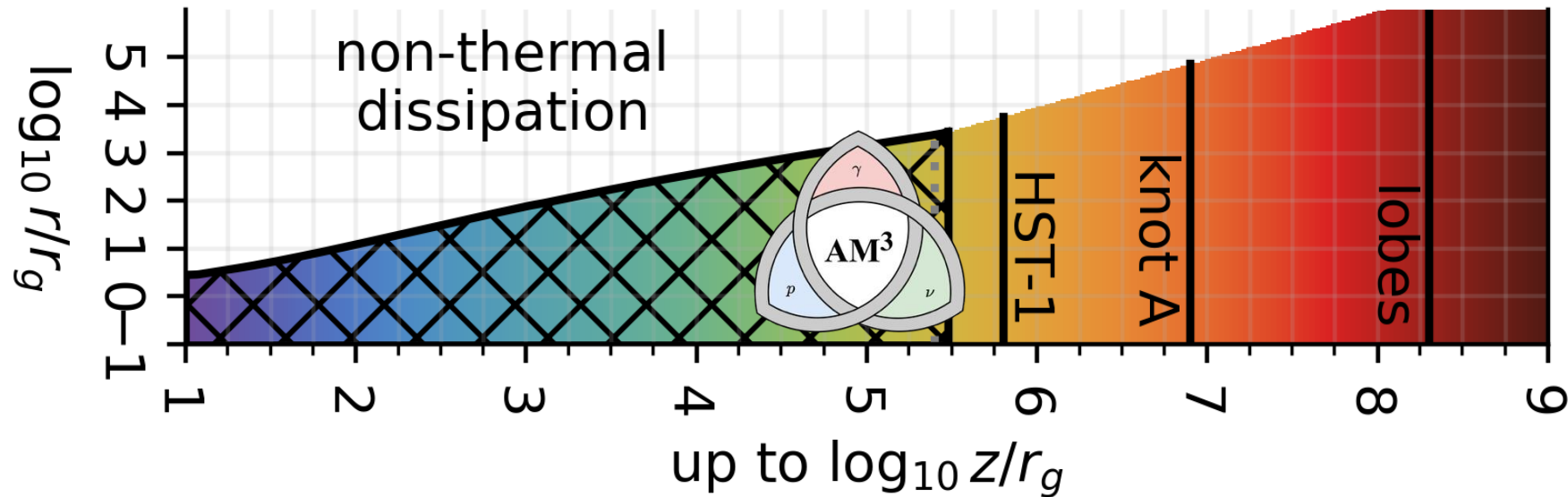
- × now on conda-forge
 - installation simply via `conda/mamba install am3`
- × Federico added quantum synchrotron cooling
- × added interface for custom escape, cooling and injection arrays
 - add your own physics
- × multiple AM³ instances using same shared kernels
 - memory efficient multi-zone modelling
- × currently working on a momentum grid update for lower energies
 - probably a version 2.0
 - **stay tuned!**



<https://gitlab.desy.de/am3/am3>

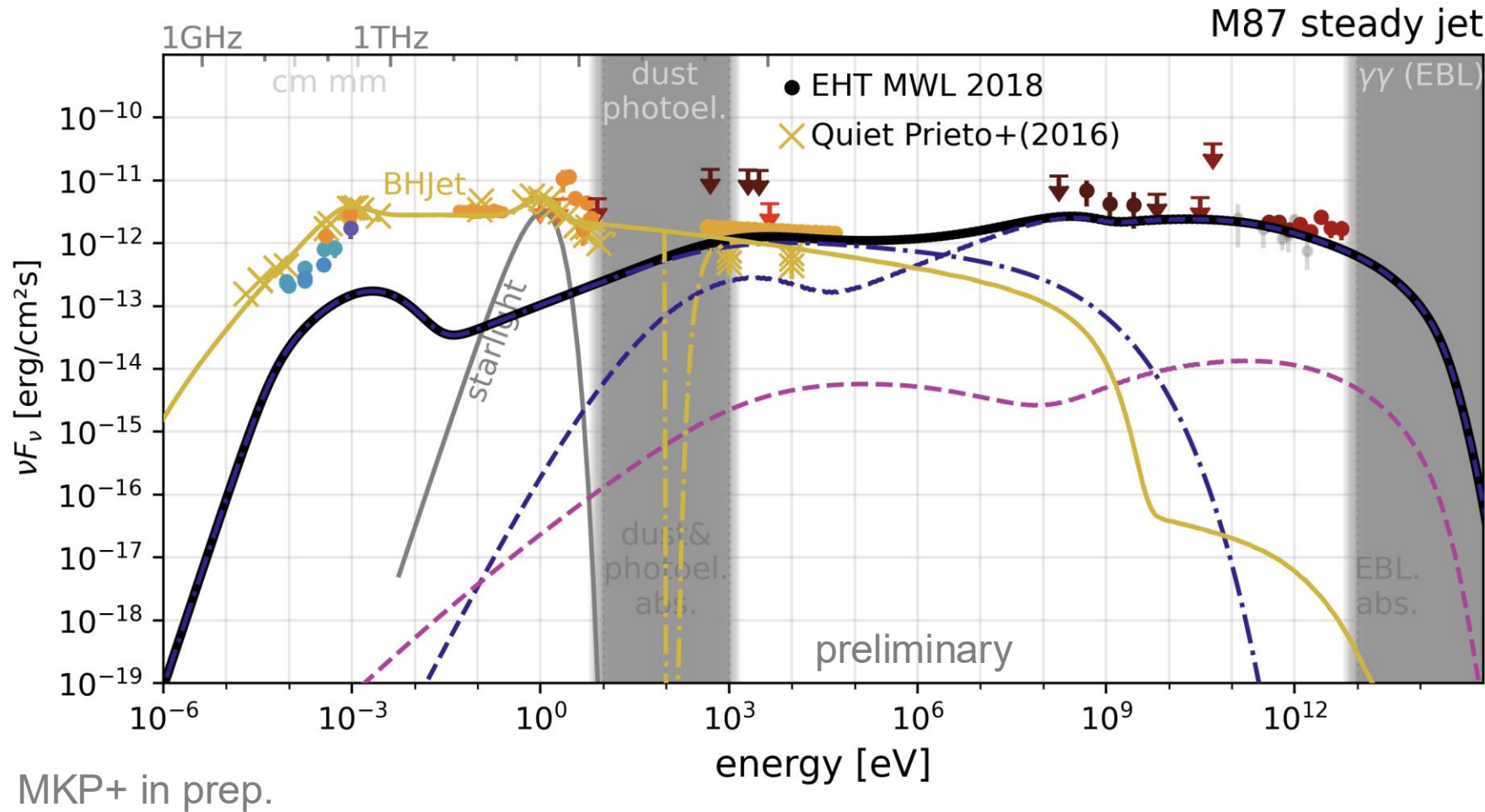
Can we perturb local conditions to explain the γ -rays?

background BHJet $\rightarrow r(z), B(z), \Gamma(z), n_\gamma(z), n_p(z), \dots$



1. location: z_{AM3}
2. size/escape: $\Delta R_{AM3} = f_{size} \times \mathcal{D}(z_{AM3}) \times c \times 3days$
3. magnetic field: $B_{AM3} = f_B \times B(z_{AM3})$
4. injected power: $P_{AM3} = f_{power} \times P_{jet}$
5. injected spectral index: s_{inj}
6. heating: $T_{e,AM3} = f_{Te} T_e(z_{AM3})$

Hot SSC blob at $10^3 r_g$



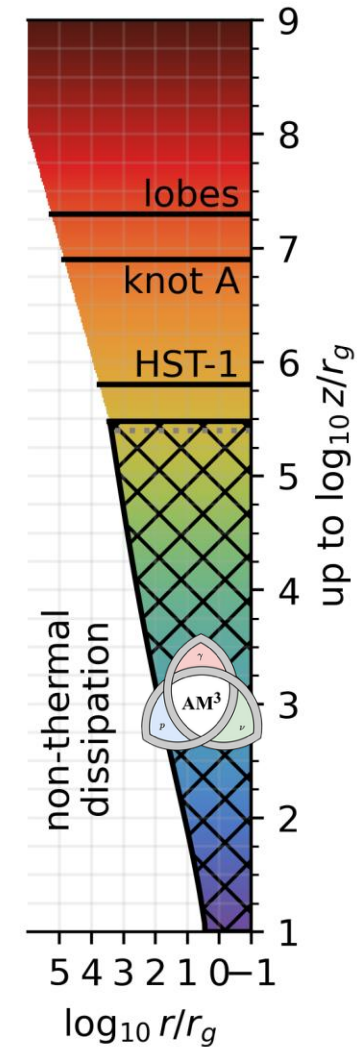
$$f_{size} = 0.1$$

$$f_B = 0.25$$

$$f_{power} = 0.13$$

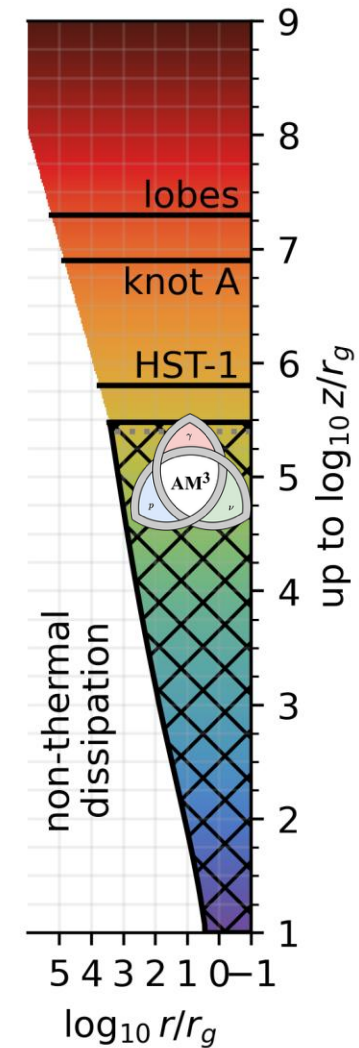
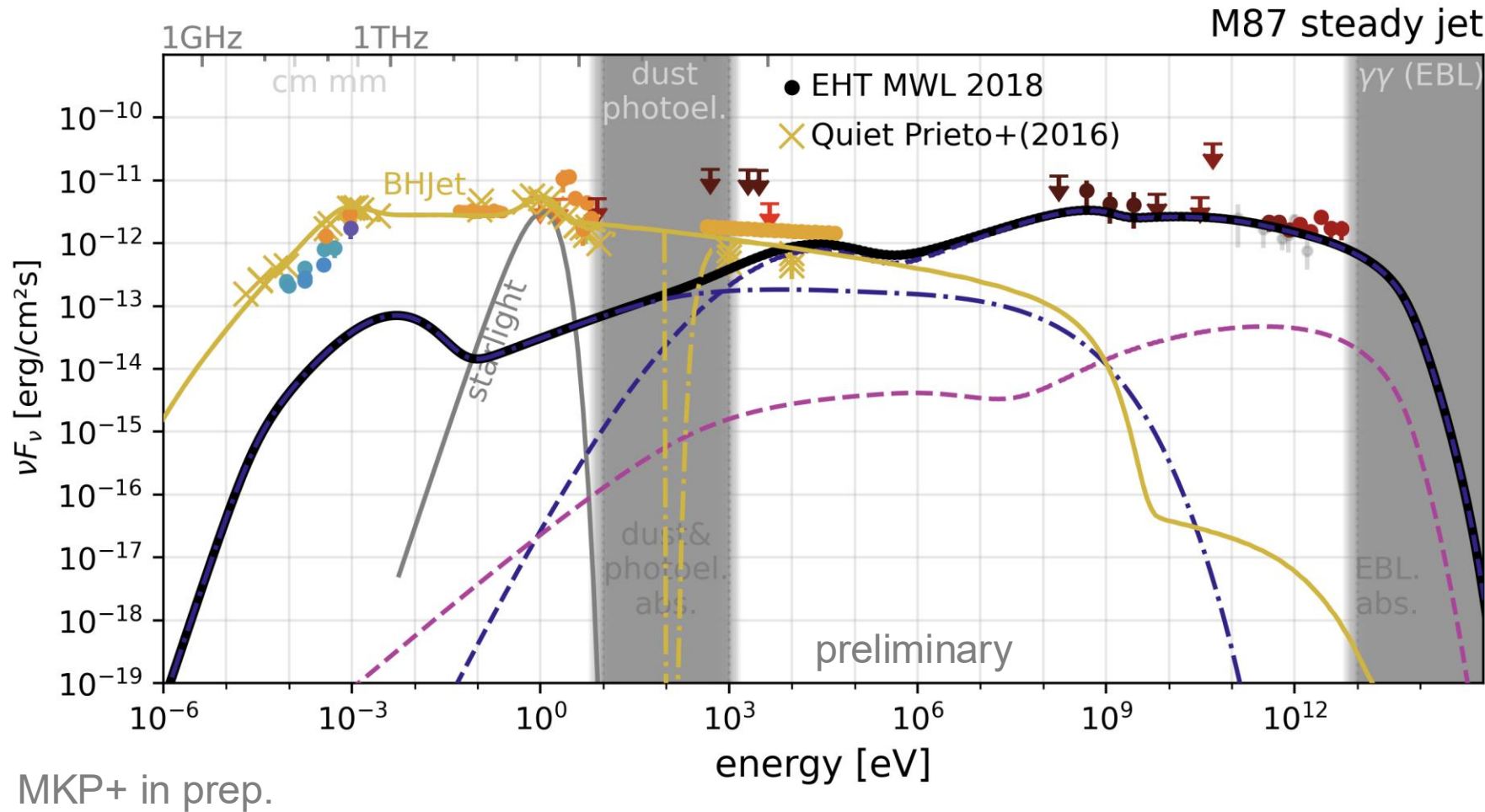
$$s_{inj} = 2.22$$

$$f_{Te} = 26$$



~5 perturbations, hard VHE & LAT spectrum

Hot SSC blob at $10^5 r_g$



$$f_{size} = 0.08$$

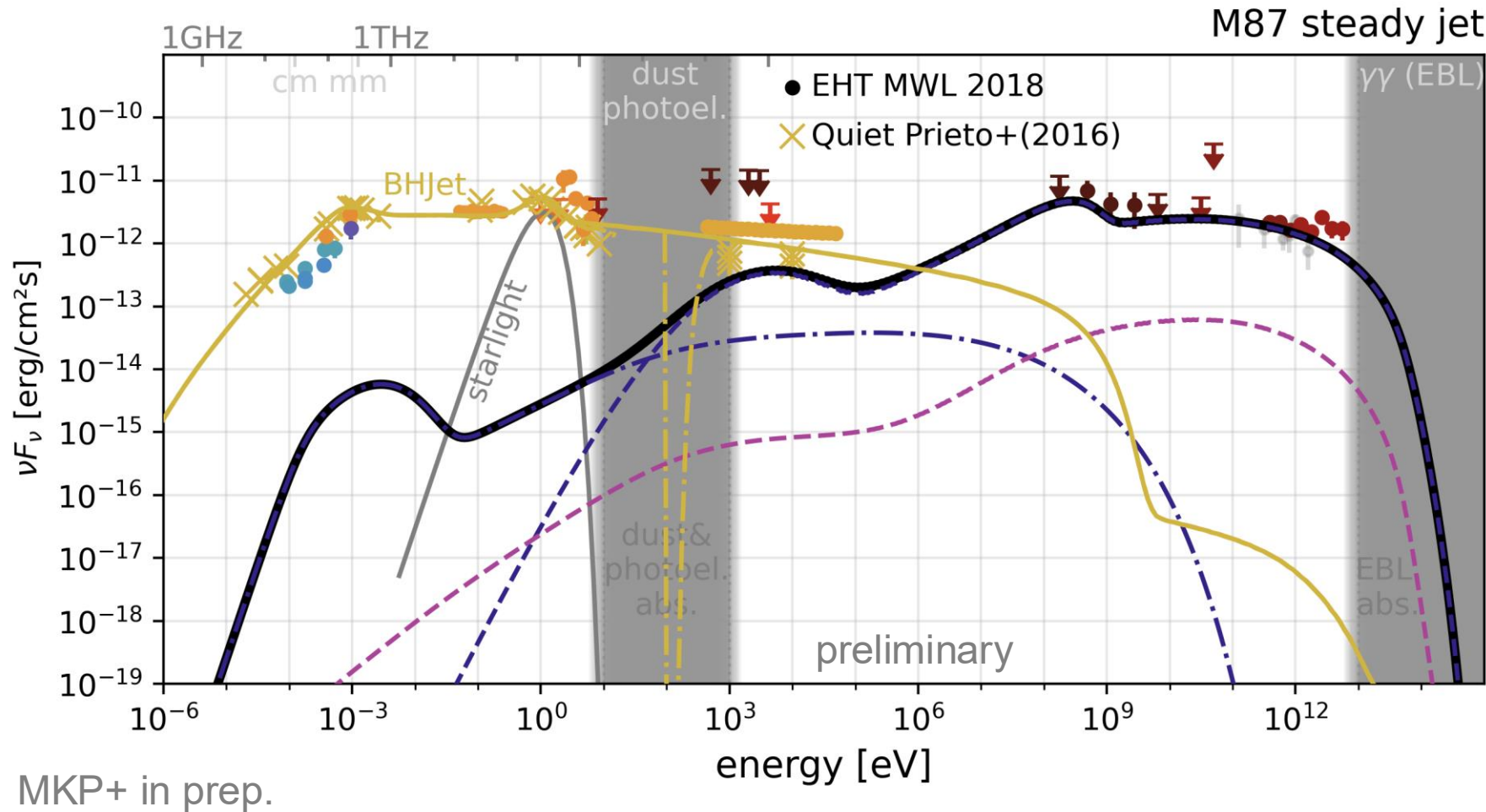
$$f_B = 25$$

$$f_{power} = 0.25$$

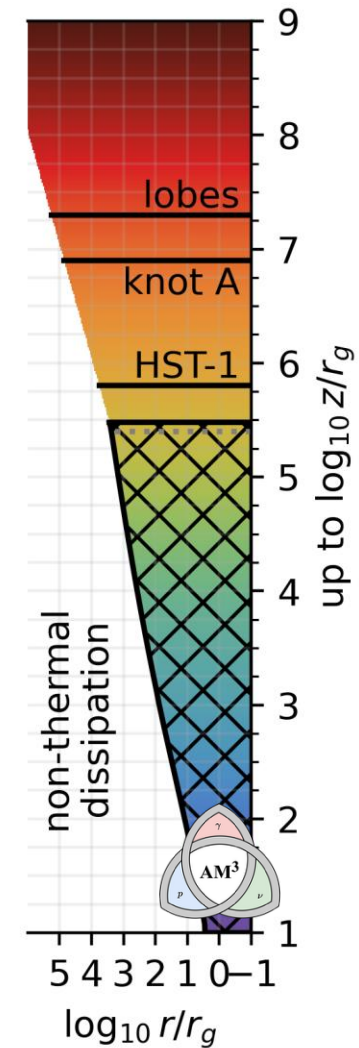
$$s_{inj} = 2.22$$

$$f_{Te} = 56$$

Hot SSC blob at $30r_g$



MKP+ in prep.



$$f_{size} = 0.07$$

$$f_B = 0.01$$

$$f_{power} = 0.21$$

$$s_{inj} = 2.0$$

$$f_{Te} = 35$$

Summary

- × M87 keeps flaring at TeV
 - physical origin unclear
- × 3-days → $\approx 10r_g$ size
- × location unconstrained
- × radio–X-ray data can be explained reasonably with steady-state model (BHJet)
- × flare as perturbation
 - possible along jet, but not most natural (5 parameters, orders of magnitude)
- × AM³: stay tuned

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Outlook

- × more systematic exploration..
- × proton injection
- × upcoming 2-month EHT MWL campaign Spring 2026 for M87

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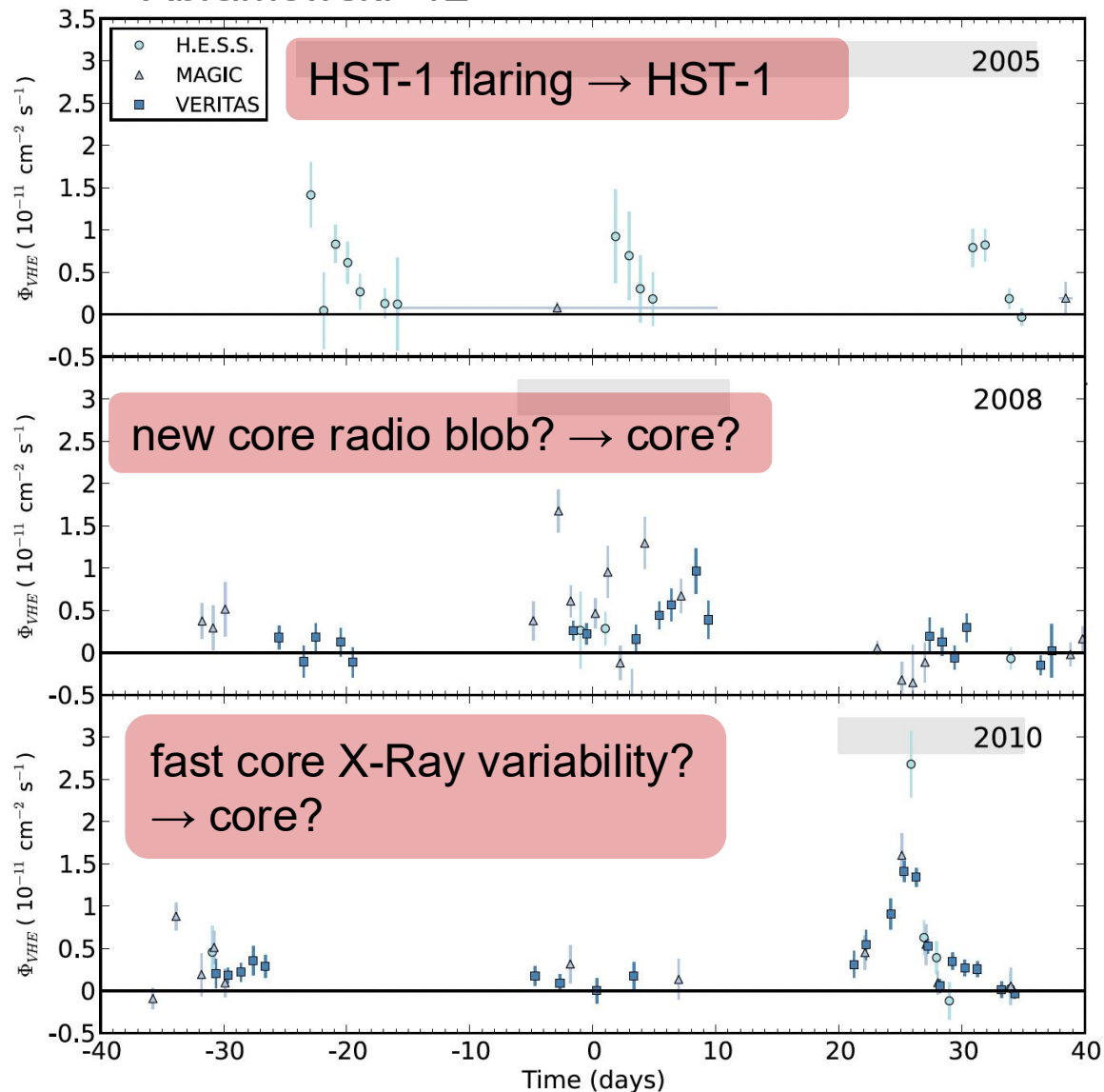
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Thank you!

Backup

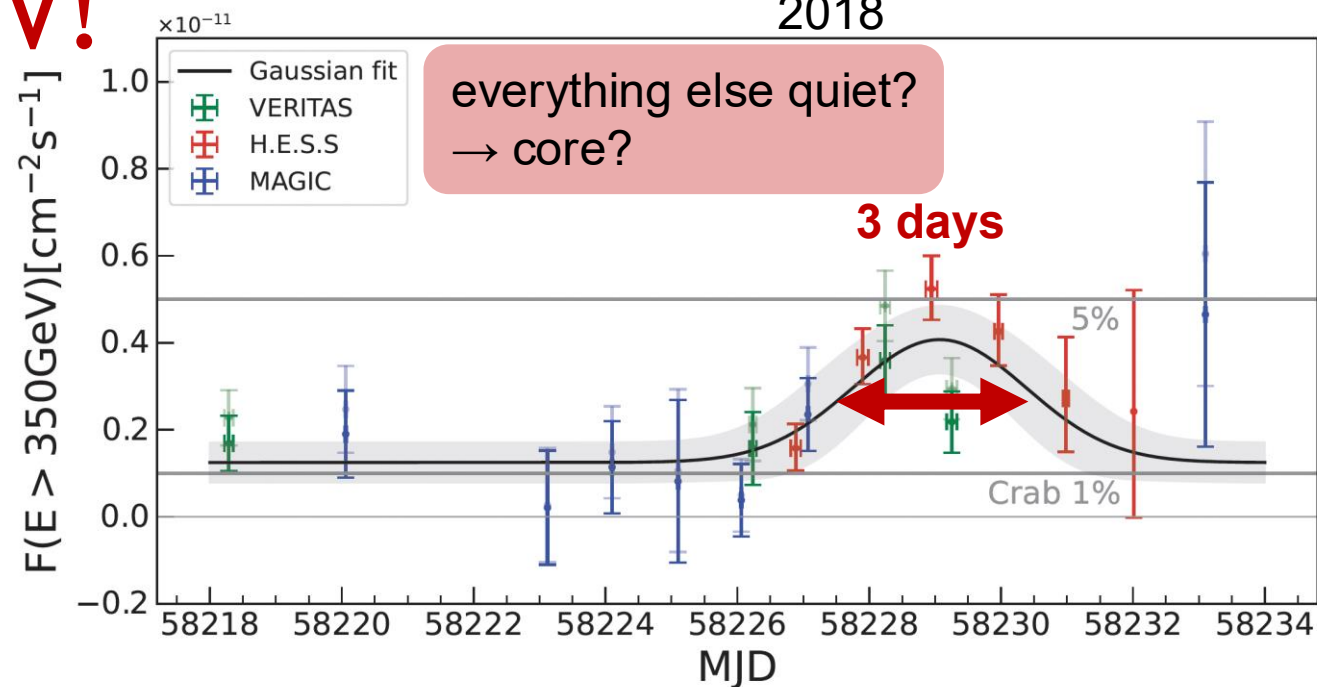
M87 keeps flaring at TeV!

Abramowski+12

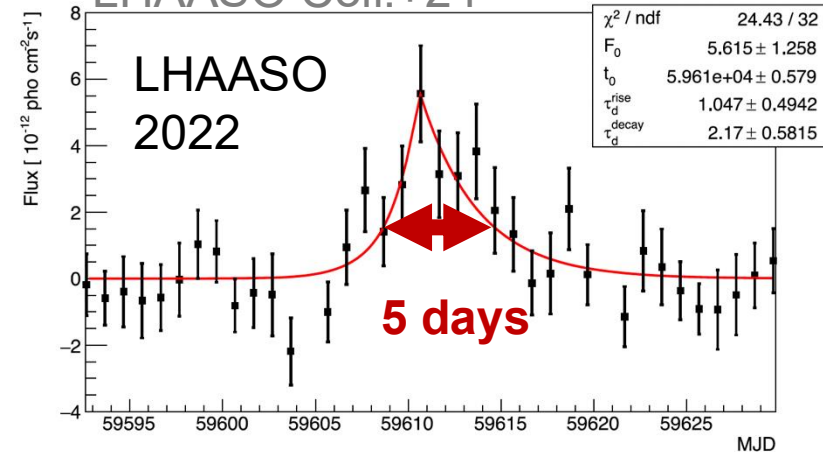


EHT MWL+24

2018

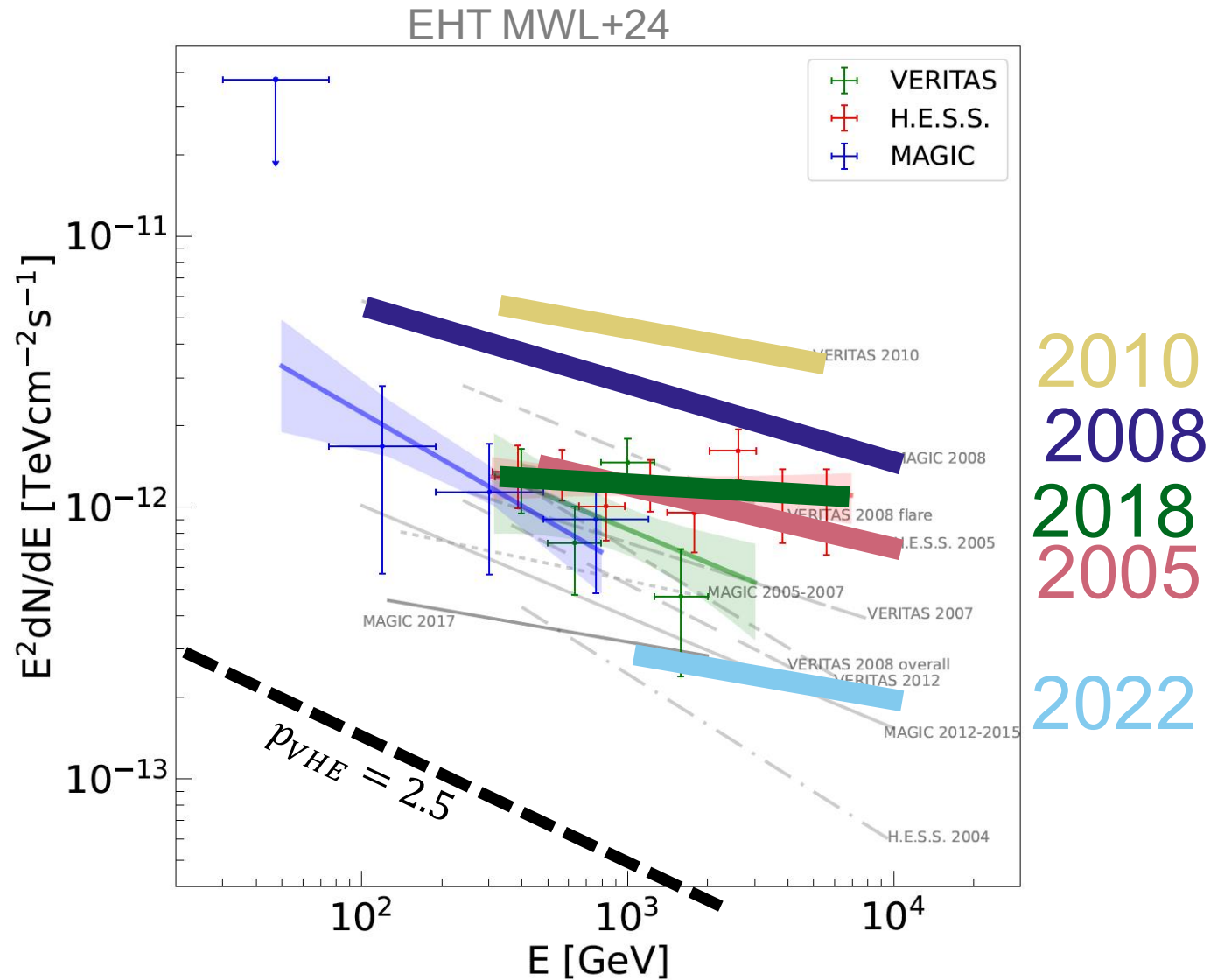


LHAASO Coll.+24



only Fermi-LAT, no MWL...

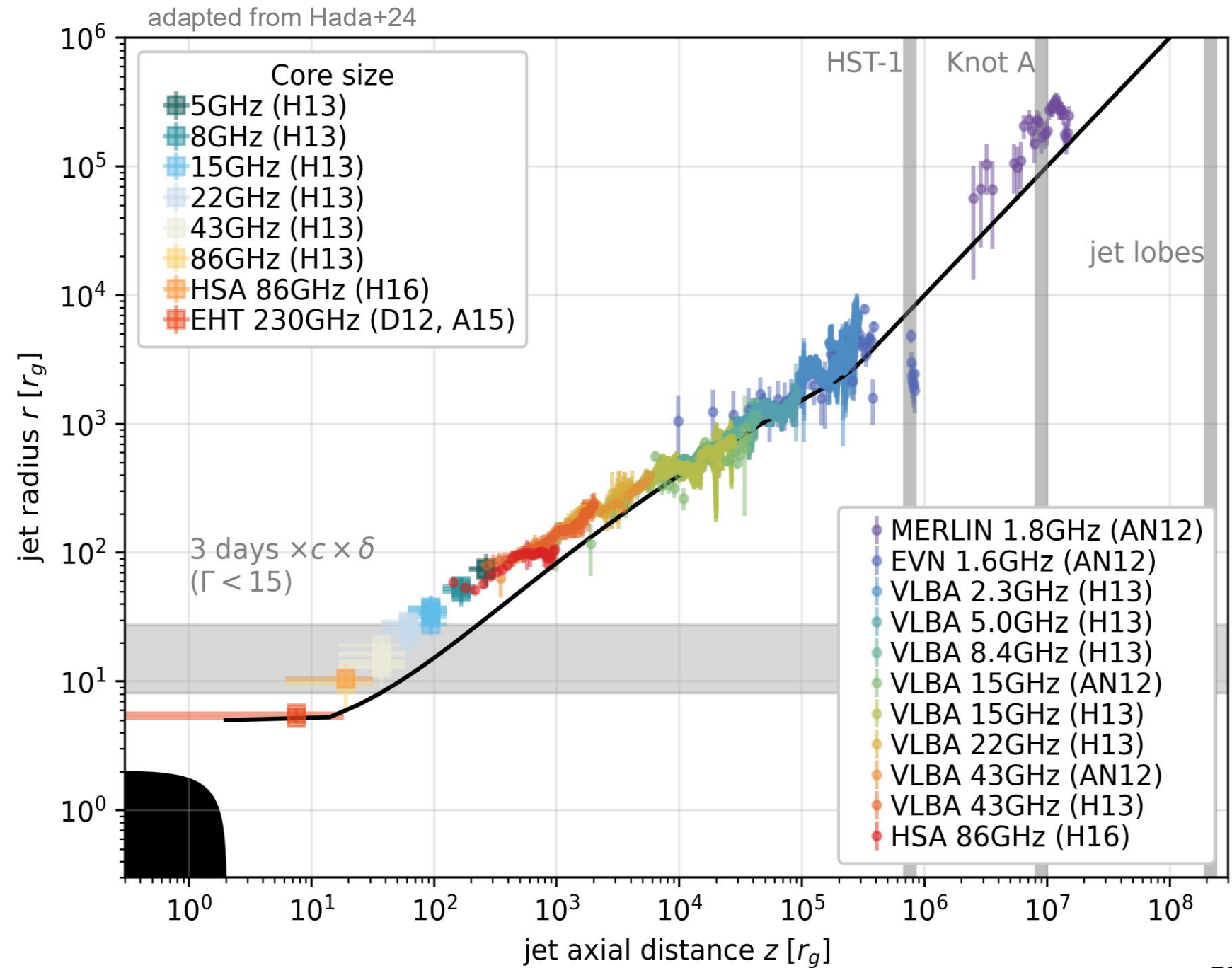
M87 VHE flare spectra



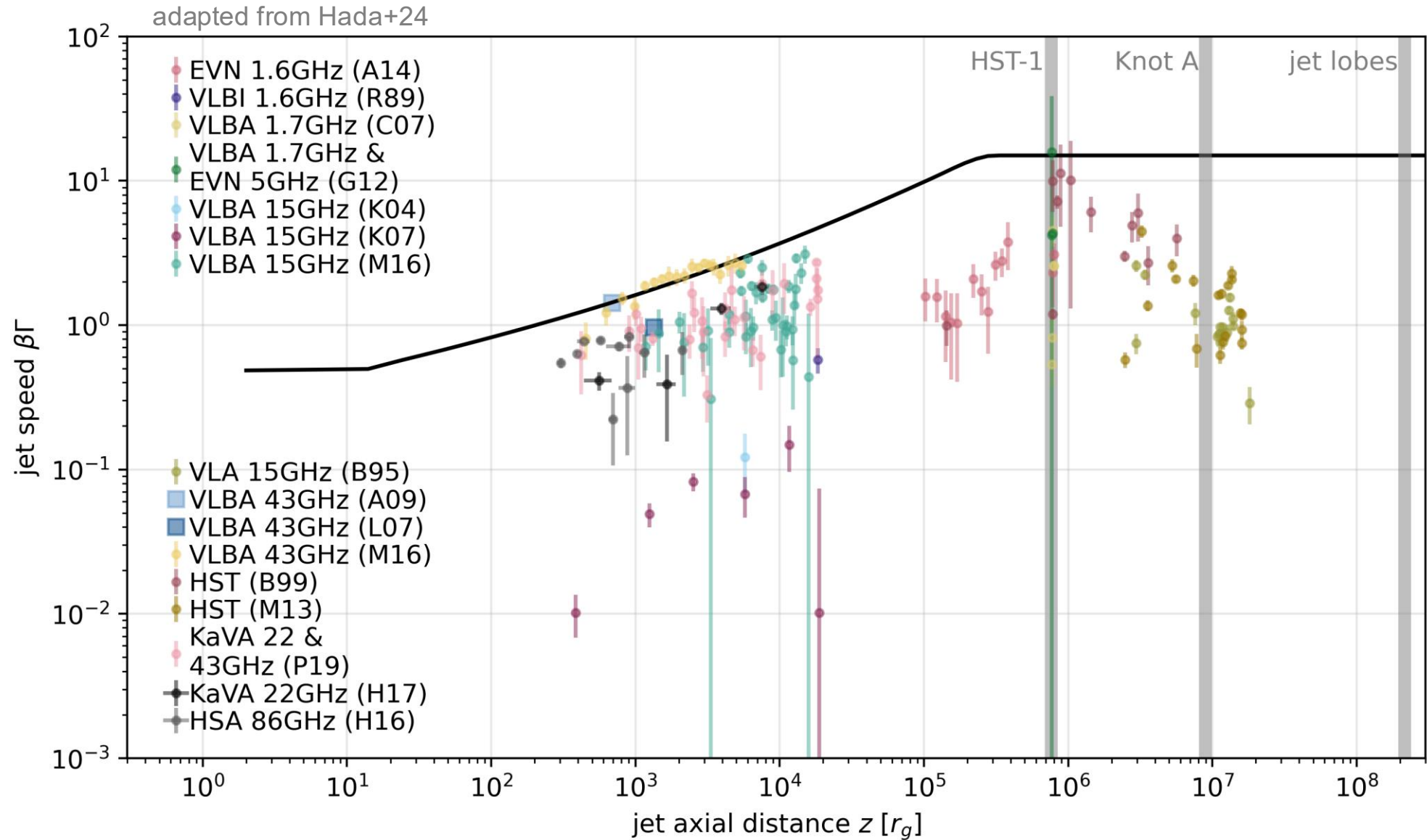
hard VHE spectra
during flare

$$\rightarrow p_{VHE} \approx 2 - 2.3$$

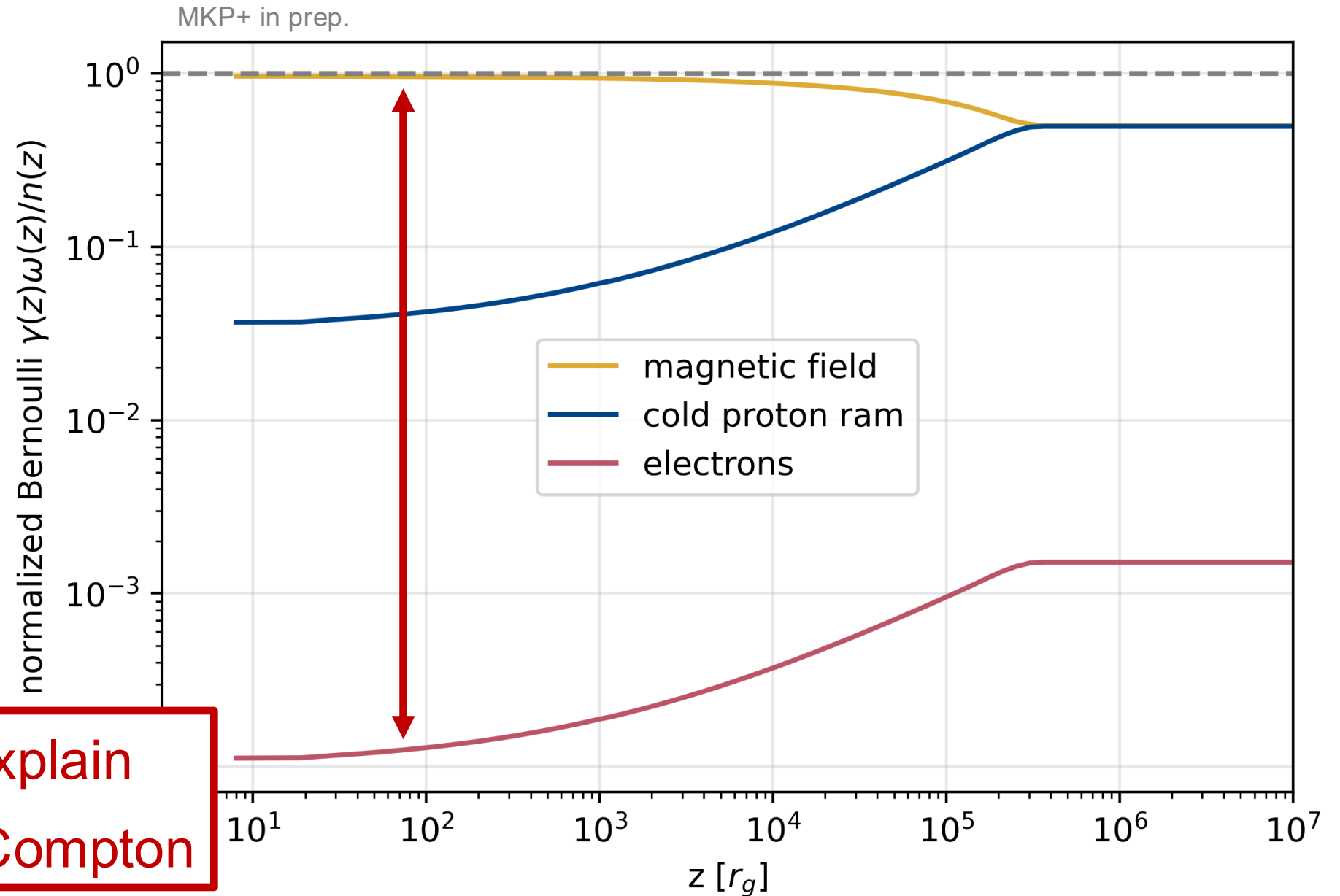
BHJet



BHJet

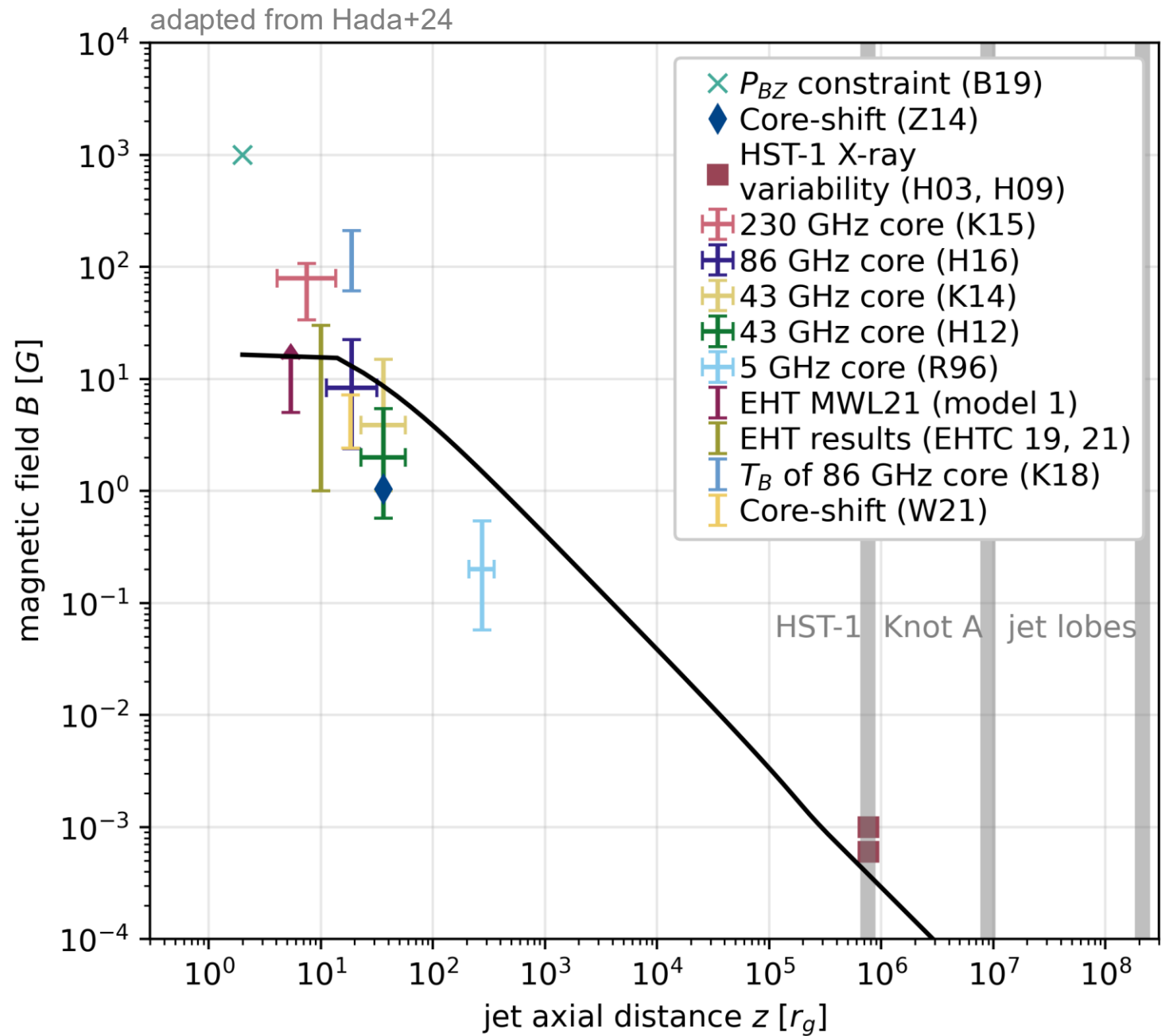


BHJet

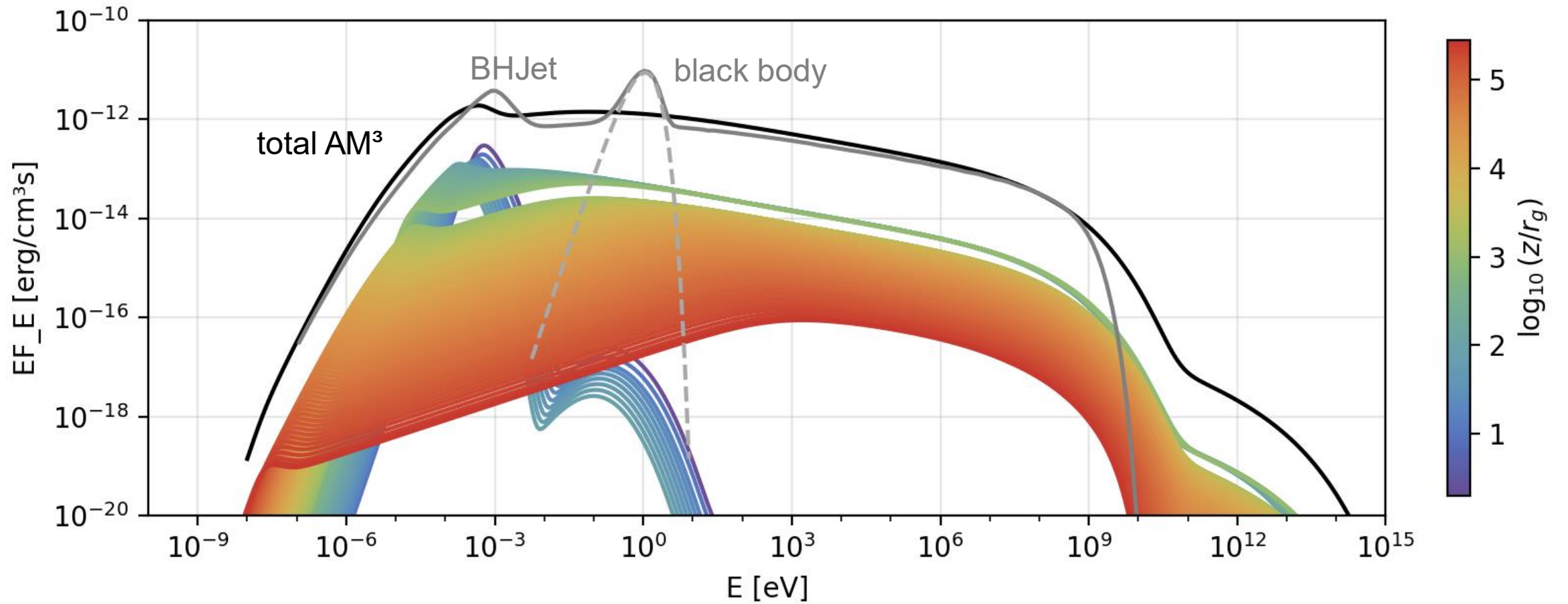


$\frac{u_B}{u_e} \gg 1 \rightarrow$ hard to explain
 γ -rays as inverse Compton

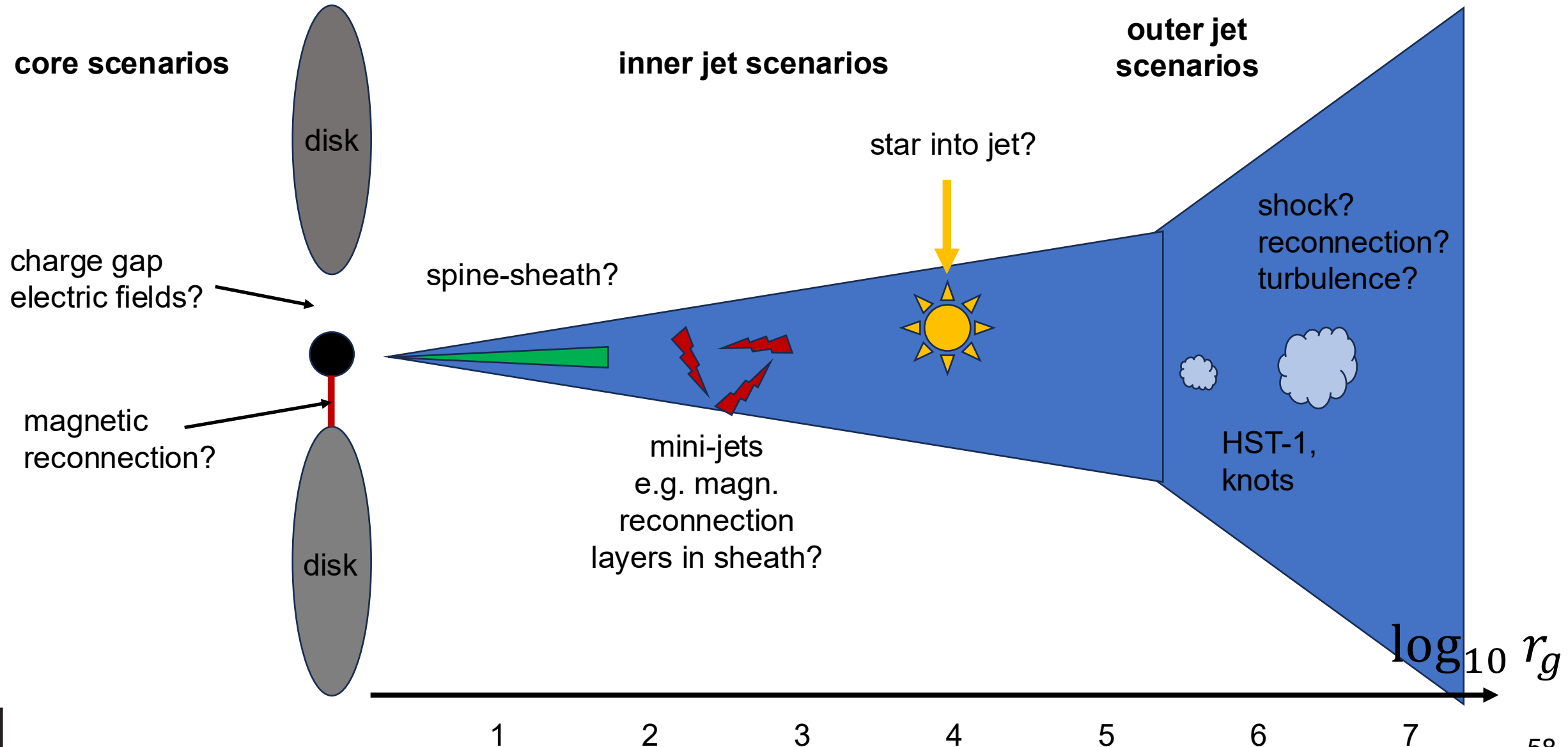
BHJet



BHJet vs AM3



Many existing flare explanation ideas..



AM³ blob parameters

- × z_{AM3} : location along jet
- × $r_{AM3} = f_{size} \times 3days \times c \times \mathcal{D}(z_{AM3})$: as a fraction of the flaring time scale
- × $t_{esc,AM3} = \frac{r_{AM3}}{c}$: escape time scale for all particles
- × $V_{AM3} = \frac{4\pi}{3} r_{AM3}^3$: just a spherical blob
- × $q_{0,AM3} = f_{power} \times \frac{P_{jet}}{V_{AM3}}$: fraction of jet power injected into blob
- × $s_{inj,AM3}, f_{Te}, f_{nth}$: injection index, el. temp. factor, non-thermal fraction
- × $B_{AM3} = f_B \times B_{BHJet}(z_{AM3})$: fraction of the magnetic field
- × $\beta\Gamma_{AM3} = f_{\beta\Gamma} \times \beta\Gamma_{BHJet}(z_{AM3})$: factor for bulk momentum
→ $\mathcal{D}_{AM3} = \Gamma_{AM3}^{-1} (1 - \beta_{AM3} \cos(\theta_{AM3}))^{-1}$: with θ_{AM3} between observer and $\vec{\beta}_{AM3}$
- × $q_{\gamma,AM3} = u'_{target,BHJet}(z_{AM3}) \times \left(\frac{\mathcal{D}_{AM3}}{\mathcal{D}_{BHJet}(z_{AM3})} \right)^2$, $E_{\gamma,AM3} = E'_{\gamma,BHJet} \frac{\mathcal{D}_{AM3}}{\mathcal{D}_{BHJet}(z_{AM3})}$