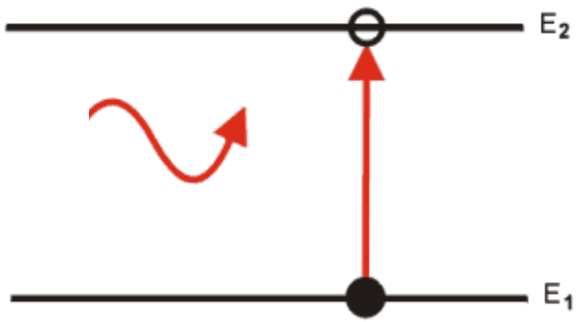
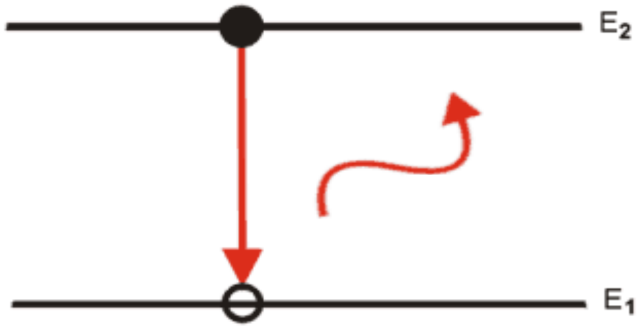




Iron beacon in the sky: Centaurus A gamma-ray emission from excitation and de-excitation of heavy ions

Koichiro Yasuda (UCLA)

Based on the ongoing collaboration work with

Yoshiyuki Inoue (University of Osaka),

Alexander Kusenko (UCLA),

Linjie Liu (University of Chinese Academy of Sciences),

Jirong Mao (Yunnan Observatories),

and Shigehiro Nagataki (RIKEN iTHEMS)

Main message

Heavier elements

(than protons)

Rich information

Main message

Heavier elements

(than protons)

Rich information

Acceleration

Main message

Heavier elements

(than protons)

Rich information

Acceleration **GeV/TeV gamma-ray**

Main message

Heavier elements

(than protons)

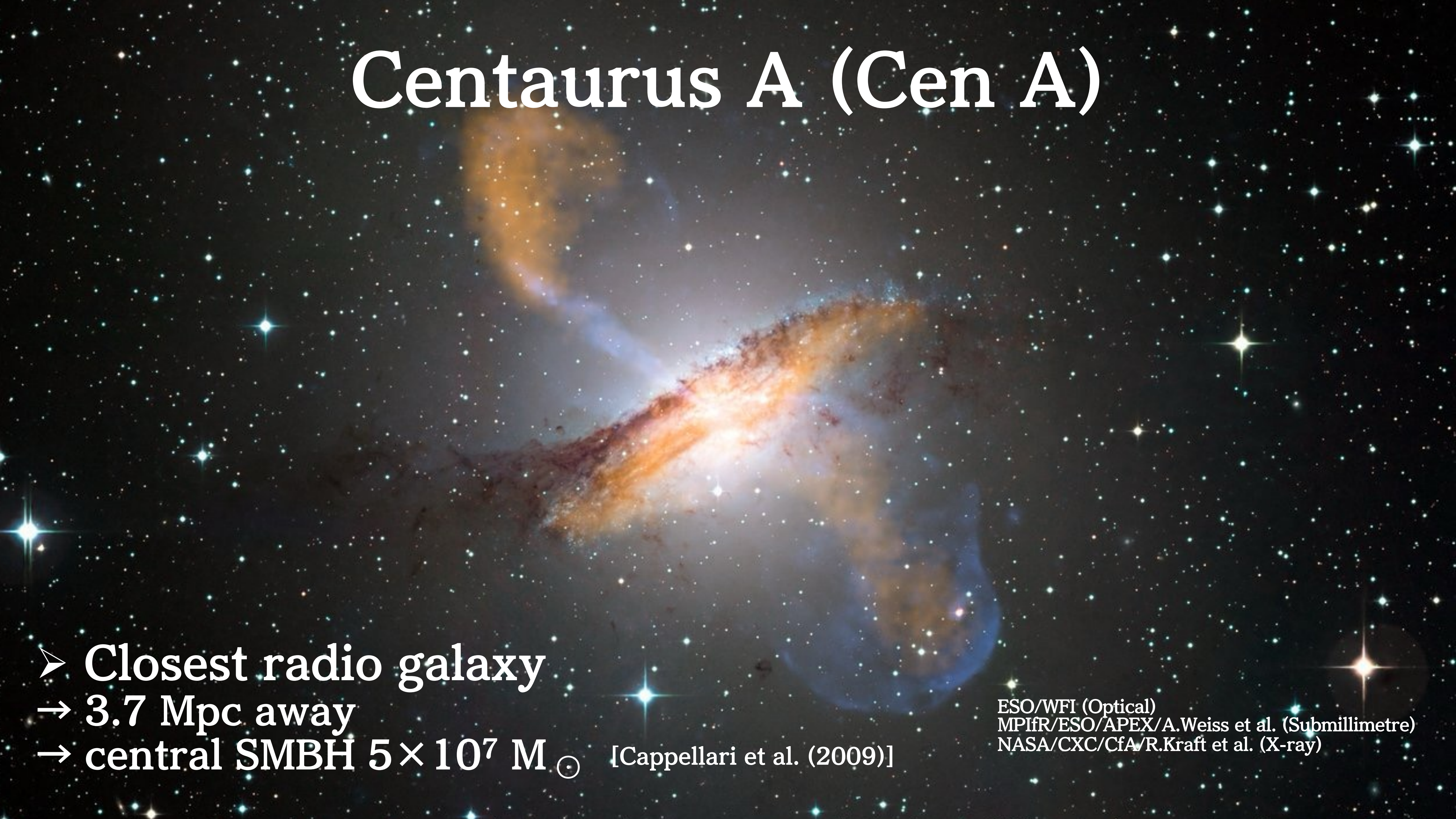
↓

Rich information

↙ ↓ ↘

Acceleration **GeV/TeV gamma-ray** **Cosmic ray**

Centaurus A (Cen A)

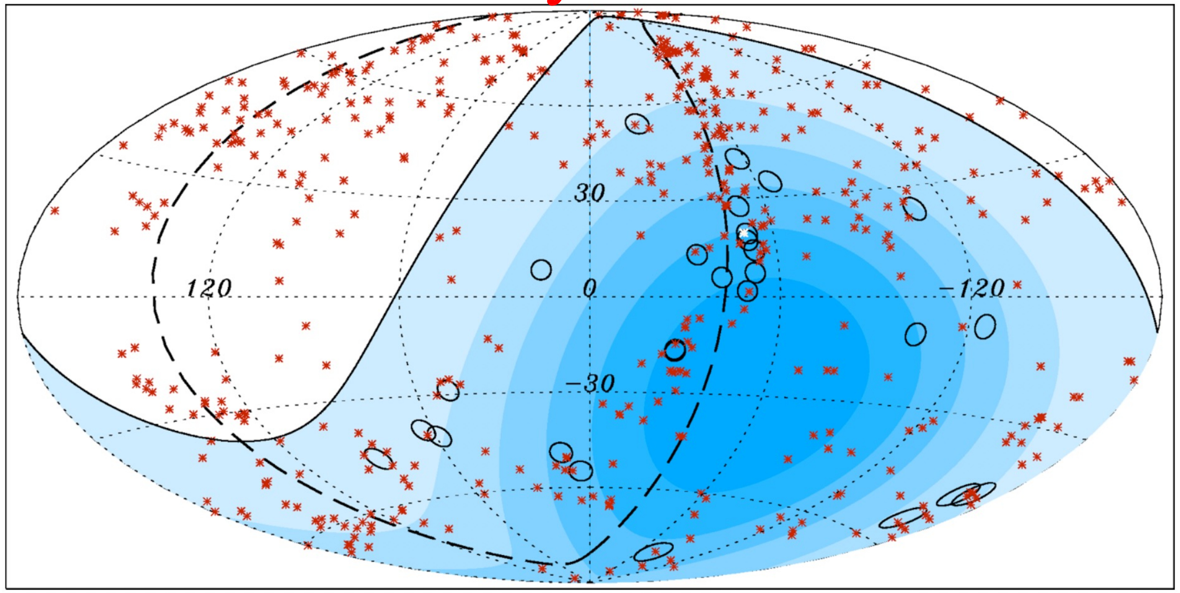


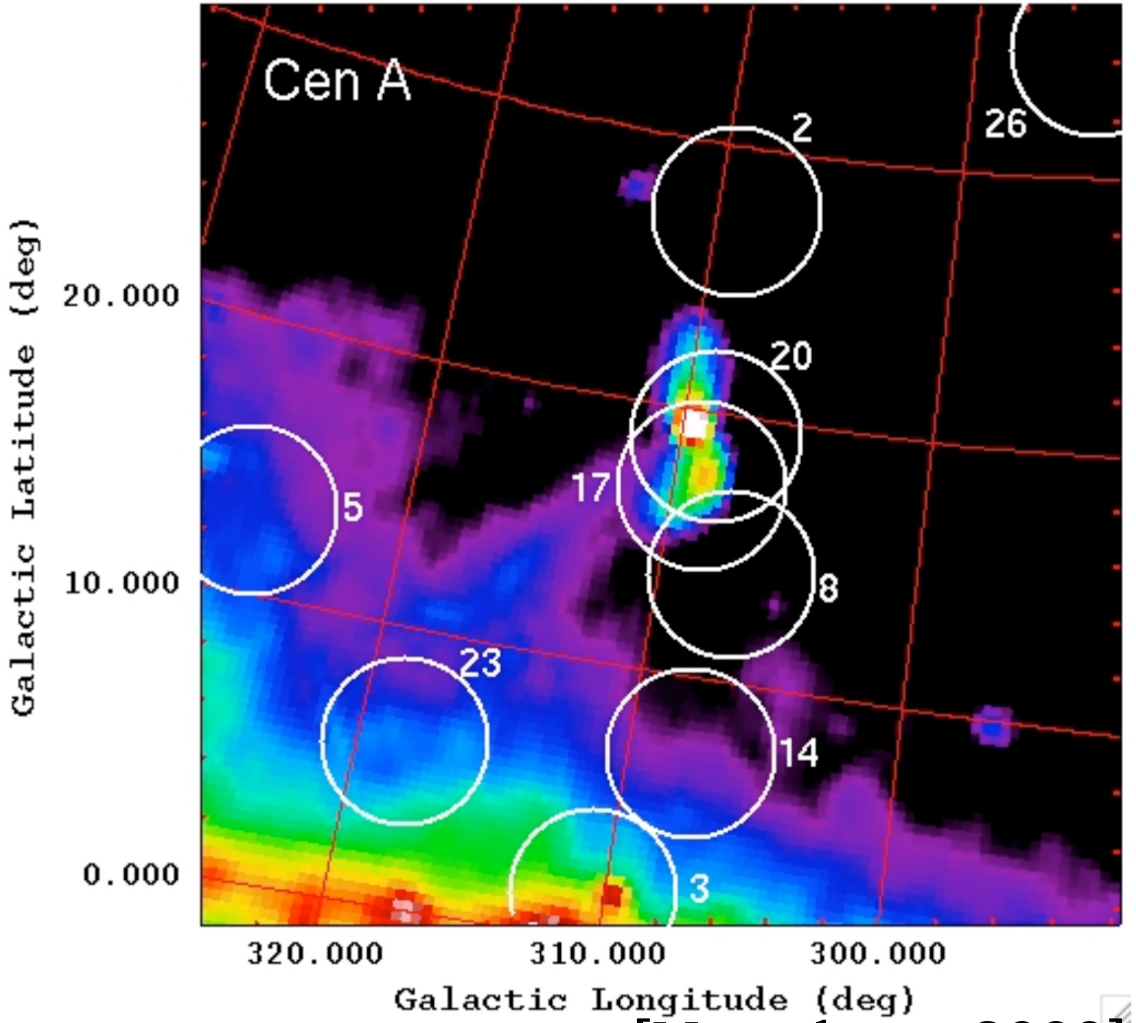
➢ Closest radio galaxy
→ 3.7 Mpc away
→ central SMBH $5\times10^{7}\ M_{\odot}$ [Cappellari et al. (2009)]

ESO/WFI (Optical)
MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre)
NASA/CXC/CfA/R.Kraft et al. (X-ray)

Cen A as Cosmic Accelerator?

x: Positions of nearby AGNs

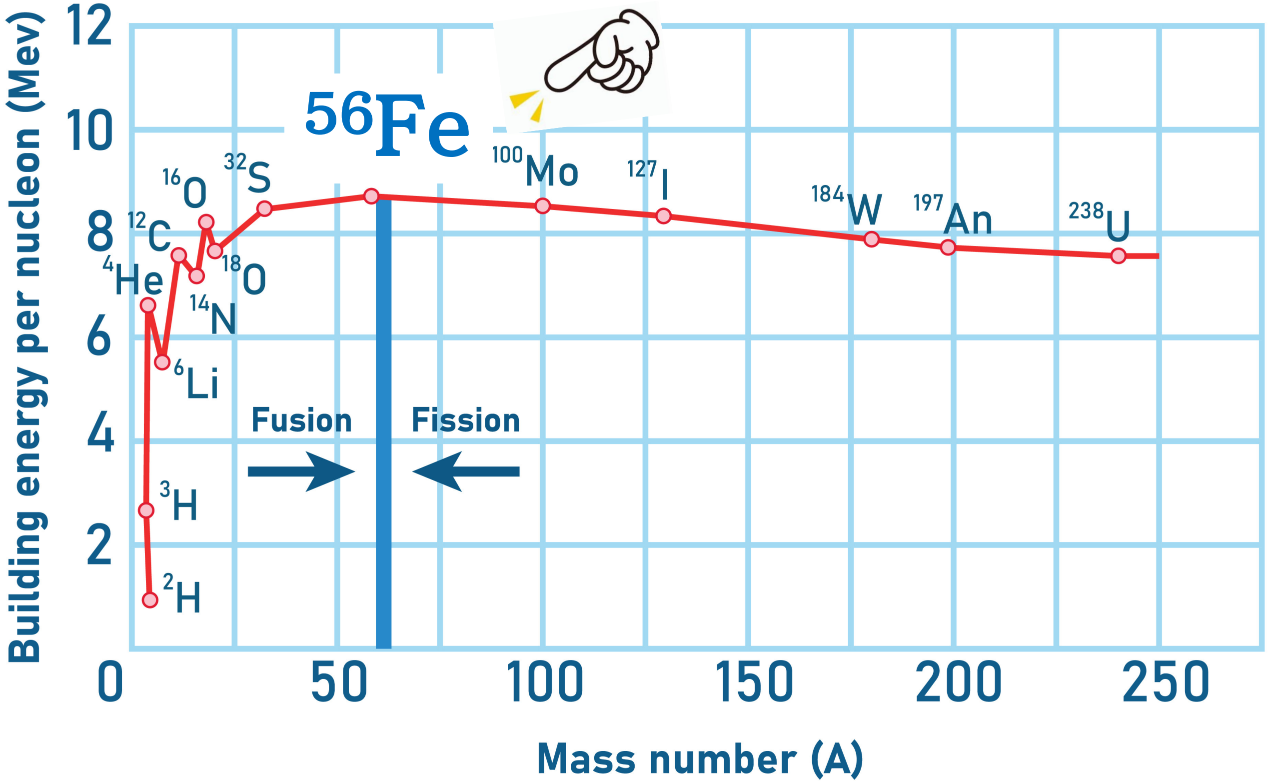


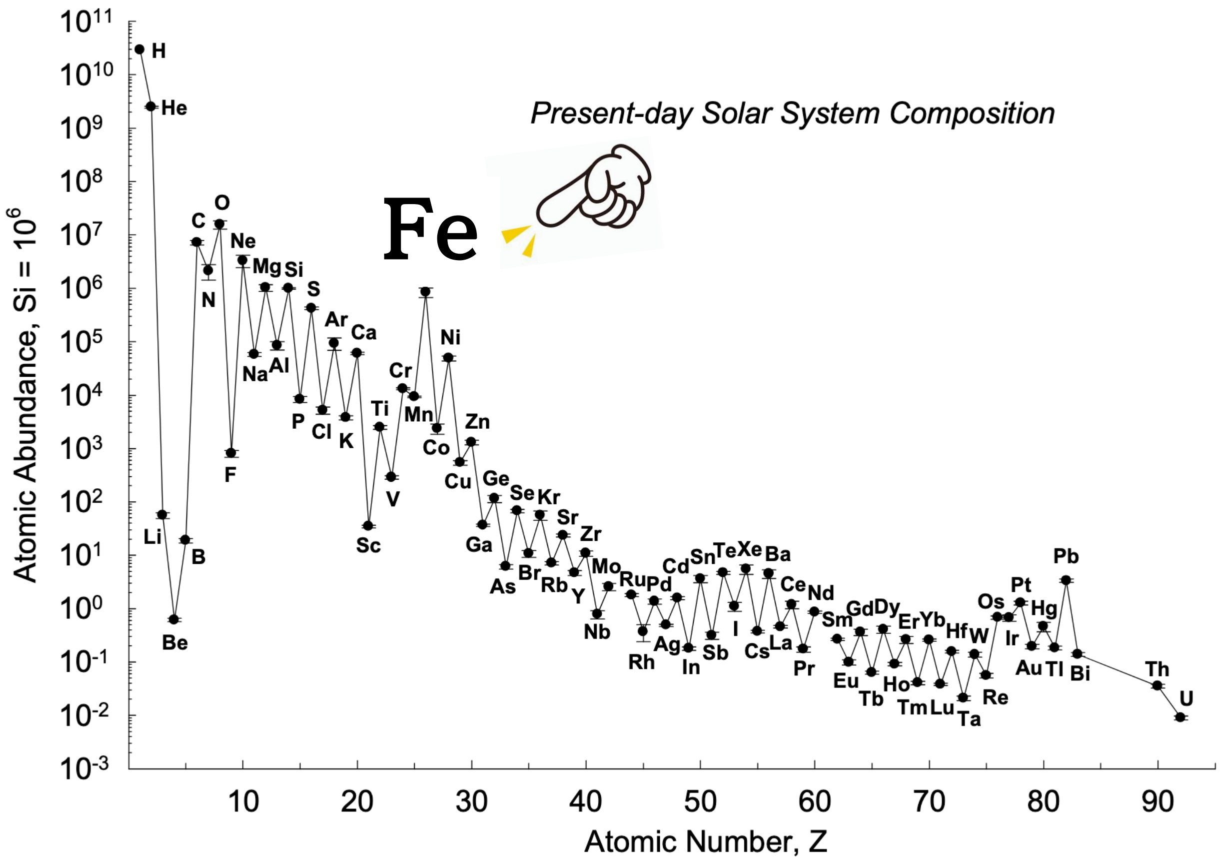


[Moscalenco 2009]

- ➢ Pierre Auger Observatory
- → Cosmic ray signals are observed
- ➢ Signal from Cen A direction
- → 4σ excess at Energy > 40 EeV
- → favored heavy nuclei contents

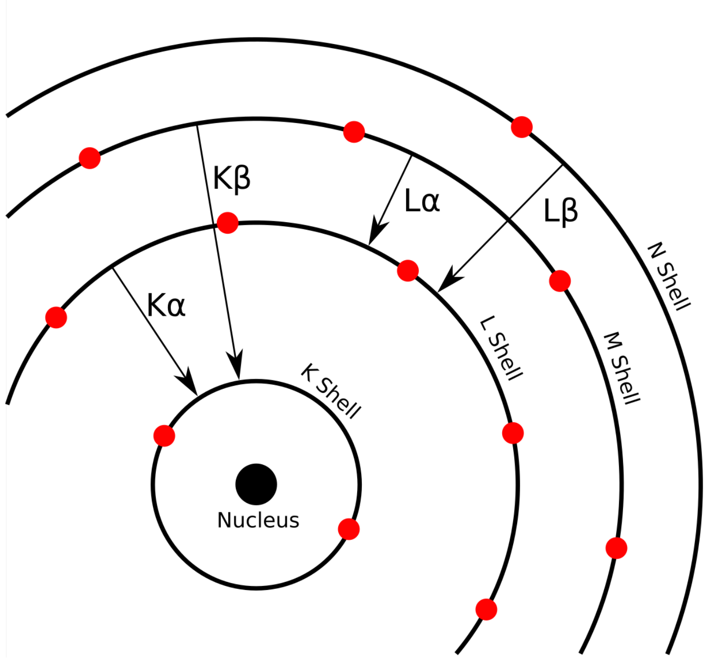
Our focus: Fe

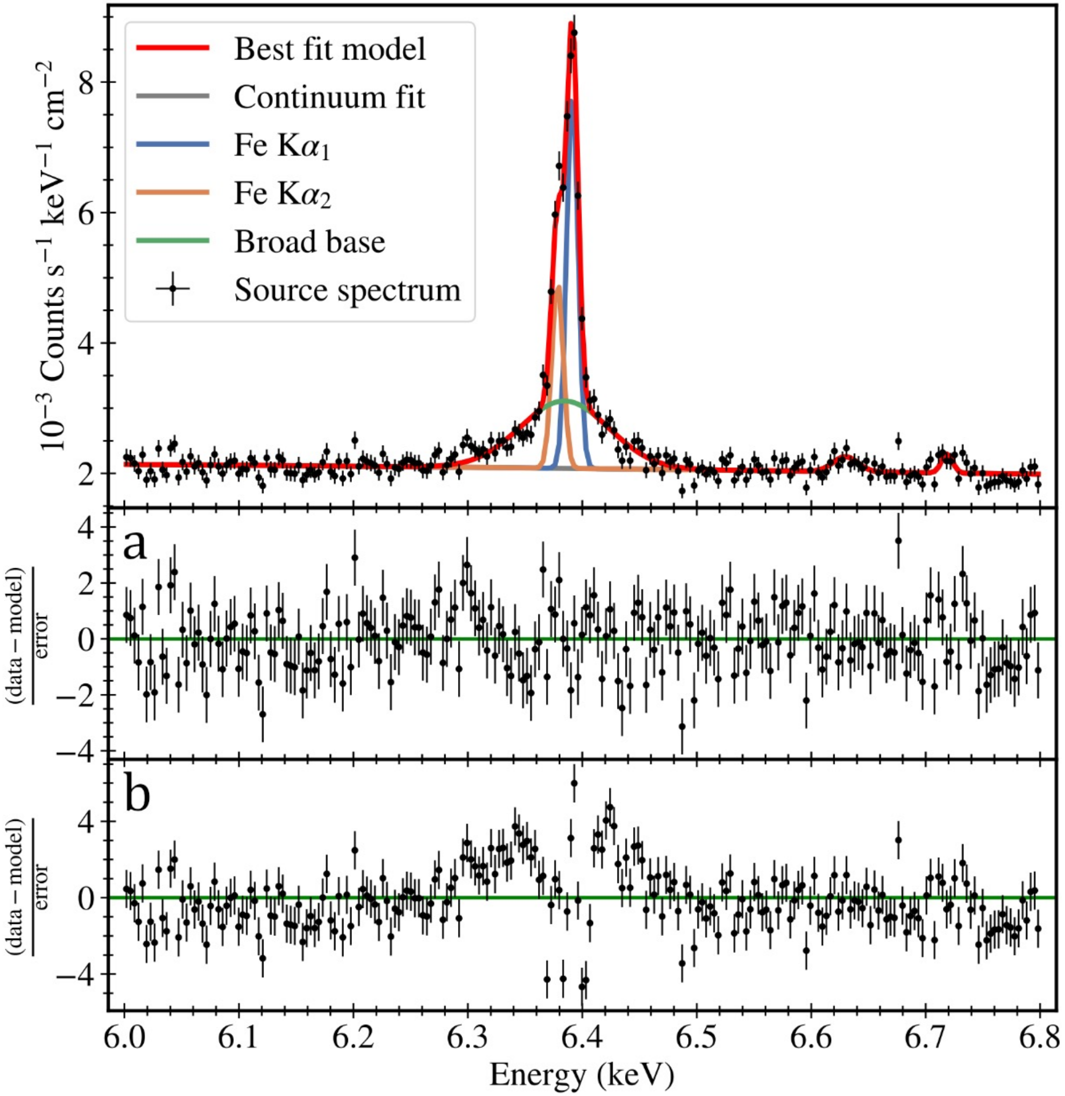




- ➢ Nuclear binding energy
→ Group of Fe isotopes are the most tightly bound
- ➢ Solar abundance shows an “Fe peak”

The sign of Fe





- ➢ **X-ray observation**

→ Fe Kα atomic emission

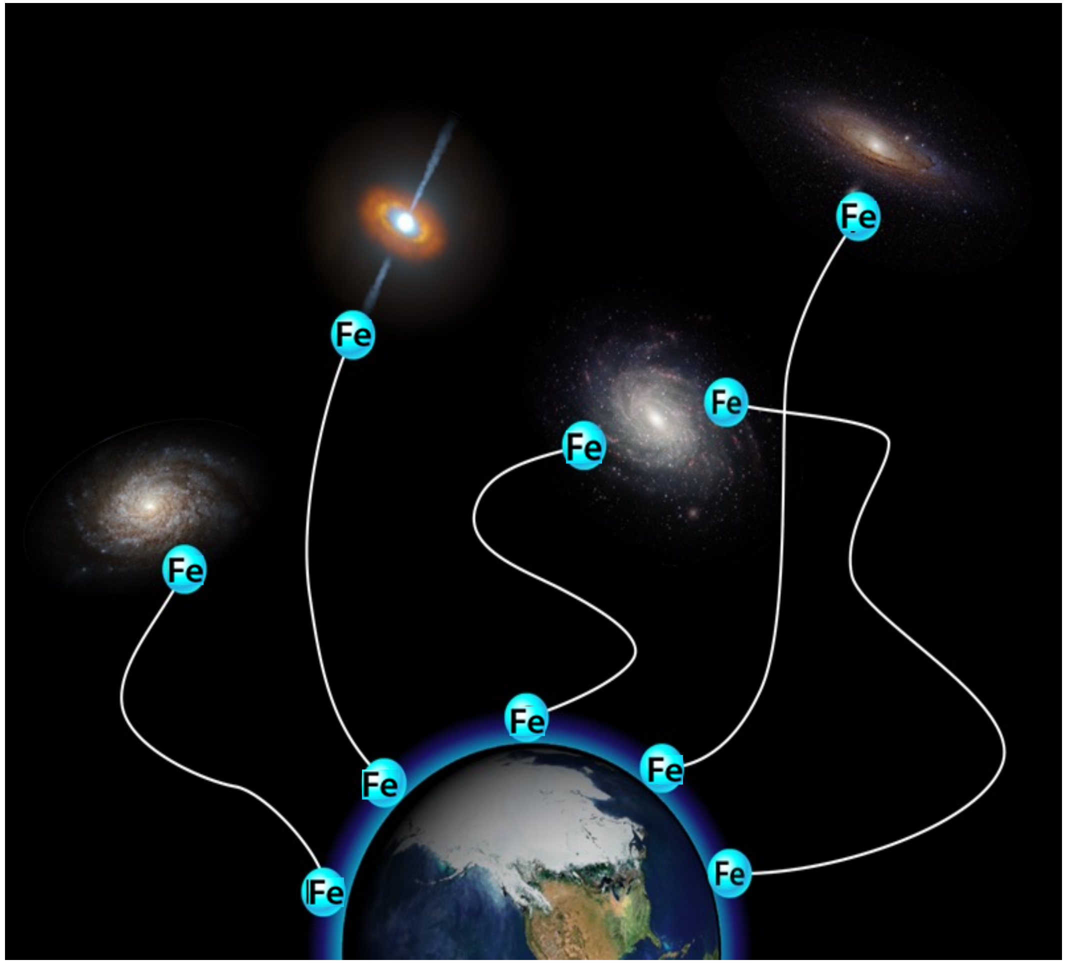
- ➢ **Sign of jet Fe loading**

→ Fe are also loaded in the jet

[XRISM/Resolve 2025]

Our focus: Fe

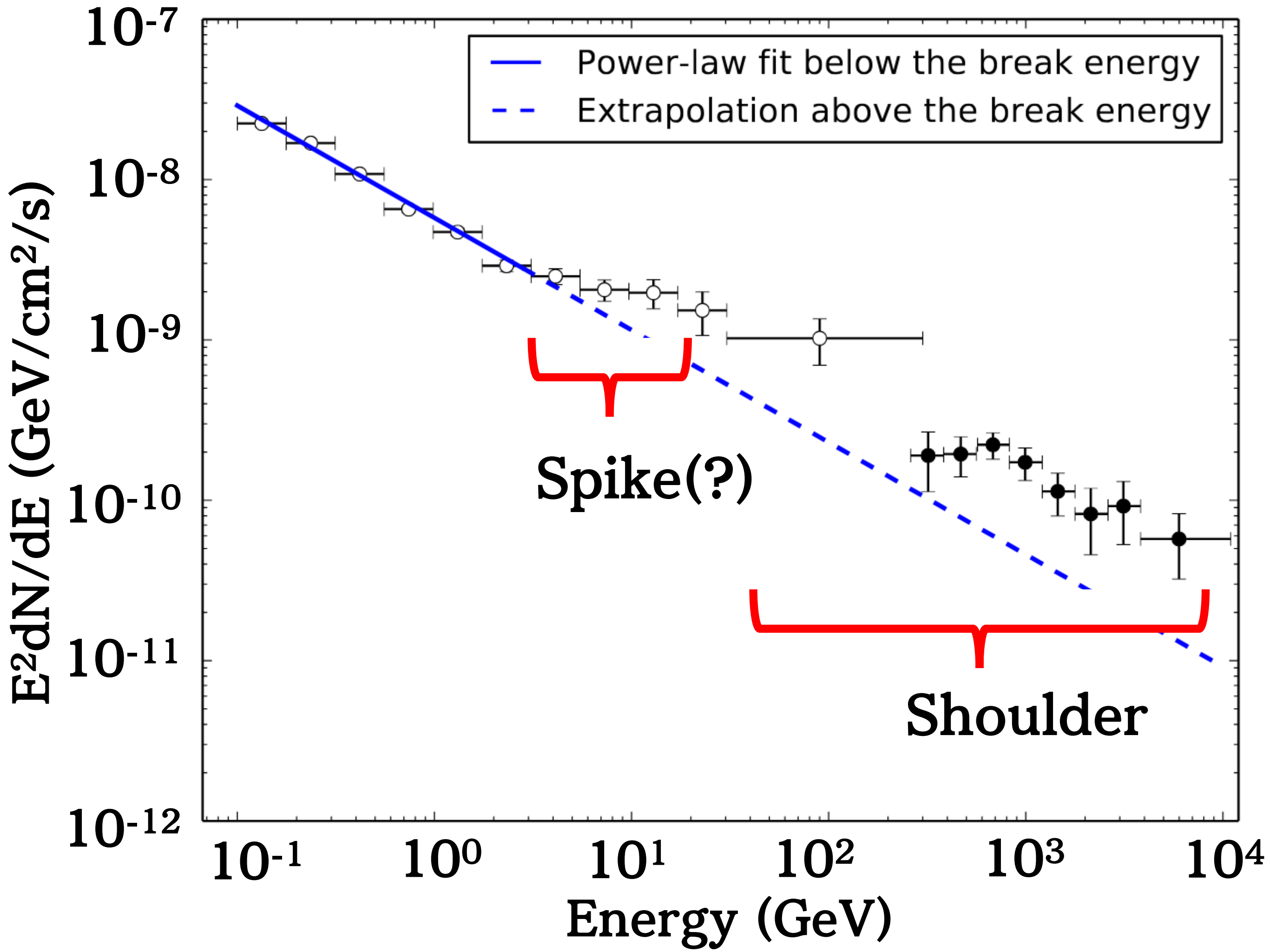
- **Direct confirmation of Fe ?**
→ not performed for Cen A
→ prevented by the magnetic deflection
- **Motivated direction**
→ test if Cen A jet contains Fe nuclei
→ Propose possible gamma-ray signs



Puzzling signals from Cen A

➢ Fermi + H.E.S.S. studies
→ spectral hardening > GeV
→ cannot be simple power-law
➢ Characteristic GeV-TeV
→ 100 GeV-10 TeV: "Shoulder"
→ 1GeV- 10 GeV: "Spike(?)"

[Abdalla et al. (2018) from H.E.S.S. collaboration]



Possible Explainations

- Very many scenarios

→ multi-zone SSC emissions [Petropoulou 2014]

→ Photohadronic interactions [Sitarek 2010]

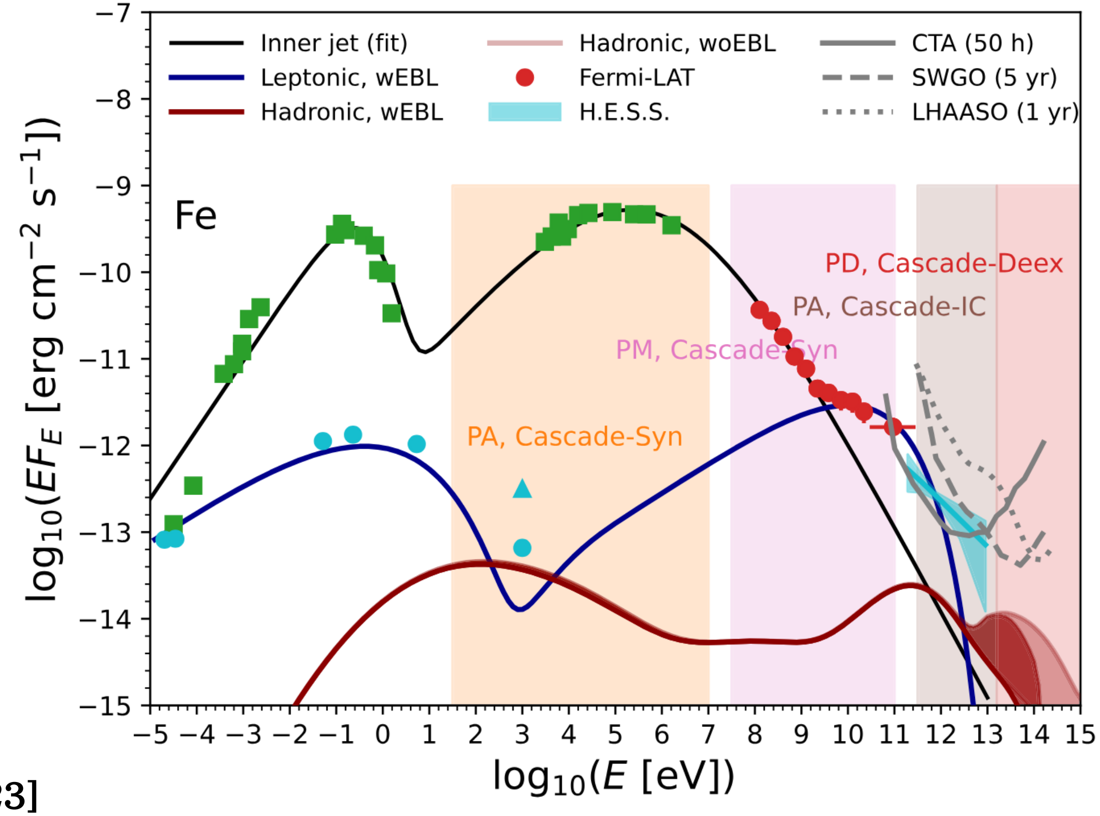
→ Gamma-ray induced pair cascades

[Hardcastle 2011]

→ IC of Bkg photon fields [Hardcastle 2011]

- Contributions from heavy nuclei

→ photodisintegration of Fe nuclei [Zhang Murase 2023]

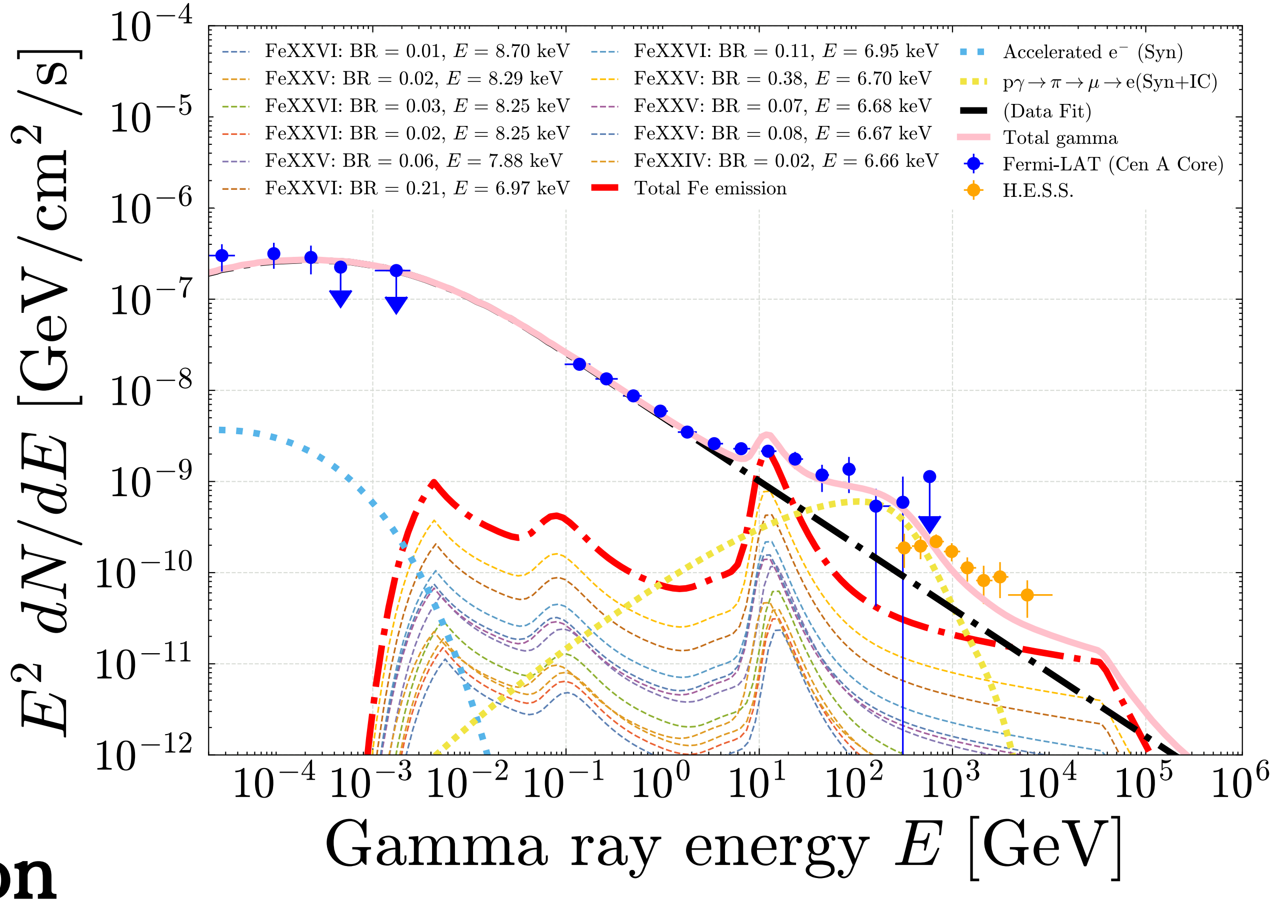


[Zhang, Murase (2023)]

- We address another possible channel!

Summary

- ➢ **15 years of Fermi-LAT**
- → GeV-TeV shoulder + spike
- ➢ **Cen A gamma ray**
- → CMB + EBL + AGN disk photons
- → *Shoulder:* (IC + Syn) of photopion
- → *Spike:* Cycles of Fe excitations/de-excitations
- ➢ **Possible Implications**
- → Future probe of heavy element acceleration/composition
- → Motivates cosmic ray anisotropy searches



Observational Facts

- ➢ kpc scale jet [Kataoka et al. (2006)]
- ➢ Bolometric luminosity

→ 10^{43} erg/s [Borkar et al. (2019)]

- ➢ Jet power

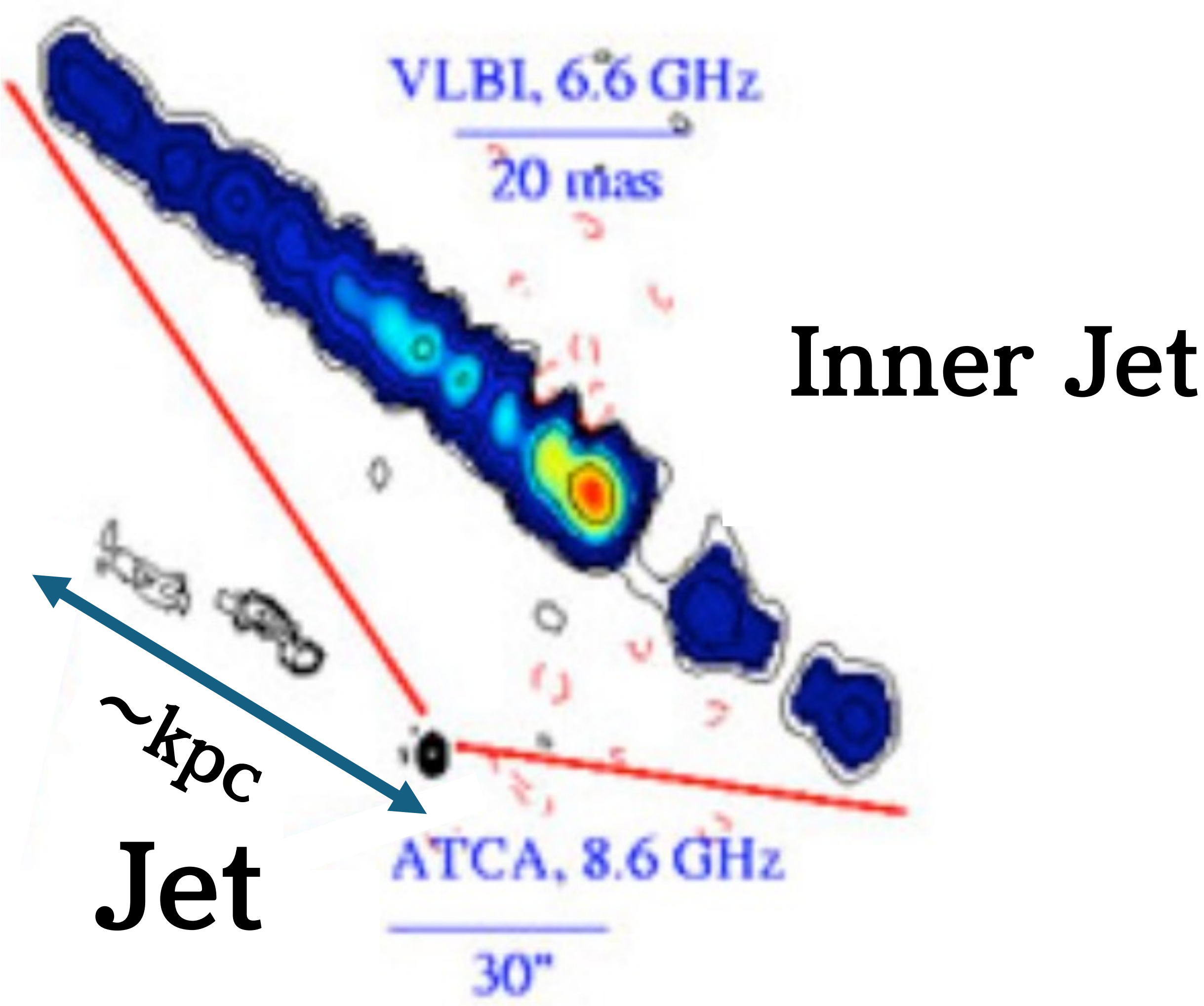
→ $10^{43} - 10^{44}$ erg/s [Borkar et al. (2019)]

- ➢ Magnetic field

→ $< 80\ \mu$G [Borkar et al. (2019)]

- ➢ Jet bulk motion

→ $\Gamma = 1.05$ [Snios et al. (2019)]



Model setup

- **Photon fields** [Ichikawa et al. (2015), Iwata et al. (2024)]

→ CMB + EBL + standard disk photons

→ Dusty torus: 1300 K Blackbody

- **Emission region**

→ 1 kpc from centeral SMBH

→ 0.5 kpc Blob size + B = 40 μG

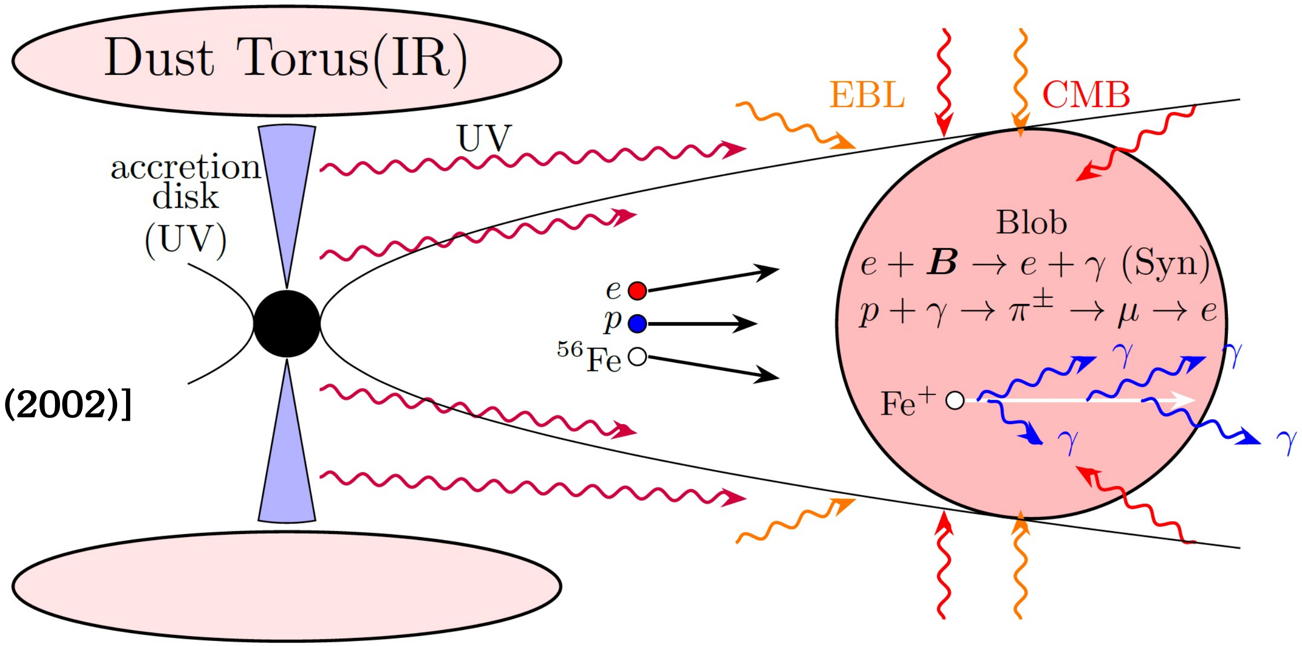
[Kraft et al. (2002)]

- **Jet bulk motion**

→ Γ = 1.05 [Snios et al. (2019)]

- **Jet component**

→ protons, Fe, electrons



Model setup

- **Jet compositions**

→ Simple power law model

$$\frac{\mathrm{d}N}{\mathrm{d}E}(E) \propto E^{-p} \qquad (p = 2.15)$$

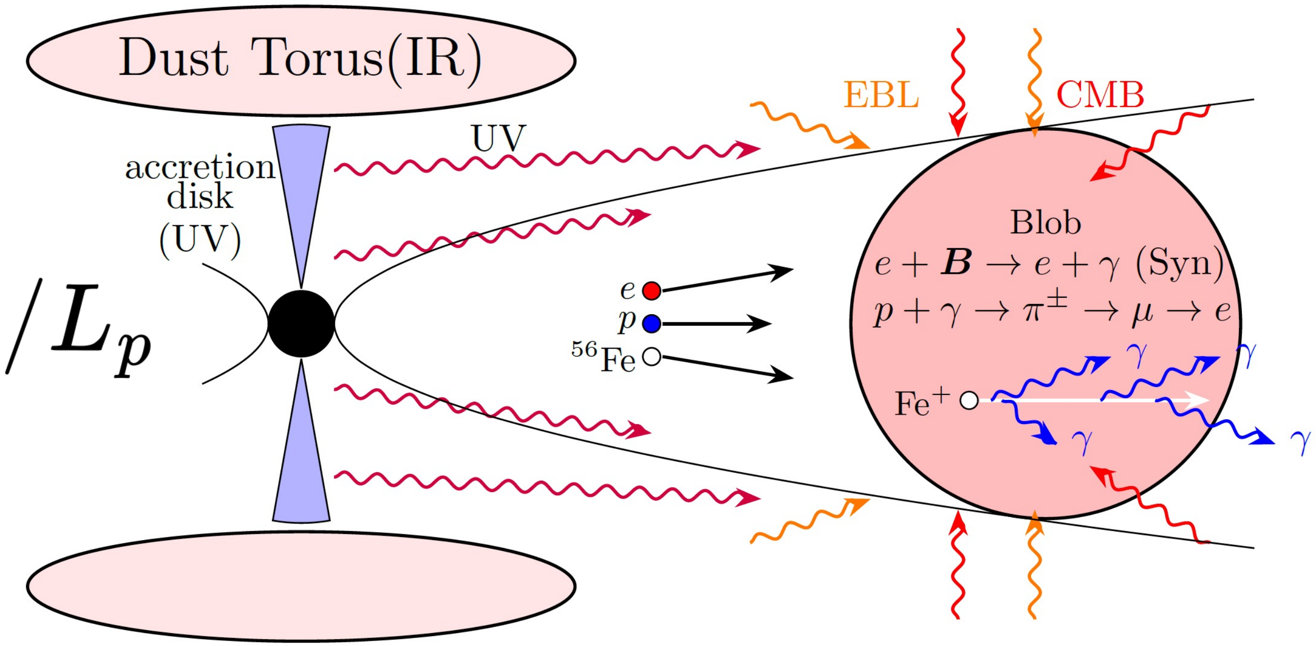
→ Solar abundance [Fe]/[p] → L_{Fe}/L_p

- **Jet electrons**

→ mass ratio (m_e/m_p) → L_e/L_p

→ Synchrotron cooling cutoff

$$\frac{\mathrm{d}N_e}{\mathrm{d}E}(E) \propto E^{-p} \exp\left(\frac{E}{10^{14}\,\mathrm{eV}}\right)$$



Initial power by components

- ➤ Jet power observation

→ $10^{43} - 10^{44}$ erg/s

- ➤ Source of uncertainty

→ methodology

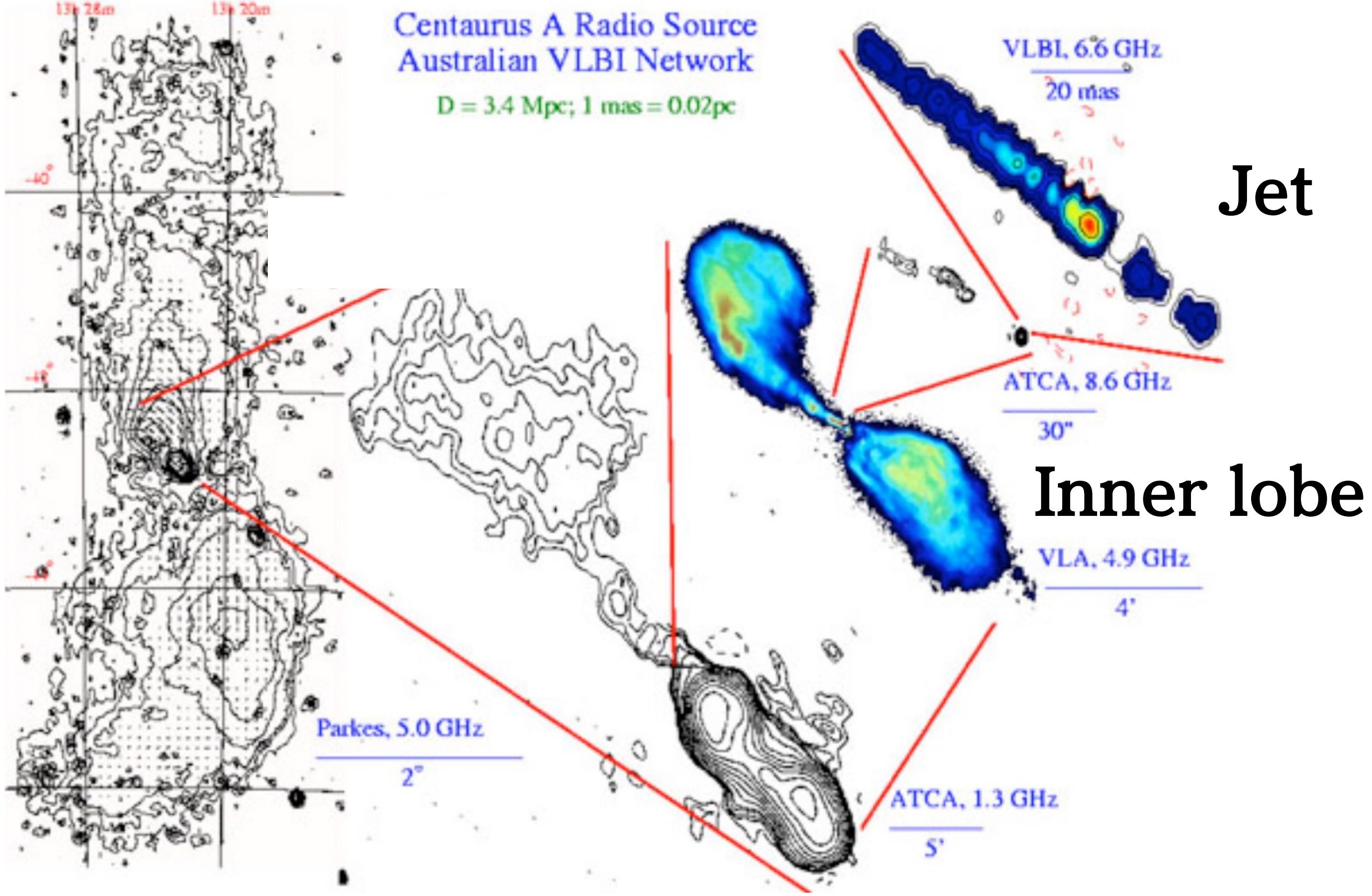
→ physical phase of jet-lobe

(1) Inner-lobe-based (X-ray cavity)
(enthalpy)/(sound-crossing age)

(2) Giant-lobe-based (radio-γ SED)
(total energy)/(dynamical age)

- ➤ We choose

→ $L_{jet} = 10^{44}$ erg/s

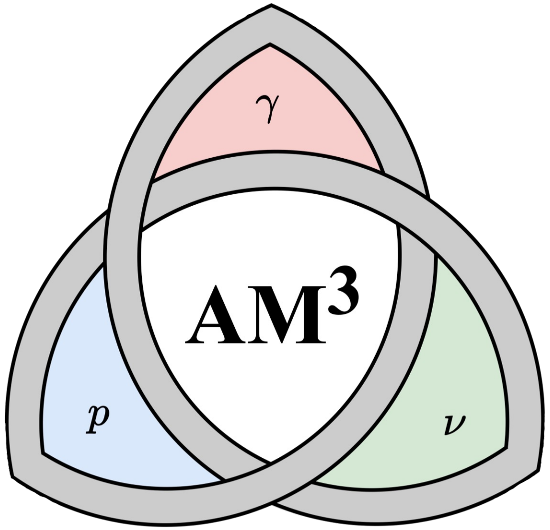


Leptohadronic Modeling

- **AM³ software** [Klinger et al., ApJS 275 4 (2024)]

→ Astrophysical Multi-Messenger Modeling

Input:
- Photon fields
- Injected leptohadronic spectrum
- B field strength + Escape time (Region size)



Output:
- **Neutrinos and Gamma-rays**
  - → p γ
  - → subsequent e/p external IC, Synchrotron

and other subdominant processes

Kusenko, Voloshin (2011)

Cycles of H-like Fe photon emissions

- **Photon field distribution**

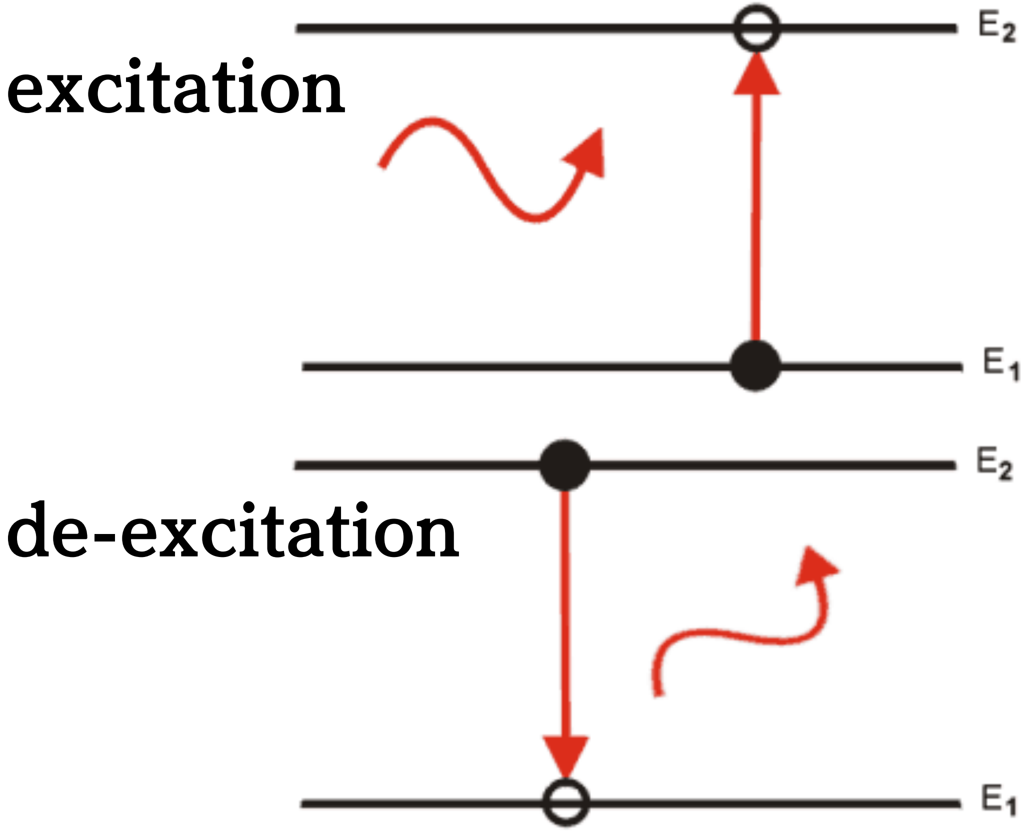
$$n_{\rm ph} = n_{\rm CMB} + n_{\rm EBL} + n_{\rm disk} + n_{\rm torus}$$

$$\left(n_{\rm CMB} = \frac{1}{e^{\omega/T} - 1} \right)$$

- **Transition energy**

$$\Delta_n = \left(1 - n^{-2}\right) \varepsilon_Z$$

$$\varepsilon_Z = Z^2 Ry = \frac{m_e \alpha^2 Z^2}{2}$$



Terminated by ionization

Rate of H-like Fe cycles (Z = 26)

➢ Radiative transition rate

→ dipole approximation

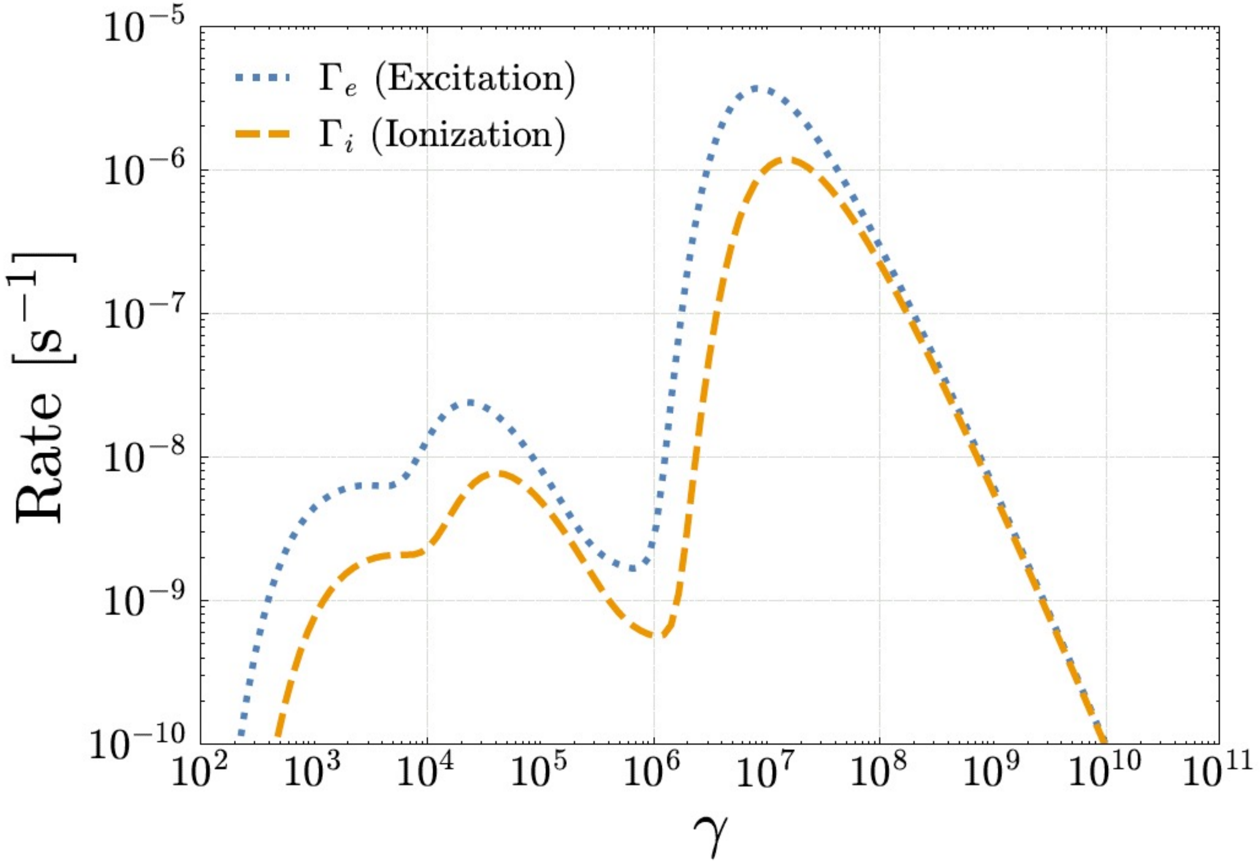
$$\Gamma_e(\gamma) = \frac{2\alpha}{3} a_Z^2 \sum_{n=2}^{\infty} |\langle nP| \boldsymbol{r} |1S\rangle|^2 \chi(\gamma, Z, \Delta_n)$$

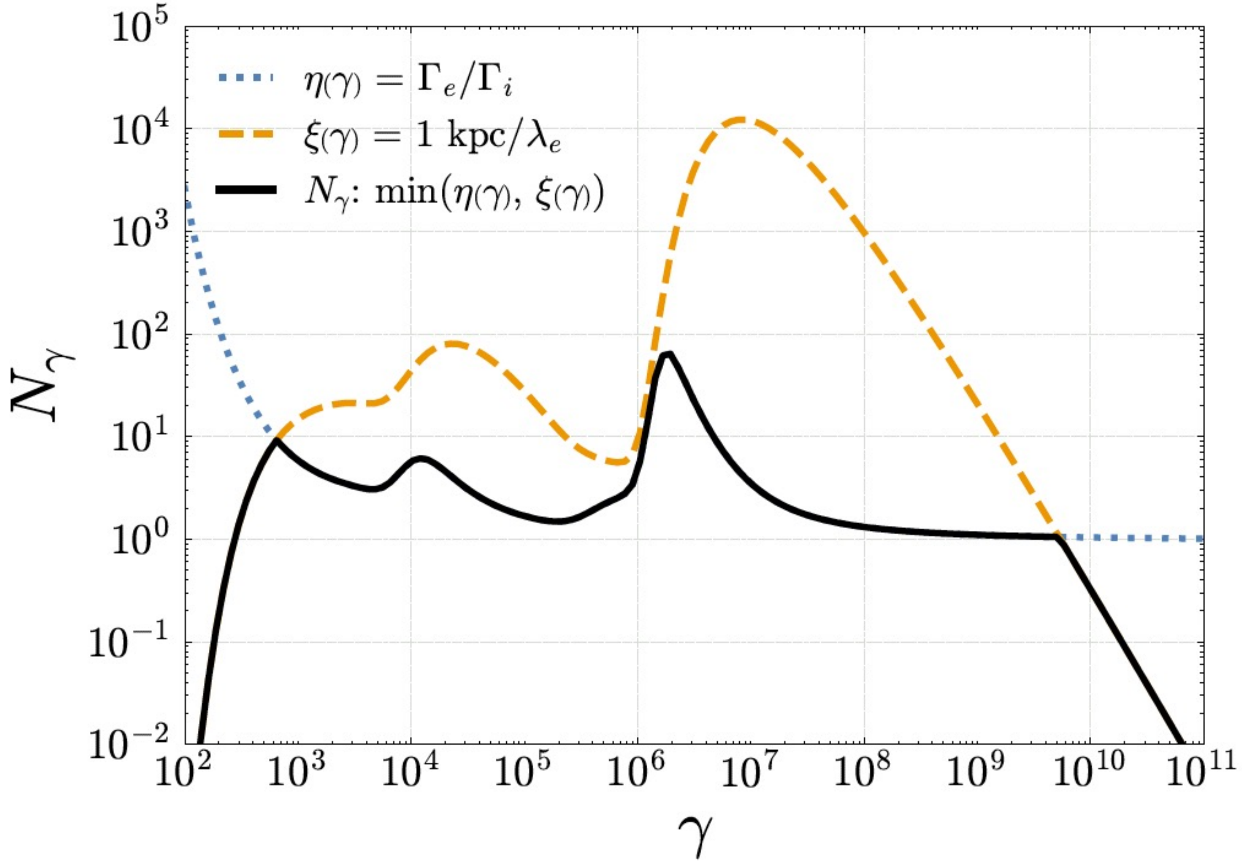
$$\Gamma_i(\gamma) = \frac{2\alpha}{3} a_Z^2 \int_1^{\infty} \mathrm{d}w \; s(w) \, \chi(\gamma, Z, w\varepsilon_Z)$$

$$\chi(\gamma, Z, \Delta_n) = \frac{2\pi\Delta_n^2}{\gamma^2} \int_{\nu_{\min}}^{\infty} \mathrm{d}\nu \; n_{\mathrm{ph}}(\nu) \,,$$

$$\left(s(w) = \frac{128}{w^3} \frac{1}{1 - \exp\left(-\frac{2\pi}{\sqrt{w-1}}\right)} \times \exp\left[-\frac{2}{\sqrt{w-1}} \arctan\left(\frac{2\sqrt{w-1}}{2-w}\right)\right] \right)$$

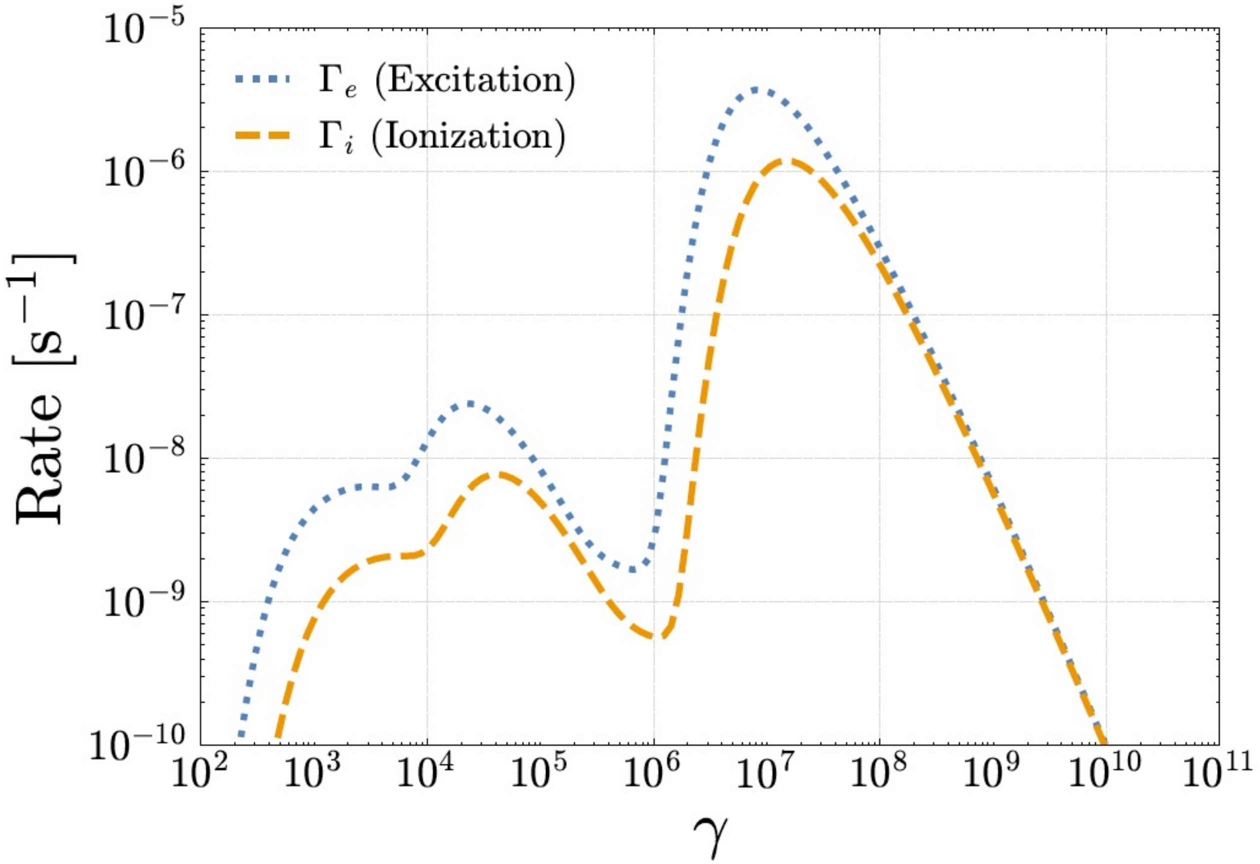
Expected number of interactions

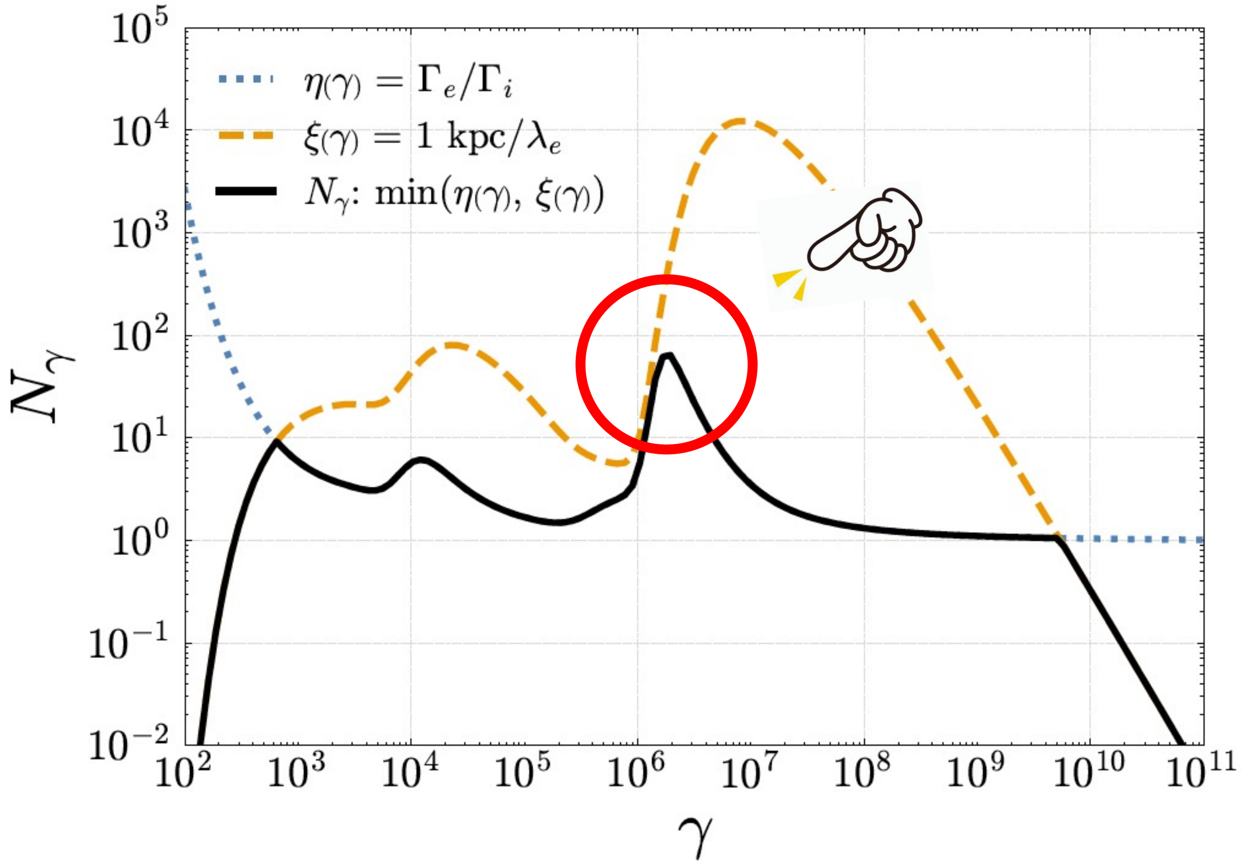




- Γ_e vs Γ_i determine the # of cycles N_γ

Expected number of interactions





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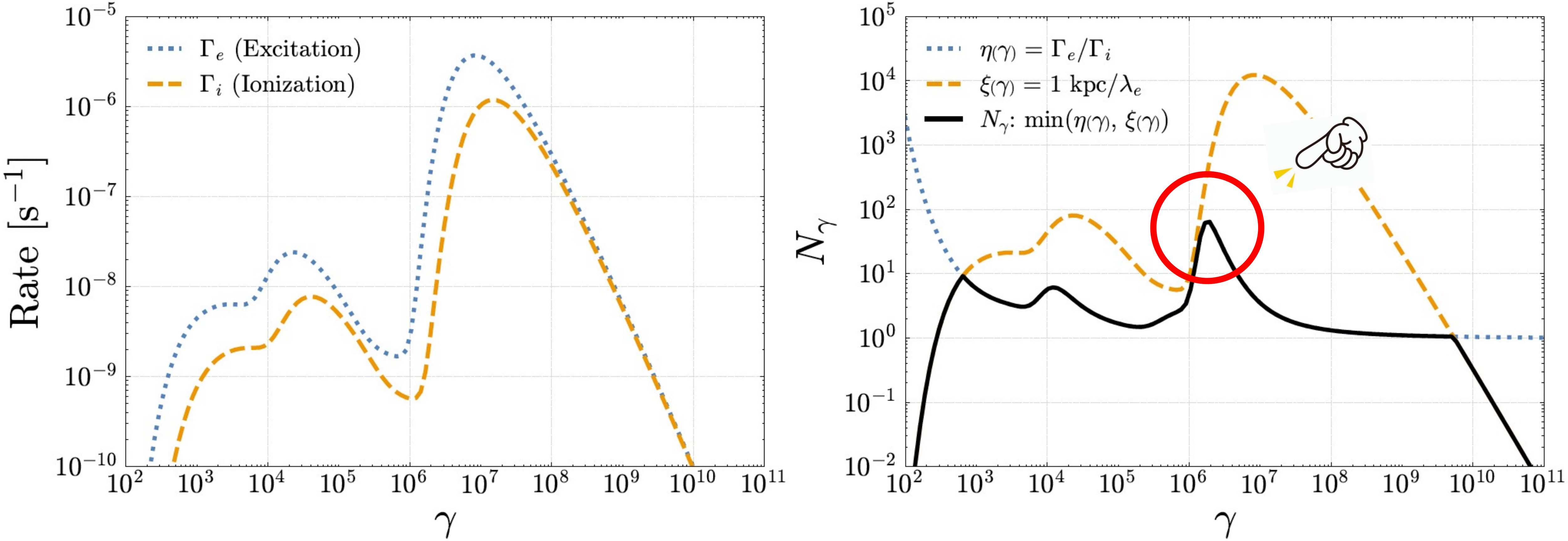


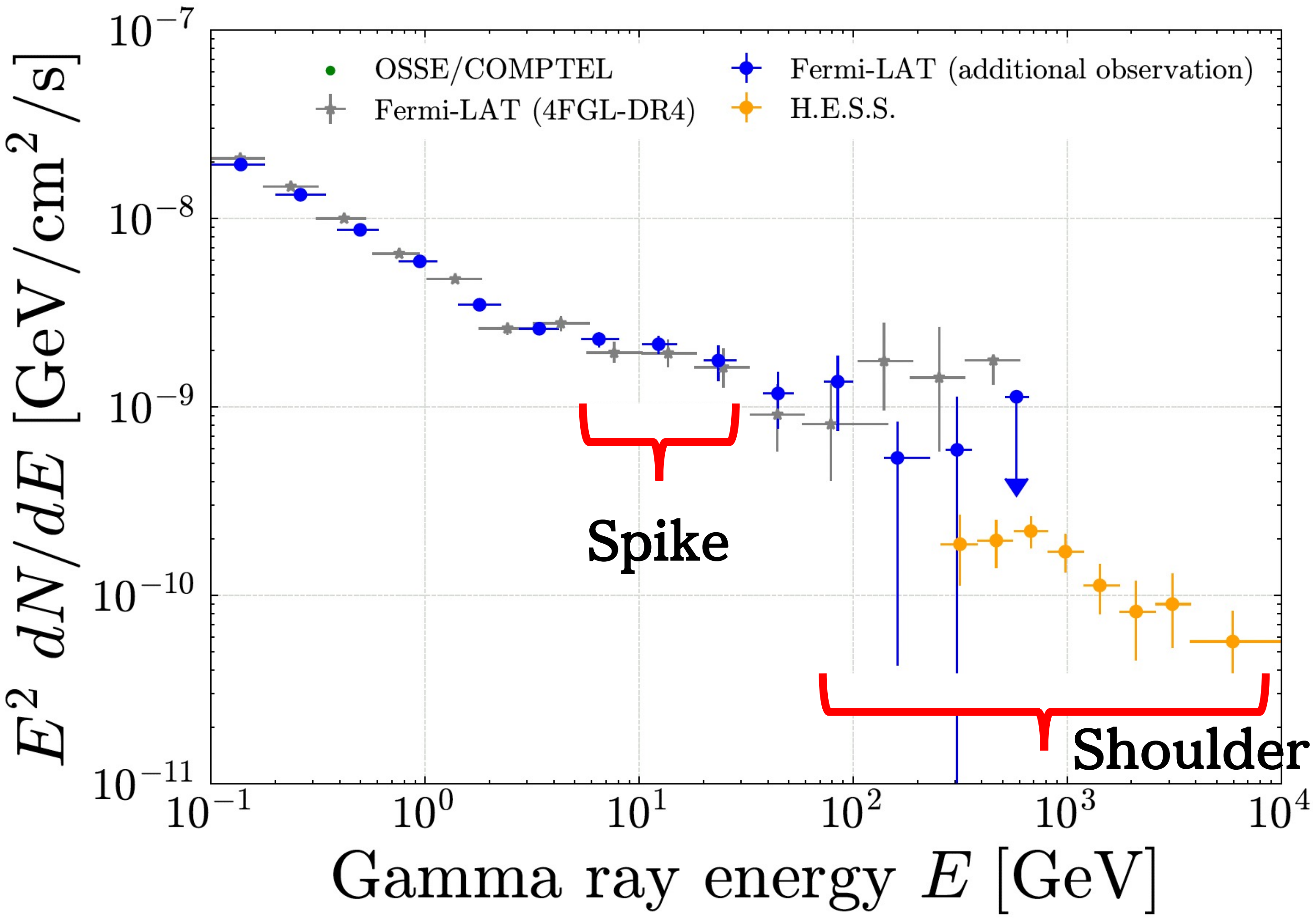
- Lifetime of the Fe ions < Fe β-decay timescale

$$F_\gamma = N_\gamma F_{\mathrm{Fe}}$$

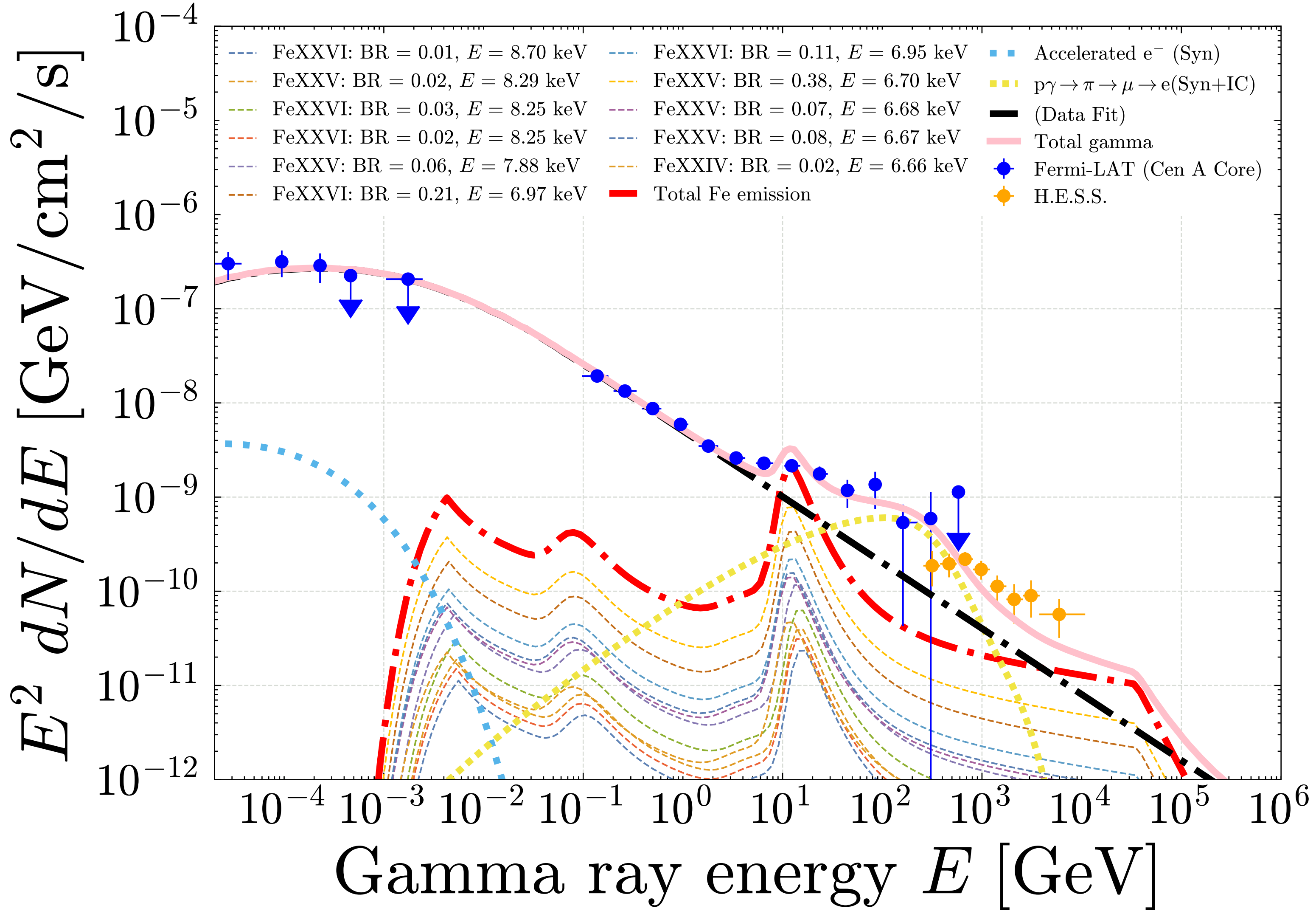
15 yrs of Fermi-LAT data + H.E.S.S.

- ➢ **Why more analysis?**
  → Model leads ~13 GeV spike
  → optimized binning

- ➢ **Additional analysis**
  → 15 yrs (2008 Aug – 2023 Nov)
  → Shoulder feature still exists



Result (Preliminary)



Power-law index: $p = 2.15$

$$L_p = 10^{44}\ \mathrm{erg/s}$$
$$L_e = 5.6 \times 10^{40}\ \mathrm{erg/s}$$
$$L_{\mathrm{Fe}} = 5 \times 10^{39}\ \mathrm{erg/s}$$

Emission levels
Branching ratio

Taken from
AtomDB public database

$$F_\gamma = N_\gamma F_{\mathrm{Fe}}$$

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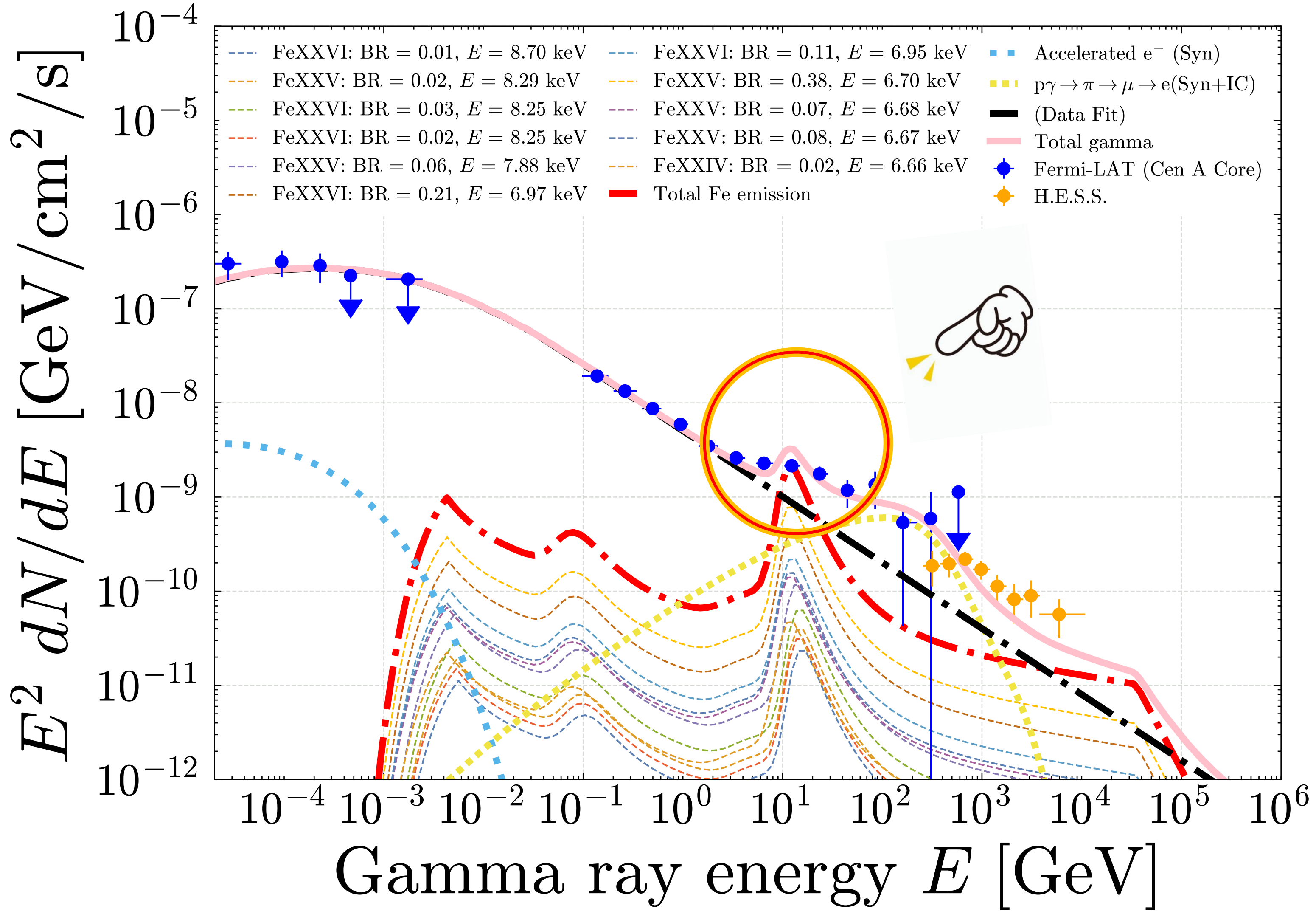

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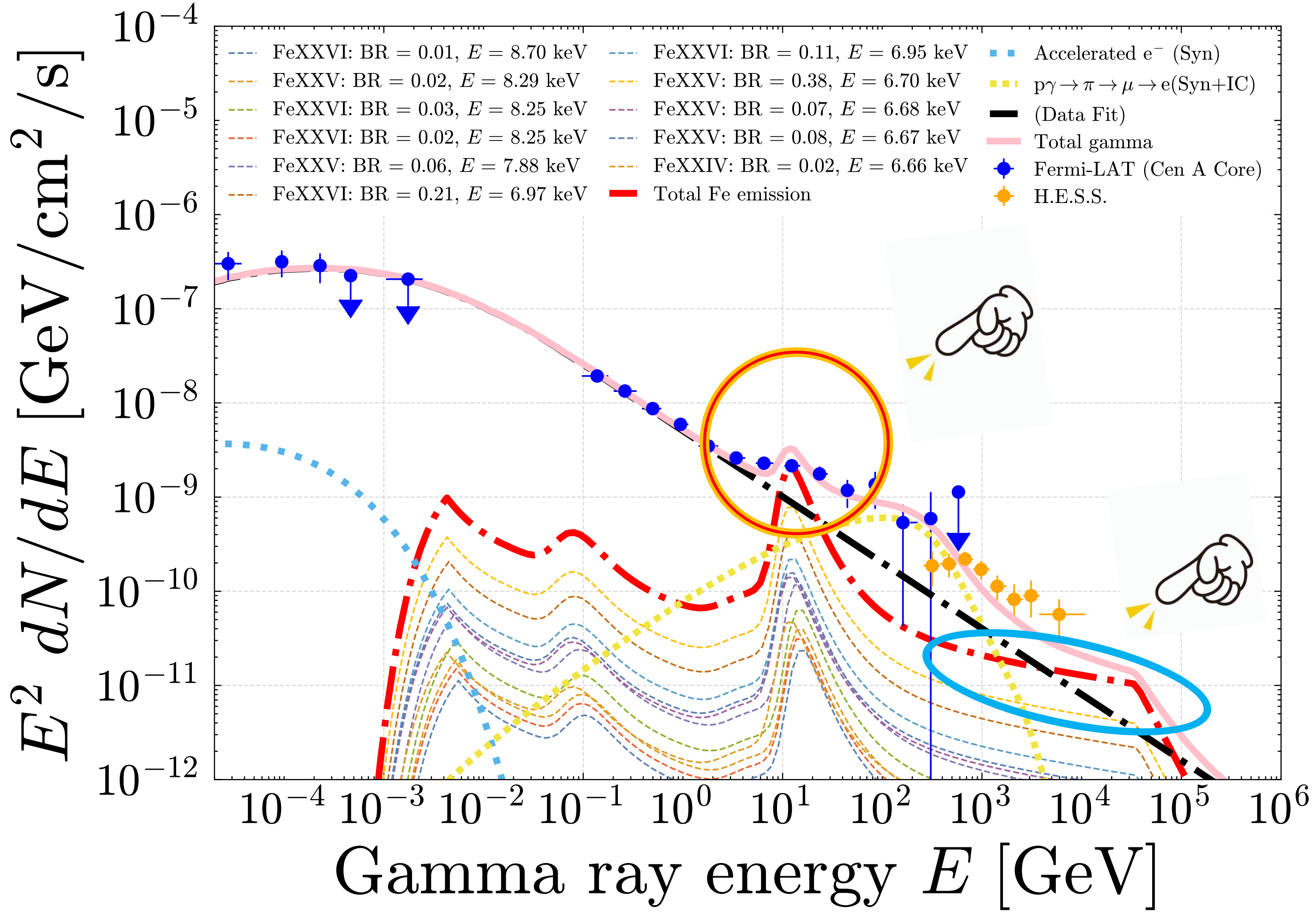

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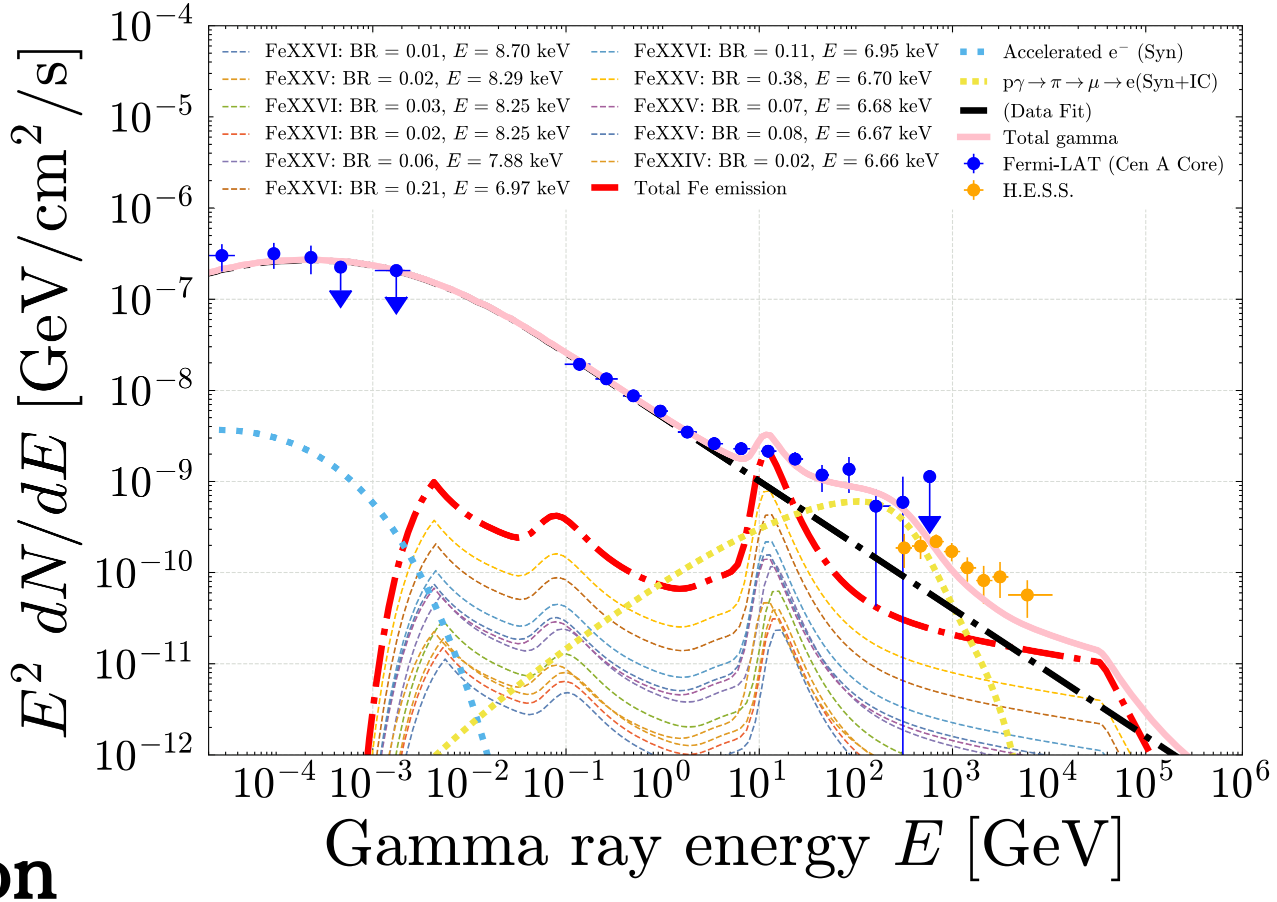
Summary



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- ➢ Possible Implications
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- → Motivates cosmic ray anisotropy searches

Backup

SMBH mass estimation

- **Dynamics**

→ stellar・gas (H_2, Hα, CO lines) dynamics

→ Doppler effects of H_2O masers

- **Time-variations (reverberation mapping)**

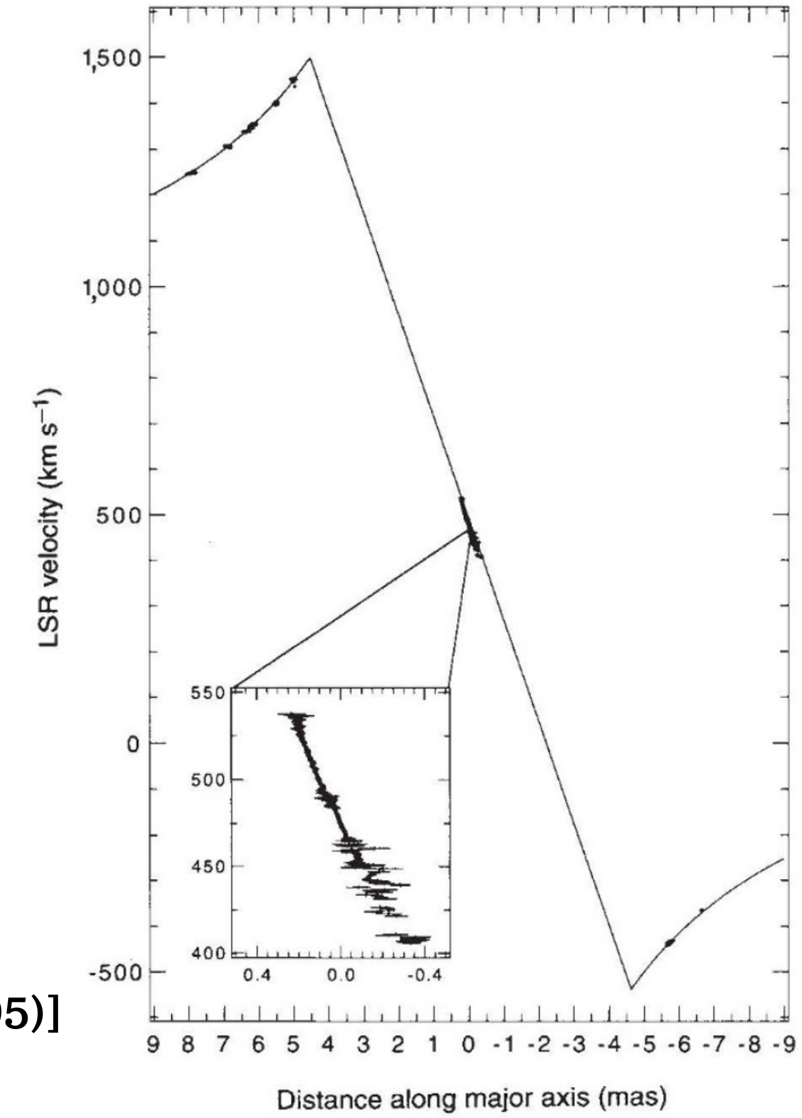
→ Time-lags between disk/plasma emissions

- **Empirical relations**

→ BH mass & Galactic bulge velocity dispersion

→ BH mass & Bulge luminosity (IR etc…)

- **Spectral fittings**



[Miyoshi et al. (1995)]