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Illuminating Black Hole Shadow with Dark Matter Annihilation

Based on arxiv:2404.16673, collaborating with
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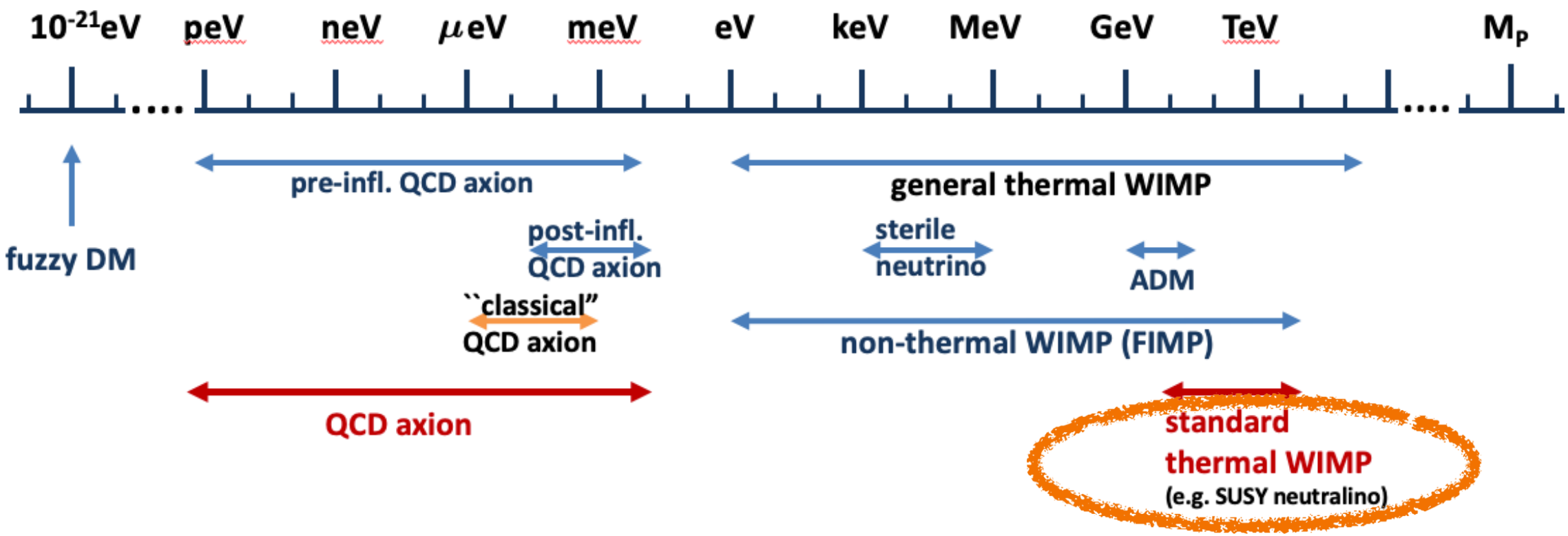
MEPA(2024) Yunnan

2024.08.25

Outlines

- WIMP Dark Matter Spike
- Plasma around the Super Massive Black Hole
- Black Hole Shadow
- Illuminating the Inner Shadow with Dark Matter

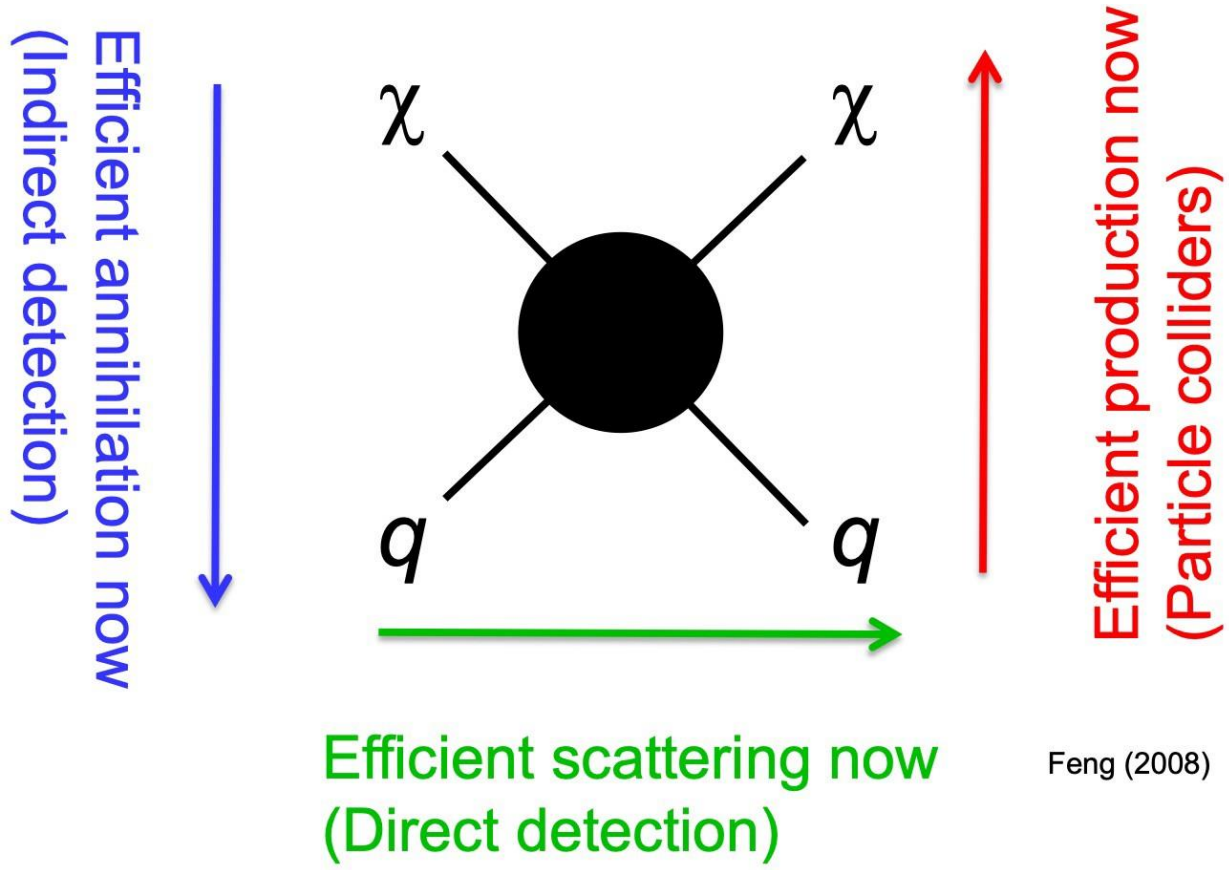
WIMP Dark Matter



2104.07634

WIMP Dark Matter

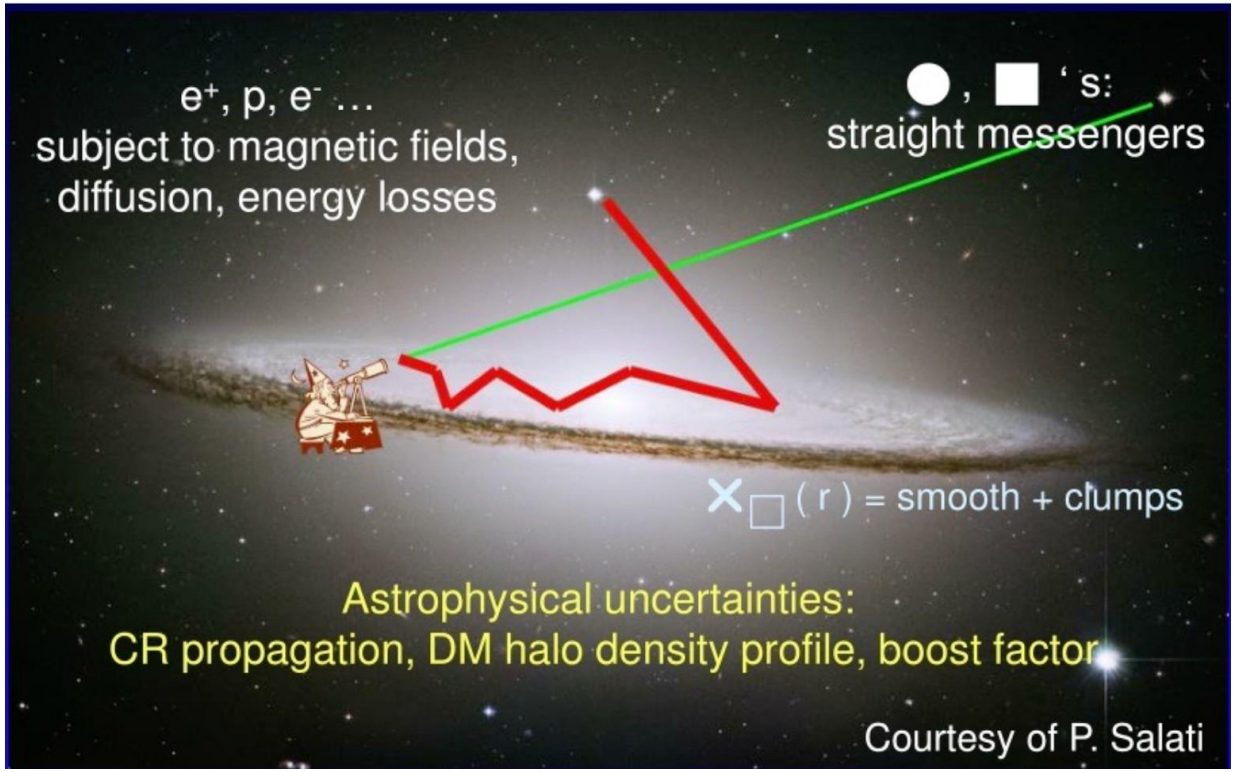
- Mass : $m_{weak} \sim \mathcal{O}(100)$ GeV
- Unseen in LHC : R-parity
- DM is cosmologically stable.



Indirect Search of galactic Dark Matter

- Targeting $e^- e^+$ from annihilation
- Signature: synchrotron radiation:
  - Denser Dark Matter
  - Stronger Magnetic Fields
  - Lower Background

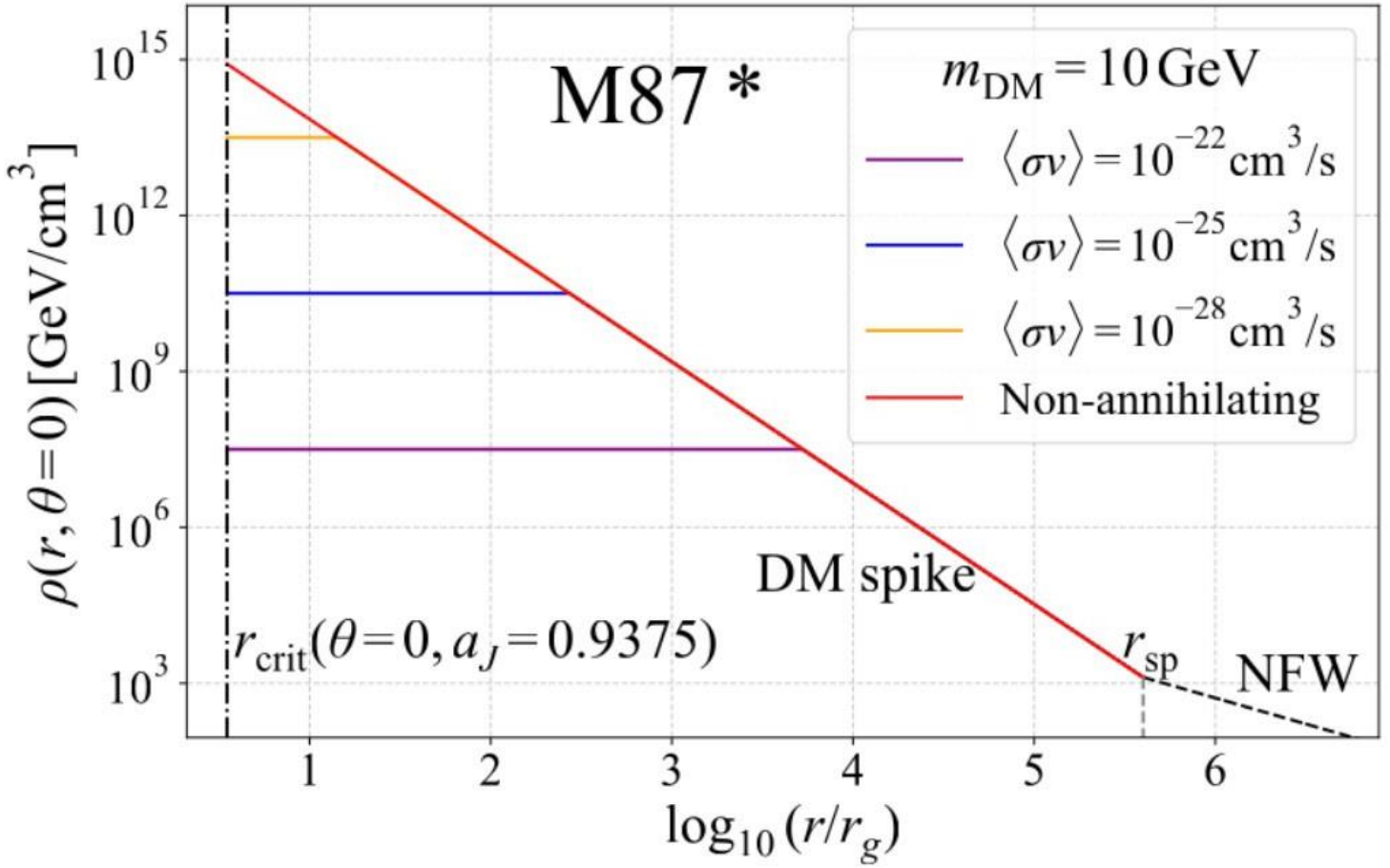
$$\chi + \chi \rightarrow q\bar{q}, W^+W^-, \ldots \rightarrow \gamma, \bar{p}, \bar{D}, e^+ \,\&\, \nu's$$



Dark Matter Profile near the SMBH

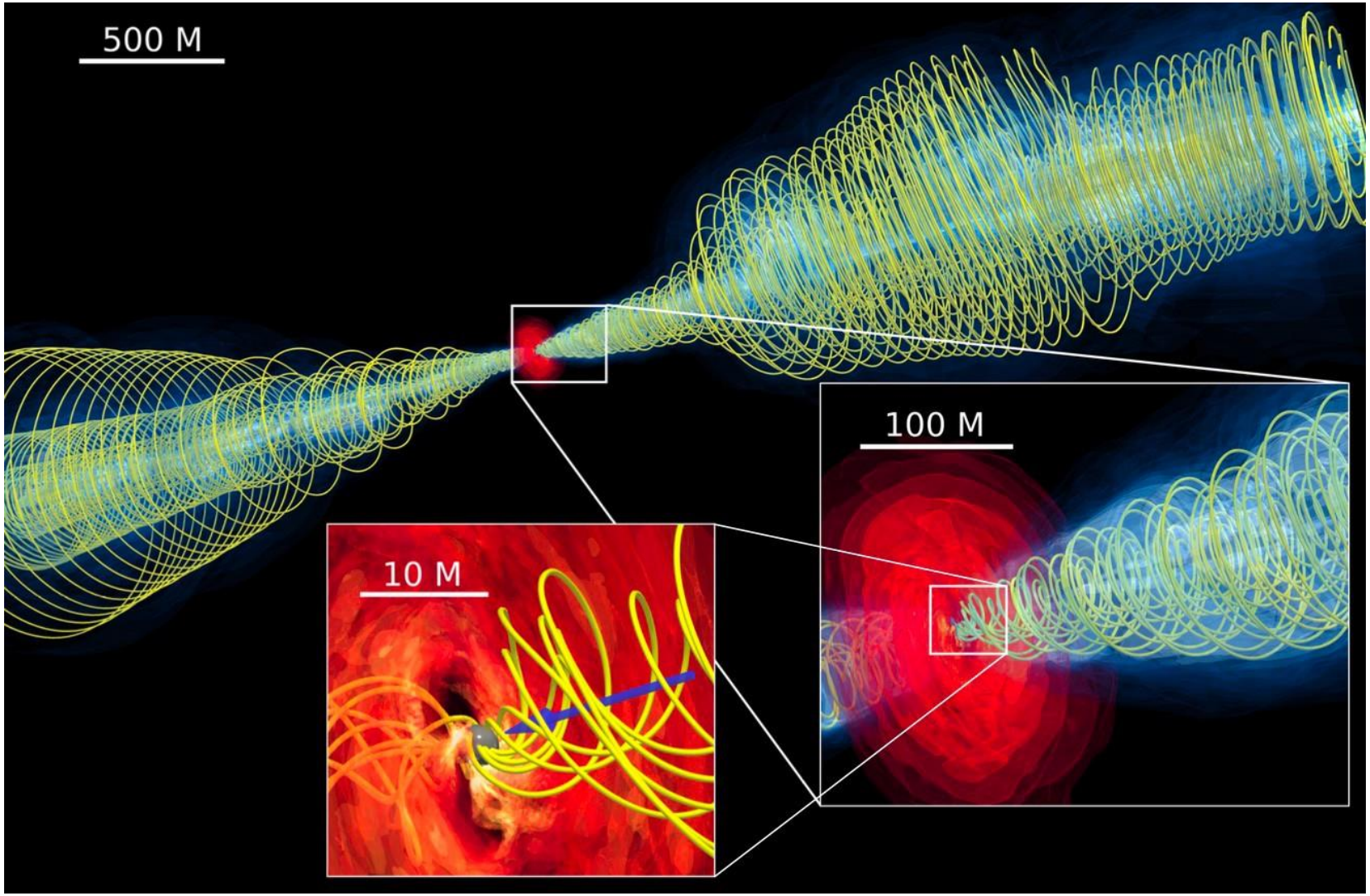
Dark Matter Spike -------- Dense DM environment

- SMBH distort the gravitational potential.
- Adiabatic growth towards a cuspy profile.
- Flat core structure due to annihilation. $\langle n\sigma v\rangle \approx H$



Accretion Flows near the SMBH

MAD model -------- Strong magnetic fields

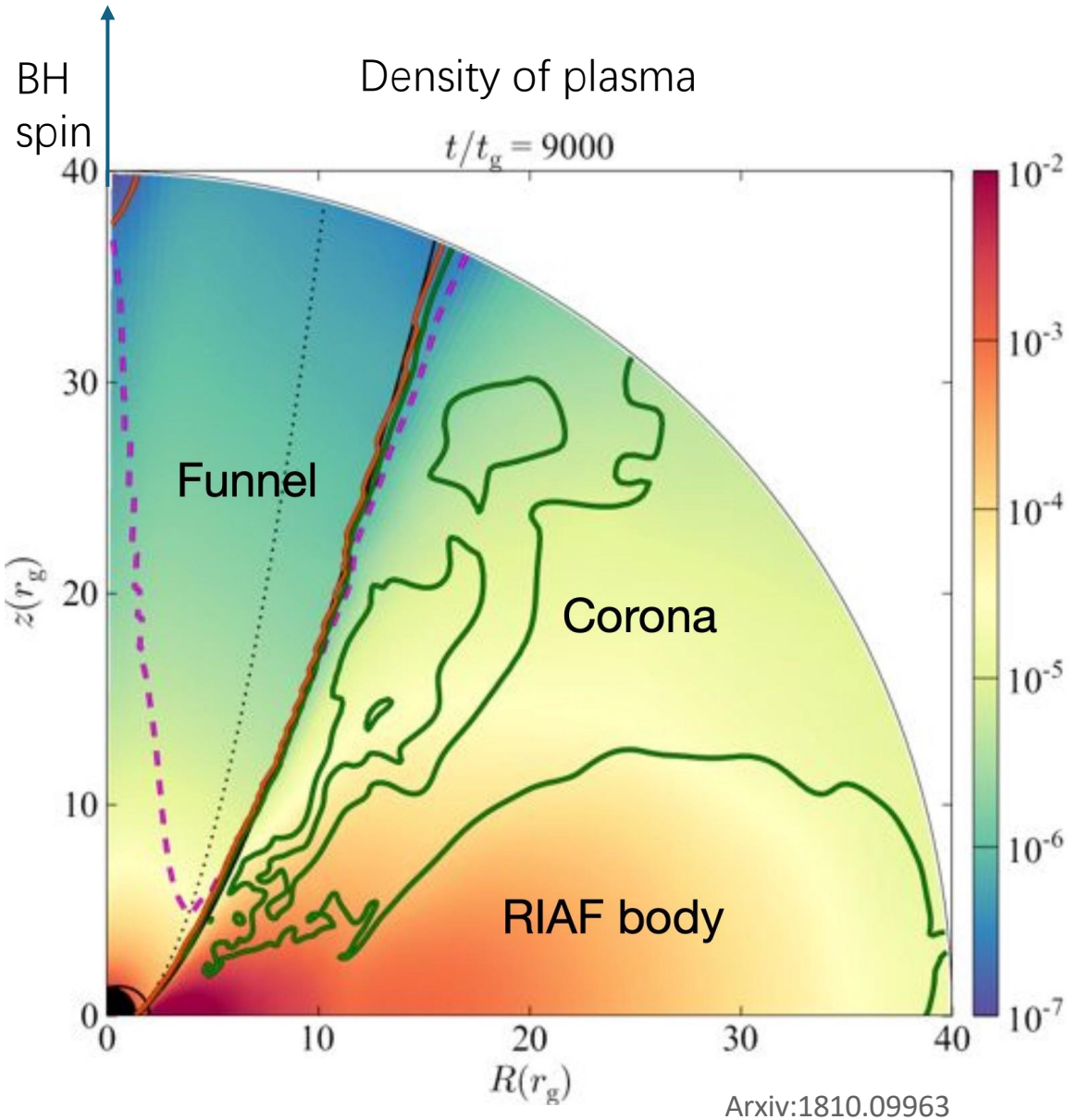


Arxiv:2111.92517

Accretion Disk and Jet

MAD model -------- Strong magnetic fields

- Magnetic Arrested Disk
  - Strong B-field
  - Inefficient Radiative Accretion Flow with high plasma density.
- Stable but Energetic Jet
  - Fast rotating, stronger B-field
  - Nearly no plasma

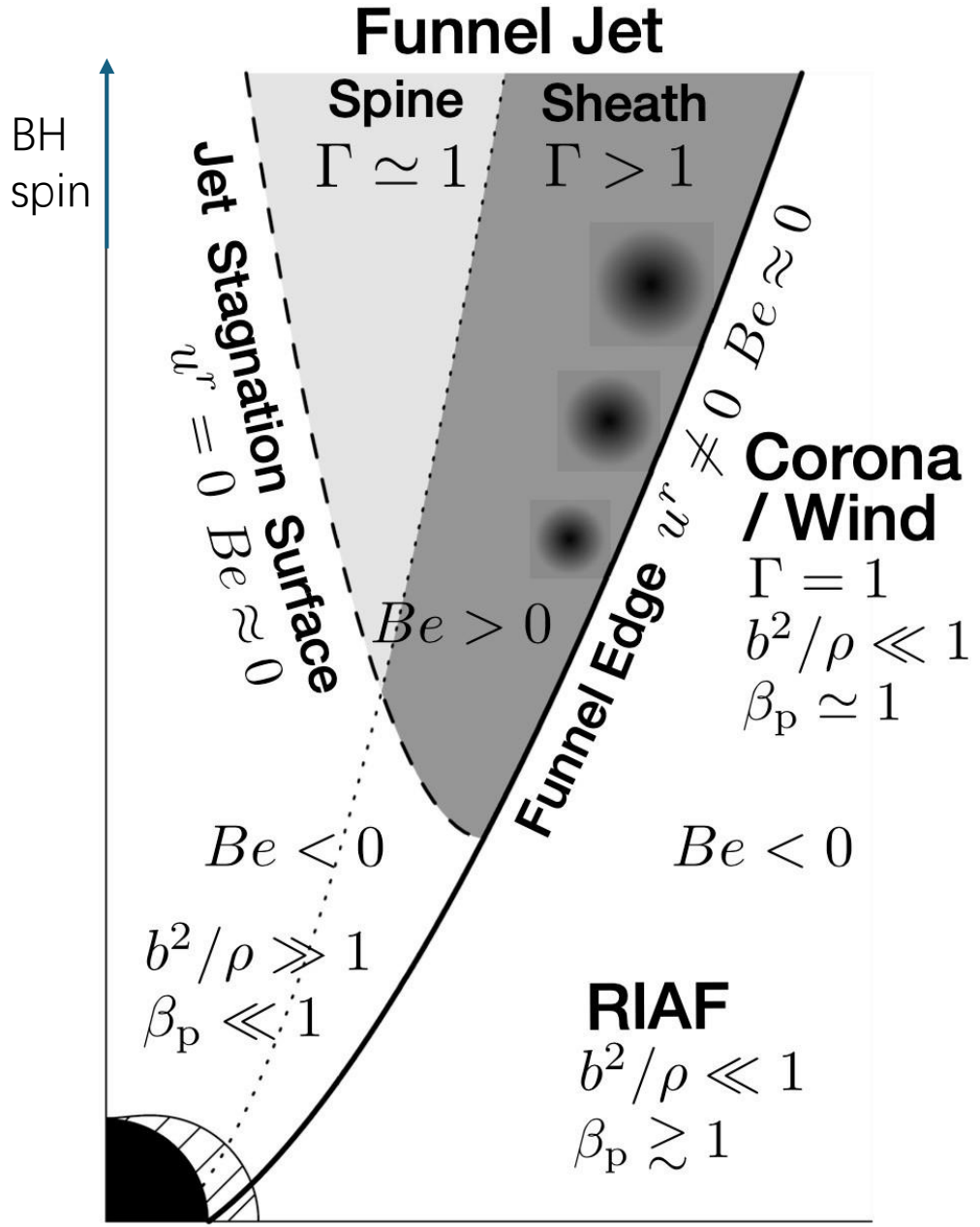


Arxiv:1810.09963

Accretion Disk and Jet

Empty Jets-------- Low Background Emission

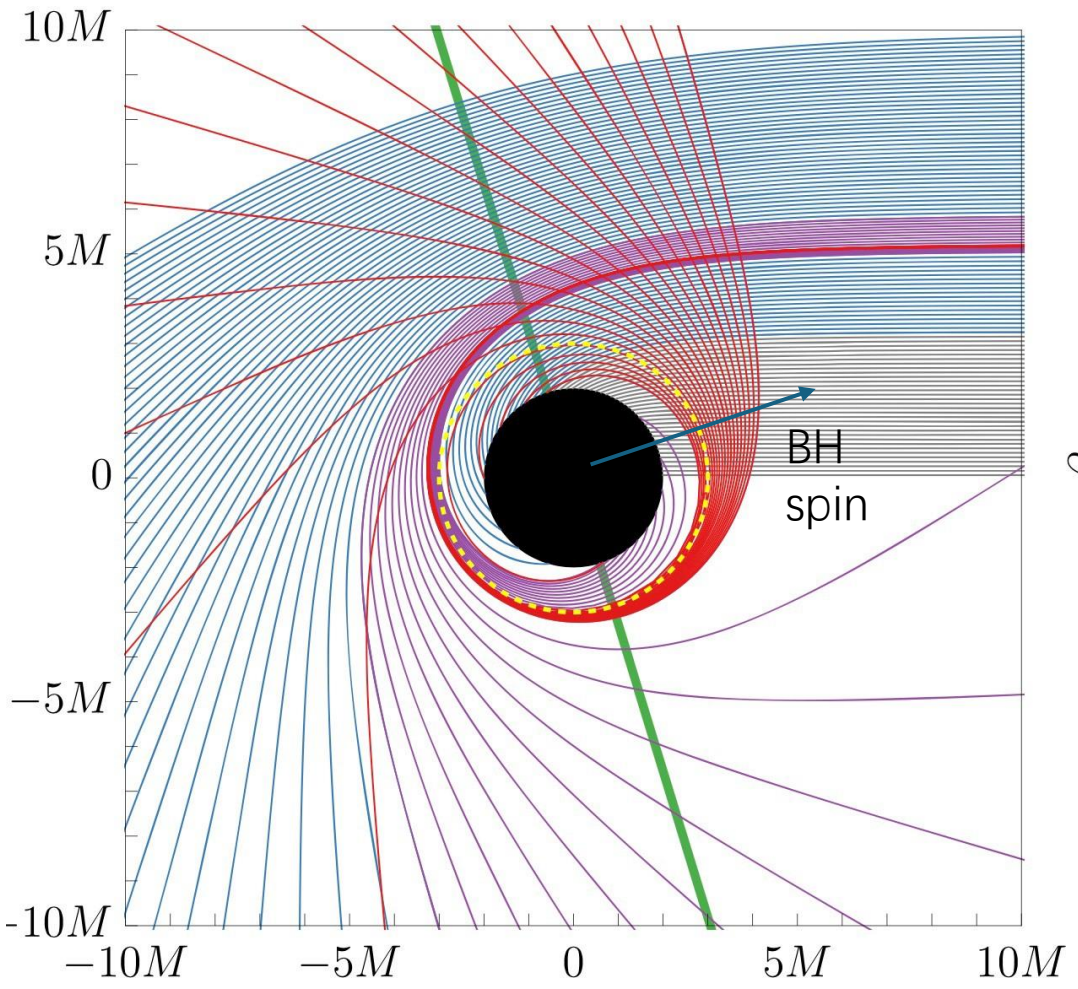
- Plasma is confined by the B-field line. $\rho_L = \frac{p_e}{eB} \approx 10^{-11} M_{\rm BH}$
- Centrifugal Force (out), Gravity(in)
- No stable solution! (Stagnation surface)

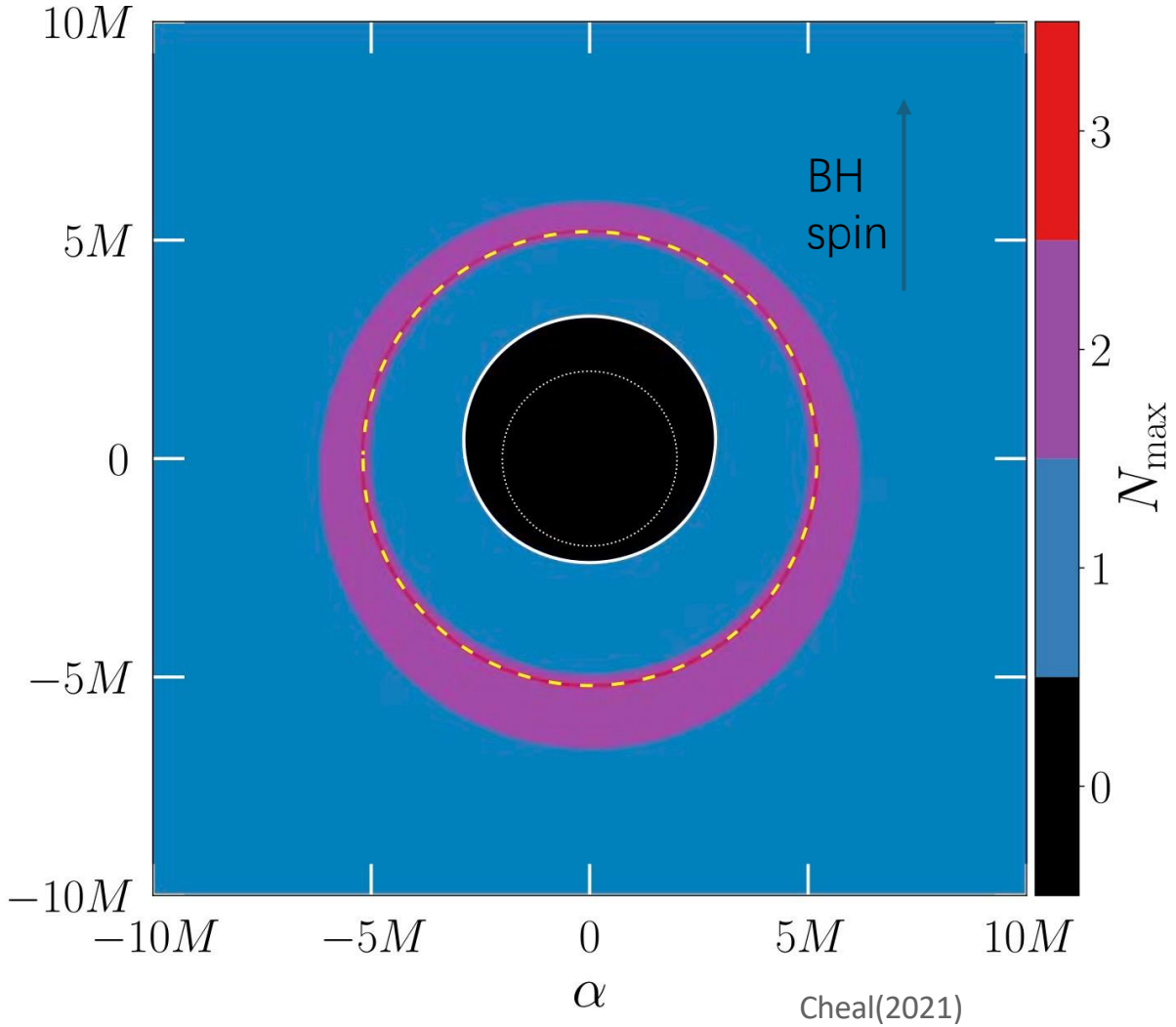


Arxiv:1810.09963

What does the Black Hole Look Like?

Photon Ring and Black Hole Shadow





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Event Horizon Telescope

The biggest ‘telescope’ ever

- Global Radio Telescopes
- VLBI : Very-Long Baseline Interferometry
- The best resolution: to see a coin on the moon

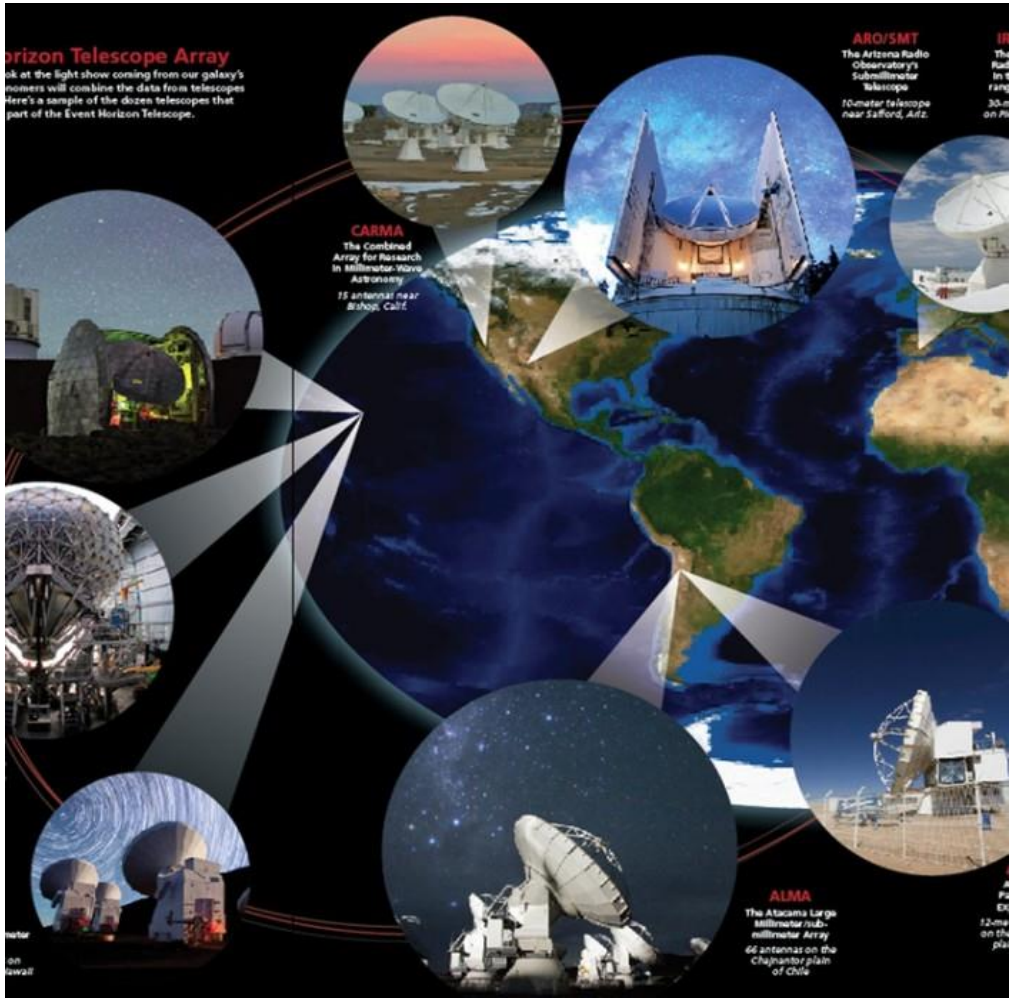
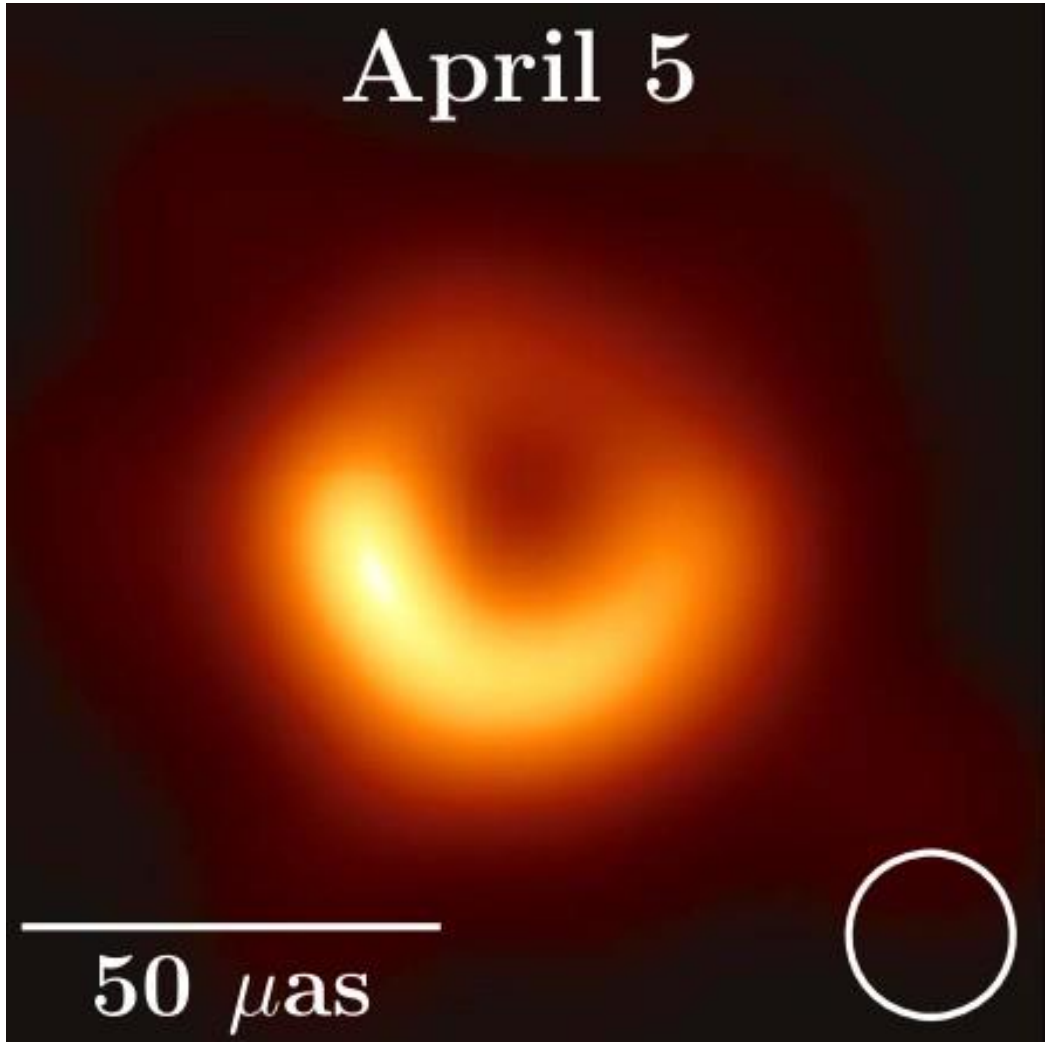


Image of the Black Hole

M87* at 230 GHz

- Clear Structure of Photon Ring and Black hole Shadow
- Dynamical Range-10%
- No visible Jet
- Polarization Shows Strong vertical B-field

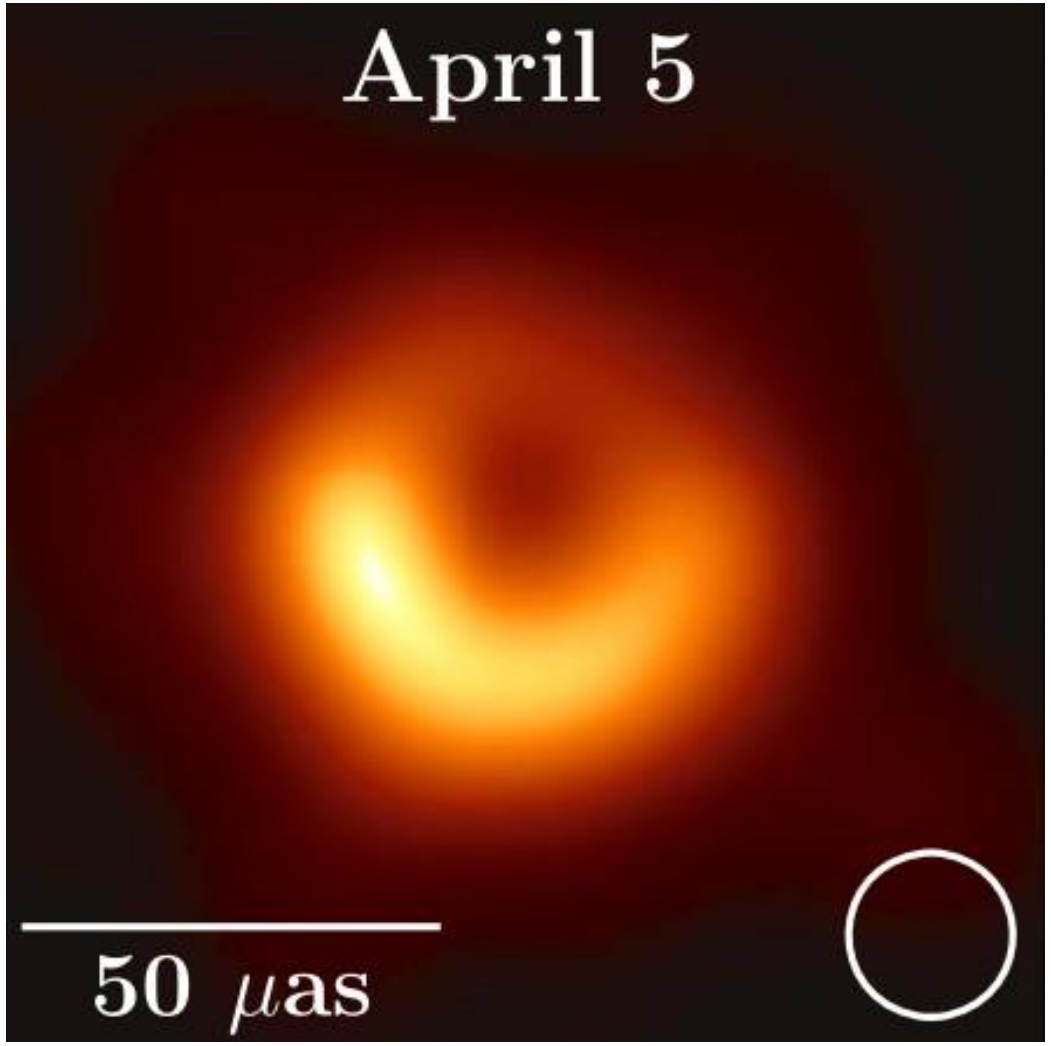


EHT M87* Paper.IV

Image of the Black Hole

Next-generation EHT

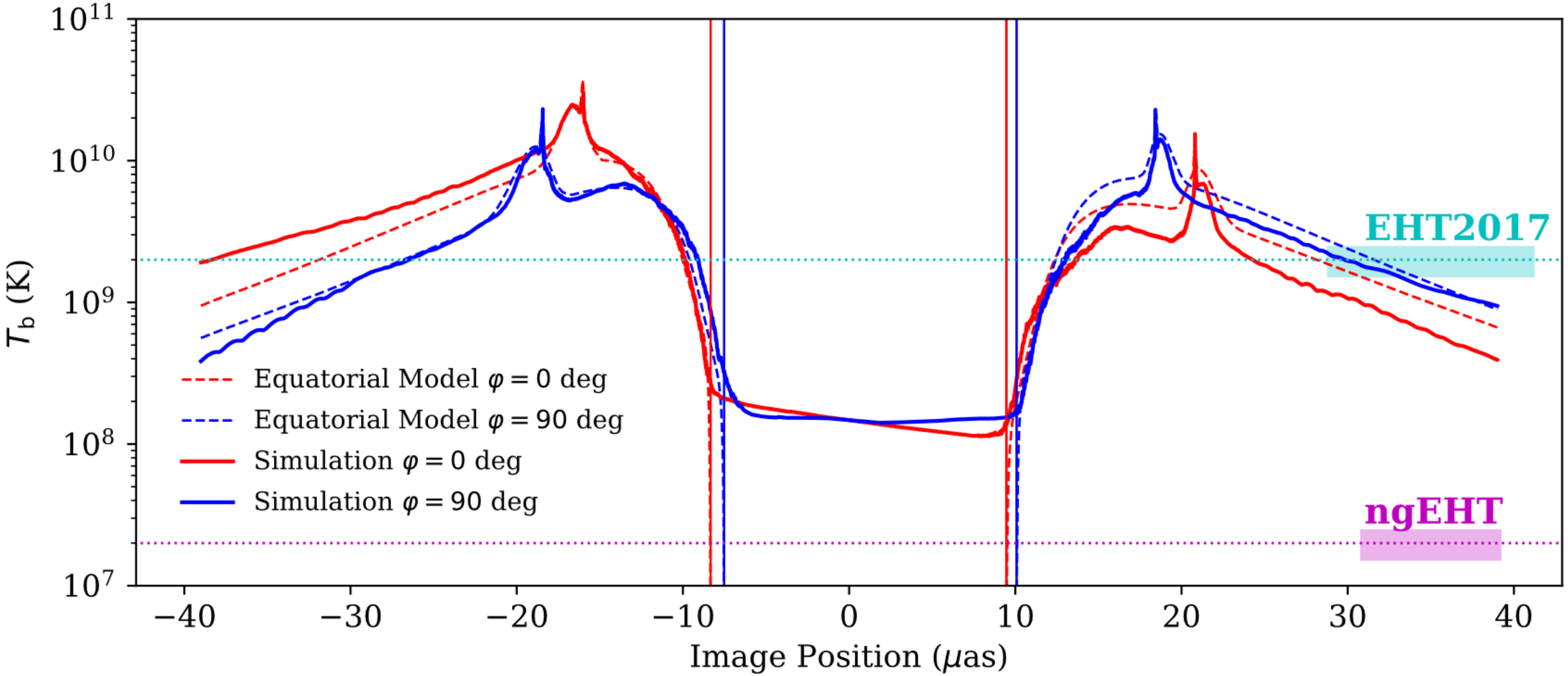
- Clear Structure of Photon Ring and Black hole Shadow-Even better resolution
- Dynamical Range:10%-0.1%
- No visible Jet- Possibly to see jet
- Polarization Shows Strong vertical B-field-Better polarization and time resolution.



EHT M87* Paper.IV

Image of the Black Hole

Dynamical Range



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Plasma Injections From Dark Matter

e^-e^+pair from dark matter annihilation

- Dark Matter annihilates into SM particles, consequently generating e^-e^+ pairs.
- ‘Static’ dark matter background provides e^-e^+ injections.—Constant Source
- e^-e^+ pairs get absorbed by the BH, or to infinite far —Long mean-free-path
- Steady distribution of e^-e^+ pairs is formed, depending on the spatial and energy transport.

$e^- e^+$ Distribution near the SMBH

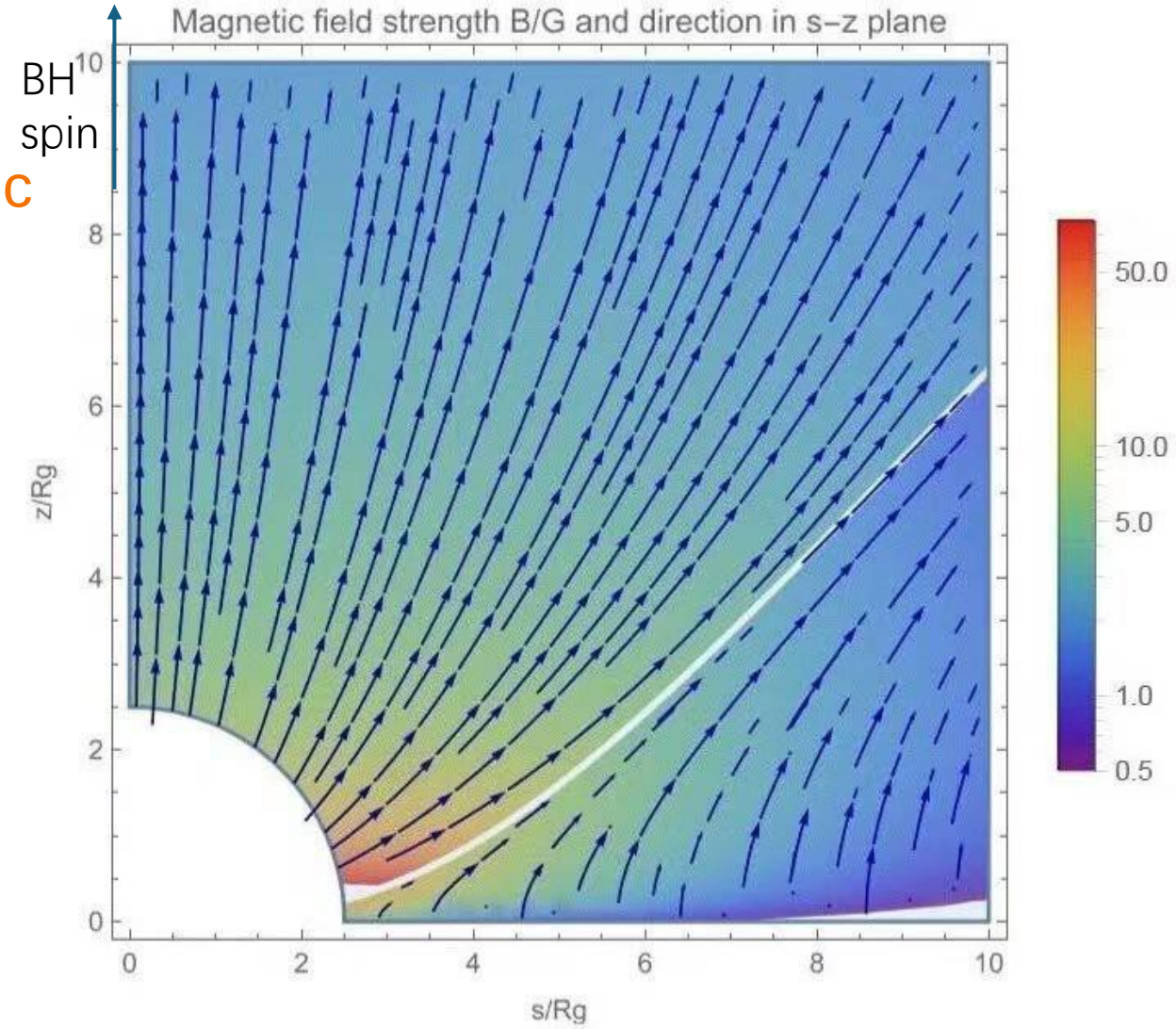
Spatial Transport

- Field Theory approach: isotropic

  $\vec{v}(x^\mu) = \vec{v}_b(x^\mu) + \vec{v}_{\text{thermal}}$

- $e^- e^+$ pairs move along the B-field Line → $\hat{v}_b$

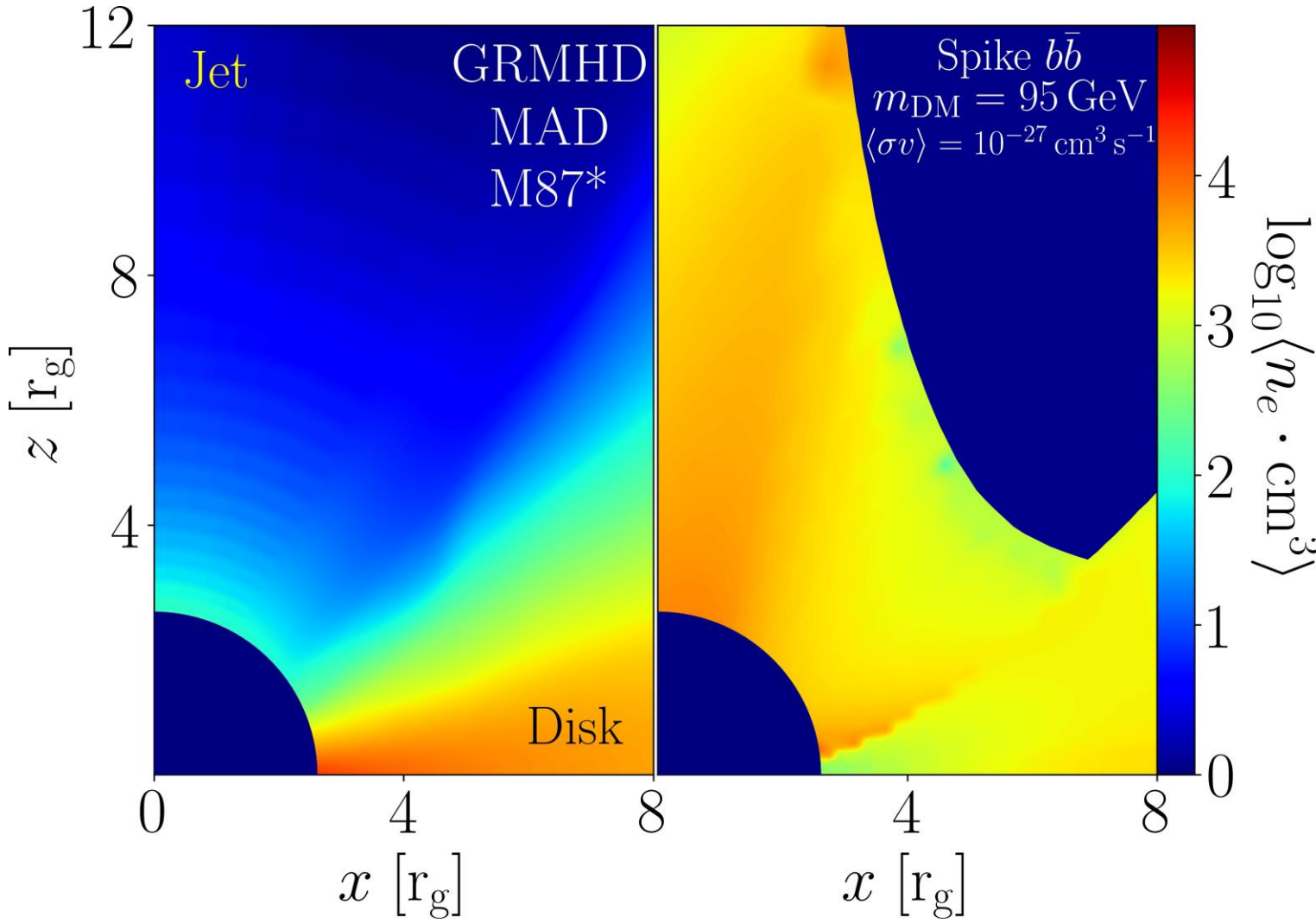
- Gravity and Centrifugal Force → $|\vec{v}_b|$



$e^- e^+$ Distribution near the SMBH

Spatial Transport

- Steady distribution of $e^- e^+$ in jet region.
- Disk Region and Jet region shows no significant difference. (Spherical DM)



$e^- e^+$ Distribution near the SMBH

Momentum Transport

- Adiabatic Compression ($\dot{p}_{\rm adi} = -p\left(\nabla \cdot \vec{v}_b\right)/3$):
  - Work -> Energy
  - Directional Compression
  - Speed dilution
- Synchrotron Radiation:

$$\dot{p}_{\rm syn} \propto B^2 p^2$$

$$\dot{p}_{\rm adi} \approx 1.03 \times 10^{-6}\,{\rm GeV\,s^{-1}} \left(\frac{p}{1{\rm GeV}}\right)\left(\frac{r}{r_g}\right)^{-1}\left(\frac{v_b}{0.1}\right),$$

$$\dot{p}_{\rm syn} \approx -2.01 \times 10^{-7}\,{\rm GeV\,s^{-1}} \left(\frac{B}{1\,{\rm G}}\right)^2\left(\frac{p}{1\,{\rm GeV}}\right)^2,$$

$$\dot{p}_{\rm brem} \approx -1.37 \times 10^{-16}\,{\rm GeV\,s^{-1}} \left(\frac{\bar{n}_{ion}}{1\,{\rm cm^{-3}}}\right)\left(\frac{p}{1\,{\rm GeV}}\right)\left(\ln\frac{p}{1\,{\rm GeV}} + 7.94\right),$$

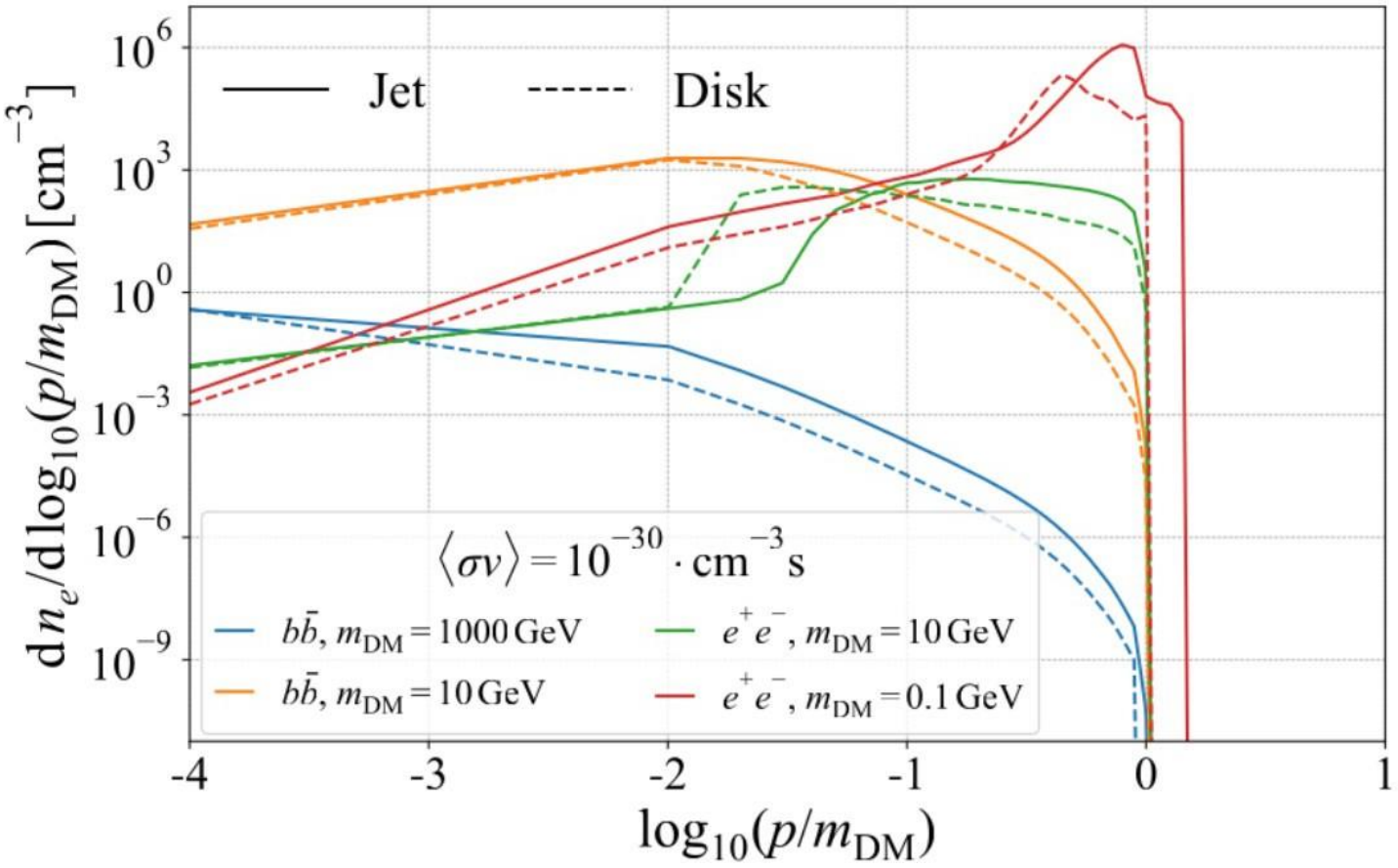
$$\dot{p}_{\rm IC} \approx -1.02 \times 10^{-16}\,{\rm GeV\,s^{-1}} \left(\frac{\bar{u}_{\rm r}}{1\,{\rm eV\,cm^{-3}}}\right)\left(\frac{p}{1\,{\rm GeV}}\right)^2,$$

$$\dot{p}_{\rm C} \approx -7.62 \times 10^{-18}\,{\rm GeV\,s^{-1}} \left(\frac{\bar{n}_e}{1\,{\rm cm^{-3}}}\right)\left[\ln\frac{p}{1\,{\rm GeV}} + \ln\frac{\bar{n}_e}{1\,{\rm cm^{-3}}} + 82.3\right]$$

$e^- e^+$ Distribution near the SMBH

Momentum Transport

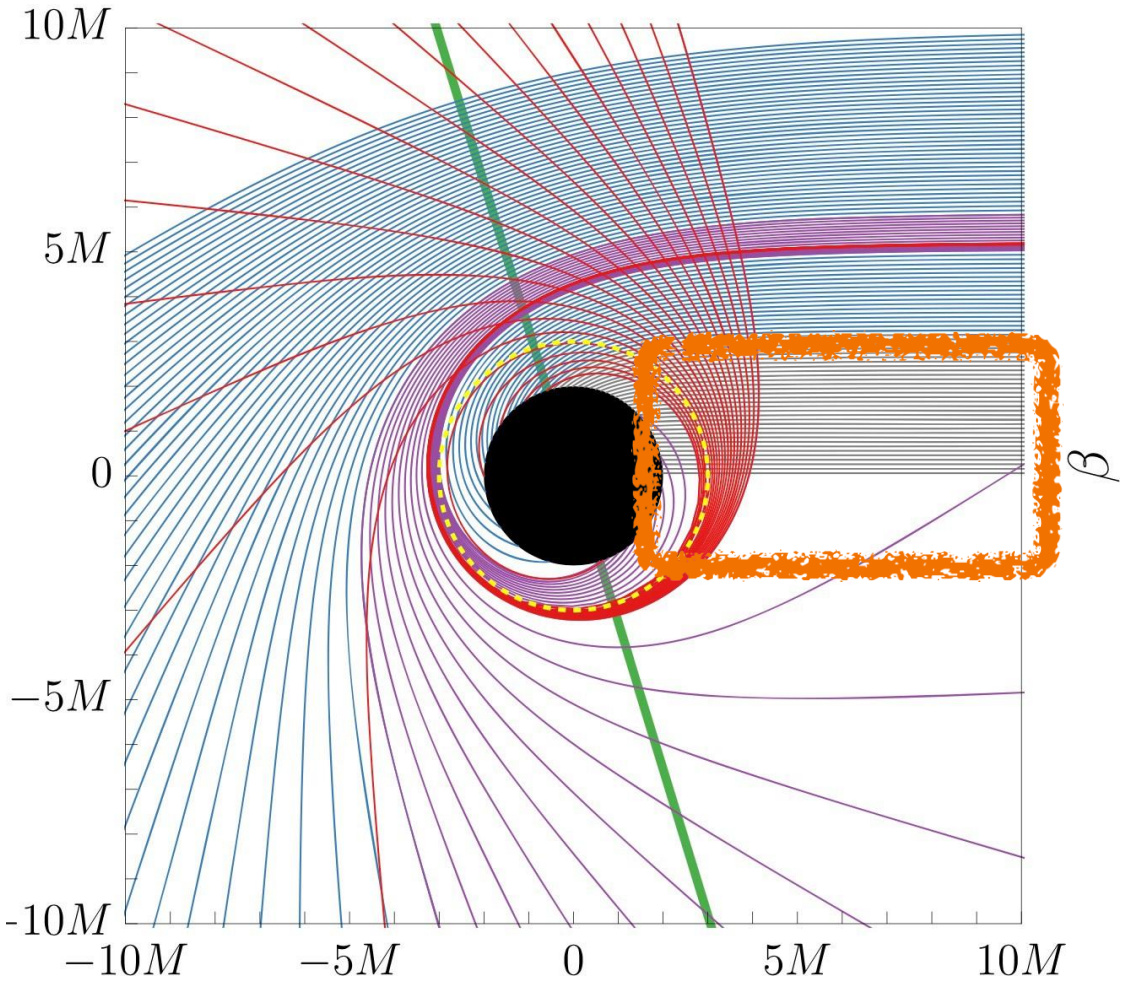
- Flat spectrum
- Balance of synchrotron loss and compression gain in Jet region.
- Purely de-acceleration in disk region.

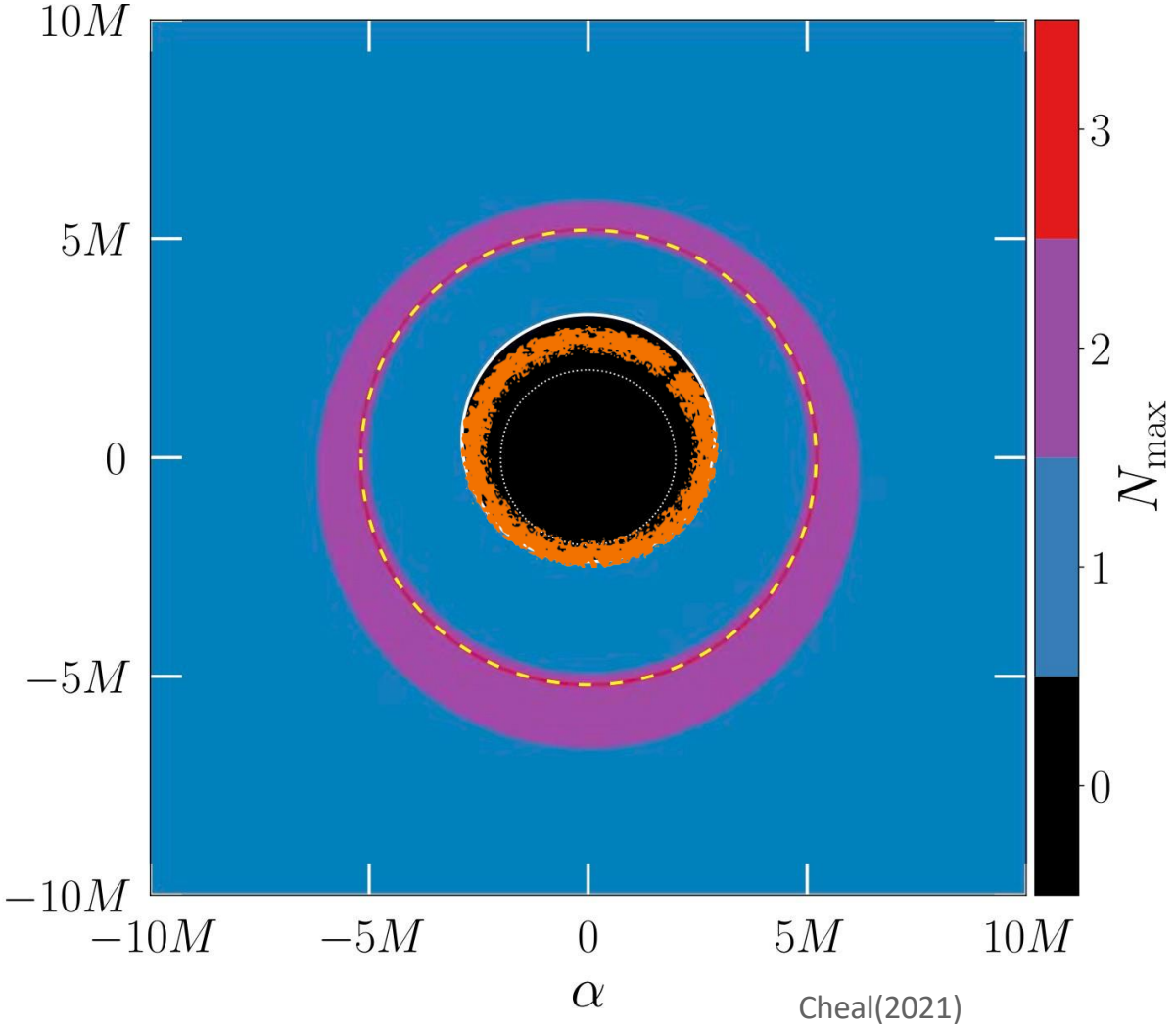


Synchrotron Cut-off at $\nu_c \approx 180\,\mathrm{GHz} \times \left(\frac{B}{7\,\mathrm{G}}\right) \times \left(\frac{p}{0.1\,\mathrm{GeV}}\right)^2 .$

Illuminating the Inner Shadow with Dark Matter

Geodesics in Jet region is lightened up





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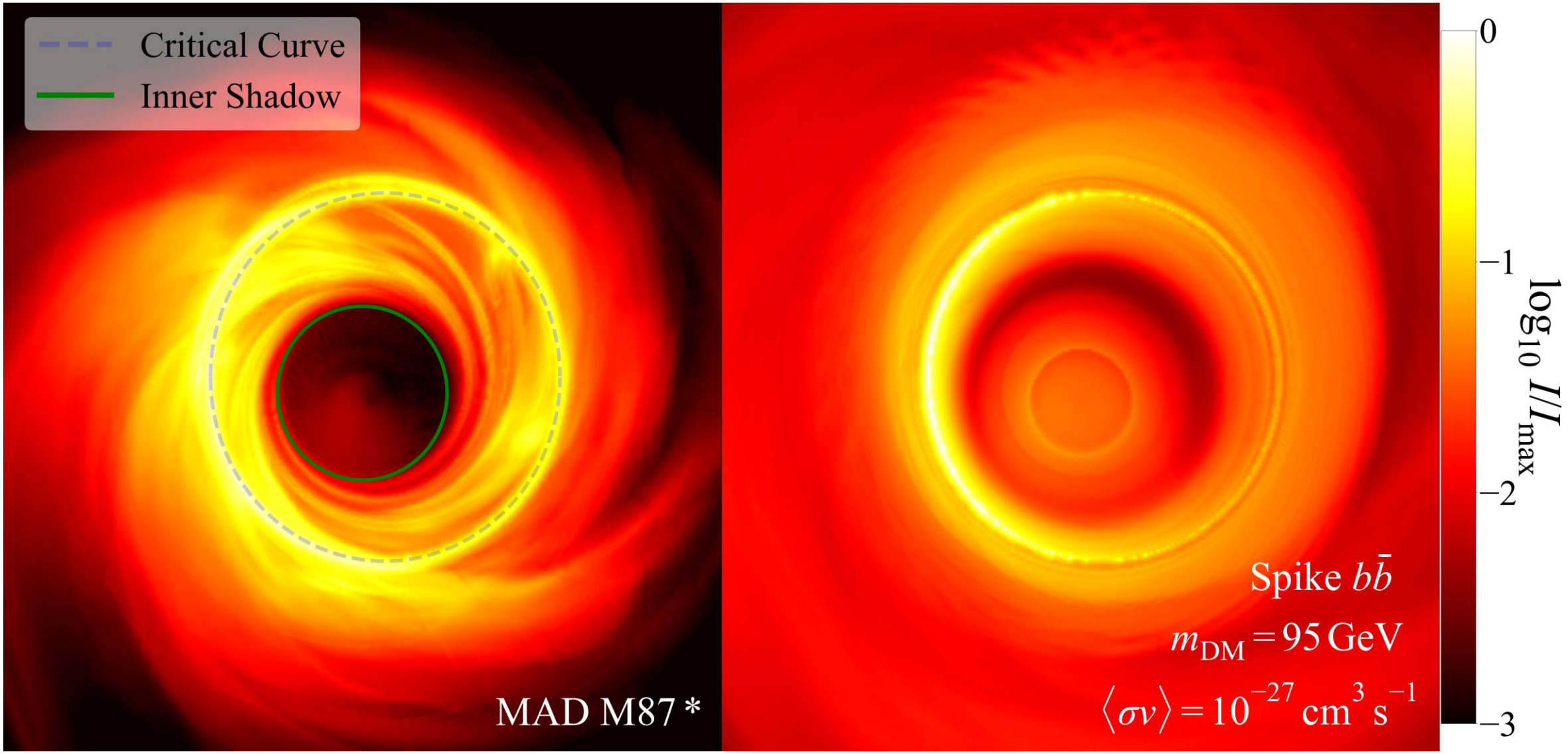
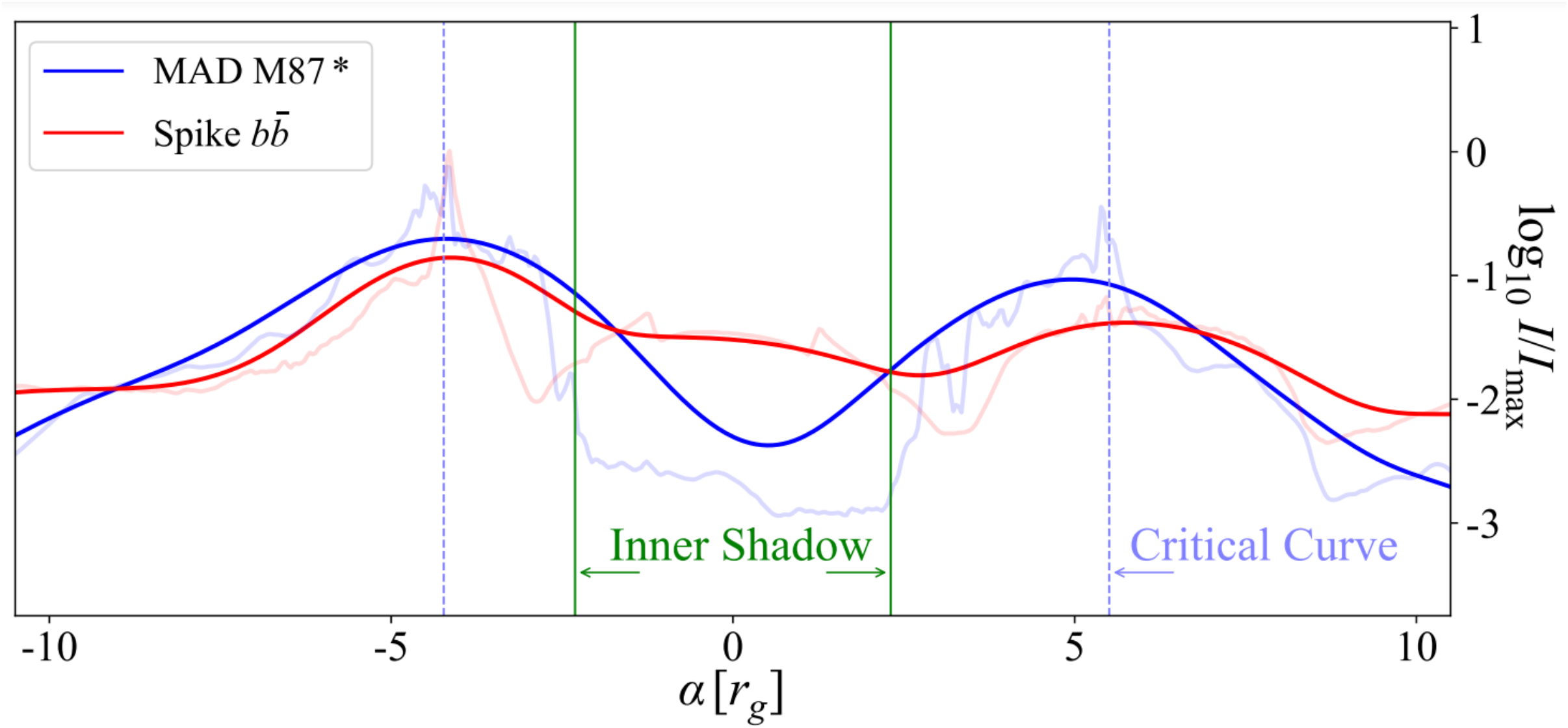
Illuminating the Inner Shadow with Dark Matter

2D log-image from numerical simulation



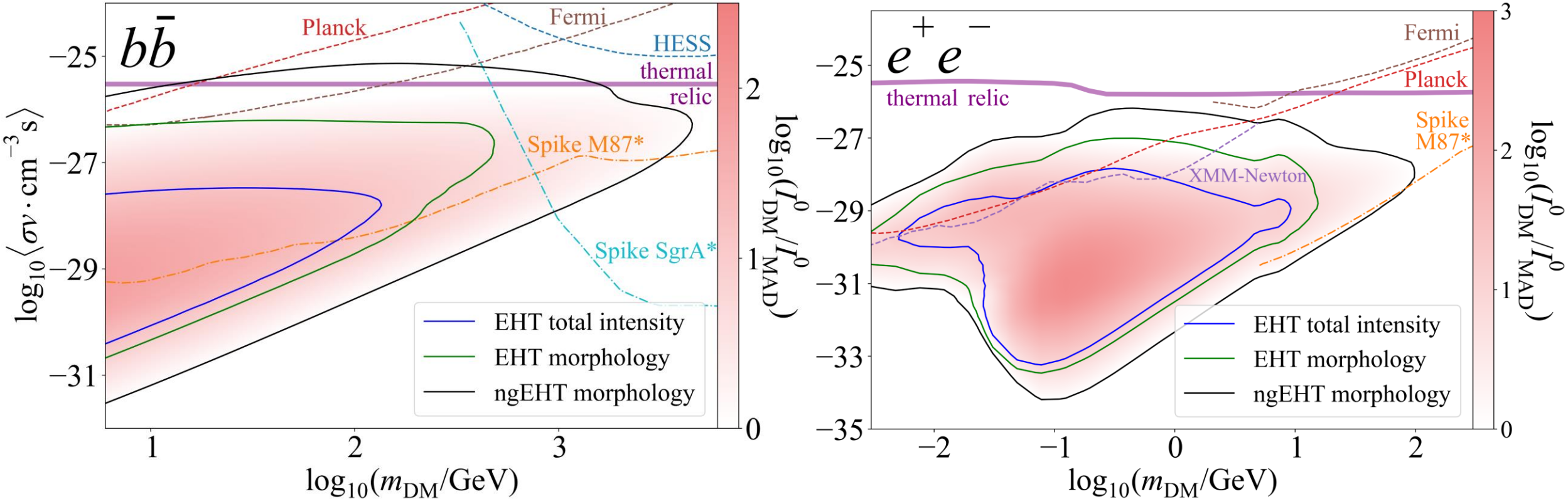
Illuminating the Inner Shadow with Dark Matter

1D slice from numerical simulation



Illuminating the Inner Shadow with Dark Matter

Constraints on dark matter annihilation cross section



Conclusion and Outlook

- Black Hole is not black.
- Black Hole Shadow is black, thus a perfect place to search for New Physics.
- WIMP Dark Matter could illuminate the black hole shadow, a smoking gun could be seen by ngEHT.
- Lunar-EHT, multi-frequency, polarizations…….

Thanks !