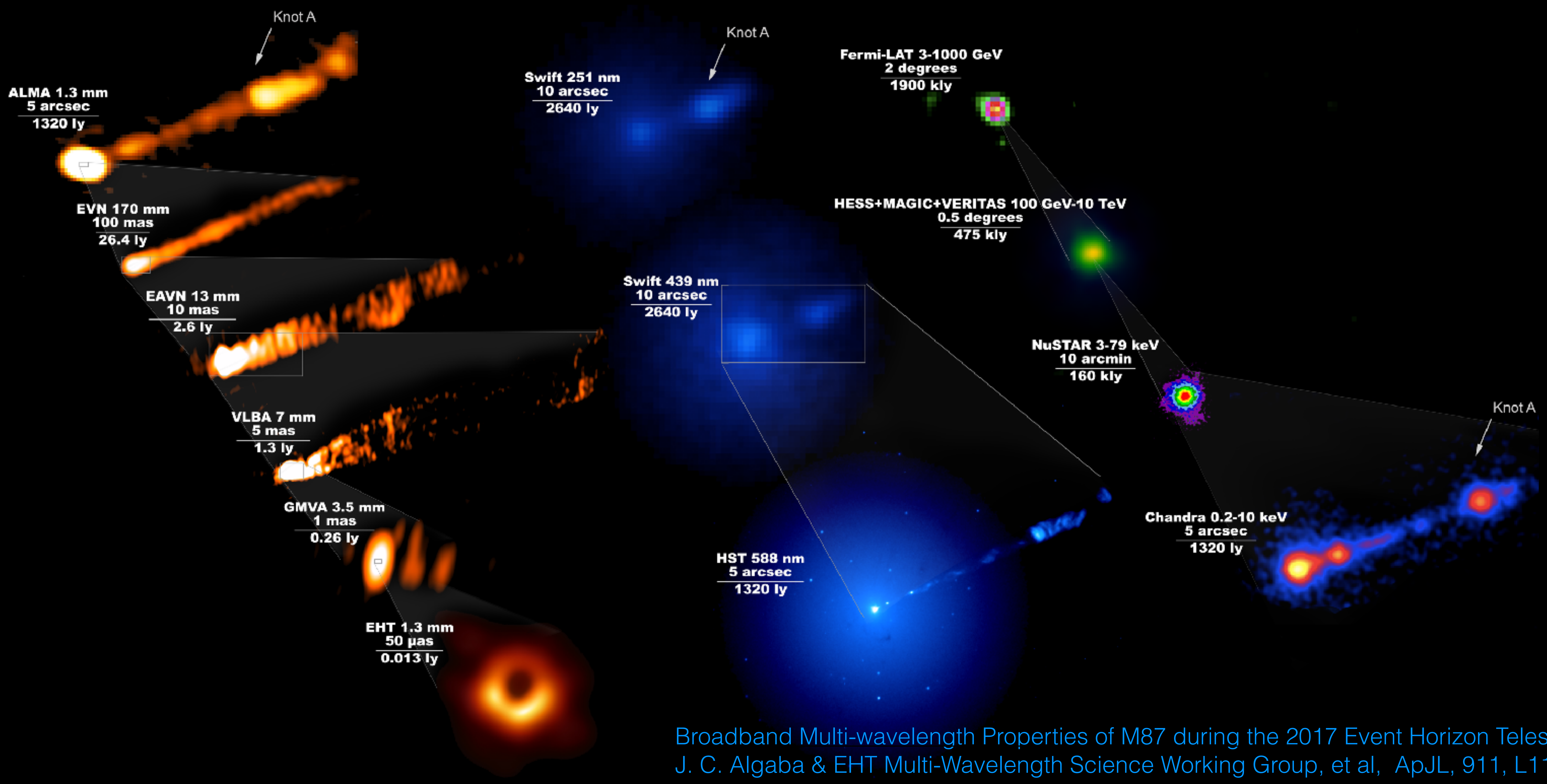
Multi-wavelength emission of M87 jet using self-consistent electron-to-proton temperature

Alejandro Cruz-Osorio
Institute for Theoretical Physics,
Goethe University Frankfurt, Germany

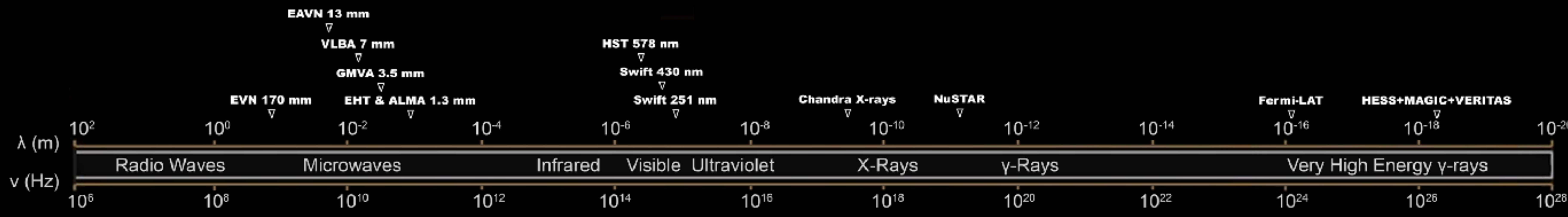
In collaboration with: Claudio Meringolo, Christian Fromm, Yosuke Mizuno, Sergio Servidio & Luciano Rezzolla

Workshop on Kinetic Models of Relativistic Plasmas, Dublin, February 28 2023

Simultaneous observation of multi-frequency emission of M87

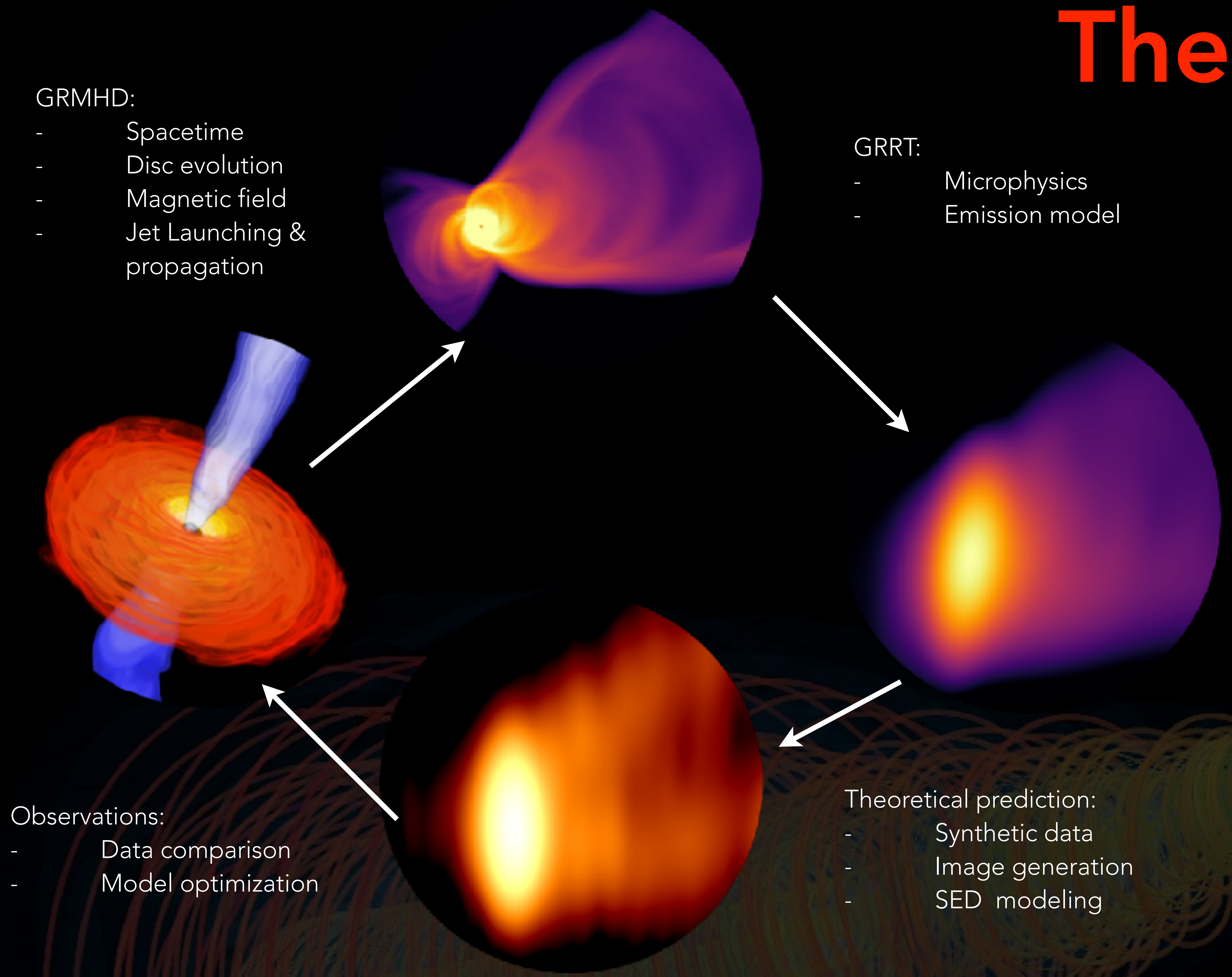


Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign ,
J. C. Algaba & EHT Multi-Wavelength Science Working Group, et al, ApJL, 911, L11, 2021



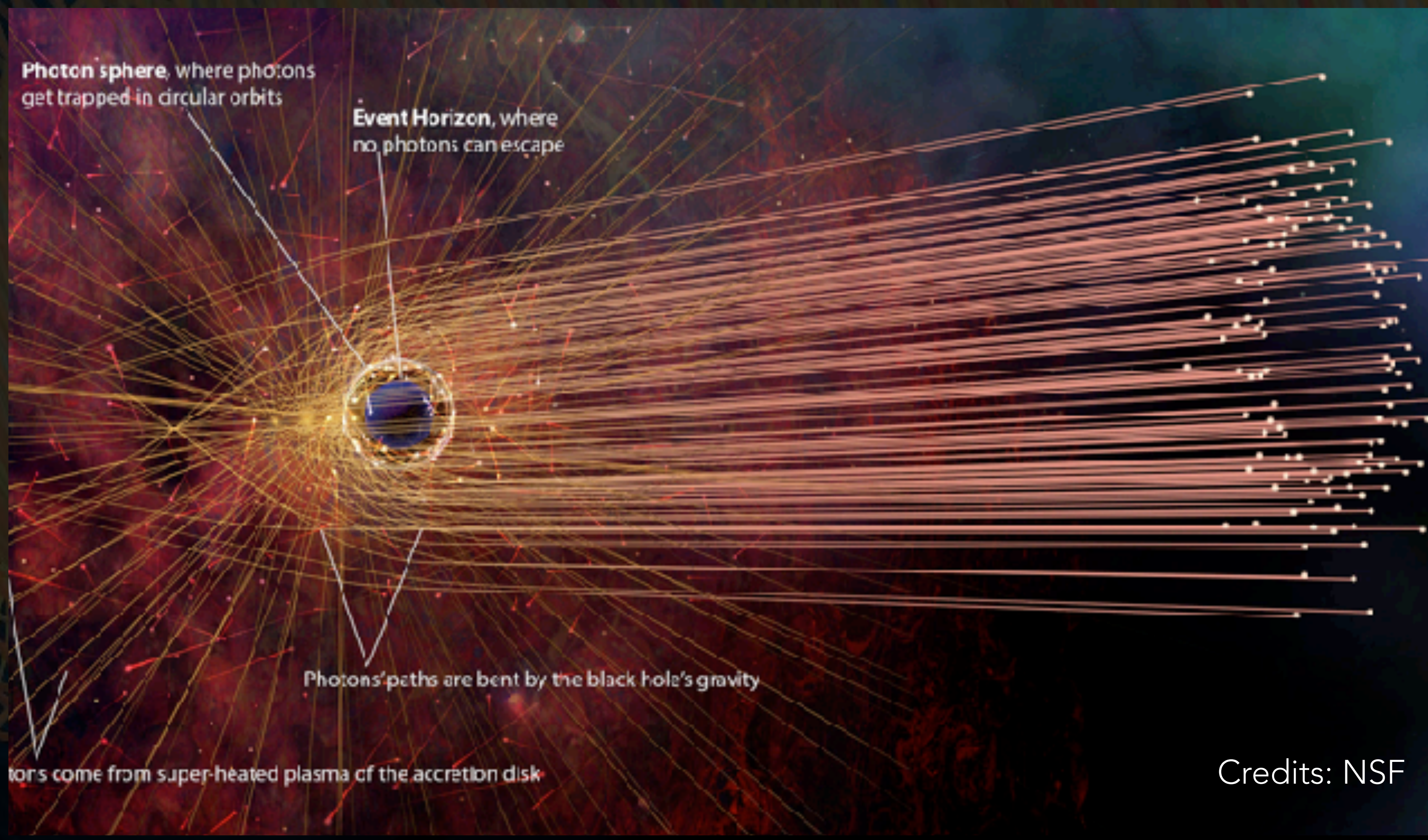
mage Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; ne Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

Theory ⟷ Observation



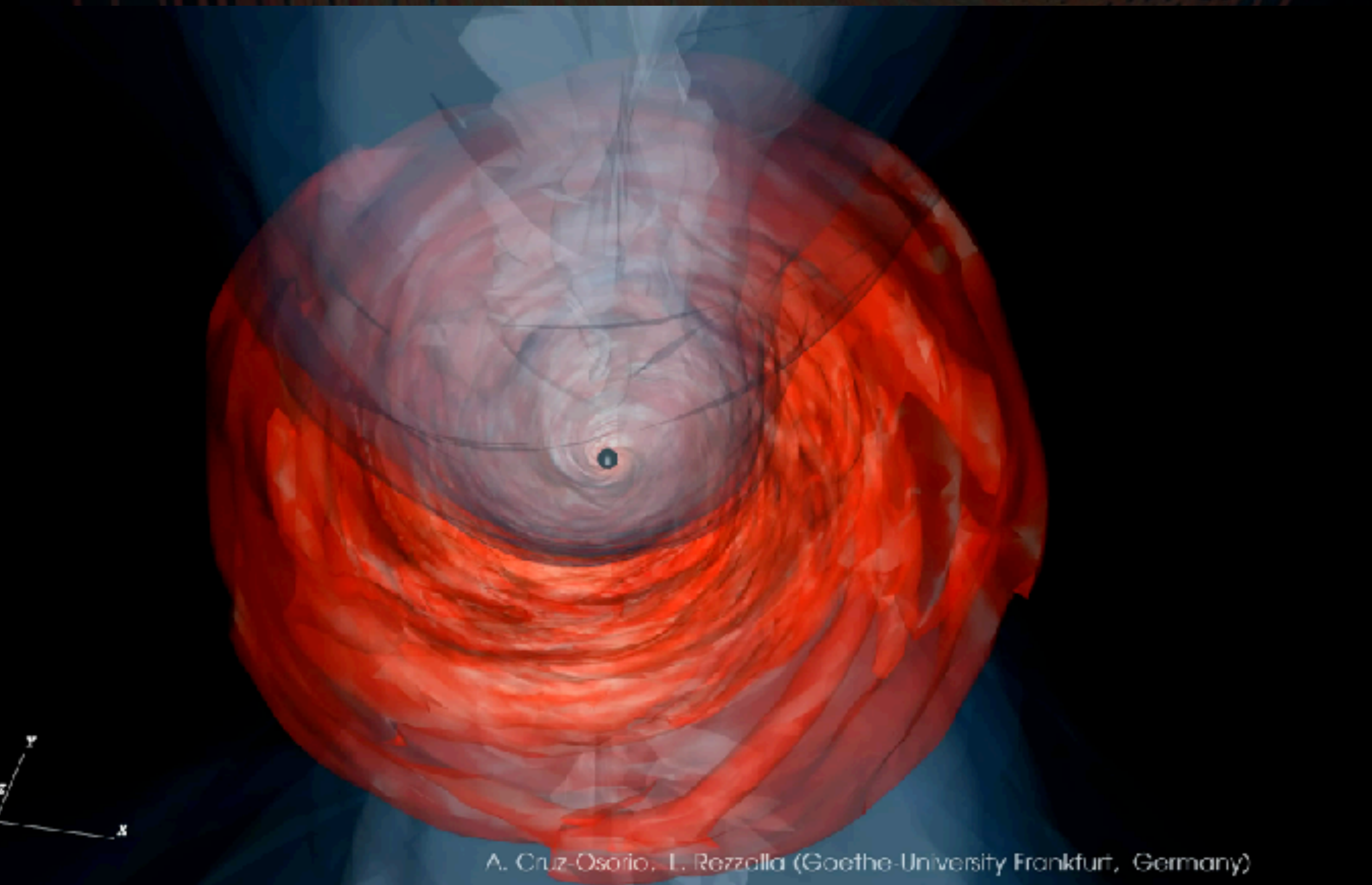
- General Relativistic Magnetohydrodynamics
- General Relativistic Radiative Transfer
- Thermal & Non-Thermal Particles
- Synchrotron Emission
- Parametric temperature model

Geodesic trajectories around Black Hole

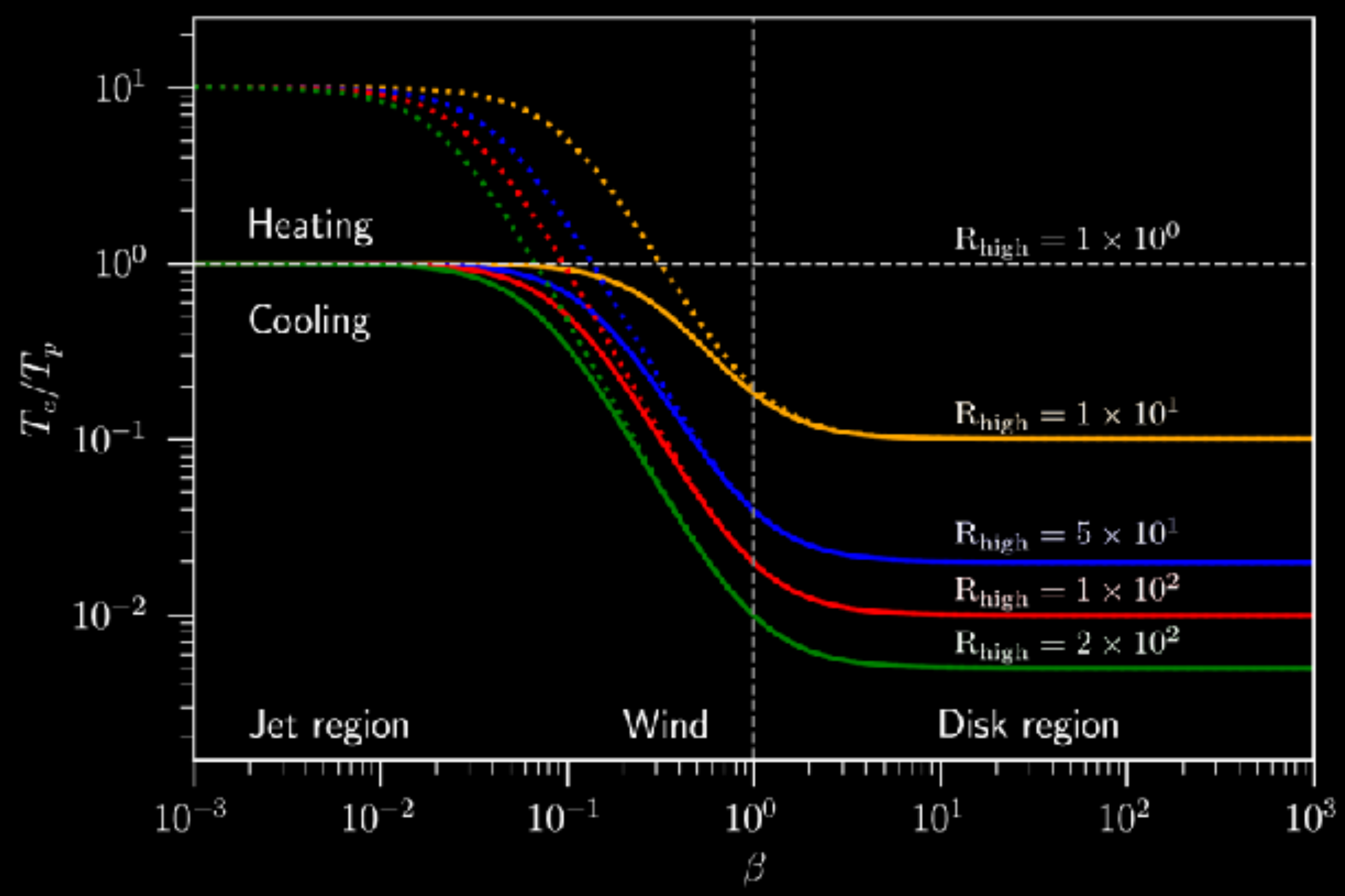


Credits: NSF

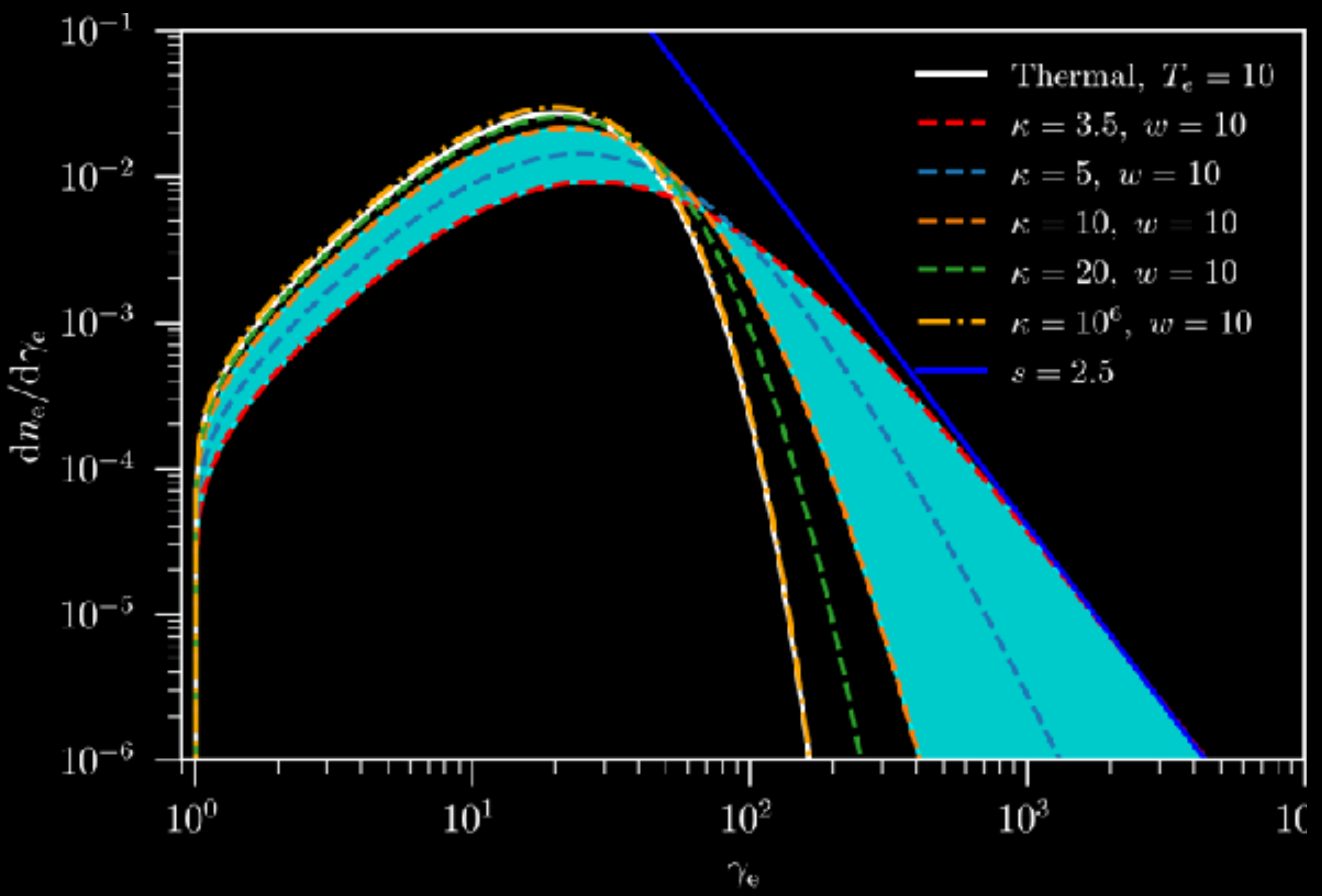
GRMHD simulations



Electron Temperature (R-Beta Model)



Non-Thermal Electron Distribution Function



GRMHD simulations with BHAC code

(https://bhac.science/)

O. Porth, Computational Astrophysics and Cosmology, 4(1), 1 (2017)

H. Olivares, Astronomy & Astrophysics, 629, A61 (2020)

- Ideal GRMHD equations

$$\nabla_\mu(\rho u^\mu) = 0\,, \quad \nabla_\mu T^{\mu\nu} = 0\,, \quad \nabla_\mu {}^*F^{\mu\nu} = 0\,,$$

Perfect fluid with ideal gas EoS

- Spacetime: Kerr black hole with spins

$a_\star = -0.94,\ -0.5,\ 0.0,\ 0.5,\ 0.94$

- Accretion model: SANE & MAD

- Fishbone & Moncrief torus, constant angular momentum
- Weak poloidal magnetic field ($\beta := p_{\rm gas}/p_{\rm mag} = 100$).
- SANE & MAD, ideal gas equation of state $\hat{\gamma} = 4/3$.
- Simulation time up $t = 10000M$ (SANE) and $15000M$ (MAD)

GRRT simulations with BHOSS code

(Raytracing)

Z. Younsi et al (2012)

ACO et al (2022)

- Radiative Transfer equations

$$\frac{d\tau_\nu}{d\lambda} = \gamma^{-1}\alpha_{0,\nu}\,, \qquad \frac{d\mathscr{I}}{d\lambda} = \gamma^{-1}\left(\frac{j_{0,\nu}}{\nu^3}\right)\exp\left(-\tau_\nu\right)\,,$$

$\mathscr{I} = I_\nu/\nu^3$ is the Lorentz invariant specific intensity

I_ν is the specific intensity,

τ_ν is the optical depth,

j_ν is the emission coefficients, and

α_ν absorption coefficients at the frequency ν

$\gamma^{-1} = \nu_0/\nu = -k_\alpha u^\alpha|_\lambda / k_\beta u^\beta|_\infty$ is energy shift between observer's and co-moving frame

k_α is the wave vector of the photon.

Electron-to-Proton Temperature

$$\Theta_{\rm e} = \frac{p m_{\rm p}/m_{\rm e}}{\rho T_{\rm ratio}}, \quad T_{\rm ratio} \equiv \frac{T_{\rm p}}{T_{\rm e}} = \frac{R_{\rm low} + R_{\rm high}\beta^2}{1+\beta^2},$$

T_e —> Electron temperature $\quad$ m_e —> Electron mass

T_p —> Proton temperature $\quad$ m_p —> Proton mass

Moscibrodzka, M., Falcke, H., & Shiokawa, H. 2016, Astronomy & Astrophysics, 586, A38 (2016)

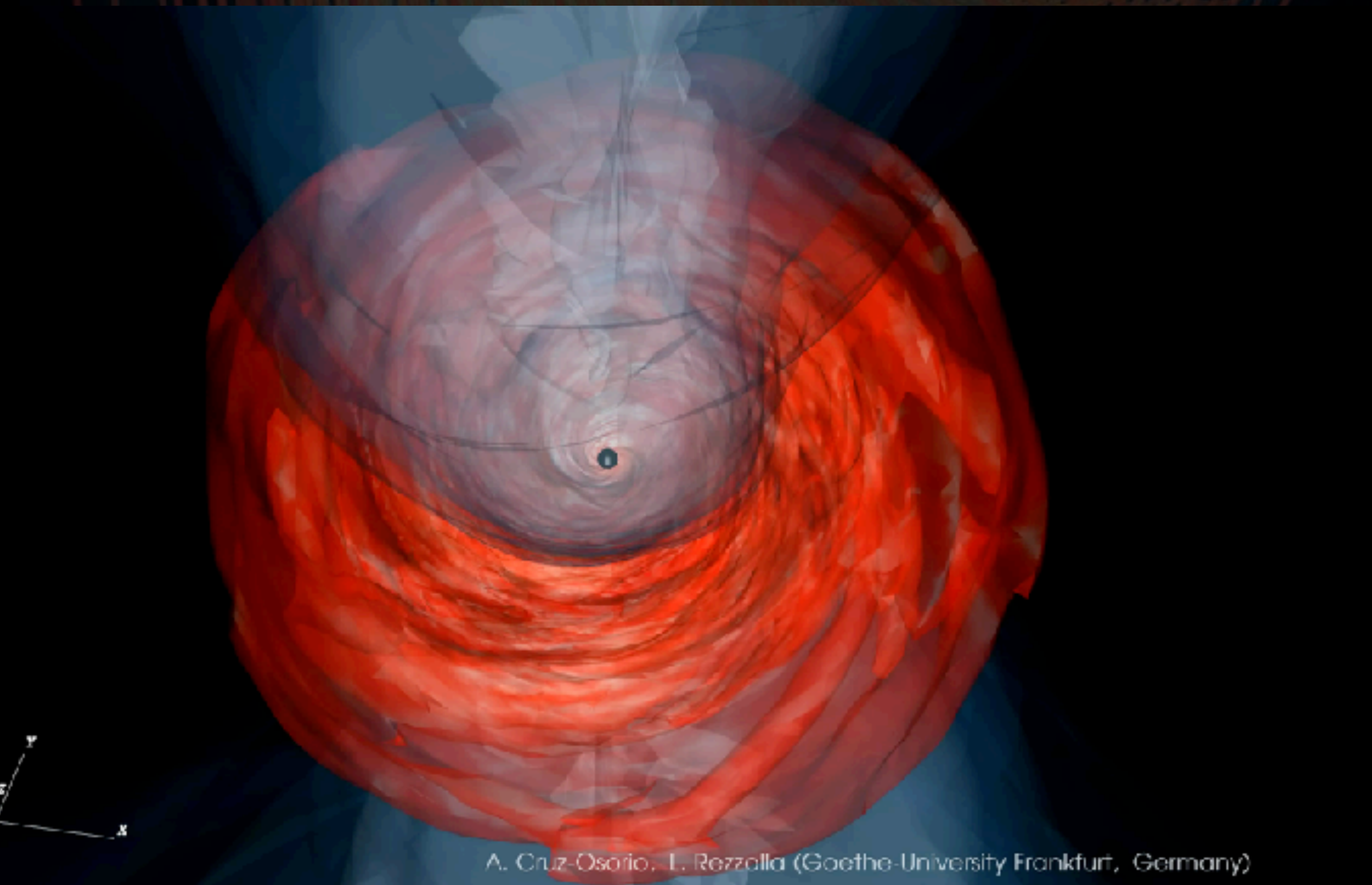
Non-thermal eDF

$$\frac{dn_{\rm e}}{d\gamma_{\rm e}} = \frac{N}{4\pi}\gamma_{\rm e}\sqrt{\gamma_{\rm e}^2 - 1}\left(1 + \frac{\gamma_{\rm e}-1}{\kappa w}\right)^{-(\kappa+1)}$$

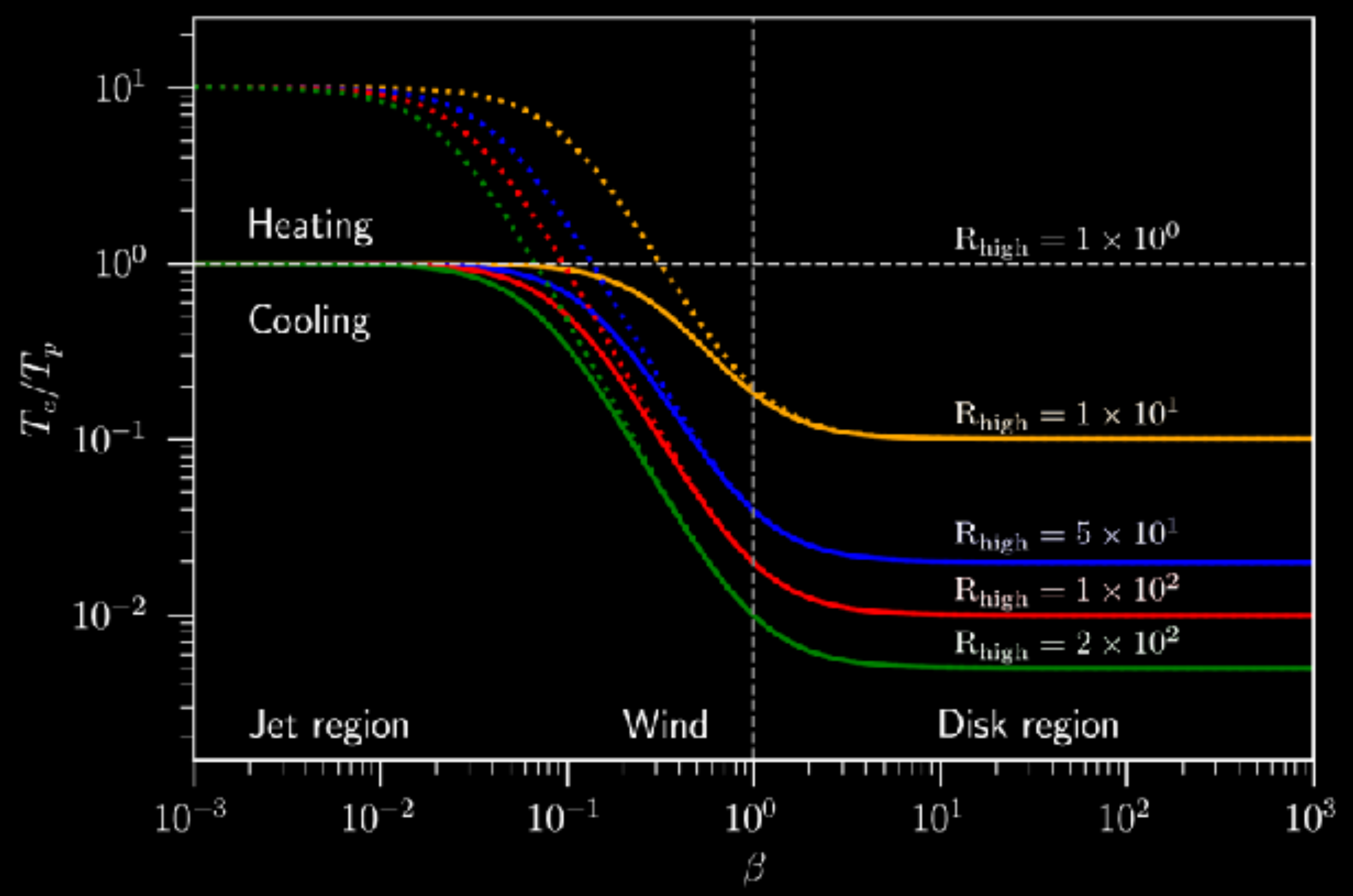
n_e is the density number of electrons, γ_e electron Lorentz factor, T_e electron temperature, w width of energy of the kappa distribution, κ power-law exponent of a non-thermal particle.

Vasyliunas (1968), Xiao et.al. 2006, Leung (2011), Pandya et. al. 2016

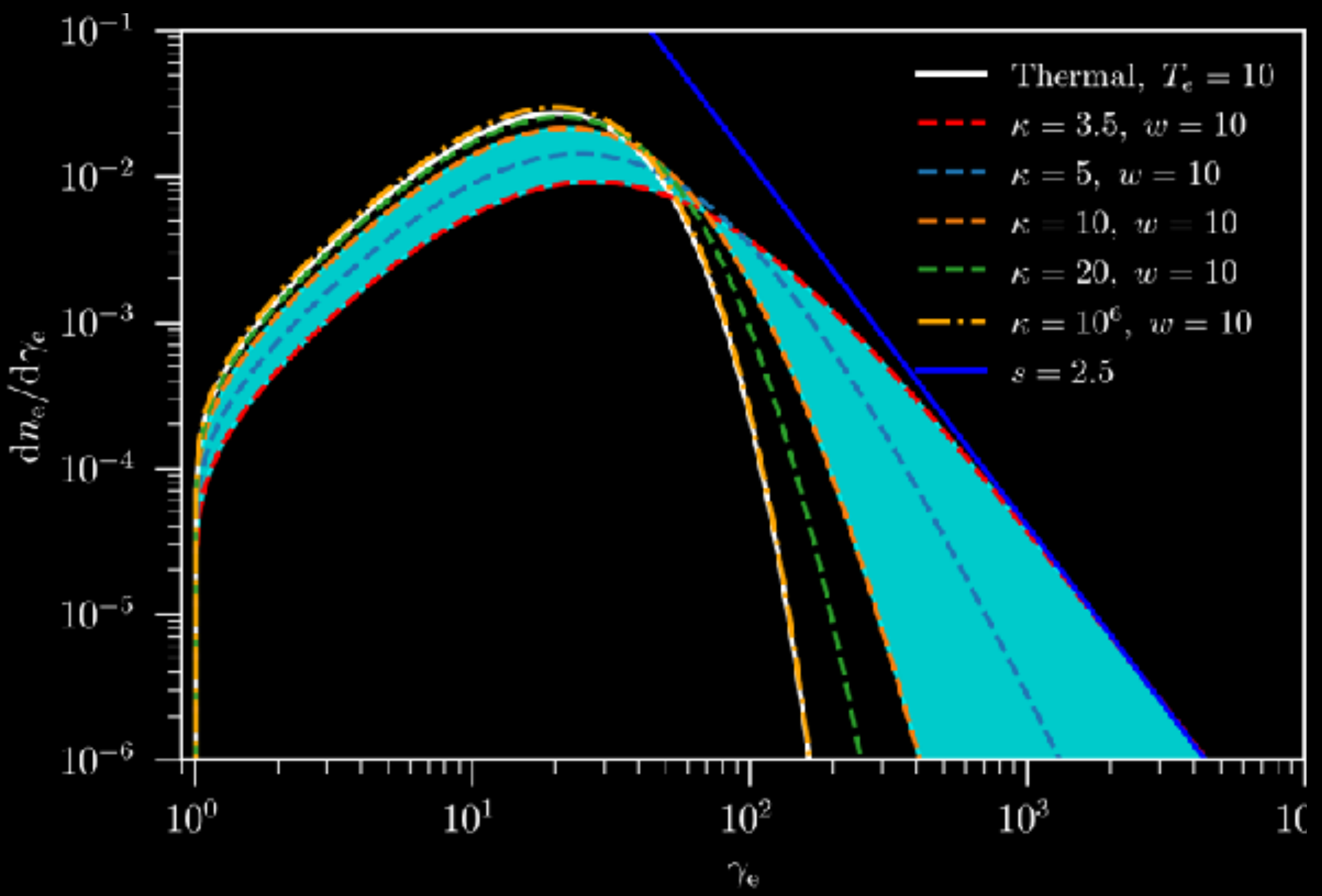
GRMHD simulations



Electron Temperature (R-Beta Model)

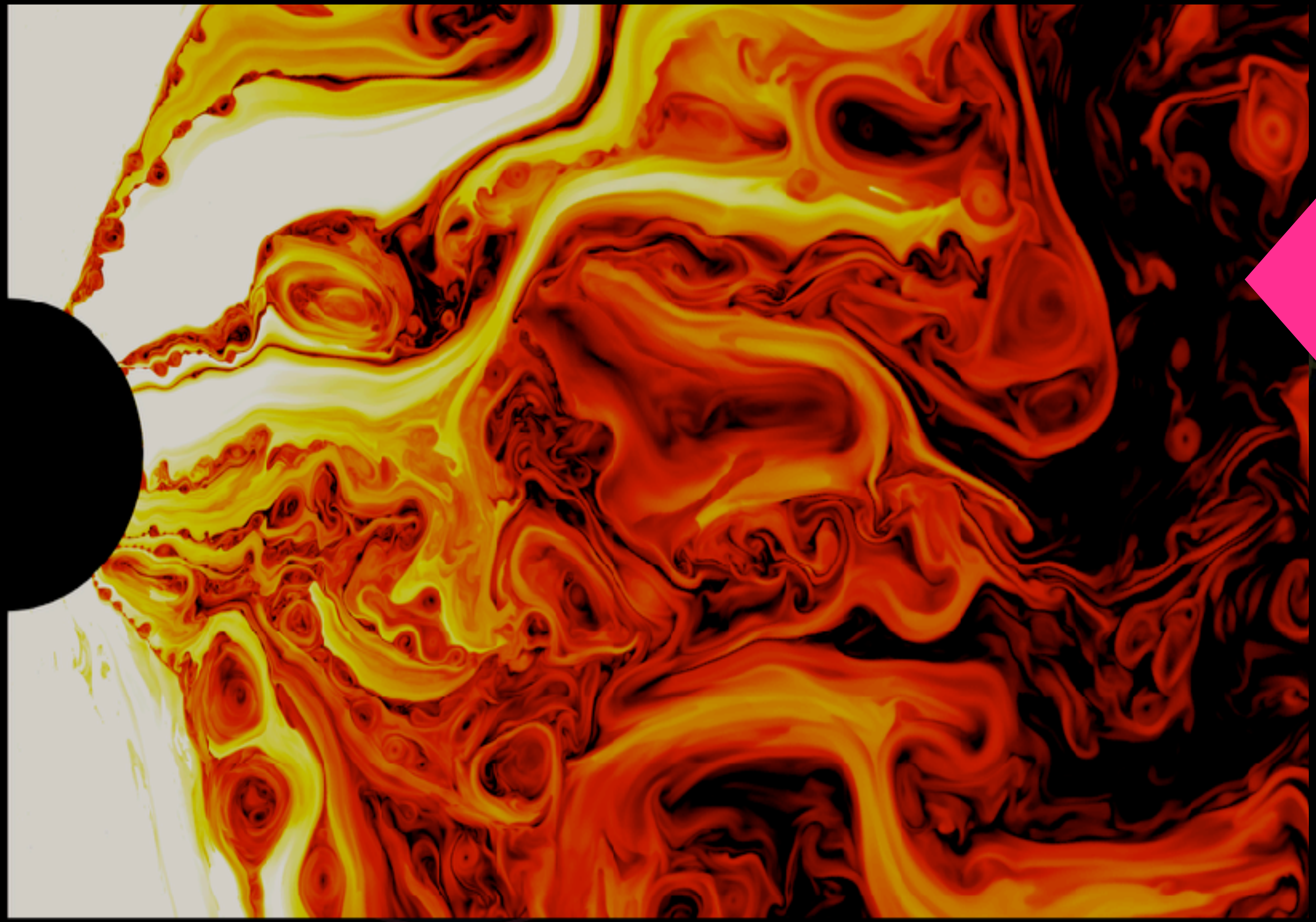


Non-Thermal Electron Distribution Function



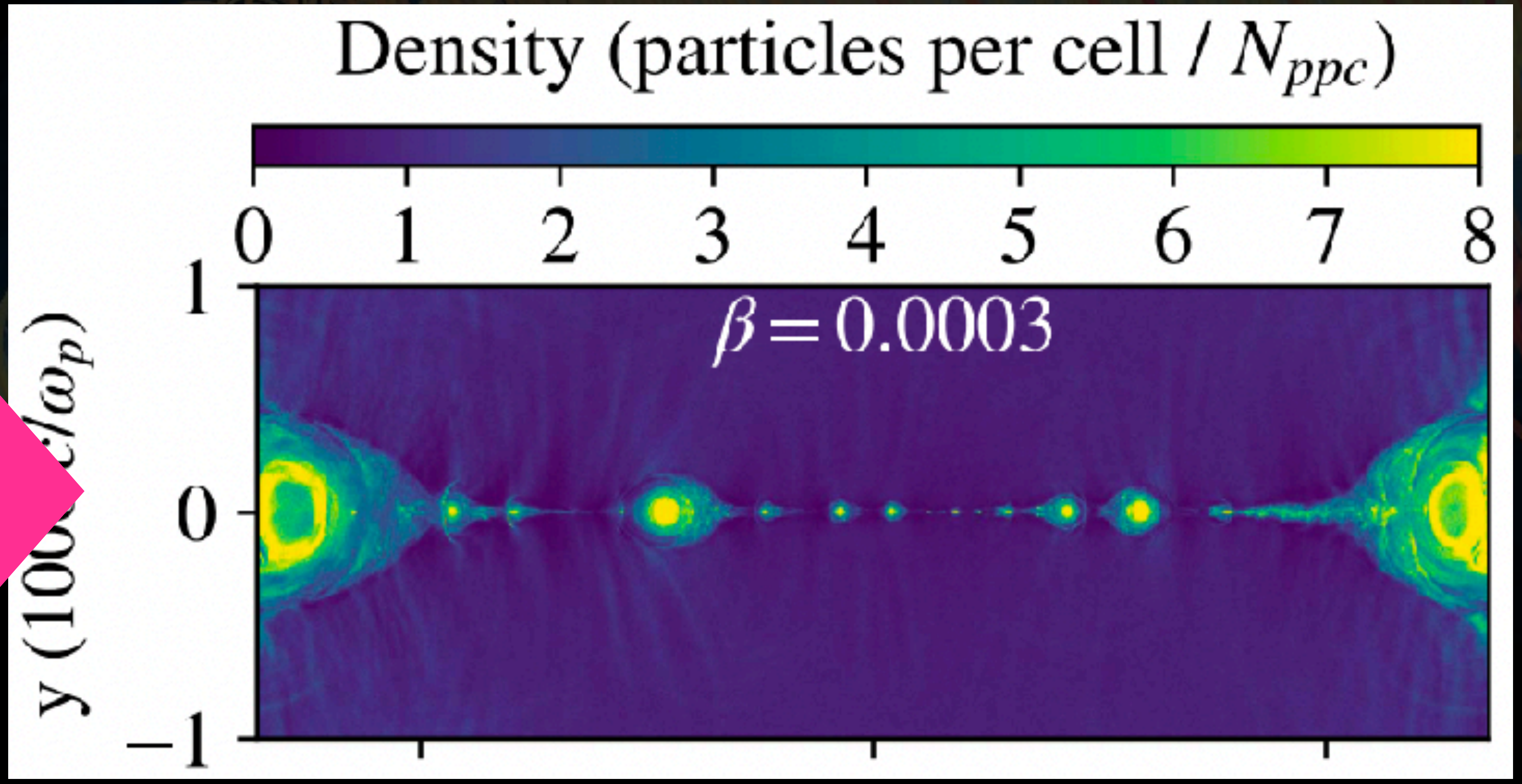
From Micro to Macro scales: First Approach

Accretion onto a Black Hole



Bart Ripperda, Fabio Bacchini, Alexander A. Philippov ApJ 900 100 (2020)

Harris Current Sheet (PIC simulations)



$$w := \frac{\kappa - 3}{\kappa}\Theta_e + \frac{\varepsilon}{2}\left[1 + \tanh(r - r_{inj})\right]\frac{\kappa - 3}{6\kappa}\frac{m_p}{m_e}\sigma$$

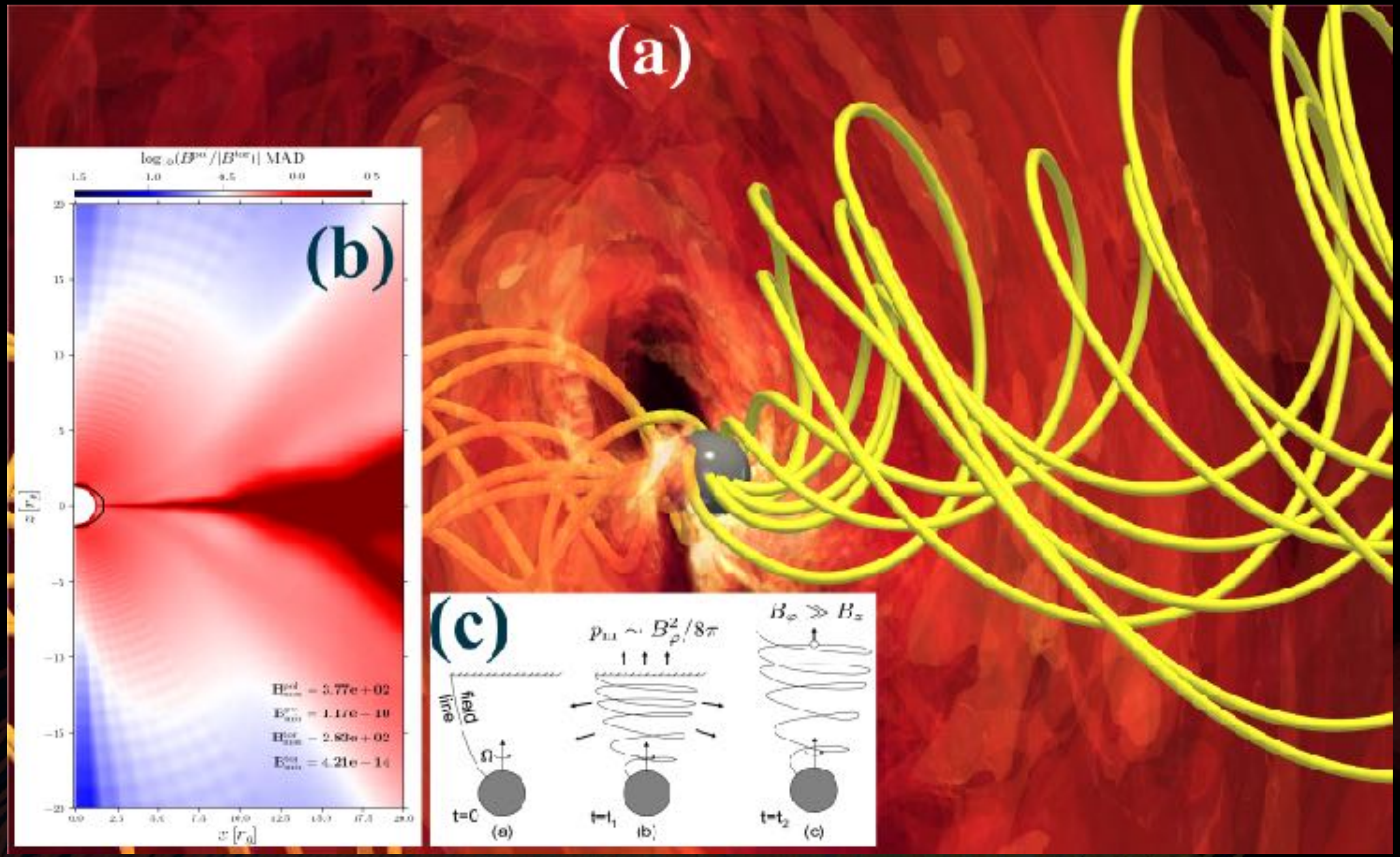
$$\kappa := 2.8 + 0.7\sigma^{-1/2} + 3.7\sigma^{-0.19}\tanh(23.4\sigma^{0.26}\beta)$$

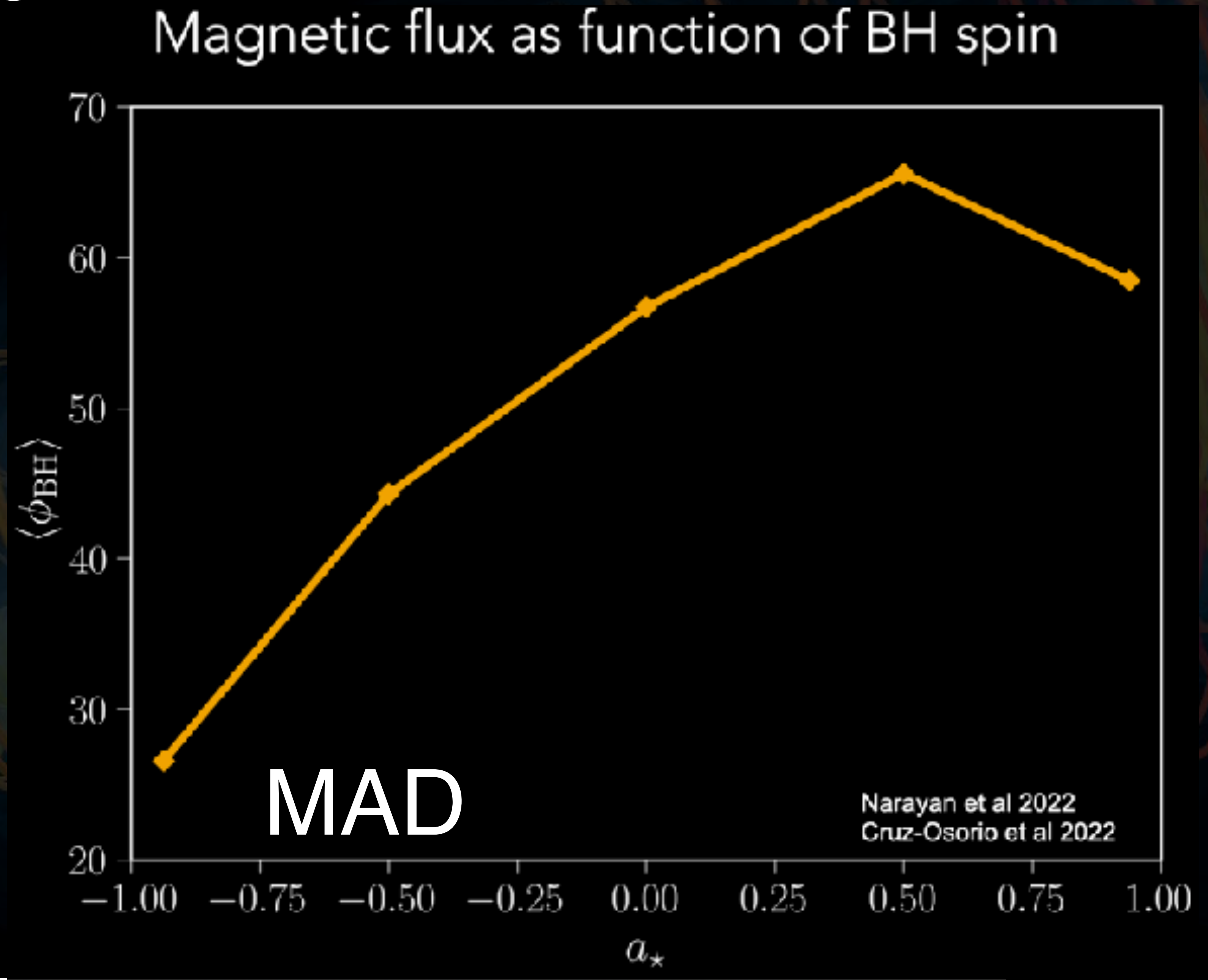
r_{inj} —> is the particle injection location

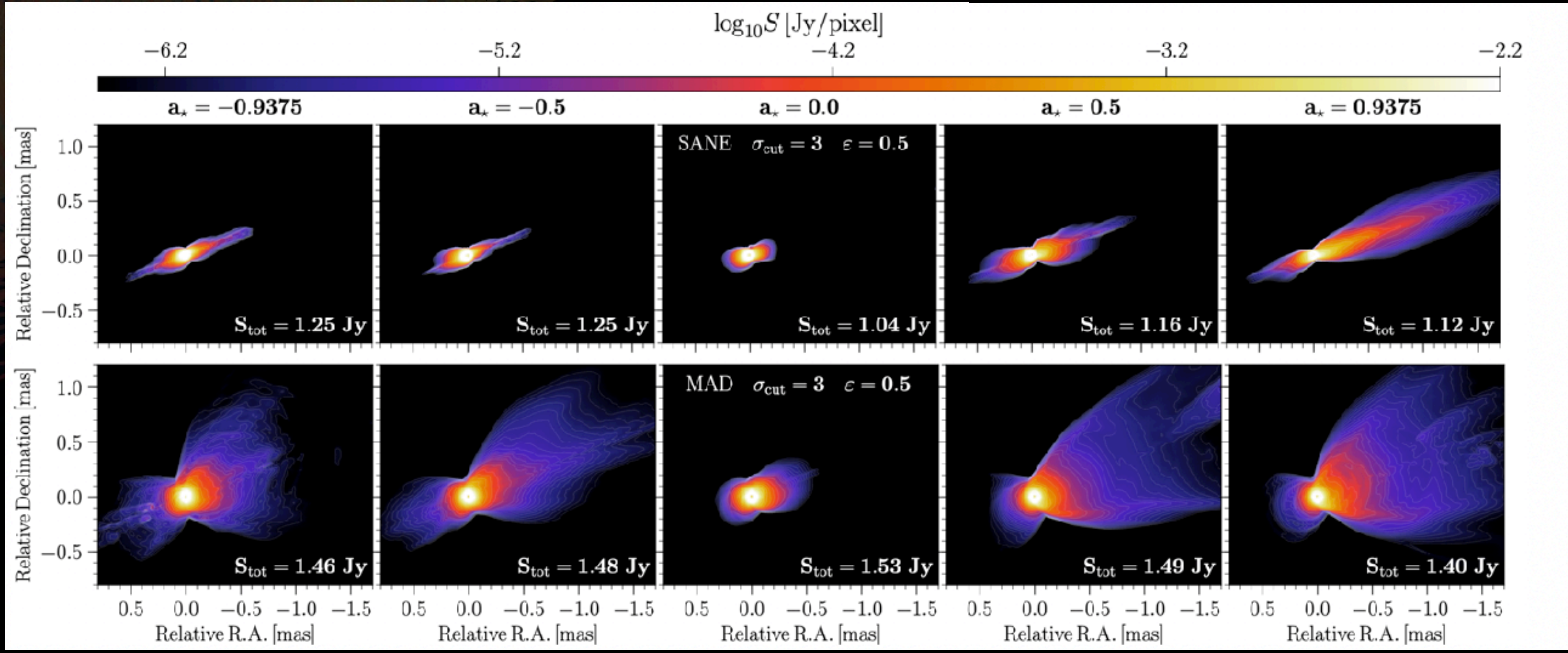
ε —> efficiency magnetic energy

Davelaar et.al. 2019, Ball et. al. 2018, Joonas Nättilä et. al. 2021,
Comisso & Sironi 2018, 2019, Rowan et al 2017, Werner et al 2018, Sironi et al 2016.

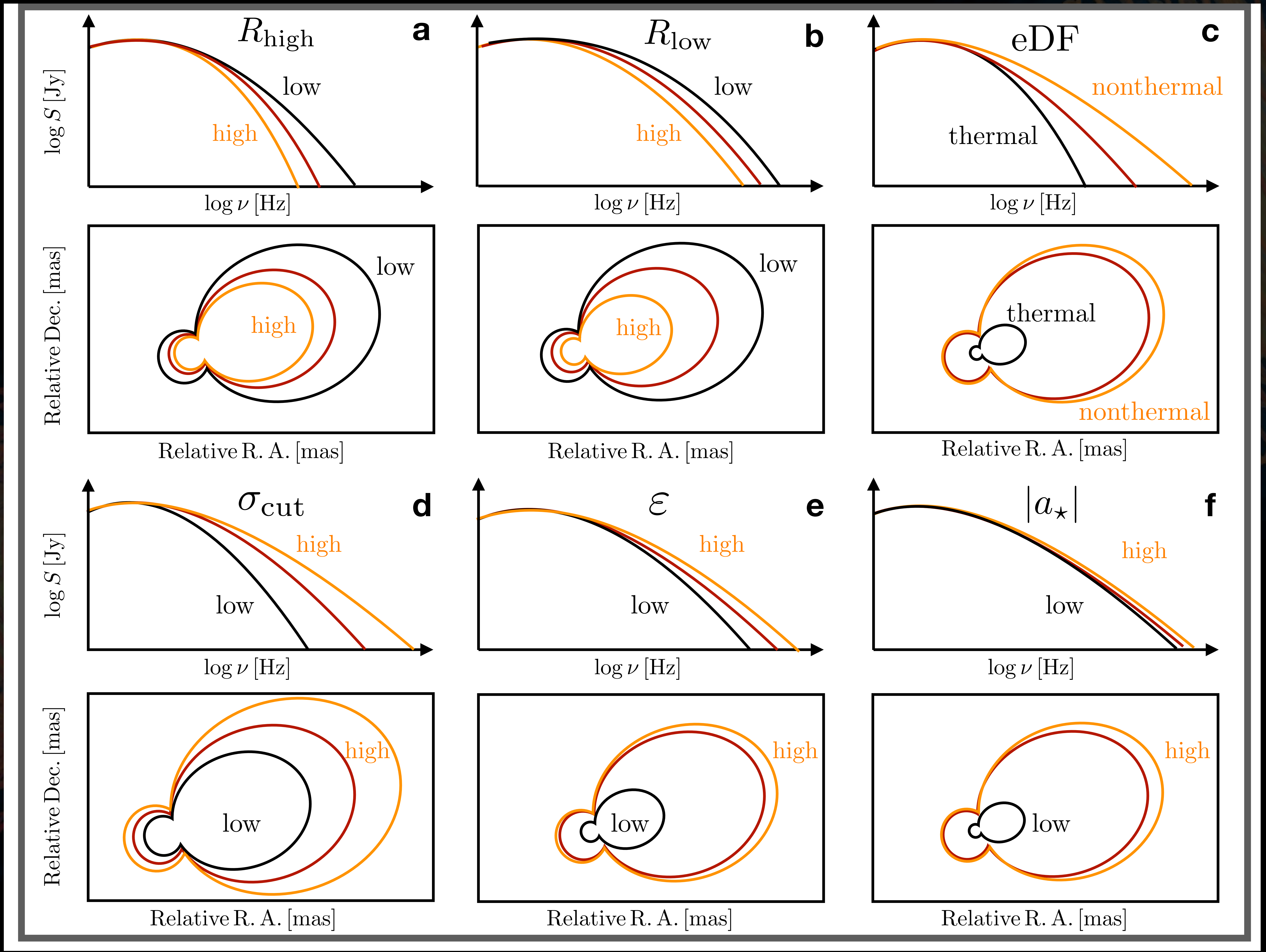
Blandford-Znajek jet launching mechanism







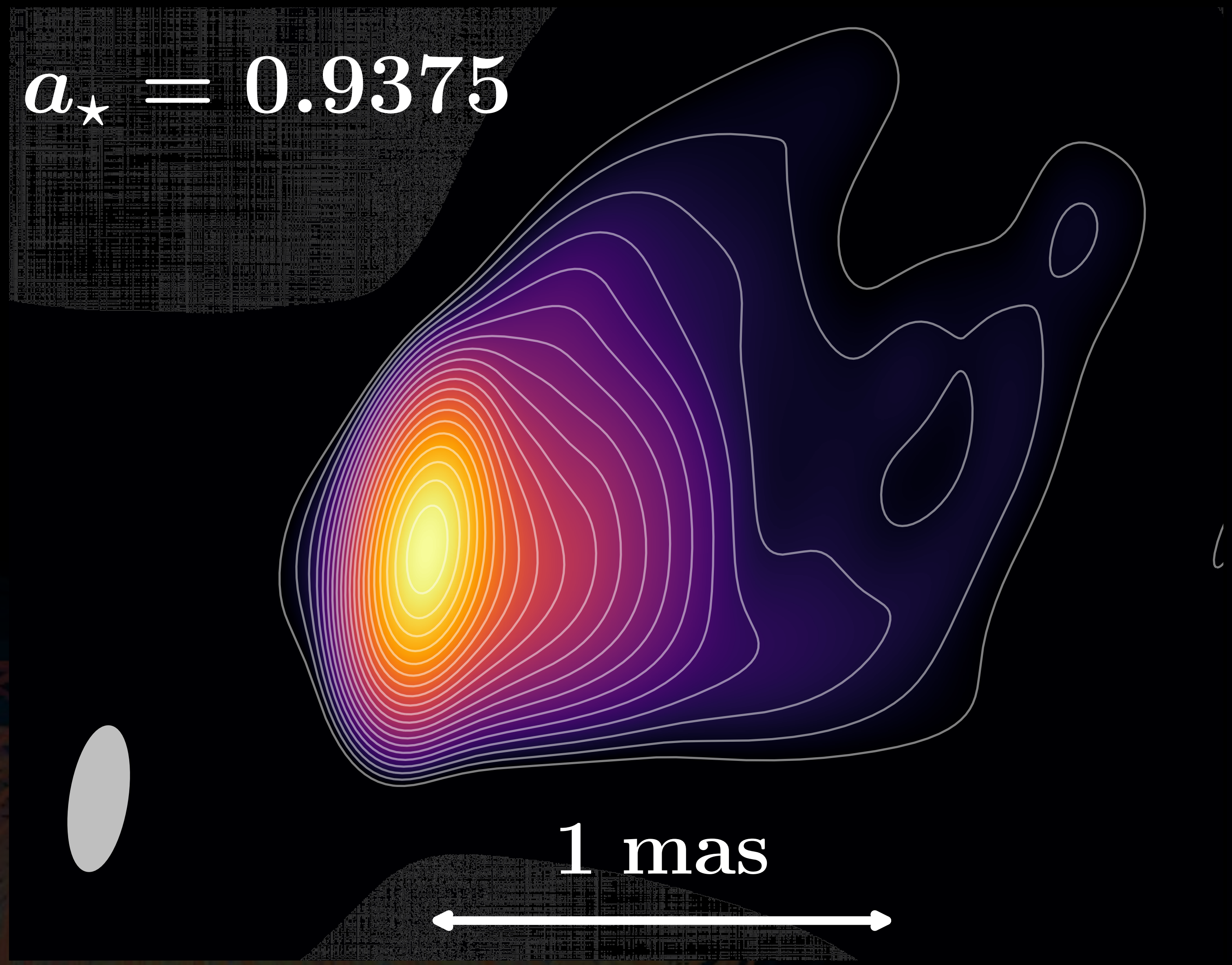
Impact of parameters on SED & jet morphology

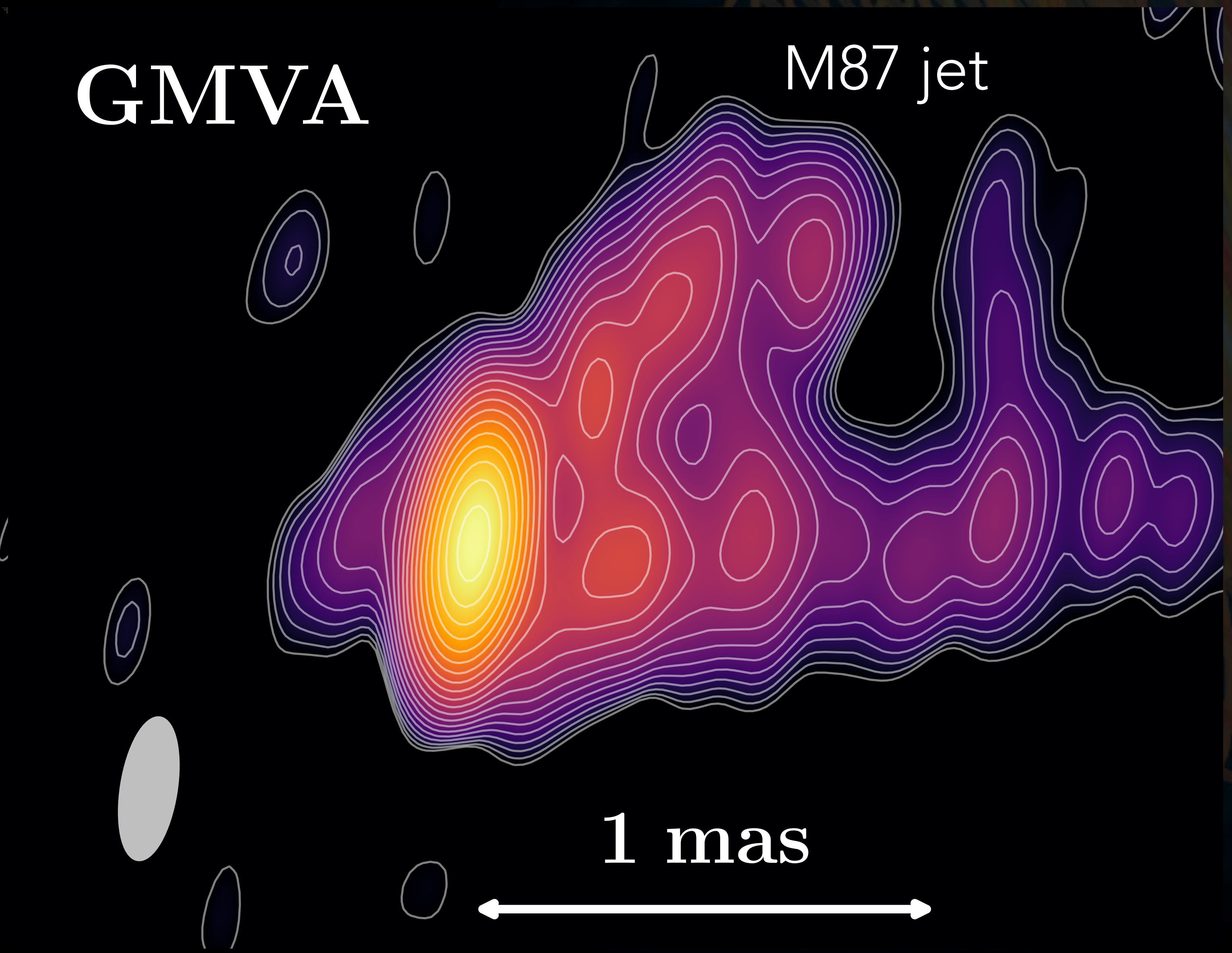


$$j_{\nu,\mathrm{tot}} \propto \exp\left(-R_{\mathrm{high}}^{2/3}\nu^{1/3}\right) + \nu^{-(\kappa-2)/2}\left[1/R_{\mathrm{high}} + \varepsilon\sigma\right]^{\kappa-2}$$

Christian M. Fromm, ACO, Yosuke Mizuno, Antonios Nathanail, Ziri Younsi, Oliver Porth, Hector Olivares, Jordy Davelaar, Heino Falcke, Michael Kramer, Luciano Rezzolla, Astronomy and Astrophysics **2022**

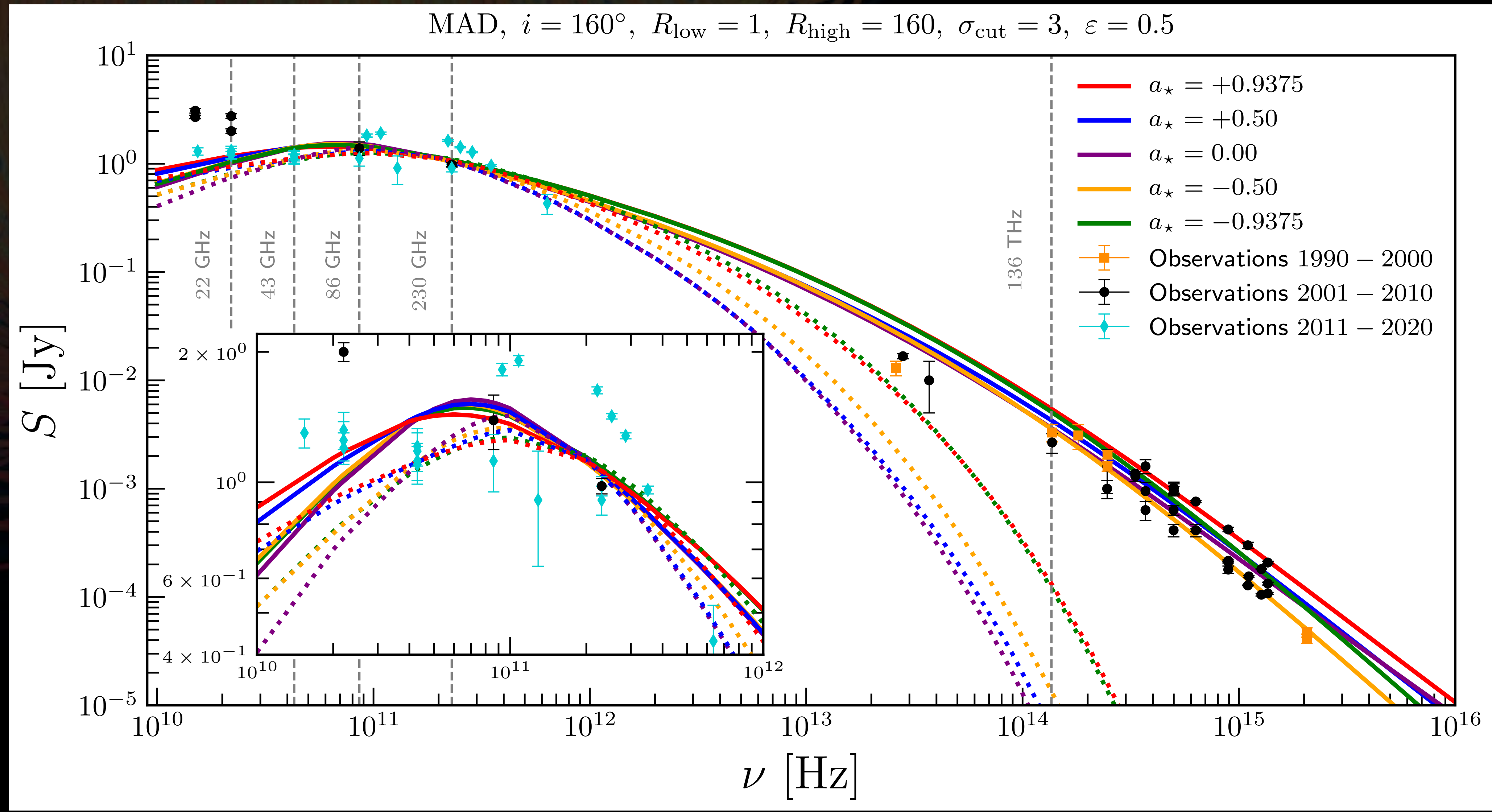
M87 jet morphology, jet width & SED

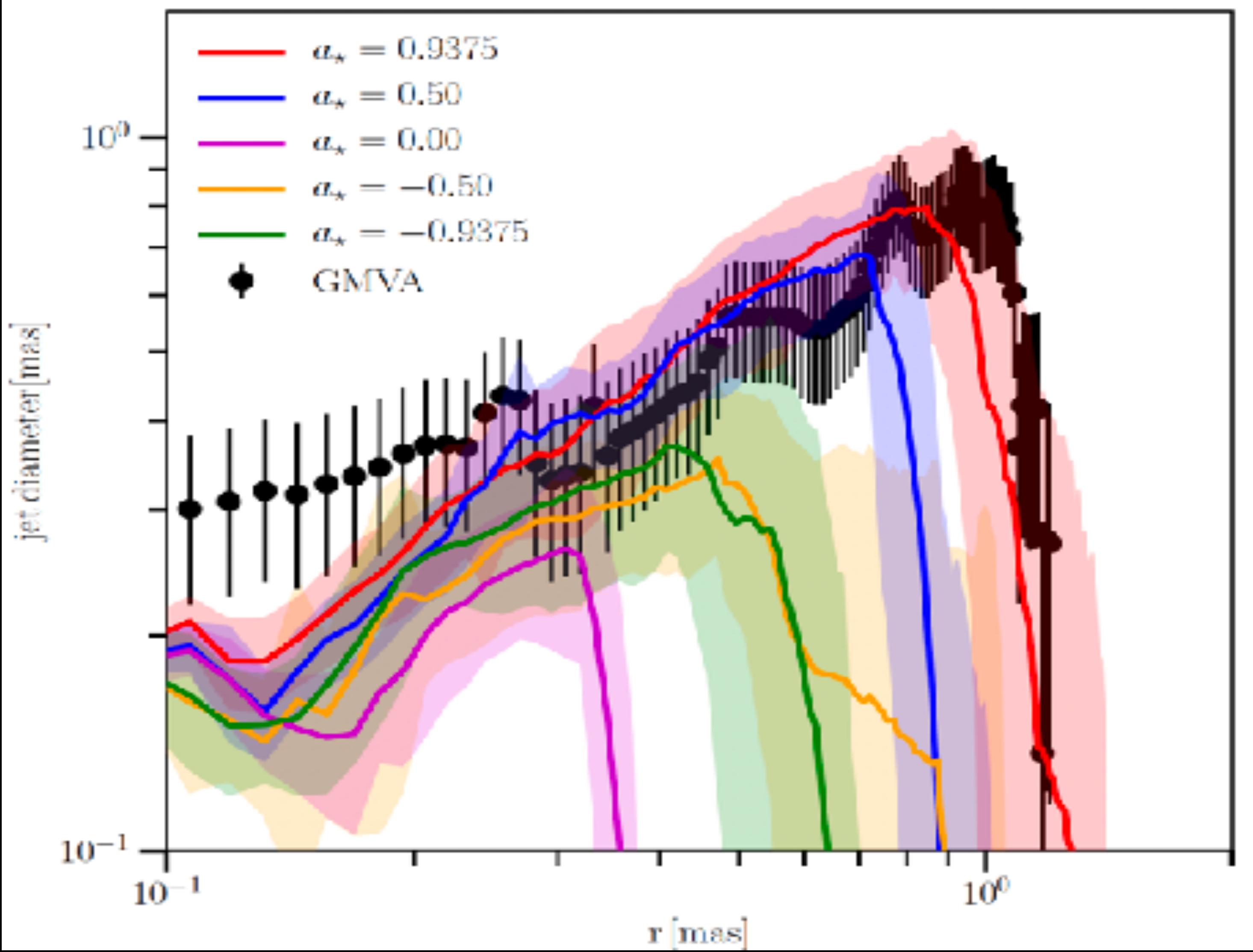




GMVA: Kim et. al. Astronomy & Astrophysics 616, A188 (2018).

Spectrum:
Doeleman et. al. 2012,
Akiyama et. al. 2015
Prieto et. al. 2016,
Kim et. al. 2018



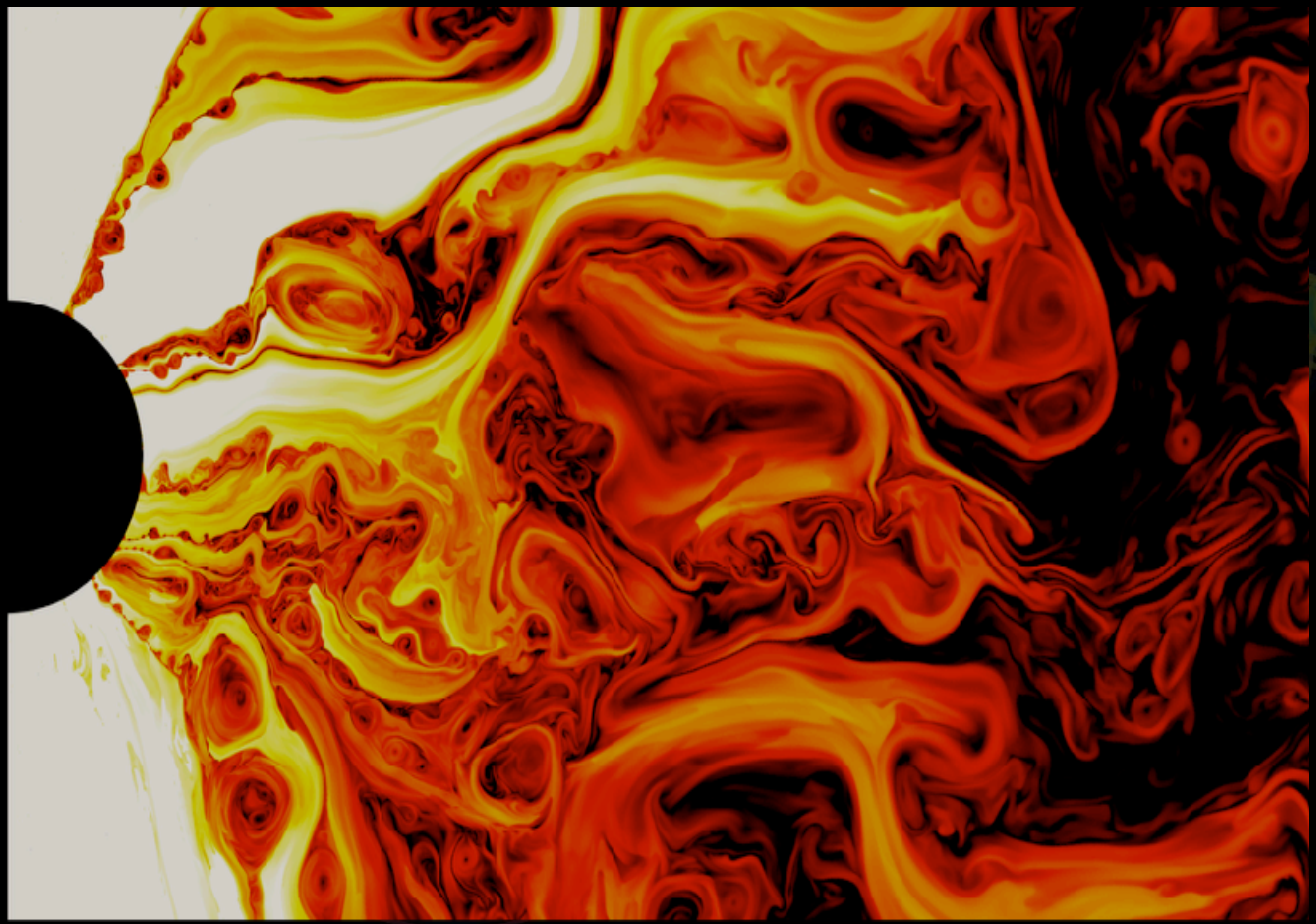


ACO, Christian M. Fromm, Yosuke Mizuno, Antonios Nathanail, Ziri Younsi, Oliver Porth, Jordy Davelaar, Heino Falcke, Michael Kramer, Luciano Rezzolla, Nature Astronomy **6**, pages 103–108 (2022)

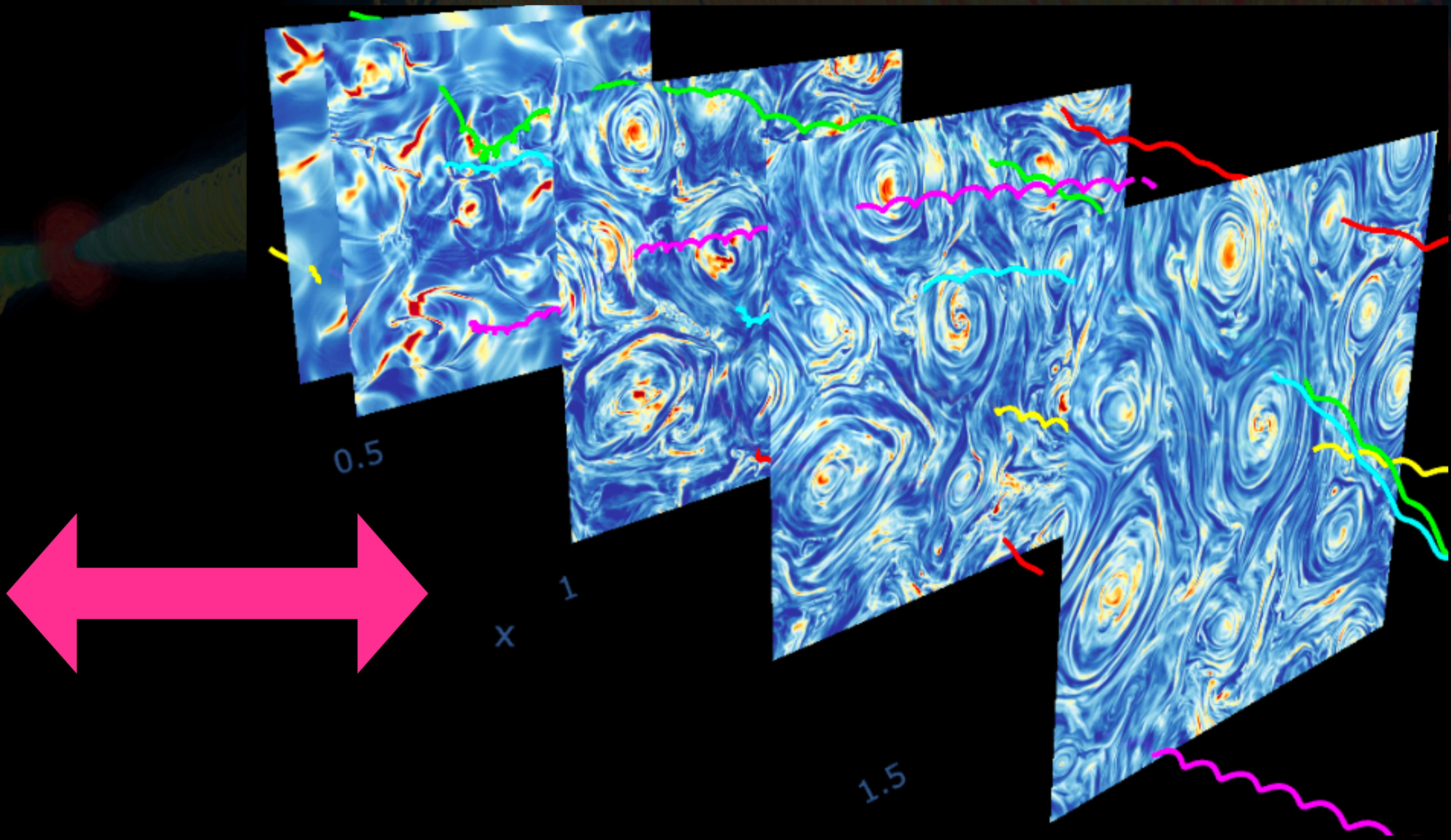
From Micro to Macro scales: Second Approach

Accretion onto a Black Hole

Turbulence (PIC simulations)

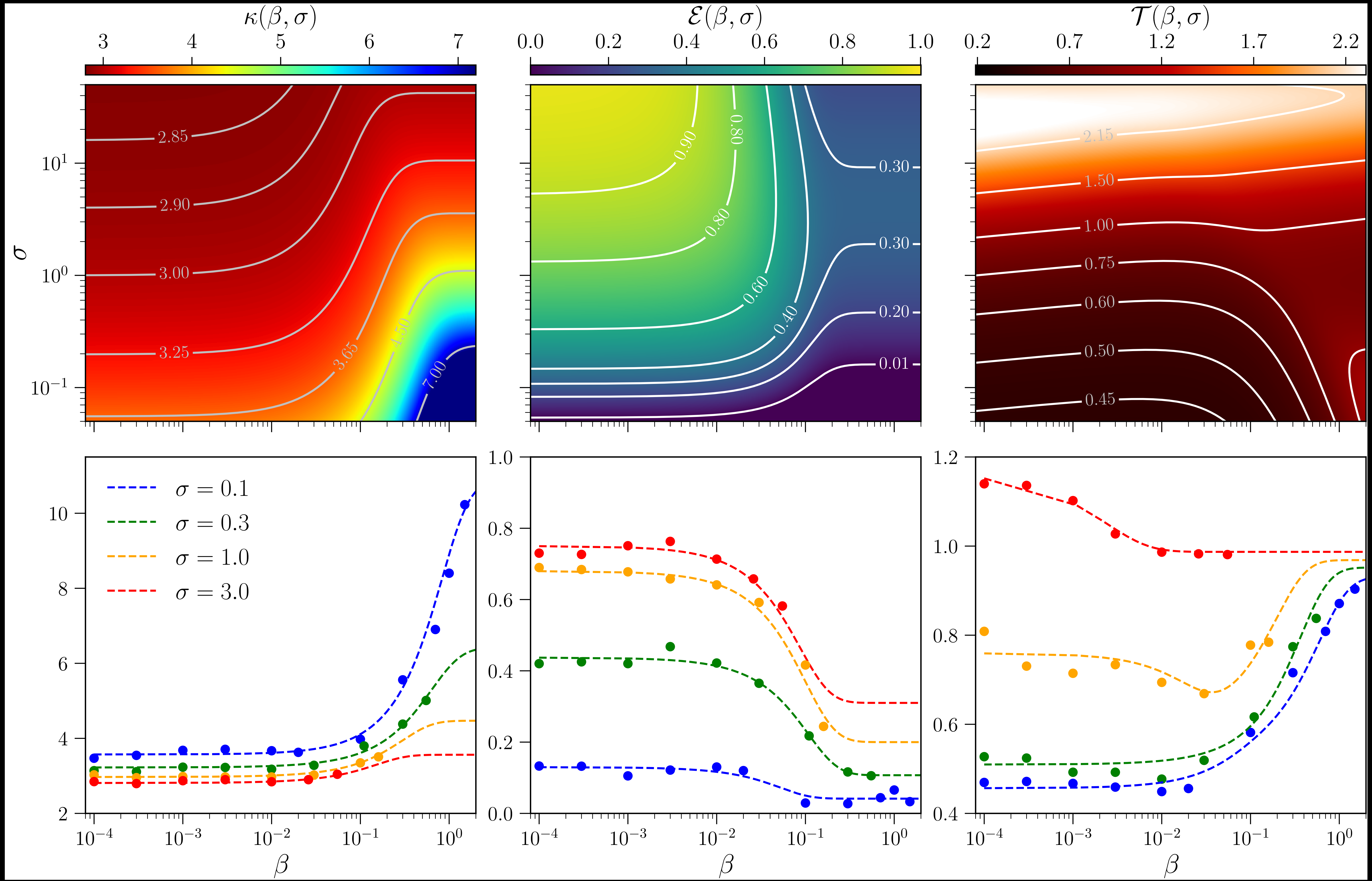


Bart Ripperda, Fabio Bacchini, Alexander A. Philippov *ApJ* **900** 100 (2020)



See Sergio Servidio's talk on Wednesday !

Power law, efficiency & electron-to-proton temperature from PIC turbulence simulations



Claudio Meringolo, Alejandro Cruz Osorio, Luciano Rezzolla, Sergio Servidio, ApJ (2023)

Non-thermal power-law

$$\kappa(\beta,\sigma) = k_0 + \frac{k_1}{\sqrt{\sigma}} + k_2\,\sigma^{-6/10}\tanh\left[k_3\,\beta\,\sigma^{1/3}\right]$$

Efficiency to generate non-thermal particles

$$\mathscr{E} := \frac{\int_{\gamma_0}^{\infty}\left[dN/d\gamma - f_{\rm MJ}(\gamma,\theta)\right](\gamma-1)\,d\gamma}{\int_{\gamma_0}^{\infty}(dN/d\gamma)(\gamma-1)\,d\gamma}$$

$$\mathscr{E}(\beta,\sigma) = e_0 + \frac{e_1}{\sqrt{\sigma}} + e_2\,\sigma^{1/10}\tanh\left[e_3\,\beta\,\sigma^{1/10}\right]$$

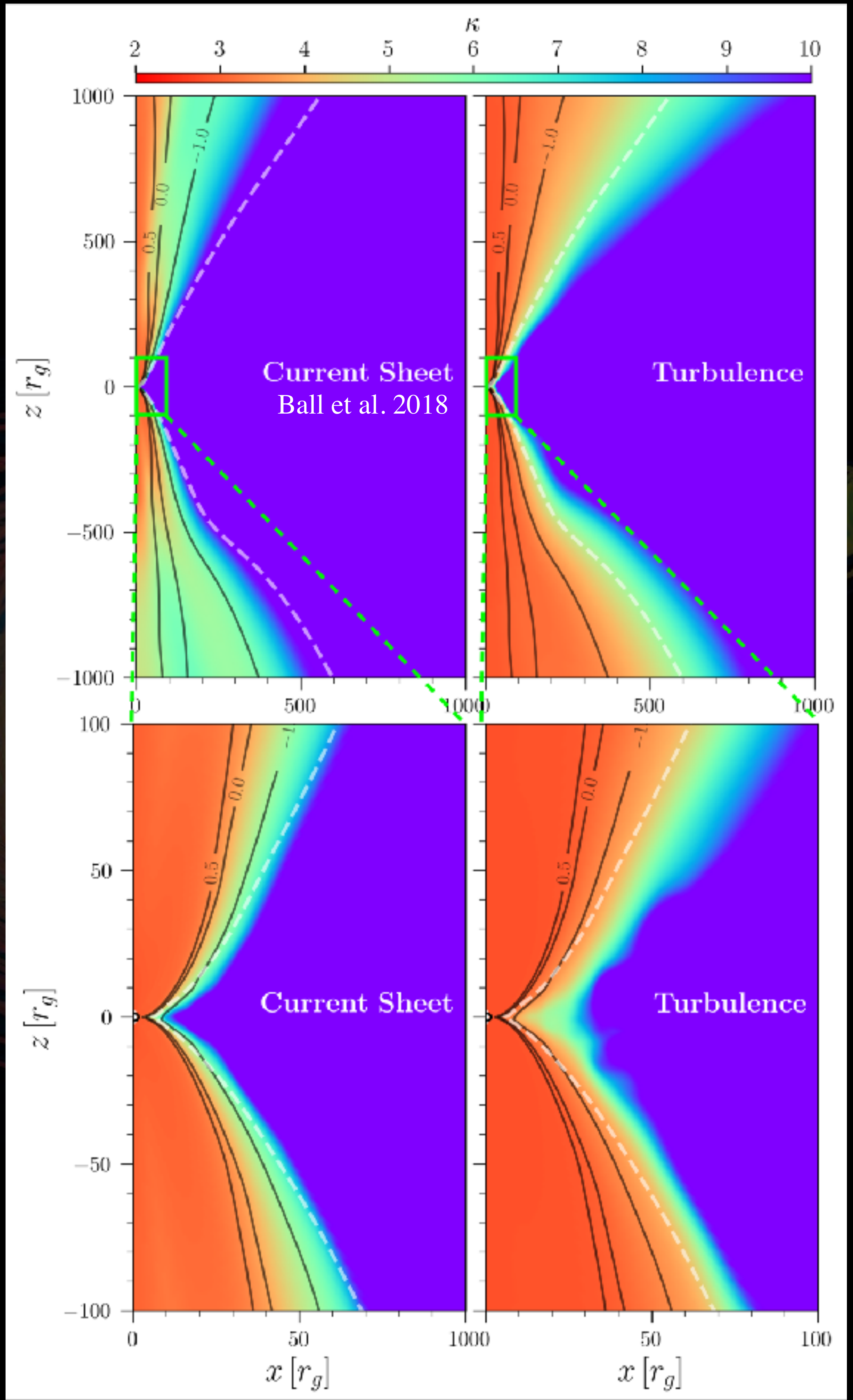
Electron-to-Proton temperature ratio

$$\mathscr{T}(\beta,\sigma) = t_0 + t_1\,\sigma^{\tau_1}\tanh\left[t_2\,\beta\,\sigma^{\tau_2}\right] + t_2\,\sigma^{\tau_3}\tanh\left[t_3\,\beta^{\tau_4}\,\sigma\right]$$

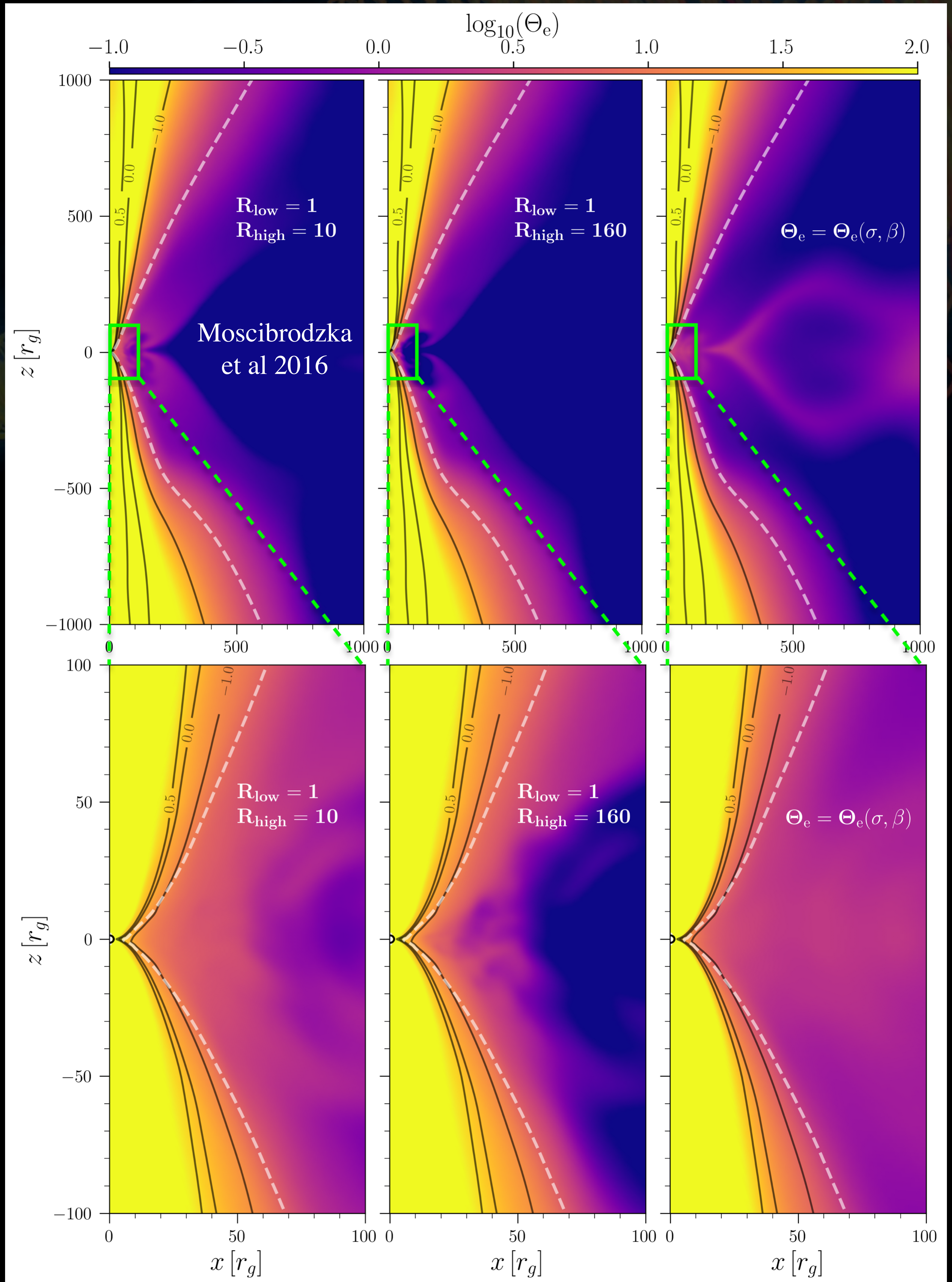
See Sergio Servidio's talk on Wednesday !

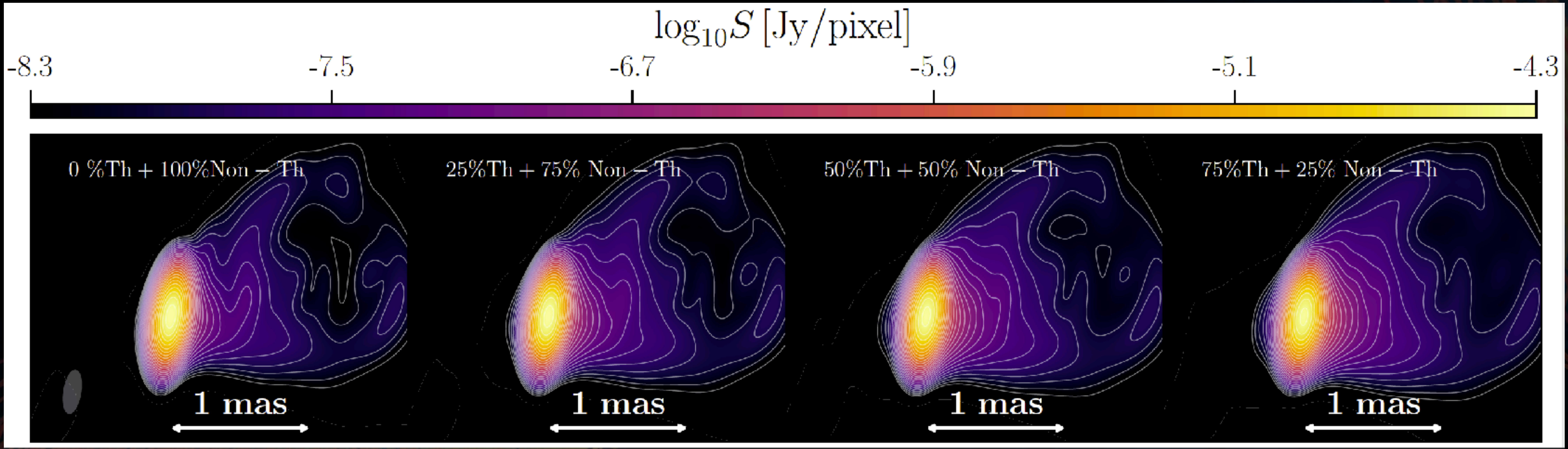
Connection to the GRMHD simulations …

Non-Thermal particle population



Electron temperature

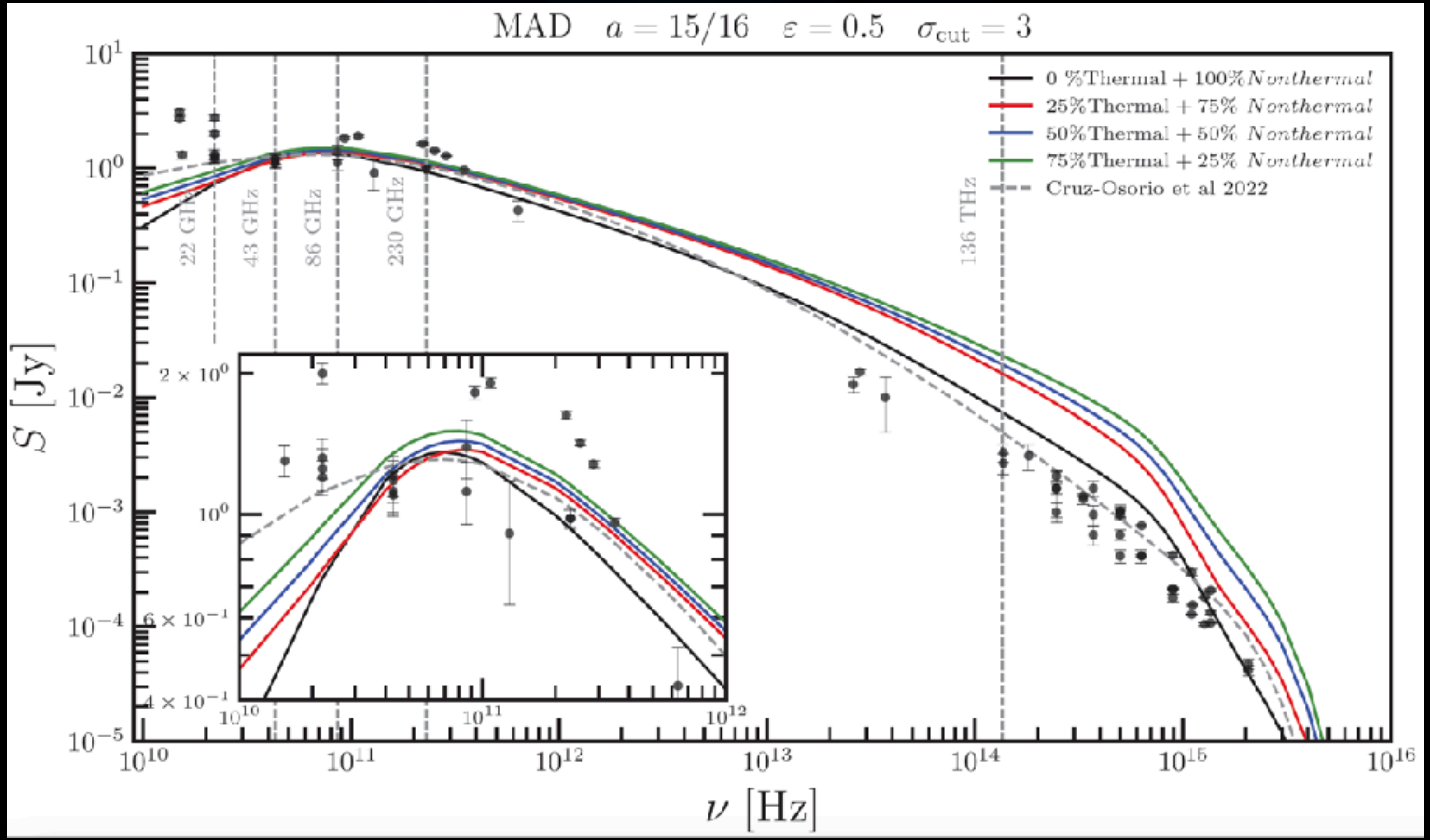




Mixed Thermal & Nonthermal emission

$$j_\nu = (1-\epsilon) j_{\nu,th} + \epsilon j_{\nu,Nonth}$$

$$\epsilon(\sigma,\beta) = \xi(1-e^{-\beta^{-2}})(1-e^{-\sigma^2/\sigma_{min}^2})$$



Final Comments:

- ✓ Two electron-to-proton temperature models: R-beta and Nonparametric from PIC simulations
- ✓ Presented a phenomenological model of jet limb brightening
- ✓ Comparison of 86GHz GMVA image and observed multifrequency spectrum
- ✓ Constrained model parameters
- ✓ We explored the effects of using mixed thermal & nonthermal emission

- Microphysical plasma relations are useful for modelling of Black Hole shadows and Relativistic Jets

GOETHE UNIVERSITÄT FRANKFURT AM MAIN
ITP Institute for Theoretical Physics
JETSET
Marie Skłodowska-Curie Actions
Event Horizon Telescope
erc
HORIZON EUROPE