Workshop: Kinetic physics of astrophysical plasmas

Multimessenger emissions from active galactic nuclei

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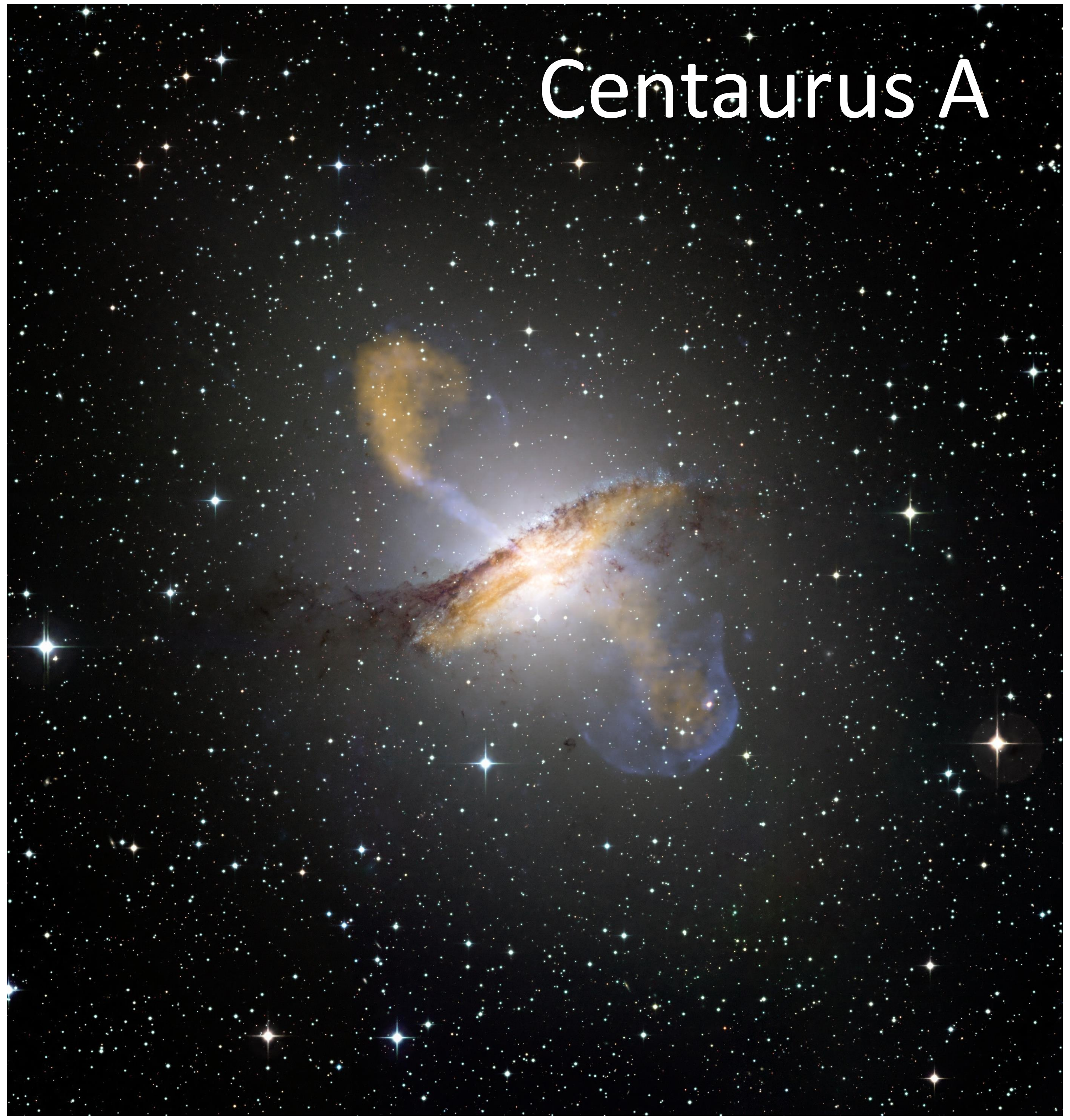
Active Galactic Nuclei

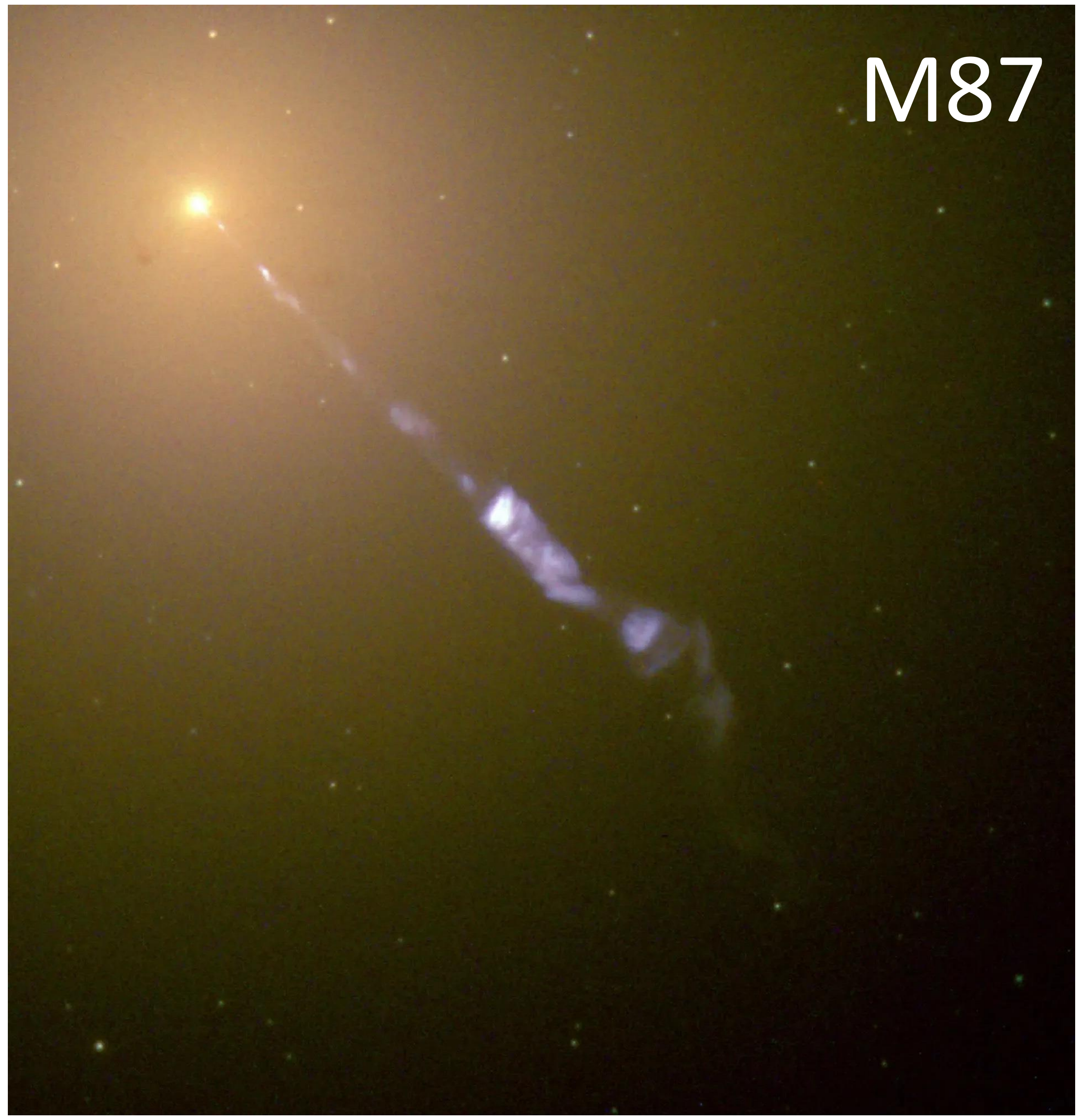
Jets from active galactic nuclei (AGN) are among the most energetic phenomena in the Universe and play a central role in regulating energy on galactic and intergalactic scales.

- Transport energy to the kpc scale, and influence their local environment.
- Transported energy is dissipated at different scales:
  - Parsec scales: standing knots, etc.
  - Kpc scales: mass entrainment, etc. (FRI).
  - Even farther: lobes (FRII).

See Blandford+19, Perucho 19, Hardcastle & Croston 2020 for reviews!



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



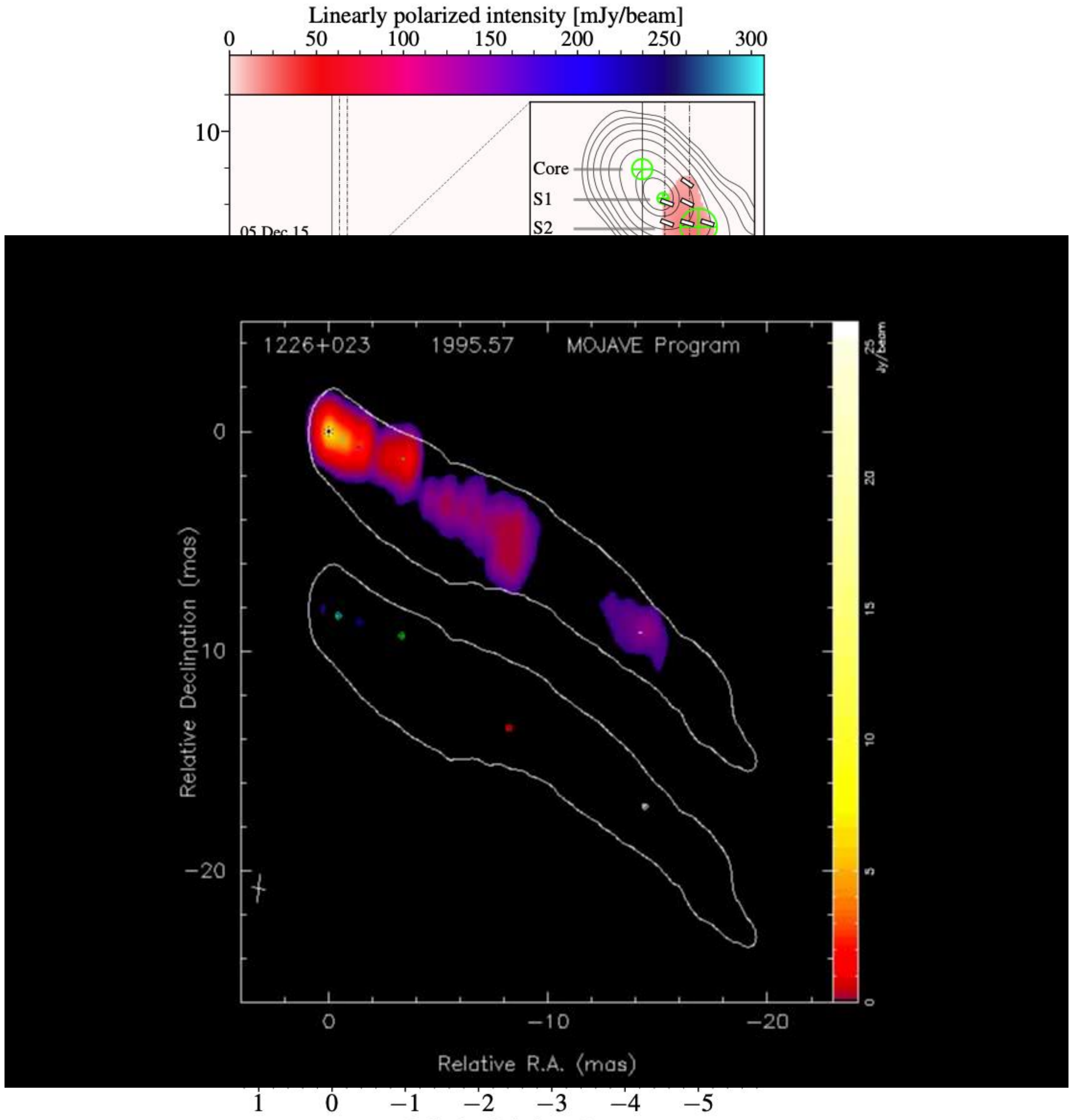
NASA and the Hubble Heritage Team (STScI/AURA)

What do we observe?

In radio band (VLBI), the jet appears as a stream of a relativistic & highly dynamical plasma.

What we know (Wehrle+ 16, Lister+19, 21, Kim+ 20):

- Doppler boosting (relativistic enhancement of the non-thermal emission from the jet)
- "Shock-shock" interactions (standing vs. moving radio knots - interpreted as shocks).
- Correlation between radio activity and jet dynamics



MOJAVE program - OVRO 15 GHz (Lister+19)

VLBA images of 3C 273 during the 2016 outburst with total and linearly polarized radio intensity (Kim+20).

What do we observe?

High-energy band:

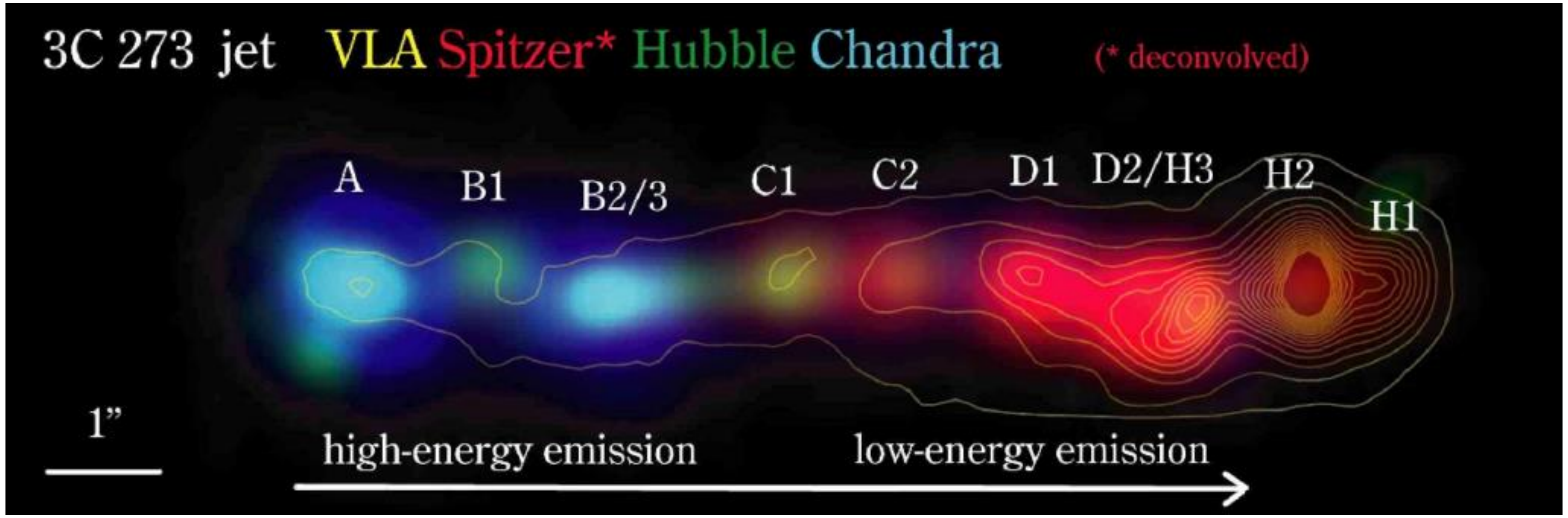
At high frequencies, both standing and moving emission regions can be spatially resolved in nearby sources, allowing direct tracing of jet substructure (Harris & Krawczynski 06)

Wavelength-dependent variability:

Variability timescales strongly depend on the observing band, reflecting the size and location of the emission region:

- **Radio band:** typically shows variability on timescales from months to years, associated with larger-scale jet structures (Kankkunen, Tornikoski & Hovatta 2026)
- **Gamma-ray band:** can exhibit variability down to hours or even minutes, indicating compact emission regions close to the central engine (Aharonian+07 , Ackermann+16)

See Böttcher+19, Hovatta & Lindfors 19 for reviews!



Combined images of 3C 273 (see legend) (Uchiyama+06).

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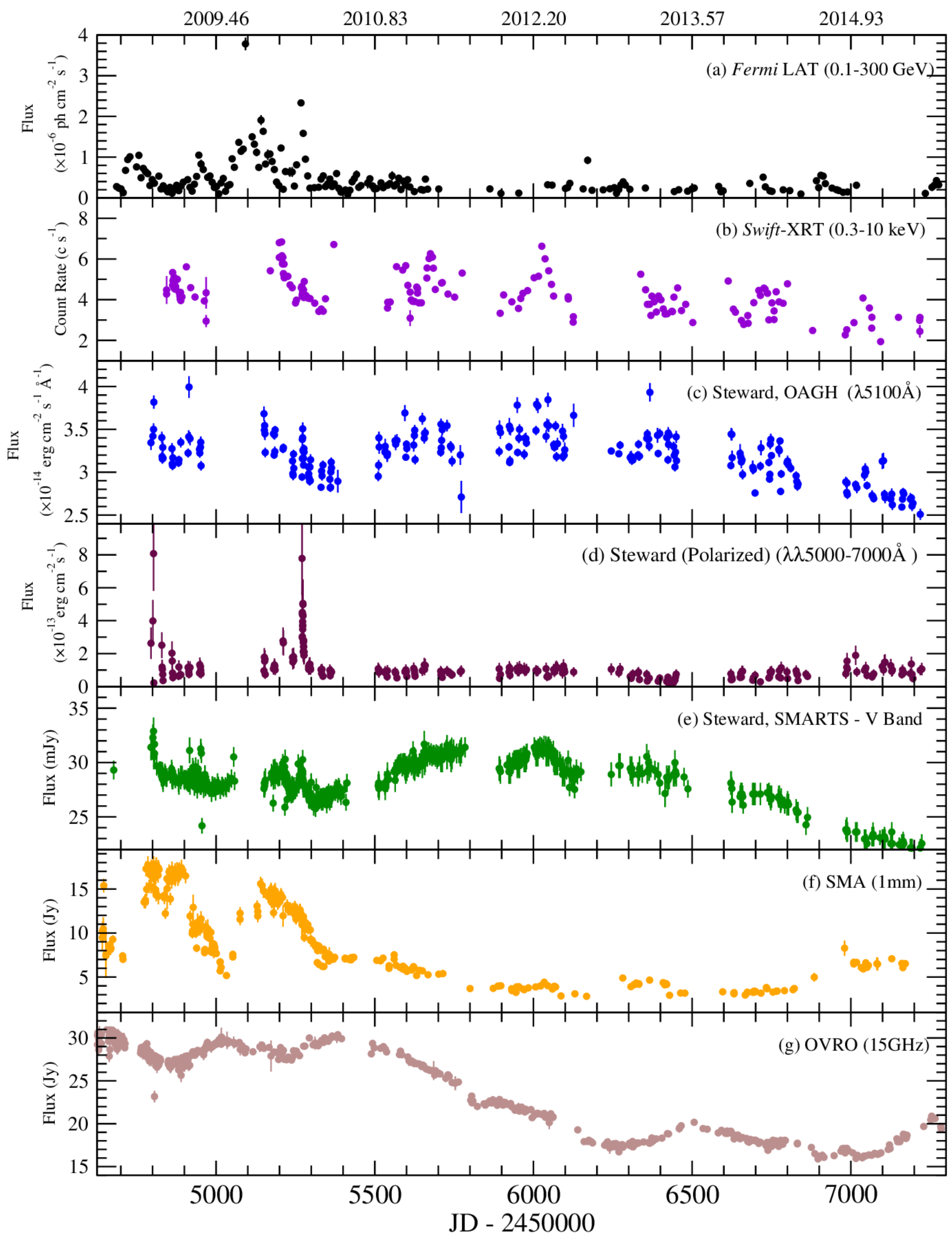


Multi-wavelength light curves (see legend) of 3C 273 (Fernandes+20).

Jet as accelerators

High energy emissions imply high energy particles!

Particles needs to be accelerated (and re-accelerated) along the jets.

Diffusive shock acceleration (DSA)

Particles are accelerated at relativistic shocks via repeated shock crossings and scattering on magnetic turbulence.

Its efficiency depends on magnetic field geometry, turbulence level, and particle confinement, setting the maximum energy.

See: Blandford & Ostriker 1978, Marcowith+20

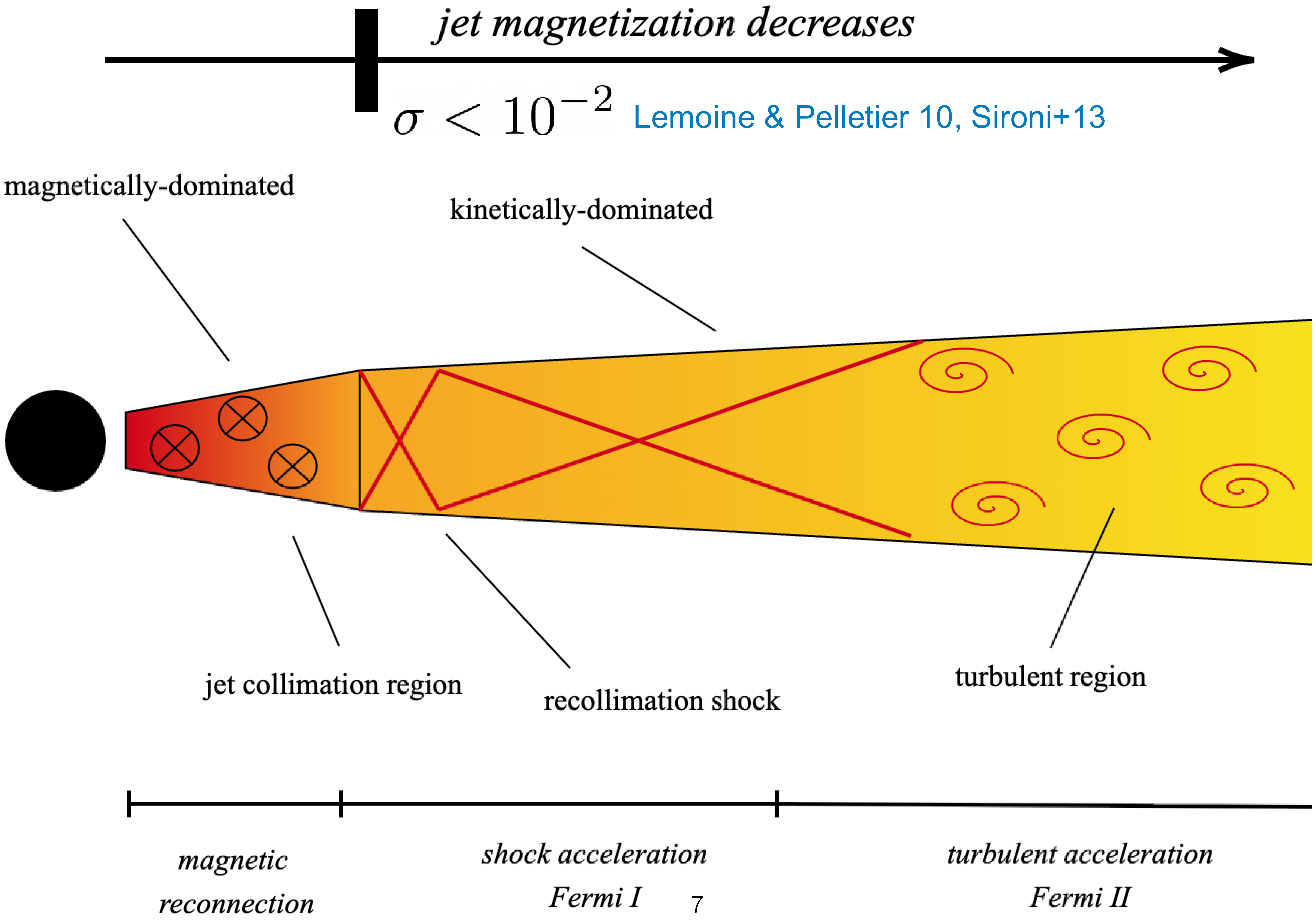
Magnetic reconnection

Particles are accelerated in current sheets where oppositely directed magnetic fields reconnect and release energy explosively.

It is efficient in highly magnetized (Poynting-flux dominated) regions and can produce rapid, localized particle energization.

See: Kagan+15, Comisso & Sironi 19, 22

Jet as accelerators



Composition of jet

$$e^{\pm} + \vec{B} \Rightarrow \Phi_{\rm syn} \qquad \Phi_{\rm syn} + e^{\pm} \Rightarrow \Phi_{\rm SSC}$$

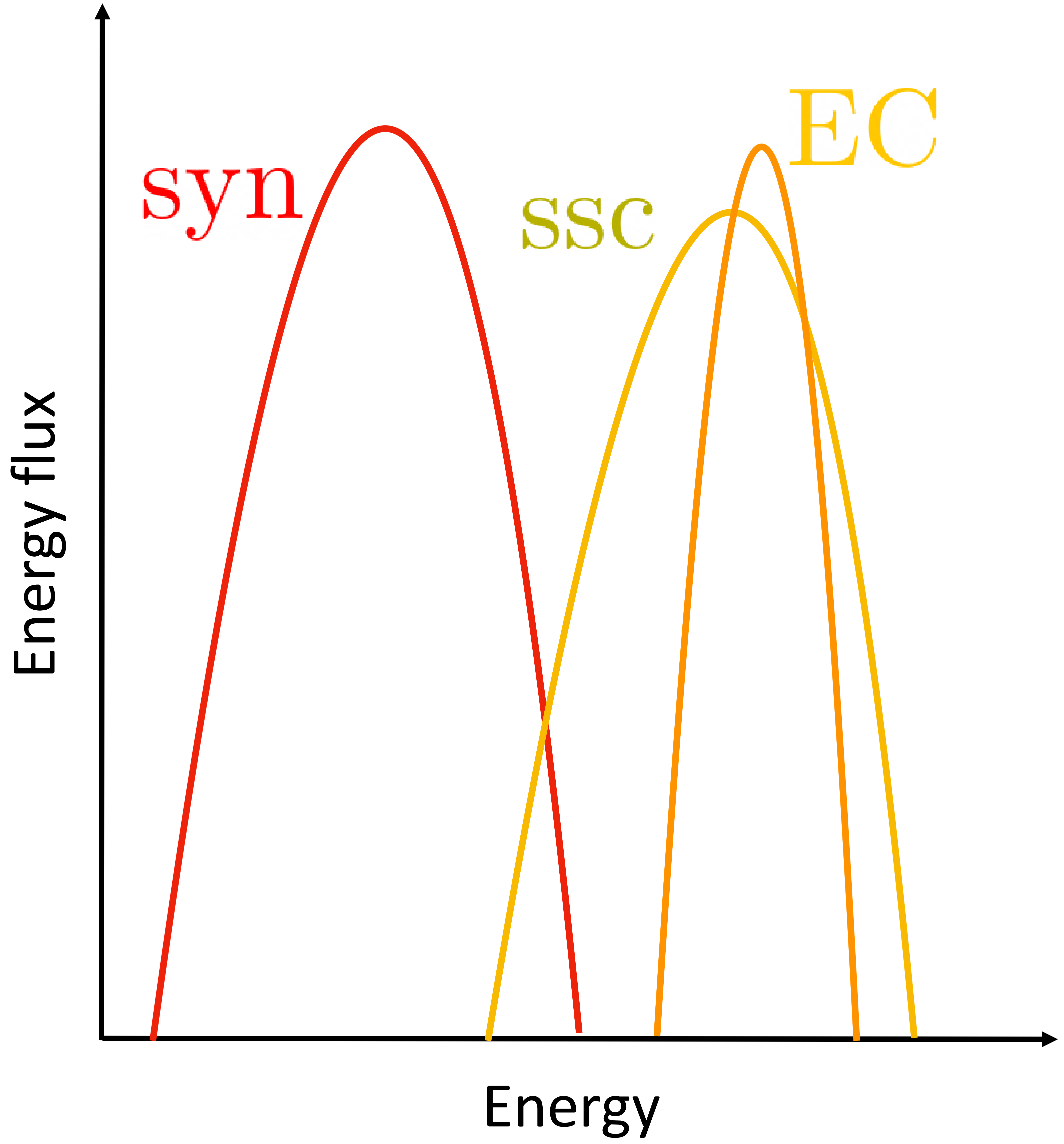
$$\Phi_{\rm ext} + e^{\pm} \Rightarrow \Phi_{\rm EC}$$

Leptons (electrons/positrons):

- **Firmly established in AGN jets**; produce non-thermal emission via synchrotron and inverse Compton (Ghisellini 10); naturally injected in electromagnetic jet-launching scenarios such as Blandford–Znajek (Blandford & Znajek 77)

Hadrons (protons):

- Presence remains uncertain; may be **cold** (dynamically important but radiatively inefficient) or **relativistic** (contributing to high-energy emission) (Sikora & Madejski 00; Celotti & Ghisellini 08)
- Possible origins: baryon loading from accretion disk winds (Blandford & Payne 82), entrainment via Kelvin–Helmholtz instabilities (Perucho+05), cumulative mass loading from jet–star interactions (Bosch-Ramon+12; Wykes+15, Fichet DC+26)



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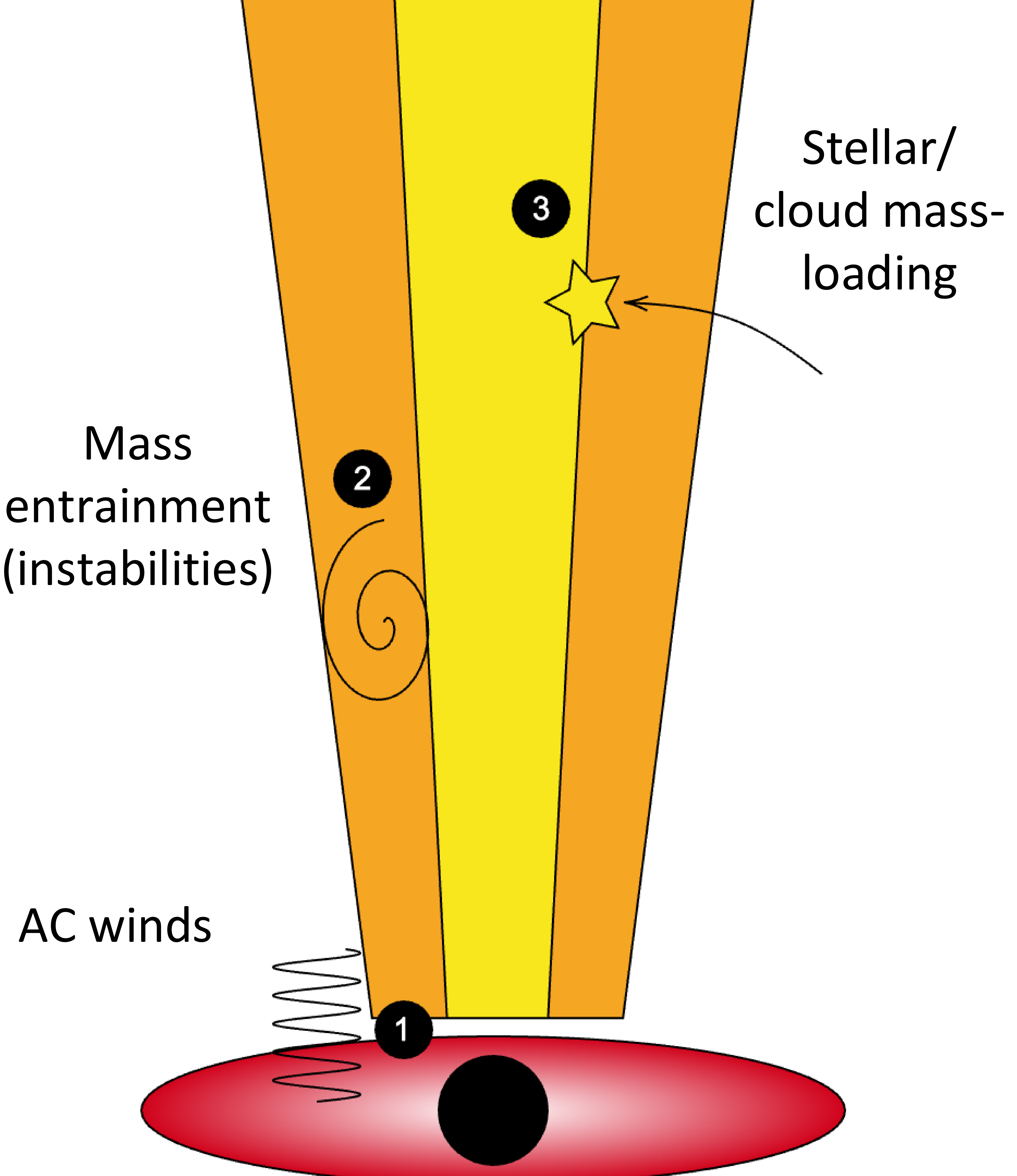


Neutrino detections?

p–γ: interactions with ambient photon fields; efficient in compact, radiation-rich regions; typically higher-energy neutrinos (Mannheim 93, Mücke+00, Kelner & Aharonian 08)

p–p: collisions with ambient matter; dominant in denser environments; generally more calorimetric (Kelner, Aharonian & Bugayov 06)

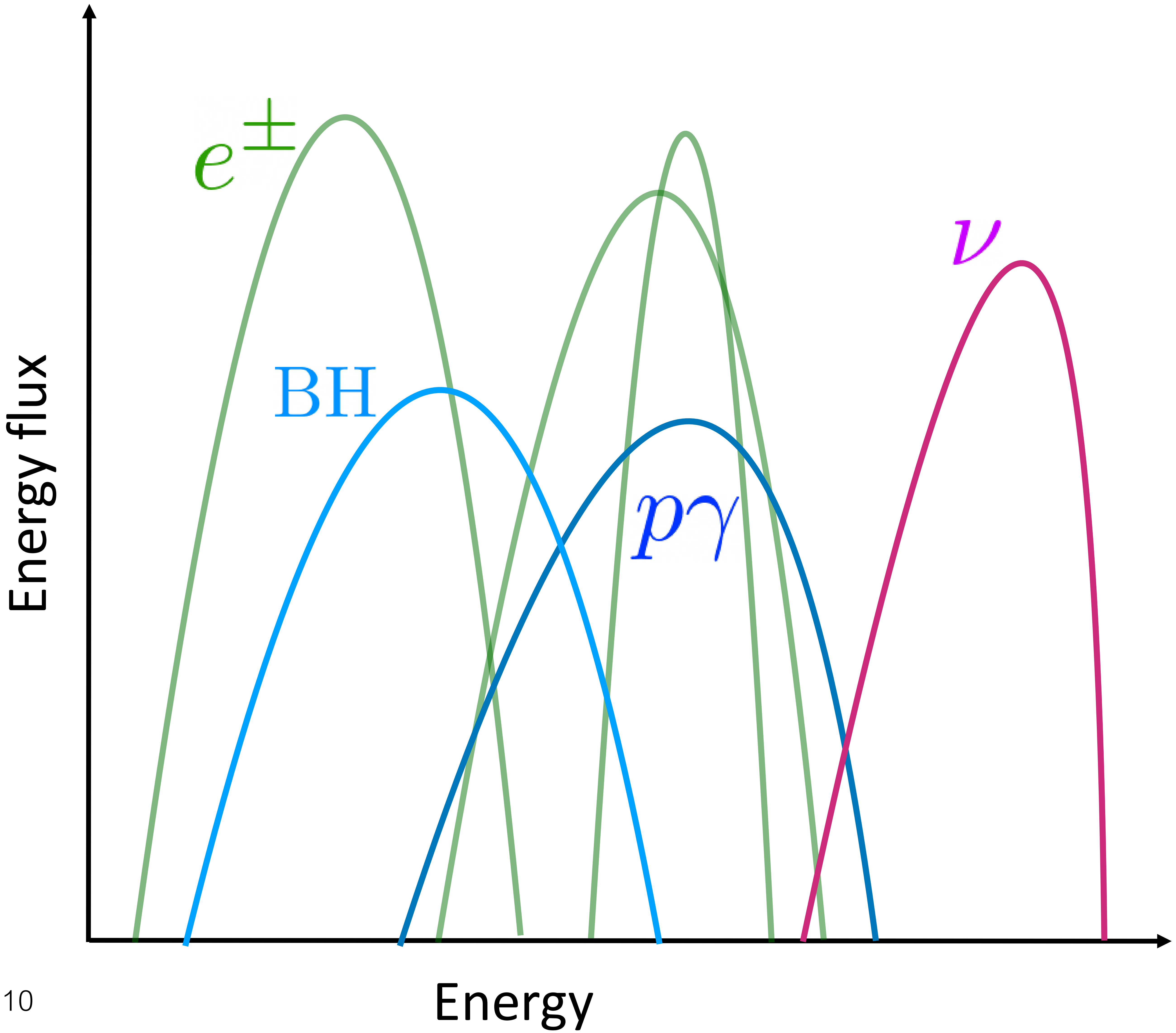
→ Both channels produce TeV–PeV neutrinos via pion decay (Murase & Stecker 23)

Neutrino observatories: IceCube (Aartsen+17) and KM3NeT (Adrián-Martínez+16): detect Cherenkov light from secondary charged particles in ice/water; reconstruct direction and energy from light patterns

$$p + \Phi_{\rm syn} + \Phi_{\rm ext} \Rightarrow \Phi_{{\rm syn},p\gamma} + \nu_\mu + \bar{\nu}_\mu + \nu_{\rm e} + \bar{\nu}_{\rm e}$$

$$p + \Phi_{\rm syn} + \Phi_{\rm ext} \Rightarrow \Phi_{\rm syn,BH}$$

$\Phi_{\rm e^\pm}$



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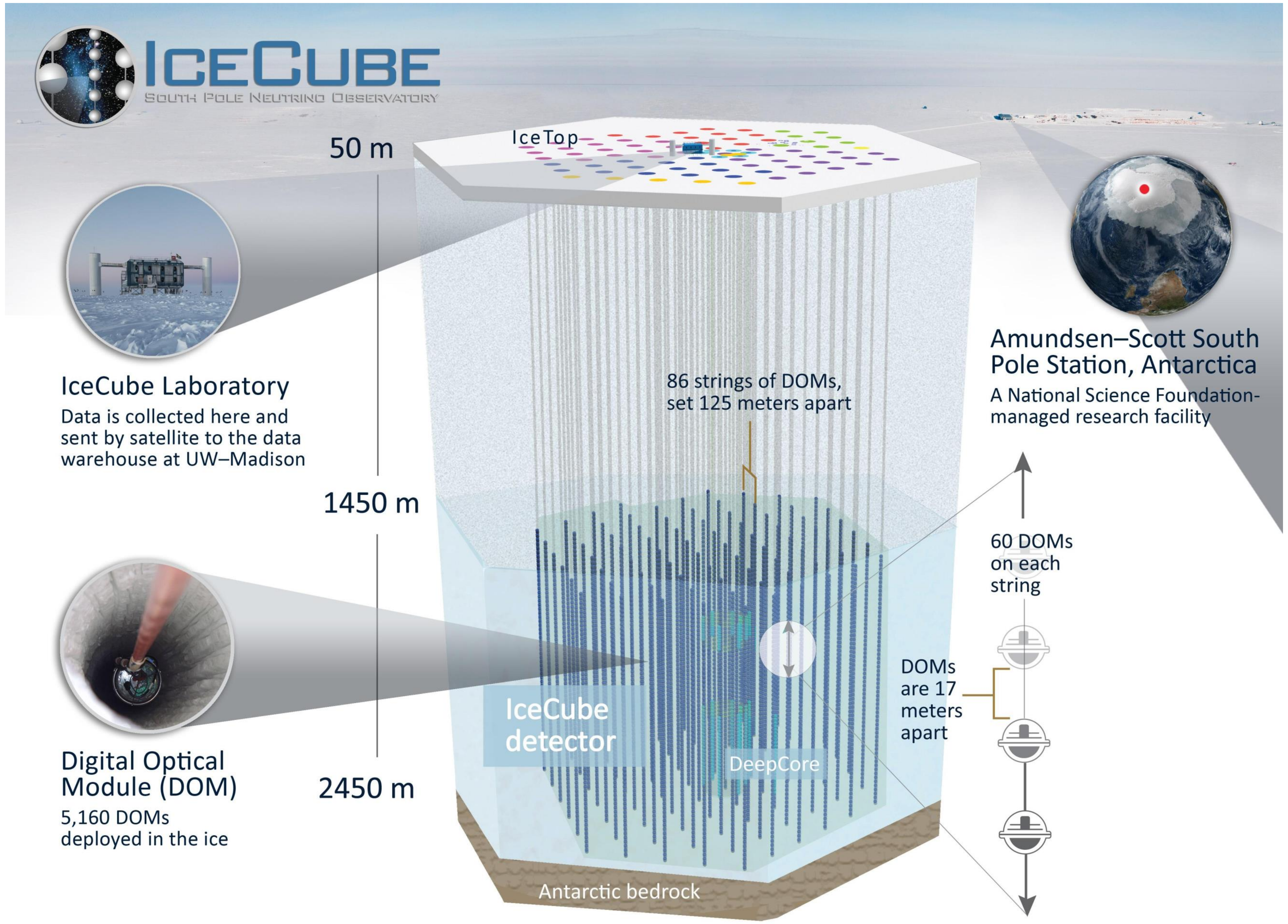


IceCube - University of Wisconsin-Madion

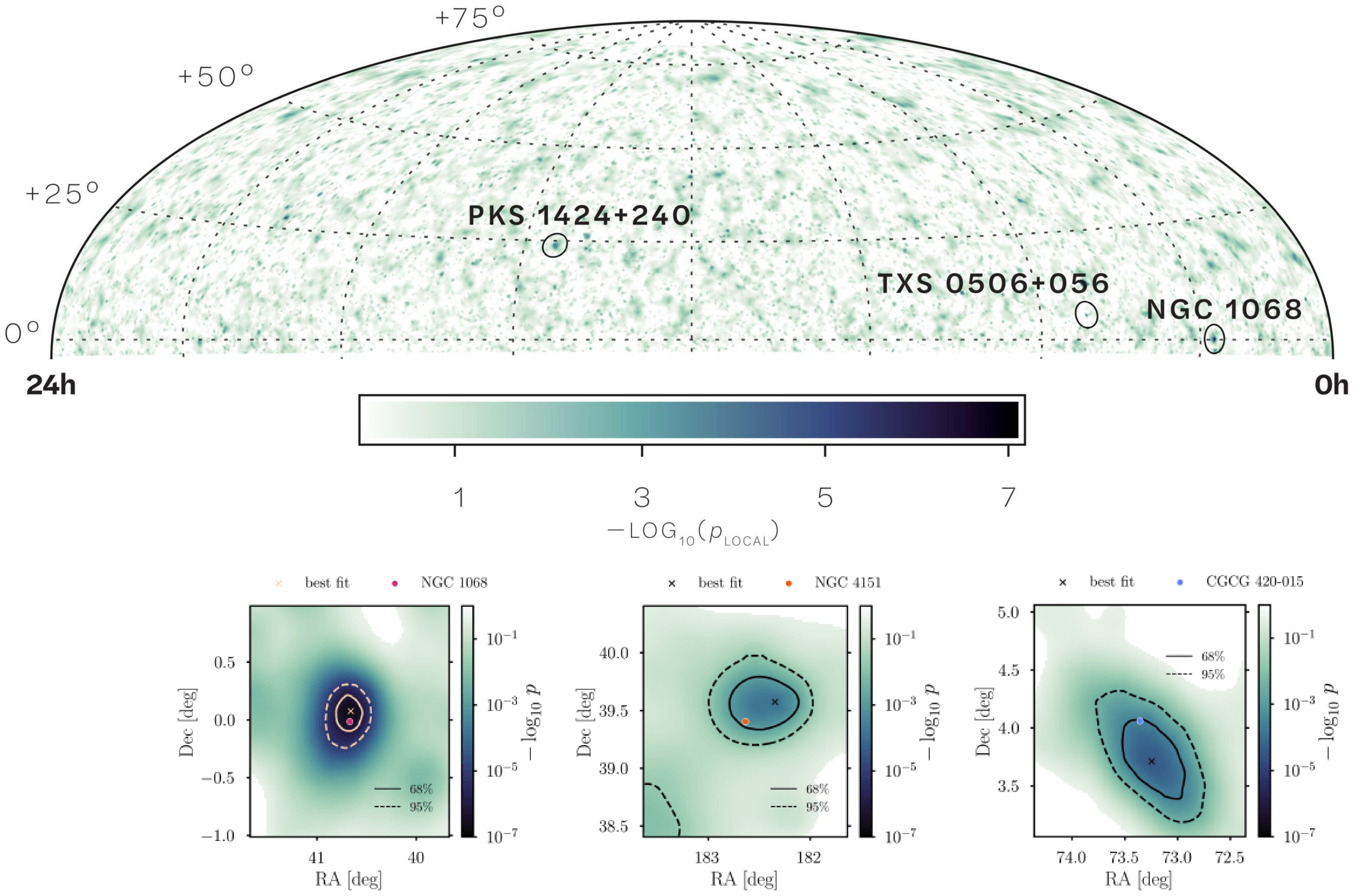
Neutrino detections?

Current status (diffuse flux)

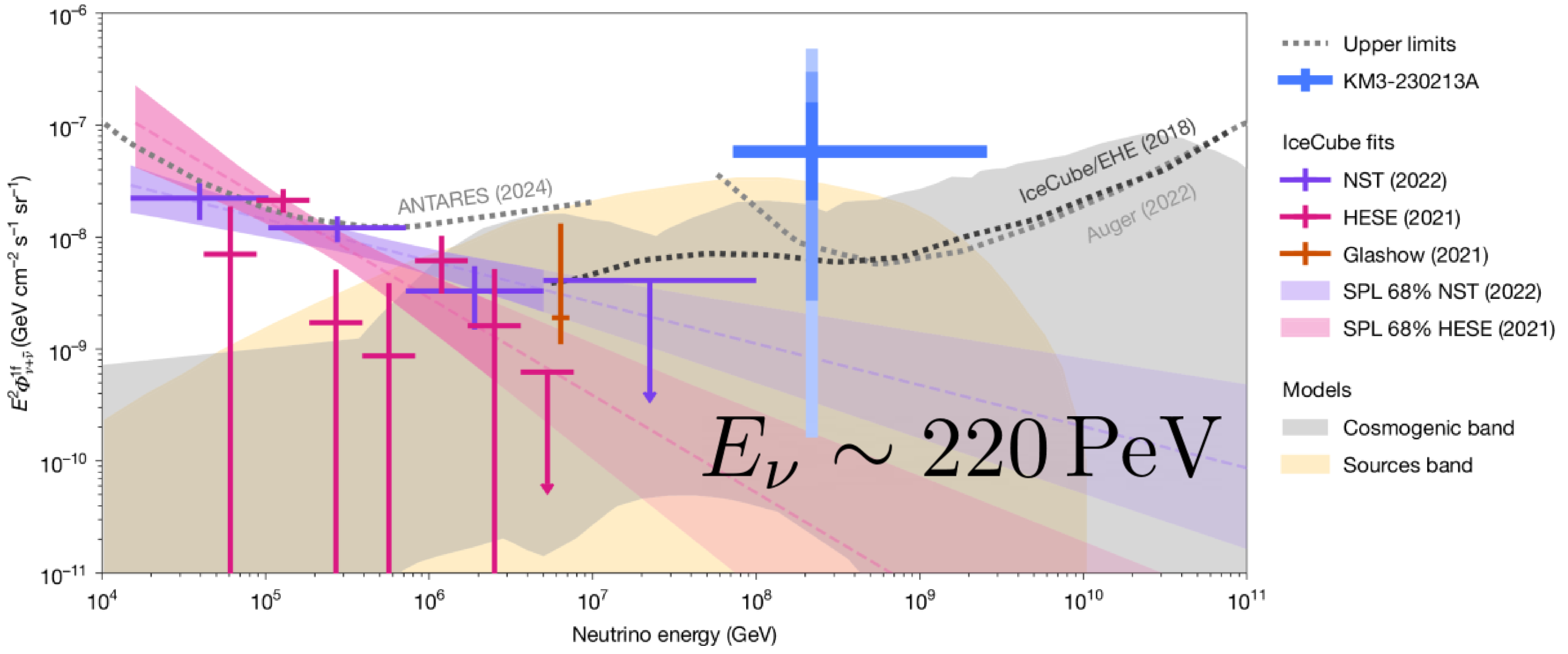
- The astrophysical neutrino flux has been established at >6σ significance (IceCube Collaboration+13), but its origin remains largely unknown — evidence exists only for a handful of individual sources (TXS 0506+056, NGC 1068, Galactic Plane) (IceCube Collaboration+18, 22, 23, 25)

Individual-source searches

- Beyond TXS 0506+056 (3σ) and NGC 1068 (4.2σ), only sub-threshold hints exist: PKS 1424+240 (3.3σ, Abbasi+22; Padovani+22) and PKS 0735+178 coincident with IceCube-211208A during its brightest multi-wavelength flare, corroborated by Baikal, Baksan and KM3NeT (Sahakyan+23)



IceCube Collaboration+24

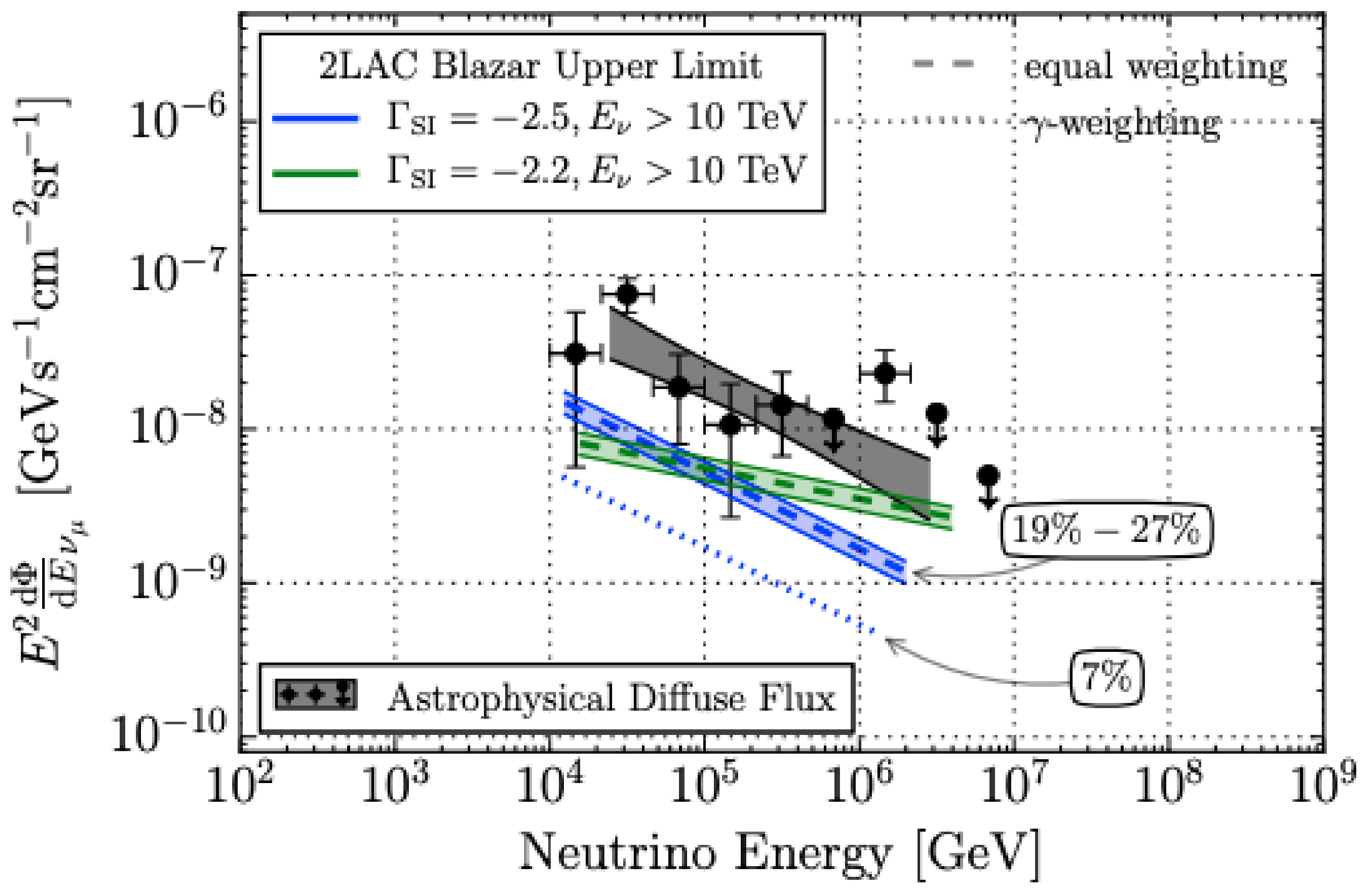


KM3Net Collaboration+25

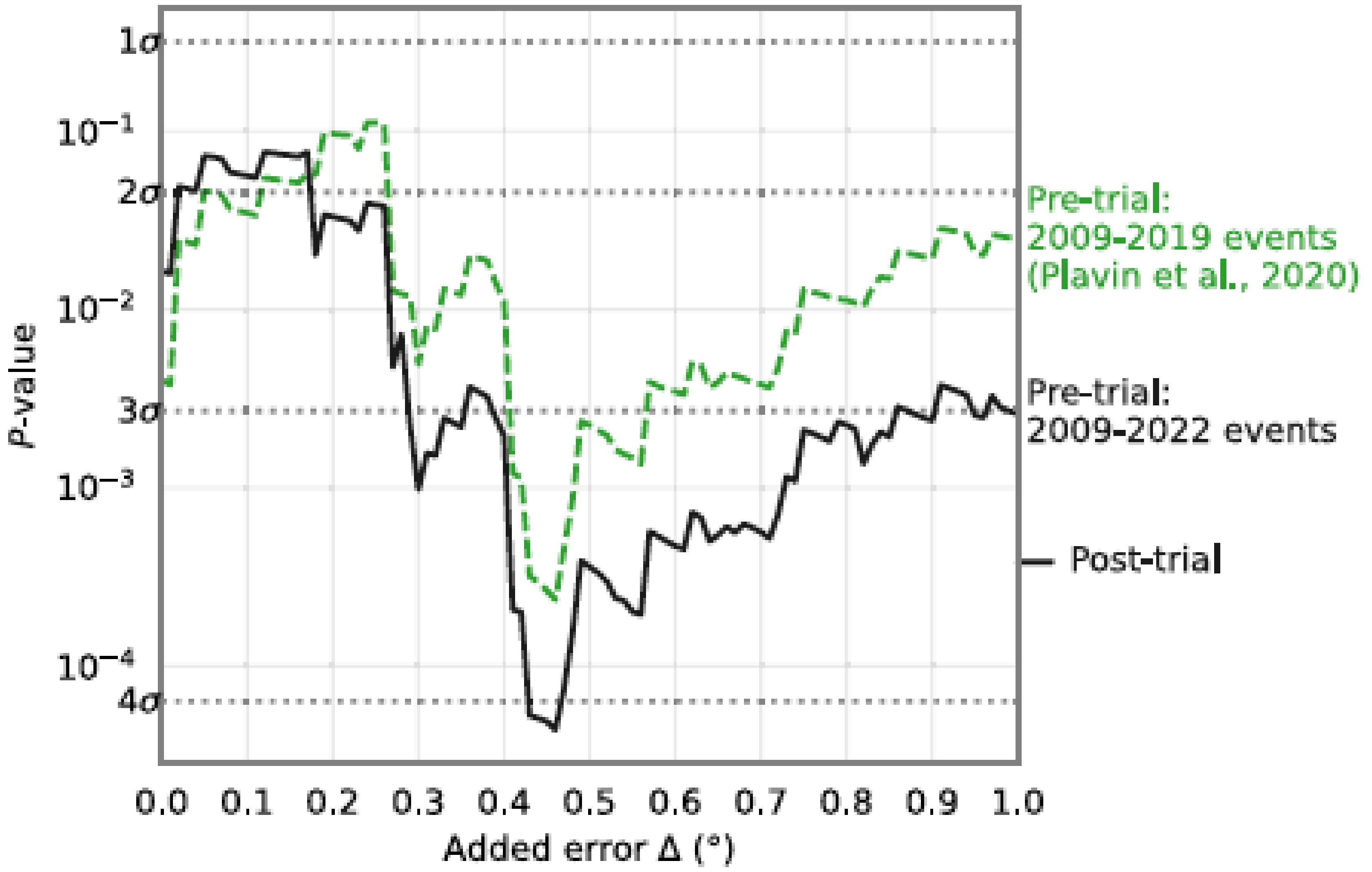
Neutrino detections?

Population-level studies

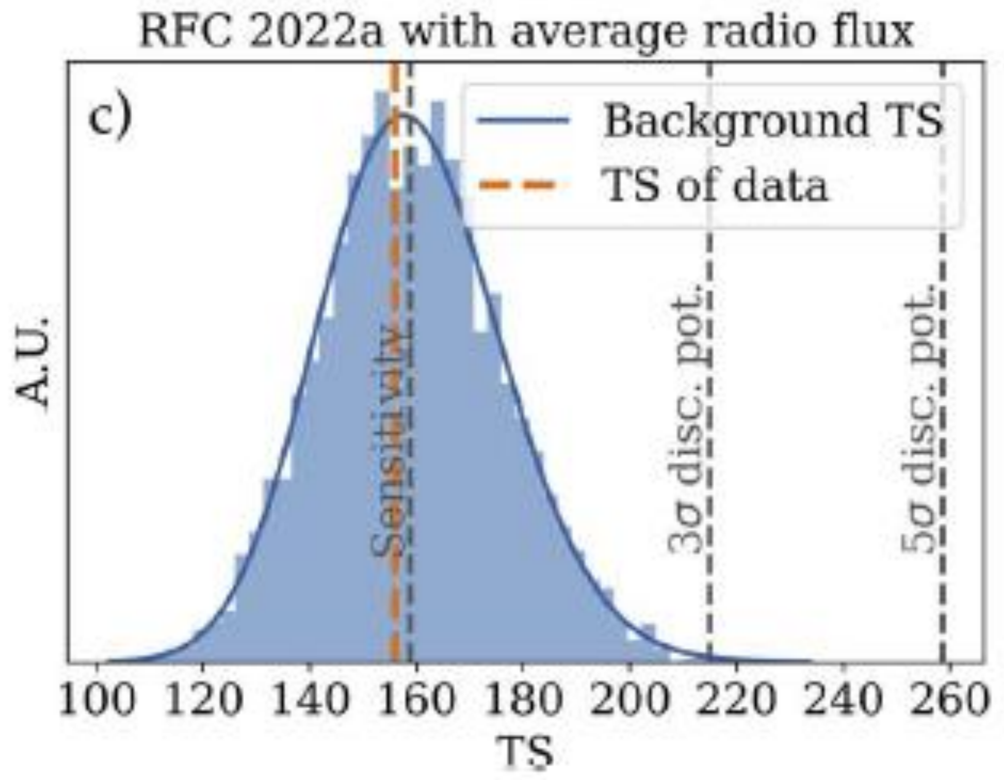
- Stacking analyses of Fermi-LAT blazar populations (2LAC, 3FHL, 1FLE) consistently find no significant neutrino excess, constraining the **blazar contribution to ≤15–27% of the diffuse flux** (IceCube Collaboration+17, 22; Smith+20).
- Radio-blazar correlation claimed (Plavin+23) but not confirmed by IceCube (Abbasi+23).
- Latest GeV-AGN stacking (13 yr) and hard X-ray AGN stacking (12 yr) both find no jet population signal (IceCube Collaboration+25).



IceCube Collaboration+17



Plavin+23



Abbasi+23

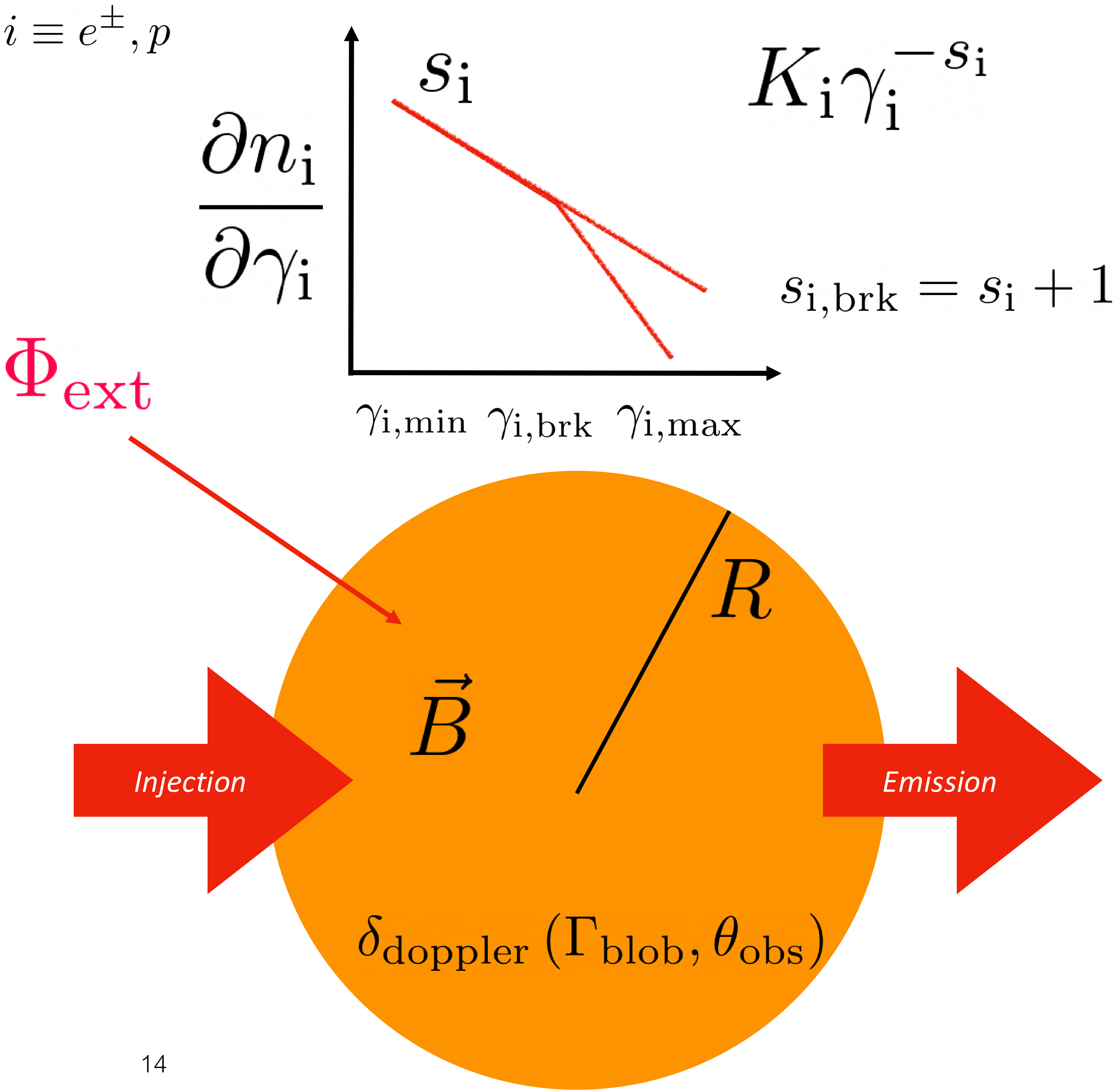
Analytical model: basis

"One-zone" model (see Cerruti 20, Sol & Zech 22)

- Model the source as a spherical region, magnetized and moving relativistically.
- Relativistic particles are injected, with/out an external photon field (accretion disk, BLR, etc.): multi-zone!
- 1D solver:

$$\frac{\partial n_{\rm i}}{\partial t}(\gamma_{\rm i}, t) = \underbrace{-\frac{\partial}{\partial \gamma_{\rm i}}\left[\dot{\gamma}_{\rm i} n_{\rm i}\right]}_{\text{cooling}} - \frac{\overbrace{n_{\rm i}}^{\text{escape}}}{t_{\rm esc}} + \underbrace{Q_{\rm i}(\gamma_{\rm i}, t)}_{\text{injection}}$$

- Steady-state $\partial_t n_{\rm i} = 0$ / time-dependent evolves until it convergence $t_{\rm var} \gg t_{\rm cool}, t_{\rm esc}$



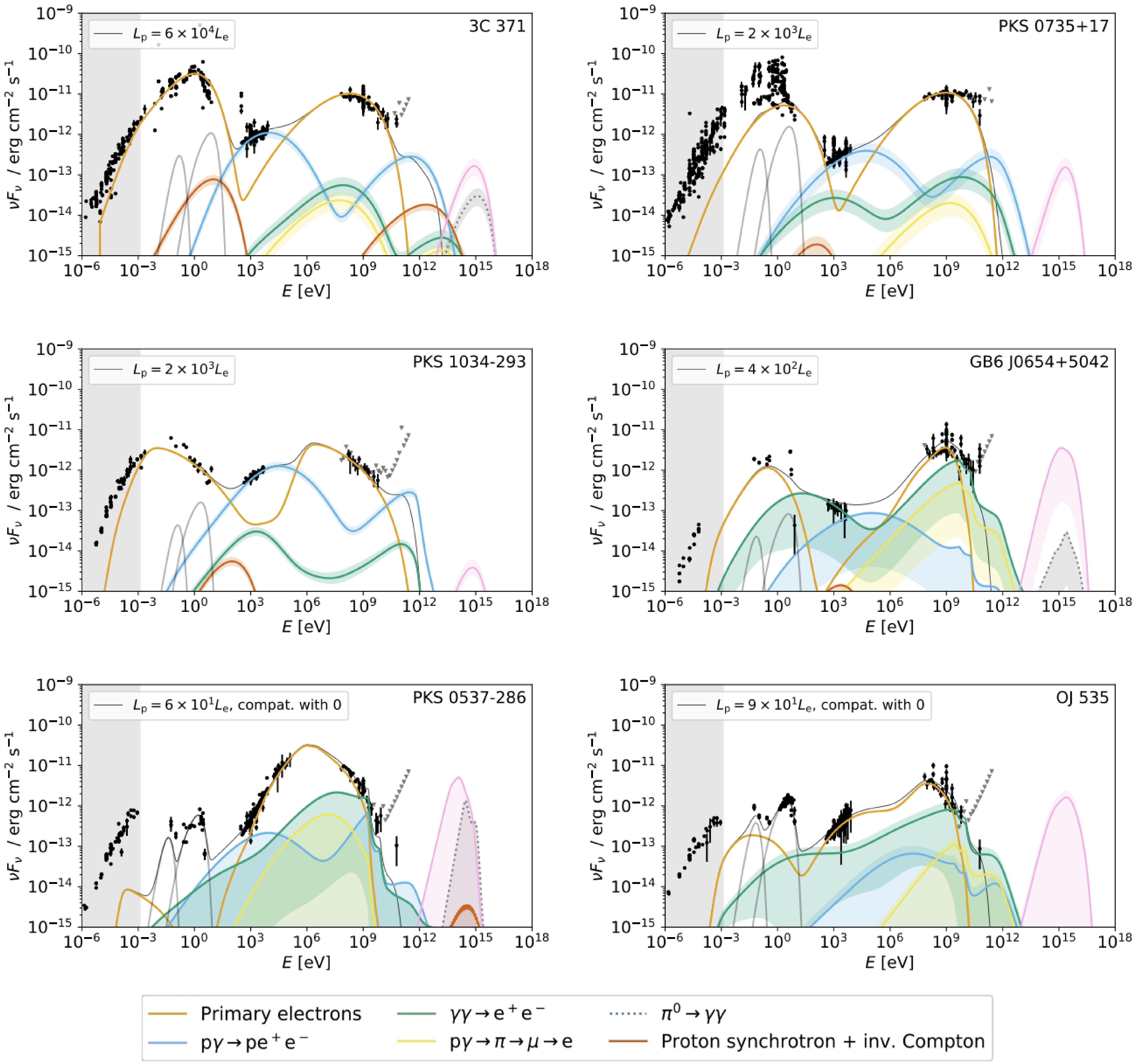
Analytical model: highlights

Key results

- **BLR external photon fields boost neutrino production via pγ** interactions, move hadronic gamma rays down to X-ray/MeV energies through EM cascades (Rodrigues+19, 24)
- The largest self-consistent leptohadronic blazar sample to date (324 sources) finds the **gamma-ray-bright blazar population contributes ~20% of the diffuse IceCube flux**, consistent with stacking upper limits (Rodrigues+24)
- Multi-zone models are favored, motivating alternatives: black hole corona (Le Bihan+26), stochastic multi-dissipation models (Wang+24, Lemoine & Rieger 25)

Code comparison

- First systematic cross-code comparison of 5 leptohadronic codes finds ±10% agreement on leptonic processes but up to **±40% on hadronic secondaries and neutrino spectra** (Cerruti+24)



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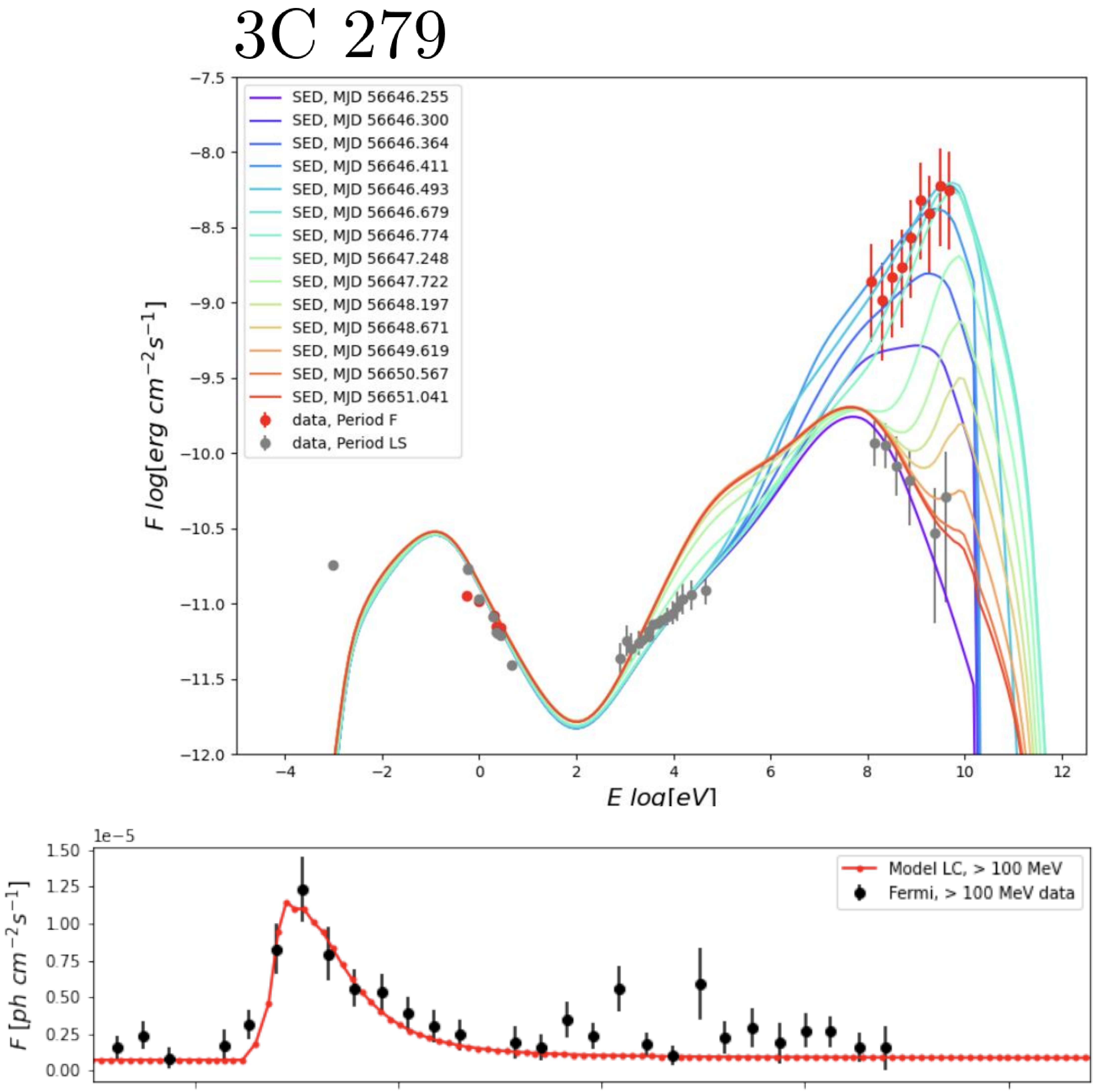

Le Bihan+25, EMBLEM code (Dmytriiev+21)

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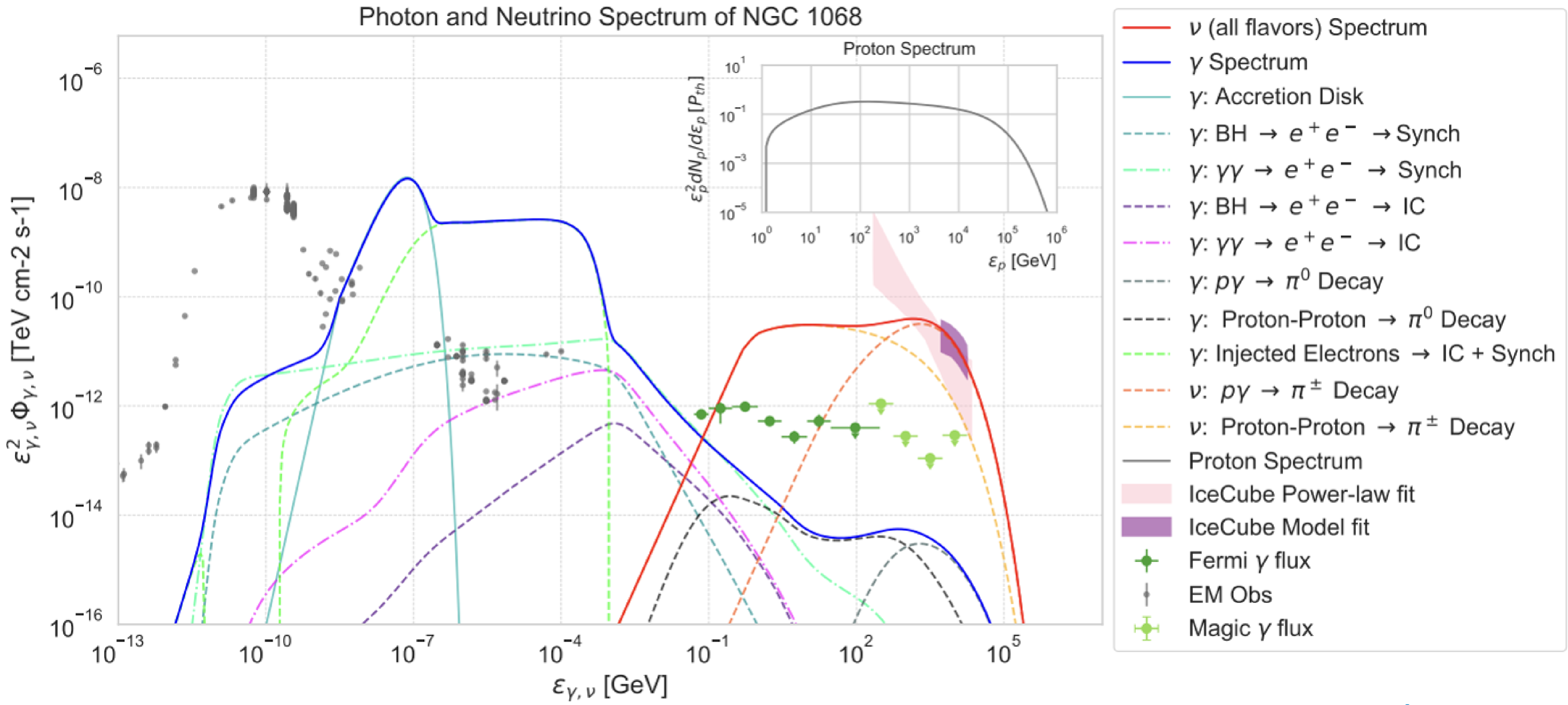
NGC 1068



Le Bihan+26

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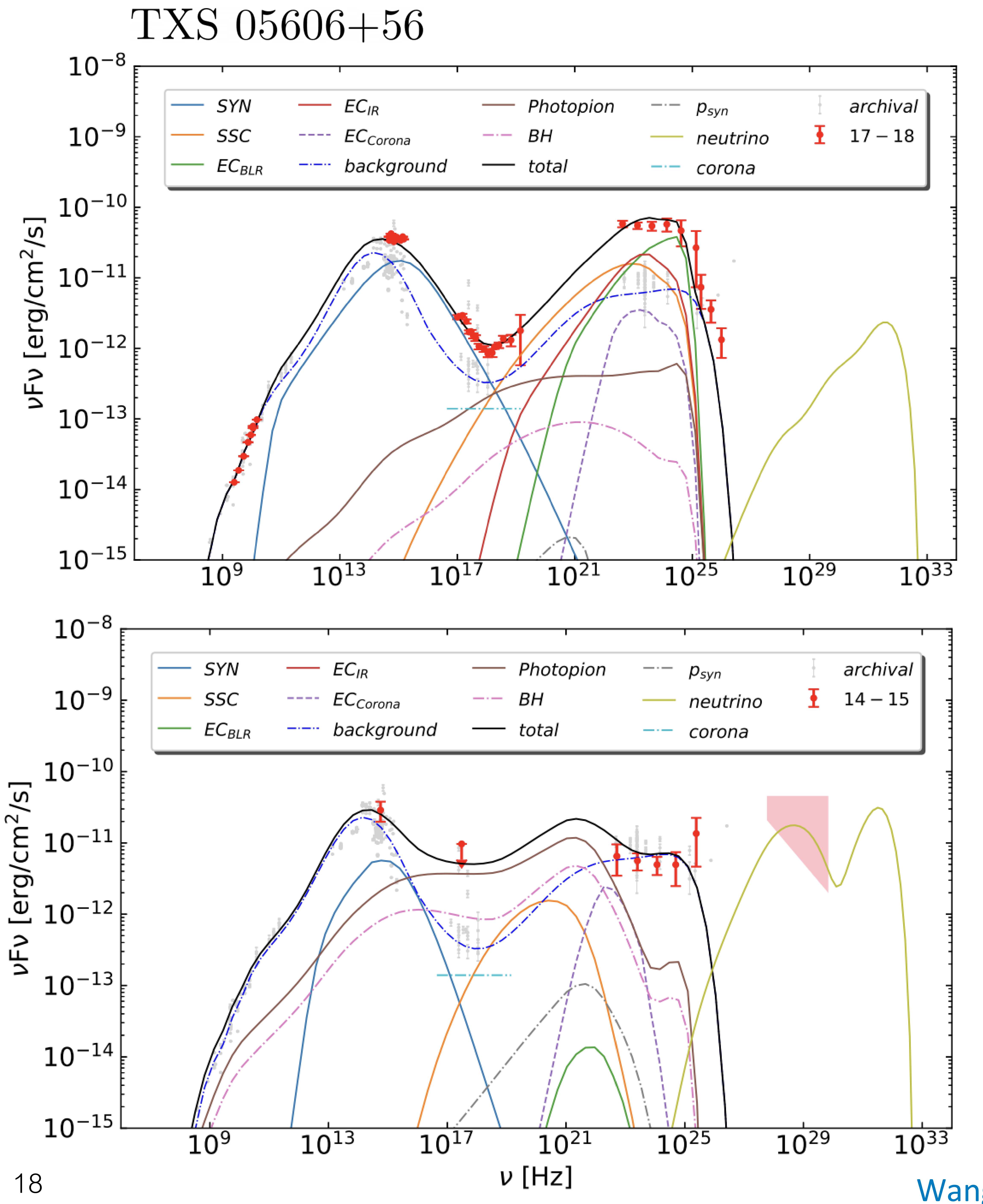

Wang+24

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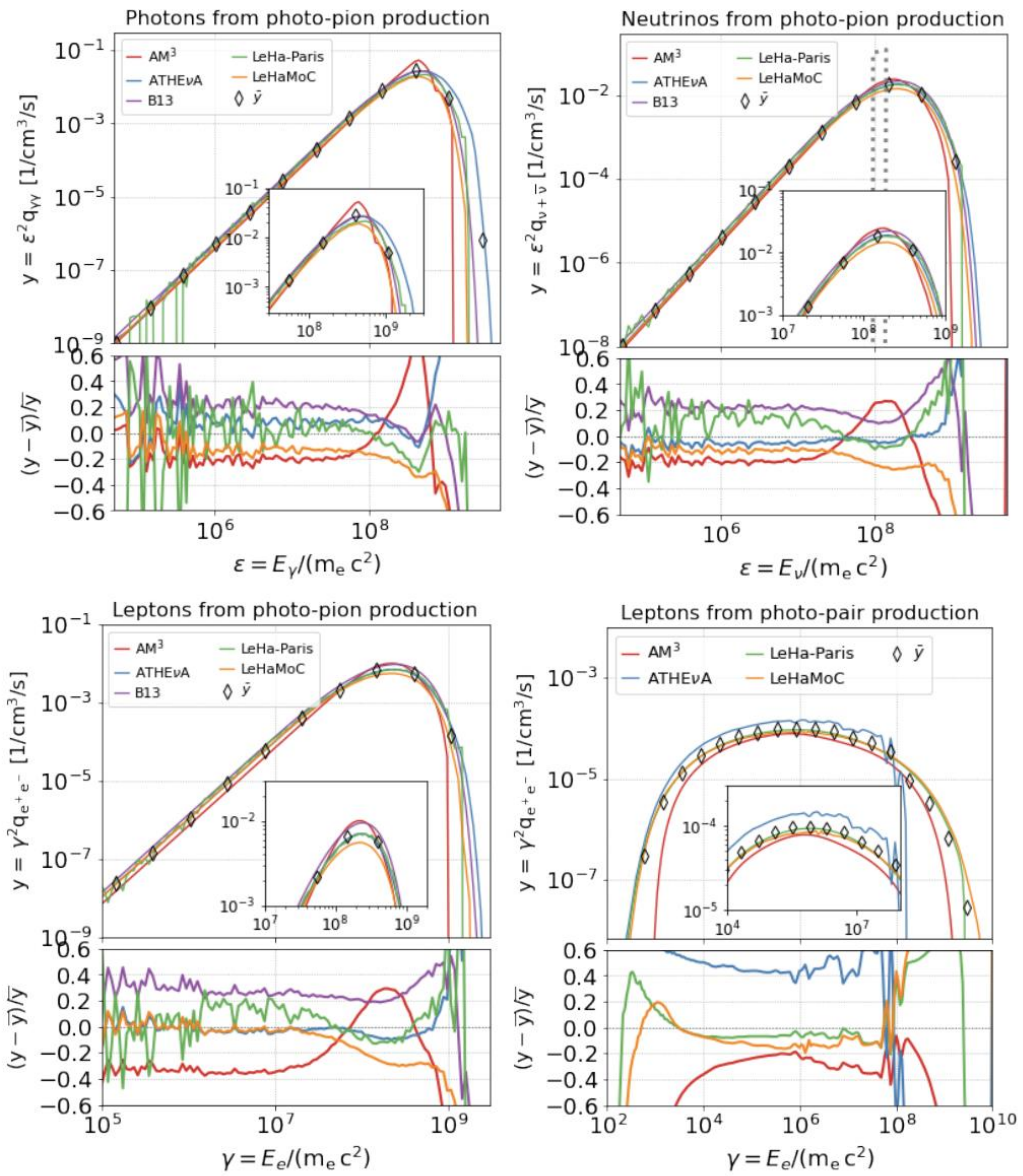


Cerruti+24

Fluid simulations…

Basis

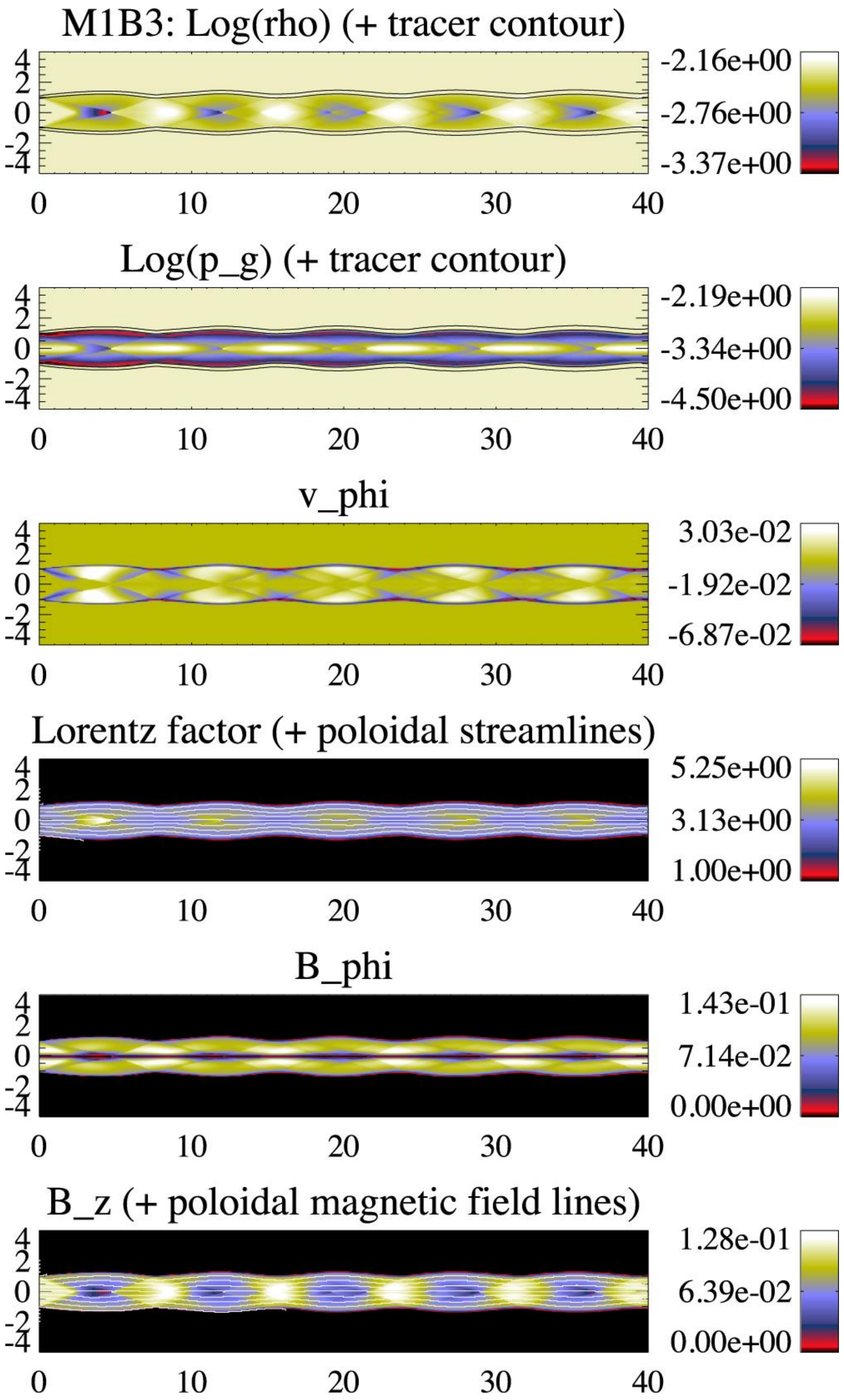
- 2D/3D simulations of AGN jets at pc scales: lot of public codes (PLUTO, AMRVAC - Keppens+12, Mignone+17) and proprietary codes (e.g. in València, 2D Ratpenat (Perucho+10), 3D Lóstrego (Lòpez-Miralles+22))

State of the art

- Jets develop recollimation shocks when over-pressured (Mizuno+15, Martí+16, Fromm+18, Fichet DC+21, 22)
- KH, kink and centrifugal instabilities disrupt jet structure, drive turbulent mixing and collimation (Gourgouliatos+18, Perucho 19, Bodo+19).
- 2D overestimates instabilities, while 3D enables realistic turbulent mixing (Costa+24).

Link between jet dynamics and radiation?

Addition of non-termal particles (NTP)



Fuentes+18

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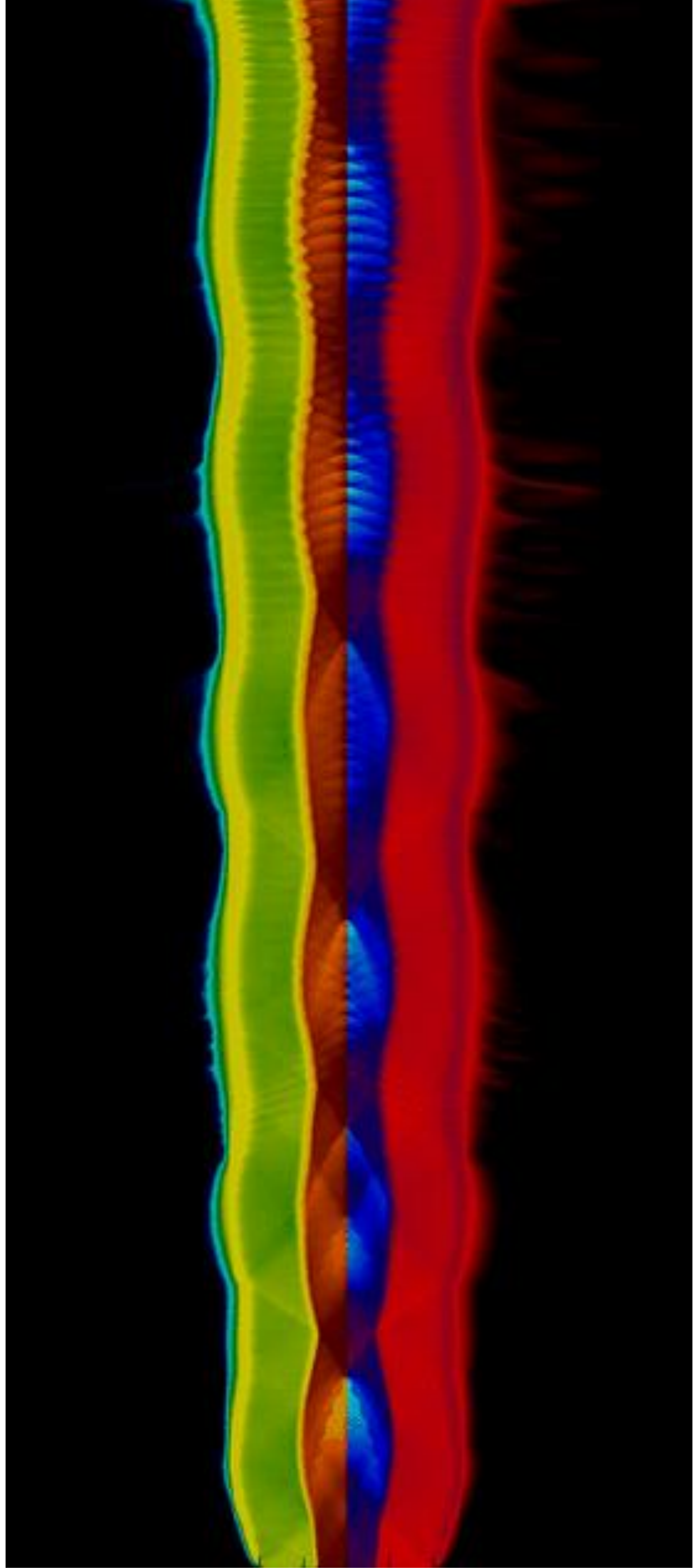

Fichet DC+21

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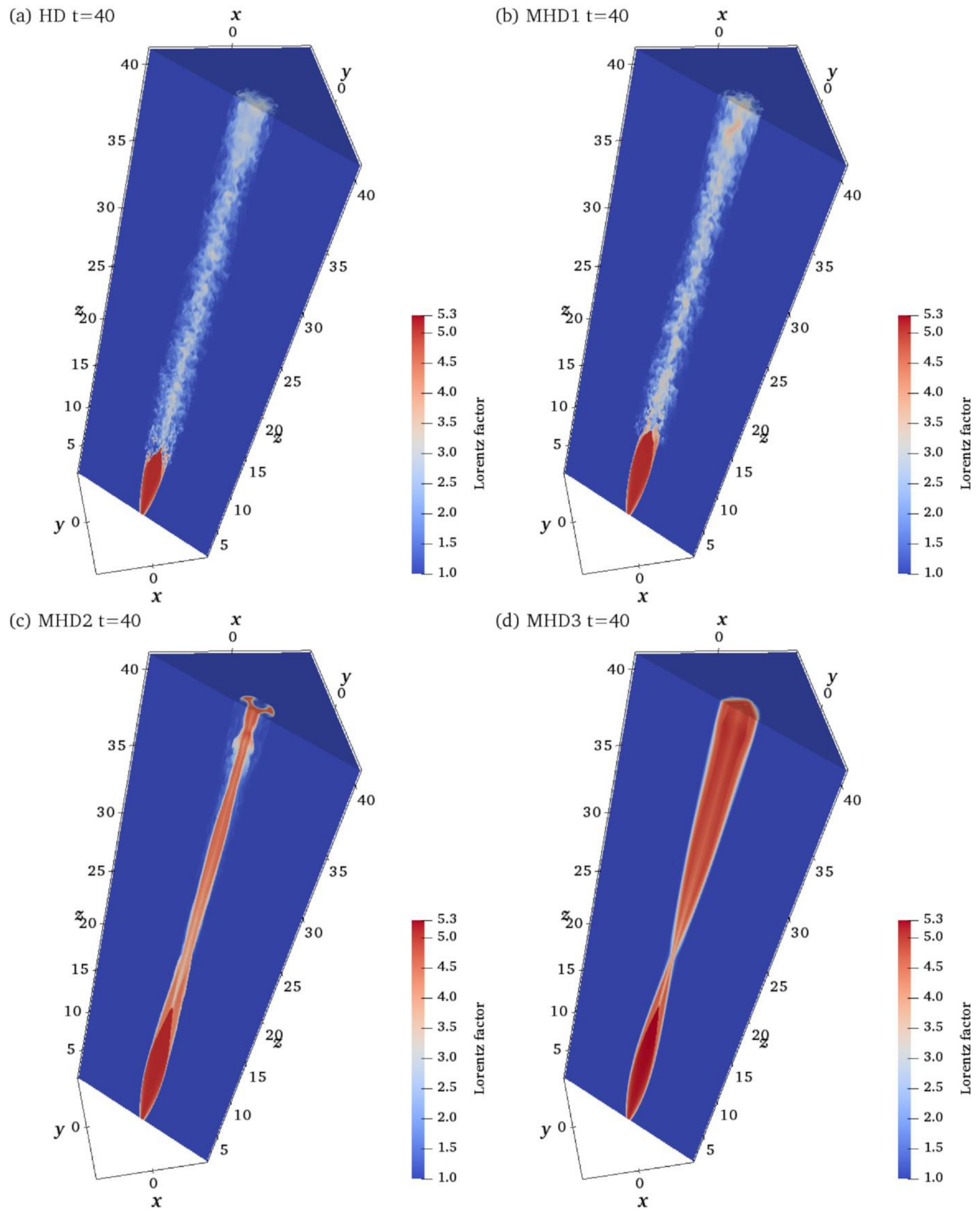


Matsumoto+21

Fluid simulations…

Jones+99, Fichet DC+ 22

$$\frac{\partial N_i(E,t)}{\partial t} + \underbrace{\nabla \cdot (\mathbf{v}\, N_i)}_{\text{advection on grid}} + \frac{\partial}{\partial E}\left[\underbrace{-\frac{E}{3}(\nabla\cdot\mathbf{v})\, N_i}_{\text{adiabatic}} + \underbrace{\dot{E}_l\, N_i}_{\text{radiative losses}}\right] = \underbrace{Q_i(E,t)}_{\text{injection}}$$

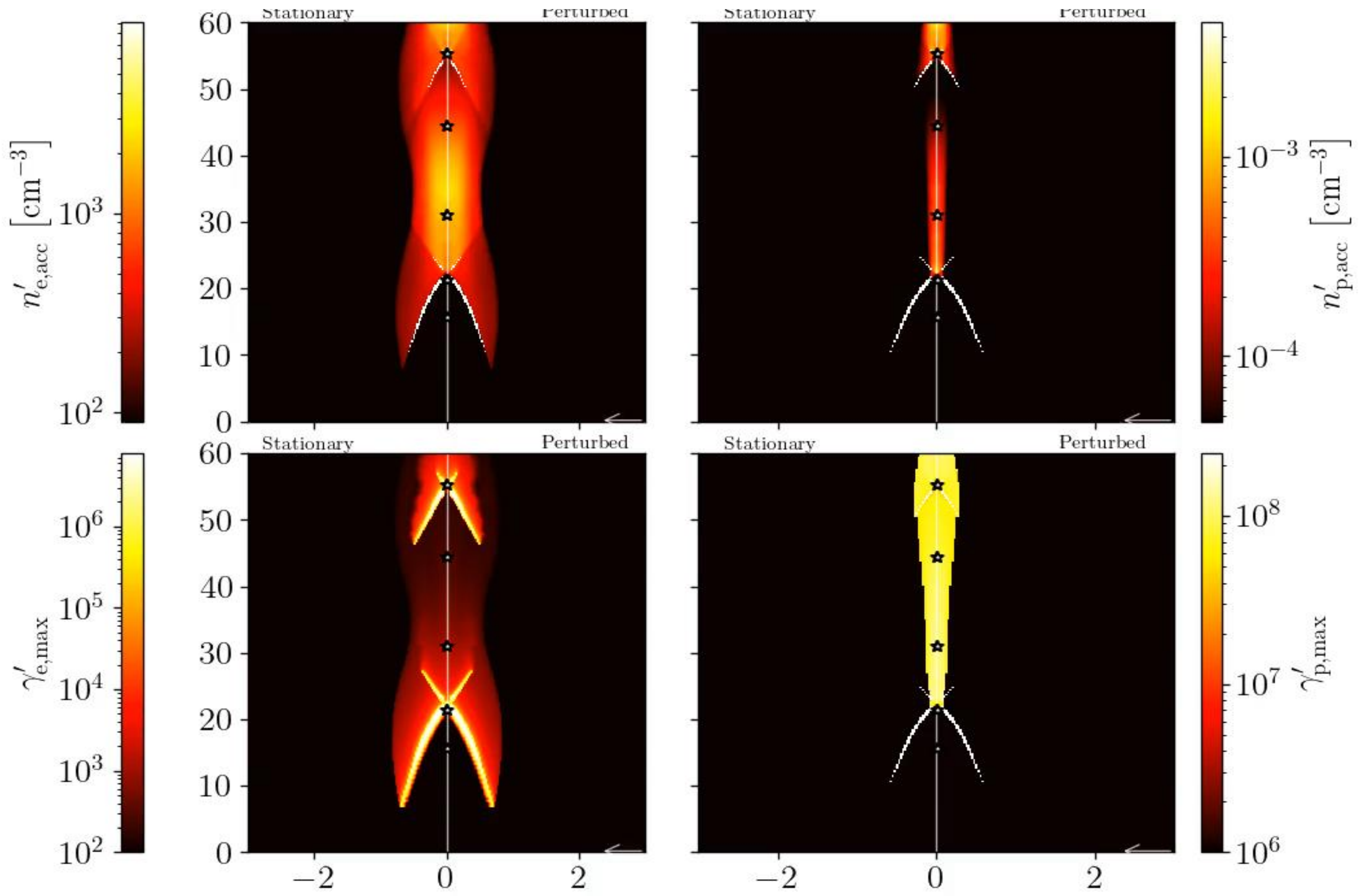
Eulerian (NTP as fluid on grid)

- Binned N(E) advected with MHD eqs; DSA, synchrotron/IC, adiabatic losses (Jones+99, Van Eerten+10, Fichet DC+22, in prep).
- Cold protons injected as source terms.
- grid-coupled, CR back-reaction possible
- numerical diffusion, no individual spectral history

Lagrangian (NTP as macro-particles)

- Macro-particles advected along streamlines, each carrying own N(E) (Vaidya+18, Kramer+24, Elley+26, Bhuyan+26).
- Protons content inferred from thermal fluid.
- sharp spectral histories, full Stokes, ex-situ flexibility
- interpolation artifacts, sampling convergence

Fichet DC+ In prep, Ratpenat code



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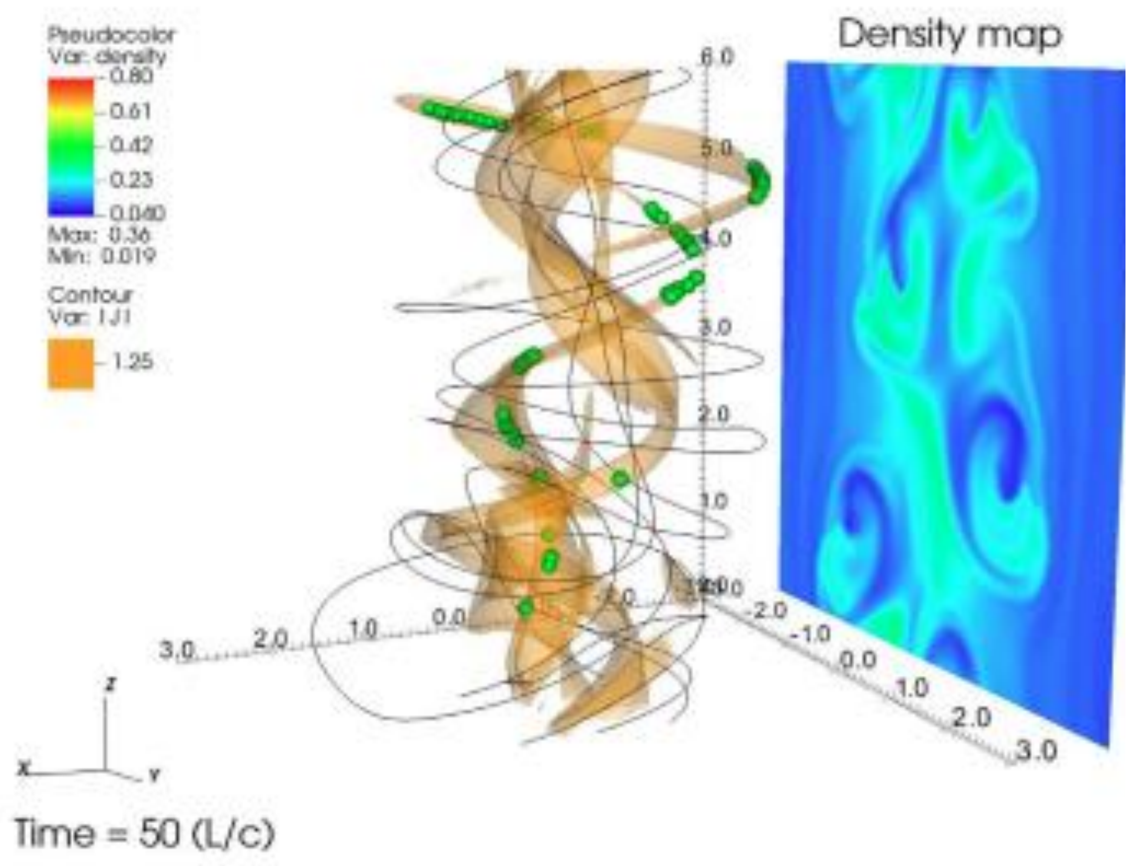
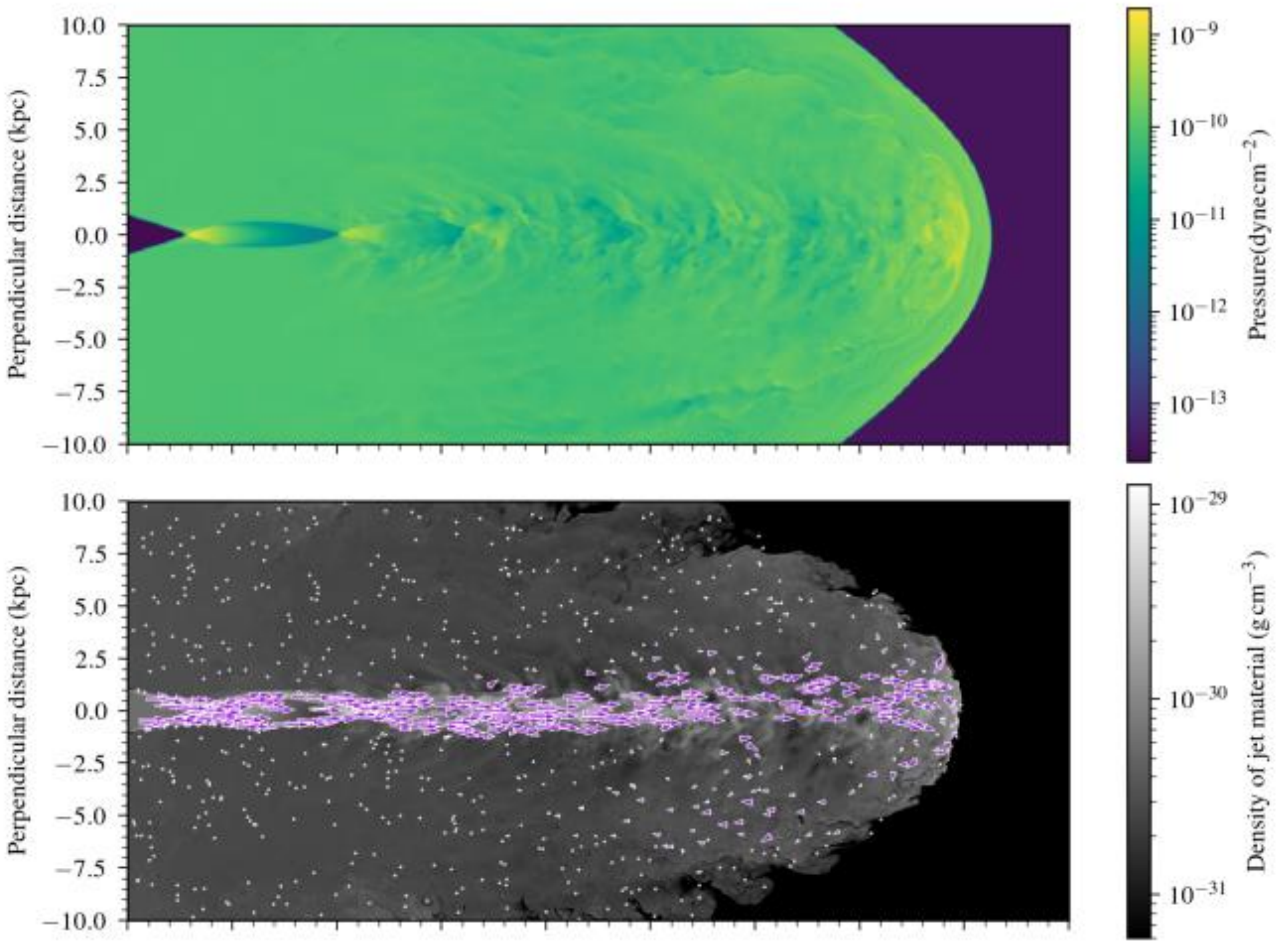
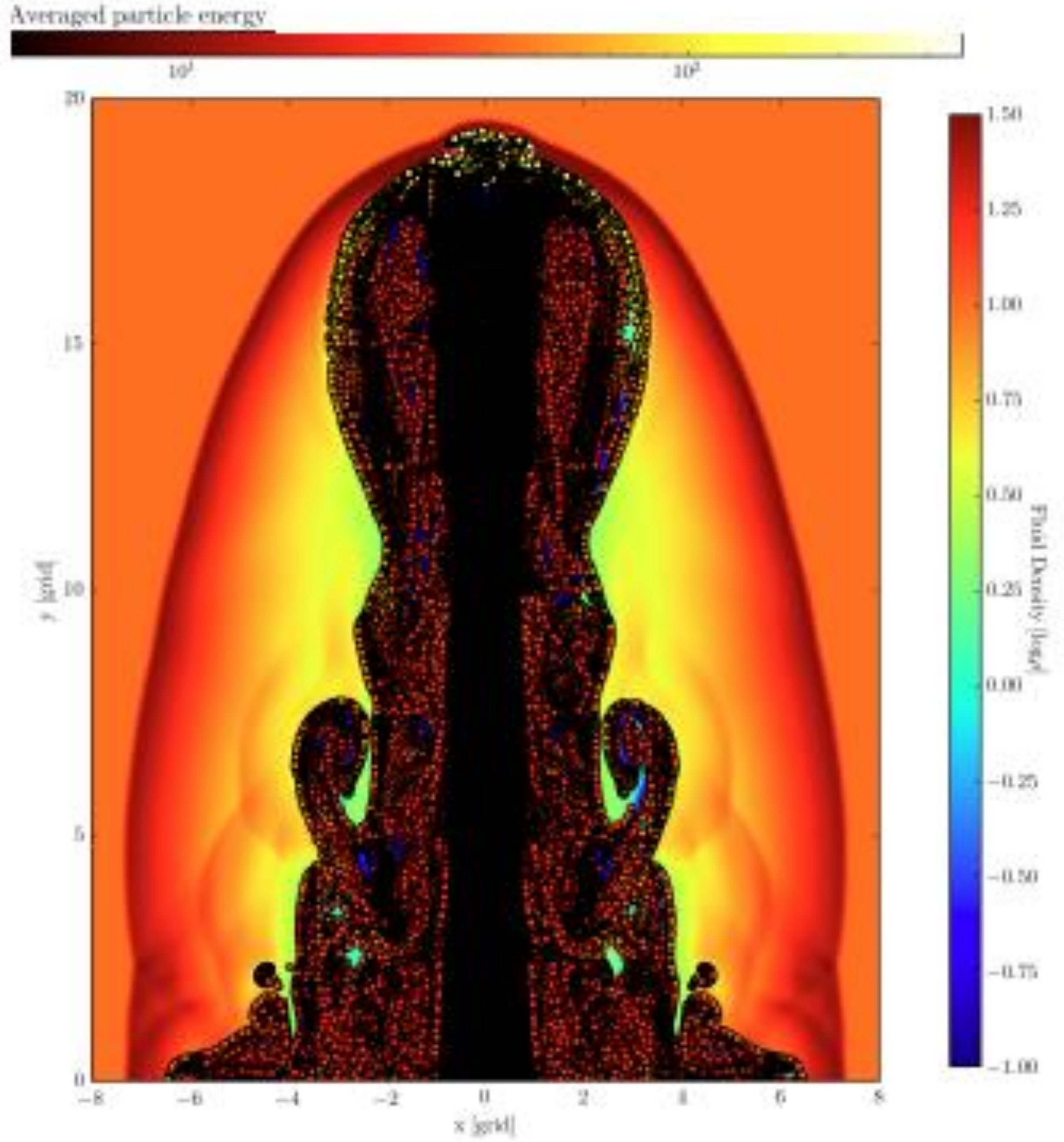


Medina-Torrejón+21



Elley+26



Kramer+24

CR transport

$$\underbrace{\nabla_\mu(u^\mu f_0)}_{\text{advection}} + \underbrace{\nabla_\mu q^\mu}_{\text{spatial diffusion}} + \frac{1}{p^2}\frac{\partial}{\partial p}\Bigg[\underbrace{-\frac{p^3}{3} f_0 \nabla_\mu u^\mu}_{\text{adiabatic}} + \underbrace{\langle \dot{p}\rangle_l f_0}_{\text{radiative losses}} \underbrace{-\Gamma_{\rm visc}\, p^4 \tau \frac{\partial f_0}{\partial p}}_{\text{shear acceleration}} \underbrace{-p^2 D_{pp}\frac{\partial f_0}{\partial p}}_{\text{Fermi II}} \underbrace{-p\,(p^0)^2\, \dot{u}_\mu q^\mu}_{\text{non-inertial}}\Bigg] = 0$$

Webb+89

Lagrangian particle transport

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}(\mathbf{x}_p)$$

Vaidya+18

… and radiative transfer!

In code / post-processing

- Synchrotron ray-tracing from (R)MHD snapshots via thermal → non-thermal scaling relations (Porth+11; Fromm+16, Kramer & MacDonald 21)
- Dedicated RT codes: RIPTIDE (Fichet de Clairfontaine+22), RADMC-3D (Kramer+24), R-JET (Hirotani+25), RAPTOR (Bronzwaer+18)
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Neutrino production

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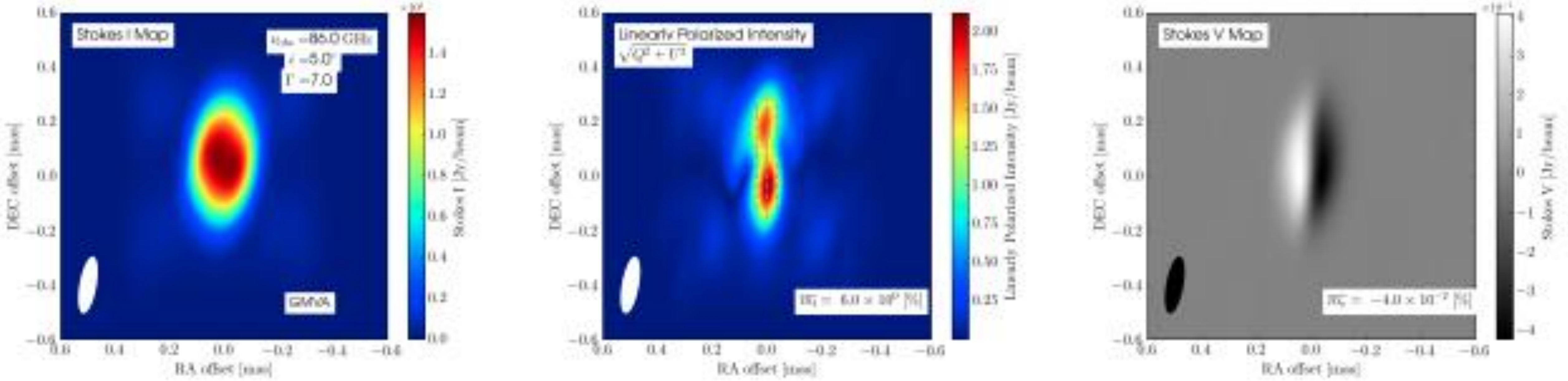

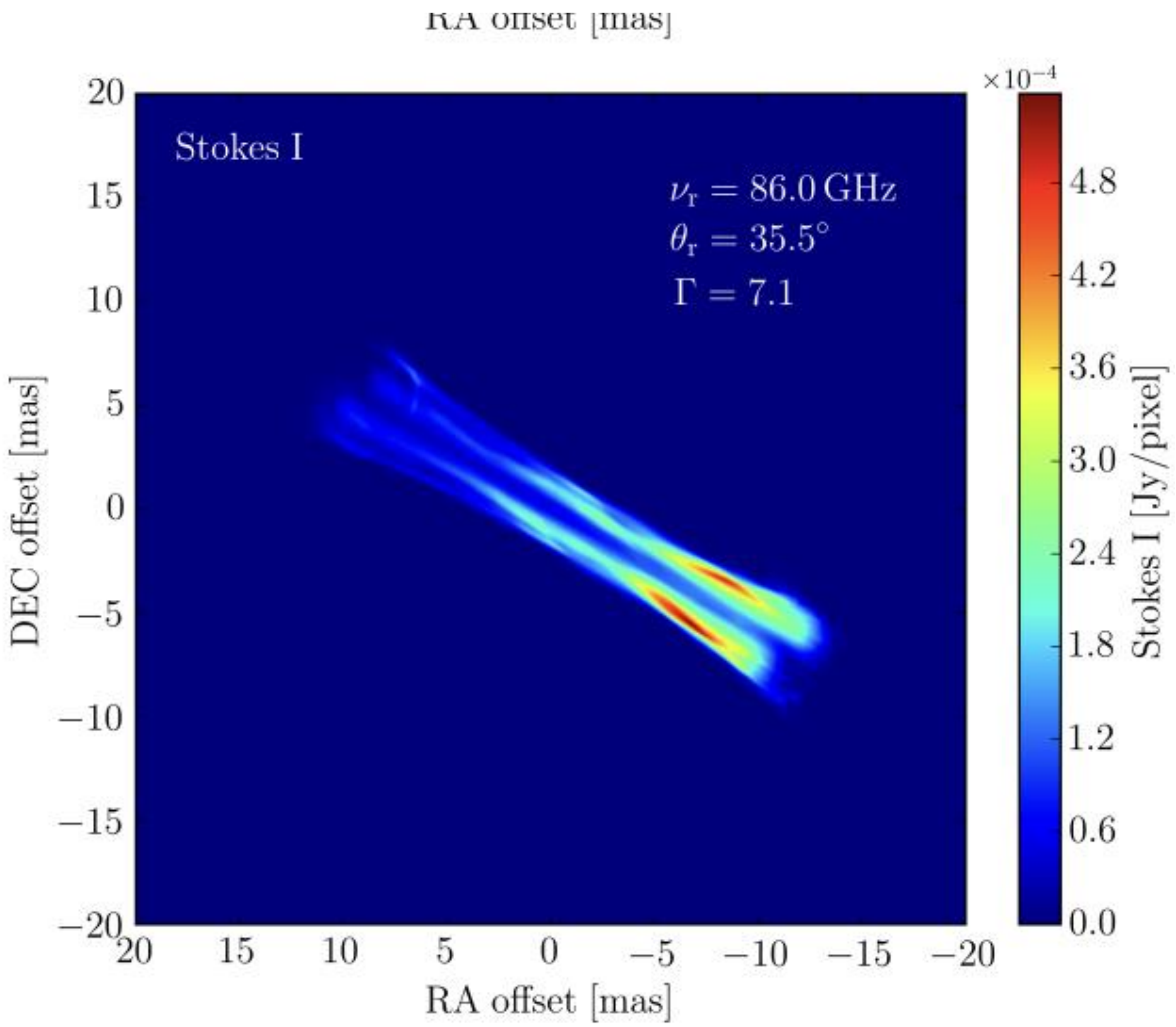

Kramer+24

… and radiative transfer!

Fichet DC+22

In code / post-processing

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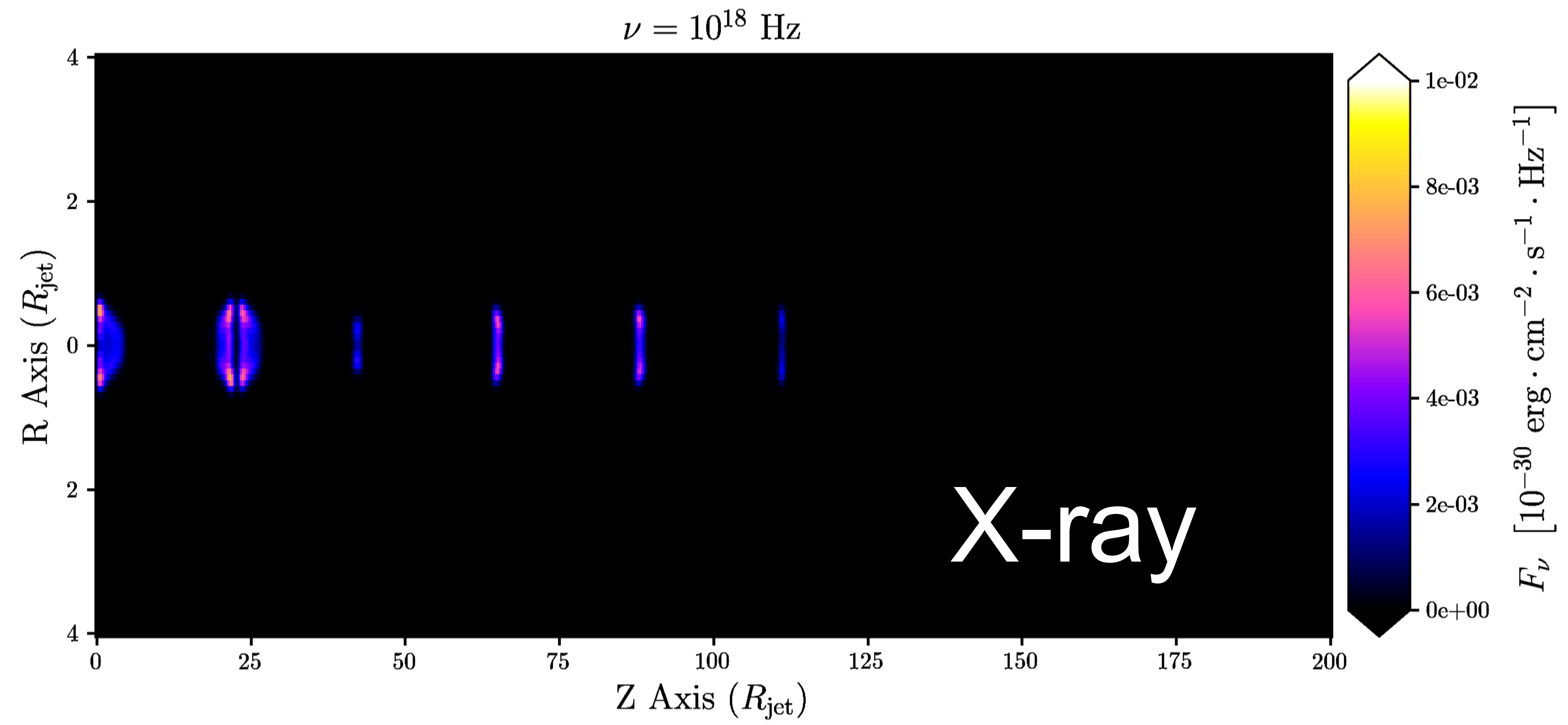

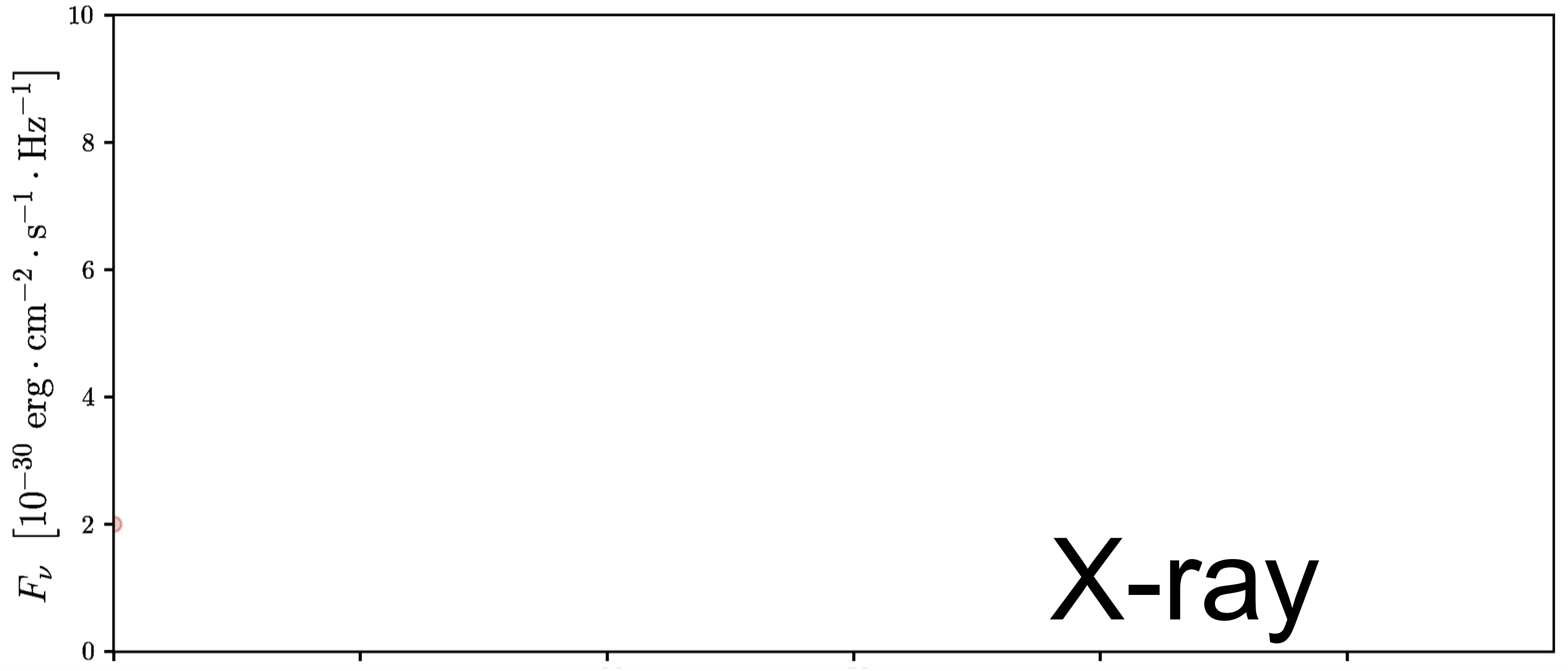

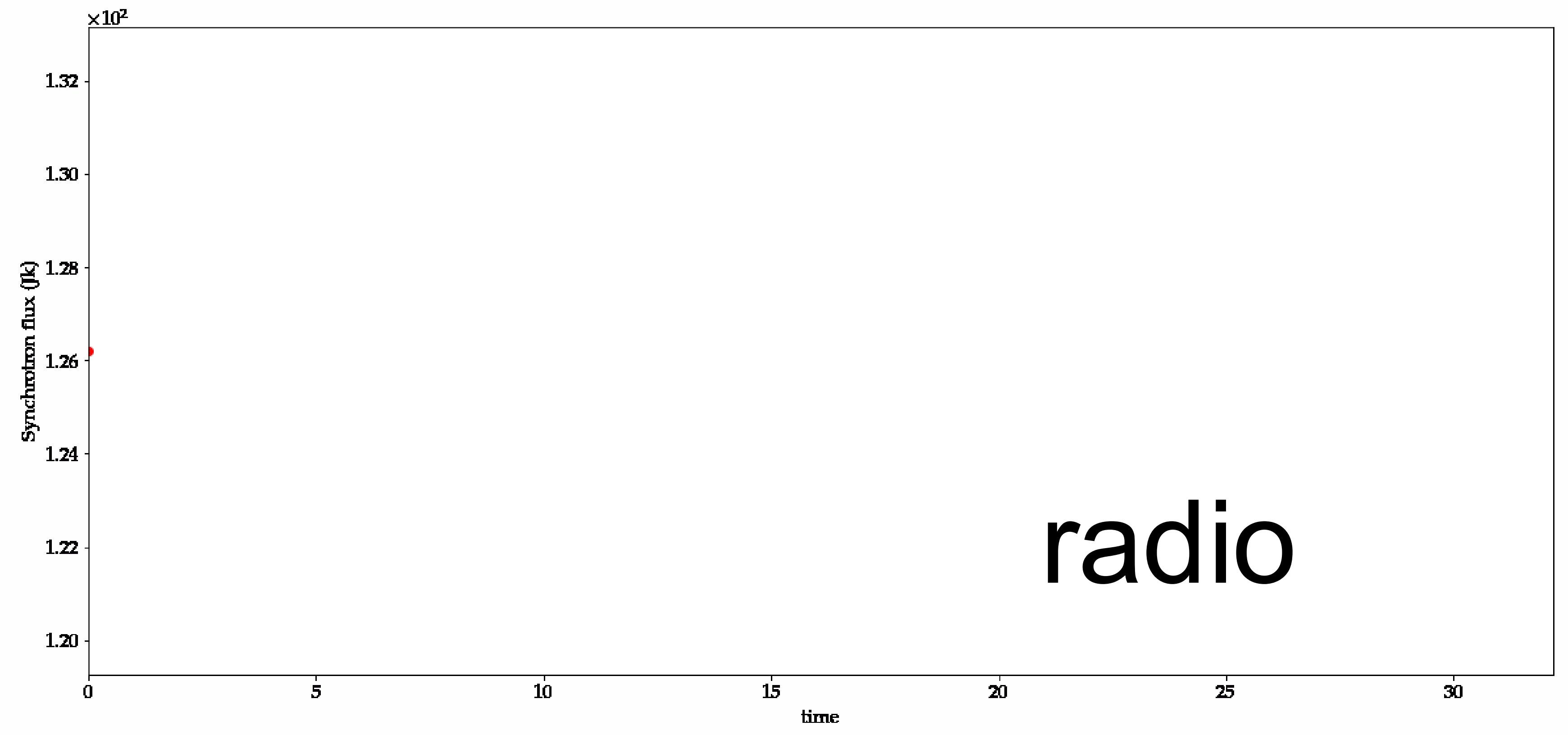

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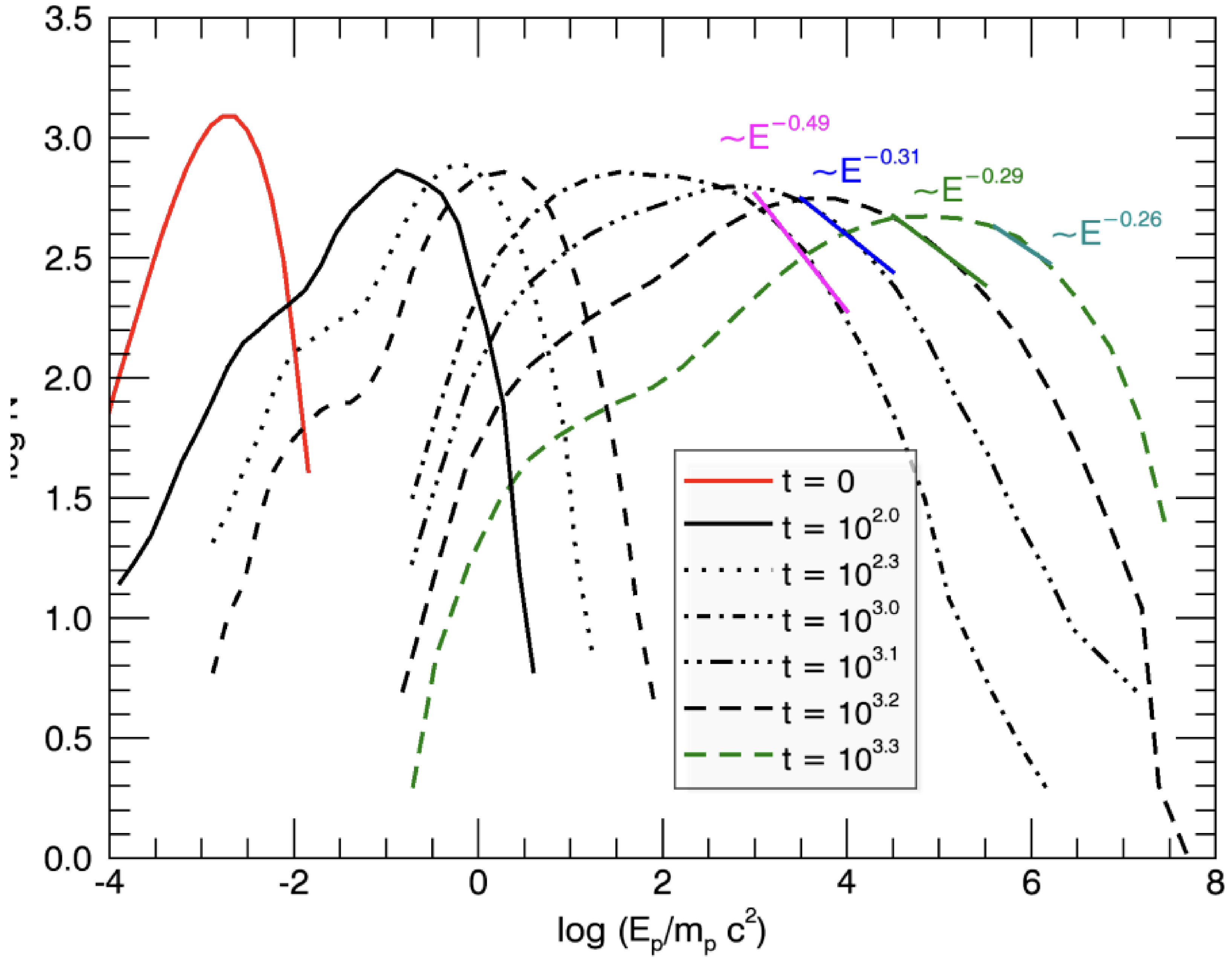
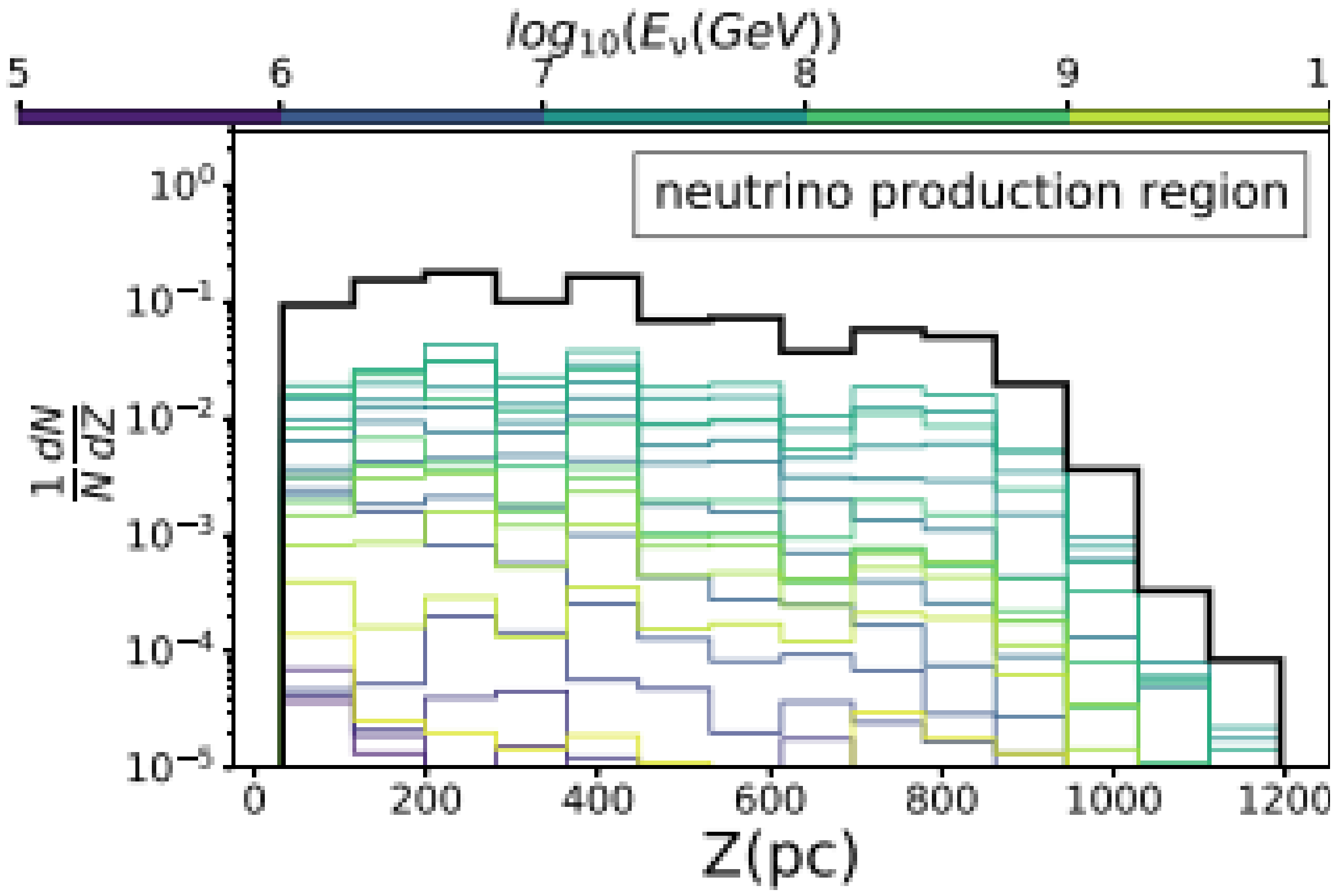
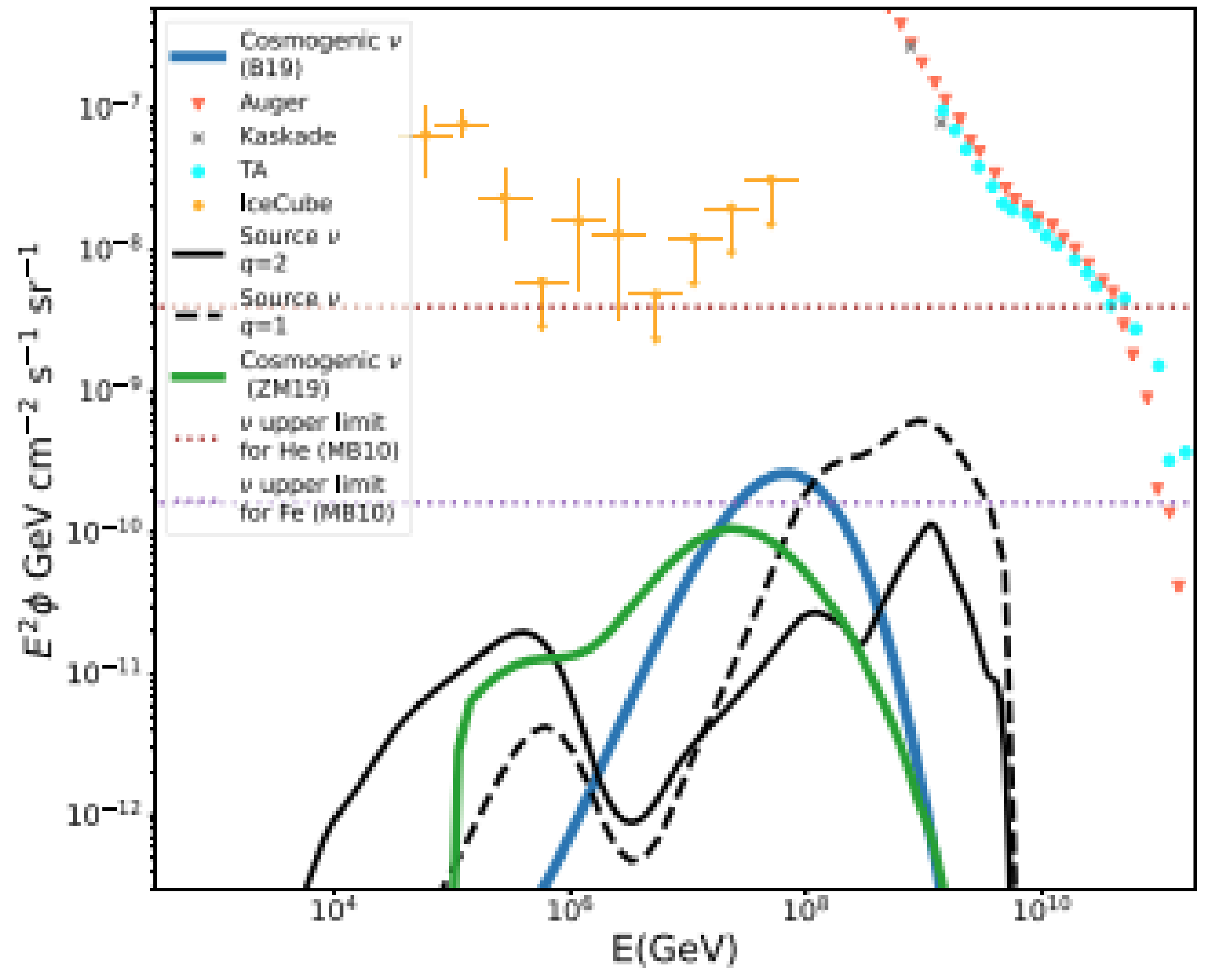


Medina-Torrejón+21





Mbarek+23

… and radiative transfer!

In code / post-processing

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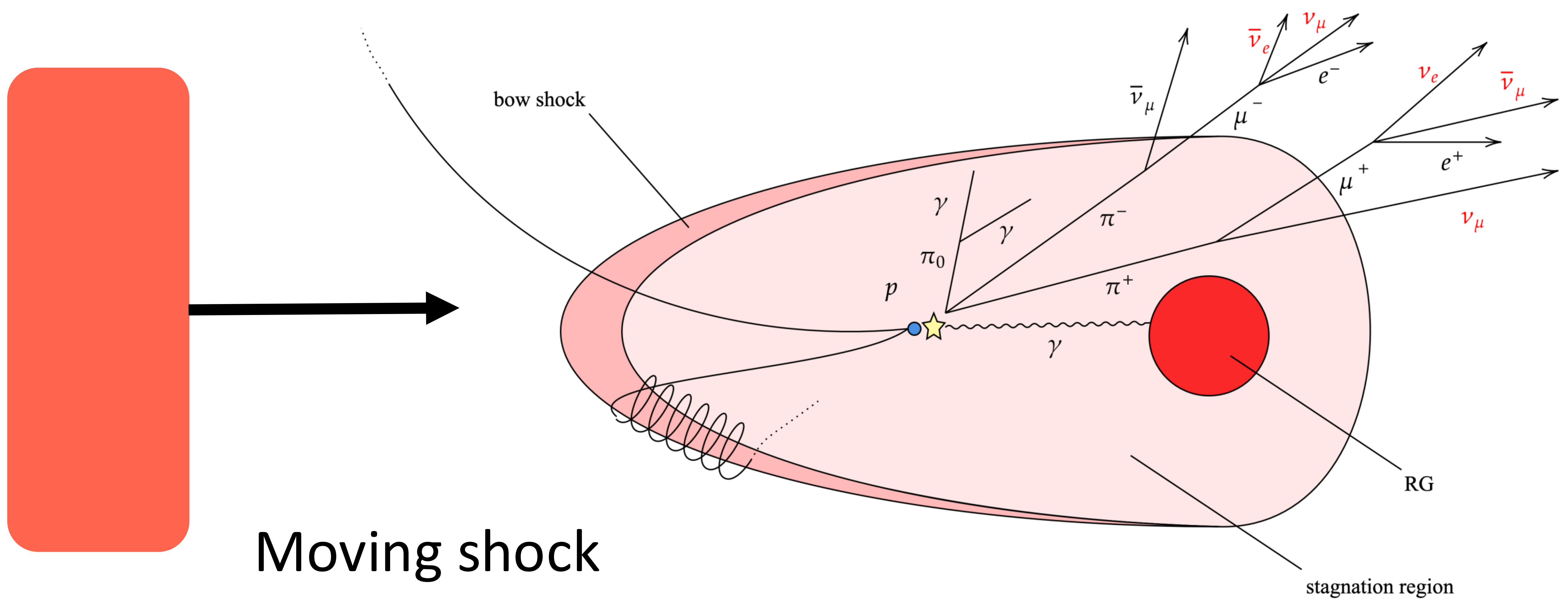

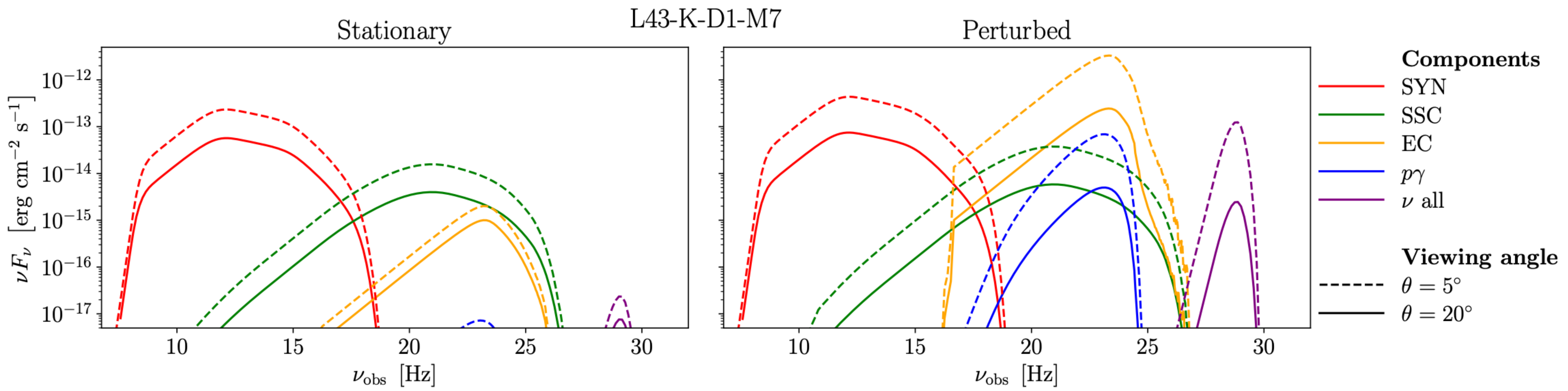

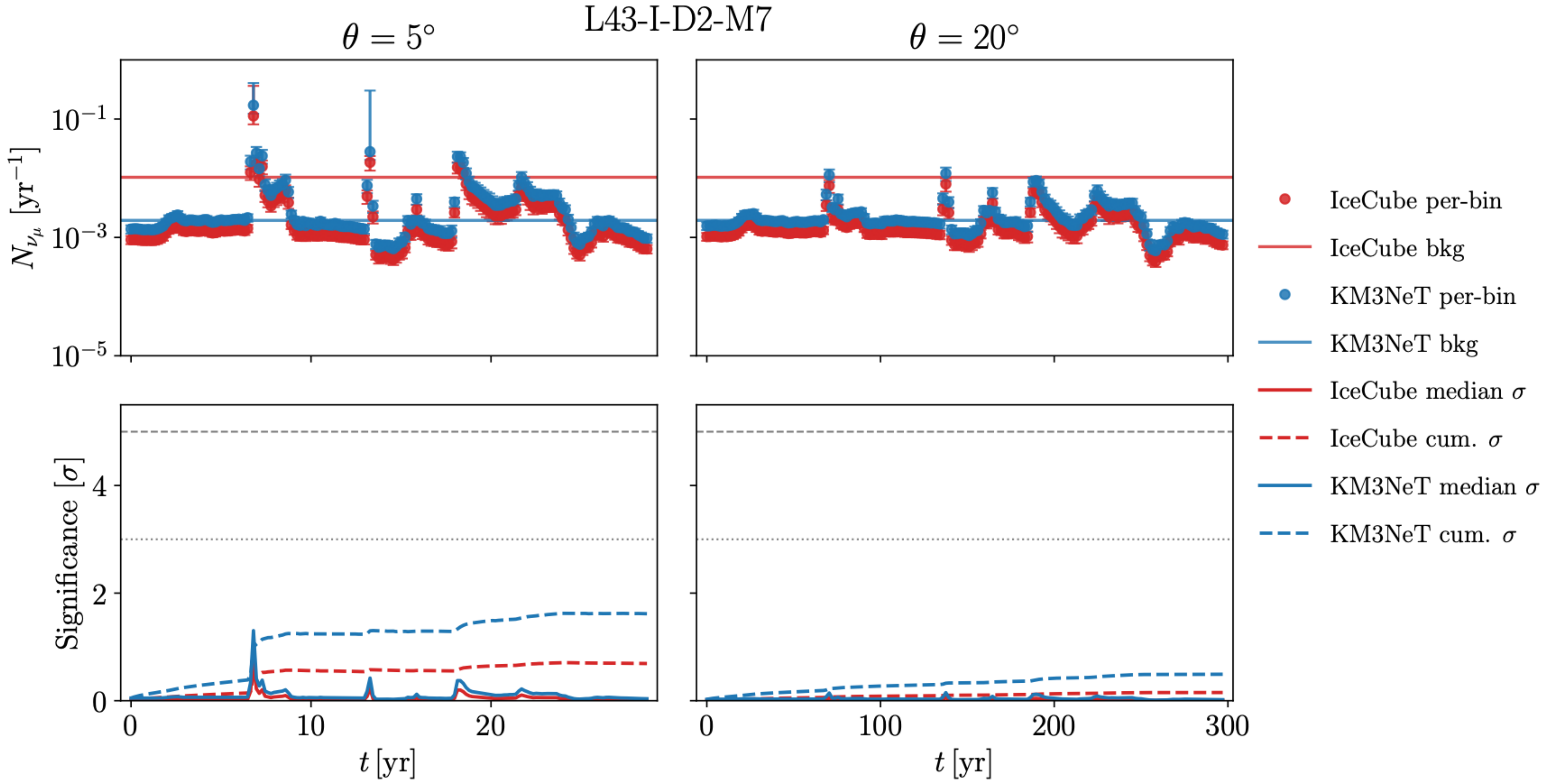

Fichet DC+ In prep, RIPTIDE code

Conclusion: where do we stand?

Where & how are CRs accelerated to PeV+ in jets? What drives transient neutrino flares? Why individual hints if blazars contribute ≲20% of the diffuse flux?

- **Acceleration mechanisms / DSA & reconnection** are established in principle, but their relative role, efficiency and maximum energy in real jets remain open.
- **Leptons firmly established; hadrons still uncertain:** TXS 0506+056, NGC 1068 and the Galactic Plane give the first individual neutrino sources.
- **Leptohadronic models** bound the diffuse blazar contribution at ≲20% (Rodrigues+24); matching individual IceCube events under one-zone assumptions demands Lp ≳ L_Edd, motivating multi-zone alternatives.
- **RMHD + relativistic electrons** are mature: synthetic multi-wavelength and polarization maps comparable to VLBI (RIPTIDE, RADMC-3D, RAPTOR) and to kpc-scale radio polarimetry (BRAiSE).
- **Caveat — shock acceleration is not self-consistent:** RMHD models inject a prescribed power-law spectrum at shocks; the underlying microphysics (injection efficiency, slope, e/p ratio, maximum energy) must be calibrated against PIC simulations (Sironi & Spitkovsky 11, Caprioli & Spitkovsky 14, Park+15, Crumley+19).
- **RMHD + relativistic protons** is emerging: structured jets with shocks, reconnection or stellar baryon loading produce transient PeV neutrinos with proton budgets significantly below one-zone requirements.
- **Next frontier:** couple hadronic losses to 3D RMHD — per-source models and population-level predictions testable by KM3NeT and IceCube-Gen2.