High-energy neutrinos from relativistic magnetic reconnection in black-hole coronae

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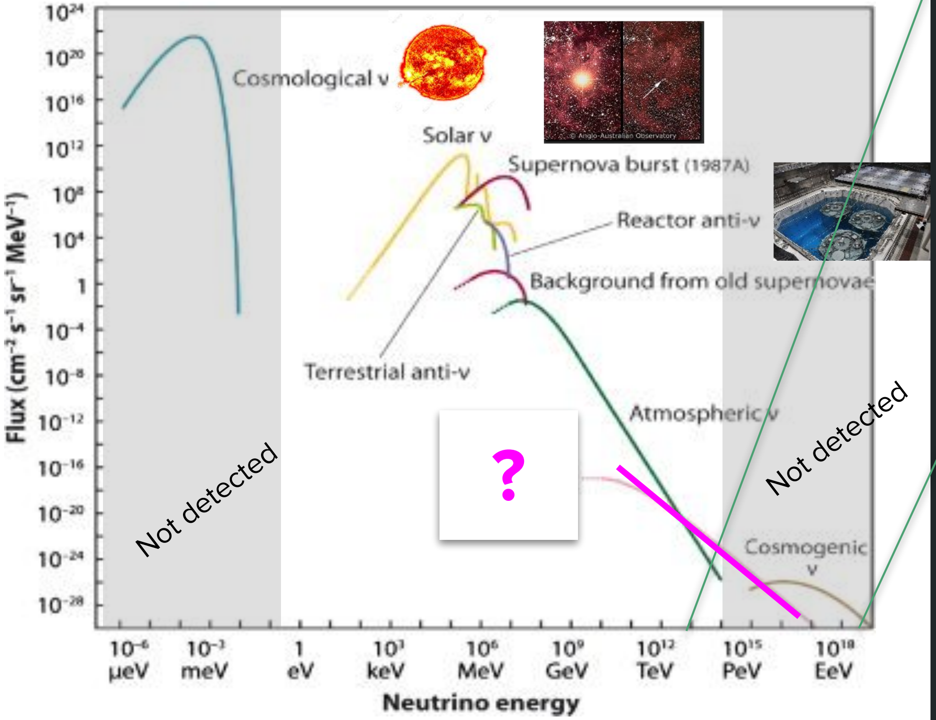
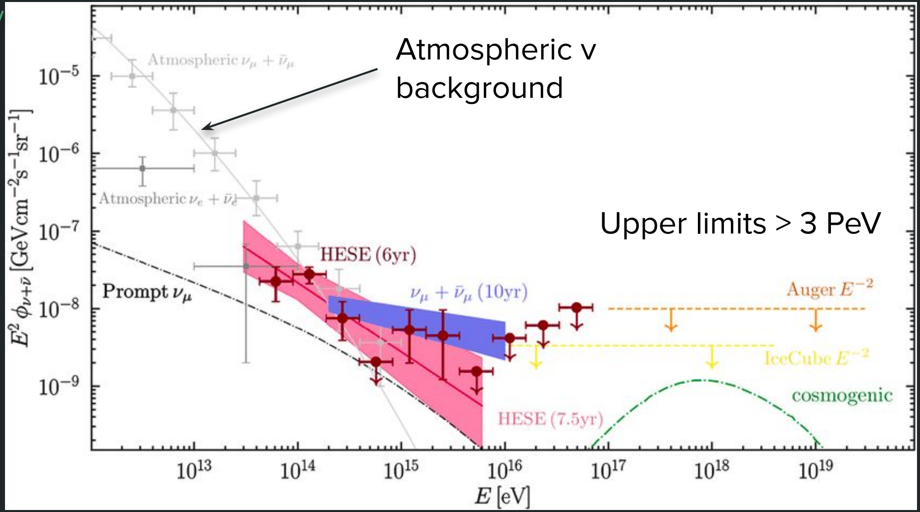
Introduction

The neutrino (ν) flux spectrum



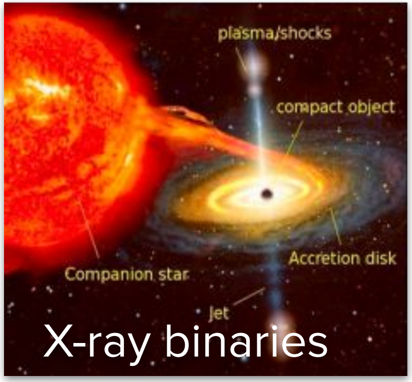
Katz & Spiering 2012, PPNP

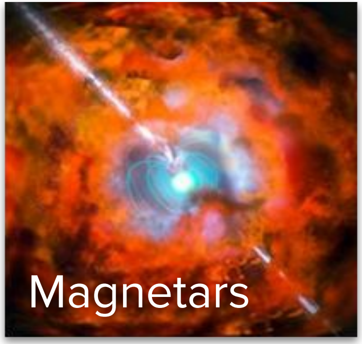
Kheirandish, A. 2020, A&SS

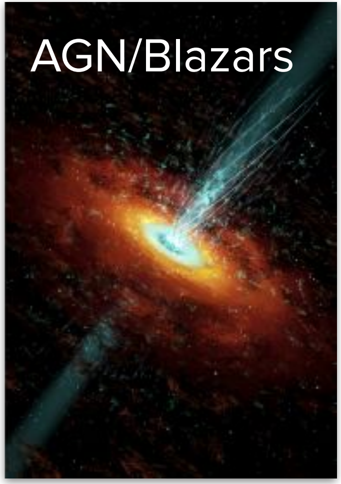


- Detection of HE ν (E > 10 TeV) ➔ evidence for presence of hadronic accelerators
- Sources of HE ν are still not known ➔ hints for AGN/blazars

A zoo of astrophysical ν sources

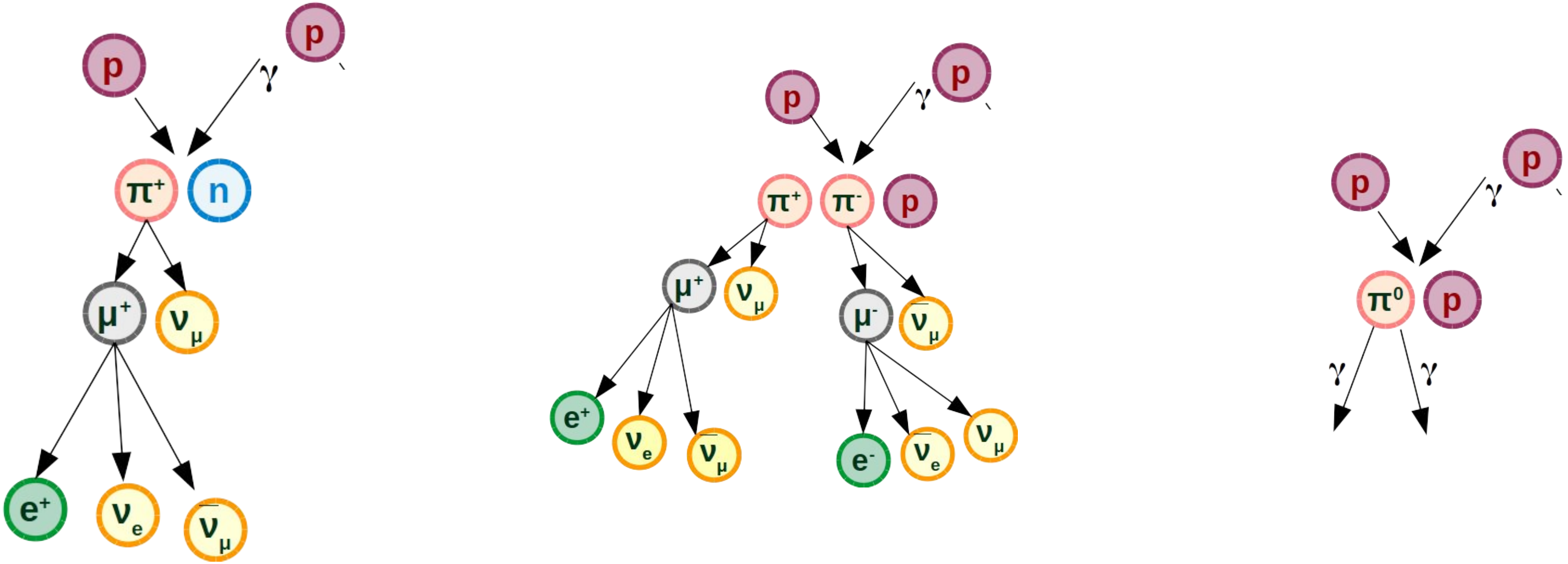






How are high-energy neutrinos produced ?

Photopion production process and/or p-p collisions



Photohadronic (pγ) interactions

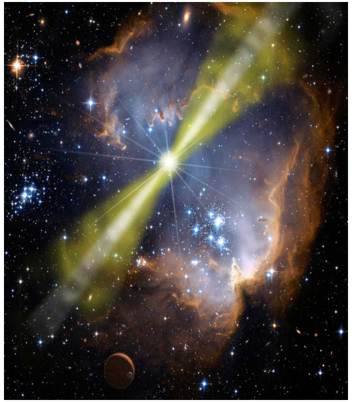
$$\tau_{p\gamma} \sim \sigma_{p\gamma} \cdot n_{\gamma,target} \cdot R$$

Photon number density

Typical source size

Abundant radiation fields

Active Galaxies



Gamma-Ray Bursts

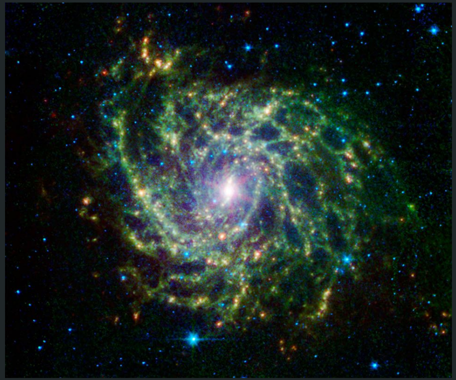
p-p inelastic collisions

$$\tau_{pp} \sim \sigma_{pp} \cdot n_{gas} \cdot R$$

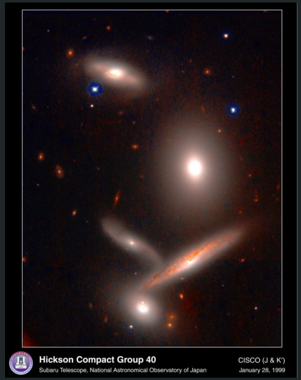
Cold proton number density

Typical source size

Abundant gas



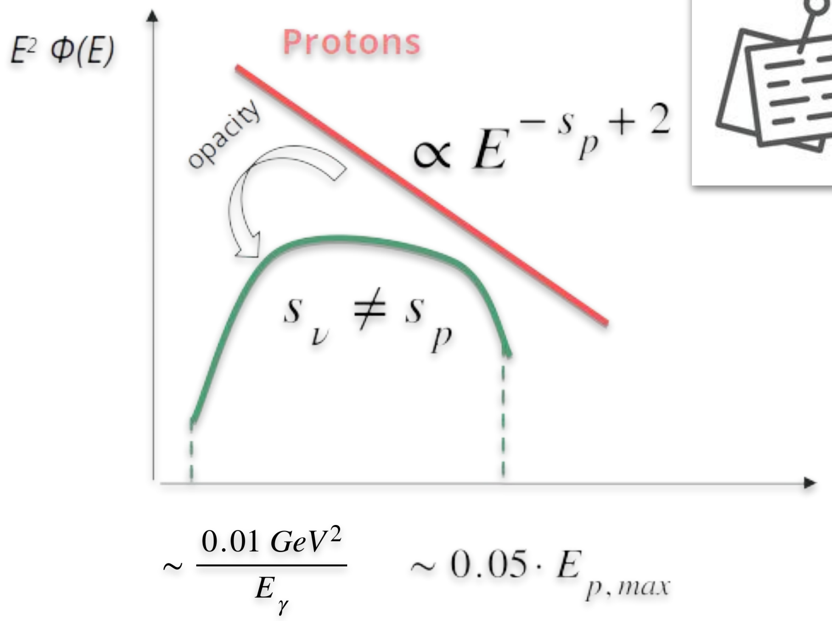
Star-forming galaxies



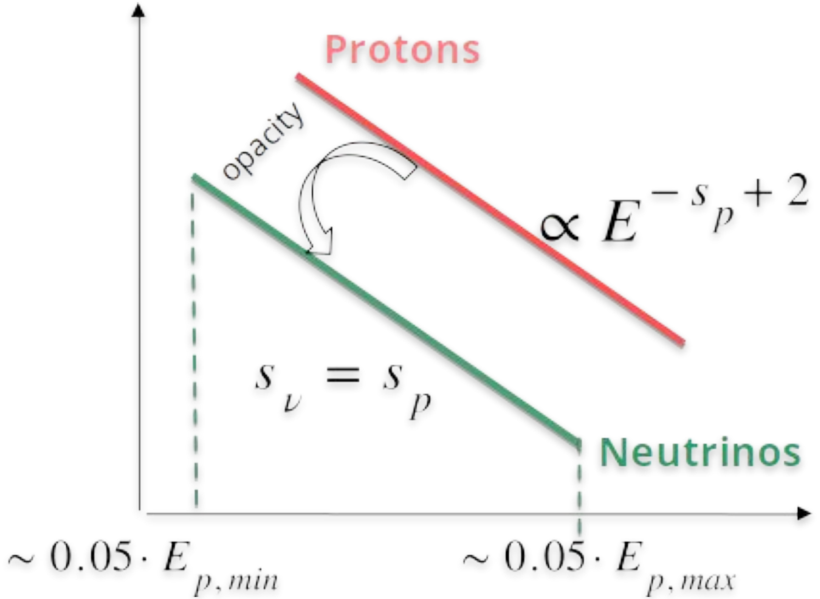
Galaxy groups/clusters

Production spectra of secondaries

Photohadronic (pγ) interactions

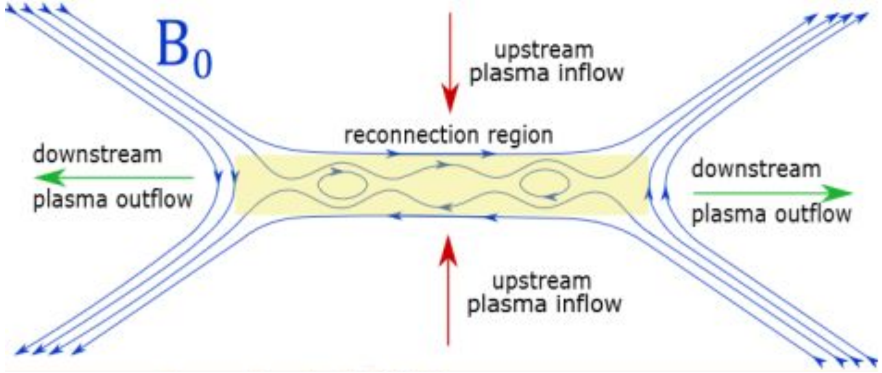


p-p inelastic collisions



How are protons accelerated ?

Magnetic reconnection



French et al., 2022

- Reconnection dissipates magnetic energy ➔ heat, bulk kinetic energy, non-thermal particle energy
- Particles can gain energy via: E-field at X-points, curvature-drift, compression of plasmoids …
- Reconnection can efficiently accelerate particles (ions & electrons) to power-law distributions

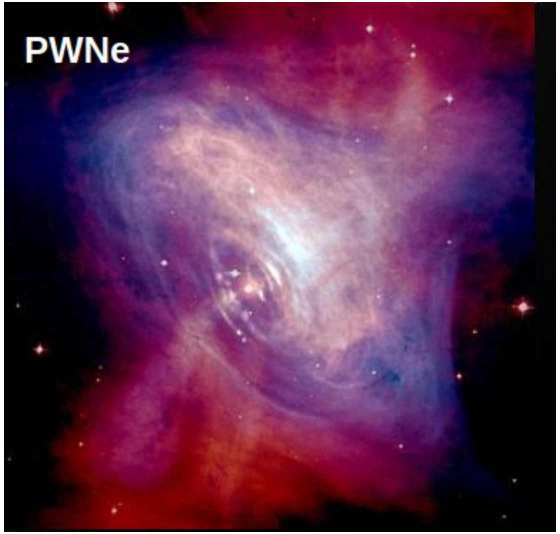
Relativistic magnetic reconnection

Relativistic magnetic reconnection

Plasma magnetization

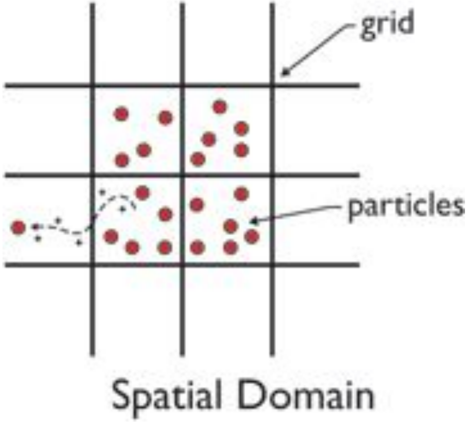
$$\sigma = \frac{B^2}{4\pi\rho c^2} >> 1$$

Accreting BHs



Credit:: Kyle Parfrey

Particle-in-Cell (PIC) method (1)



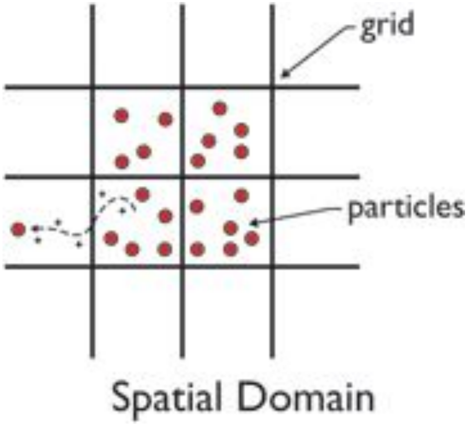
Move particles under Lorentz force

Deposit current (due to particle motion in cells) onto the grid

Solve for E, B fields on the grid points

Interpolate E,B from the grid to the particle positions in the cell

Particle-in-Cell (PIC) method (2)

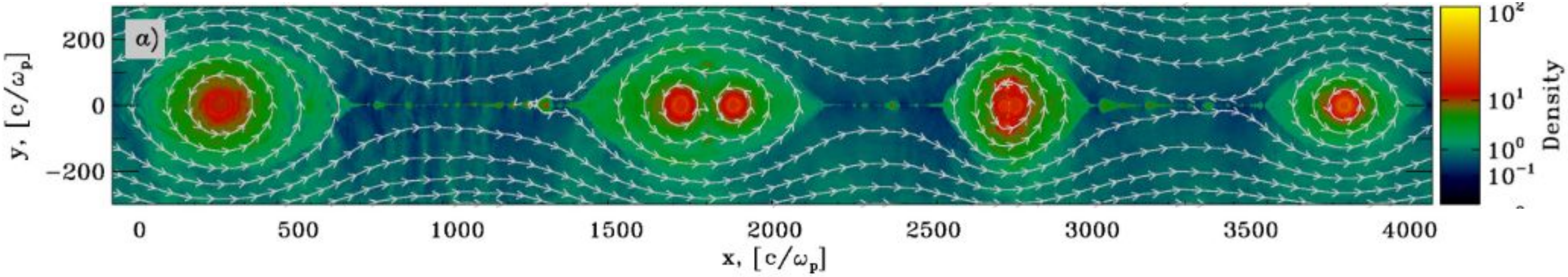


Plasma frequency

$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$$

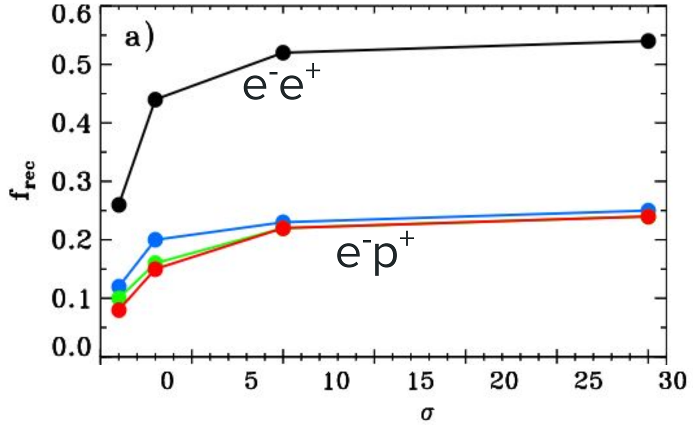
- Fully self-consistent method ➔ ideal for studying nonlinear phenomena (e.g. tearing instability)
- Tiny length scales (c/ω_p) and timescales (ω_p^{-1}) need to be resolved ➔ expensive simulations requiring super- computing, usually limited in spatial and temporal domains
- Findings from PIC have to be extrapolated to the astrophysical scales

Results from 2D PIC simulations – Global properties



Tearing instability of initial current sheet ➔ plasmoid chain and secondary current sheets

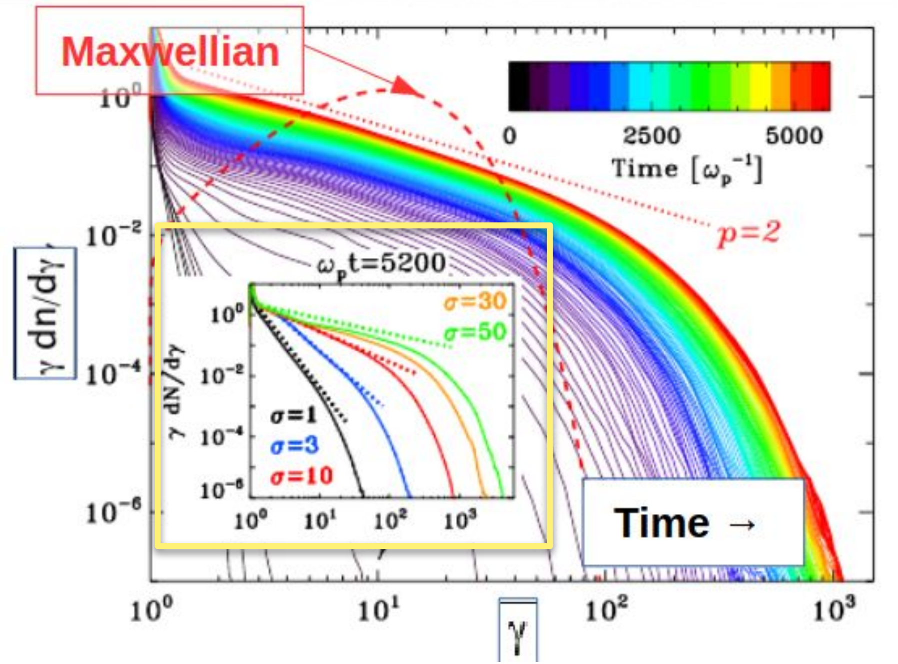
- Dissipation efficiency up to 50% (e^-e^+) or 25% (ep) without guide fields
- Rough energy equipartition between magnetic fields and non-thermal particles



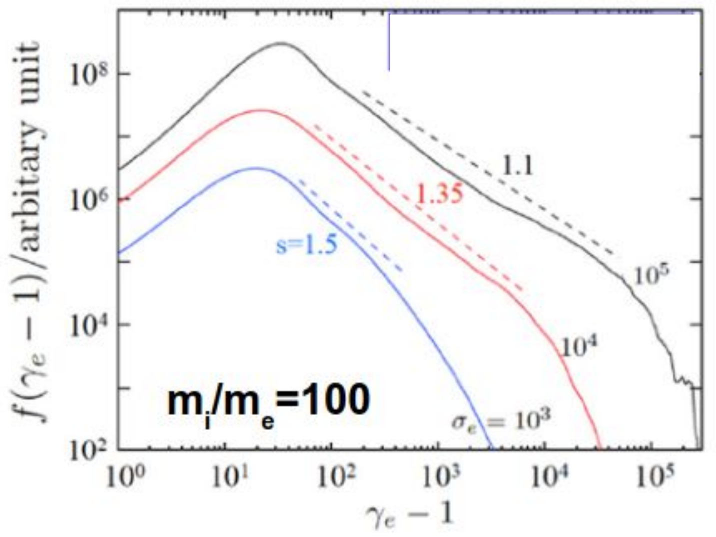
Sironi, Petropoulou, Giannios 2015, MNRAS

Results from 2D PIC simulations – particle spectra

e-e+ plasma



ep plasma

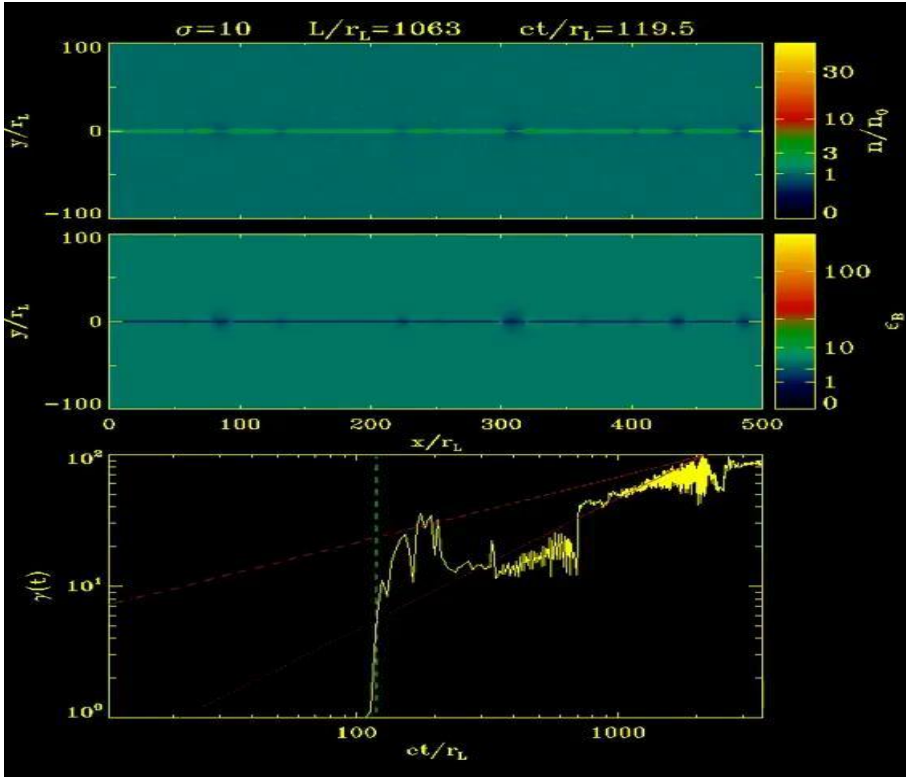


Power-law slope depends on σ

➜ harder spectra for σ >> 1

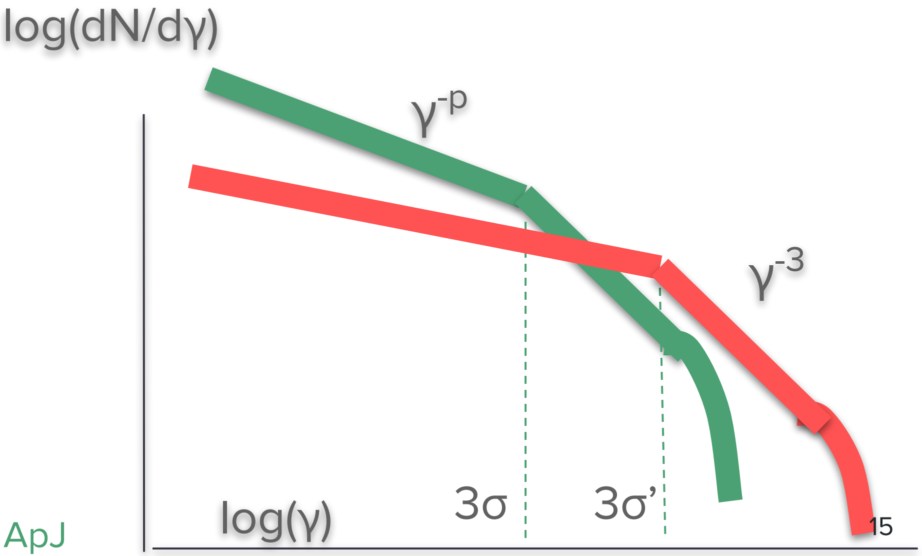
Sironi & Spitkovsky 2014; Guo et al. 2016, Werner et al. 2016

Results from 2D PIC simulations – acceleration



- 1st-stage rapid acceleration at magnetic null points (X-points) up to ~3σ
- 2nd-stage slow acceleration beyond 3σ trapped in plasmoids

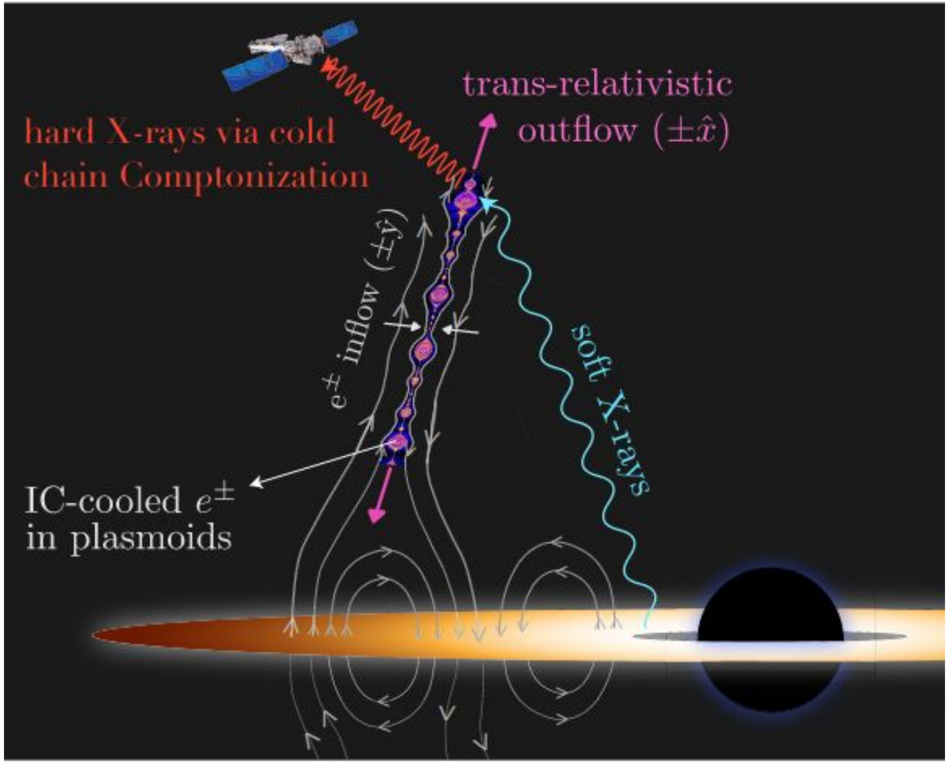
Click here



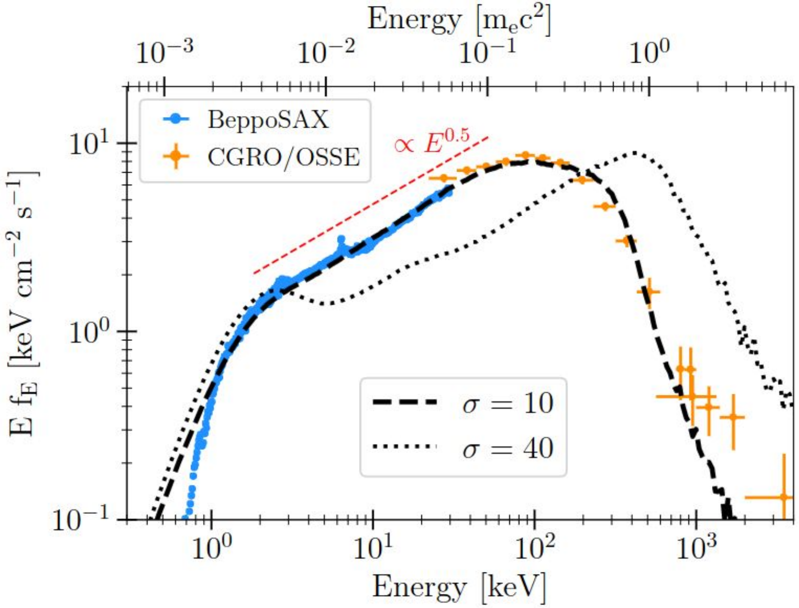
Petropoulou & Sironi, 2018 MNRAS; Hakobyan et al. 2021, ApJ

Radiative 2D PIC simulations

Click here



Cyg X-1 in the hard state

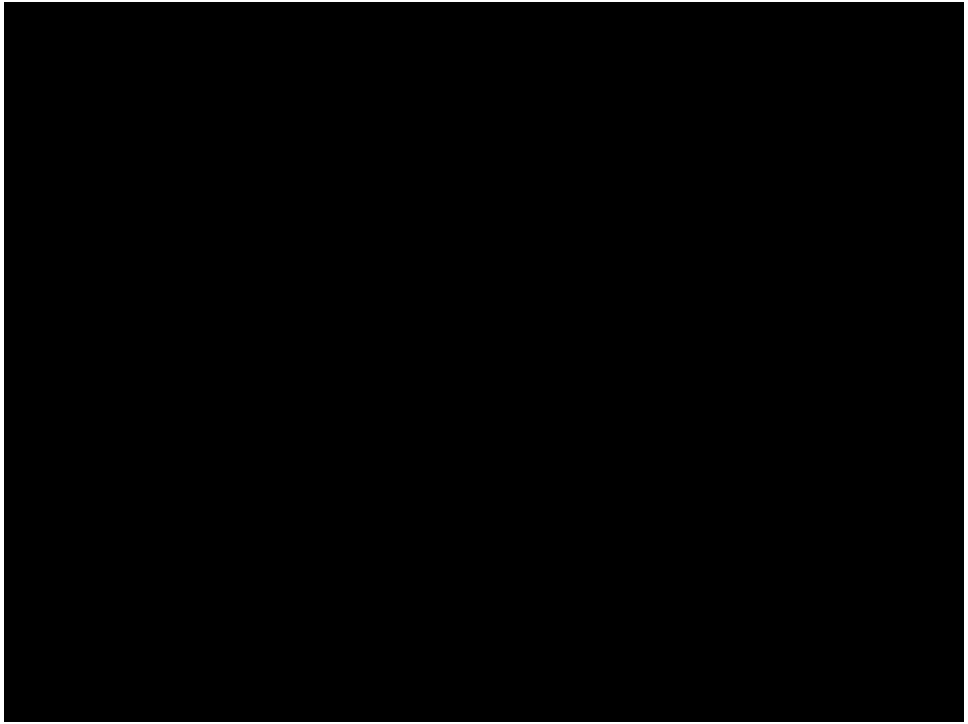


Hard X-ray flux ~ magnetic energy density

Shridhar, Sironi, Beloborodov, 2021, ApJ

Recent results from 3D PIC simulations

e-e+ plasma

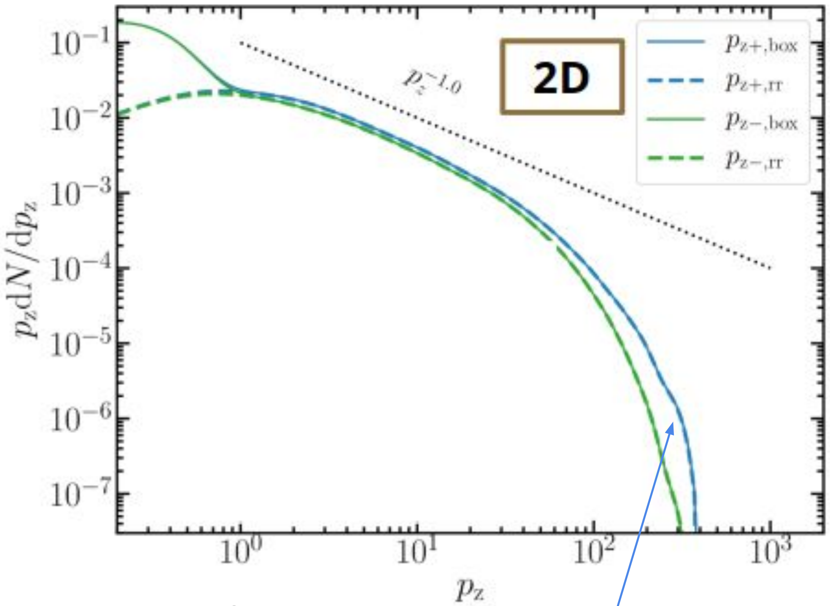


- σ=10, guide field = 0.1 Bo
- Typical length scale: L= 1560 c/ω_p
- Outflow boundary conditions in x
- Periodic boundary conditions in z
- 2 plasma injectors along y

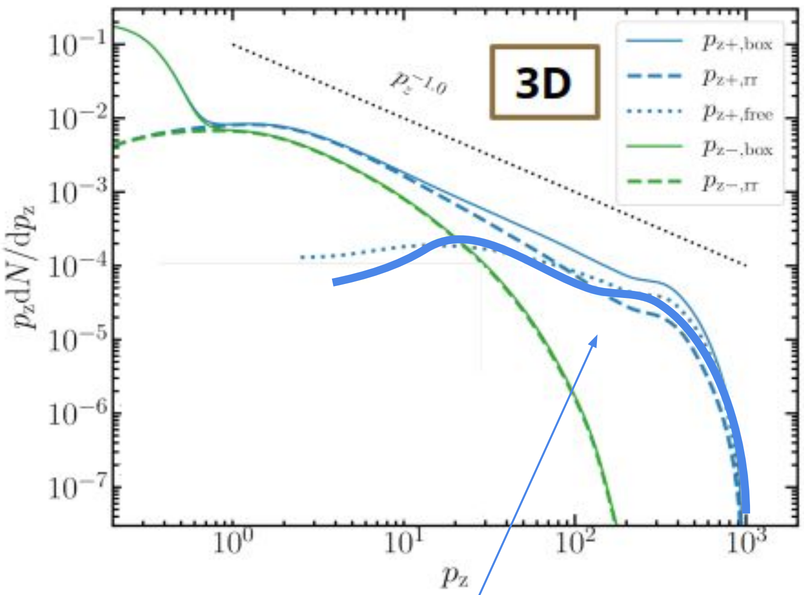
Zhang, Sironi, Giannios, 2021, ApJ

Results from 3D PIC simulations - time average spectra

Zhang, Sironi, Giannios, 2021, ApJ



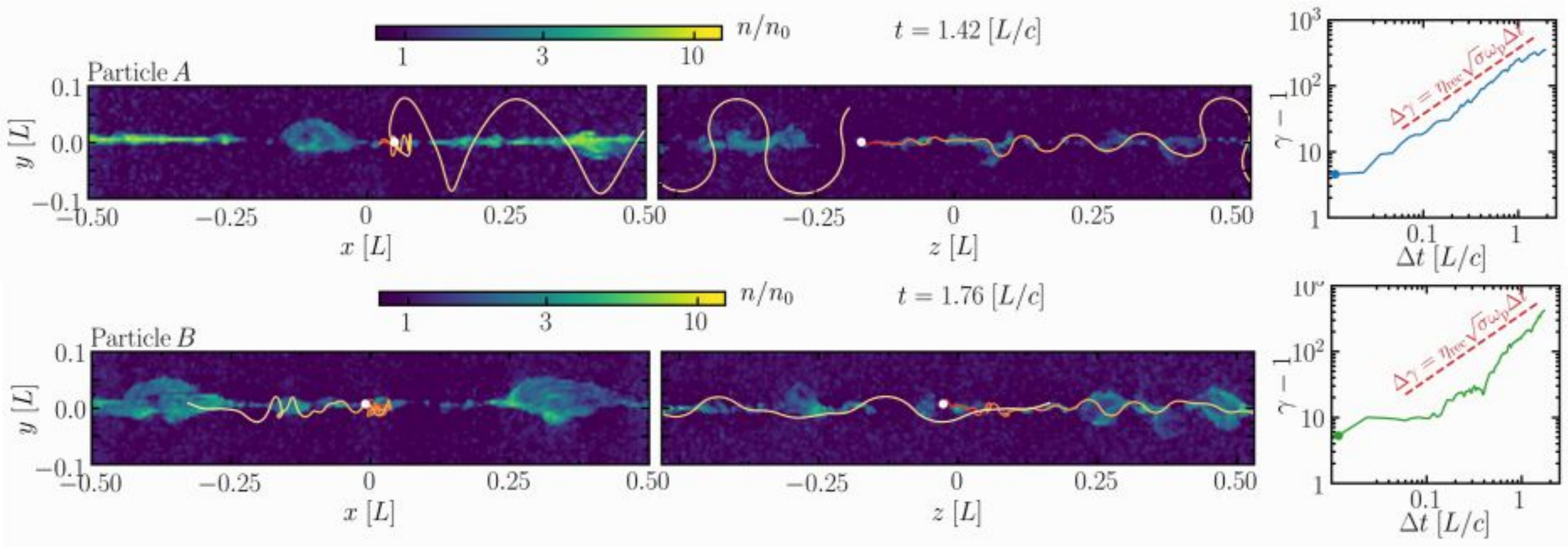
Very few high-energy particles in the upstream



High-energy (free) particles in the upstream

Results from 3D PIC simulations – acceleration

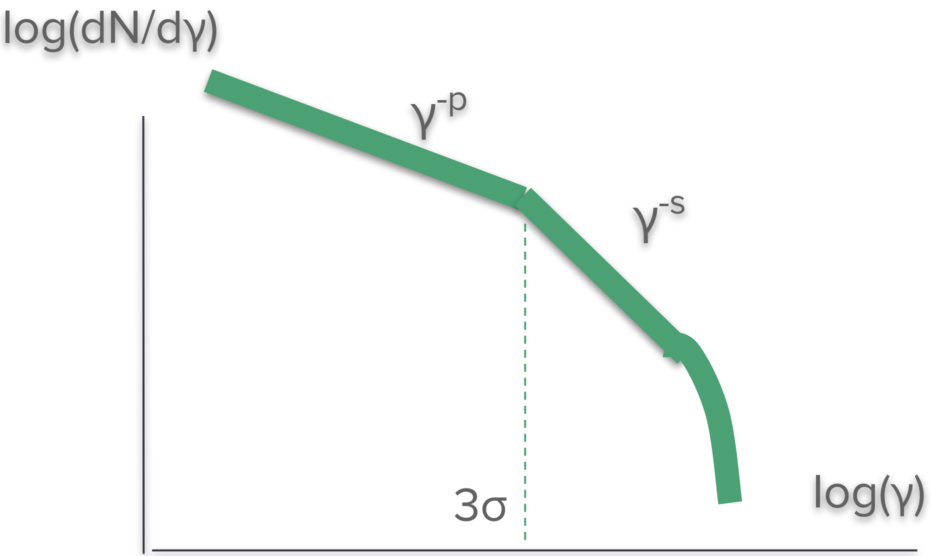
Zhang, Sironi, Giannios, 2021, ApJ



Fast acceleration beyond 3σ of particles moving in the upstream along z

$$\dot{\gamma} = \frac{\Delta\gamma}{\Delta t} \approx \frac{eE_{\rm rec}}{mc}\beta_z \approx \beta_z \eta_{\rm rec}\sqrt{\sigma}\omega_{\rm p}$$

The particle spectrum in 3D reconnection



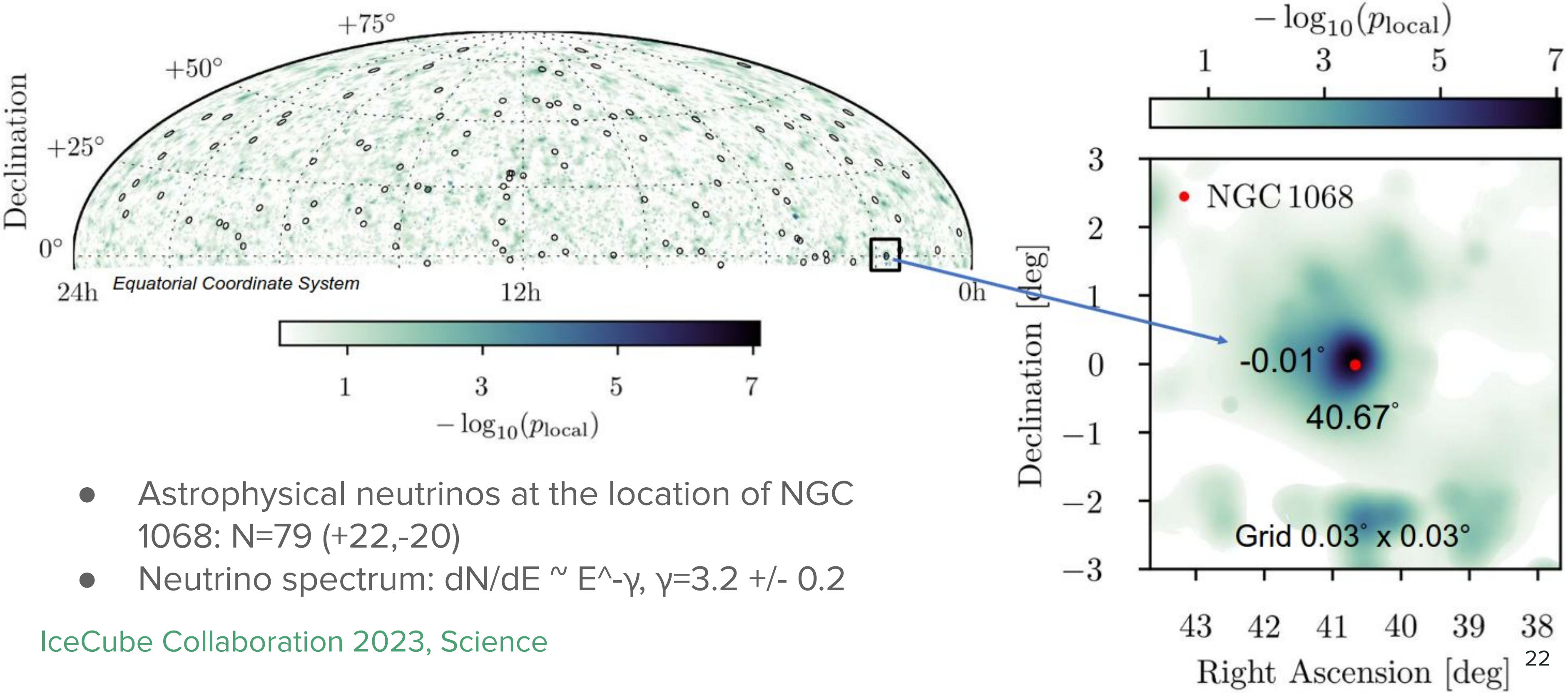
- “Injection phase”: acceleration at X-points up to ~3σ, with p(σ) and p ➔ 1-1.3 for σ >> 1

- Acceleration beyond 3σ, with s being independent of σ:
  - s ~2 (zero guide field)
  - s > 2 (non zero guide field)

See also: Werner & Uzdensky 2017, Chernoglazov et al. 2023

NGC 1068 as a neutrino source

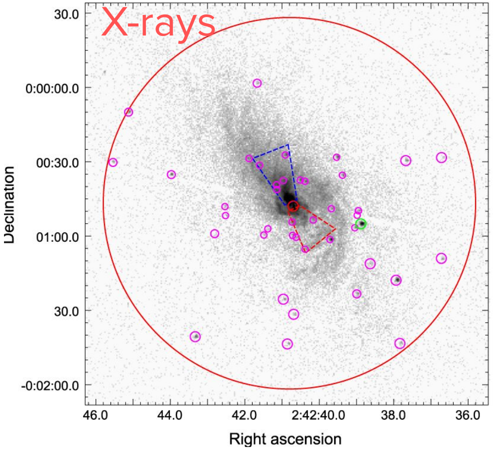
A “hot spot” in the IceCube neutrino sky map



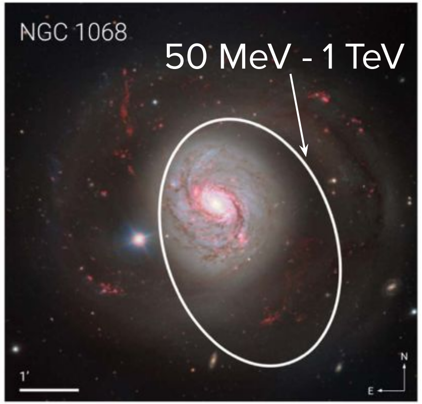
- Astrophysical neutrinos at the location of NGC 1068: N=79 (+22,-20)
- Neutrino spectrum: dN/dE ~ E^-γ, γ=3.2 +/- 0.2

IceCube Collaboration 2023, Science

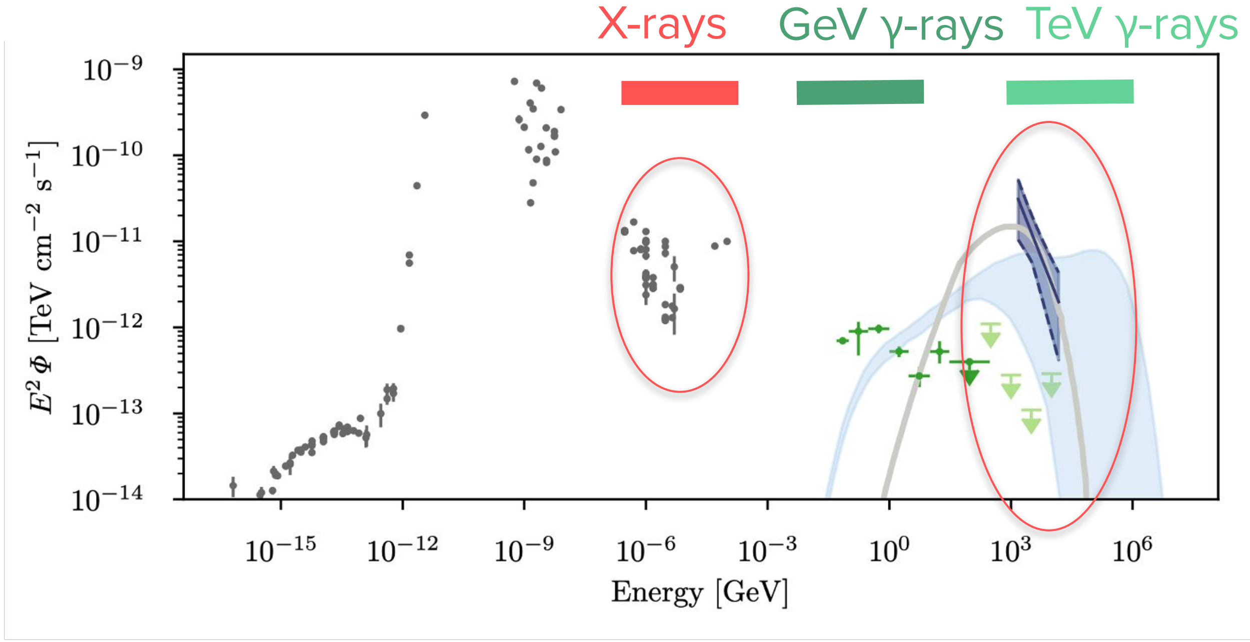
A multi-wavelength view



Bauer et al. 2015

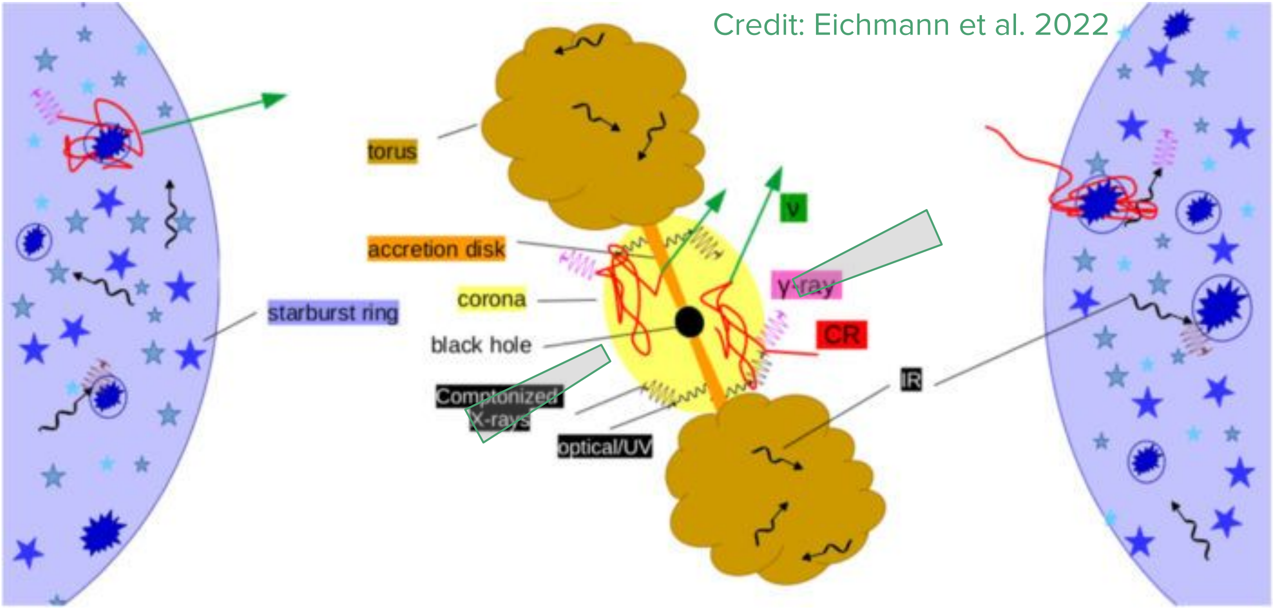


IceCube Collaboration 2023, Science



Ajello, Murase, McDaniel, 2023, ApJ

NGC 1068: a complex environment

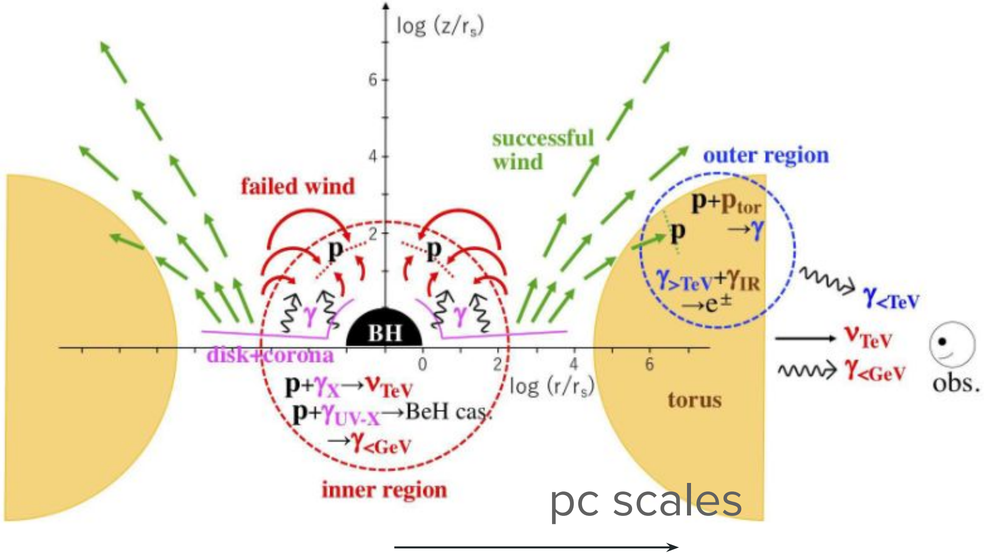


Credit: Eichmann et al. 2022

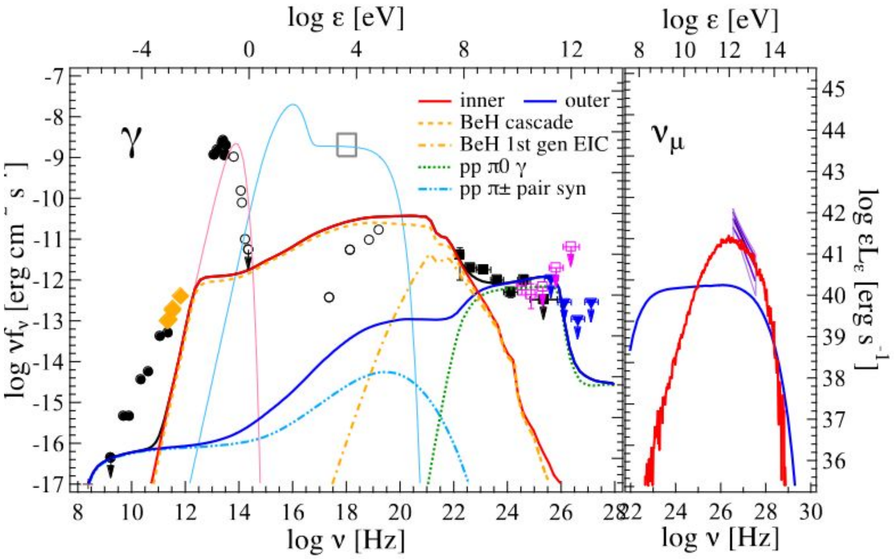
Many potential sites for proton acceleration and neutrino production

NGC 1068: many theoretical models

“Multi-zone” models



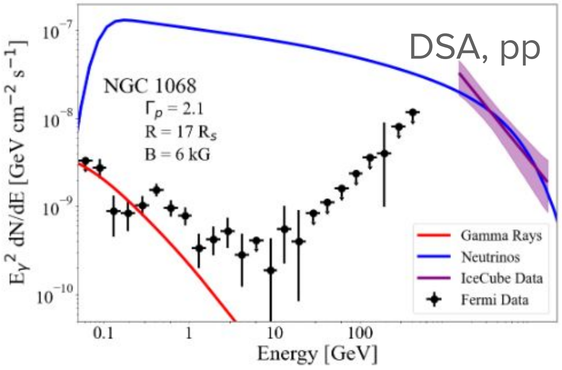
Inoue, Cerruti et al. (arXiv:2207.02097)



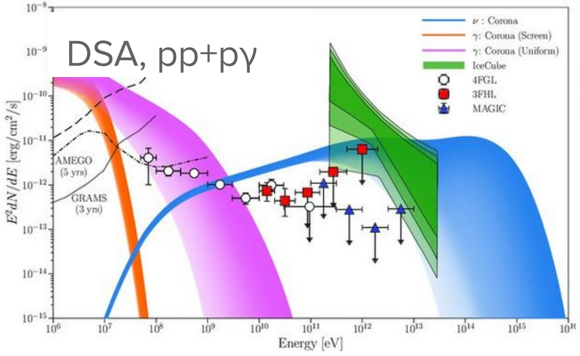
See also Eichmann et al. 2022

NGC 1068: many theoretical models

“Coronal” models

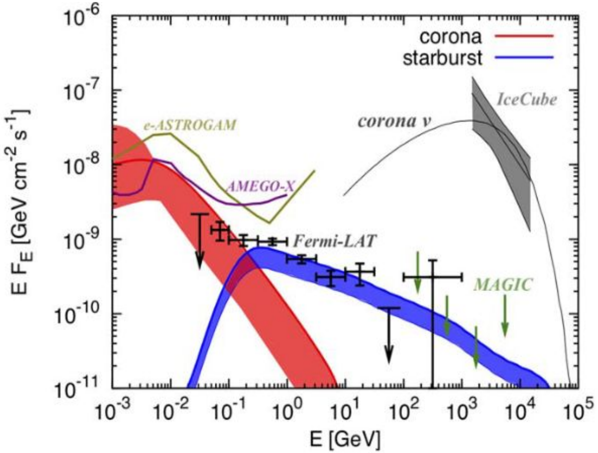


Blanco et al. (arXiv:2307.03259)



Inoue, Khangulyan, Doi, 2020, ApJ

Magnetic dissipation, pp+pγ



Ajello, Murase, McDaniel, 2023, ApJ (see also Murase et al. 2020, Murase 2022)

A constrained, reconnection-based model for NGC 1068

Fiorillo et al. 2023 (arXiv:2310.18254)

Our model

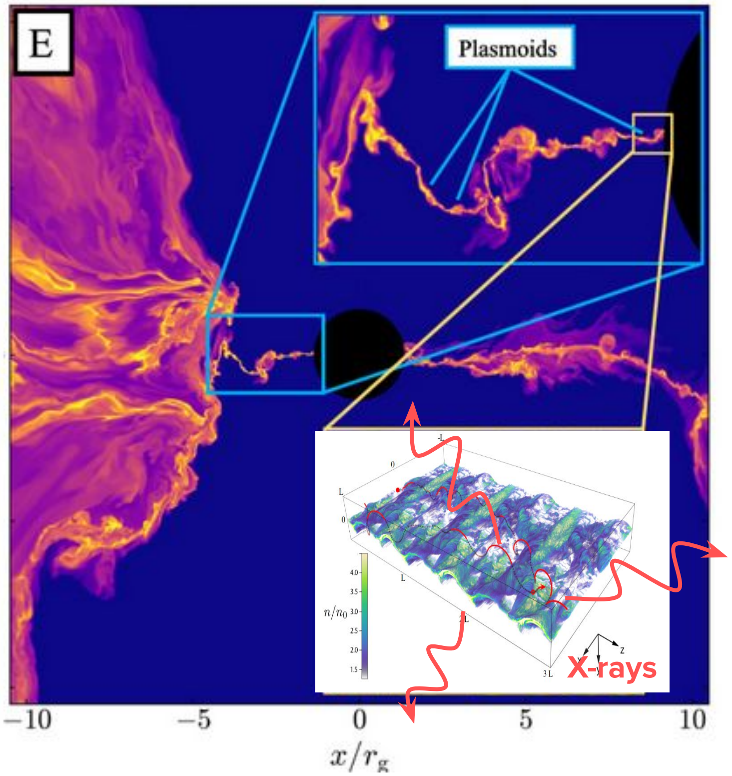


Image from Ripperda et al. 2022, ApJL

Magnetic energy density

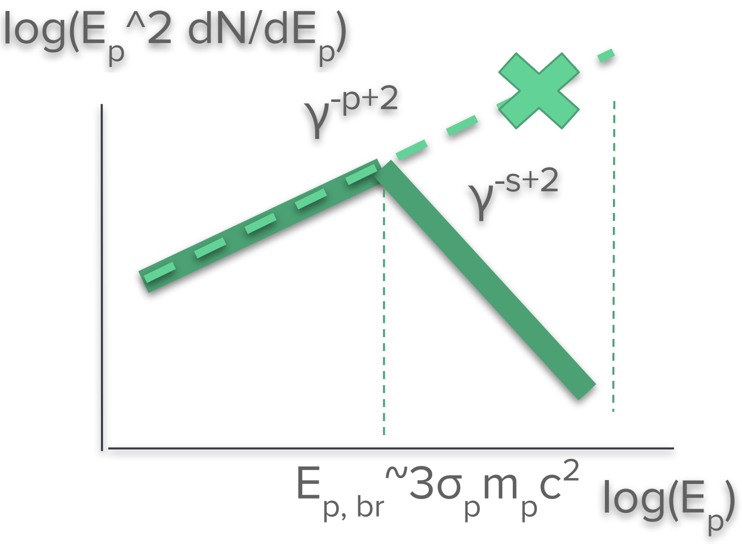
~ 0.1 → Relativistic proton energy density

~ 0.5 → Comptonized X-ray flux

Thomson opacity ~ 0.5 → Pair density

$$n_e \simeq 10^{12}\,\beta_{-1}^{-1}\left(\frac{LM_7}{5r_g}\right)^{-1}\,\mathrm{cm}^{-3}$$

Our model



Magnetic energy density

Relativistic proton energy density

+

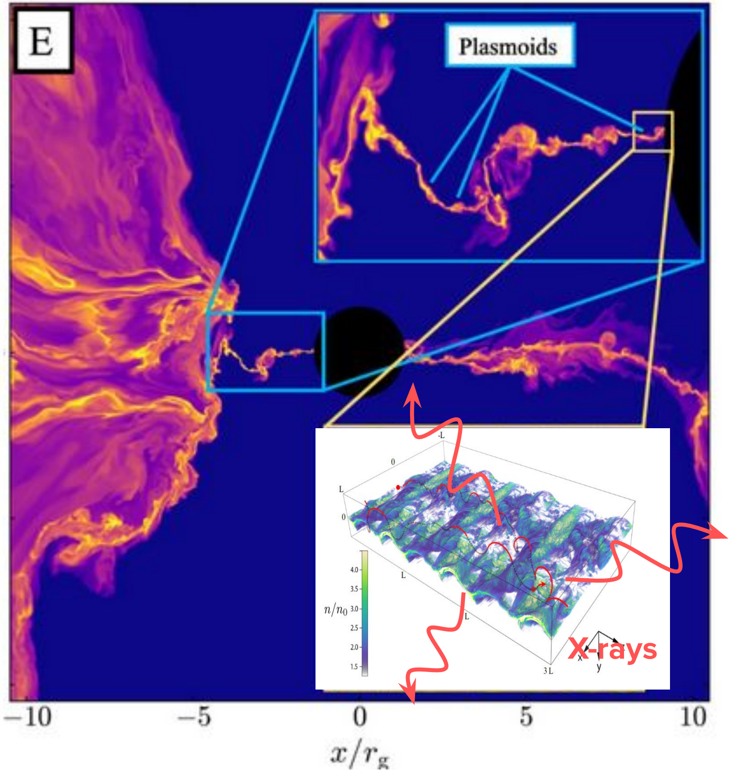
Proton spectrum

Comptonized X-ray flux

Thomson opacity ~ 0.5

Pair density

Our model



Magnetic energy density

Relativistic proton energy density

Comptonized X-ray flux

+

Thomson opacity ~ 0.5

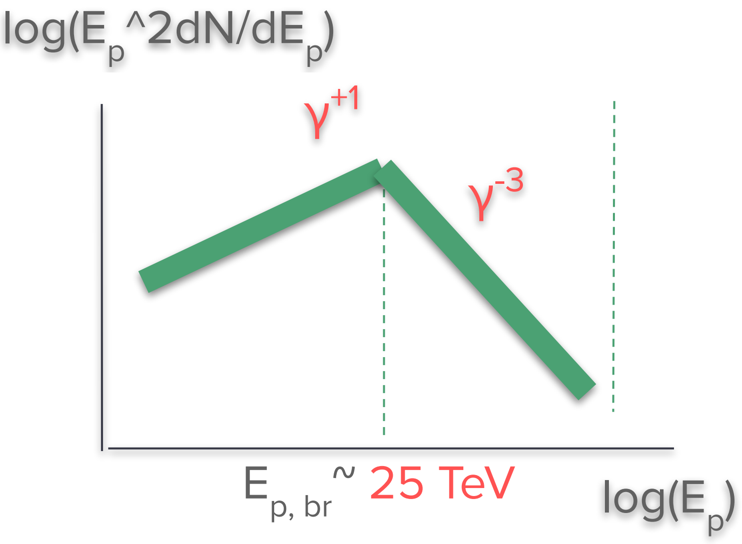
Proton spectrum

pγ

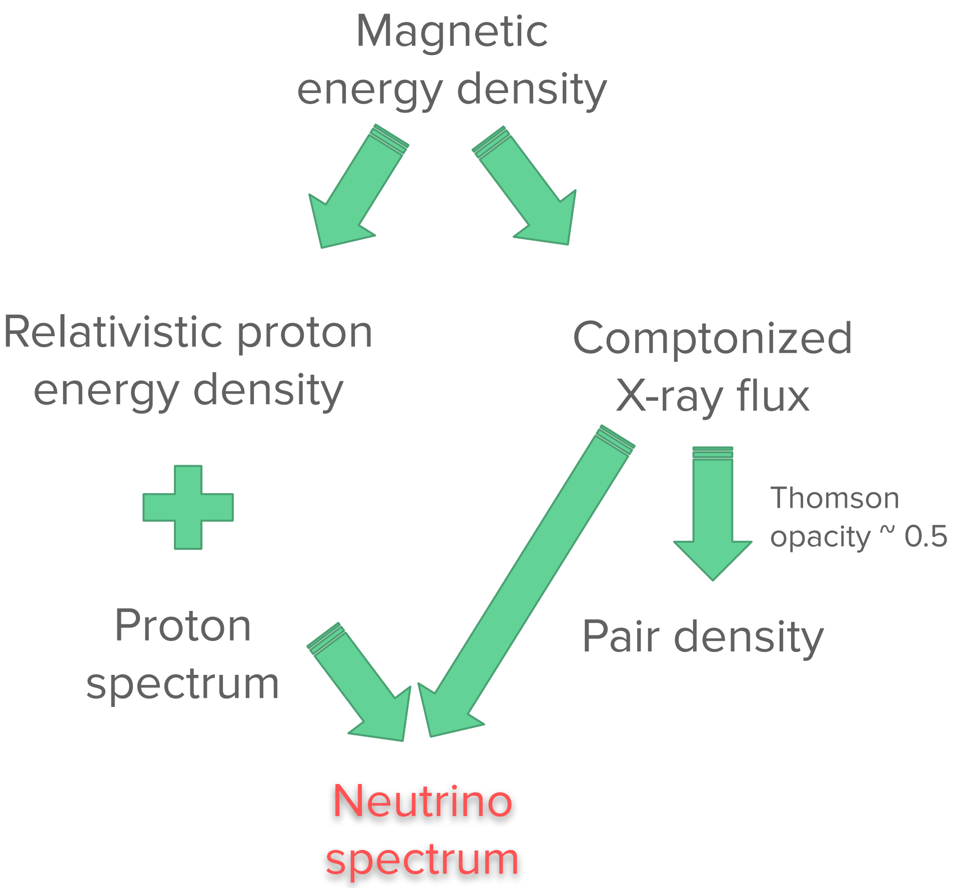
Pair density

Neutrino spectrum

Our model

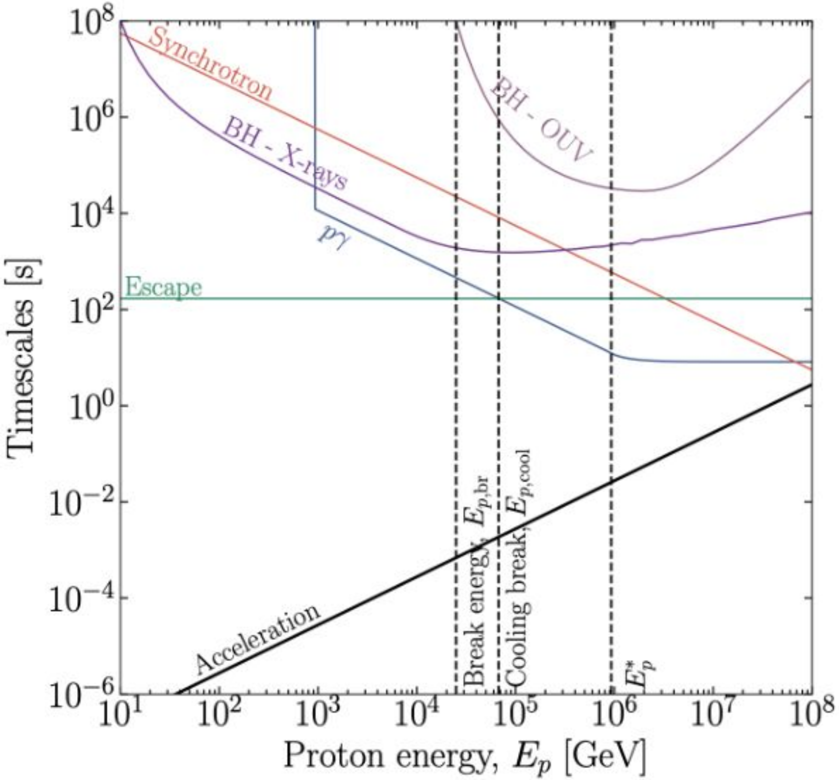


log(E_p^2dN/dE_p)
γ^{+1}
γ^{-3}
$E_{p,\ br}$ ~ 25 TeV
log(E_p)



Magnetic energy density
Relativistic proton energy density
Comptonized X-ray flux
Thomson opacity ~ 0.5
Proton spectrum
Pair density
Neutrino spectrum

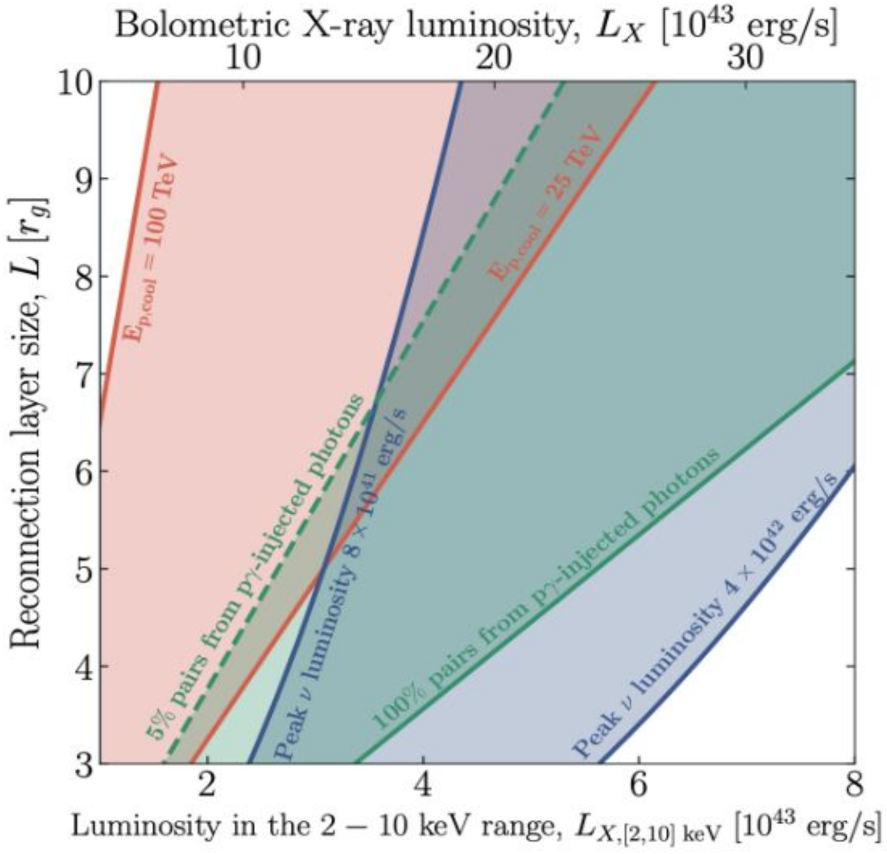
Hierarchy of proton energy scales



- $E_{p,br}$: break of proton spectrum, inferred from peak of ν spectrum.
- $E_{p,cool}$: pγ cooling time = escape time from the reconnection layer.
- E_p^* : change of photo-hadronic efficiency (dependent on the lower cutoff of the X-ray spectrum).
- $E_{p,rad}$: pγ cooling time = acceleration time.

$$E_{p,\mathrm{br}} \lesssim E_{p,\mathrm{cool}} < E_p^* < E_{p,\mathrm{rad}}$$

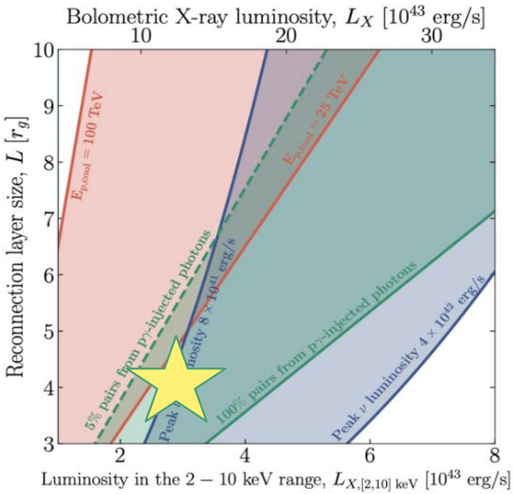
A constrained problem

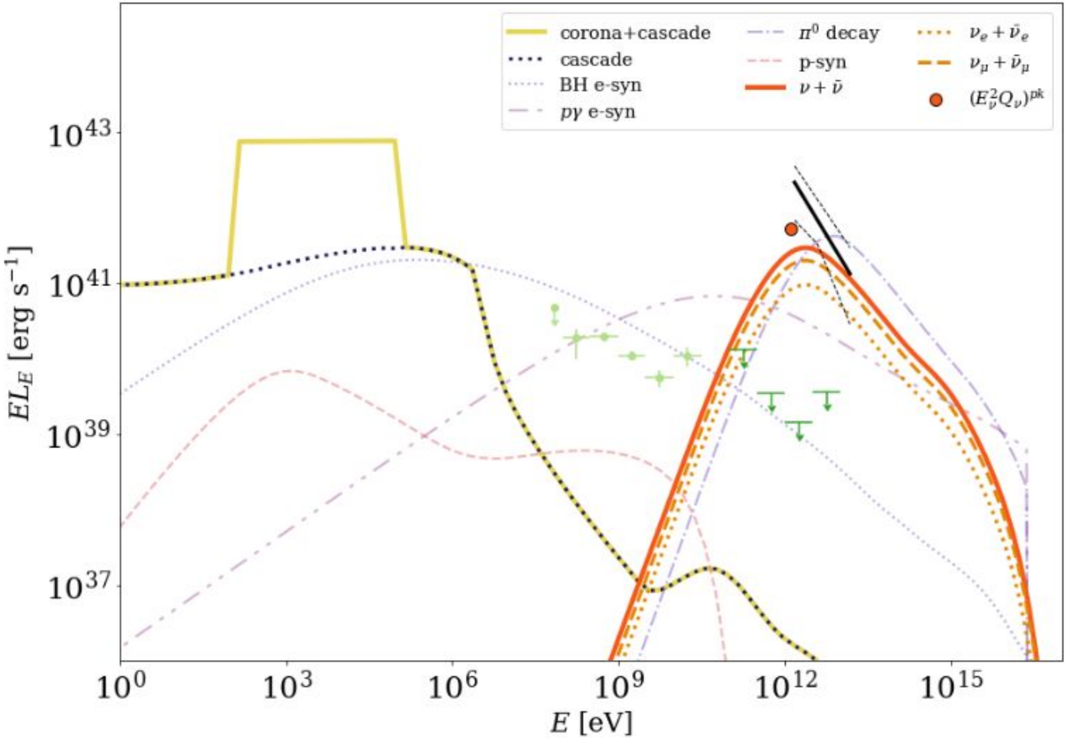


Constraints:

- $E_{p,br}$ ~25 TeV (from peak neutrino energy)
- $E_{p,br}$ ~ $E_{p,cool}$ ➔ almost calorimetric limit
- L_ν ~ (0.8-4)*1E+42 erg/s (all flavor)
- L_X ~ (1-6)*1E+43 erg/s (2-10keV)

Results





- Compact corona: L~ (3-10)*Rg
- Highly magnetized corona: σ_e ~ 1E+2 and σ_p~1E+5

Click here

- Pairs from the proton-initiated cascade may account for most of the leptons required by Thomson opacity

Conclusions & Outlook

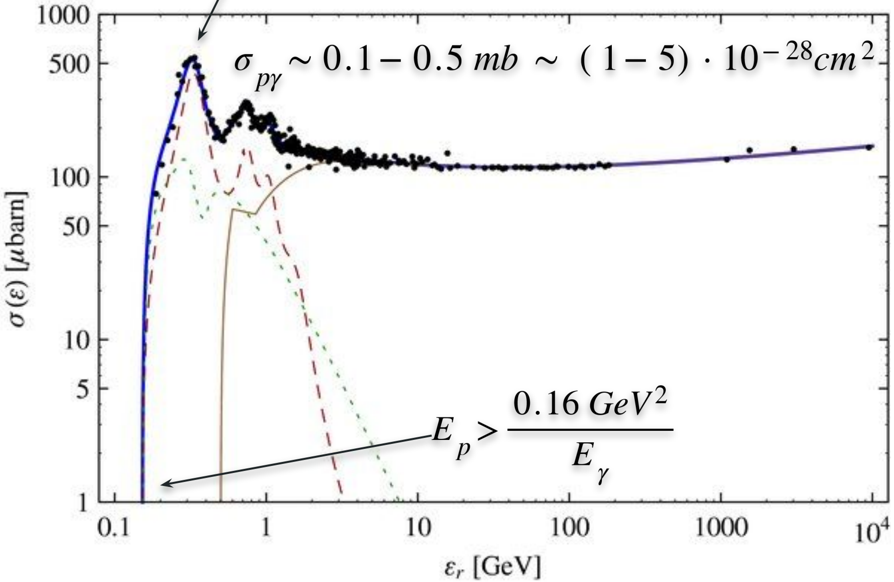
- Sources of diffuse astrophysical neutrino flux are still unknown, but there are strong hints that AGN cores and jets are neutrino emitters.
- Relativistic magnetic reconnection is a fast acceleration process, leading to (broken) power-law particle distributions.
- Magnetic dissipation in a compact, strongly magnetized corona could power hard X-ray and TeV emission from NGC 1068.

- What does our model predict for other Seyfert galaxies?
- What is the role of pairs from $p\gamma$ interactions in shaping the Comptonized X-ray spectrum?
- 3D simulations of magnetic reconnection in high proton-sigma plasmas are needed for an accurate characterization of the post-break spectrum.

Backup slides

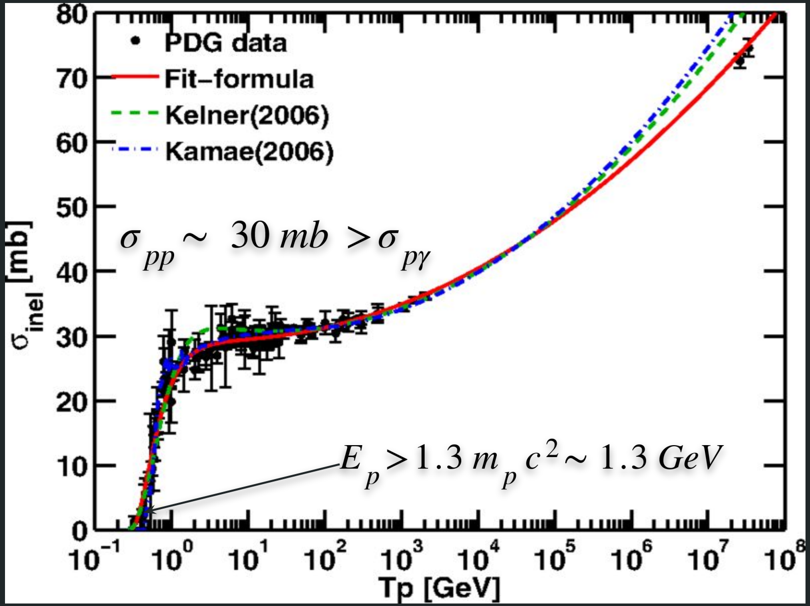
Photohadronic (pγ) interactions

$$p + \gamma_{target} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \left(Br = 2/3 \right) \\ n + \pi^{+} \left(Br = 1/3 \right) \end{cases}$$



P-P inelastic collisions

$$p + p_{gas} \rightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$



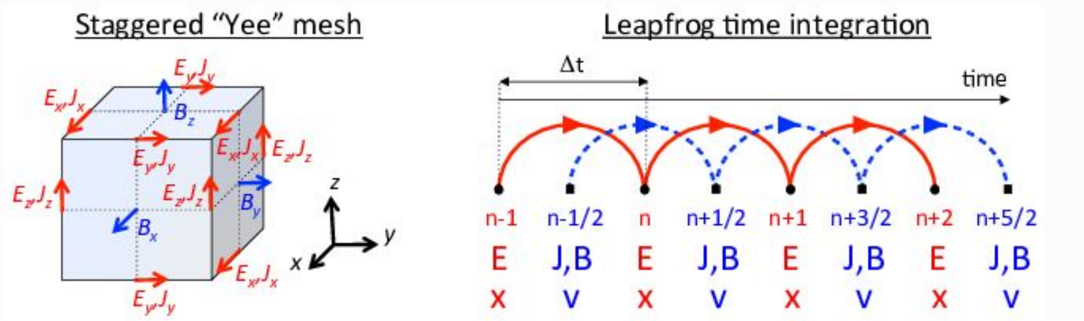
Particle-in-Cell (PIC) method

Particle pusher

$$\frac{d\mathbf{x}}{dt} = \mathbf{v},$$
$$\frac{d(\gamma\mathbf{v})}{dt} = \frac{q}{m}(\mathbf{E} + \mathbf{v}\times\mathbf{B}),$$

$$\frac{\mathbf{x}^{i+1} - \mathbf{x}^{i}}{\Delta t} = \mathbf{v}^{i+1/2},$$
$$\frac{\gamma^{i+1/2}\mathbf{v}^{i+1/2} - \gamma^{i-1/2}\mathbf{v}^{i-1/2}}{\Delta t} = \frac{q}{m}\left(\mathbf{E}^{i} + \bar{\mathbf{v}}^{i}\times\mathbf{B}^{i}\right).$$

Field solver



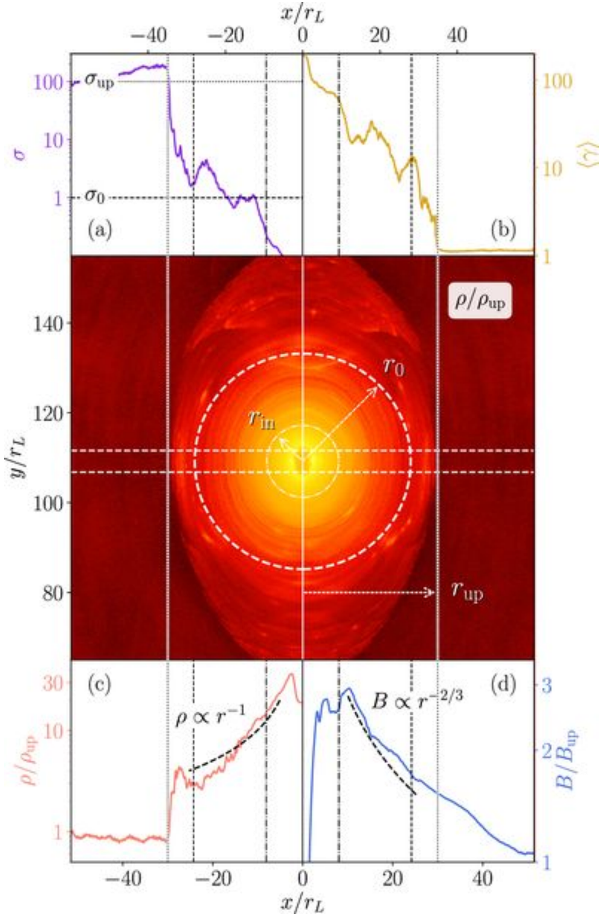
$$\begin{aligned}
\frac{\partial\mathbf{B}}{\partial t} &= -\nabla\times\mathbf{E} \\
\frac{\partial\mathbf{E}}{\partial t} &= \nabla\times\mathbf{B} - \mathbf{J} \\
\nabla\cdot\mathbf{E} &= \rho \\
\nabla\cdot\mathbf{B} &= 0
\end{aligned}$$

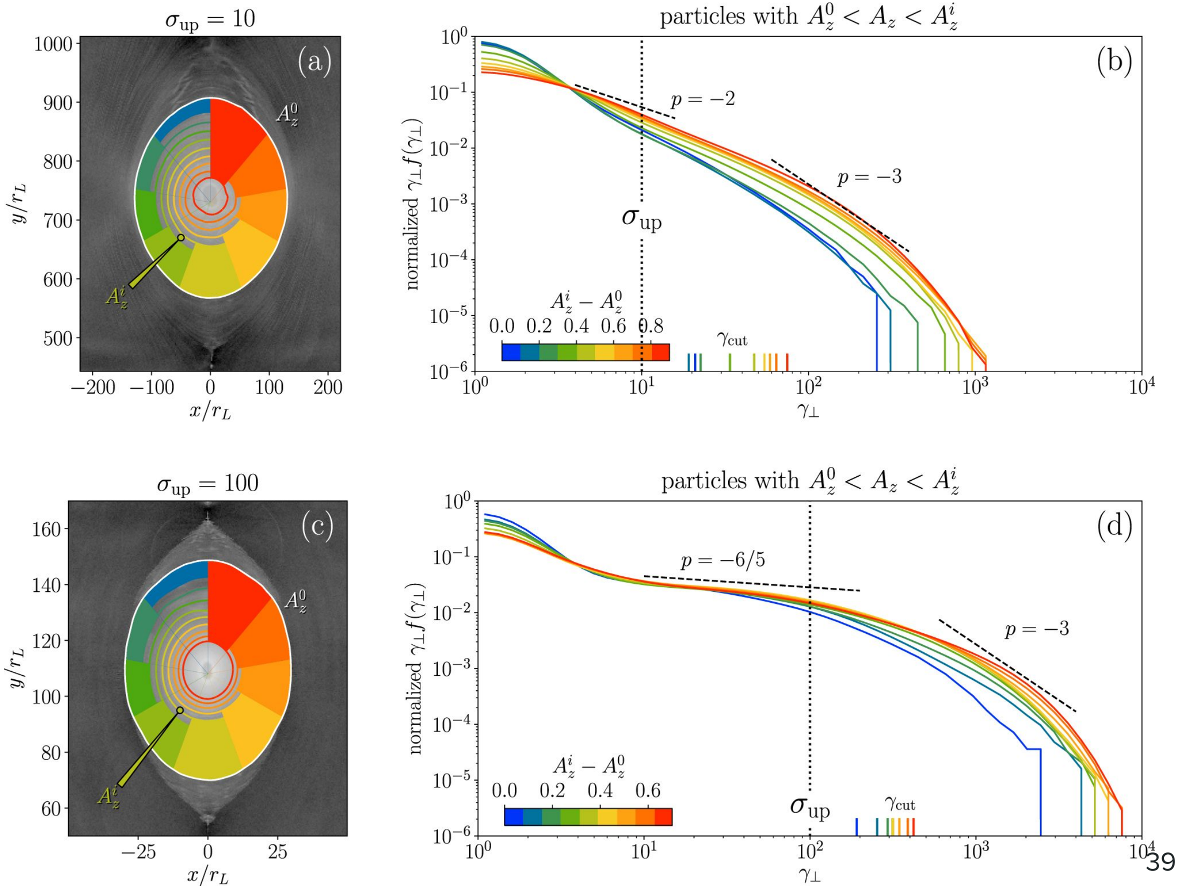
$$D_t G|^{n}_{i,j,k} = \left(G|^{n+1/2}_{i,j,k} - G|^{n-1/2}_{i,j,k}\right)/\Delta t$$

$$D_x G|^{n}_{i,j,k} = \left(G|^{n}_{i+1/2,j,k} - G|^{n}_{i-1/2,j,k}\right)/\Delta x$$

Plasmoid internal structure and particle distribution

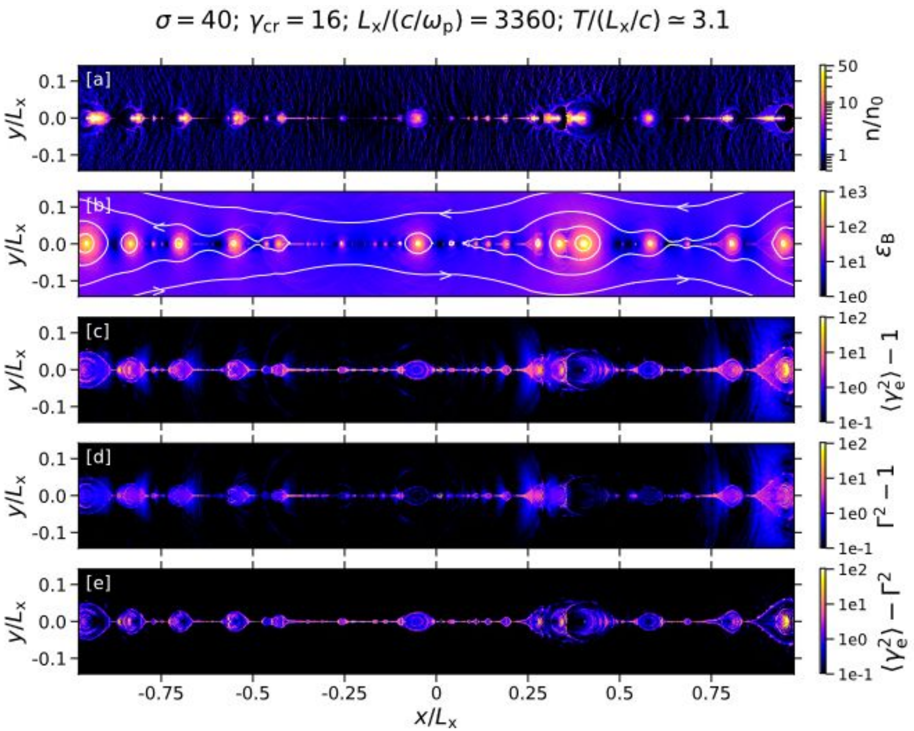
Click here



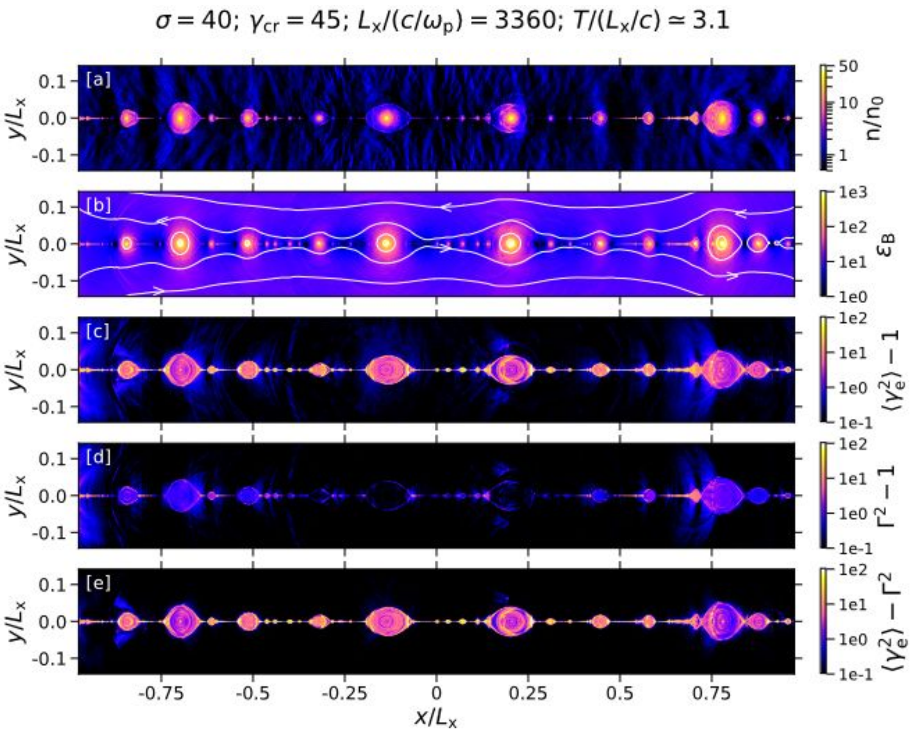


Impact of IC cooling on plasmoid chain

Click here



(i) Strong IC cooling

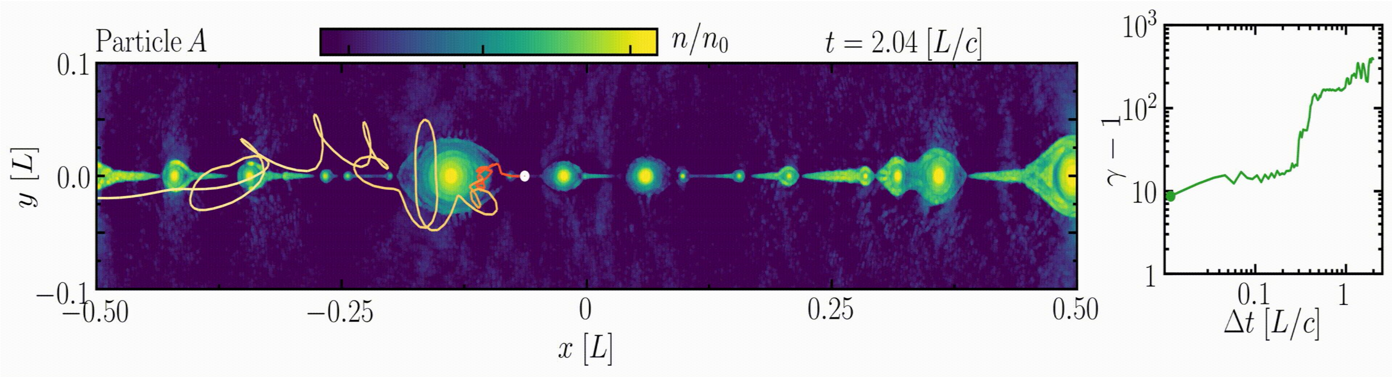


(ii) Moderate IC cooling

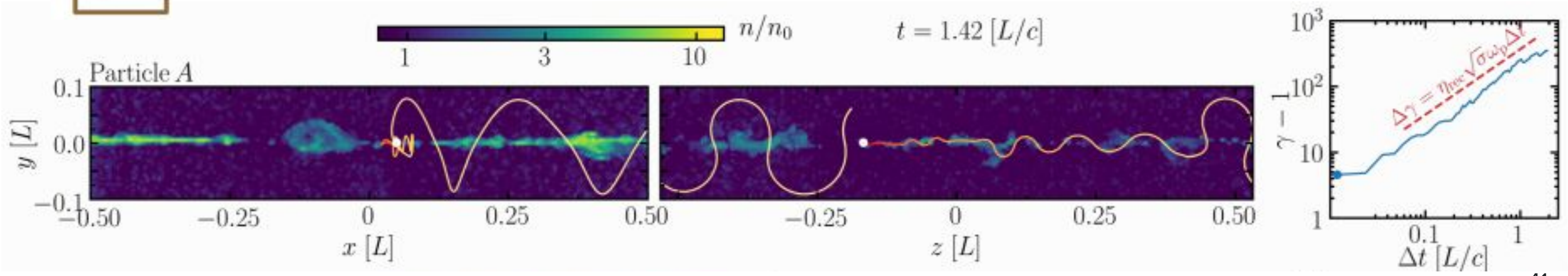
Particle trajectories in 2D vs 3D simulations

Zhang, Sironi, Giannios, 2021, ApJ

2D

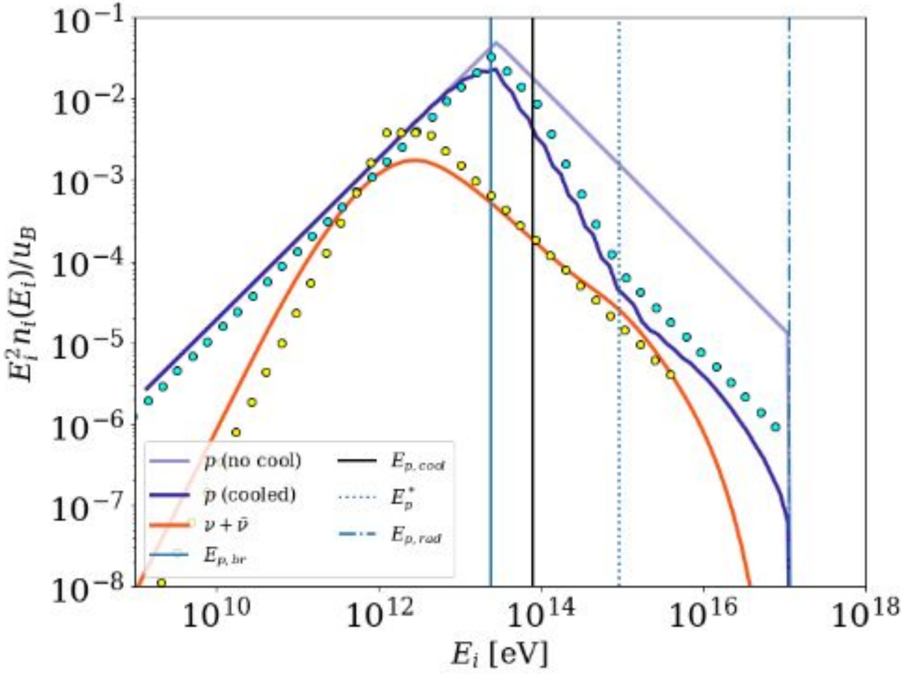


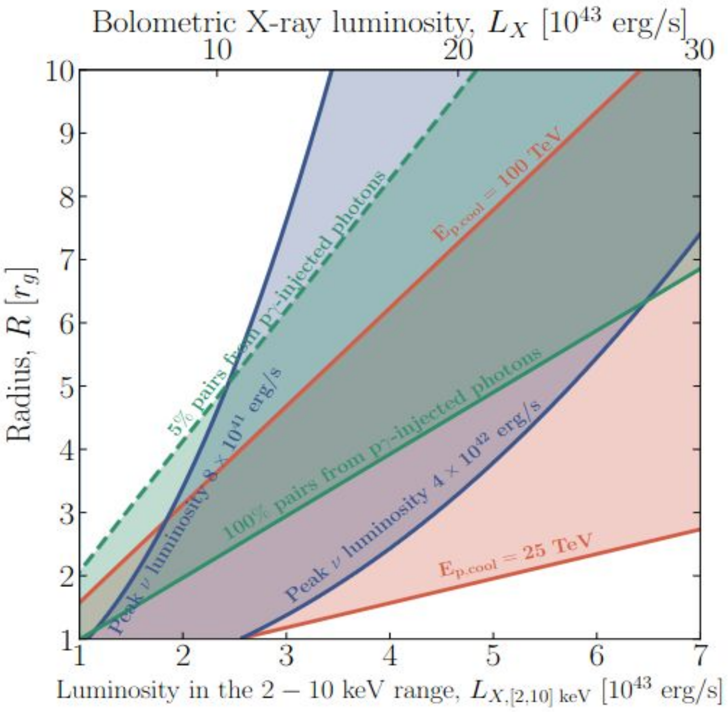
3D



Proton and neutrino spectra from NGC 1068

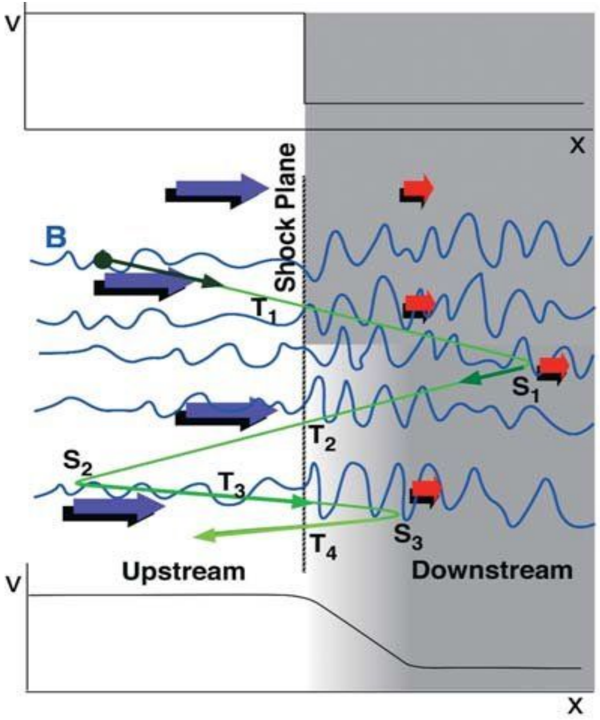
Click here





How are protons accelerated ?

Shock acceleration



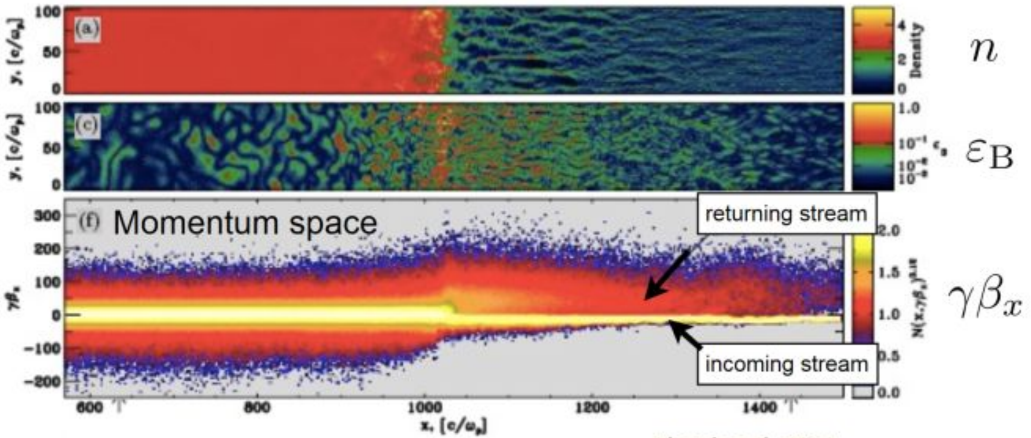
Möbius & Kallenbach, 2005, ISSI Scientific Reports Series

- Shocks dissipate bulk kinetic energy ➔ internal energy, non-thermal particle energy
- Fermi acceleration ➔ particles gain energy via multiple scatterings across a velocity gradient (there is also shock-drifting, ...)
- Shocks can efficiently accelerate particles with power law distributions, unless we consider
  - High magnetization σ plasma
  - Superluminal shocks

Relativistic shocks

$$\boxed{\begin{array}{c}\sigma = 0 \\ \gamma_0 = 15\end{array}}$$

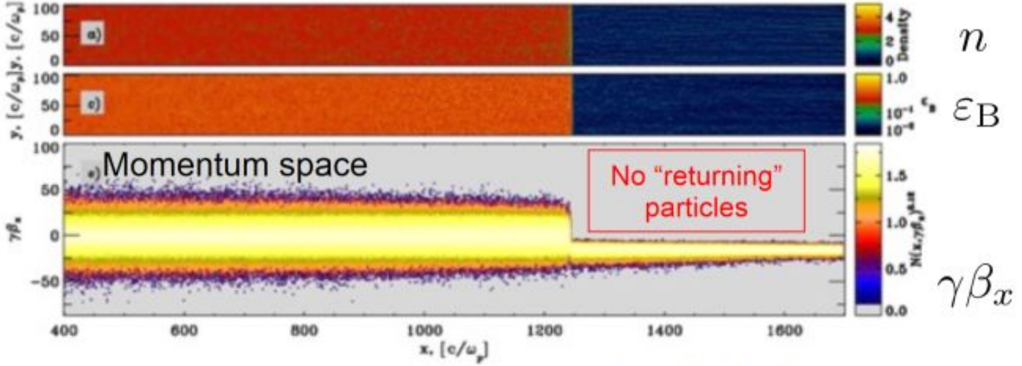
Low-σ shocks:
- returning particles
- filamentation instabilities



Sironi et al. 2013

$$\boxed{\begin{array}{c}\sigma = 0.1 \\ \gamma_0 = 15\end{array}}$$

High-σ shocks:
- no returning particles
- no turbulence



Sironi & Spitkovsky 2011