lecture 2. particle acceleration and astrophysical sources of high-energy particles

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Advanced Astroparticle Physics

NPAC M2

2024-2025

in today's class...

- **shocks**
  - Euler equations
  - jump conditions
  - shocks in astrophysics
- **cosmic accelerators**
  - requirements
  - sources

acceleration mechanisms

acceleration paradigms

top-down models

- cosmic strings
- topological defects
- super-heavy dark matter
- Z-bursts
- other exotic mechanisms

bottom-up models

- electromagnetic acceleration
- gravitational acceleration

Fermi 2nd order: stochastic shock acceleration

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

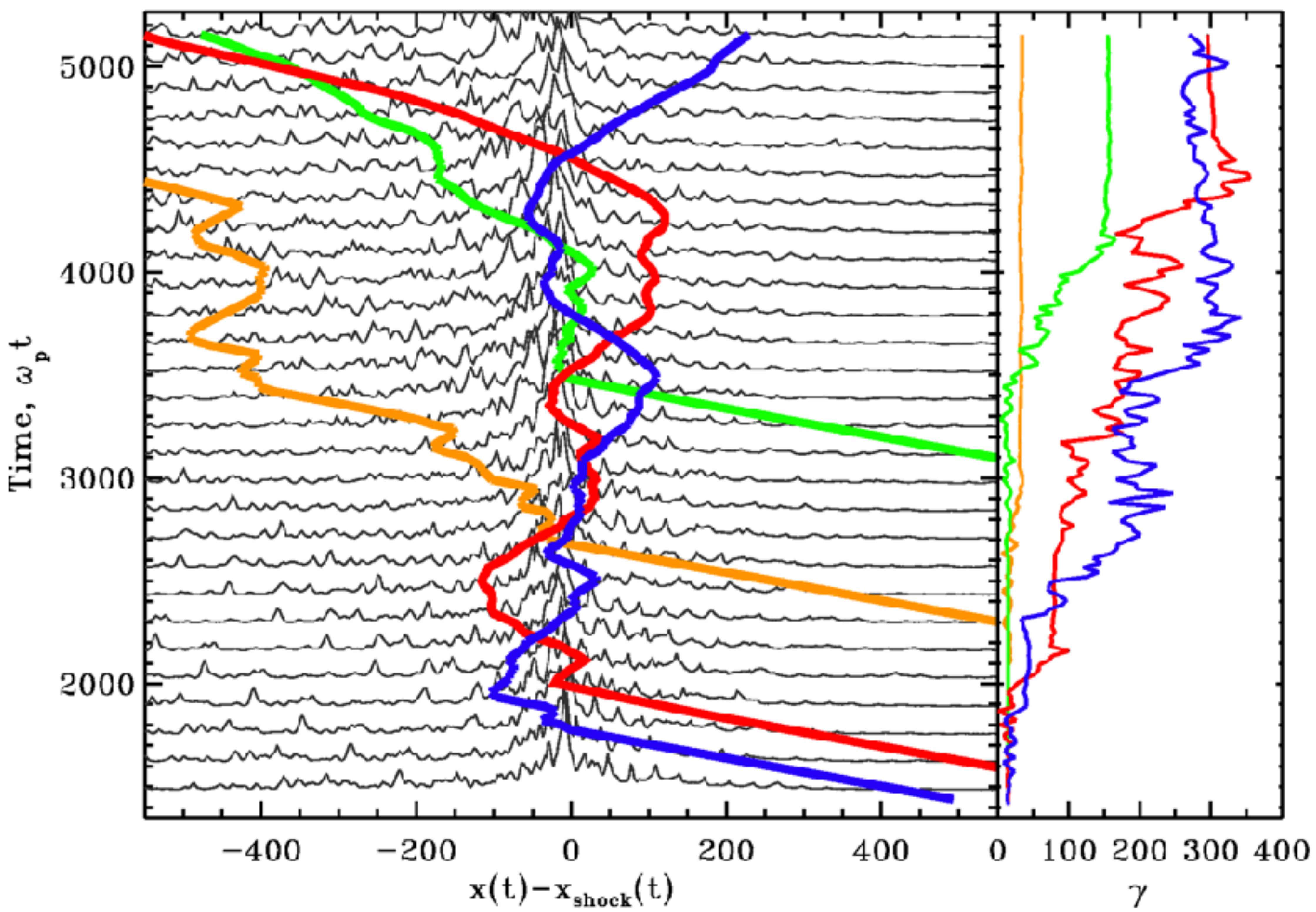
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

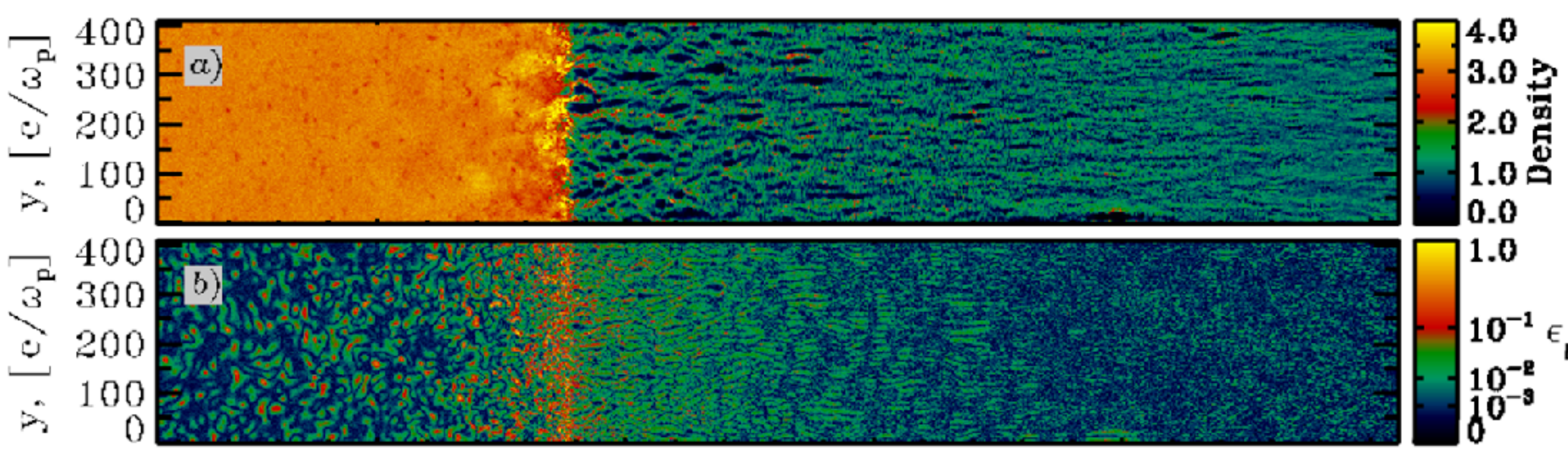
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

Fermi 1st order: diffusive shock acceleration

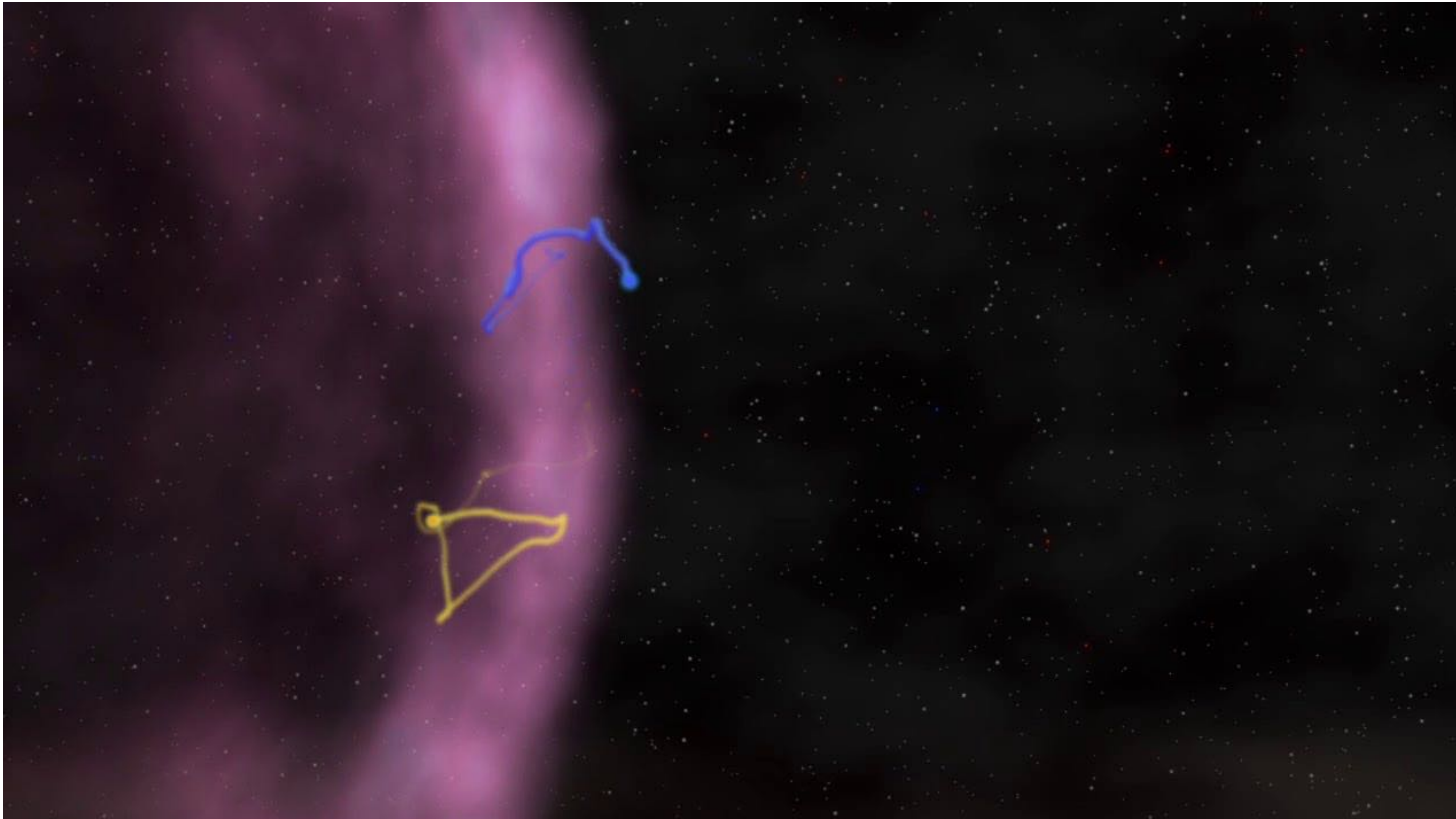
Spiatkovsky. Astrophys. J. Letters 682 (2008) L5. arXiv:0802.3216.



- shock acceleration naturally leads to power laws
- spectral indices around ~2
- 2D PIC simulations by Spitkovsky 2008
- relativistic shock efficiency: ~10%

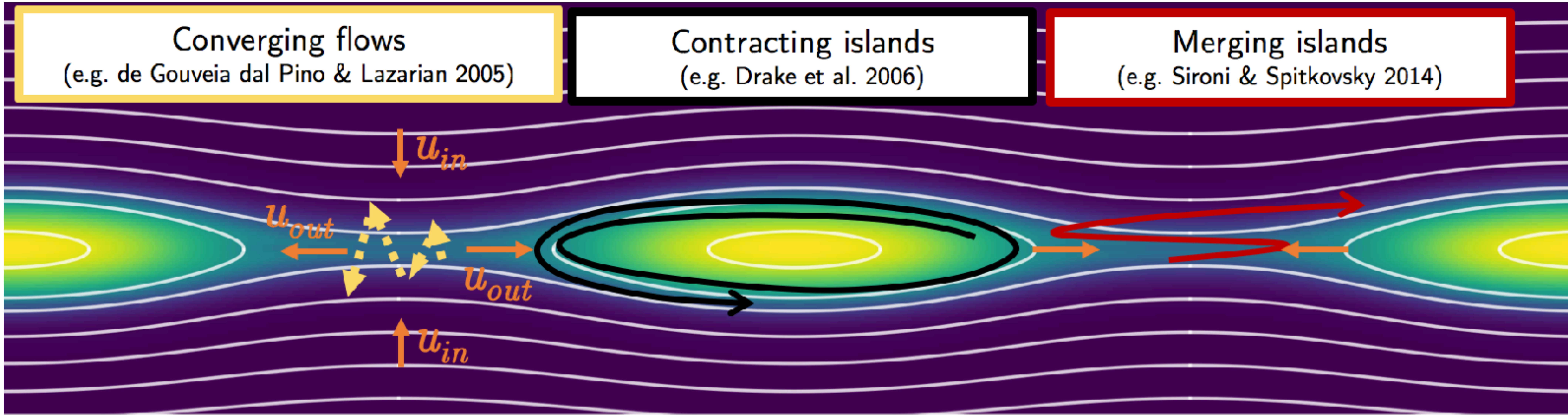


Fermi 1st order: diffusive shock acceleration



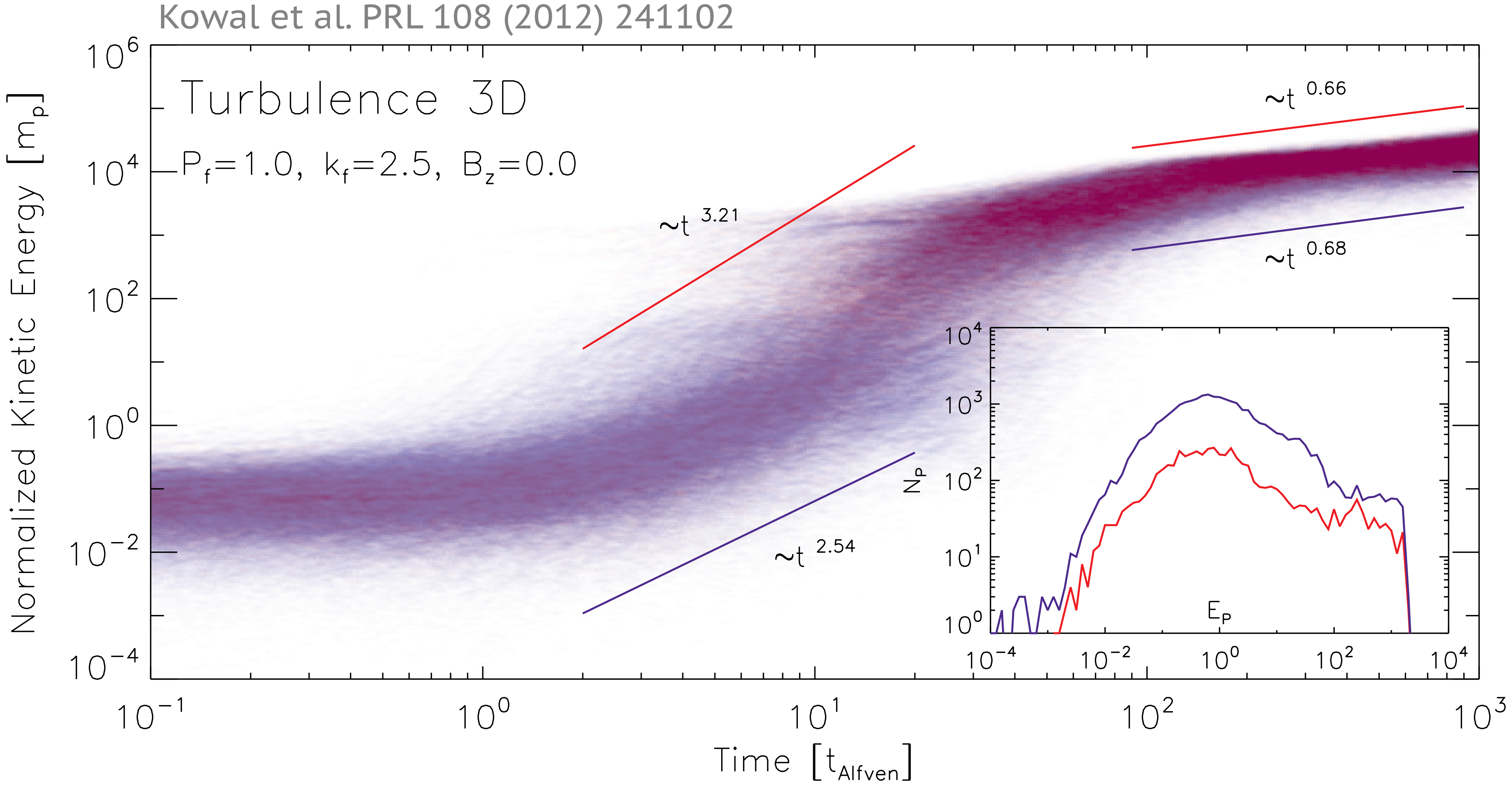
https://www.youtube.com/watch?v=jA0v1Mh_Oq8

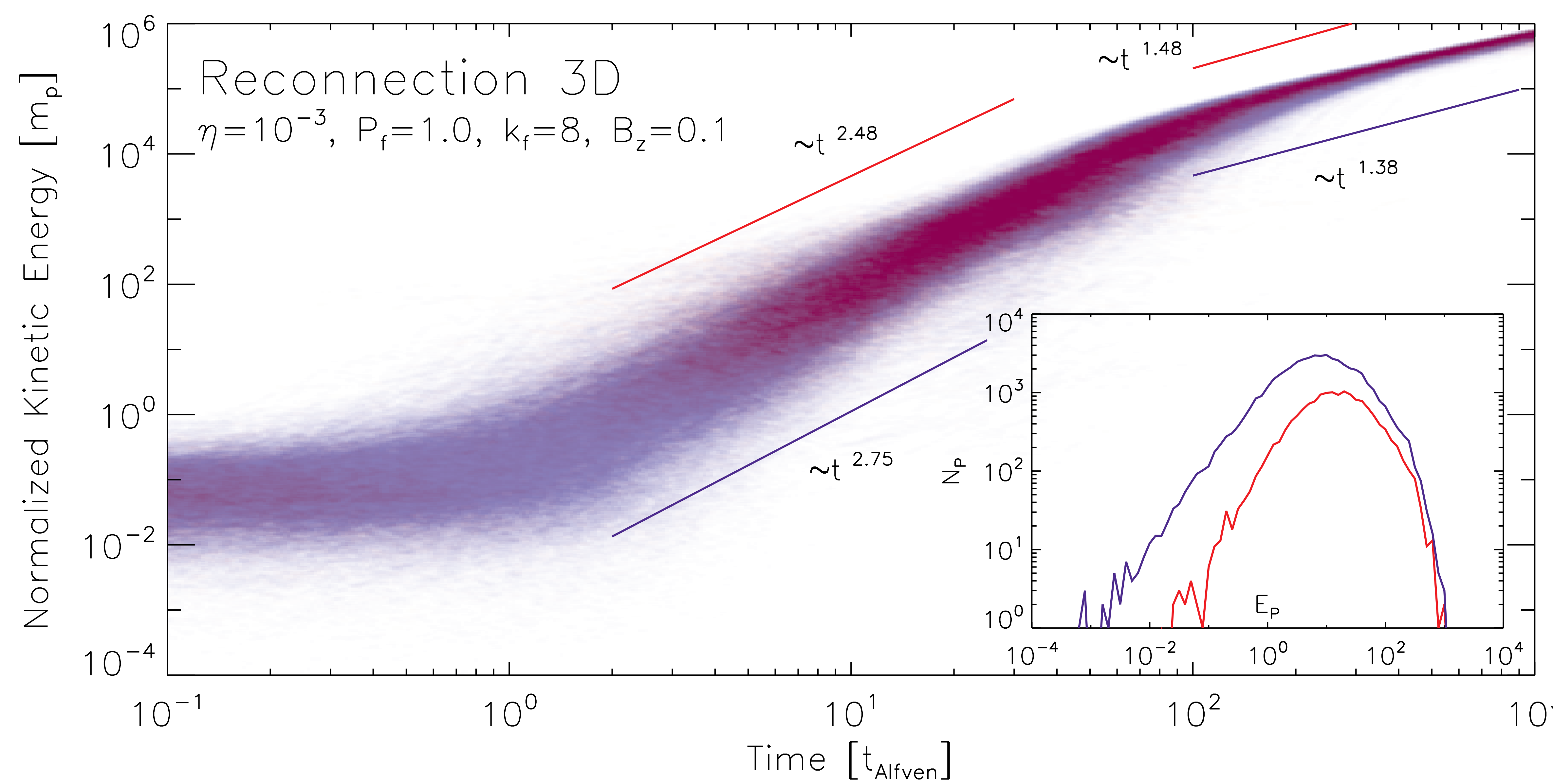
acceleration via magnetic reconnection



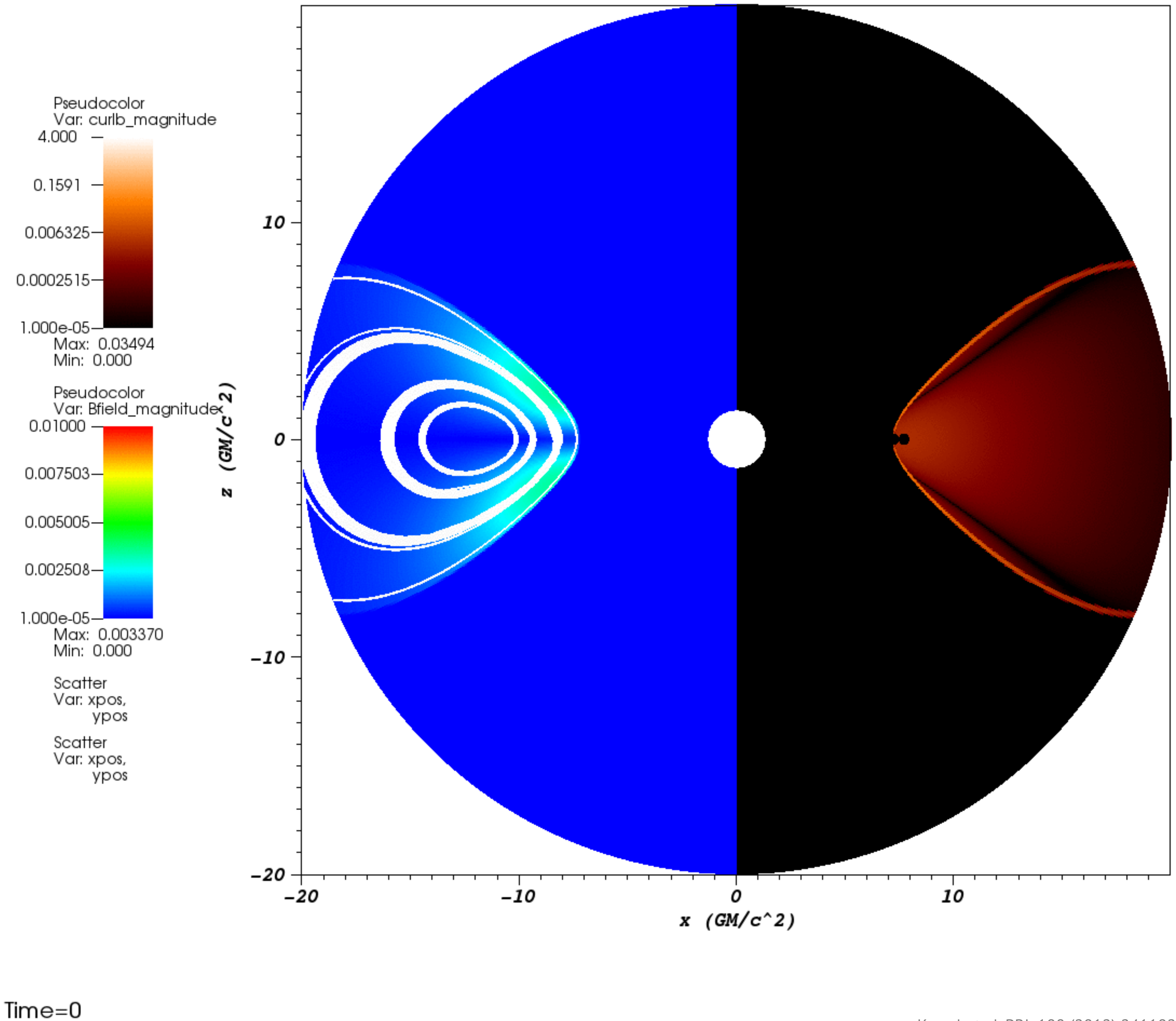
Matthews et al. New Astron. Rev. 89 (2020) 101543. arXiv:20023.06587

Kowal et al. PRL 108 (2012) 241102





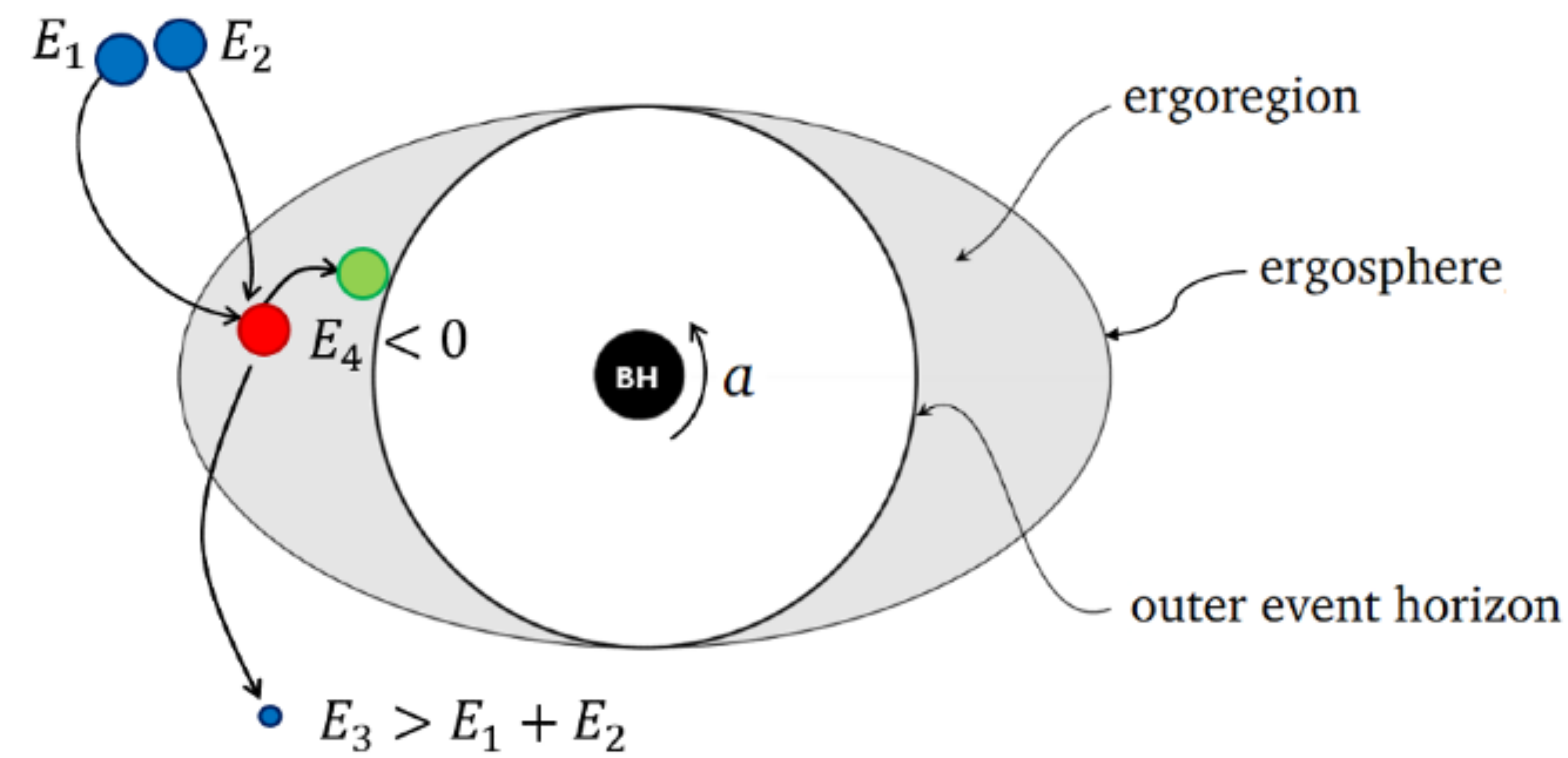
magnetic reconnection



Kowal et al. PRL 108 (2012) 241102

bottom-up models. gravitational acceleration

- acceleration via gravitational scattering (Penrose processes)
- rotating black holes (Kerr) can accelerated particles to *arbitrarily high energies* *[Bañado, Silk, West 2009]*
- generally: $E_3 > E_1 + E_2$ and $E_4 < 0$
- the efficiency of such mechanism in real circumstances is unclear *[Kimura+ 2011; Harada & Kimura 2014]*



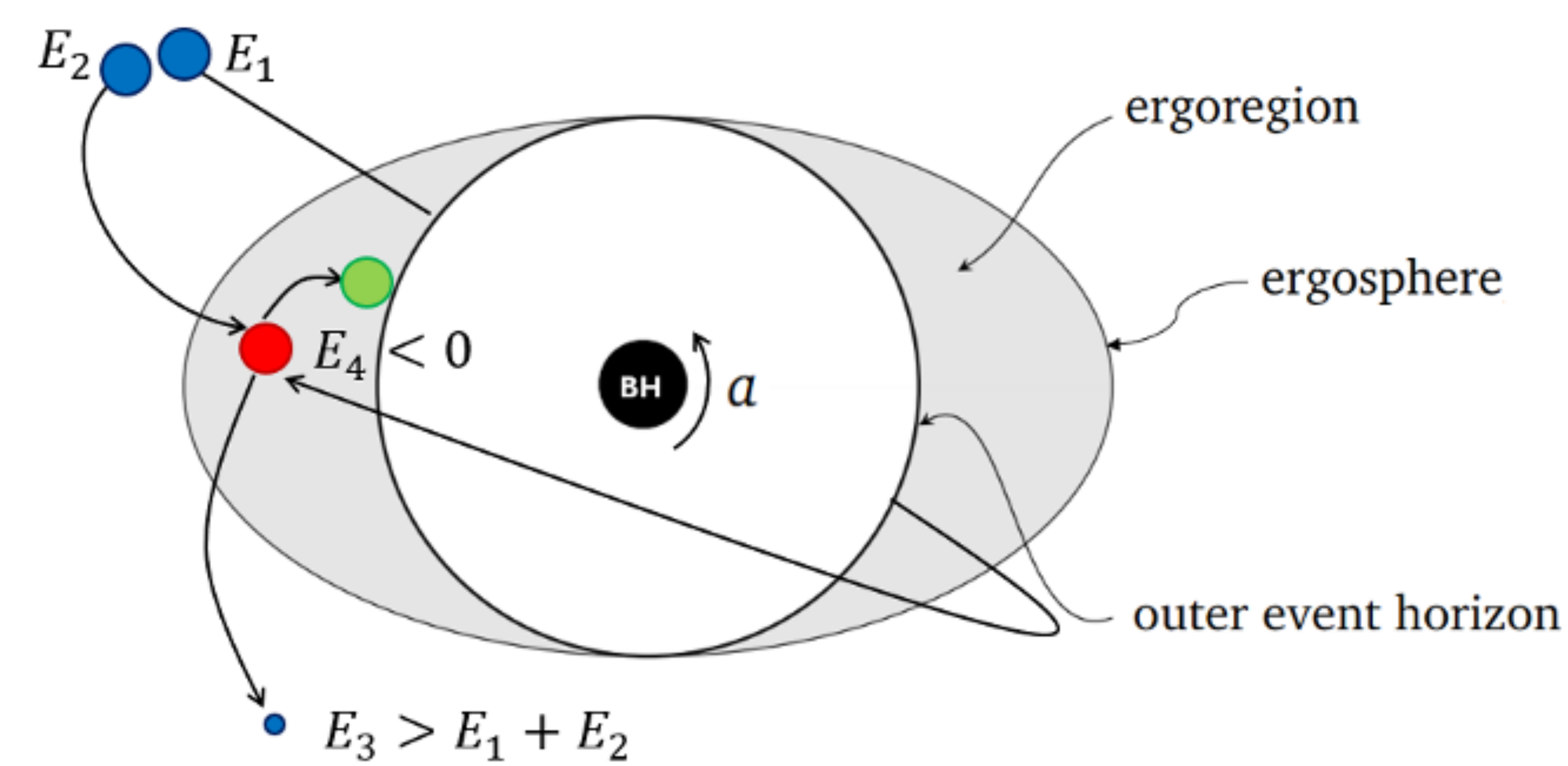
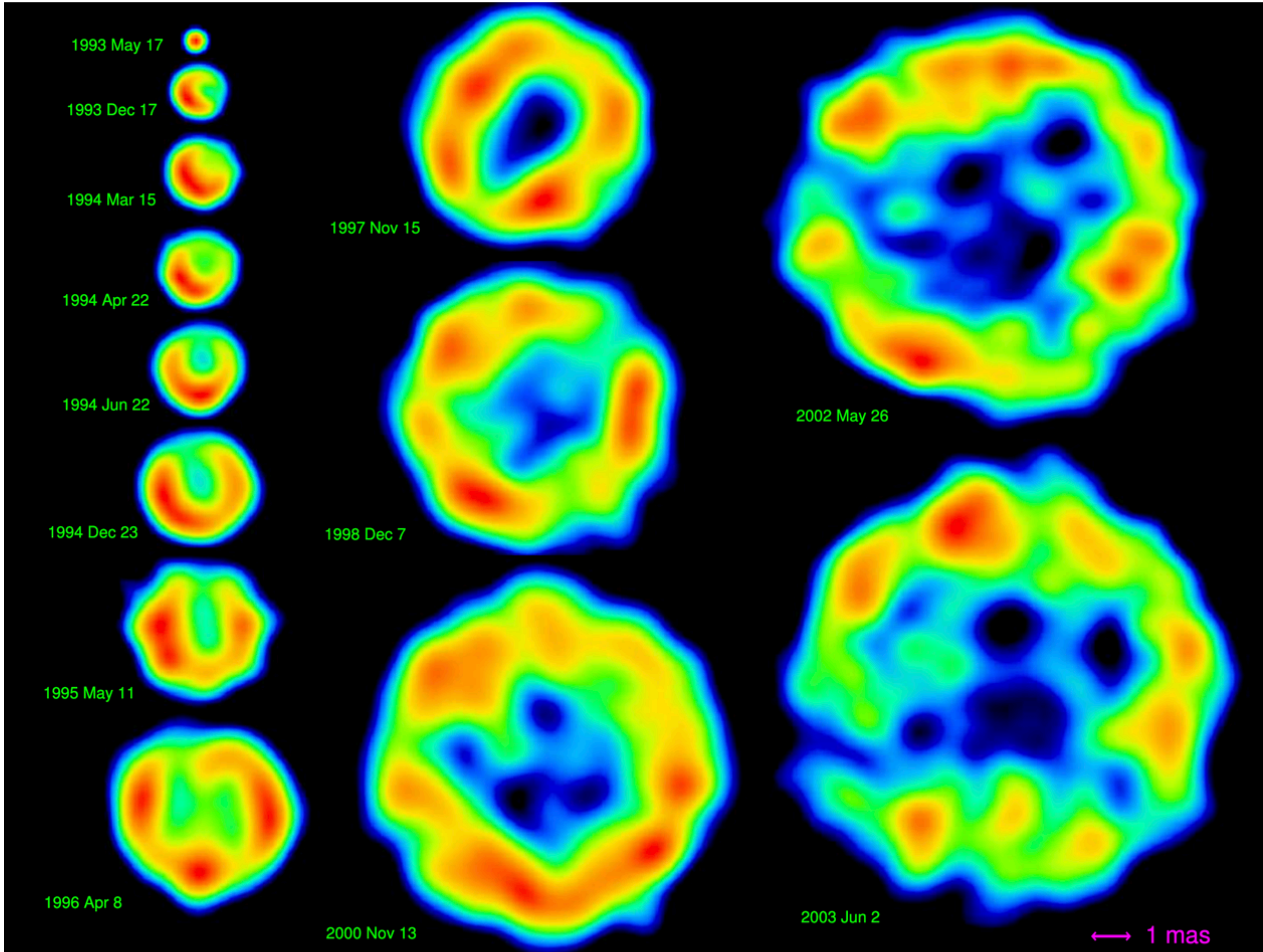


Image credits: A. Svyatkovskyy

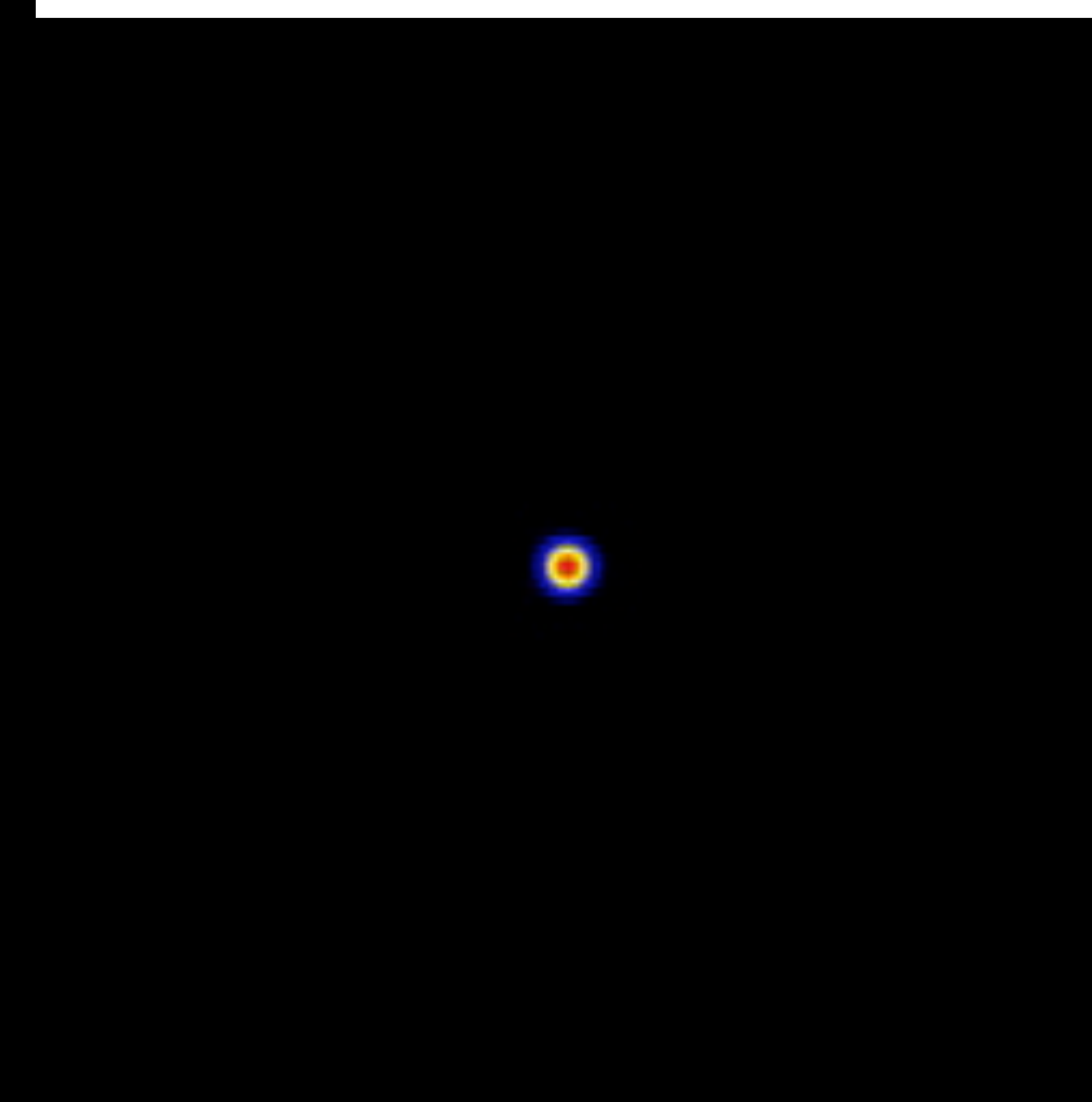
shocks

supersonic waves: Mach cone

supernova expansion



- **supernova SN1993J**
- host galaxy: M81
- observations in radio
- initial shock: 20000 km/s

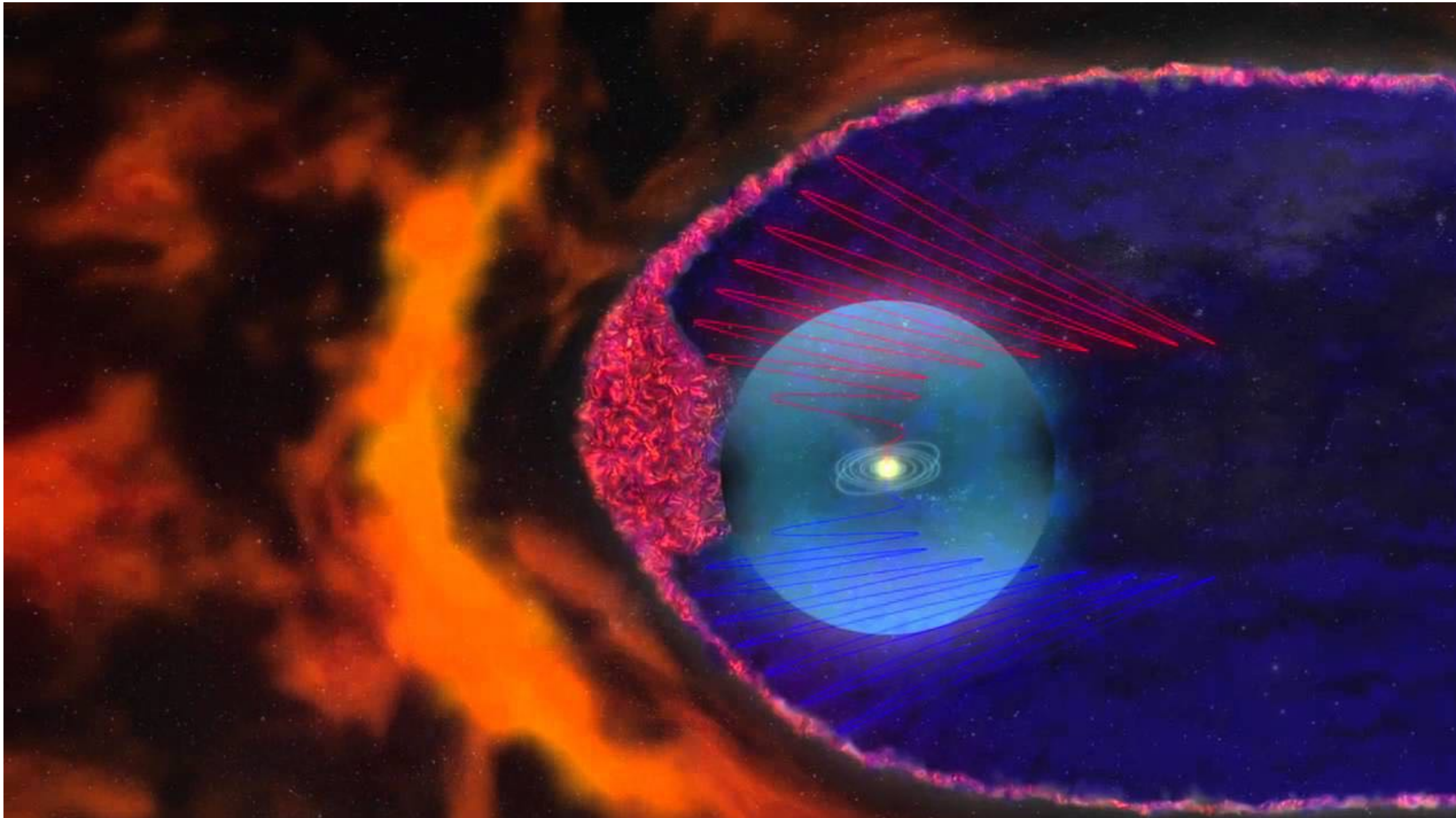


M. Bietenholz. PoS 072 (2009) 064. Proc. IX EVN Symposium.

the end of the solar system

https://en.wikipedia.org/wiki/Heliosphere#/media/File:Interstellar_medium_annotated.jpg

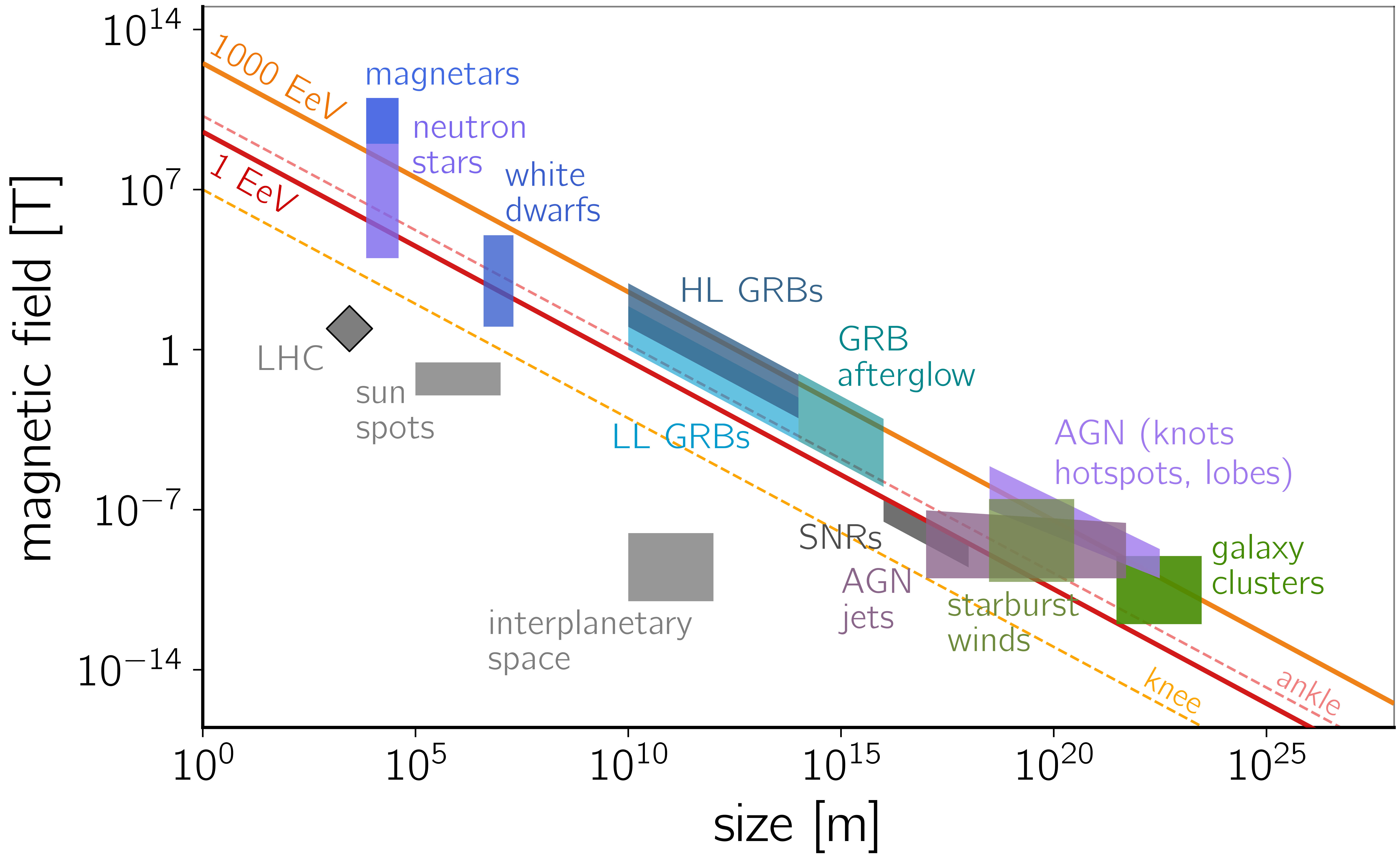
Voyager at the end of the Solar System



cosmic accelerators

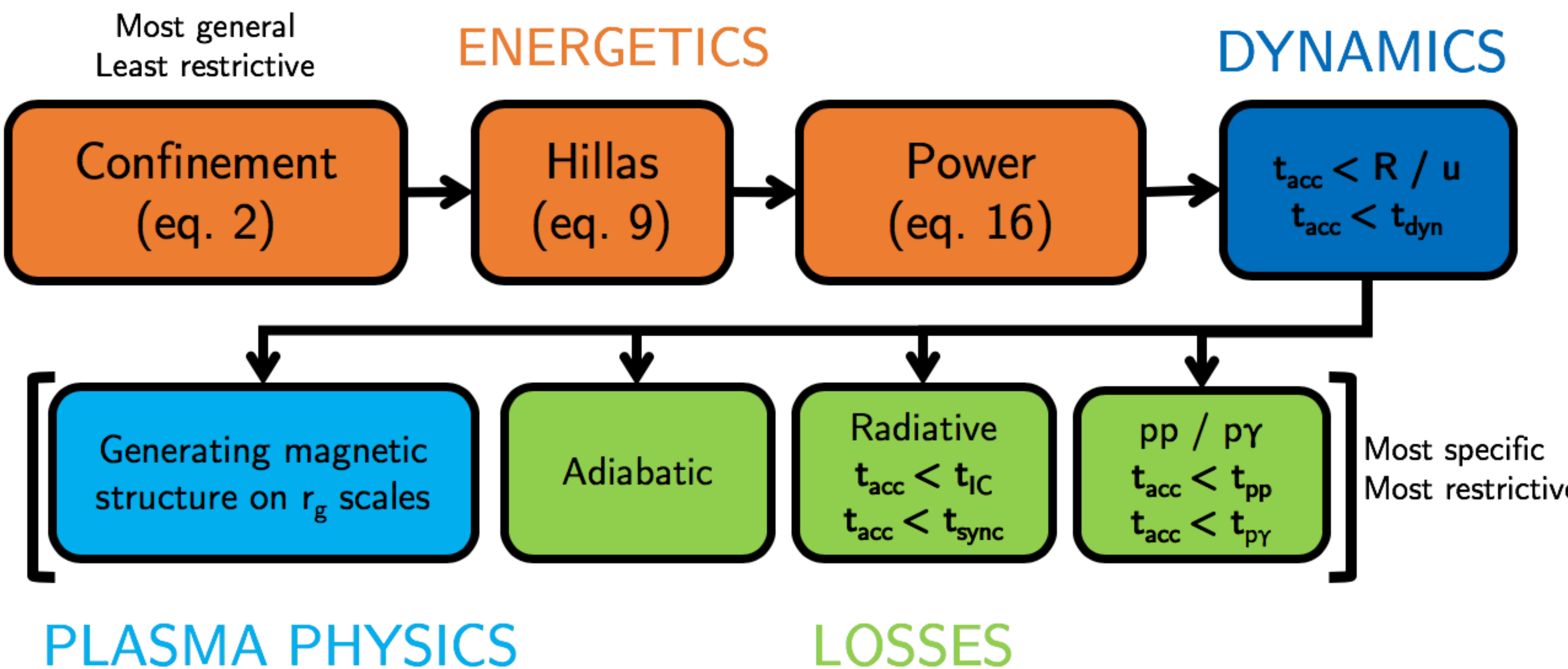
bottom-up models. electromagnetic acceleration

Alves Batista. arXiv:2412.17201



Hillas criterion $E_{\text{max}} \sim 2qv_{\text{sh}}BR_{\text{L}} \sim 10^{19}Z\left(\frac{B}{\text{nT}}\right)\left(\frac{R}{\text{kpc}}\right)$ eV

what sets the maximum energy of a source?

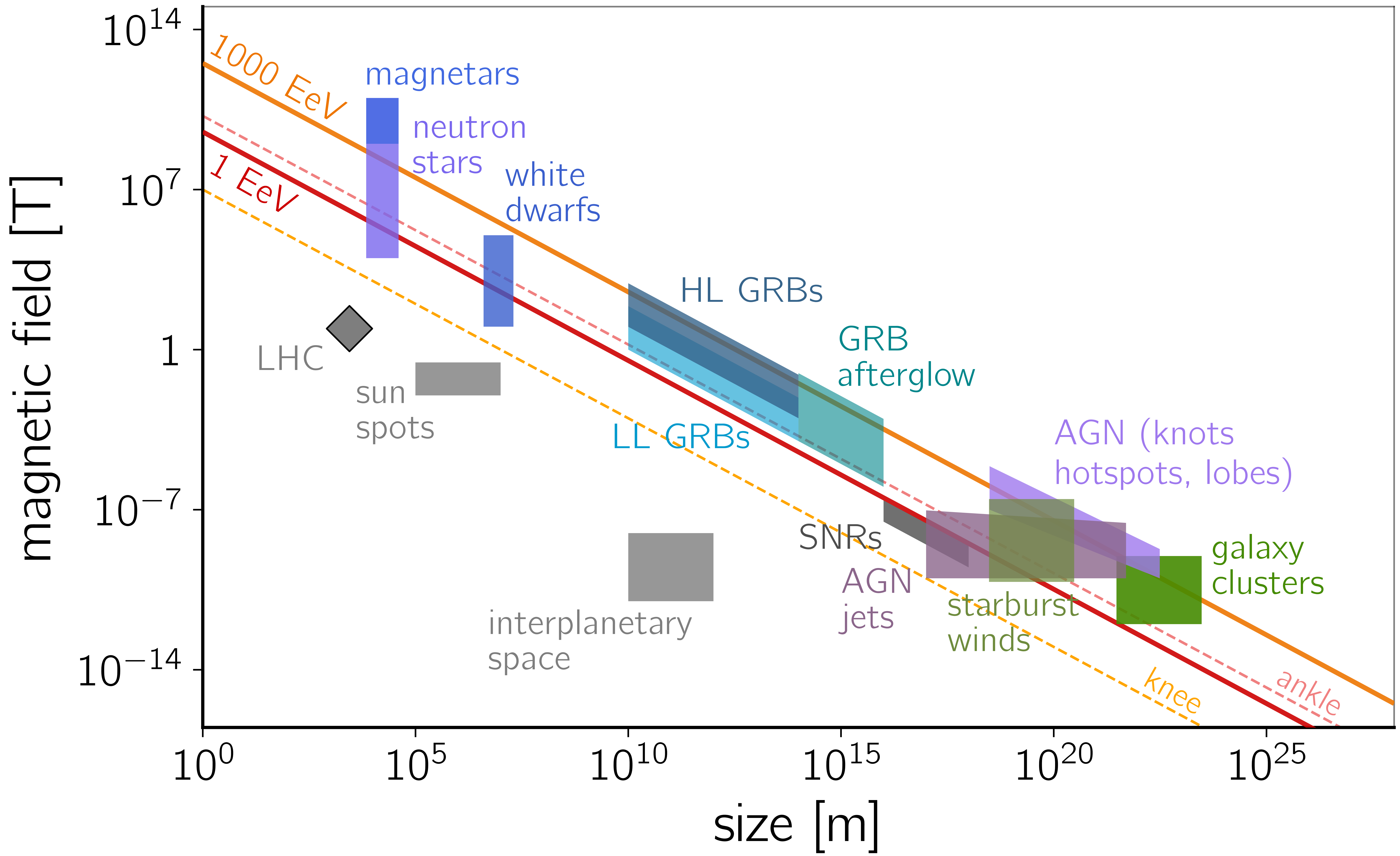


Matthews et al. New Astron. Rev. 89 (2020) 101543. arXiv:20023.06587

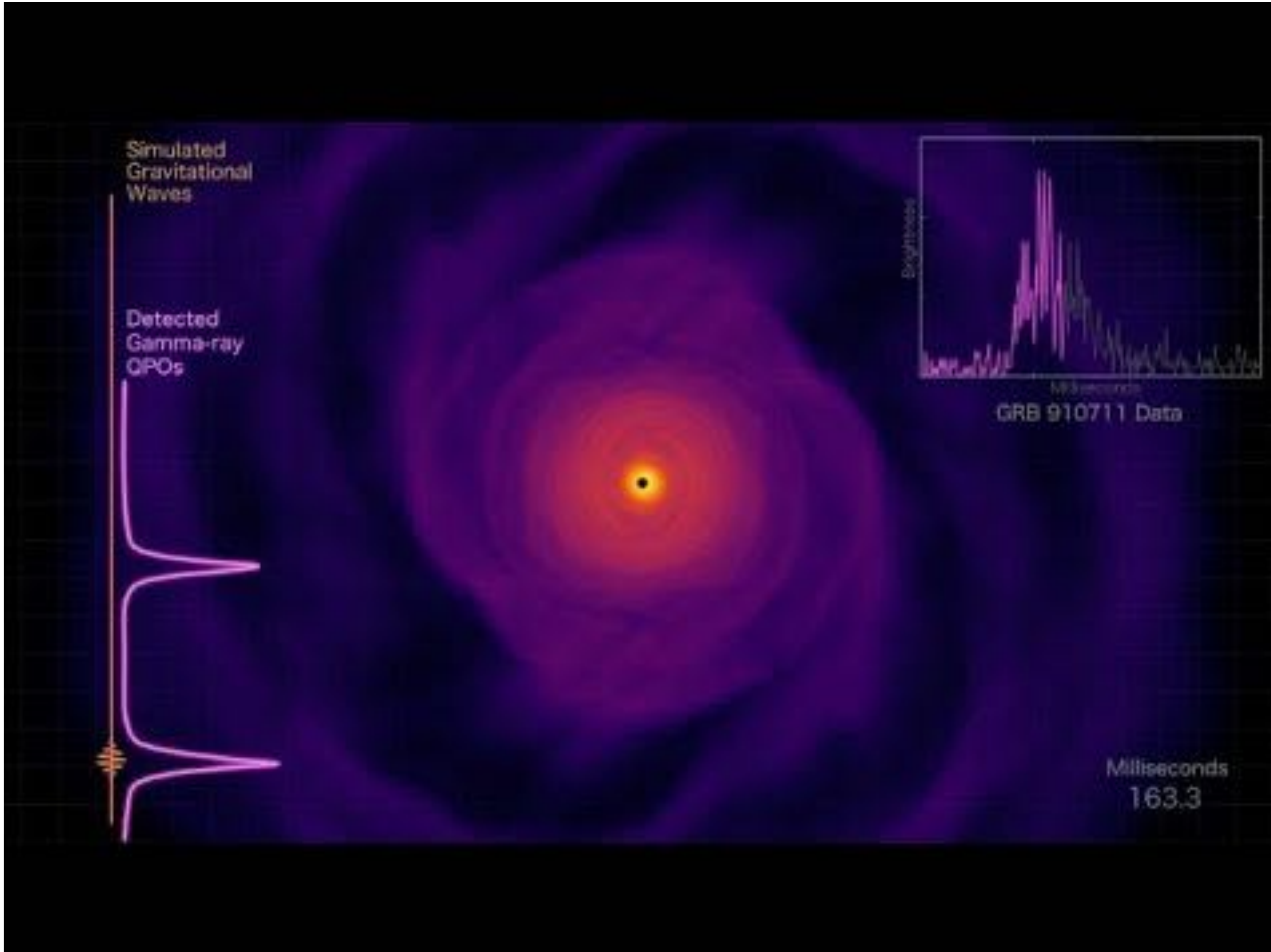
sources of high-energy messengers

bottom-up models. electromagnetic acceleration

Alves Batista. arXiv:2412.17201



gamma-ray bursts

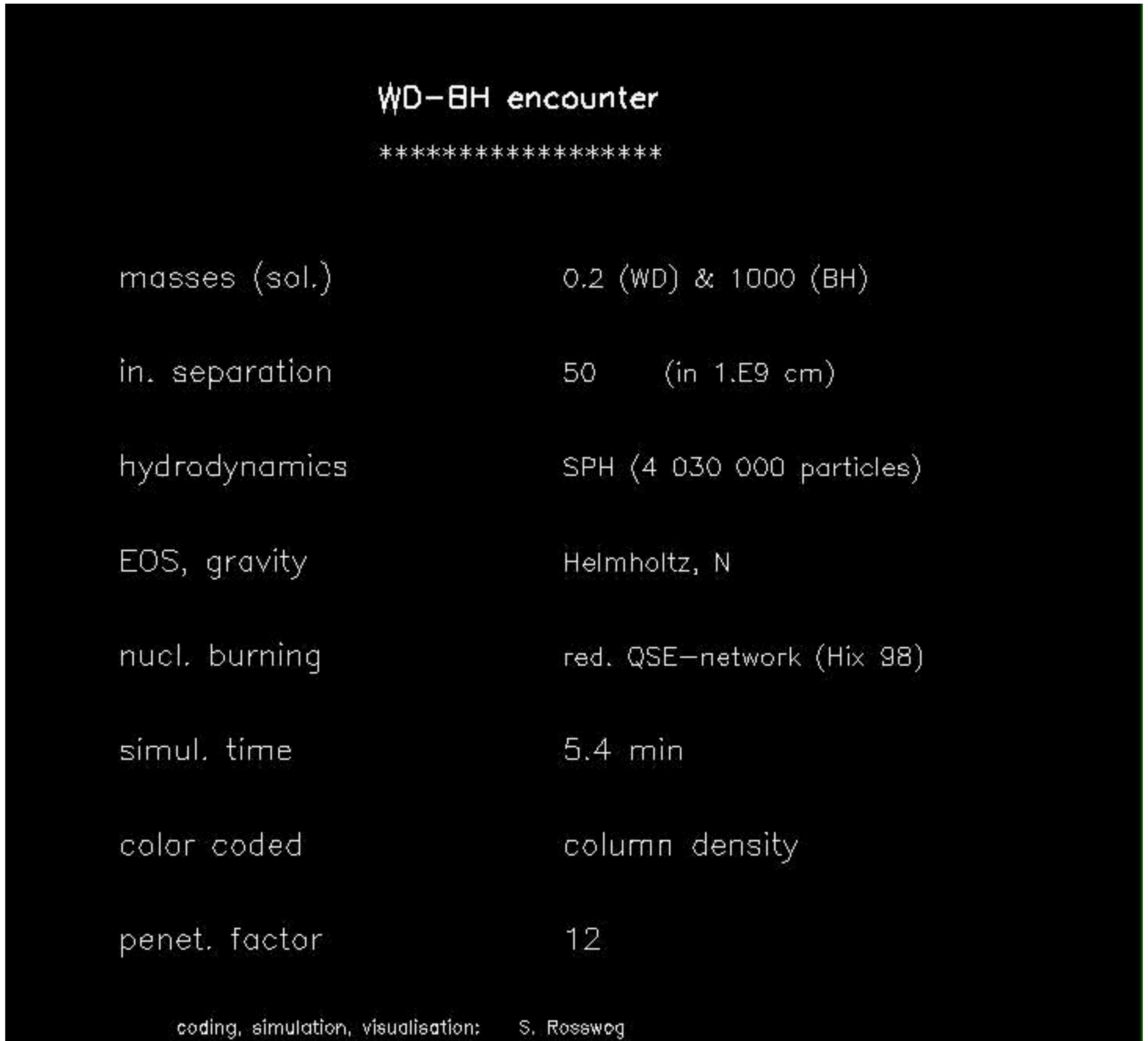


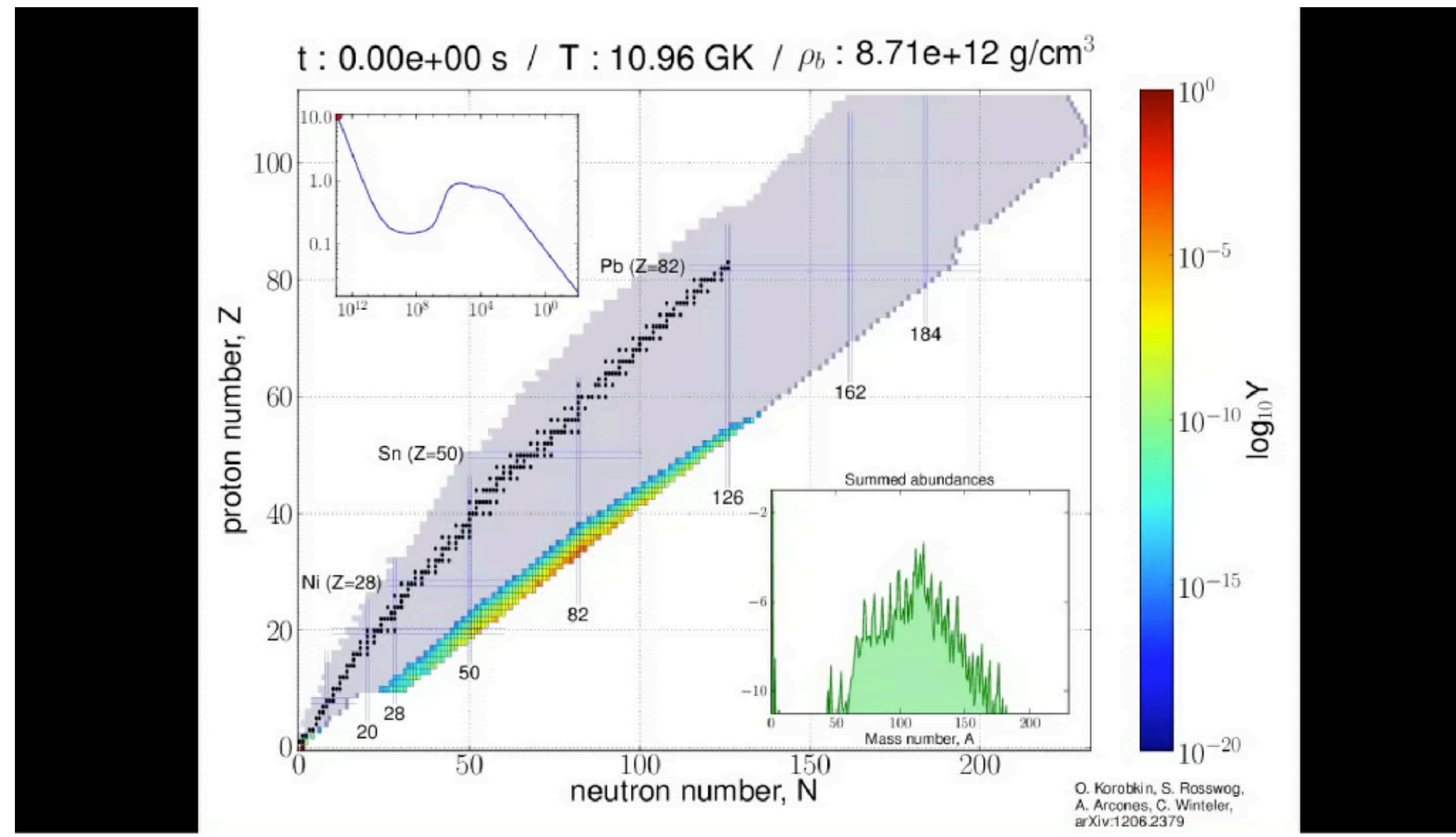
Credits: NASA. https://www.youtube.com/watch?v=IMcU2m5YbFE

Credits: H. Shiokawa. https://www.youtube.com/watch?v=L97YdjsnWS0

tidal disruption events : WD+BH

Alves Batista & Silk. Phys. Rev. D 96 (2017) 103003. arXiv:1702.06978





Rosswog et al. ApJ 695 (2009) 404. arXiv:0808.2143

Korobkin et al. MNRAS 426 (2012) 1940. arXiv:1206.2379