GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Physics of Particle Acceleration to UHE

Pasquale Blasi
Gran Sasso Science Institute

October 3, 2024 - In memory of Venya


Memory Lane
I arrived in L'Aquila in 1994 to start my Ph.D. together with a few other people you might know…

Memory Lane

- February 1994, From CP violation in B_0-B_0 mixing to white dwarves and the Colgate mechanism (explode things in decreasing density)
- 1994 - Navarra and Ginzburg… from SNR1987a to anomalous γ's
- 1995 - Clusters of Galaxies —- Venya and Vladimir Ptuskin
- 1996 - Relativistic shocks — Venya and Bohdan Hnatyk
- July 1997 - End of the Ph.D.… offer from Ray Protheroe… ops no, by David Schramm
- December 1997 - David passes…
- 1998 - Super-heavy relics - Venya and Alex Vilenkin
- 2007: Venya passes the baton to me, Editor of Astroparticle Physics (now Damiano)
- 2012: neutrinos from PopIII stars - back to the bright phase of an old idea
- Continued collaboration with Roberto and Venya and a deep friendship that continued to the very end
- Venya did not teach only a lot of Physics,.. he was proud of saying that he could teach a way to be a physicist … and he taught me the art of story telling, in which he was not less of a master

What do we need to understand?

- A couple of decades ago it would have been unthinkable to think of nuclei as UHECR
- Now it is unthinkable to ignore nuclei and **R_{max}~5 EV** … much easier problem of particle acceleration
- Disturbingly **hard source spectra** required (perhaps what we get is heavily affected by phenomena occurring around the sources or en route)
- Yet extra-Galactic protons appear to have a much different spectrum than nuclei
- Issue of transition from Galactic to extra-Galactic CRs crucial and not understood
- **How can one not consider this a "disappointing model"?**

OUTLINE

- ☑ Particle acceleration at relativistic shocks and some applications
- ☑ Stochastic particle acceleration in relativistic turbulence
- ☑ Particle acceleration at fast rotating neutron stars
- ☑ Starburst galaxies and UFOs
- ☑ Particle acceleration during large scale structure formation

See talk by D. Caprioli for acceleration in jetted sources

SIMPLE CONSIDERATIONS

- **MOST OF THE UNIVERSE IS IN A PLASMA STATE: THE ONLY ELECTRIC FIELDS YOU GET ARE INDUCED BY PLASMA MOTION: δE~(V/c)B**

- **ONLY ELECTRIC FIELDS CAN CHANGE THE PARTICLE ENERGY**

$$\frac{dp}{dt} = q\frac{V}{c}B \rightarrow \frac{dE}{dt} \approx qVB$$

If the electric field could stay coherent over a scale R and the particles were moving at c then

$$E_{max} \approx qBR$$

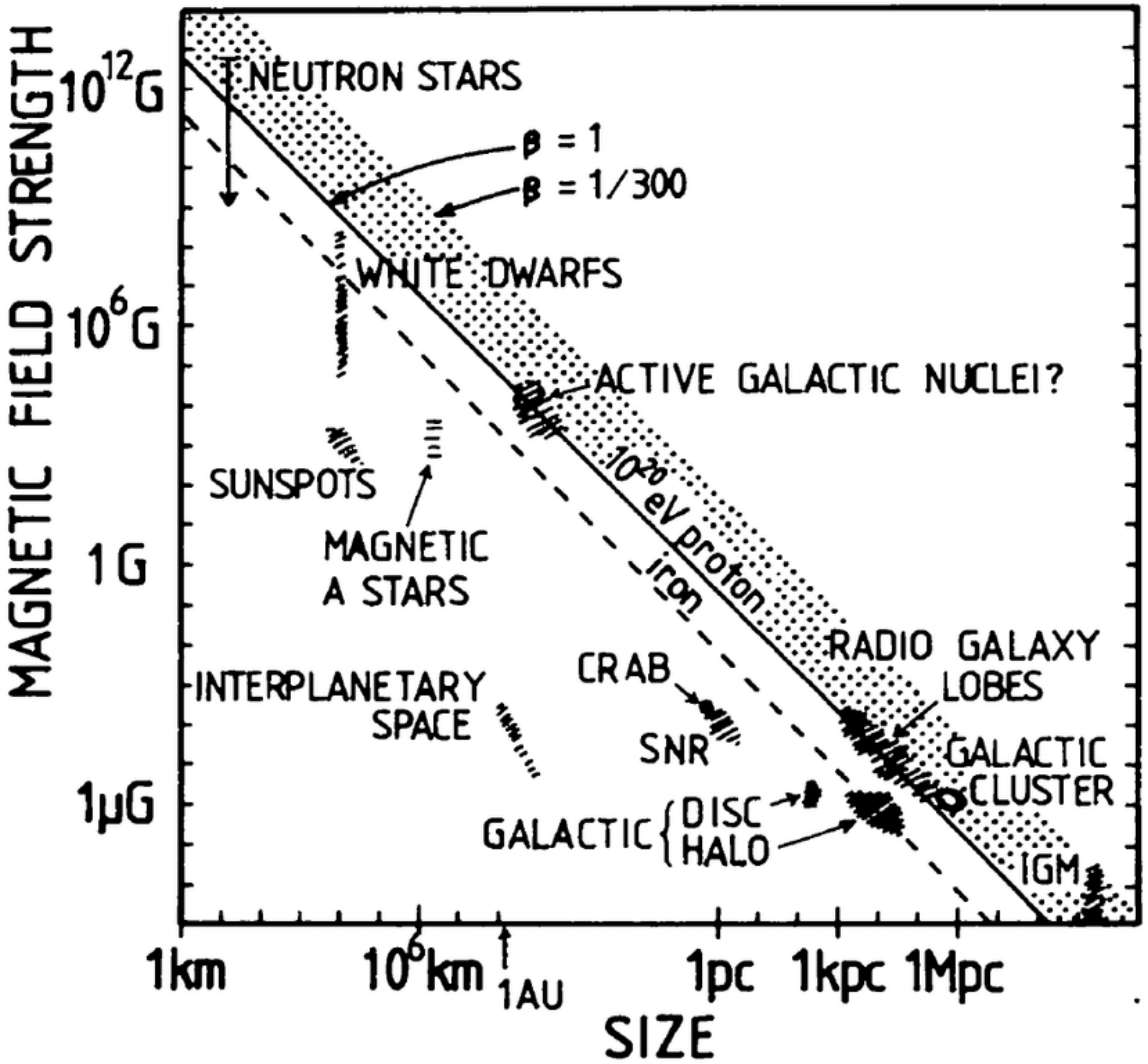
Hillas Criterion

But in a plasma this does not usually happen (unless some specific conditions are fulfilled)

Hence: **NEED TO STAY IN THE ACCELERATION REGION MUCH LONGER THAN R/c**

Simple things to catch your attention

The Hillas Plot (1984)



But do not be fooled:

- The Hillas Plot only provides the absolute most optimistic picture, since it ignores the details of the acceleration process
- Most of the sources are unable to reach this limit
- Energy losses are not taken into account
- Notice the absence of GRBs and Starburst galaxies

Nowadays we know that the requirement on the acceleration are much weaker (Max Energy 5×10^{18} Z eV)

GENERAL LIMITS ON ACCELERATORS OF UHECR

IN THE NON RELATIVISTIC CASE ONE CAN WRITE A GENERIC EXPRESSION:

$$\frac{1}{3}\frac{E(eV)}{300ZB}\frac{c}{u} = \xi R \quad \xi < 1$$

THIS IMPLIES THAT:

$$\epsilon_B = \frac{B^2}{4\pi} > 9.8 \times 10^{-8}\frac{E(eV)^2}{Z^2\beta^2\xi^2 R^2}$$

THE SOURCE ENERGETIC MUST BE AT LEAST AS LARGE AS THE MAGNETIC ONE:

$$L = \frac{1}{2}\rho u^3 4\pi R^2 > 1.8 \times 10^{46} erg/s \left(\frac{E}{Z10^{20}eV}\right)^2 \left(\frac{\xi}{0.1}\right)^{-2} \beta^{-1}$$

PROBABLY THE ONLY NON RELATIVISTIC SOURCES THAT MAY SATISFY THIS BOUND ARE LARGE SCALE STRUCTURE FORMATION SHOCKS AND ONLY MARGINALLY, ALTHOUGH NOTICE THE ROLE OF Z

THIS RESULT CAN BE GENERALIZED TO THE CASE OF RELATIVISTIC SOURCES WITH LORENTZ FACTOR Γ (Waxman 2005)

B’ → MAGNETIC FIELD IN THE COMOVING FRAME

E’=E/Γ → PARTICLE ENERGY IN THE COMOVING FRAME

THE CONDITION FOR MAXIMUM ENERGY IS:

$$\frac{2\pi}{c}\frac{E'}{ZeB'} = \frac{2\pi}{c}\frac{E}{ZeB'\Gamma} < T_{dyn} \approx \frac{r}{c\Gamma}$$

WHICH IMPLIES:

$$B' > \frac{E}{ZeB'r} \rightarrow \epsilon'_B = \frac{B'^2}{4\pi} > \left(\frac{E}{ZeB'r}\right)^2 /4\pi$$

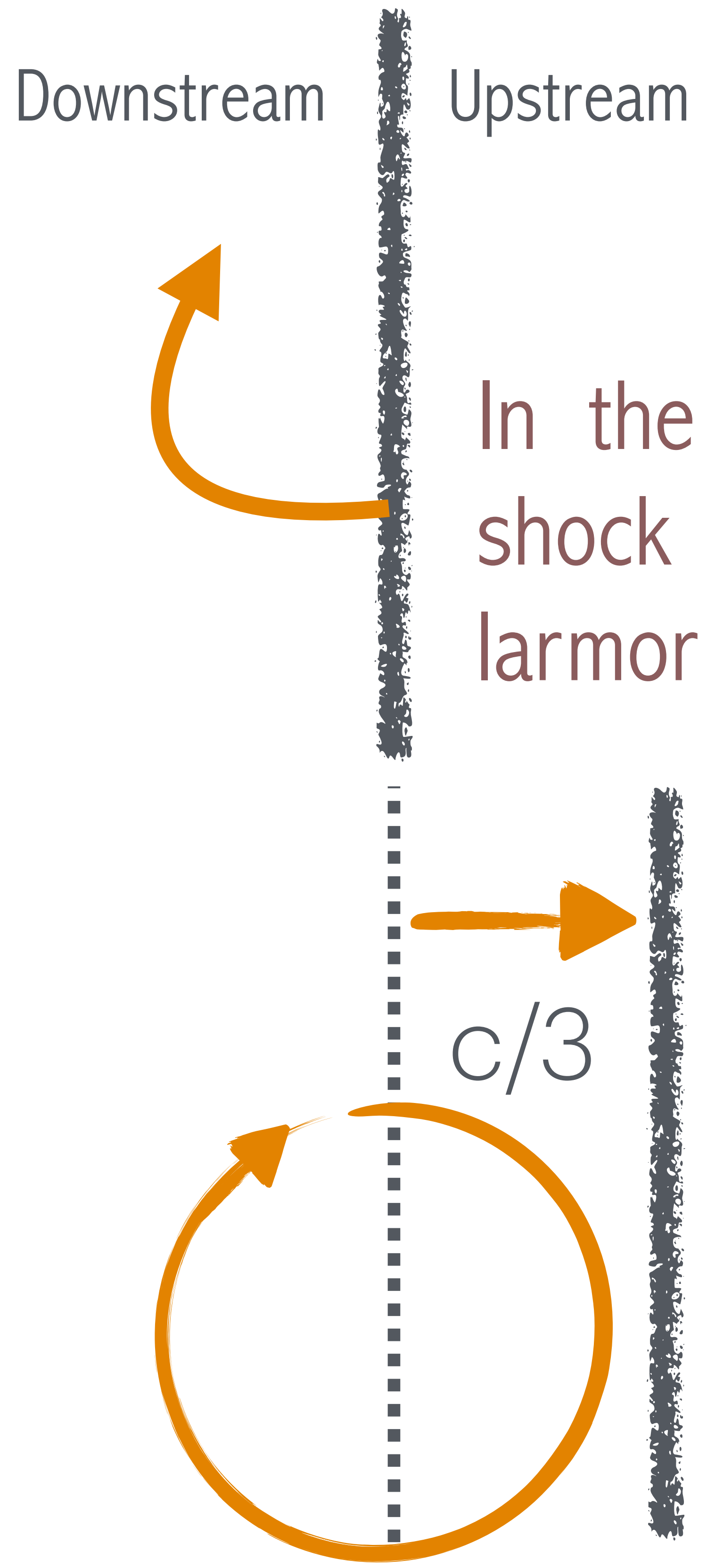
AND FINALLY THE SOURCE ENERGY INPUT MUST SATISFY:

$$L > 4\pi r^2 c\Gamma^2 \epsilon'_B = c\Gamma^2 (2\pi E/Ze)^2 \approx 10^{47}\Gamma^2 \left(\frac{E}{Z\ 10^{20} eV}\right)^2 erg/s$$

THIS IS HUGE AND ONLY THE UPPER END OF THE AGN AND GRB APPEAR TO SATISFY THIS BOUND, ALTHOUGH NOTICE THE ROLE OF Z

Acceleration at Relativistic Shocks

- One would expect the same process as DSA (Kirk & Schneider, Ostrowsky, PB&Vietri, …) $N(E) \sim E^{-2.3}$
- We speculated that the energy of the particles would increase by Γ^2 each time it crosses the shock…
- But the fact that the shock and the particles are all moving at the speed of light complicates things
- The distribution function of the accelerated particles is anisotropic in any frame
- The spectrum becomes not universal if acceleration occurs at all



In the time of one gyration the shock has moved more than one larmor radius: particles are stuck

NEED FOR SMALL SCALE TURBULENCE FOR THE MECHANISM TO WORK

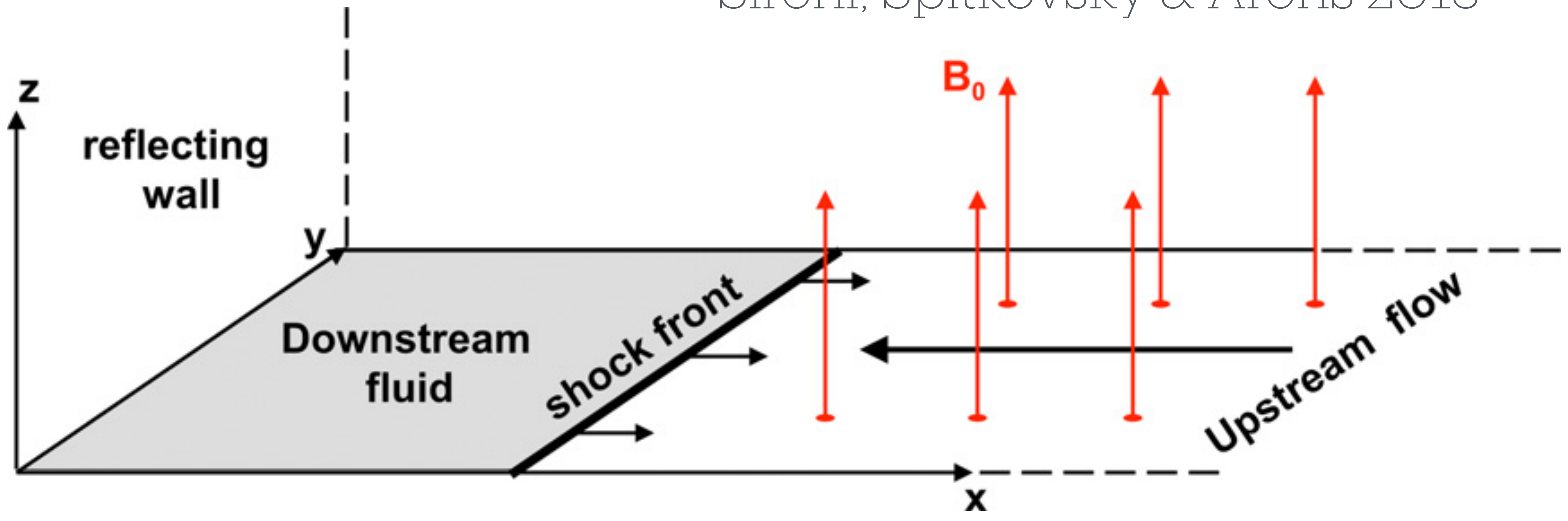
The Modern Era

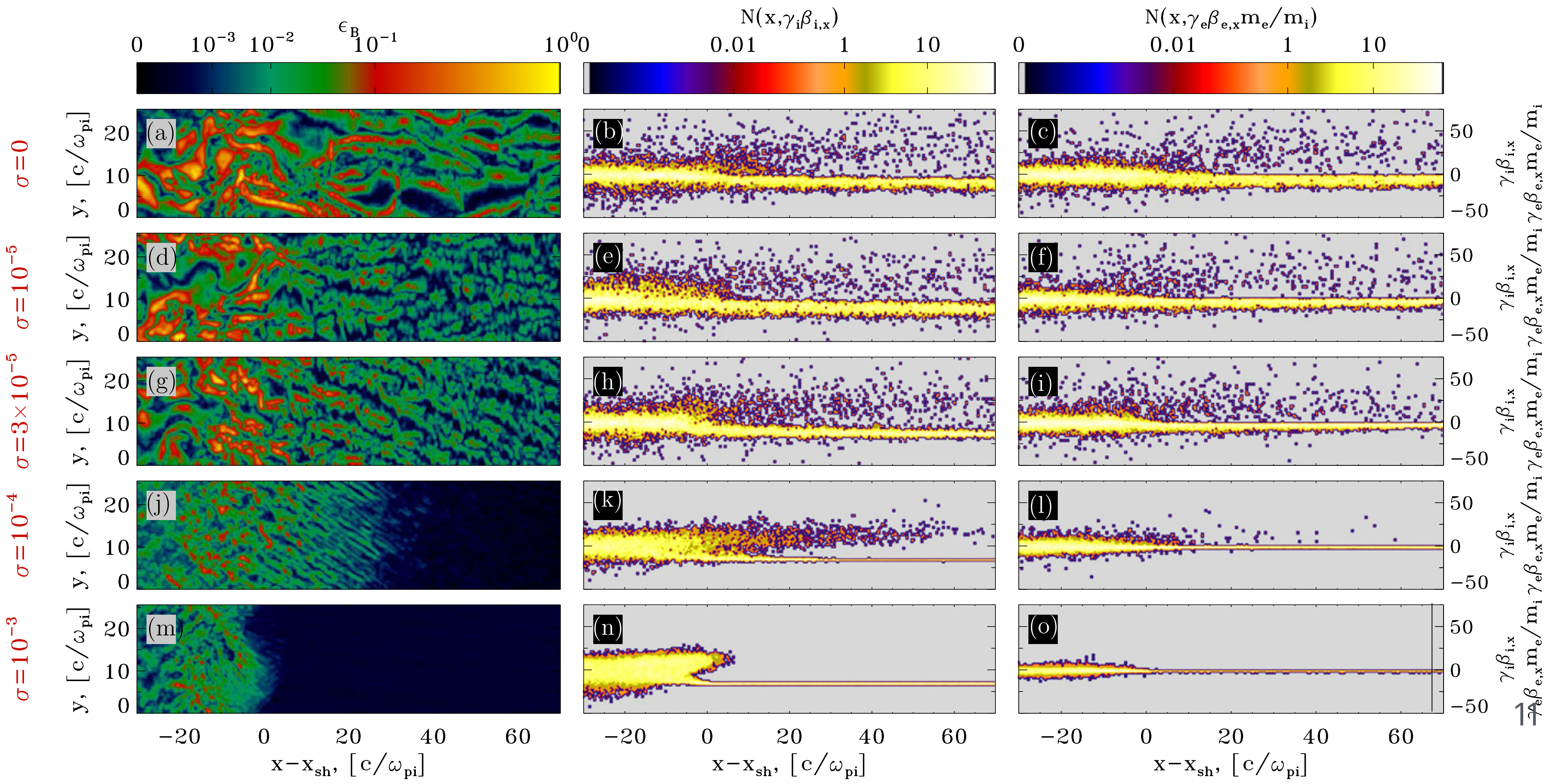
- PIC simulations show that the formation of a relativistic shock is mediated by Weibel instability
- This process is heavily dependent upon the magnetisation of the upstream medium (**σ<3x10^{-5}**)
- Particle acceleration is also there only in that case and **E_{max}~$t^{1/2}$** (small scale turbulence)

$$\sigma = \frac{B_{\rm ISM}^2}{4\pi n m_i c^2} \simeq 0.5 \times 10^{-9} B_{\rm ISM,-5.5}^2 n_0^{-1}$$

Lorentz invariant magnetisation

Sironi, Spitkovsky & Arons 2013





Application to GRBs

Sironi, Spitkovsky & Arons 2013

For a typical GRB exploding in the wind of the pre-burst progenitor star, the magnetisation is:

$$\sigma = \frac{B_{\rm W}^2}{4\pi n m_i c^2} \simeq 1.7 \times 10^{-8} B_{{\rm W},-5}^2 n_{-0.5}^{-1}$$

small enough that acceleration does take place (**σ<3x10^{-5}**).

The Lorentz factor of the shock follows the Blandford & McKee (1976) behaviour:

$$\Gamma(R) = \left(\frac{17 E_0}{16\pi n m_i c^2}\right)^{1/2} R^{-3/2}$$

The analog of the Sedov phase (deceleration phase) starts at:

$$R_{\rm dec} \simeq 1.3 \times 10^{17} E_{0,54}^{1/3} \Gamma_{0,2.5}^{-2/3} n_0^{-1/3} \ {\rm cm}$$

Hence the maximum Lorentz factor (in the lab frame) is:

$$\gamma_{{\rm sat},i}^{\rm up} \simeq 8.0 \times 10^7 \ E_{0,54} \, n_0^{-1} \, \sigma_{-9}^{-1/4} R_{17}^{-3}$$

Stochastic Acceleration in a Relativistic Plasma

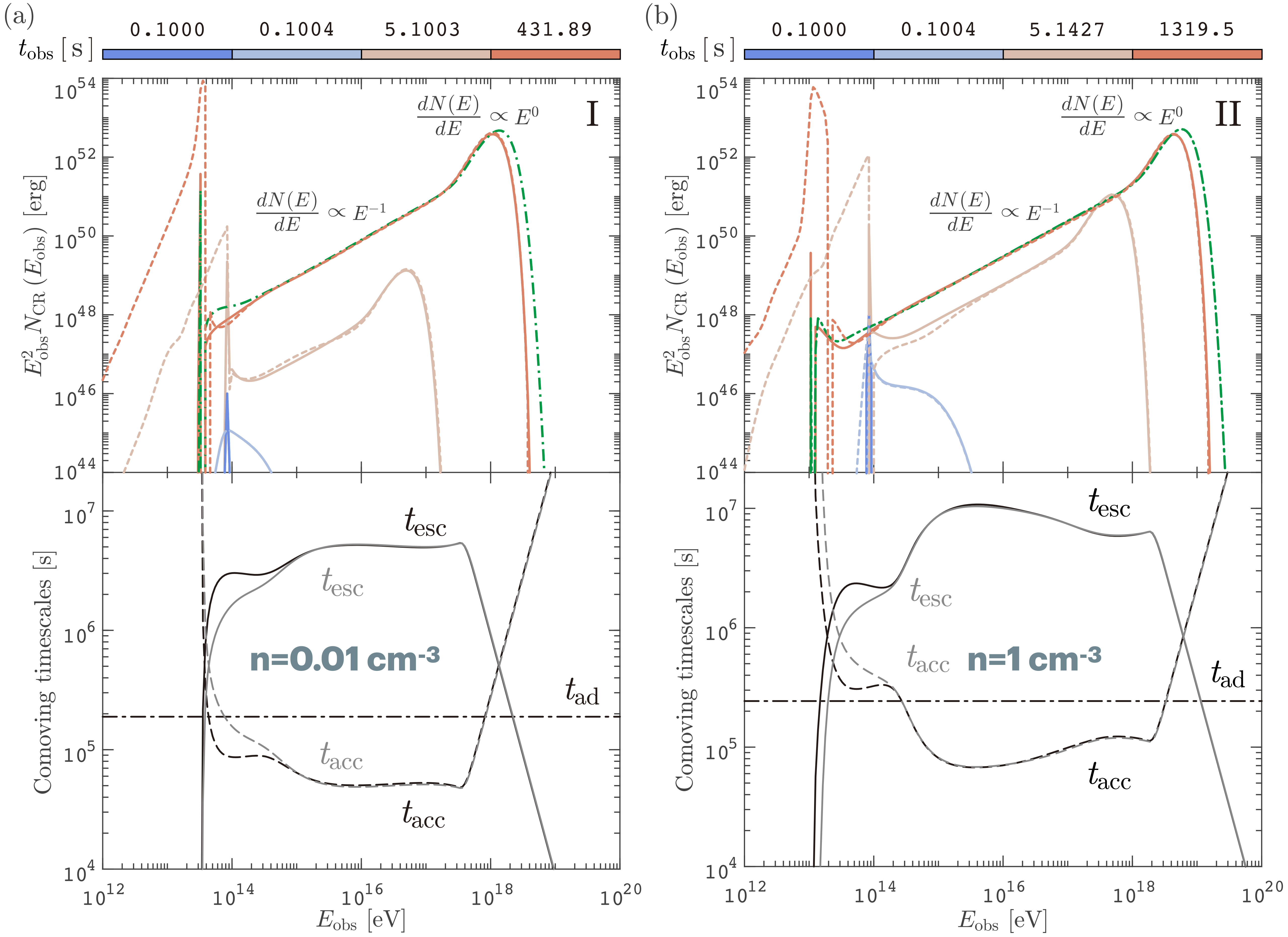
- Large scale turbulence advected downstream of the FS leads to stochastic acceleration in a B-field: $B = \sqrt{32\pi\epsilon_B n m_p c^2 \Gamma^2}$

- Spatial diffusion and p-diffusion are connected: $D_{zz}D_{pp} \sim p^2 v_A^2$

- In the ultra-relativistic case $v_A = c/3^{1/2}$

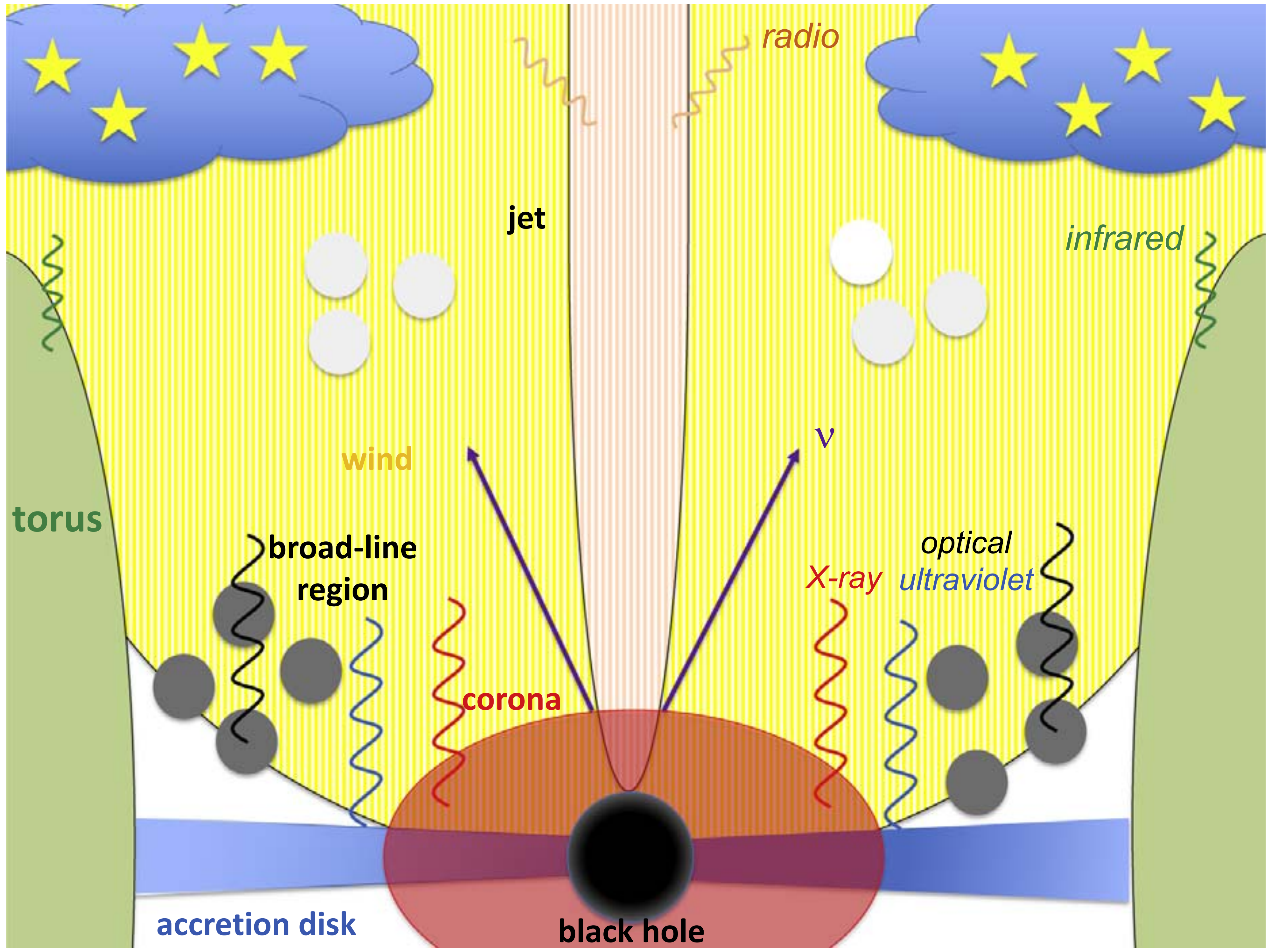
- The time scale for escape and acceleration are related through $$t_{esc}(E) = \frac{R^2}{\Gamma^2 D_{zz}(E)} = \frac{R^2}{\Gamma^2 v_A^2 t_{acc}(E)}$$

- **The spectrum can be shown to be harder than E^{-2} and depends on the spectrum of the turbulence**



Zhang+, 2021

The case of the hidden cocoons (Berezinsky 1977)



Murase, 2022

Turbulent acceleration would lead to acceleration with an absolute upper limit at

$$r_L(E_{max}) = L \equiv \lambda R_s \rightarrow E_{max} = 8 \times 10^{10} GeV\, \chi M_7^{1/2} \beta_P^{-1/2} \tau_T^{-1/2}$$

but the actual maximum energy is limited by Bethe-Heitler pair production and is <100 TeV

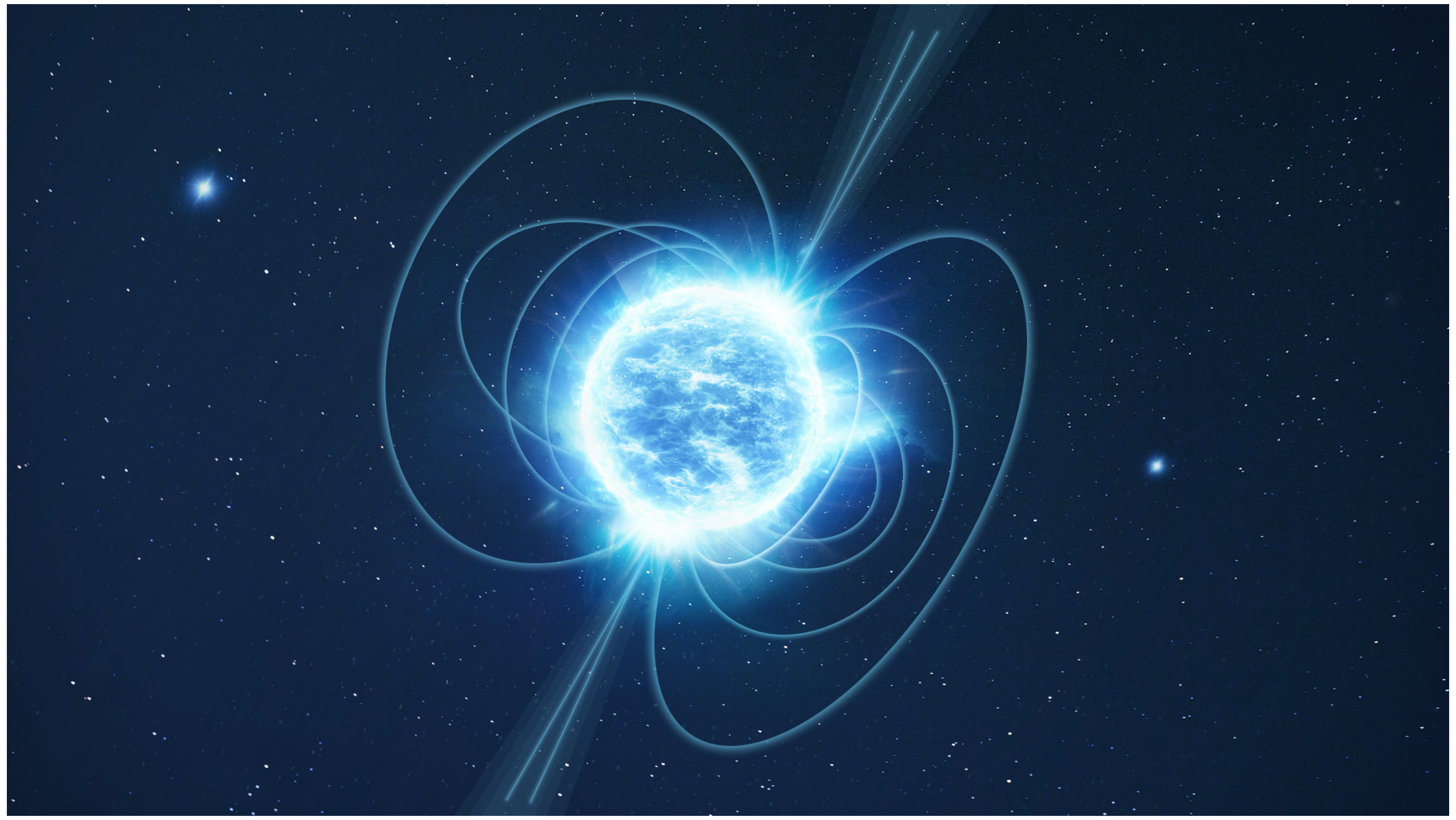
So, it looks like we might have found the sources of high energy neutrinos but at least most of them cannot be the source of UHECRs...

...because E_{max} is not high enough...

...and because they cannot escape the corona

Acceleration in a fast rotating neutron star

(PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)



Extraction of nuclei from the surface

The electric field associated with the rotation of magnetised sphere is

$$\mathcal{E} = \frac{2\pi R_\star B}{Pc} \sim 6.3 \times 10^{14}\, B_{13} R_{\star,6} P_{-3}^{-1}\,\mathrm{V\,cm^{-1}}$$

to be compared with the binding energy of nuclei in the lattice that forms the surface of the NS (with lattice spacing l):

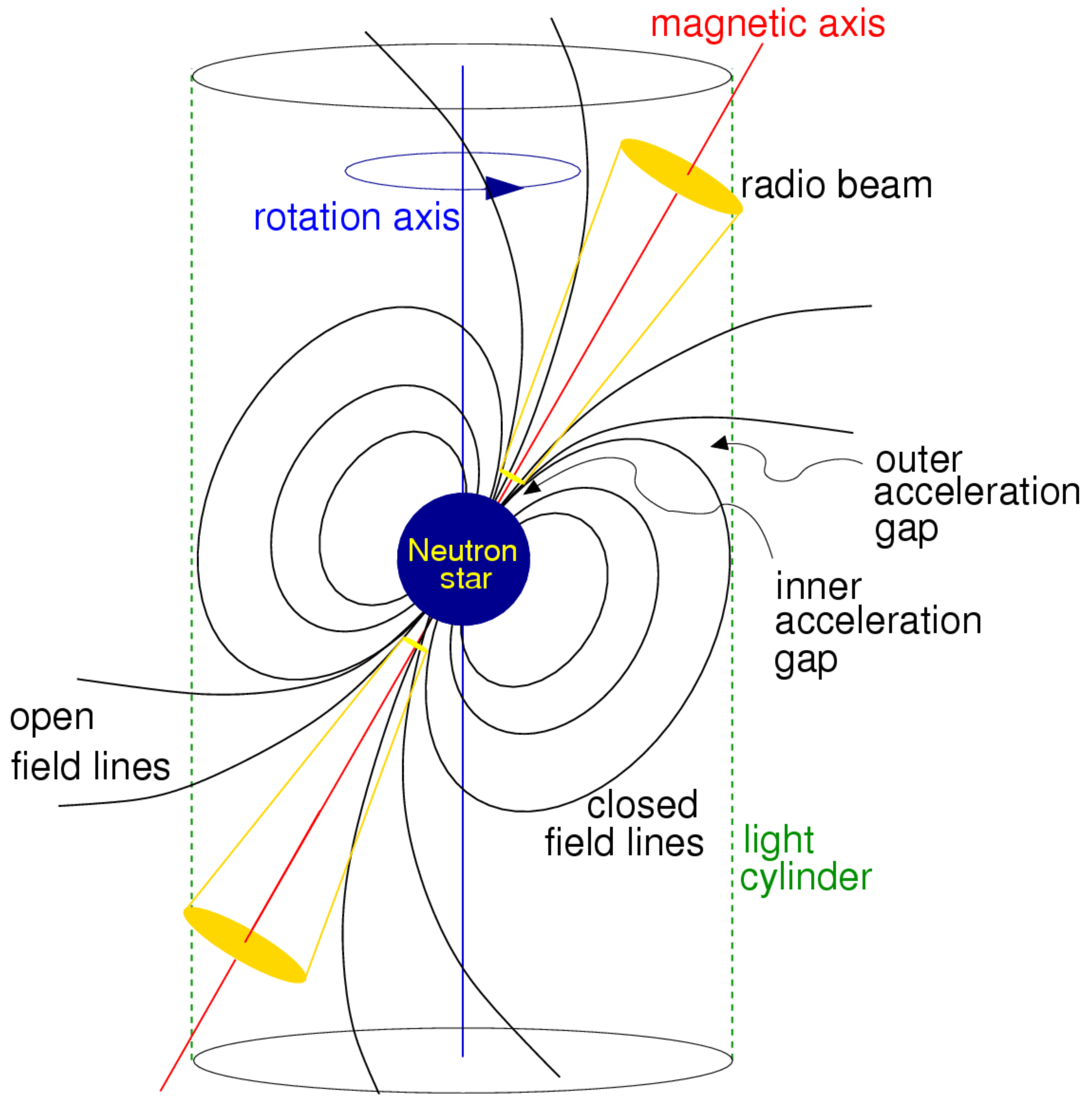
$$\mathcal{E}_0 = 14\,\mathrm{keV}/(Zel) \sim 5.4 \times 10^{11}\, Z_{26}^{-1} l_{-9}^{-1}\,\mathrm{Vcm^{-1}}$$

The induced electric field survives for a short distance from the surface of the NS, since it gets screened by the intense production of electron-positron pairs that short circuit it. The total available potential is

$$\Phi = \frac{2\pi^2 B R_\star^3}{P^2 c^2} \sim 6.6 \times 10^{19}\, B_{13} R_{\star,6}^3 P_{-3}^{-2}\,\mathrm{V} \quad \Rightarrow \quad \gamma_{\mathrm{fpd}} = \frac{Ze}{Am_p c^2}\Phi = 7 \times 10^{10}\, \frac{Z}{A} B_{13}\, P_{-3}^{-2}$$

ACCELERATION IN A FAST ROTATING NEUTRON STAR

(PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)



Acceleration of nuclei in the gap

A nucleus extracted from the surface gains energy in the electric field in the gap of size ξR_L where R_L is the size of the light cylinder ($R_L = cP/(2\pi) \sim 4.8 \times 10^6\, P_{-3}\,\mathrm{cm}$) but suffers severe curvature losses:

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{Ze\Phi}{Am_pc^2}\frac{2\pi}{\xi P} - \frac{8\pi^2}{3cP^2}\frac{Z^2e^2}{Am_pc^2}\gamma^4 \longrightarrow \gamma_{\mathrm{curv}} = \left(\frac{3\pi BR_\star^3}{2ZecP\xi}\right)^{1/4} \sim 1.1\times 10^8 Z_{26}^{-1/4}\xi^{-1/4}B_{13}^{1/4}P_{-3}^{-1/4}R_{\star,6}^{3/4}$$

A nucleus of iron extracted from the surface and surviving curvature losses is also bombarded from behind by thermal photons emitted from the hot star surface. This causes photo-disintegration of the nuclei, which end up having a mixed composition at exit.

$$\epsilon_{\gamma,\mathrm{th}} = k_B T \sim 86\,\mathrm{eV}\,T_6$$

Energy of thermal photons

$$\bar{\epsilon}_{A\gamma} = 18.31 A_{56}^{-0.21}\,\mathrm{MeV}$$

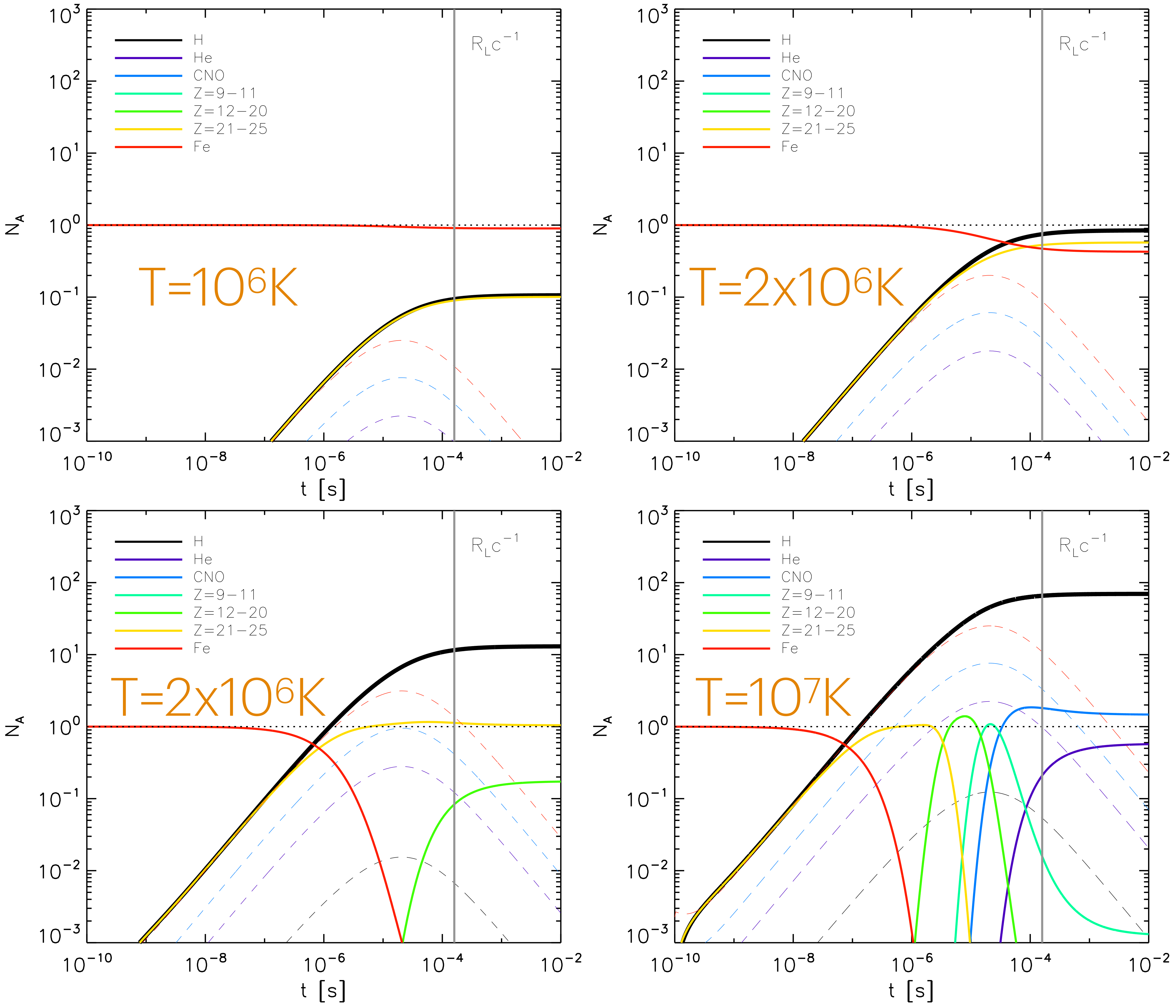
Threshold for Giant Dipole resonance

$$\gamma_{A,\mathrm{thres}} = \frac{\bar{\epsilon}_{A\gamma}}{\epsilon_{\gamma,\mathrm{th}}} \sim 2.1\times 10^5\, A_{56}^{-0.21}\, T_6^{-1}$$

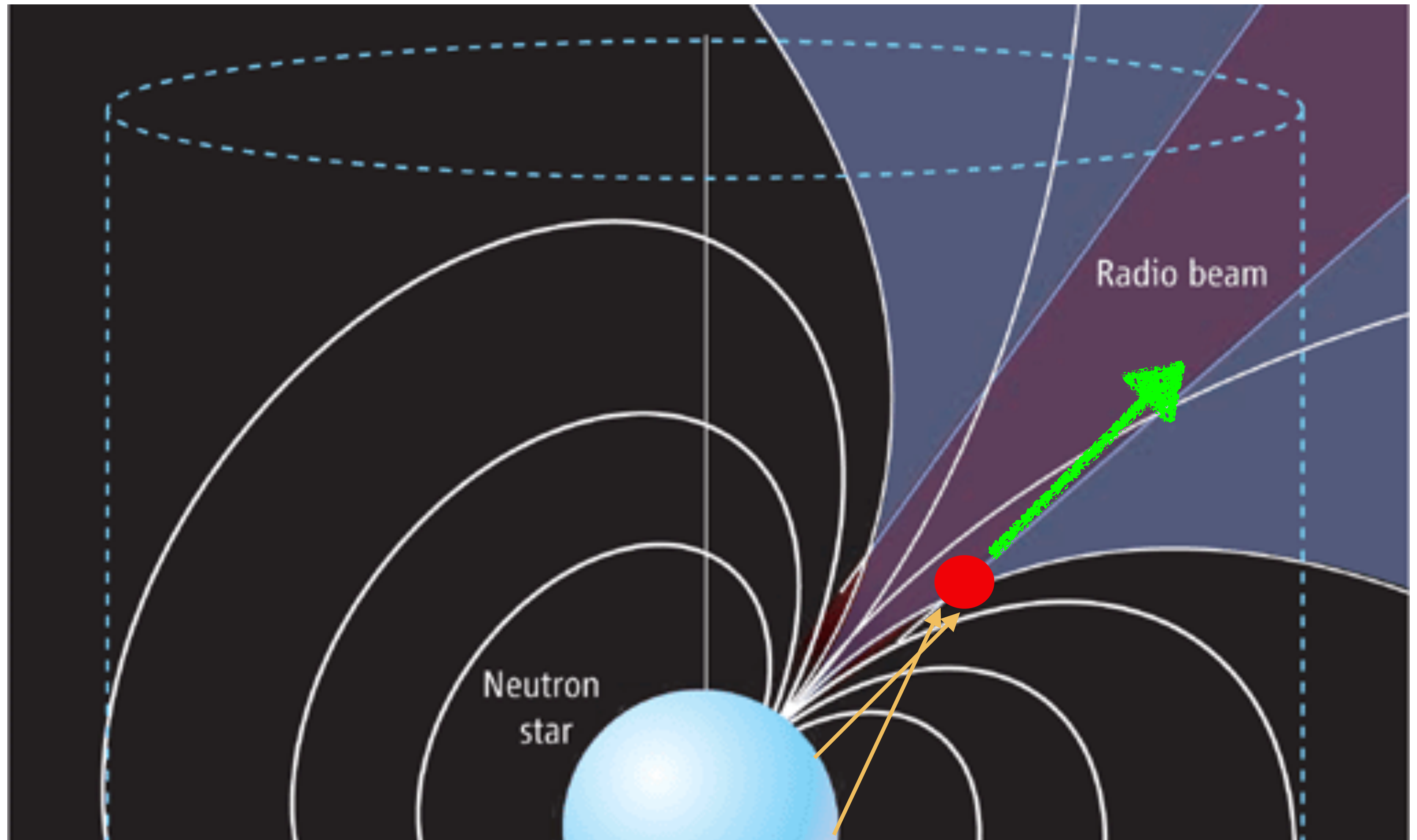
Threshold for photo-disintegration

Acceleration in a fast rotating neutron star

(PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)



- Depending on the temperature of the surface of the NS the photo-disintegration of Fe nuclei leads to a mixed composition
- The amount of mixture depends on the temperature
- Take into account that the photo-disintegration occurs in a very anisotropic, time-dependent scenario



Acceleration in a fast rotating neutron star

Gone with the wind (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)

The general picture is that once the particles reach the light cylinder, they can take part in the wind, namely they move with the wind Lorentz factor, EVEN IF THEY SUFFERED LOSSES EARLIER ON!

$$\dot{E}_{\rm p} = (8\pi B_\star^2 R_\star^6)/(3c^3 P^4) \rightarrow \dot{N}\gamma_{\rm w} mc^2 \equiv 2\kappa m_e c^2 \dot{N}_{\rm GJ}\gamma_{\rm w}\,(1+x_A)$$

$$x_A \equiv m_A/(2\kappa Z m_e)$$

Multiplicity (κ)

$$\dot{N}_{\rm GJ} = e^{-1}(\dot{E}_{\rm p} c)^{1/2}$$

Goldreich-Julian density

It follows that the wind Lorentz factor can be estimated as follows:

$$\gamma_{\rm w}(t) \simeq (1-\eta_B)\frac{\dot{E}_{\rm p}}{\dot{N}mc^2} \sim 3\times 10^9\,(1-\eta_B)(1+x_A)^{-1}(1+t/t_{\rm sd})^{-1}\kappa_4^{-1}P_{{\rm i},-3}^{-2}B_{13}R_{\star,6}^3$$

Notice that it drops down with time!!!

$$t_{\rm sd} = \frac{9Ic^3P_{\rm i}^2}{8\pi^2B^2R^6} \sim 3.1\times 10^7\,{\rm s}\,I_{45}B_{13}^{-2}R_{\star,6}^{-6}P_{{\rm i},-3}^2$$

Spin down time of the pulsar

Acceleration in a fast rotating neutron star

Gone with the wind (PB, Epstein & Olinto 2000, Arons 2003, Kotera, Amato & PB 2015)

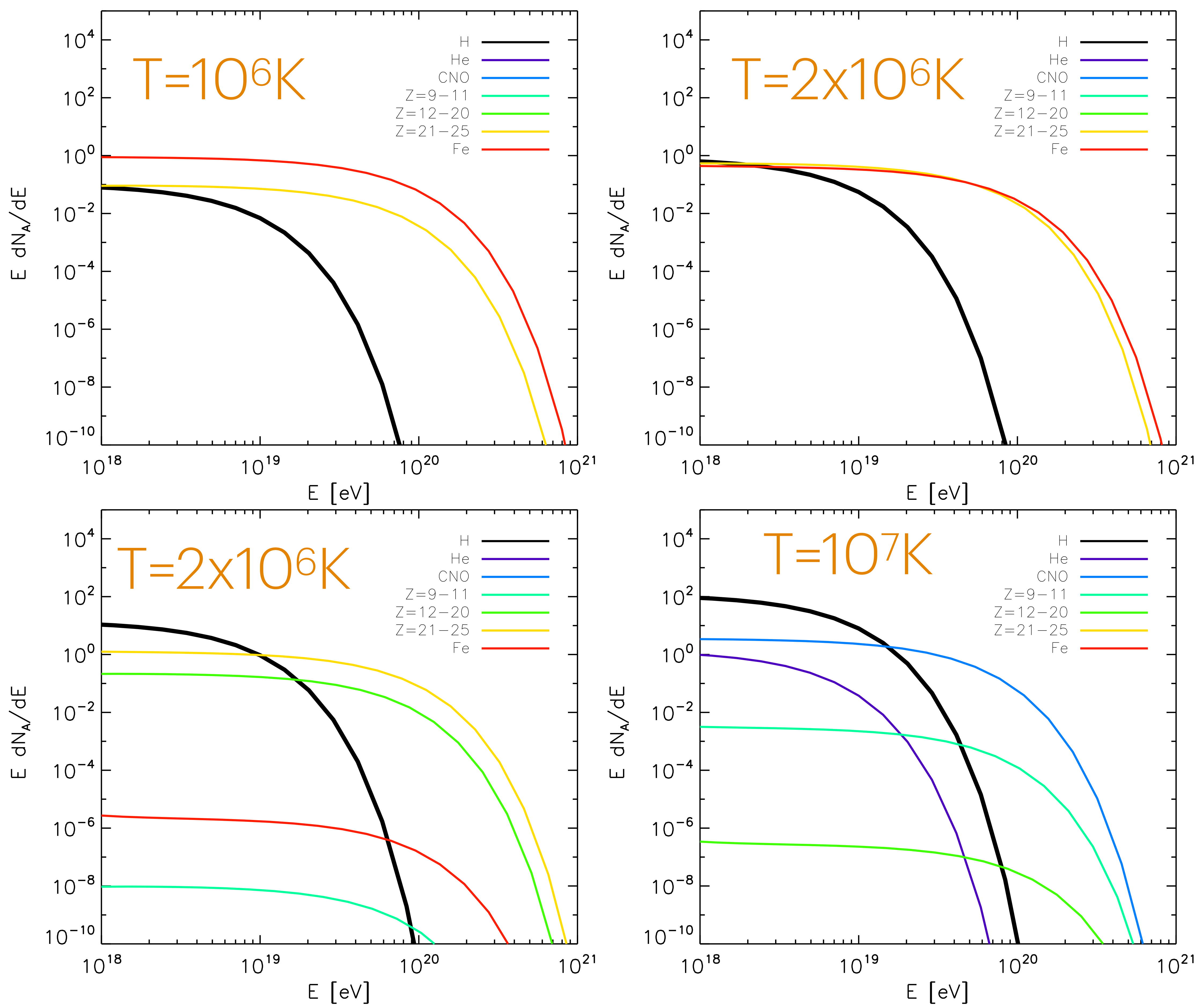
Since the Lorentz factor of the wind decreases, the energy of the particles also decreases in time and results in a SPECTRUM (PB, Epstein & Olinto 2000):

$$E_{\rm CR}(t) = E_0\,(1+t/t_{\rm sd})^{-1}$$
$$\sim 1.2\times10^{20}\,{\rm eV}\,\eta A_{56}\kappa_4 I_{45} B_{13}^{-1} R_{\star,6}^{-3}\, t_{7.5}{}^{-1} \quad \text{for}\quad t > t_{\rm sd}$$

and the spectrum is:

$$\frac{{\rm d}N_{\rm CR}}{{\rm d}E} = \int_0^\infty {\rm d}t \dot{N}_{\rm GJ}(t)\delta\left(E - E_{\rm CR}(t)\right) = \frac{\dot{N}_{\rm GJ}(0)t_{\rm sd}}{E} \sim \mathbf{E^{-1}}$$

Very hard spectrum!!!



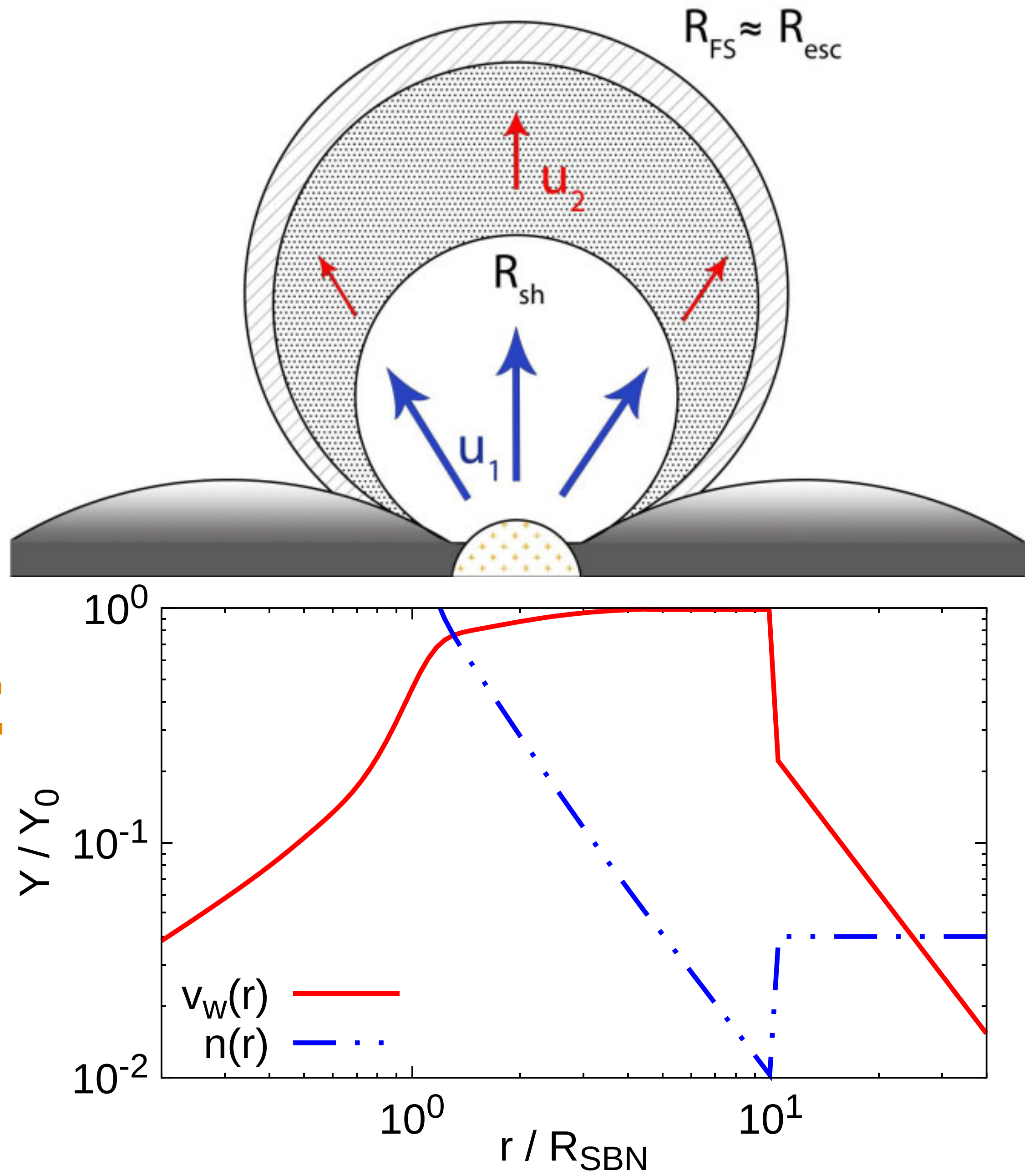
Kotera, Amato & PB 2015

Acceleration in Starburst Galaxies

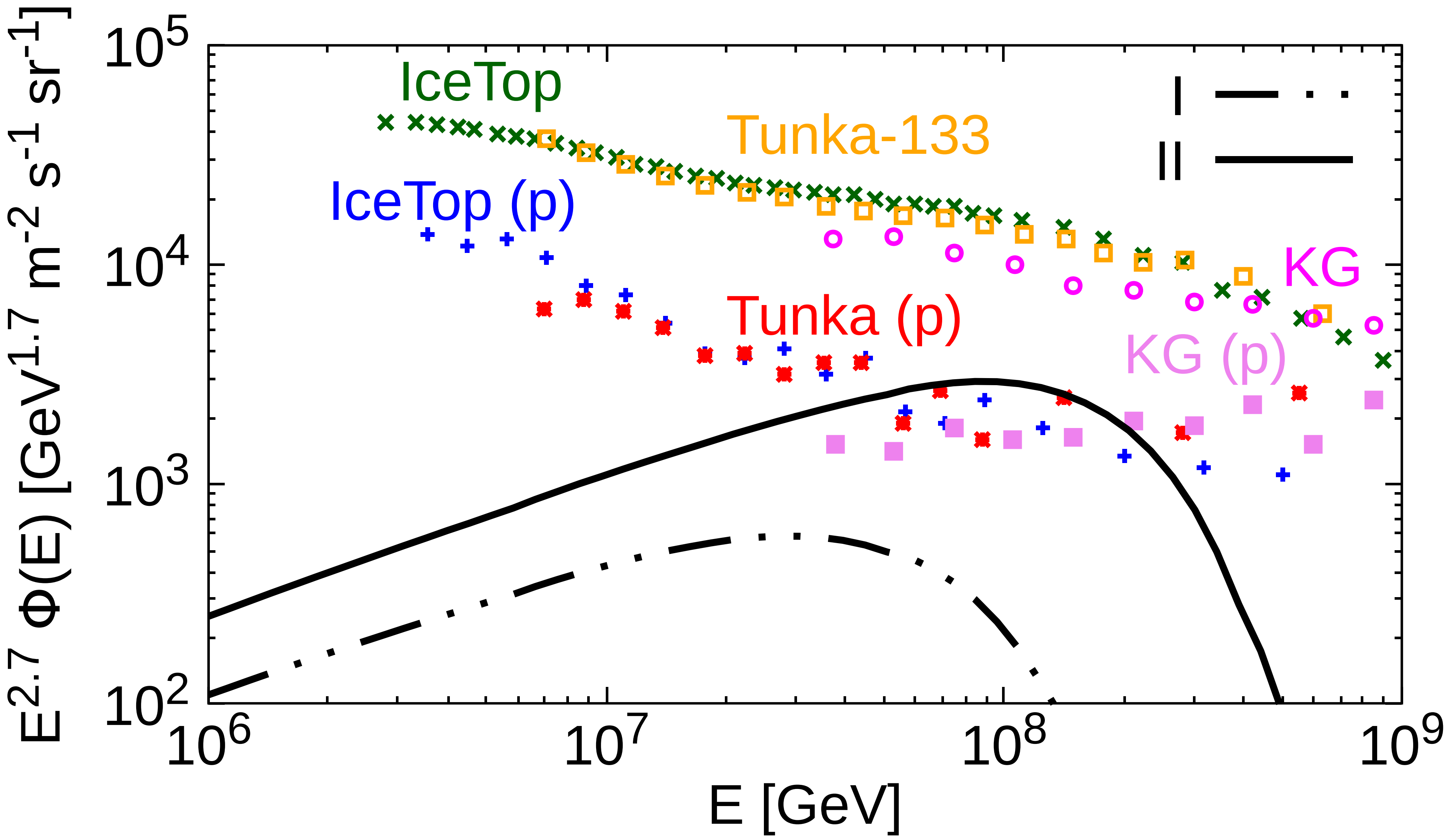
Particle acceleration is expected to take place at the termination shock of the collective wind induced by the star forming region

The acceleration at the termination shock is standard DSA at a newtonian shock, but in spherical symmetry

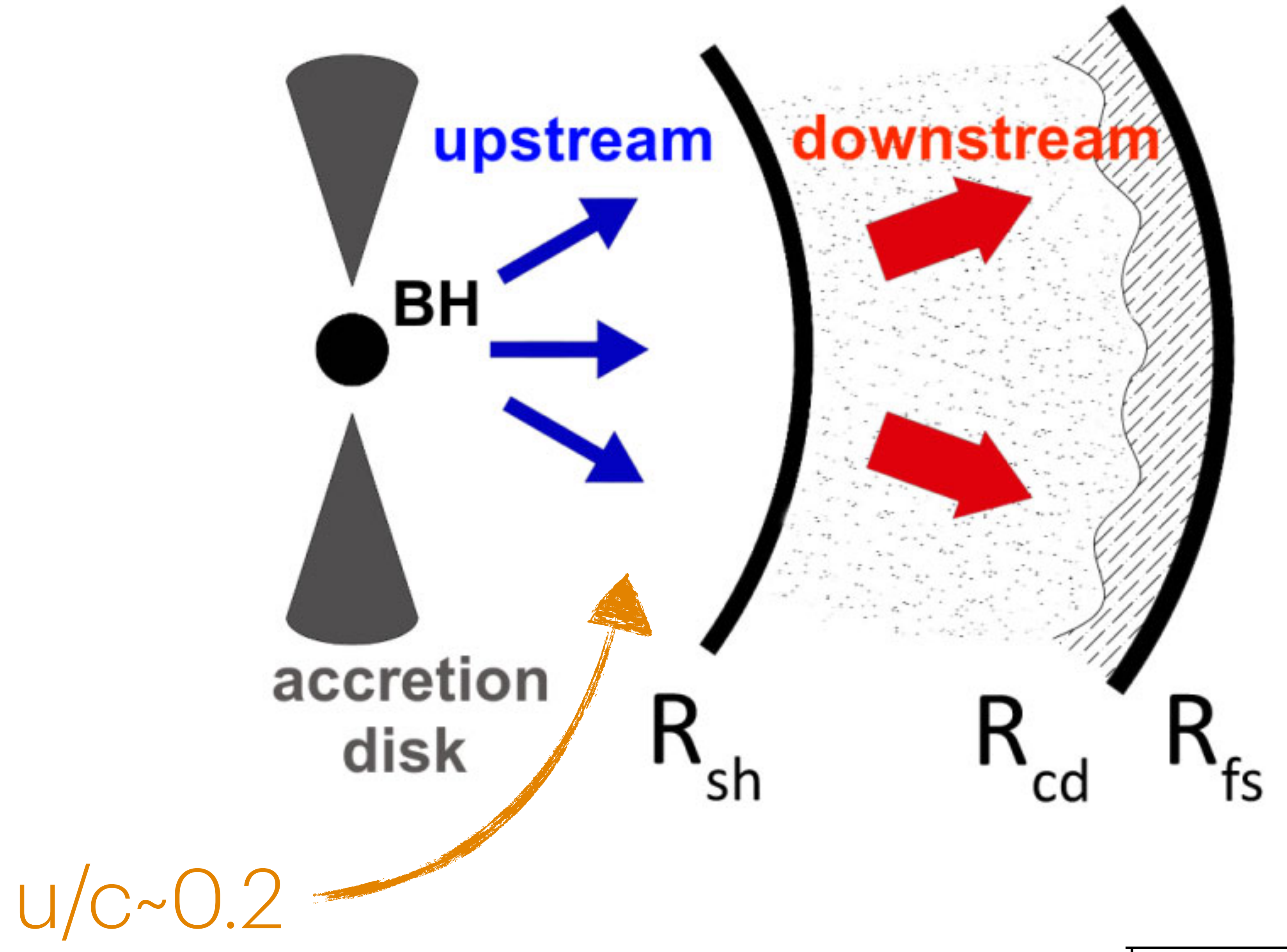
The maximum energy is fixed by geometry and **IT IS NOT SUFFICIENT TO REACH THE OBSERVED MAXIMUM RIGIDITIES!**



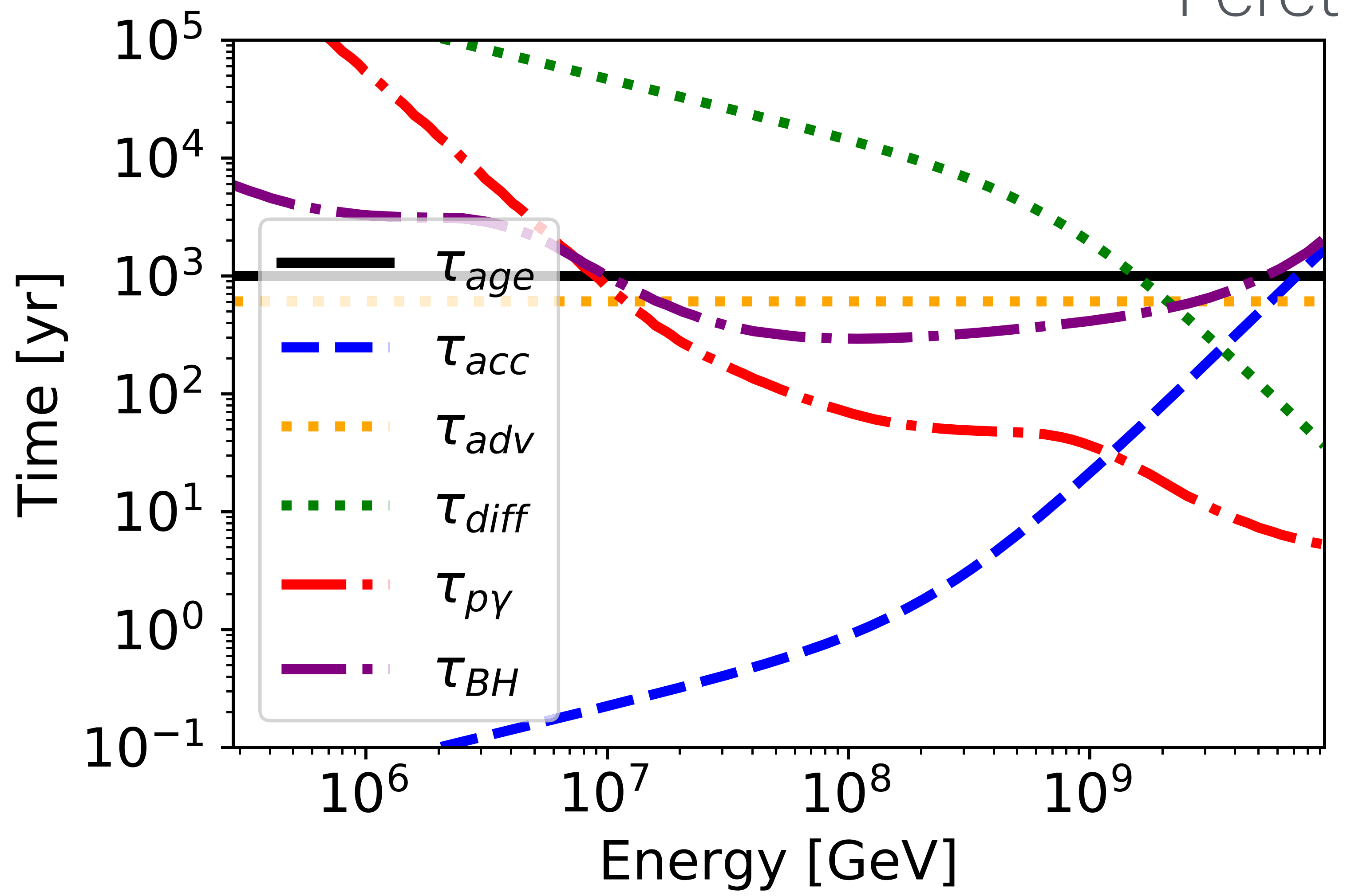
Peretti+ 2022

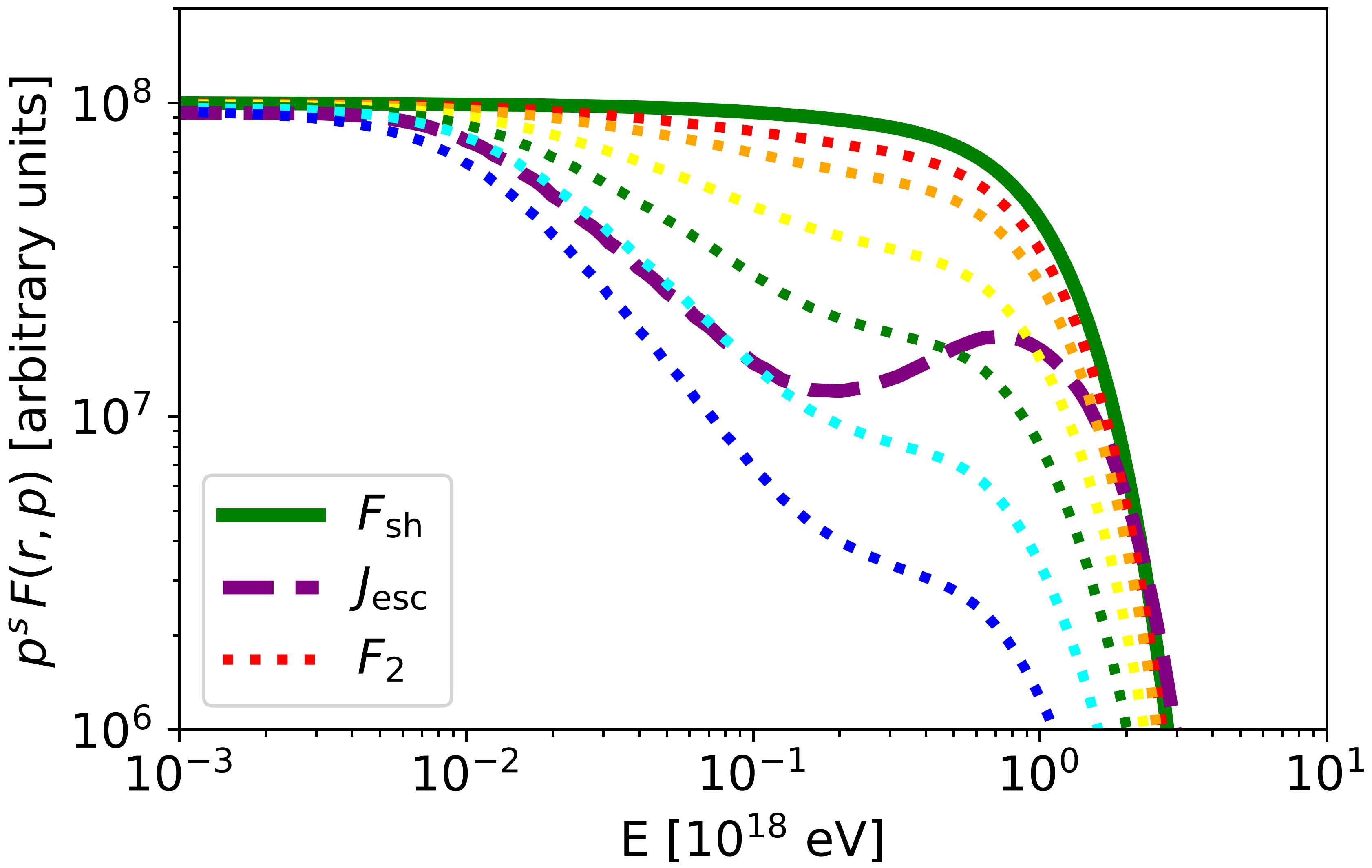


Acceleration in Ultra-Fast-Outflows (UFO)



Peretti+ 2023





ACCELERATION AT ACCRETION SHOCKS IN LSS

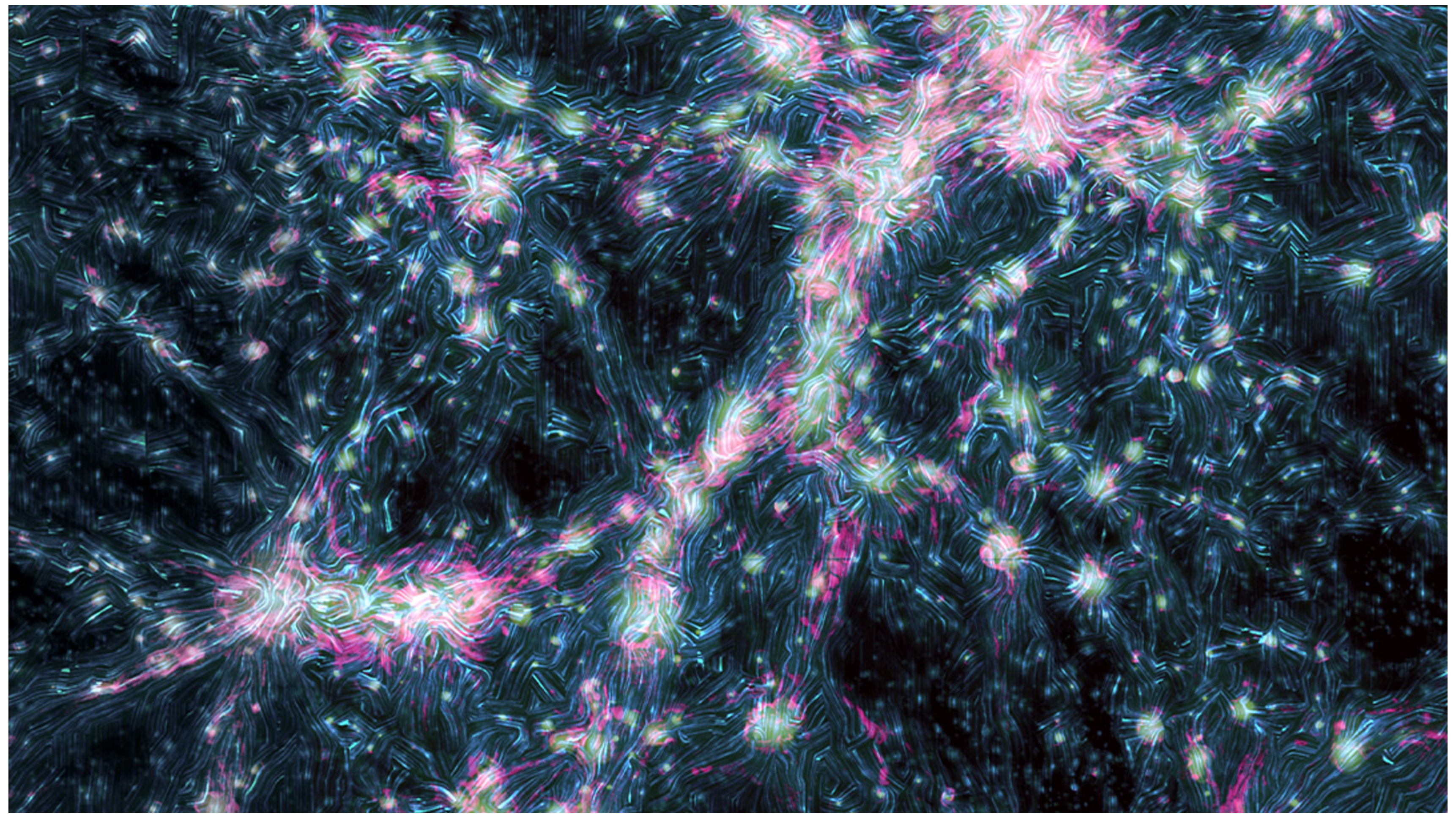
- Large scale structures, such as clusters and superclusters of galaxies, are firmed through two processes: mergers of smaller structures and accretion of gas over cosmological scales (Bertschinger 1985)

- The mergers typically lead to weak shocks inside the structures, as it must be, because each structure is virialized to its own thermal velocity, which is of the same order of magnitude as the free fall velocity...

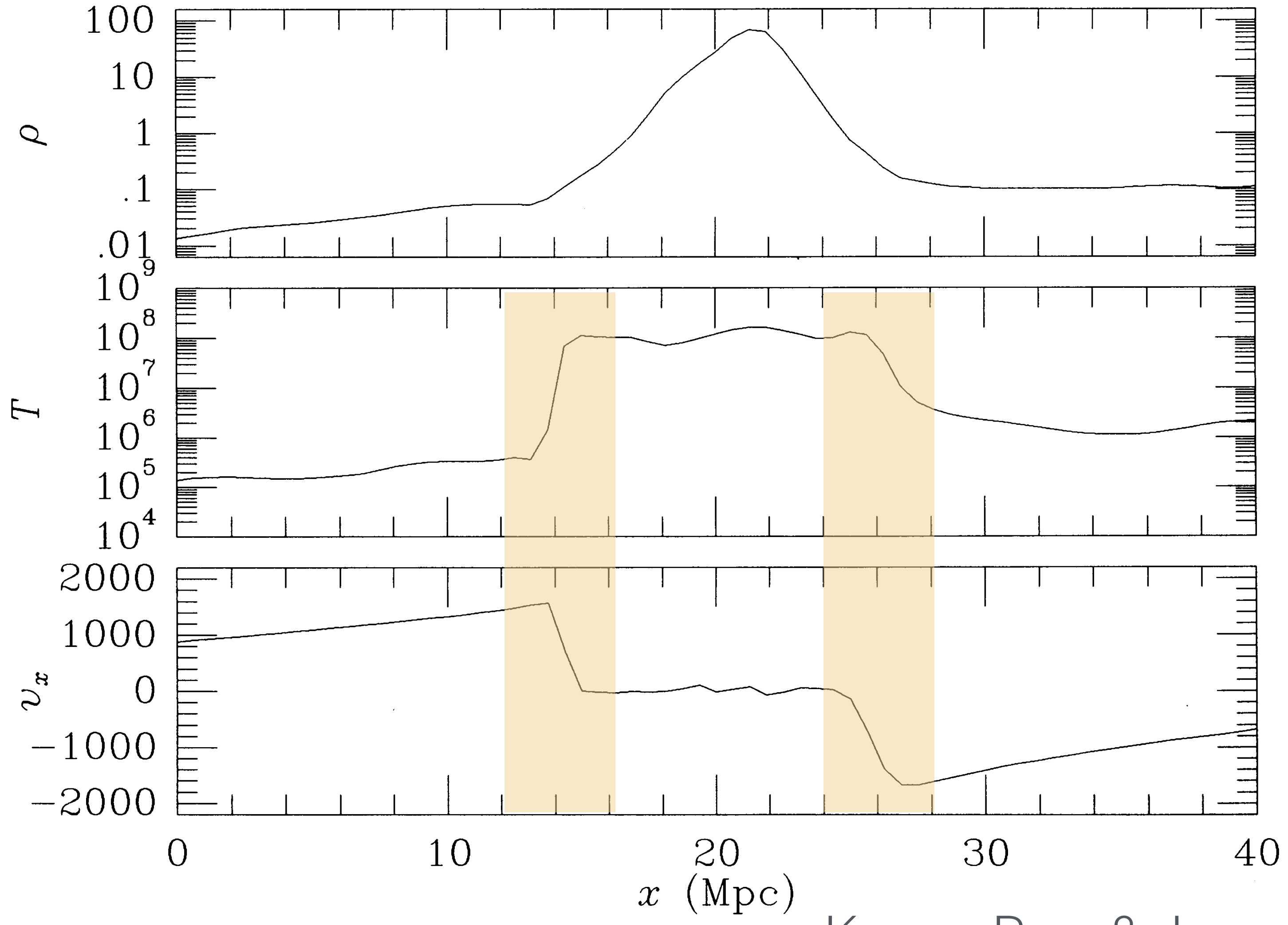
- Hence the Mach number of the merger shocks formed in two equal size structure is of order unity, while the Mach number of the merger between a small and a large cluster can be higher.

- The accretion of gas onto a LSS develops a strong shock in the outskirts of the cluster

- The shocks developing in the LSS filaments are tightly related to this accretion phenomenon



F. VAZZA, D. WITTOR AND J. WEST, 2023



Kang, Ryu & Jones 1996

THE ASTROPHYSICAL JOURNAL, 487:529–535, 1997 October 1

CLUSTERS OF GALAXIES AS STORAGE ROOM FOR COSMIC RAYS

V. S. BEREZINSKY,[1] P. BLASI,[1,2] AND V. S. PTUSKIN[3]
Received 1996 September 6; accepted 1997 May 9

ABSTRACT

It is demonstrated that clusters of galaxies are able to keep cosmic rays for a time exceeding the age of the universe. This phenomenon reveals itself by the production of the diffuse flux of high-energy gamma and neutrino radiation due to the interaction of the cosmic rays with the intracluster gas. The produced flux is determined by the cosmological density of baryons, Ω_b, if a large part of this density is provided by the intracluster gas. The signal from relic cosmic rays has to be compared with the flux produced by the late sources, which can be considered as a background in the search for cosmic-ray production in the past. We calculate this flux considering the normal galaxies and active galactic nuclei (AGNs) in the clusters as the sources of cosmic rays. Another potential cosmic-ray source is the shock in the gas accreting to a cluster. We found that this background is relatively high: the diffuse fluxes produced by relic cosmic rays are of the same order of magnitude that can be expected from AGNs in the clusters. In all cases the predicted diffuse gamma-ray flux is smaller than the observed one, and the diffuse neutrino flux can be seen as the small bump at $E \sim 10^6$ GeV over the atmospheric neutrino flux. A bright phase in the galaxy evolution can be a source of the relic cosmic rays in clusters, revealing itself by diffuse gamma and neutrino radiation. We found that the observation of a signal from the bright phase is better for an individual cluster.

The diffusive confinement of CRs in clusters of galaxies has numerous implications that are still being checked with gamma and neutrino telescopes. The processes of particle acceleration in clusters are thought to be potentially related to UHECR. The magnetic fields in the accretion filaments are believed to affect the transport of UHECRs

Clusters as storage rooms of CR: mergers

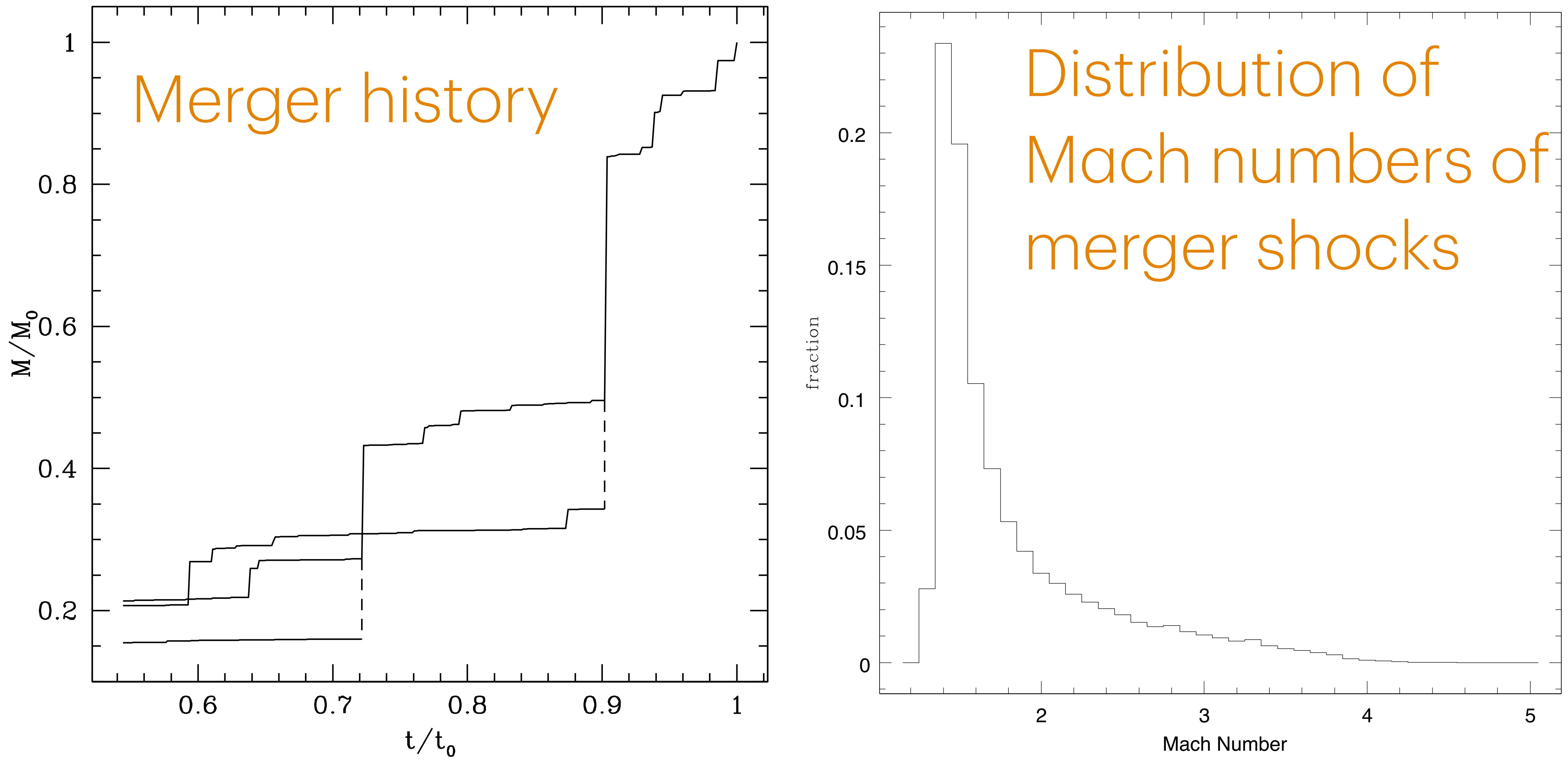
- Particle acceleration in clusters can take place during merger shocks

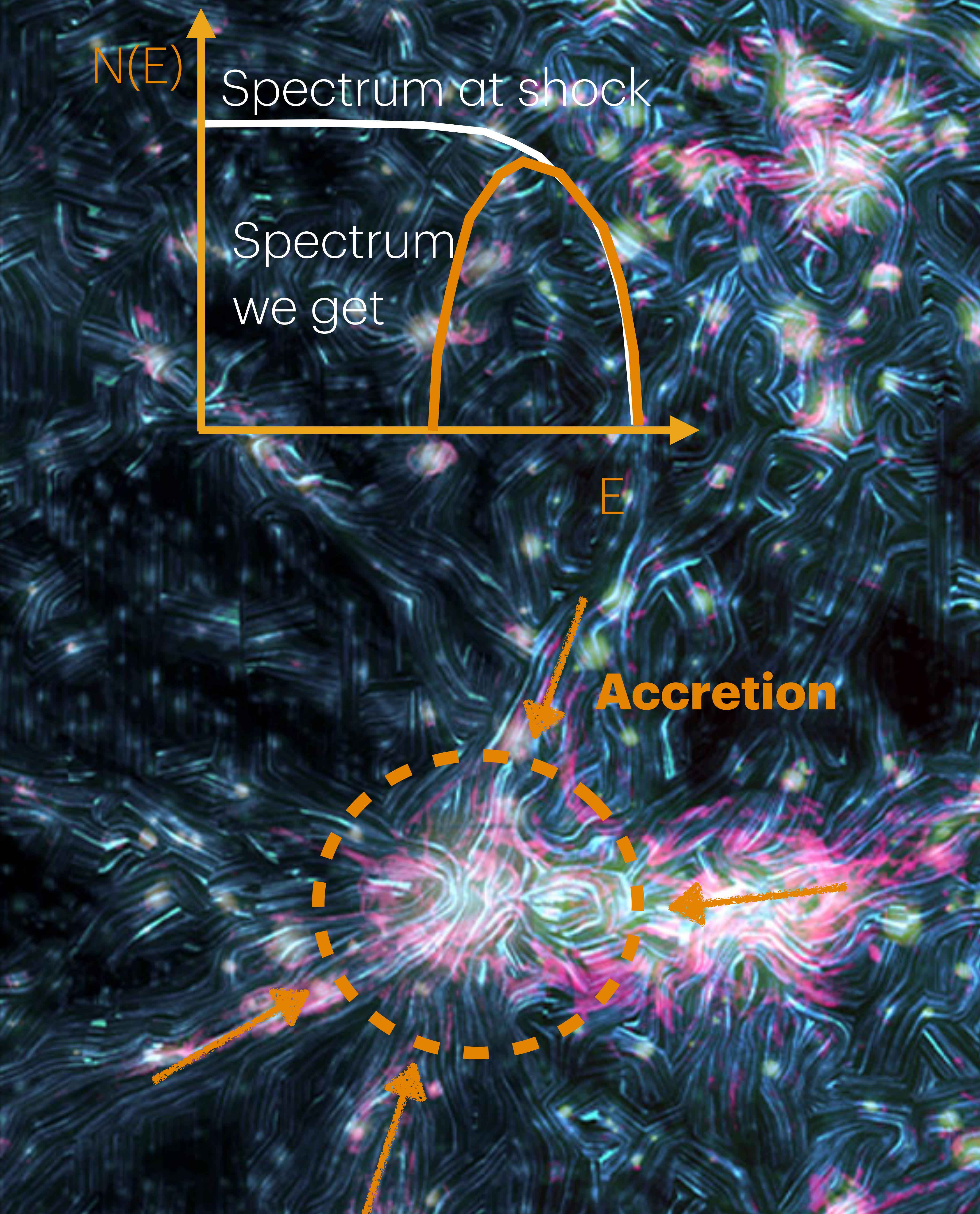
- ...at accretion shocks

- ... or inside one of the hundred of astrophysical objects (galaxies, AGN, ...) that are hosted by the cluster

- The spectra are different in these cases

Gabici & PB 2003





F. VAZZA, D. WITTOR AND J. WEST, 2023

- Accretion occurs in the outskirts of the cluster —> shocks with M>10 where the IGM is processed and heated up to 10^8 K
- For massive clusters there are the conditions for streaming instability to be induced
- Particle acceleration to EeV possible
- Careful: we are sitting in the upstream (hard spectrum at Earth)

Summary

- Giant change in paradigm from the times of AGASA and HiRes
- A change provided by reliable observation of the mass and spectrum…
- Plenty of classes of sources are able to reach EeV energies
- The source spectrum required by observations is weird (effects in the source or en route) but not absurd (reacceleration, turbulent acceleration, reconnection, upstream of a cluster shock)
- The picture that arises for the origin of UHECR and the transition from the Galactic component is complicated, not a simple, elegant picture as one would expect from a well behaved mother Nature (disappointing model)