Particle acceleration to extreme energies

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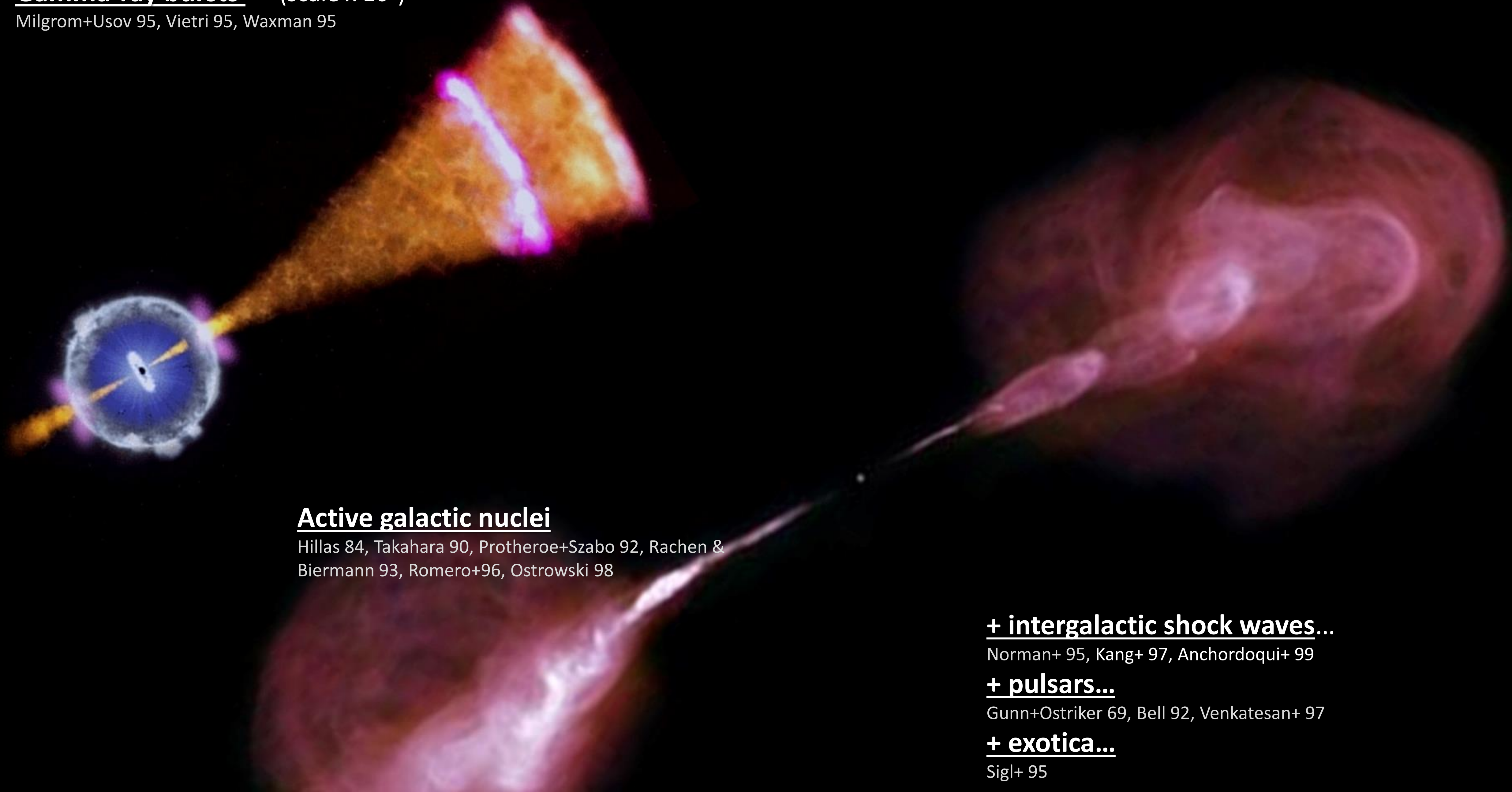
Usual suspects… twenty years ago…

Gamma-ray bursts (scale x 10^5)

Milgrom+Usov 95, Vietri 95, Waxman 95



Active galactic nuclei

Hillas 84, Takahara 90, Protheroe+Szabo 92, Rachen & Biermann 93, Romero+96, Ostrowski 98

+ intergalactic shock waves…

Norman+ 95, Kang+ 97, Anchordoqui+ 99

+ pulsars…

Gunn+Ostriker 69, Bell 92, Venkatesan+ 97

+ exotica…

Sigl+ 95

Usual suspects... now...

Powerful transients: high and low luminosity GRBs, relativistic SNe, fast spinning magnetars/pulsars...

High luminosity GRB:
Milgrom + Usov 95, Vietri 95, Waxman 95, Rachen + Meszaros 96, Gallant + Achterberg 99, Pelletier + Kersale 00, Dermer + Humi 01, Waxman 01, Scully + Stecker 02, Gialis + Pelletier 03, Waxman 04, Rieger + Duffy 06, Asano+ 09, 10, Razzaque+ 10, Giannios 10, Eichler + Pohl 11, Metzger+ 11, Baerwald+ 15, Globus+ 15, Asano + Meszaros 16, Samuelsson+ 19

Low-luminosity GRBs / Relativistic SNe:
Murase+ 06, Budnik+ 08, Wang+ 08, Liu+ 11, Chakraborti+ 11 , Liu + Wang 12, Zhang + Murase 18, Zhang+ 18, Boncioli+ 19

Magnetar WNe/ Pulsar WNe :
Bell 92, Blasi+ 00, de Gouveia dal Pino + Lazarian 01, Arons 03, Vietri+ 03, Fang+ 13, Lemoine+ 15, Fang+ 18, Kirk + Giancinti 19

Blazar/Radio-galaxy jet+lobe:
Takahara 90, Rachen + Biermann 93, Ostrowski 98, Farrar + Piran 00, Tinyakov + Tkachev 01, Gorbunov+ 02, Lyutikov + Ouyed 07, Atoyan+Dermer 08, Gorbunov + 08, Dermer+ 09, Hardcastle+ 09, O'Sullivan+ 09, Dermer + Razzaque 10, Gopal-Krishna+ 10, Biermann+ deSouza 12, Murase+ 12, Ptuskin+ 13,Caprioli 15, Wang + Loeb17, Eichmann+ 18, Liu+ 17, Resconi+ 17, Kimura+ 18, Matthews+ 18,19,Fang + Murase18,Rieger 19

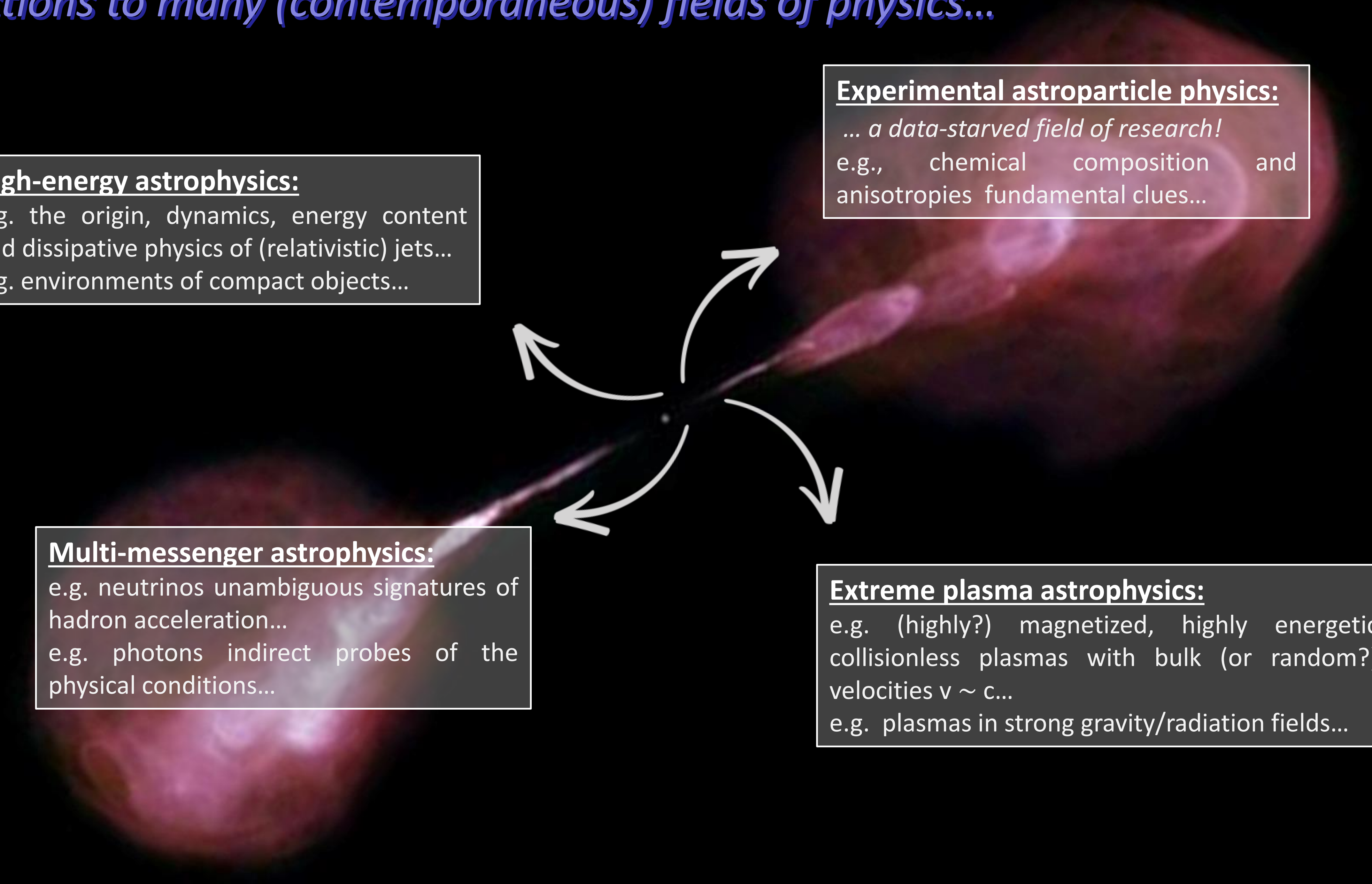
Active galactic nuclei:

AGN Core:
Protheroe + Szabo 92, Boldt + Ghosh 99, Levinson 00, Levinson + Boldt 00, Torres+ 02, Dempsey + Rieger 09, Istomin + Sol 09, Neronov + 09, Rieger + Aharonian 09, Dutan + Caramete 14, Moncada+ 17

+ intergalactic shock waves (clusters, starbursts)...
Norman+95, Kang+ 97,Anchordoqui+ 99, + 01, Murase+ 08, Kotera +09, Malkov +11, Anchordoqui 18, Romero+ 18

+ other transients: e.g. tidal disruption events...
Farrar+Piran14, Alves Batista + Silk 17, Biehl+18, Guepin+18

Connections to many (contemporaneous) fields of physics…



High-energy astrophysics:

e.g. the origin, dynamics, energy content and dissipative physics of (relativistic) jets…

e.g. environments of compact objects…

Experimental astroparticle physics:

… a data-starved field of research!

e.g., chemical composition and anisotropies fundamental clues…

Multi-messenger astrophysics:

e.g. neutrinos unambiguous signatures of hadron acceleration…

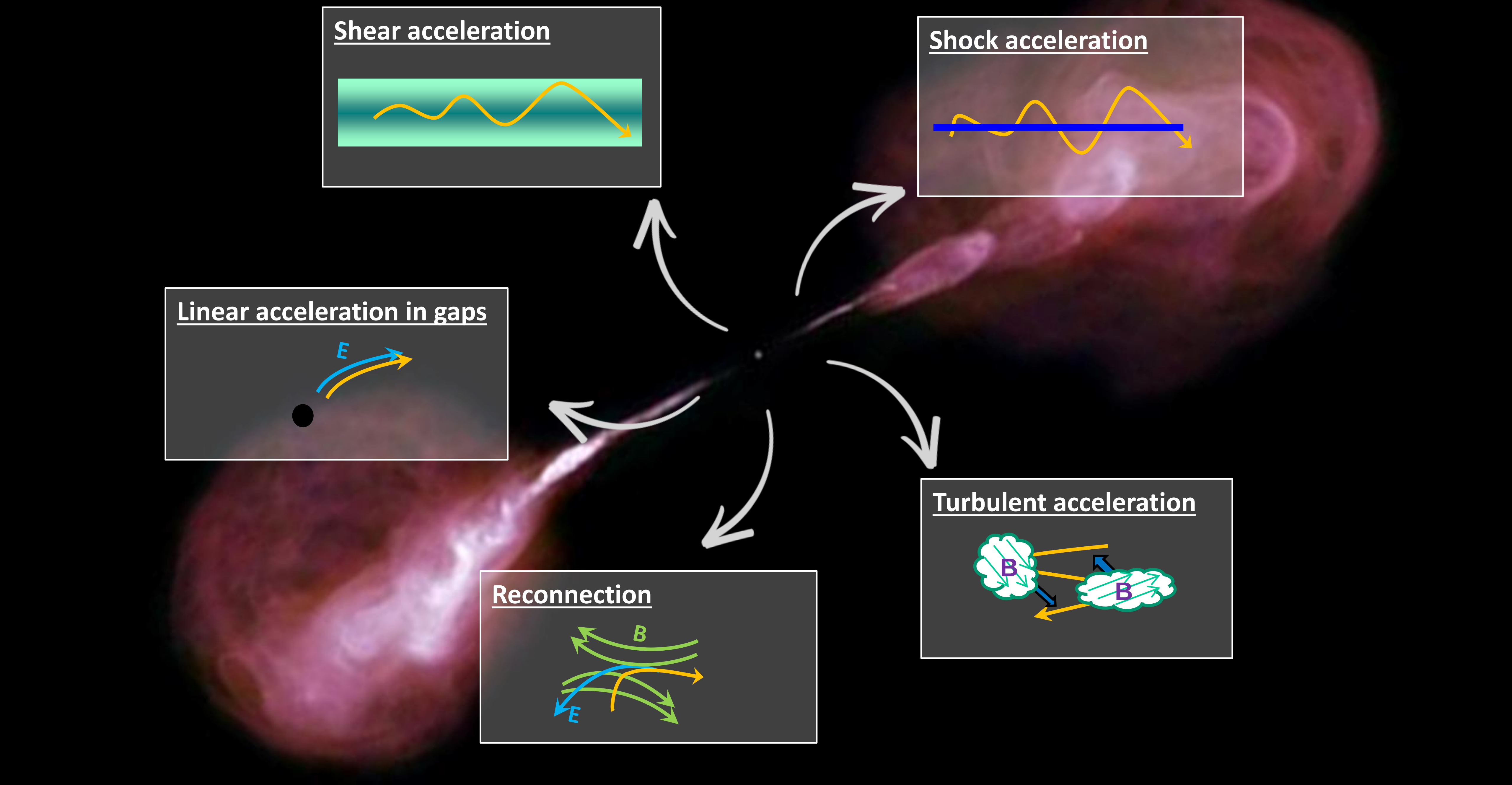
e.g. photons indirect probes of the physical conditions…

Extreme plasma astrophysics:

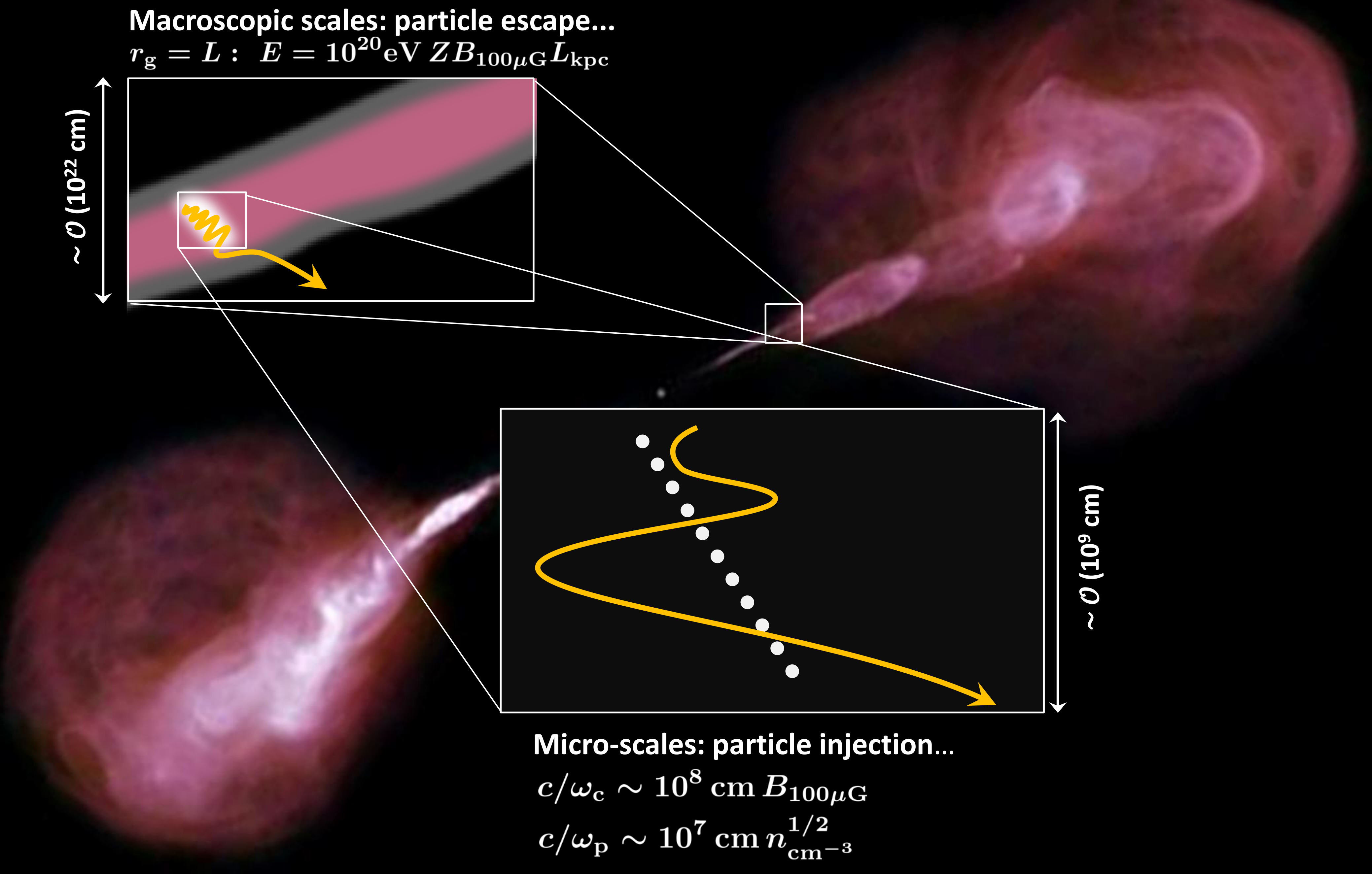
e.g. (highly?) magnetized, highly energetic collisionless plasmas with bulk (or random?) velocities $v \sim c$…

e.g. plasmas in strong gravity/radiation fields…

Various (more or less known) acceleration scenarios…



A challenge of scales...



Particle acceleration as multi-scale, nonlinear process

… in many (most?) situations, accelerated particles feed back on the electromagnetic environment

⇒ need to go beyond the test particle description!

accelerated particles + magnetic field ⟶ turbulence

multi-scale cascade ⟵ turbulence

particle transport

particle acceleration

accelerated particles + backgrounds⟶ radiation

pair production ⟵ radiation + radiation

radiation ⟵ pair production

plasma composition + dynamics ⟵ pair production

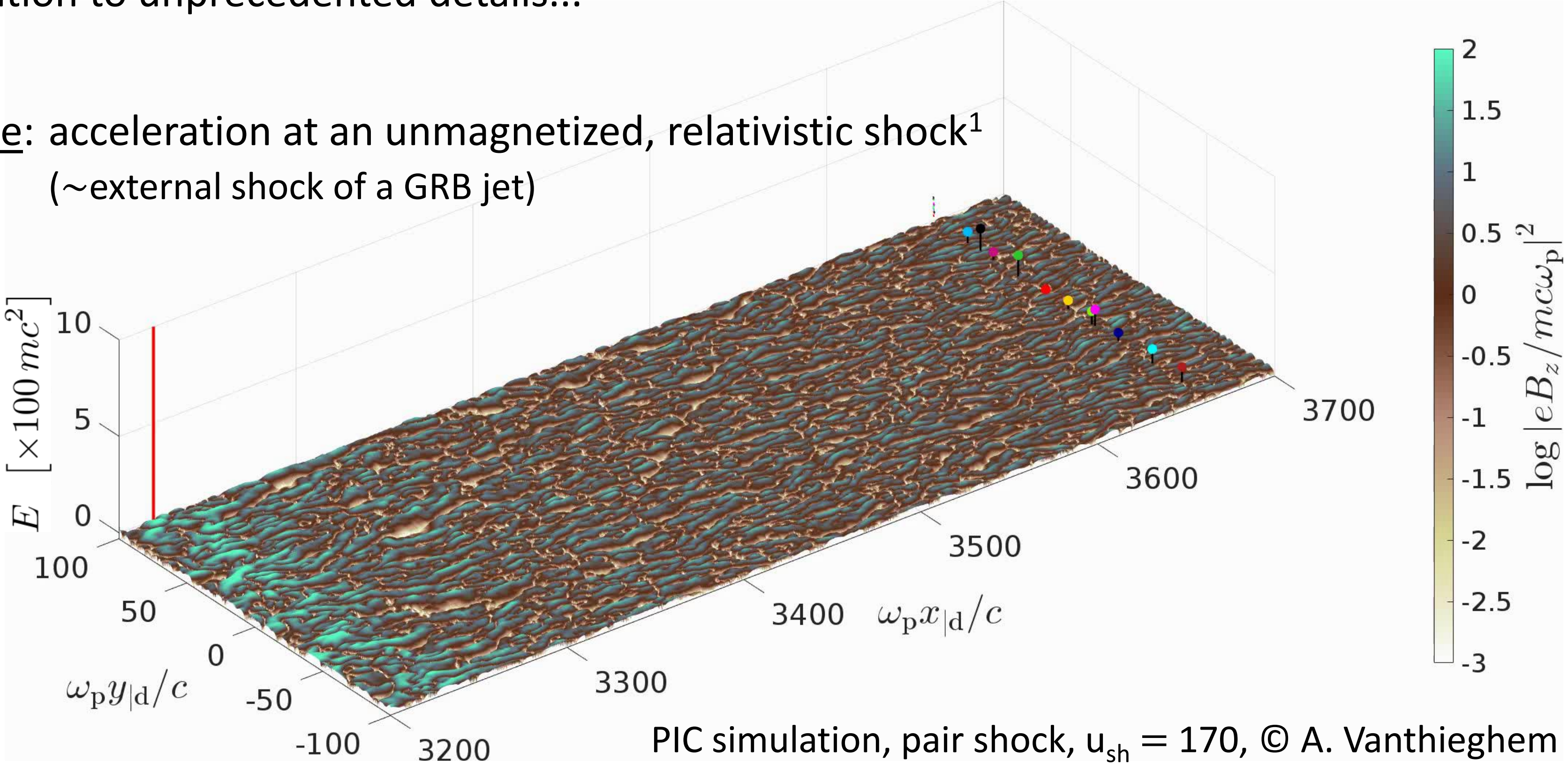
Particle acceleration as multi-scale, nonlinear process

… in many (most?) situations, accelerated particles feed back on the electromagnetic environment

⇒ need to go beyond the test particle description!

… HPC numerical simulations (Monte Carlo, particle-in-cell, MHD+PIC, hybrid …) allow to explore the physics of acceleration to unprecedented details...

<u>example</u>: acceleration at an unmagnetized, relativistic shock[1]
(~external shock of a GRB jet)



PIC simulation, pair shock, $u_{sh} = 170$, © A. Vanthieghem

magnetic field self-generated by accelerated particles on microscopic length scales

… an important caveat to keep in mind: ab initio simulations remain limited to small scales…

Refs.: 1. Medvedev+Loeb99,…, Kato08, Spitkovsky08, …, ML+19

Particle acceleration to extreme energies

Outline:

1. **The view from phenomenology: top-down, from large to small scales**

2. **The view from microphysics: bottom-up, from first principles**

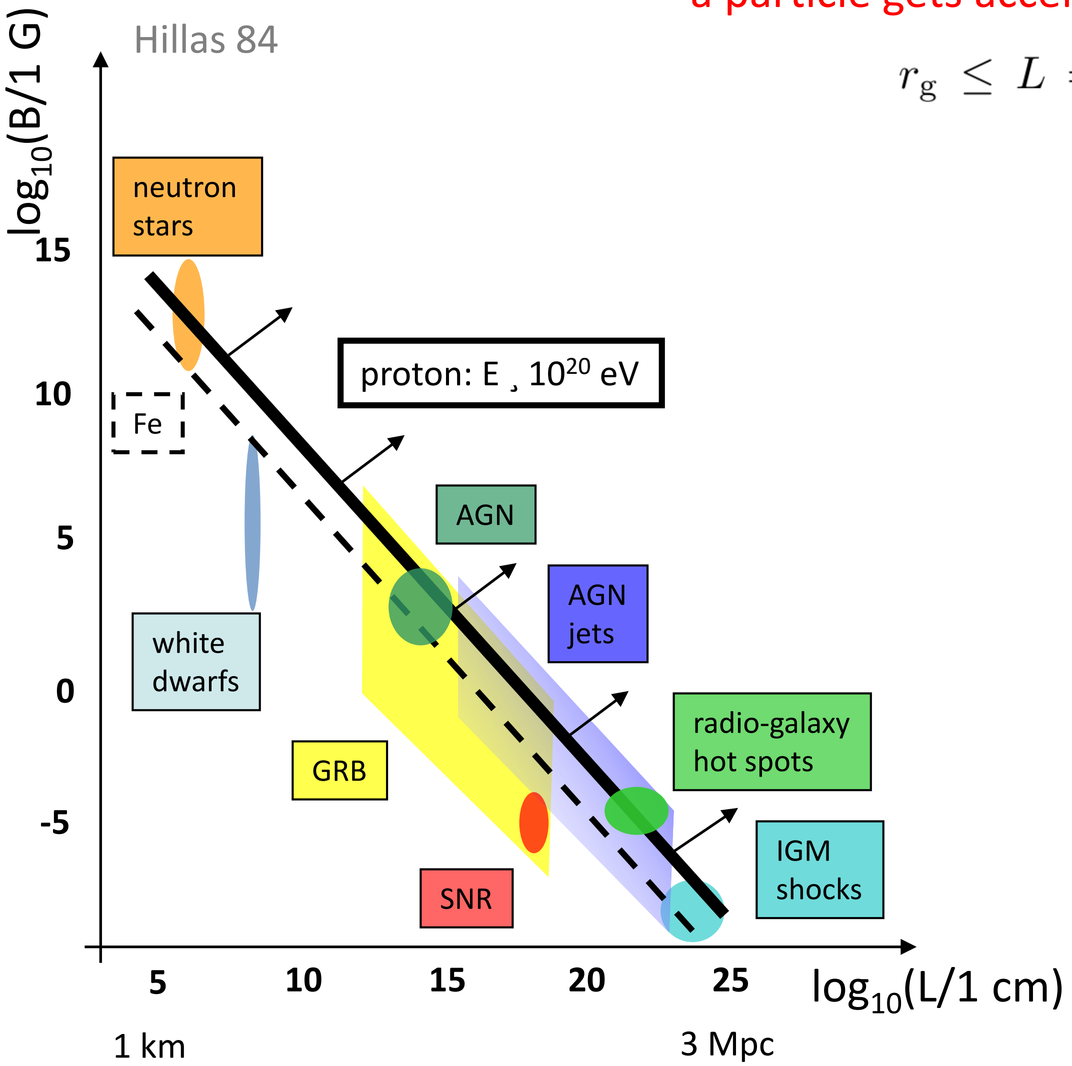
3. **Discussion: clues and issues**

Acceleration – Hillas bound

<u>a simple criterion:</u> to find which object ***might*** be a source of UHE cosmic rays:

a particle gets accelerated as long as it is confined in the source:

$$r_{\rm g} \leq L \Rightarrow E \leq 10^{20}\,{\rm eV}\,Z B_{\mu{\rm G}} L_{100\,{\rm kpc}}$$



1. necessary, but by no means sufficient (losses, age…)

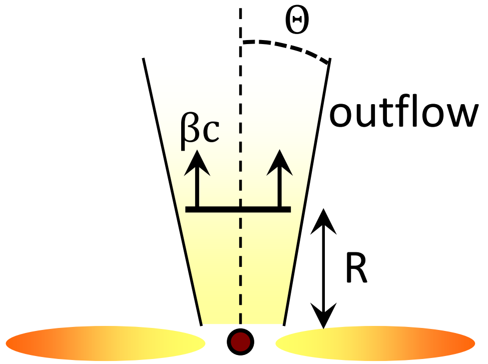
E_{conf}: $r_g(E_{conf}) = L$, the best you can hope for…

$\Rightarrow$acceleration challenge: reach E_{conf}

2. watch out for relativistic effects

accelerators are likely relativistic sources…

A luminosity bound for acceleration in outflows



→ a generic model: acceleration in some relativistic outflow

write acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm g}$

$\boldsymbol{t_{\rm g} \equiv \frac{p}{eB}}$ **gyrotime,** $\boldsymbol{t_{\rm scatt}}$ **scattering timescale**

… comparing t_{acc} and age $t_{dyn} = R/(\beta\Gamma c)$ bounds the (magnetic) luminosity of the source to reach UHE:

$$t_{\rm acc} \le t_{\rm dyn} \Rightarrow E_{\rm obs} \le \mathcal{A}^{-1} ZeBR/\beta$$

… magnetic luminosity of the source: $L_B = 2\pi R^2 \Theta^2 \frac{B^2}{8\pi} \Gamma^2 \beta c$

$$\boxed{\Rightarrow\ L_{\rm tot} \ge L_B \ge 10^{45}\ \ldots\ \mathcal{A}^2 \left(\frac{E}{Z \times 10^{20}\,{\rm eV}}\right)^2\ {\rm erg/s}}$$

… some typical examples:

low lum. AGN: $L_{bol} \ll 10^{45}$ ergs/s

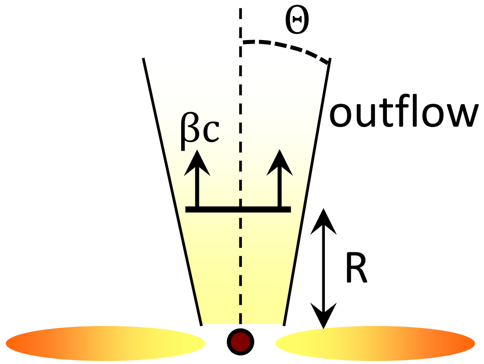
high lum. AGN: $L_{bol} \sim 10^{46}$-10^{48} ergs/s

Crab pulsar: $L_{bol} \sim 10^{39}$ ergs/s

high lum. GRBs: $L_{bol} \sim 10^{52}$ ergs/s

Refs.: Norman+95, Blandford 00, Aharonian 02, Waxman 04, Lyutikov+Ouyed 07, Lemoine+Waxman 09,…

A luminosity bound for acceleration in outflows



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$$\boxed{L_{\rm tot} \geq 10^{45} \ \ldots \ \mathcal{A}^2 \left(\frac{E}{Z \times 10^{20}\,{\rm eV}}\right)^2 \ {\rm erg/s}}$$

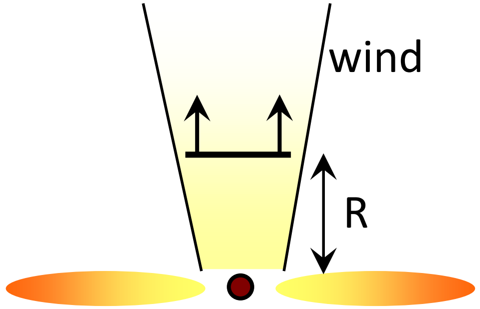
Note:

+ accounts for possible self-amplification of magnetic field by accelerated particles!

– assumes an outflow: not applicable to static sources, e.g. gaps or stochastic acceleration in lobes of radio-galaxies…

Refs.: Norman+95, Blandford 00, Aharonian 02, Waxman 04, Lyutikov+Ouyed 07, Lemoine+Waxman 09,…

A luminosity bound for acceleration in outflows



→ a generic model: acceleration in some relativistic outflow

write acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

→ *A* >> 1 in most acceleration scenarios:

e.g. in Fermi-type, **A** ~ interaction time / energy gain

sub-relativistic Fermi I: $\mathcal{A} \gtrsim 1/\beta_{\rm sh}^2$ ($\beta_{\rm sh}$ shock velocity/c)
(saturation: Bohm regime!)

sub-relativistic stochastic: $\mathcal{A} \gtrsim 1/\beta_{\rm A}^2$ ($\beta_{\rm A}$ turb. velocity/c)

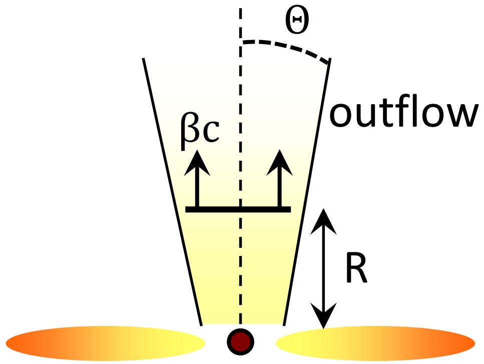
relativistic Fermi: $\mathcal{A} \sim t_{\rm scatt}/t_{\rm g}$ (TBD!)

relativistic reconnection: $\mathcal{A} \gtrsim 10$

→ strong limit: $$L_{\rm tot} \geq 10^{45} \ \dots \ \mathcal{A}^2 \left(\frac{E}{Z \times 10^{20}\,{\rm eV}}\right)^2 {\rm erg/s}$$

Refs.: Norman+95, Blandford 00, Aharonian 02, Waxman 04, Lyutikov+Ouyed 07, Lemoine+Waxman 09,…

A luminosity bound for acceleration in outflows



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… comparing t_{acc} and age $t_{dyn} = R/(\beta\Gamma c)$ bounds the (magnetic) luminosity of the source to reach UHE:

$$\boxed{L_{\rm tot} \geq 10^{45} \; \ldots \; \mathcal{A}^2 \left(\frac{E}{Z \times 10^{20}\,\rm eV}\right)^2 \; \rm erg/s}$$

→ a direct consequence: chemical composition (Z) controls the phenomenology!
(very few candidates for low Z, many more for high Z!)

+ to go further: $\ldots\, \mathcal{A}^2 \propto \dfrac{t_{\rm scatt}}{t_{\rm g}} \begin{cases} u^2 & (u \gg 1) \\ 1/u & (u \ll 1) \end{cases}$ (u 4-velocity of outflow)

$\Longrightarrow$ favors relativistic (mildly?) sources…
+ optimal acceleration to reach confinement energy: $t_{acc} \sim t_g$!

Top - down… some lessons learned…

Three critical properties of UHECR sources:

→ a large (apparent) source density[1]: $\Delta t_{\rm magnetic}\, \dot{n}_{\rm UHECR}$ or $n_{\rm UHECR} \gtrsim 10^{-5}\,/{\rm Mpc}^3$

→ a high output of cosmic rays[2]: $\dot{e}_{\rm UHECR} \sim 10^{44}\,{\rm erg/Mpc^3/yr}$

… a non-trivial constraint: e.g. $L_{UHE}/L_\gamma \sim 10$ for HL GRBs…
e.g. $L_{UHE}/L \sim \mathcal{O}(1\%)$ for radio-galaxies…

→ a high magnetic luminosity: $L_{\rm tot} \gtrsim 10^{45}\,{\rm erg/s}\ \ldots \left(\frac{t_{\rm acc}}{t_{\rm g}}\right)^2 \left(\frac{E/Z}{10^{20}\,{\rm eV}}\right)^2$

… leading contenders, for accelerating intermediate nuclei (Z ~ 10):

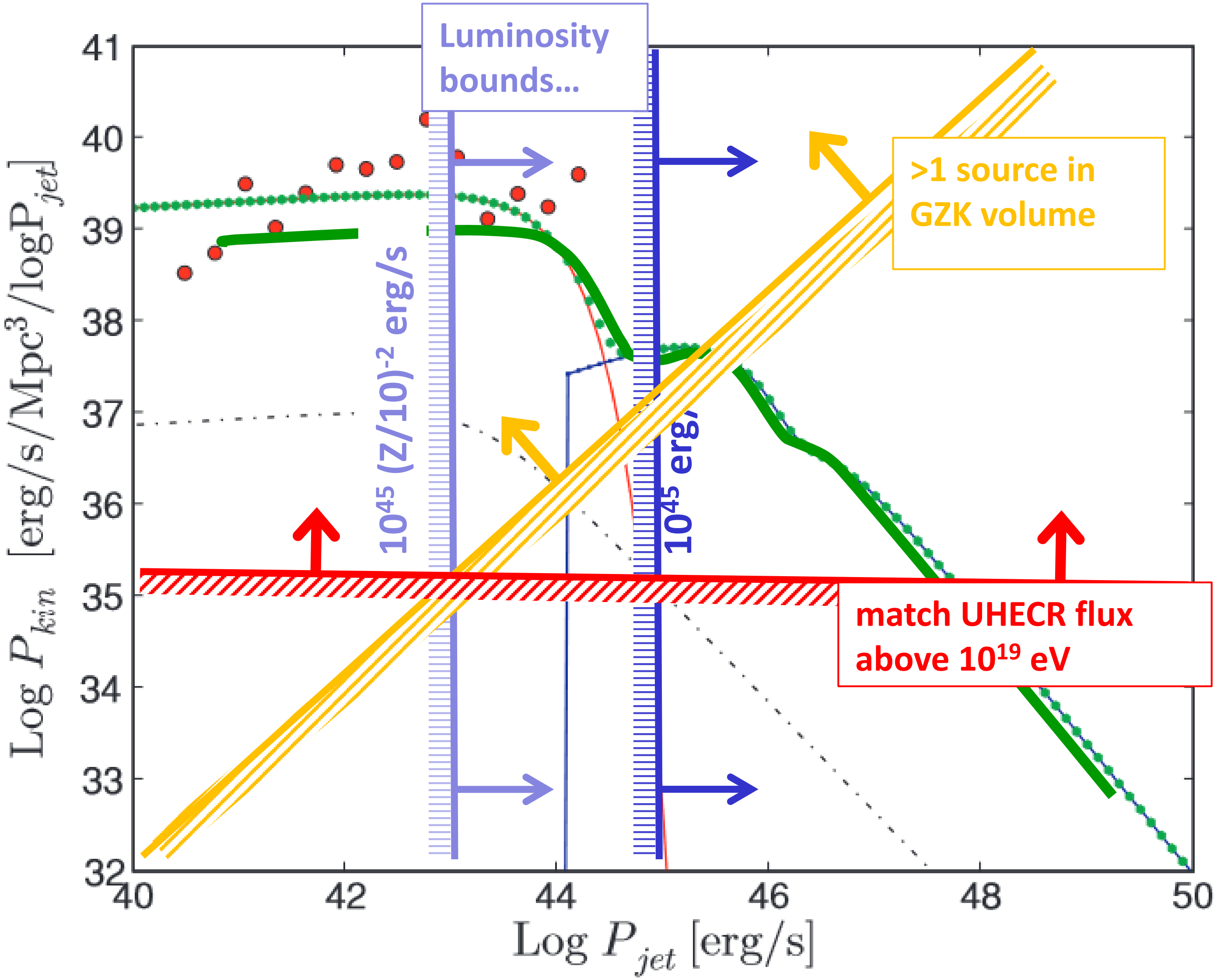
→ powerful radio-galaxies, $L \sim 10^{44}$ erg/s, u ~ 1 …
→ relativistic supernovae (LLGRB), $L \sim 10^{44}$ erg/s, u ~ 1 …

… need extreme sources for accelerating light nuclei (Z ~ 1):

→ gamma-ray bursts, fast-spinning magnetar/pulsar wind nebulae…
→ most powerful FRII like radio-galaxies

Refs.: 1. e.g. Auger13 2. e.g. Waxman 95, Katz+10

The view from phenomenology… the radio-galaxy population…



Körding+ 07

… local radio-galaxies barely satisfy the luminosity bound: accelerate Z ~ 10+ nuclei?

Particle acceleration to extreme energies

<u>Outline</u>:

1. **The view from phenomenology: top-down, from large scales to small scales**

    → constraints from $L_{\rm tot}$, $n_{\rm UHECR}$, $\dot{e}_{\rm UHECR}$
    → for minimal constraints, search for: $t_{\rm acc} \sim t_{\rm g}$ at UHE

2. **The view from microphysics: bottom-up, from first principles**

3. **Discussion: clues and issues**

Particle acceleration from first principles (?)

→ Lorentz force: $$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right)$$

… but, $\boldsymbol{E} \longleftrightarrow \boldsymbol{B}$ in a change of reference frame: rely on Lorentz scalars $\boldsymbol{E}.\boldsymbol{B}$ and $\boldsymbol{E}^2 - \boldsymbol{B}^2$ …

<u>Acceleration à la Fermi:</u> **highly conducting plasma…** $\boldsymbol{E} \cdot \boldsymbol{B} = 0 \text{ and } \boldsymbol{E}^2 - \boldsymbol{B}^2 < 0$

→ **generic for UHECR**?

… corresponds to ideal Ohm's law $\boldsymbol{E} = -\boldsymbol{v}_p \times \boldsymbol{B}/c$… (on timescales >> micro, comoving electric field is screened out)

→ Fermi-type scenarios: magnetized turbulence, shear flows, shock waves

<u>"Linear" accelerators:</u> **non-MHD flows…** $\boldsymbol{E} \cdot \boldsymbol{B} \neq 0 \text{ or } \boldsymbol{E}^2 - \boldsymbol{B}^2 > 0$

→ acceleration can proceed unbounded along **E** (or at least $\mathbf{E}_{\parallel}$)…

→ gaps in magnetospheres

→ reconnection

Particle acceleration in electrostatic gaps

→ Gaps: regions where plasma density cannot screen out parallel electric fields, e.g. of rotating magnetospheres

… in gaps: acceleration as in linear accelerators,

$$E_{\rm max} \simeq q|\boldsymbol{E}|L_{\rm gap} = q\Delta\phi \text{ (voltage drop)}$$

$$E_{\rm max} \sim 10^{19}\,{\rm eV}\;Z\,\frac{M_{\rm BH}}{10^9 M_\odot}\,\frac{L_{\rm gap}}{r_{\rm BH}}\,\frac{B}{100\,{\rm G}}$$

→ Motivations: observations of rapid flares from AGN, up to TeV energies[1]

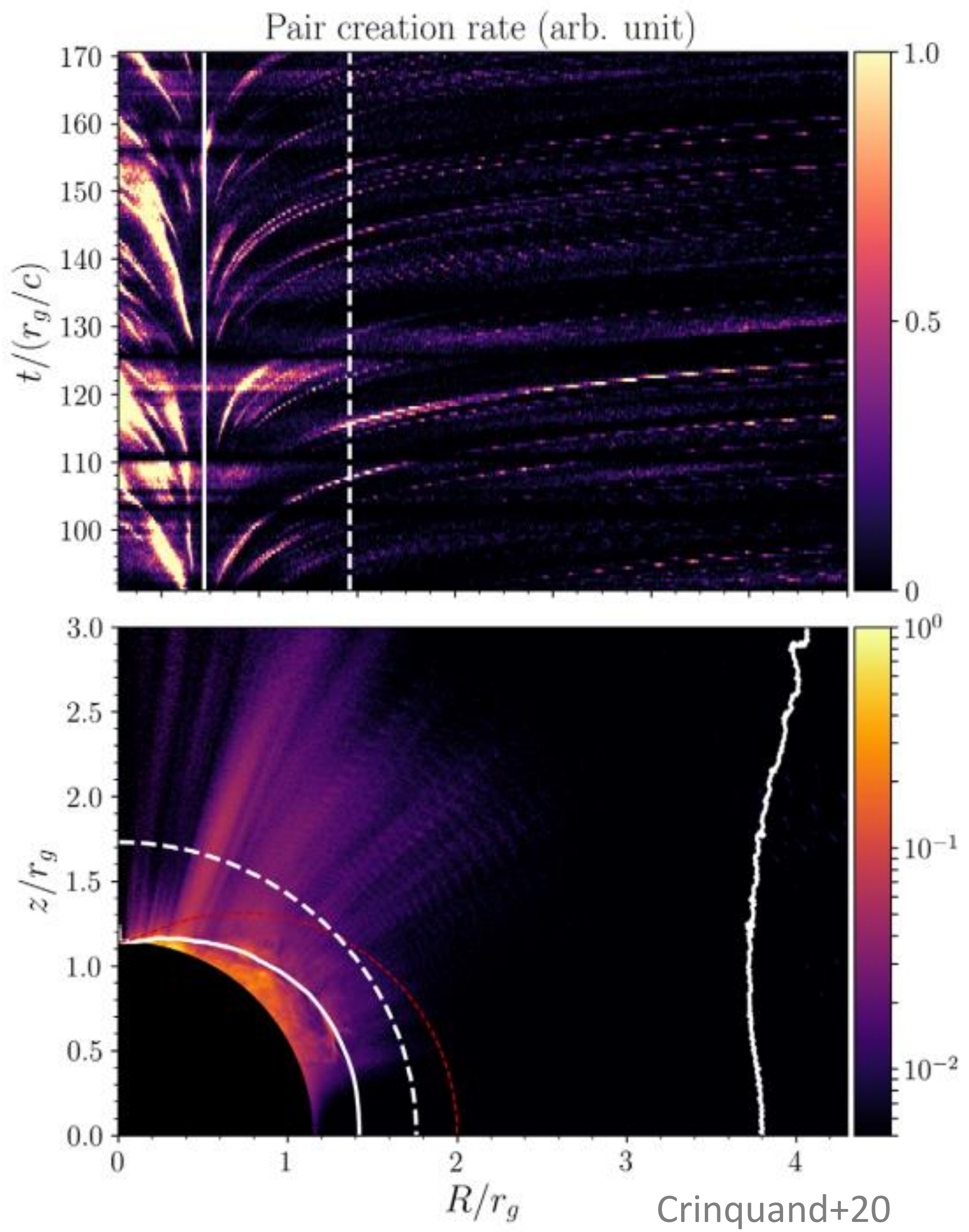
→ Issues/questions:

→ value of L?

(input from kinetic simulations of BH magnetospheres[2])

→ injection of hadrons in gaps?[3]

→ energy losses/photodisintegration, maximal energy?



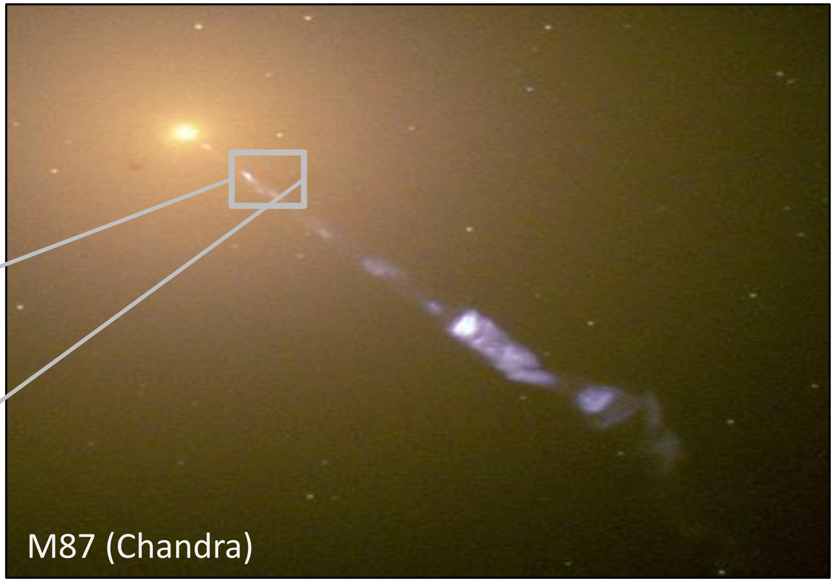
Crinquand+20

Refs.: 1. e.g. Rieger+Aharonian08 2. Levinson+Cerutti18,Chen+Yuan20,Crinquand+20,21 3. e.g. Levinson00

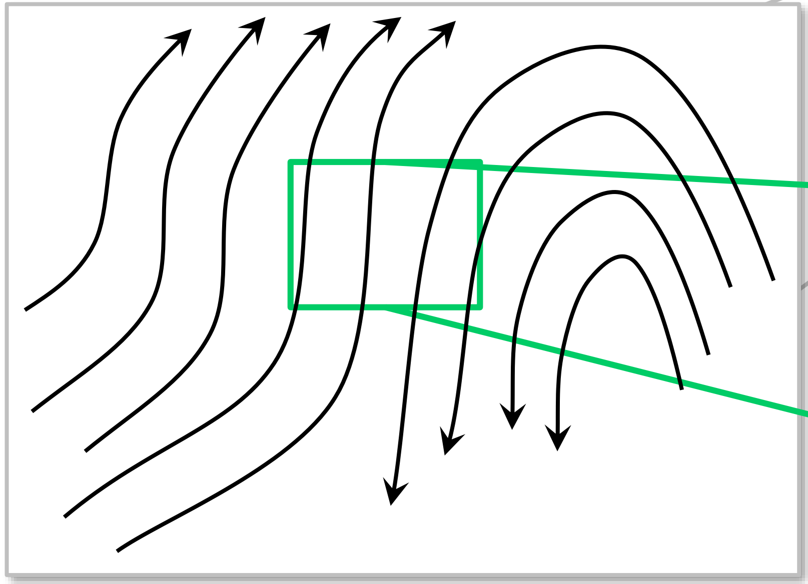
Acceleration in reconnection regions

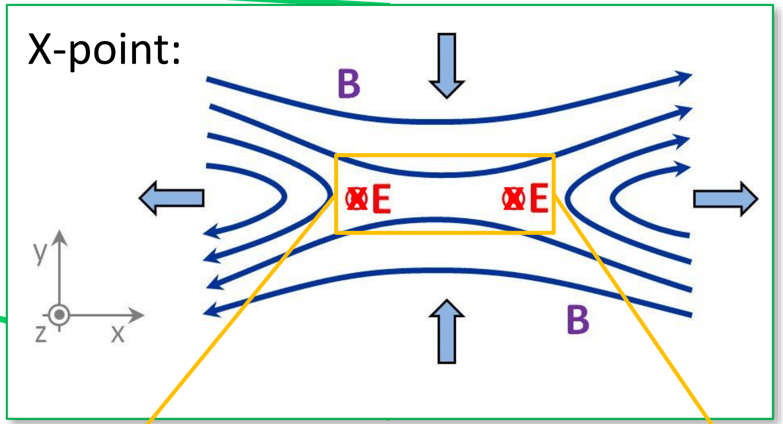
→ reconnection: dissipation of magnetic energy through interchange of field lines of opposite polarity

→ wrt UHECR: e.g. reconnection of tangled field in jets[1]...



M87 (Chandra)





here: $\boldsymbol{E}\cdot\boldsymbol{B} \neq 0$ or $\boldsymbol{E}^2 - \boldsymbol{B}^2 > 0$

⇒ linear accelerator

Refs.: 1. Giannios+10,...

Acceleration in reconnection regions

→ reconnection: dissipation of magnetic energy through interchange of field lines of opposite polarity

→ wrt UHECR: e.g. reconnection of tangled field in jets…

→ Lessons from kinetic HPC simulations[1]:

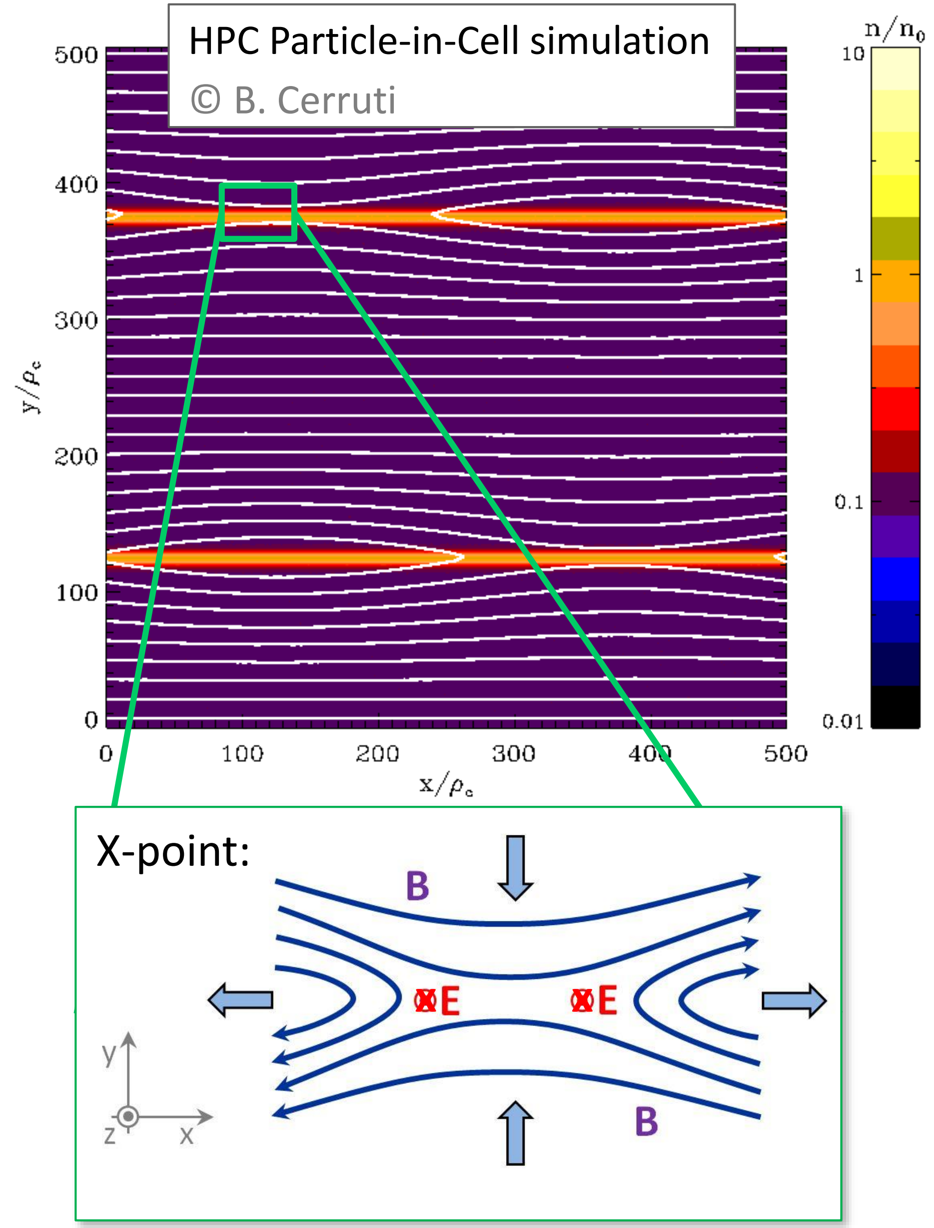
… particle acceleration fast and efficient in relativistic (magnetically dominated) regime

magnetization $\boldsymbol{\sigma = \dfrac{\textbf{magnetic e. density}}{\textbf{plasma e.density}}}$

… particle acceleration through E_z at X-point

$$E_z = -\beta_{y,\mathrm{in}} B_x \Rightarrow t_{\mathrm{acc}} \simeq \frac{t_{\mathrm{g}}}{\beta_{\mathrm{in}}}$$

β_{in} "reconnection rate" determines t_{acc} at X-point, as large as 0.1 in relativistic regime…

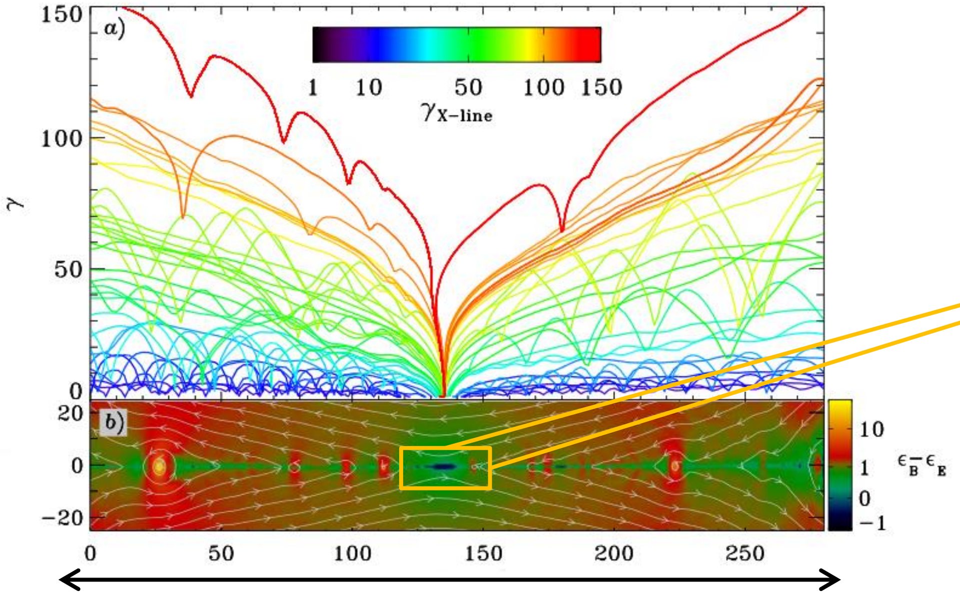


Refs.: 1. e.g. Zenitani+Hoshino 01,…,Cerutti+12, Melzani+13,Sironi+Spitkovsky14,Guo+14,Kagan+15, Werner+16,Petropoulou+Sironi18…

Acceleration in reconnection regions

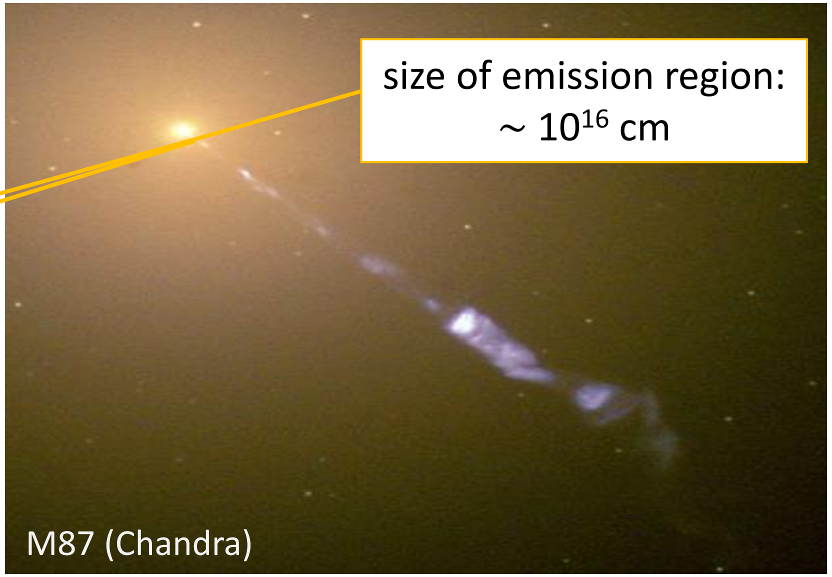
from numerical simulations…

… to actual astrophysical objects!



$\sim\, 10^6\ {\rm cm}\ n_{e,4}^{-1/2}$

Kagan+15



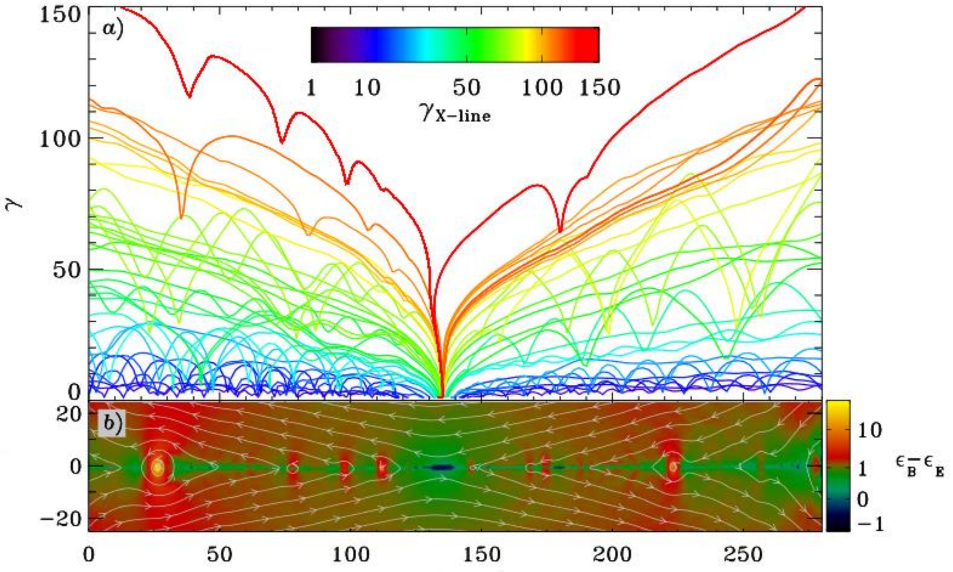
X-points are small scale features… unless magnetic field can confine particle in reconnection region, most of acceleration takes place through Fermi processes in surrounding velocity structures (turbulence?)…

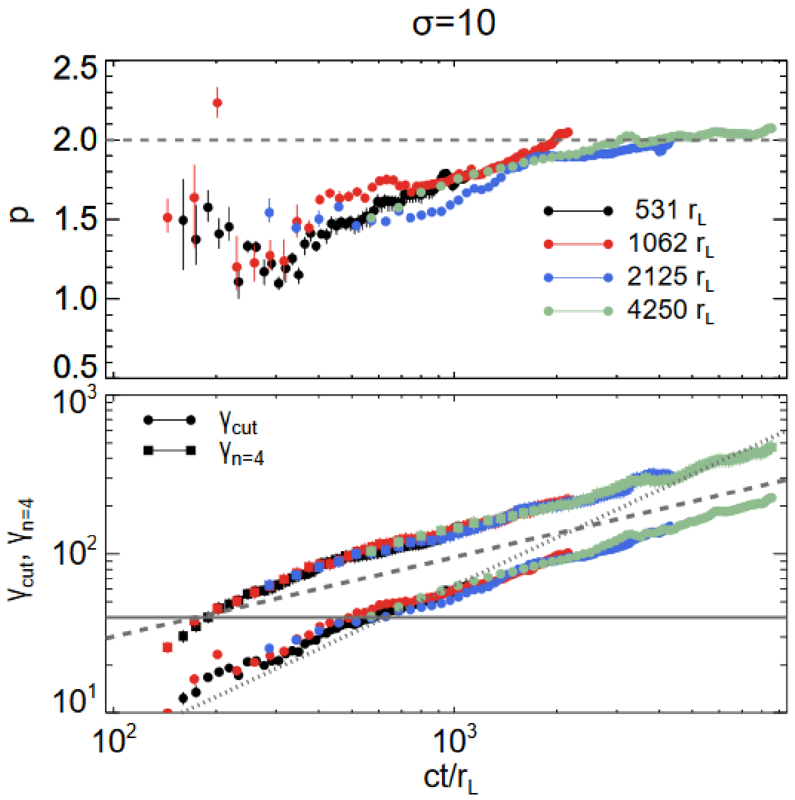
… in practice: ``confinement'' limit $E_{\rm max}/mc^2 \sim {\rm a\ few} \times \sigma$

⇒ requires huge magnetizations for direct acceleration to UHE at X-point

Acceleration in reconnection regions

→ acceleration proceeds in two stages[1,2]:





(1) acceleration in dissipation regions…

→ fast rate: $t_{acc} \sim 0.1\ t_g$
→ hard powerlaws with p<2 if $\sigma \gtrsim 1$…
… but a cut-off[1] at Lorentz factor ~4σ (escape!)

(2) acceleration in surrounding turbulence…

→ softer powerlaws…
→ slow acceleration[2]: $t_{acc} \propto t_g^{\ 2}$ …
i.e. t_{acc} / t_g increases with energy: unlikely to reach UHECR…

(larger simulations needed to probe long term!)

Refs.: 1. Kagan+15, Werner+16 2. Werner+16, Petropoulou+Sironi 18

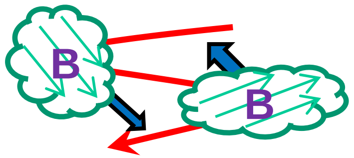
Fermi-type acceleration to UHE

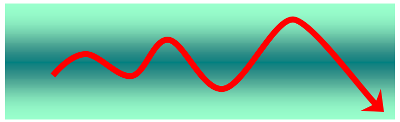
→ Lorentz force: $\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right)$ … what is the origin of ***E***?

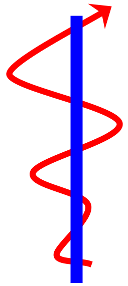
1. Acceleration à la Fermi: **highly conducting plasma…**

→ **large scale physics** (↔ very high energies?): corresponds to ideal Ohm's law $\boldsymbol{E} = -\boldsymbol{v}_E \times \boldsymbol{B}/c$…

→ **Fermi-type scenarios: magnetized turbulence, shear flows, shock waves**







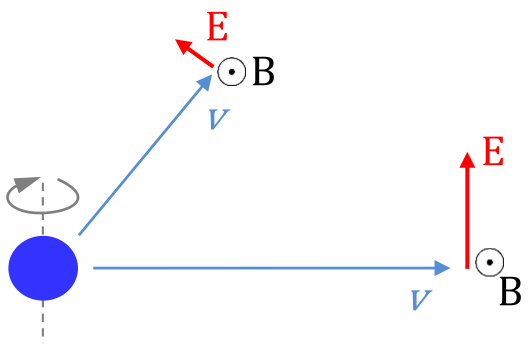
→ two essential characteristics:

1. *E* vanishes in local frame: **what truly matters is the spatial variation of the velocity field!**
   ⇒ classification of Fermi scenarios according to topology of velocity fields…

2. scattering is essential to explore *E* fields through cross-*B* transport: **need turbulence**!

Cross-B transport: magnetized rotators as extreme accelerators?

→ **magnetized rotator / unipolar inductor:** magnetized, highly conducting, rotating plasma, leading to a potential drop between the poles and the equator, due to the motional electric field **E** = -**v** x **B** /c (← Fermi type acceleration)



at large distances: ~radial wind + ~azimuthal B

e.g. in a fast rotating magnetar wind, voltage drop allows for[1]

$$E_{\rm max} \sim 0.6 \times 10^{22}\, Z \left(\frac{B}{10^{15}\,{\rm G}}\right) \left(\frac{R}{10\,{\rm km}}\right)^3 \left(\frac{P}{1\,{\rm ms}}\right)^{-2} {\rm eV}$$

... key question: how to experience the voltage drop?

... incorporate turbulence in fast rotators?[2]

... transport across the magnetic field lines is the key limitation of Fermi acceleration processes!

... in most Fermi scenarios: $t_{acc} \propto t_{scatt}$

Refs.: 1. e.g. Gunn & Ostriker 69, Venkatesan+ 97, Blasi+00, Arons 03 2. ML19

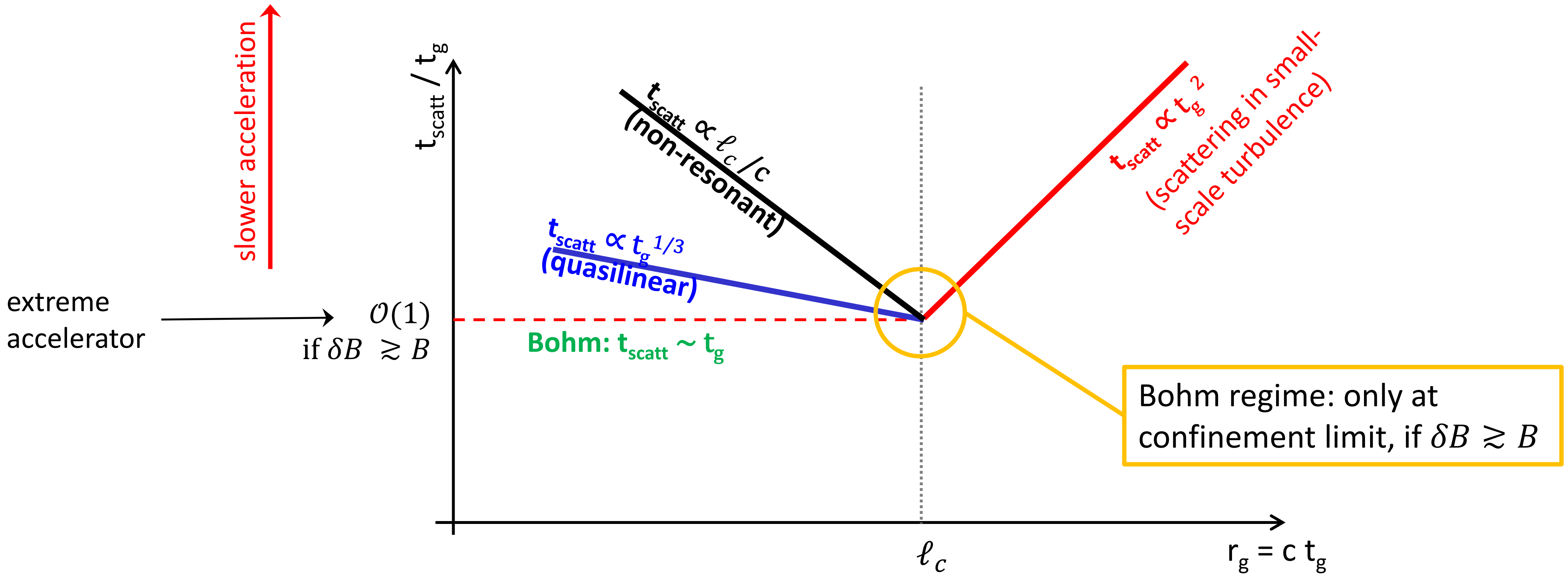
Fermi acceleration: the issue of scattering

→ generic scaling: $t_{\rm acc} \simeq \dfrac{t_{\rm scatt}}{\beta_E^2}$ (applies to original Fermi, shock, turbulence… here $\beta_E \lesssim 1$)

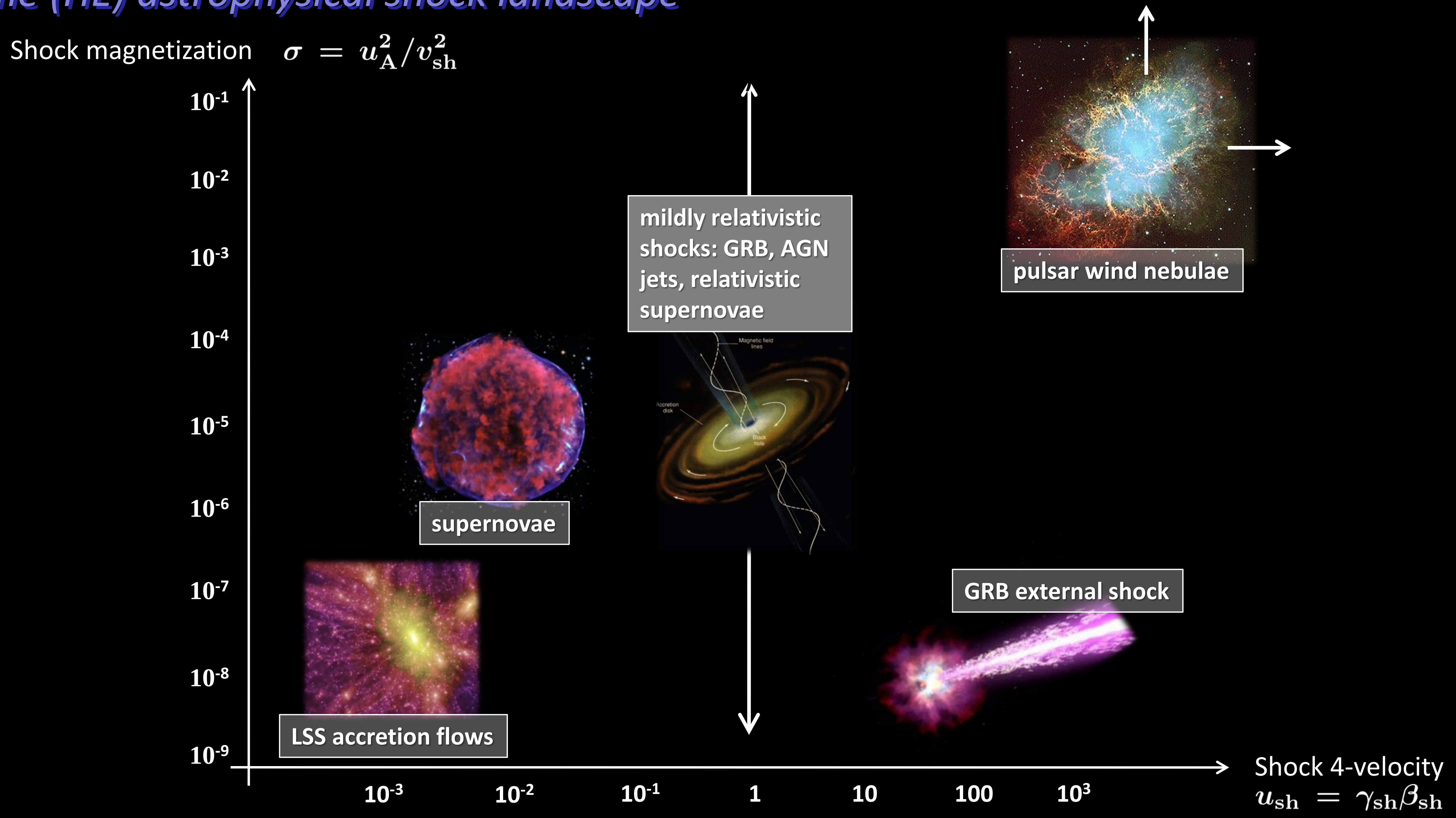
→ <u>scattering timescale $t_{\rm scatt}$</u>: time it takes to deflect the particle by an angle of the order of unity,

$$t_{\rm scatt} \sim t_{\rm g}^{\alpha} \left(\ell_{\rm c}/c\right)^{1-\alpha}$$ (l_c coherence length scale of turbulence)

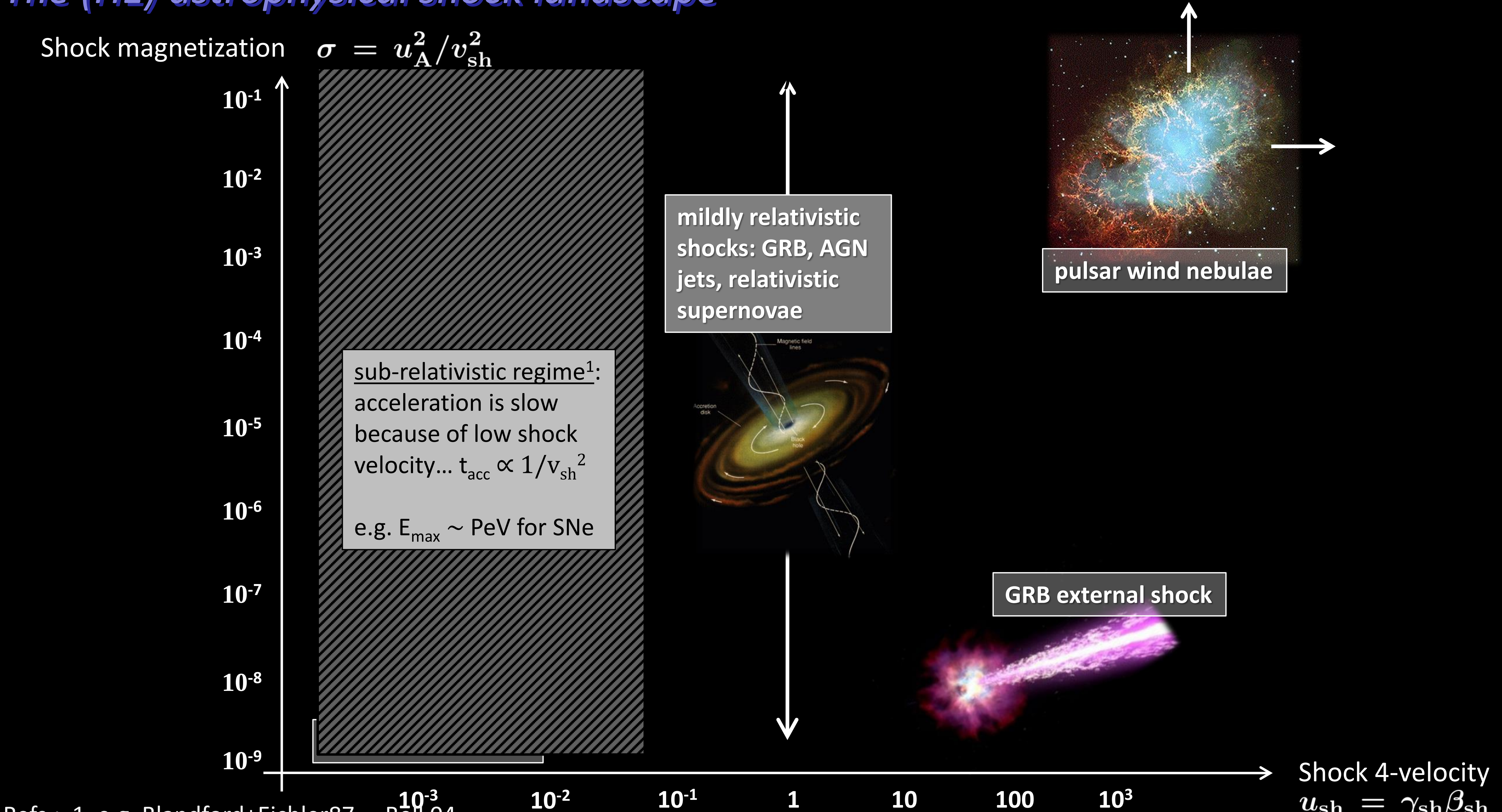
… in absence of specific information, **assume (too often!):** **α = 1 Bohm regime**



The (HE) astrophysical shock landscape

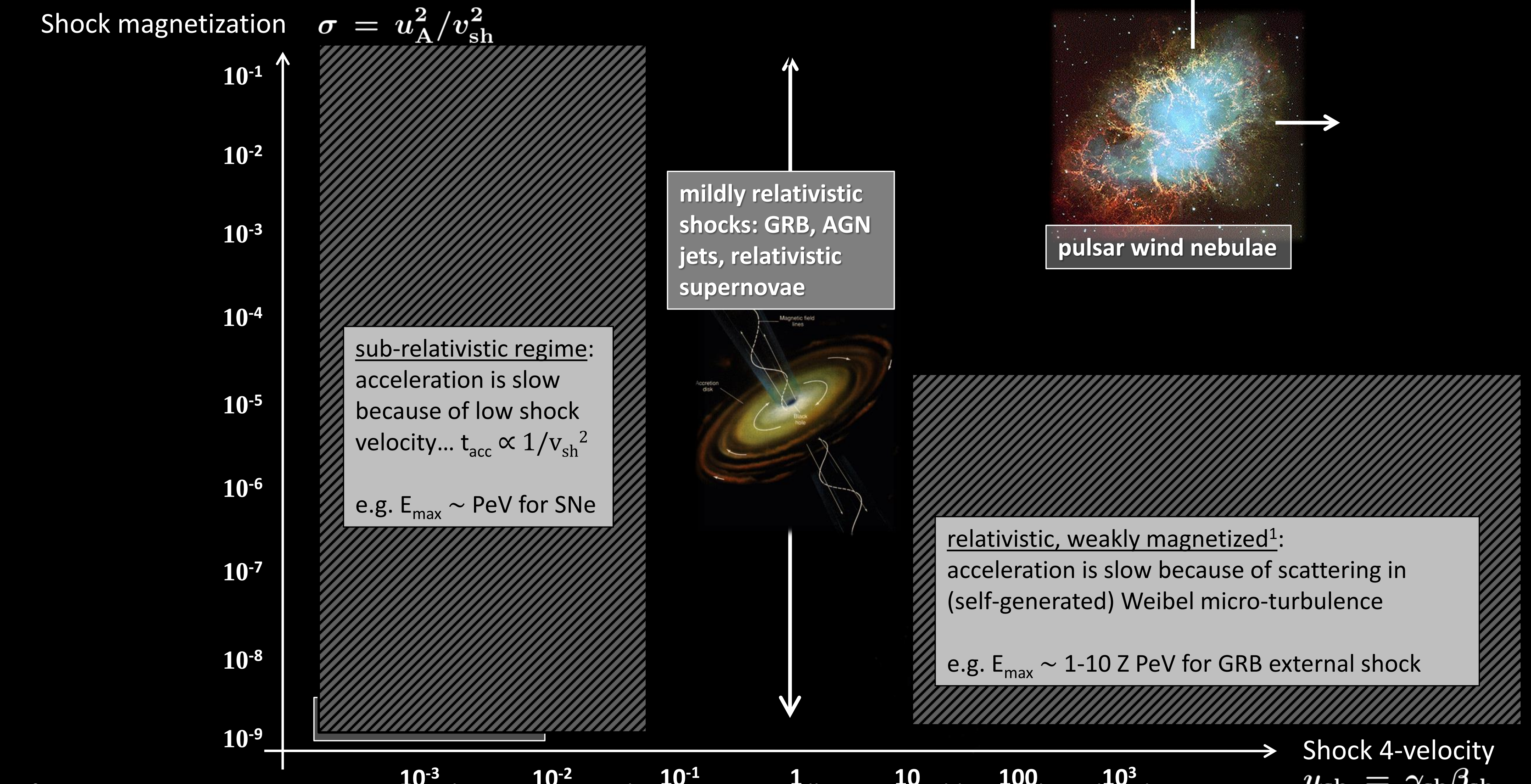


The (HE) astrophysical shock landscape



Refs.: 1. e.g. Blandford+Eichler87,… Bell 04, …

The (HE) astrophysical shock landscape

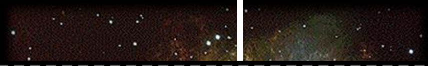


Refs.: 1. e.g. ML+06, Niemiec+06, Spitkovsky08, Sironi+Spitkovsky 09,ML+Pelletier 10, Eichler+Pohl11, Plotnikov+13, Sironi+13,…

The (HE) astrophysical shock landscape

Shock magnetization $\sigma = u_{\mathrm{A}}^2/v_{\mathrm{sh}}^2$

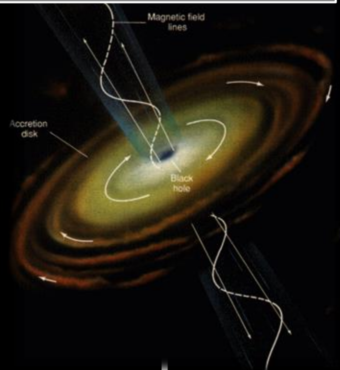
10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}



relativistic, magnetized[1]:
acceleration is inhibited by external magnetic field (superluminal shocks!)…

caveat! Physics of PWNe[2]?
→extreme accelerators with $t_{acc} \sim t_g$

mildly relativistic shocks: GRB, AGN jets, relativistic supernovae



sub-relativistic regime:
acceleration is slow because of low shock velocity… $t_{acc} \propto 1/v_{sh}^2$

e.g. $E_{max} \sim$ PeV for SNe

relativistic, weakly magnetized:
acceleration is slow because of scattering in (self-generated) Weibel micro-turbulence

e.g. $E_{max} \sim$ 1-10 Z PeV for GRB external shock

Shock 4-velocity $u_{\mathrm{sh}} = \gamma_{\mathrm{sh}}\beta_{\mathrm{sh}}$

10^{-3}, 10^{-2}, 10^{-1}, 1, 10, 100, 10^{3}

Refs.: 1. e.g. ML+06, Niemiec+06, Sironi+Spitkovsky 09, ML+Pelletier 10, Sironi+11,13,…
2. e.g. Kirk+09,…, Amato15,…

The (HE) astrophysical shock landscape

Shock magnetization $\sigma = u_{\mathrm{A}}^2 / v_{\mathrm{sh}}^2$

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

mildly relativistic shocks: GRB, AGN jets, relativistic supernovae

relativistic, magnetized:
acceleration is inhibited by external magnetic field (superluminal shocks!)

caveat: physics of PWNe, most efficient accelerators known?

sub-relativistic regime:

… most promising regime: mildly magnetized, mildly relativistic shocks:

→ quasi-parallel configuration allows for efficient acceleration (?)

→ large precursor length scales allow for development of MHD instabilities on large scales (?)

→ stochastic shock-drift in oblique configuration (?)

… to be demonstrated[1]!

(→ Virginia Bresci, PhD@IAP)

…tized:
…se of scattering in
…icro-turbulence

…GRB external shock

10^{-3} 10^{-2} 10^{-1} 1 10 100 10^{3}

Shock 4-velocity $u_{\mathrm{sh}} = \gamma_{\mathrm{sh}} \beta_{\mathrm{sh}}$

Refs.: 1. e.g. Crumley+19

Shear acceleration

→ Fermi shear acceleration: … the electric field cannot be boosted away globally, particles gain energy by exploring the shear gradient…

… acceleration timescale: $t_{\rm acc} \sim \dfrac{\Delta r^2}{t_{\rm scatt}} \dfrac{1}{\Delta u^2/\gamma_u^2}$

(at $t_{\rm scatt} \ll \Delta r$)

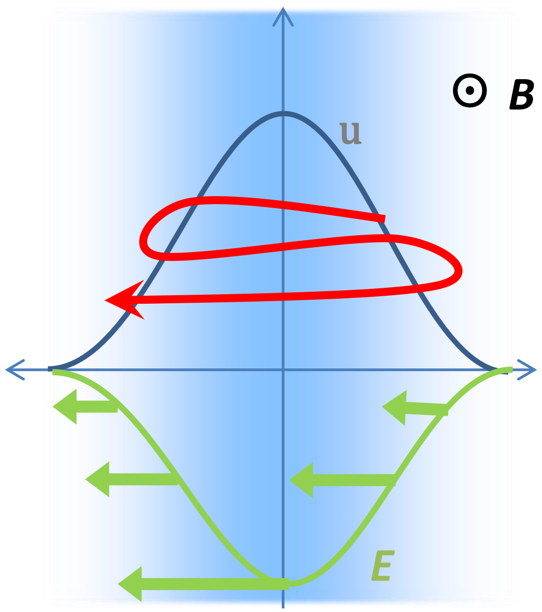
⇒ inefficient at low energies, since $t_{\rm scatt} \nearrow$ p, requires a seed population of particles

… if $\ell_c \sim \Delta r$, at confinement energy $r_g \sim \Delta r$,

⇒ $t_{\rm scatt} \sim r_g \sim \Delta r$ ⇒ $t_{\rm acc} \sim r_g$ for $\Delta u \sim u \sim 1$

⇒ **optimal for (mildly?) relativistic shear!**

e.g. a structured jet



particles with larger mean free paths explore larger gradient of ***E*** ⇒ faster acceleration…

⇒ reacceleration of a population of energetic CRs in mildly relativistic shear may reach confinement energy…

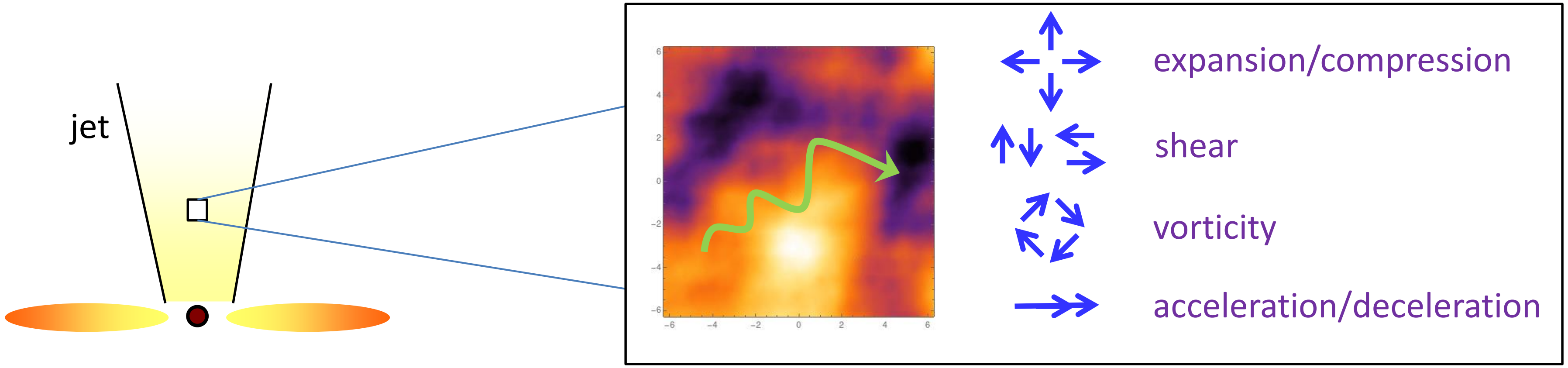
(note: efficient scattering needs $\delta B/B \sim 1$: how does turbulence impact shear acceleration?)

Refs.: e.g. Rieger+Duffy 04, 06, 08, Liu+ 17, Kimura+18, Rieger 19, Webb+ 18,19, ML 19

Generalized Fermi acceleration in a large-scale, turbulent flow

… particle random walks in structured (or random) MHD flow of (large) scale ℓ_c …

… what truly controls acceleration is the velocity variation: ⊃ shear, compression etc.



→ expect[1] $t_{\rm acc} \sim \ldots \frac{\ell_c}{\langle \delta u^2 \rangle}$ (note: δu is a 4-velocity! Fast in relativistic regime)

… slow at low energies ($t_{acc} \gg t_g$) … but fast at high energies (where $c\, t_g \sim \ell_c$)

⇒ **$t_{acc} \sim t_g$ appears possible at confinement energy**

Refs.: e.g. Bykov+Toptygin 81, Ptuskin 88, …, Ohira 13, ML19, Demidem+20

Particle acceleration in magnetized turbulence

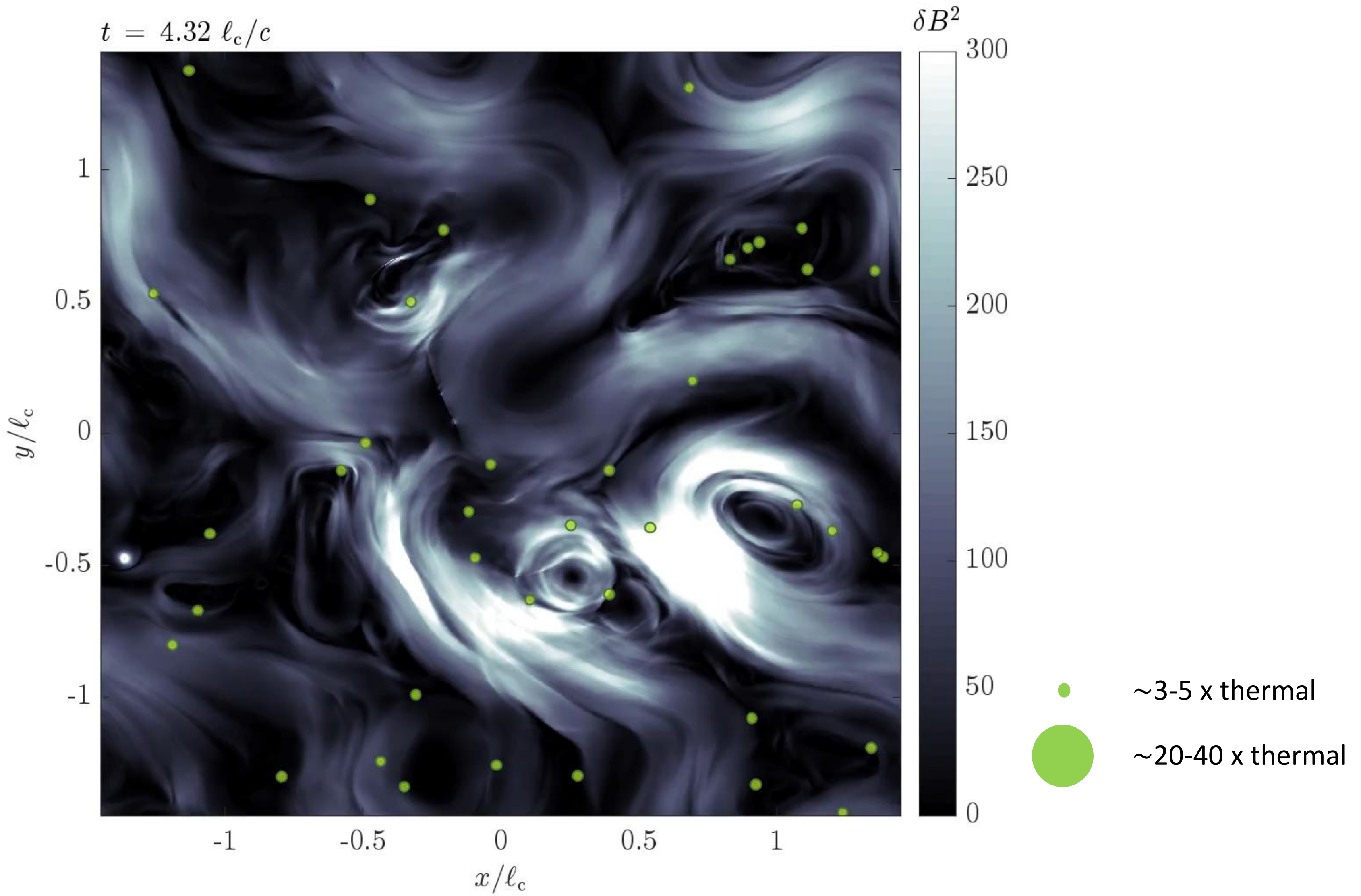
→ HPC kinetic simulations have started to probe particle acceleration in large-scale turbulence[1]…

⇒ particle acceleration fast in relativistic regime $\sigma \gtrsim 1$ ($v_A \sim c$)

… acceleration timescale:

$$t_{\rm acc} \sim \frac{c\,\ell_c}{\langle \delta u^2\rangle} \sim \frac{\ell_c}{\sigma c}$$

ℓ_c : coherence scale,
$\langle\delta u^2\rangle \sim u_A^{\ 2} = \sigma$

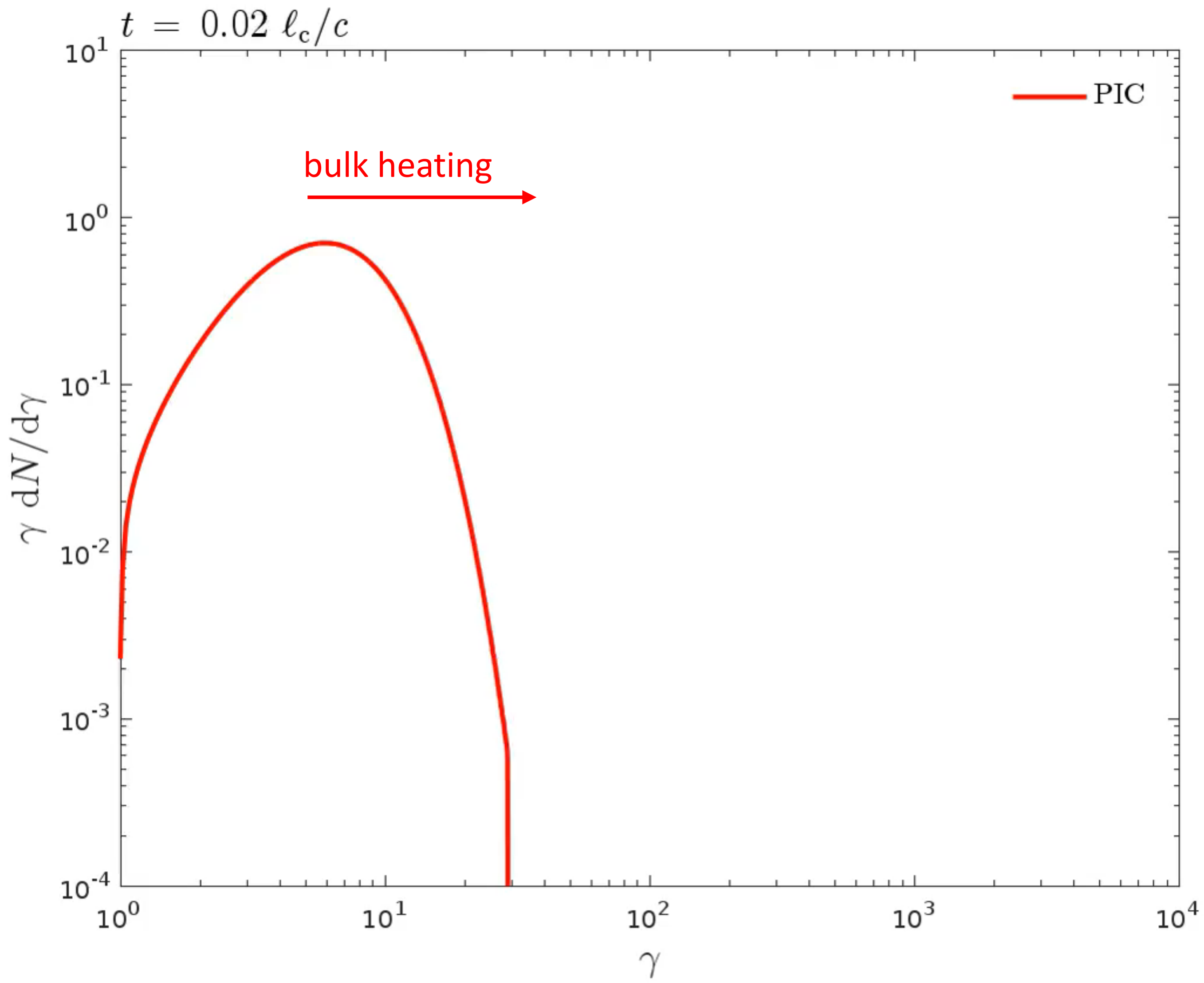


© V. Bresci, L. Gremillet, M. L.: 2D PIC, driven turb., e^+e^-, $10\,000^2$, $\delta B/B \sim 3$, $\sigma \sim 1$

Refs.: e.g. Zhdankin+17,18,19, Comisso+Sironi19,20, Wong+19,…

Spectra from stochastic acceleration

→ **a surprise:** turbulence produces powerlaw spectra (even in closed box!)…
not the Maxwellian type distribution as expected from phenomenology!



Note: Fokker-Planck solution assumes infinite reservoir of energy!

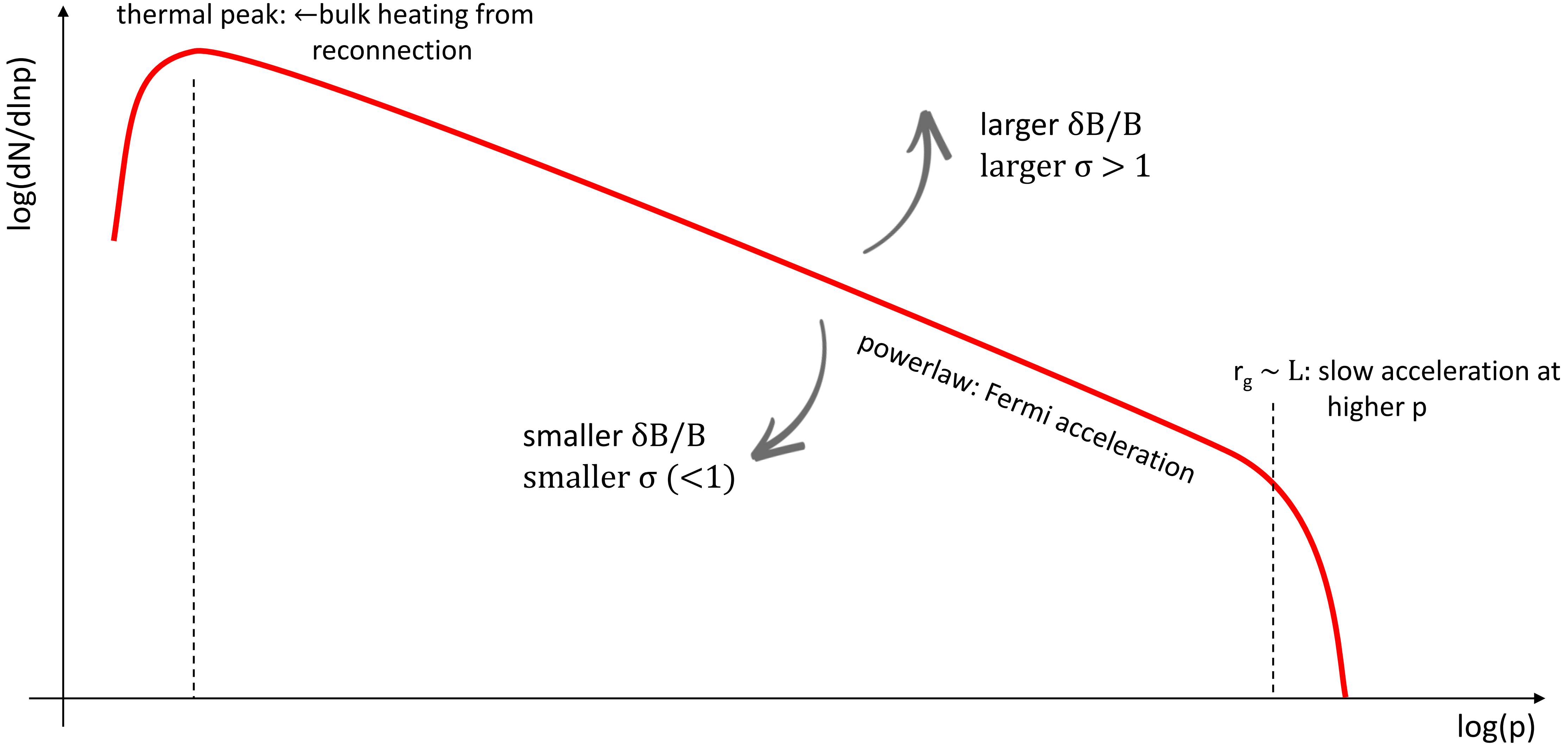
In reality: turbulent/magnetic energy reservoir mostly converted to bulk heating… and into particle acceleration as a soft powerlaw…

@ $\sigma \sim 1$, $\delta B/B \sim 1$:

$$\frac{dN}{dp} \propto p^{-s} \quad \text{and} \quad s \sim 3$$

Spectra from stochastic acceleration

→ **a surprise:** turbulence produces powerlaw spectra (even in closed box!)…
not the Maxwellian type distribution as expected from phenomenology! (see [1] for interpretation)



Refs.: 1. ML+Malkov 20, ML21

Particle acceleration to extreme energies

Summary:

1. **The view from phenomenology: top-down, from large to small scales**

→ constraints from $L_{\rm tot}$, $n_{\rm UHECR}$, $\dot{e}_{\rm UHECR}$
→ for minimal constraints, search for: $t_{\rm acc} \sim t_{\rm g}$ at UHE

2. **The view from microphysics: bottom-up, from first principles**

→ improved knowledge from kinetic numerical simulations (on small scales!)
→ mildly relativistic shocks or shear, $(\sigma > 1)$ turbulence equally interesting for UHE
→ in mildly relativistic regime, a common trait: $t_{\rm acc} \sim t_{\rm g}$ at $r_g \sim \ell_c$

3. **Discussion: clues and issues**

Clues and issues: signatures from extreme Fermi accelerators

→ recall, no direct counterpart for transient sources ($\Delta t \gtrsim 10^5$ yr due to scattering in B fields)…
⇒learn from modelling of astrophysical sources!

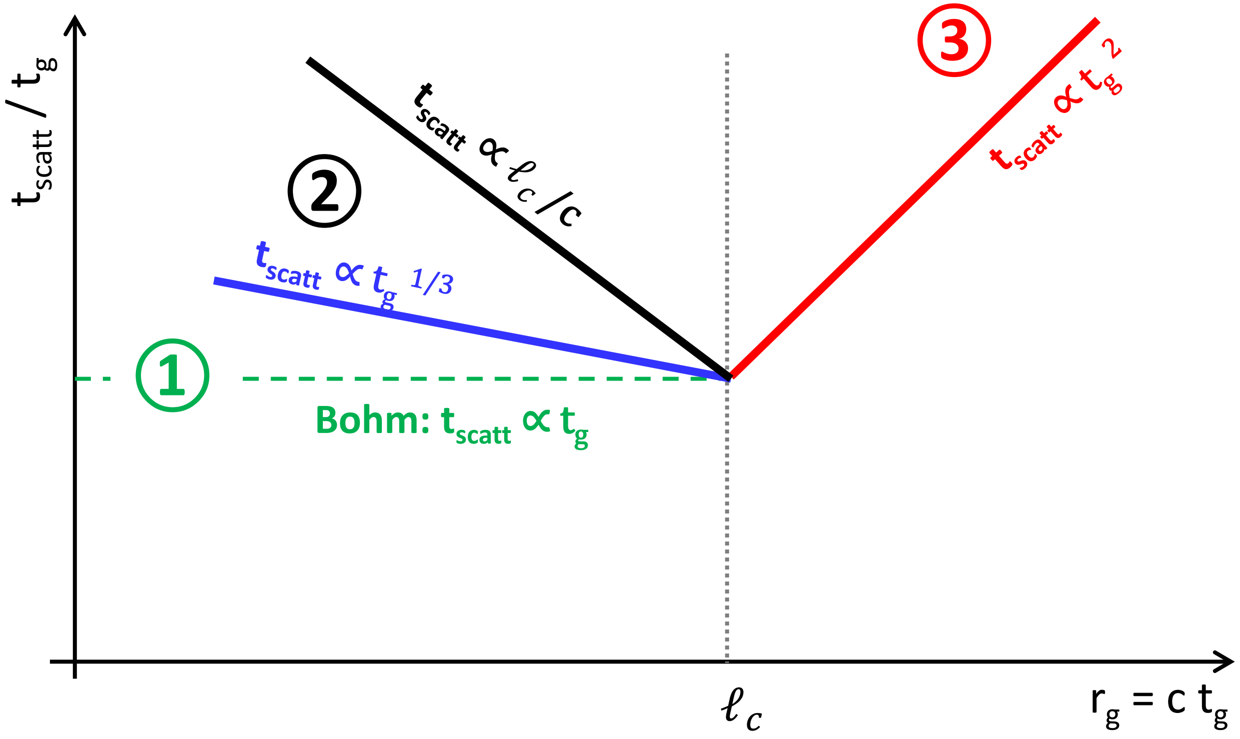
1 : extreme accelerator if $\beta_E \sim 1$, synchrotron from e at radiation reaction limit:

$$t_{\rm acc} \simeq \mathcal{A}\, t_{\rm L} \Rightarrow \epsilon_{\rm syn,max} \sim 100\, \mathcal{A}^{-1}\,{\rm MeV}$$

(up to Lorentz boost)

2 : non-extreme for e, but can reach confinement (Hillas) limit for ions if:
3 $\boldsymbol{\beta_E \sim 1, \ell_c \sim}$ source size, $\boldsymbol{\delta B \gtrsim B}$,
in absence of energy losses…

⇒ for e, signatures below gamma-domain, X-ray and below?



→ an accelerator that does not look extremal for leptons… may be extremal for ions if

$\boldsymbol{\beta_E \sim 1}$, $\boldsymbol{\ell_c \sim}$ **source size,** $\boldsymbol{\delta B \gtrsim B}$ (+t_{acc} does not decrease with energy)

Clues and issues: signatures from extreme Fermi accelerators

→ recall, no direct counterpart for transient sources ($\Delta t \gtrsim 10^5$ yr due to scattering in B fields)…
⇒learn from modelling of astrophysical sources!

1 : extreme accelerator if $\beta_E \sim 1$, synchrotron from e at radiation reaction limit:

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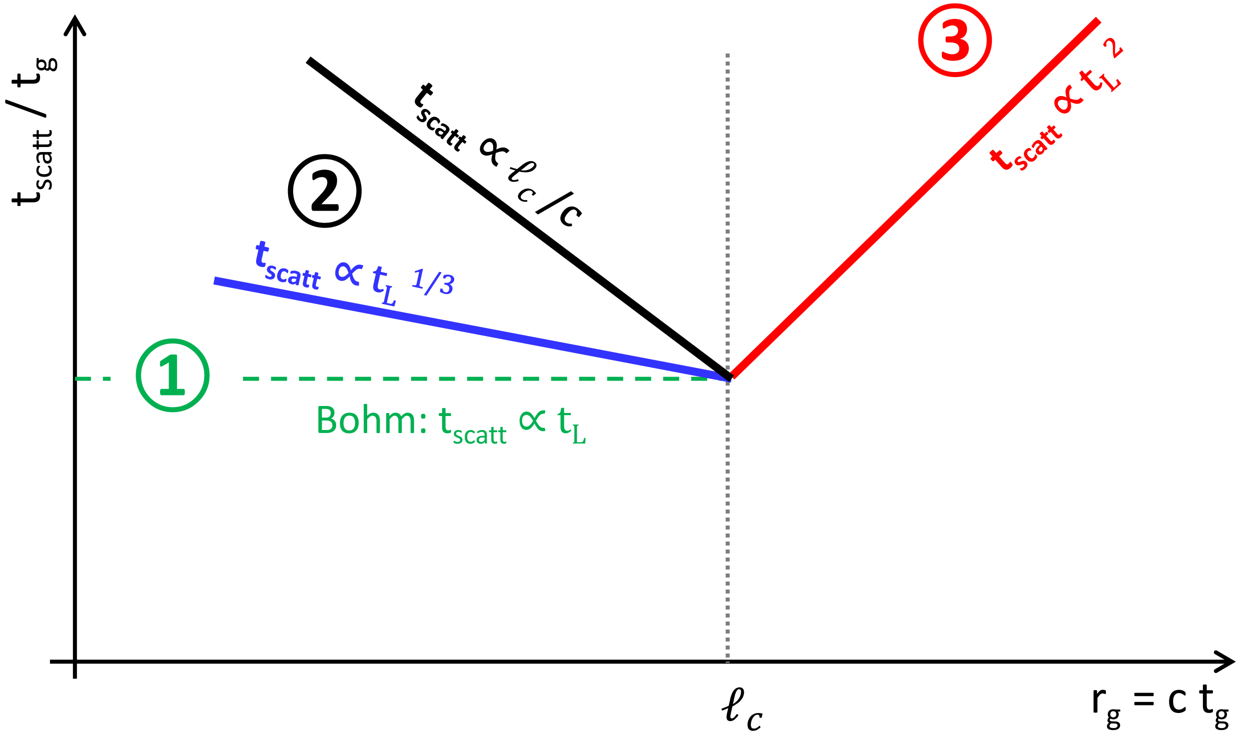


→ however, an extreme case: acceleration of fossil HE CR population in some large-scale flow
⇒ weak or no radiative signatures !?
⇒ search strategy: direct identification from arrival directions?

Clues and issues: the spectral slope s ... $dN/dp \propto p^{-s}$

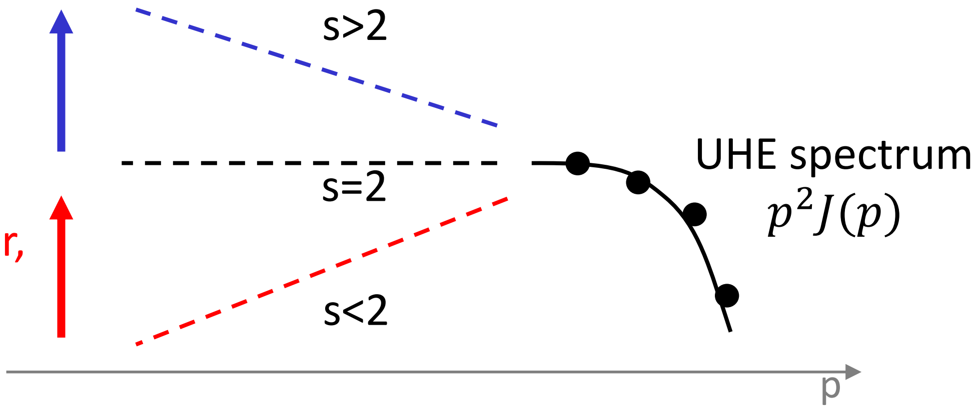
→ in acceleration scenarios, shock acceleration generically predicts s ~ 2...
... harder or softer indices are possible for other schemes (reconnection,... turbulence)

generic behavior:
- high magnetization $\sigma > 1 \Rightarrow$ hard spectra
- low magnetization $\sigma < 1 \Rightarrow$ soft spectra

→ issue of energy conservation (!):

soft s requires more input / source,
$L_{UHECR} \times (E_{UHE}/E_{min})^{s-2}$

hard s requires a large initial energy reservoir,
e.g. $\sigma \sim (E_{UHE}/E_{min})^{2-s}$



⇒ most conservative choice: s ~ 2 inside source (?)

Clues and issues: the spectral slope s … $dN/dp \propto p^{-s}$

→ **in acceleration scenarios, shock acceleration generically predicts s ~ 2…**
… harder or softer indices are possible for other schemes (reconnection,… turbulence)

generic behavior:
- high magnetization $\sigma > 1 \Rightarrow$ hard spectra
- low magnetization $\sigma < 1 \Rightarrow$ soft spectra

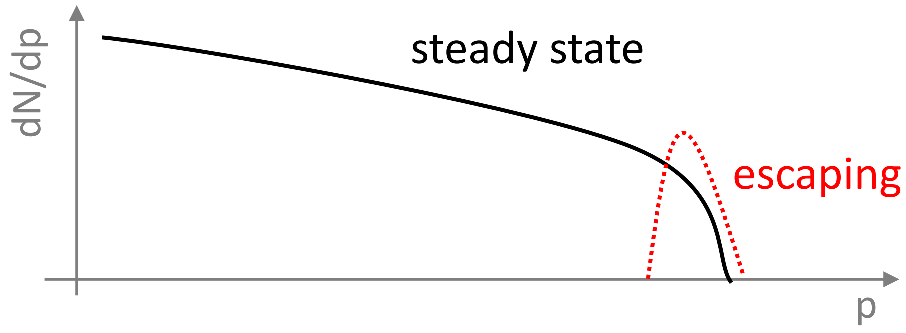
→ **however, recall that escape can remodel the spectrum[1]:**

$$\frac{\mathrm{d}N_{\rm esc}}{\mathrm{d}t\mathrm{d}p} = \frac{1}{t_{\rm esc}(p)}\frac{\mathrm{d}N}{\mathrm{d}p} \qquad (t_{\rm esc} \sim L^2/t_{\rm scatt})$$

(+other effects: source population[2], interactions[3]…)

⇒ **low E cut, or hard slope?**

e.g.:



Refs.: 1. e.g. Ohira+10, … 2. e.g. Kachelriess+Semikoz06 3. e.g. Globus+15, Unger+15, …

Clues and issues: the chemical composition

→ **chemical composition, or rigidity E/(eZ) at a given energy, controls the phenomenology at ultra-high energies:**

(1) sources of 10^{20}V are much more extreme than sources of 10^{18}V particles:

… e.g., a few candidate sources for 10^{20}eV protons vs *dozens* of candidate sources of 10^{20}eV iron…

(2) light particles leave stronger signatures of their sources:

… e.g., anisotropies at ultra-high energies with deflections of a few deg, vs large deflections for iron-like primaries

… e.g., secondary photons and neutrino signals

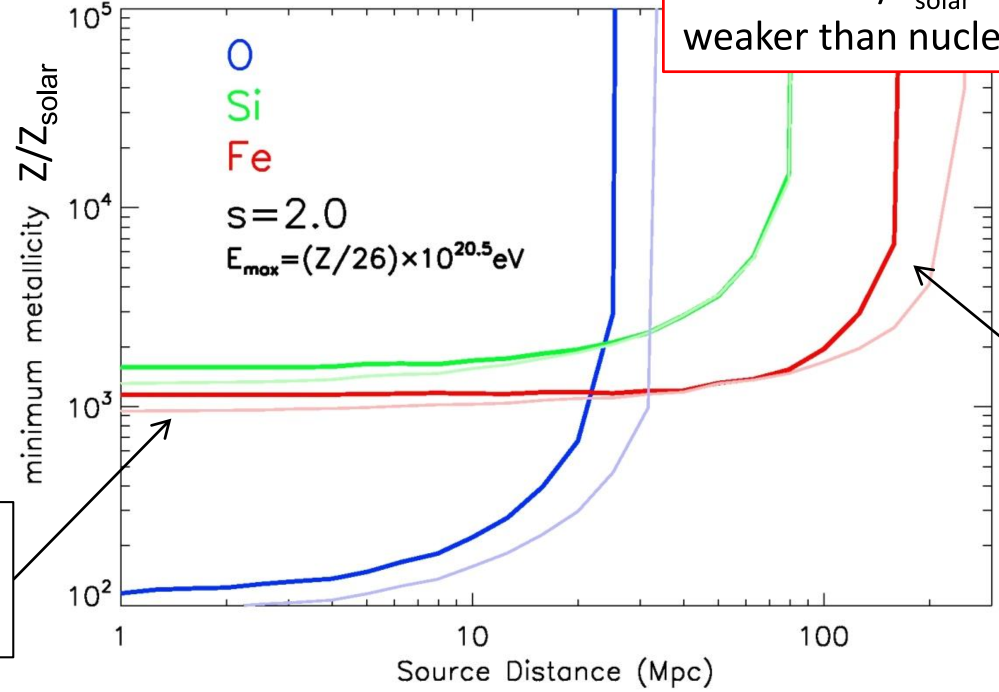
⇒ if light nuclei exist at GZK: search for extreme sources of *ultra-high rigidity* particles!

→ related issue: how to better constrain the composition: direct measurements, diffuse backgrounds?

Clues and issues: (small-scale) anisotropies at GZK

→ if anisotropic signal >E is due to heavy nuclei, then one should detect a stronger anisotropy signal associated with protons of same magnetic rigidity at >E/Z eV... **where are the accompanying protons?**[1]
(argument independent of intervening magnetic fields)

minimum Z/Z_{solar} to ensure that proton signal is weaker than nuclei signal, for different nuclei



close-by source:
no photo-dis.
Z → p

remote source:
secondary p's
from photo-dis. of
>2E nuclei produce
anisotropies at E/Z

→ to assume that the anisotropies are produced by heavy nuclei thus requires a source metallicity:

if Fe at UHE: $Z > 1000\ Z_{solar}$ … if Si at UHE: $Z > 1600\ Z_{solar}$ … if O at UHE: $Z > 100\ Z_{solar}$

… a clue on the source: ambient material from stellar collapse? or a fraction of protons at UHE?

Refs.: 1. ML + Waxman 09, Auger 11, Liu+13

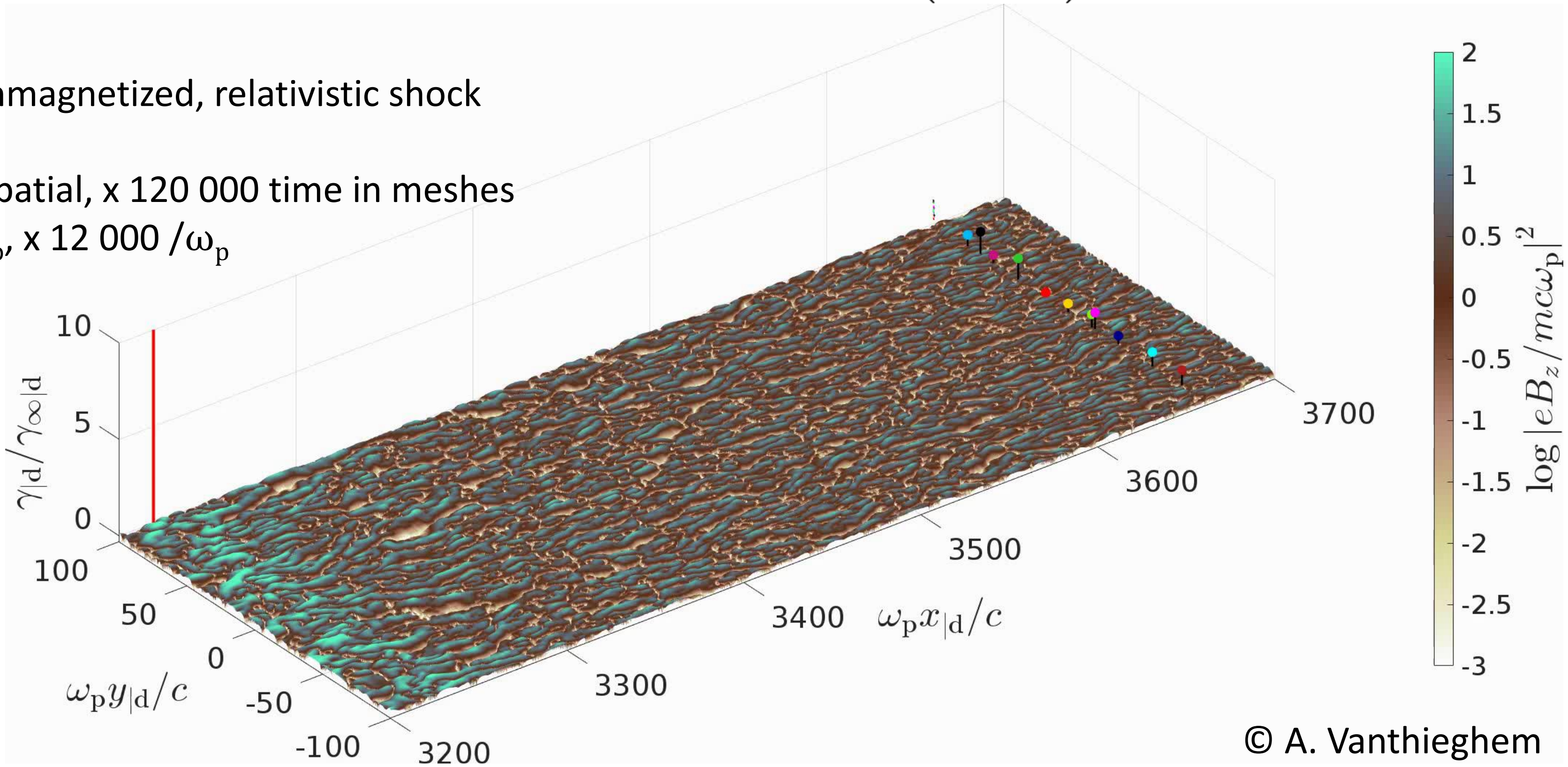
Clues and issues: from microphysics to macrophysics

→ Numerical PIC simulations are ideal tools to reproduce ab initio the acceleration of particles in astrophysical sources…
however: they need to resolve the smallest length scale…

$$c/\omega_{\rm c} \equiv \frac{m_e c^2}{eB} \sim 10^6\,{\rm cm}\ B_{\rm mG}^{-1} \qquad\qquad c/\omega_{\rm pe} \equiv \left(\frac{m_e c^2}{4\pi n e^2}\right)^{1/2} \sim 10^6\,{\rm cm}\ n_{1\,{\rm cm}^{-3}}^{-1/2}$$

PIC simulation of an unmagnetized, relativistic shock

size: 120 000 x 2 000 spatial, x 120 000 time in meshes
12 000 x 200 c/ω_p, x 12 000 $/\omega_p$
cost: ~1 M CPUhr



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→ **strategy to bridge the gap between microscopic and macroscopic scales ?**

Topics for discussion?

→ One accelerator, from injection at low E to UHE…

… or a sequence of accelerators, working in different energy ranges?

→ Consequences for radiative signatures? Search strategy?

→ Are there protons at UHE? ⇒ Search strategy/constraints for extreme accelerators?

→ Spectral slope: a clue on acceleration, escape or transport?

→ Theory side: making progress toward bridging the gap in scales: micro → macro?

→ ??