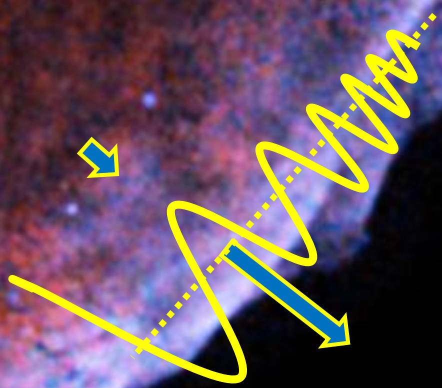
Physics of cosmic ray acceleration
-- Theoretical aspects --

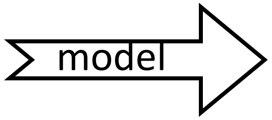
Martin Lemoine
Institut d'Astrophysique de Paris
CNRS, Université Pierre & Marie Curie

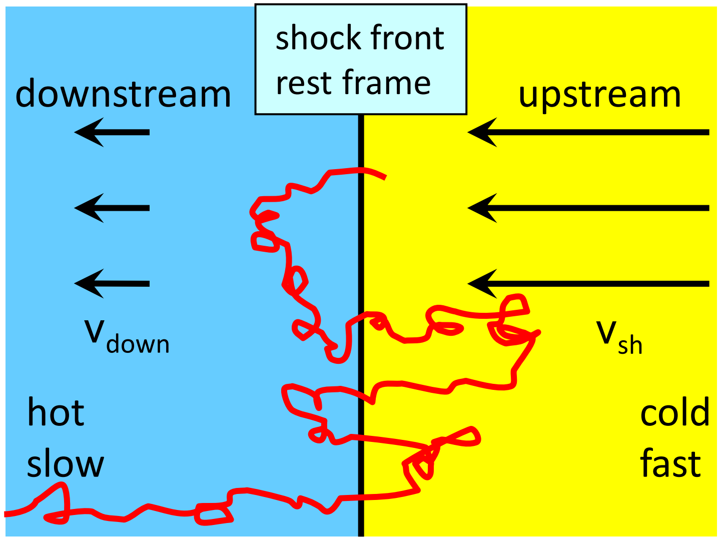
<u>Outline:</u>

1) Motivations & Methods
2) Phenomenology
3) Theory



Particle acceleration at supernovae shock fronts





particles get accelerated as they bounce back and forth across the shock wave

→ virtues of 1st order Fermi acceleration at supernovae shock waves:

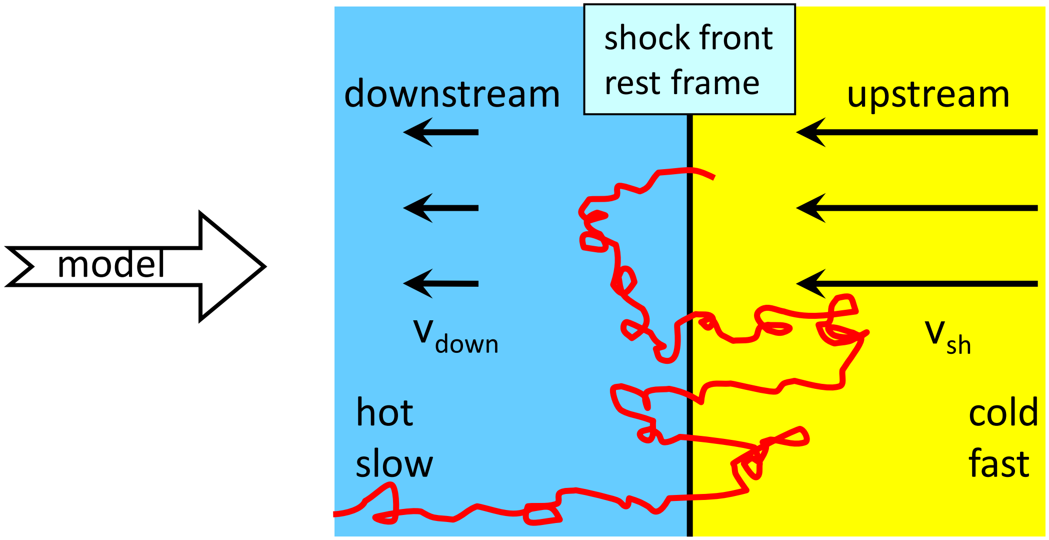
- a « universal » acceleration mechanism: depends only on a few parameters (magnetization, shock velocity, composition)

- highly efficient in energy conversion: typically 10% of the blast wave energy converted into the cosmic-ray population.

- provides a near universal power-law with equal energy per log interval

Particle acceleration at supernovae shock fronts

e.g. Drury 83, Blandford & Eichler 87, Kirk 94



particles get accelerated as they bounce back and forth across the shock wave

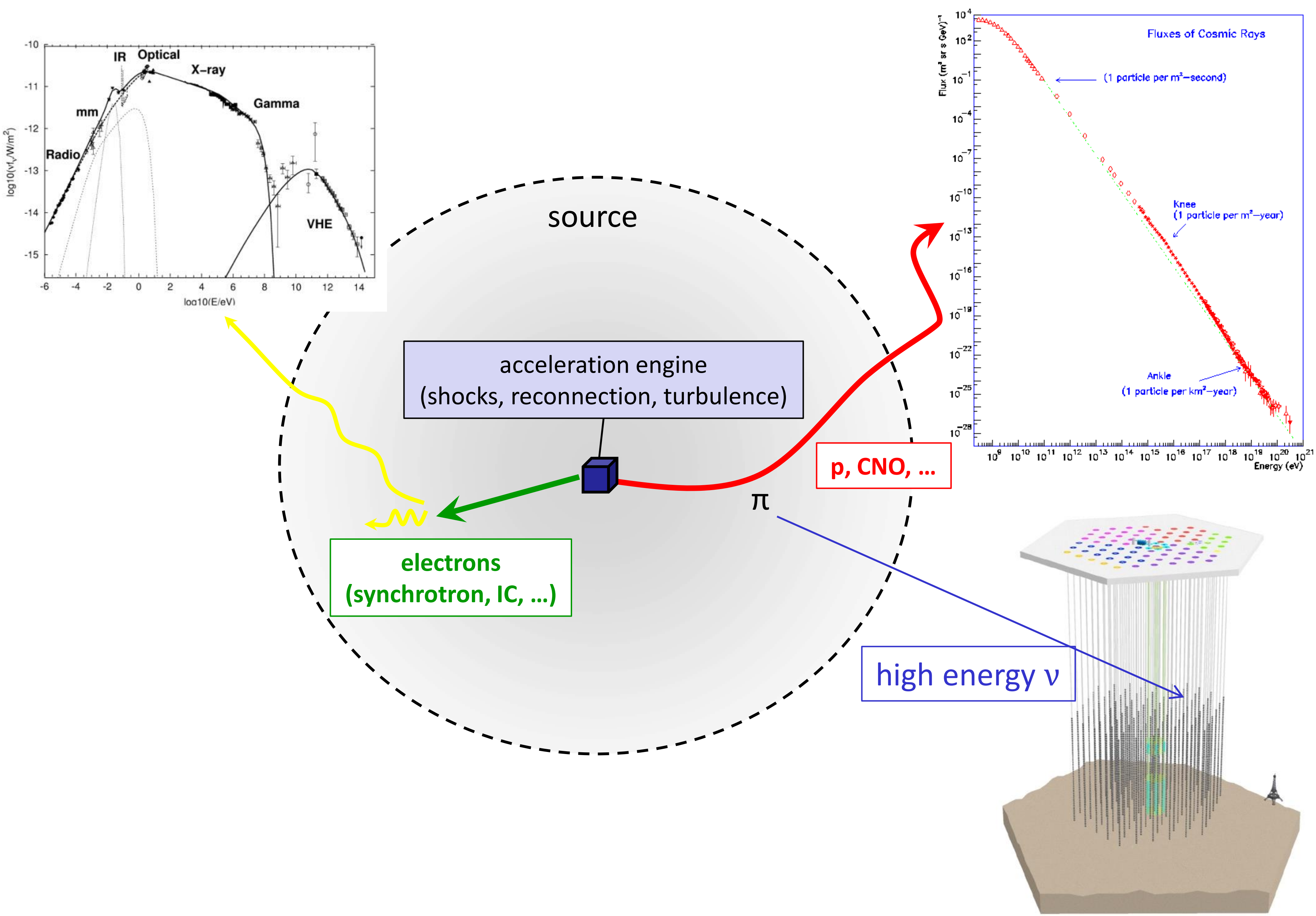
<u>Energy gain per cycle:</u> $\left\langle \frac{\Delta E}{E} \right\rangle \simeq \beta_{\rm sh}$

<u>Probability of escape:</u> … at each cycle, particles can escape downstream through advection, with probability $P_{\rm esc} \sim \beta_{\rm sh}$

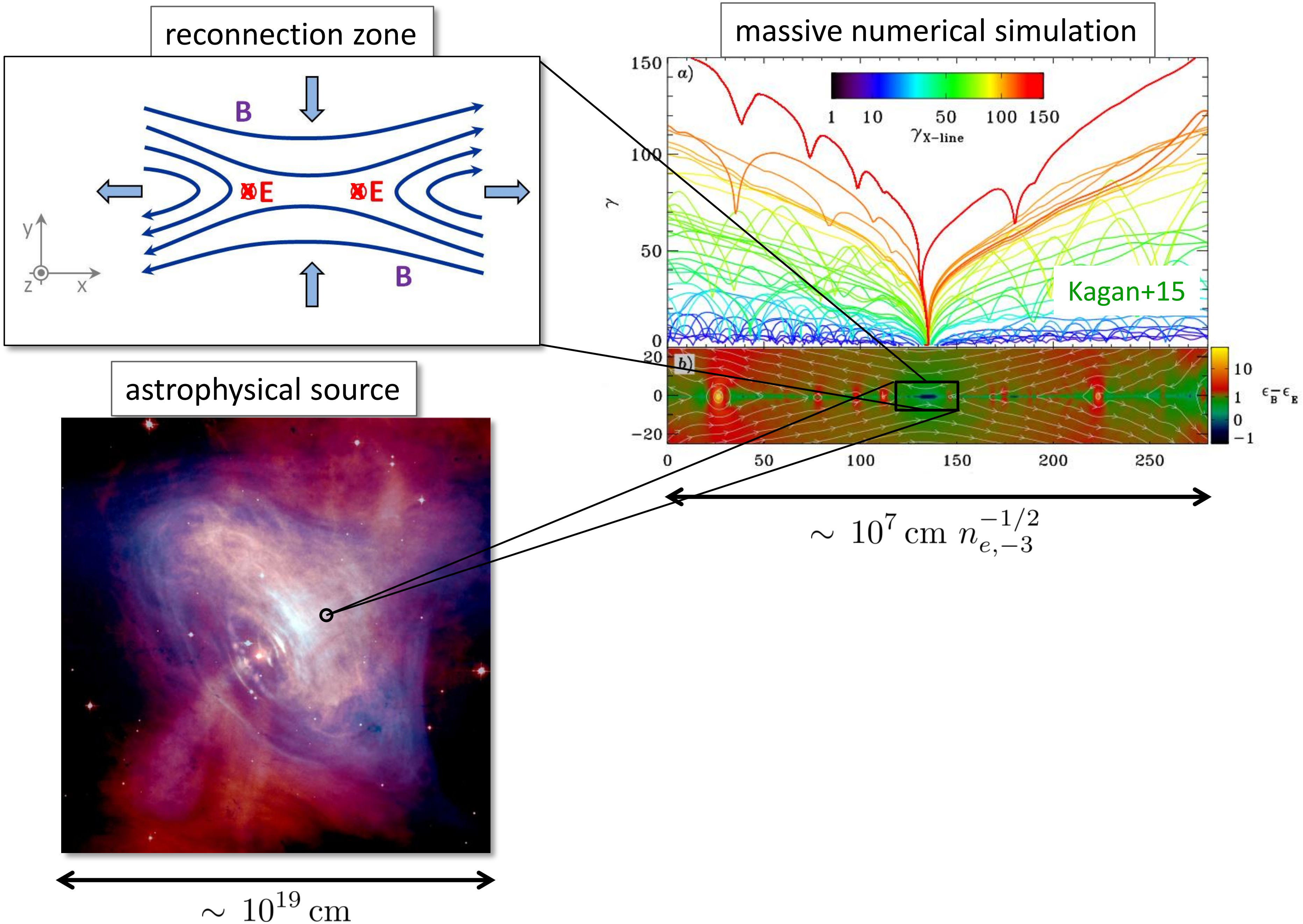
<u>Return timescale:</u> $t_{\rm res.} \simeq \frac{t_{\rm scatt}}{\beta_{\rm sh}}$

<u>Acceleration timescale:</u> $t_{\rm acc.} = \left(t_{\rm res.|u} + t_{\rm res.|d}\right) / \langle \Delta E/E \rangle \approx t_{\rm scatt}/\beta_{\rm sh}^2$

Motivations : cosmic rays + multi-messenger astrophysics

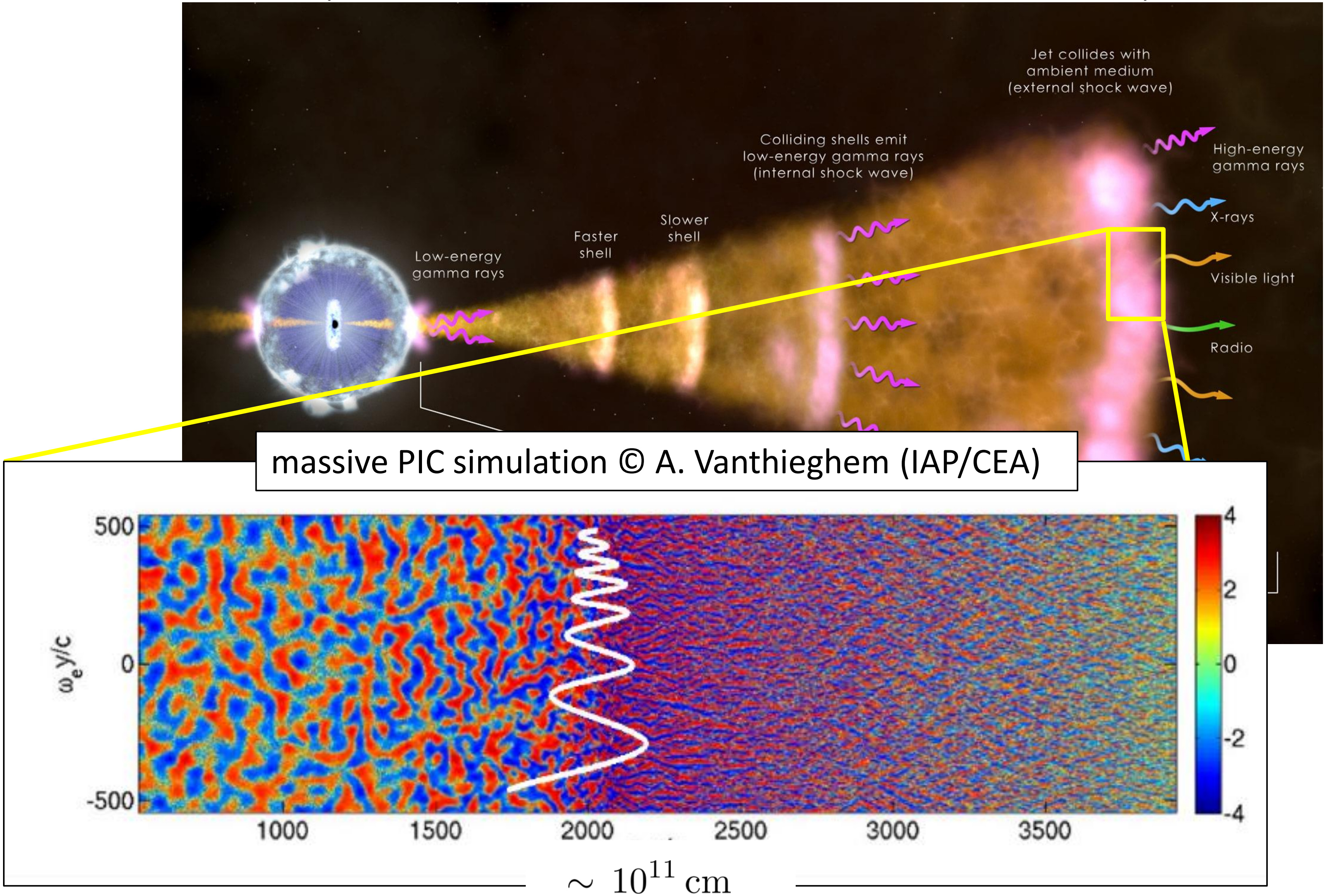


Micro-scales of acceleration vs macro-scales of astrophysics



Micro-scales of acceleration vs macro-scales of astrophysics

$\sim 10^{17}$ cm



$\sim 10^{11}$ cm

Methods...

Experimental data

source

acc. engine

Phenomenology / large scale physics:

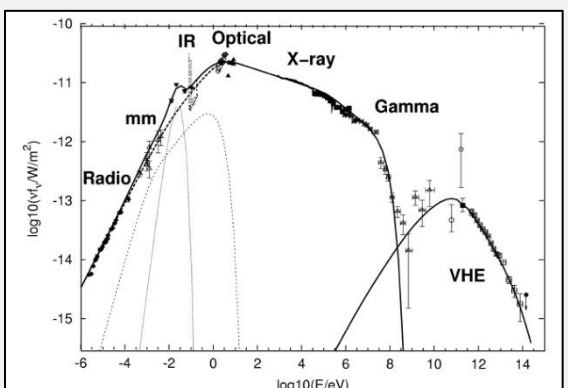
- model the accelerator …

$$t_{\rm acc} = \mathcal{A}\, t_{\rm g}$$

$$\frac{{\rm d}N}{{\rm d}\gamma} \propto \gamma^{-s}$$

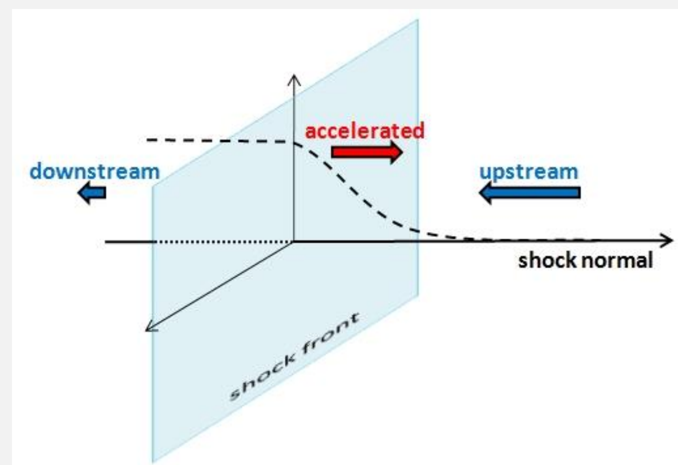
- model the source: radiative backgrounds, turbulence etc.

⇒ spectra etc.



Acceleration physics / microphysics:

- idealize the environment…
- work out acceleration physics: efficiency, spectrum, back reaction and turbulence generation etc.



- note : $c/\omega_p \sim 10^7$ cm n_0 …

Some of the main questions (on the phenomenological side)

Origin of non-thermal / high energy photon spectra:

→ **Acceleration + radiation physics in very different environments:**
e.g., leptonic vs hadronic channels in SNRs, GRBs, PWNe, AGNs, CoGs etc.,
e.g., which dissipation/acceleration mechanism, which radiative process…

Origin of cosmic rays:

→**How robust is the connection between sub-PeV CRs and SNRs ?**

→ **Where are the PeVatrons ?**

→ **Origin and nature of CRs in the intermediate region PeV – EeV ?**

→ **What is the source of >EeV cosmic rays?**

Origin of high energy neutrinos:

→ **Do Galactic sources contribute, which/how and at what level?**

→ **Where are the super-PeVatrons?**

Phenomenology vs observations vs microphysics

Example 1: magnetic amplification in the precursor of supernovae remnant shocks

→ maximal energy for test-particle protons :

$$E_{\rm max} \simeq \beta_{\rm sh} e B R \sim 10 - 20\,{\rm TeV}\ B_{\mu{\rm G}} n_0^{-1/3}$$

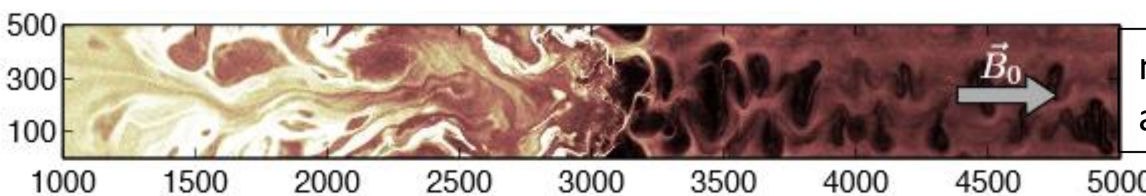
→ cosmic ray phenomenology: smooth turn-over at the knee ~ 2 10^{15} eV suggests that E_{max} is at least E_{knee}… suggesting

$$B \sim 100\,\mu{\rm G}$$

… this already assumes that $t_{scatt} \sim t_g$ … whereas in a generic turbulent setting, one expects a much less efficient $t_{scatt} \gg t_g$…

→ thin X-ray rims of supernova remnants ~10TeV electrons:

$$\nu_{\rm syn} \propto B E_e^2 \quad \text{and} \quad \ell_{\rm syn} \propto B^{-2} E_e$$



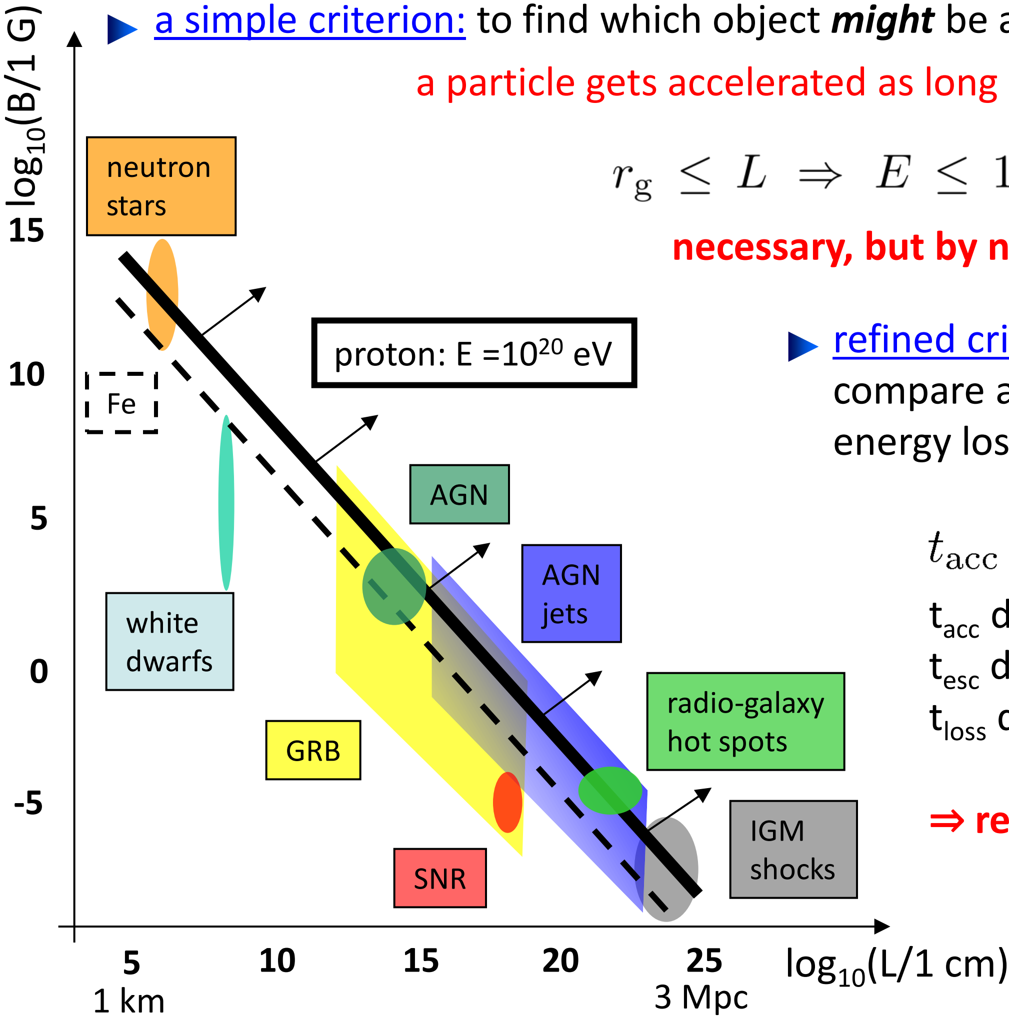
microphysics of a shock front

→ plasma instabilities in the precursor of the shock front, seeded by cosmic rays, amplify B: determine the relevant instabilities, understand their non-linear behavior and saturation, their scalings with the SNR characteristics, etc…

…maximal energy: one unsolved crucial point for microphysics…

Phenomenology vs observations vs microphysics

Example 2: acceleration to ultra-high energies ~ 10^{20} eV



▶ a simple criterion: 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:

$$r_g \leq L \;\Rightarrow\; E \leq 10^{20}\,\mathrm{eV}\, Z\, B_{\mu G}\, L_{100\,\mathrm{kpc}}$$

Hillas 84

necessary, but by no means sufficient!

▶ refined criterion:

compare acceleration timescale with energy loss timescale and escape timescale

$$t_{acc} \leq t_{loss},\quad t_{esc}$$

t_{acc} depends on acceleration mechanism...

t_{esc} depends on magnetic field...

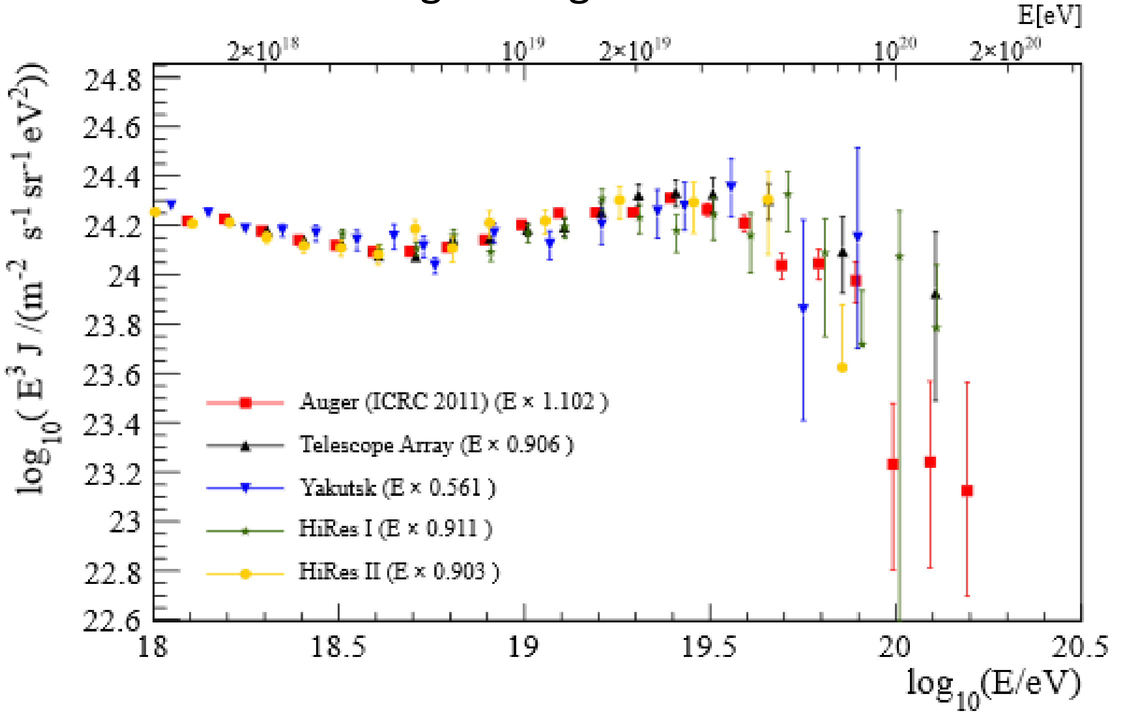
t_{loss} depends on environment...

⇒ requires an object by object study...

Norman et al. 95

Phenomenology vs observations vs microphysics

Example 2: acceleration to ultra-high energies $\sim 10^{20}$ eV



acceleration timescale: $t_{acc} = \mathcal{A}\,\frac{p}{eBZ} \quad \Rightarrow \quad L_B \gtrsim 10^{45}\, Z^{-2} \mathcal{A}^2 E_{20}^2 \,\mathrm{erg/s}$

high luminosity AGN: $L_{bol} > 10^{45}$ erg/s

Cen A: $L_{jet} \sim 10^{43}$ erg/s

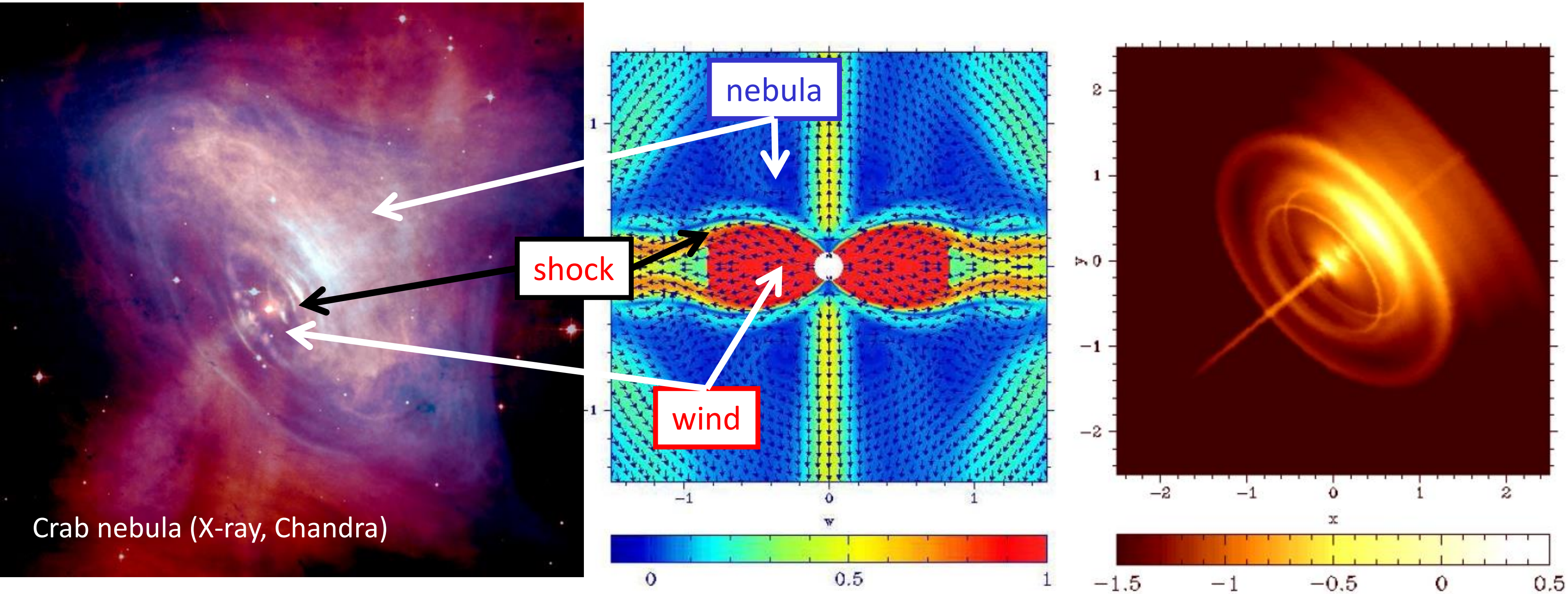
gamma-ray bursts: $L_{bol} \sim 10^{52}$ erg/s

⇒ only most powerful (relativistic) sources, at least for UHE protons…

… but: to go further eventually solve microphysical issues… e.g., t_{scatt} vs t_g ? origin of B ?

Phenomenology vs observations vs microphysics

Example 3: the unknown dissipation + acceleration physics of PWNe…



Modelling of the nebular emission:

- synchrotron emission seen up to 100MeV, inverse Compton emission beyond…

… and recall: $$t_{\rm acc} \simeq \mathcal{A}\frac{p}{eB} \Rightarrow \epsilon_{\rm syn,max} \simeq \mathcal{A}^{-1}\frac{m_e c^2}{\alpha_{\rm e.m.}} \sim 100\,\mathcal{A}^{-1}\,{\rm MeV}$$

- electrons are heated up to a Lorentz factor ~ 10^6 … maximal Lorentz factor ~ 10^9 !
- Crab flares with maximal energy >100MeV on >day timescales !

- physics of the termination shock? Moderate magnetization, Lorentz factor ~ 10^4 - 10^6 ?!

Acceleration physics and scenarios

Standard lore:

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

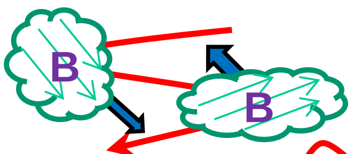
Ideal MHD: $\boldsymbol{E}_{|\mathrm{p}} \simeq 0$ in plasma rest frame

→ ***E*** field is 'motional', i.e. if plasma moves at velocity $\boldsymbol{v}_\mathrm{p}$: $\boldsymbol{E} \simeq -\frac{\boldsymbol{v}_\mathrm{p}}{c} \times \boldsymbol{B}$

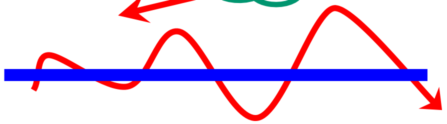
→ need some force or scattering to push particles across *B*

→ lower bound to acceleration timescale: $t_\mathrm{acc} = \frac{p}{\beta_\mathrm{p} e B} = \frac{t_\mathrm{g}}{\beta_\mathrm{p}}$

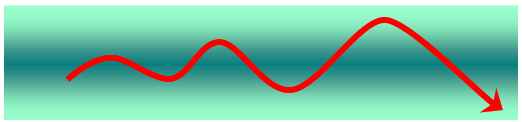
→ examples: - turbulent Fermi acceleration



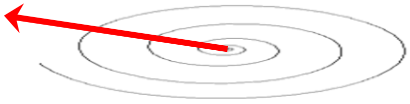
- Fermi acceleration at shock waves



- acceleration in sheared velocity fields

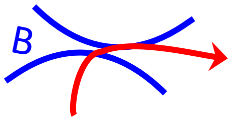


- magnetized rotators



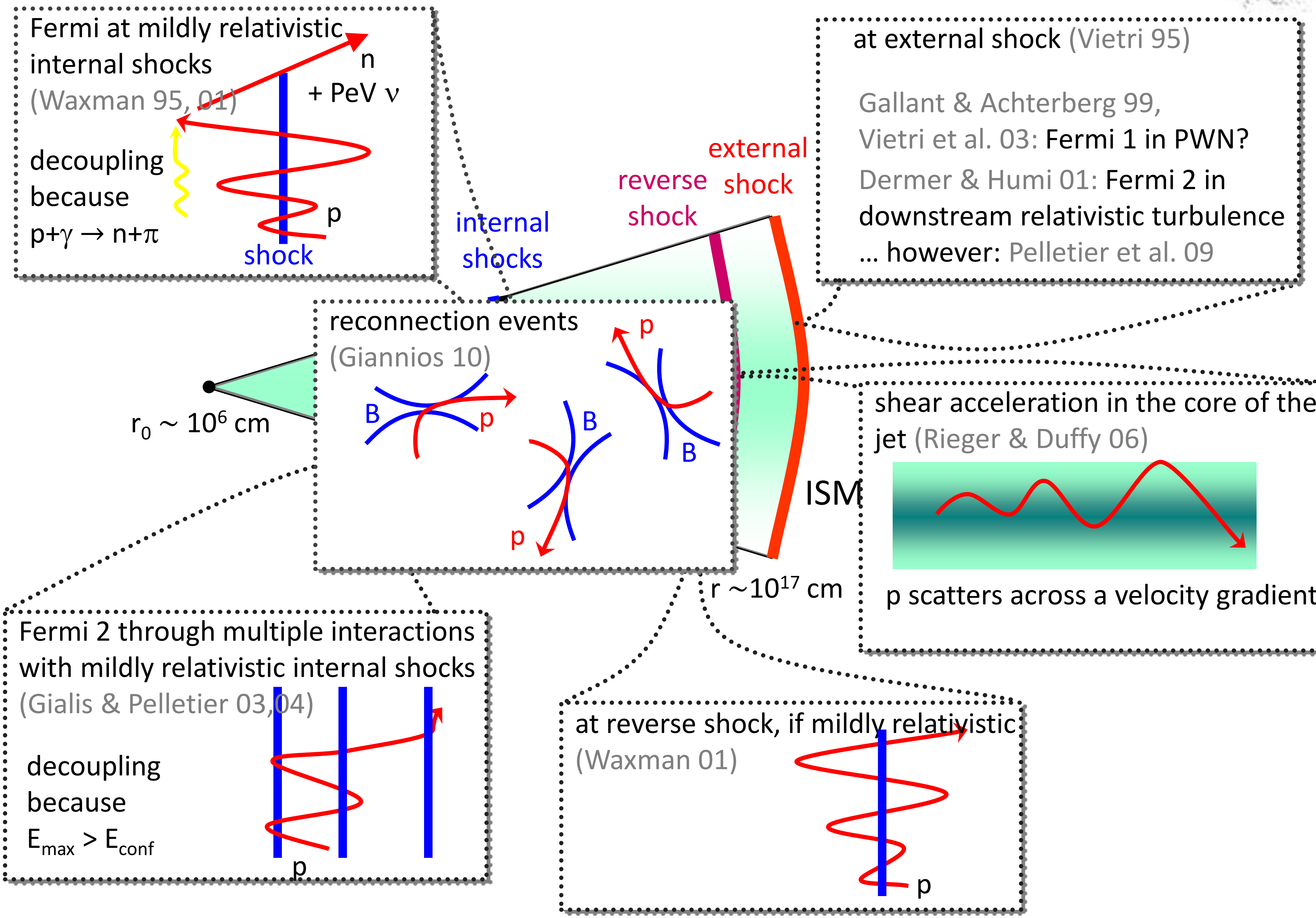
Beyond MHD:

→ examples: - reconnection



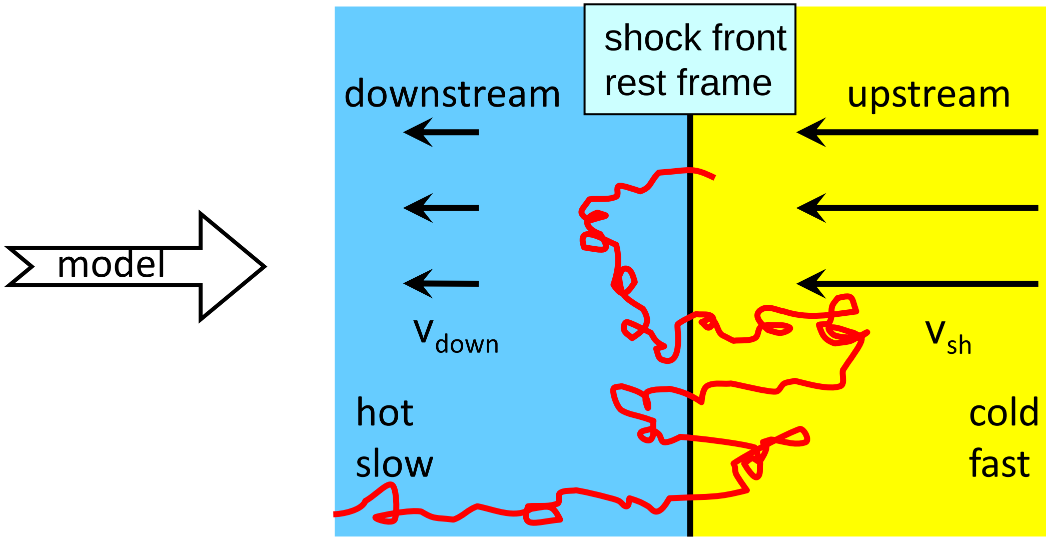
- gaps

Acceleration to UHE in gamma-ray bursts fireballs



Non-relativistic 1st order Fermi acceleration

e.g. Drury 83, Blandford & Eichler 87, Kirk 94



particles get accelerated as they bounce back and forth across the shock wave

Test-particle approximation !

Energy gain per cycle: $\left\langle \frac{\Delta E}{E} \right\rangle \simeq \beta_{\rm sh}$

Probability of escape: … at each cycle, particles can escape downstream through advection, with probability $P_{\rm esc} \sim \beta_{\rm sh}$

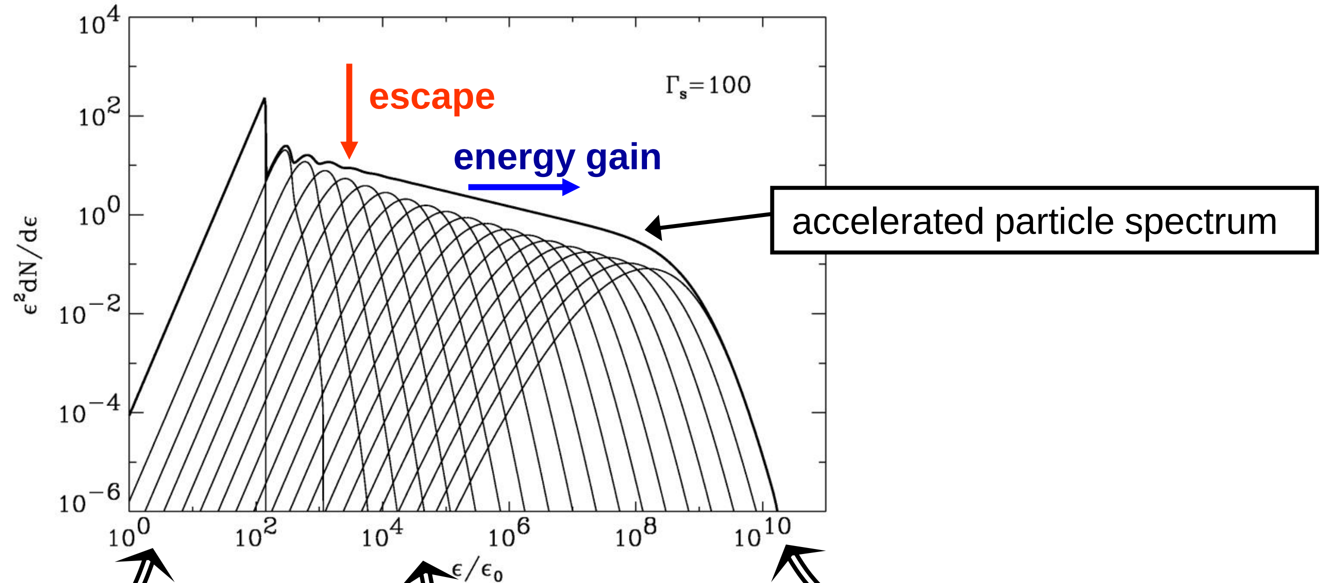
Return timescale: $t_{\rm res.} \simeq \frac{t_{\rm scatt}}{\beta_{\rm sh}}$

Acceleration timescale: $t_{\rm acc.} = \left(t_{\rm res.|u} + t_{\rm res.|d}\right) / \langle \Delta E/E \rangle \approx t_{\rm scatt}/\beta_{\rm sh}^2$

Issues in diffusive shock acceleration

Spectral index is a function of energy gain and escape probability

$dN/dE \propto E^{-s}$, with $s = 1 - \ln(1 - P_{esc})/\ln(1 + \Delta E/E) = 2.0$ in non-relativistic strong shocks



Main open questions:

injection

crucial issue for e, w/o heating:

$r_{L,e} << r_{L,p} \sim \Delta_{shock}$

source of heating?

non-linear acceleration

CR modify jump conditions in the precursor...

CR also amplify B_{up} through streaming instabilities...

maximal energy and escape

how is escape realized?

maximal energy?

resulting spectrum integrated over SN evolution?

+ dependence on the obliquity of the background magnetic field, on the external source of turbulence, on the scattering properties, etc.

Main questions… on theory side

Acceleration physics:

→ for each acceleration scenario, seek to determine the spectrum (power-law? index?), the maximum energy, the energy output (E_{cr}/E_{tot}), and possible radiative signatures… going beyond the test-particle approximation!

→ for each acceleration scenario, how does one match the microphysical approach with phenomenology on source spatial scales?

→ Shock acceleration… back-reaction of accelerated particles and long-term evolution?

→ Reconnection… large-scale / long-term picture? 3D geometry ?

→ Turbulence… realistic model of stochastic acceleration ?

→ role of other acceleration scenarios ?

→ connection to source properties: escape of particles, backreaction of environment…

Future research directions

Phenomenology:

→ **data driven… very strong connection to experimental data**

→ **refine radiative signatures for future experiments: e.g. polarisation, high energy signals…**

→ **exploit multi-messenger connections: photons vs neutrinos in particular**

→ **pin down and understand PeVatrons**

→ **some concern relative to UHECR theory: chemical composition at UHE?**

Theory:

→ **establish a bridge between simulations, theory and phenomenology…**
… to study particle acceleration in more realistic settings, e.g.:

- **acceleration in a variety of conditions: low/high magnetization, sub-relativistic or relativistic etc.**
- **extend theory+simulations on large temporal + spatial scales**
- **include back-reaction of accelerated particles, radiation etc.**