Physics of cosmic ray acceleration
-- Theoretical aspects --

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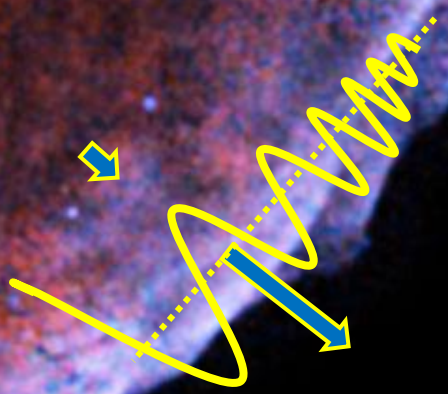
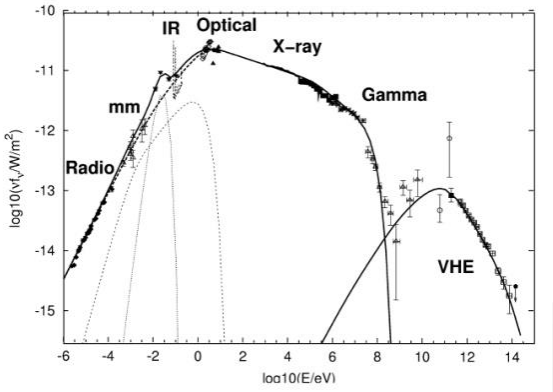
Outline:

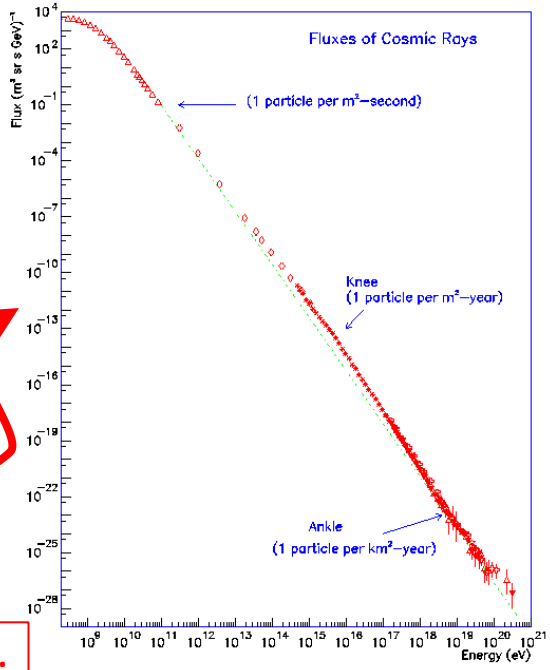
1) Motivations & Methods
2) PNHE:
   a) Main questions
   b) Recent developments
   c) Future research directions
   d) PNHE



Thanks to: Jean Ballet, Guillaume Dubus, Alexandre Marcowith, Robert Mochkovitch

Motivations : cosmic rays + multi-messenger astrophysics





source

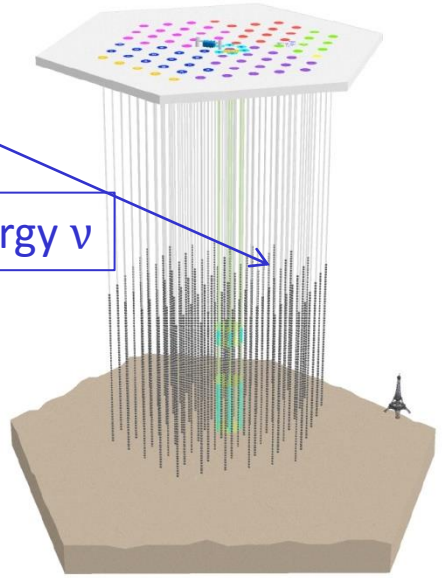
acceleration engine
(shocks, reconnection, turbulence)

p, CNO, …

π

electrons
(synchrotron, IC, …)

high energy ν



Methods

Experimental data

Phenomenology / large scale physics:

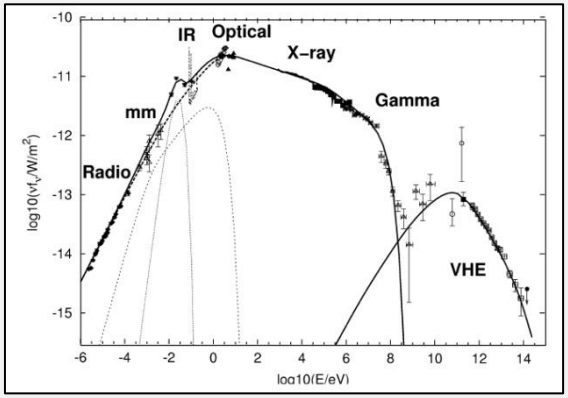
- model the accelerator …

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

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

- model the source: radiative backgrounds, turbulence etc.

⇒ spectra etc.

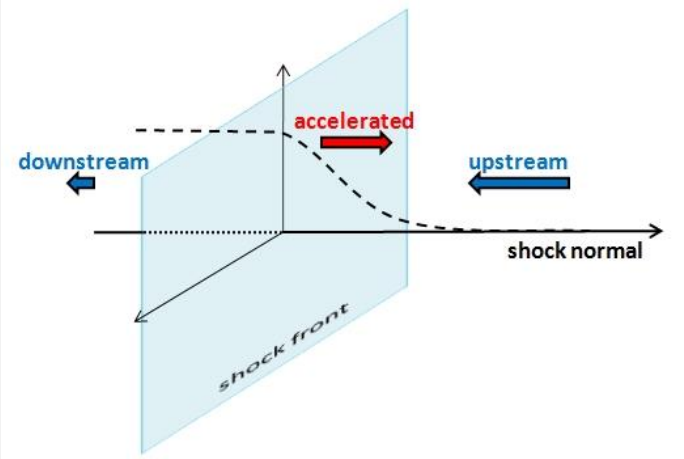


source

acc. engine

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 …

Phenomenology vs observations vs microphysics

Example: magnetic amplification in the precursor of supernovae remnant shocks

→ maximal energy for test-particle protons :

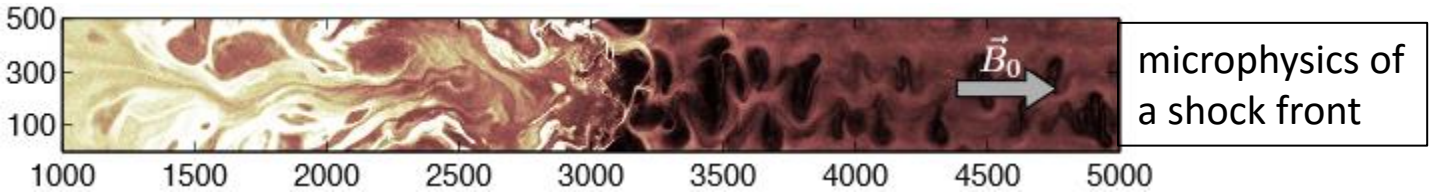
$$E_{\rm max} \simeq \beta_{\rm sh} eBR \sim 10 - 20\,{\rm TeV}\ B_{\mu{\rm G}} n_0^{-1/3}$$

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

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

→ thin X-ray rims of supernova remnants interpreted as thin cooling layer of ~10TeV electrons:

$$\nu_{\rm syn} \propto BE_e^2 \quad \text{and} \quad \ell_{\rm syn} \propto B^{-2}E_e^{-1} \Rightarrow B \sim 100\,\mu{\rm G}$$

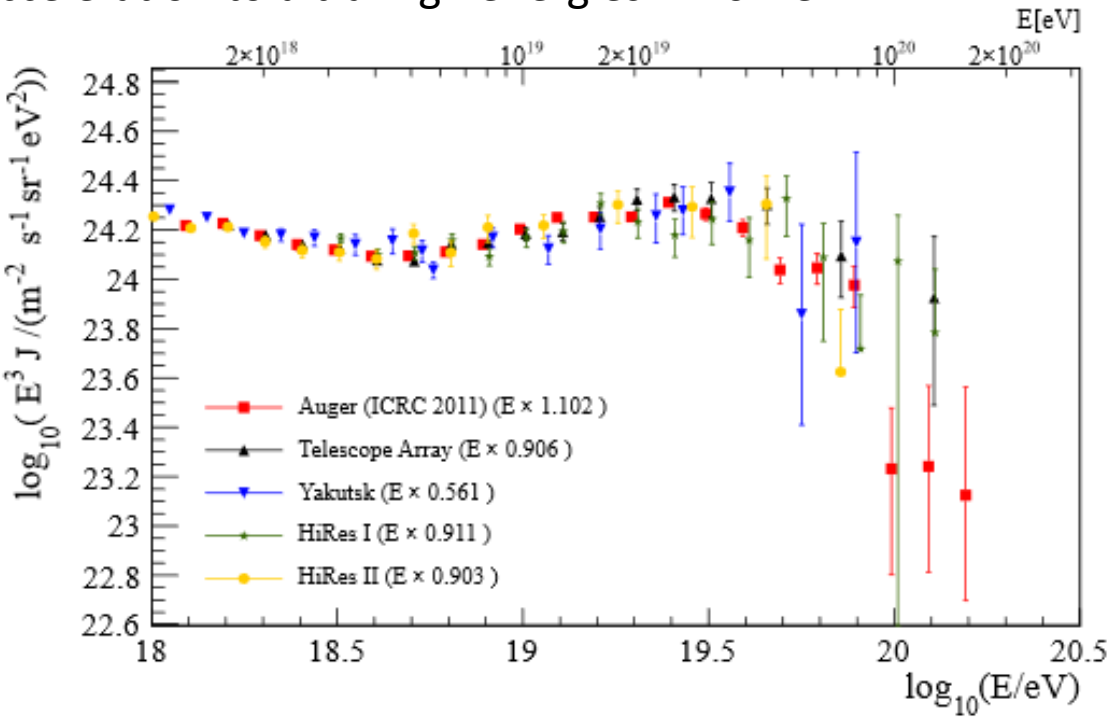


→ plasma instabilities in the precursor of the shock front, seeded by cosmic rays, amplify B: determine the relevant instabilities, understand their non-linear behavior and saturation, their scalings with the SNR characteristics, etc…

…maximal energy: one unsolved crucial point for microphysics…

Phenomenology vs observations vs microphysics

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



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

low luminosity AGN: $L_{bol} < 10^{45}$ erg/s

high luminosity AGN: $L_{bol} \sim 10^{46}$-10^{47} erg/s

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

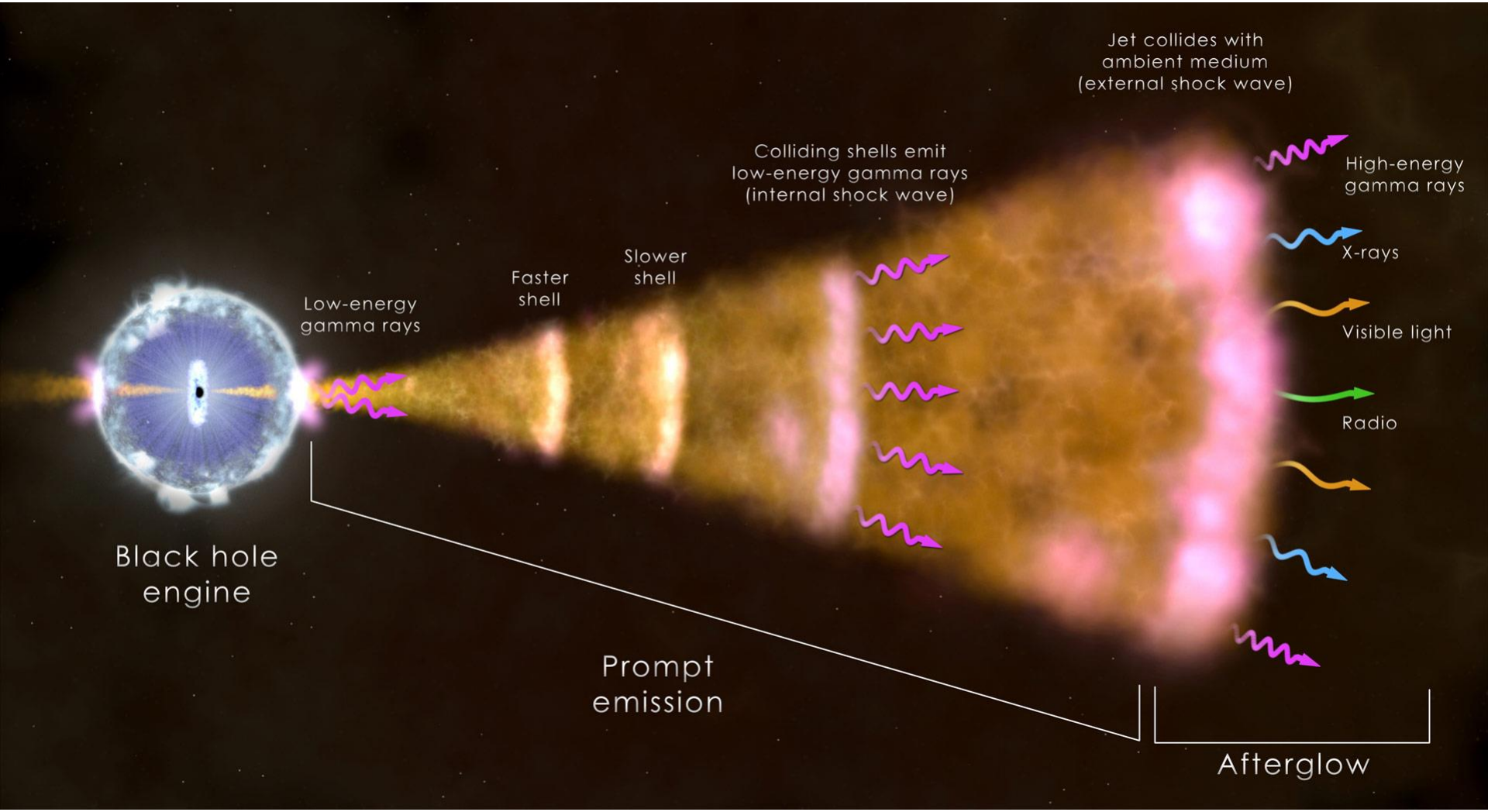
gamma-ray bursts: $L_{bol} \sim 10^{52}$ erg/s

⇒ only most powerful AGN jets, GRBs or young pulsars for UHE protons...

to go further: solve the microphysics...

Phenomenology vs observations vs microphysics

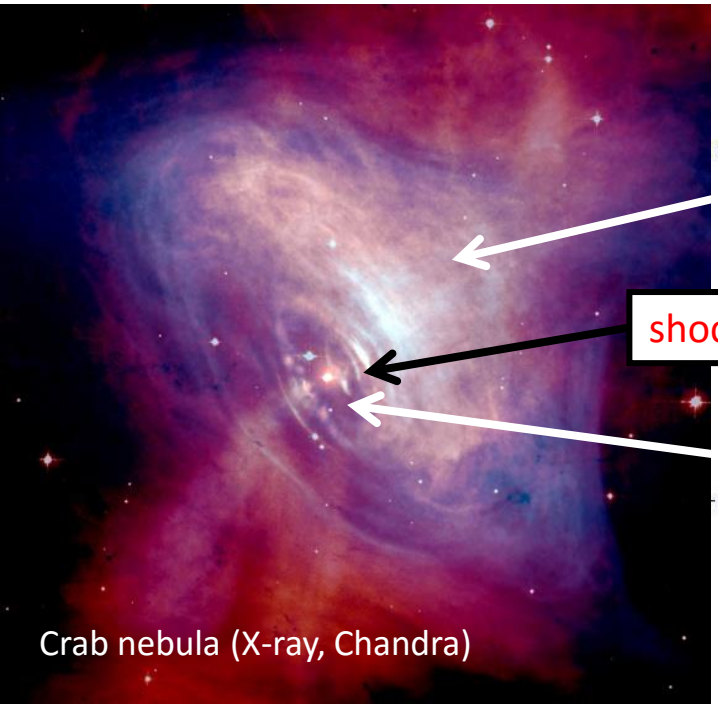
Example 3: the unknown hidden dissipation agents in relativistic winds (GRBs, AGNs, + PWNe) acting in different ranges of magnetization and flow velocity…

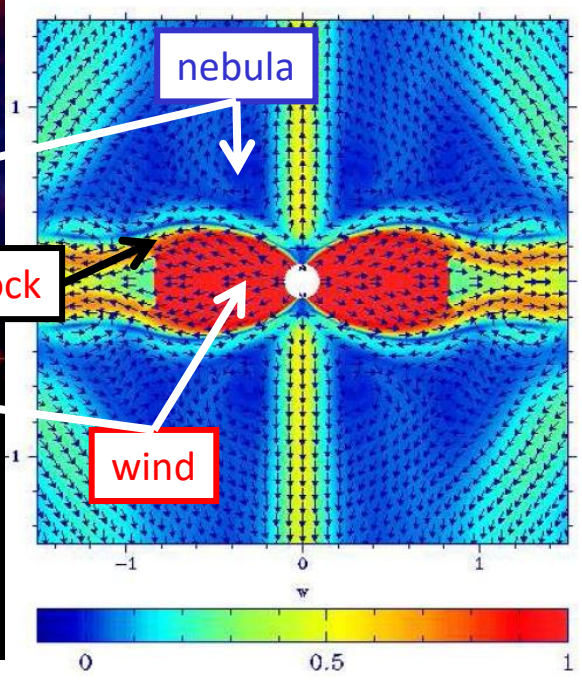


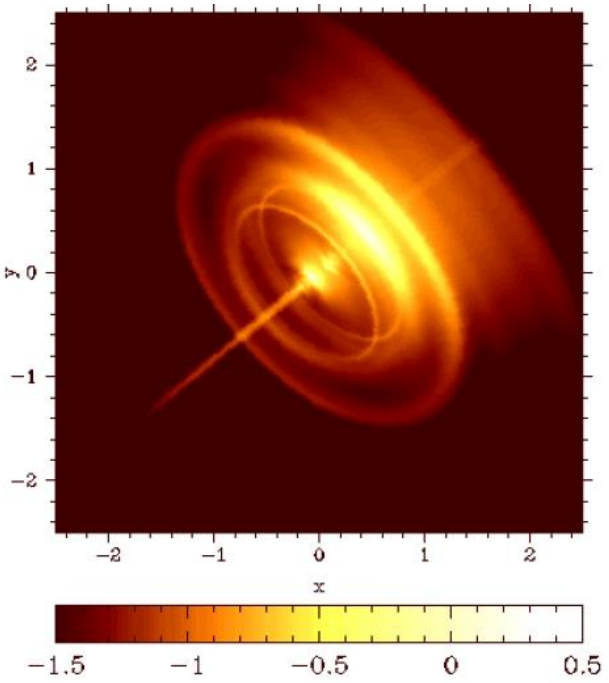
shocks, reconnection, turbulence, others: each with pros + cons, no clear picture

Phenomenology vs observations vs microphysics

Example 4: the unknown dissipation + acceleration physics of PWNe…







Modelling of the nebular emission:

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

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

- electrons are heated up to a Lorentz factor ~ 10^6 …
- acceleration proceeds up to 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 ?!

Main questions… on 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?

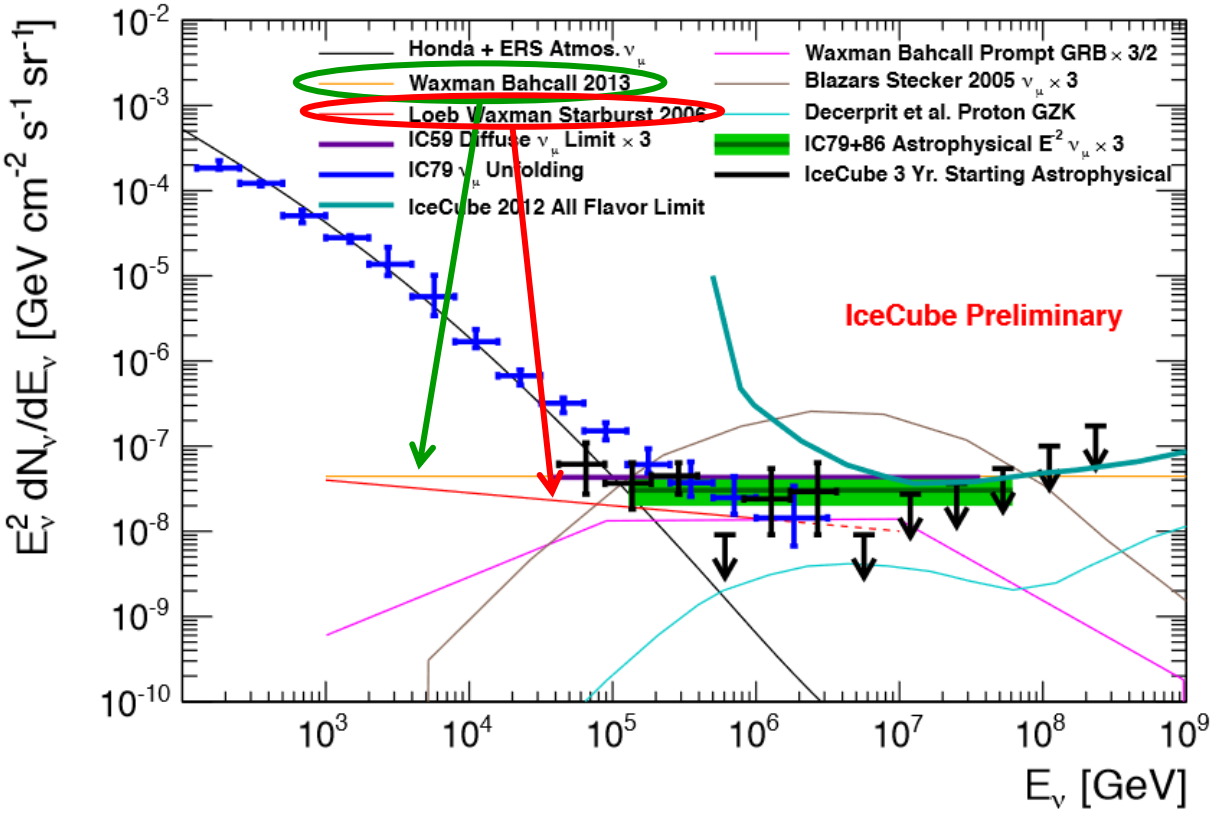
Origin of high energy neutrinos:

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

→ What are their sources (extra-Galactic PeVatrons?)

Main questions: origin of high E neutrinos

Origin of Ice Cube high energy neutrinos: which (extra-Galactic?) PeVatron ?



… extrapolating the associated gamma flux to low energies is in tension with diffuse gamma-ray background… ??

… the observed flux at Ice Cube matches nicely the WB bound: a connection to high energy cosmic ray physics?

Main questions… on theory side

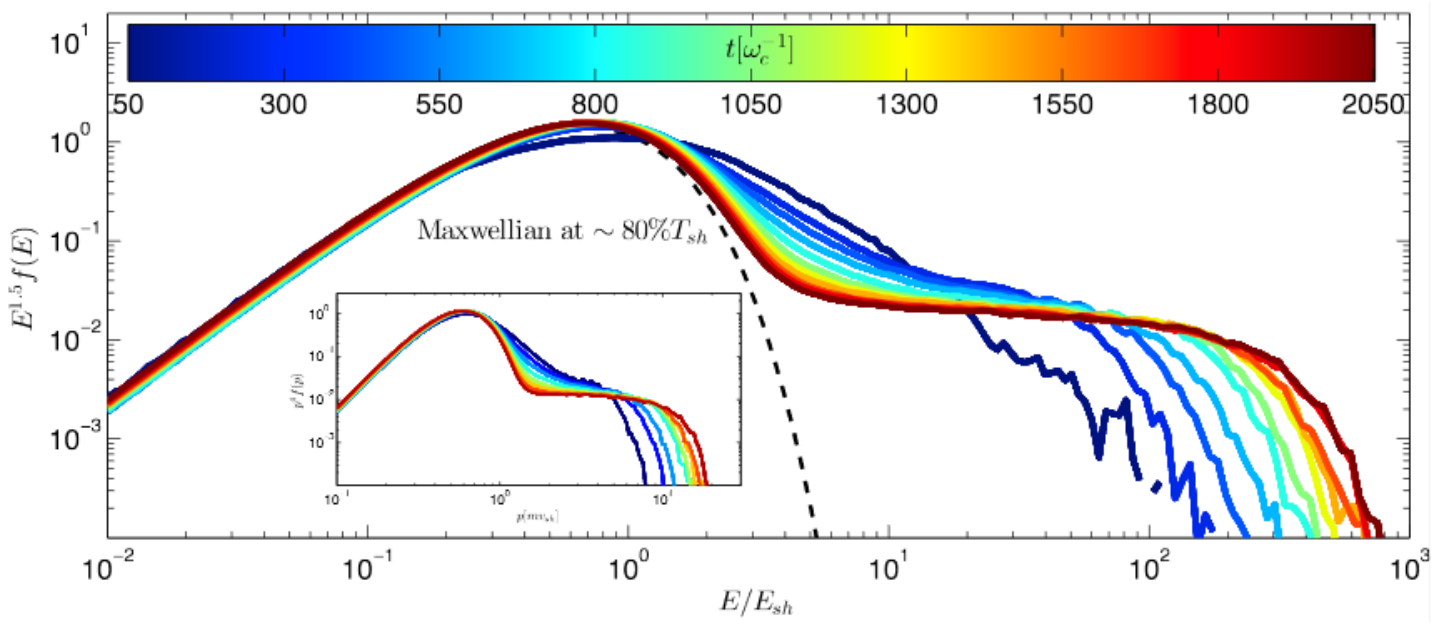
Acceleration physics: **efficiency, spectrum, maximum energy**

→ 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 ?



Some important recent developments

On the experimental side!

→ High energy astrophysical neutrinos, gravitational waves and a wealth of data in high energy gamma-ray astronomy (γ variability, high E photons), CR experiments…
… data driven field of research!

On the theoretical/phenomenological side:

→ exploration of reconnection physics spurred by phenomenology…

→ emergence of particle-in-cell simulations of ab initio dynamics of acceleration…

→ basic principle: N-body simulations solving the Maxwell-Vlasov system of particles and fields

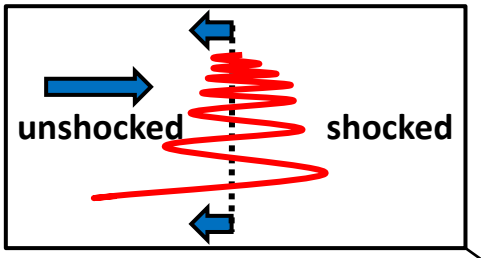
→ allow to compute the full non-linear dynamics of plasmas + accelerated particles in (so far) simplified geometries / environments (e.g. 2D in space, 3D in momentum)

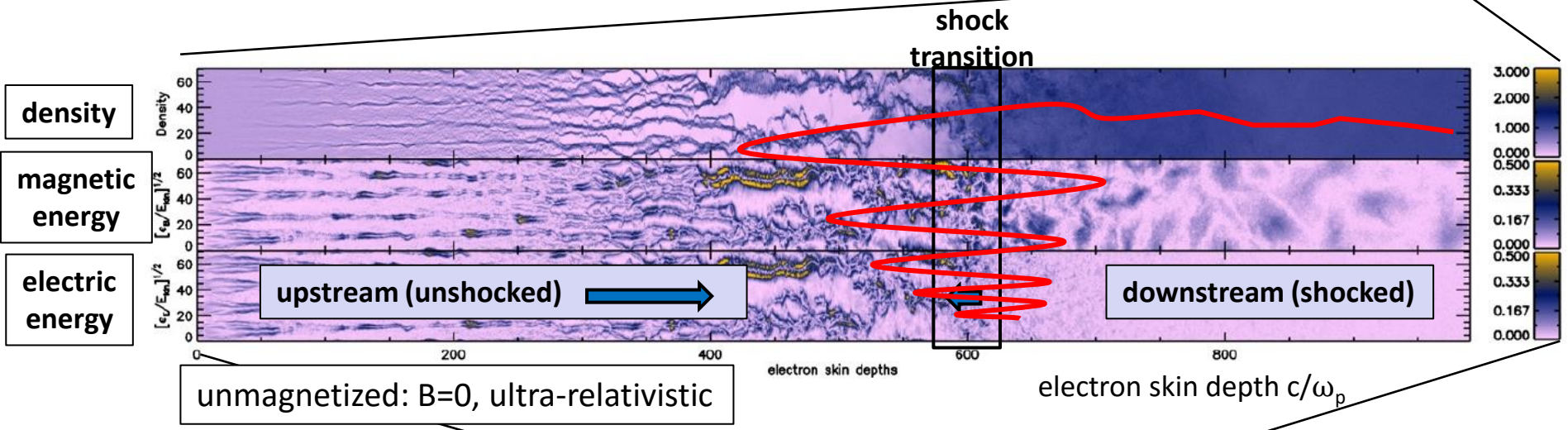
→ allow to simulate the generation of the first decade (so far) of energy spectrum of accelerated particles: address two crucial problems, injection and back-reaction

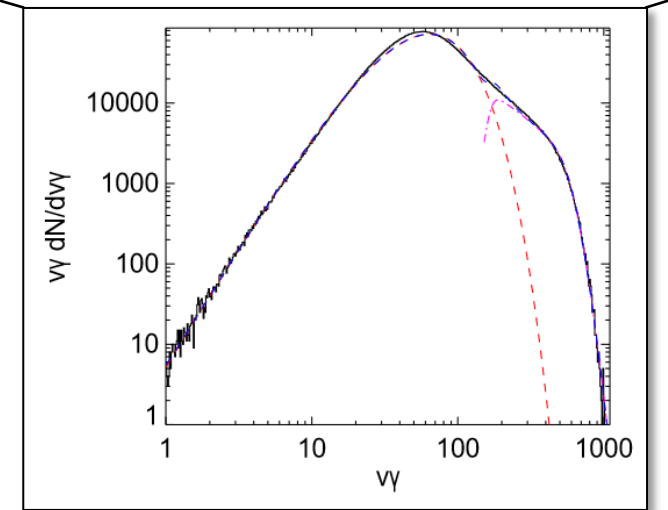
… a 'revolution' in high-E astrophysics likely comparable to that of N-body simulations in cosmology…

The PIC revolution

Emergence of PIC simulations:

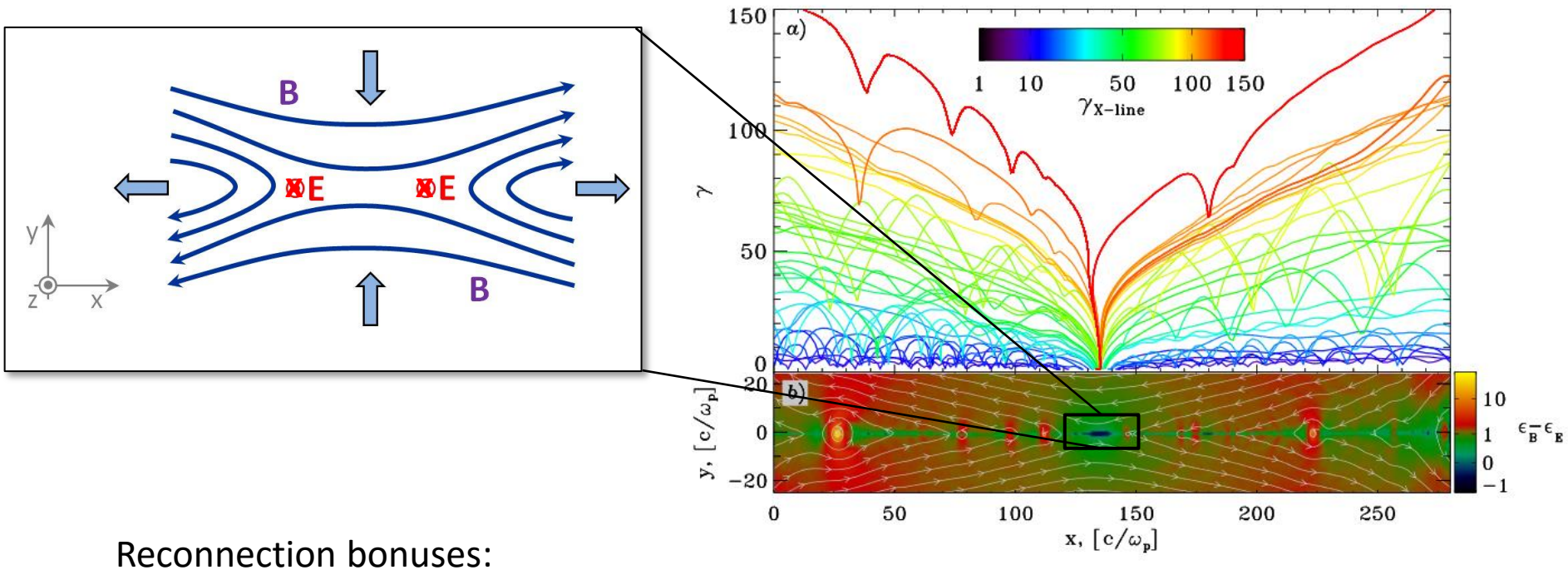






Haugbolle 11

Exploring reconnection physics



Reconnection bonuses:

→ a small scale phenomenon… with possibly relativistic bulk velocities…
… leads to fast acceleration timescale $t_{acc} \propto p/(eB)$ (in first stages at least!)
(motivates jet in jet model for explaining fast variability of blazars)

→ maximal energy beyond synchrotron burn-off limit because E>B in diss. region
(motivates reconnection for explaining Crab flares!)

→ power-law emergence due to competition vs energy and escape

The French community

Phenomenology:

→ present (and active!) on all topics…

→ CR origin: ~ 15-20 *p* from sub-PeV to super-EeV
(1 p = a substantial fraction of one permanent)

→ gamma-rays: ~ 30 *p*

→ neutrinos: ~ 3-5 *p* (slightly under-represented as compared to US?)

Microphysics:

→ present (and active!) on theoretical side: ~ 5 *p*

→ a clear under-representation on numerical side: ~ 5 *p*,
… signalling a clear delay in France with respect to the PIC revolution…
(PIC community exists in solar system studies and laser-plasma community)…

… ANR MACH project (PI: Alexandre Marcowith): see F. Casse
… B. Cerutti hired in 2015…
… PhDs to come…

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 PIC 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 acc. particles, and radiation
- study role of turbulence (in particular, turbulence in relativistic outflows)

Role of PNHE

→ **support theory!** (+ thanks for past support!)

→ financial support for theoretical research programmes which cannot receive funding from experiments or others : 1-2 k-euros / year for travels / *p*…?

→ support for meetings: 3-5 k-euros / year / meeting

→ organize a yearly « PNHE Theory meeting » on a particular topic (going beyond acceleration), which would change every year: 3-5 k-euros / year…?

→ examples of meetings:

→ **Particle acceleration in relativistic outflows:** national workshop at IPAG, Dec. 2015, 30 participants, supported by PNHE and IPAG (∼3 k-euros)

→ **Beyond a PeV**: international workshop at IAP Sept. 2016, 40 participants, supported by PNHE + IAP + ILP …
call for contributions to come before the Summer