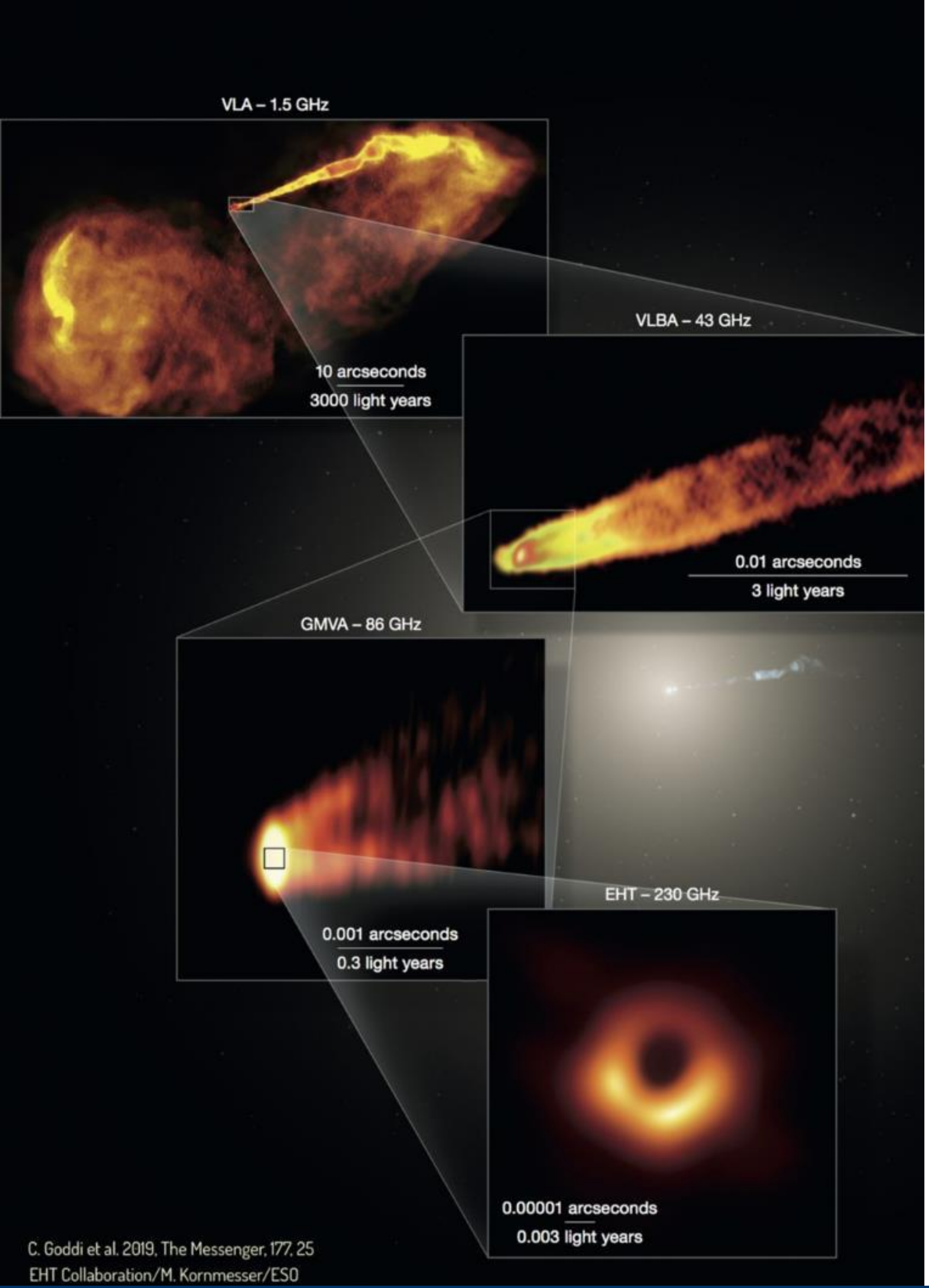

Particle acceleration in extreme environments

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… modelling the origin of VHE particles from astrophysical sources:

→ remarks, issues and techniques

→ scenarios: shocks, reconnection, turbulence

→ conclusion & perspectives

Particle acceleration: energization of a fraction of the plasma to VHE

→ extreme environments:

… realm of relativistic astrophysics: relativistic outflows & temperatures, high magnetization, high compactness

→ relativistic jets and winds (GRBs, PWNe, blazars, binaries, micro-quasars), vicinity of compact objects (BH, NS)

→ main parameters and generic acceleration processes:

… main parameters: | plasma velocity and Lorentz factor $(\beta_E\, c, \Gamma_E)$, or Alfvén $(\beta_A c, \Gamma_A)$, or shock $(\beta_{\rm sh} c, \Gamma_{\rm sh})$

magnetization parameter $\sigma =$ magnetic energy dens. / plasma e. dens. $= \Gamma_A^2 \beta_A^2$

… main scenarios: Fermi at (relativistic) shocks, reconnection (at $\sigma \gtrsim 0.1$), turbulence (at $\sigma \gtrsim 0.1$)

→ generic motivation:

… multi-messenger astrophysics $(\gamma - \nu\ -$ CR) connection and the origin of non-thermal radiation

… acceleration to VHE-UHE in relativistic sources: $E \sim \beta_E\, B$ leads to Hillas bound on $\varepsilon_{\rm max} \sim e\, \beta_E\, B\, L\, Z$

Acceleration schemes

→ two broad categories (Fermi's argument):

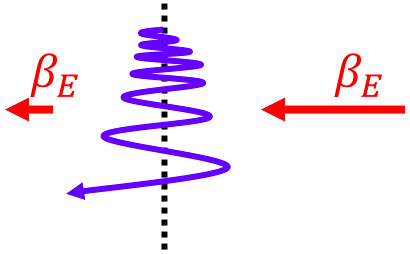
… on large ("astrophysical") scales, $\mathbf{E} = -\boldsymbol{\beta}_E \times \mathbf{B}$ derives from motion of magnetized plasma

… on small (∼"kinetic") scales, non-ideal electric fields, parallel to $\mathbf{B}$, or even larger than $\mathbf{B}$

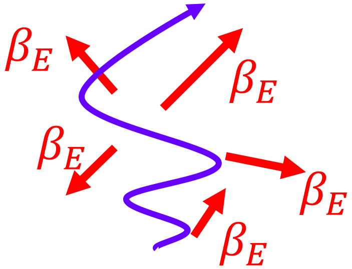
… large vs small: large is ≫ $r_{\mathrm{g,\,th}} \sim 10^8\ \mathrm{cm}\ \ T_4^{1/2} B_{\mu\mathrm{G}}^{-1}$ $c/\omega_{\mathrm{pi}} \sim 10^7\ \mathrm{cm}\ \ n_0^{-1/2}$

→ Fermi acceleration: $\mathbf{E} = -\boldsymbol{\beta}_E \times \mathbf{B}$ … acceleration by interactions with regions of different $\boldsymbol{\beta}_E$

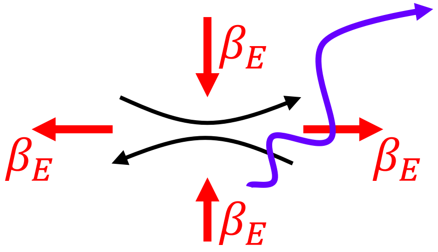
shock wave



turbulence

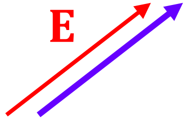


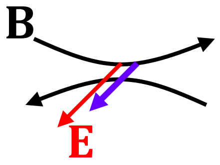
reconnection (outside X-point)



→ in non-ideal **E** fields: existence of (localized) $\mathbf{E} \parallel \mathbf{B}$ or $E > B$ leads to fast linear acceleration, unimpeded by $\mathbf{B}$

… application: **electrostatic gaps** and **reconnection (X-point)**





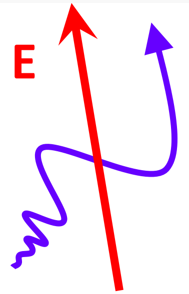
→ talk by B. Crinquand

By necessity, a multi-pronged approach, from num. sim. to theory to phenomenology

→ a needle in a haystack:

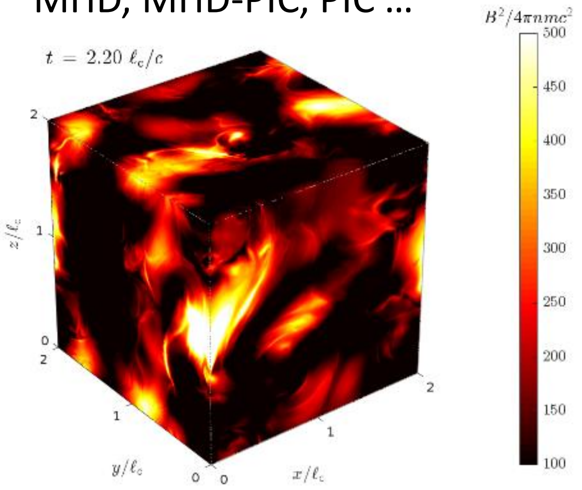
scales(acceleration) ≪ ≪ scale(source)

+ nonlinear, multiple scale physics



<u>Numerical simulations</u>

MHD, MHD-PIC, PIC …



<u>Theory</u>

schemes: shock, turbulence, reconnection?

test-particle vs self-consistent picture?

extrapolation to large scales?

<u>Applications</u>

→ predictions: $t_{\rm acc}$, $\varepsilon_{\rm max}$, $\mathrm{d}n/\mathrm{d}\varepsilon$

… to be used in transport equations

Numerical schemes for modeling particle acceleration

→ **test-particle:** particle tracking through Monte Carlo in prescribed e.m. geometry

+ direct (simple + cheap) estimates of particle energy distribution
- omits backreaction of HE particles on their environment (e.g. instabilities)

→ **particle-in-cell (PIC):** plasma $\sim$ collection of macroparticles evolved self-consistently with $\mathbf{E}, \mathbf{B}$

+ self-consistent description of injection, acceleration including nonlinear feedback processes
+ virtual experiment, crucial to developing intuition and building model
- must resolve smallest scales (gyroradius, skin depth): cannot probe astrophysical scales
- costly: limited in dimensionality

→ **magnetohydrodynamics + particles:** background plasma in MHD + module tracking HE particles + module for feedback

+ allows to describe flow dynamics on large scales ($\sim$up to source)
+ feedback can be included by coupling HE particles and MHD background
- cannot model injection process of HE particles

Numerical schemes for modeling particle acceleration

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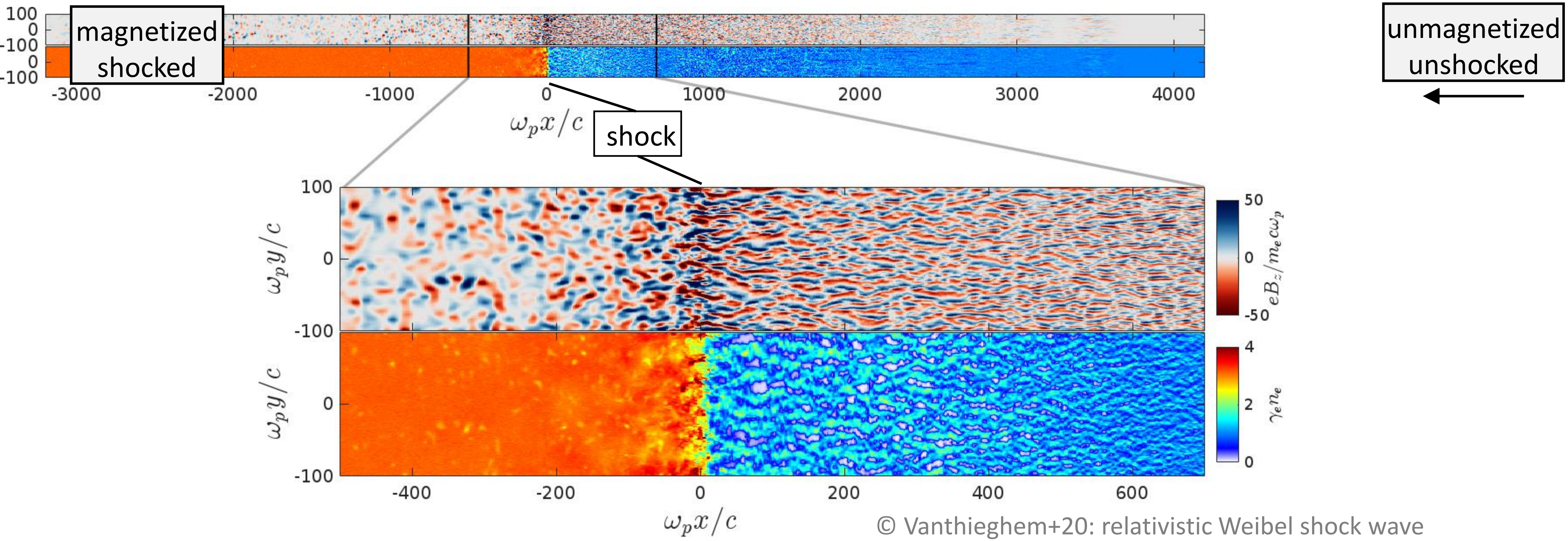

© Vanthieghem+20: relativistic Weibel shock wave

Numerical schemes for modeling particle acceleration

→ **magnetohydrodynamics + particles:** background plasma in MHD + module tracking HE particles + module for feedback

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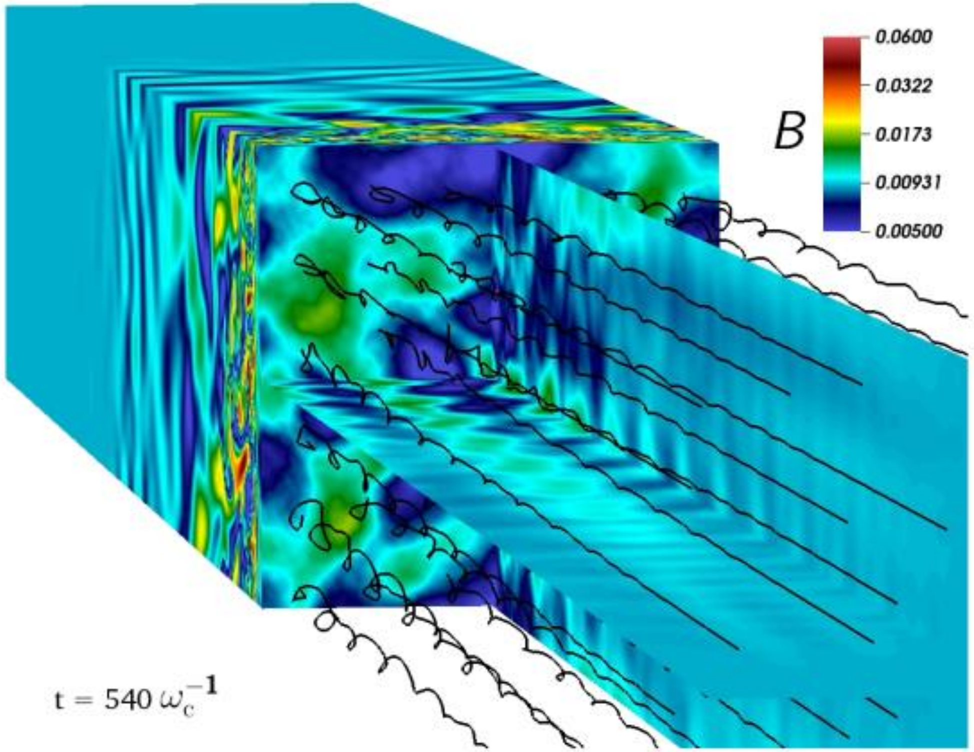


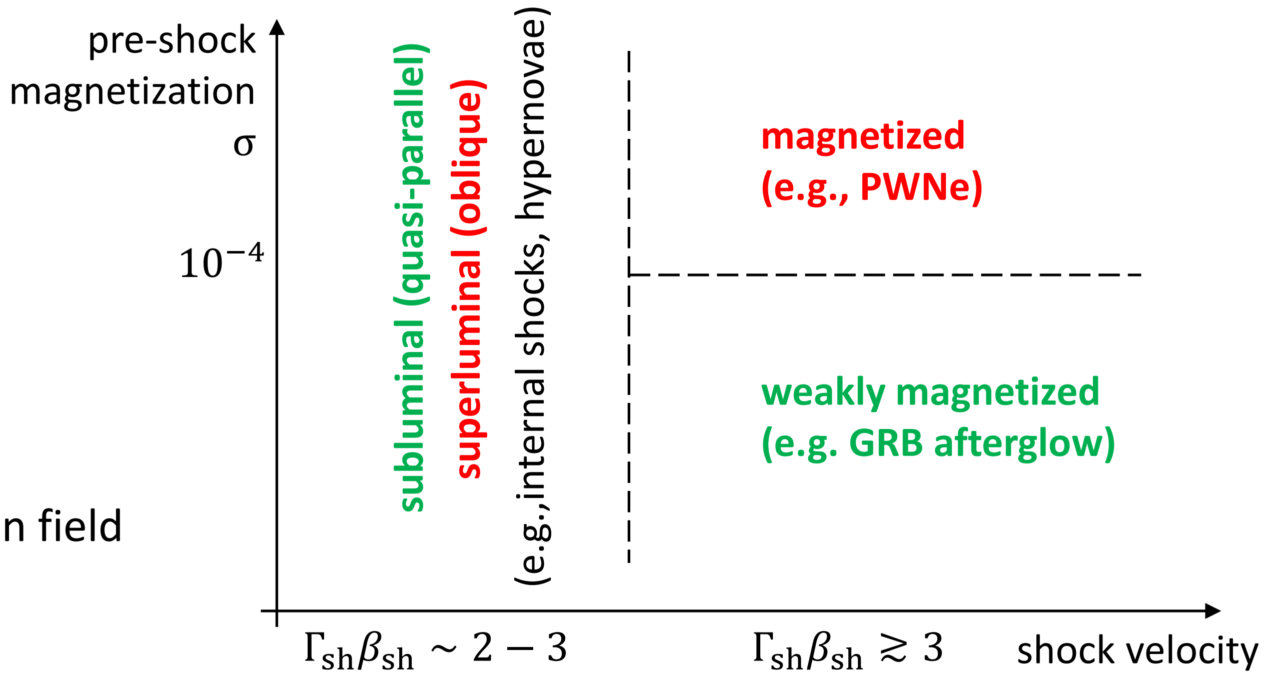
© van Marle+21: 3D MHD-PIC sim. of parallel shock

(Relativistic) shock acceleration -- overview

→ basic scheme:

… systematic acceleration through scattering on pre- and post-shock turbulence

… issue: in relativistic regime, post-shock plasma moves away from shock at $\sim c/3 \Rightarrow$ prevents acceleration unless scattering is strong



→ main parameters & features:

… key parameter: magnetization σ + obliquity of mean field i.e., moderate magnetization ⇒ no acceleration

… spectral index: $s \simeq 2. \rightarrow 2.3$

… acceleration rate: <Bohm at weak magnetization

→ applications and open questions:

… magnetized ultra-relativistic: termination shock of PWNe (do they accelerate particles?), magnetars outbursts

… weakly magnetized ultra-relativistic: GRB afterglow (ISM $\sigma \sim 10^{-8}$)

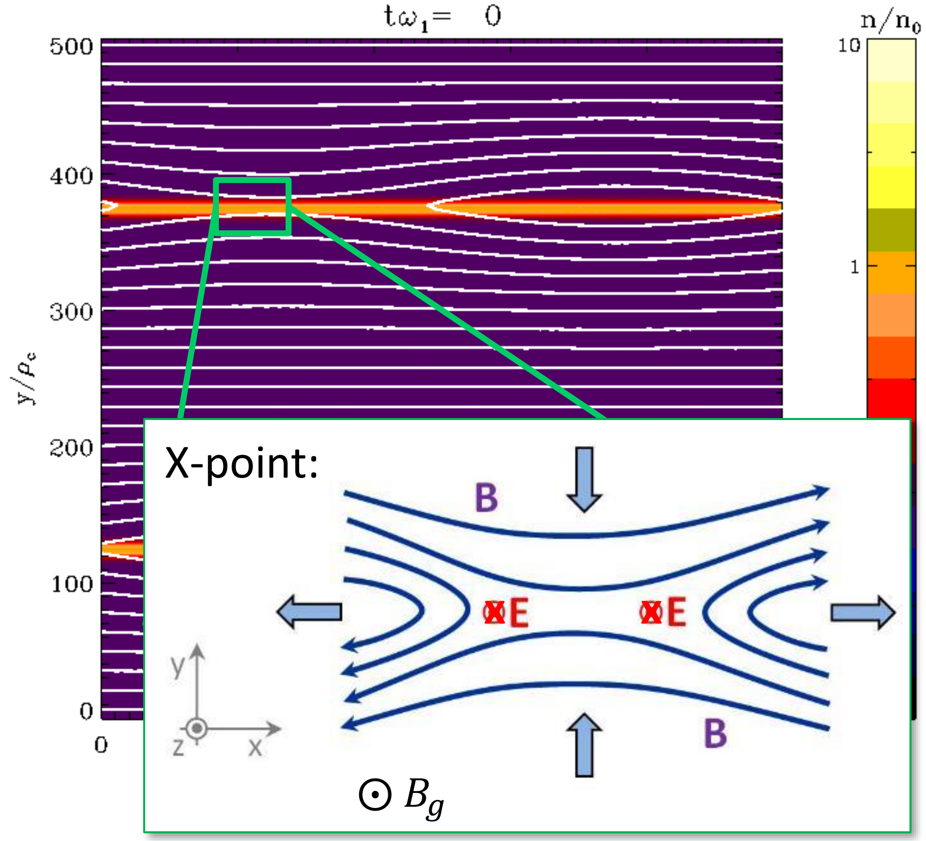
… mildly relativistic regime: can accelerate at high rate in quasi-parallel configuration (internal shocks in jets, shocks in micro-quasars, outflows from BH etc) …

… open question: long timescales, in particular for mildly relativistic, still poorly explored (+on long timescales)

(Relativistic) reconnection -- overview

→ basic scheme:

… reconnection of field lines of opposite polarity dissipates magnetic energy in diffusion region (X-point), generates plasma motion (in and out)
… different regions for acceleration: in diffusion region through non-ideal field, outside through Fermi processes in flows



© B. Cerruti

→ main parameters & features:

… key parameters: σ + guiding (non-annihilating) magnetic field B_g

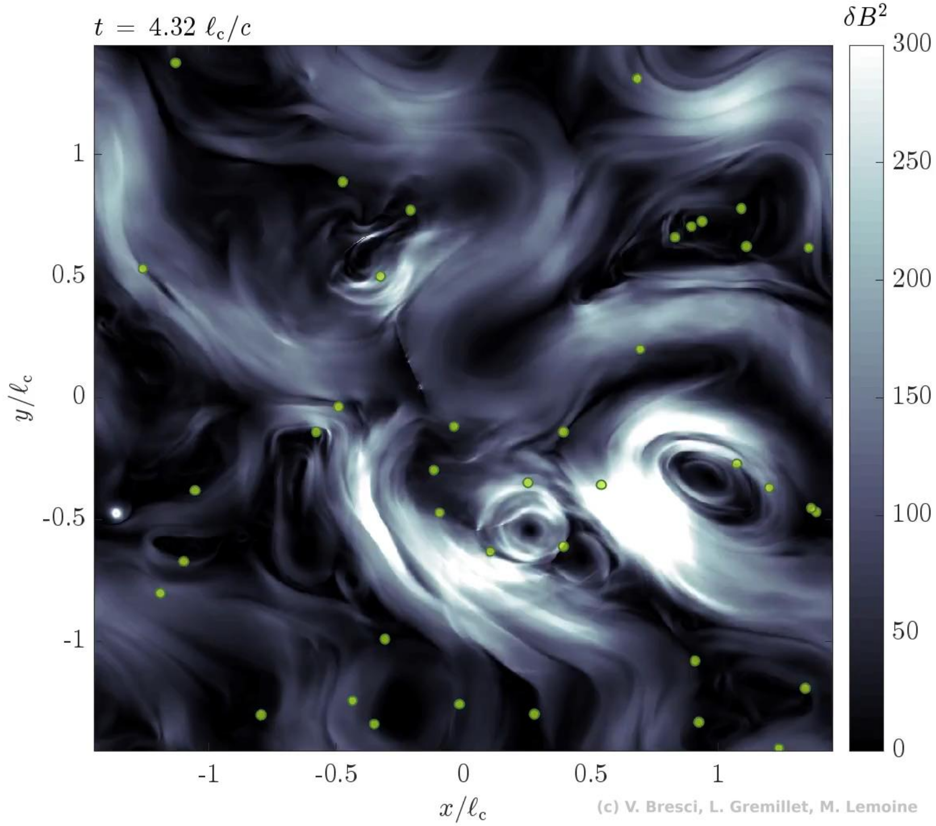
… spectral index: mean energy $\sim \sigma\, mc^2$, spectral slope $s \simeq 4 \;\rightarrow 2$ (harder with larger σ, lower B_g)
… acceleration rate: $\sim$Bohm up to mean energy, slower above

→ applications and open questions:

… $\sigma \gg 1$: in vicinity of compact objects (NS, BH), e.g. rapid flares with mean energy $\sim \sigma\, mc^2$

… open question: extrapolation of microscopic simulations to macroscopic (+3D) reconnection? Connection with turbulence?

(Relativistic) turbulence -- overview



→ basic scheme:

… particle acceleration through interaction with random electric fields

→ main parameters & features:

… key parameters: σ + guiding (non-turbulent) magnetic field B_g + duration of turbulence excitation

… spectral index: mean energy $\sim \sigma\, mc^2$, spectral slope $s \simeq 4\ \rightarrow 2$ (harder with larger σ, lower B_g)

… acceleration rate: independent of energy

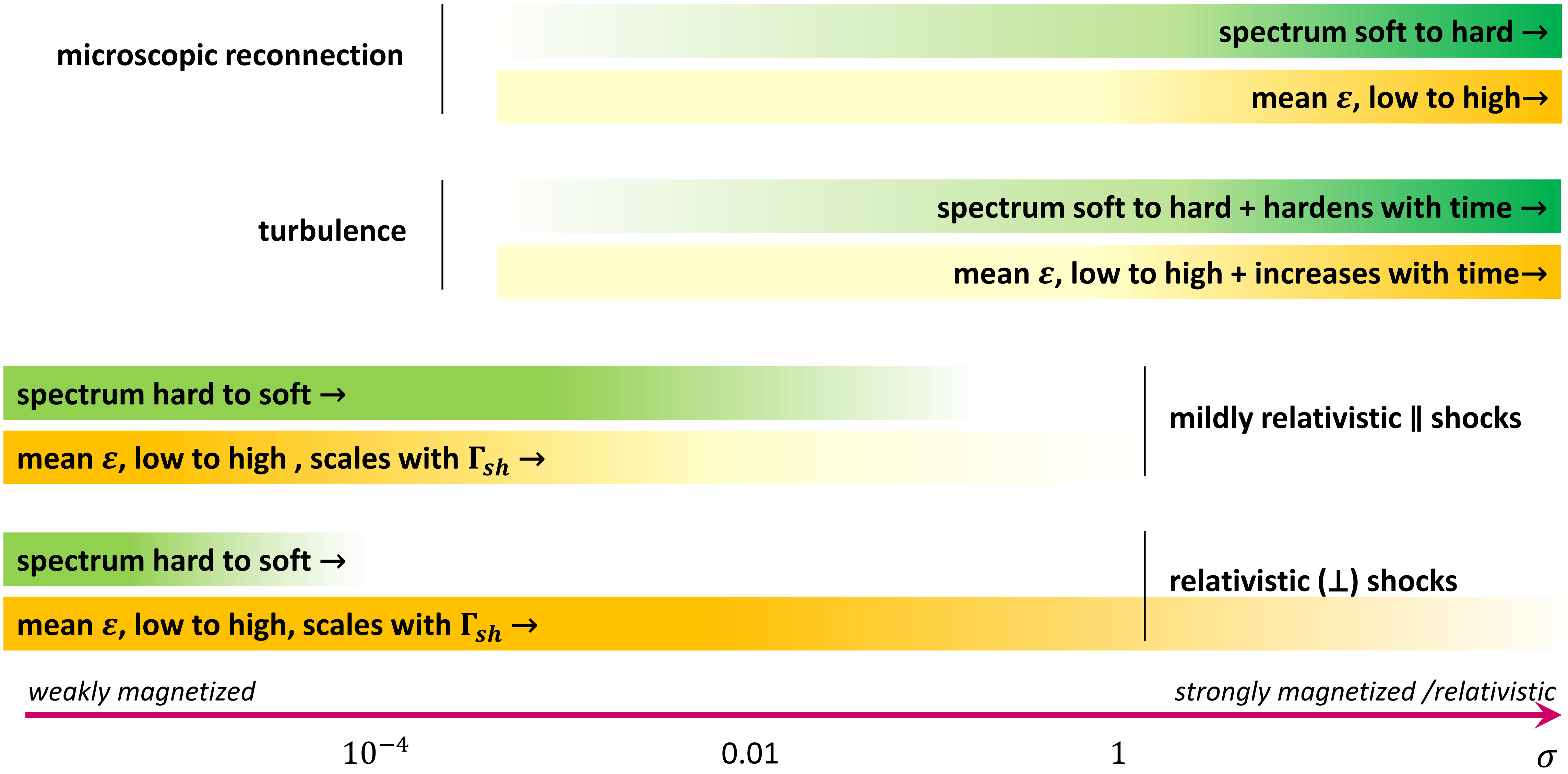
→ applications and open questions:

… turbulence generic in astrophysical plasmas: a universal acceleration mechanism

… e.g., acceleration in relativistic jets, BH accretion disks, coronae, PWNe

… open questions: so far, simulations at $\sigma > 0.01$ and $\delta B/B_g \sim 1$… other regimes? At large scale separation $r_{\rm gyroradius}(\varepsilon)\ /\ \ell_{\rm coherence}$? Injection fraction? Origin of electric field?

Landscape of acceleration scenarios vs magnetization…



magnetization: σ = magnetic energy dens. / plasma energy dens.

e.g, in the interstellar medium, $\sigma \sim 10^{-9}$… but in VHE sources, $\sigma \gtrsim 0.01$

Conclusions

→ overall:

… important progress in last 1-2 decades in relativistic regime on theoretical + numerical (PIC) side

→ a sharper view on the parameter space

→ a new bottom-up (first principles) approach to the origin of non-thermal radiation in HE sources

… many open questions remain…

… French community active on all topics

→ current questions and perspectives:

… key question: how to bridge the gap in scales between microscopic (plasma scales, PIC) and macroscopic (source)?

→ ongoing development of GPU-PIC: will increase dimensionality, dynamic range, but cannot solve above issue

… what happens when parameter space of microscopic physics is (mostly) uncovered?

→ increasing need to connect recipes of acceleration with dynamical, realistic model of the source

→ MHD-PIC (or variants) most promising technique

→ recommendations:

→ develop (GR)(R)MHD-PIC techniques in French community: hire & train

→ connect expertise in particle acceleration with expertise in source modeling (e.g., ATPEM topical workshops?)