MACROS 2013 - Paris

Hybrid simulations of ion acceleration at non-relativistic shocks

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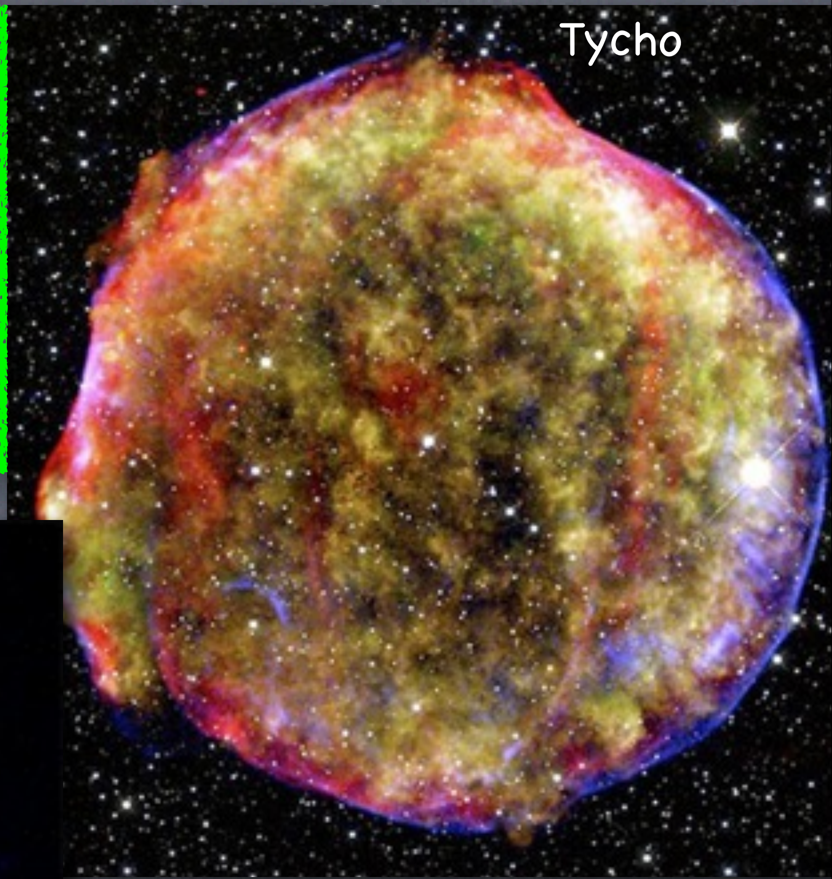
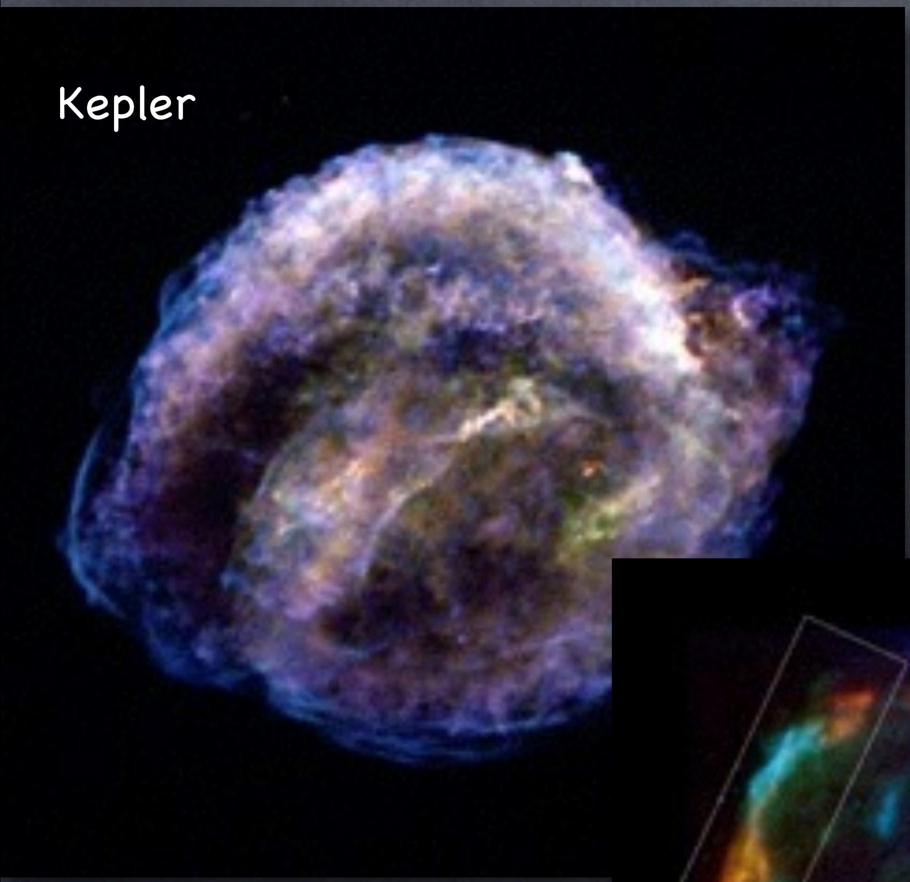
Princeton University

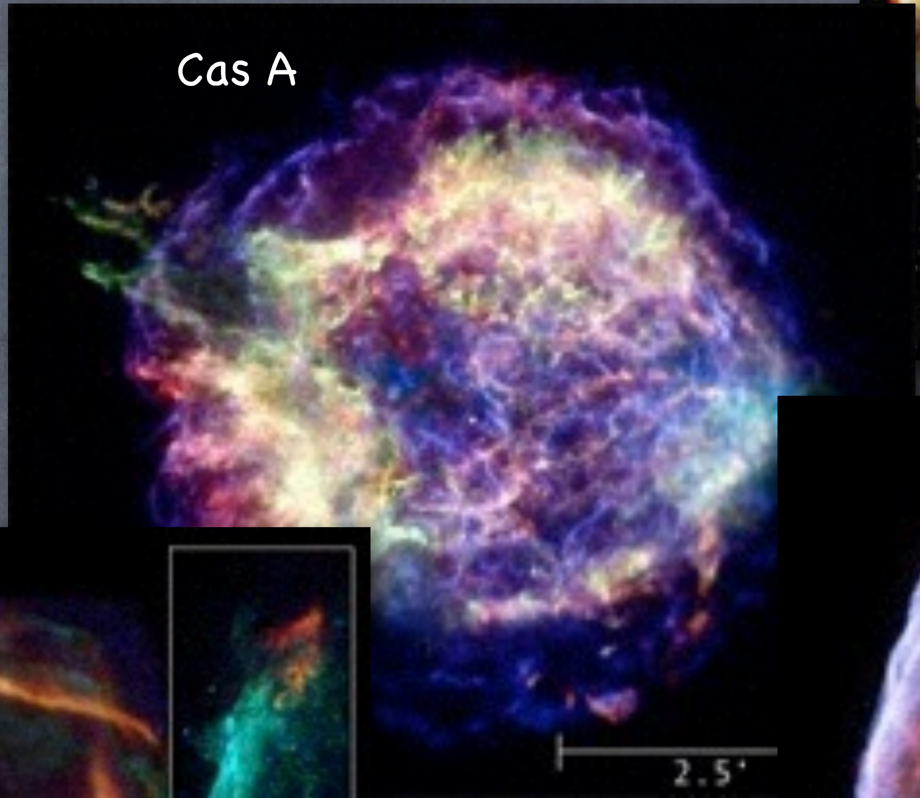
In collaboration with: Anatoly Spitkovsky (Princeton)

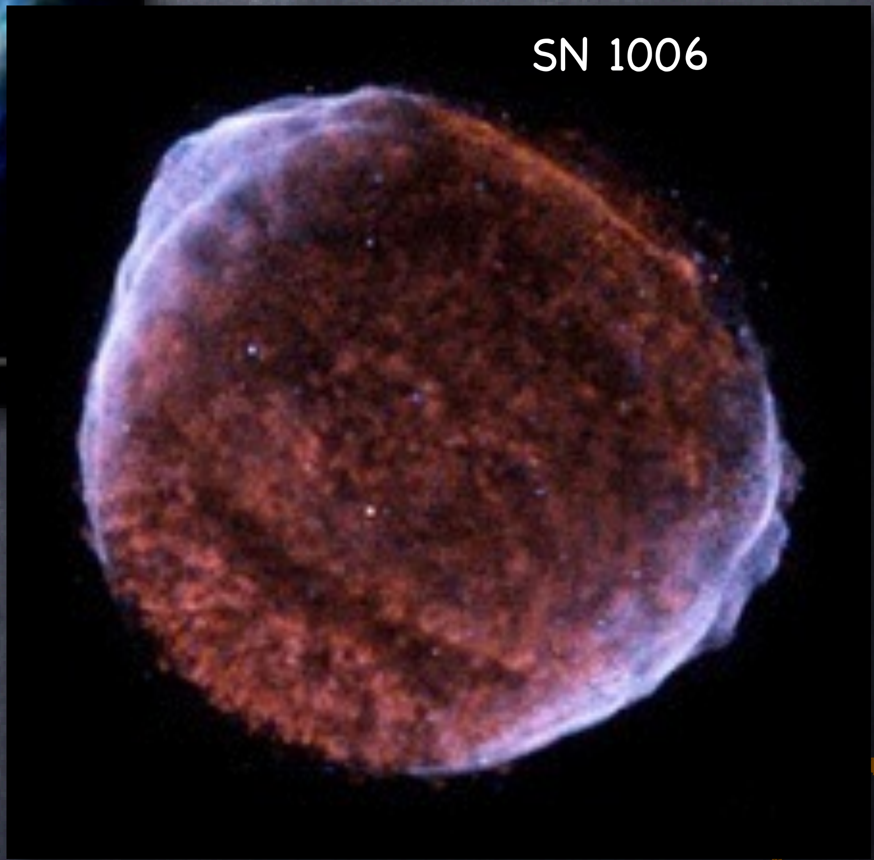
The SNR paradigm for Galactic CRs

- Energetics (10-20% efficiency)
- Mechanism producing power-laws
- Acceleration up to the knee (E=3Z PeV)









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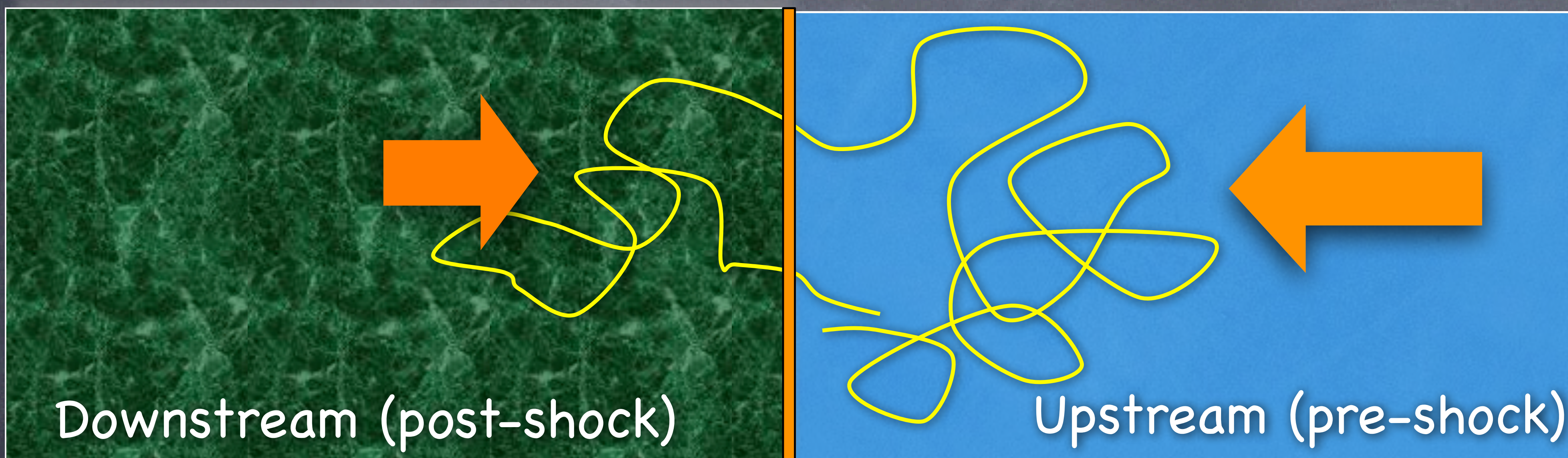

Test-particle squeezed between converging flows

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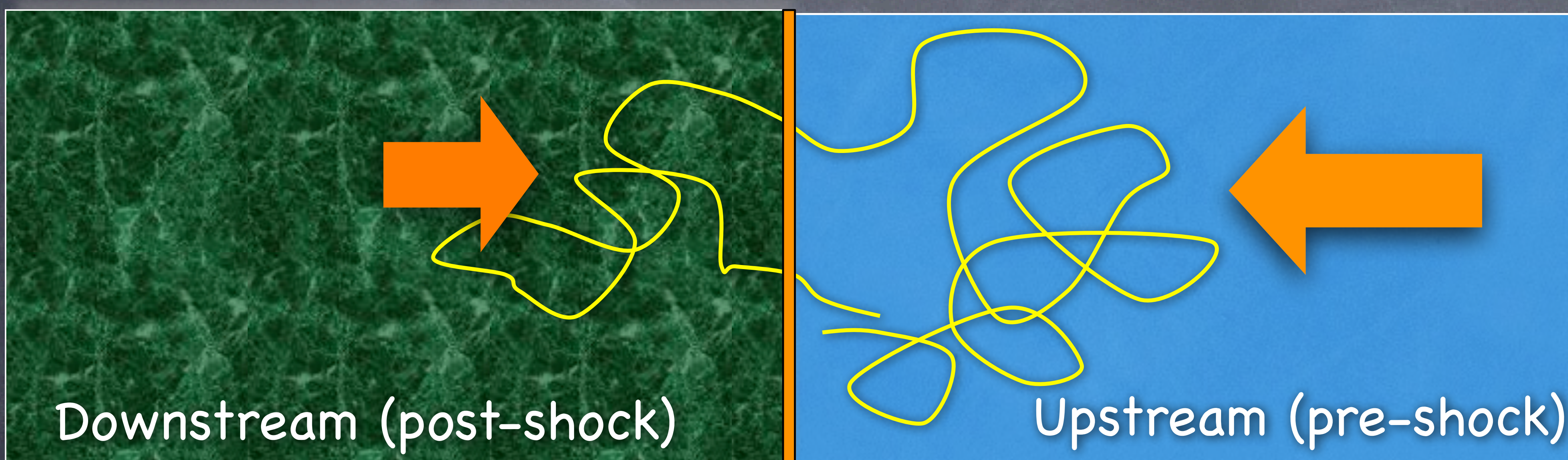
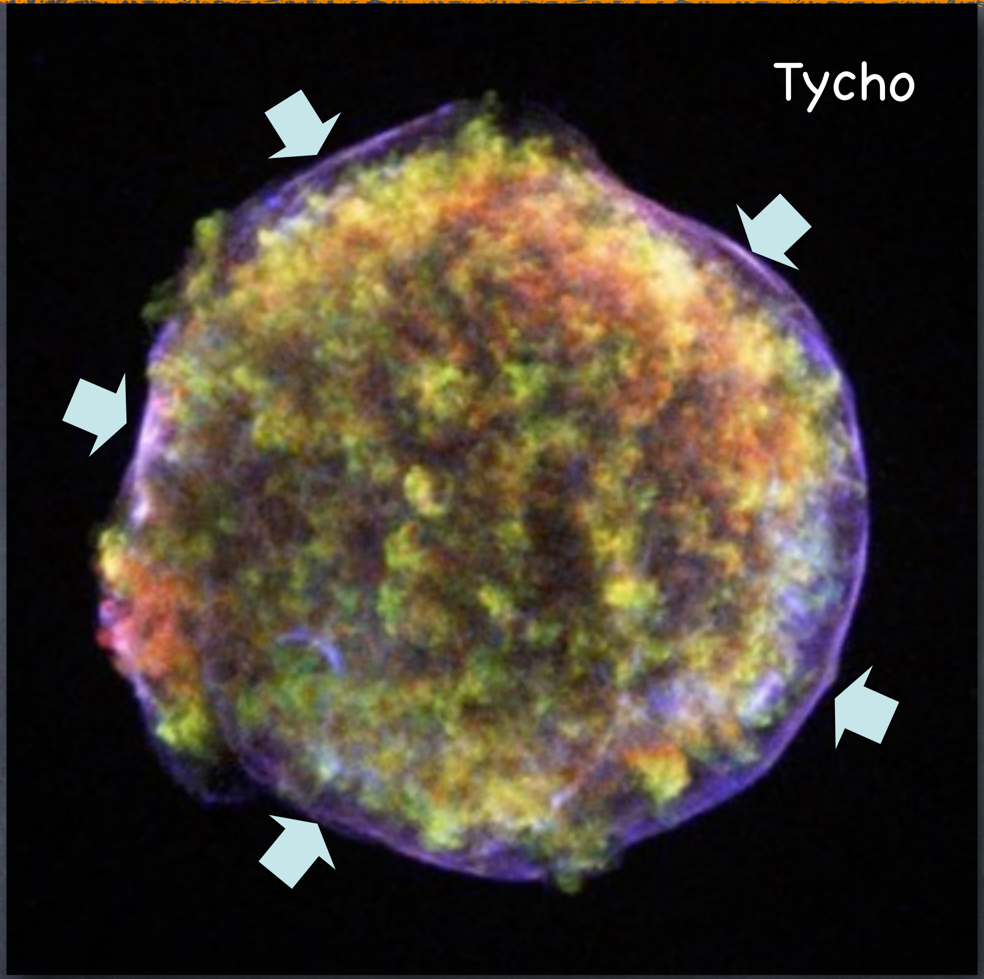


Test-particle squeezed between converging flows

- DSA produces power-law $p^{-\alpha}$ in momentum, depending on the compression ratio $R=u_1/u_2$ only. For strong shocks: $\alpha=4$ (i.e., $\propto E^{-2}$)

Evidence of magnetic field amplification



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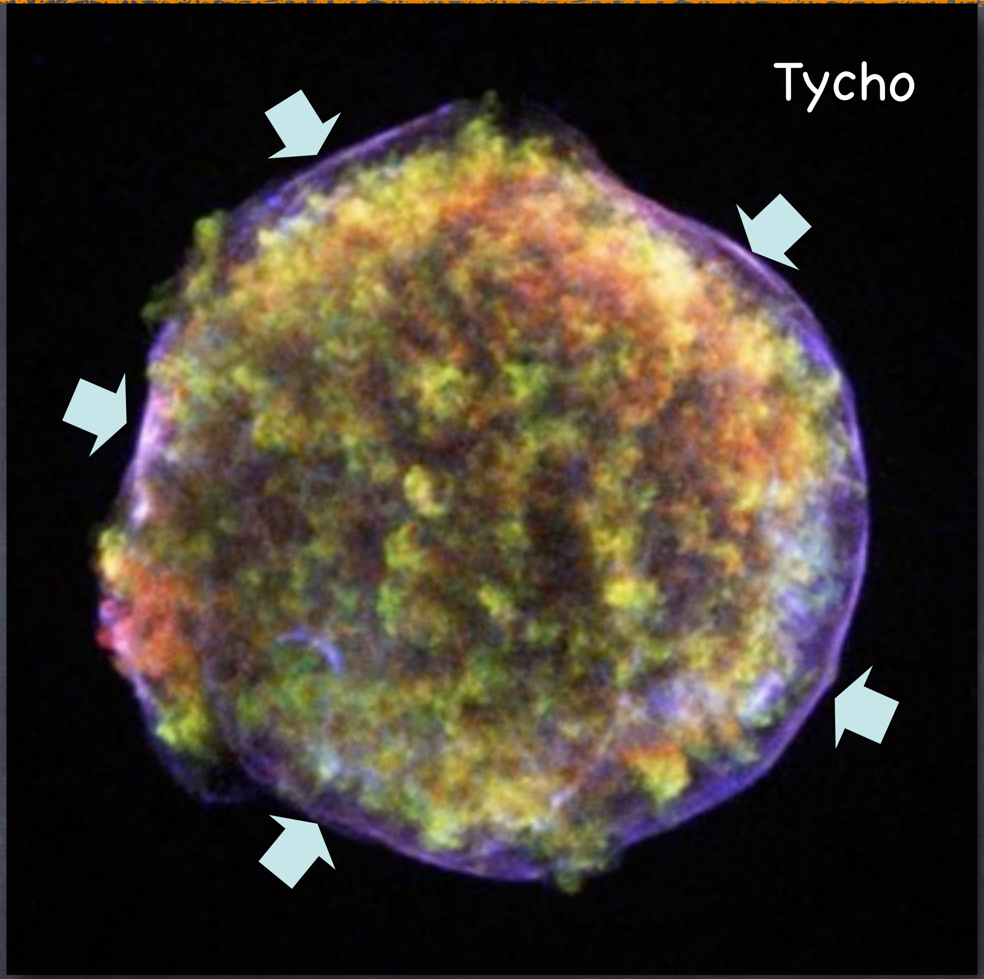

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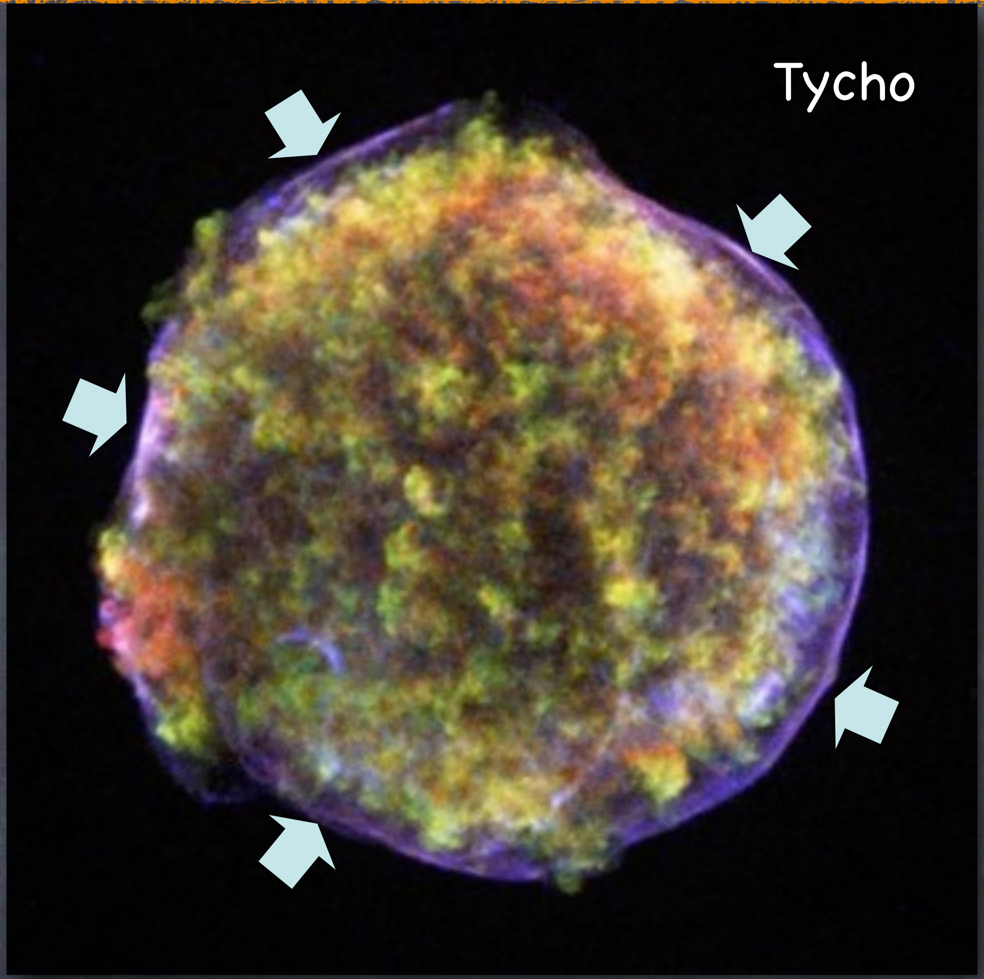

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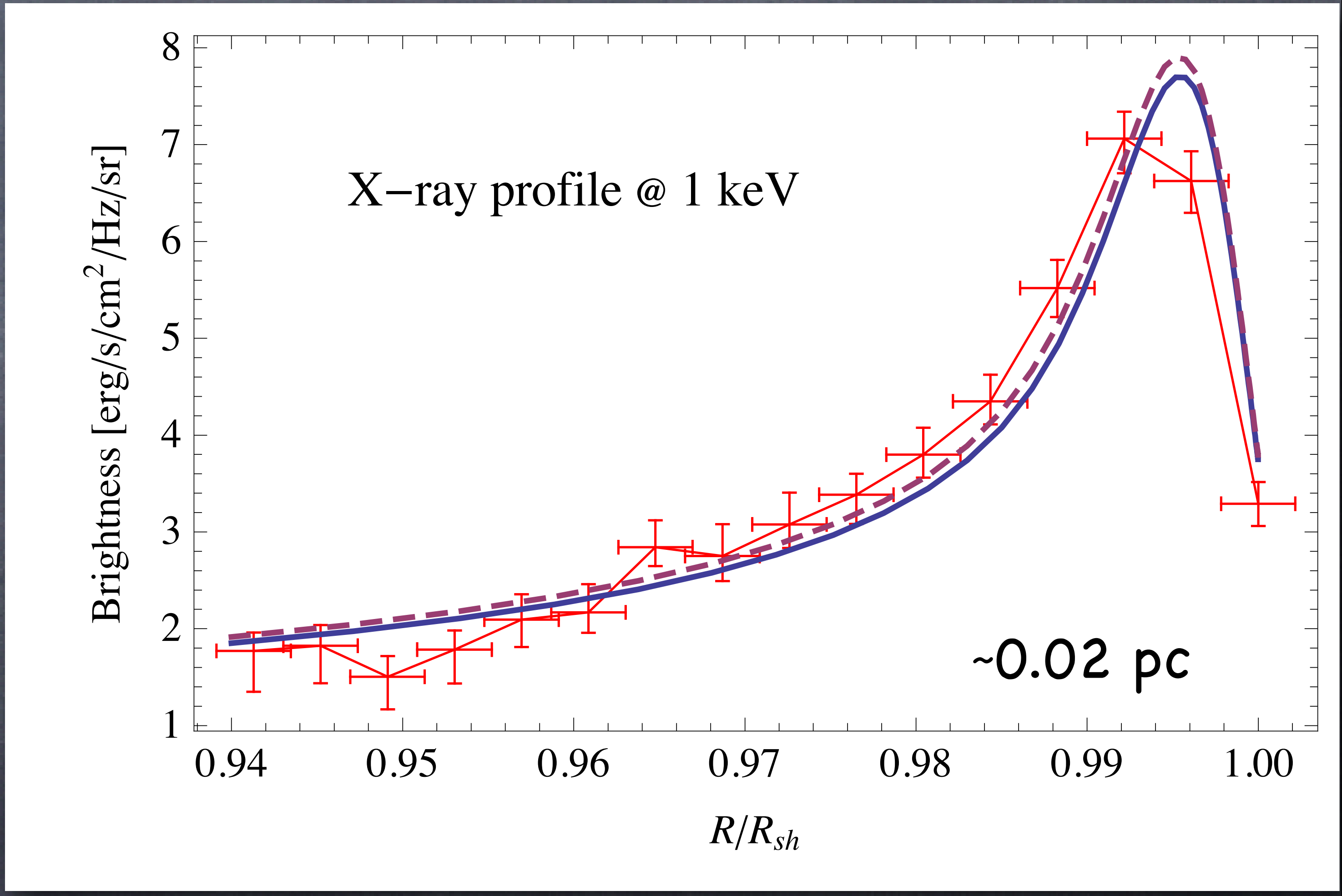

Morlino & Caprioli, 2012

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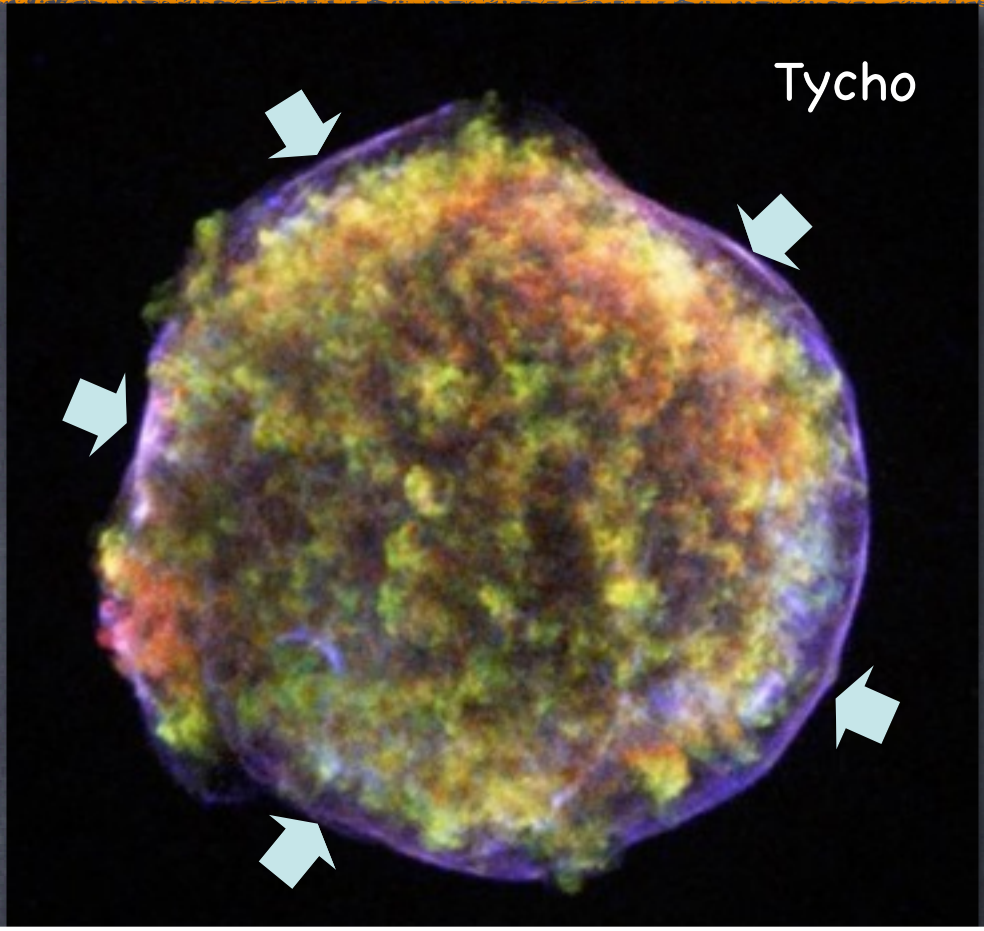

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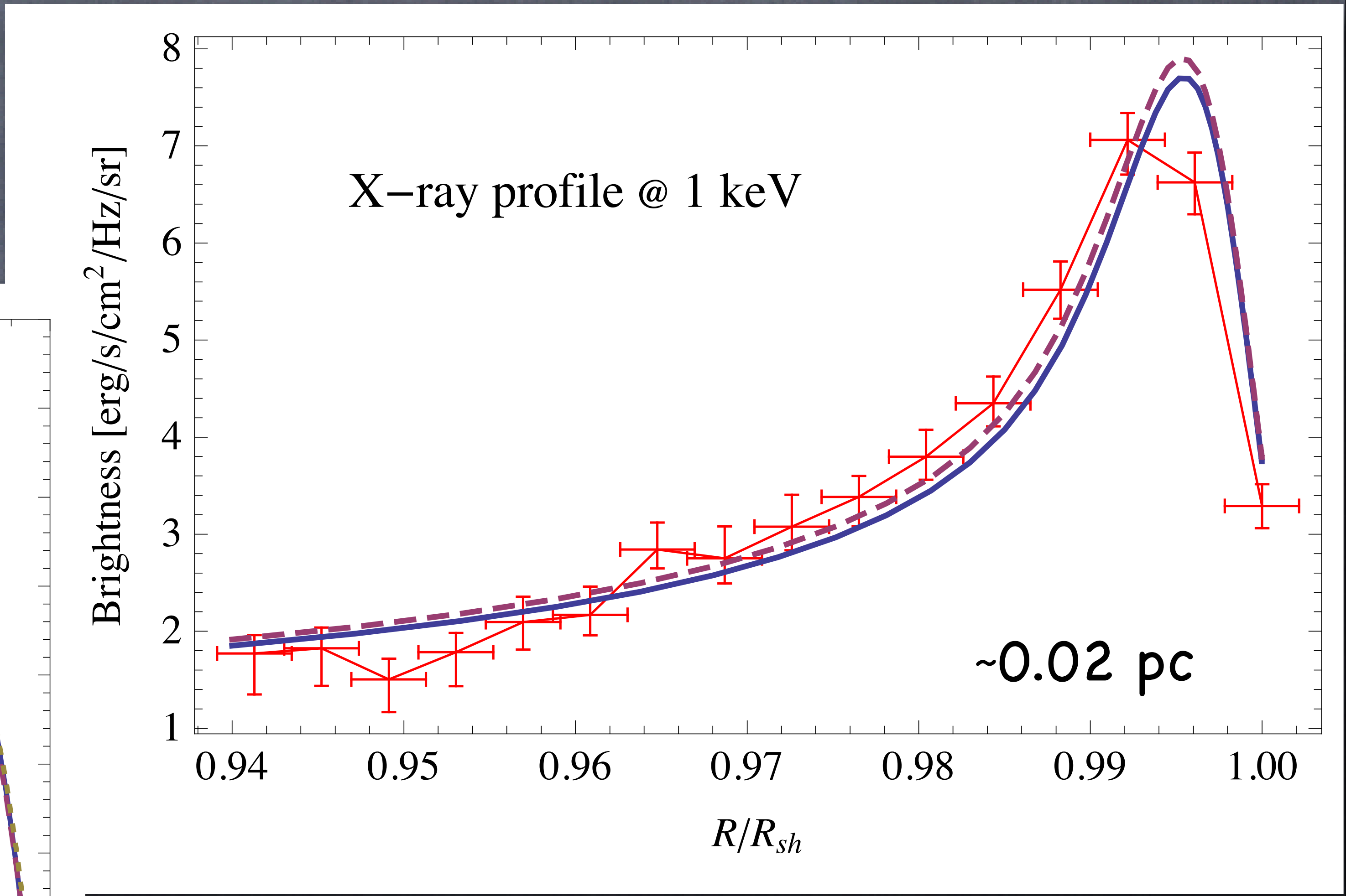

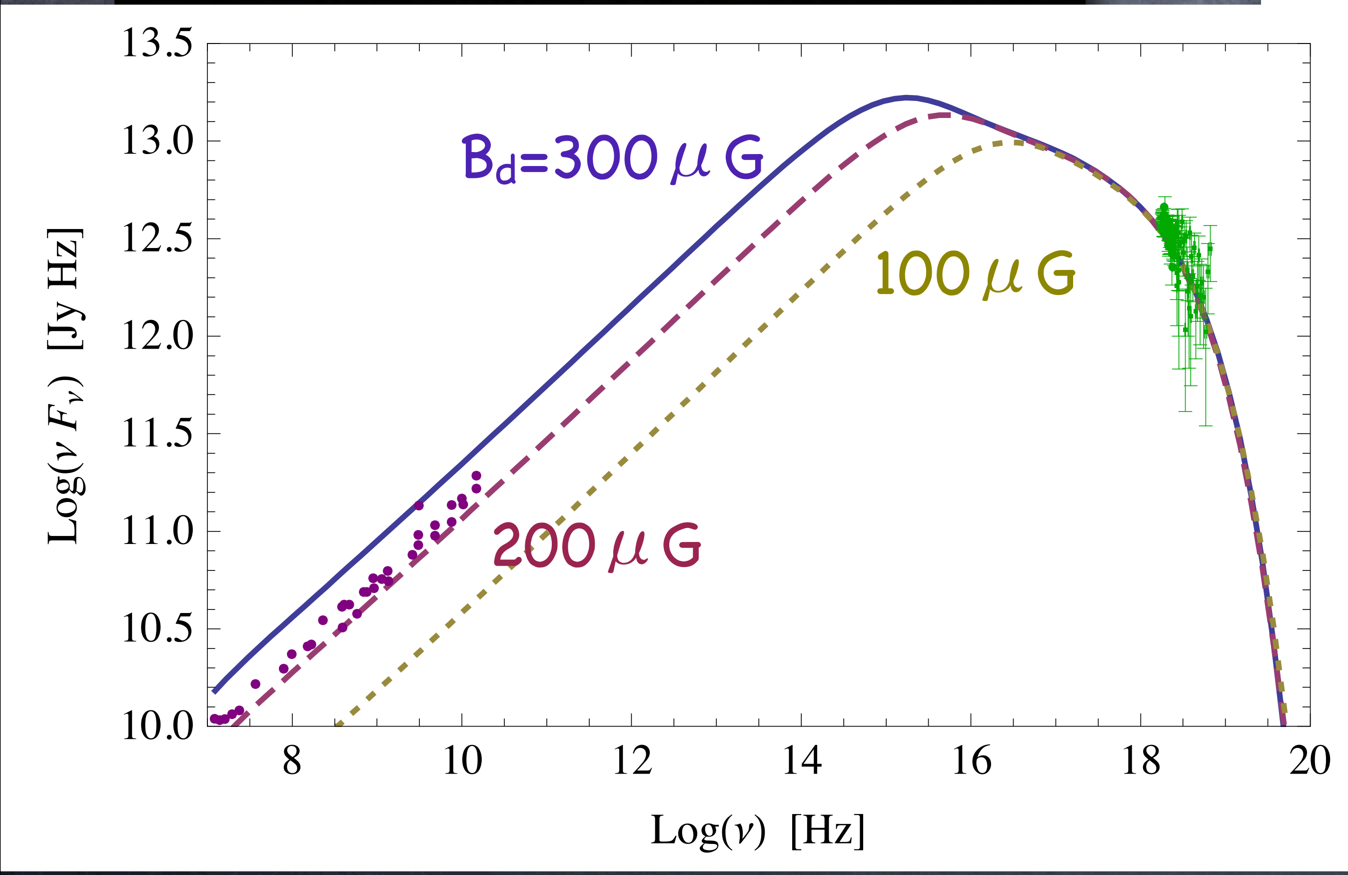

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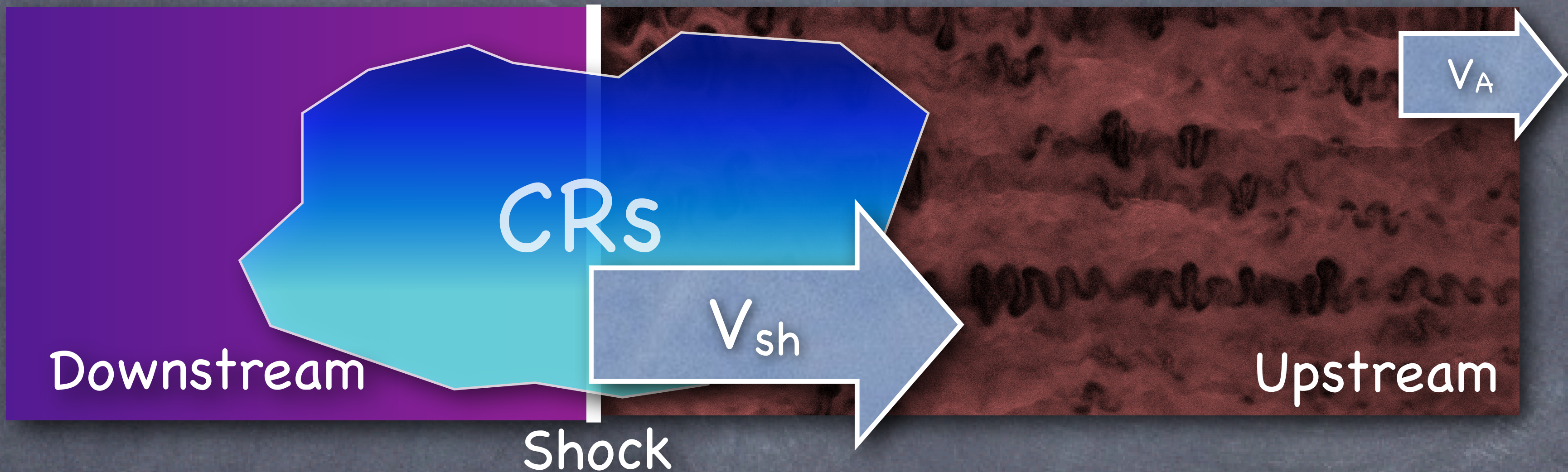

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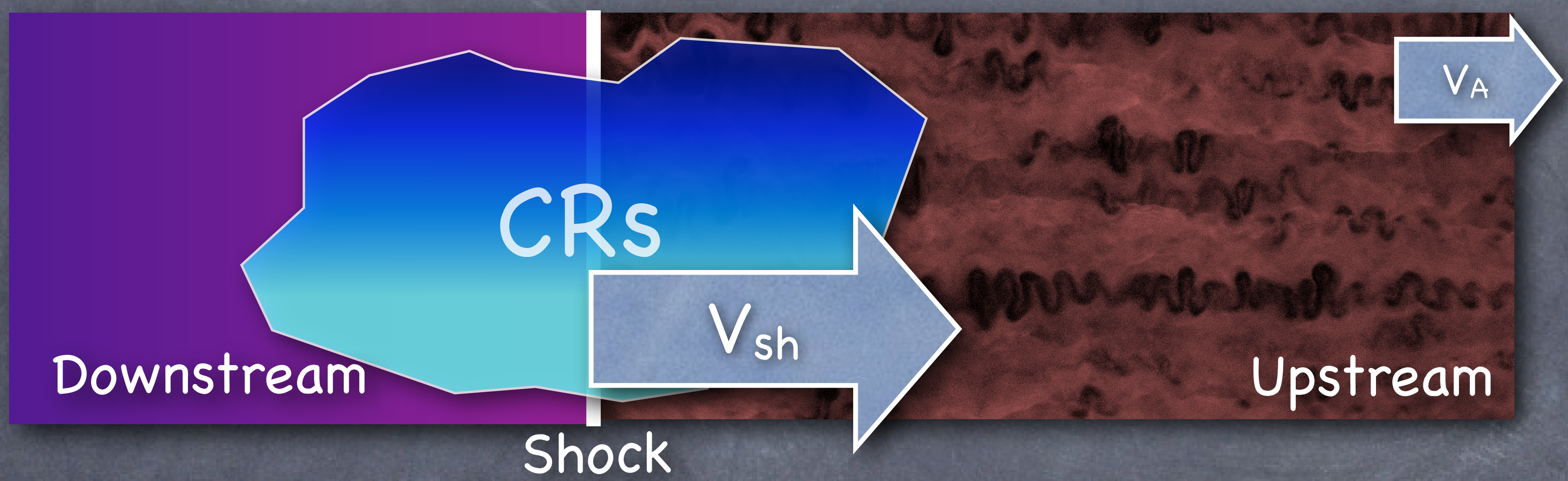

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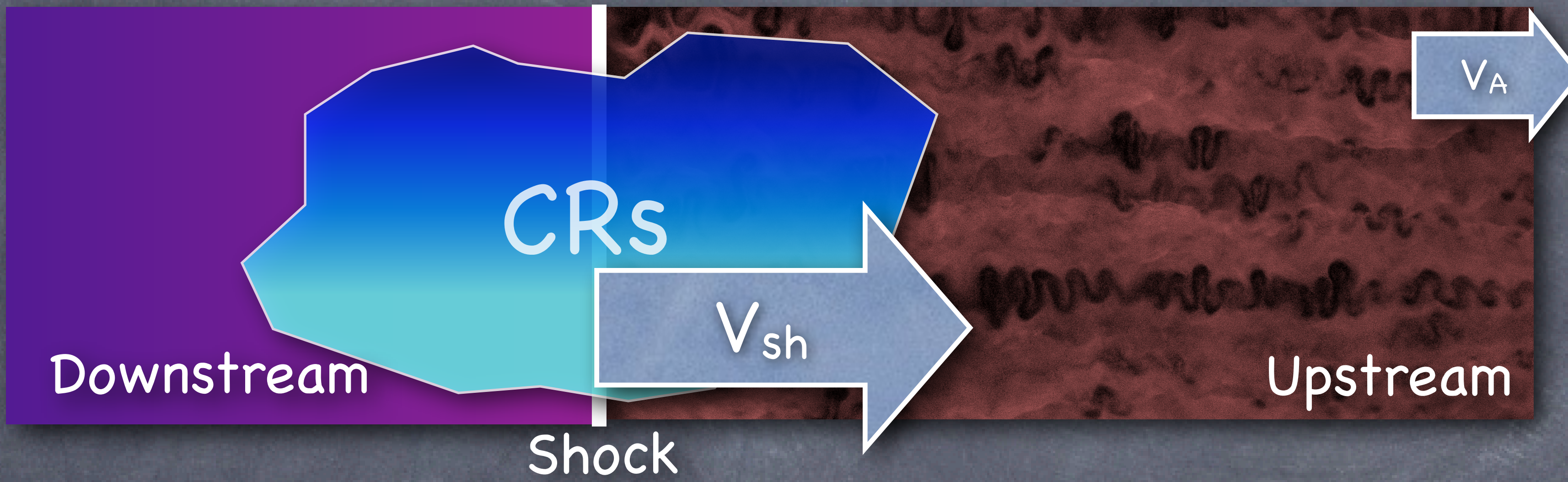

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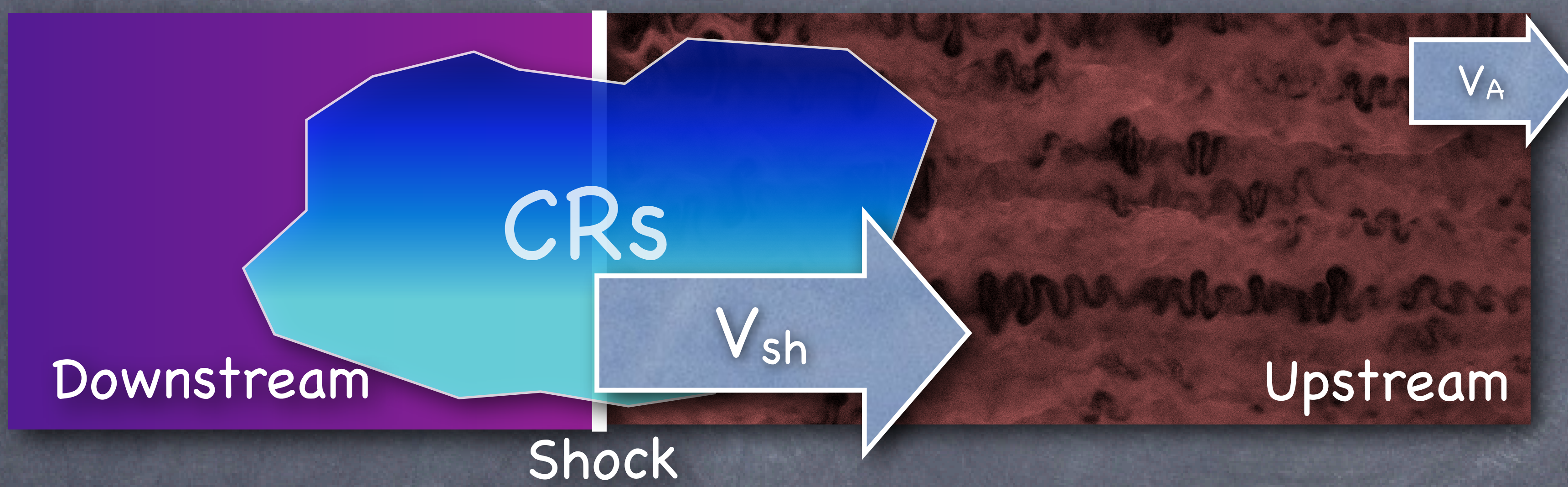

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  - With self-generated diffusion in δ B, $E_{max} \sim 5 \times 10^6$ GeV (Blasi et al. 2007)

Conclusions?

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- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- How do CRs scatter on the self-generated B?
- When is acceleration efficient?

Collisionless shocks

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- Mediated by collective electromagnetic interactions
- Sources of non-thermal particles and emission

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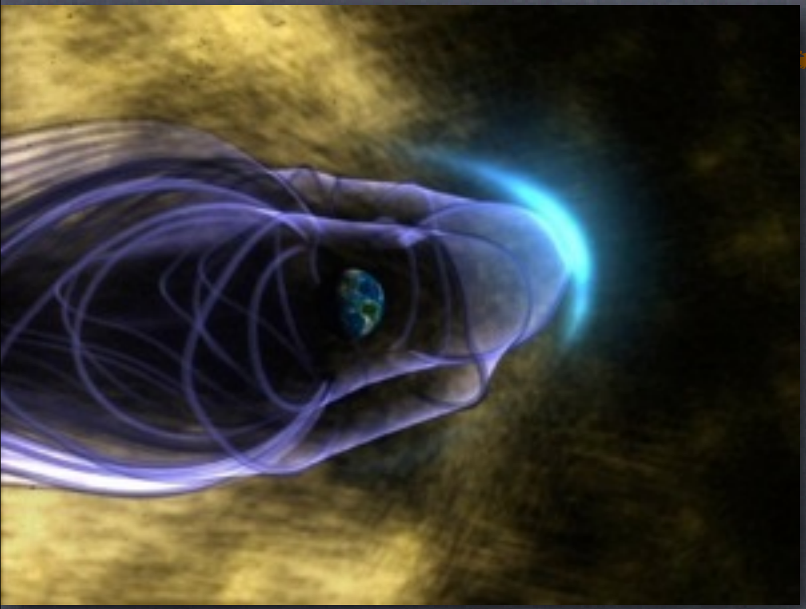

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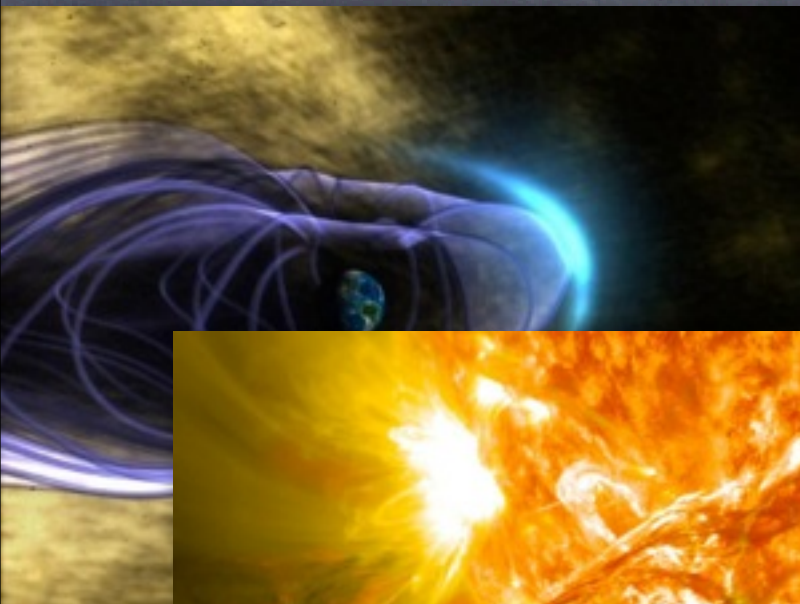

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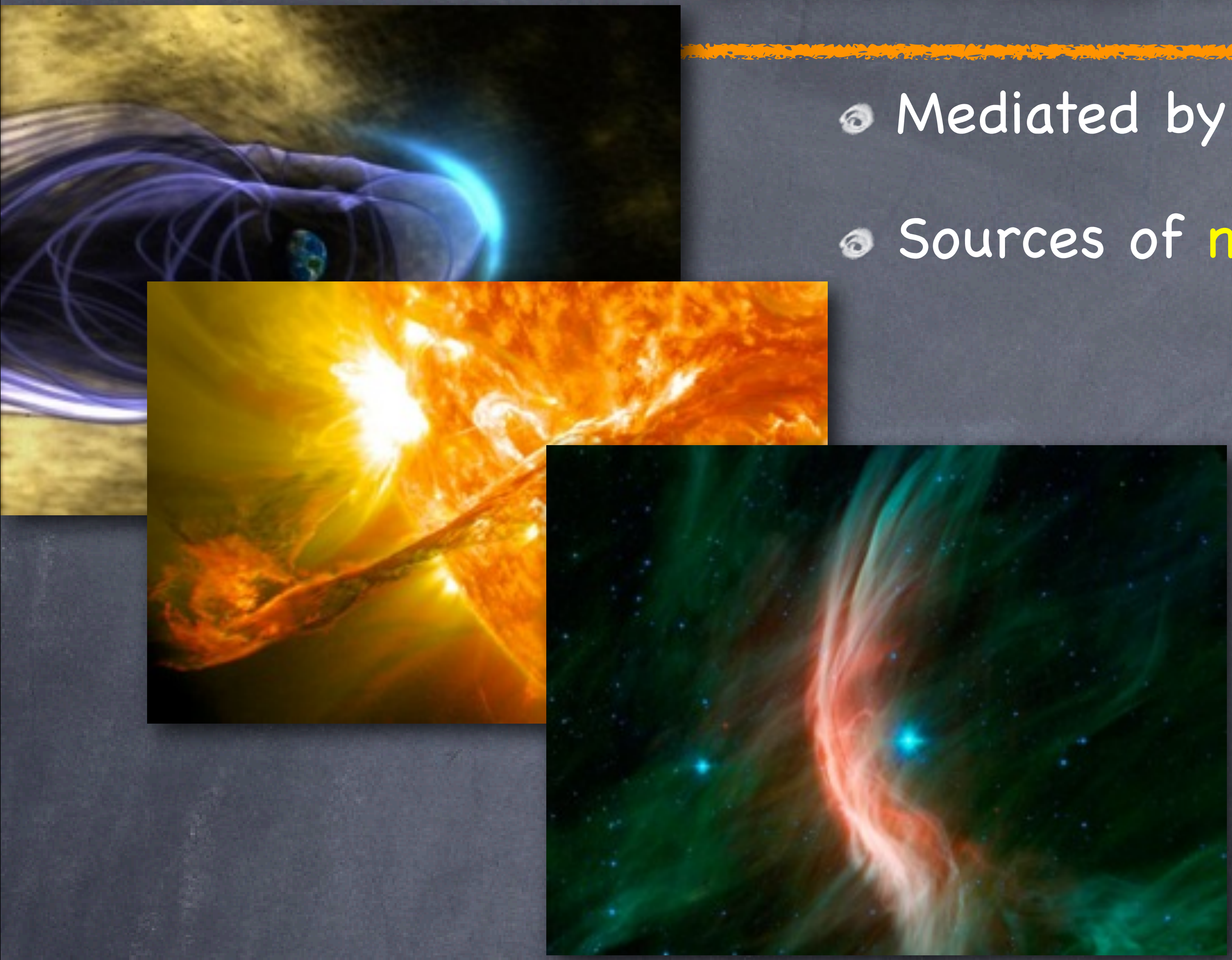

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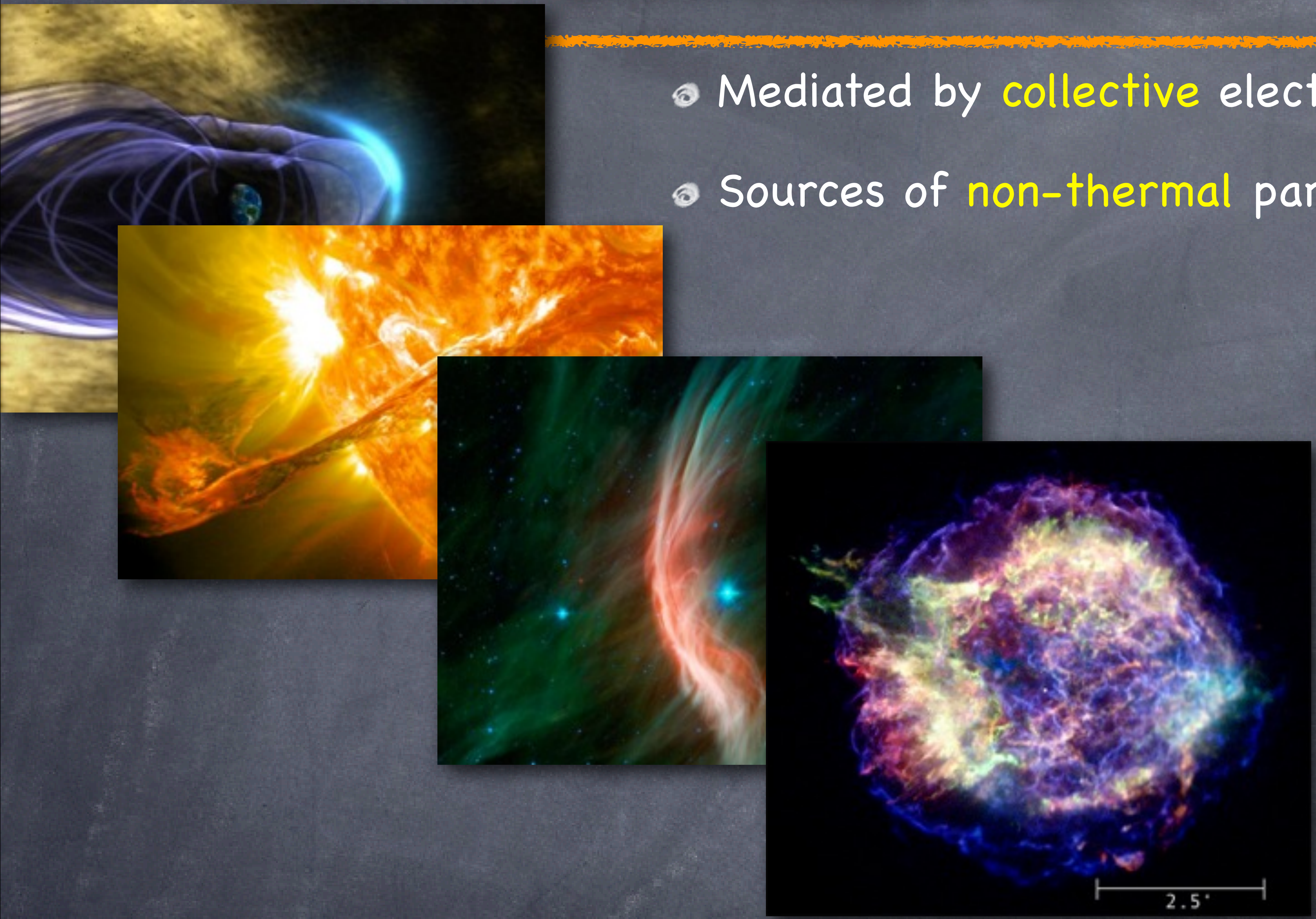

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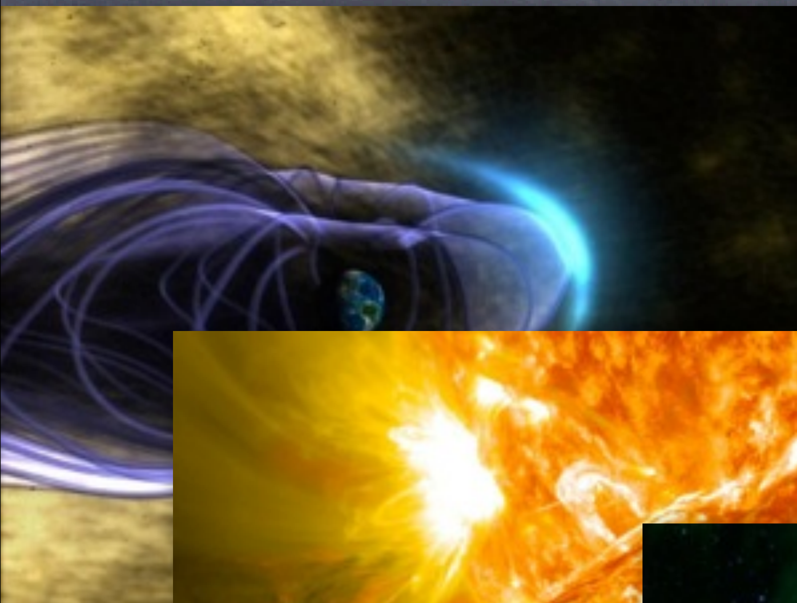
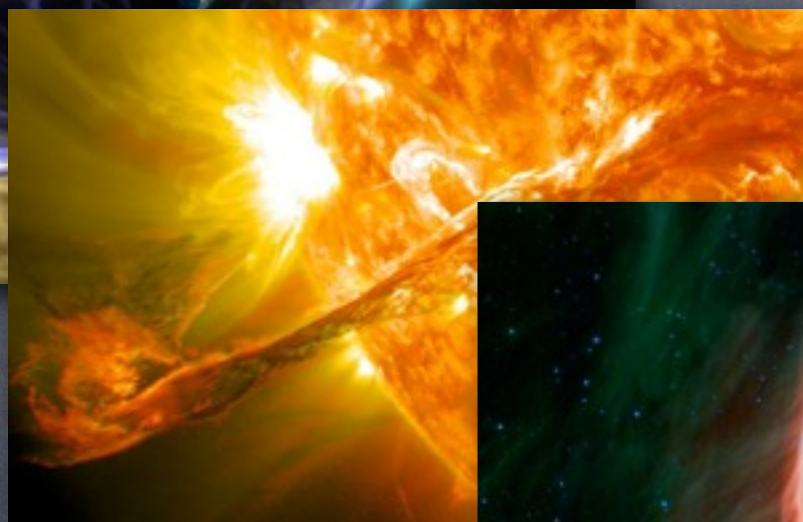
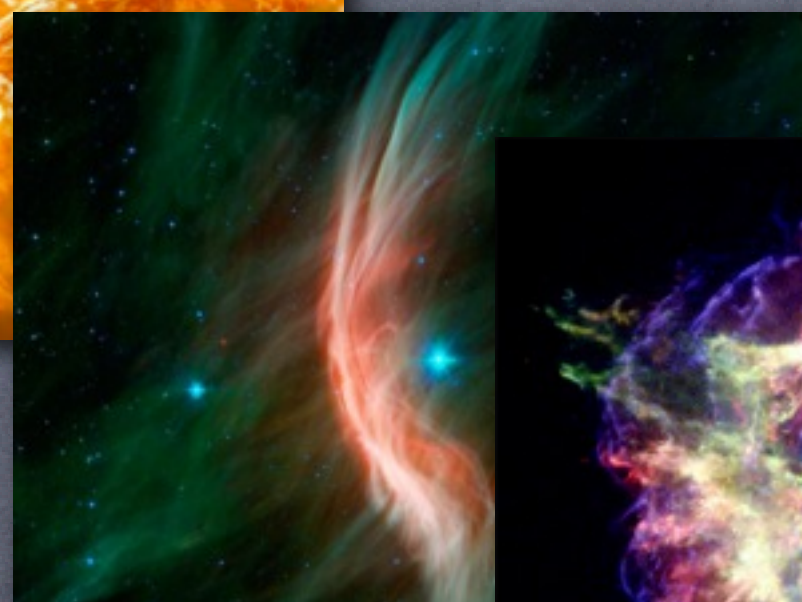
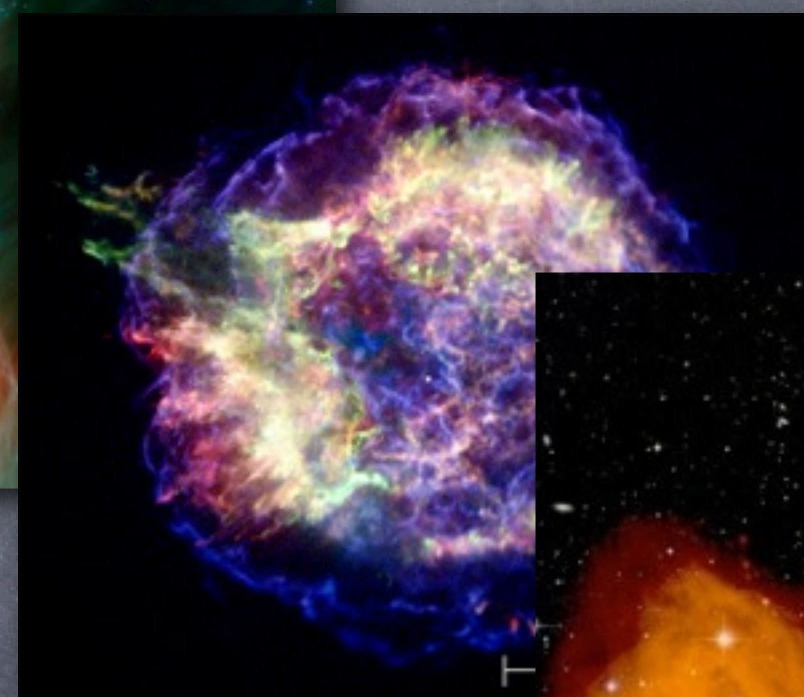
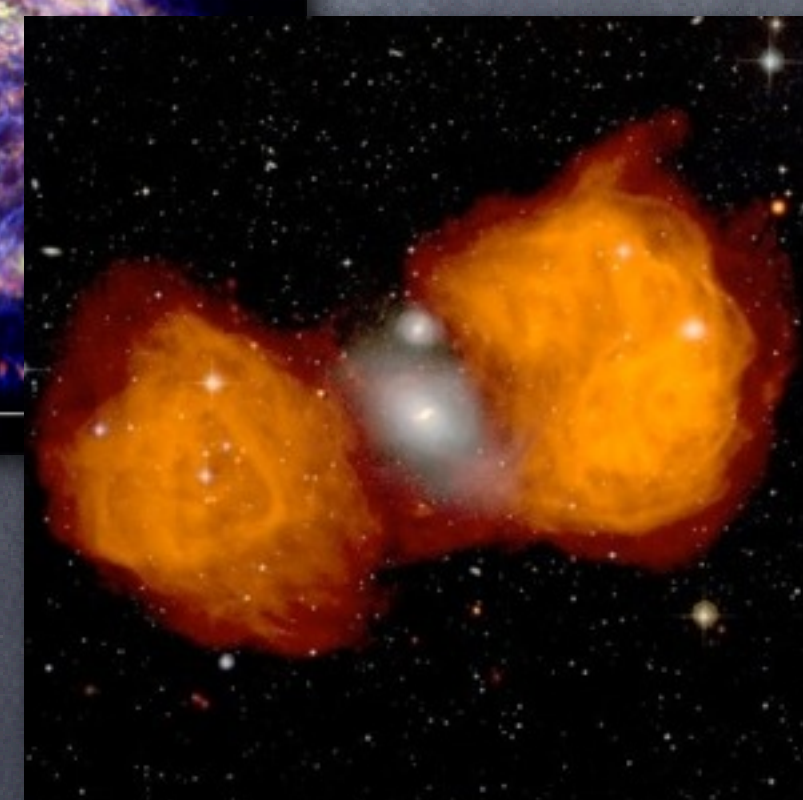

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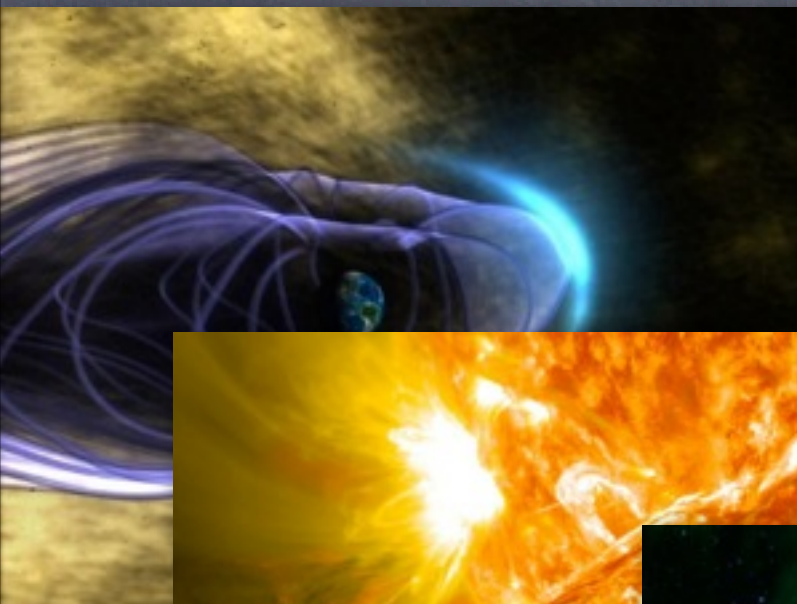

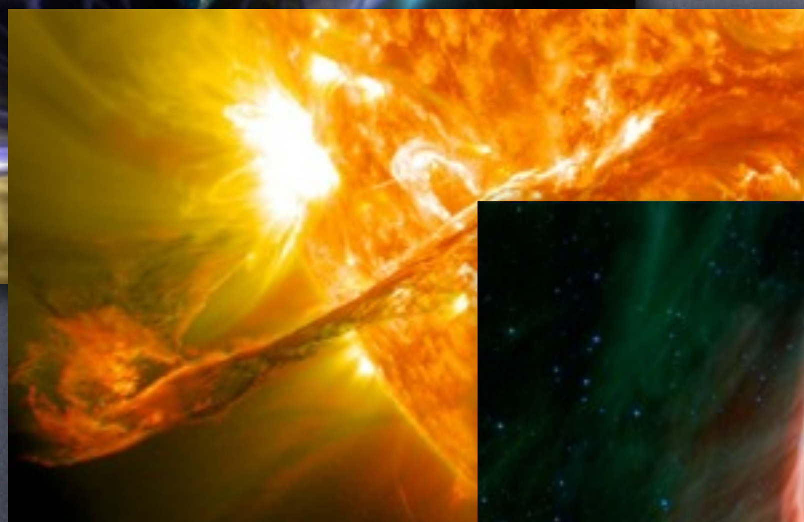

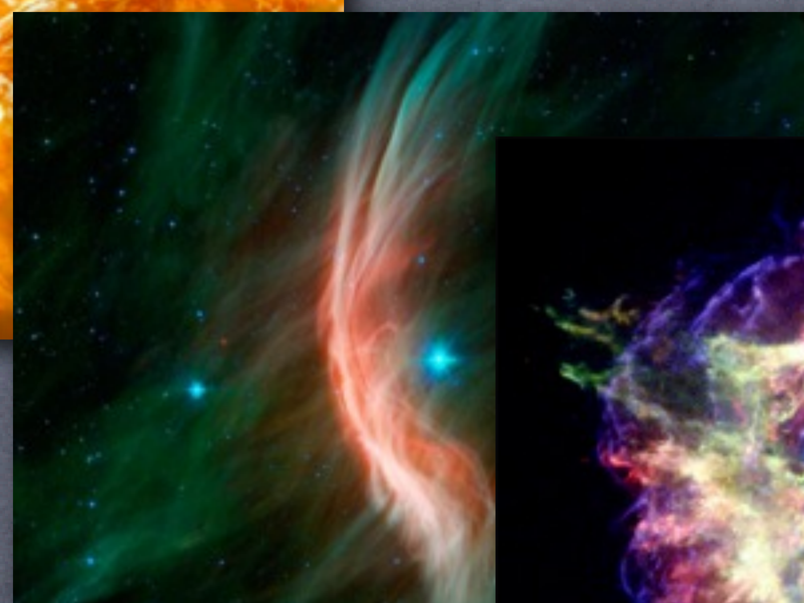

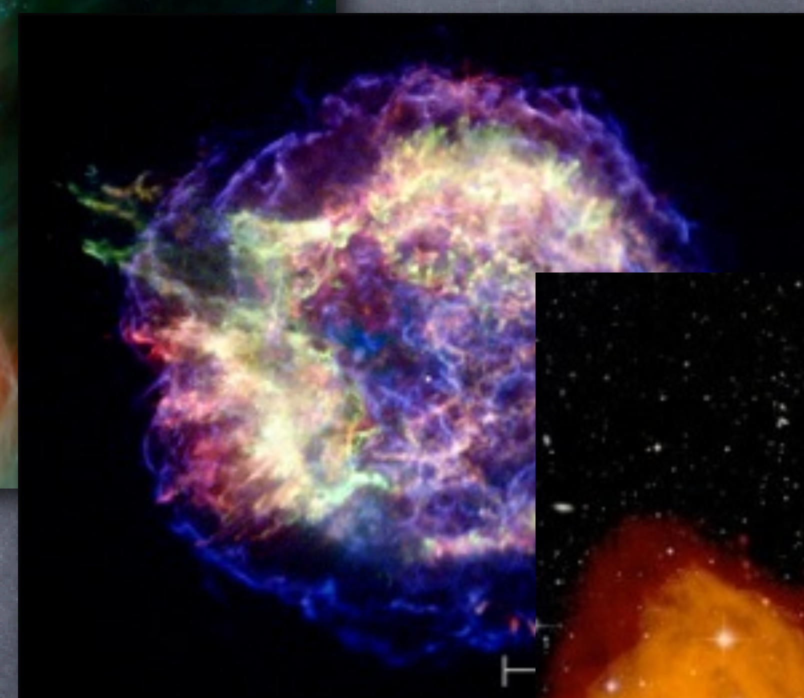

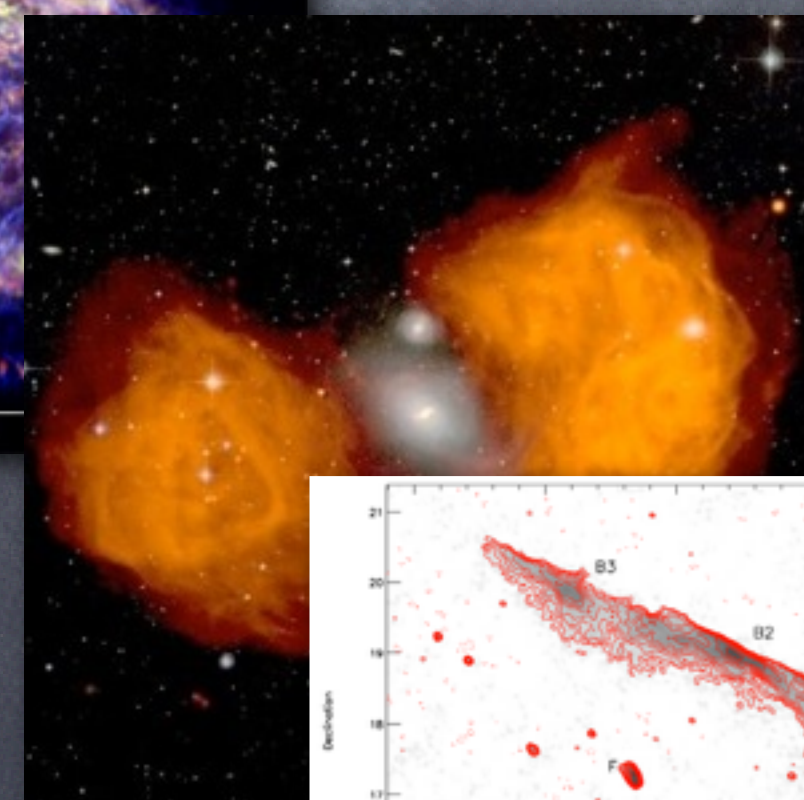

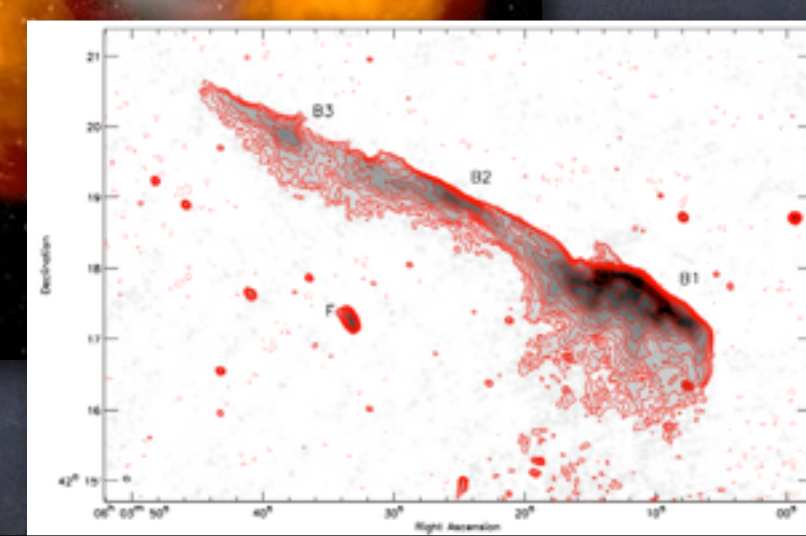

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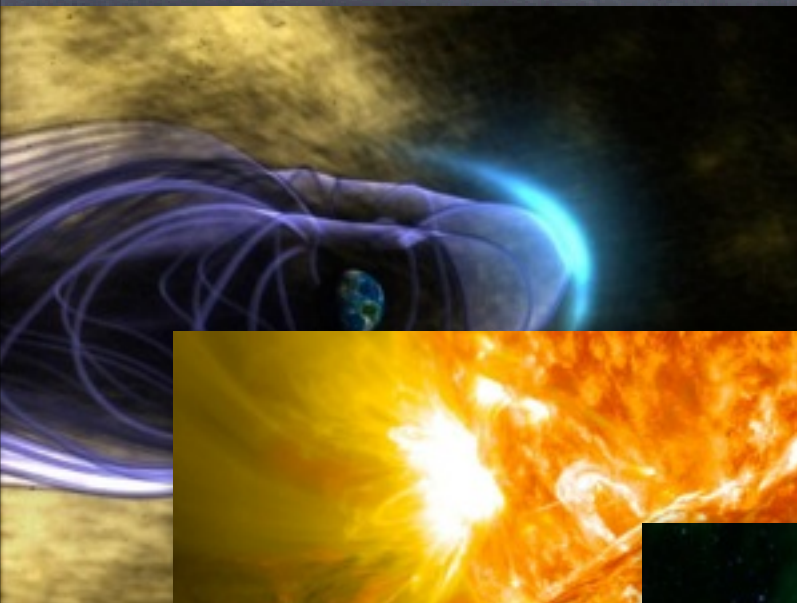

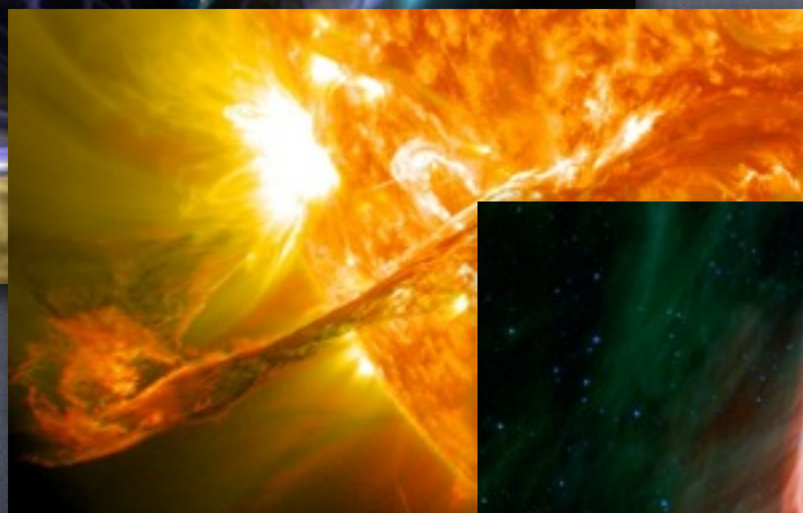

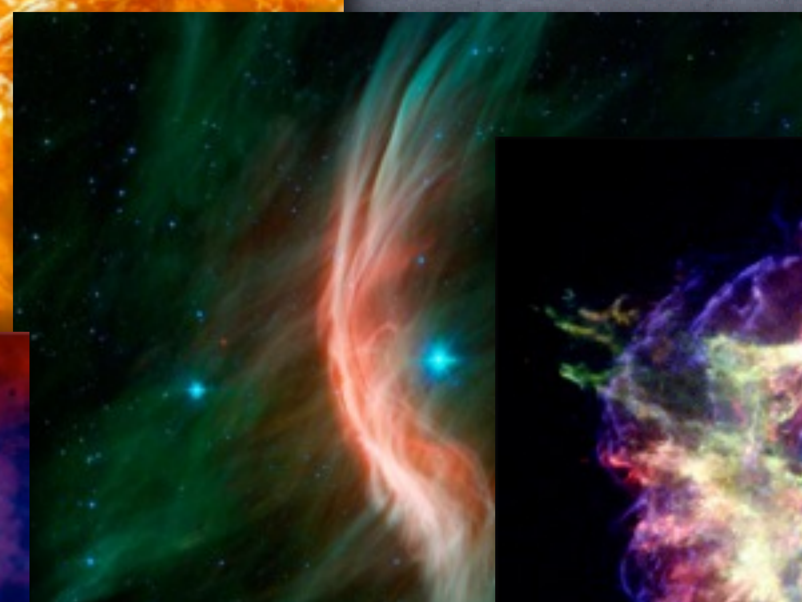

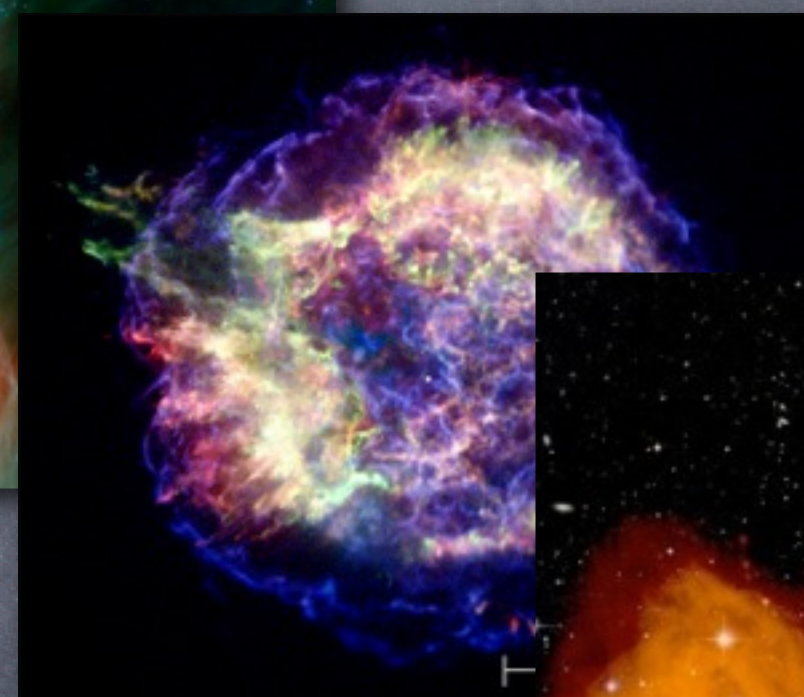

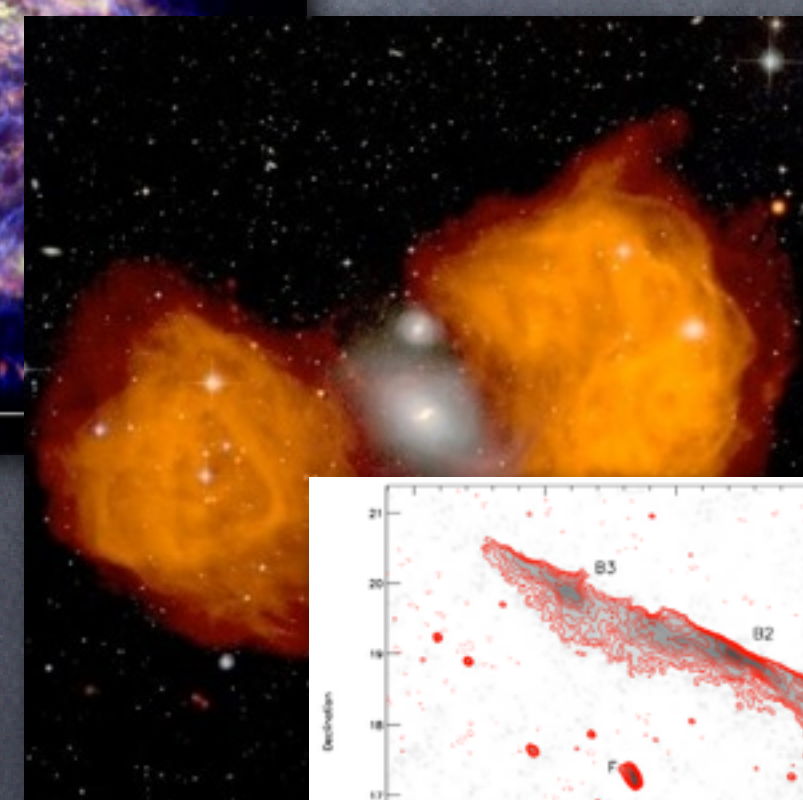

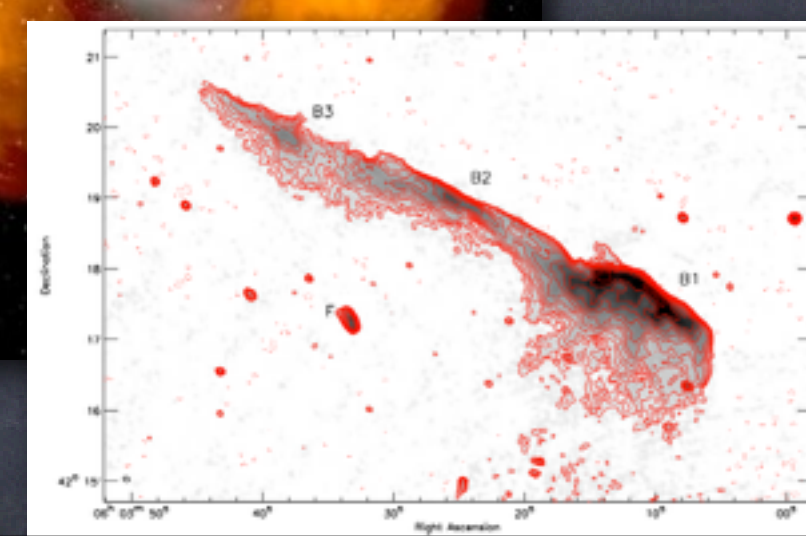

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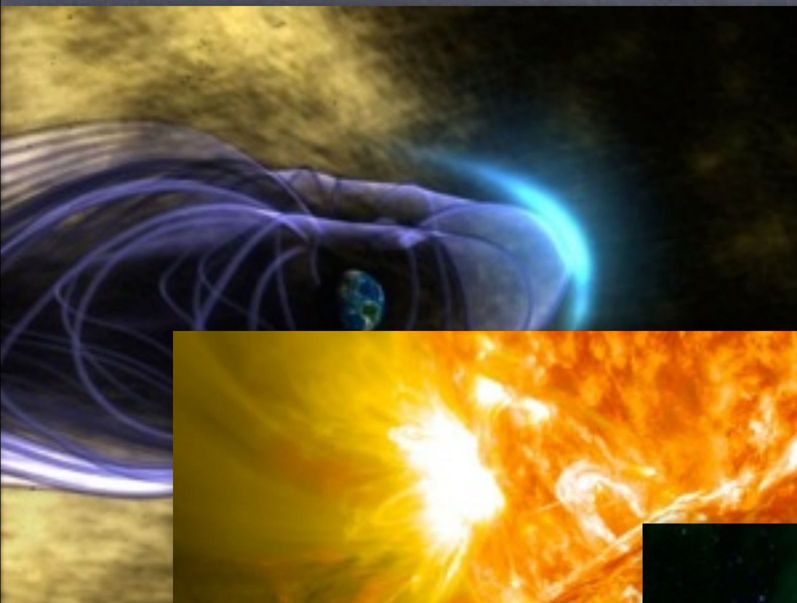
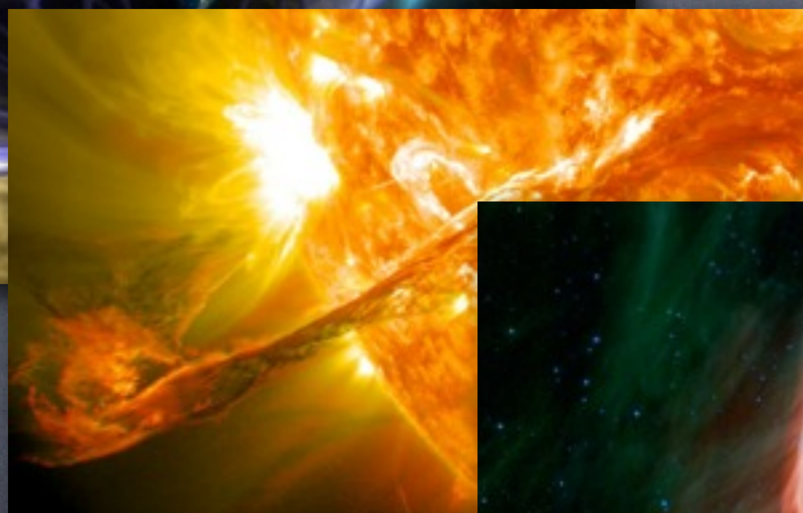
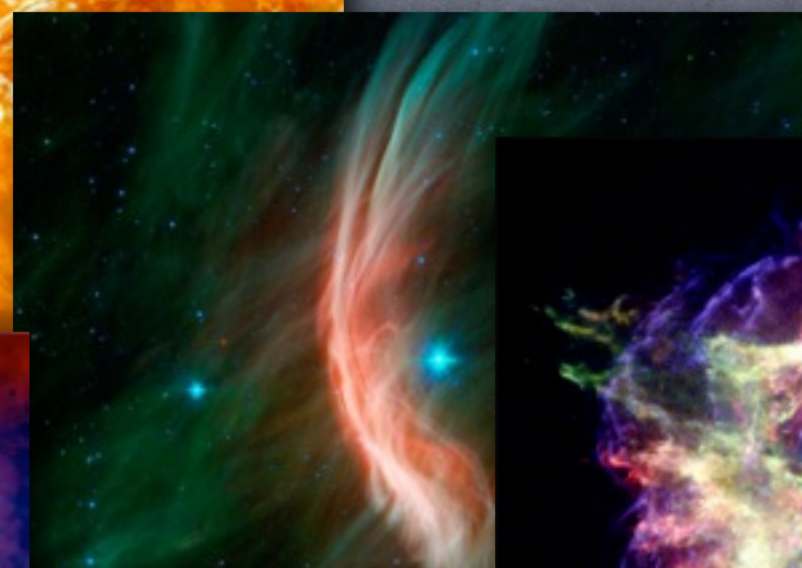


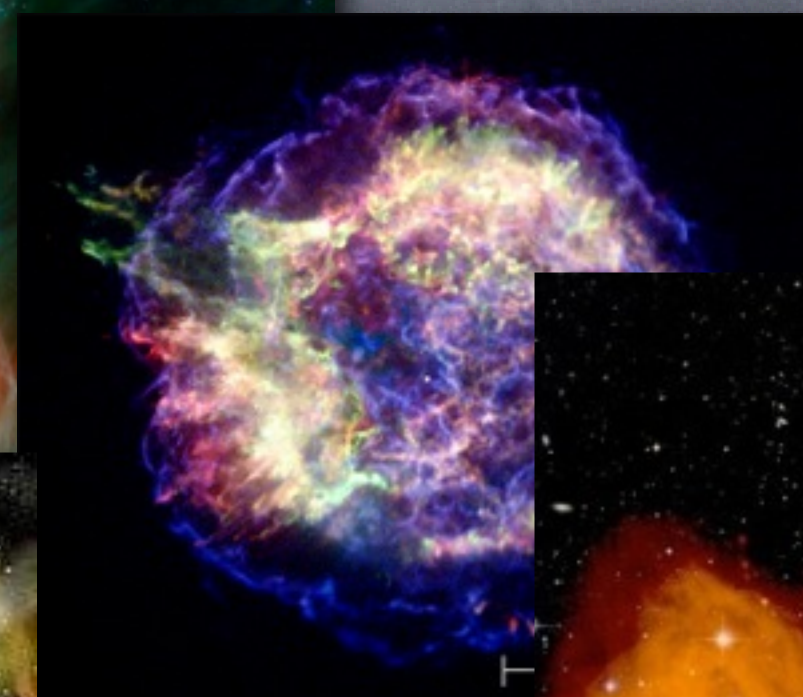
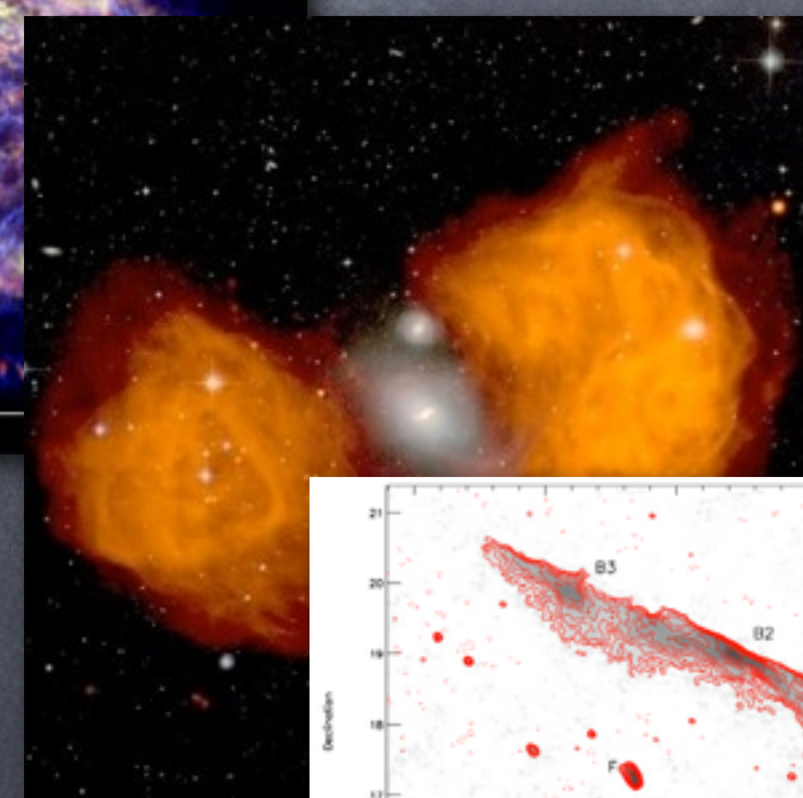
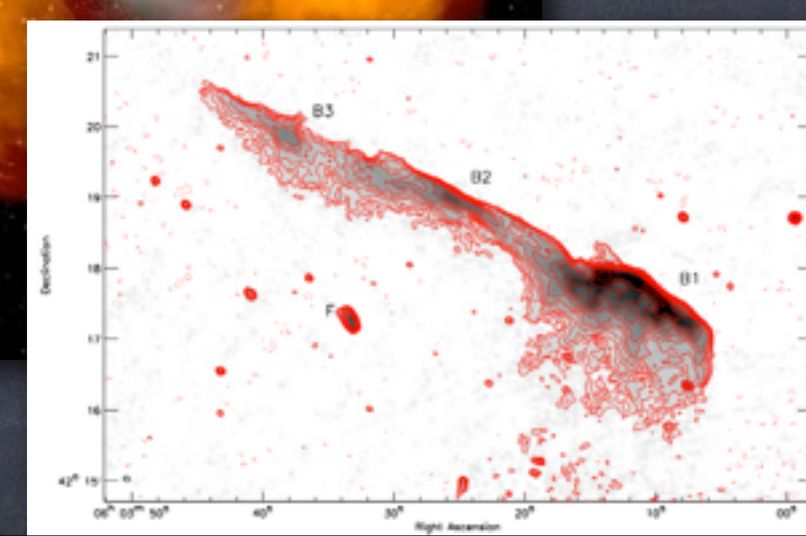

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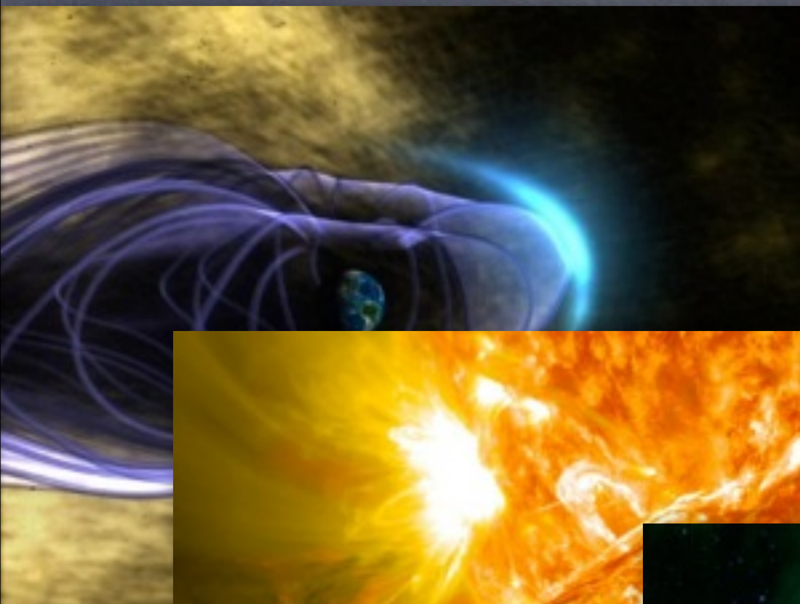

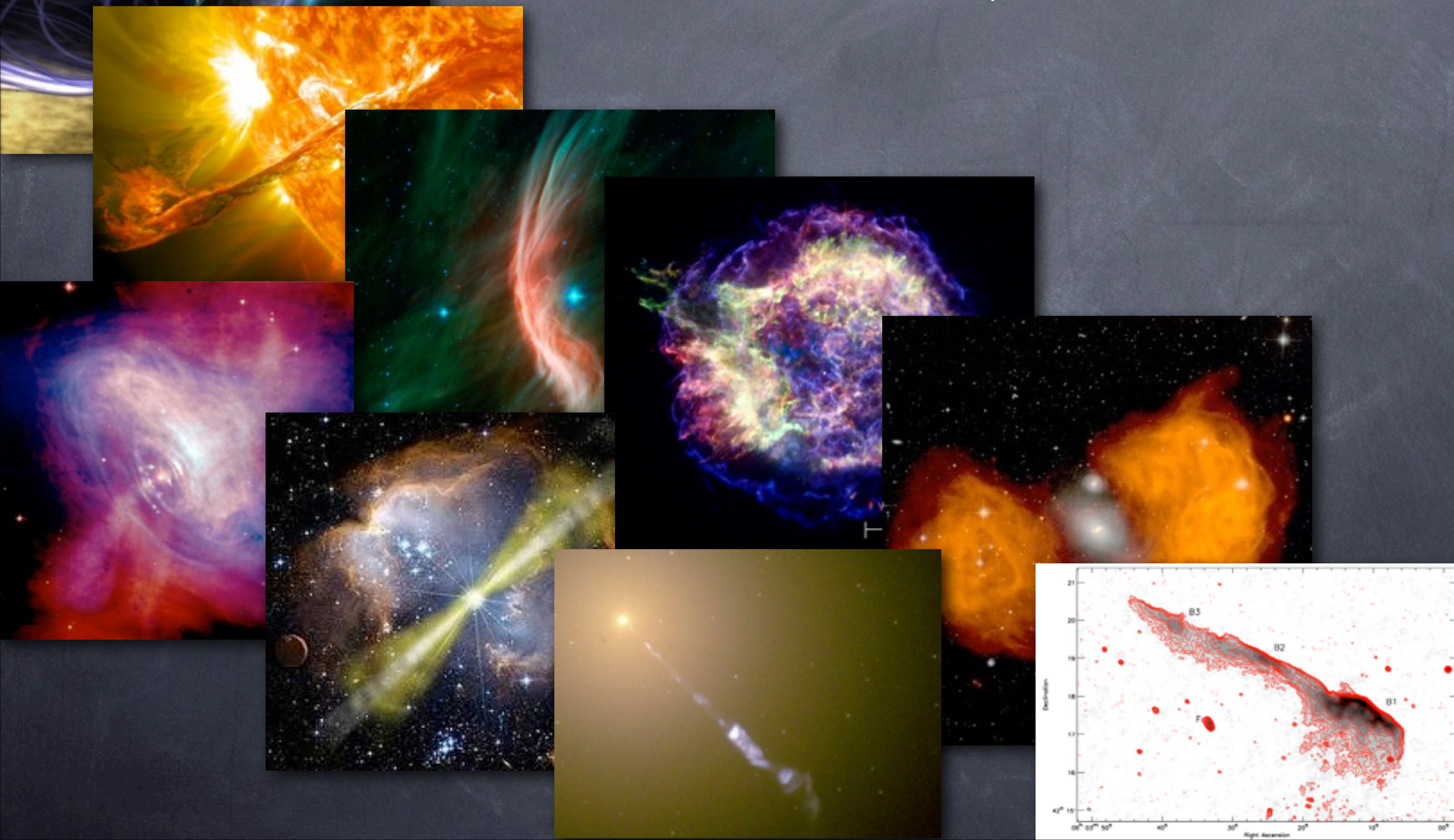

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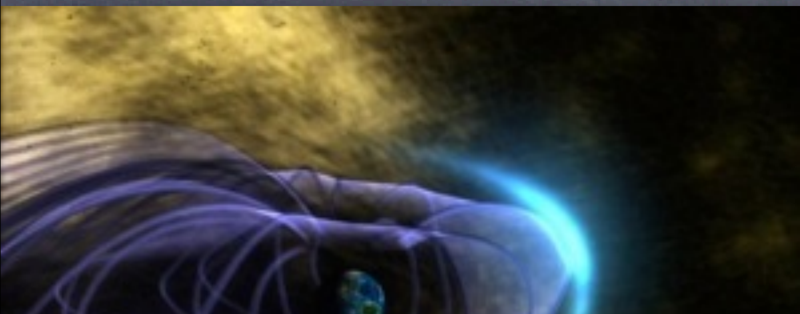

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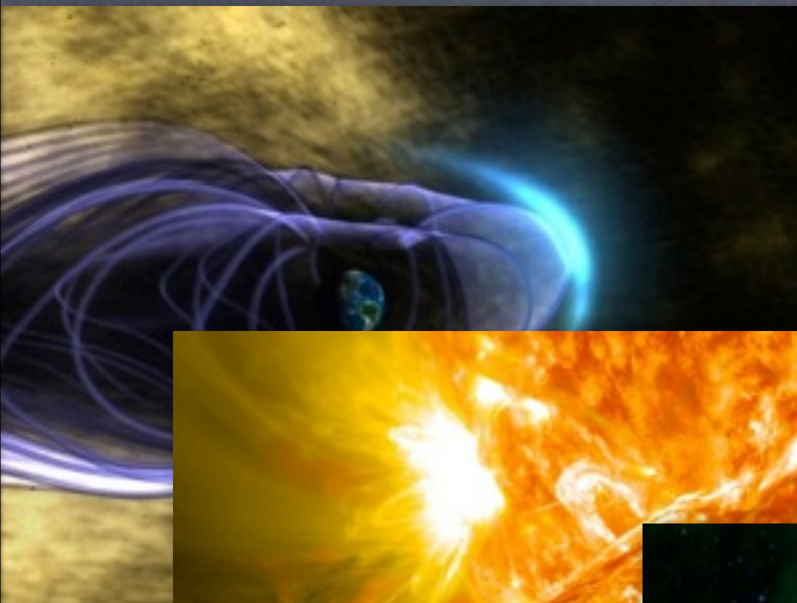
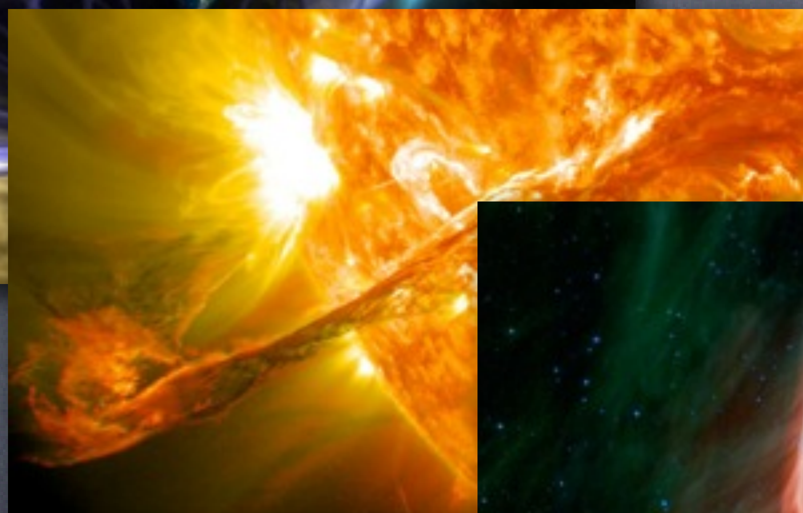
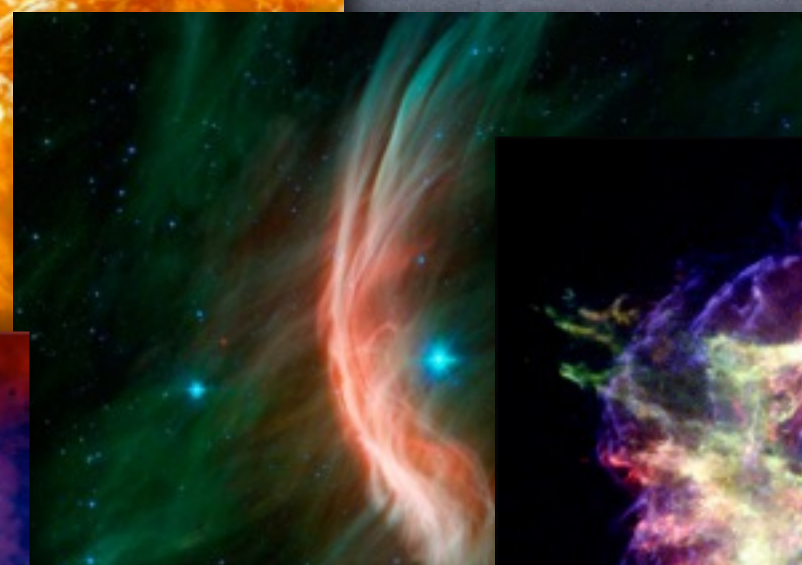
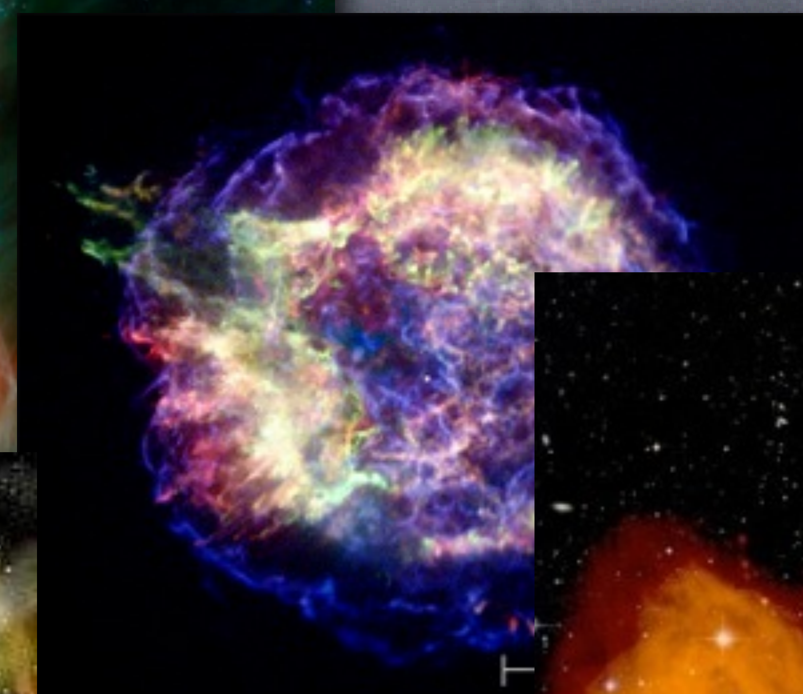
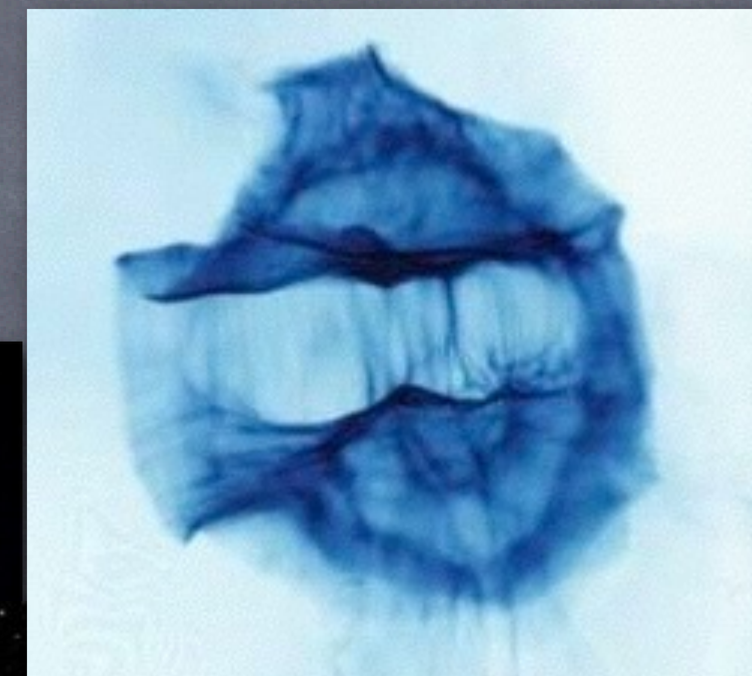


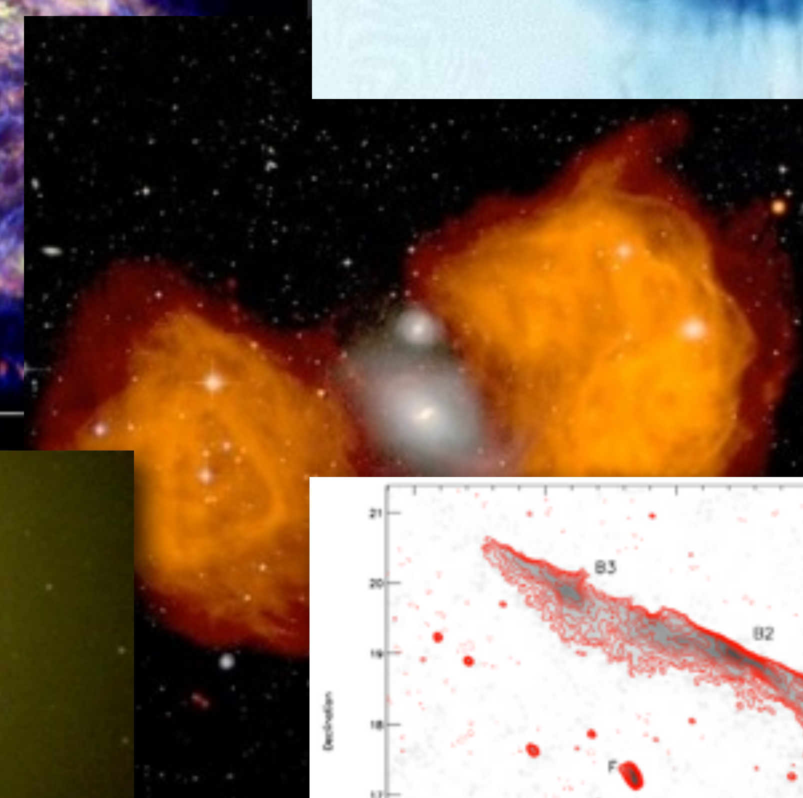

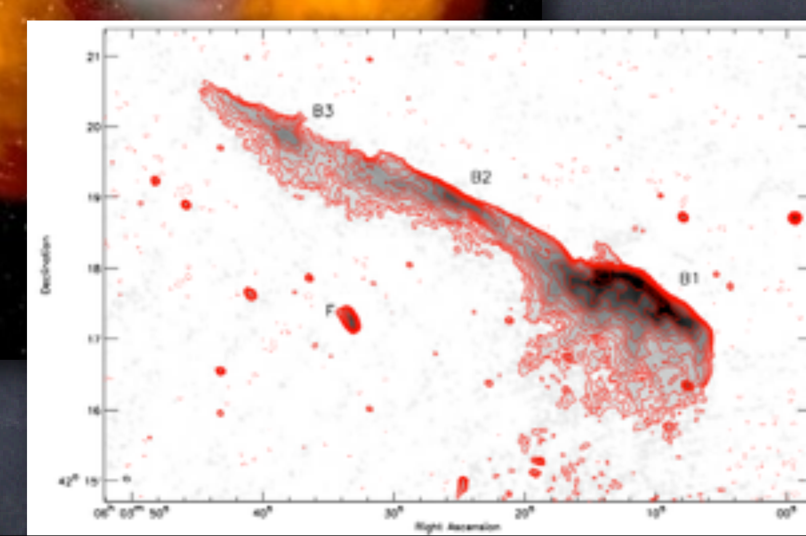

Acceleration from first principles

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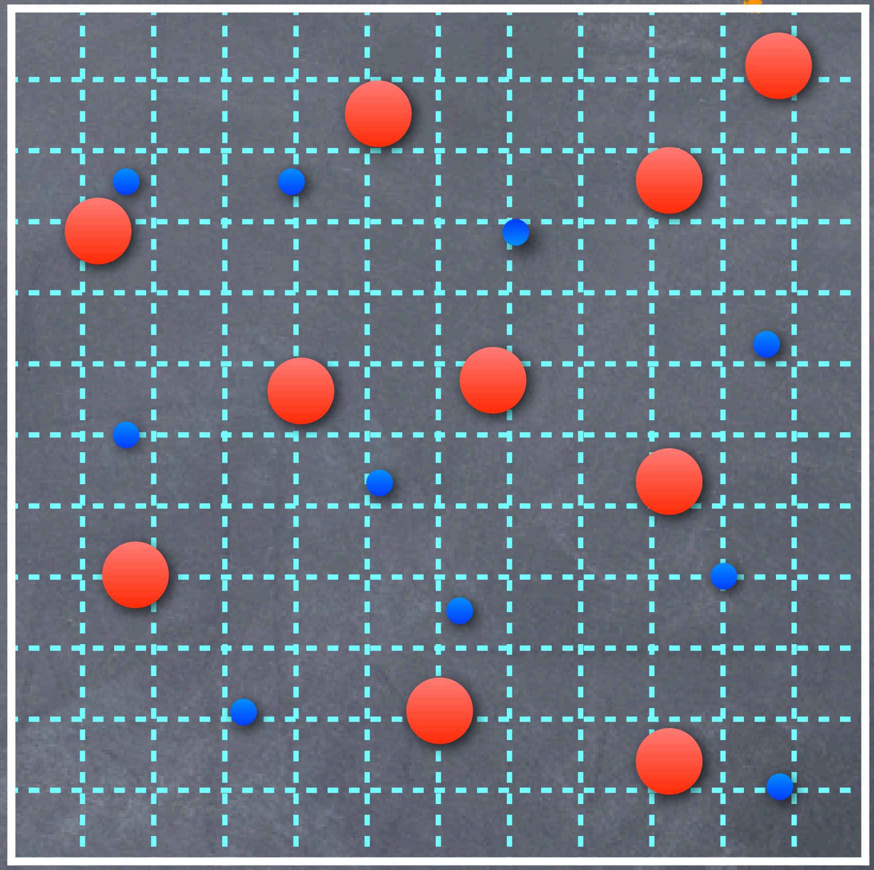
- Full particle in cell approach
  (Spitkovsky 2008, Niemiec et al. 2008, Stroman et al 2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park et al 2012, Niemiec at al 2012,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



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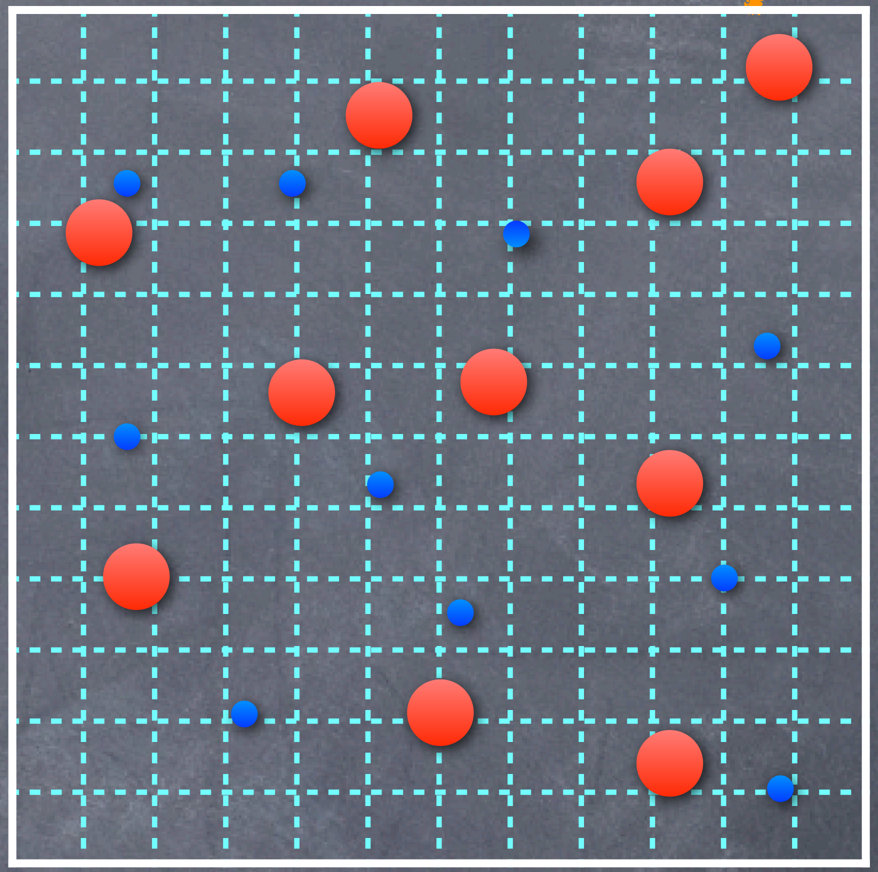
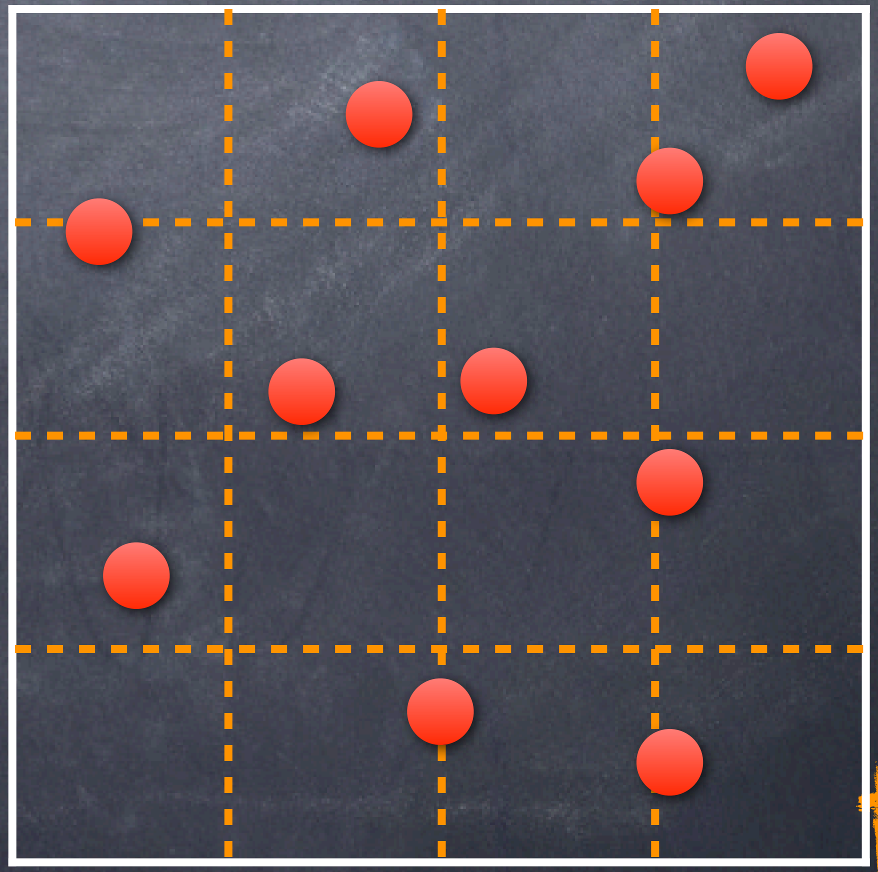
- Hybrid approach:
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, Caprioli & Spitkovsky 2013,...)
  - massless electrons for more macroscopical time/length scales





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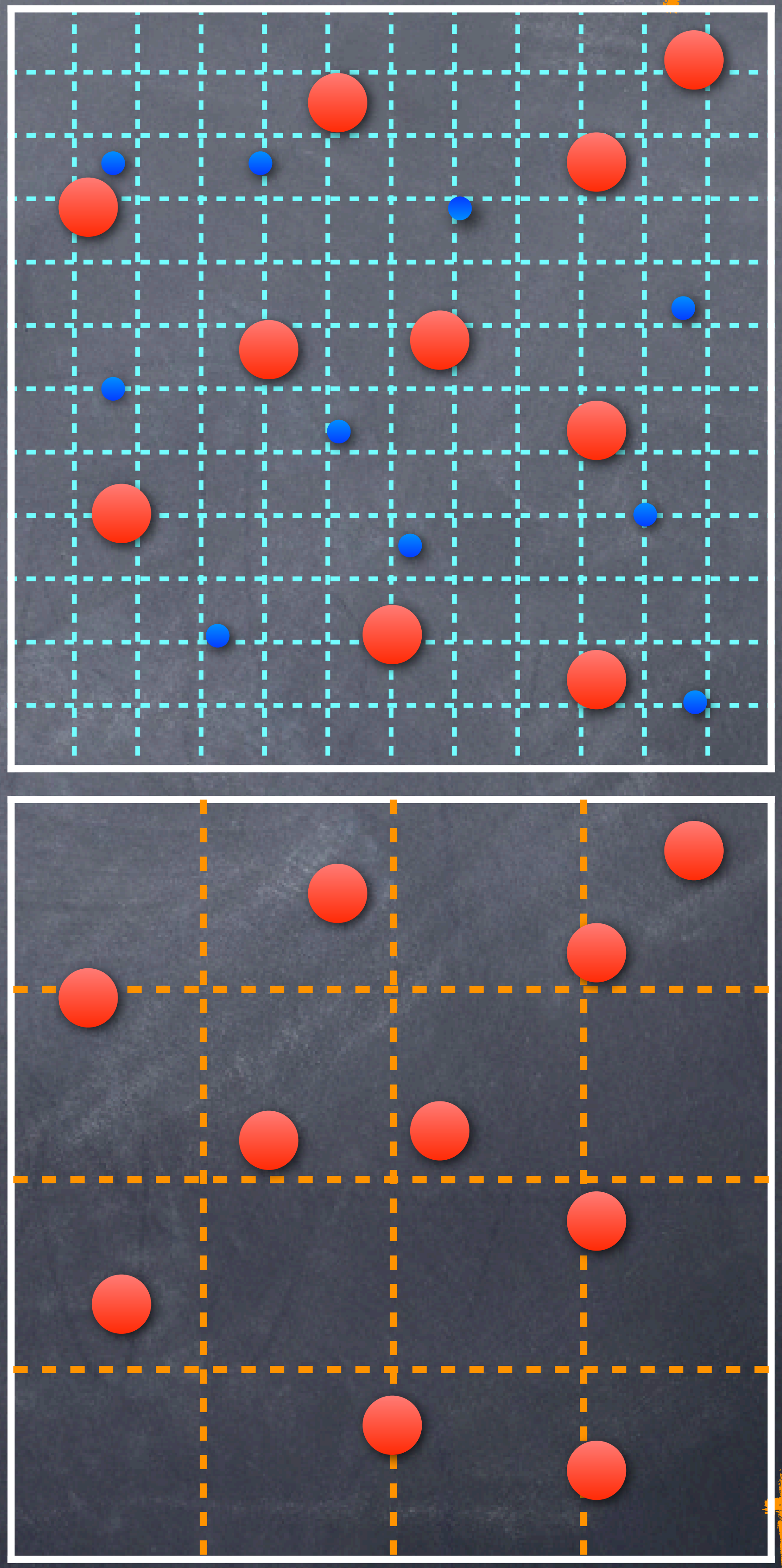

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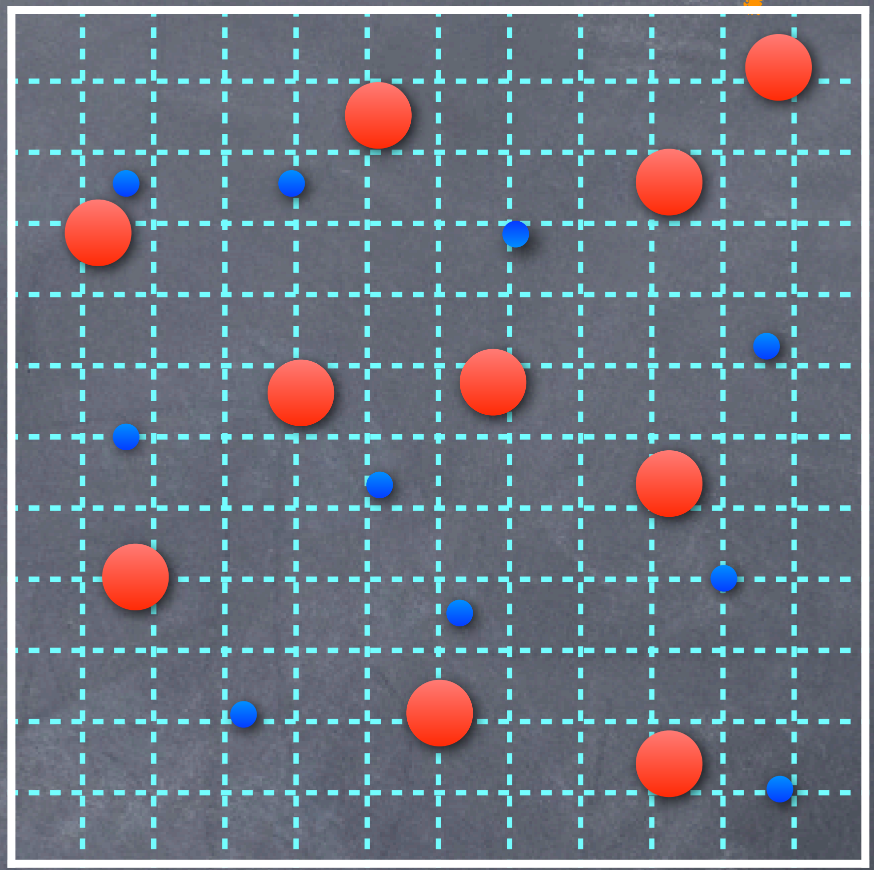
- **Full particle in cell** approach
  (Spitkovsky 2008, Niemiec et al. 2008, Stroman et al 2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park et al 2012, Niemiec at al 2012,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- **Hybrid approach**:
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, Caprioli & Spitkovsky 2013,...)
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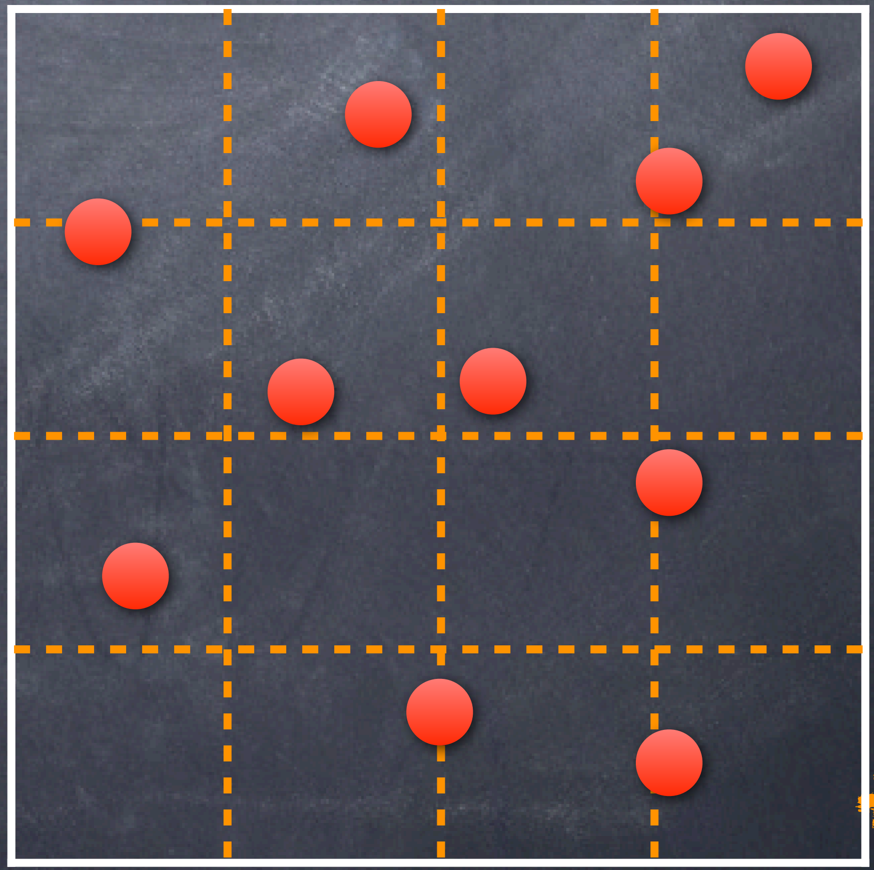

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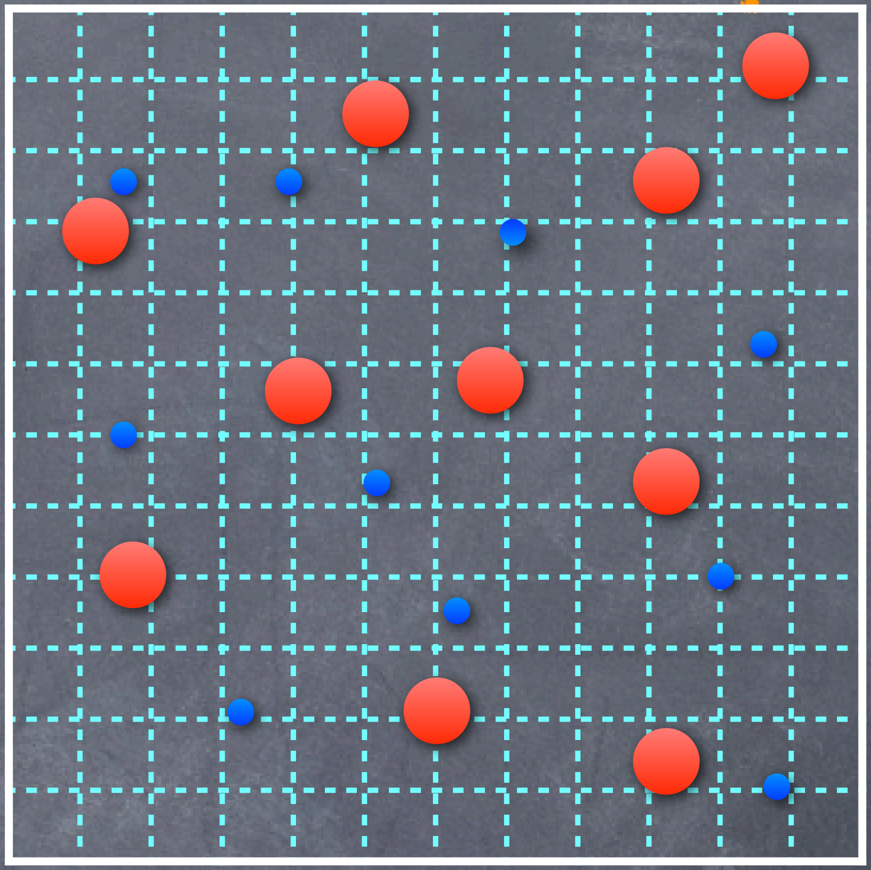

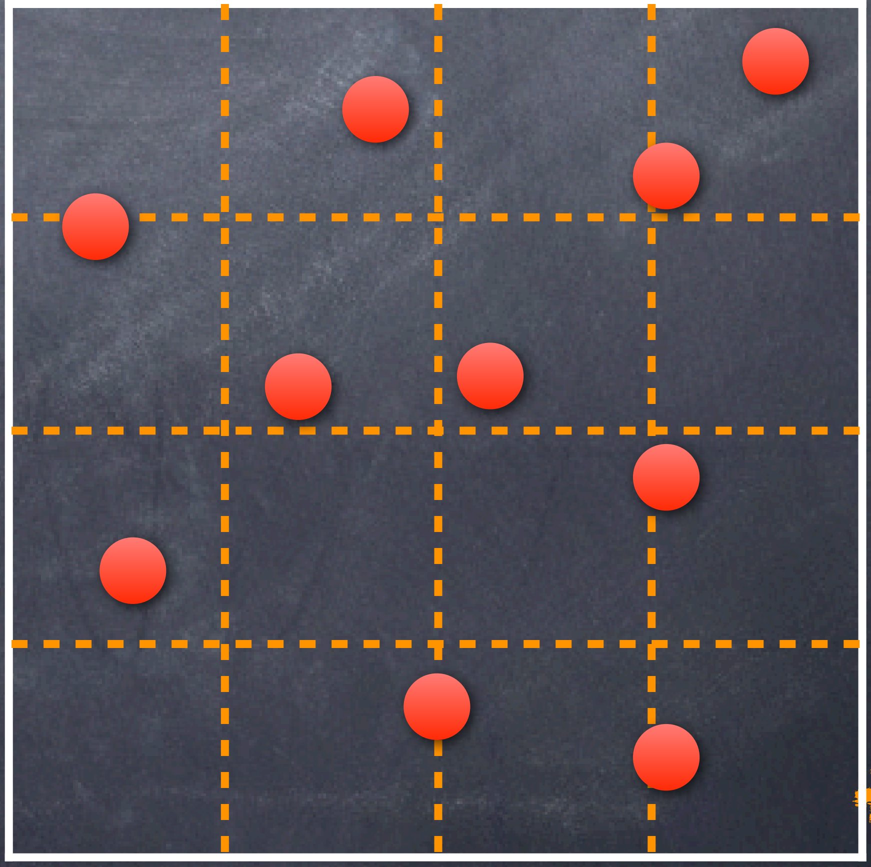

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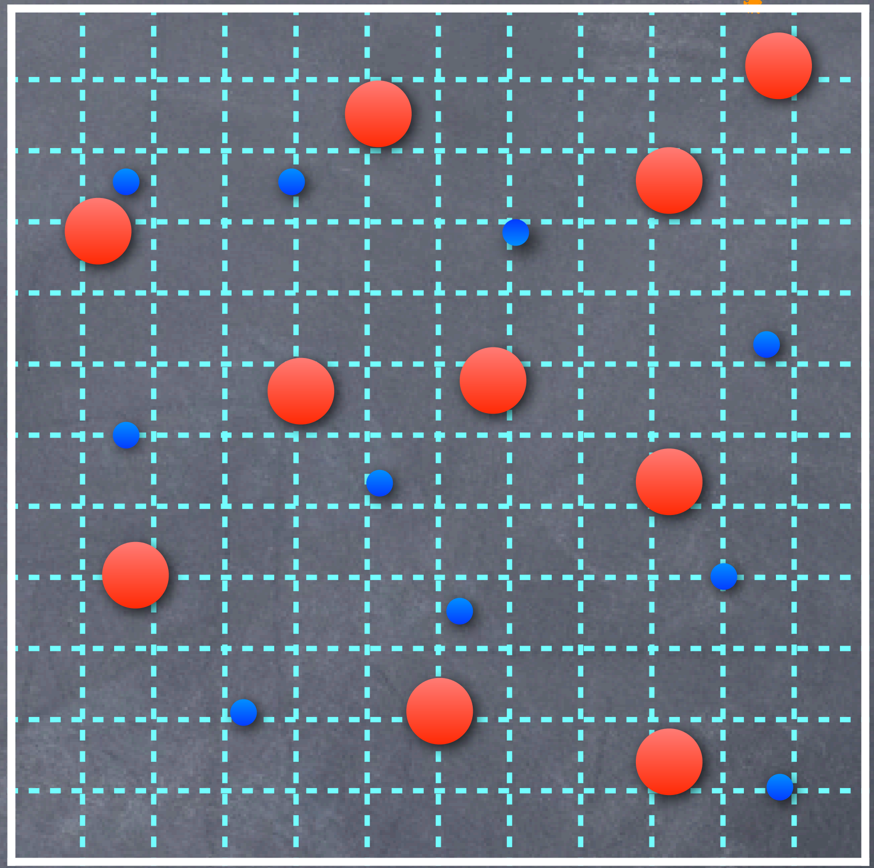

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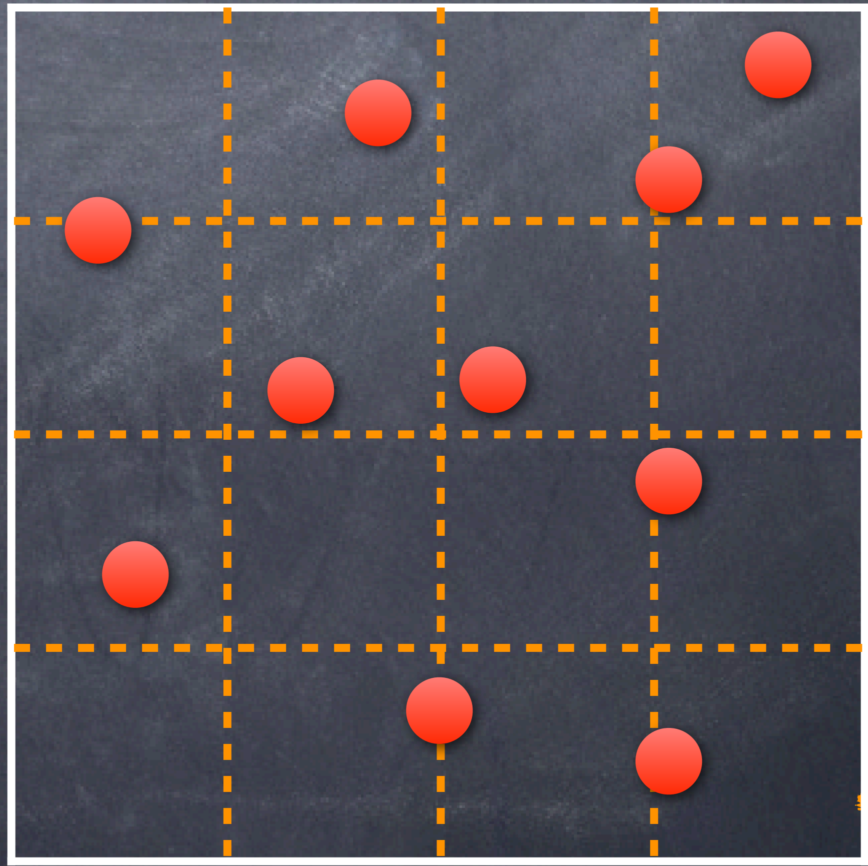
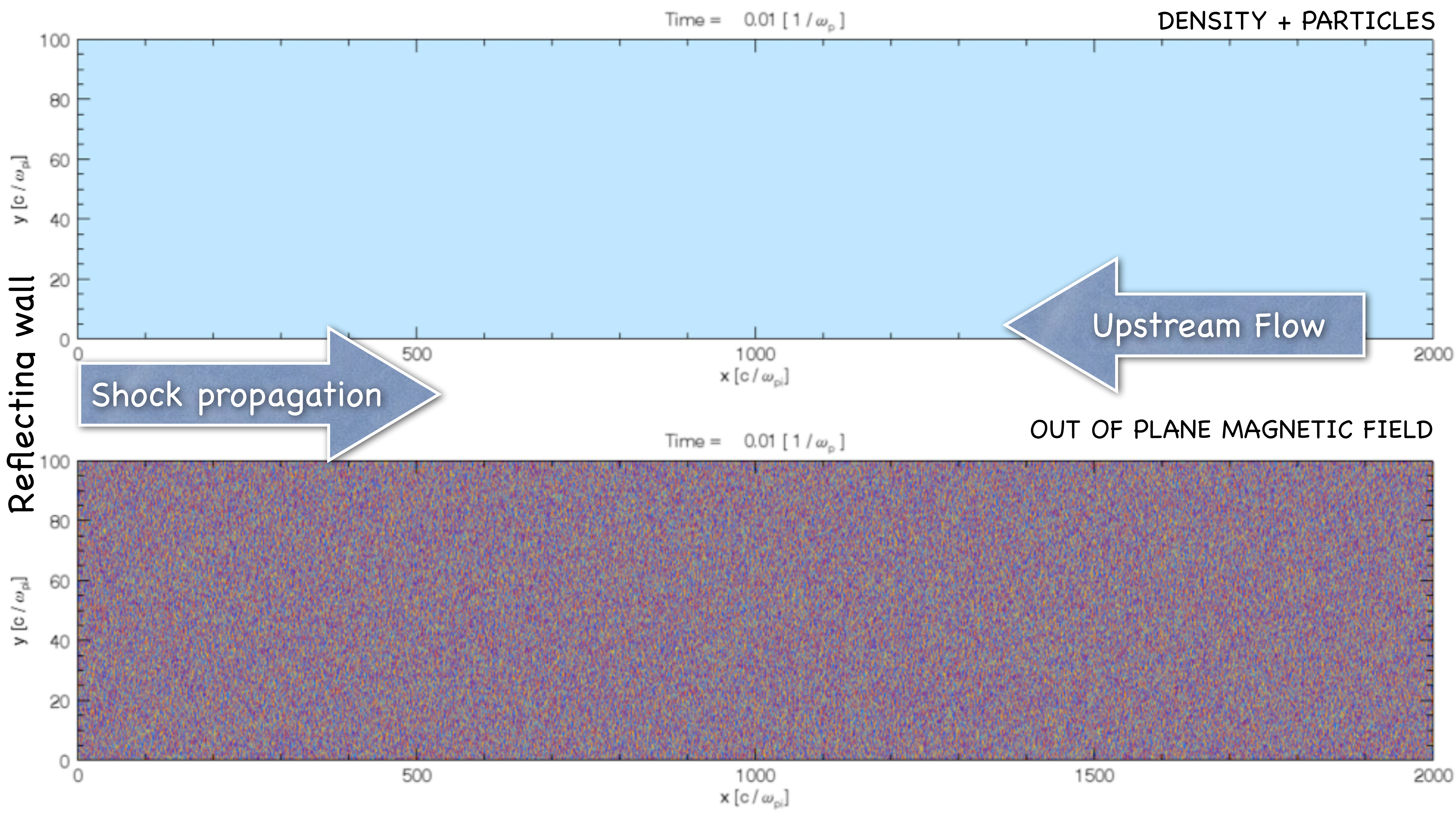


Hybrid simulations of collisionless shocks



- **dHybrid** code (Gargaté et al, 2007)

Initial B field

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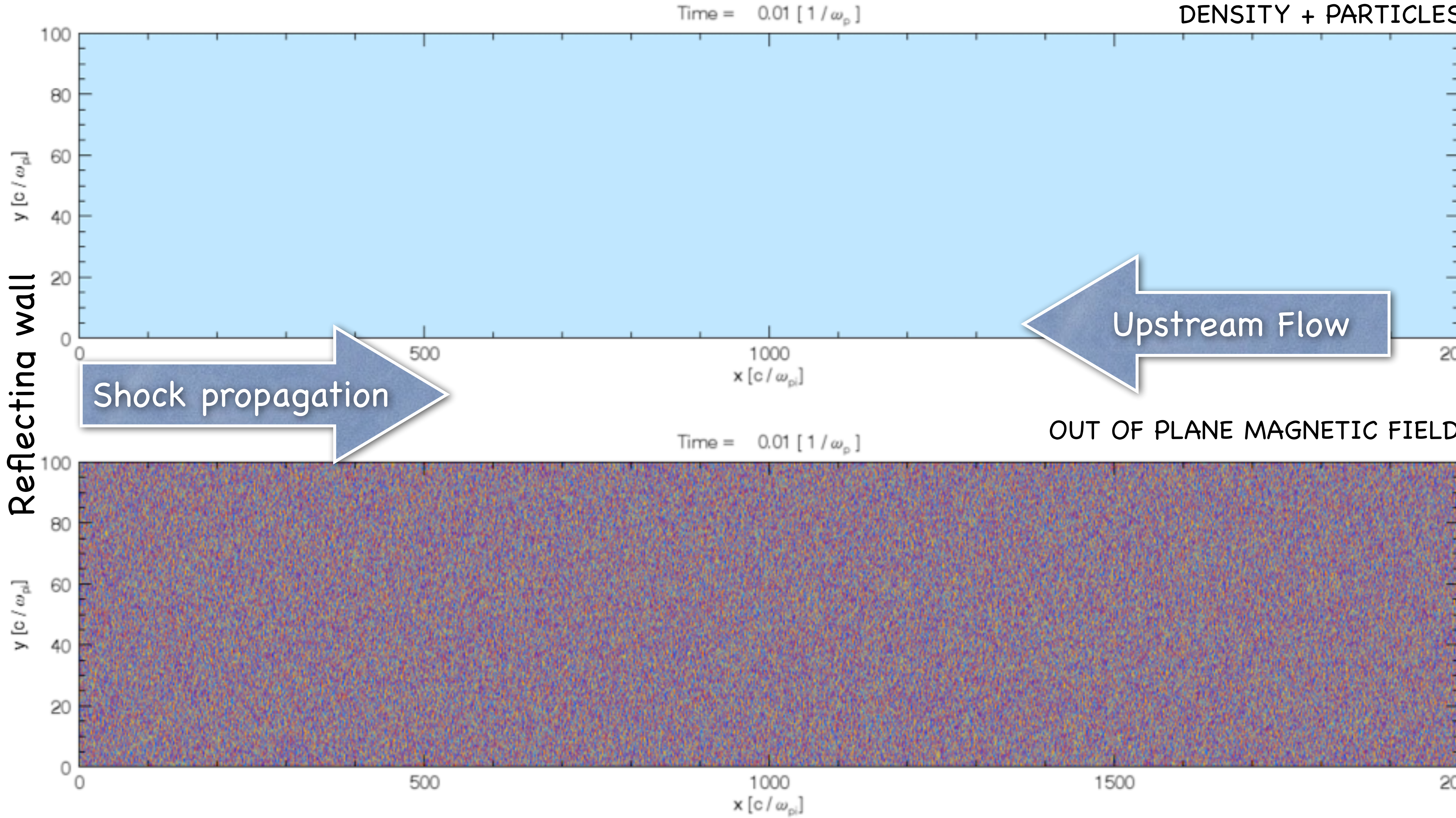

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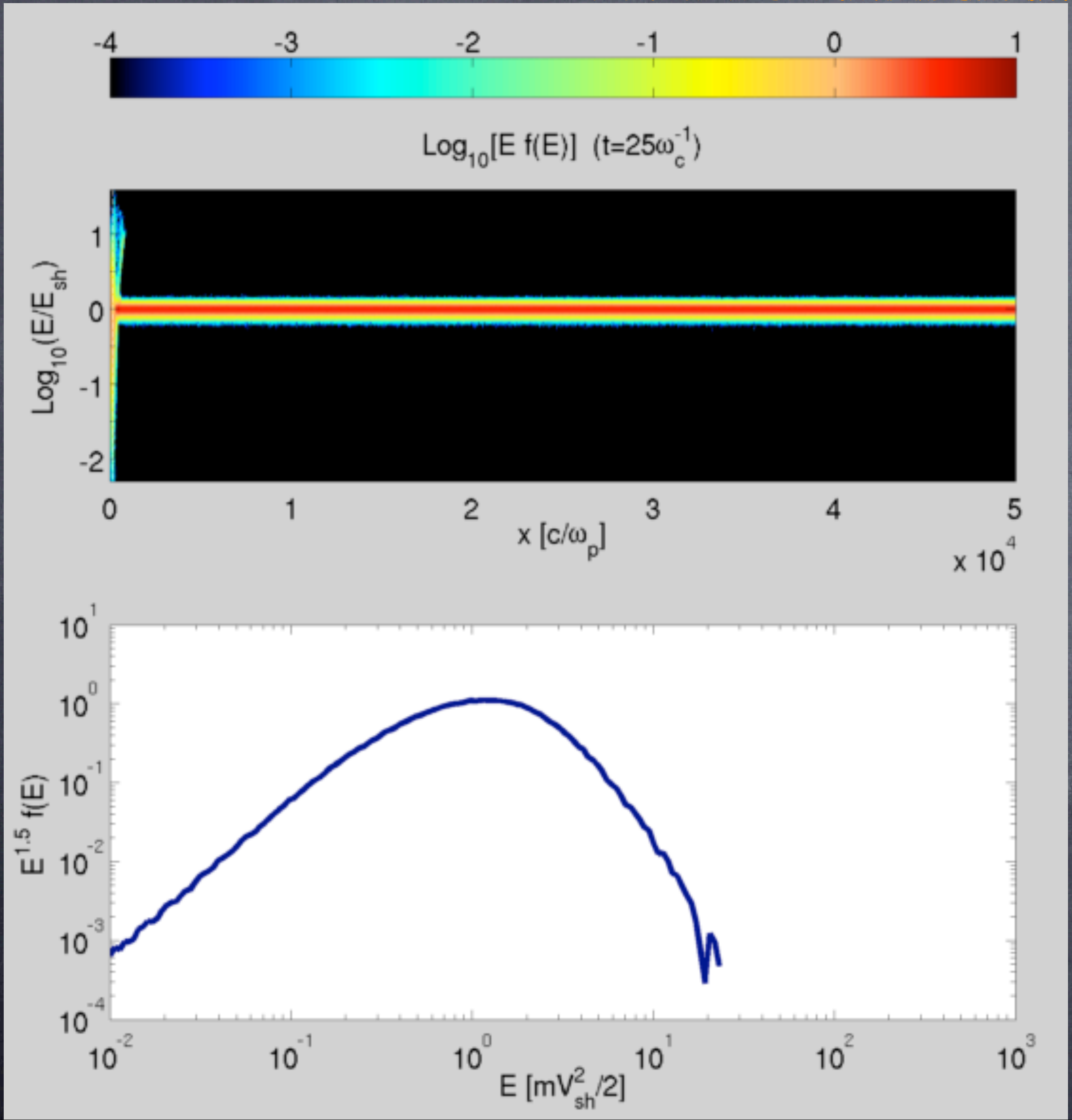
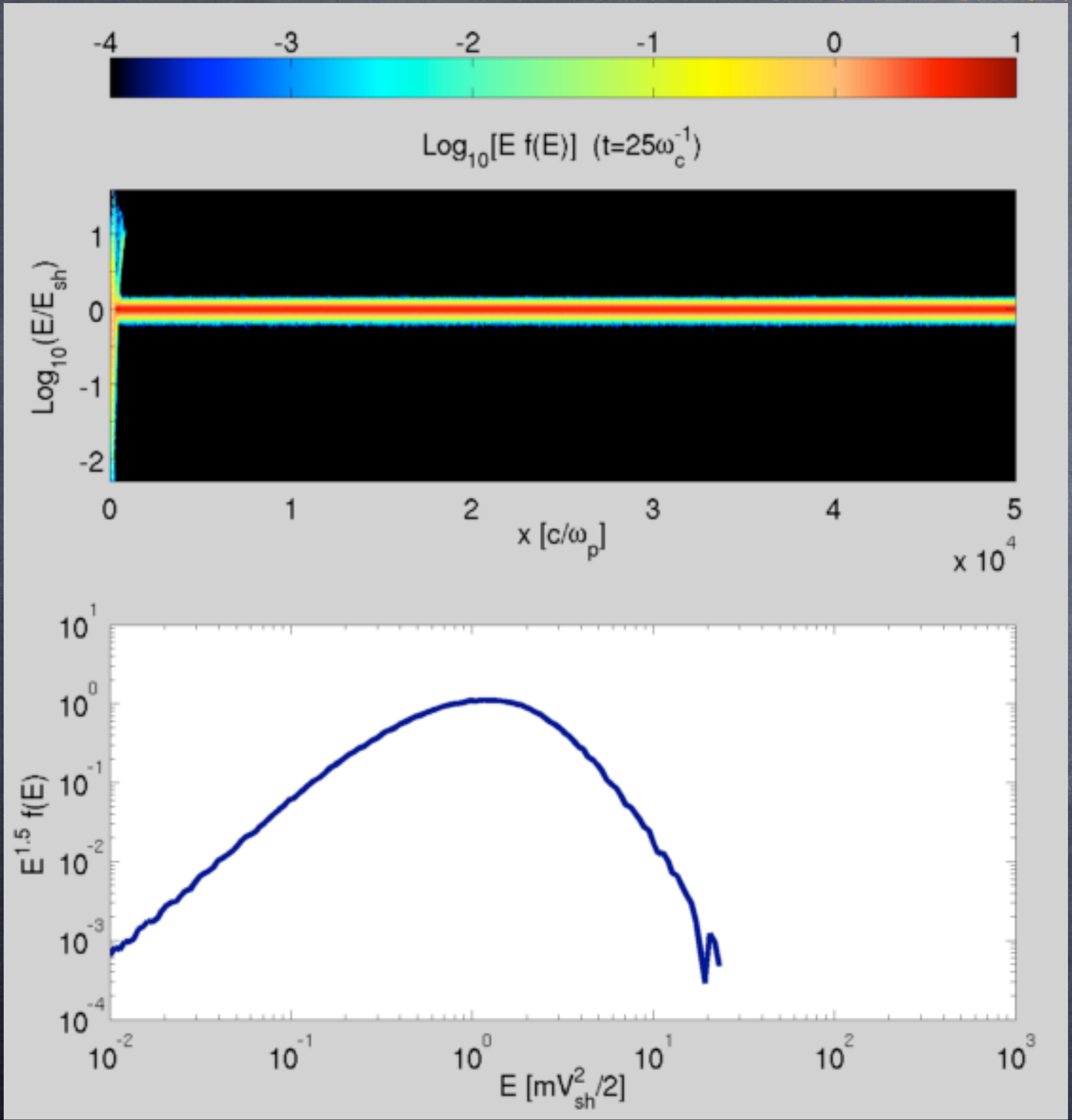
Initial B field

Spectrum evolution



DC & Spitkovsky, arXiv:1310.2943

Spectrum evolution

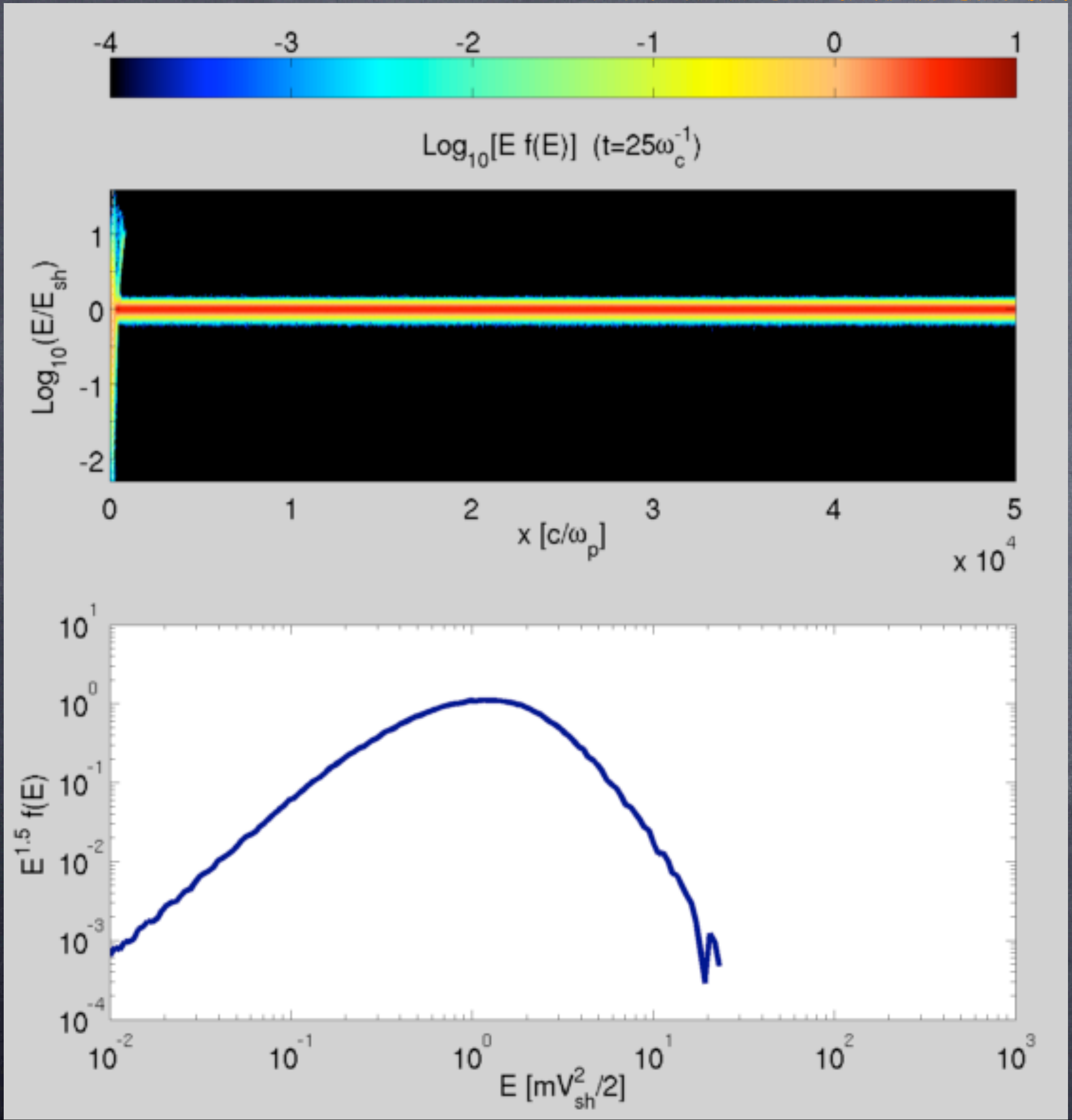


First-order Fermi acceleration:

$f(p) \propto p^{-4}$

$4\pi p^2 f(p)dp = f(E)dE$

Spectrum evolution



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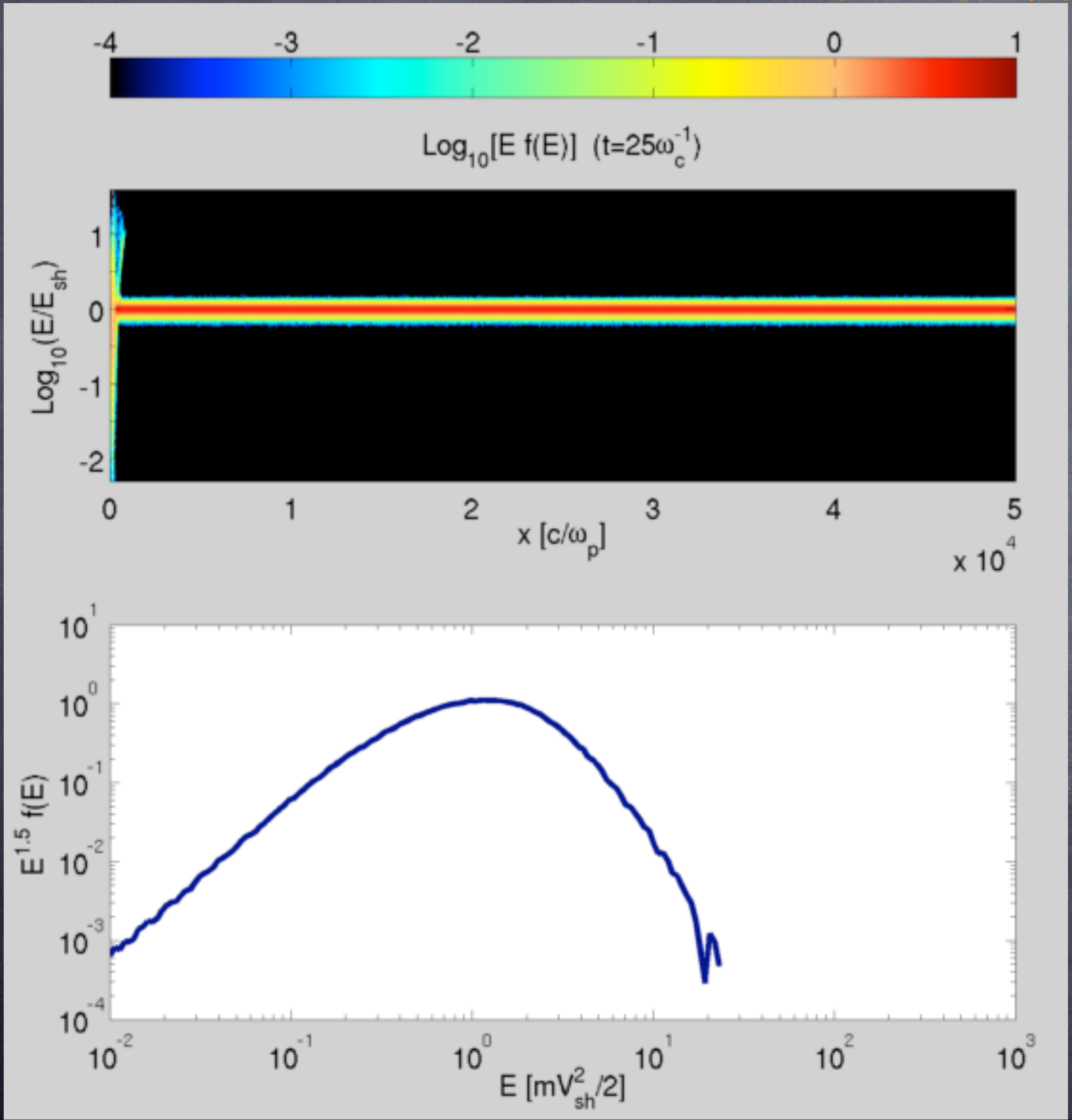

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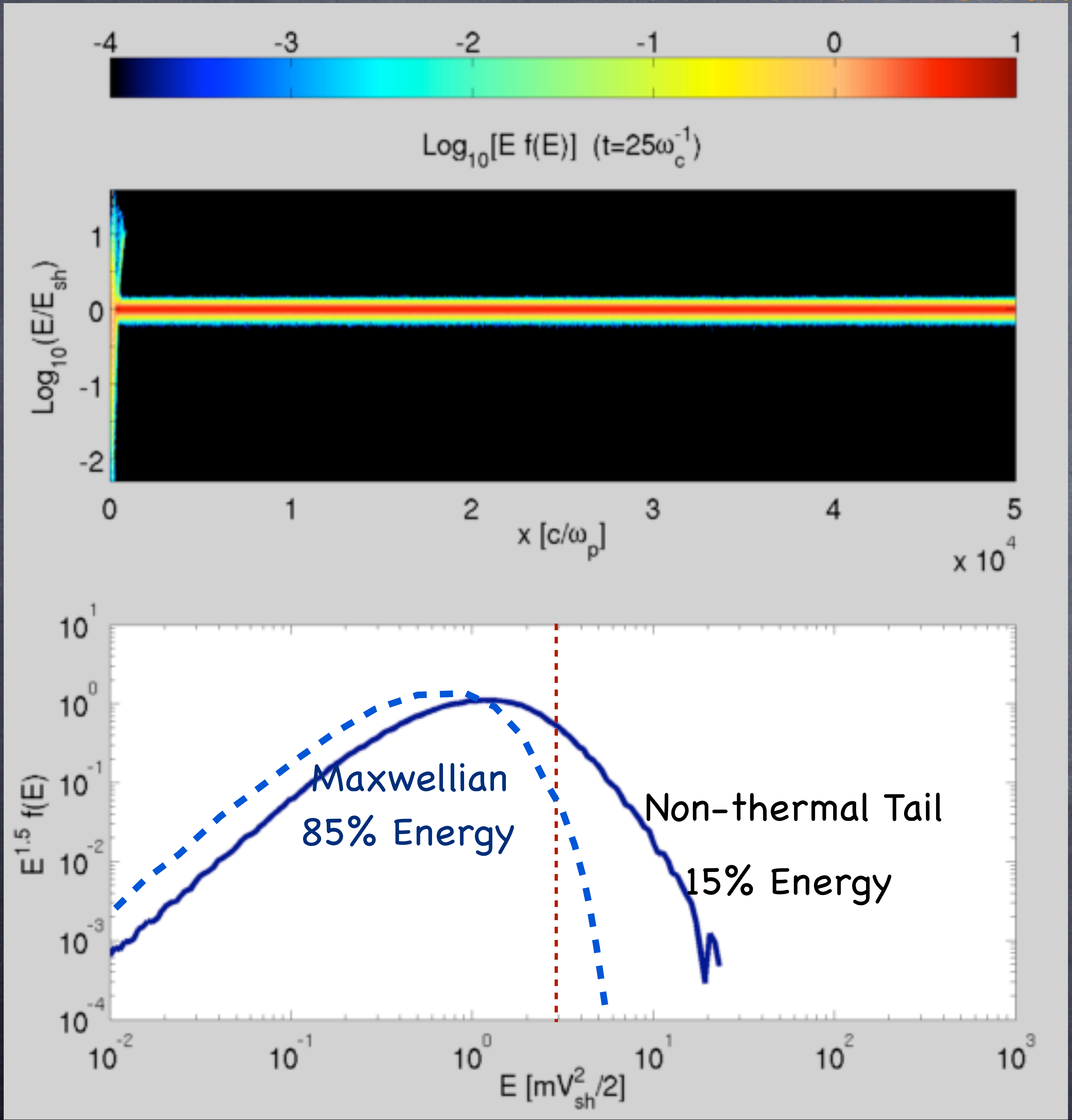

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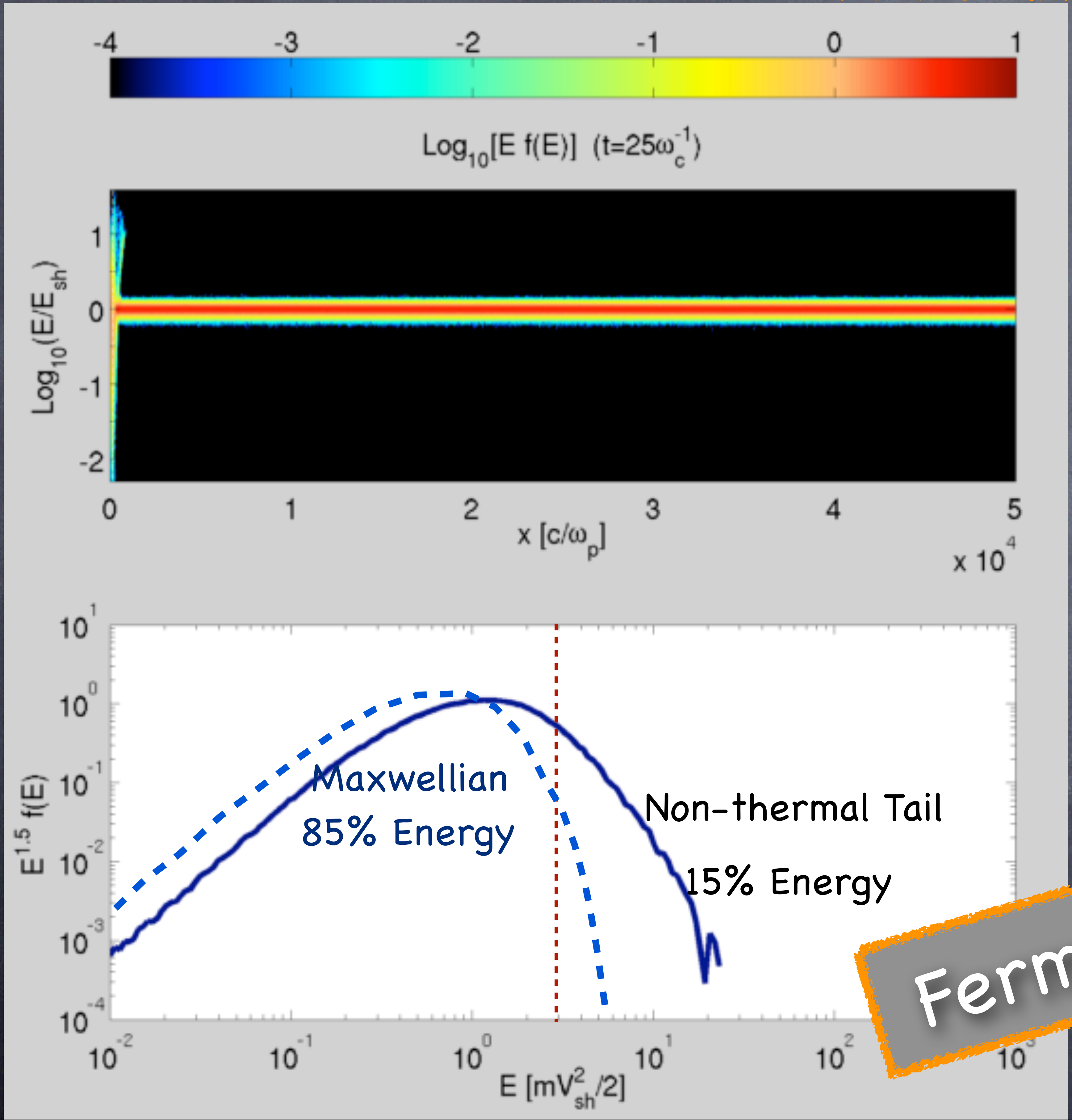

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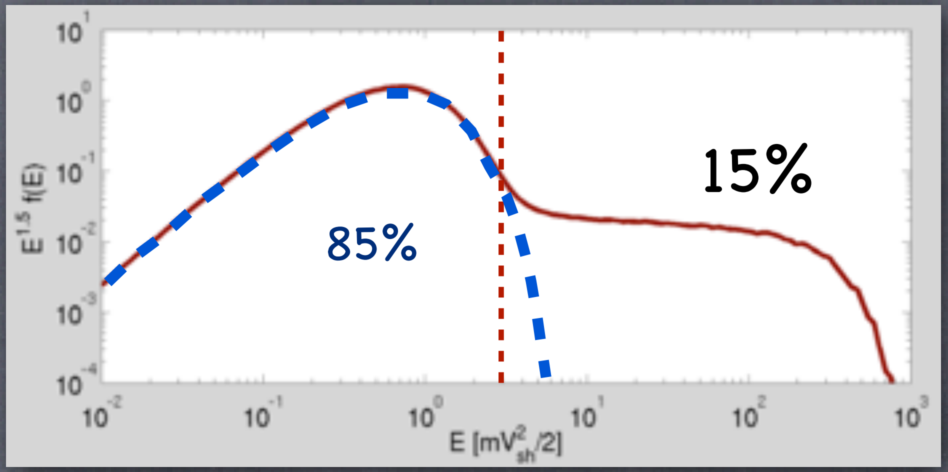
Fermi acceleration

DC & Spitkovsky, arXiv:1310.2943

Outline



Outline

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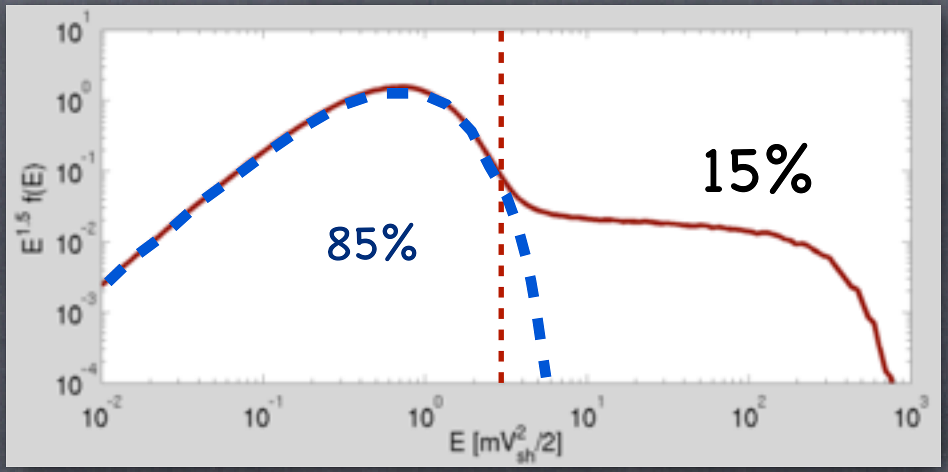

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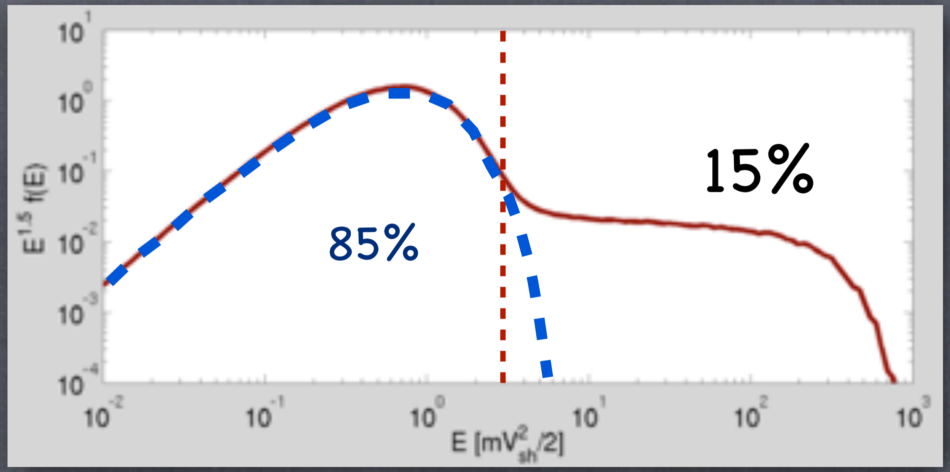

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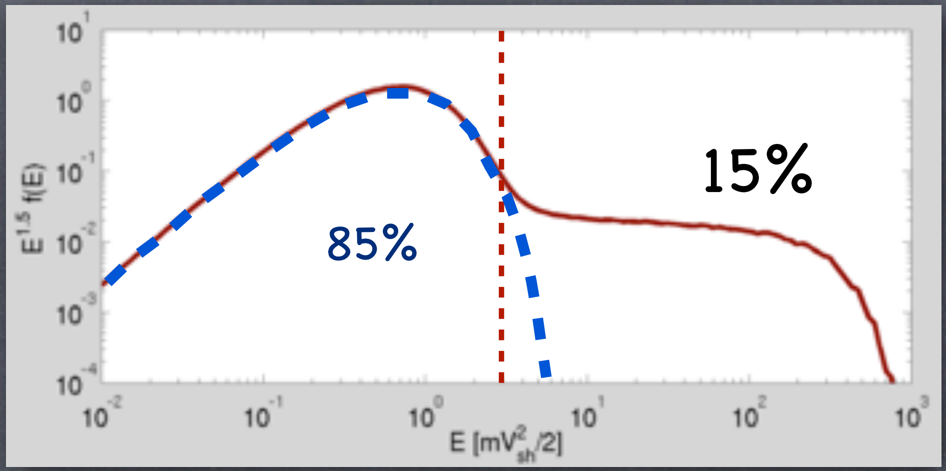
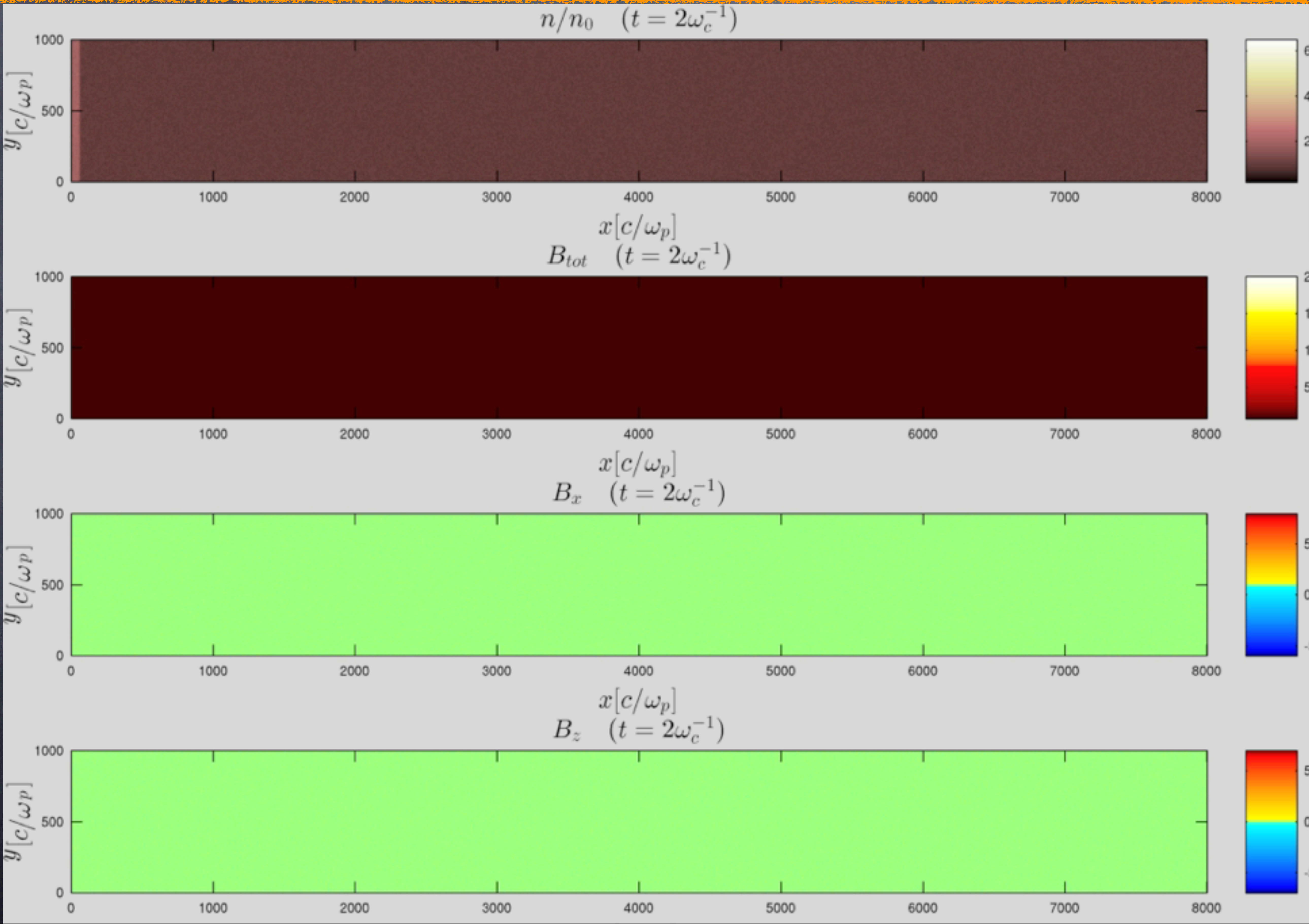


Filamentation instability



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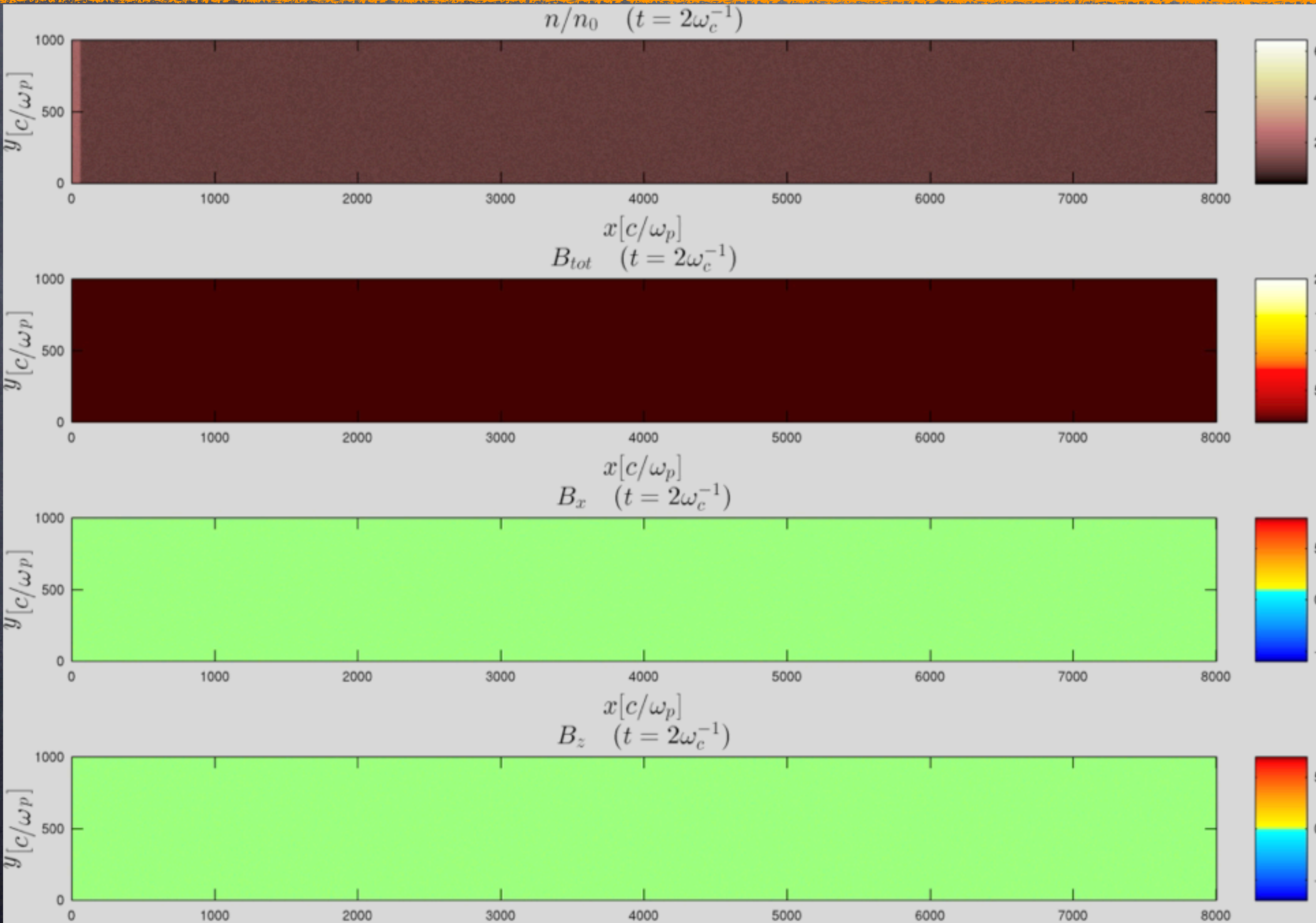
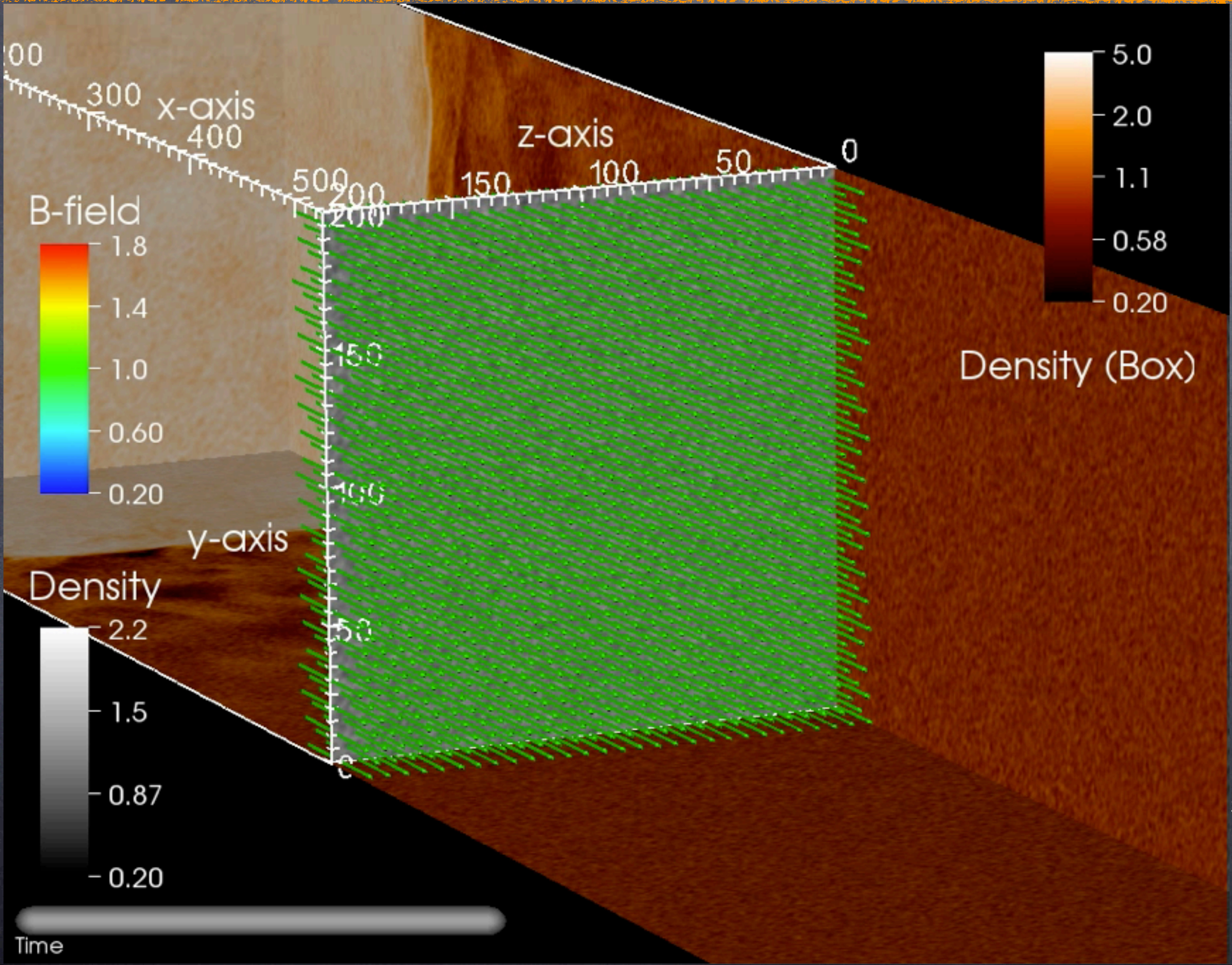


3D simulations of a parallel shock



Caprioli & Spitkovsky, 2013

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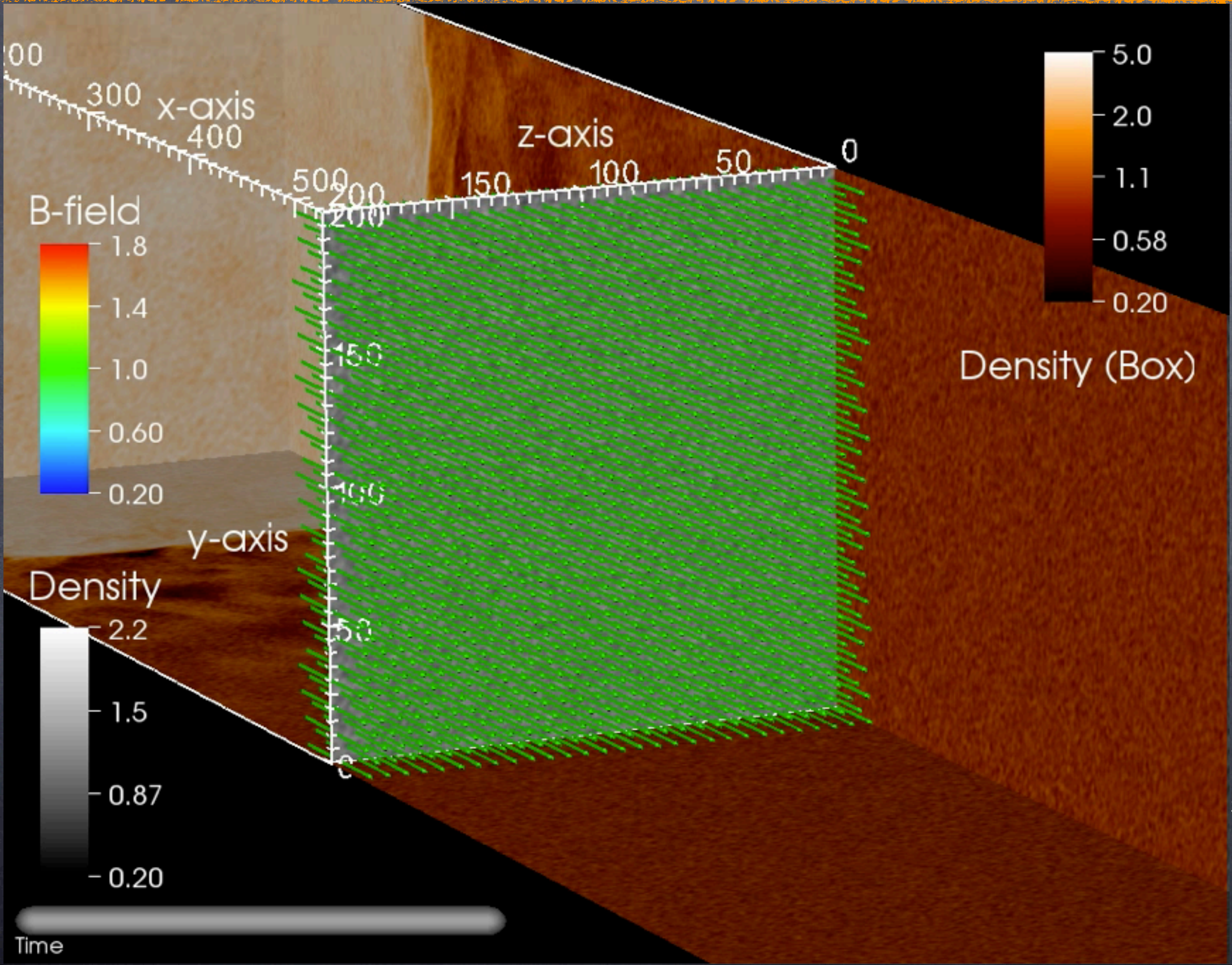

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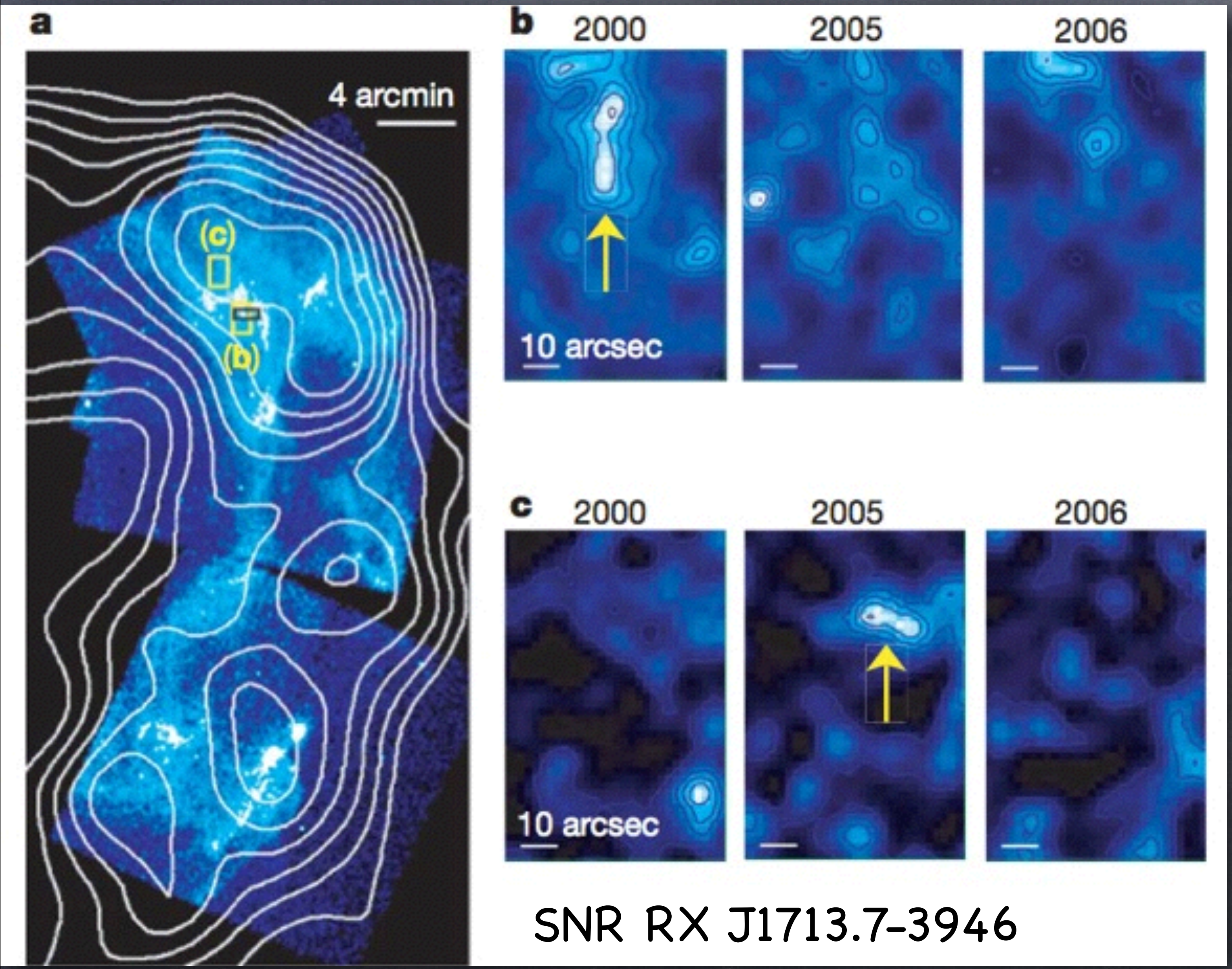
Knots and filaments



Uchiyama et al 2007

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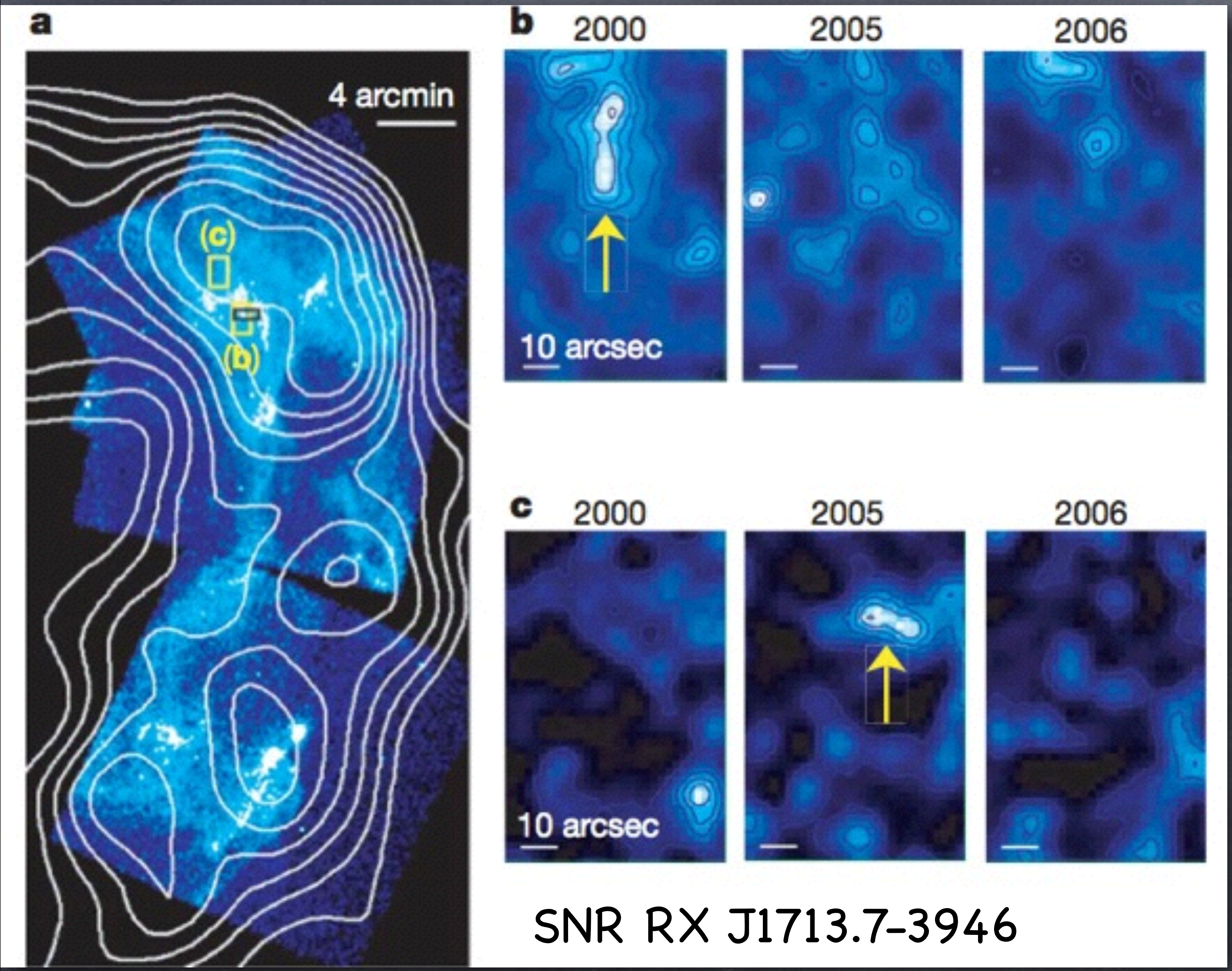

Uchiyama et al 2007

- Knots $\delta B/B \sim 100$

Knots and filaments

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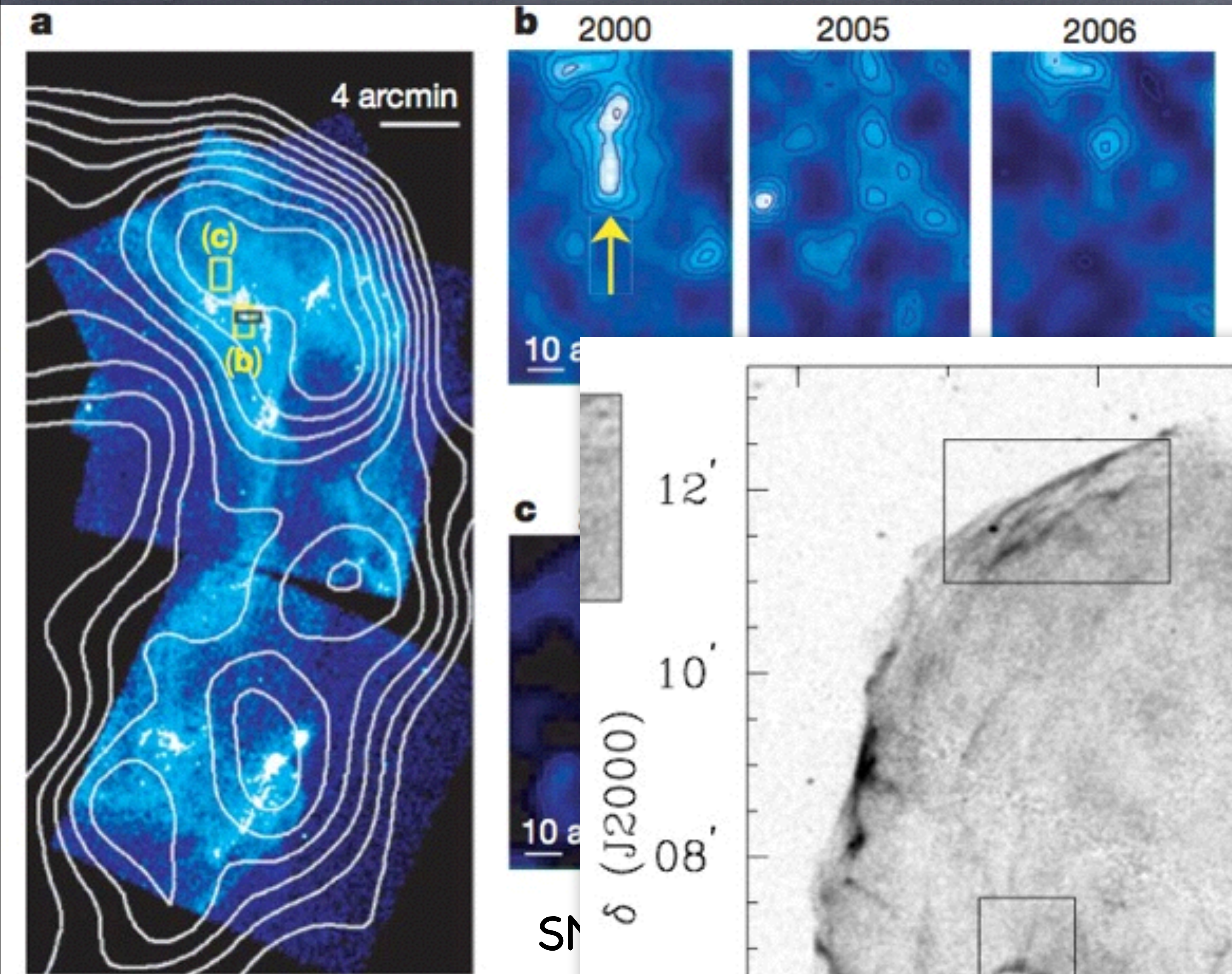
- Radial filaments



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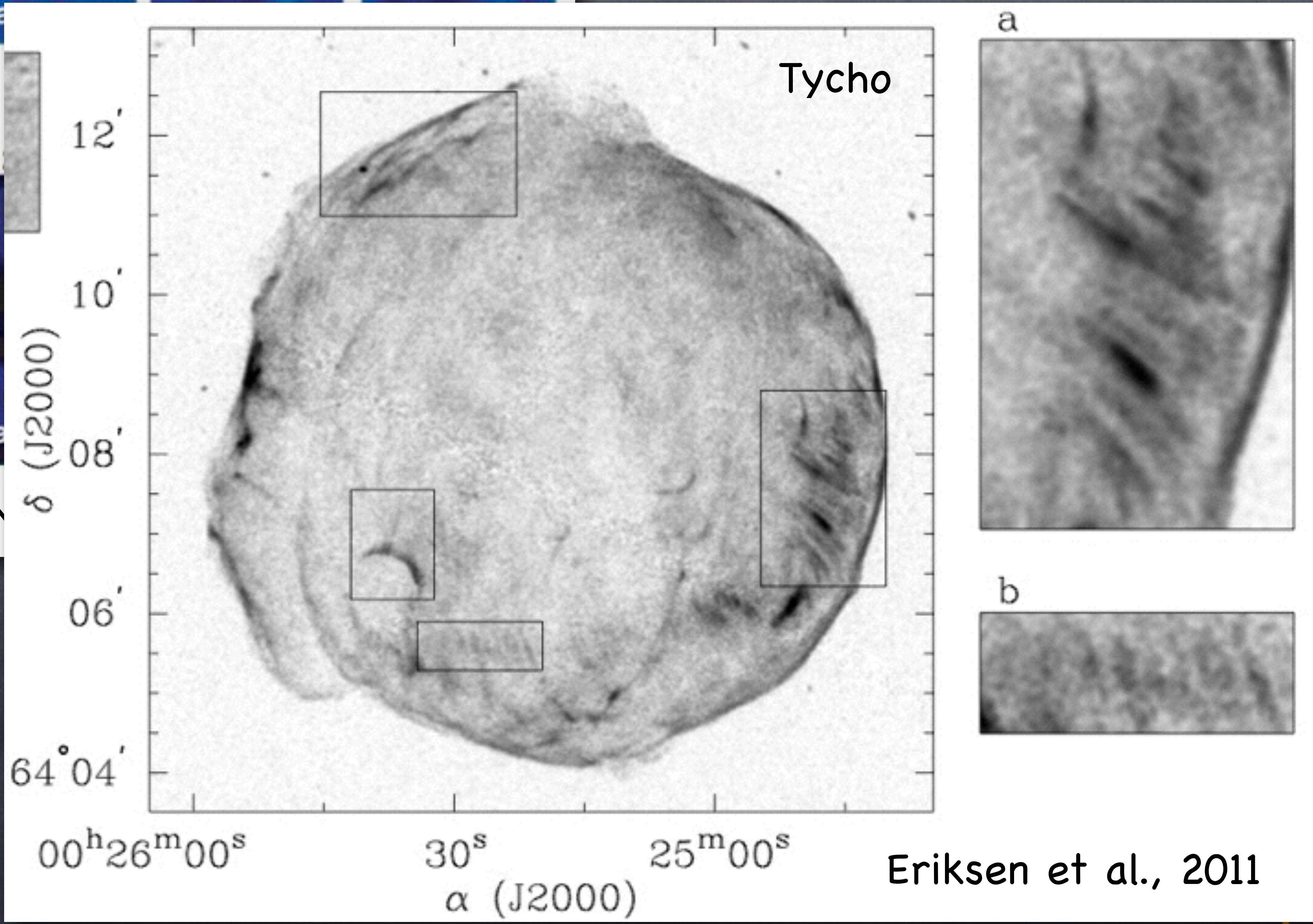
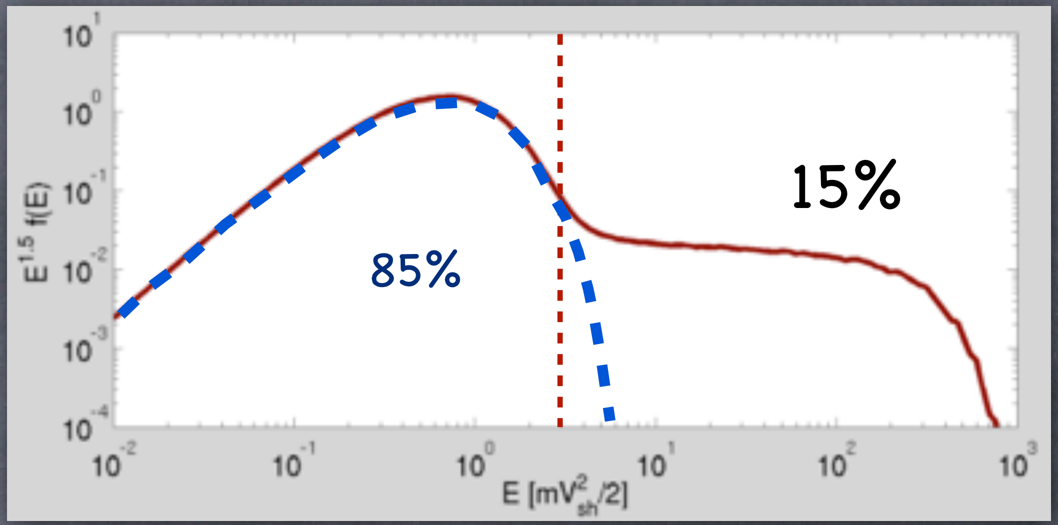
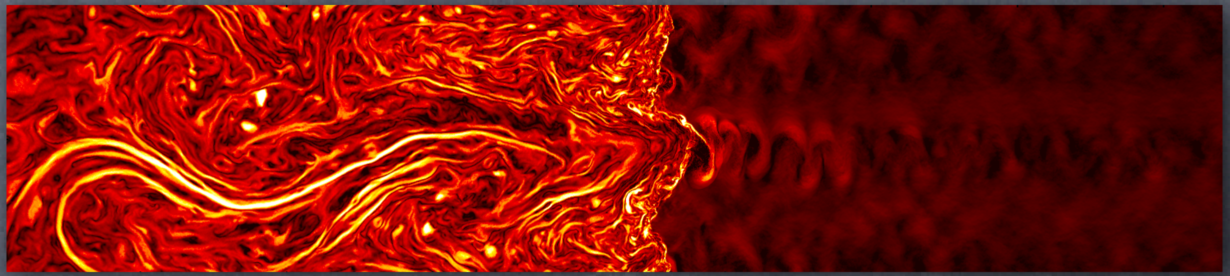


Eriksen et al., 2011

Outline





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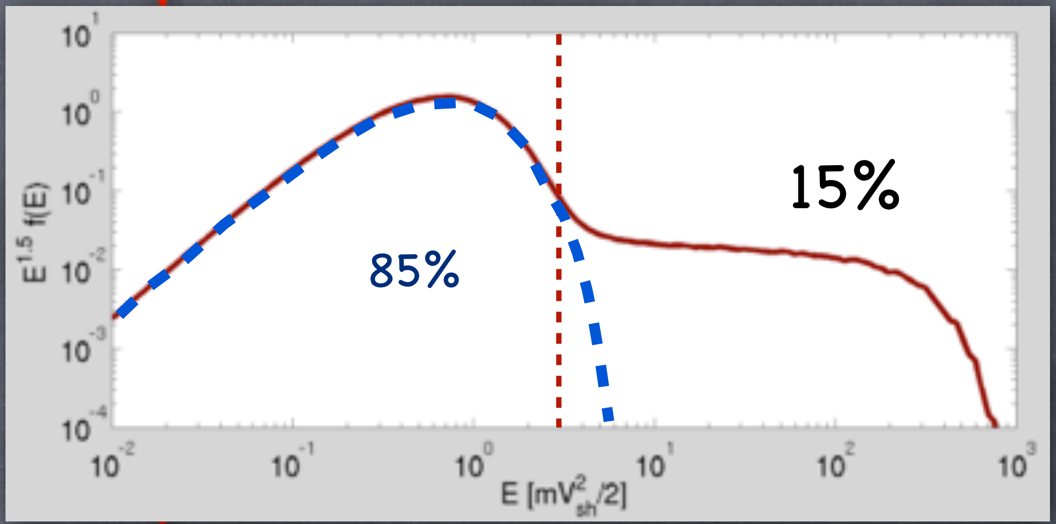

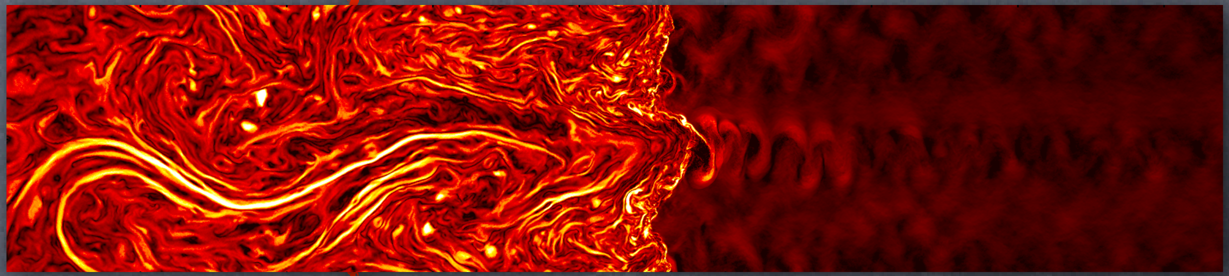

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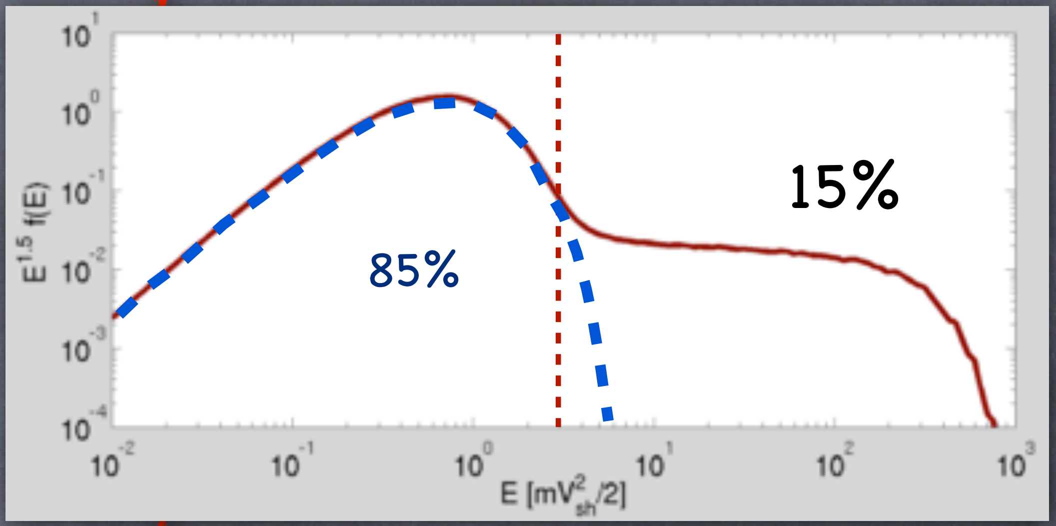
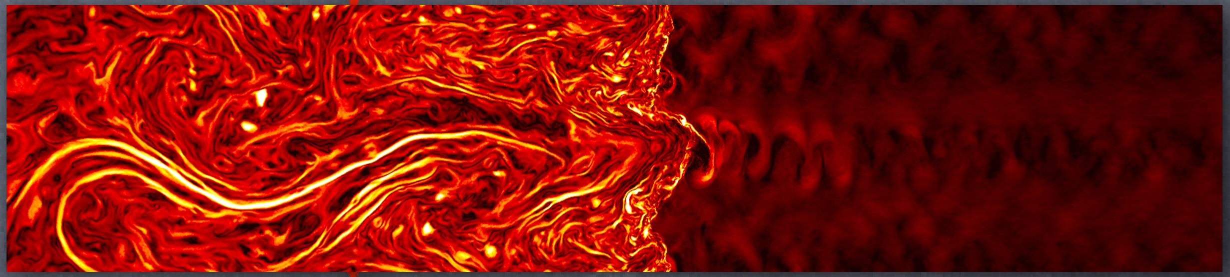




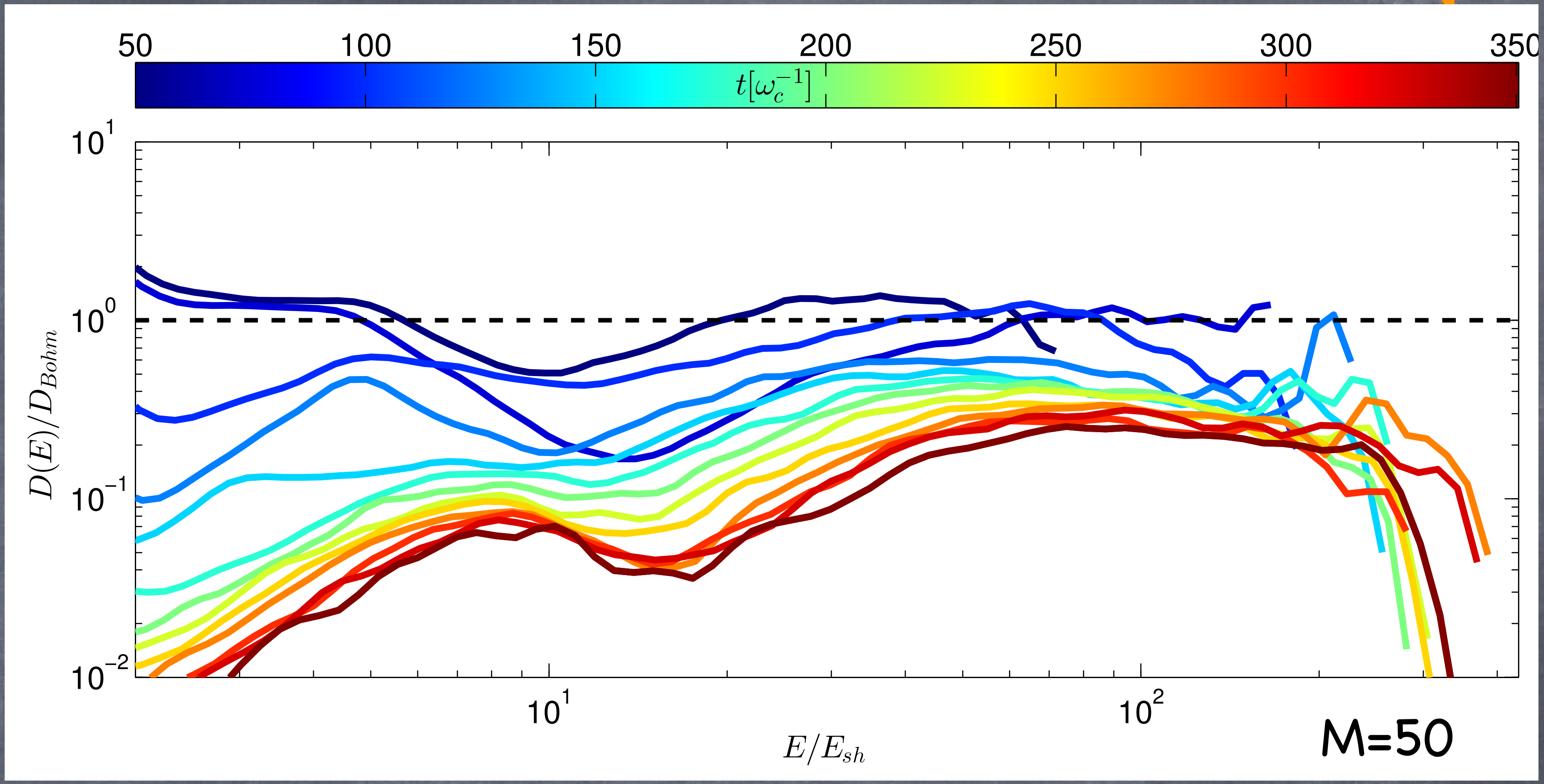
Time evolution

- Diffusion coefficient (averaged over the upstream)

- $\delta B/B \gtrsim 1$, F(k) const:

  Bohm diffusion!

$$D_{sg}(E) = \frac{8}{3\pi} \frac{D_B(E)}{\mathcal{F}(k)}$$



DC & Spitkovsky, in prep

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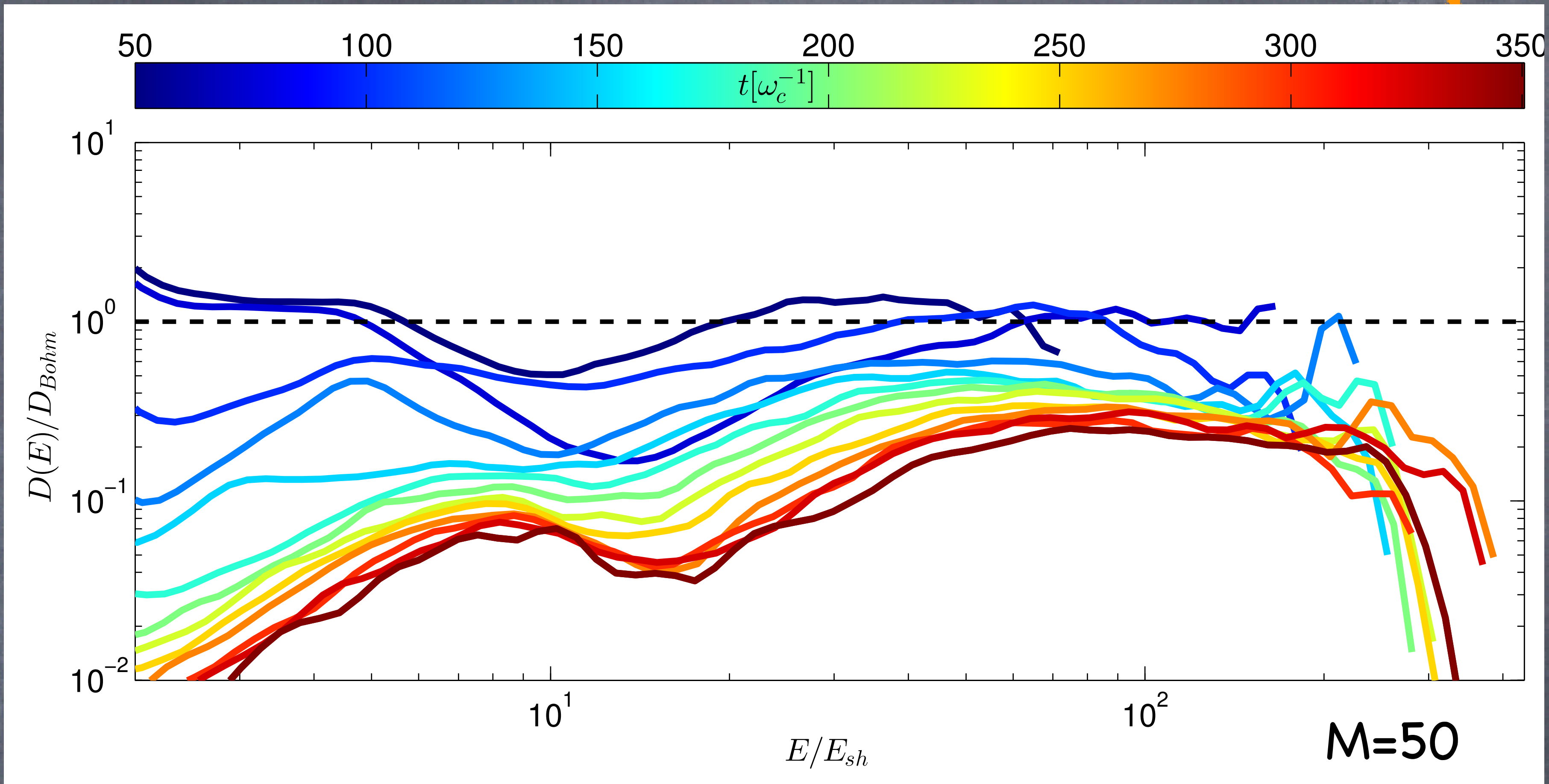
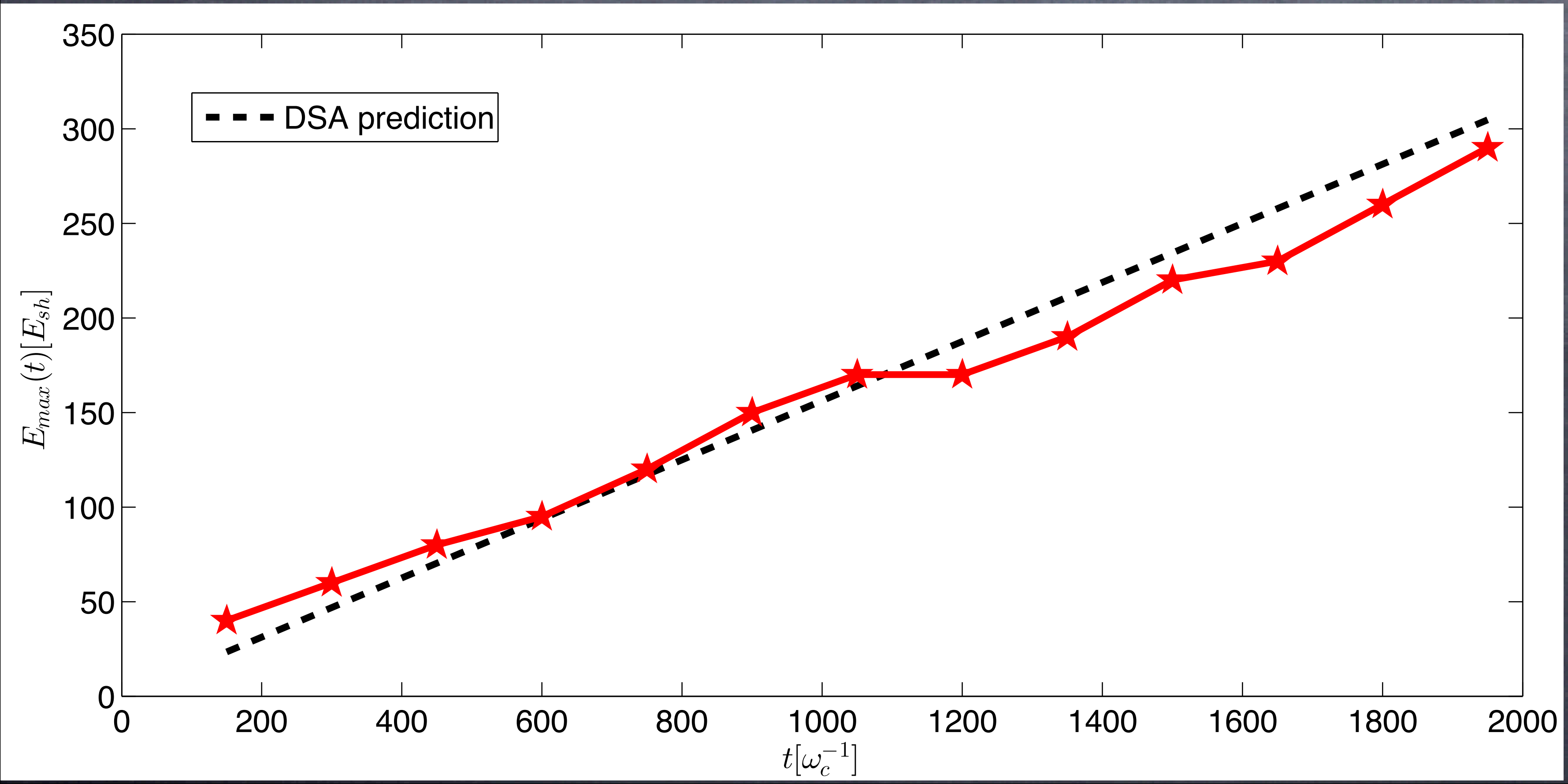


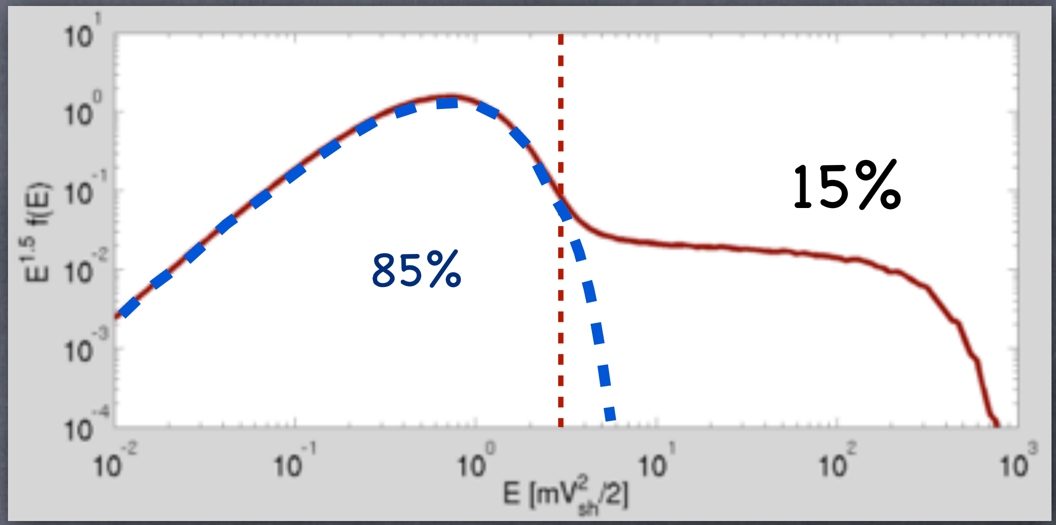


- Evolution of $E_{max}(t)$ for M=20 parallel shock

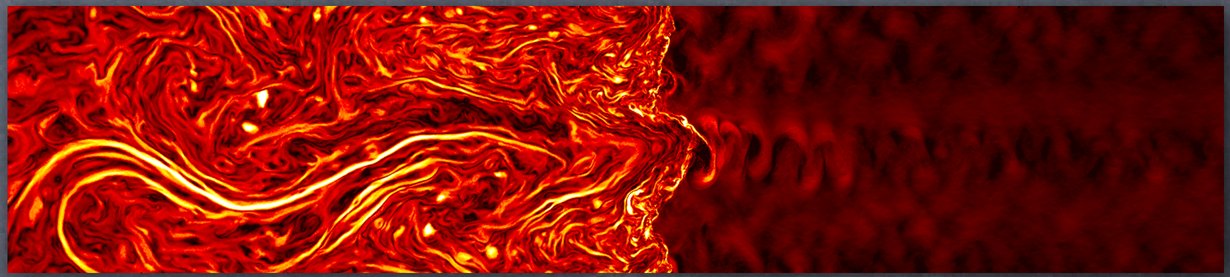
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$

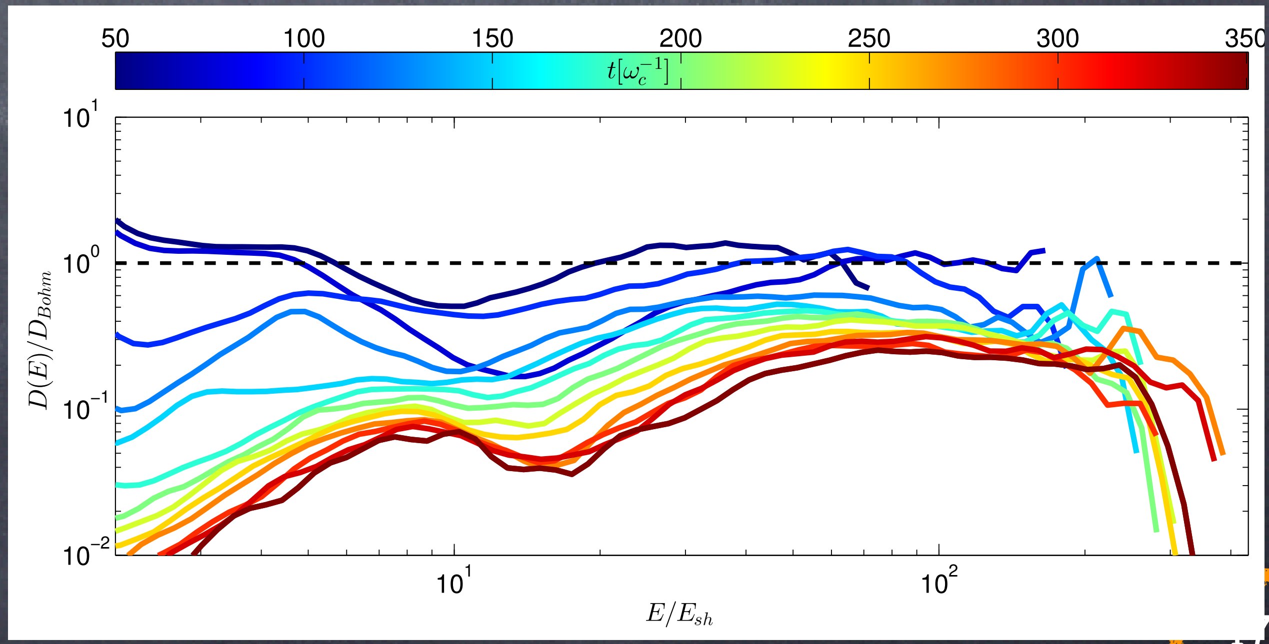
DC & Spitkovsky, in prep

Outline



15%
85%
E^1.5 f(E)
E [mV²sh/2]





50
100
150
200
250
300
350
t[ωc⁻¹]
D(E)/DBohm
E/Esh

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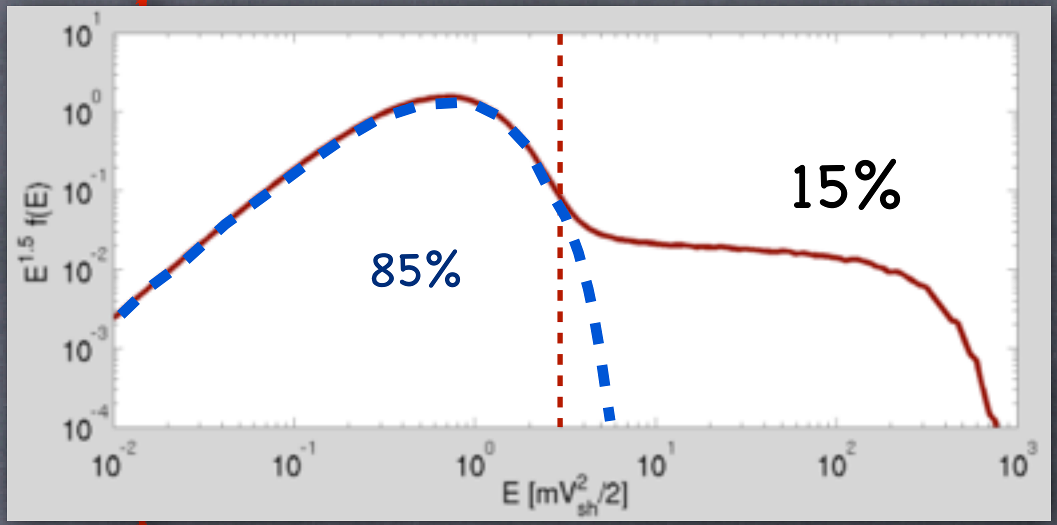
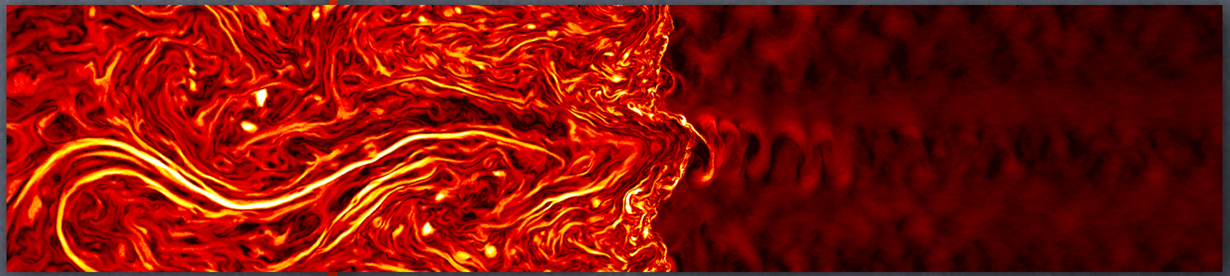
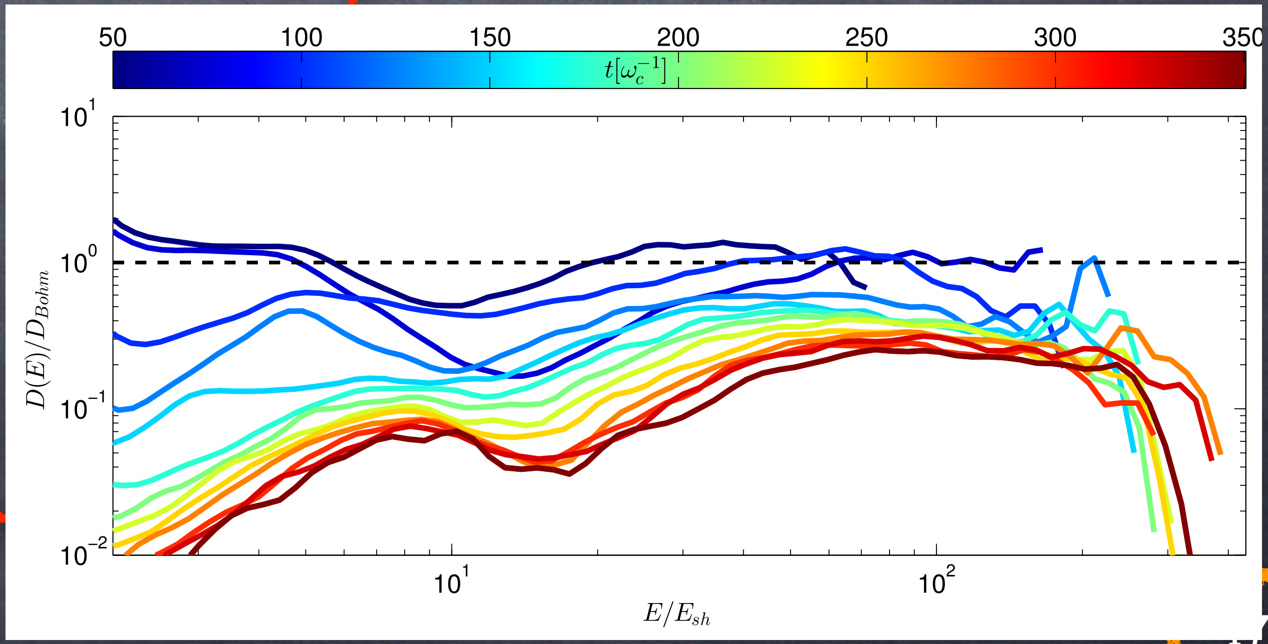
    - Bohm diffusion in δB
- When is DSA efficient?







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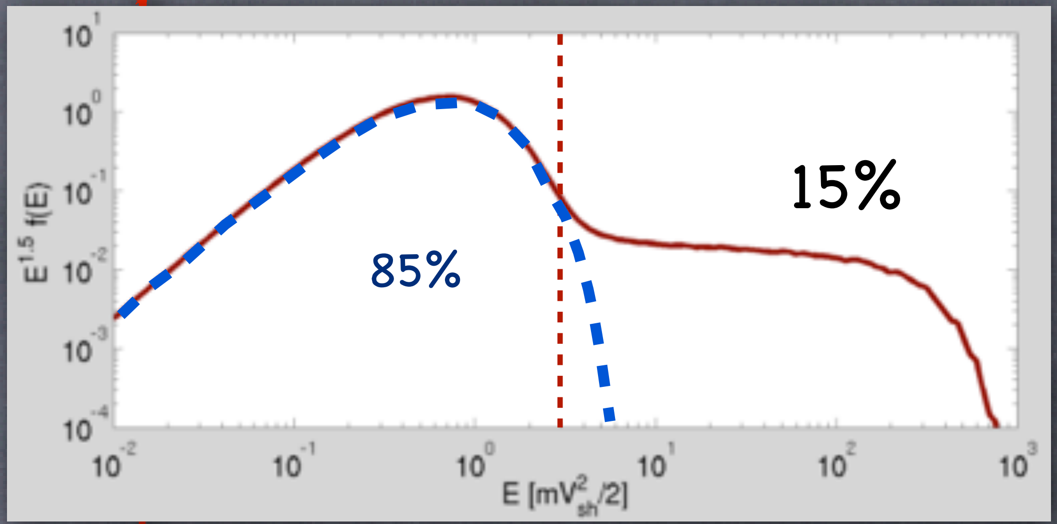

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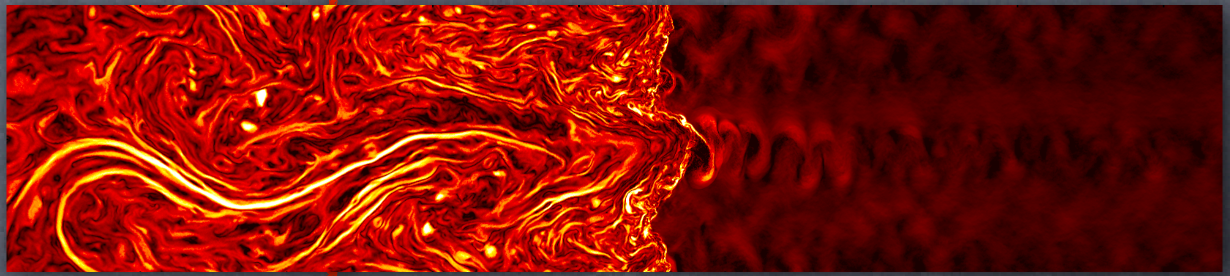

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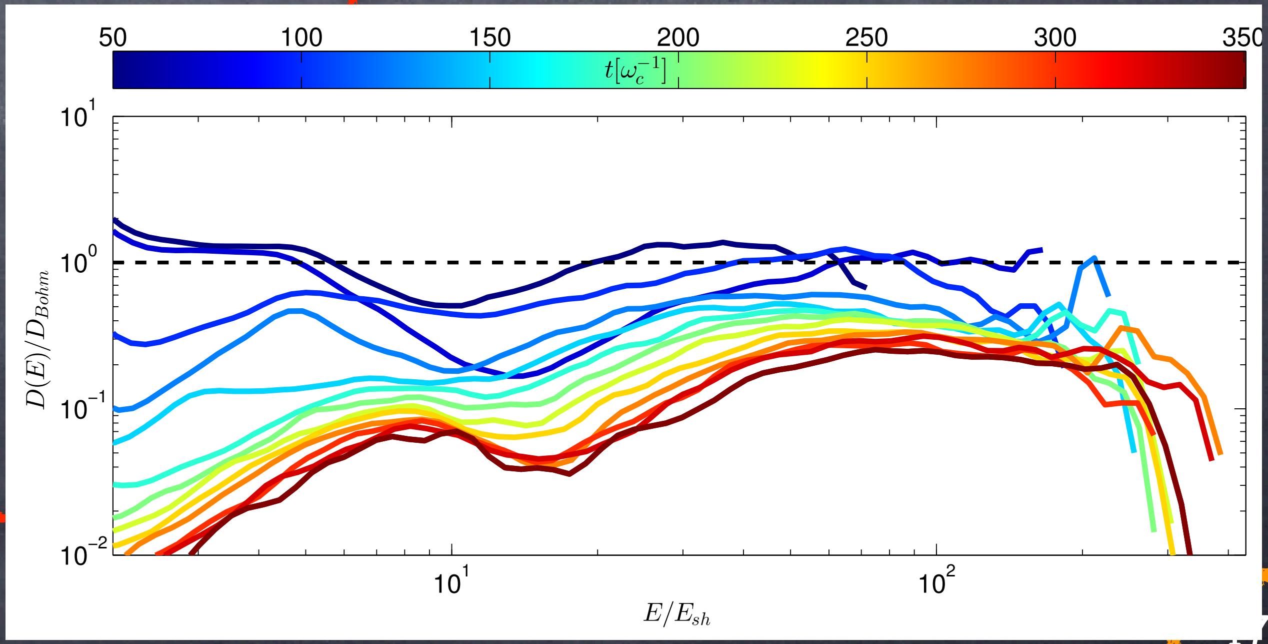
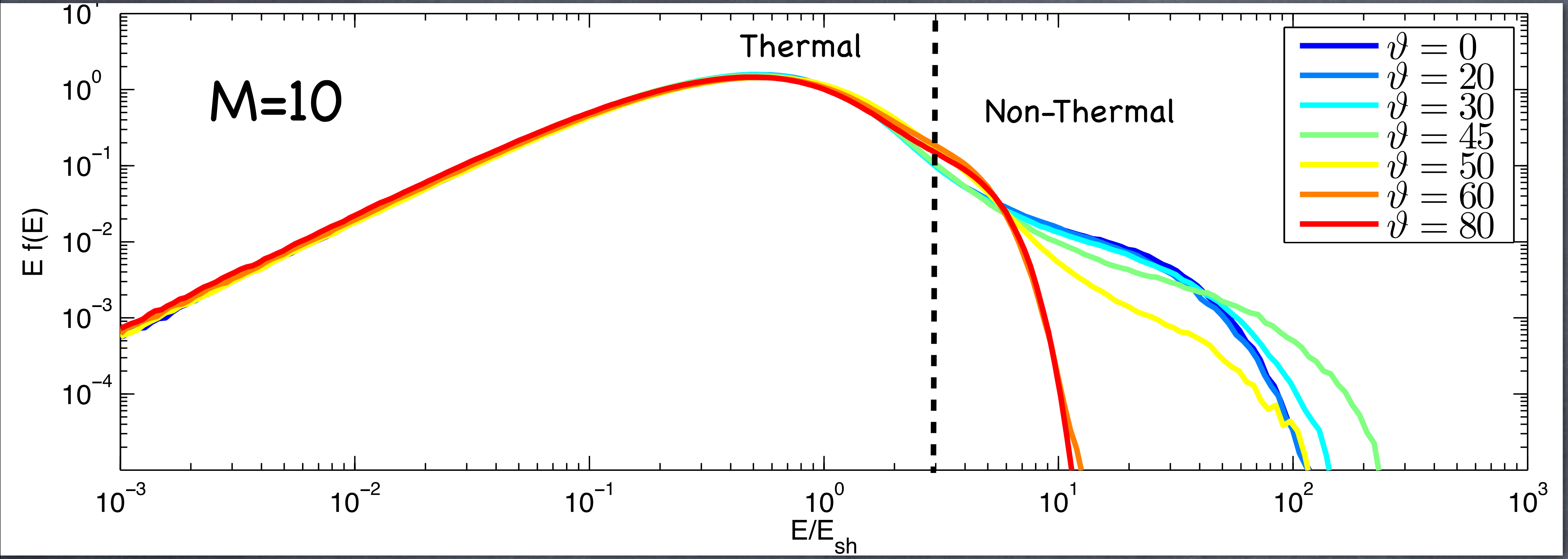
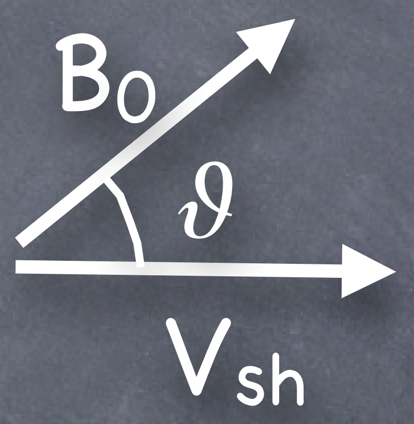


Parallel vs Oblique shocks





DC & Spitkovsky, arXiv:1310.2943

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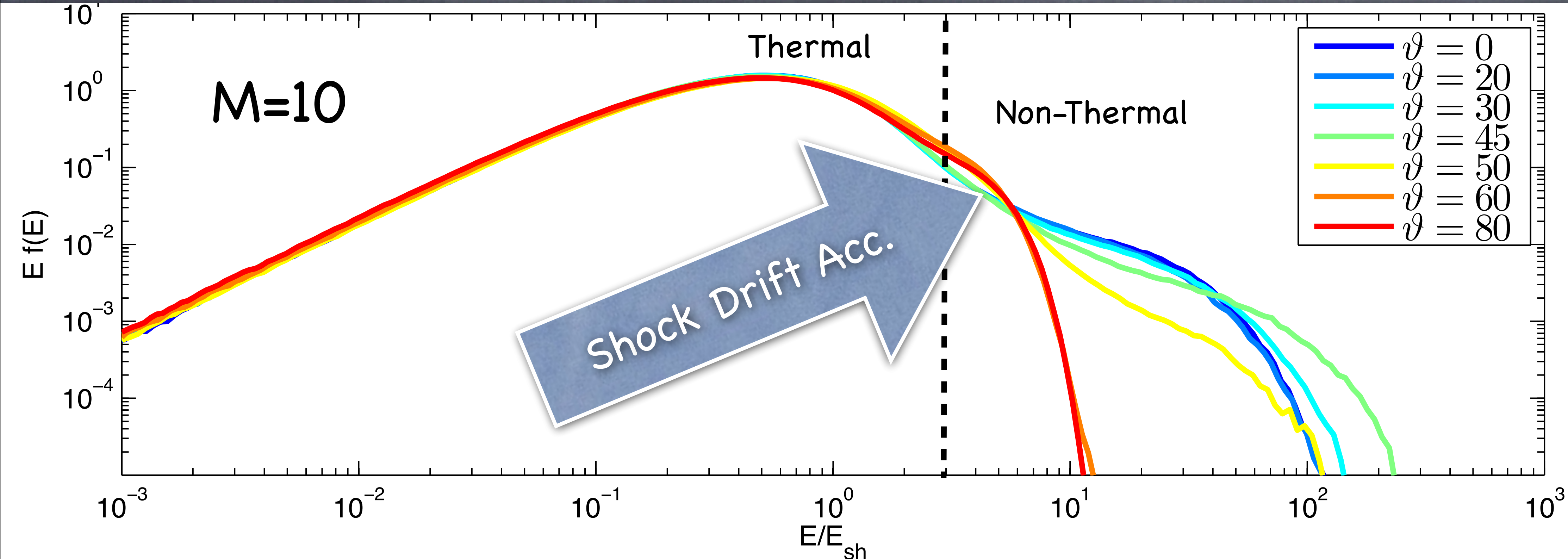

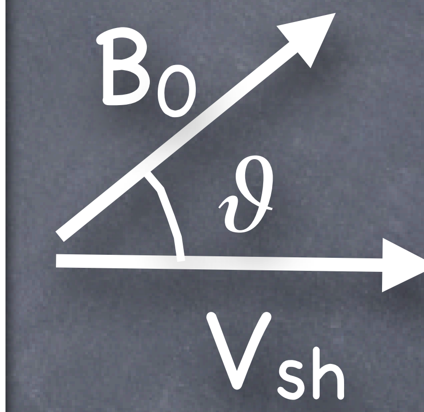

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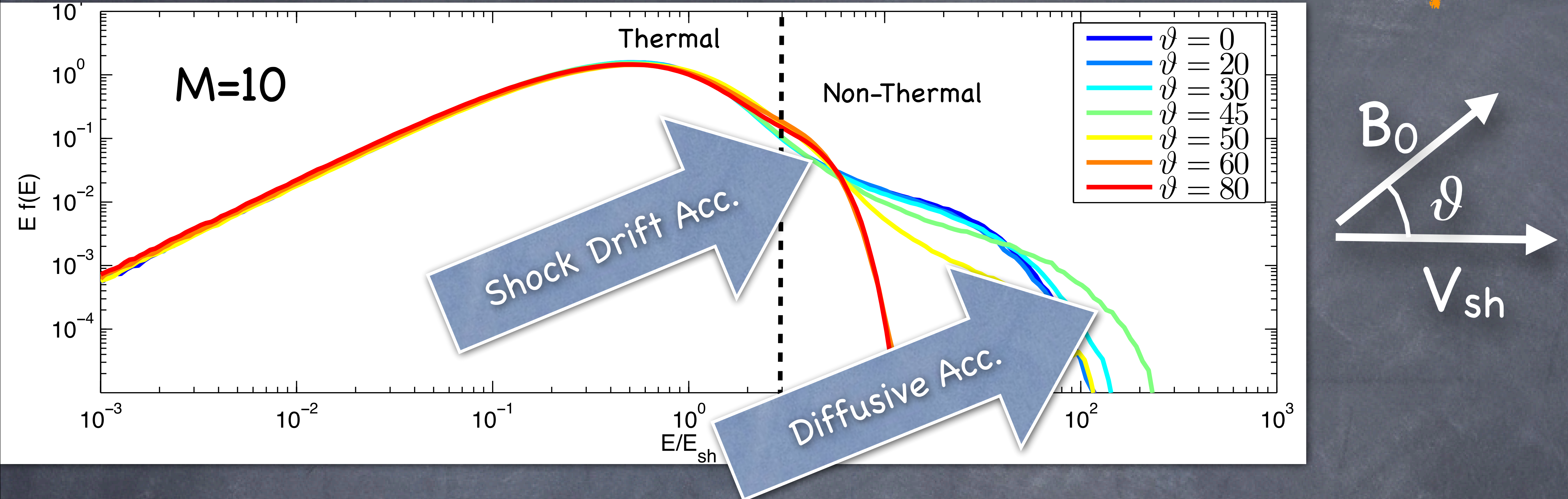

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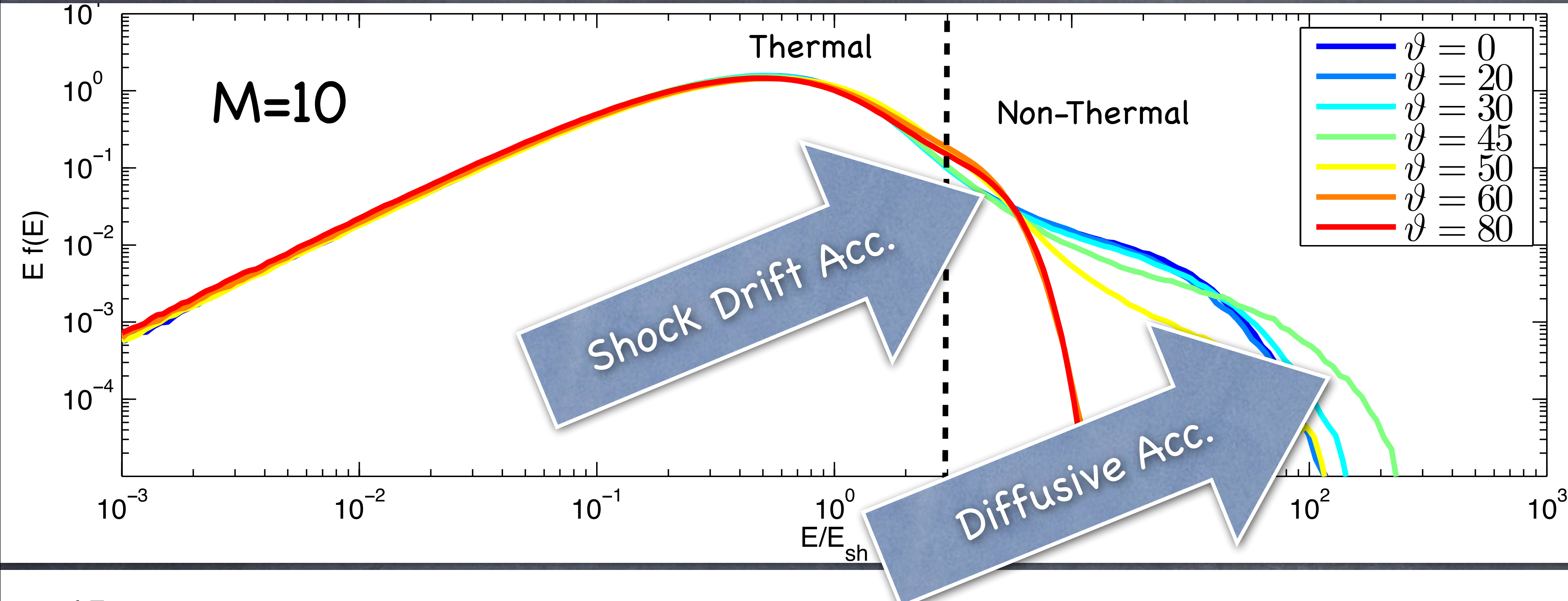
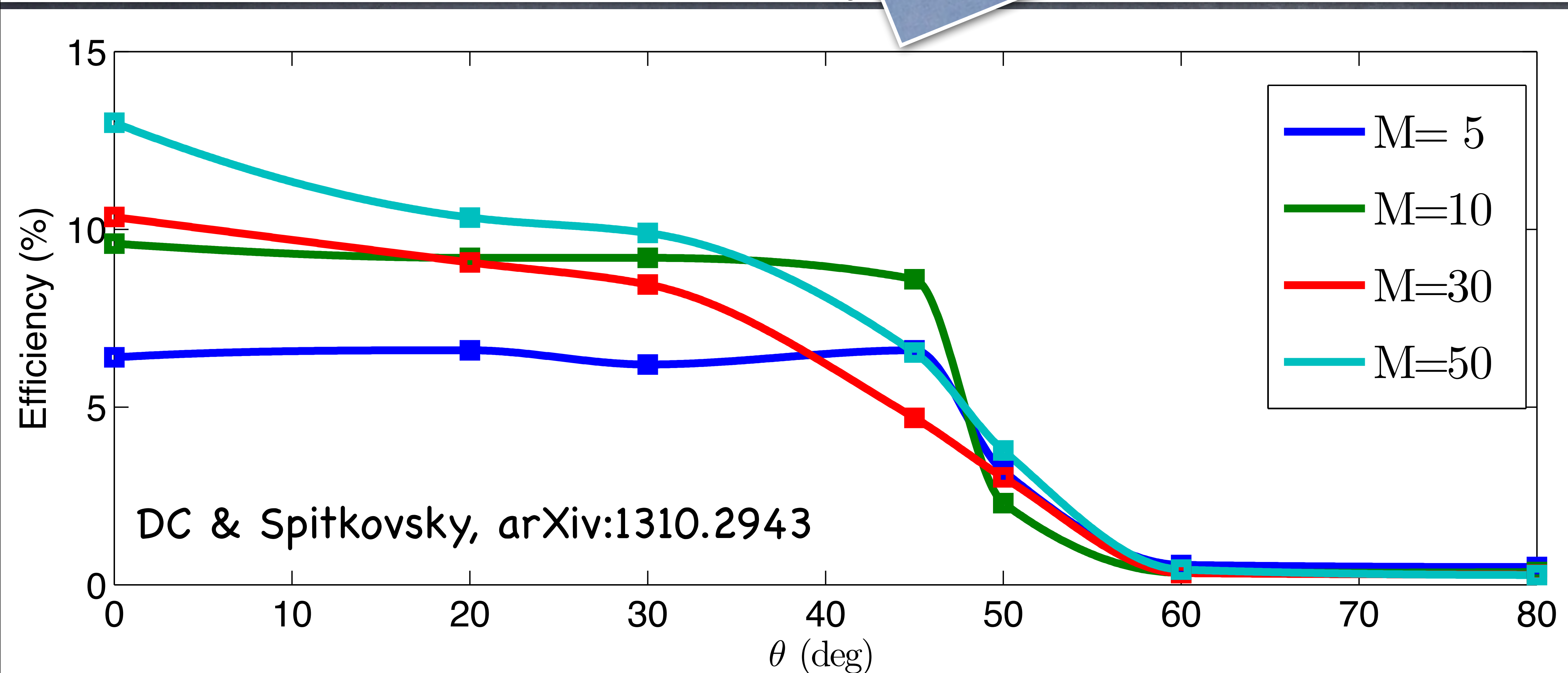
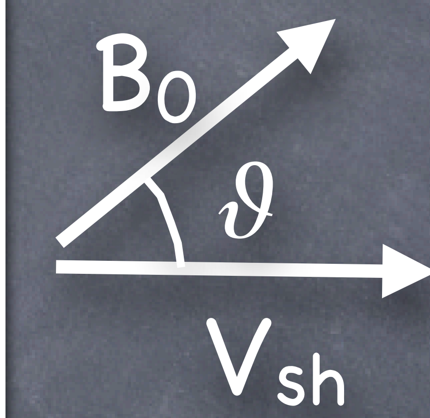




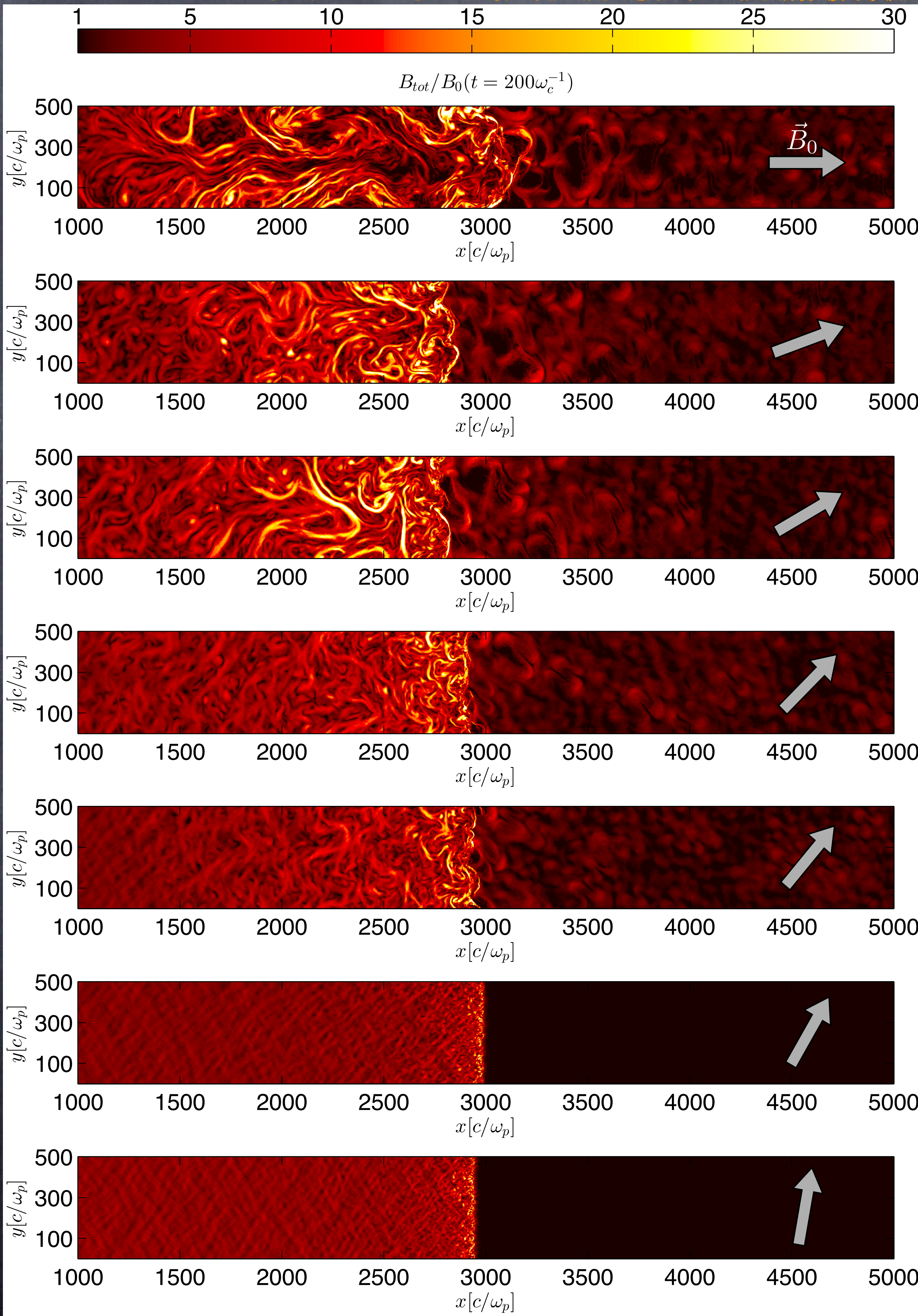


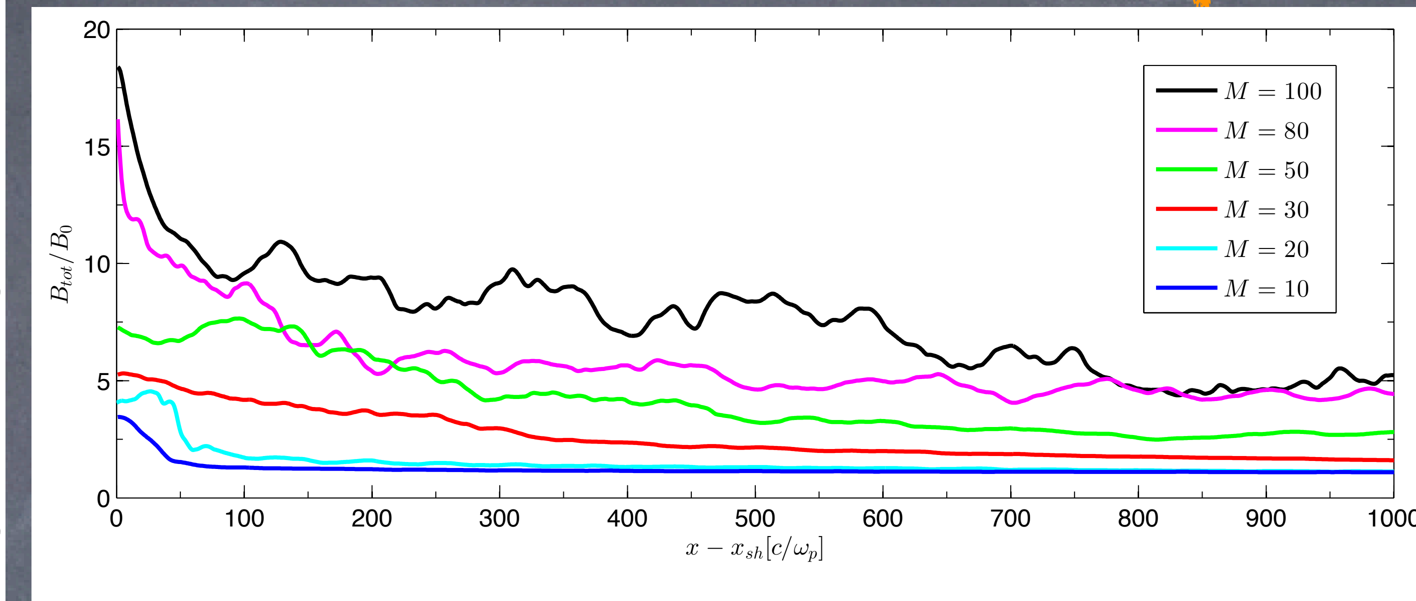
Each point is a state of the art simulation (10^9 particles)

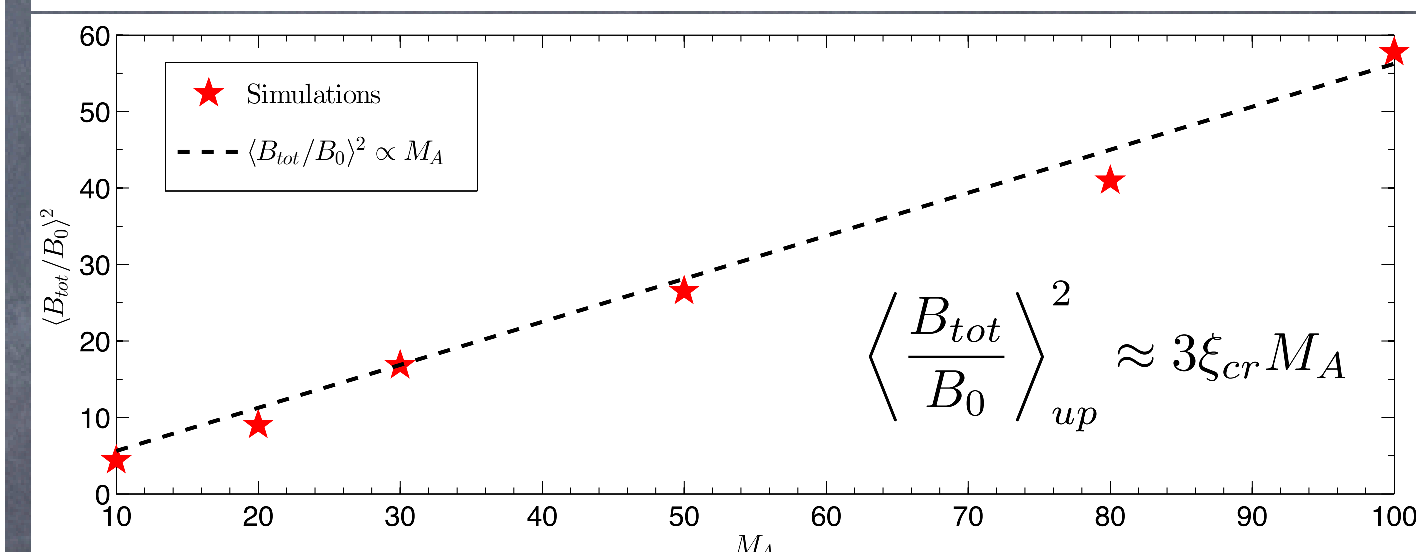
Computation time: almost

2×10^6 cpu h!

Dependence on inclination and M

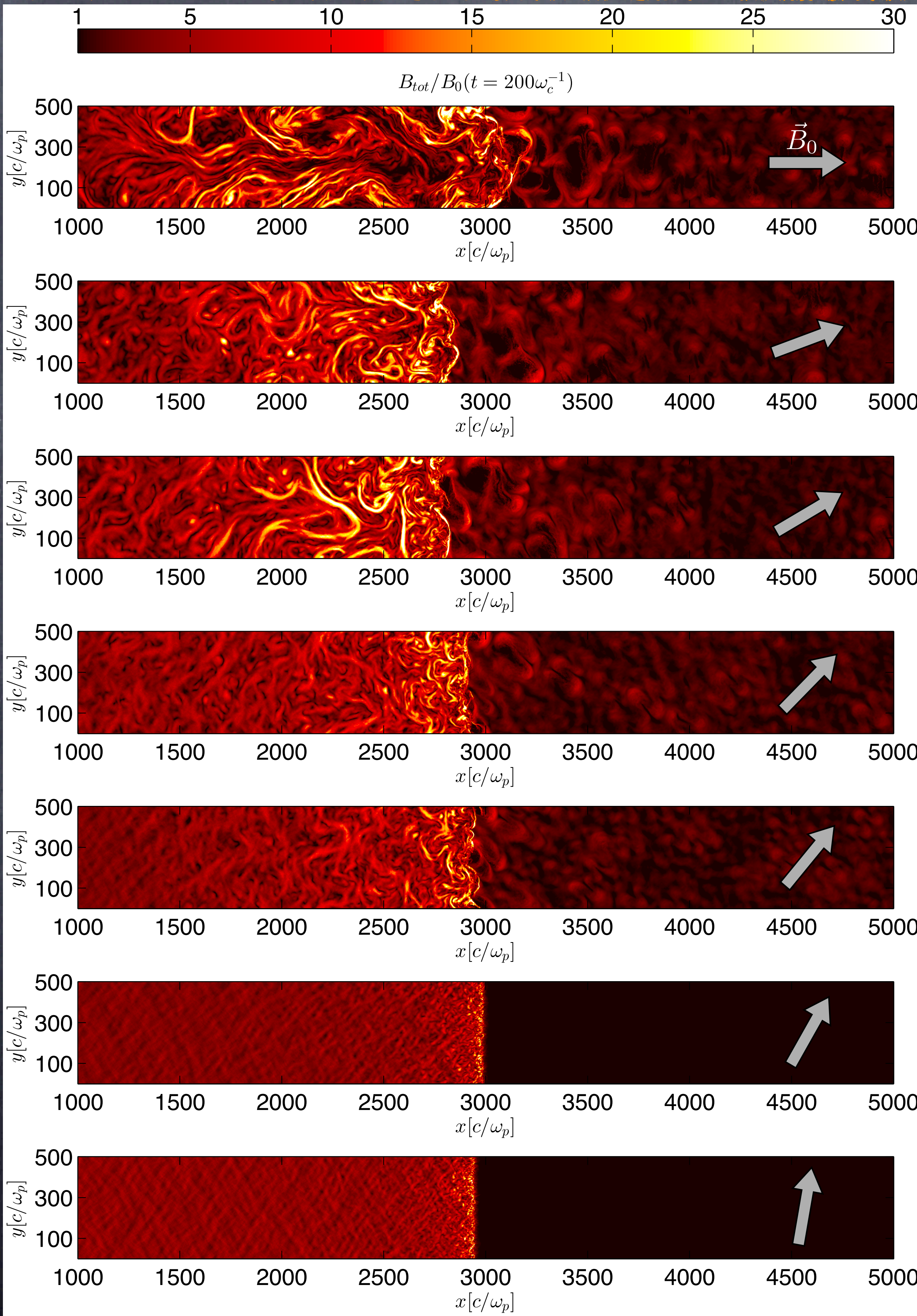


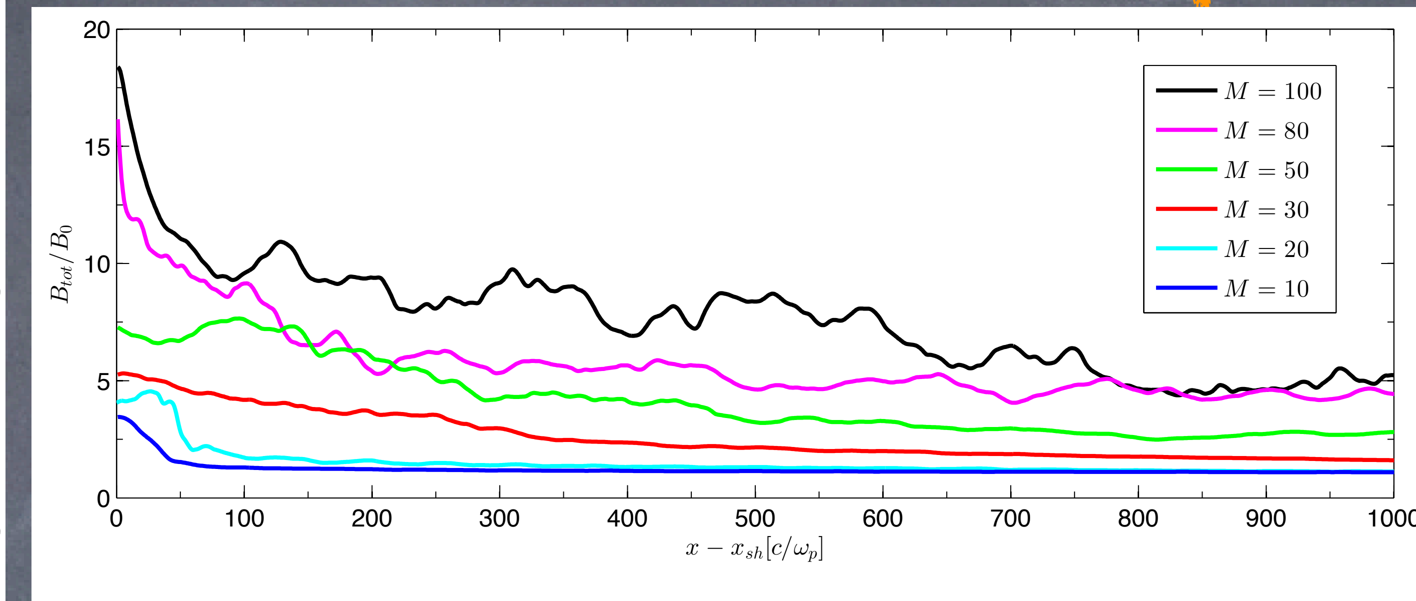


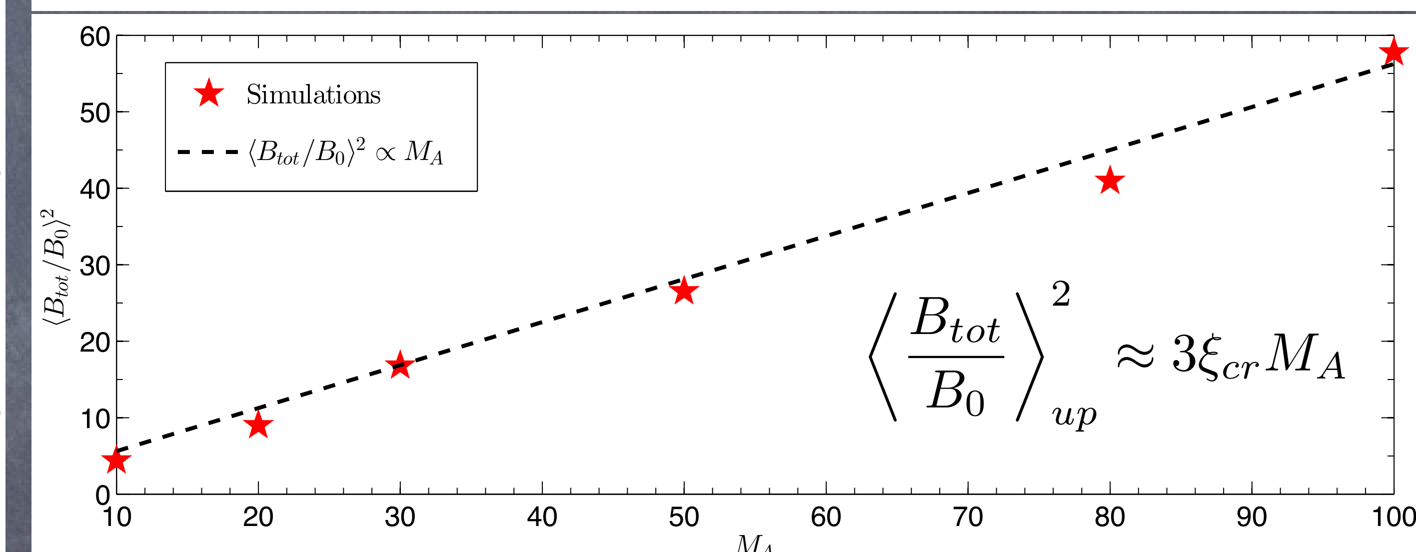


More B-field amplification for stronger shocks!

Dependence on inclination and M

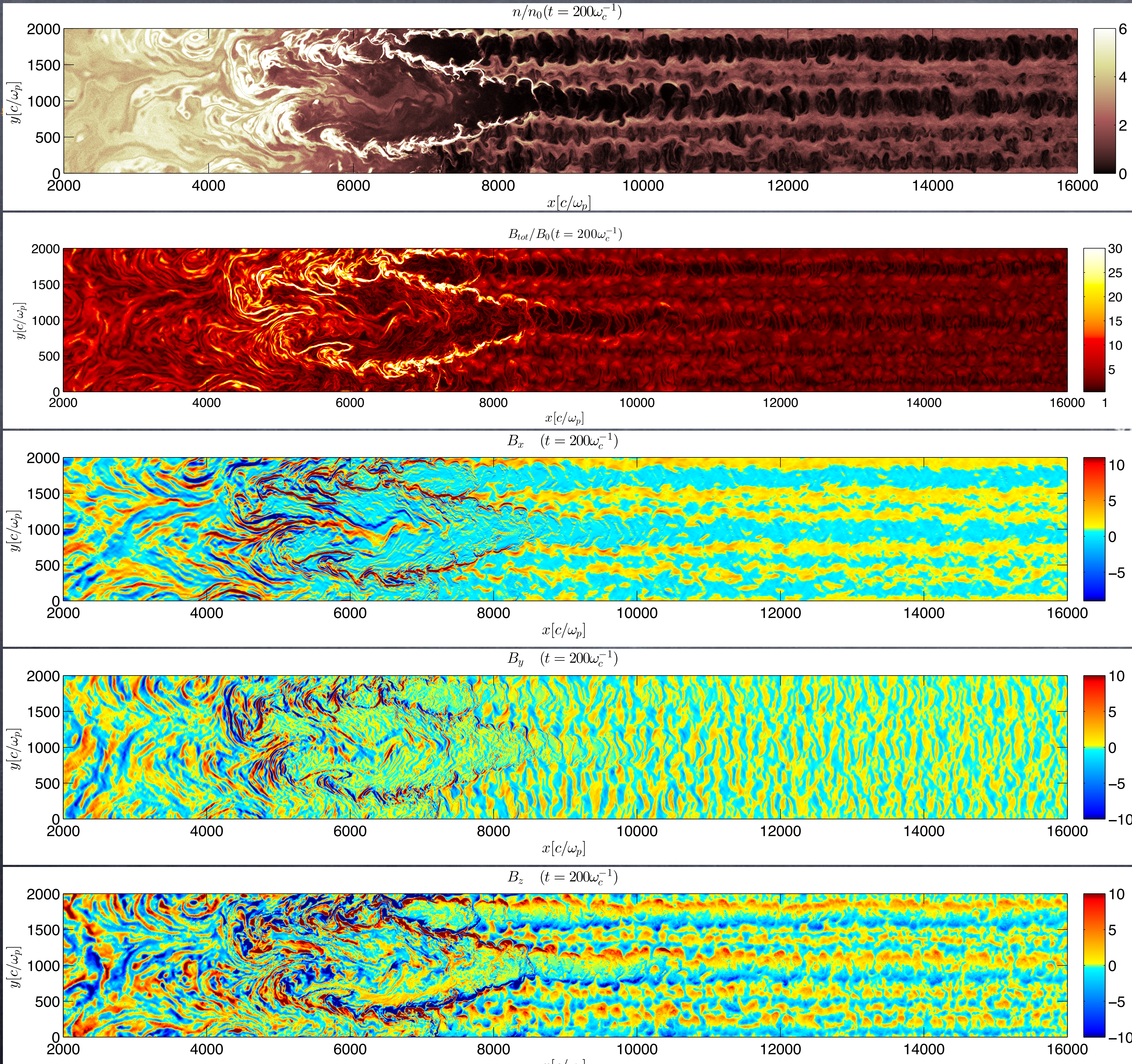






- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!



Preliminary

M=100 case

Total δB/B larger than 10 in the precursor!

Very hard to study in the hybrid limit

SN 1006: a parallel accelerator

X-ray emission
(red=thermal
white=synchrotron)

SN 1006: a parallel accelerator

X-ray emission
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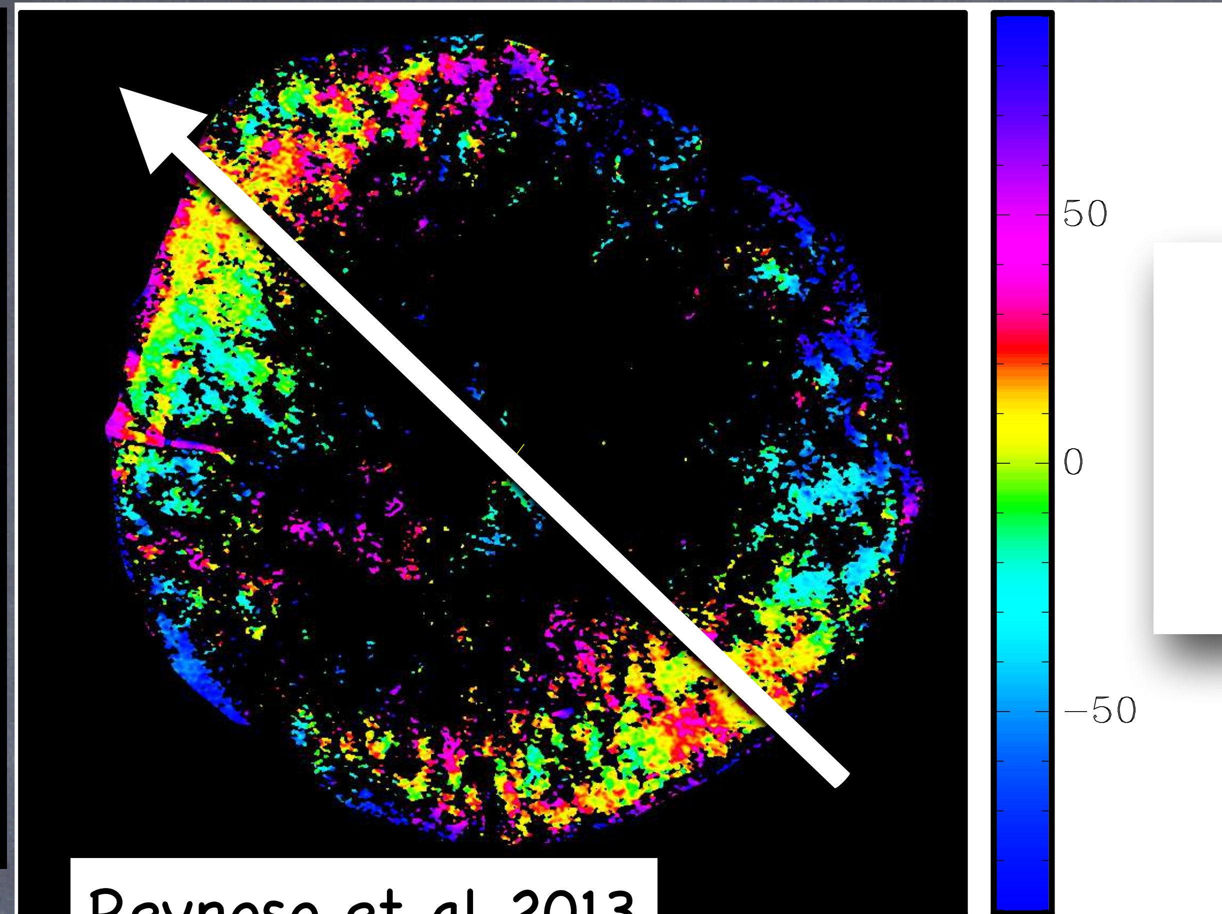
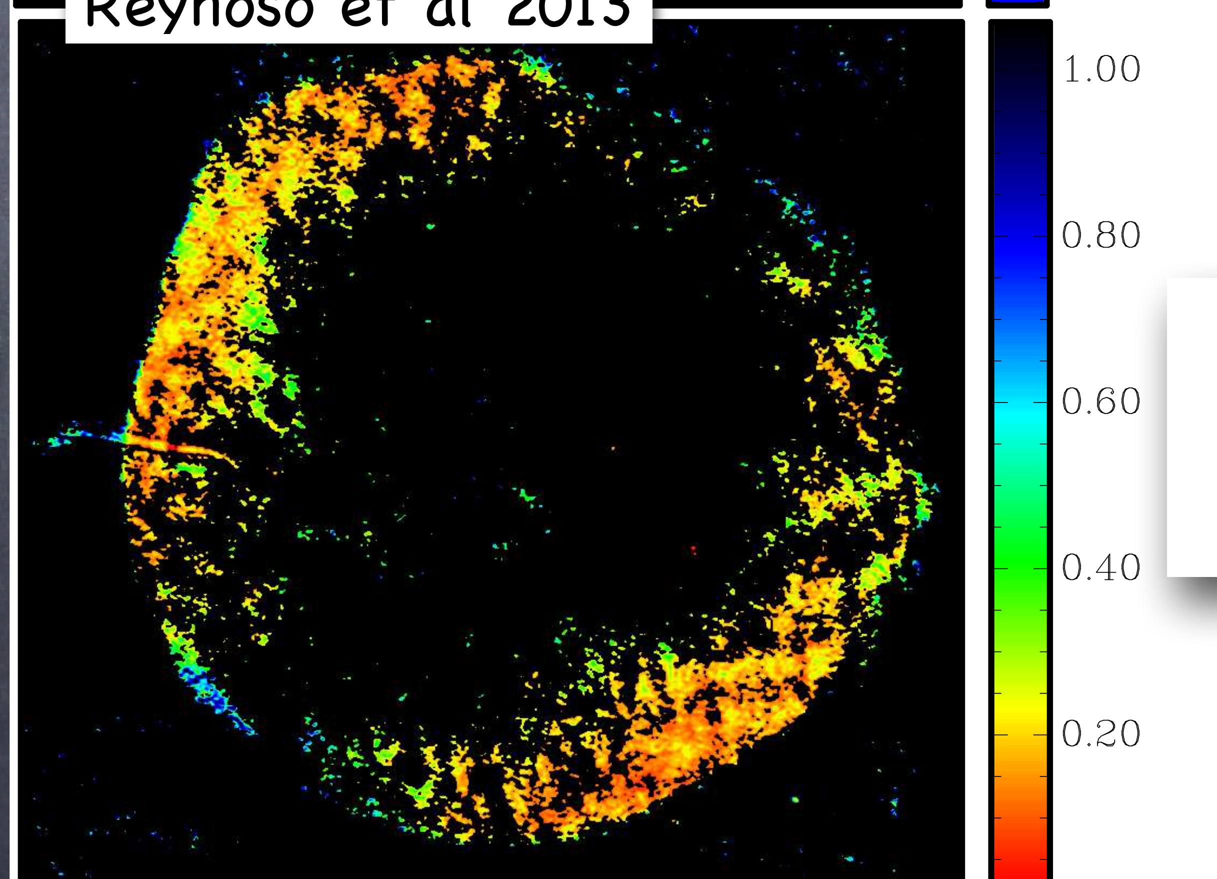


Reynoso et al 2013

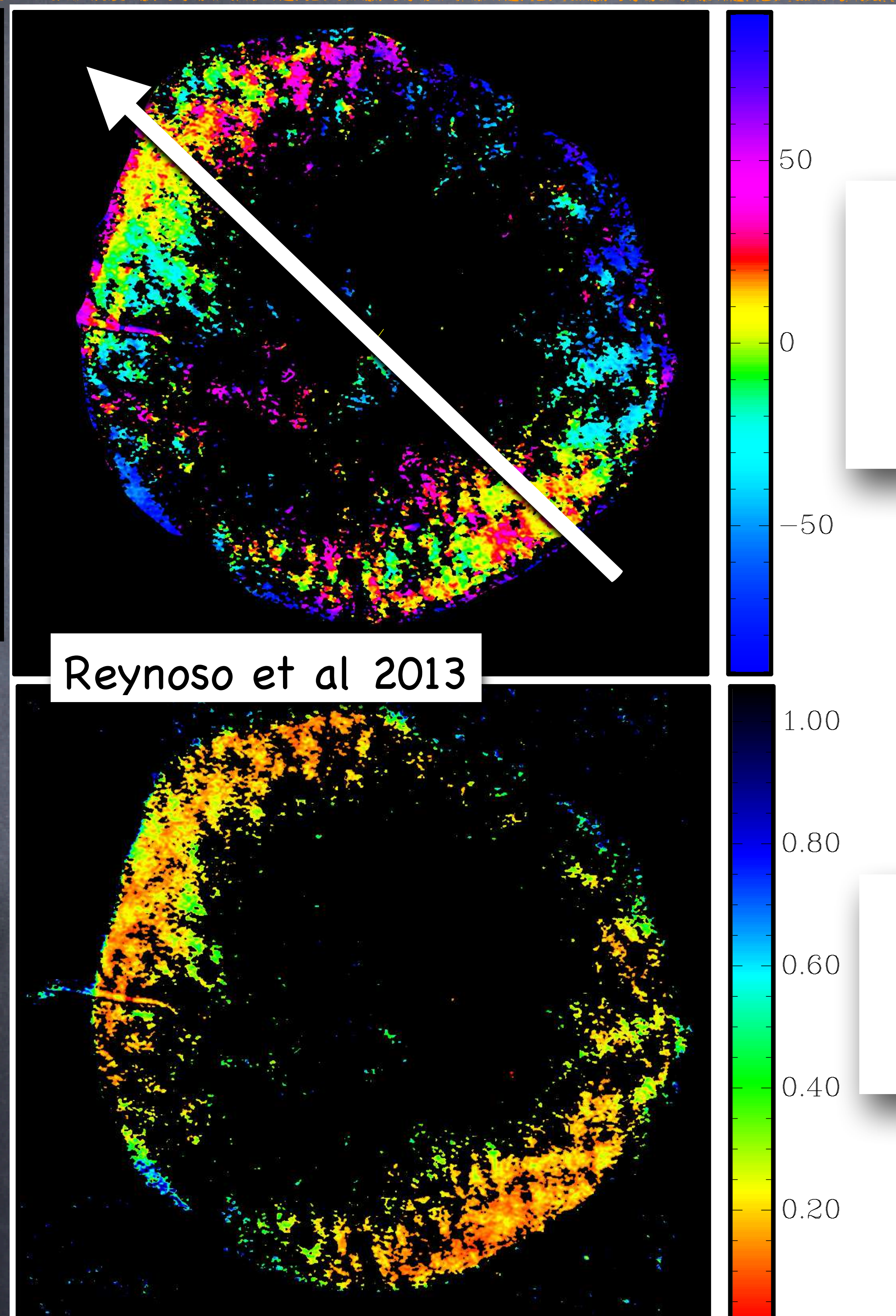
Inclination of the B field wrt to the shock normal



Polarization
(low=turbulent
high=ordered)

SN 1006: a parallel accelerator

X-ray emission
(red=thermal
white=synchrotron)



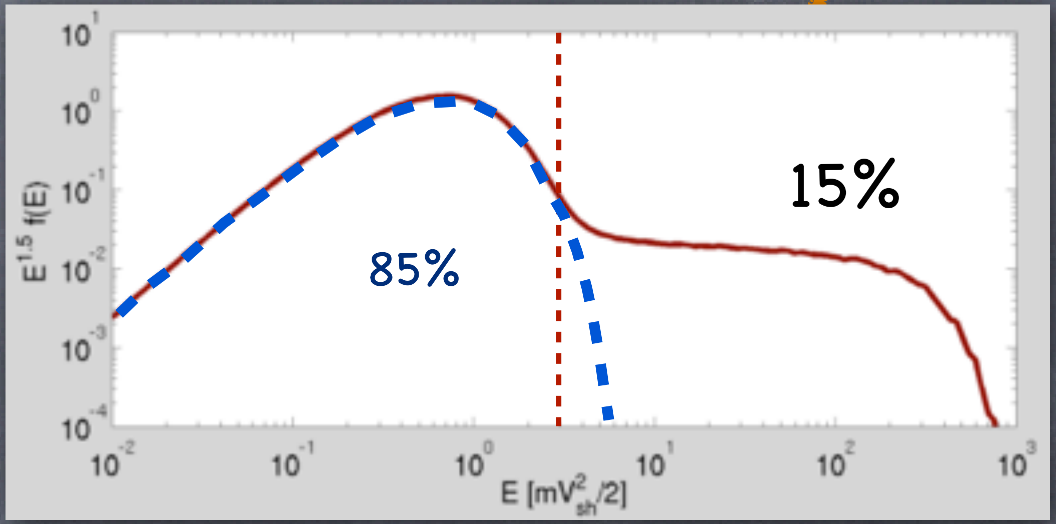
Reynoso et al 2013

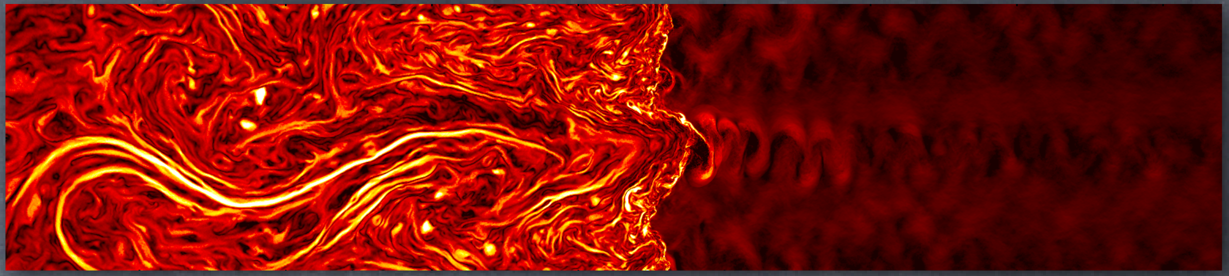
Inclination of the B field wrt to the shock normal

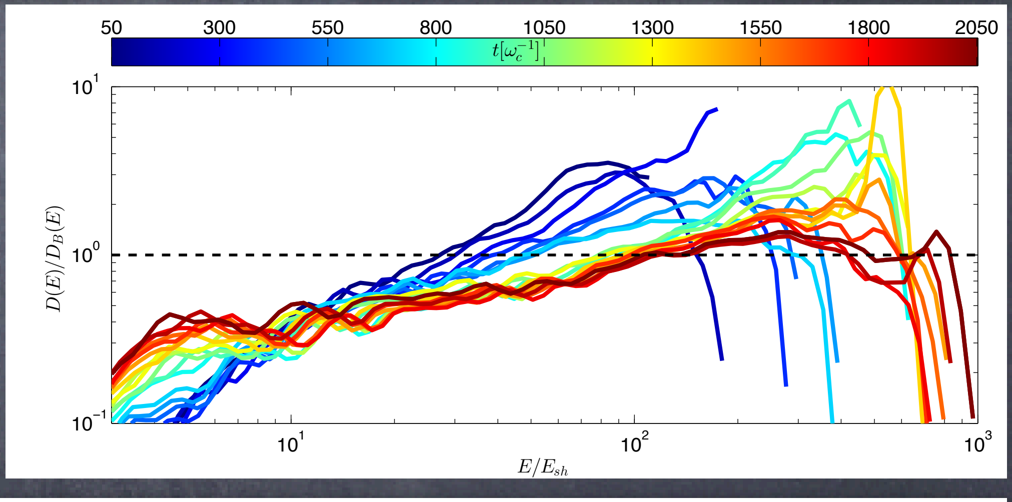
Polarization (low=turbulent high=ordered)

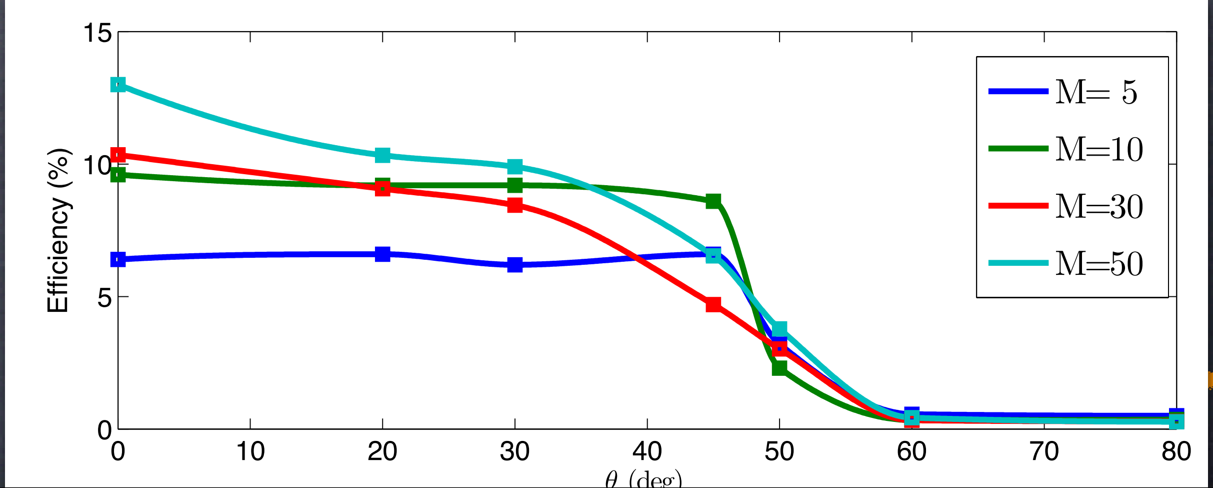
Magnetic field amplification and particle acceleration where the shock is parallel

Outline


85%
15%
E [mV²sh/2]
E1.5 f(E)

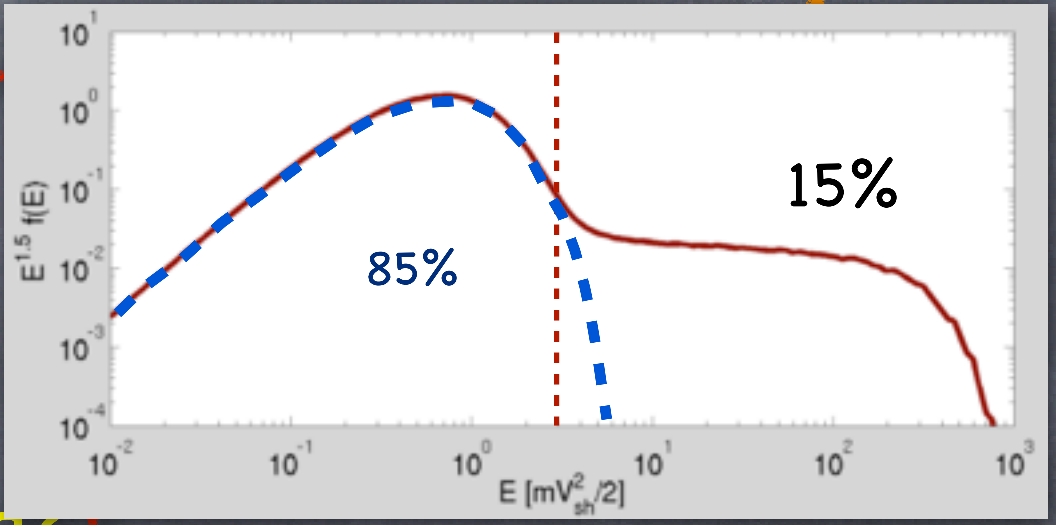


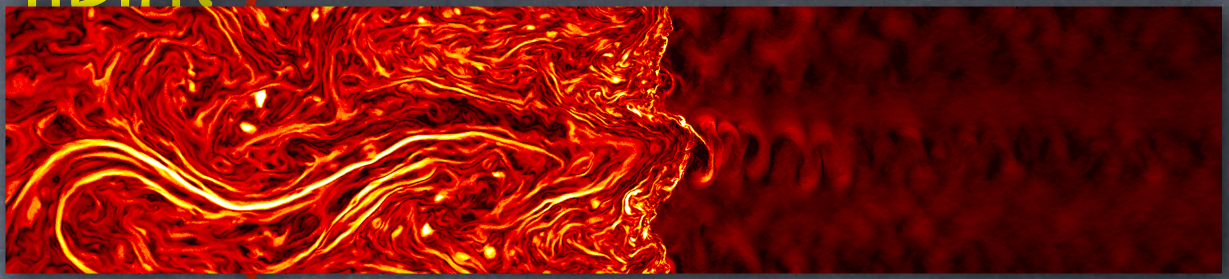

50 300 550 800 1050 1300 1550 1800 2050
D(E)/D_B(E)
E/E_sh

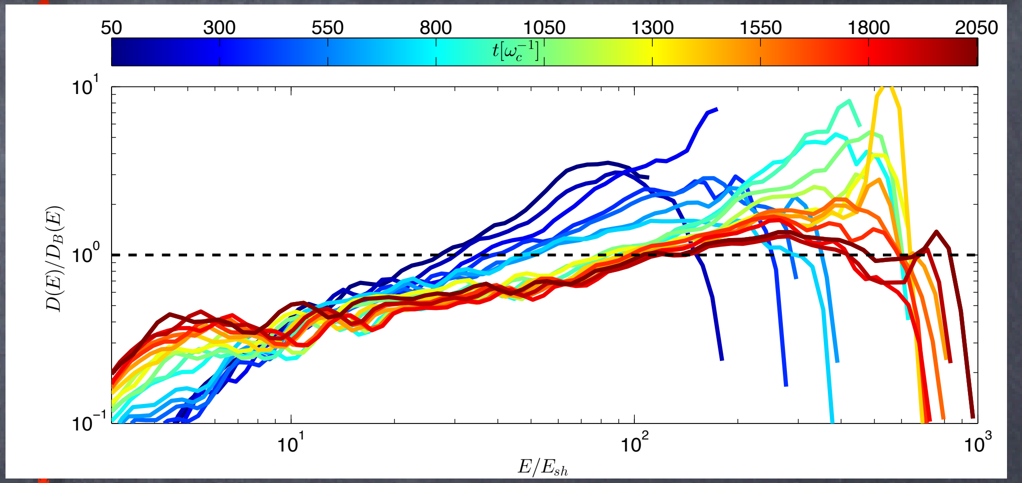

M= 5
M=10
M=30
M=50
Efficiency (%)

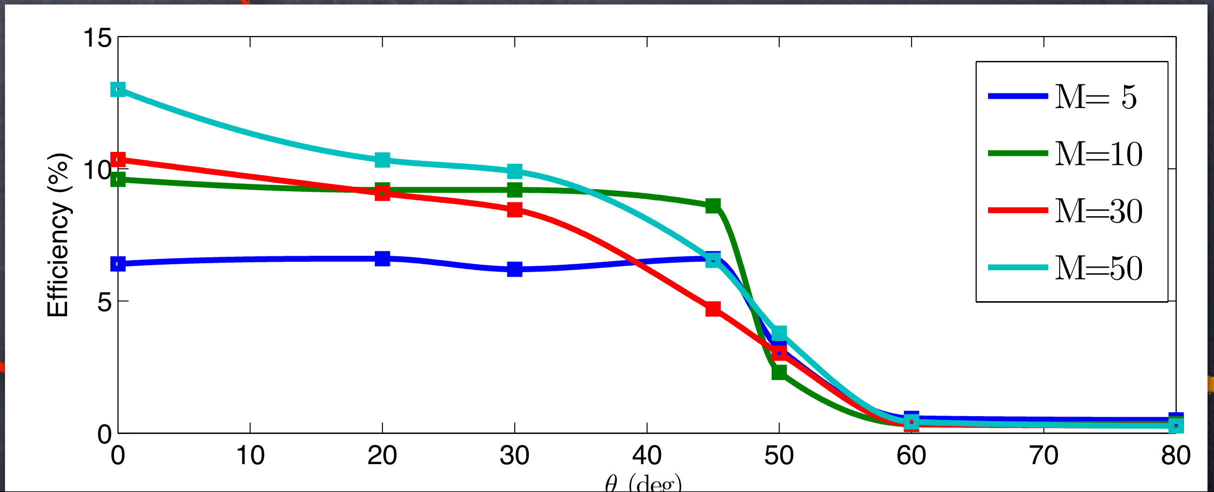
Outline

- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%
- How do CRs amplify the magnetic field?
  - Filamentation instability
- How do CRs scatter on the self-gen B?
  - Bohm diffusion (in δB?)
- Where is DSA efficient?
  - At parallel, strong shocks



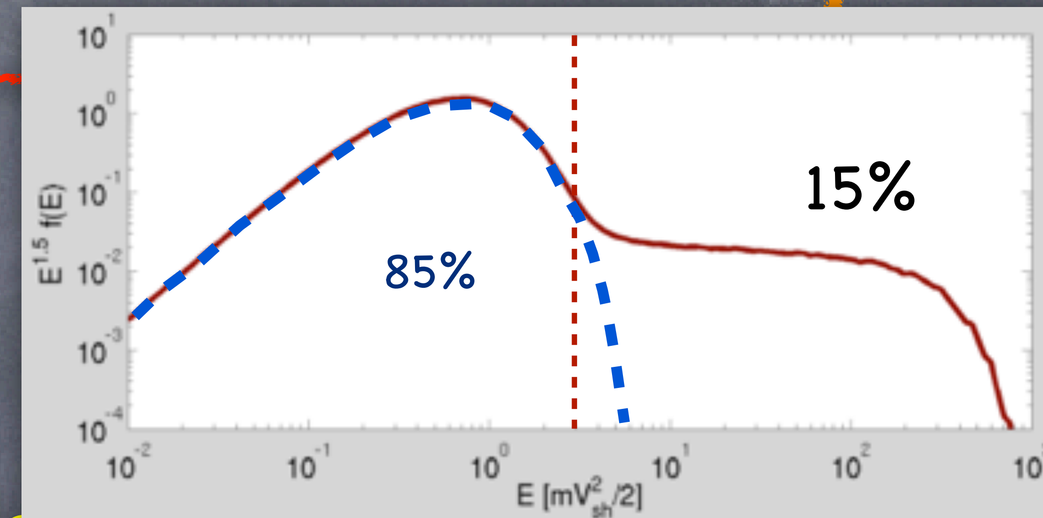




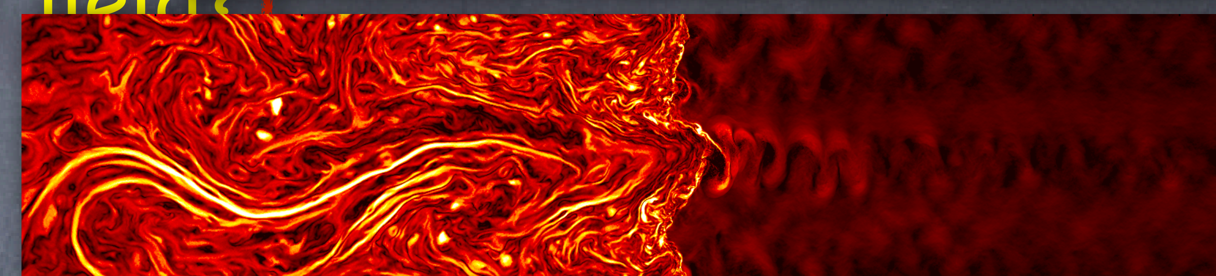


Outline

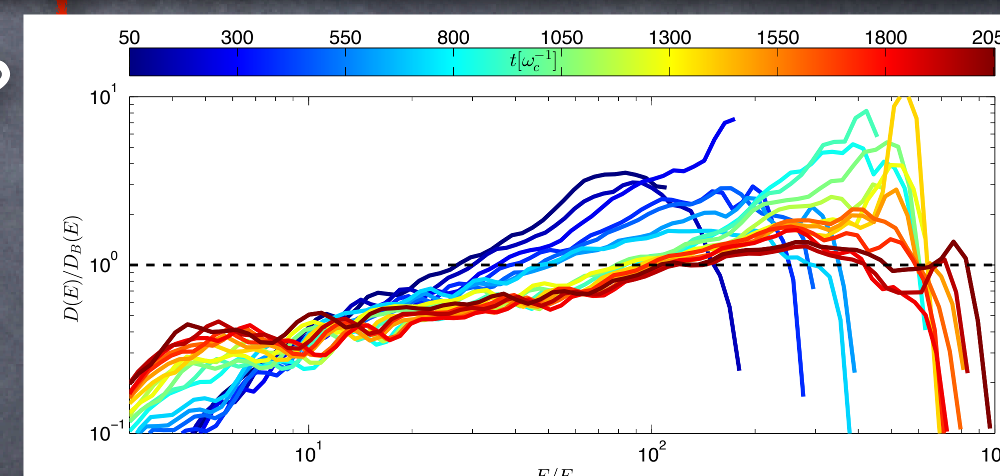
- Is acceleration at **shocks** efficient?
  - Hybrid simulations: >15%



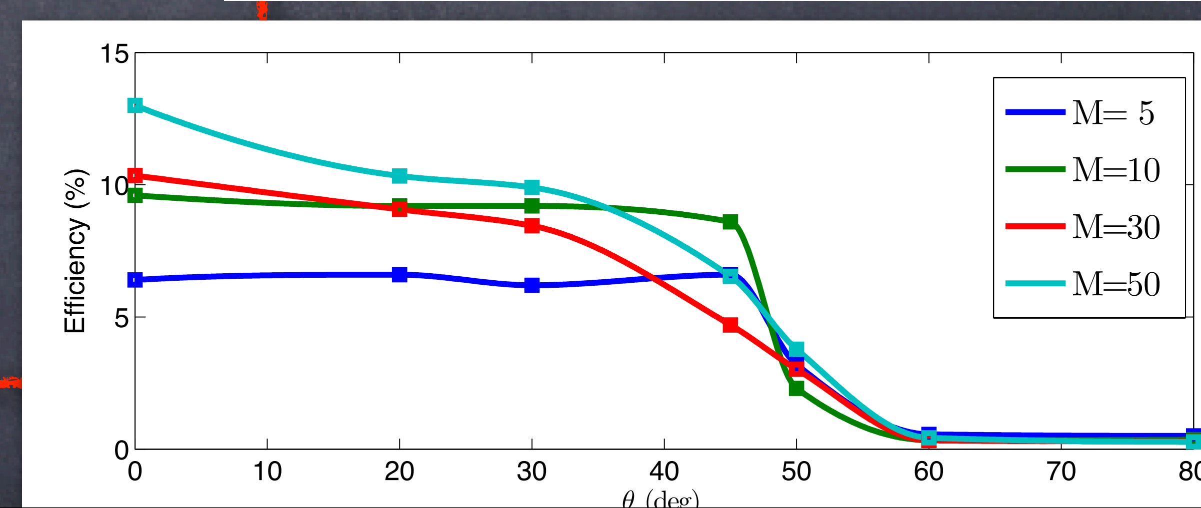
- How do CRs **amplify** the **magnetic field**?
  - **Filamentation instability**



- How do CRs **scatter** on the self-gen B?
  - **Bohm** diffusion (in δB?)



- Where is DSA **efficient**?
  - At **parallel**, strong shocks



Future perspectives

SN1006 rim - HST

Future perspectives

- Particle - wave interaction from simulations

SN1006 rim - HST

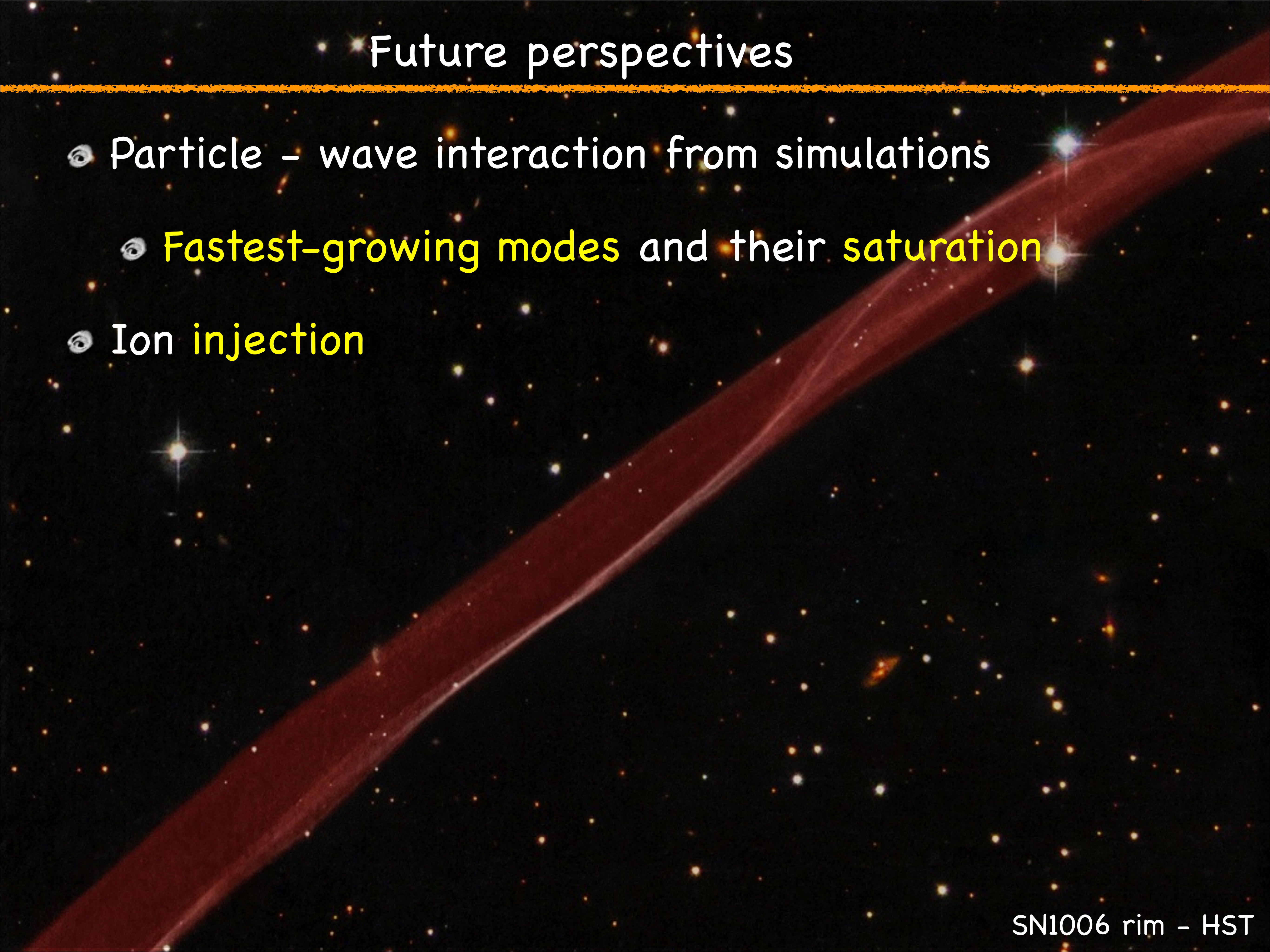
Future perspectives

- Particle - wave interaction from simulations
  - Fastest-growing modes and their saturation

SN1006 rim - HST

Future perspectives

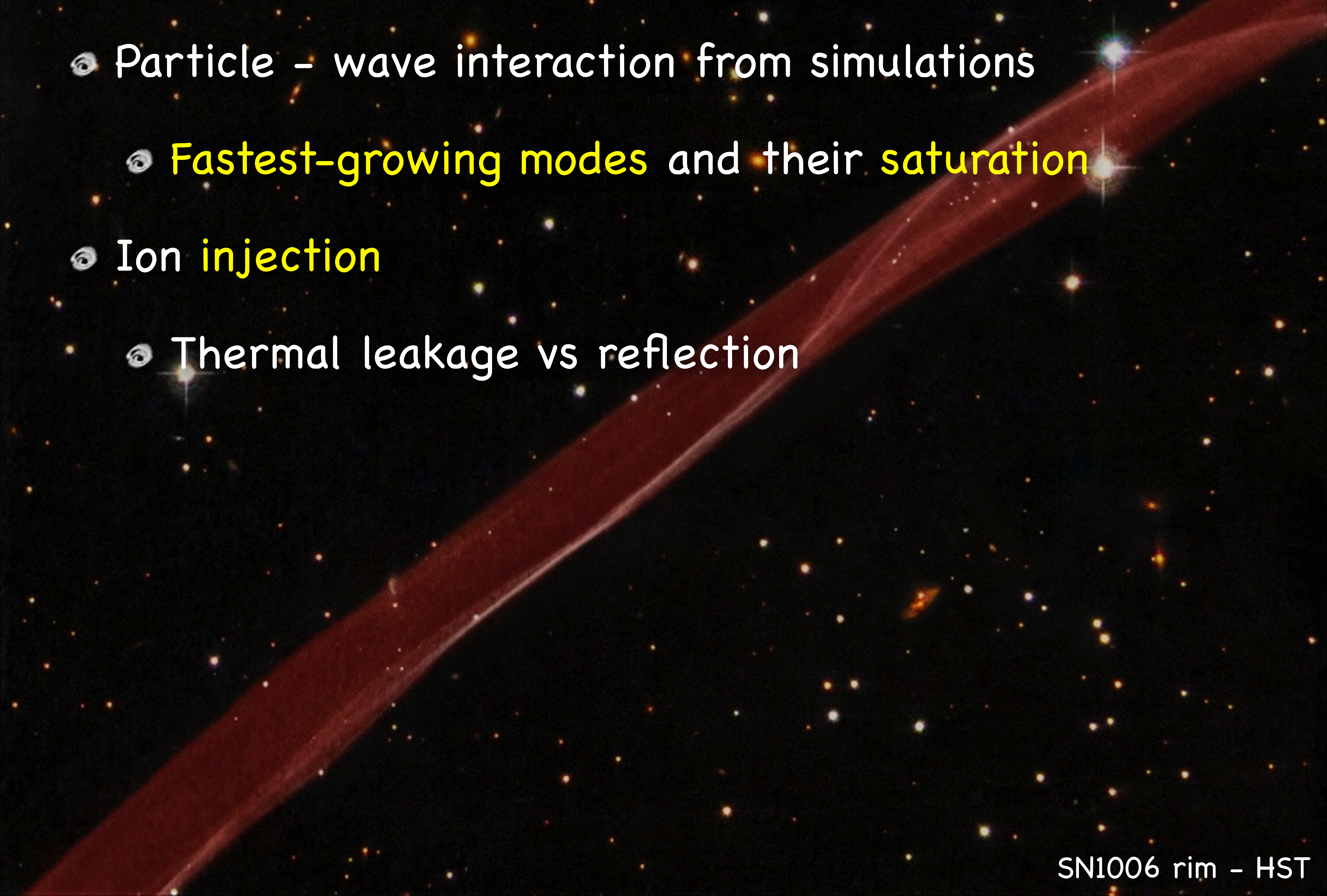
- Particle - wave interaction from simulations
  - Fastest-growing modes and their saturation
- Ion injection



SN1006 rim - HST

Future perspectives

- Particle - wave interaction from simulations
  - Fastest-growing modes and their saturation
- Ion injection
  - Thermal leakage vs reflection



SN1006 rim - HST

Future perspectives

- Particle - wave interaction from simulations
  - Fastest-growing modes and their saturation
- Ion injection
  - Thermal leakage vs reflection
- Electron Physics (injection, thermalization...)

SN1006 rim - HST

Future perspectives

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SN1006 rim - HST

Future perspectives

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  - Thermal leakage vs reflection
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- Need to go to higher M and bigger boxes

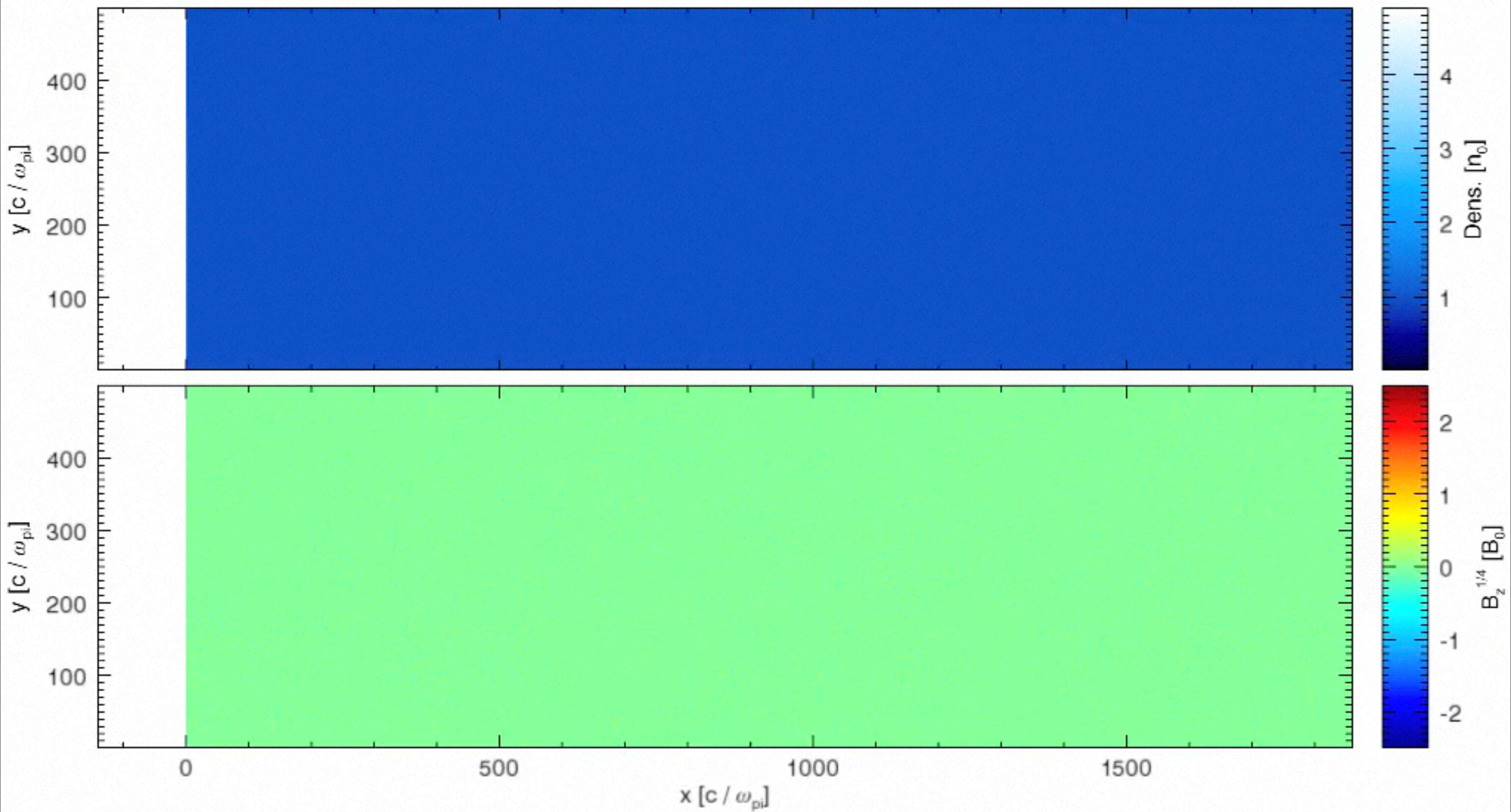
SN1006 rim - HST

Future perspectives

- Particle - wave interaction from simulations
  - Fastest-growing modes and their saturation
- Ion injection
  - Thermal leakage vs reflection
- Electron Physics (injection, thermalization...)
- Shocks in partially-neutral media (Blasi, ...DC 2012)
- Need to go to higher M and bigger boxes
  - Super-Hybrid (with X. Bai, A. Spitkovsky and L. Sironi)

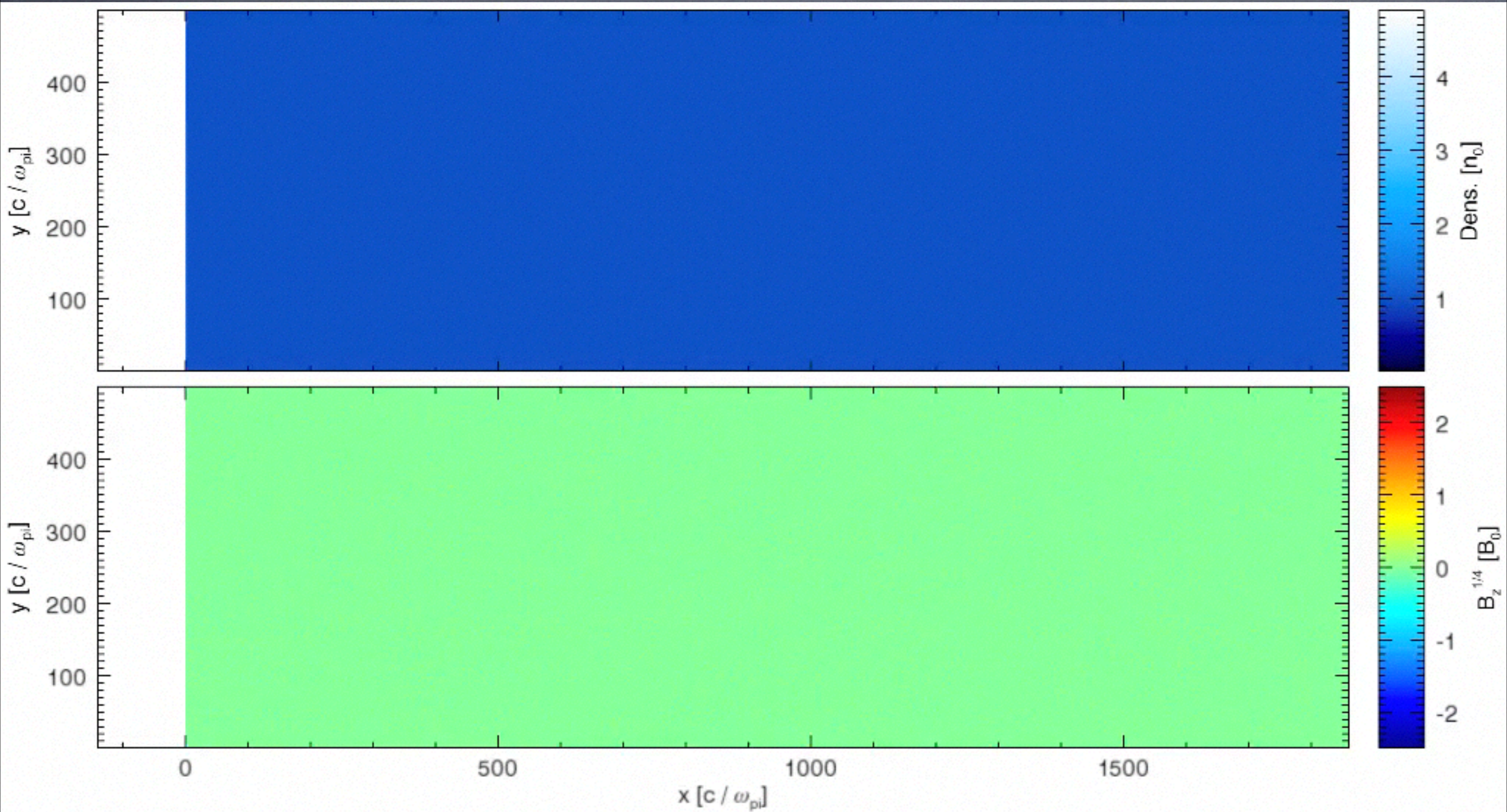
SN1006 rim - HST

Thank you!



y [c / ωpi]
400
300
200
100
Dens. [n0]
4
3
2
1
B_z^{1/4} [B0]
2
1
0
-1
-2
0
500
1000
1500
x [c / ωpi]

Thank you!



400
300
200
100
y [c / ω_pi]
4
3
2
1
Dens. [n_0]
400
300
200
100
y [c / ω_pi]
2
1
0
-1
-2
B_z^1/4 [B_0]
0
500
1000
1500
x [c / ω_pi]