宇宙線加速機構の解明に向けたプラズマ粒子シミュレーション

重点課題9サブ課題C

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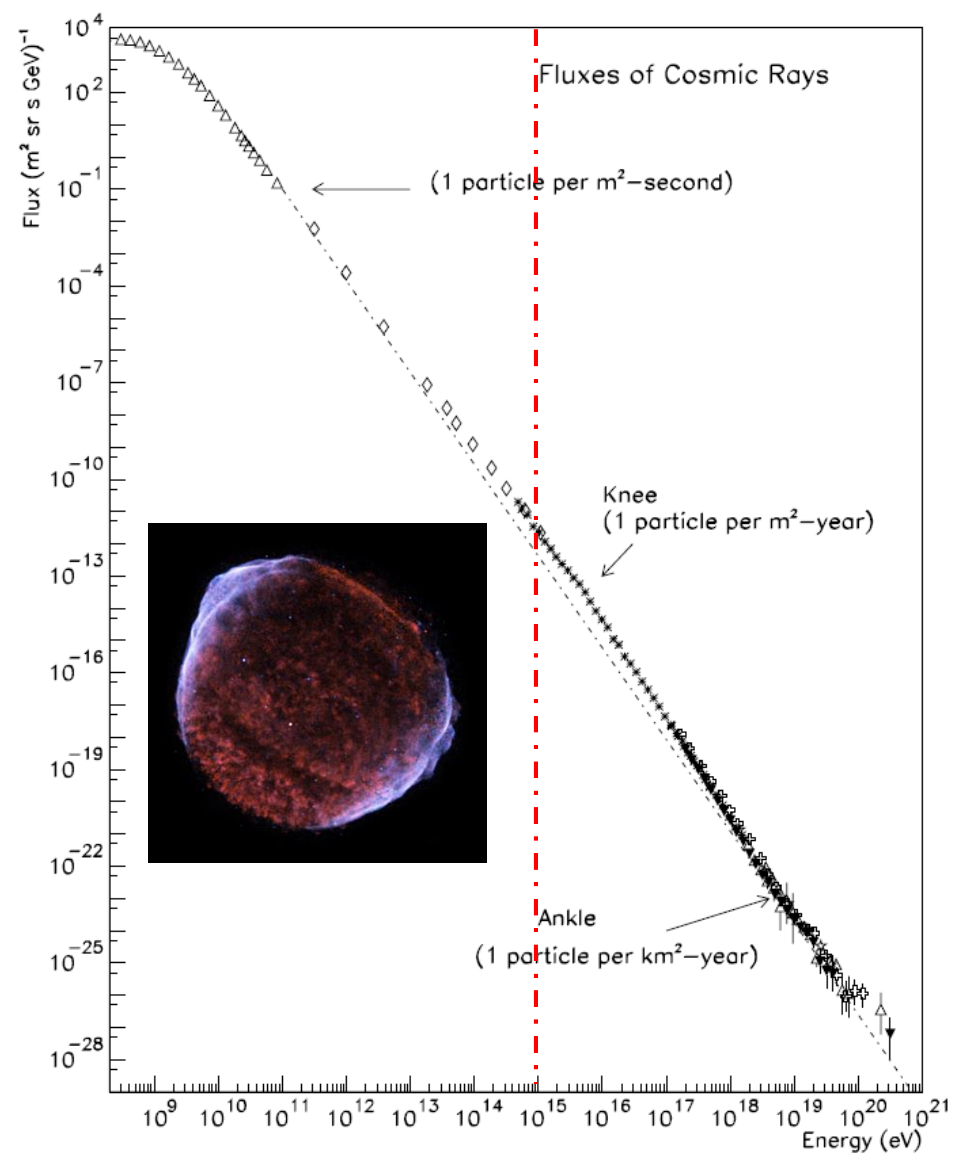
宇宙線の起源

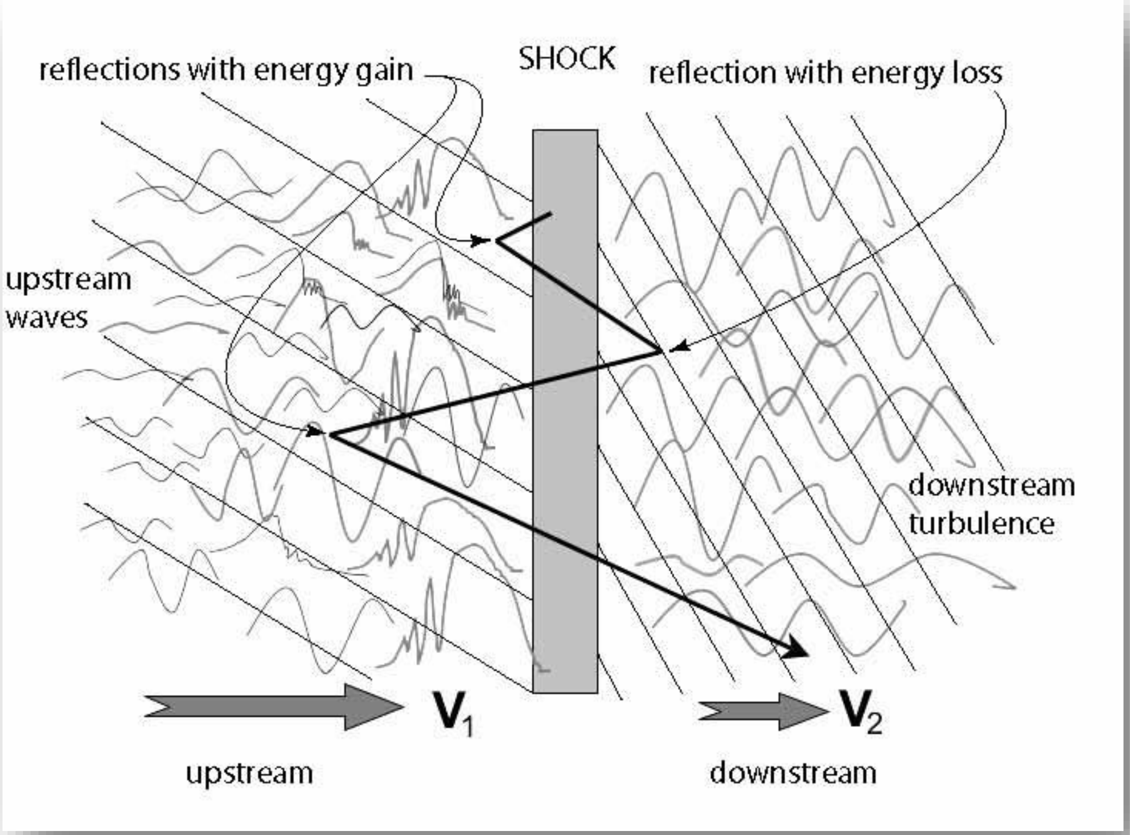


Swordy 01

- **どこから？**
  - ✓~ 10^{15} eV まで - 銀河系内
    - 電波、X 線（シンクロトロン放射）
    - ガンマ線（逆コンプトン散乱、パイ中間子崩壊）
  - ✓10^{15} - 10^{20} eV - 銀河系外
    - ニュートリノ（IceCube@千葉大ICEHAP）
- **どうやって？**
  - ✓超新星残骸衝撃波
    - 非相対論的 ($V_{sh} < c$)
  - ✓宇宙ジェットなどに伴う衝撃波
    - 相対論的 ($V_{sh} \sim c$)

➢陽子・電子などの荷電粒子の衝撃波近傍での加速を理解する必要がある

Diffusive Shock Acceleration (DSA)

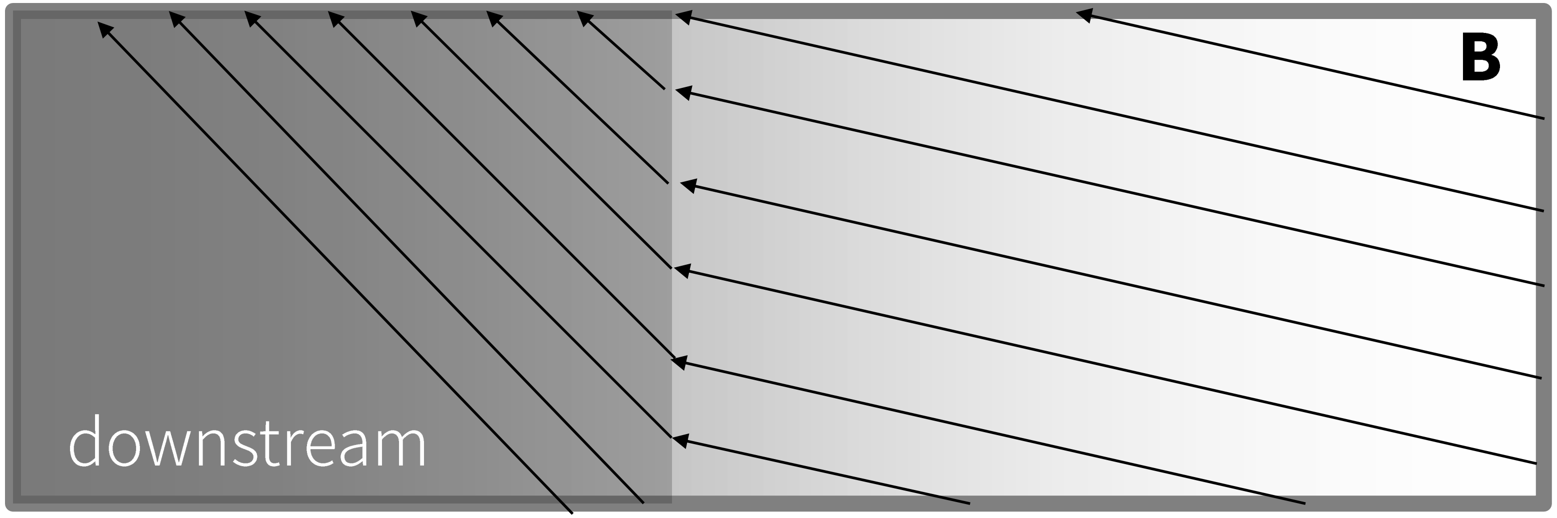


Treumann & Jaroschek 08

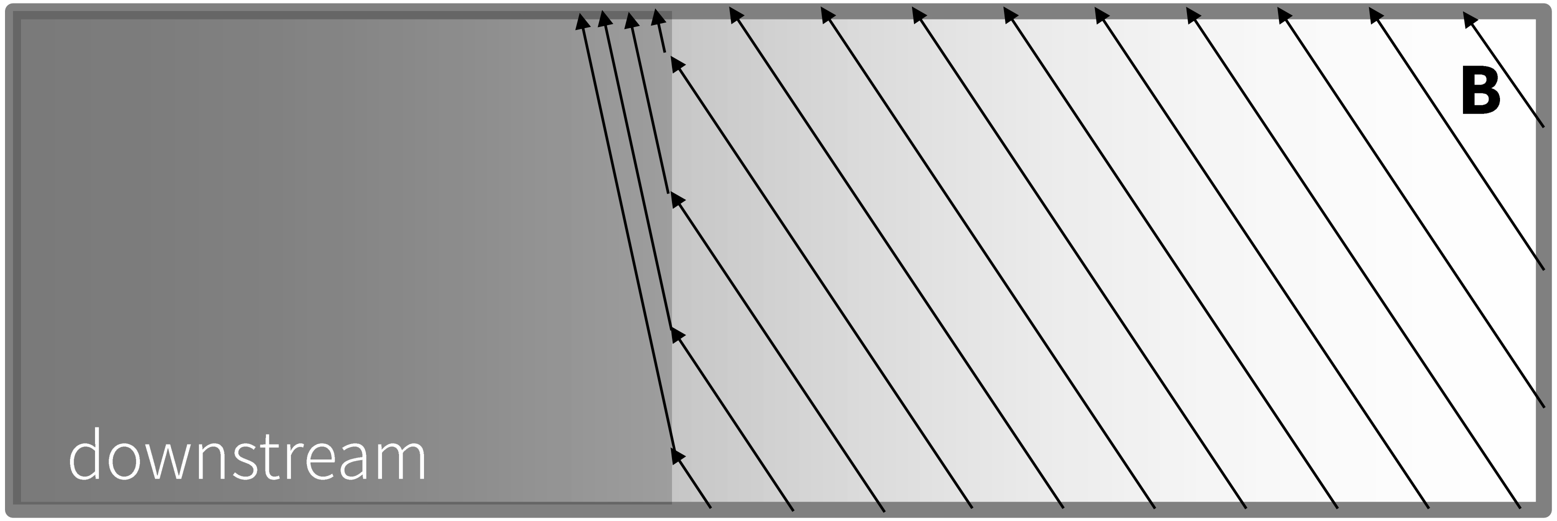
- V_1-V_2 > 0 (div(V)<0) → head-on
- 1st order Fermi acceleration
- Energy spectral index γ = r+2/r-1, where r is the compression ratio
- γ=2 for strong shocks (r=4)

Parallel / Perpendicular shocks

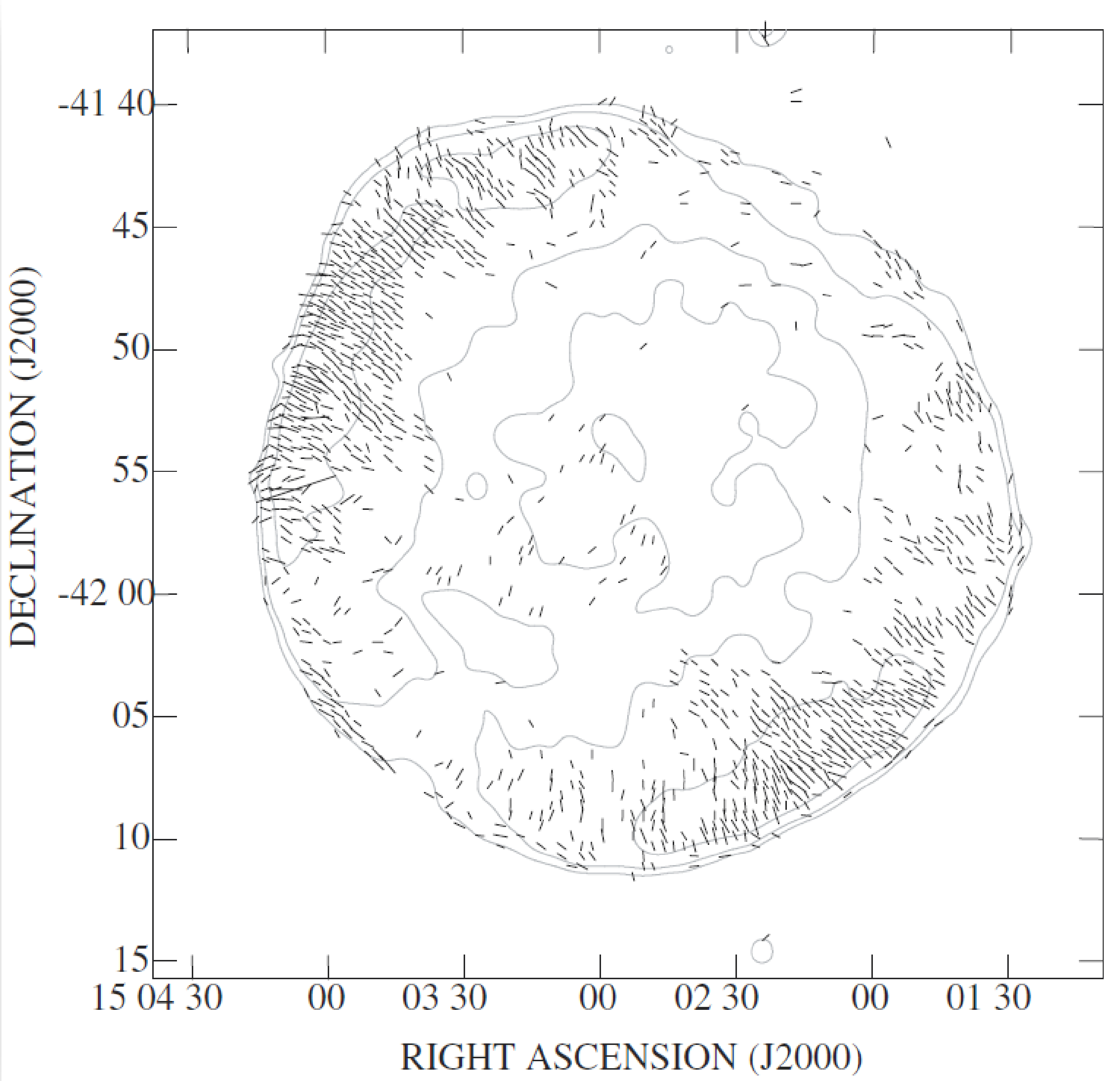
Parallel shock (Θ_{Bn} < 45 deg.)



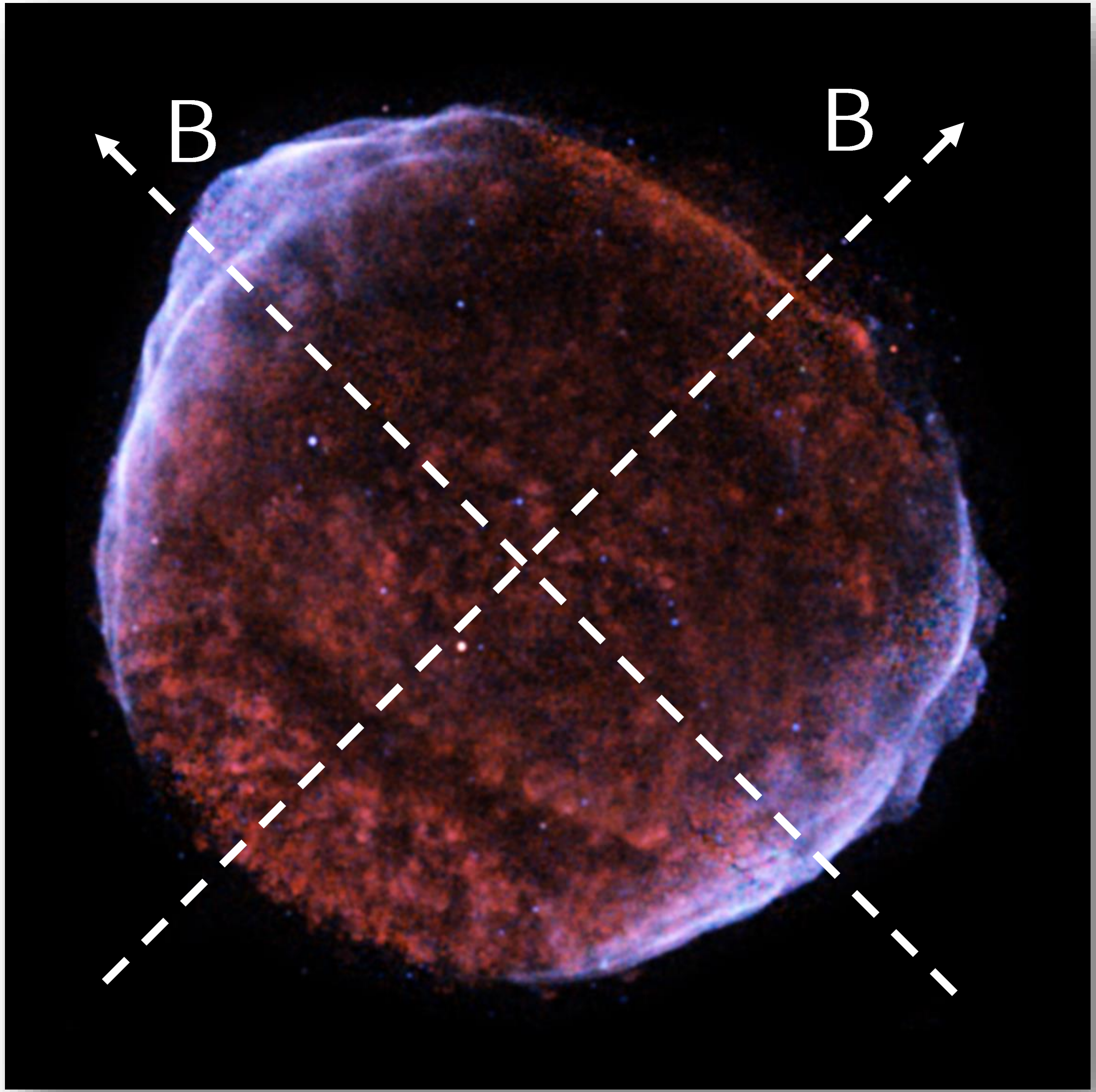
Perpendicular shock (Θ_{Bn} > 45 deg.)



Which do you prefer, ⫽ or ⊥ shock?

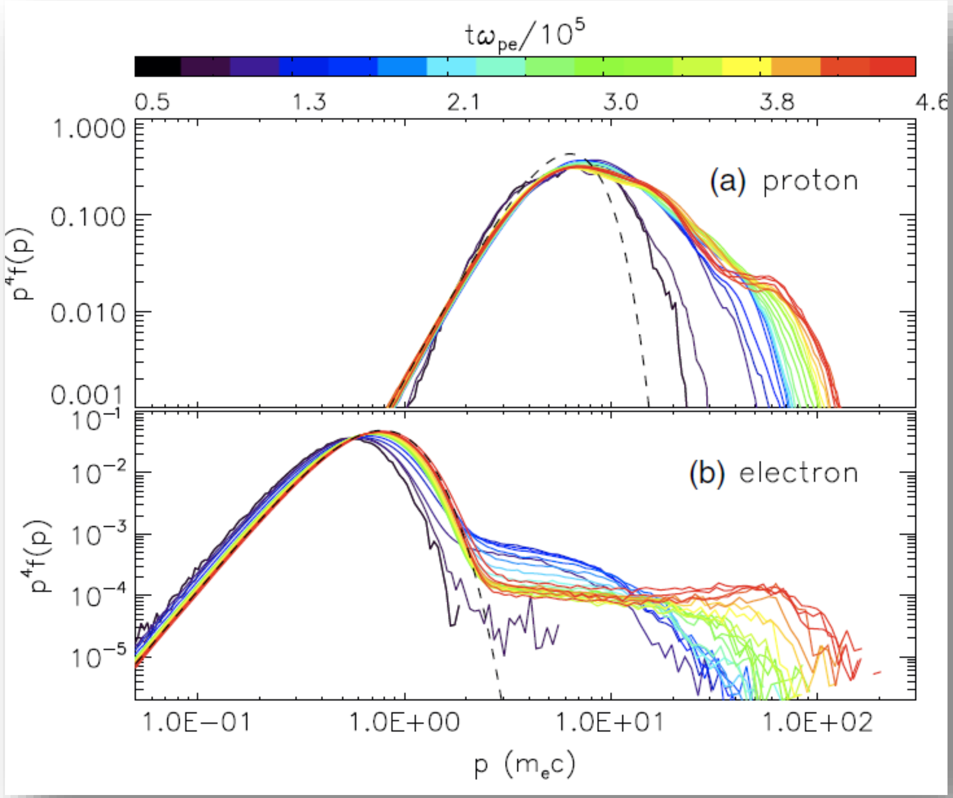


Reynoso+ '13



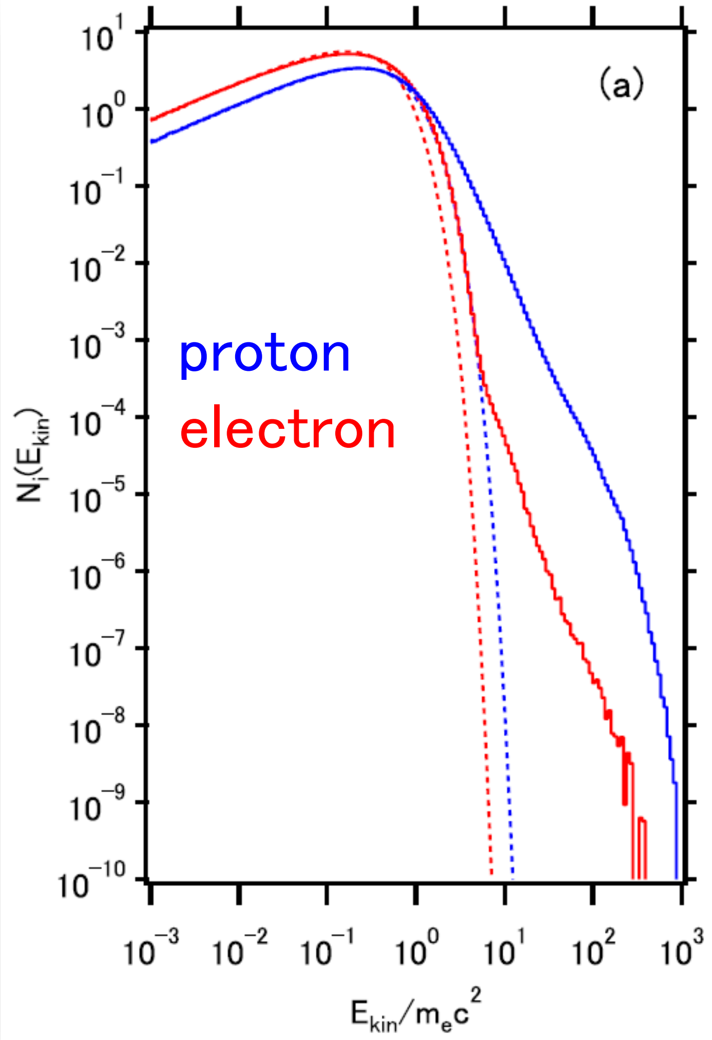
Chandra X-ray observation

e^- accelerations in // shocks



Park+ 15 PRL

- 1D PIC simulations
- Both p^+ & e^- accelerations
- Electron injection: SDA
- Shown only recently



Kato 15 ApJ

Current understanding of shock accelerations from PIC & Hybrid simulations

	Parallel shocks	Perpendicular shocks
p^+	**Yes** 1D PIC simulations & 2D-3D hybrid simulations (Capriori & Spitkovsky, 2014abc)	**NO** From 2D-3D hybrid simulations (Capriori & Spitkovsky, 2014abc) **YES** If charge exchange included Ohira, PRL, 2013; submitted
e^-	**May be possible** but still controversial Only from 1D PIC simulations in 2015	**Today's talk** Electron pre-acceleration High-M_A shocks relevant to SNR

Particle-in-Cell simulation

Vlasov eq. as particle motions

$$\frac{d\boldsymbol{x}_p}{dt} = \frac{\boldsymbol{u}_p}{\gamma_p}$$

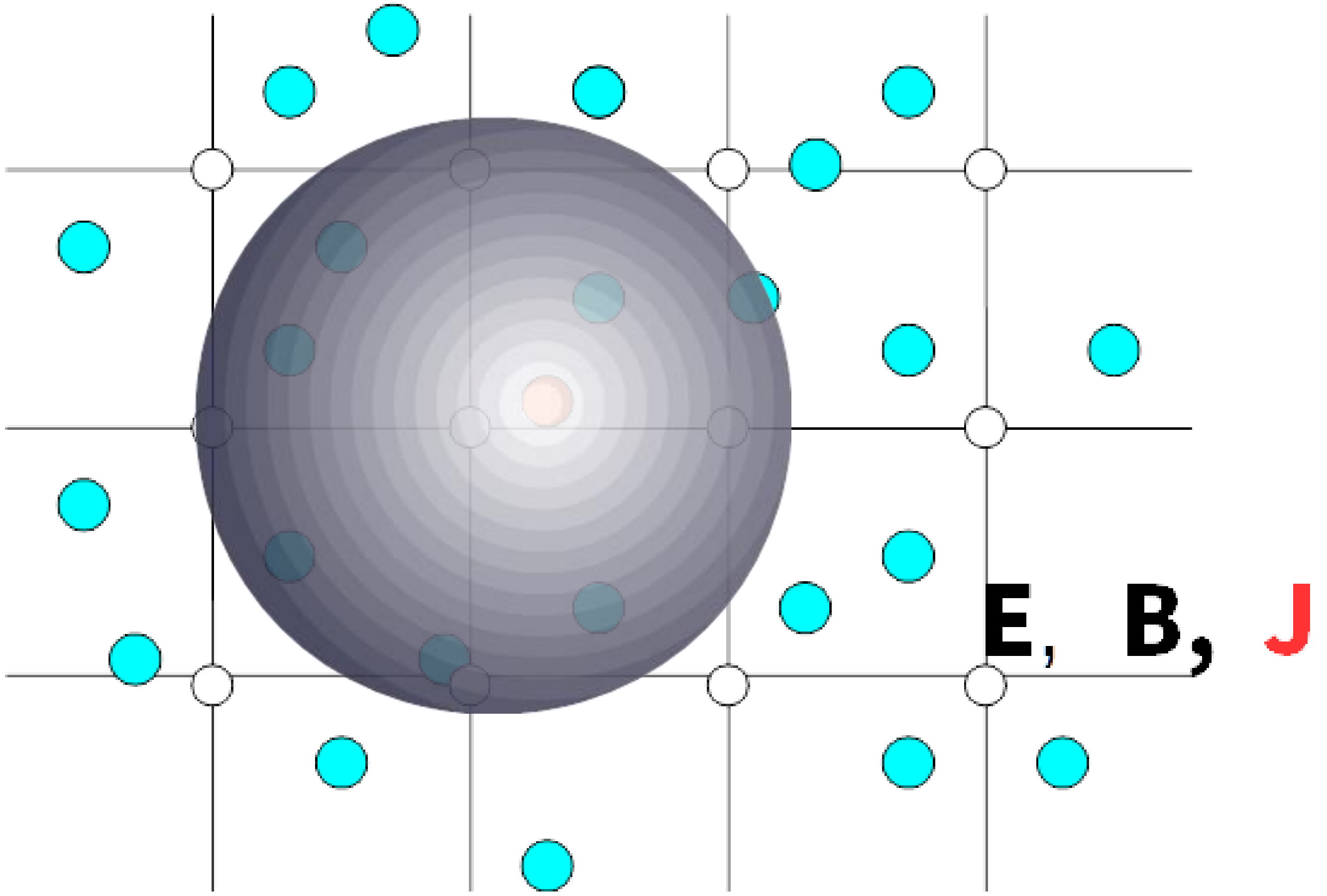
$$\frac{d\boldsymbol{u}_p}{dt} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_p}{c\,\gamma_p} \times \boldsymbol{B}\right)$$

$$\boldsymbol{J} = \sum_p q_p \frac{\boldsymbol{u}_p}{\gamma_p}$$

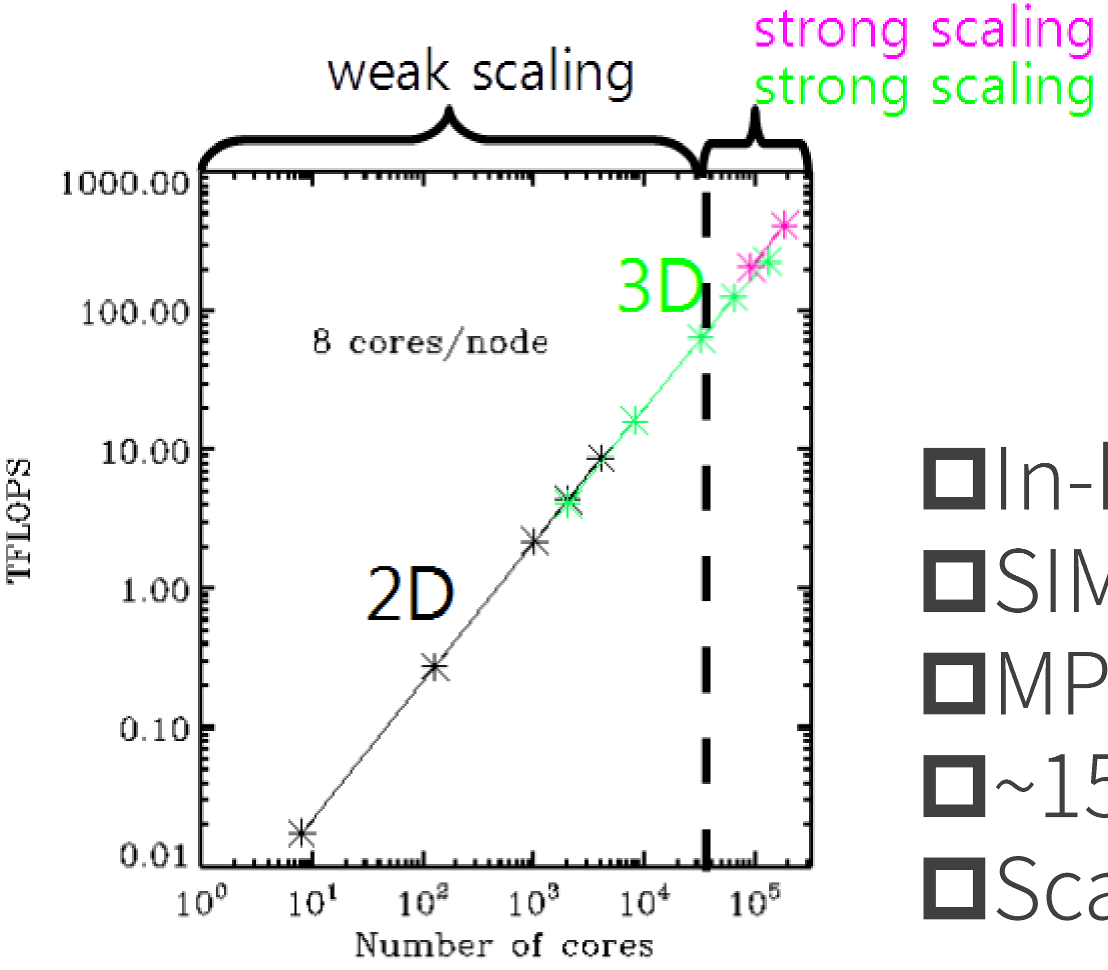
Maxwell eqs. on grid points

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\,\nabla \times \boldsymbol{E}$$

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\,\nabla \times \boldsymbol{B} - 4\pi \boldsymbol{J}$$

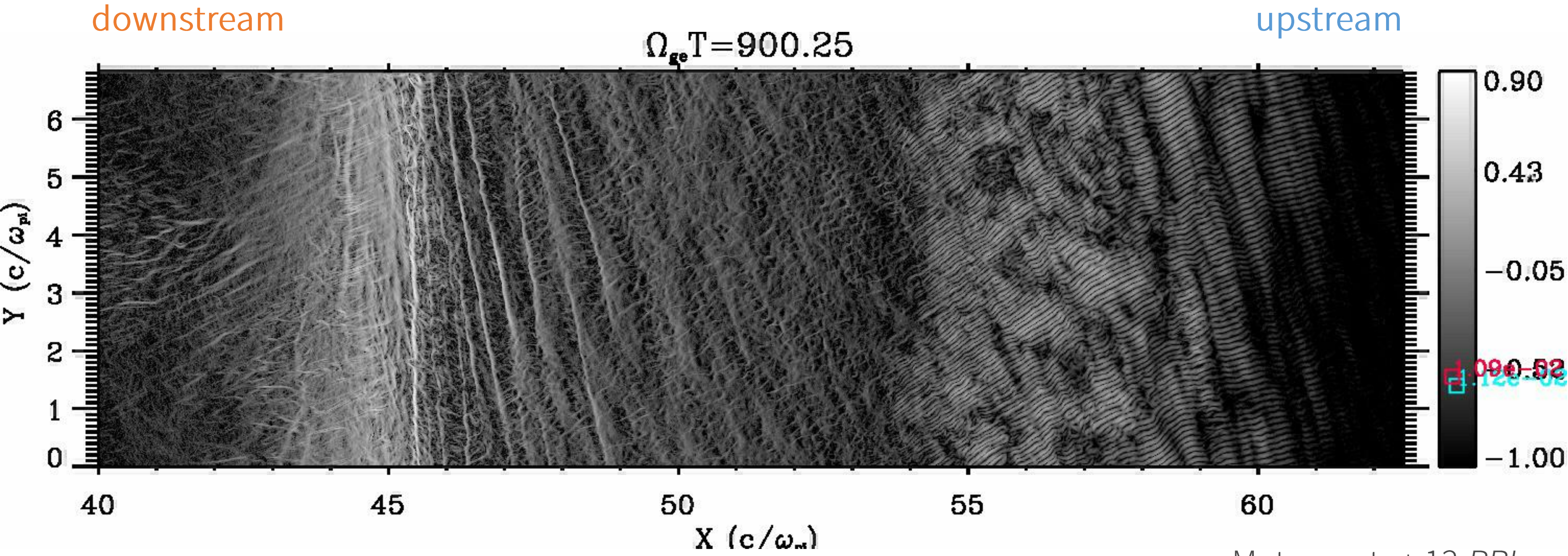


Shock experiments on supercomputer systems



- In-house 2D/3D particle-in-cell code
- SIMD Optimized on K computer
- MPI+OpenMP hybrid parallelization
- ~15% to the peak performance
- Scalable with ~10^5 cores

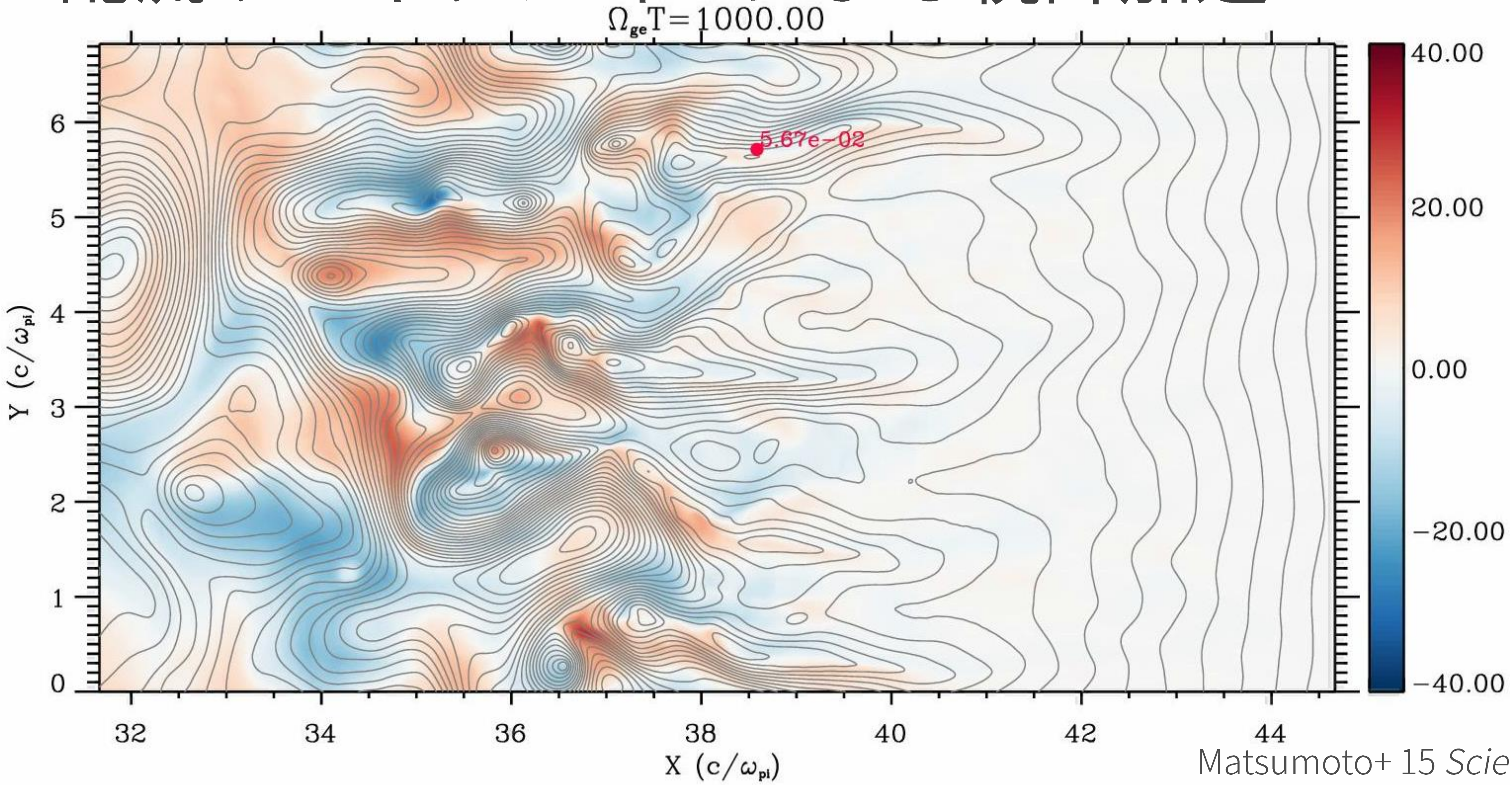
電子サーフィン加速



Matsumoto+ 13 *PRL*

gray: electrostatic field strength , squares: electron orbits

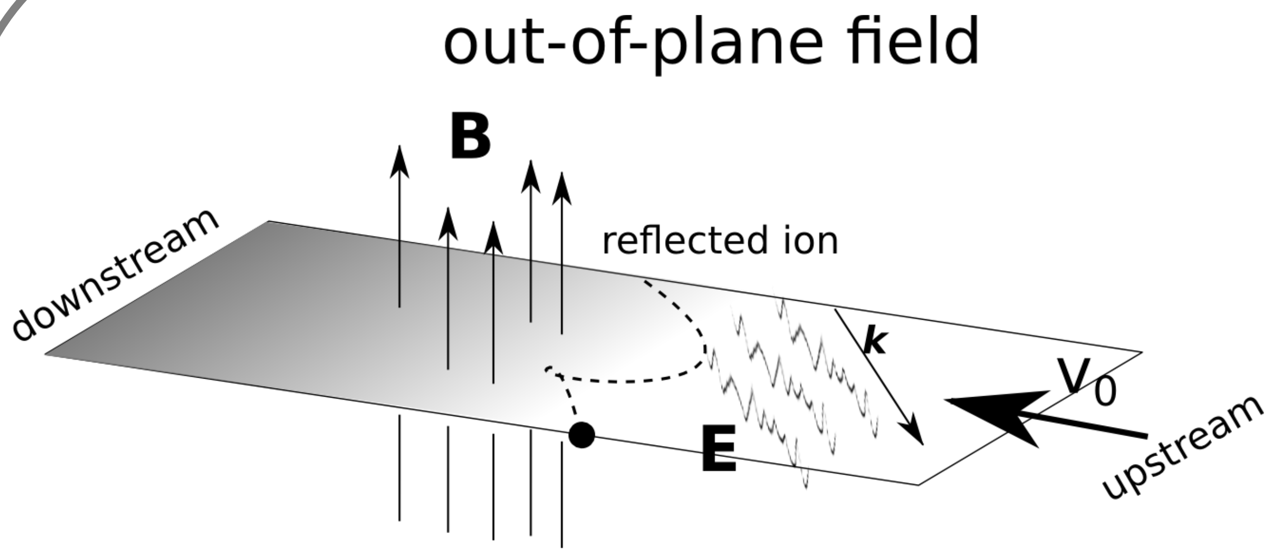
乱流リコネクションによる統計加速



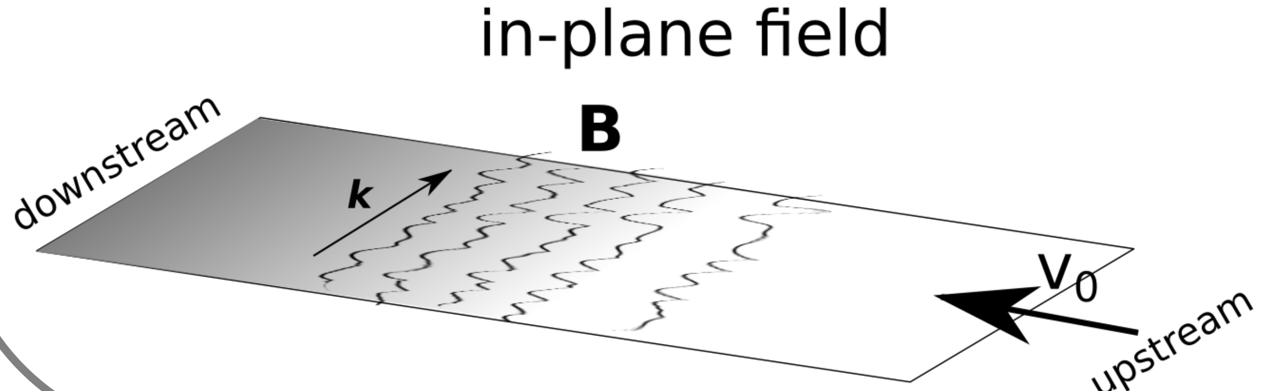
Matsumoto+ 15 *Science*

blue/red: B_z, gray: in-plane B field lines, circle: electron orbit

e^- accelerations in high M_A shocks



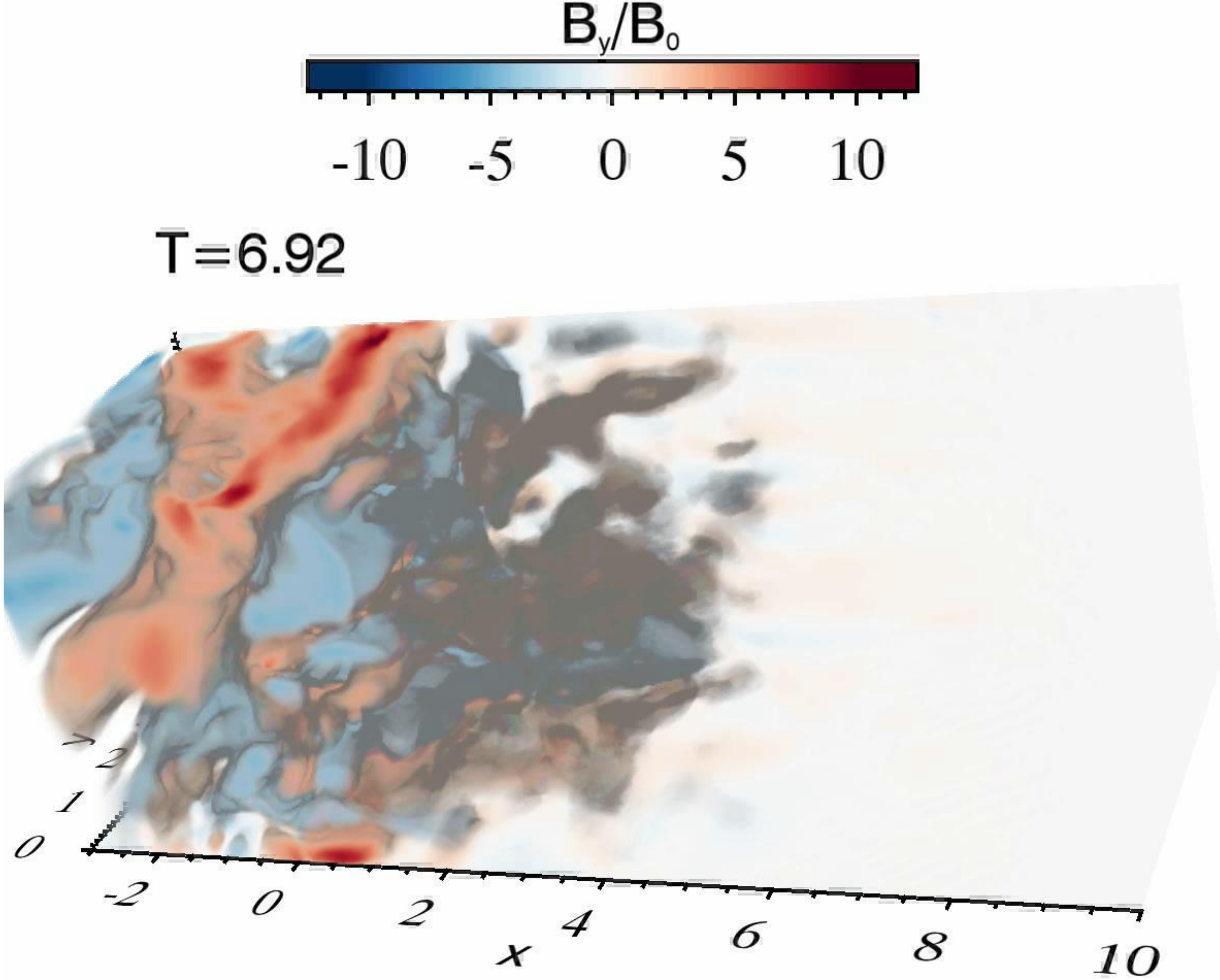
$k \perp B_0$
サーフィン加速

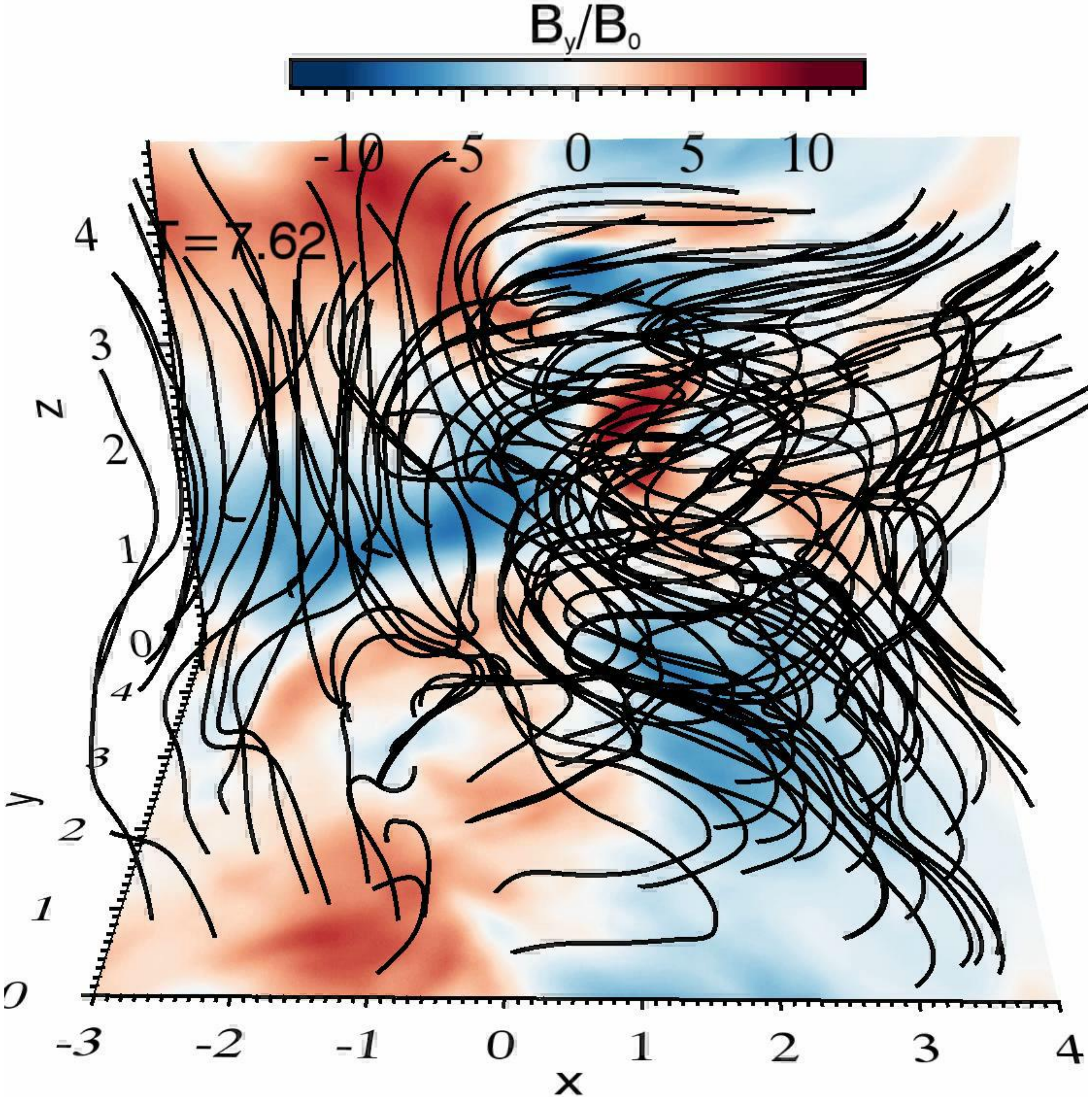


k ∥ B_0
乱流リコネクション
統計加速

Trillion-particle simulations on K computer

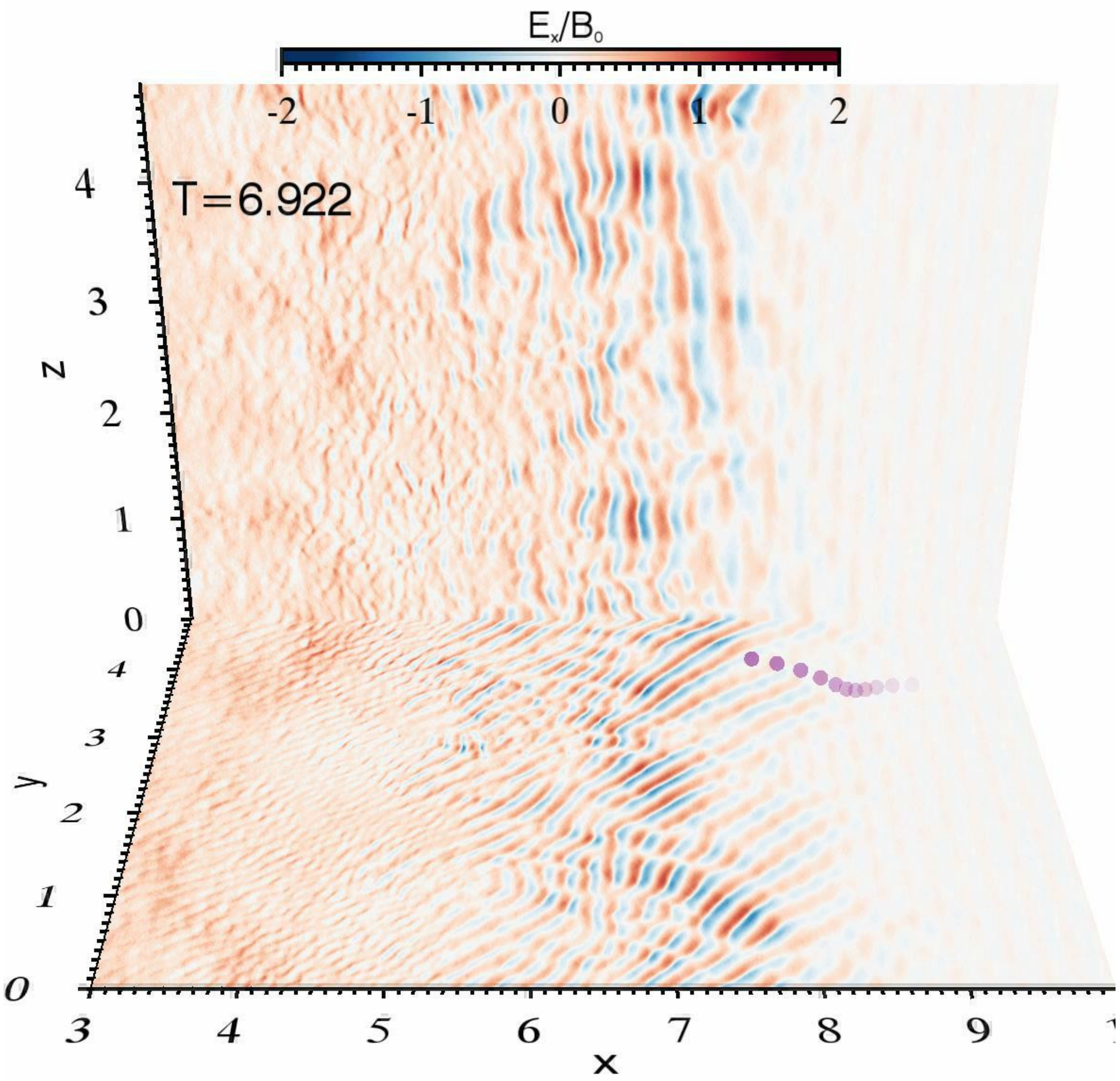
- 3D PIC simulations of quasi-perpendicular shocks
- $(N_x, N_y, N_z) = (8801, 768, 768)$
- $\sim 10^{12}$ particles (~ 100 /cell)
- On 9216 nodes (73,728 cores)
- 1 PB of data in total for analysis
- 3,000,000 node*hour / run

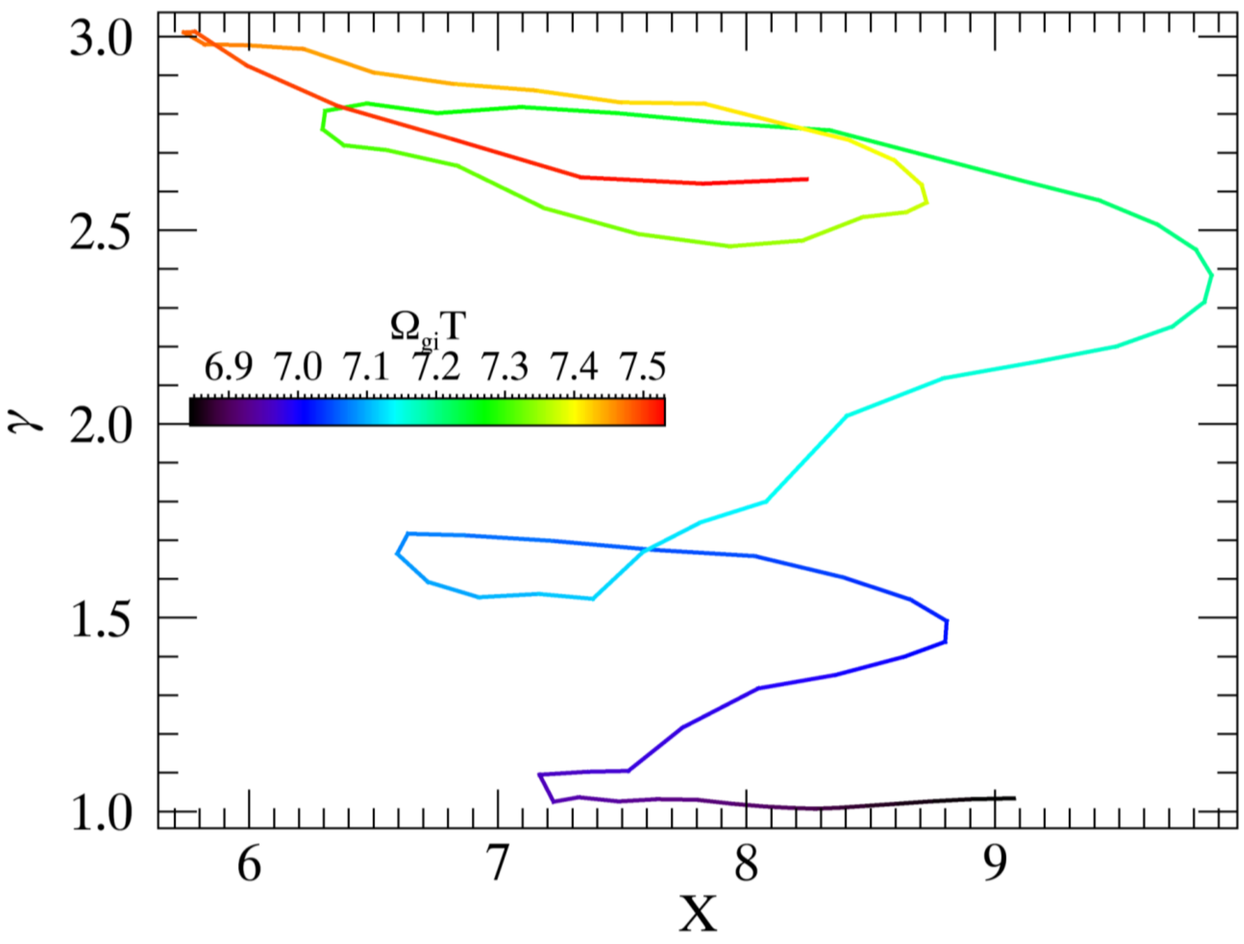

B_y/B_0
-10
-5
0
5
10
T=6.92
0
1
2
-2
0
2
4
6
8
10
x



B_y/B_0
-10 -5 0 5 10
T=7.62
z
0 1 2 3 4
y
0 1 2 3 4
x
-3 -2 -1 0 1 2 3 4

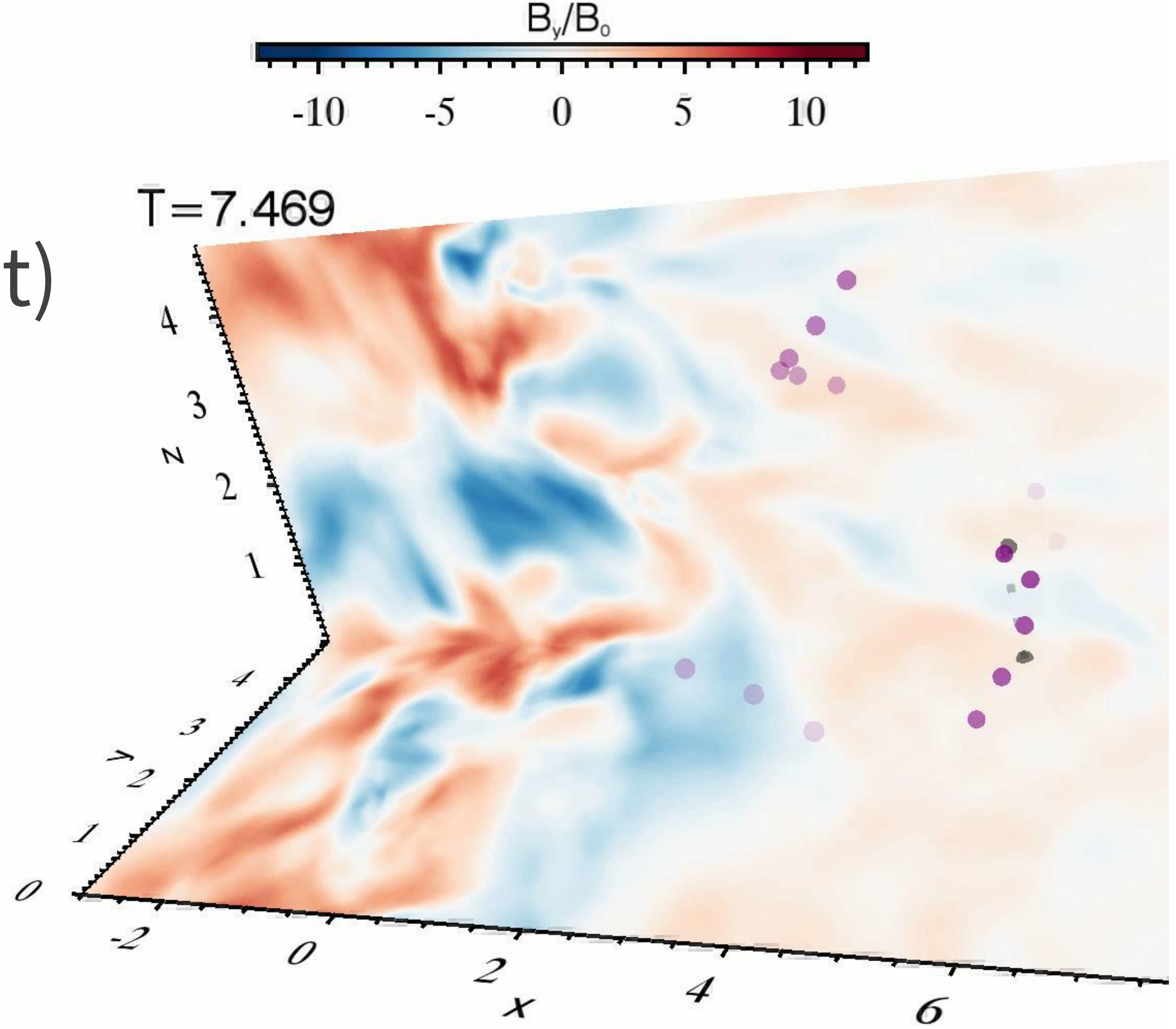
サーフィン加速（衝撃波前方）





distance from the shock front

Drift + scattering (around shock front)



Evolutions of tracer particles