ref) Takamoto+(2015), MNRAS 454, 2972.

Explosive Reconnection of the Double Tearing Mode in Poynting-Dominated Plasmas

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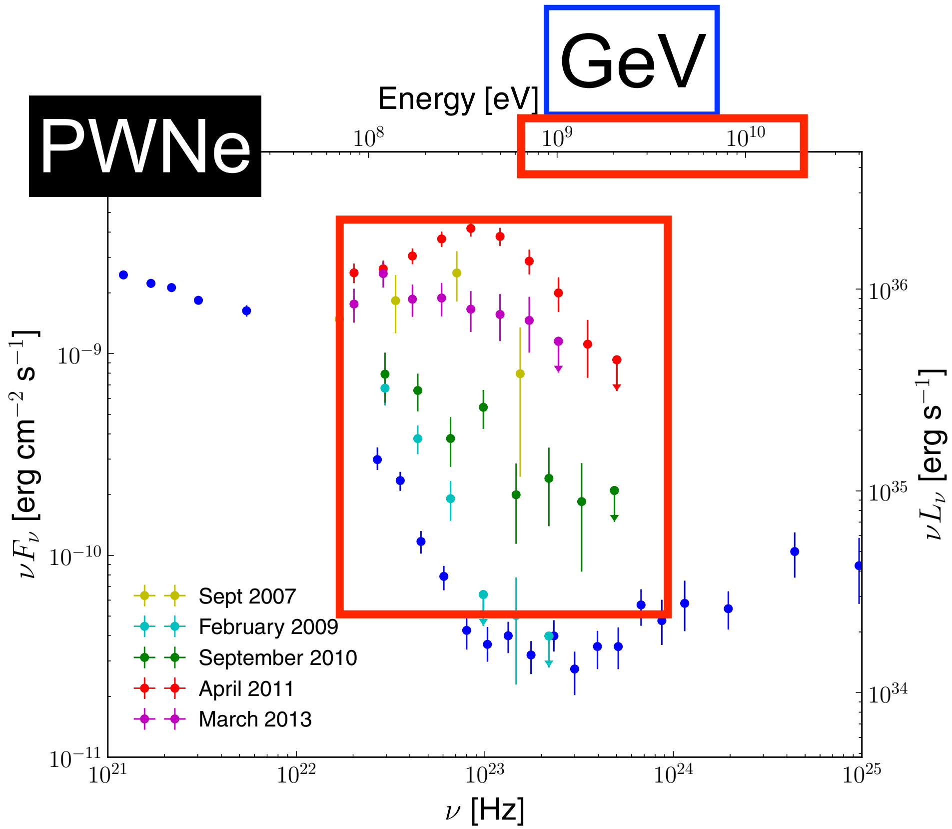
1. Introduction

2. Double Tearing Mode

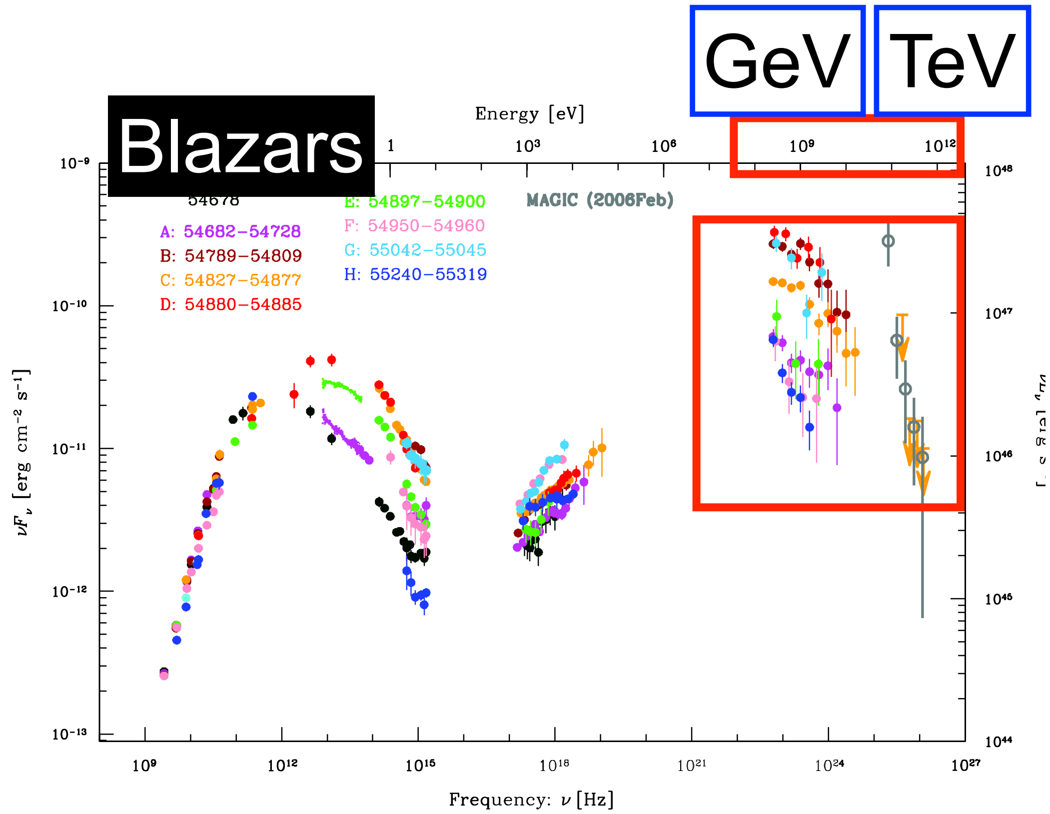
3. Spectrum Evolution

ref) Baty+(2013), MNRAS, 436, L20.
Petri+(2015),PPCF, 57, 014034.
Takamoto+(2015), MNRAS 454, 2972.

1.1. Flares from High-Energy Astrophysical Phenomena



ref) Buehler+ (2012), ApJ 749, 24.



ref) Hayashida+, (2012), ApJ 754, 114.

time scale:	8-10 hours	< days
Peak Energy:	> 350 MeV	~ GeV
spectrum:	not power-law	

1.2. Energy Conversion Processes

1. Relativistic Shock

Pros: $k_B T/mc^2 \sim \Gamma/3\sqrt{2} >> 1$ (if unmagnetized)

Cons: Magnetic field should be weak
inefficient particle accelerator in most cases?
(large escaping probability)

ref) Hoshino (2008), ApJ, 672, 940.
Giacche & Kirk (2016), arXiv:1612.04282

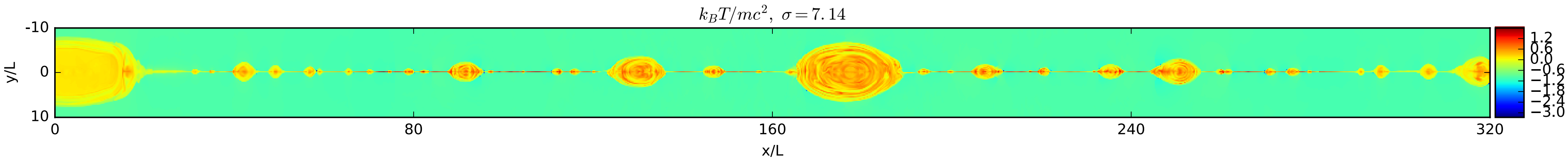
2. $\boxed{\text{Magnetic Reconnection}}$

Pros: Rapid conversion of Magnetic Field (~$10L/c_A$)
$\gamma mc^2 \sim F(\sigma)$ (increasing with σ)

Cons: current sheets are necessary
very local heating?

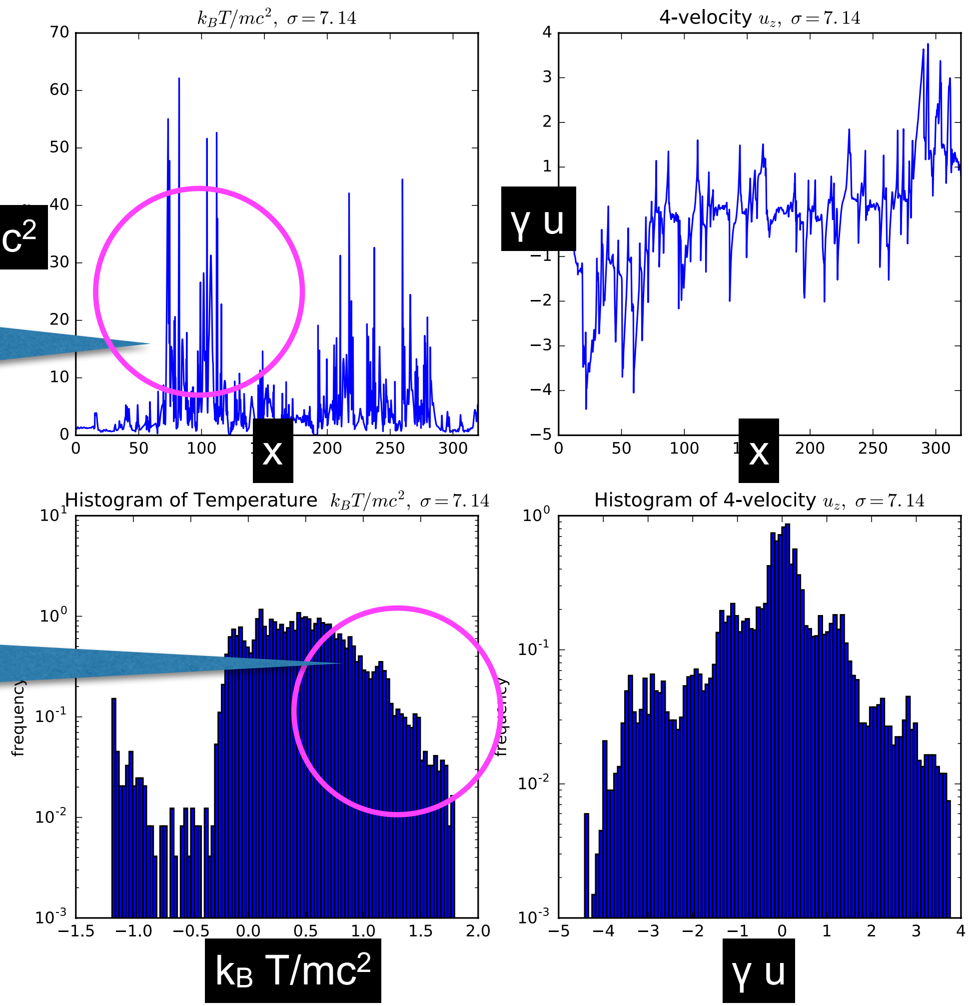
1.3 1-sheet Reconnection (Plasmoid-Chain)

ref) MT (2013), ApJ 775, 50.



hot but **very locally**

$f(T) \propto T^{-2}$



Can magnetic reconnection explain very strong bursts?

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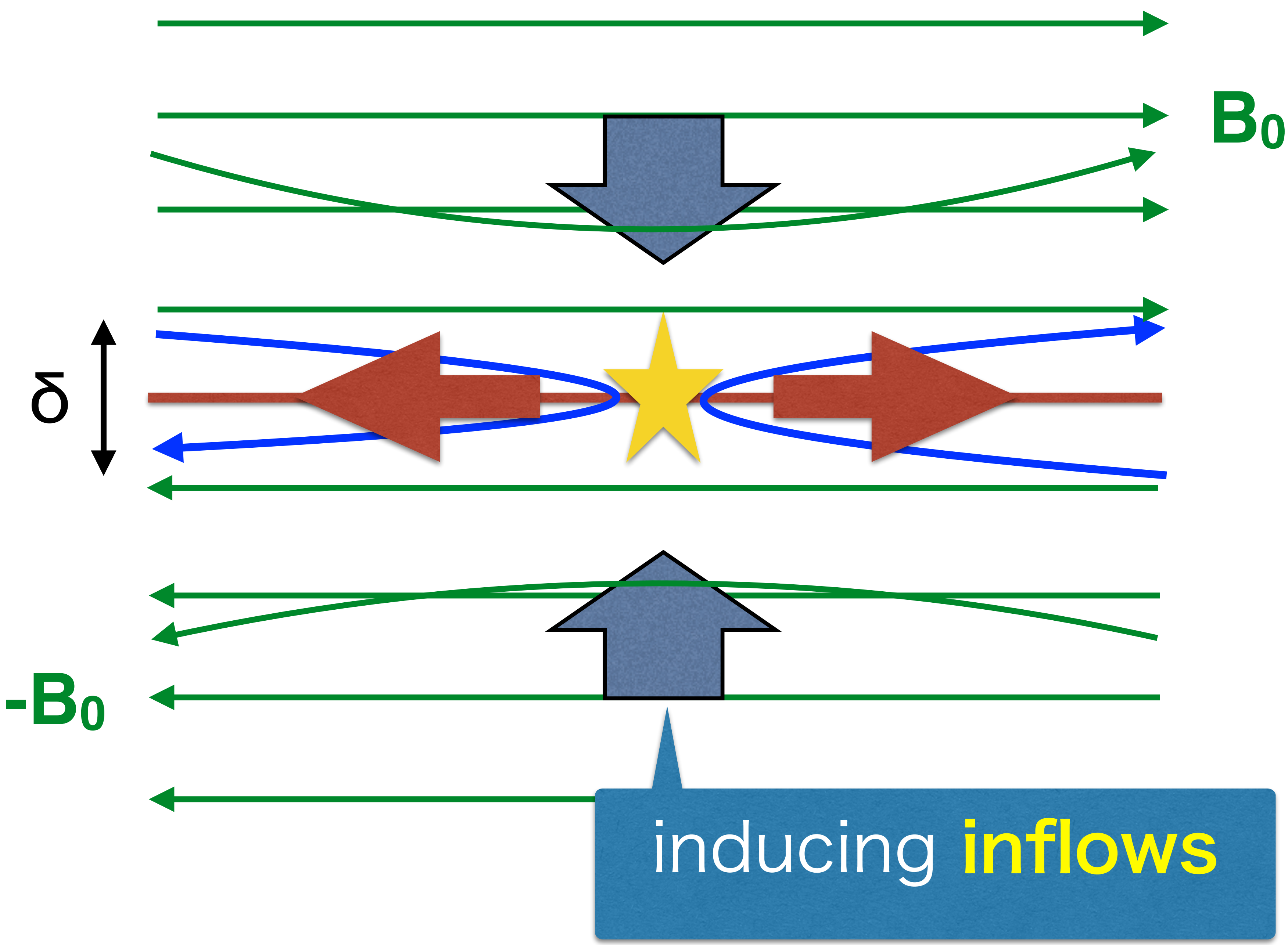
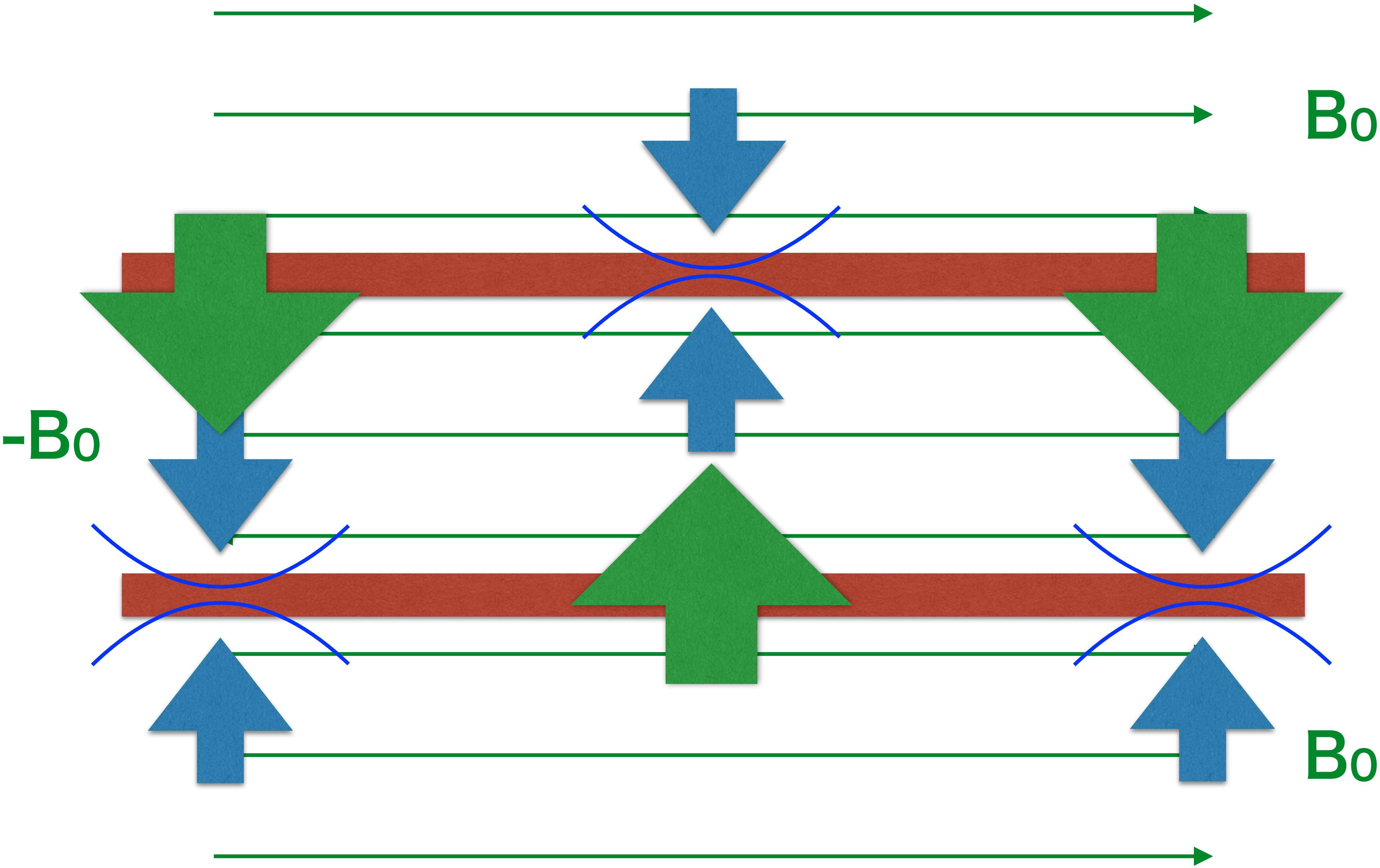
2.1. Single Tearing Mode

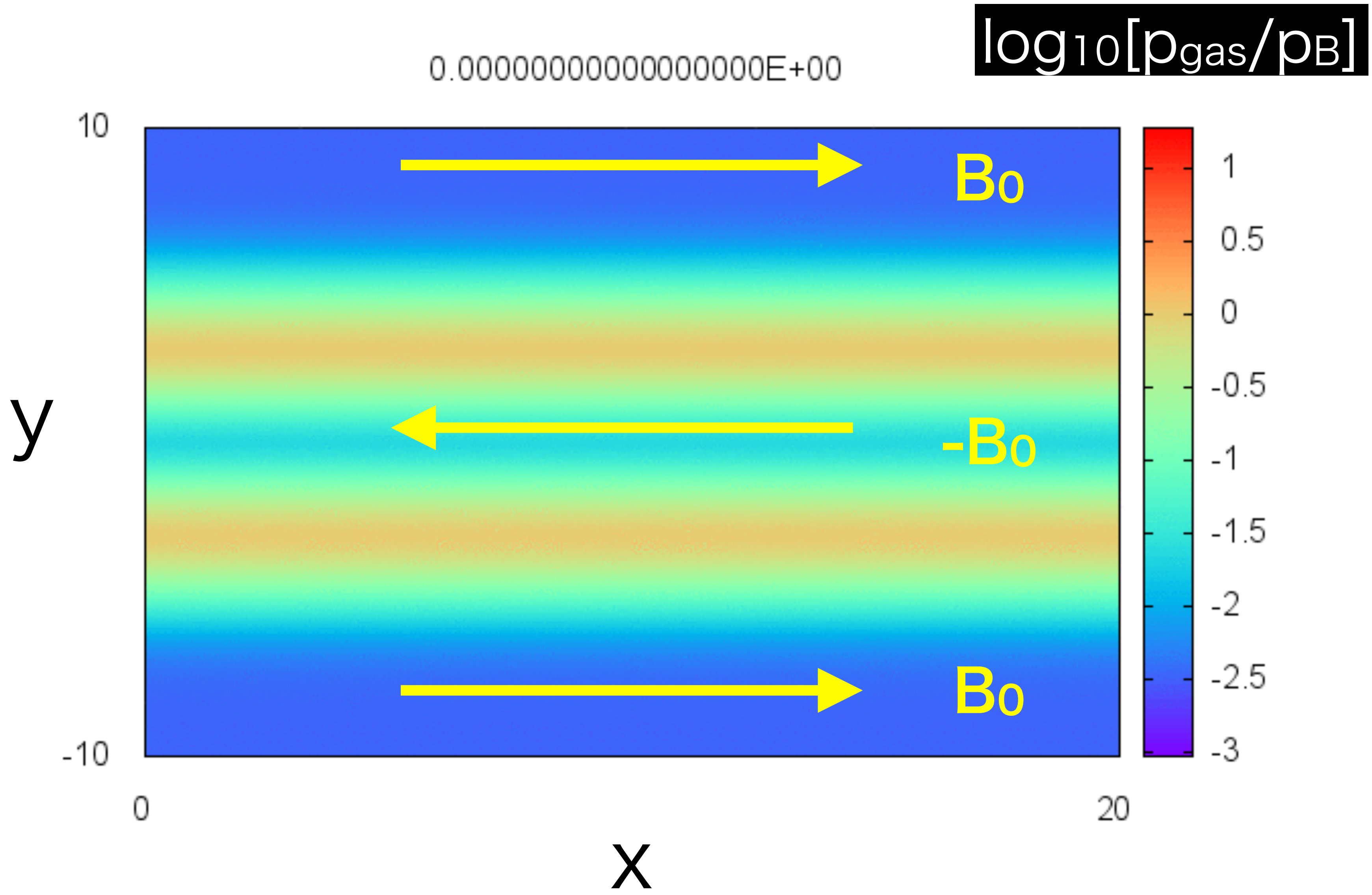


2.2. Double Tearing Mode

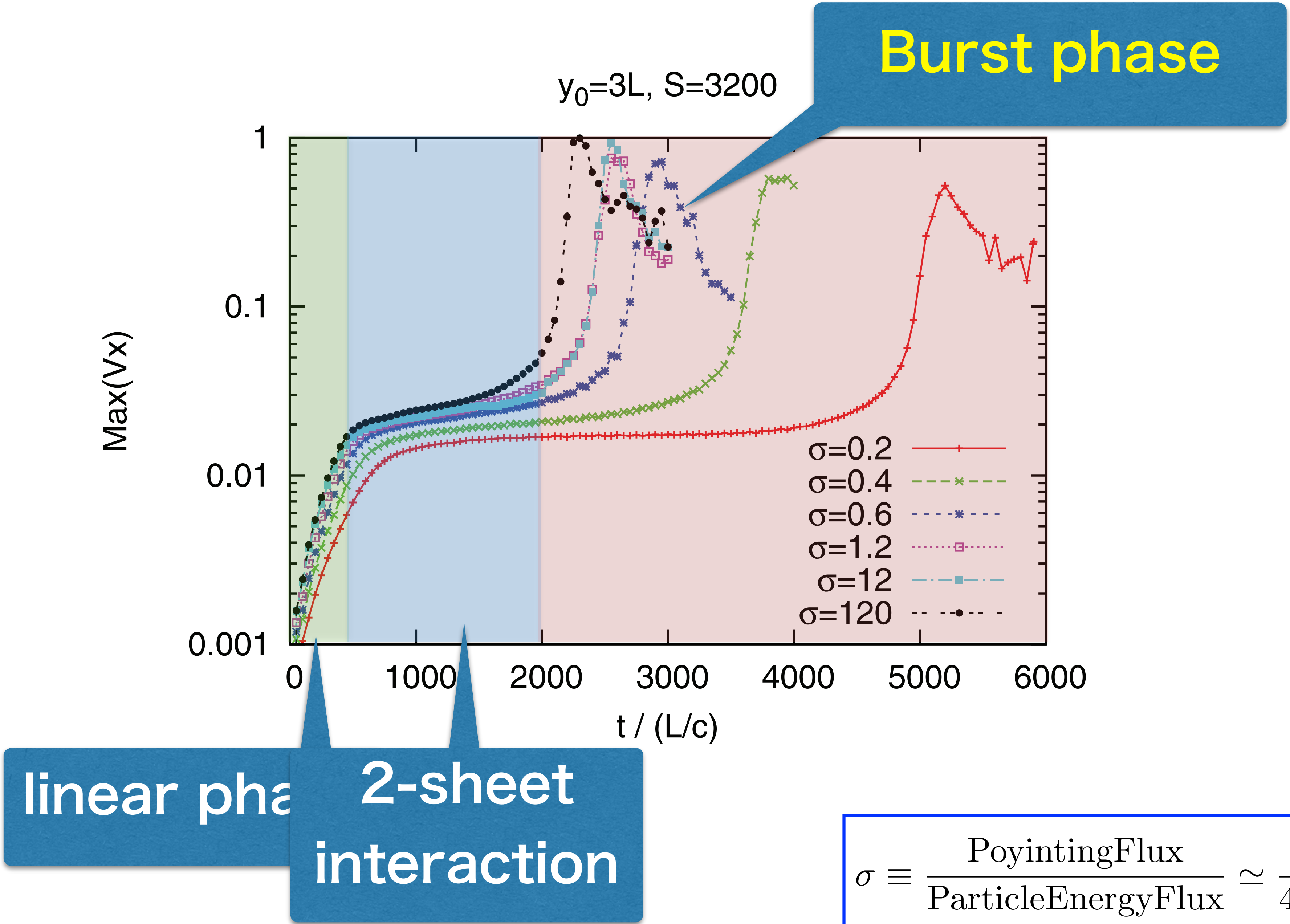


2.3. Double Tearing Mode 2

ref) Baty+(2013), MNRAS, 436, L20.
Petri+(2015),PPCF, 57, 014034.
Takamoto+ (2015), MNRAS, 454, 2972.

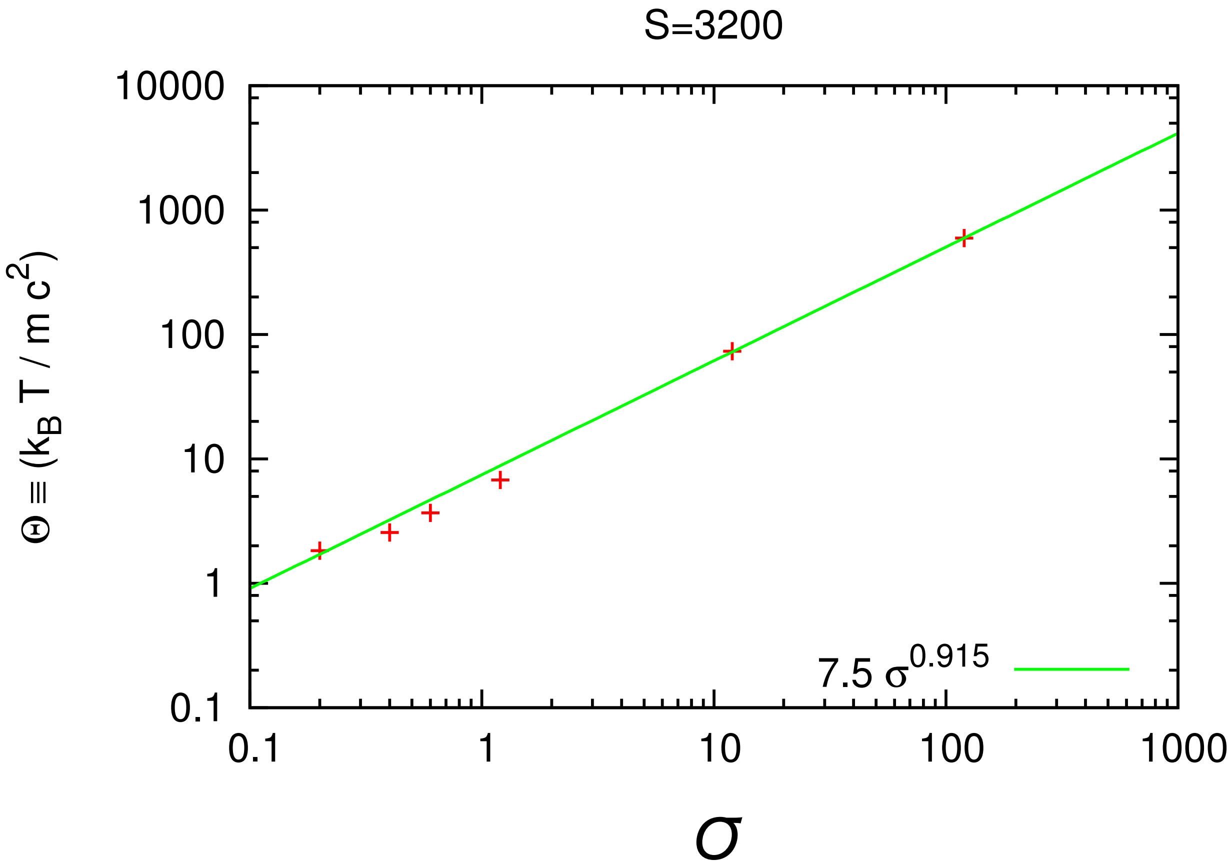


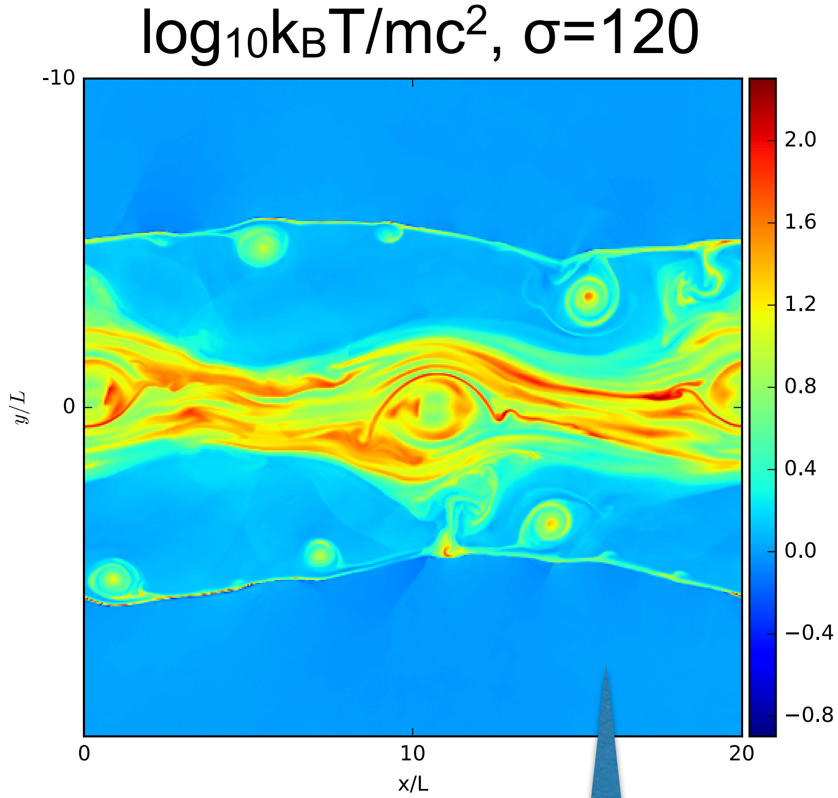
2.4. Double Tearing Mode 3



$$\sigma \equiv \frac{\mathrm{PoyintingFlux}}{\mathrm{ParticleEnergyFlux}} \simeq \frac{B^2}{4\pi w c^2 \gamma^2}$$

2.5. DTM Temperature dependence



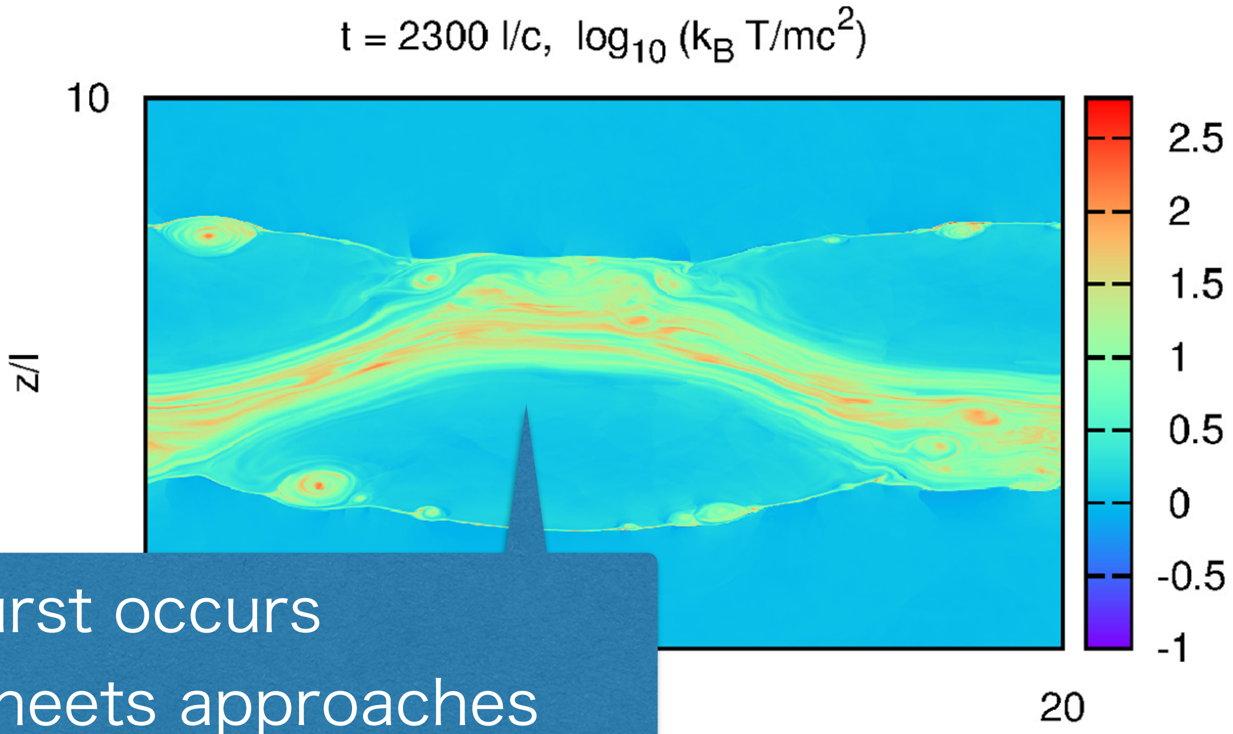


a large volume is heated

$$\frac{k_B T}{mc^2} \simeq 7.5\sigma = 7.5\frac{B^2}{4\pi w c^2 \gamma^2}$$

linear in σ

2.6. DTM Burst Timescale



burst occurs
when 2 sheets approaches
sufficiently
⇒ insensitive to geometry

$$\boxed{\tau_{\text{burst}} \sim 50 \frac{\text{sheet width}}{c}}$$

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ref) Baty+(2013), MNRAS, 436, L20.
Petri+(2015),PPCF, 57, 014034.
Takamoto+(2015), MNRAS 454, 2972.

3.1. Thermal Synchrotron Spectrum

$$\epsilon_{\rm sync} = \frac{3}{2}\gamma^2 \frac{B}{B_q} mc^2,$$

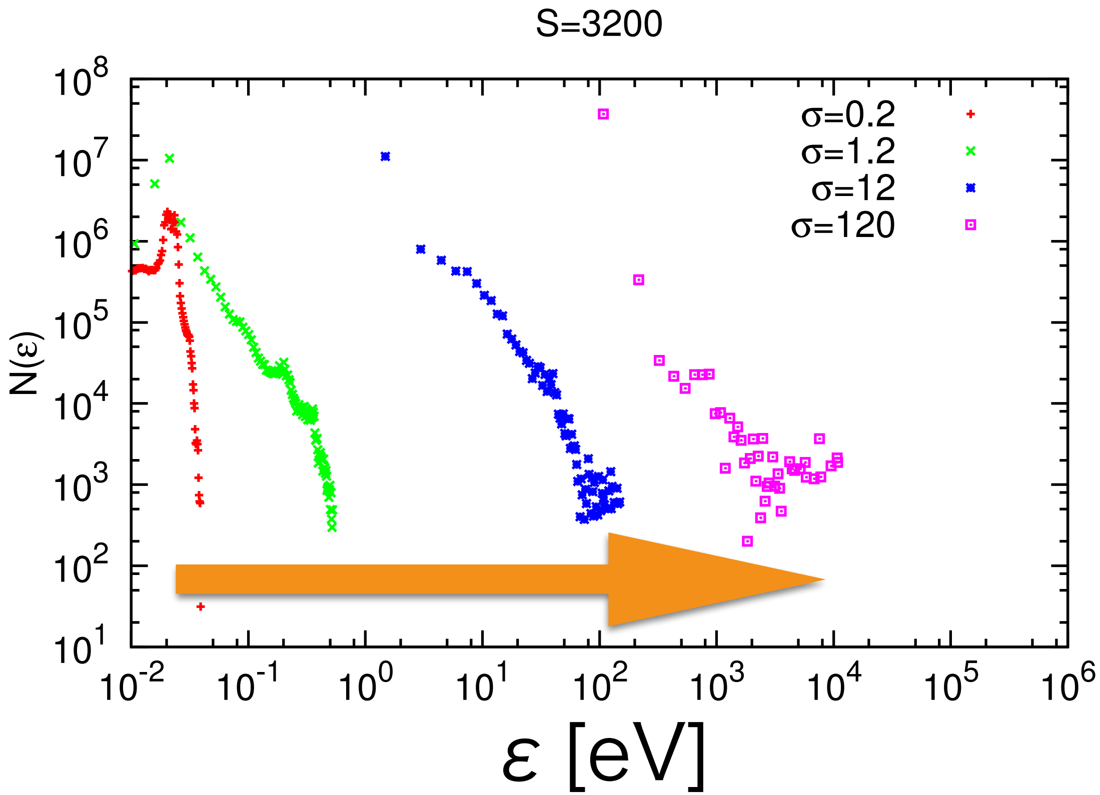
*Lorentz transform ($\Gamma_{\rm bulk}$)
*$\gamma \sim 3\, k_B T/mc^2$
*$k_B T/mc^2 \sim 7.5\,\sigma$

$$\boxed{\epsilon_{\rm sync,Lab} \sim 0.88[{\rm keV}] \left(\frac{\Gamma_{\rm bulk}}{10^2}\right) \left(\frac{\sigma}{10^2}\right)^2 \left(\frac{\bar{B}}{10^2[{\rm G}]}\right)}$$

(for thermal particles)

non-thermal tail > the above value

3.2. Applications for Crab GeV Flare



$$\epsilon_{\rm sync} = \frac{3}{2}\gamma^2 \frac{B}{B_q} mc^2,$$

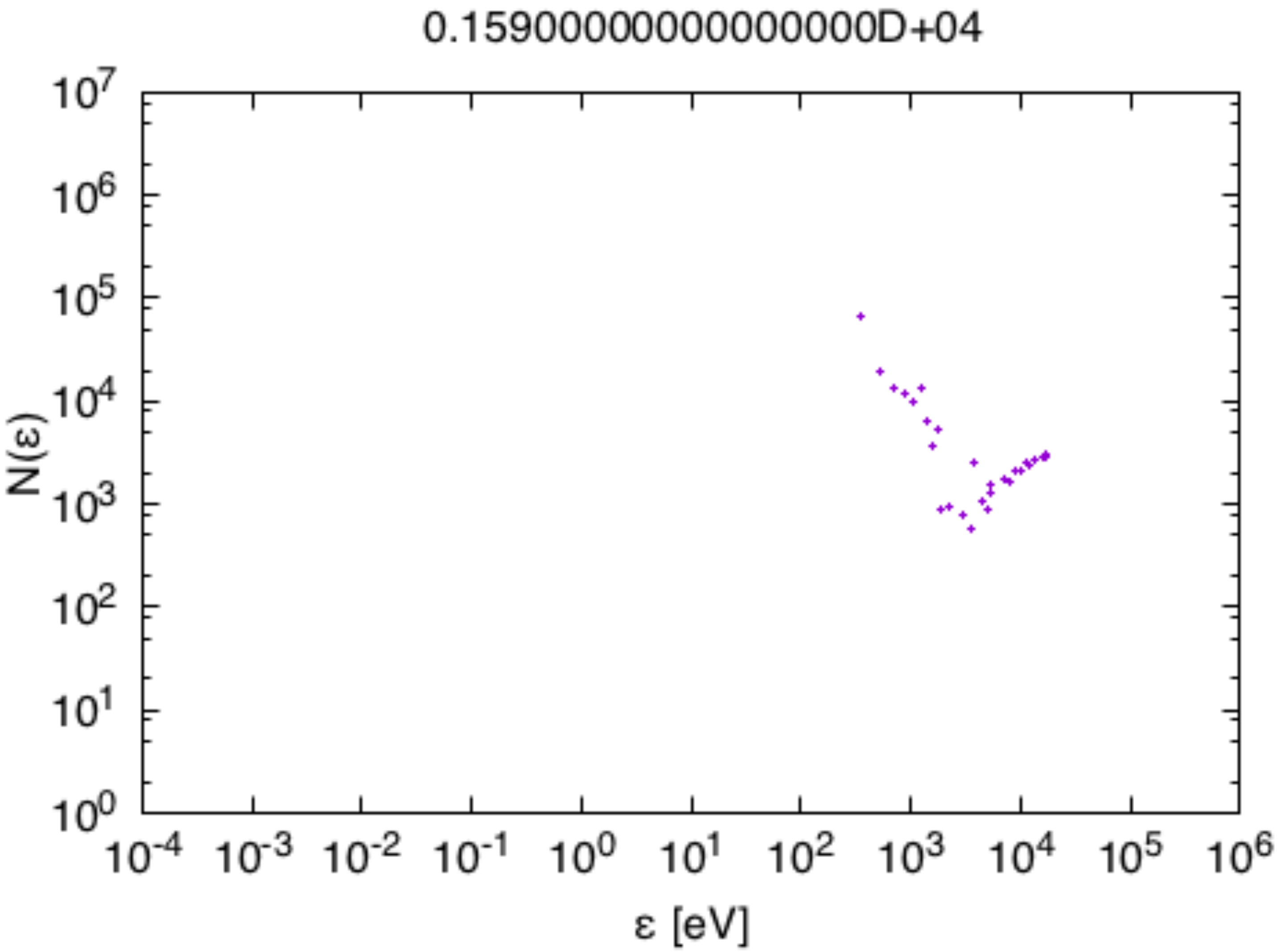
*Lorentz transform
*$\gamma \sim 3\, k_B T/mc^2$
*$B = B_L\, (r_L/r)$

$$\epsilon_{\rm sync,L} \sim 0.311[\rm eV]\ \Theta^2 \left(\frac{r}{r_{\rm L}}\right)^{-1} \left(\frac{\bar{B}}{\bar{B}_0}\right) \left(\frac{B_L}{100[\rm T]}\right)$$

$\varepsilon_{\rm sync,L} \sim 300[\rm MeV]$

(when $\sigma \sim 10^5$, $r \sim 50 r_L$, $B \sim 0.1 B_0$)

3.3. Temporal Evolution of Photon Spectrum



(when σ~120, r~50r_L, B~0.1B_0)

3.4. Time Scale

$$\boxed{\tau_{\rm burst} \sim 50 \frac{\rm sheet\ \ width}{c}}$$

Sheet width:

if **MHD** (density is sufficiently high)

→ basically no criterion

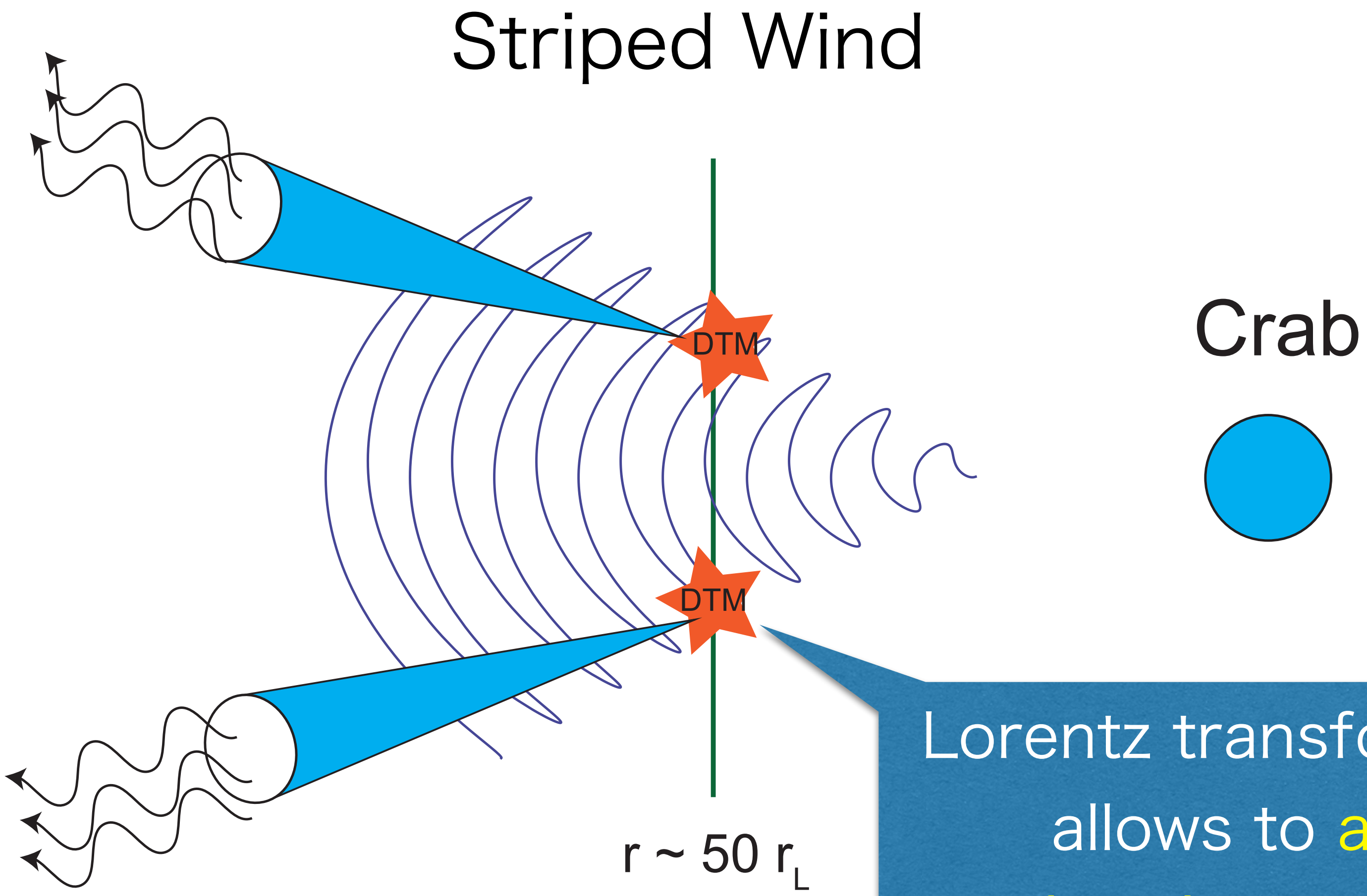
(~ $\sqrt{(\eta/\Delta t)}$ if highly collisional)

if **collisionless plasma** (low density)

→ sheet width ~ min{Gyro radius, skin depth}

(maximum energy will be limited by synchrotron cooling)

3.5. Scenario



Lorentz transformation allows to avoid acceleration energy limit ref) Takamoto+(2015), MNRAS 454, 2972.

Summary

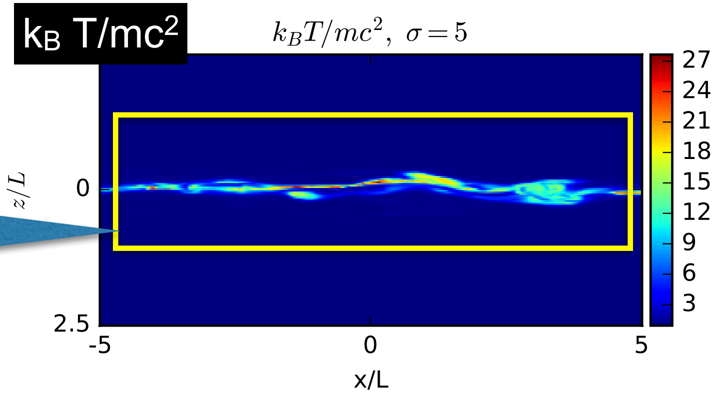
- We investigated a candidate of the strong flare origin considering **Double Tearing Mode (DTM)**.
- Double tearing mode (DTM) is a plasma instability resulting in a sudden energy release.
- The thermal synchrotron obtained by the simulations gives an energy spectrum resembling to the observations.
- The high Lorentz factor of the wind allows us to explain **energy flux** naturally.

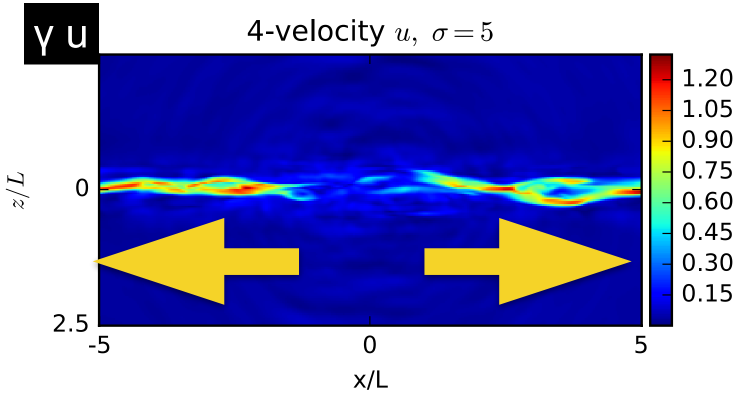
O Ma Ke

1.4 1-sheet Reconnection (Turbulent Reconnection)

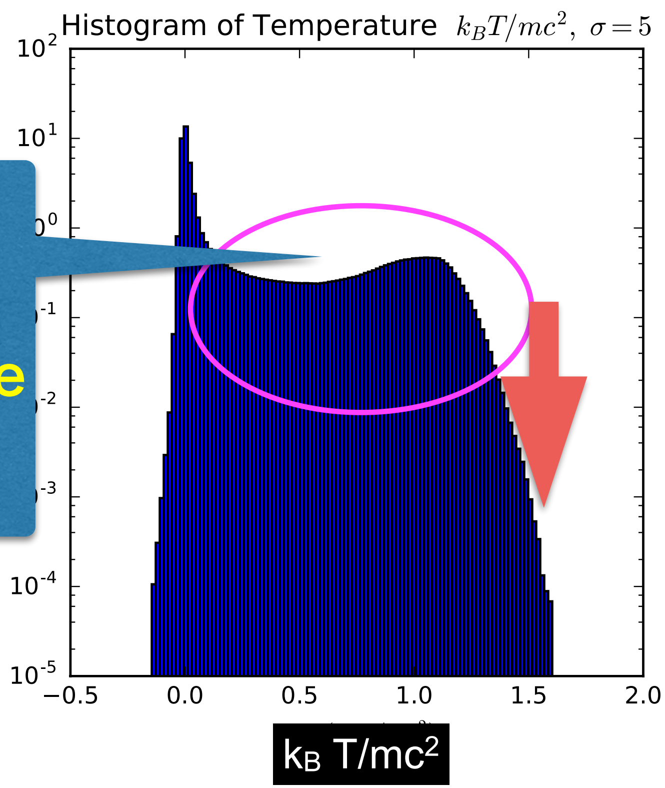
ref) MT+, (2015), ApJ 815, 16.

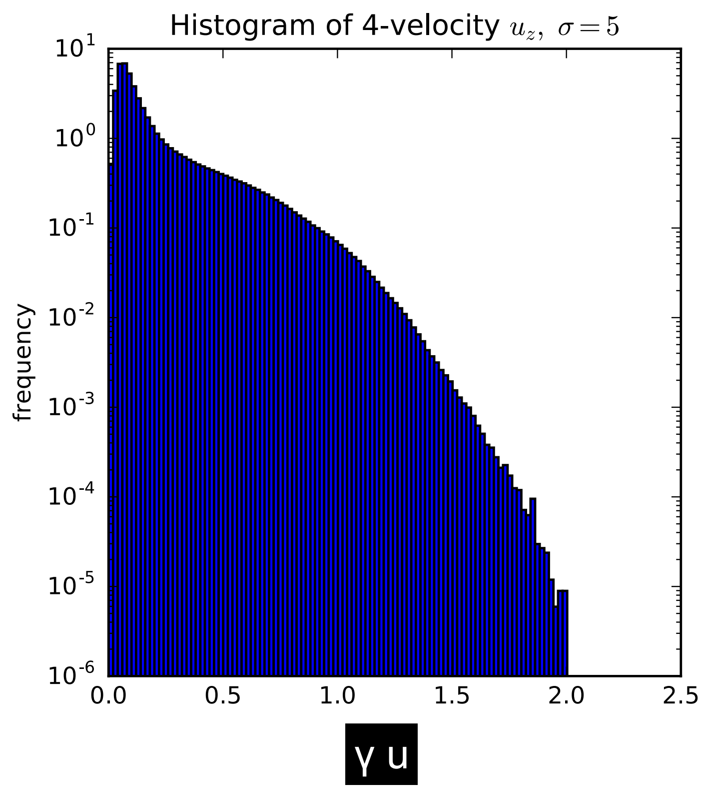
Turbulent sheet



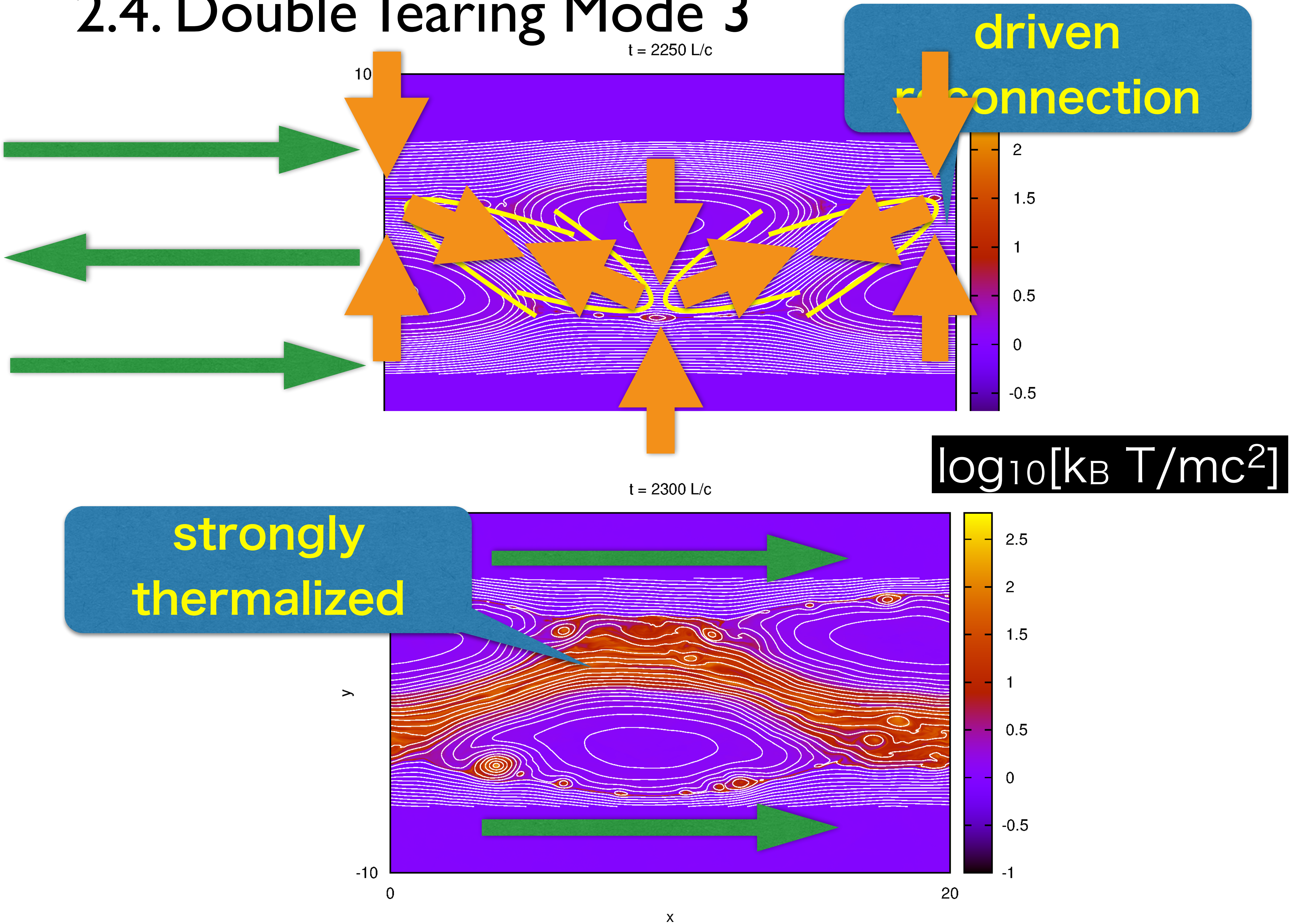


more broad
but
more moderate
and **steady**





2.4. Double Tearing Mode 3



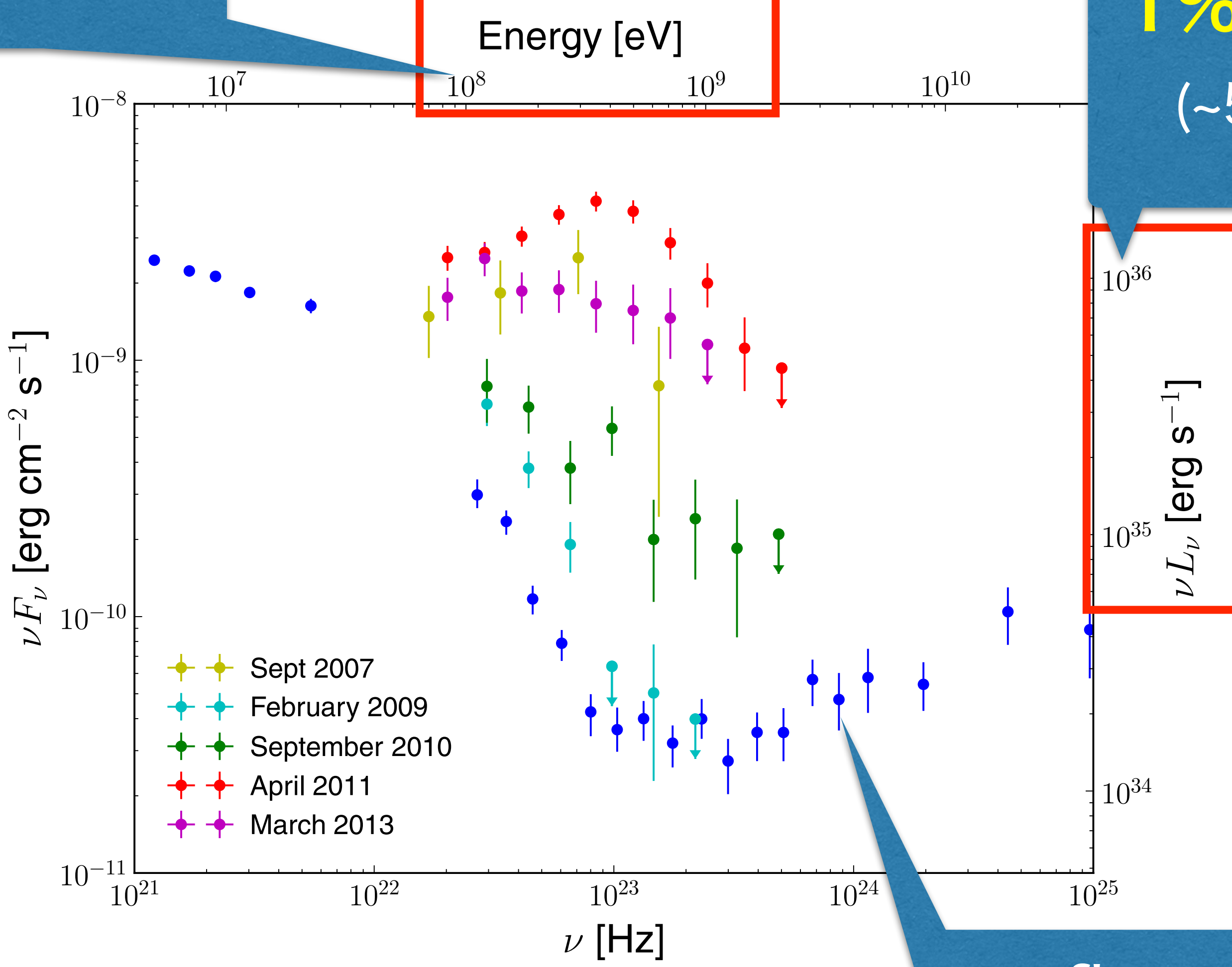
1.6. Crab Flares II

ref)Buehler+ (2012), ApJ 749, 24.
Buehler+ (2014), RPR, 77, 066901.

≳100MeV

1% of $L_{spindown}$

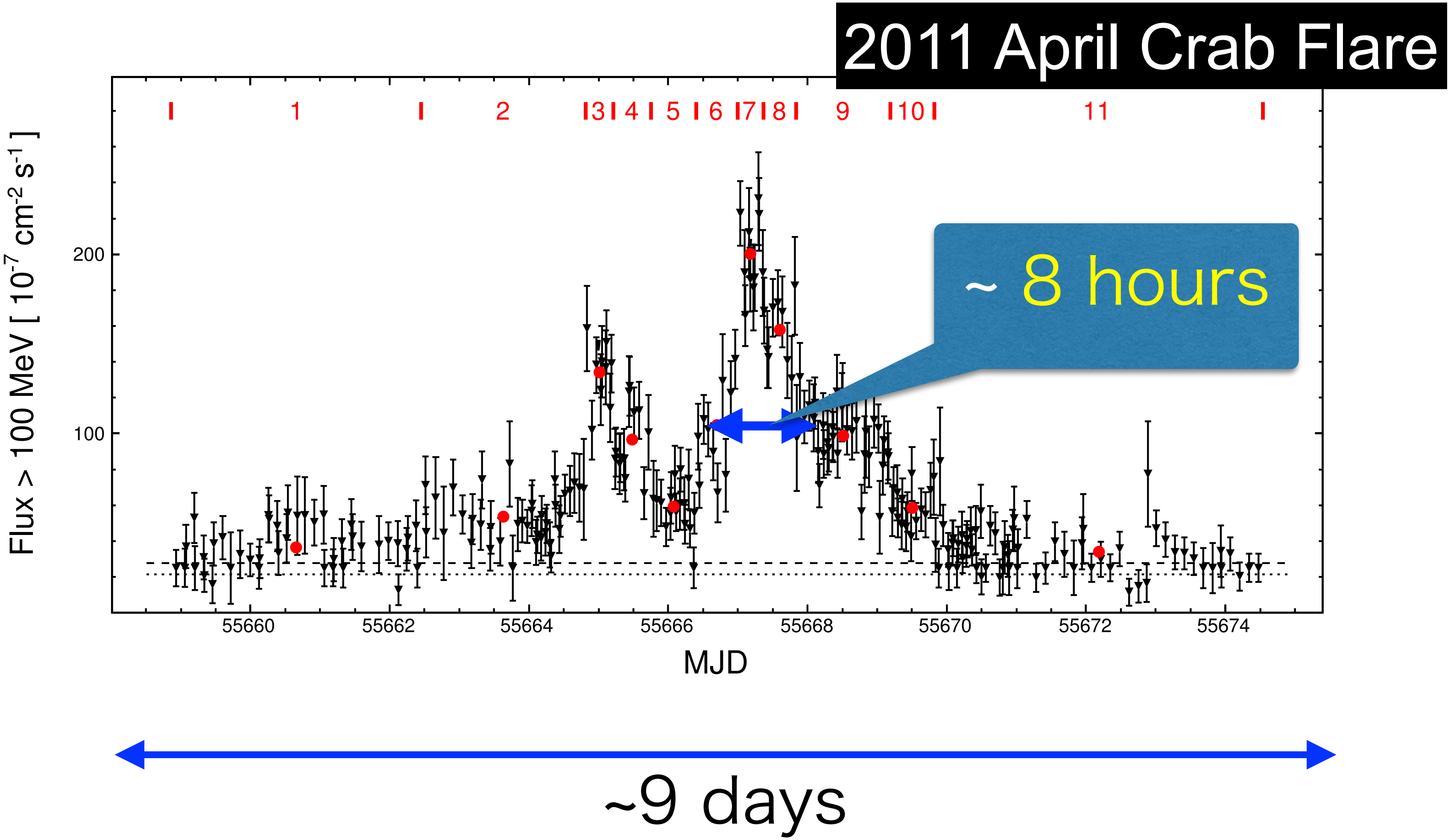
(~5×10^{38}erg/s)



no flare case

1.5. Crab Flares 1

ref)Buehler+ (2012), ApJ 749, 24.
Buehler+ (2014), RPR, 77, 066901.



Strong time variability in gamma-ray (~100MeV)!!

1.7. Theoretical Models and Difficulties I

ref) Guilbert+(1983), MNRAS,205
Uzdensky+(2011), ApJL, 737

<u>Assumption:</u> in MHD plasma ($B^2 > E^2$)

$$\left.\begin{array}{r} \tau_{\rm syn} \propto (\gamma B^2)^{-1} \\ \tau_B \propto (\gamma/B). \end{array}\right\} \Rightarrow (\gamma^2 B)_{\rm Max} = \mathrm{const.},$$

⇒ maximum radiation energy
~ 160MeV < ε_{obs}~375 MeV

$$\boxed{\epsilon_{\rm sync} = \frac{3}{2}\gamma^2 \frac{B}{B_q} mc^2 \propto \gamma^2 B}$$

1.8. Theoretical Models and Difficulties 2

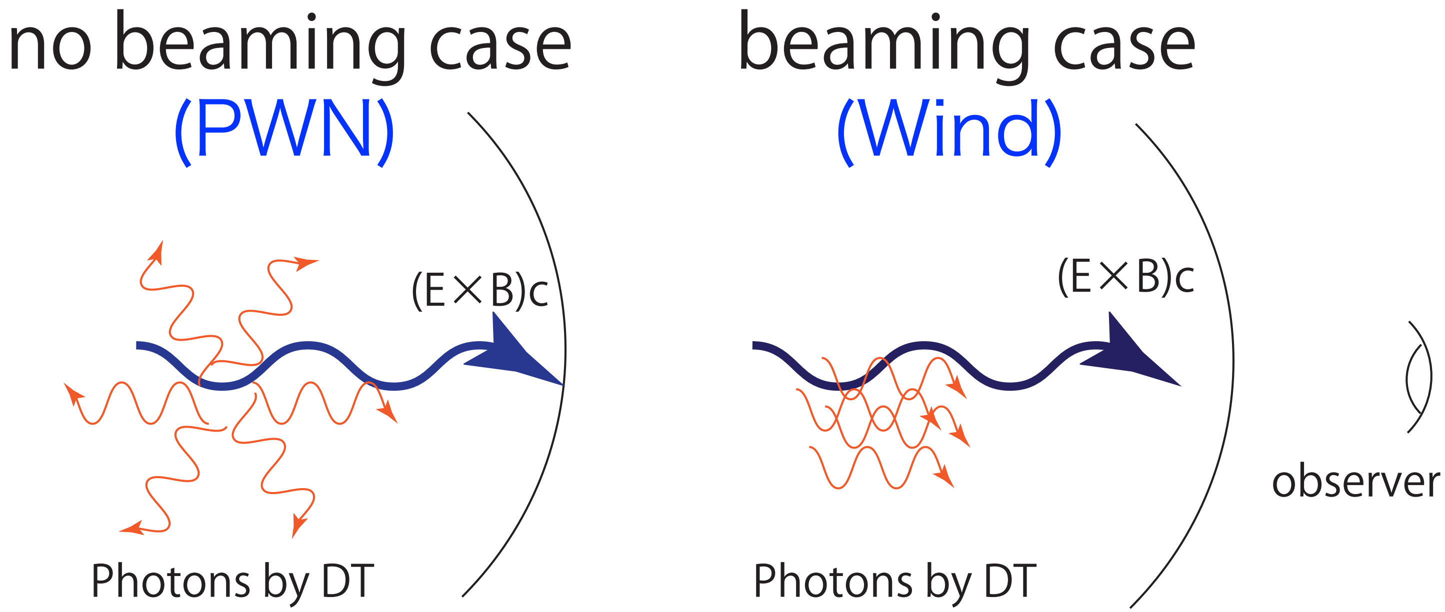
observed duration of the flares:

$$\boxed{T_{flare} \sim 10 \text{ hours}}$$

if pulsar origin: P~33[ms] << T_{flare}

if PWN origin : 1[pc]/c ~ 1yr >> T_{flare}

3.2. Radiation Energy Flux & Duration



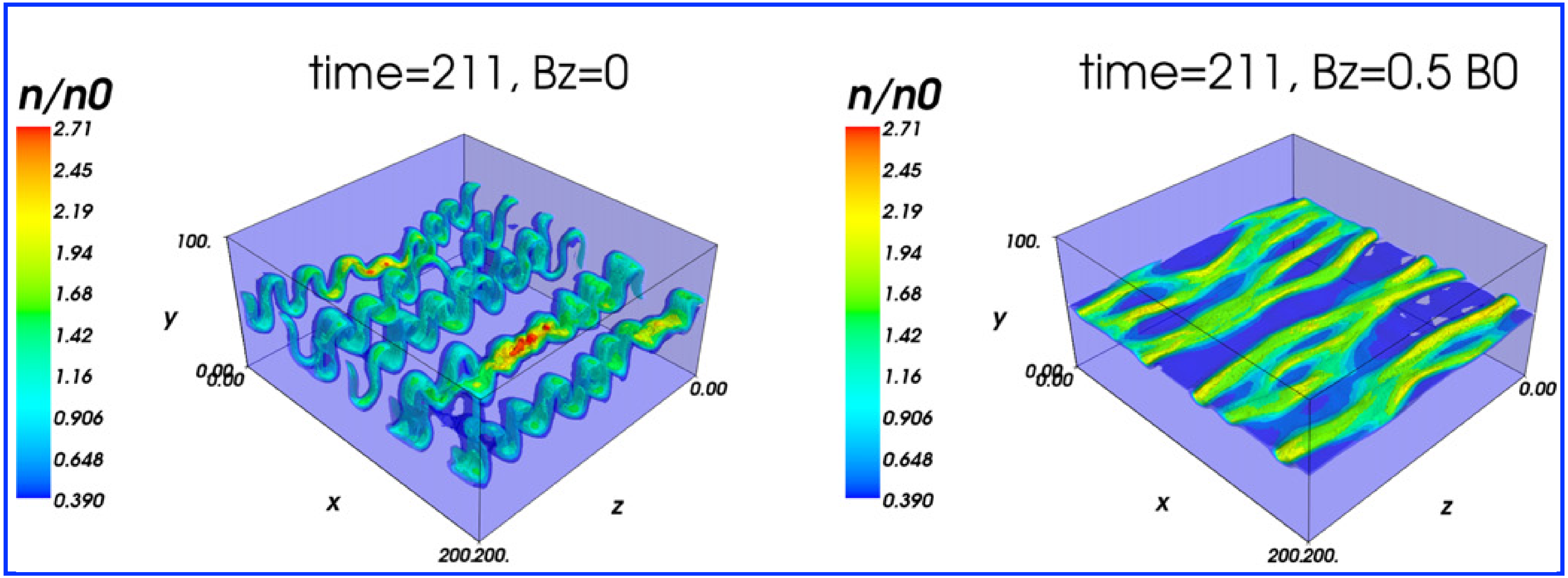
only a part of the emitted photons can be observed

1% of energy conversion is sufficient!!

($L \sim 0.01\ L_{spindown}$)

1.9. Reconnection in PWN

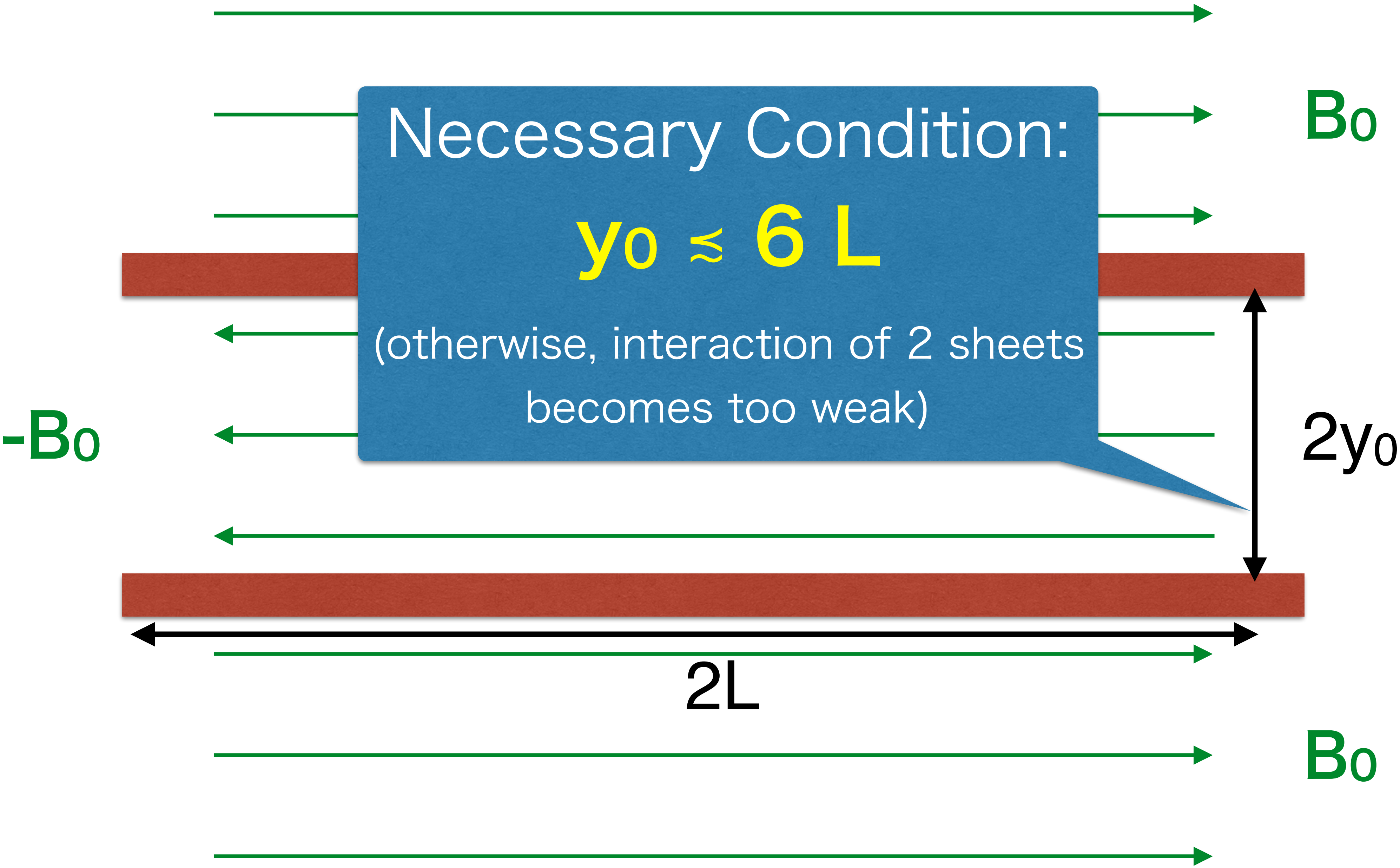
ref) Uzdensky+(2011), ApJL, 737
Cerutti+(2013), ApJ
Cerutti+(2014), ApJ, 782



<u>Condition:</u>

- a very long and coherent sheet
- very weak perturbation on particles
- weak guide field

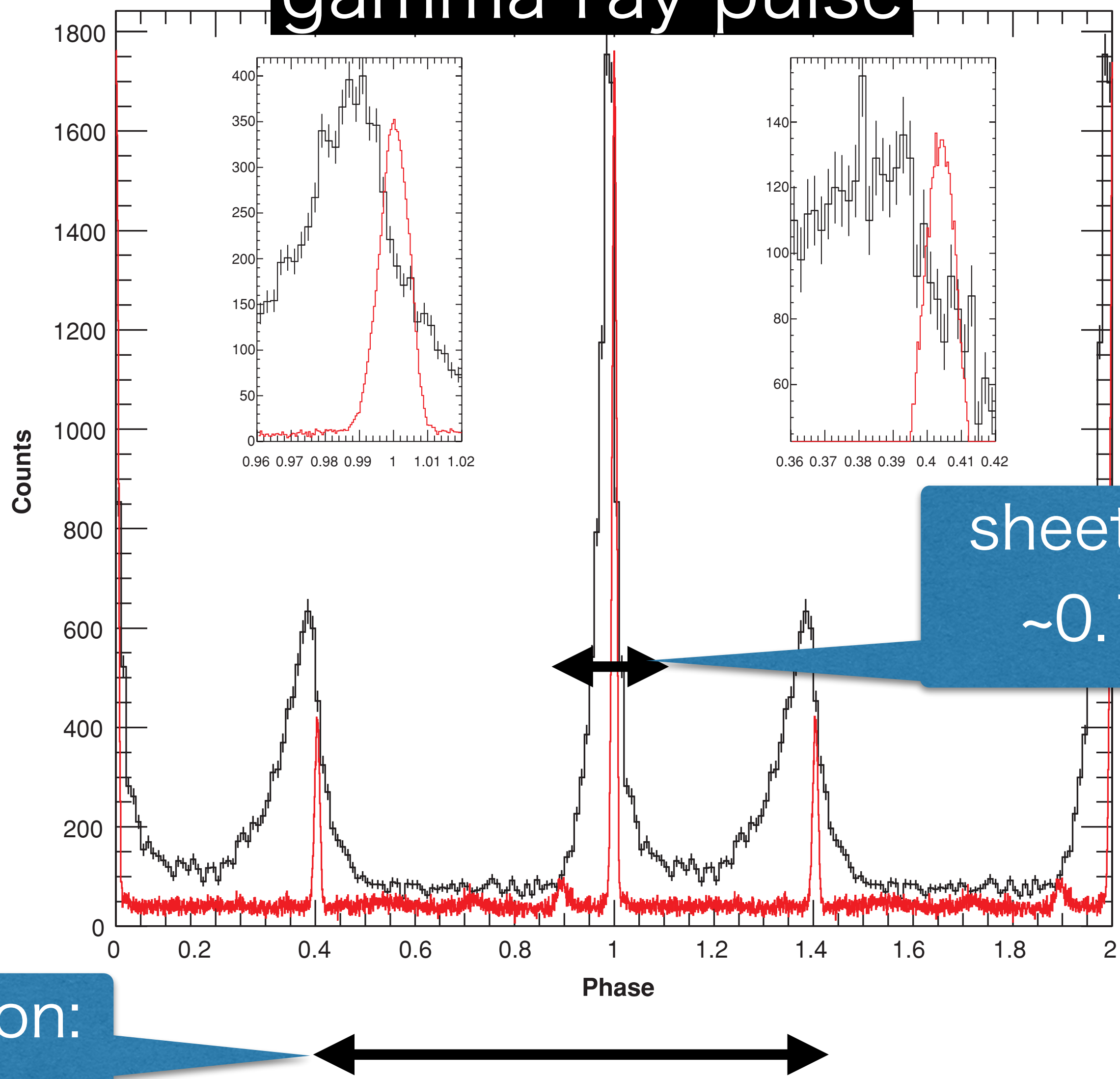
Necessary Conditions of DTM



Observed Sheet-Thickness in Wind

ref) Petri+(2005),ApJL, 627, 37.
Abdo+(2010),ApJ, 708, 1254.

gamma-ray pulse



sheet thickness:
$\sim 0.1 \times 2\pi r_L$

sheet separation:
$2\pi r_L$

3.3. Cut-off energy and Constraints on Crab Parameters

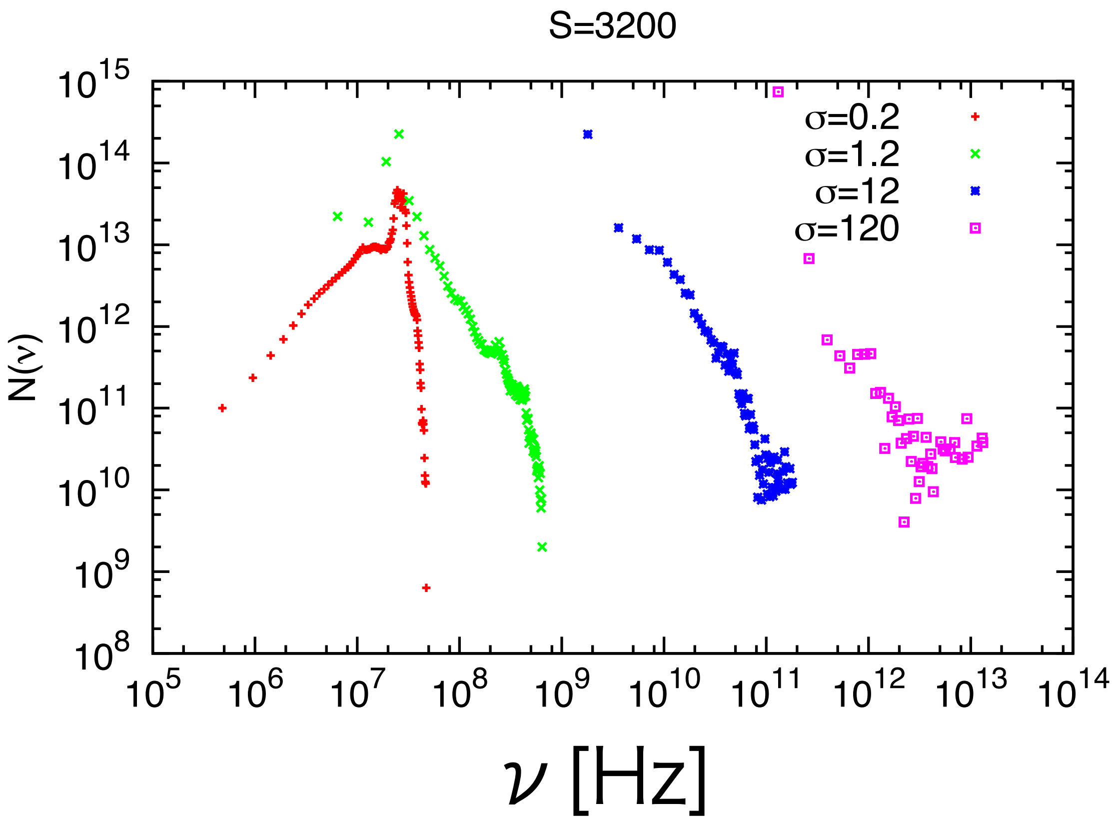
maximum energy:

DTM dynamical time ~ radiation cooling time

$$\frac{\bar{\tau}_{\rm sync}}{\bar{\tau}_{\rm dyn}} = \boxed{9.4 \times 10^5} \left(\frac{\Gamma_{\rm W}}{300}\right) \boxed{\Theta^{-1}} \left(\frac{\bar{B}}{0.05\bar{B}_0}\right)^{-2} \left(\frac{r}{50 r_{\rm L}}\right)^{2} \times \left(\frac{\bar{B}_{\rm L}}{100[{\rm T}]}\right)^{-2} \left(\frac{l/2\pi r_{\rm L}}{0.05}\right)^{-1} \left(\frac{P}{33[{\rm ms}]}\right)^{-1}.$$

$$\boxed{\epsilon_{\rm sync,L} \sim \boxed{311[{\rm MeV}]} \left(\frac{\Theta}{10^6}\right)^{2} \left(\frac{r}{50 r_{\rm L}}\right)^{-1} \left(\frac{\bar{B}}{0.05\bar{B}_0}\right) \left(\frac{B_L}{100[{\rm T}]}\right)}$$

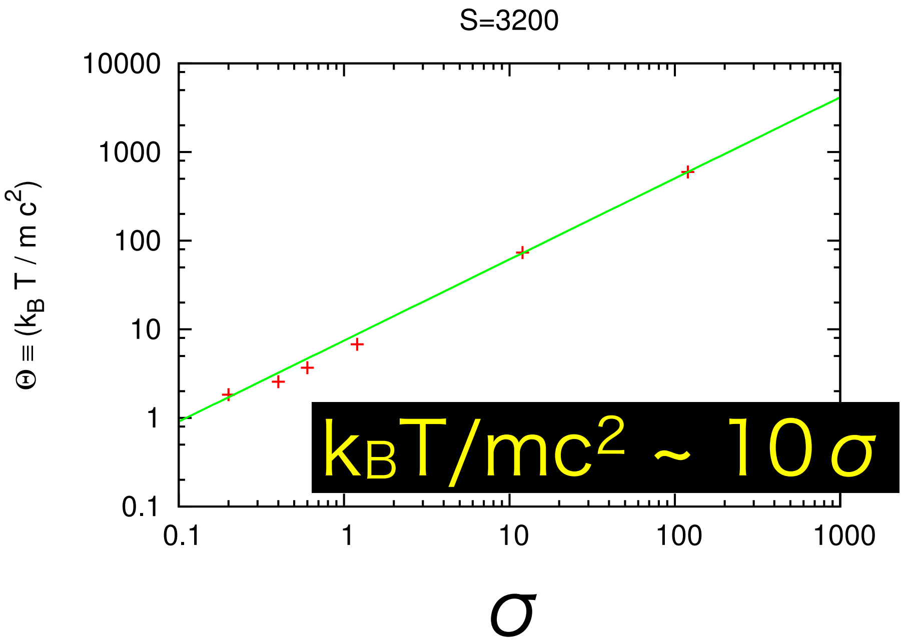
DTM in Blazar



$$\epsilon_{\rm sync} = \frac{3}{2}\gamma^2 \frac{B}{B_q} mc^2,$$

*Lorentz transform
*$\gamma \sim 3\, k_B T/mc^2$
*$B = B_L / \Gamma$
*$N(\varepsilon) = \int n\varepsilon\, dV$

$$\nu_{\rm Lab,sync} \simeq 7.53 \times 10^8 [{\rm Hz}] \left(\frac{\Theta}{10\sigma}\right)^2 \left(\frac{\sigma}{1}\right)^2 \left(\frac{B_0}{100[{\rm mG}]}\right)$$



$\nu_{\rm sync,L} \sim 10^9$[Hz]

(when $\sigma \sim 1$, $\Gamma \sim 5$, B~0.1[G])