TeV emission - GRBs' Rosseta's Stone

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ApJL , 880, 27, August 2019

Origins: From the Big Bang to Planets I-CORE

erc TReX

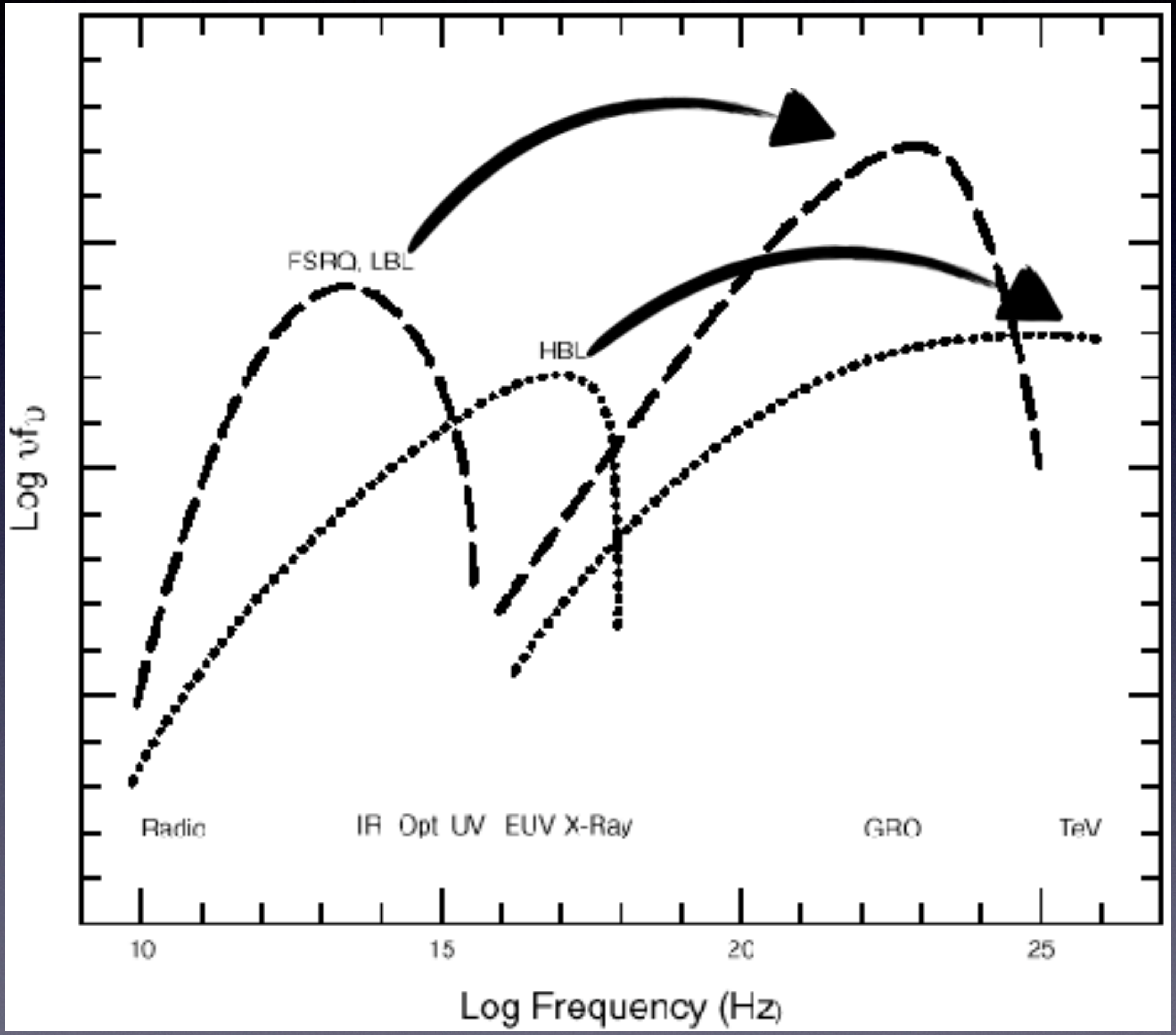
Magic sub-TeV
Mirzoyan + 19

GCN 23701

MAGIC detects the GRB 190114C in the TeV energy domain

The MAGIC telescopes detected very-high-energy gamma-ray emission from GRB 190114C. The observation started about 50s after the Swift T0. The GRB data of MAGIC shows a clear excess of gamma-ray events with the significance >20 sigma in the first 20 min (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (~60 deg.) and the presence of partial moon. After the first bright flash the source is quickly fading.

Blazars

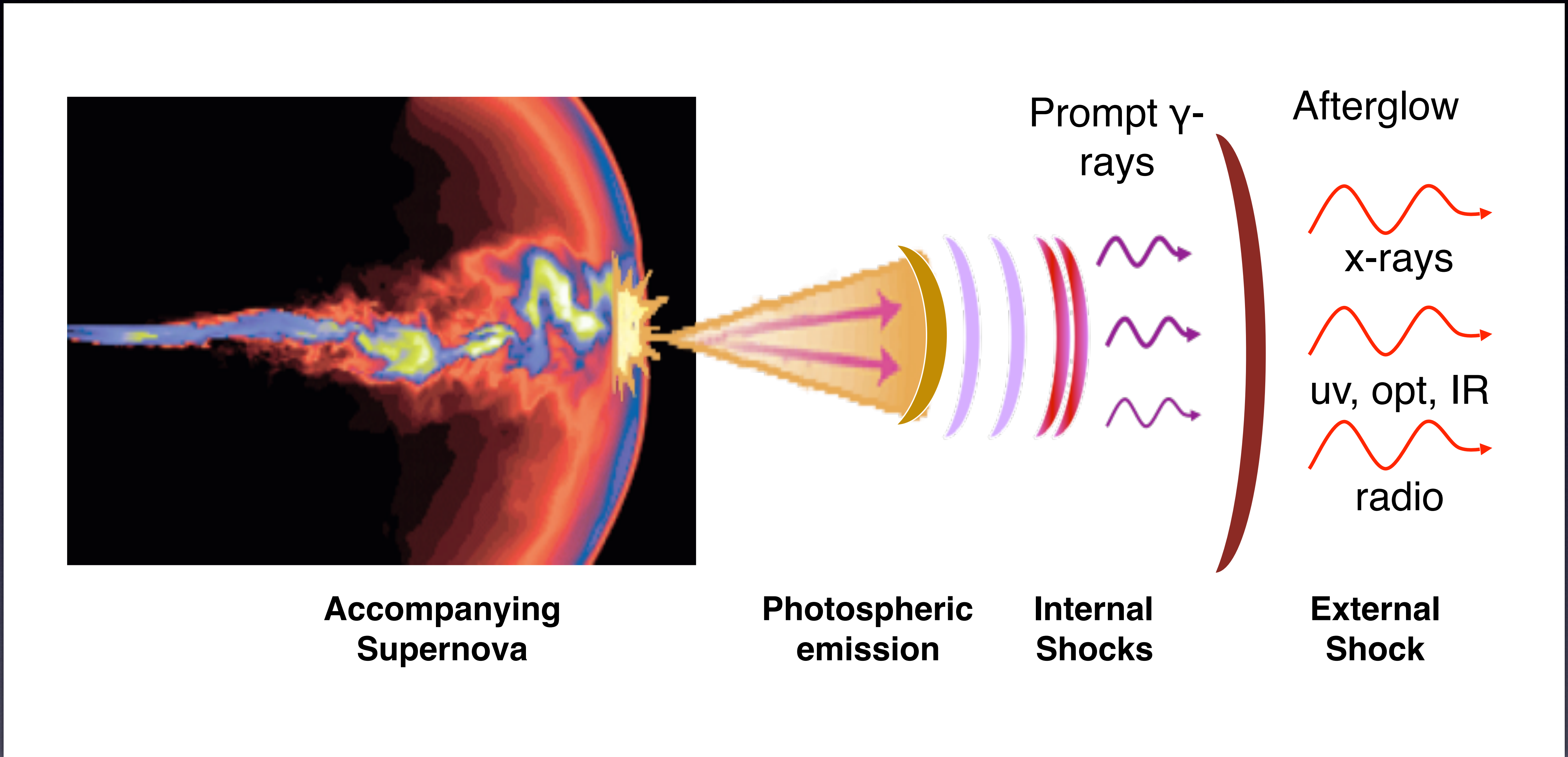


FSRQ, LBL
HBL
Log νf_ν
Radio
IR Opt UV
EUV X-Ray
GRO
TeV
10
15
20
25
Log Frequency (Hz)

Observations

- Z=0.4245 (Some TeV absorption)
- $L_{peak}^{Iso} \simeq 1.6 \times 10^{53}$ erg/sec
- $E^{Iso} \simeq 3 \times 10^{53}$ erg
- @ 70 sec $L_x^{Iso} \simeq 6 \times 10^{49}$ erg/sec
- $E_{TeV} \simeq 350$ GeV (peak below 200 GeV; flat* up to 1 TeV)
- $y = L_{Tev}^{Iso}/L_x^{Iso} \simeq 0.25$ (1/3 - 1)

A Gamma-Ray Burst Model



Numerous attempts to reveal the conditions within the emitting regions of the Afterglow - but usually degeneracy

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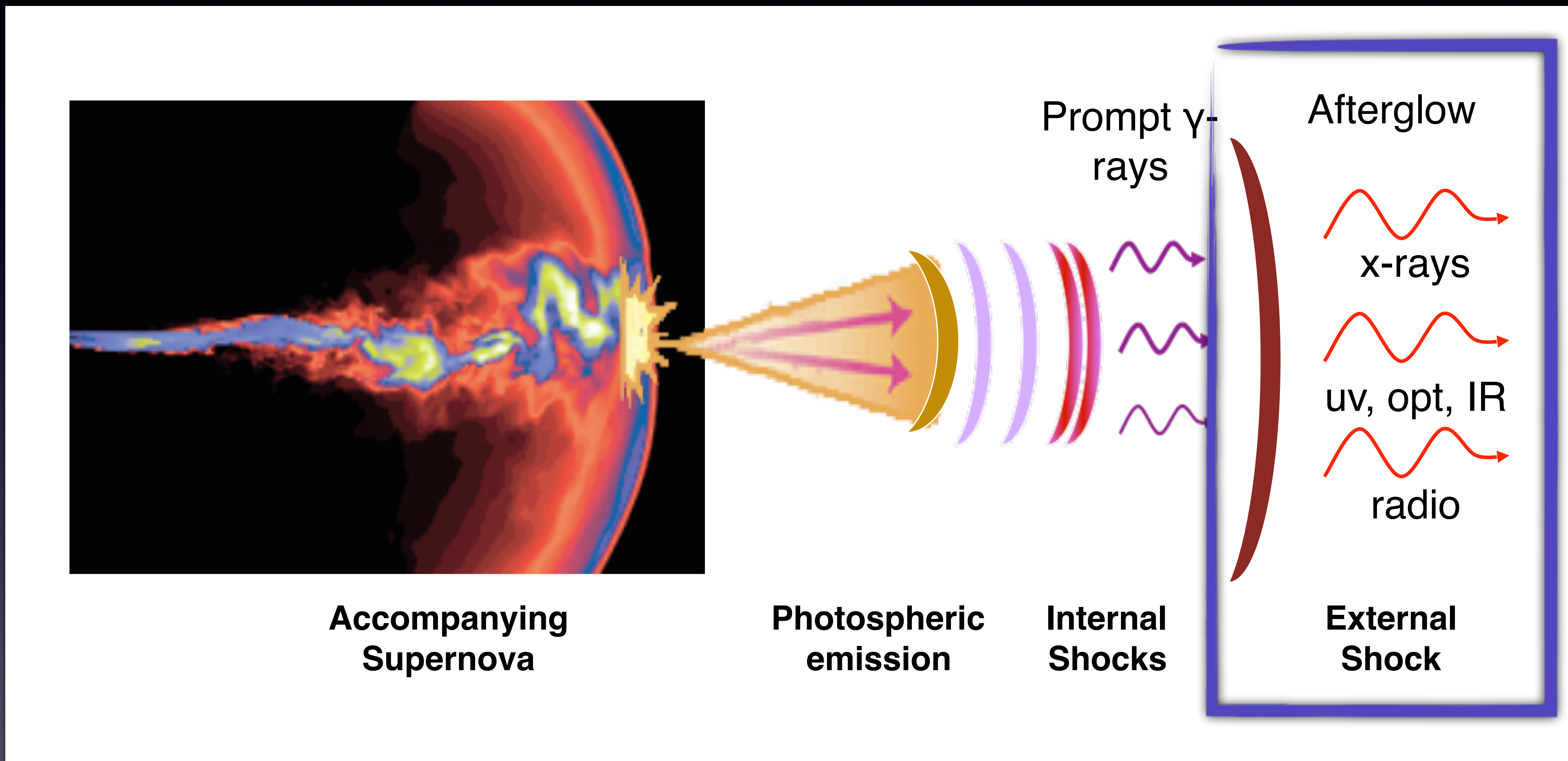
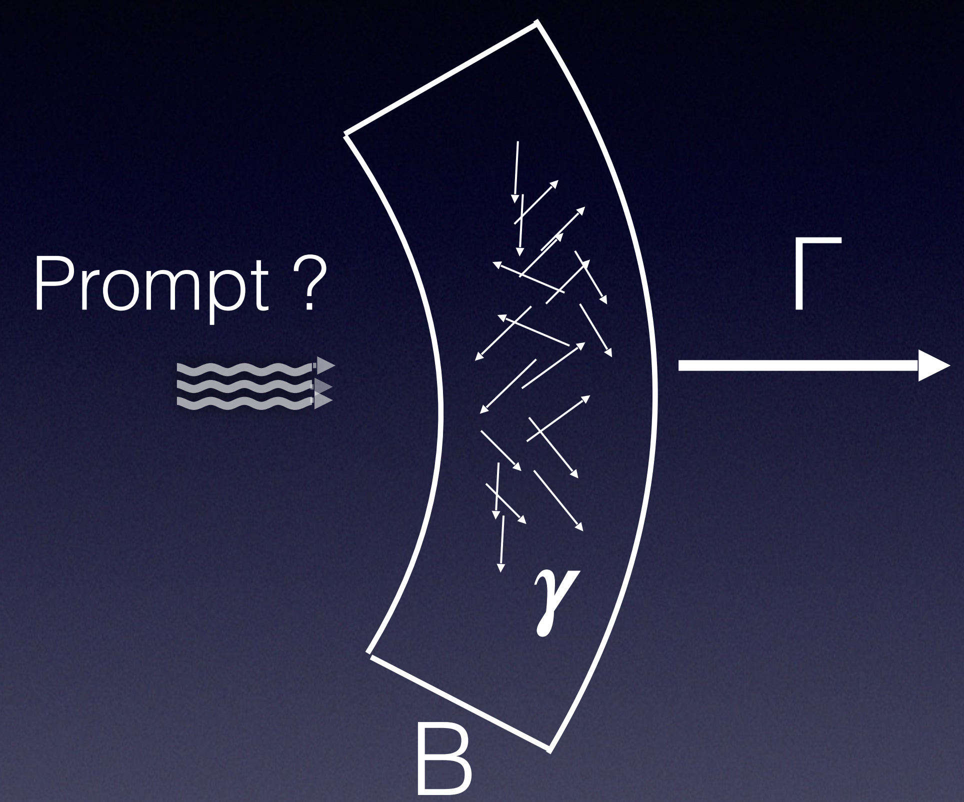


Numerous attempts to reveal the conditions within the emitting regions of the Afterglow - but usually degeneracy

The Model

- Blast wave into wind or ISM
- Single Zone



Parameters: Γ, n, t,

ε_e, ε_B that can be replaced by $y, t_{dyn}/t_{cool}, \varepsilon_R$

$\varepsilon_e \equiv e_e/e$; $\varepsilon_B \equiv e_B/e$

Origin of TeV?

- Synchrotron burn-off limit
(Acc. time $\simeq$ cooling time)
$E_{burn\text{-}off} = \Gamma m_e c^2 / \boldsymbol{\alpha} \simeq \Gamma$ 100 MeV too low .

- Bypass burn-off limit: acceleration in a weak field and emission in a strong one (e.g. Kumar & Barniol-Duran 09) or "converter" acceleration.

- => Inverse Compton

The Lorentz Factors

- $\gamma\Gamma\ m_e c^2 > E_{IC} \Rightarrow \gamma\Gamma \simeq 10^6$
- @ 70 sec and longer Γ cannot be too large
  $\Rightarrow \gamma \gtrsim 10^4$
- Not unreasonable in an external shock with
  $\gamma \simeq f(m_p/m_e)\Gamma$ (f~1/2-1/3)
- => Tev is Inverse Compton of X-rays
  (Consistent with a comparable X-ray luminosity)

Opacity

- The optical depth for pair production $\tau_{IC,x} < 1$
  The usual opacity estimates for GRBs with L_x as the source of absorbing photons

=> $\Gamma > 100$

$$\Gamma > 100 \left(\eta_a \frac{L_{X,51}^{\rm iso}}{t_2} \right)^{1/6}$$

- Somewhat different analysis if the X-rays are from "prompt" origin.

- Even this Γ requires low external density
  (e.g. $n_{ISM} < 10\ cm^{-3}$)
  => cannot expect much larger Γ
  => cannot expect much lower γ ($\gamma\,\Gamma > 10^6$)

What kind of IC?
To KN or not to KN

The usual Comptonisation energy is
$\gamma^2 E_{seed}$

If $\gamma^2 E_{seed} > \gamma m_e c^2$ we are in the
Klein Nishina (KN) regime:
$E_{IC} = \gamma m_e c^2$

What kind of IC?

The SSC Klein Nishina Energy

$$E_{\rm IC}^{\rm cr} = \Gamma \gamma_{\rm cr} m_e c^2 = \Gamma \left(\frac{B_{\rm cr}}{B}\right)^{1/3} m_e c^2$$

KN for Γ< $\Gamma_{\rm KN} \simeq 86 \, \frac{(L_{51}^{\rm iso})^{1/12}}{t_2^{1/6}}$

=> With the opacity limit (Γ>100) the system is close to KN but in regular Comptonization

The electron's Lorentz factor

Combining the Opacity and KN limits:

$$\gamma_{e,\min} \simeq \frac{E_{\rm IC}}{\Gamma m_e c^2} = \frac{10^6}{\Gamma}$$

$$\gamma_{e,\max} \simeq \left(\frac{\Gamma}{\Gamma_{\rm KN}}\right)^{3/2} \gamma_{e,\min}$$

>100 (→ Γ)

$\simeq 85$ (→ $\Gamma_{\rm KN}$)

$$\gamma_e \simeq \gamma_{e,\max} \simeq 1.5 \times 10^4$$

Efficiency

Synchrotron Flux

Fast Cooling

$$\epsilon_{\rm sy} \equiv \frac{F_{\rm sy}}{F_{\rm d}} \simeq \quad \epsilon_e \begin{cases} 1 & \text{for} \quad t_{dyn}/t_{cool} > 1 \\ t_{dyn}/t_{cool} & \text{for} \quad t_{dyn}/t_{cool} < 1 \end{cases}$$

Kinetic energy flux

Slow Cooling

(See also Sari, Narayan & TP 96)

Efficiency

Synchrotron Flux

Fast Cooling

$$\epsilon_{\rm sy} \equiv \frac{F_{\rm sy}}{F_{\rm d}} \simeq y\epsilon_m \simeq \epsilon_e \begin{cases} 1 & \text{for} \quad t_{dyn}/t_{cool} > 1 \\ t_{dyn}/t_{cool} & \text{for} \quad t_{dyn}/t_{cool} < 1 \end{cases}$$

Kinetic energy flux

Slow Cooling

(See also Sari, Narayan & TP 96)

Efficiency

$E_X^{Iso} \simeq 10^{52}$ erg.

$E_{tot}^{iso} = E_X^{Iso} / \varepsilon_{sy}$

But $\varepsilon_{sy} = y\, \varepsilon_B \simeq (0.25\text{-}1)\varepsilon_B$ (fast cooling)

$\Rightarrow E_{tot}^{iso} \simeq 5\times10^{52}$ erg $/\varepsilon_B$

$\Rightarrow \varepsilon_B > 0.005\ (E_{tot,max}^{iso} / 10^{55})$

Caveats

- L_{TeV} is underestimated because of self absorption => y is larger, maybe even > 1.
  => $\varepsilon_e > \varepsilon_B$ and ε_B can be smaller (but not tiny).

- A fraction of L_X arises from the "prompt component". This relaxes somewhat the efficiency problem but since y is unchanged the condition $\varepsilon_B > \varepsilon_e$ remains.

Partial Summary I

- The electron's Lorentz factor $\sim 10^4$
- The bulk Lorentz factor @100 sec ~ 100
- Low external density enables the sub-TeV photons to escape
- Relatively large magnetization $\varepsilon_B > 0.005$ and $\varepsilon_B \sim \varepsilon_e$
- Close to $\tau=1$
- IC slightly below the Klein Nishina regime

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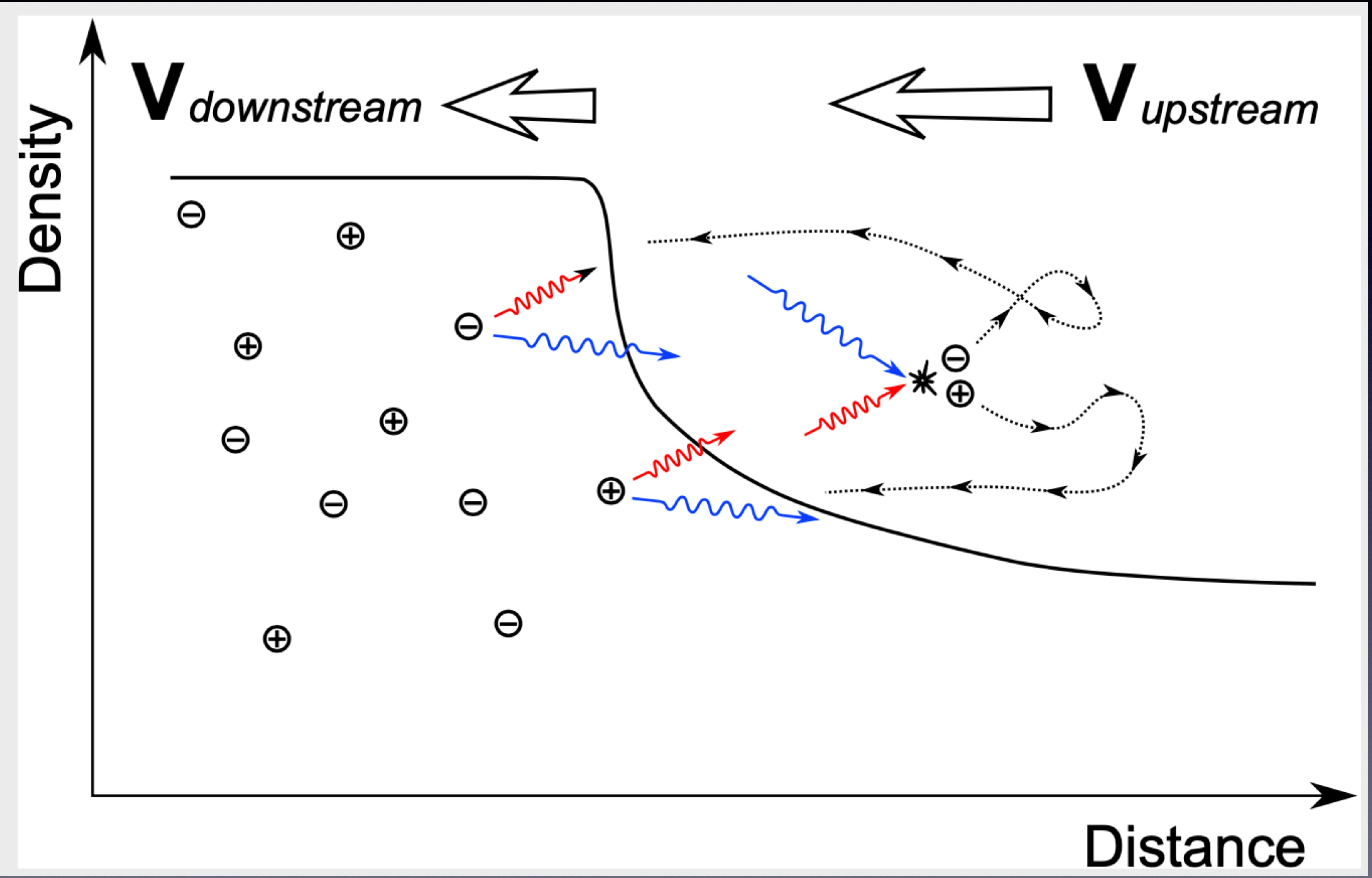
Coincidence?

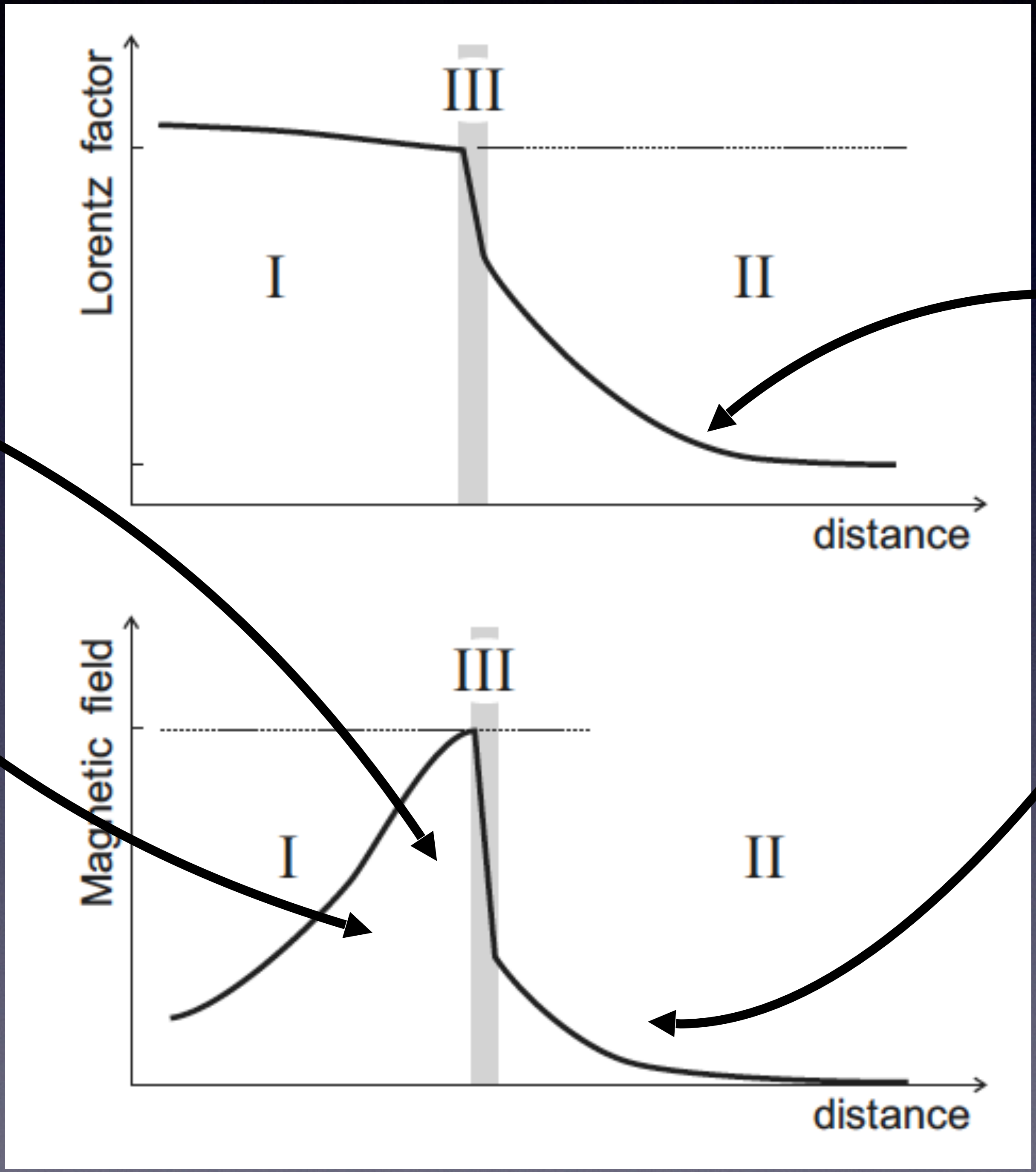
The Pair Balance Model



Derishev & TP 16

The Pair Balance Model

1) Strong magnetic field
2) Pair loading; saturation around the Klein Nishina threshold



1) Pre acceleration
2) Magnetic field build up

Derishev & TP 16

Partial Summary II

- The electron's Lorentz factor ~10^4
- The bulk Lorentz factor @100 sec ~ 100
- Low external density enables the sub-TeV photons to escape
- Relatively large magnetization $\varepsilon_B > 0.005$ and $\varepsilon_B \sim \varepsilon_e$
- Close to $\tau=1$
- IC slightly below the Klein Nishina regime
- **The configuration is consistent with the pair balance model (Derishev & TP 2016).**

nature

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Co

Nature 5

nature

Article | Published: 20 November 2019

Observation of inverse Compton emission from a long γ-ray burst

MAGIC Collaboration, P. Veres, [...] D. R. Young

Magic -
see a talk by E. Moretti

nature

Article | Published: 20 November 2019

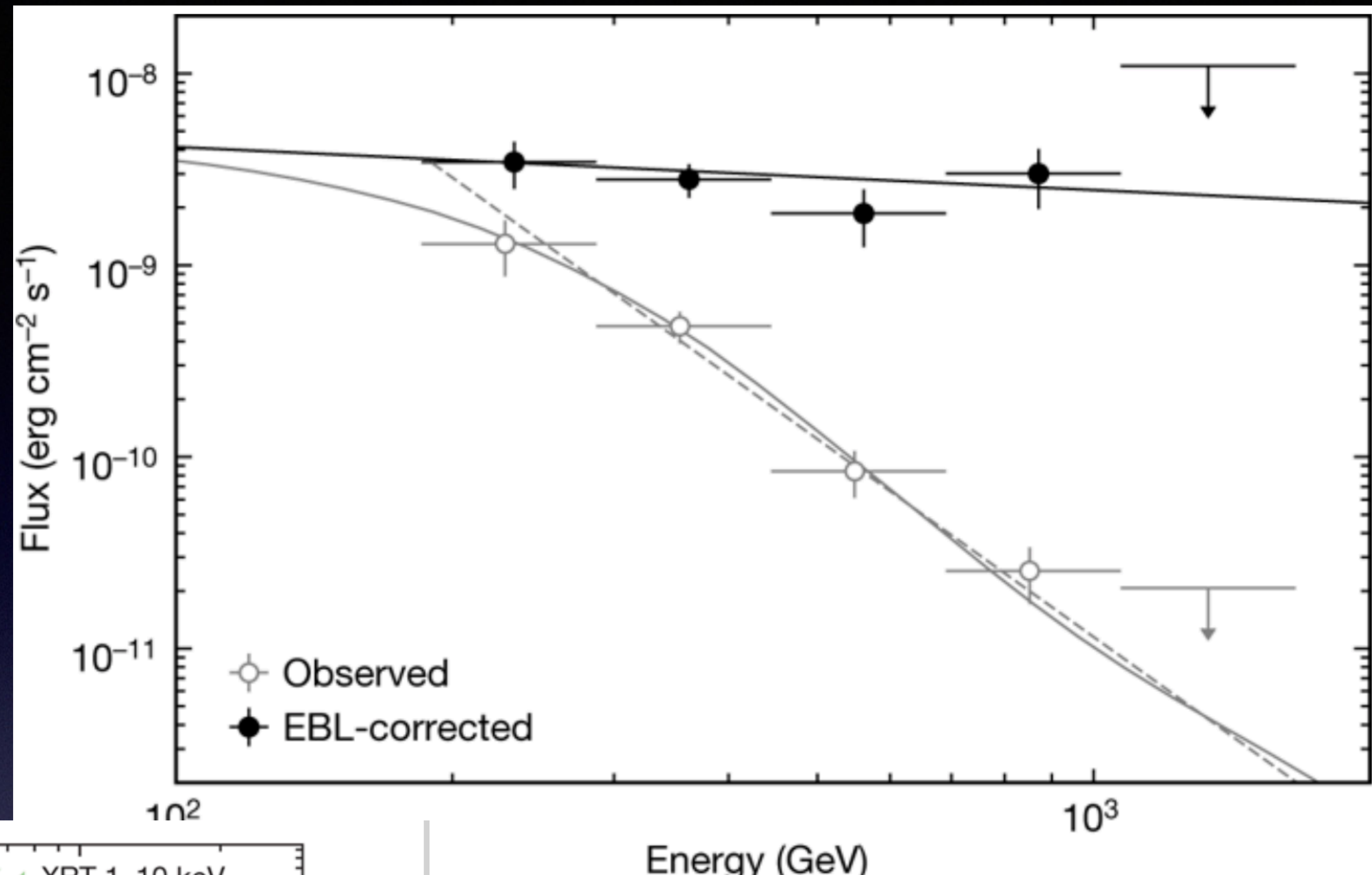
A very-high-energy component deep in the γ-ray burst afterglow

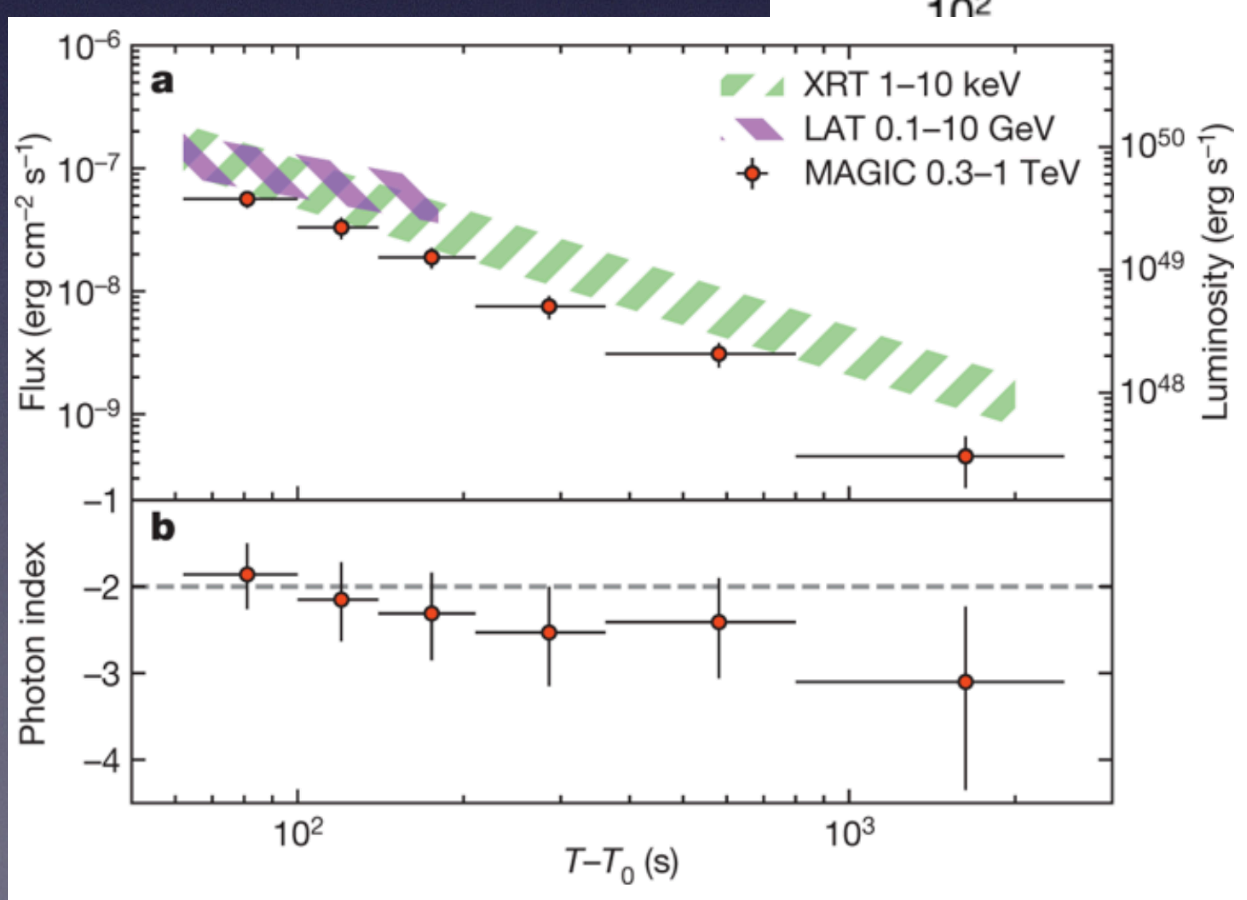
H. Abdalla, R. Adam, [...] O. J. Roberts

Nature 575, 464–467 (2019) | Cite this article

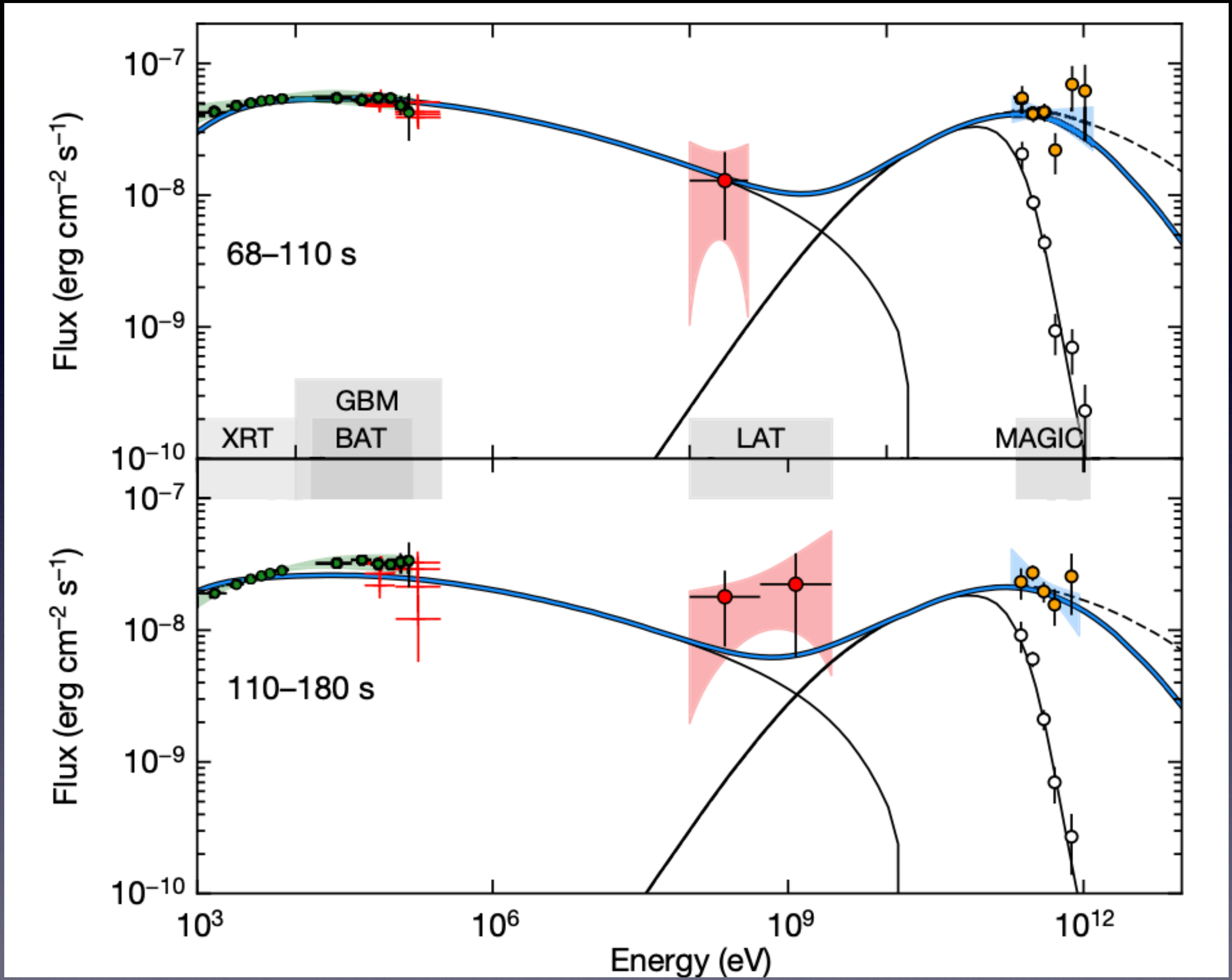
HESS -
see a talk by E. Ruiz-Velasco

1901014C (MAGIC)





~800 photons



10−7
10−8
10−9
10−10
Flux (erg cm−2 s−1)
68–110 s
GBM
XRT
BAT
LAT
MAGIC
110–180 s
10³
10⁶
10⁹
10¹²
Energy (eV)

Surprised?

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- Basic parameters 👍

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- Physical model
  Afterglow SSC with comparable values of Γ and $\boldsymbol{\gamma}$ 👍

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- Basic parameters 👍
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But

- Slow cooling 👎
- $\varepsilon_B \ll \varepsilon_e$ 👎

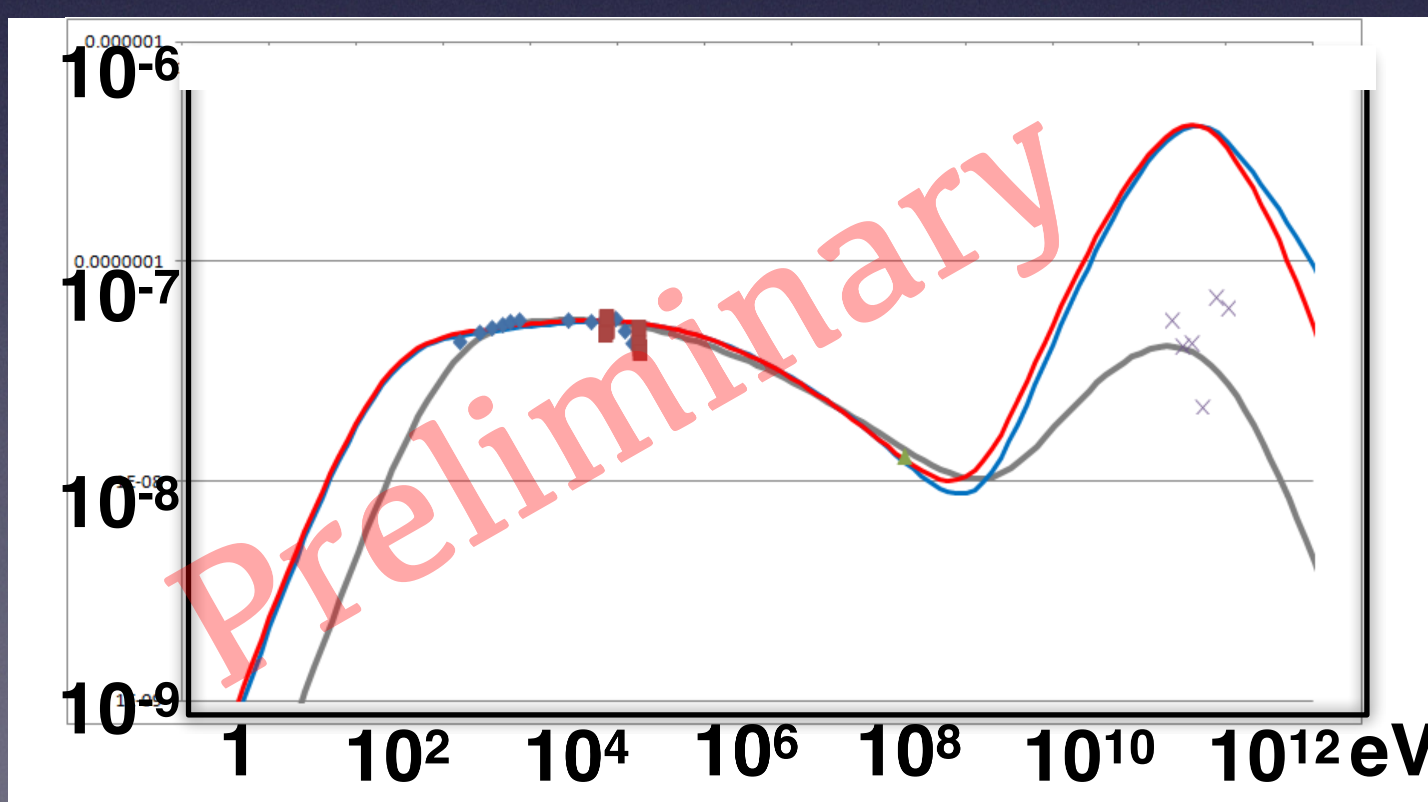
IC to Syn ratio:

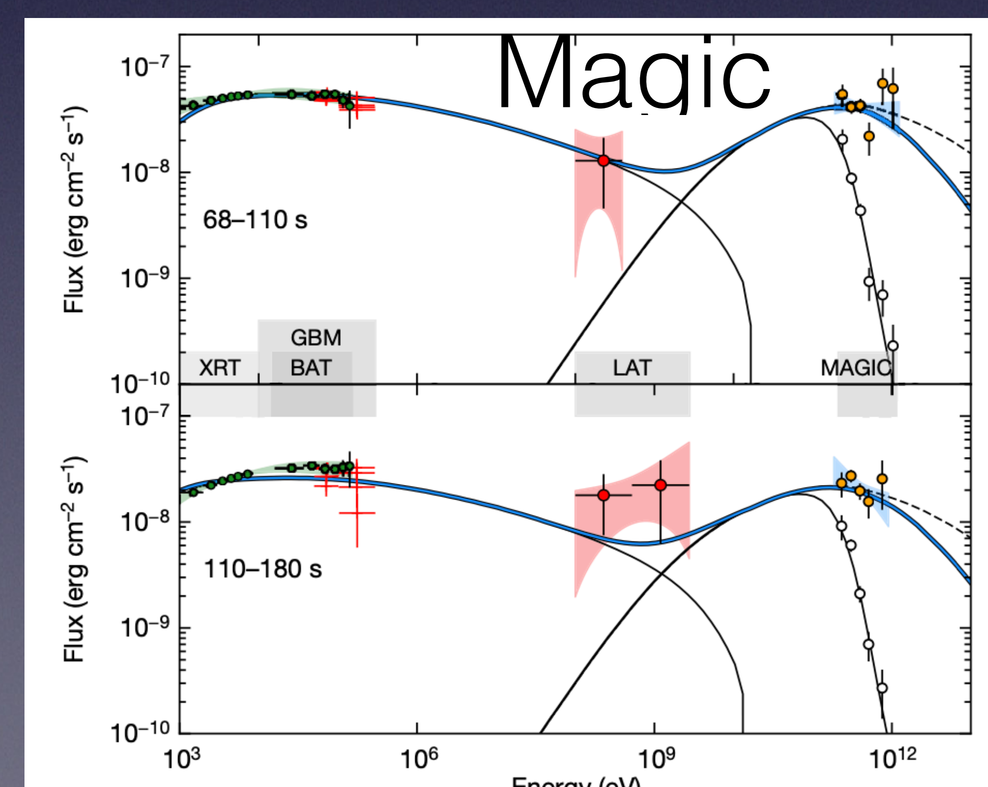
$$\frac{L_{\rm IC}}{L_{\rm syn}} = \frac{U_{\rm rad}}{U_B} = \frac{U_{\rm syn}}{U_B} = \frac{\eta U_e/(1+x)}{U_B} = \frac{\eta \epsilon_e}{\epsilon_B(1+x)} = \begin{cases} \dfrac{\eta\epsilon_e}{\epsilon_B}, & \text{if} \quad \dfrac{\eta\epsilon_e}{\epsilon_B} \ll 1\,, \\ \left(\dfrac{\eta\epsilon_e}{\epsilon_B}\right)^{1/2}, & \text{if} \quad \dfrac{\eta\epsilon_e}{\epsilon_B} \gg 1\,. \end{cases}$$

Sari & TP 96; Sari & Esin 01

$$\text{slow cooling} \quad \eta = (\gamma_c/\gamma_m)^{2-p}$$

$$\text{fast cooling} \quad \eta = 1$$





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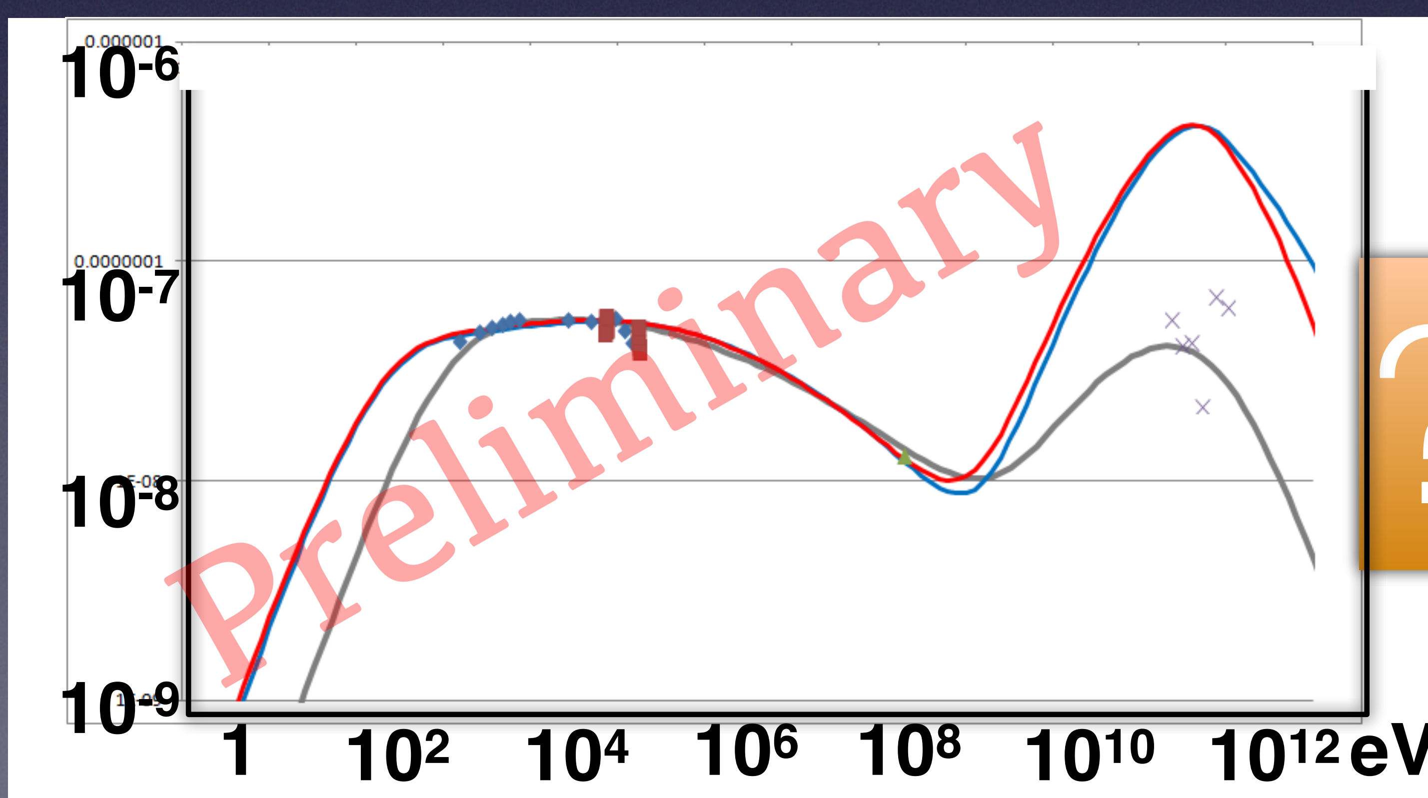
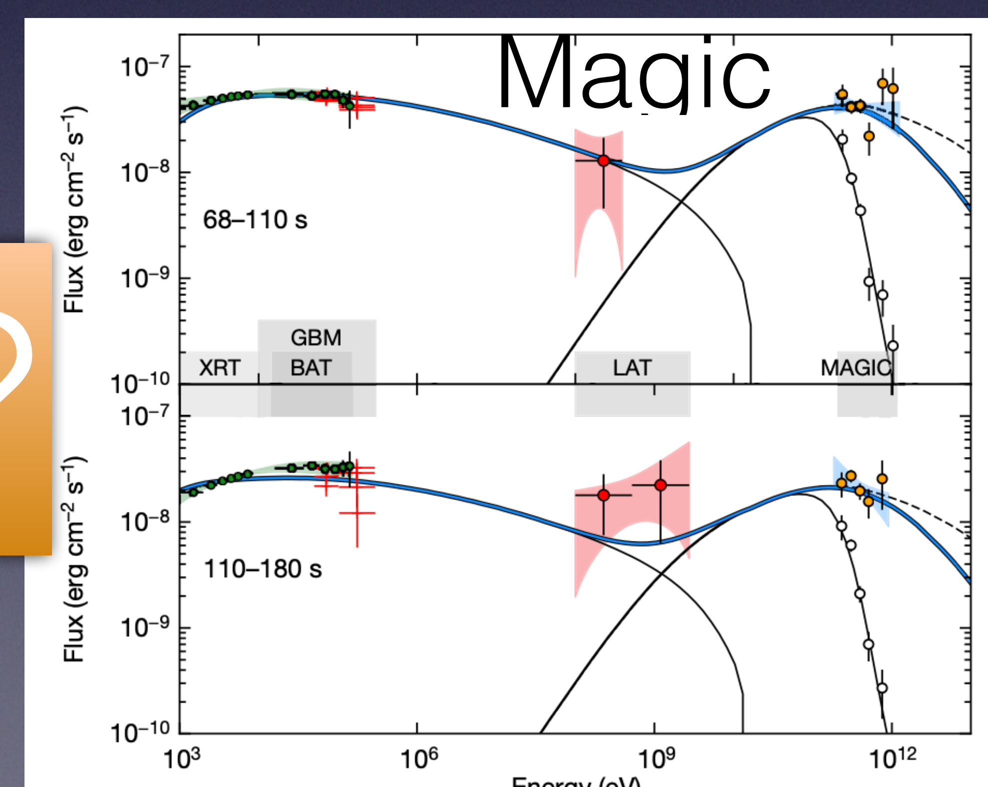
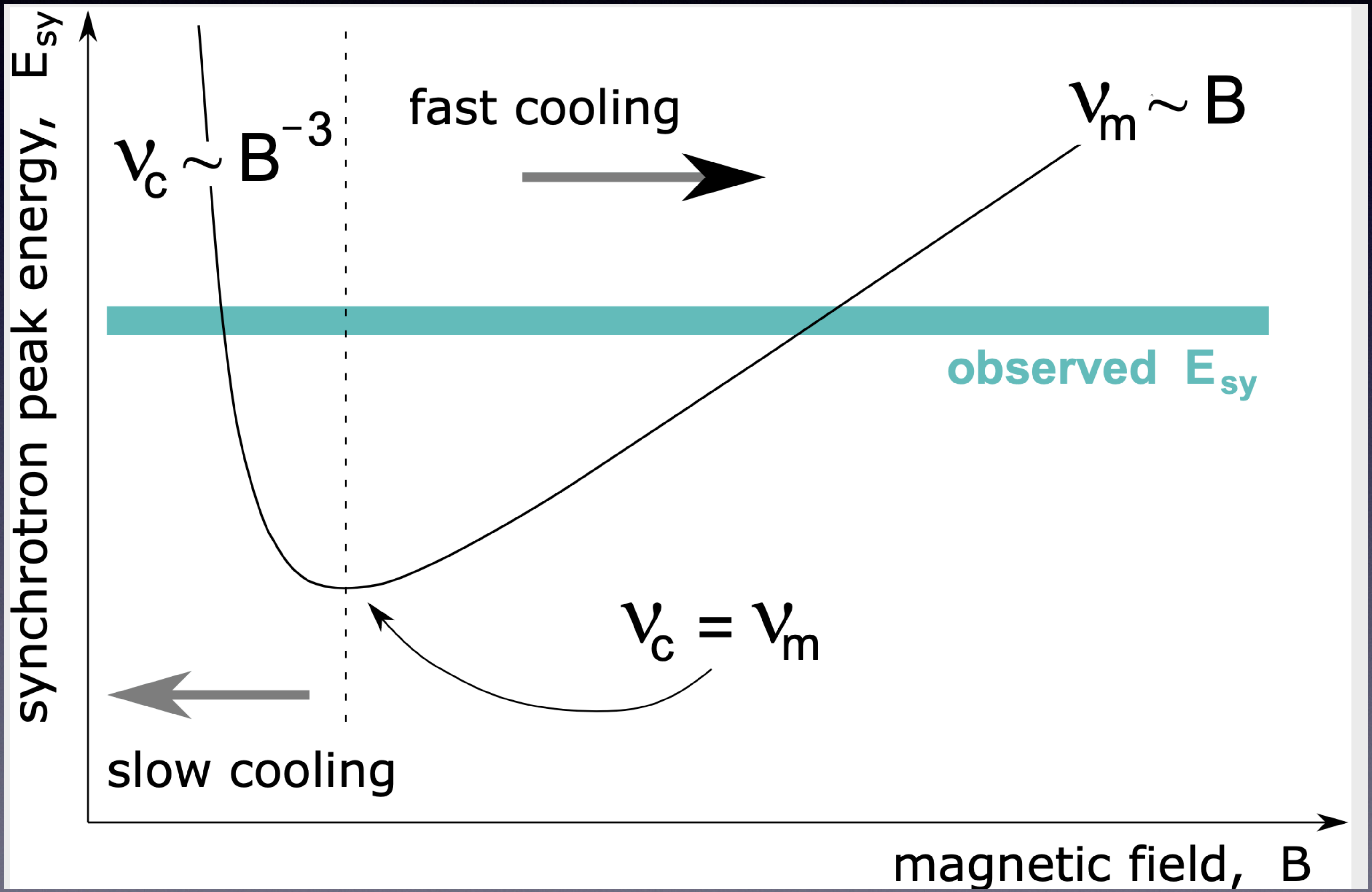


?



Breaking the Degeneracy



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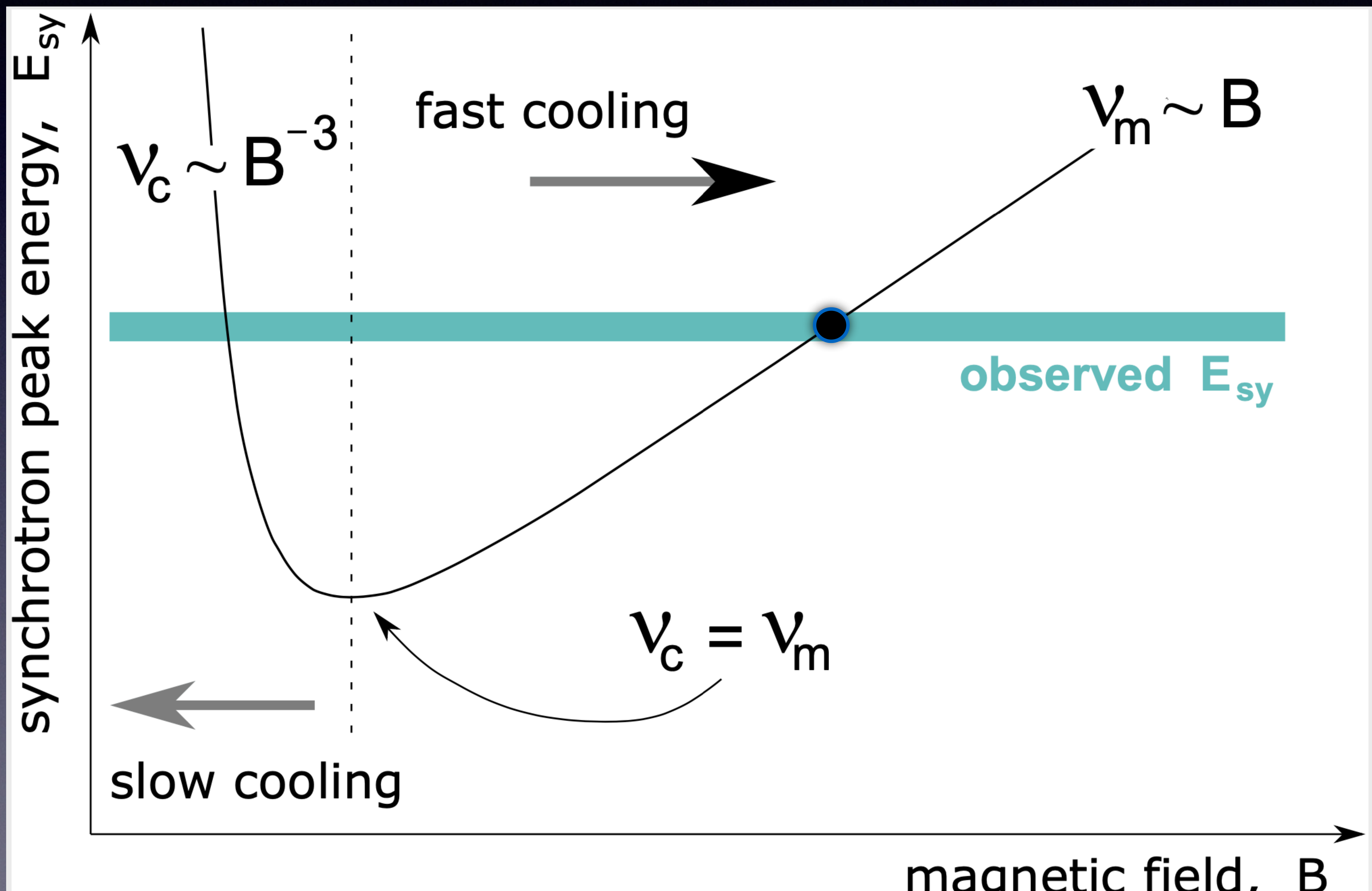
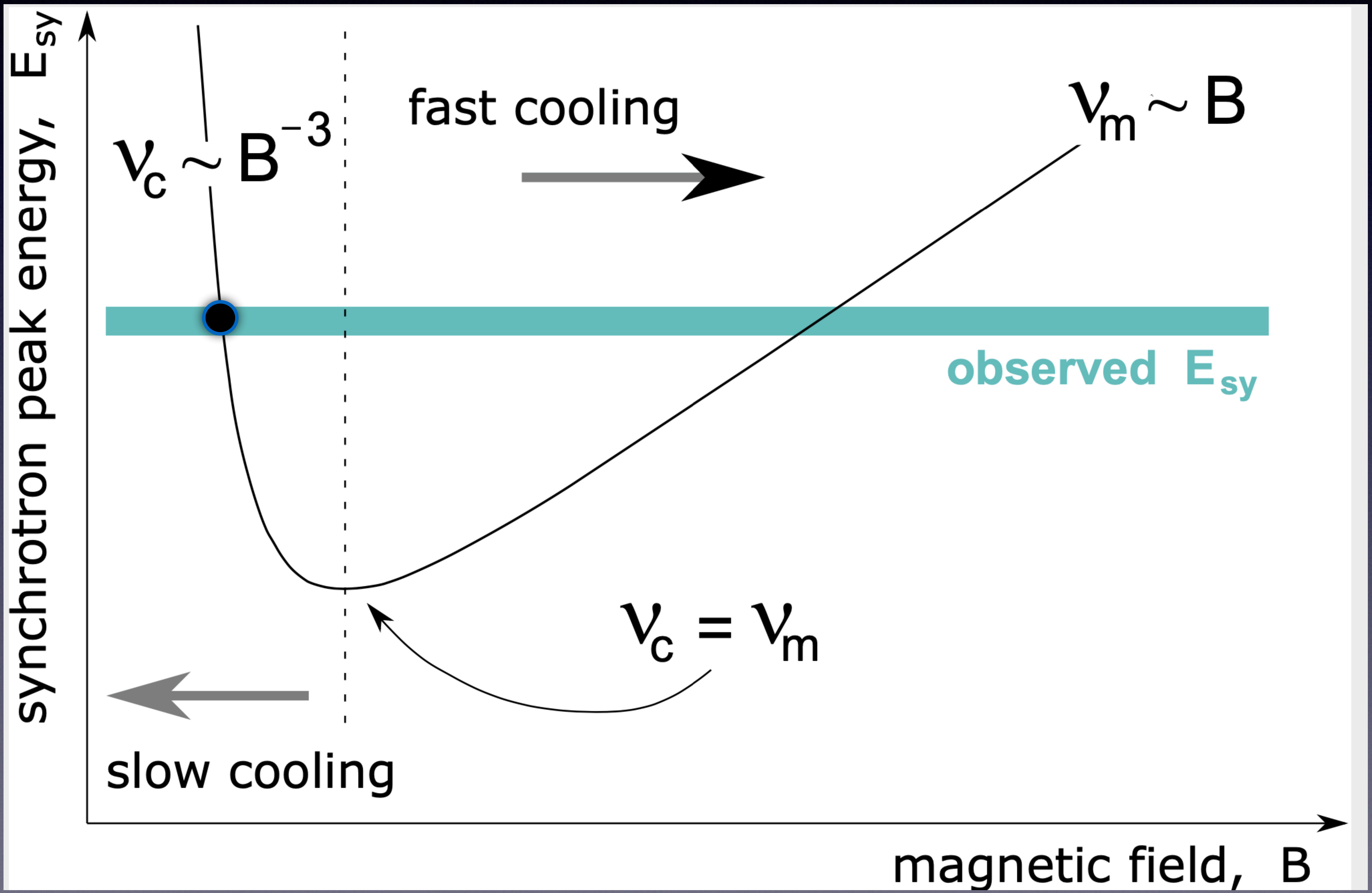
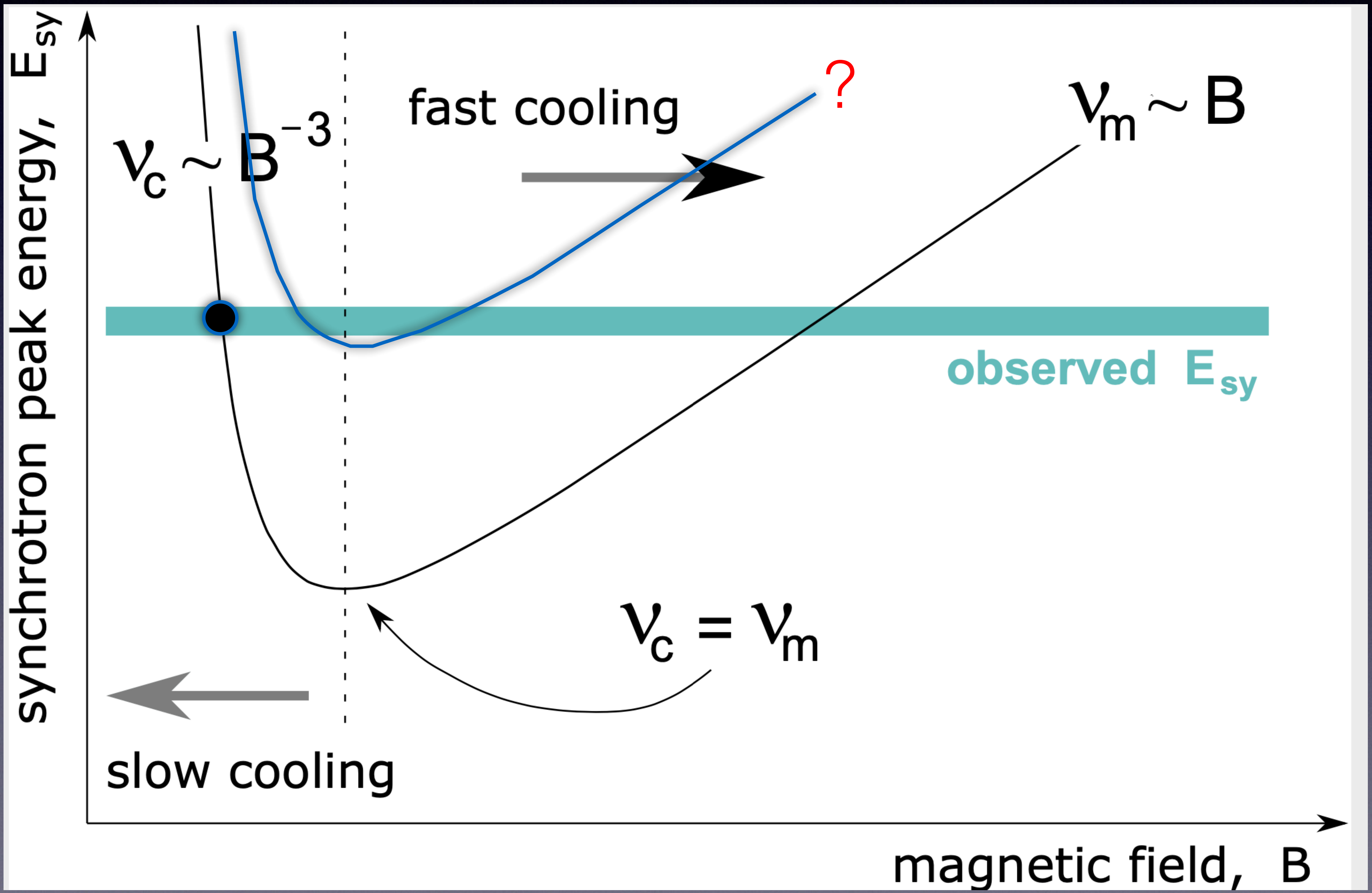
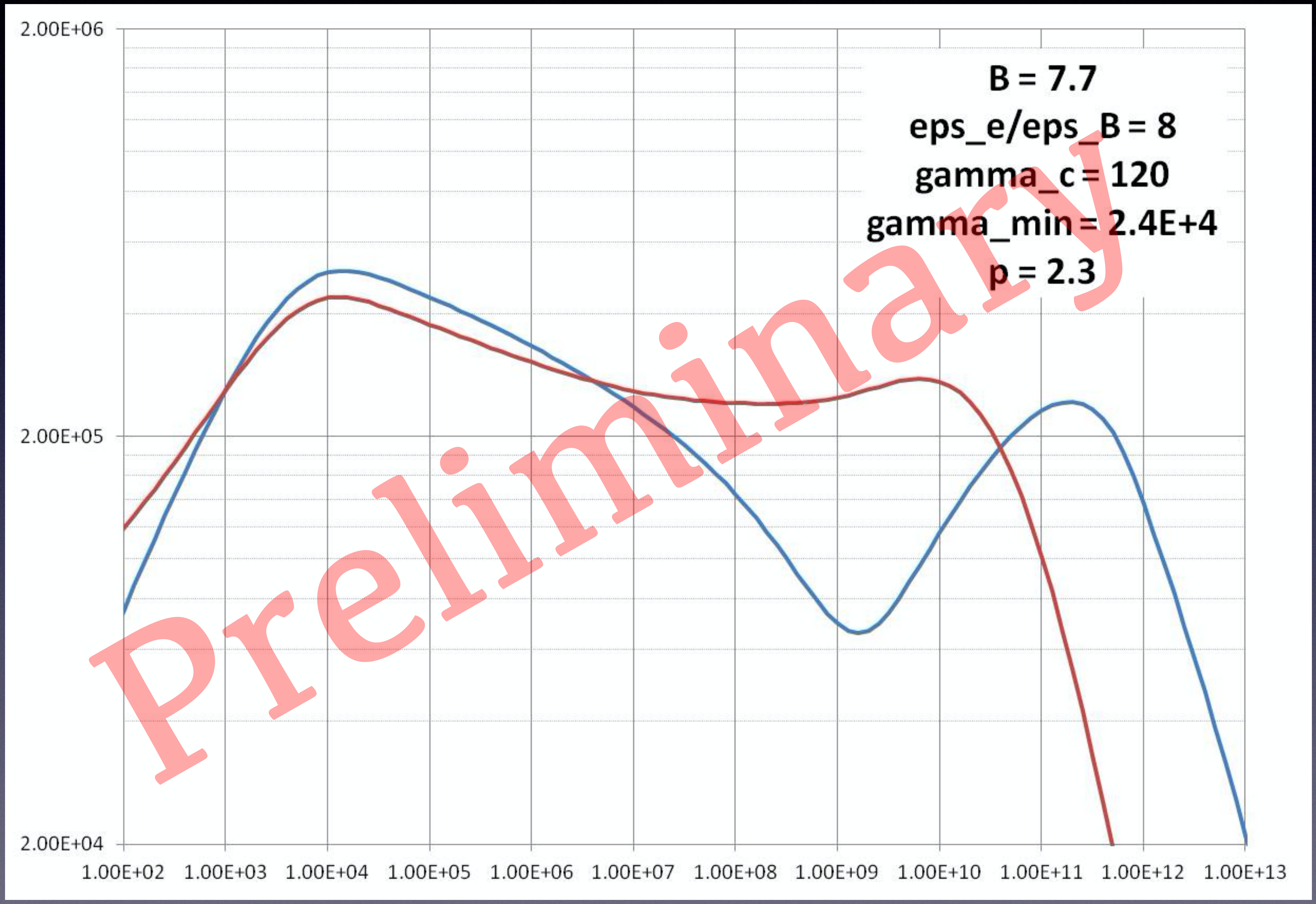


Breaking the Degeneracy



Breaking the Degeneracy





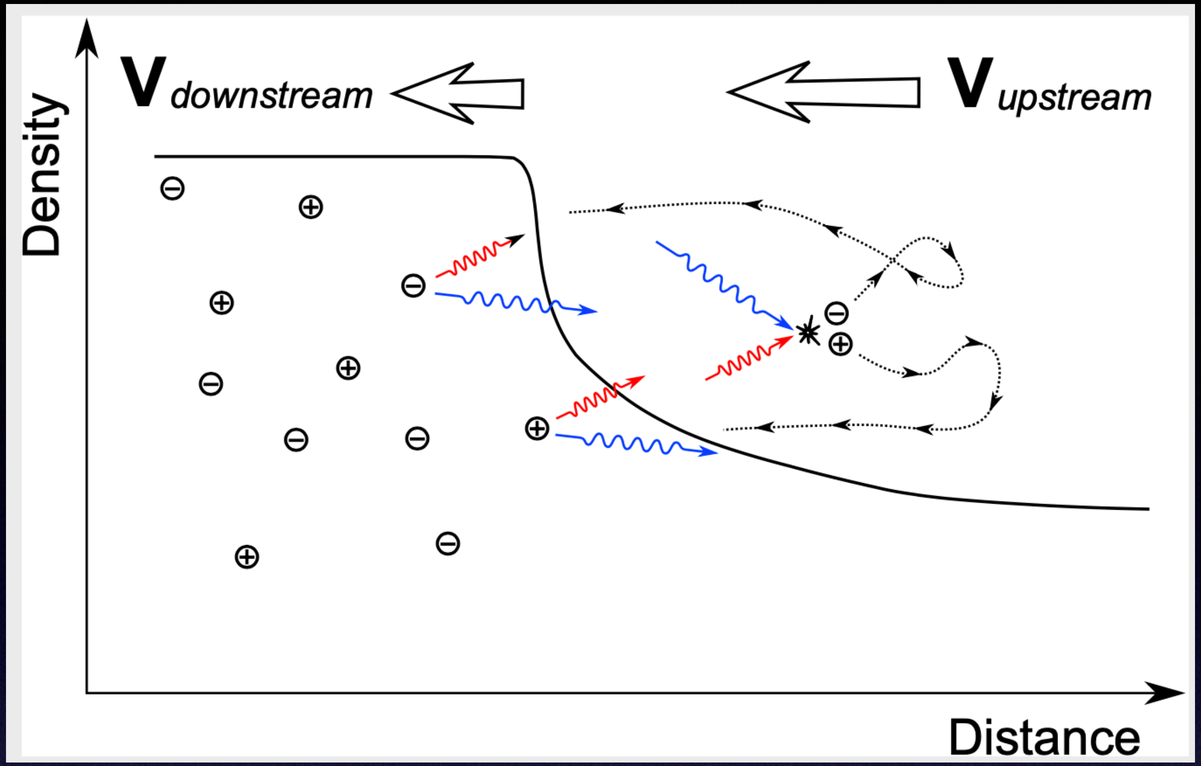
B = 7.7
eps_e/eps_B = 8
gamma_c = 120
gamma_min = 2.4E+4
p = 2.3
Preliminary
2.00E+06
2.00E+05
2.00E+04
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08
1.00E+09
1.00E+10
1.00E+11
1.00E+12
1.00E+13

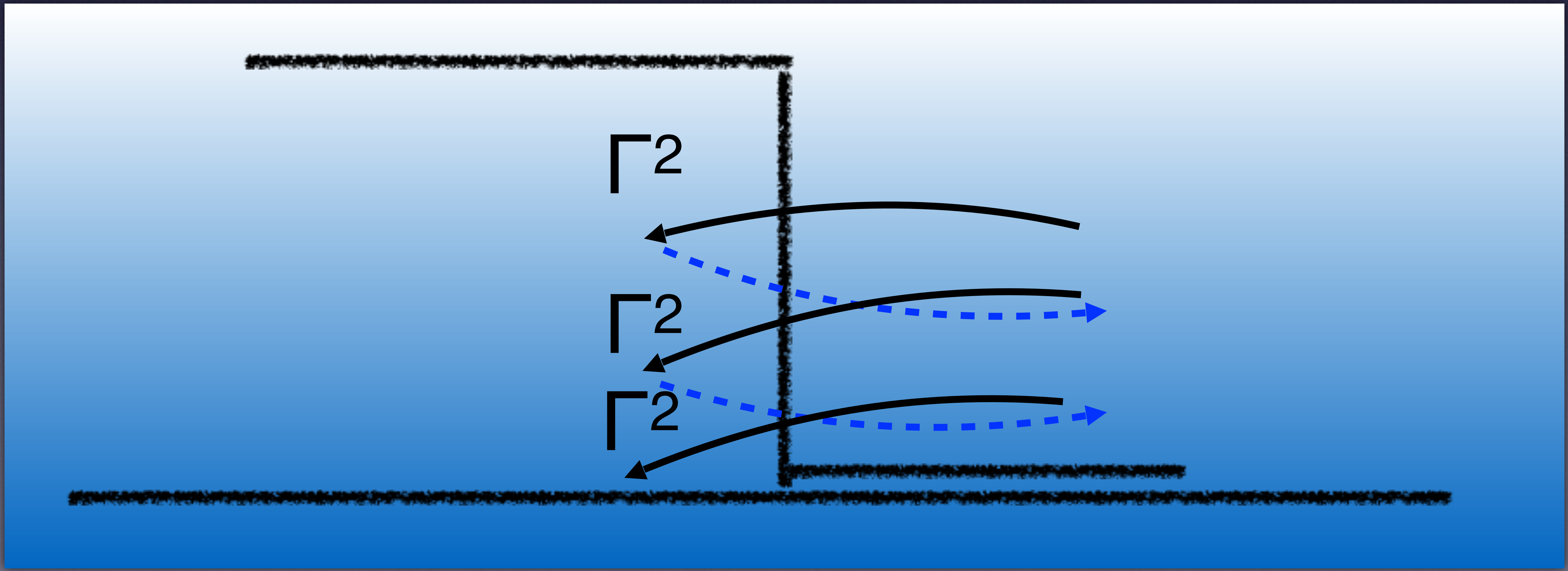
Summary

- The electron's Lorentz factor $\sim 10^4$
- The bulk Lorentz factor @100 sec ~ 100
- IC slightly below the Klein Nishina regime
- => Puzzels concerning the previously believed to be well understood afterglow modeling (even in the slow cooling regime).

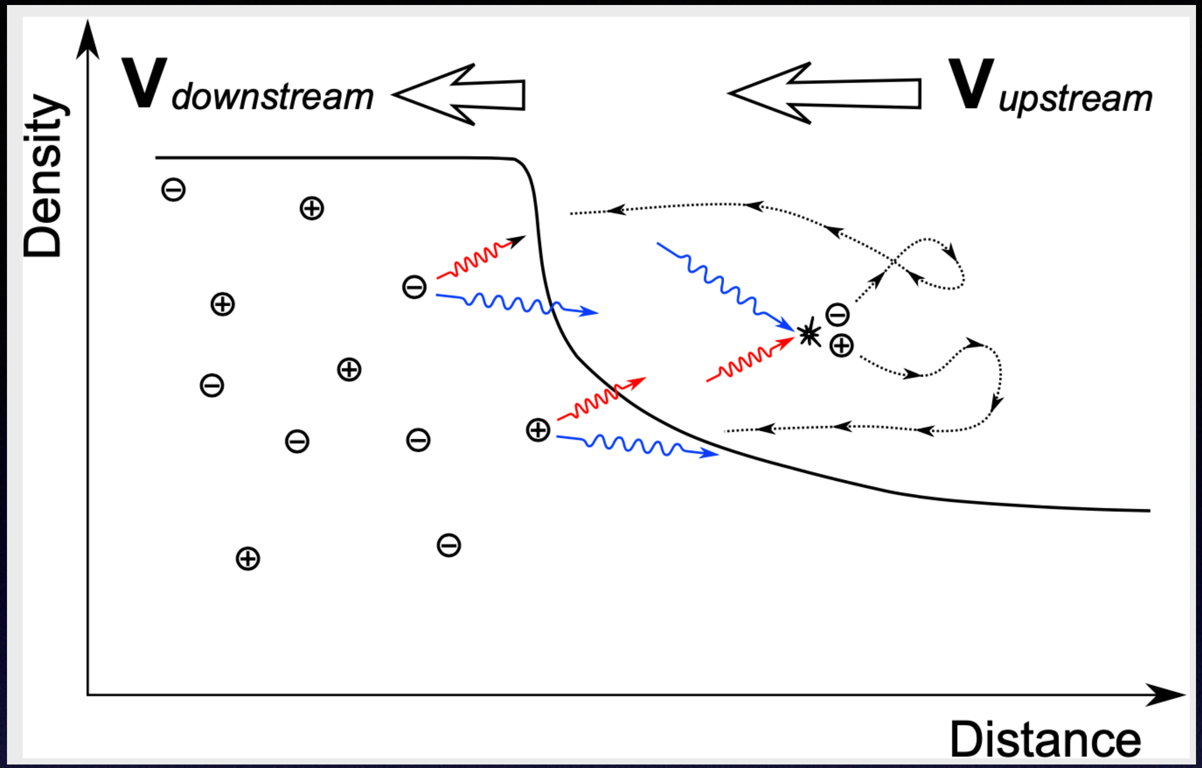
Converter acceleration

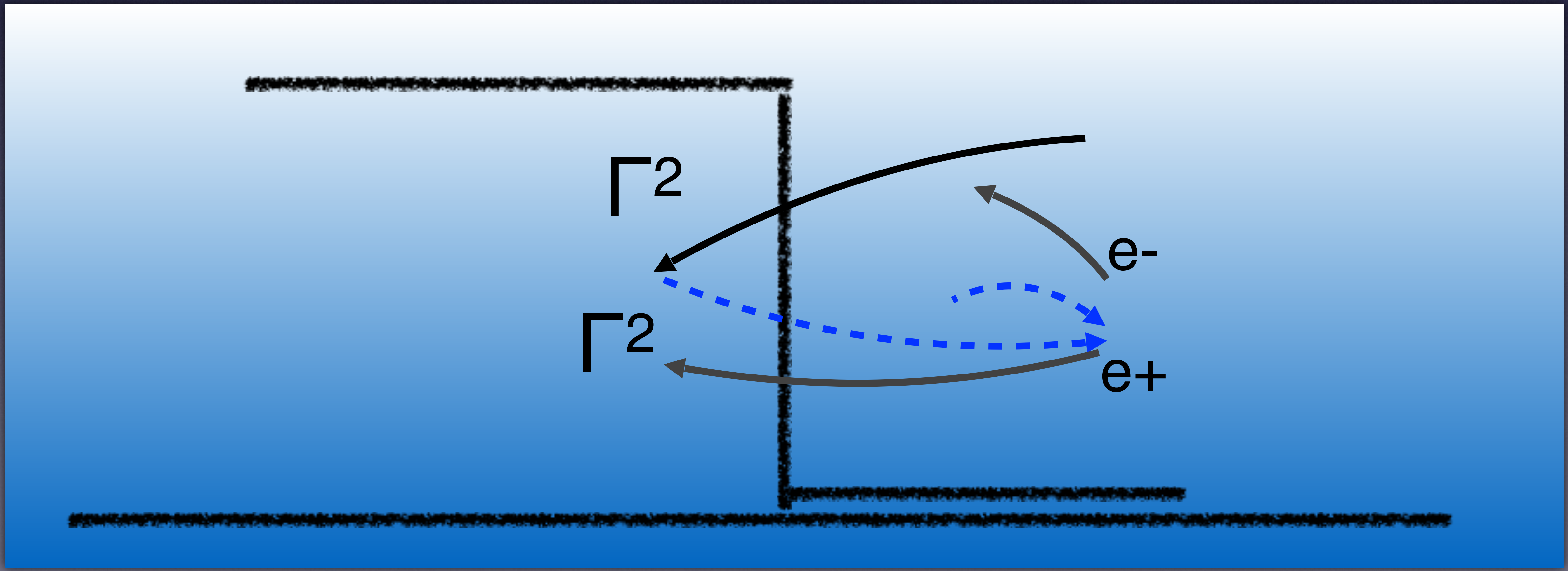
Derishev et al. (2003); Stern (2003)



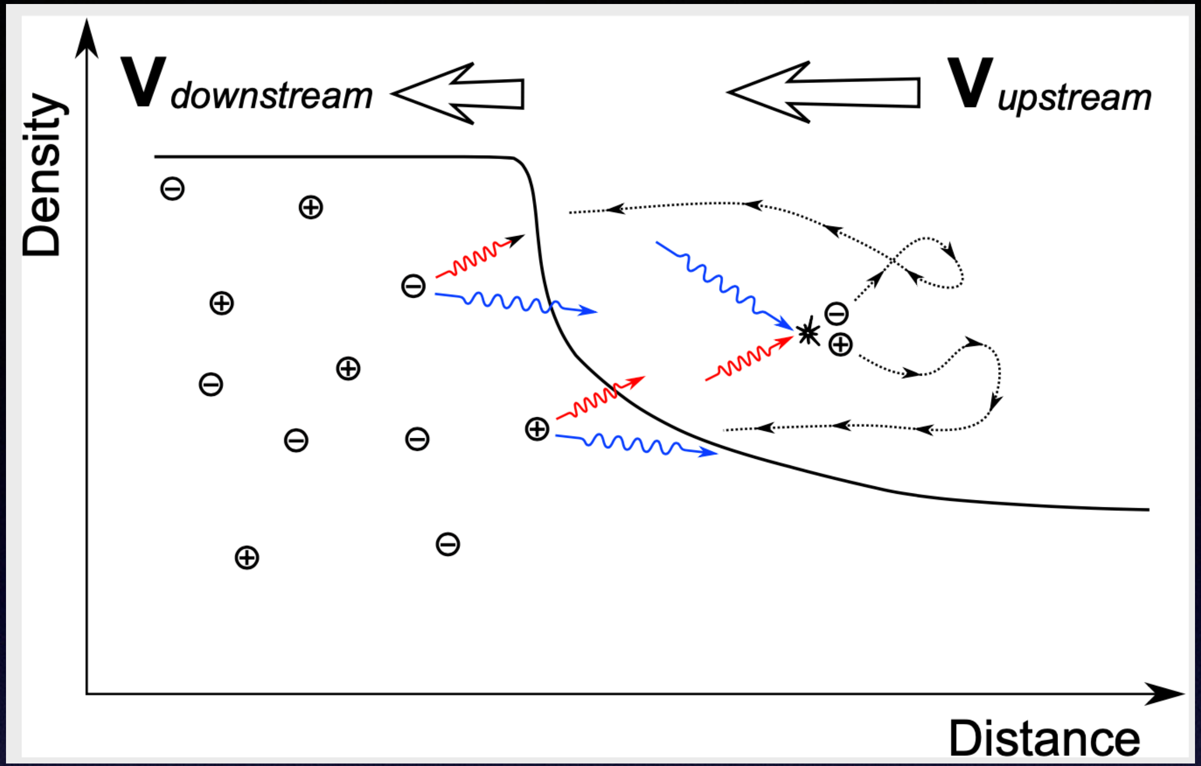


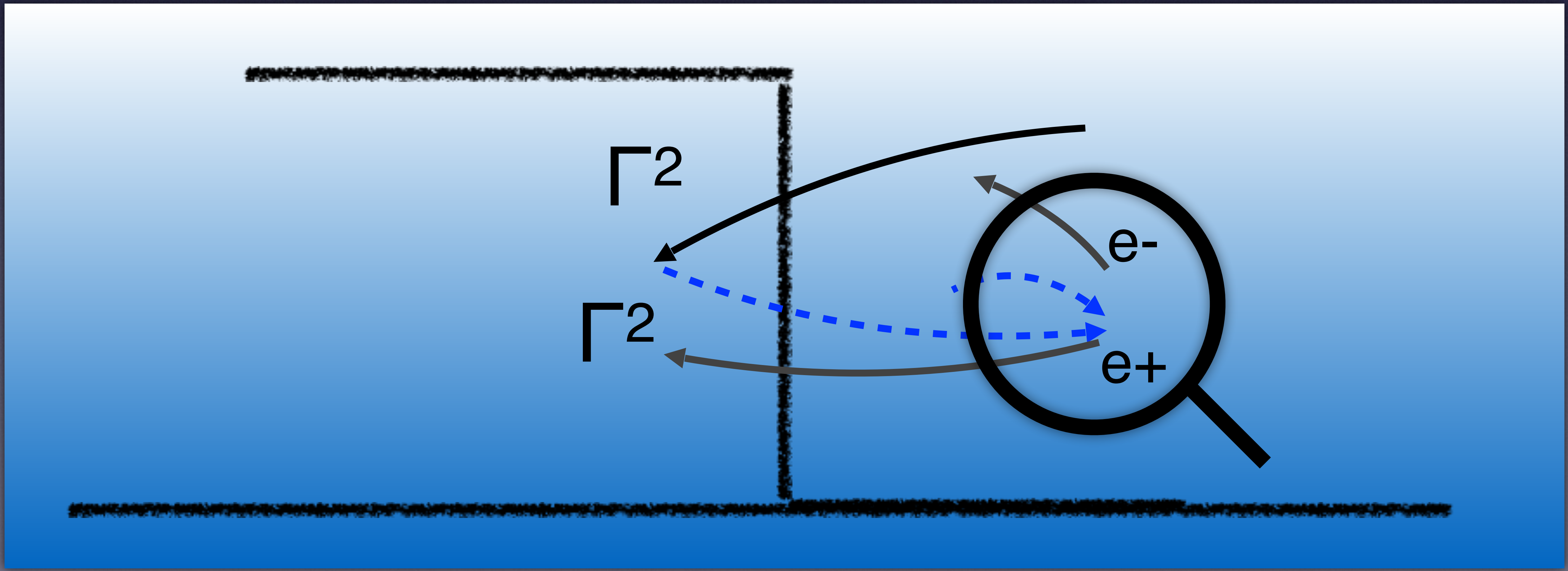
Converter acceleration via high energy (IC) photons



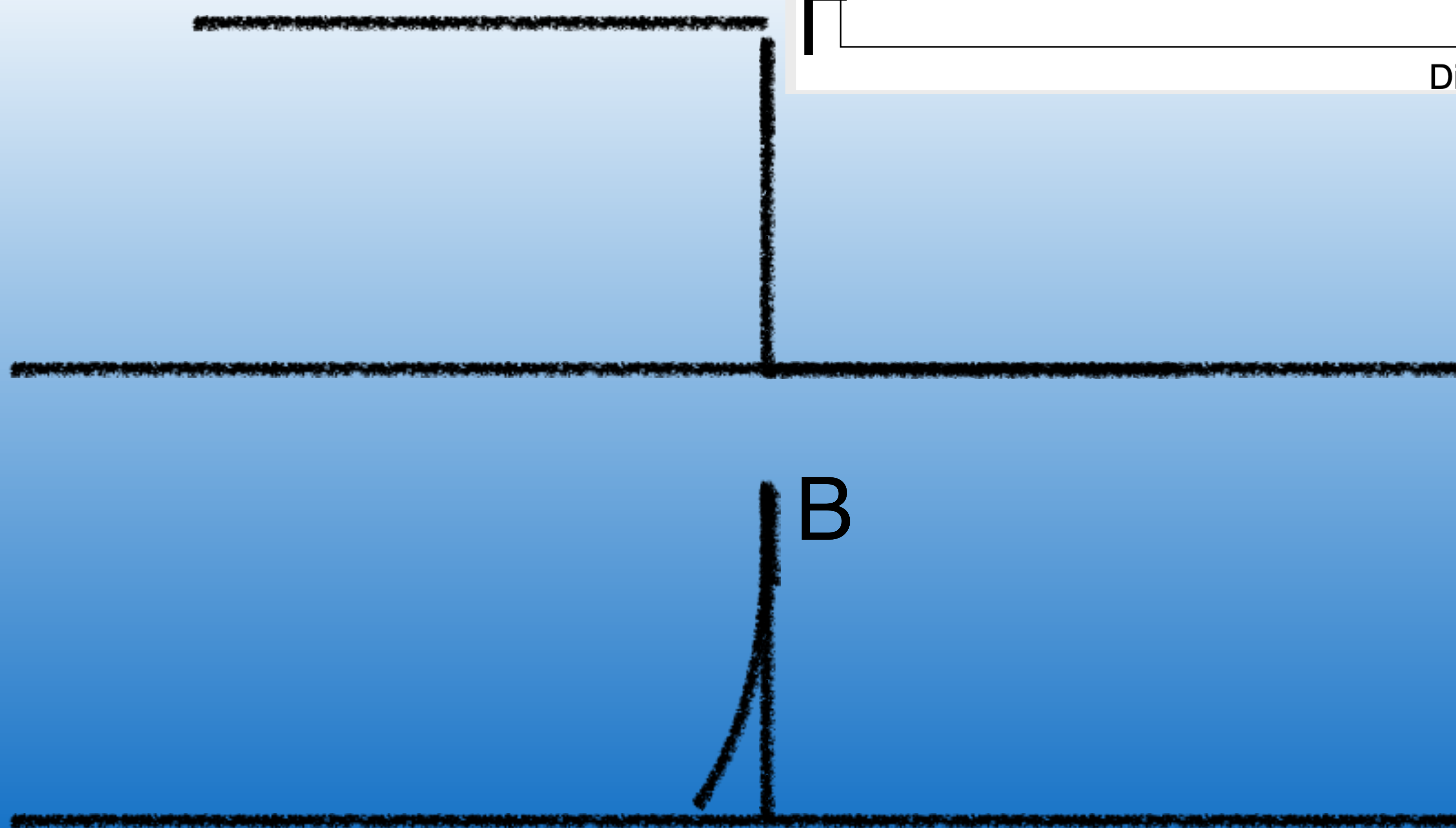


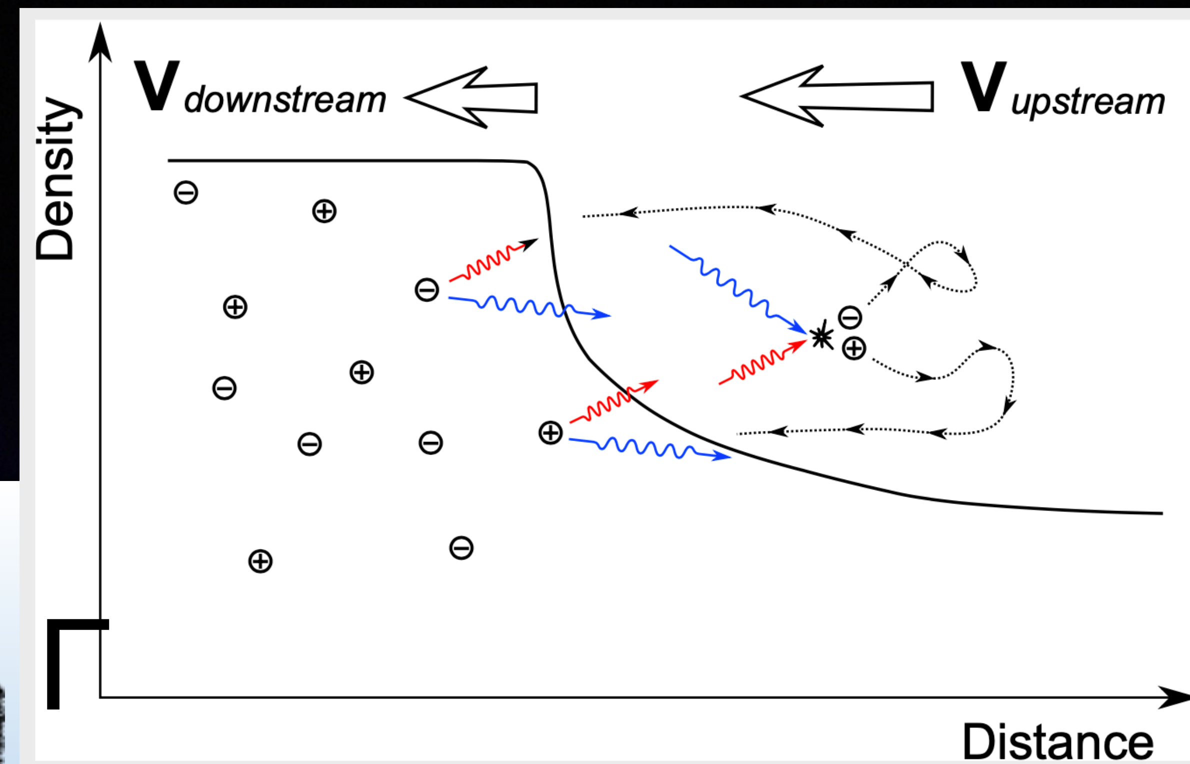
1) Accelerate the flow
2) Produce magnetic field via Weibel Instability





Modified structure





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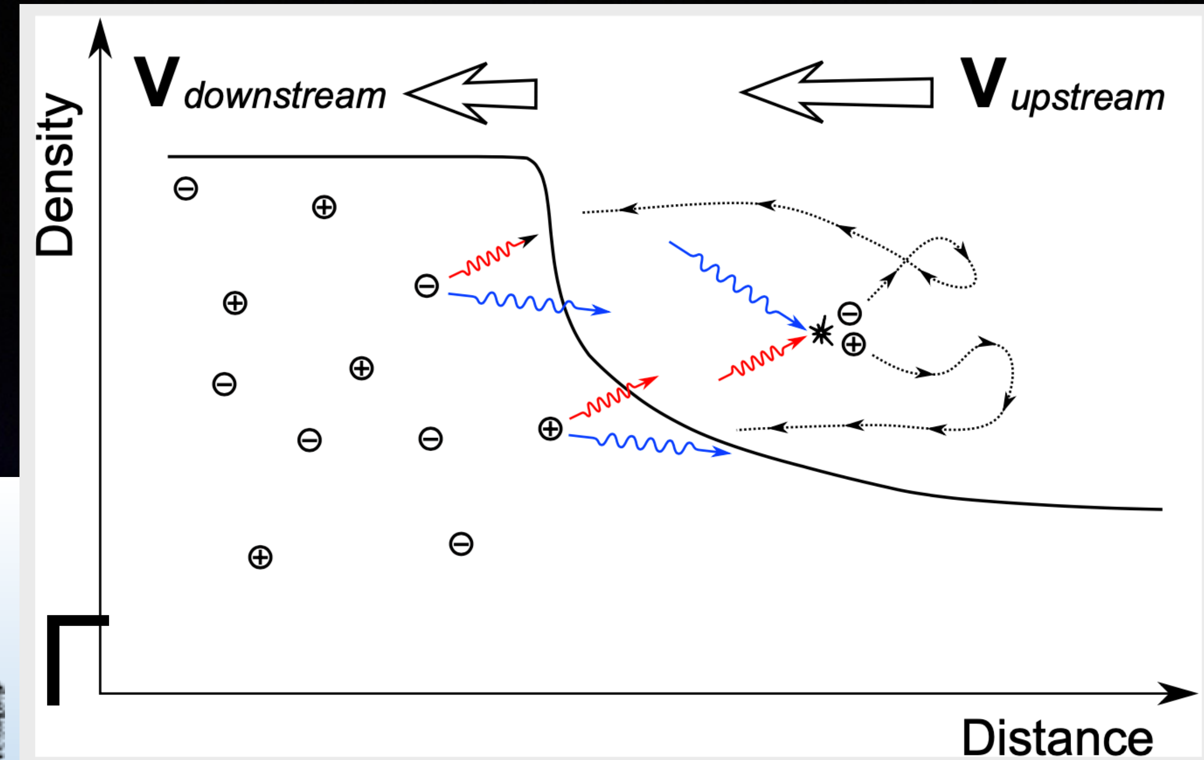

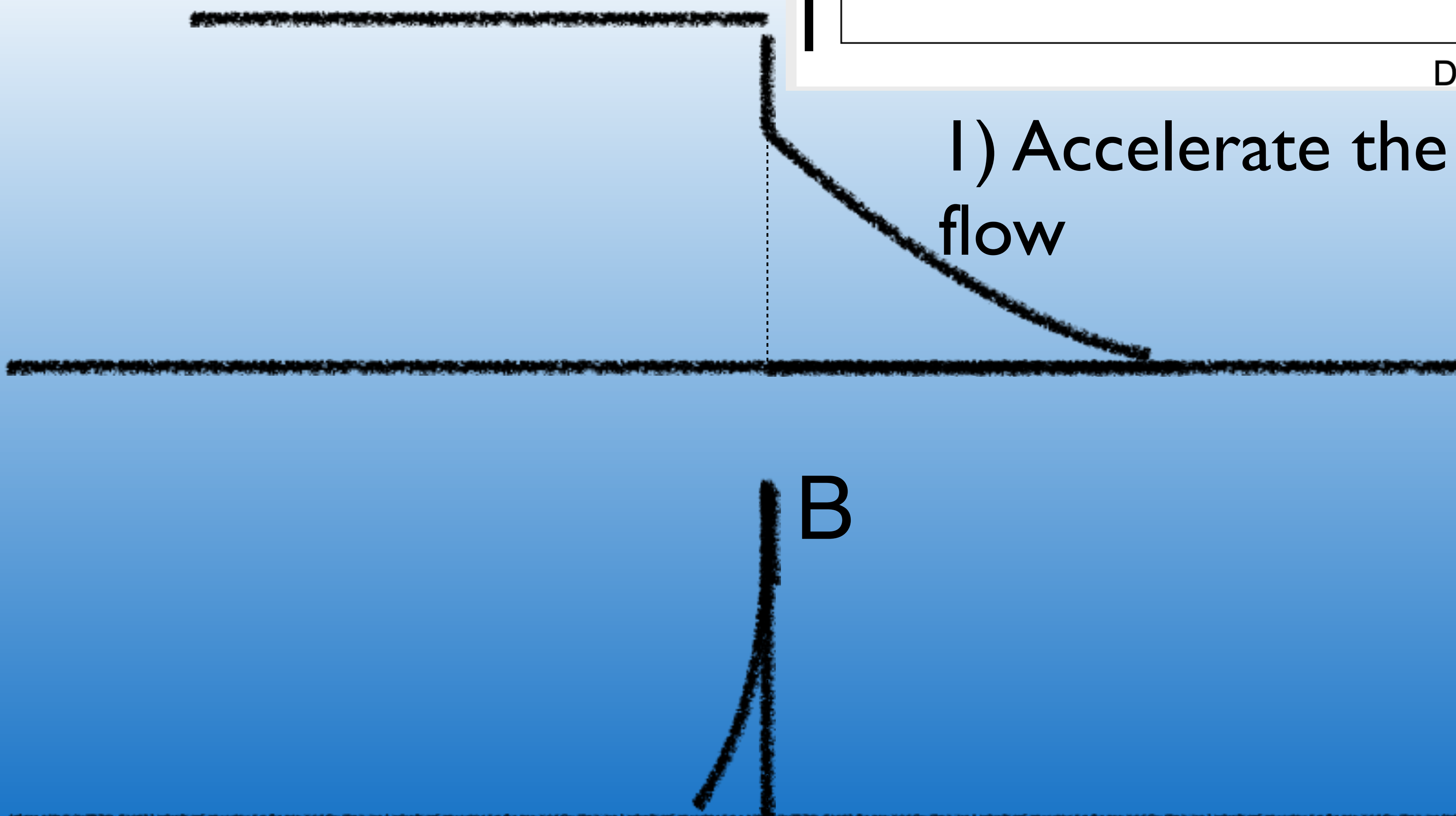

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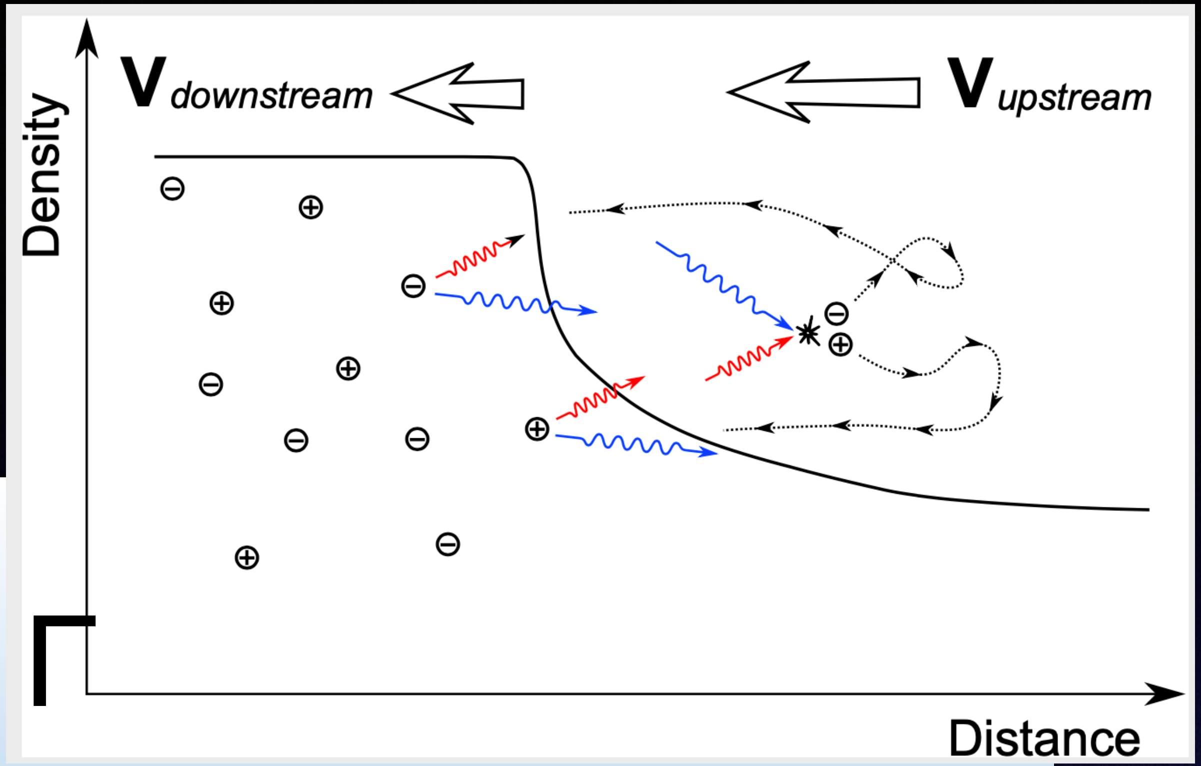

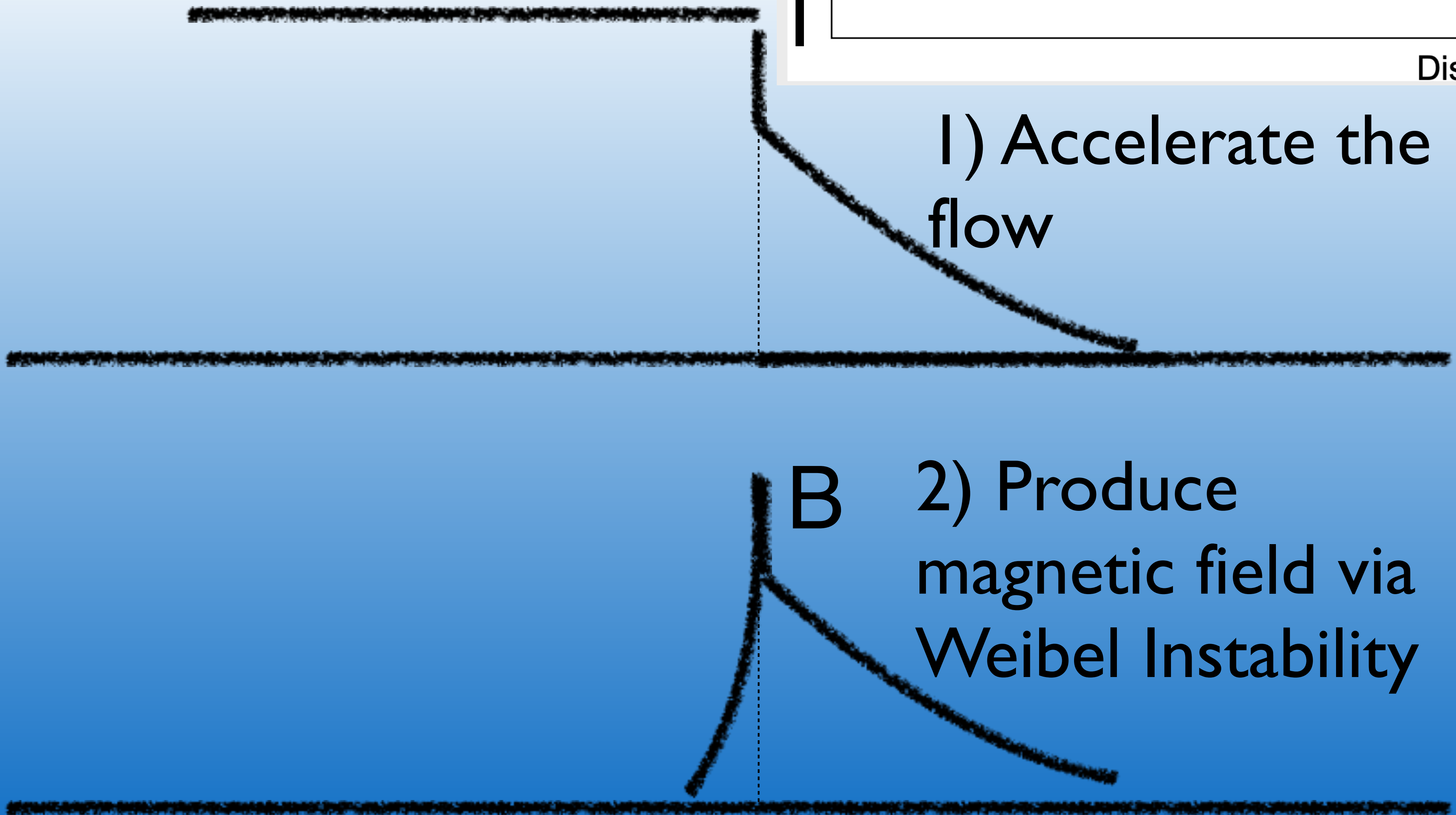

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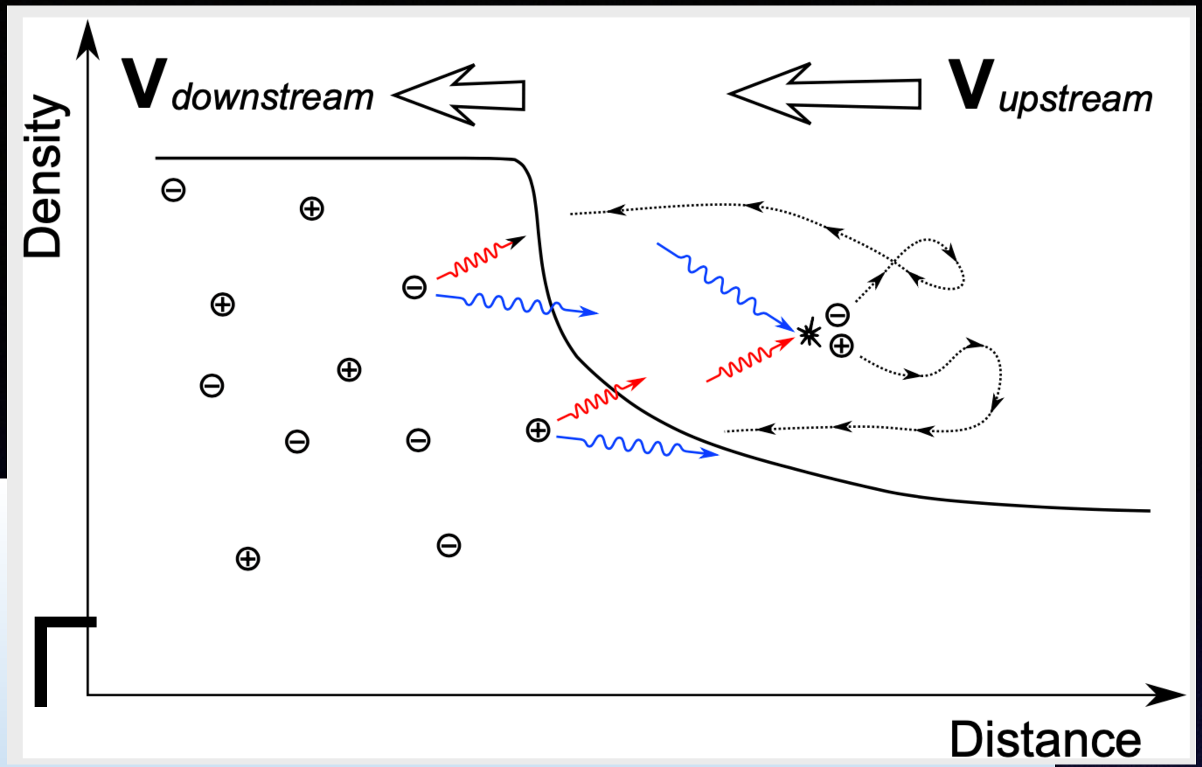
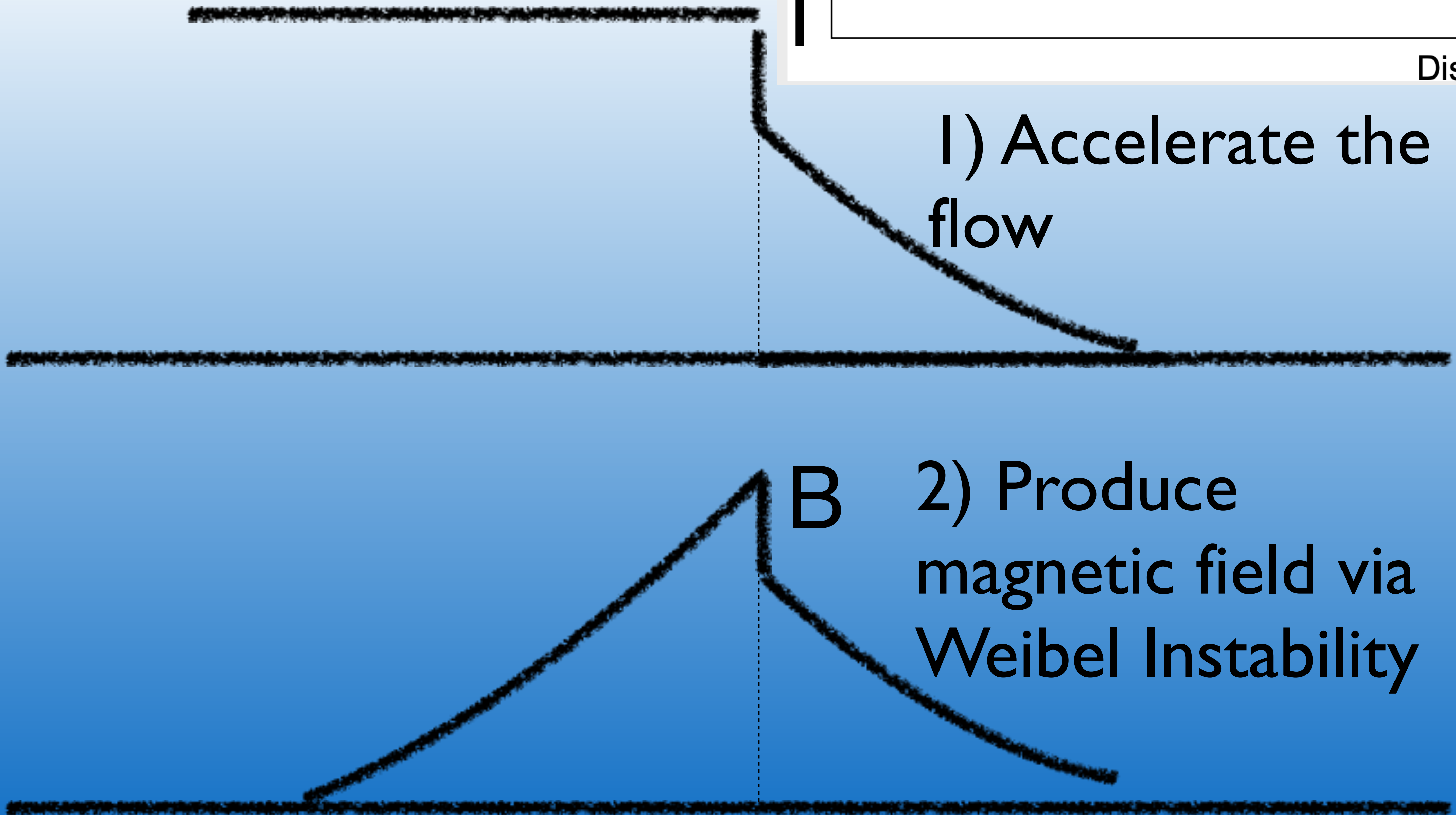
Modified structure





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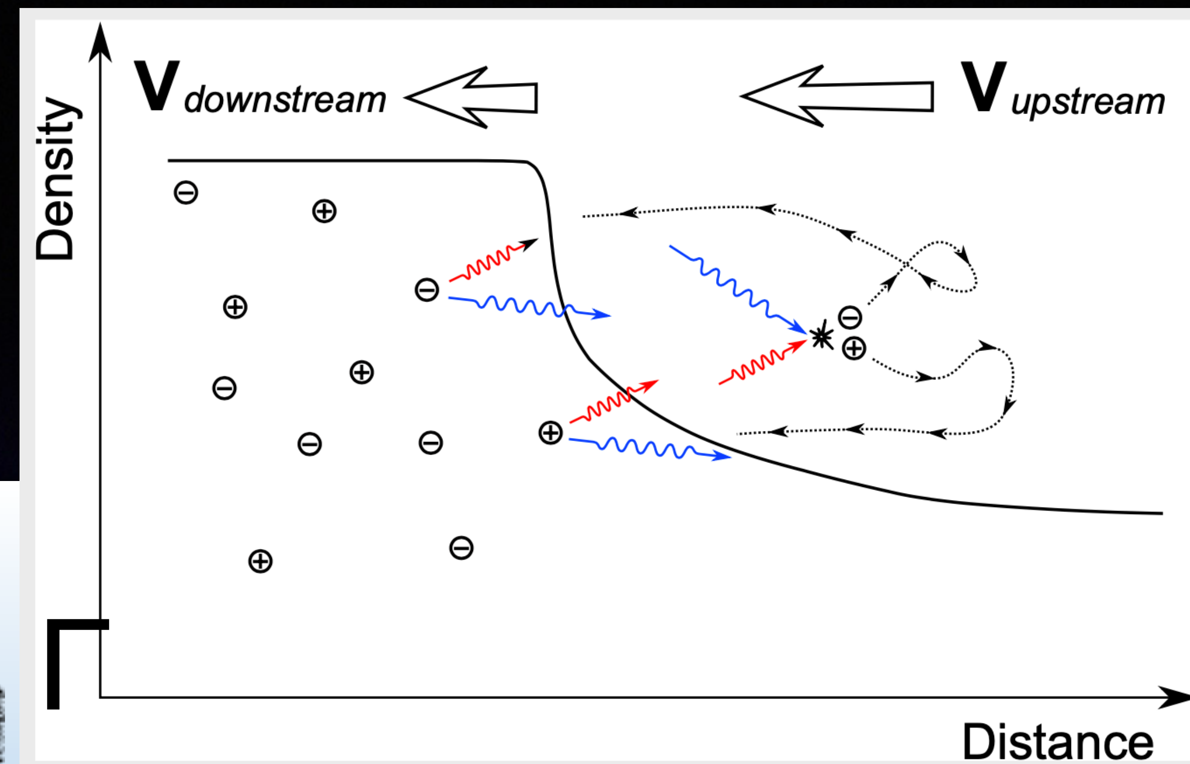

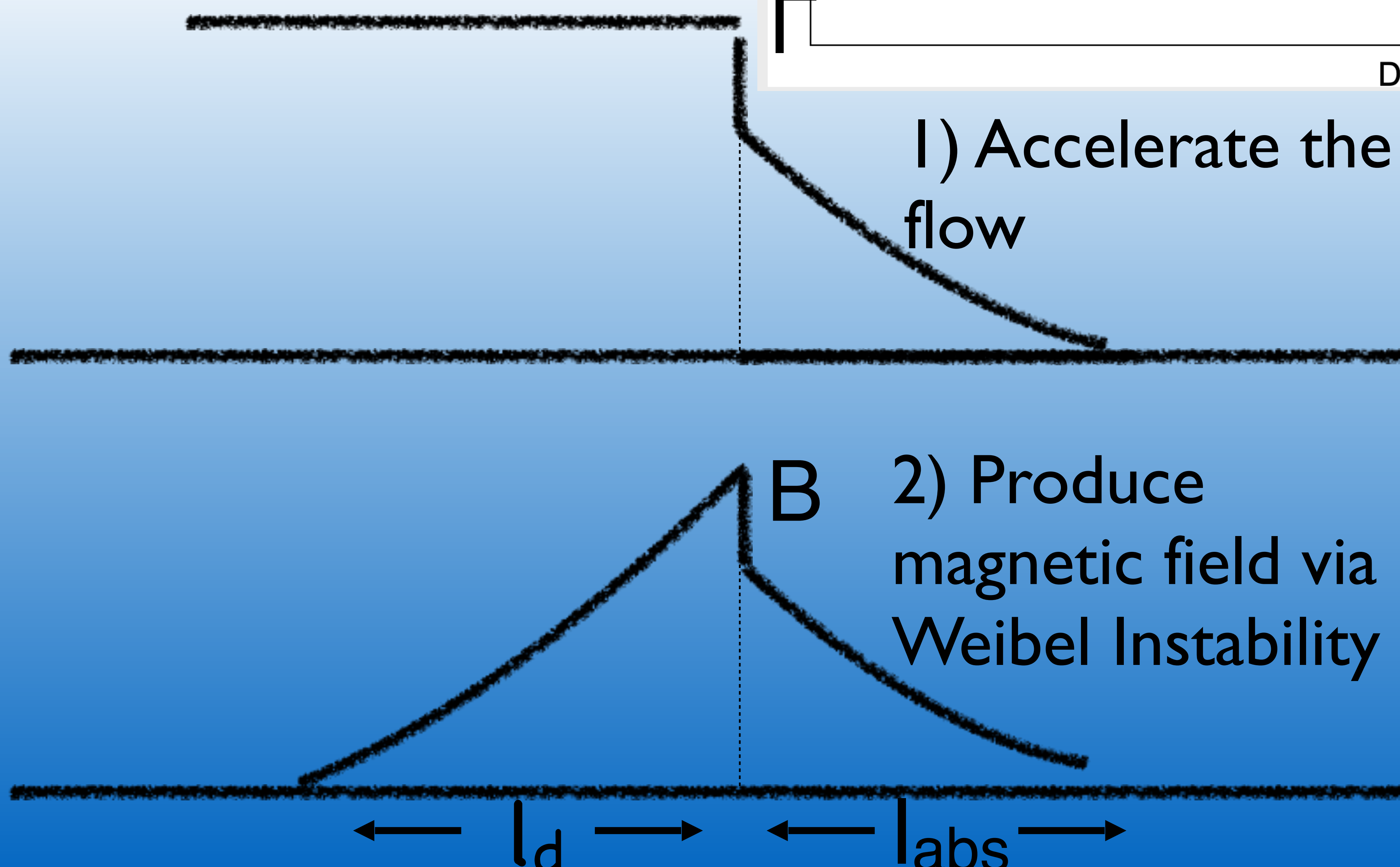

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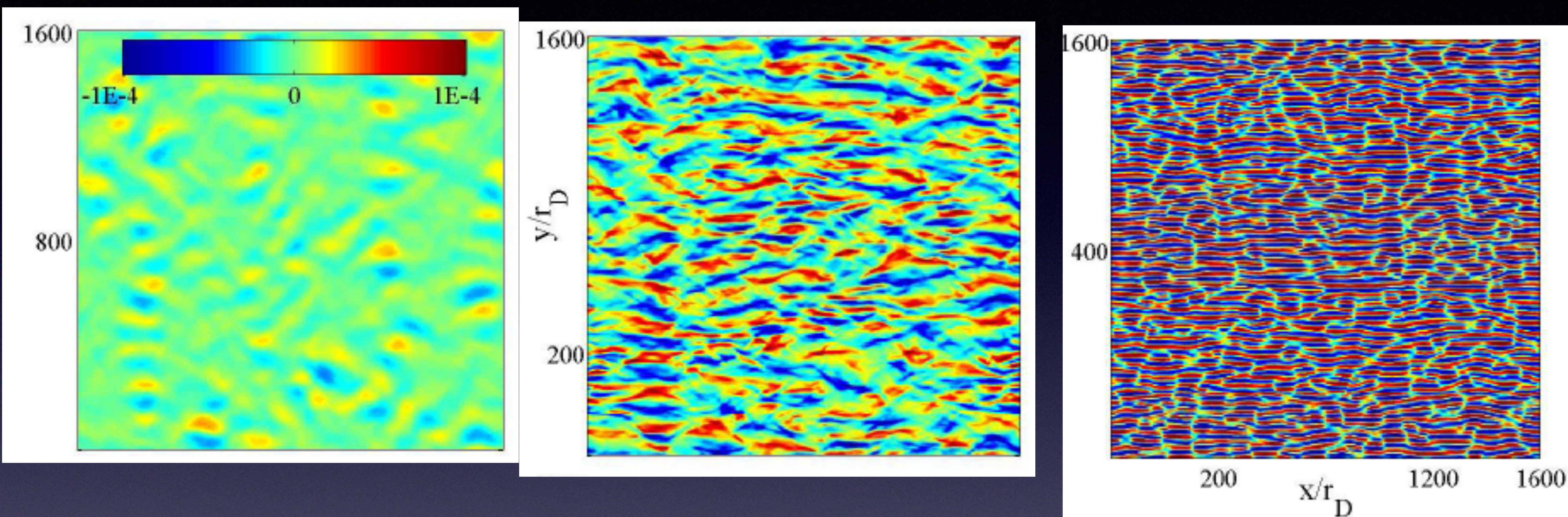
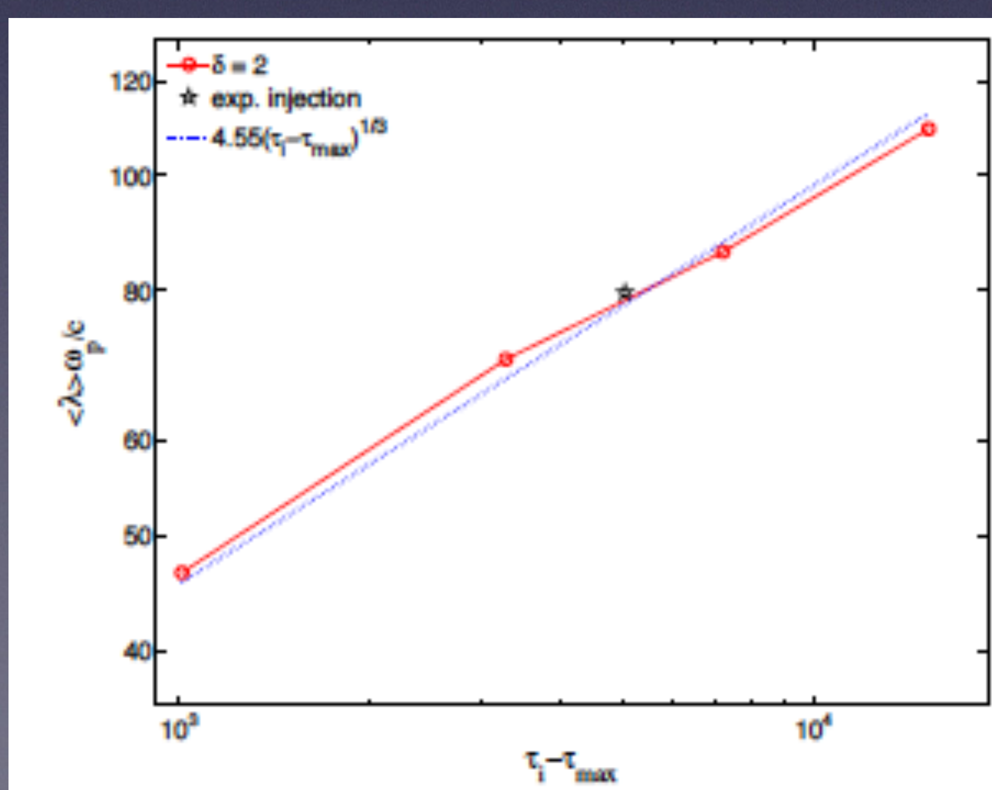
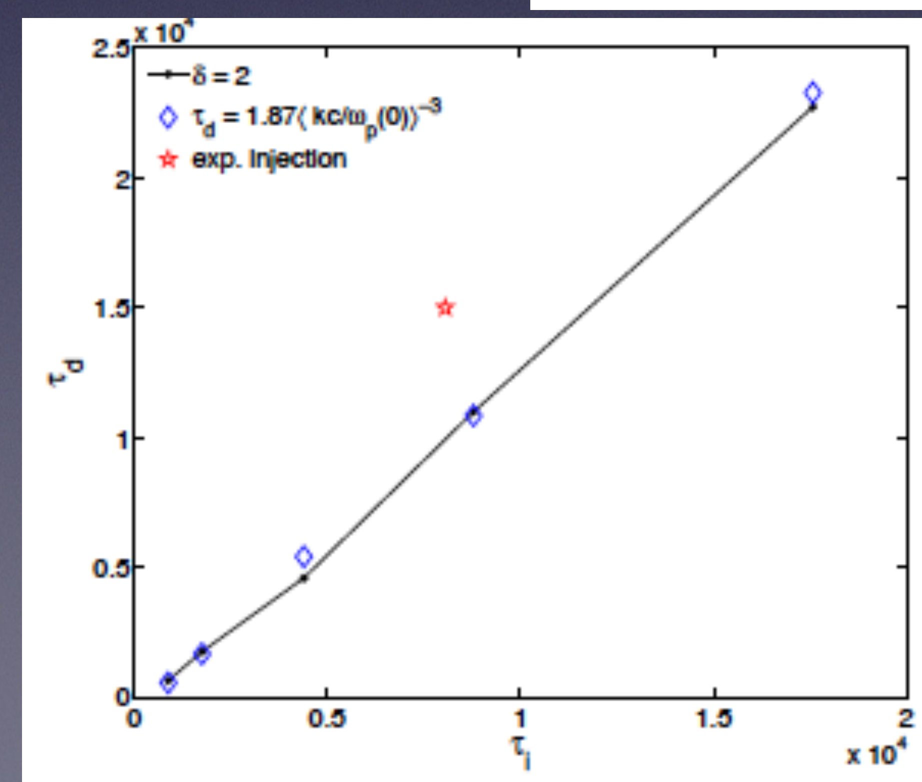
Generation and decay of B

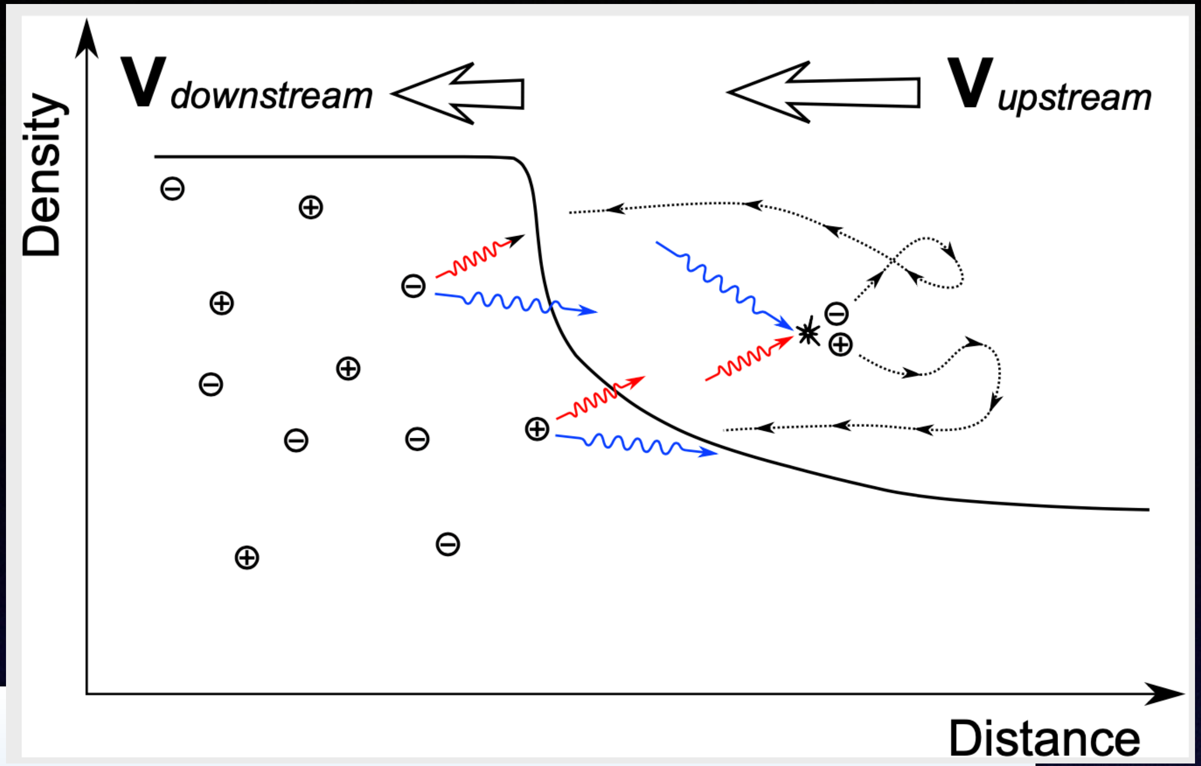
(Garasev & Derishev 16)

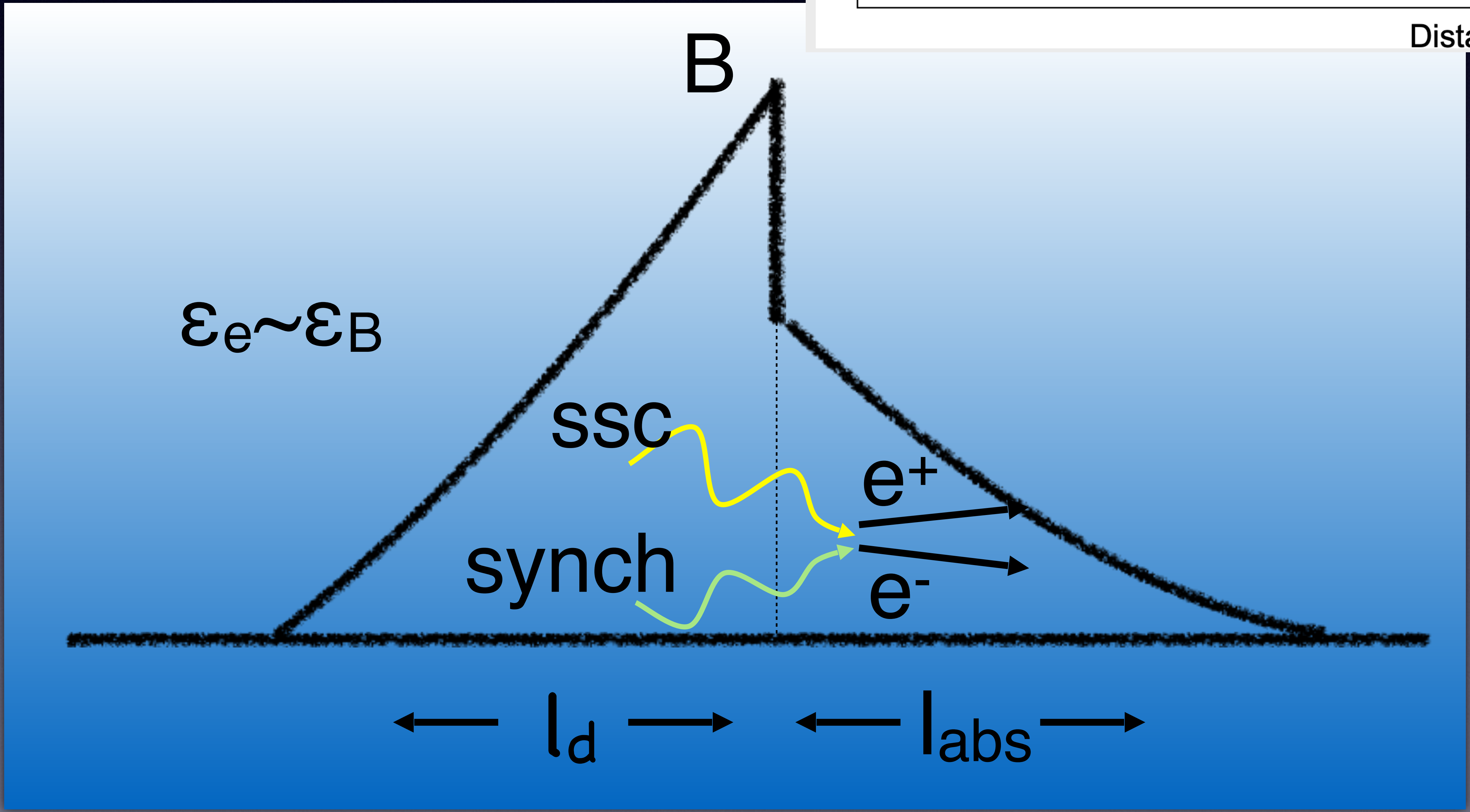




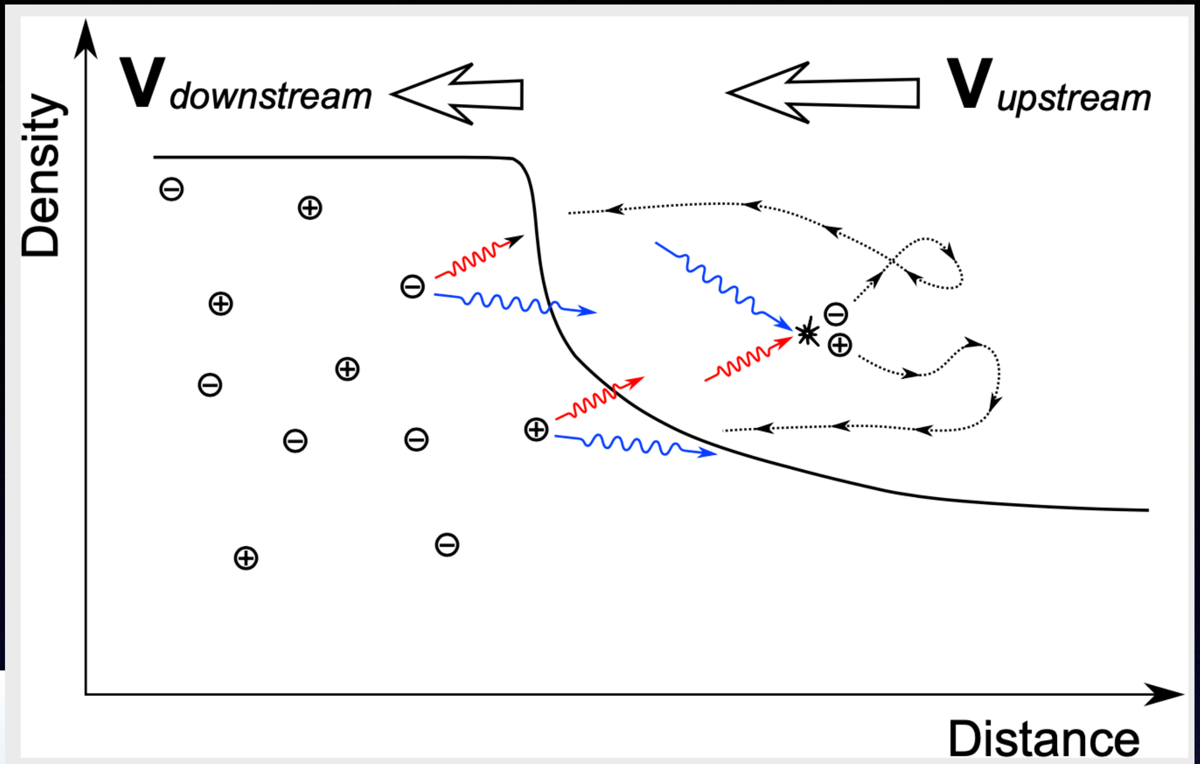


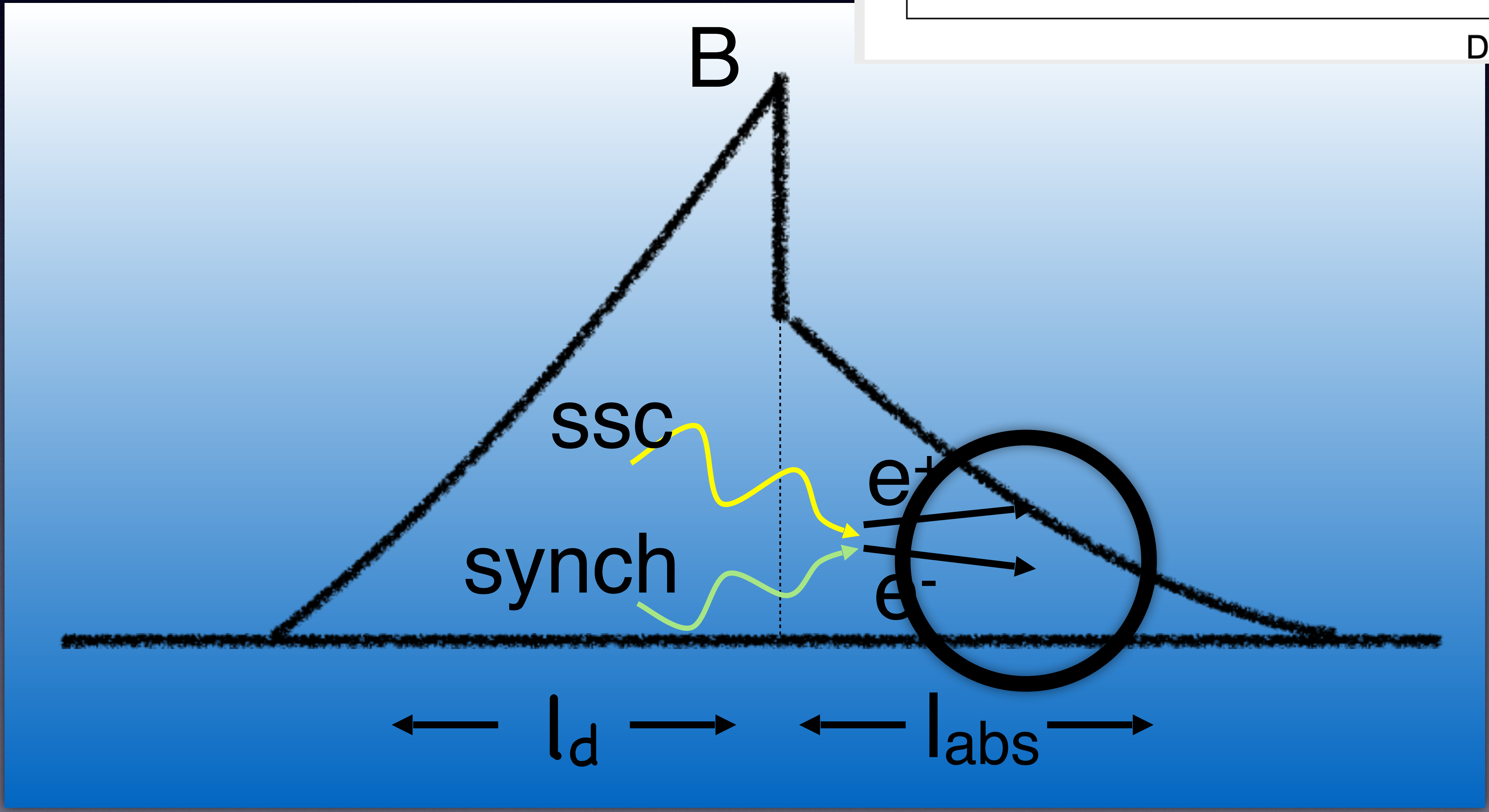
Decaying magnetic field, in the downstream, accelerates particles



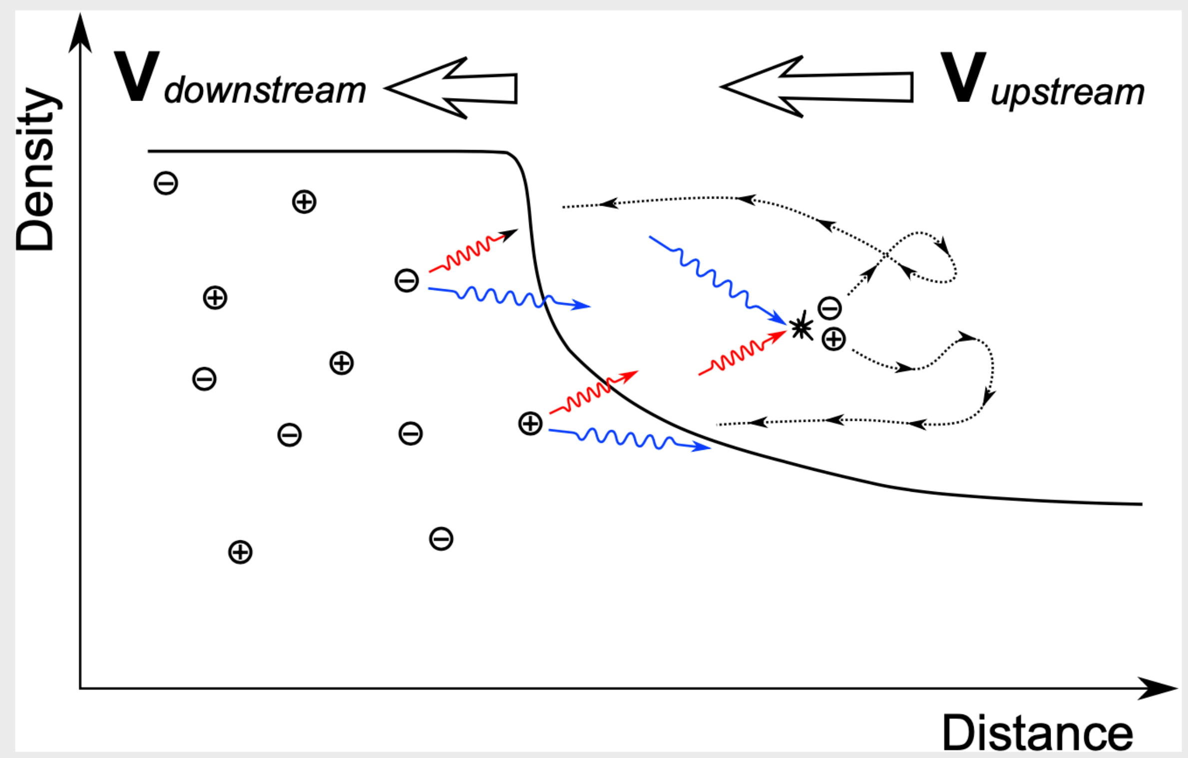


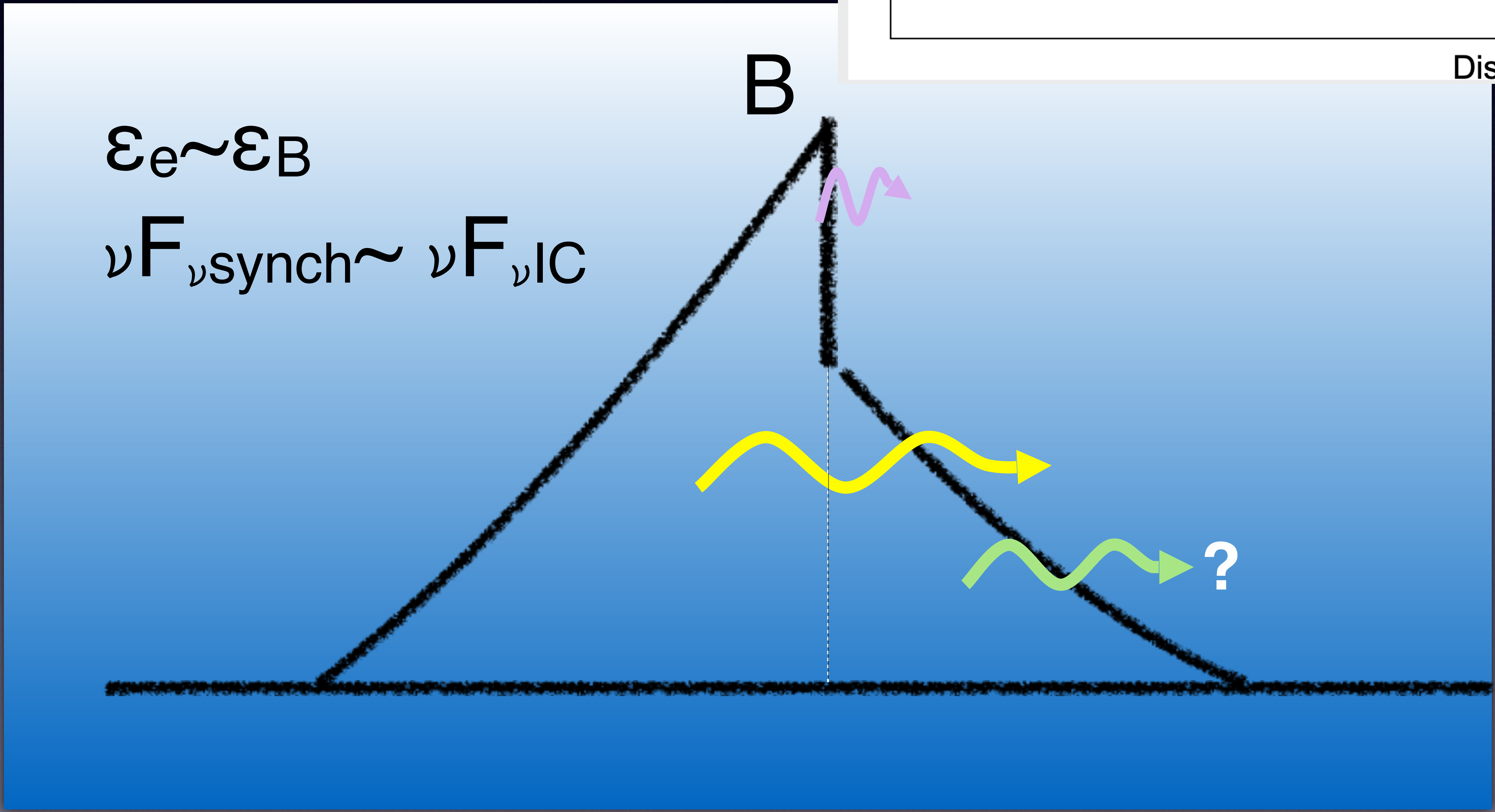
Pairs from the upstream increase the multiplicity of the downstream



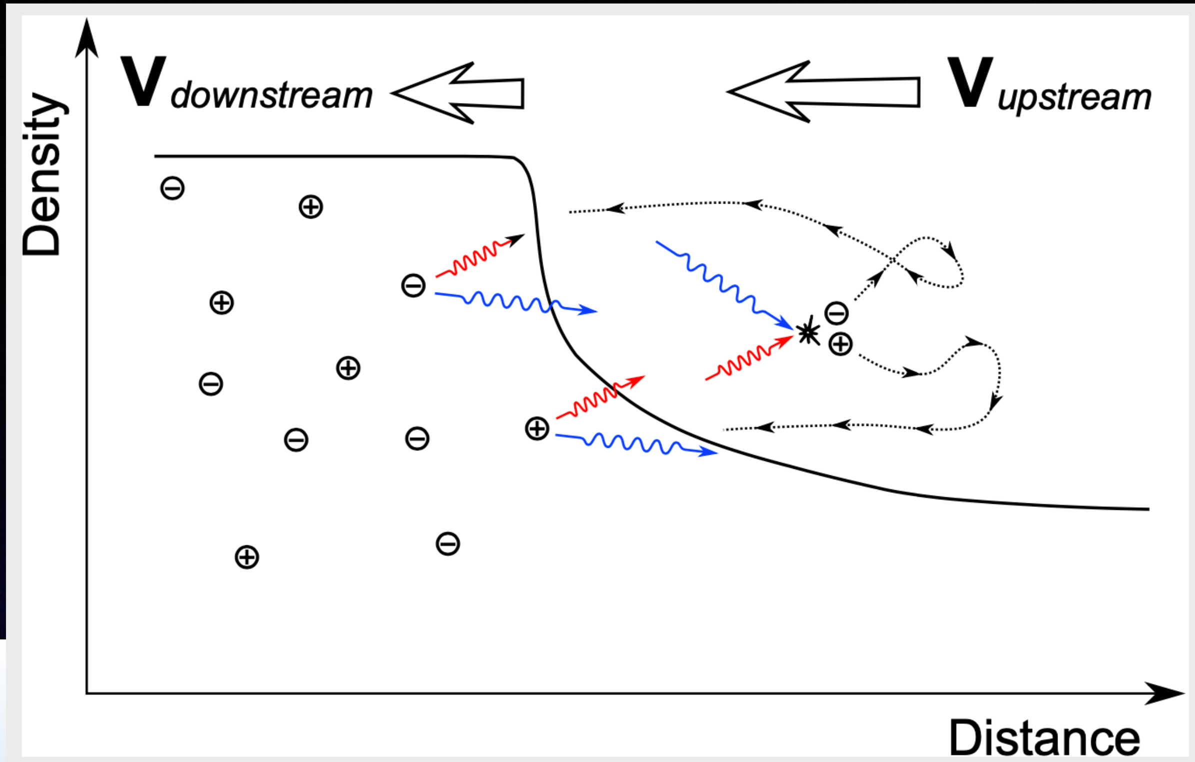


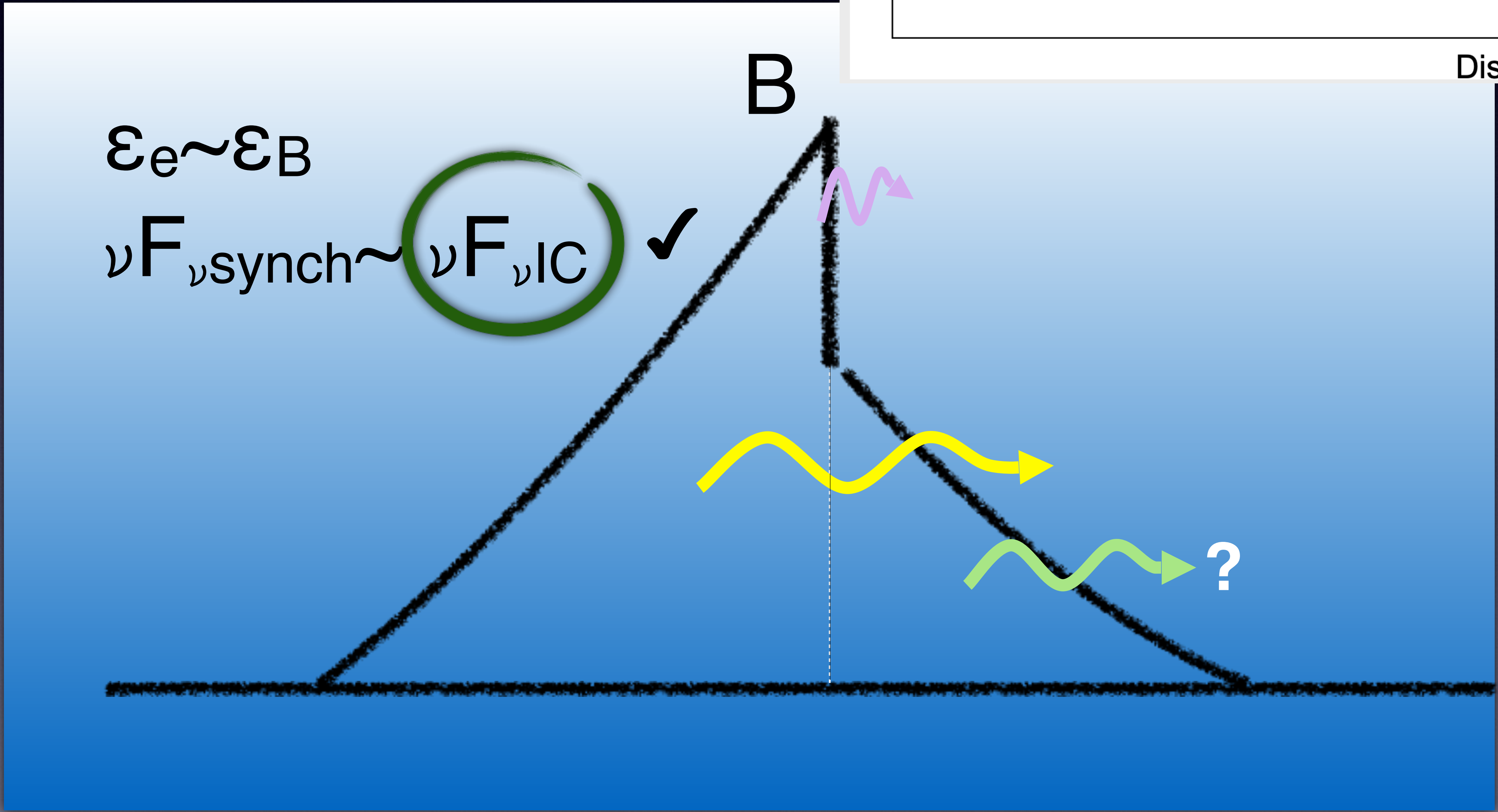
Three emission components

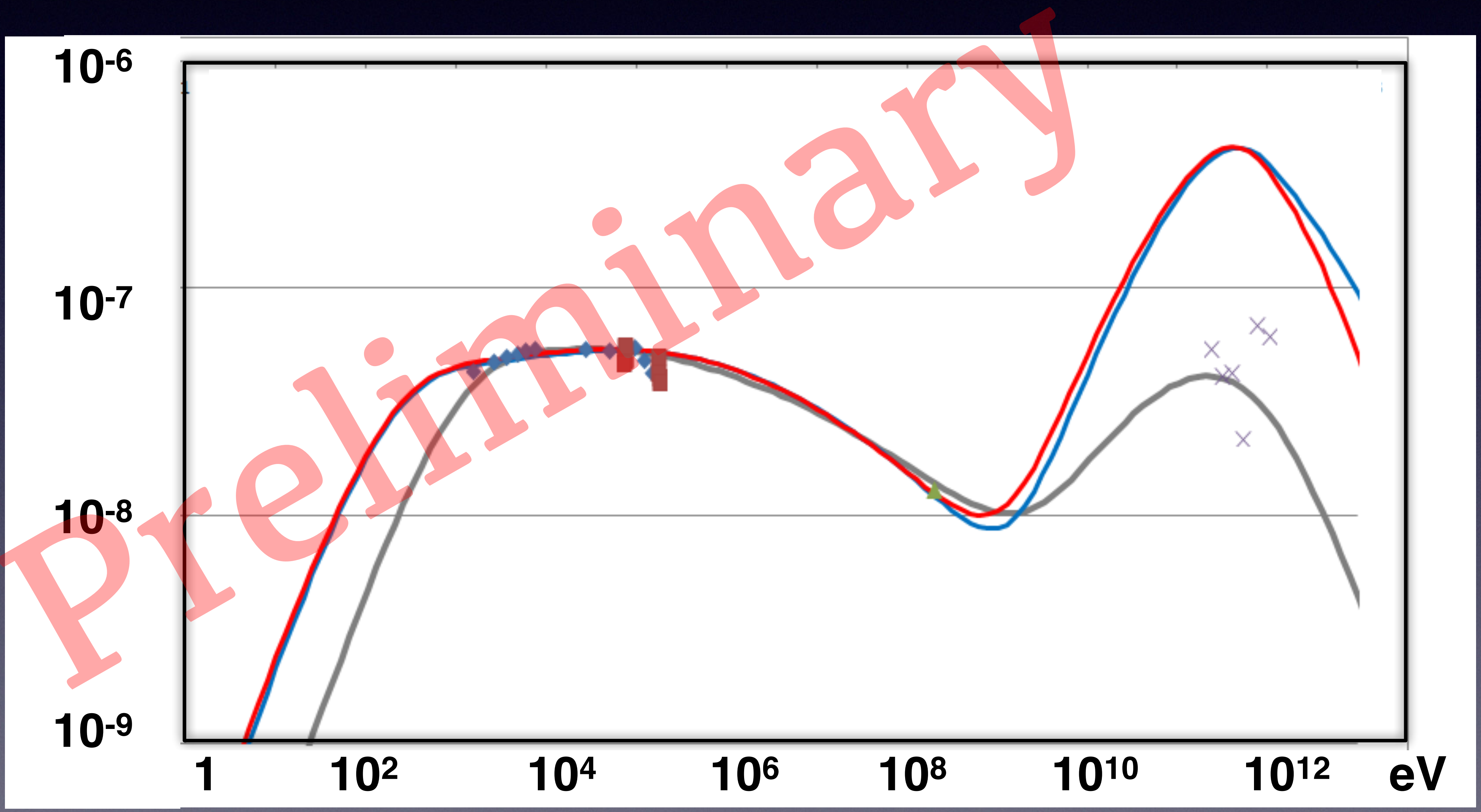




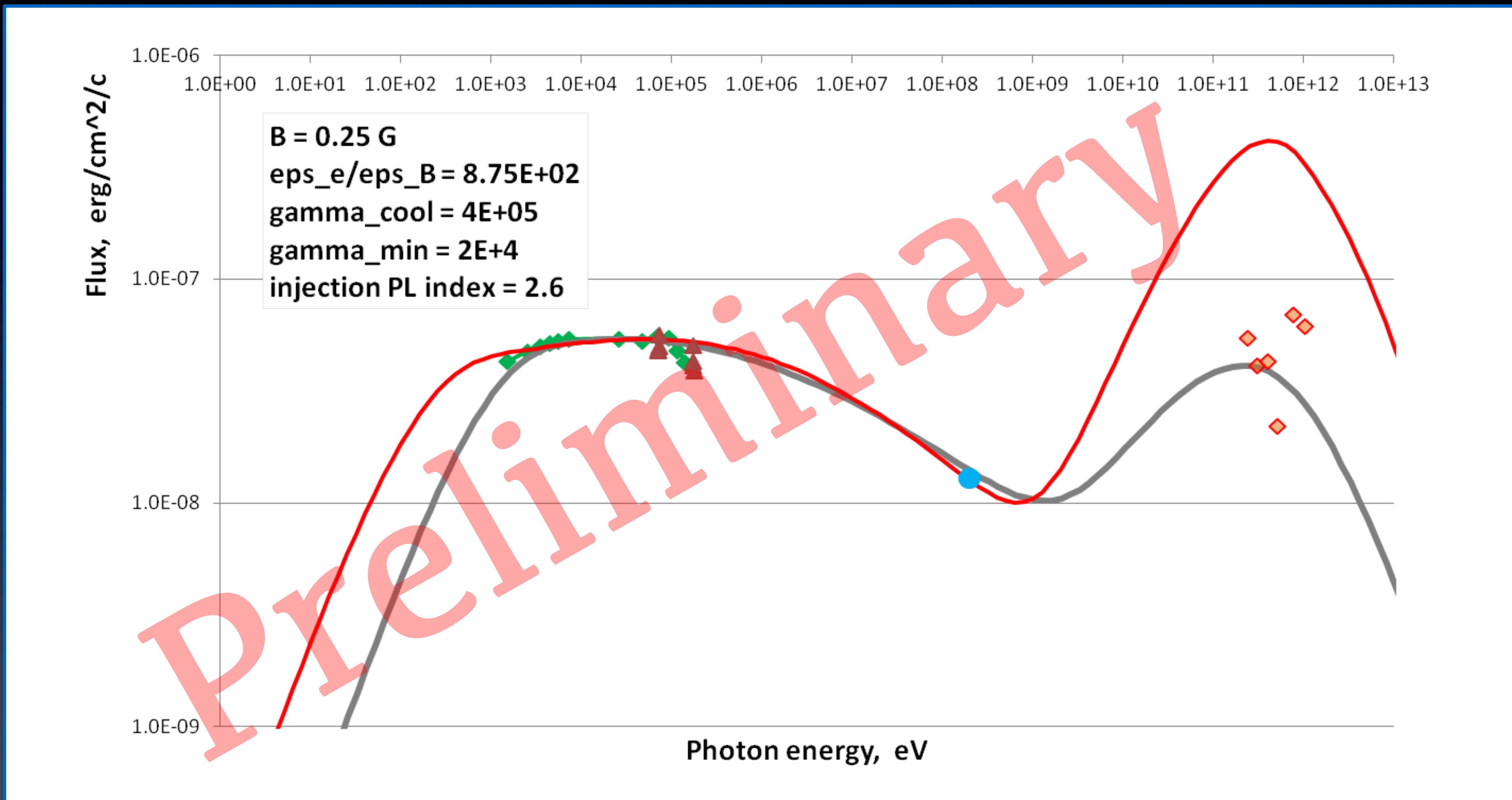
Three emission components



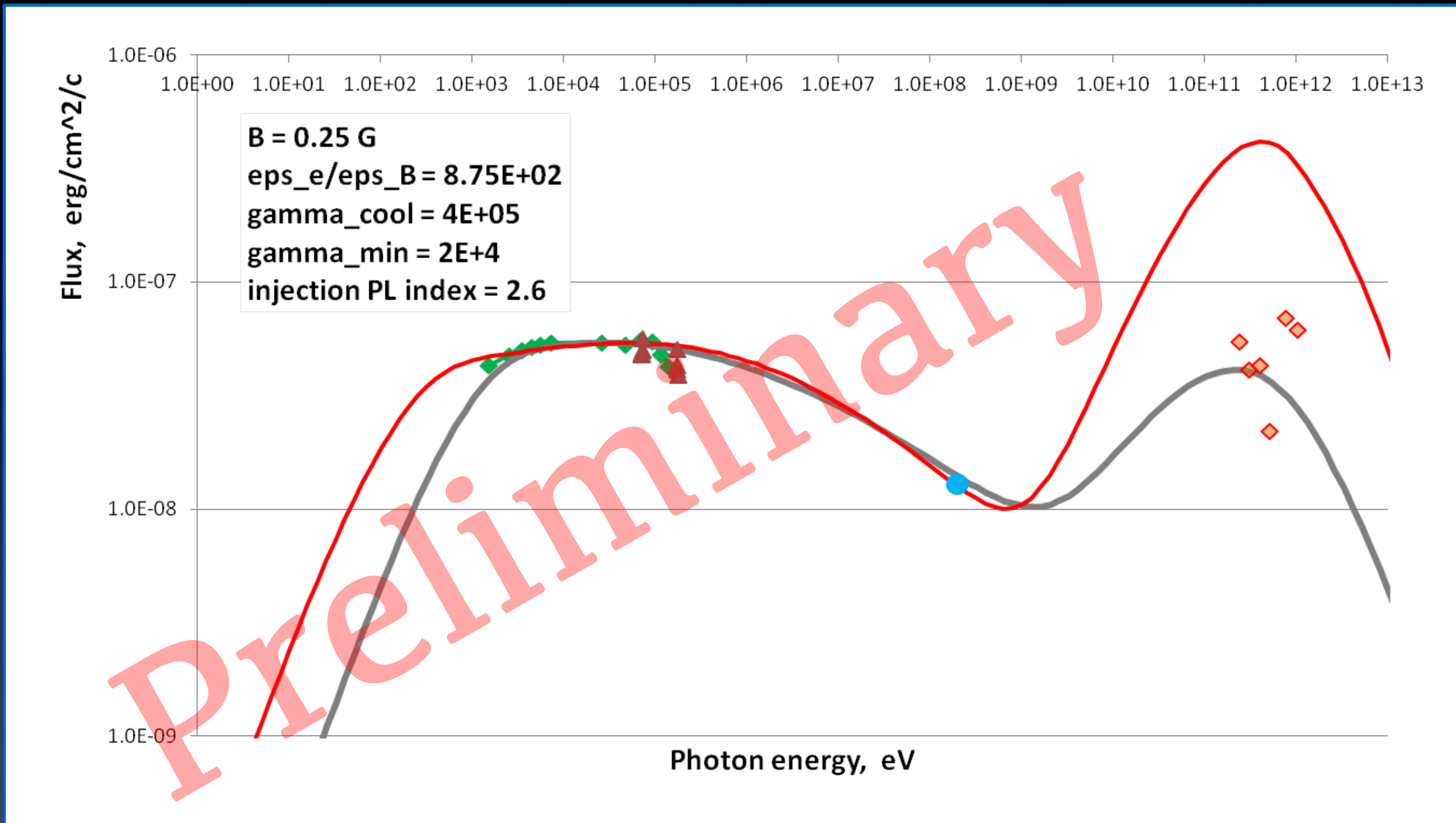




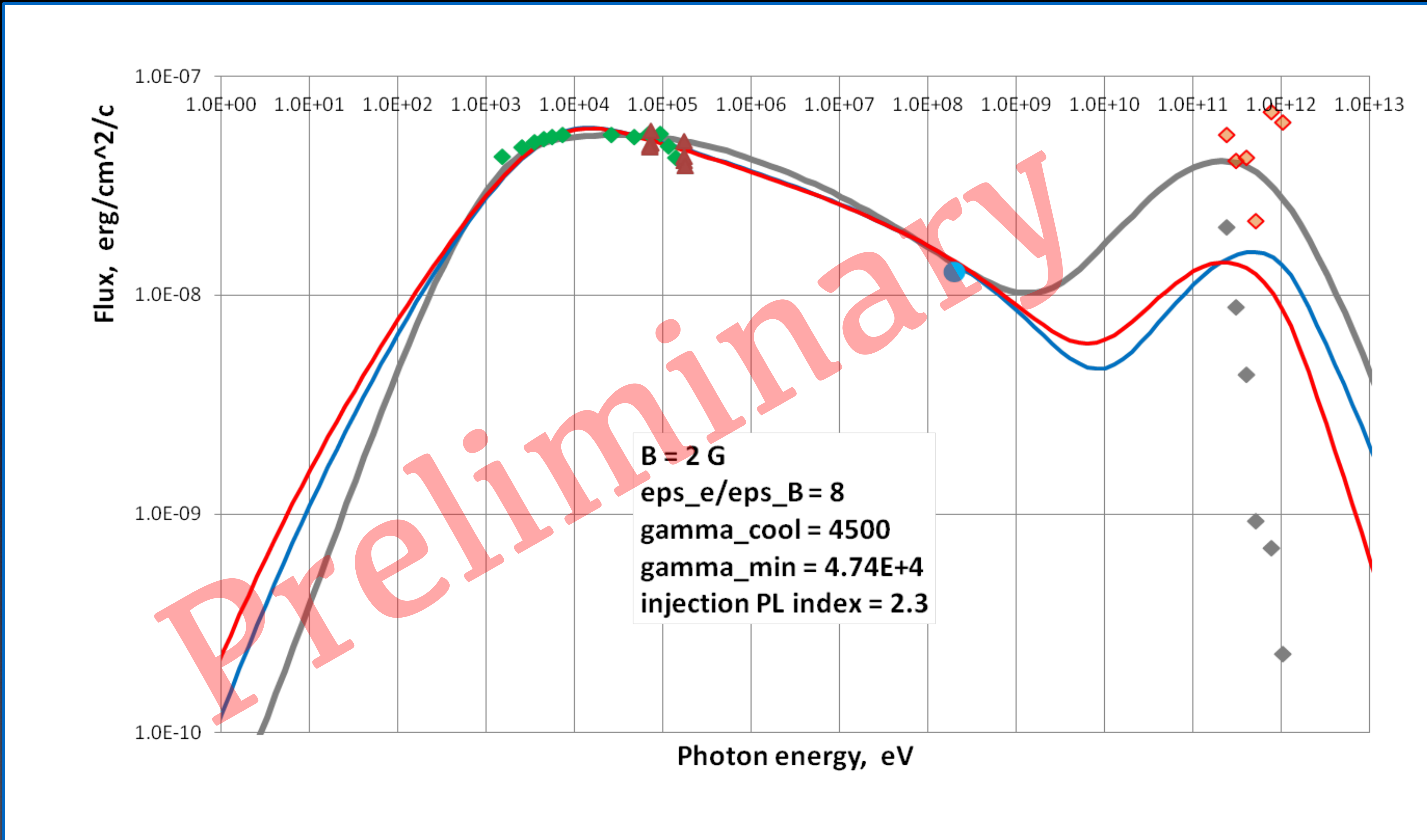
10-6
10-7
10-8
10-9
1
10^2
10^4
10^6
10^8
10^10
10^12
eV
Preliminary



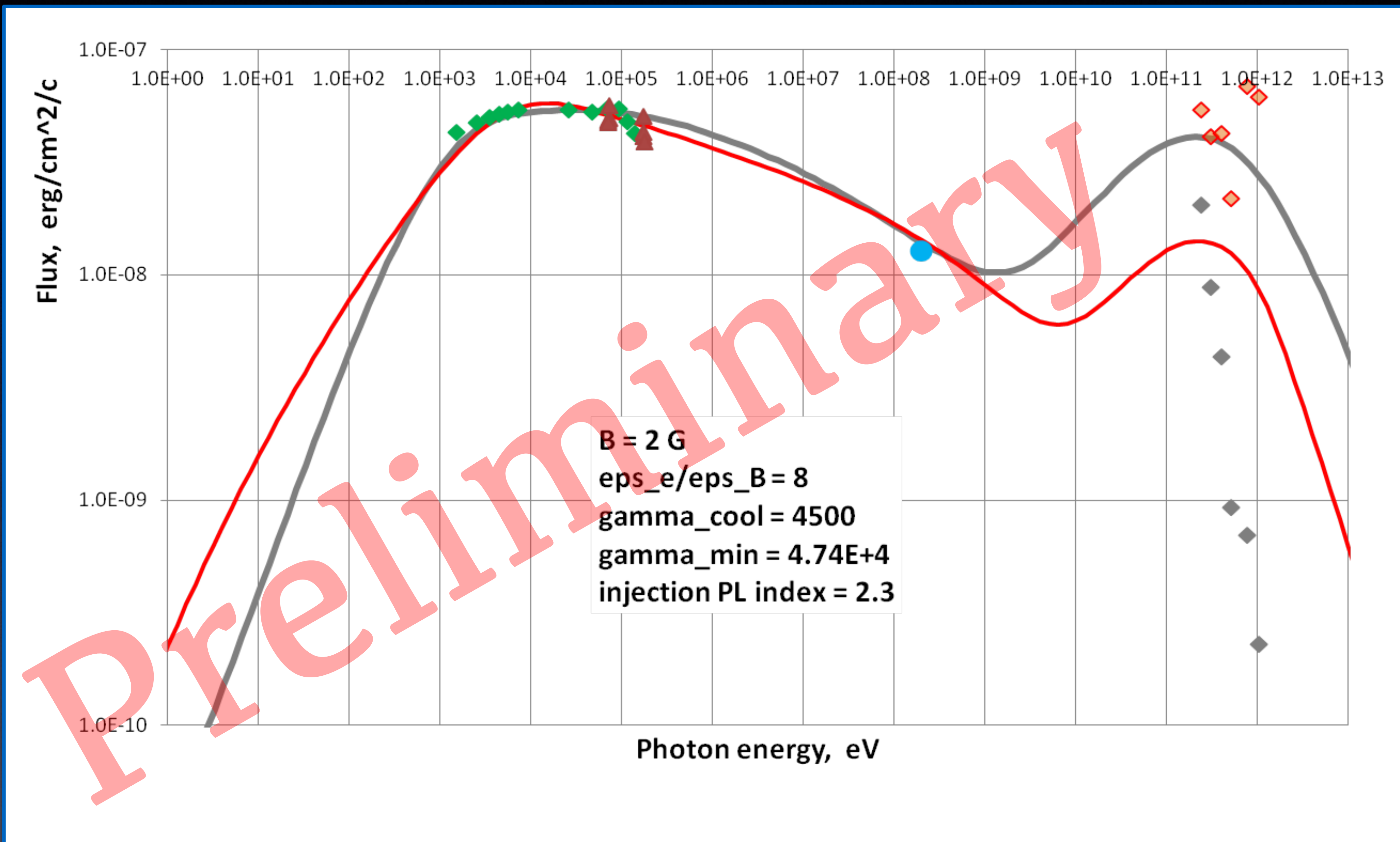
Flux, erg/cm^2/c
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13
B = 0.25 G
eps_e/eps_B = 8.75E+02
gamma_cool = 4E+05
gamma_min = 2E+4
injection PL index = 2.6
Preliminary
Photon energy, eV



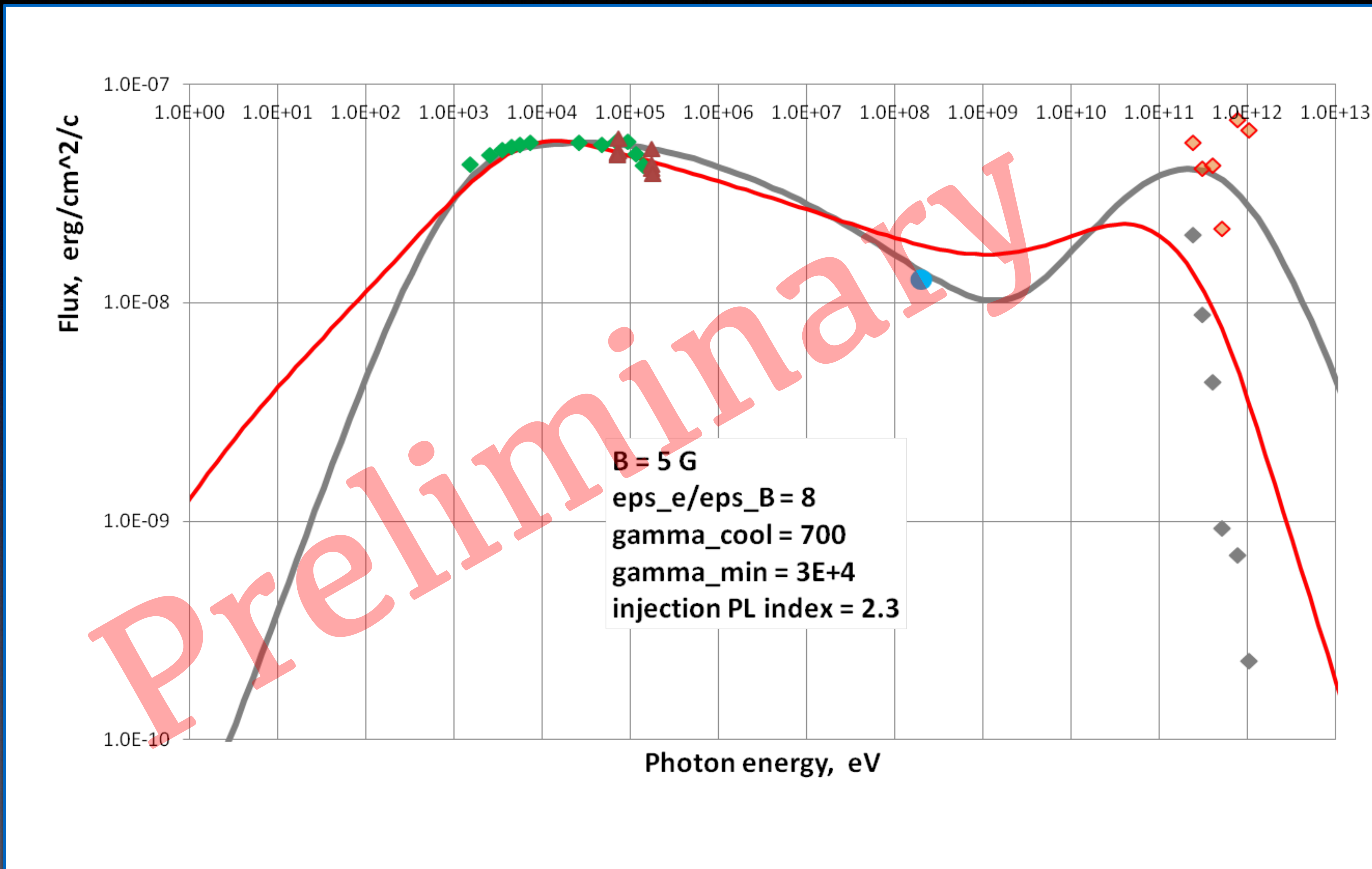
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06 1.0E+07 1.0E+08 1.0E+09 1.0E+10 1.0E+11 1.0E+12 1.0E+13
Flux, erg/cm^2/c
B = 0.25 G
eps_e/eps_B = 8.75E+02
gamma_cool = 4E+05
gamma_min = 2E+4
injection PL index = 2.6
Photon energy, eV
Preliminary



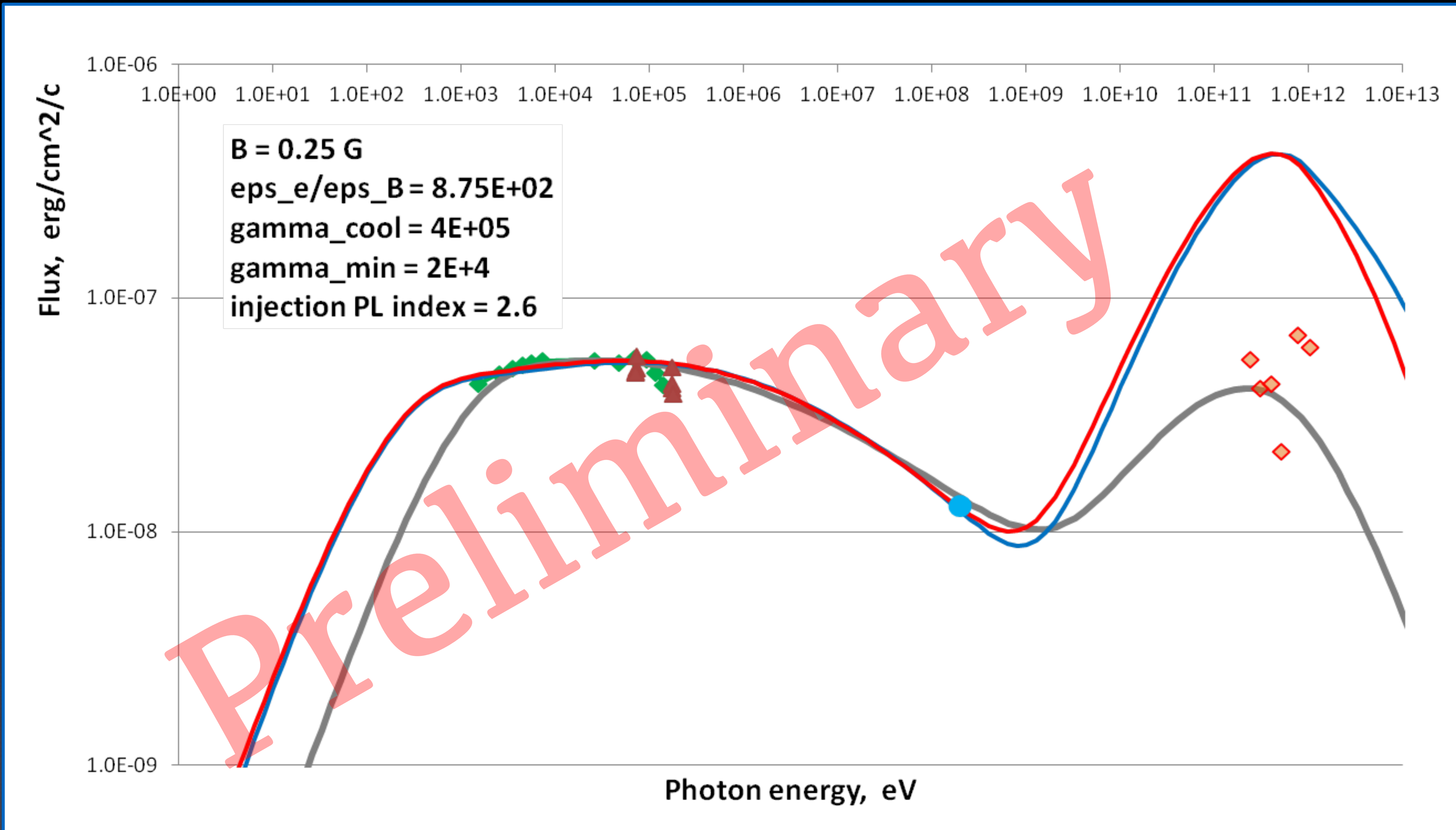
Flux, erg/cm^2/c
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13
Photon energy, eV
B = 2 G
eps_e/eps_B = 8
gamma_cool = 4500
gamma_min = 4.74E+4
injection PL index = 2.3
Preliminary



Flux, erg/cm^2/c
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13
Photon energy, eV
B = 2 G
eps_e/eps_B = 8
gamma_cool = 4500
gamma_min = 4.74E+4
injection PL index = 2.3
Preliminary



1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
1.0E+11
1.0E+12
1.0E+13
Flux, erg/cm^2/c
Photon energy, eV
B = 5 G
eps_e/eps_B = 8
gamma_cool = 700
gamma_min = 3E+4
injection PL index = 2.3
Preliminary



1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06 1.0E+07 1.0E+08 1.0E+09 1.0E+10 1.0E+11 1.0E+12 1.0E+13
Flux, erg/cm^2/c
B = 0.25 G
eps_e/eps_B = 8.75E+02
gamma_cool = 4E+05
gamma_min = 2E+4
injection PL index = 2.6
Preliminary
Photon energy, eV