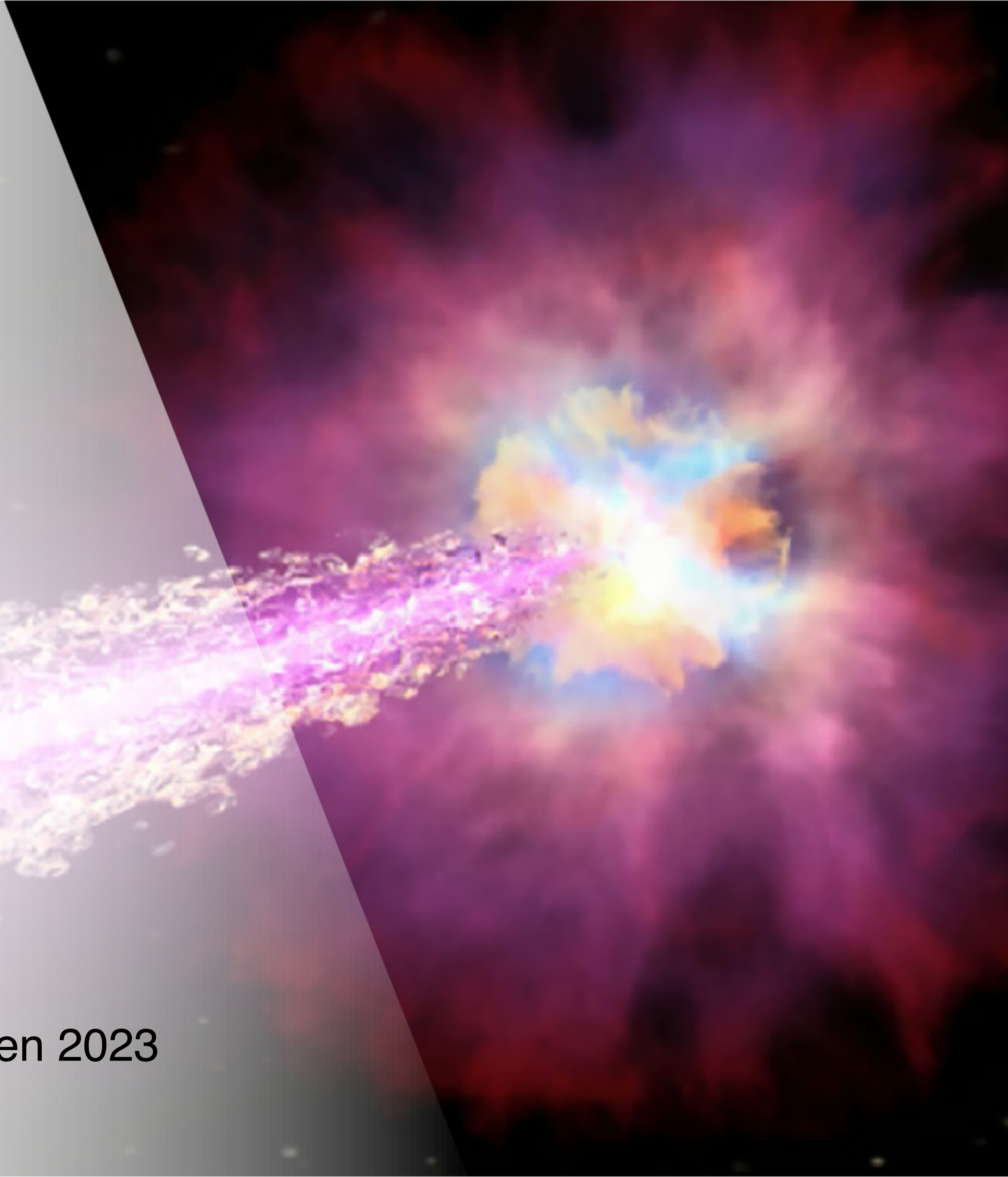
TeV emission from GRB

Tsvi Piran

Evgeny Derishev, Shotaro Yamasaki



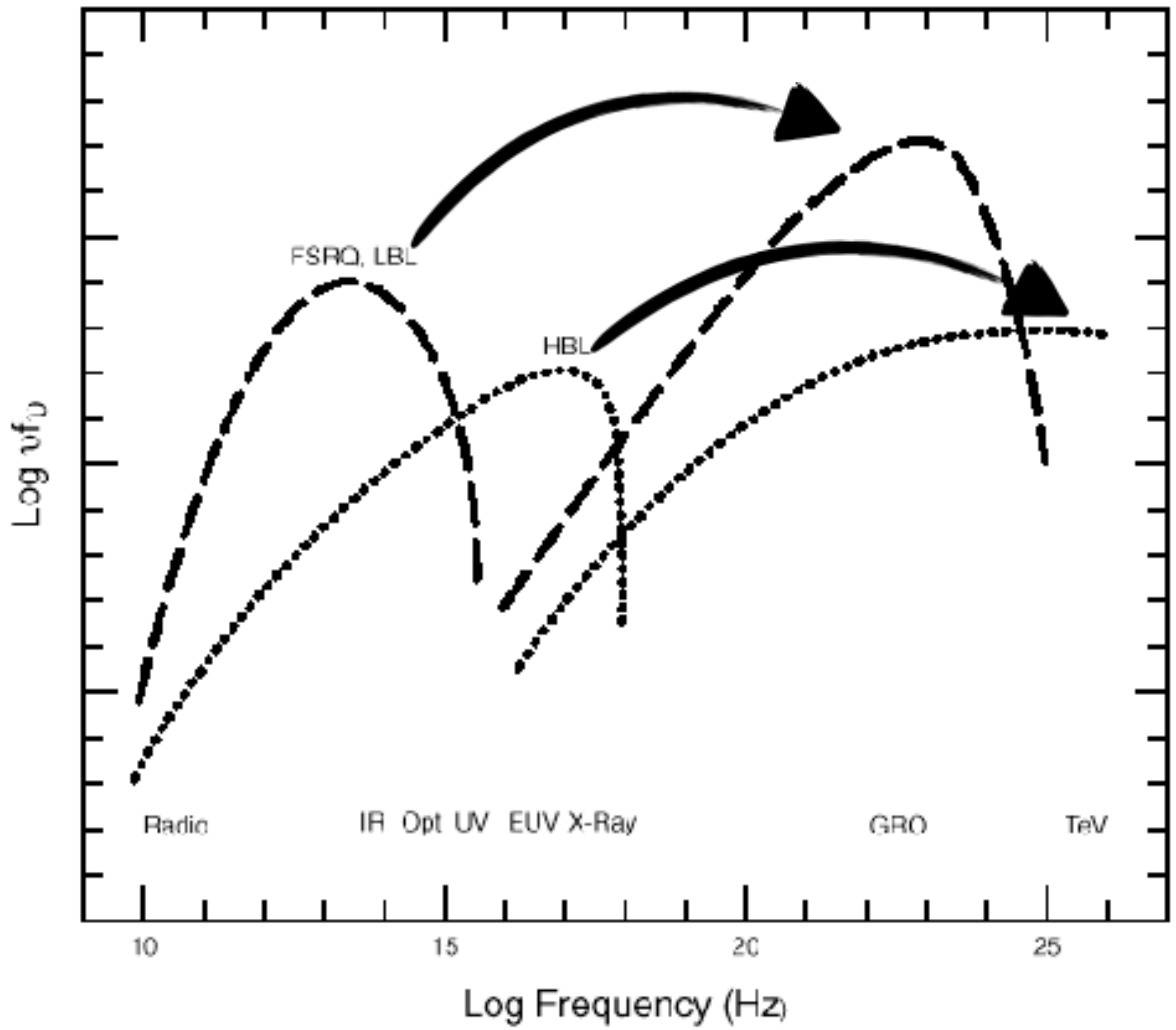
ERC
GRB
TReX
Multijets

High Redshift GRBs, Sexten 2023

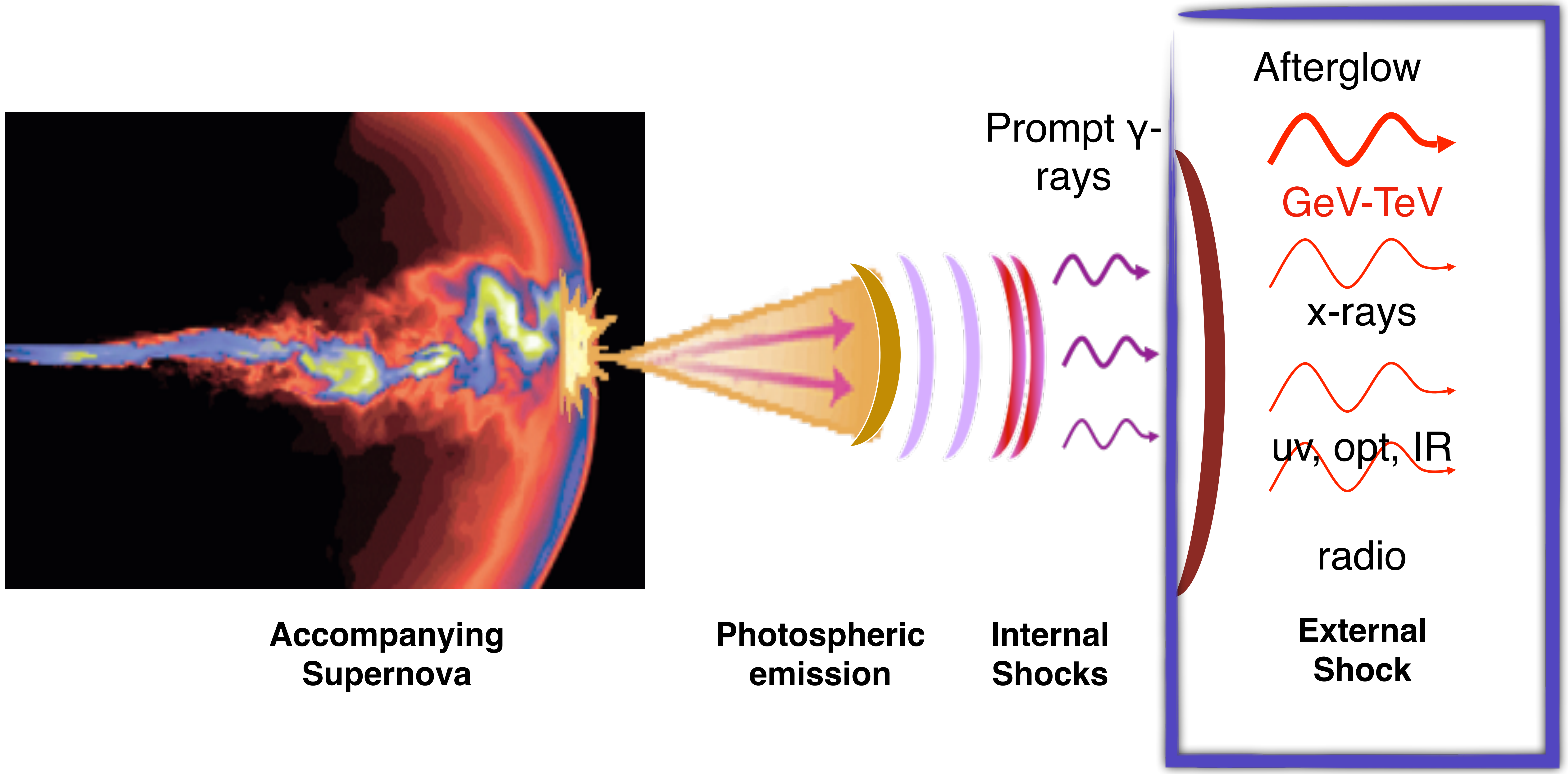
Outline

- General considerations of SSC in the Klein-Nishina regime in GRBs
- Analytic vs. full numerical modeling
- Application to GRB 190114c and the “pair balance” model
- Some remarks on GRB 221009a

Blazars


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

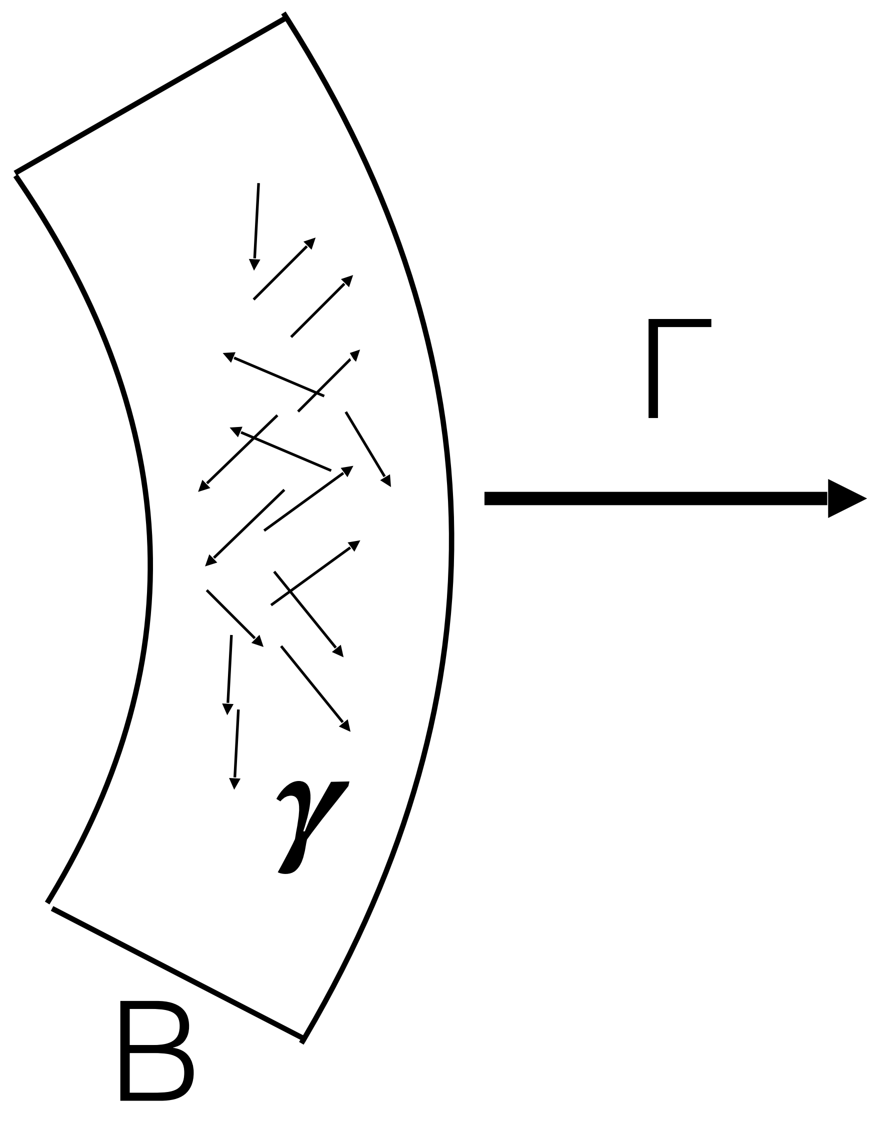
A Gamma-Ray Burst Model

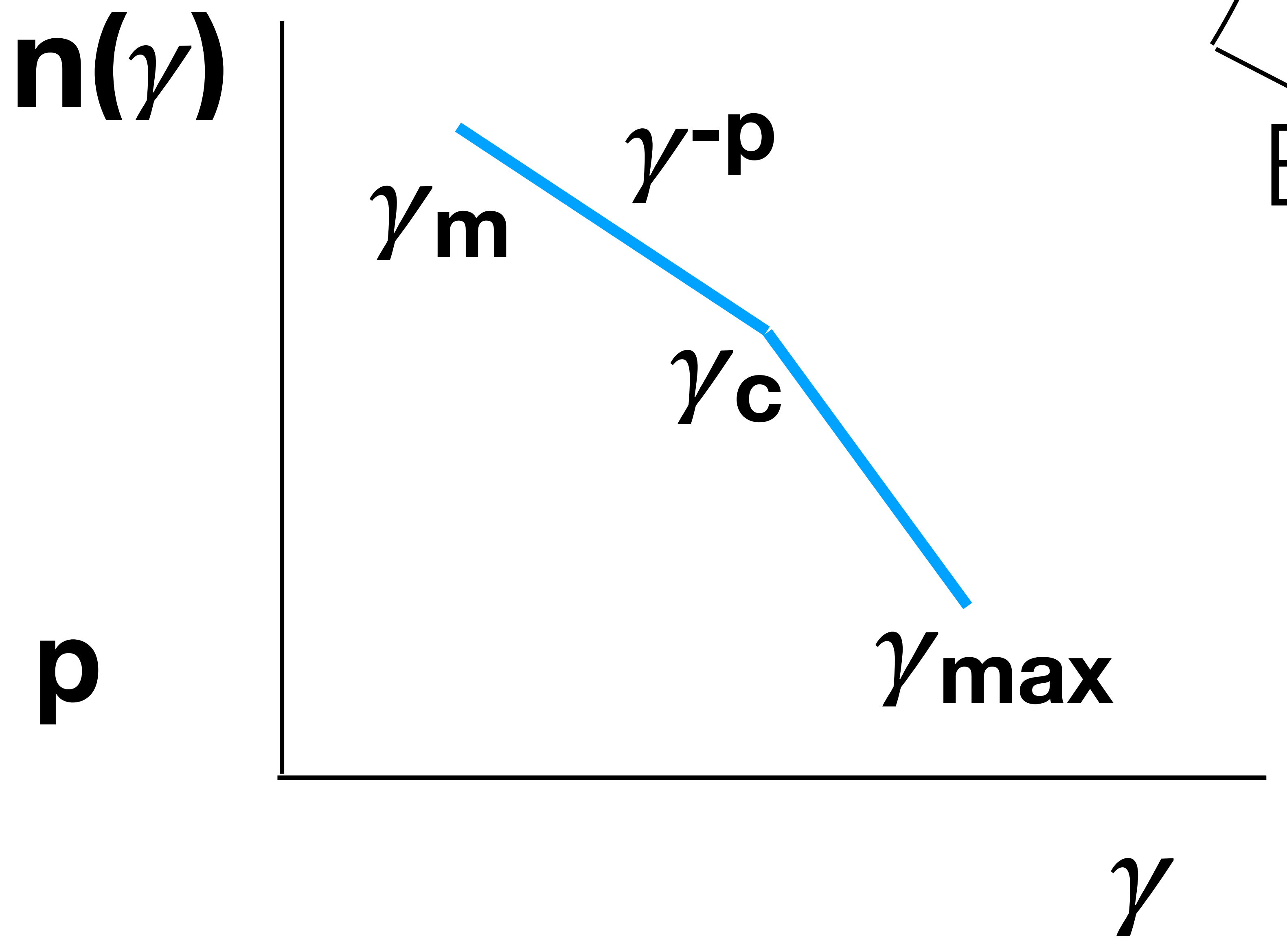


Numerous attempts to reveal the conditions within the emitting regions of the Afterglow - but degeneracy hampers these efforts

The Single Zone Model

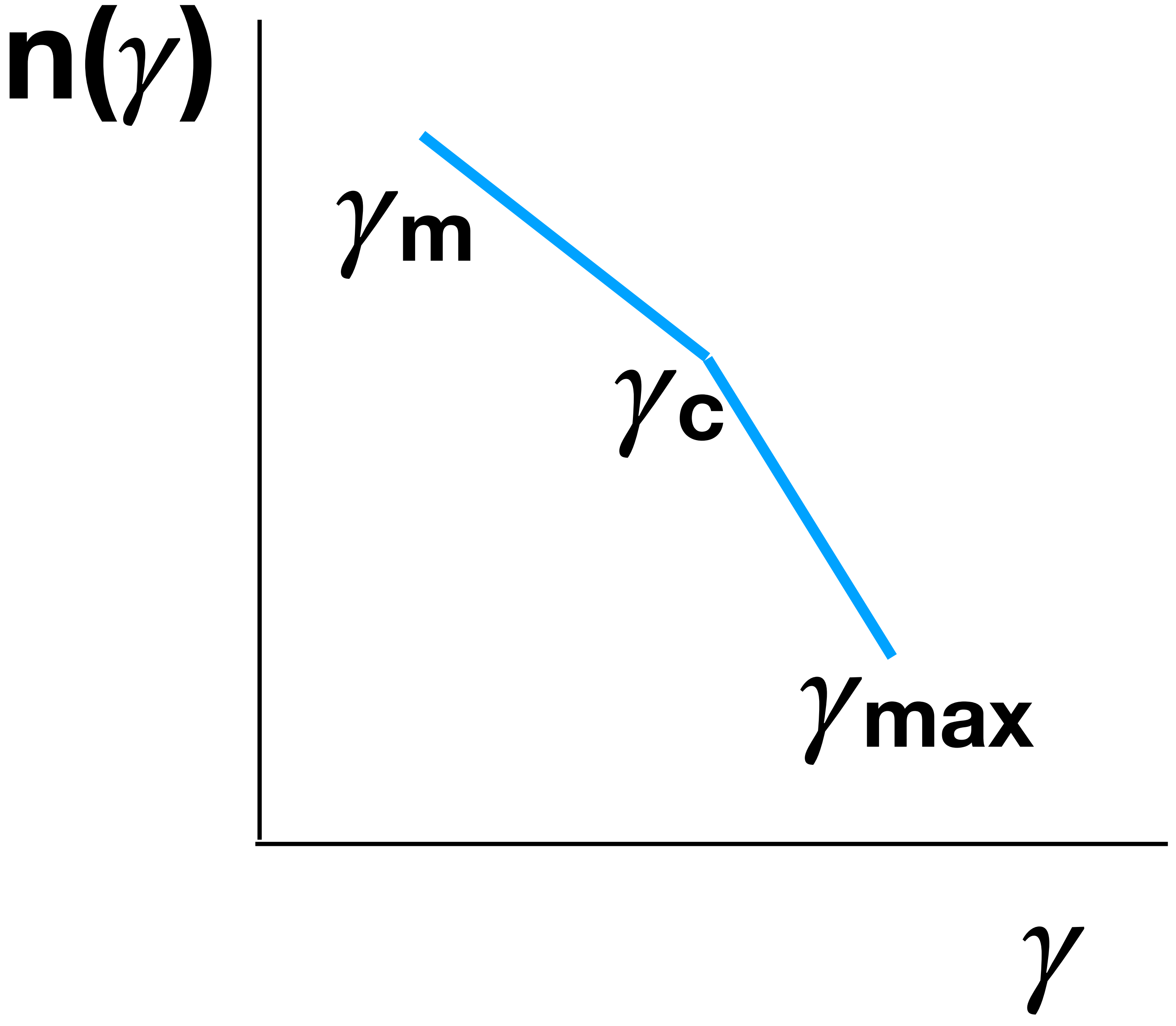
- **Blast wave into wind or ISM**
- **Single Zone**



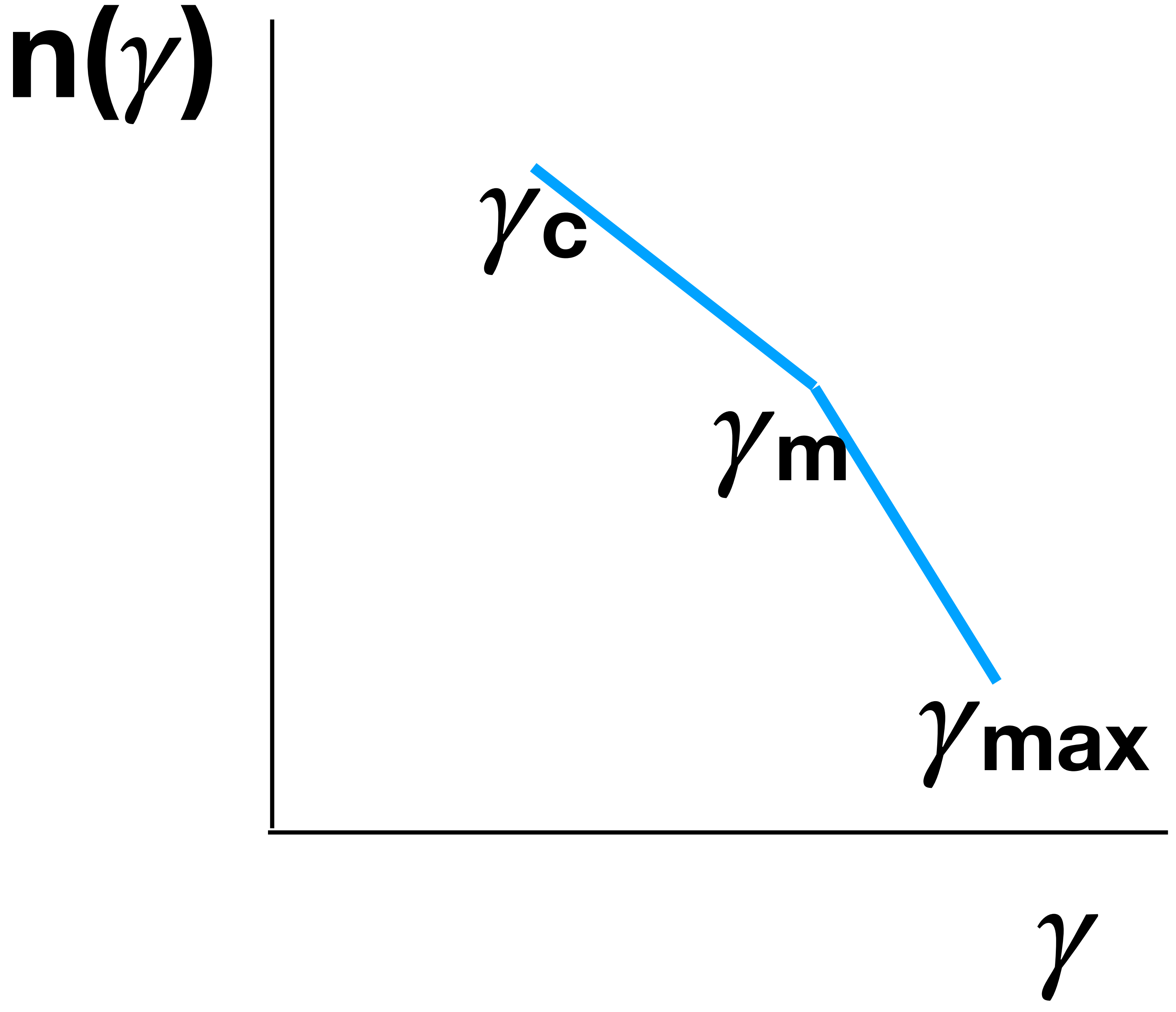


Parameters:
External: Γ, n, (t)
Internal $\varepsilon_e \equiv e_e/e$; $\varepsilon_B \equiv e_B/e$; p

The electron distribution (Synchrotron)

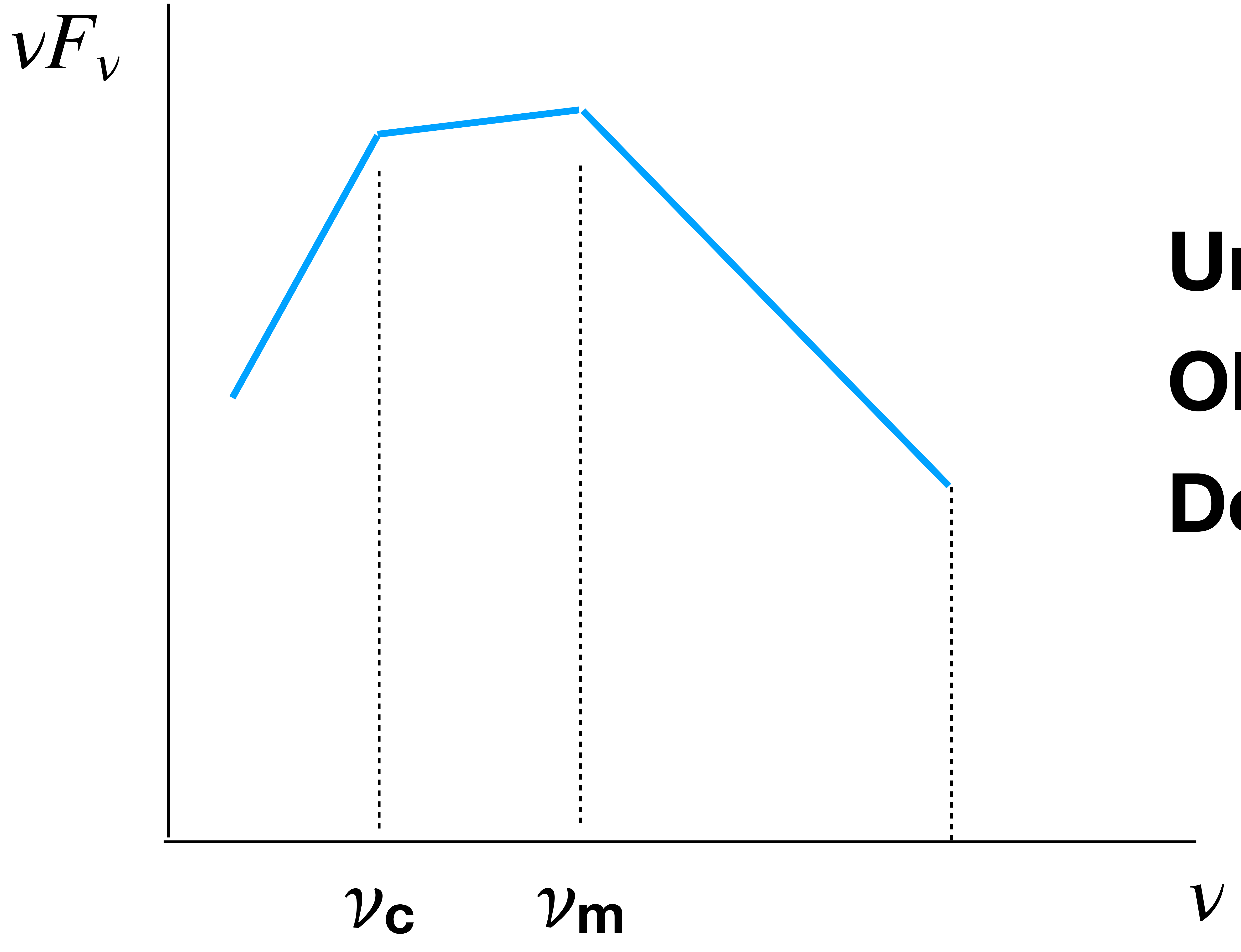


Slow Cooling



Fast Cooling

The Synchrotron Spectrum



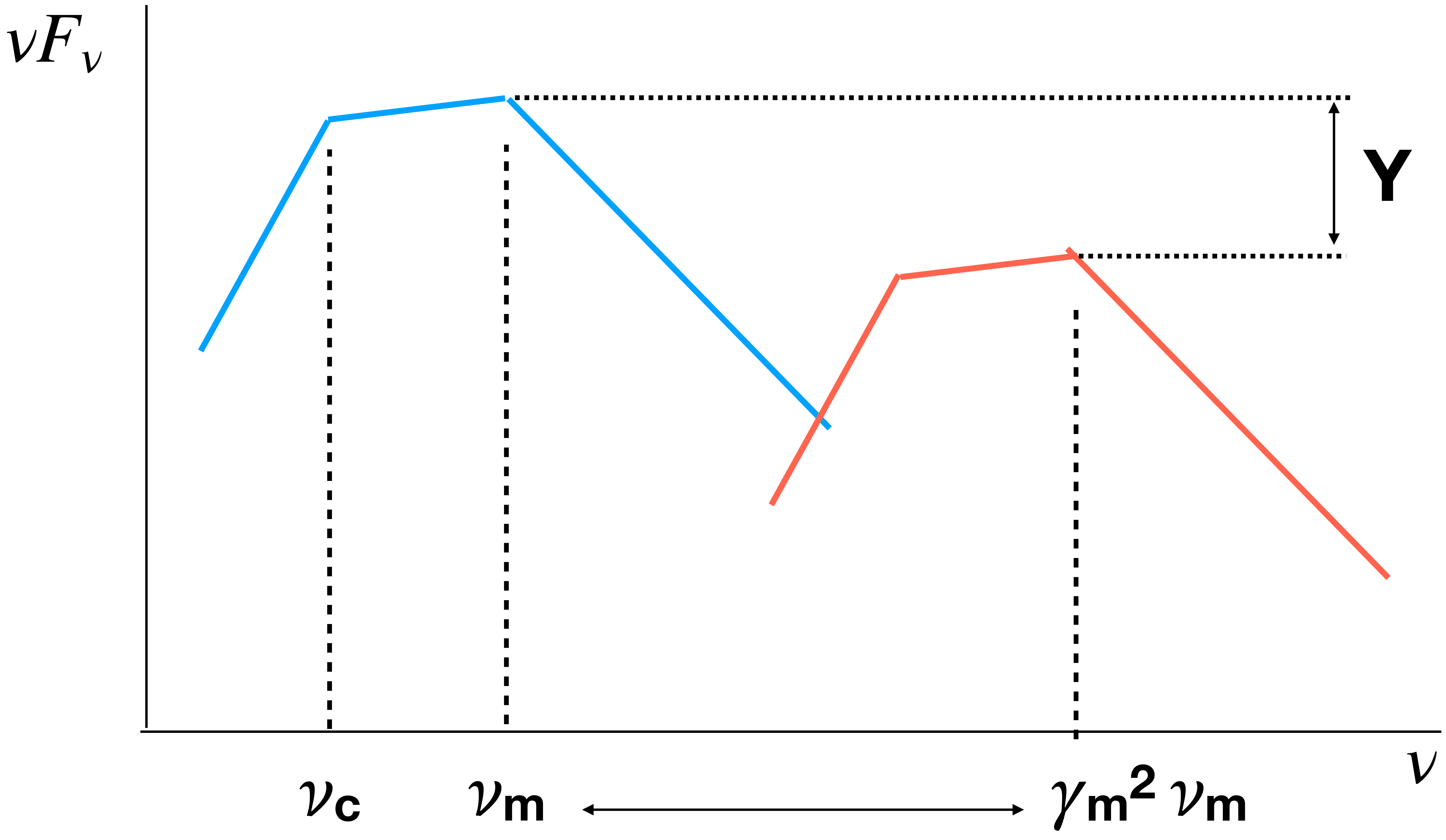
Unknown Γ, n, ε_e, ε_B, p

Observables ν_c, F(ν_c), ν_m, F(ν_m) + slope

Degeneracy unless all are known

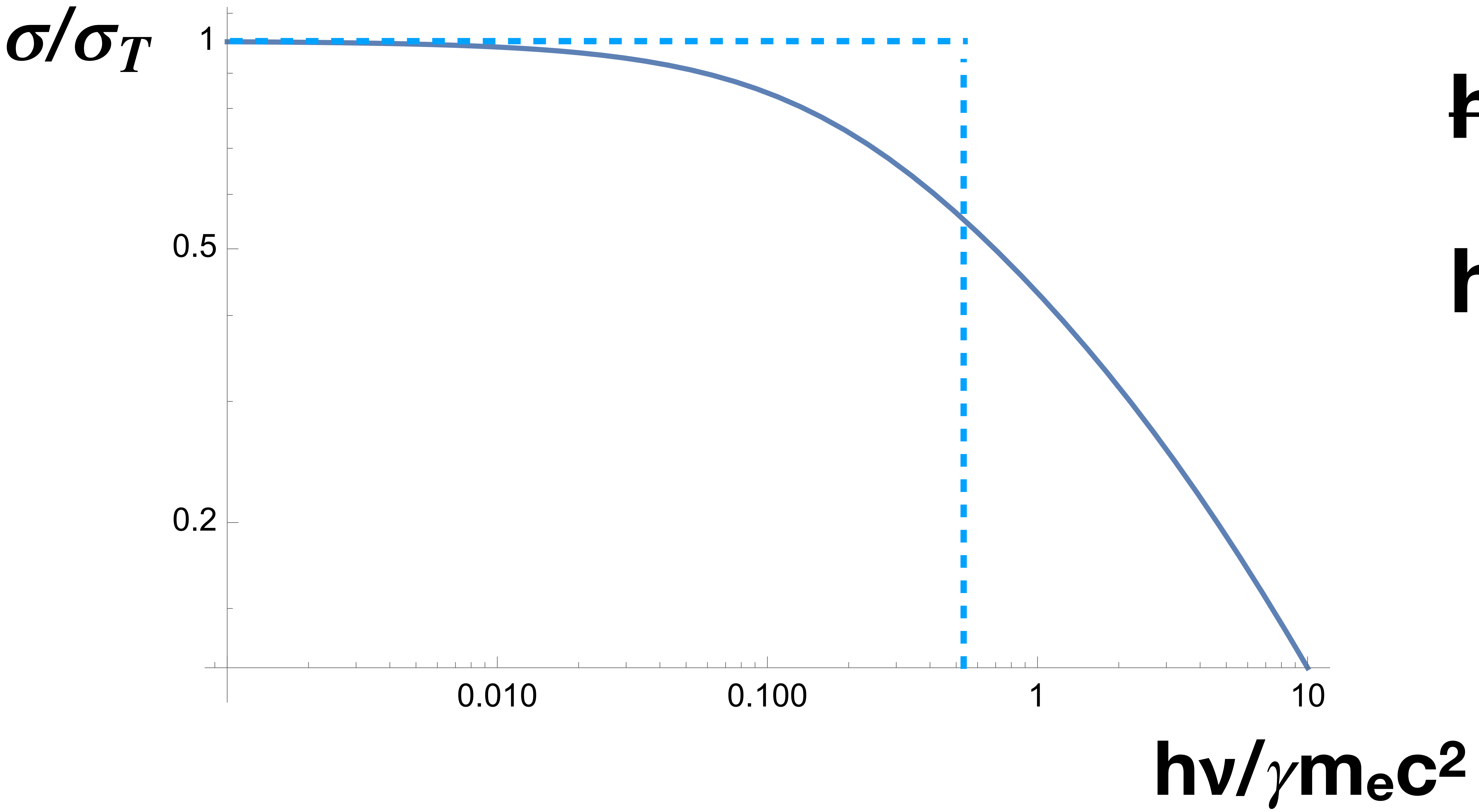
SSC in GRBs (with no Klein-Nishina)

Sari & Esin 02



Break the degeneracy

Klein-Nishina

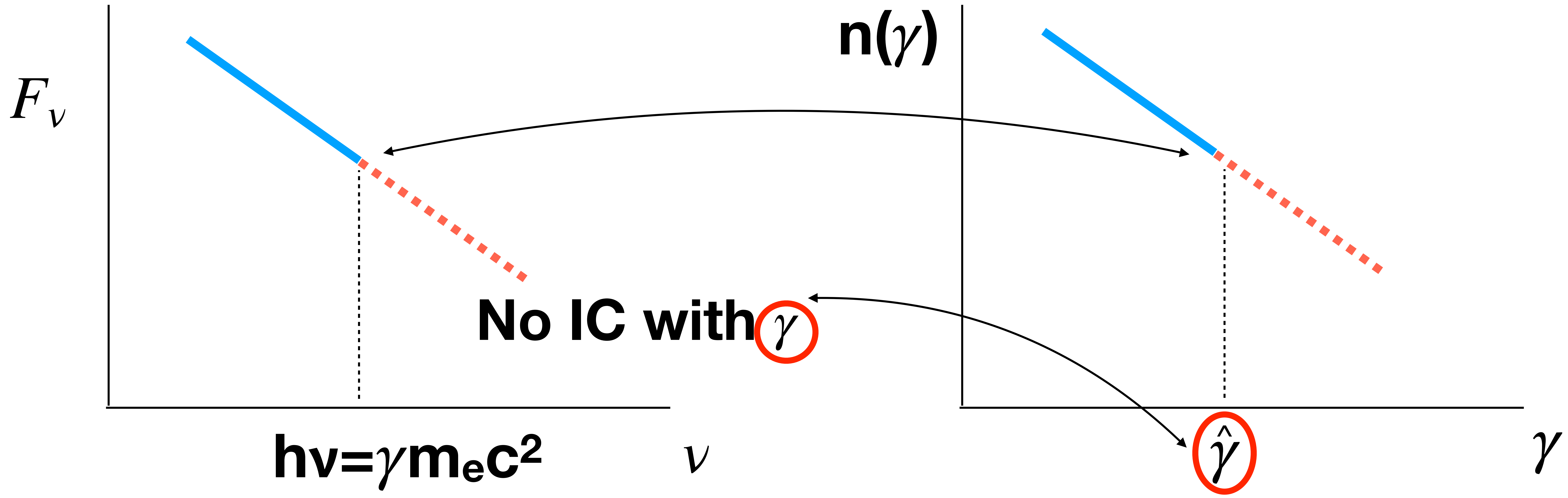


~~$h\nu$ -> $\gamma^2 h\nu$~~

$h\nu$ -> $\gamma m_e c^2$

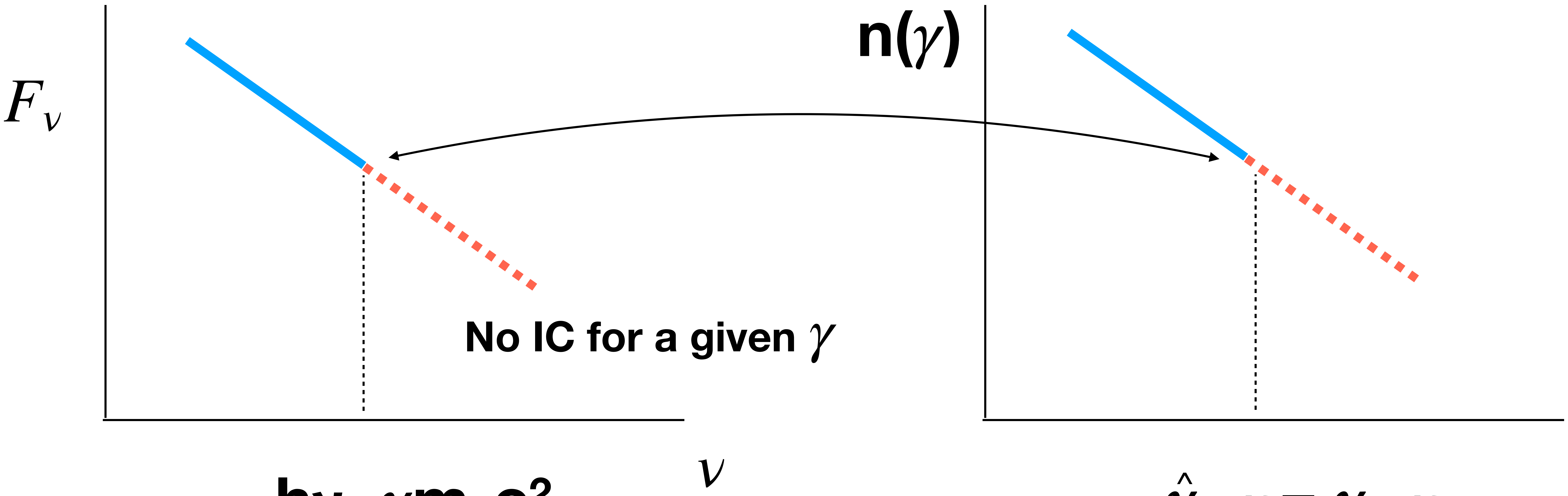
SSC with Klein-Nishina

Nakar et al., 09



No Inverse Compton on the electron with γ by Synchrotron photons produced by electrons above $\hat{\gamma}$

New break frequencies



hν=γm$_e$c^2

$\hat{\gamma}_{self} = \gamma_{self}$

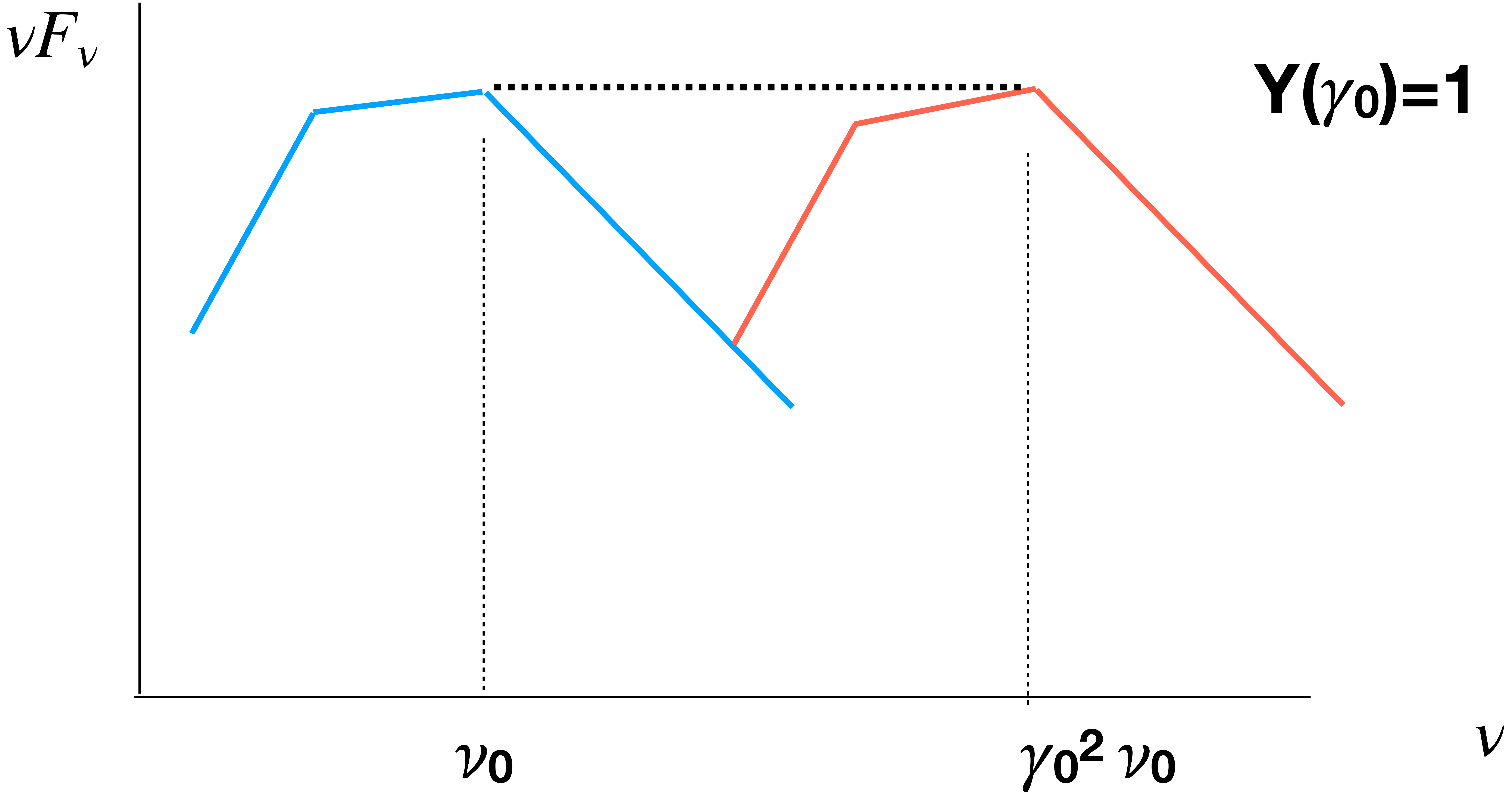
$\hat{\gamma}_m \quad ; \quad \hat{\gamma}_c$

$\gamma_{self} = \sqrt[3]{B_{sch}/B}$

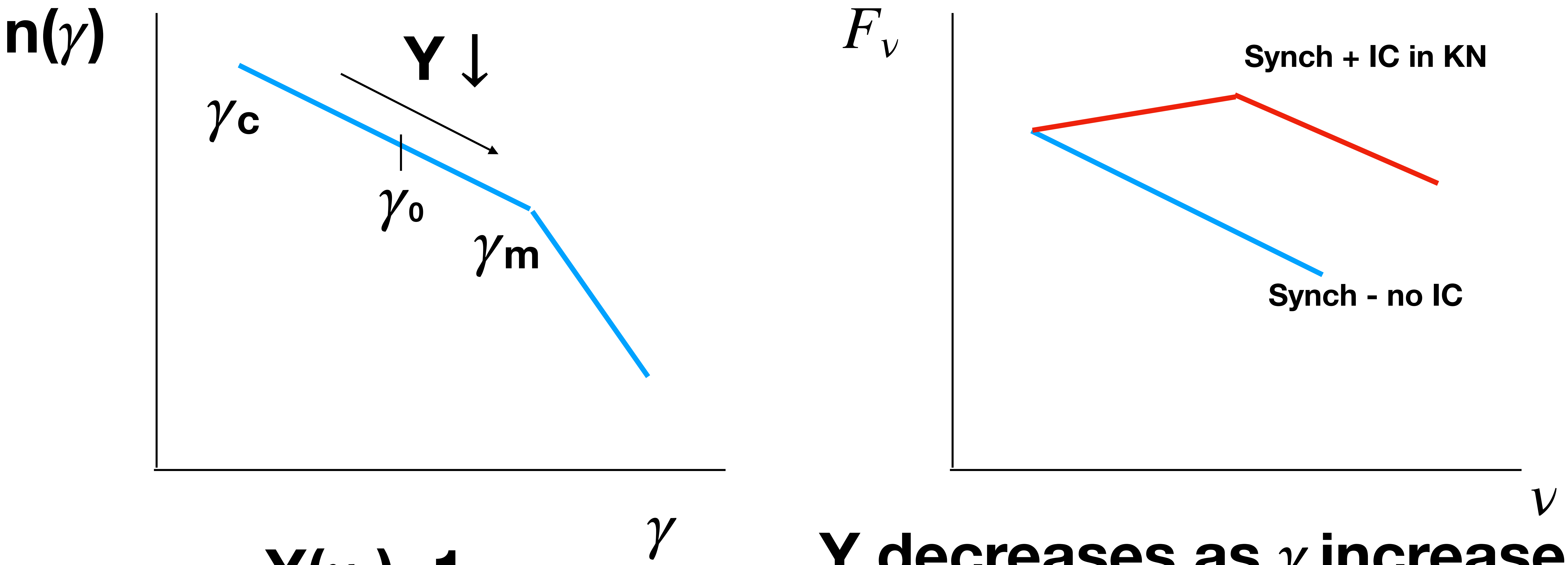
$\nu_m \rightarrow \hat{\nu}_m \qquad \nu_c \rightarrow \hat{\nu}_c$

$\nu_{self} = \hat{\nu}_{self}$

New break frequencies



New break frequencies



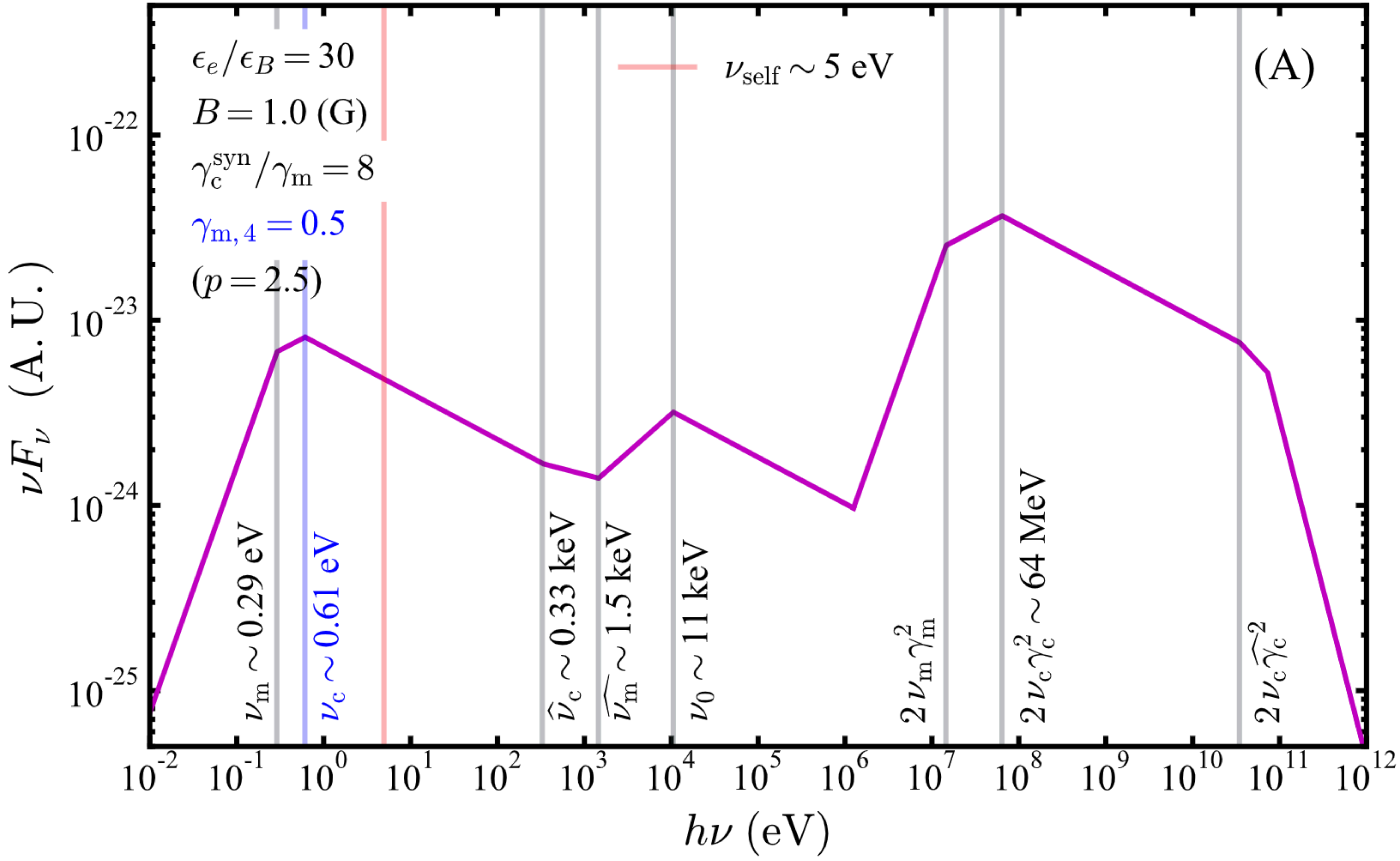
Y(γ_0)=1

Fast Cooling

Y decreases as γ increases

→ Fν increases even though Fν(synch) decreases.

New break frequencies



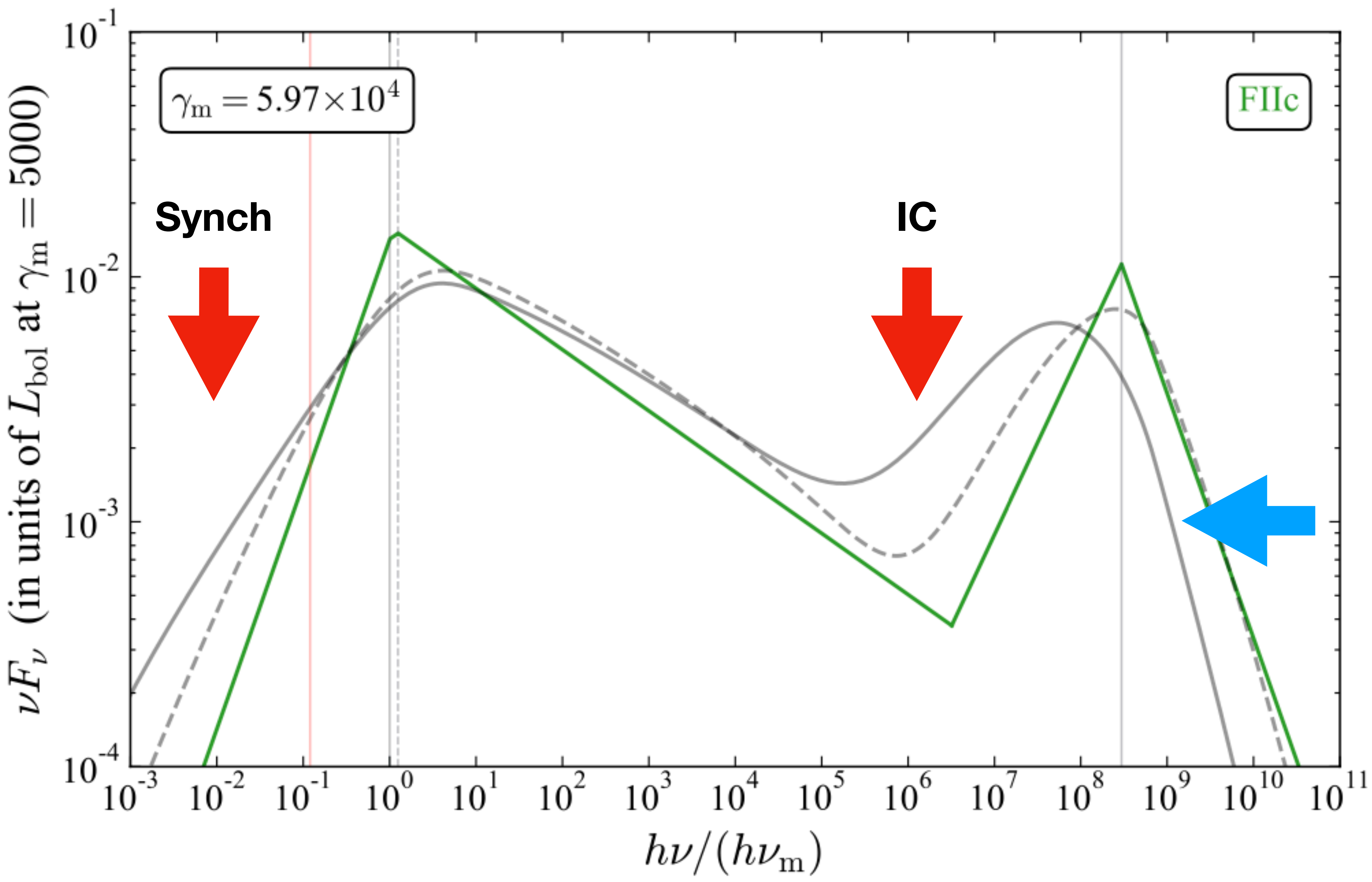
$$\nu_c \rightarrow \hat{\nu}_c$$

$$\nu_m \rightarrow \hat{\nu}_m$$

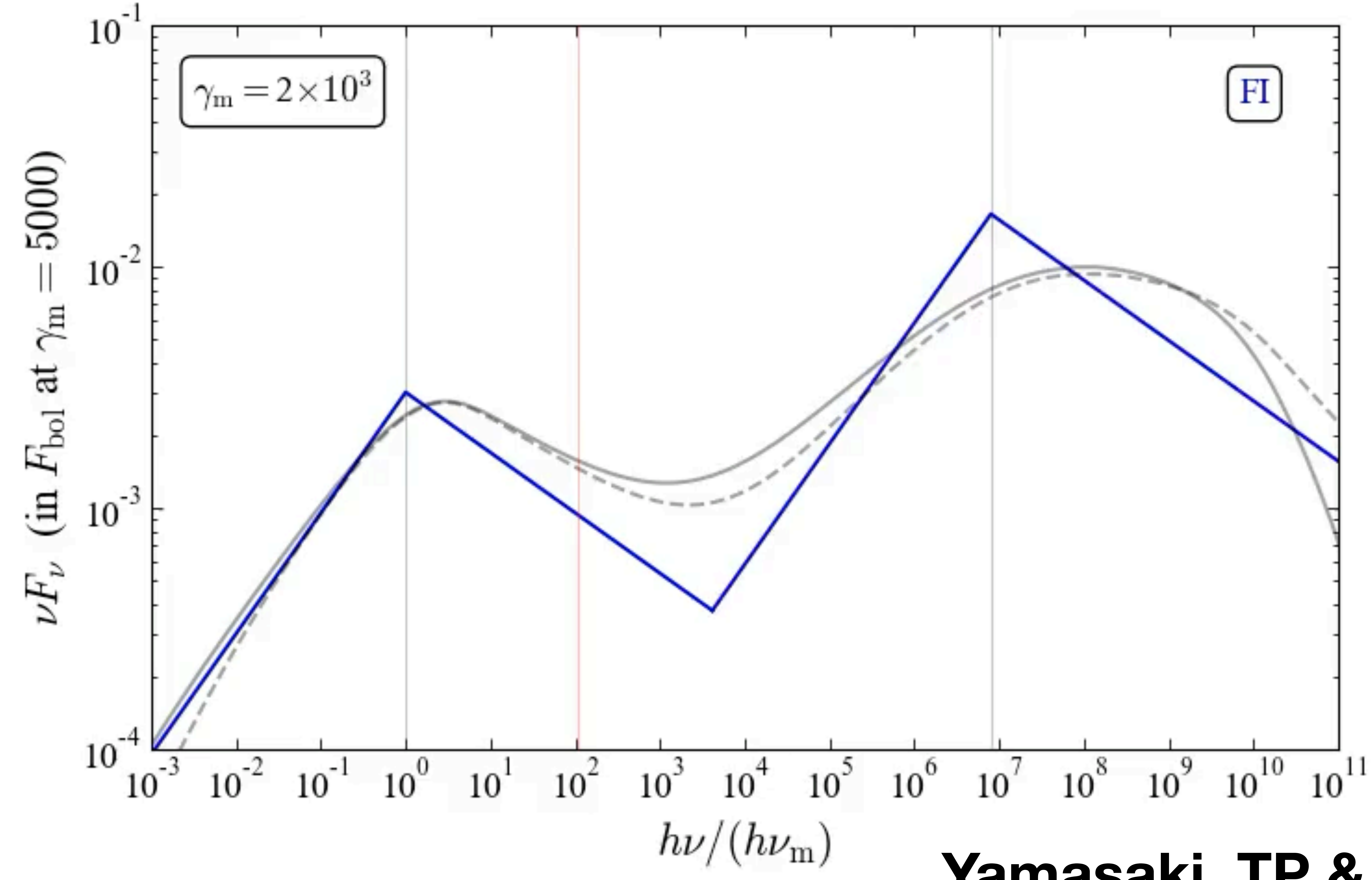
$$\nu_{self} = \hat{\nu}_{self}$$

Additional effects

- **Self Absorption:** $\gamma\gamma \rightarrow e^+e^-$
- **Secondary Synch Emission:** $e + B \rightarrow e + B + \gamma$

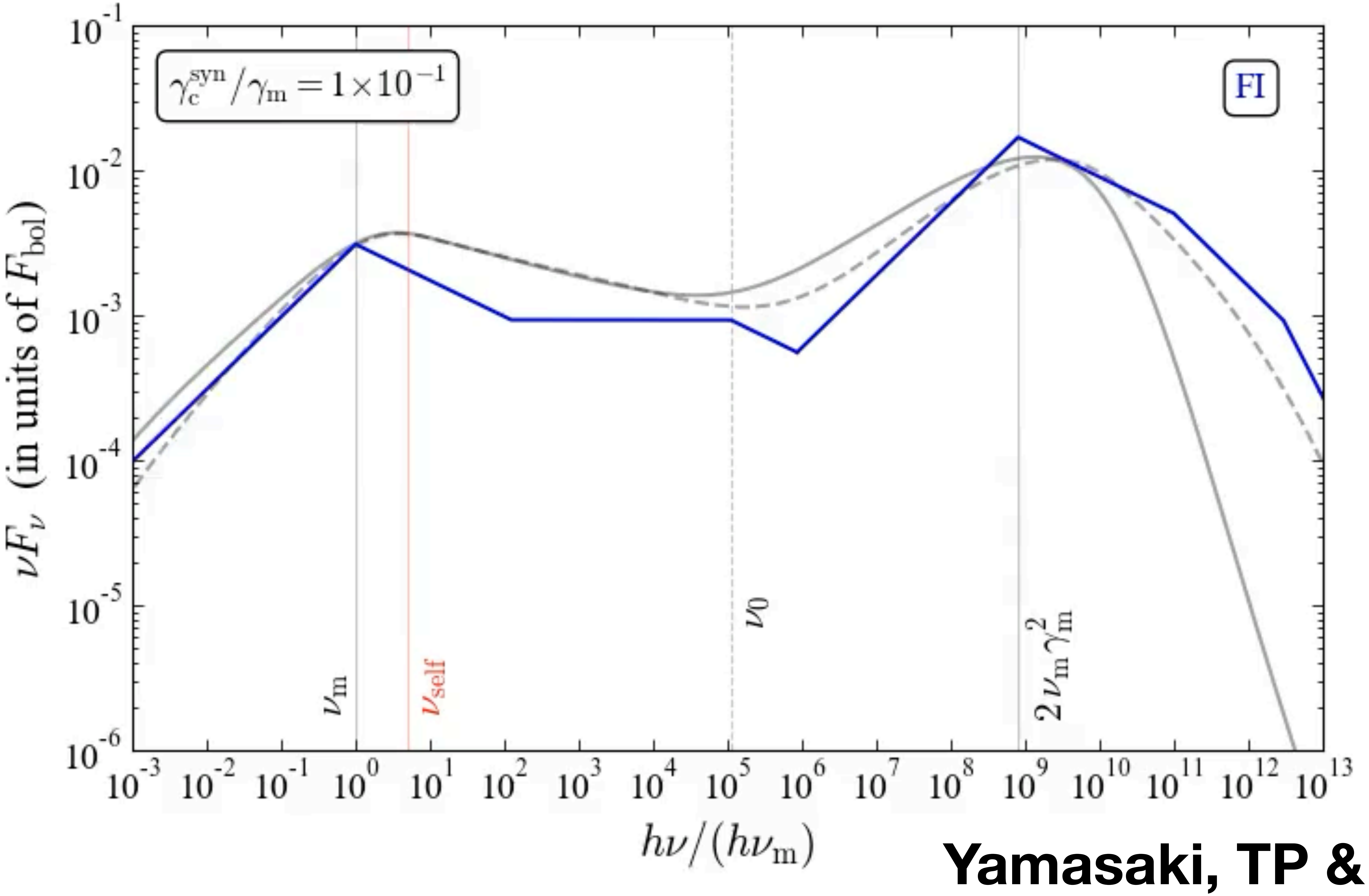


Varying γ_m



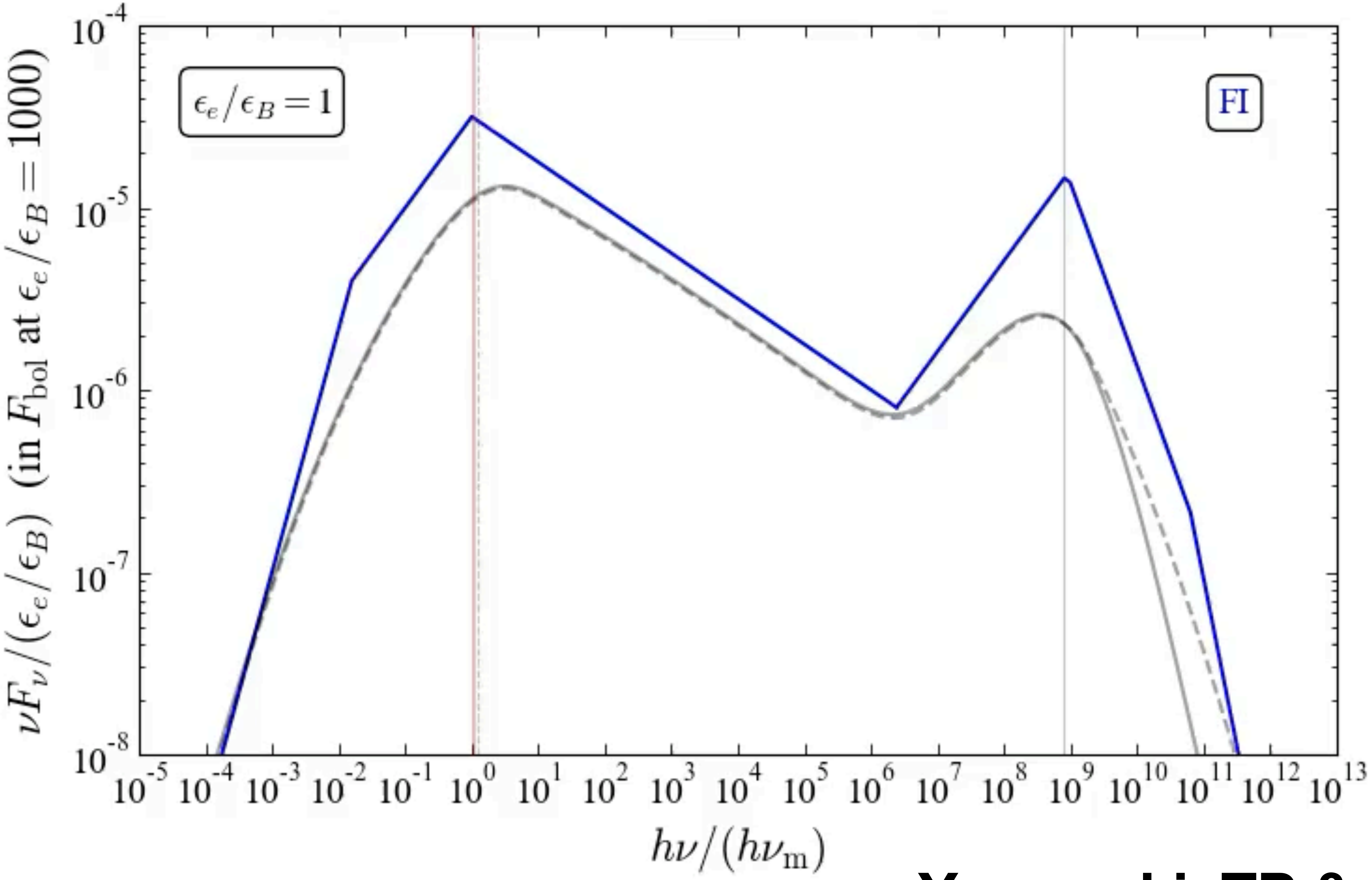
Yamasaki, TP & Derishev 23

From Fast to Slow Cooling



Yamasaki, TP & Derishev 23

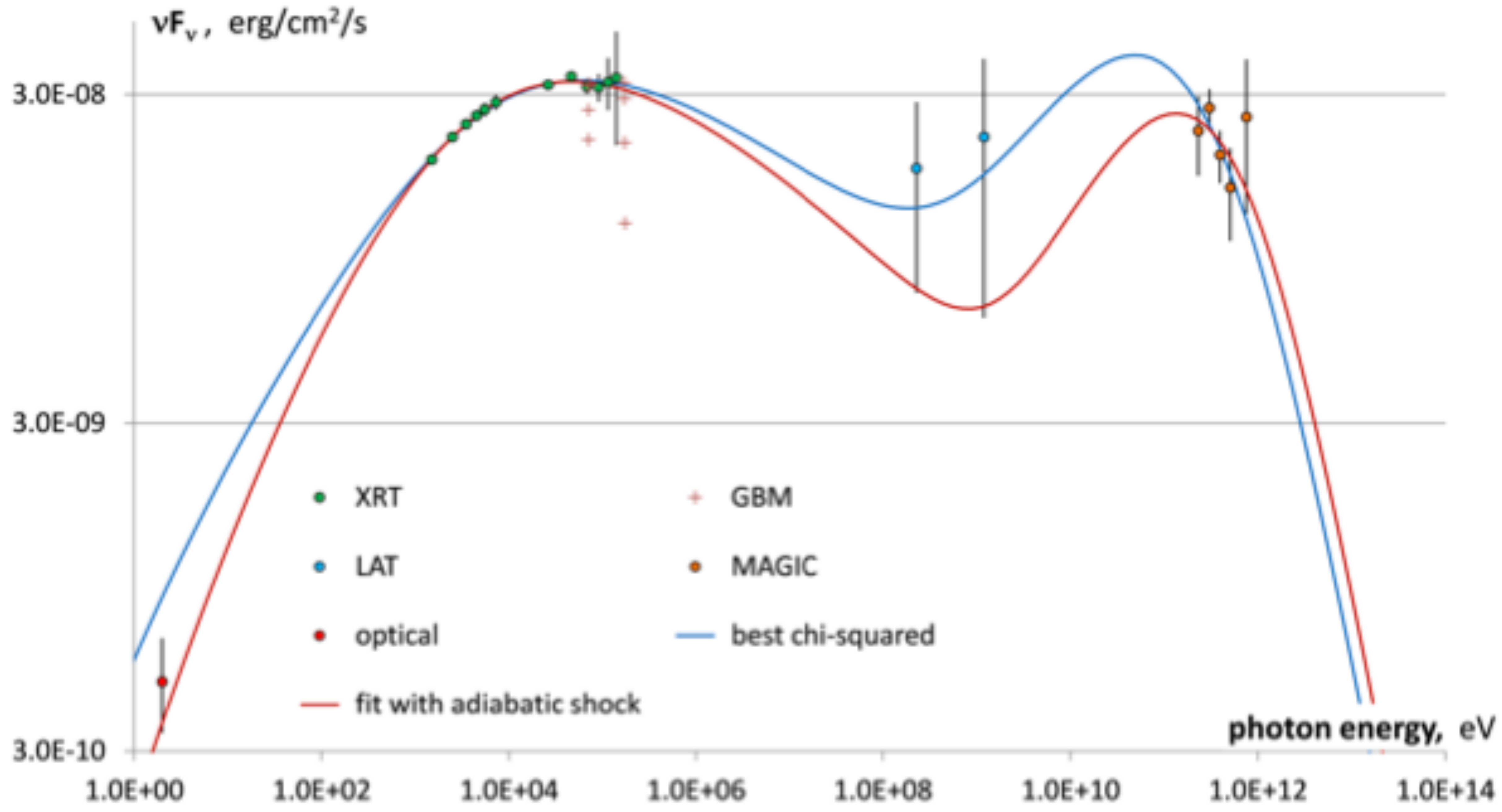
From Synch to IC



Yamasaki, TP & Derishev 22

190114c

- $Z=0.4245$ (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)
- $y = L_{Tev,iso}/L_{x,iso} \simeq 0.25$

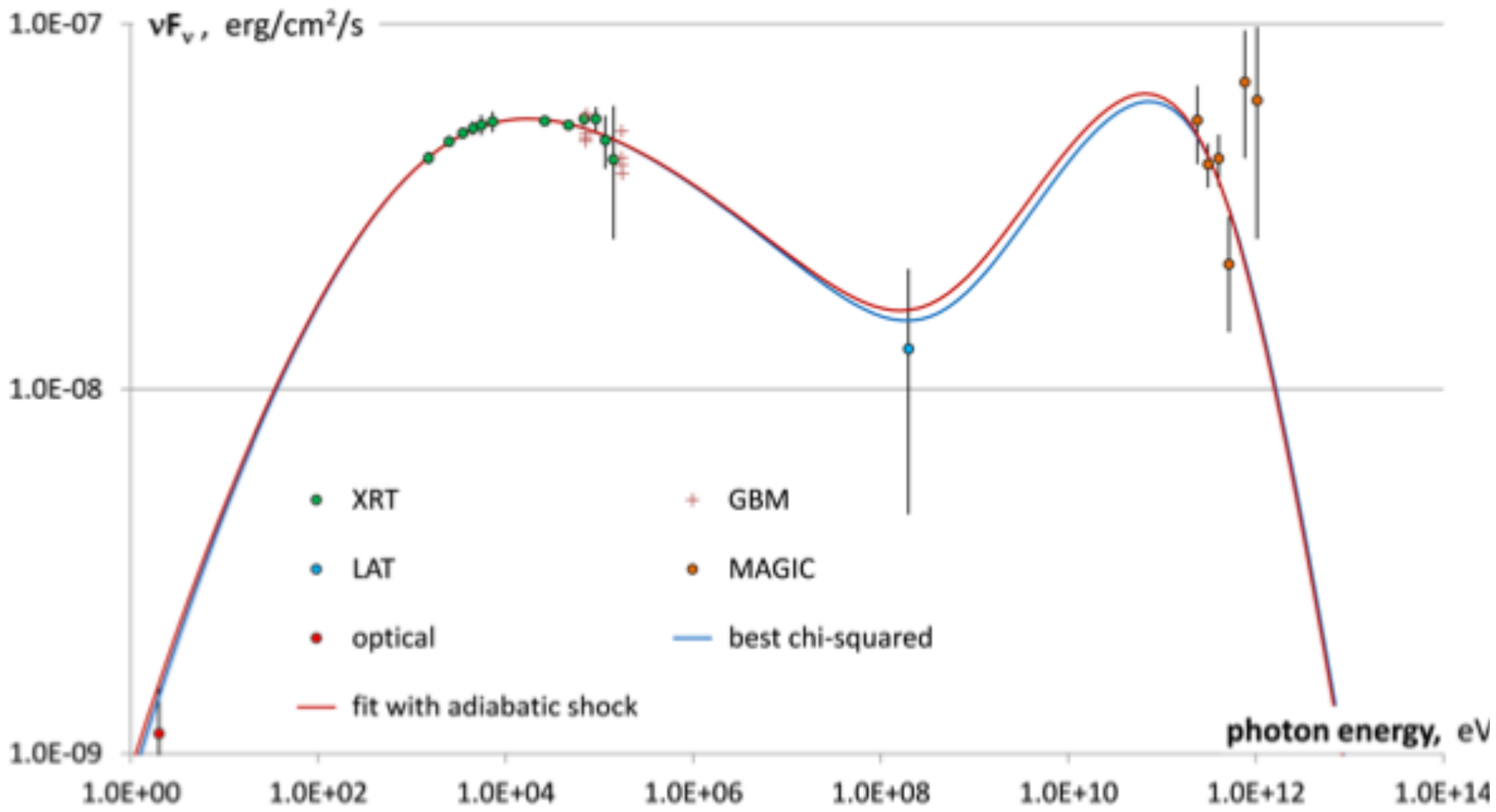


First guesses 190114c

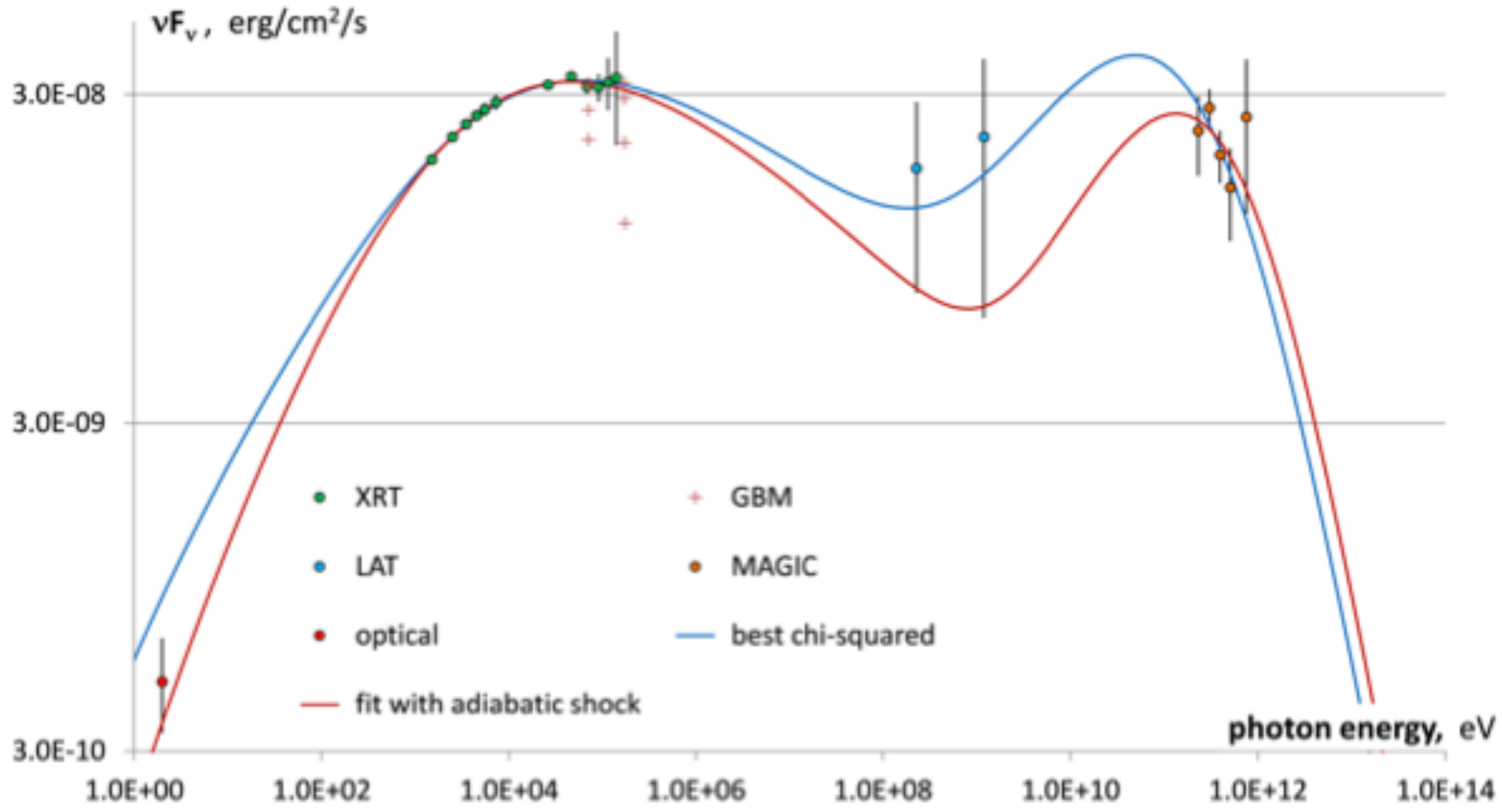
- **$\gamma\Gamma$ m$_e$c^2 > E$_{IC}$ (~TeV) => $\gamma\Gamma \simeq 10^6$**
- **@ 70 sec and longer Γ cannot be too large ($\Gamma \simeq$100) => $\gamma \gtrsim 10^4$**
- **=> Tev is Inverse Compton of X-rays (Consistent with a comparable X-ray luminosity) at the KN limit**

Detailed modeling
(Derishev & TP 2021)

- Conditions at the emitting region are determined by Γ, B, γ_m, ϵ_e/ϵ_B



Early - 90 sec



late - 145 sec

Best Fit Parameters

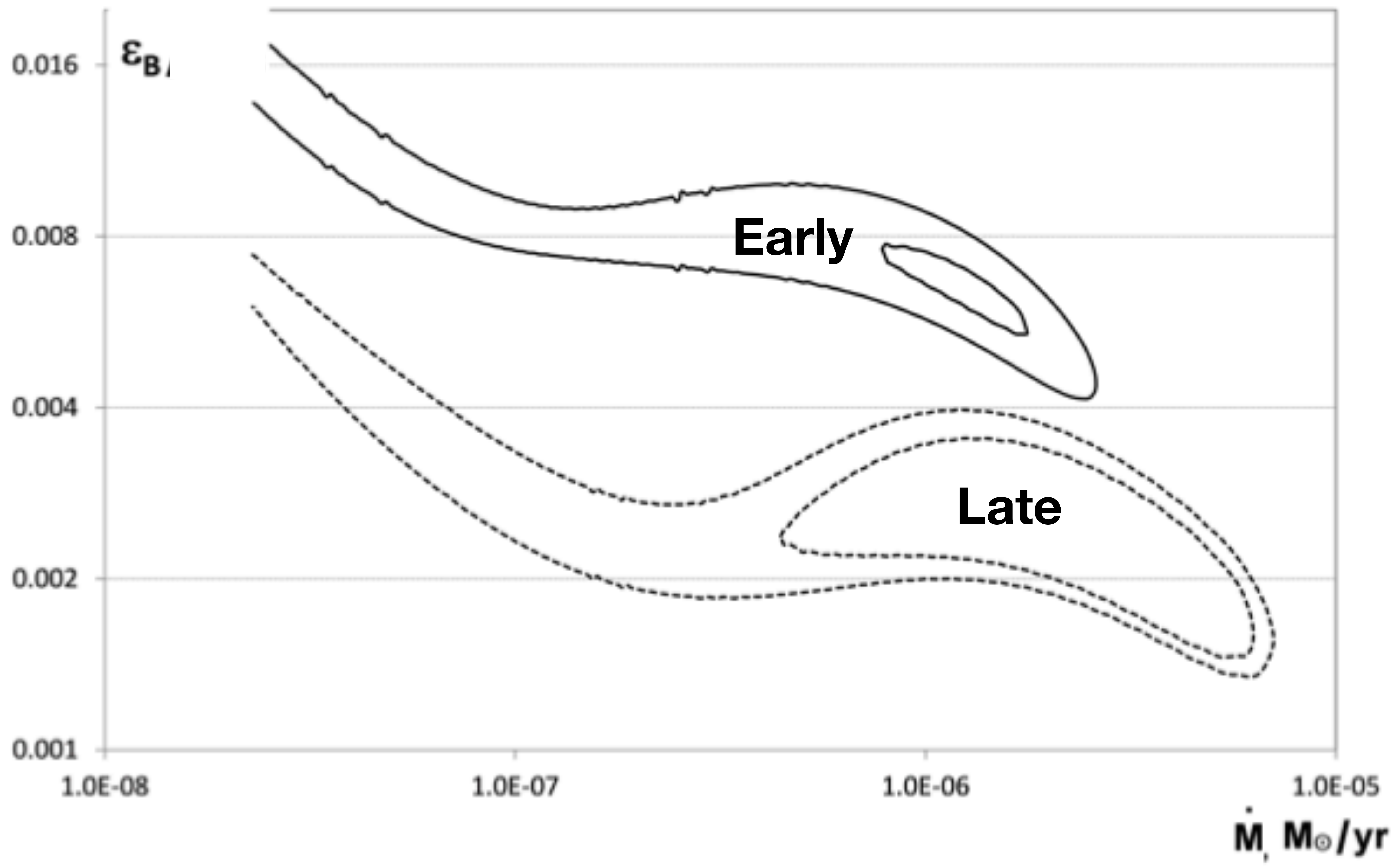
The fit didn't take into account the "pair balance" model however, the results are fully consistent with it and are inconsistent with standard afterglow modeling

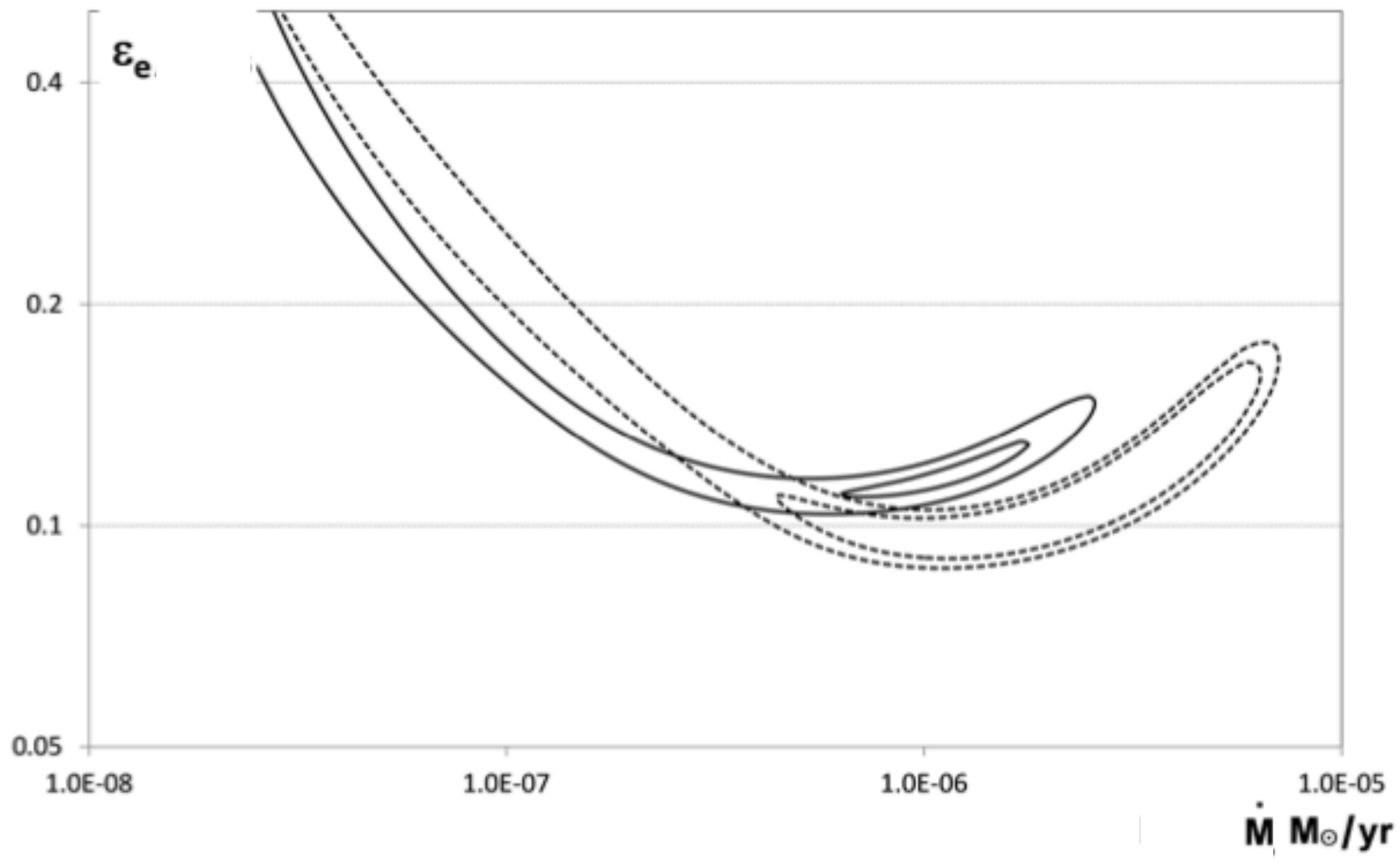
parameter	$t_{obs} = 90$ s	$t_{obs} = 145$ s
Γ	161 (109) →	143 (91)
B	4.4 G (5.7 G)	2.0 G (3.1 G)
ϵ_e/ϵ_B	20 (21)	36 (41)
γ_m	6500 (5700) →	16700 (14400)
p	2.5	2.5
E_{kin}	3×10^{53} erg	3×10^{53} erg
ϵ_B	0.0061 (0.0062) →	0.0027 (0.0026)
ϵ_e	0.12 (0.13)	0.096 (0.107)
$\dot{M}$ (wind)	$1.4 \times 10^{-6} \frac{V_w}{3000km/s} M_\odot/yr$	$1.4 \times 10^{-6} \frac{V_w}{3000km/s} M_\odot/yr$
n (ISM)	$2\ cm^{-3}$	$2\ cm^{-3}$

- Fast Cooling
- On the edge of KN regime
- $\gamma^3 B = (1.2 - 9)\ 10^{12}$

  $\gamma_m \propto \Gamma$ doesn't hold
- $\tau_{\gamma\gamma} \approx 1$ for the IC photons (25% of IC power is self absorbed)
- $\epsilon_B = 0.006 \rightarrow 0.003$ (Varies)
- Somewhat surprisingly large Γ (large energy, low external density)

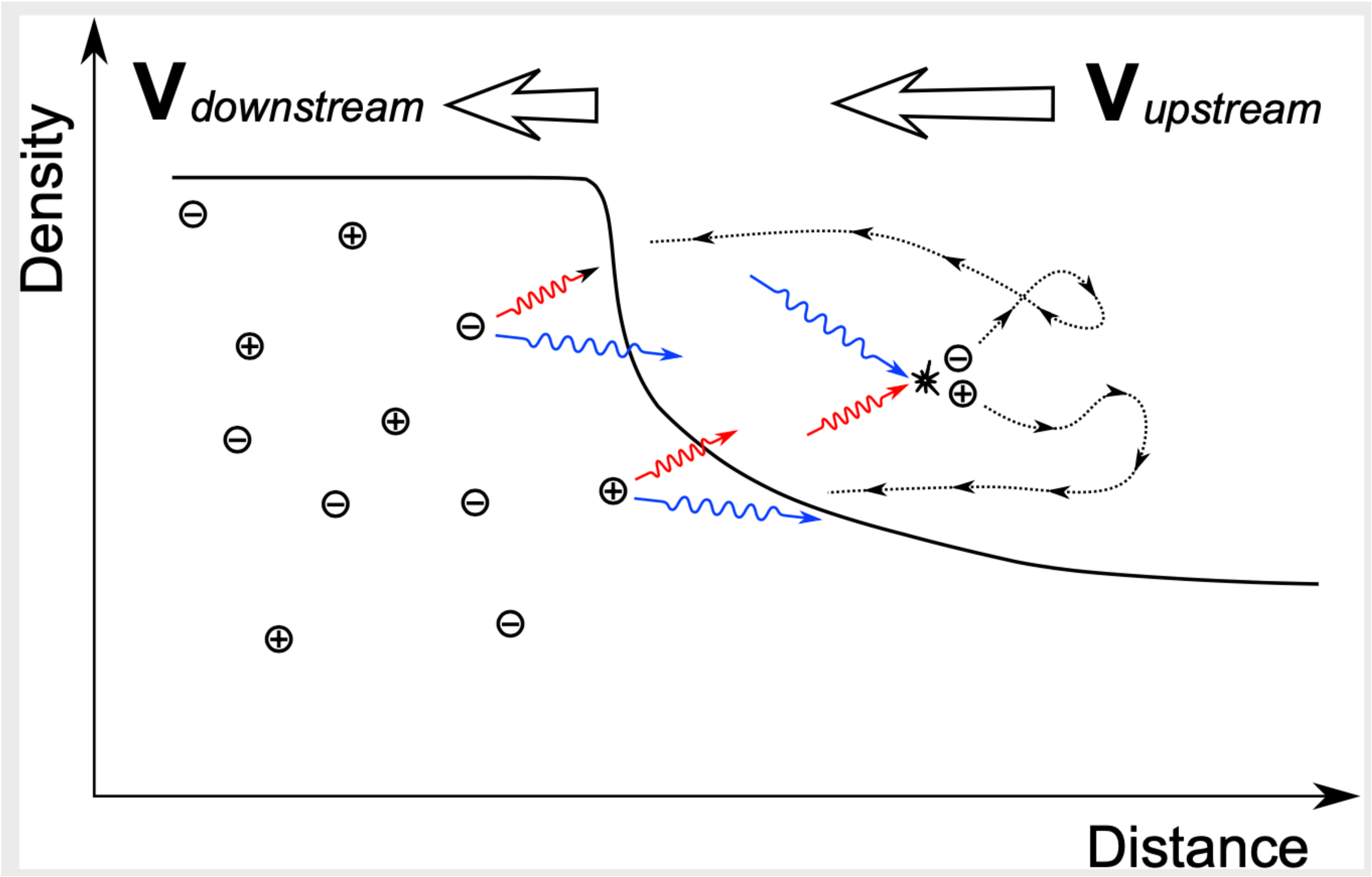
ϵ_B must vary with time

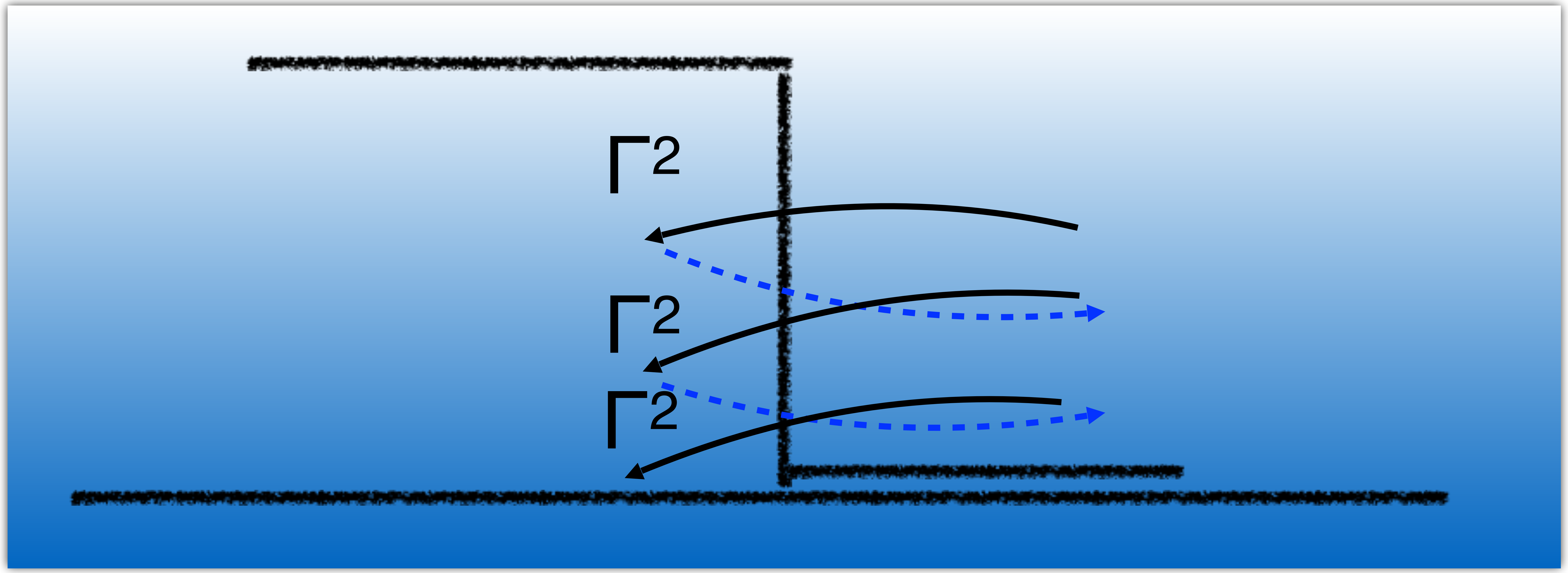




The Pair Balance model

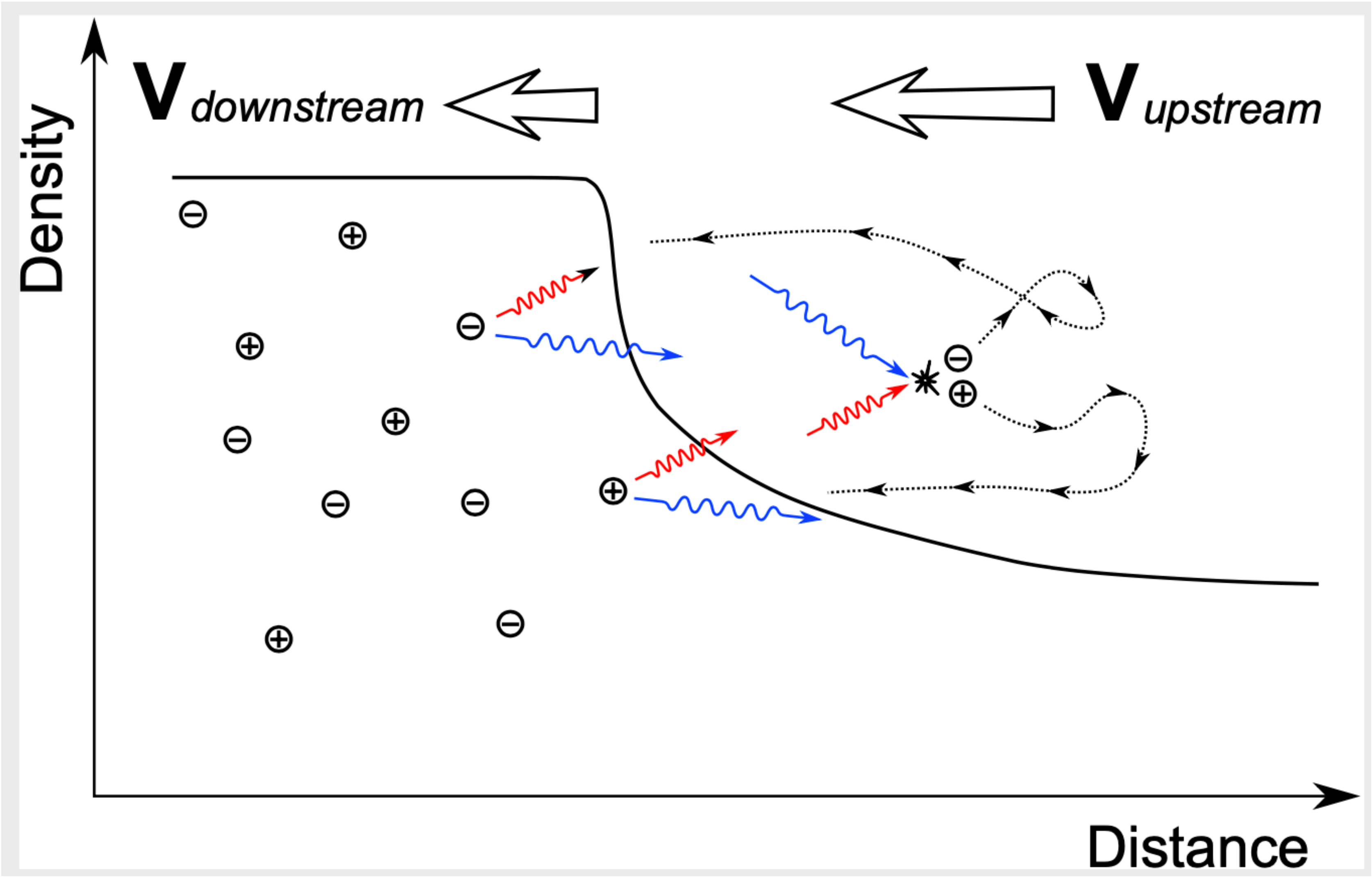
Derishev & TP 2016

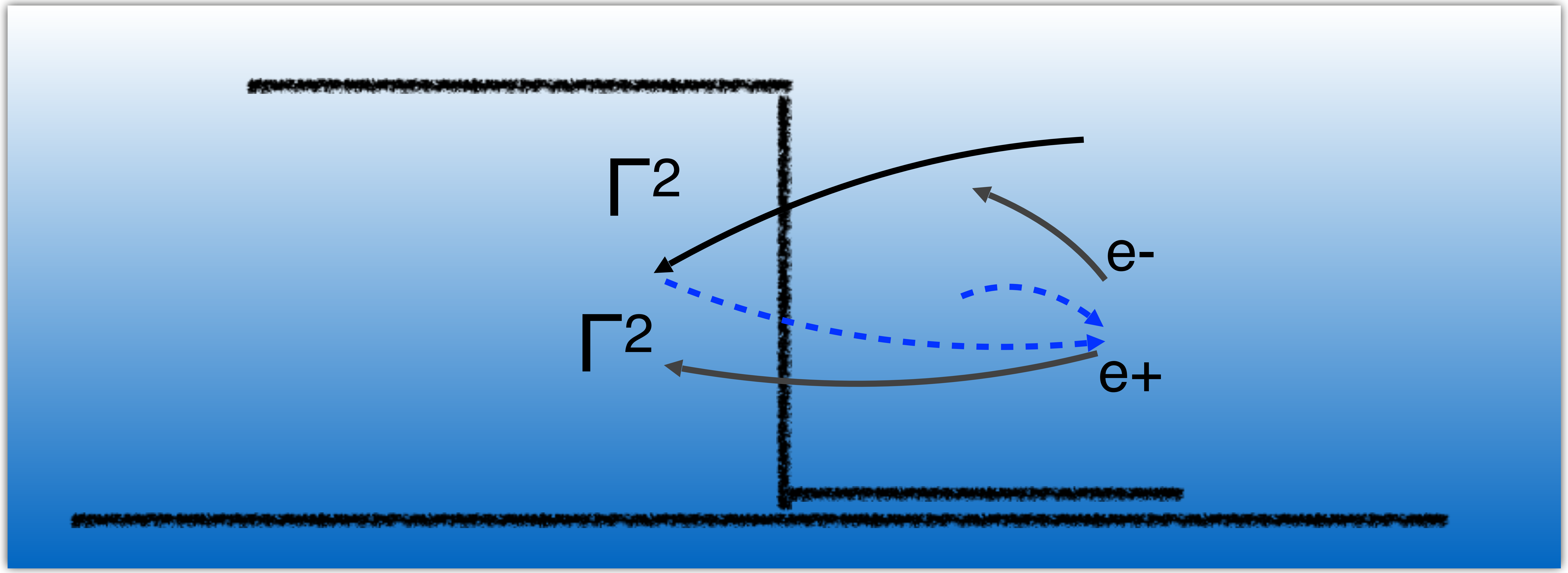




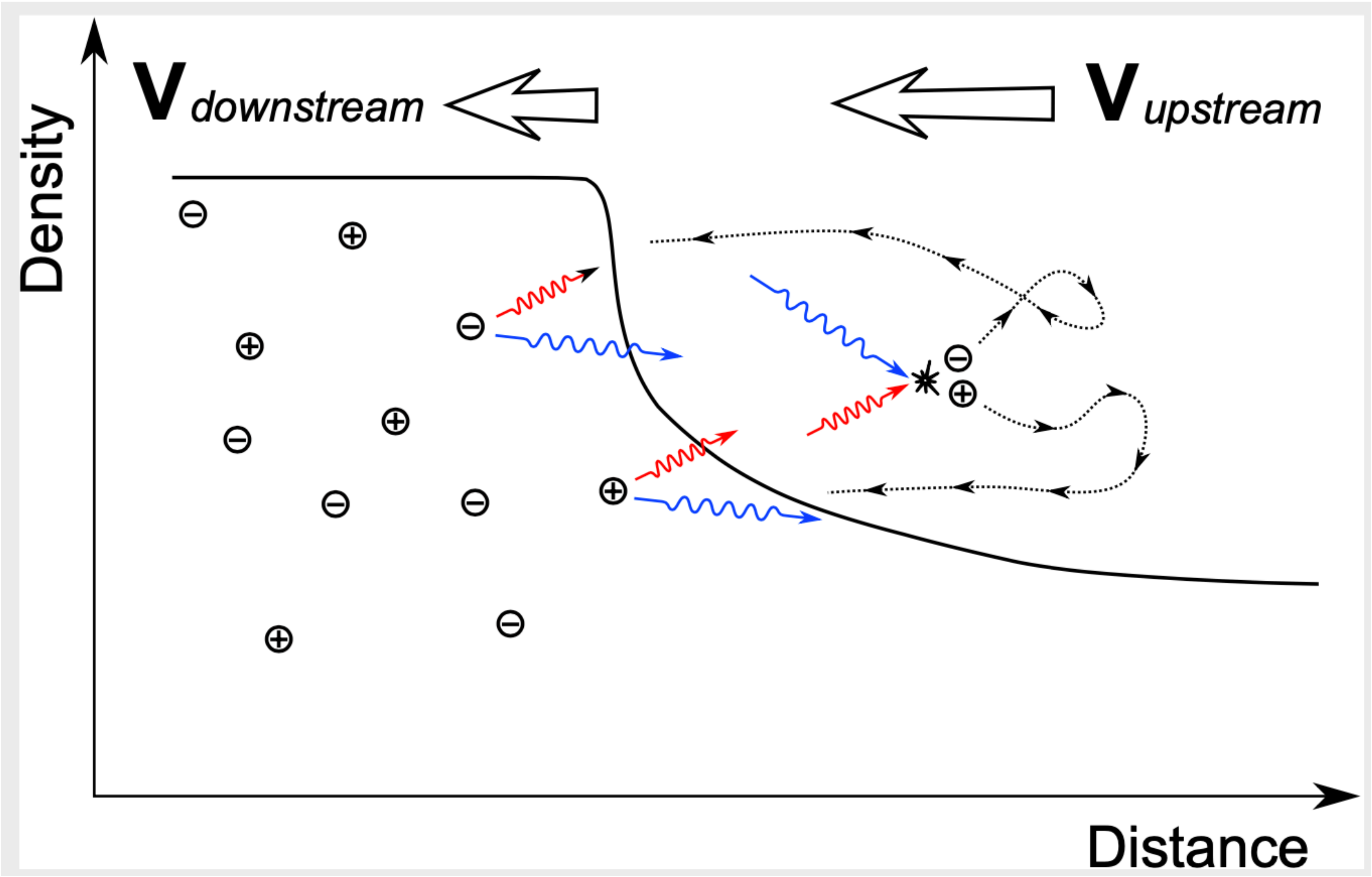
1) Pairs produced in the upstream

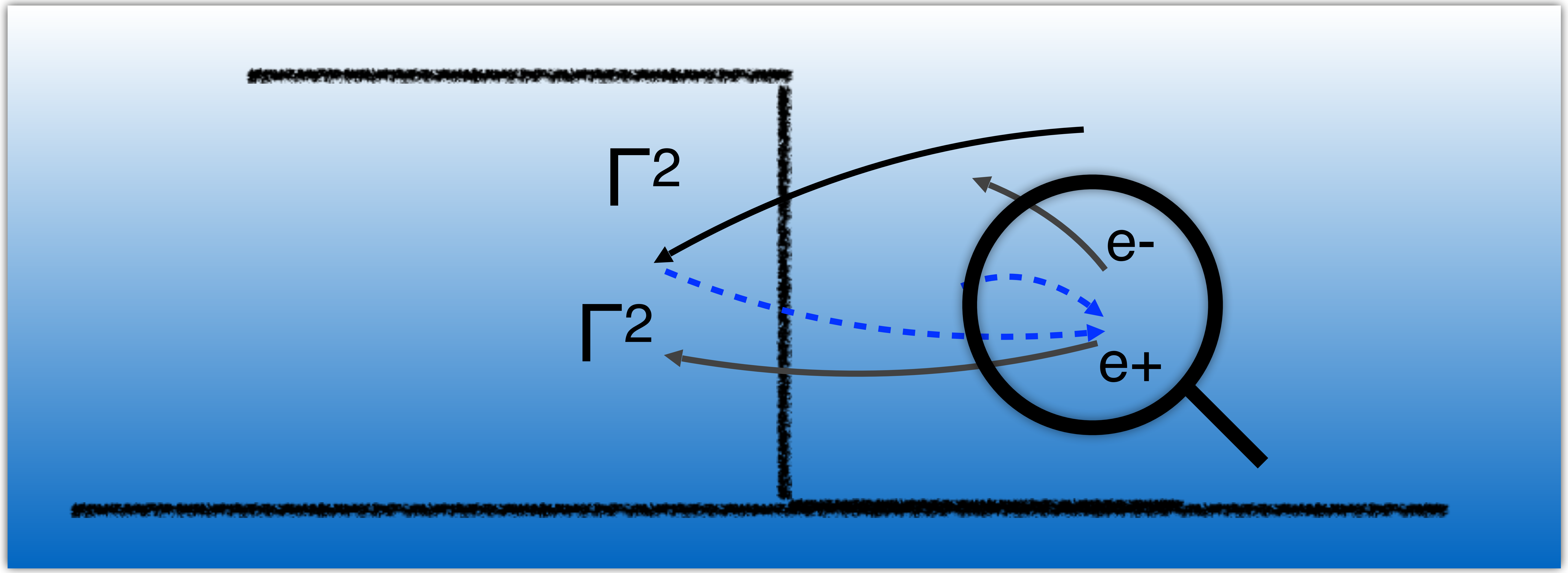
2) They are strongly accelerated once crossing the shock



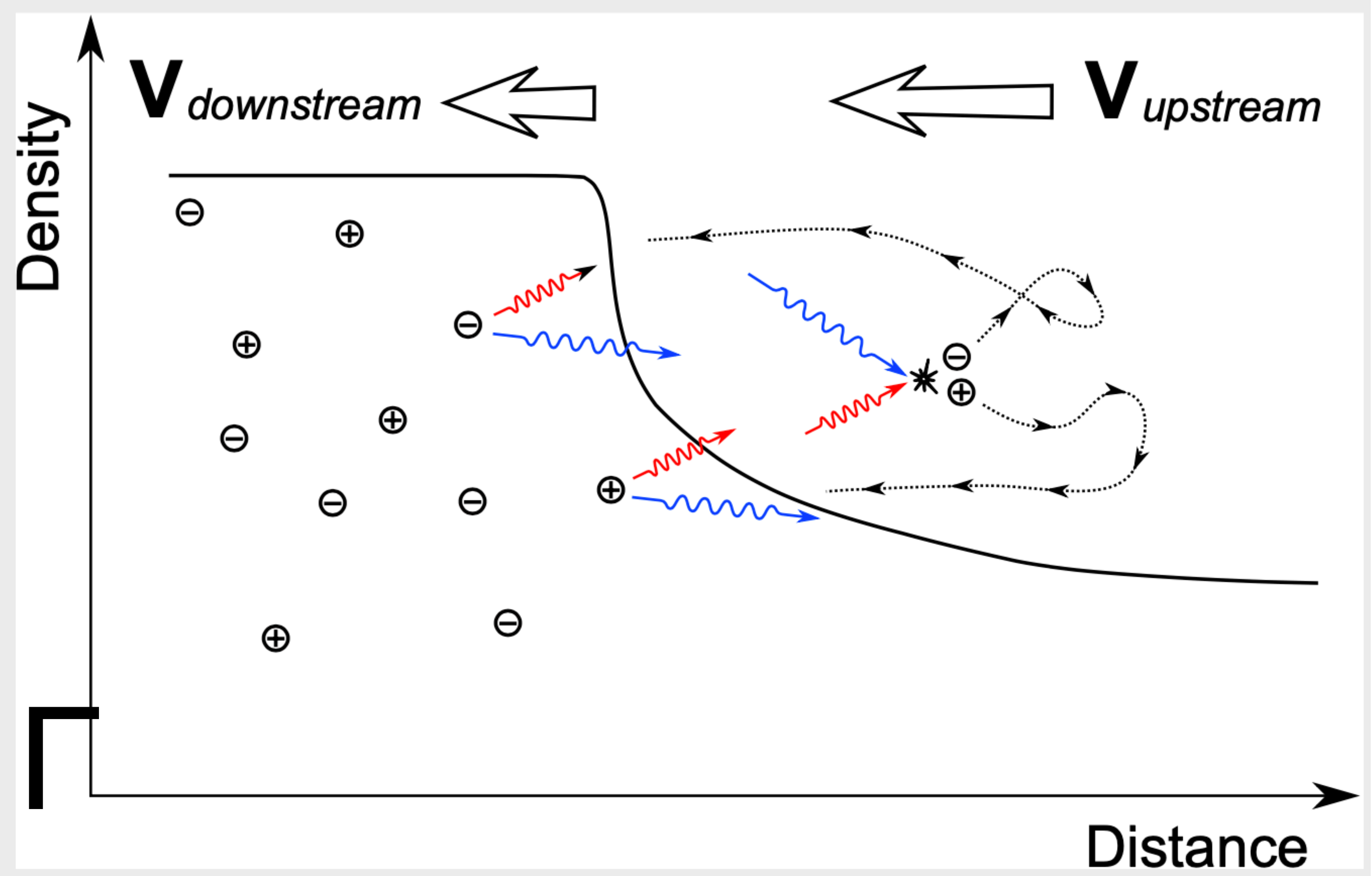


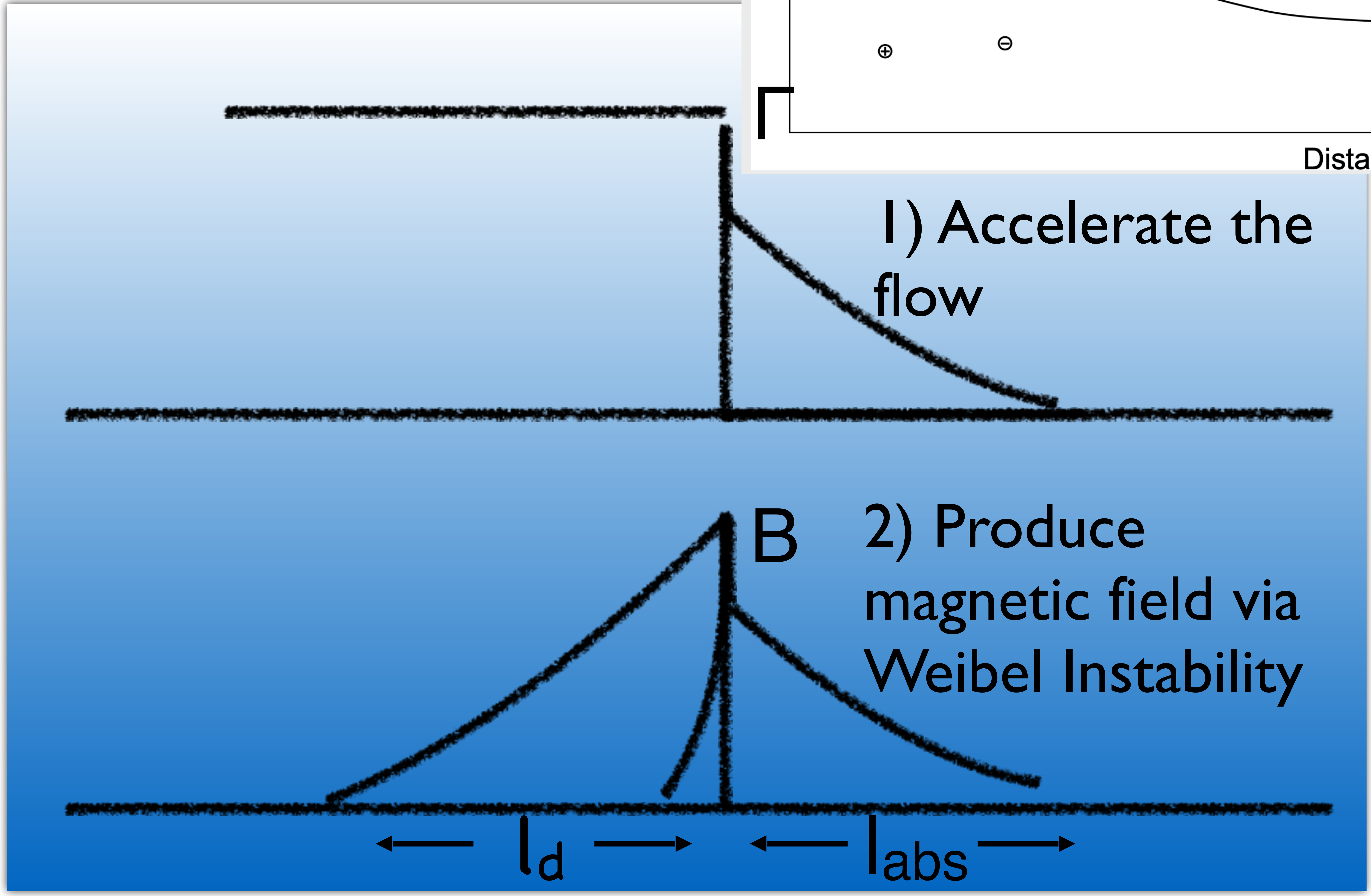
1) Accelerate the flow
2) Produce magnetic field via Weibel Instability



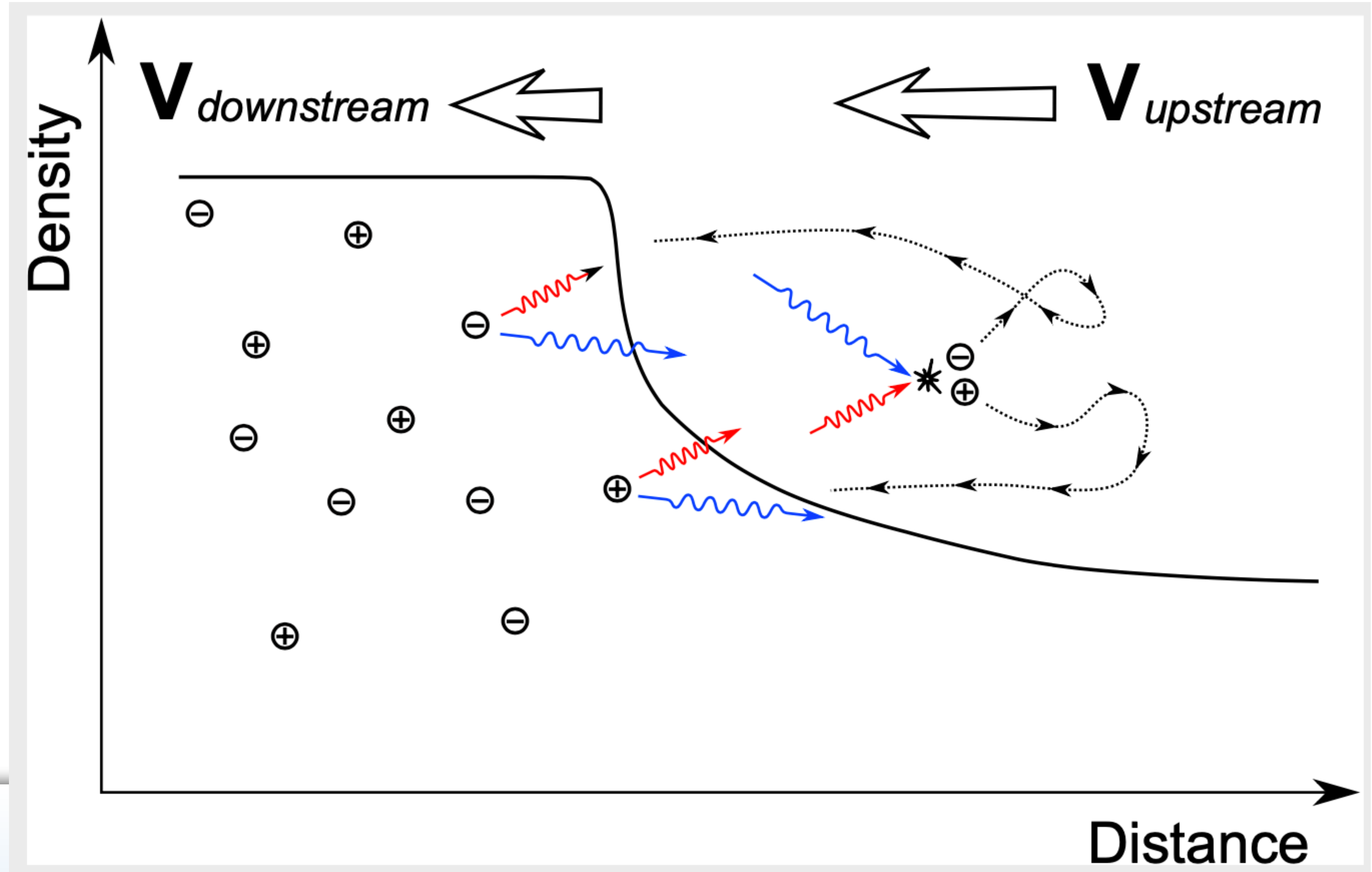


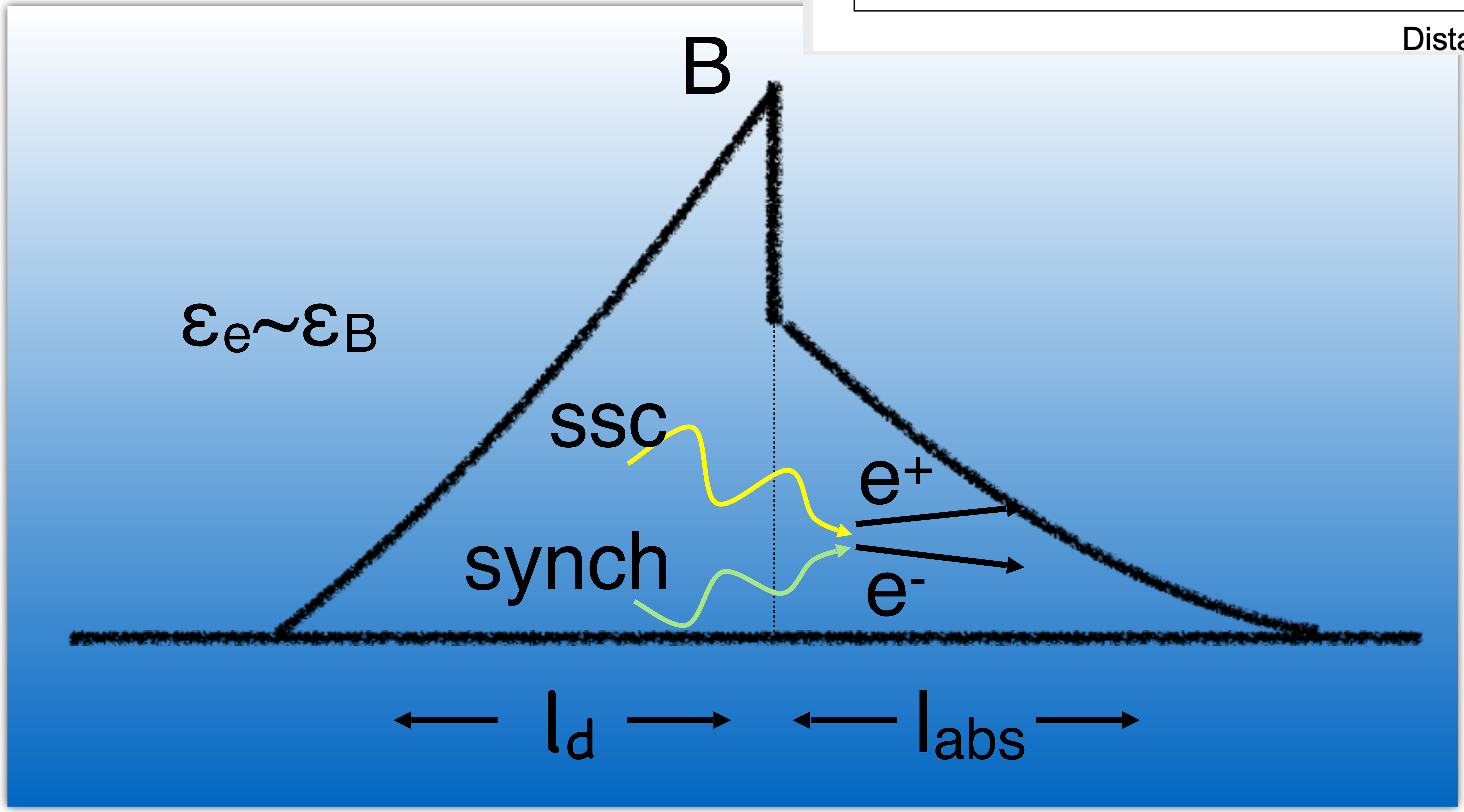
Modified structure



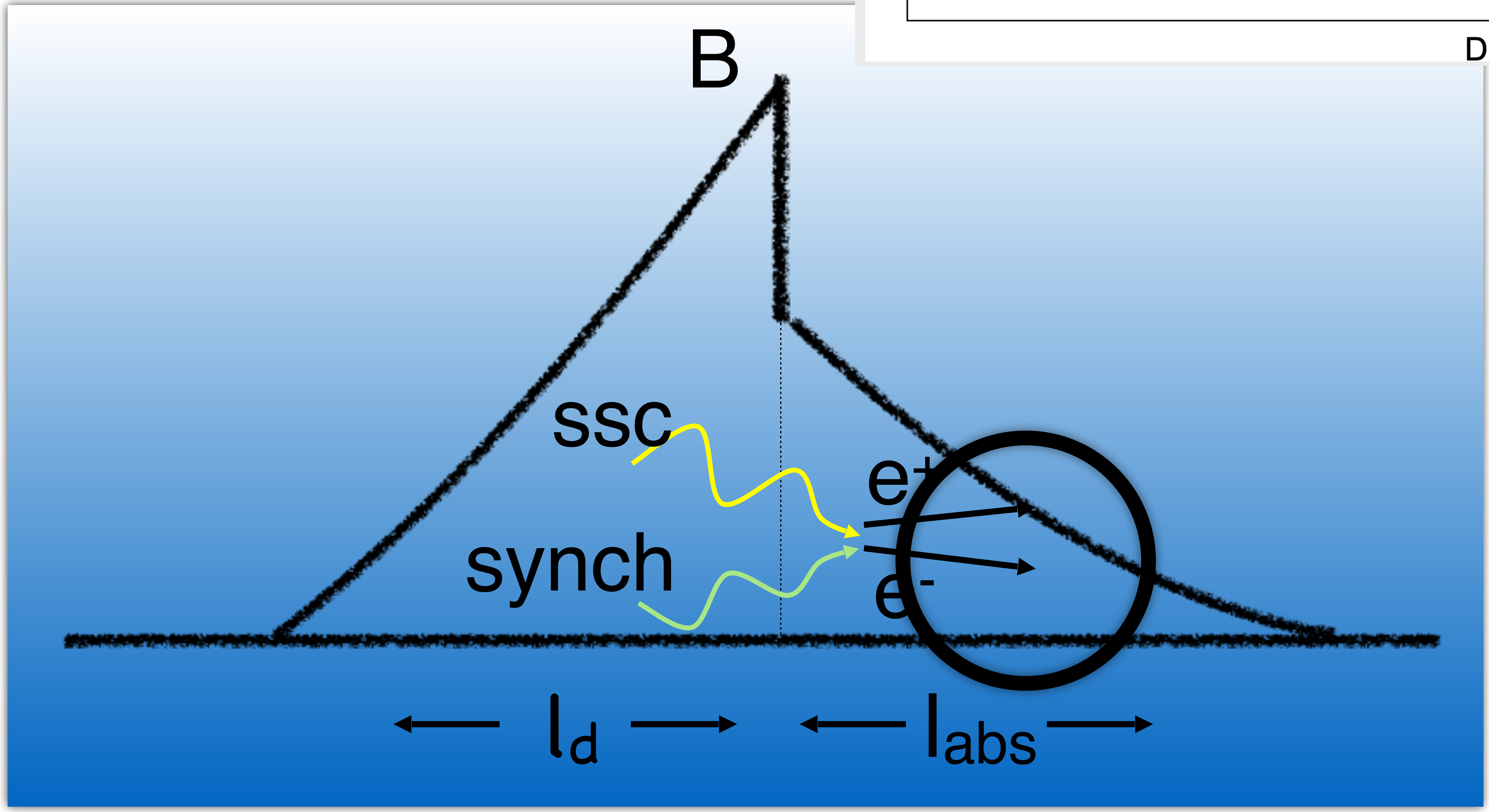


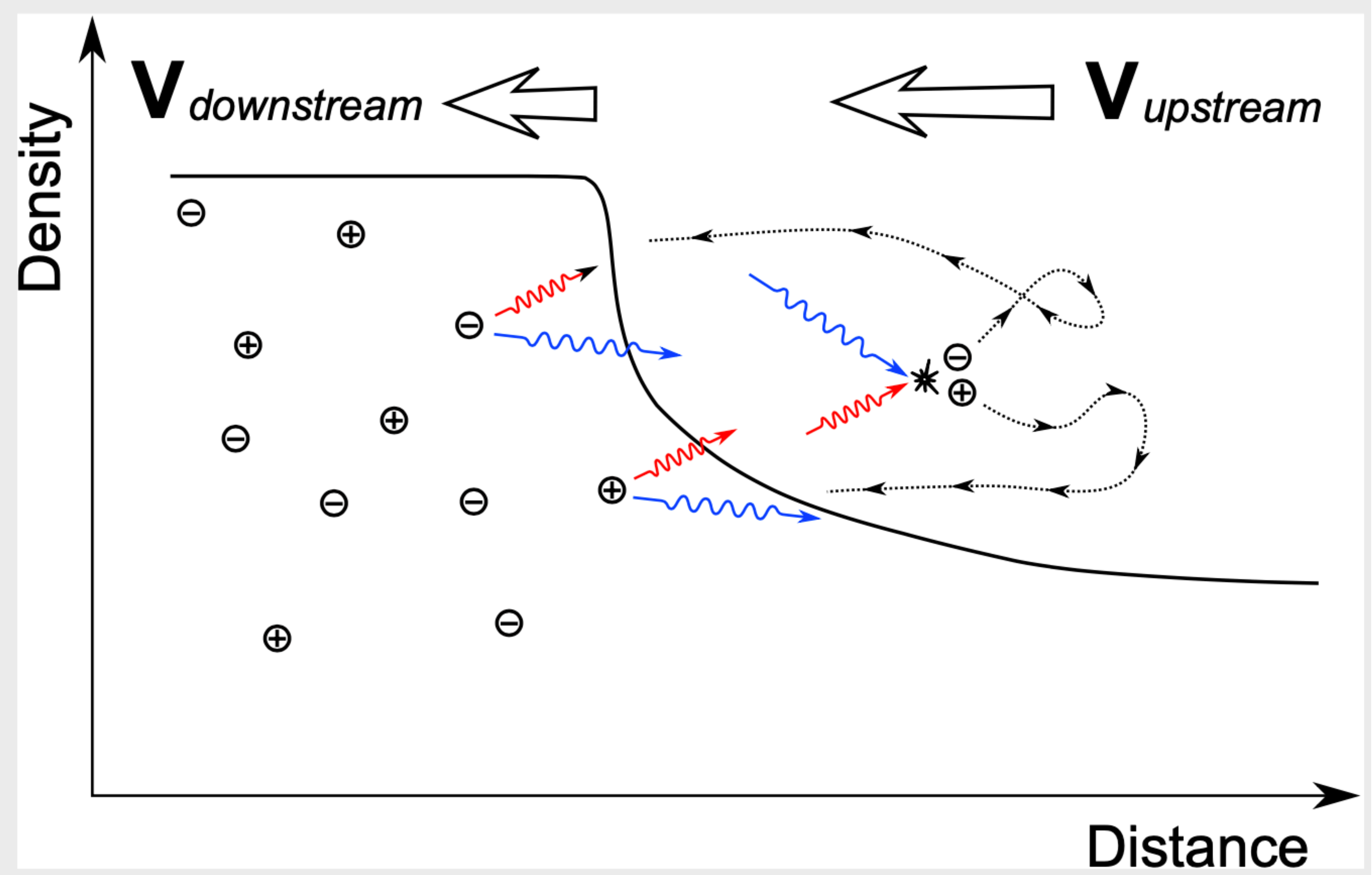
Decaying magnetic field, in the downstream, accelerates particles





Pairs from the upstream increase the multiplicity of the downstream





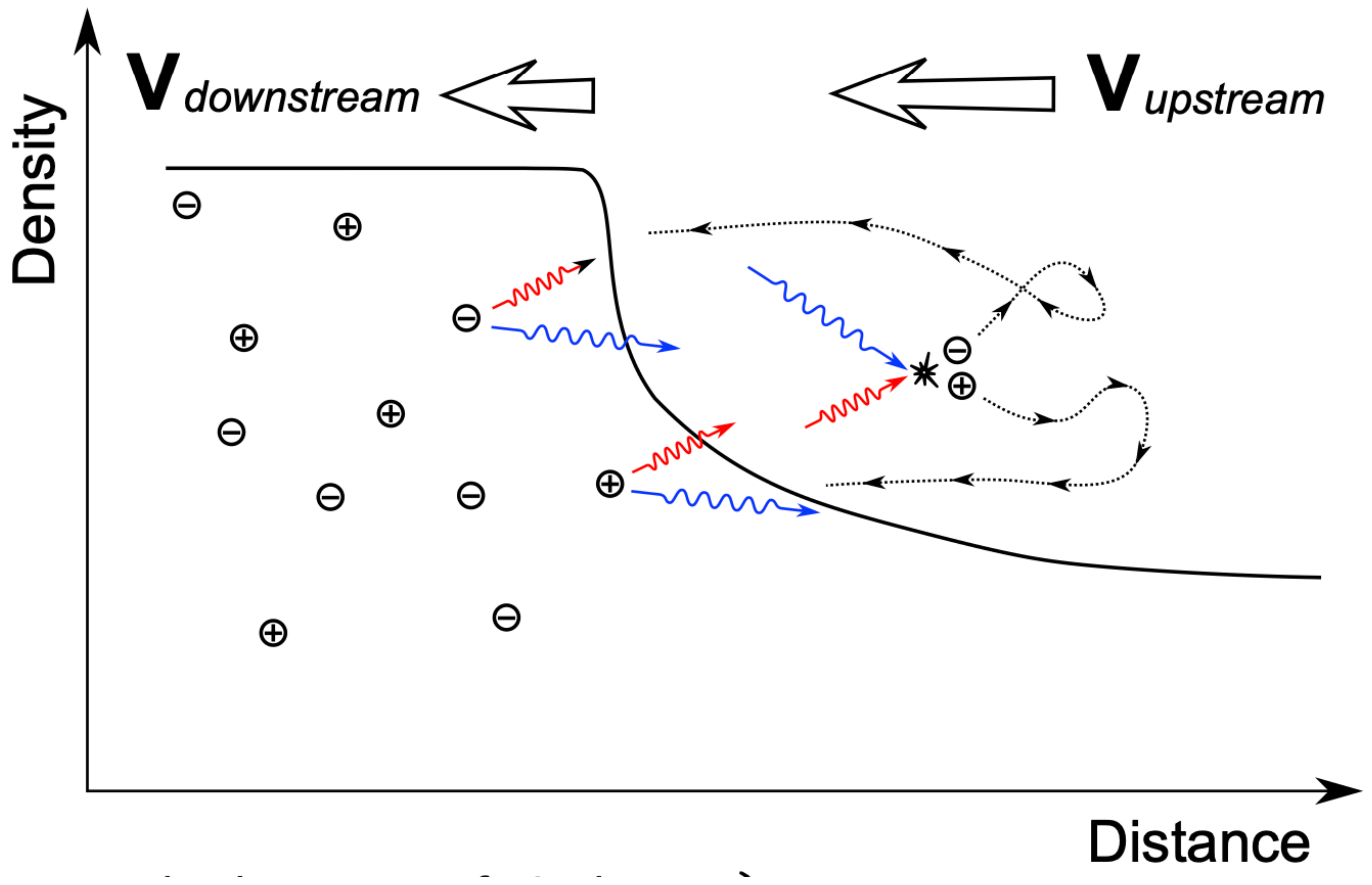
Some basic features of the Pair-Balance model

Derishev & TP 2016

- Saturation at the Klein-Nishina limit => $\gamma^3 B \approx B_{sch}$

  => $\gamma_m \propto \Gamma$ doesn't hold

- $\tau_{\gamma\gamma} \lesssim 1$ for the IC photons



GRB 221009a

- E_{iso} (prompt) ~3 x10^{54} erg; T_{90} > 600 sec
- z = 0.151 (Extremely close for a long GRB)
- Fermi-LAT E > 100MeV, flat spectrum, highest at 99.3 GeV 👏 👏
- LHASSO: More than 5000 photons at E>500GeV, highest at 18 TeV 👏👏 within 2000 sec ; $E_{TeV,iso}$ ~ 2 x10^{52} erg
- Swift - Observations only after ~3000 sec 😫😭 $E_{x,iso}$ ~ 4 x10^{51} erg *

* As implied from the observations at T>3000 sec

Optical Depth and the 18 TeV photon

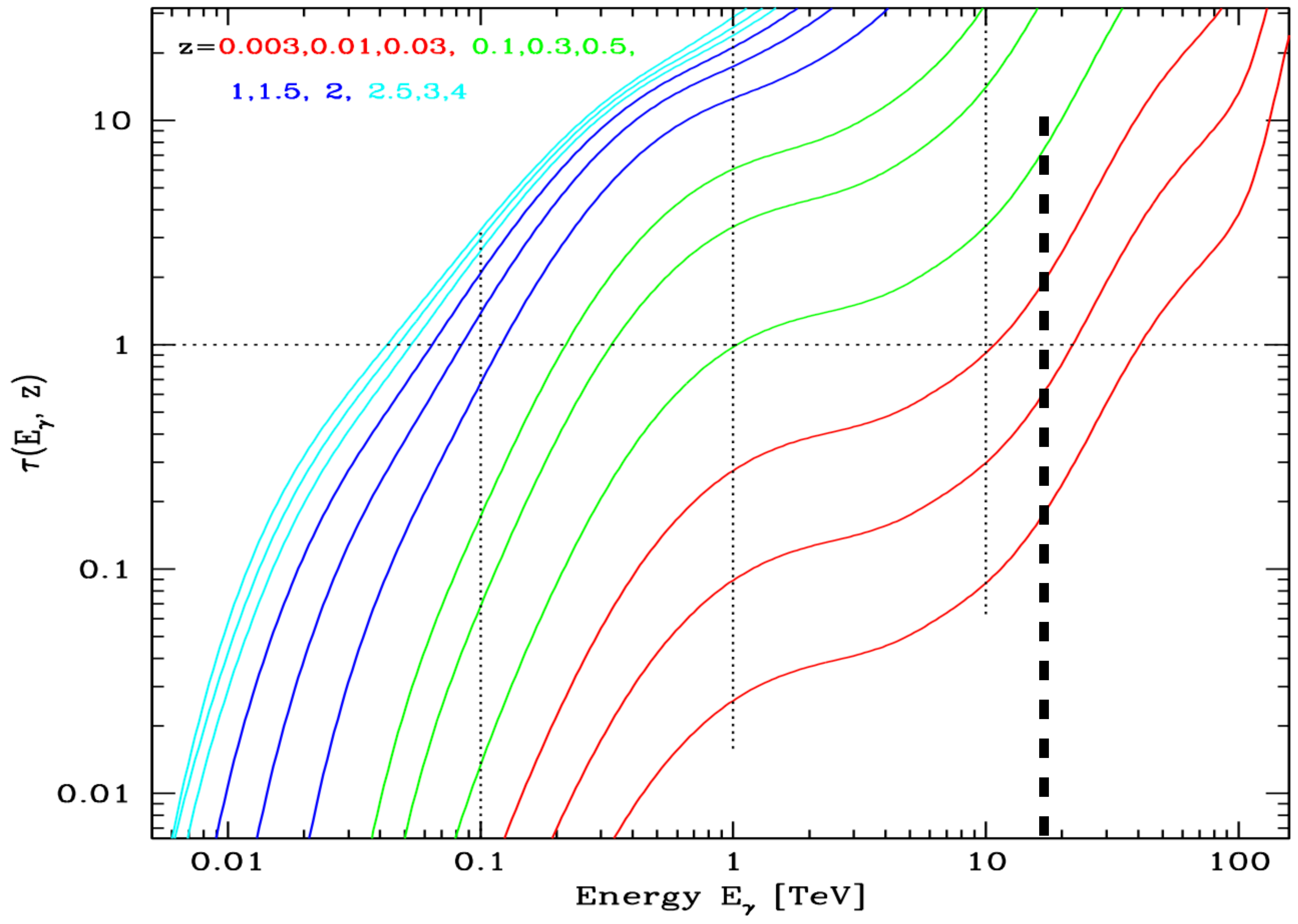


Figure 4. The optical depth by photon–photon collision as a function of the photon energy for sources located at $z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4$, from bottom to top. The fast rise at the high τ and E_γ values is due to the large volume density of CMB photons. The graph is based on the model by [82].

From: Francesini 2021

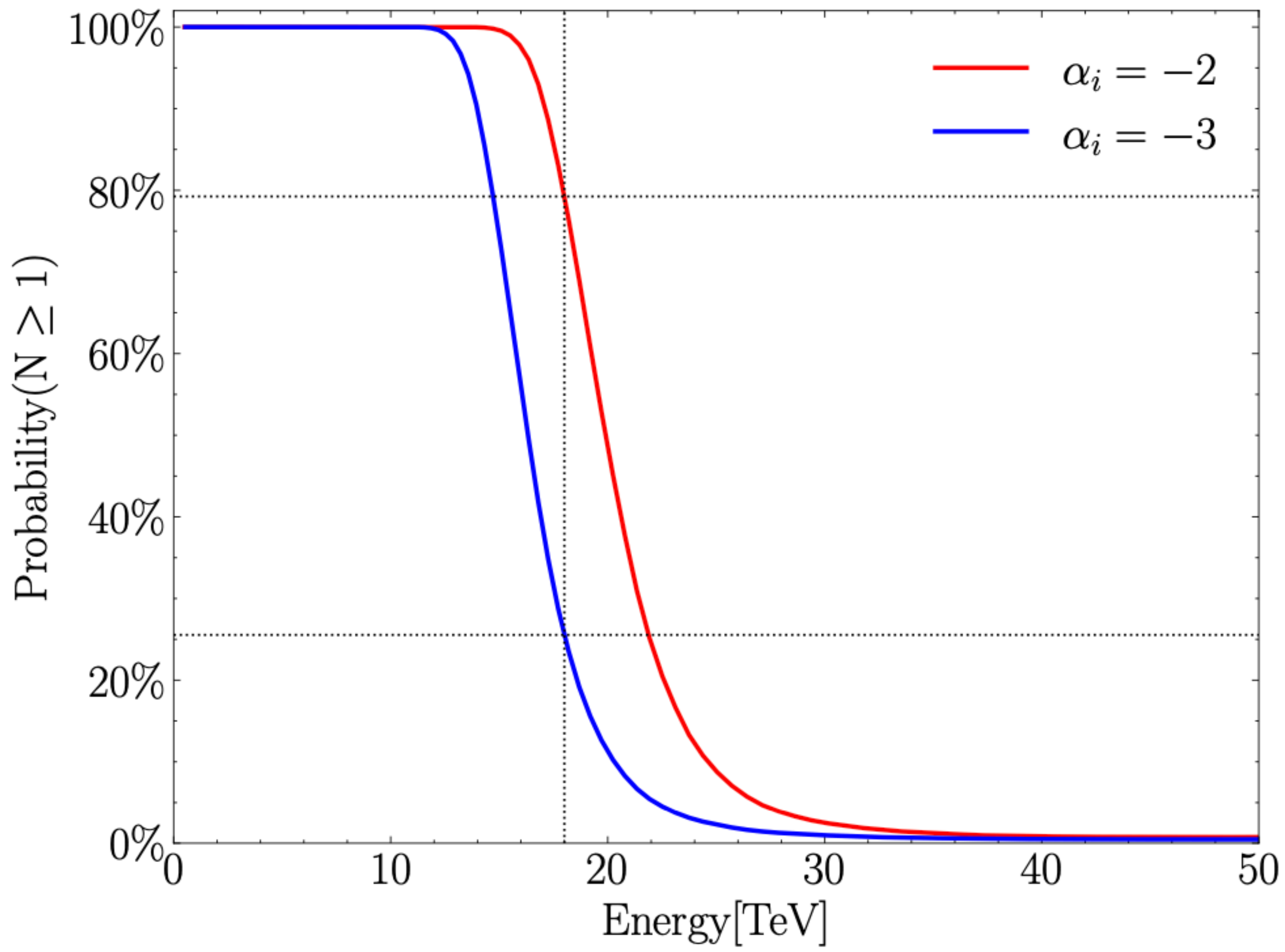


Fig. 2 Probability of predicting that LHAASO observes at least one photon from GRB 221009A within 2000 seconds. The vertical dotted line denotes 18 TeV. The coloring of curves is consistent with that of Fig. 1.

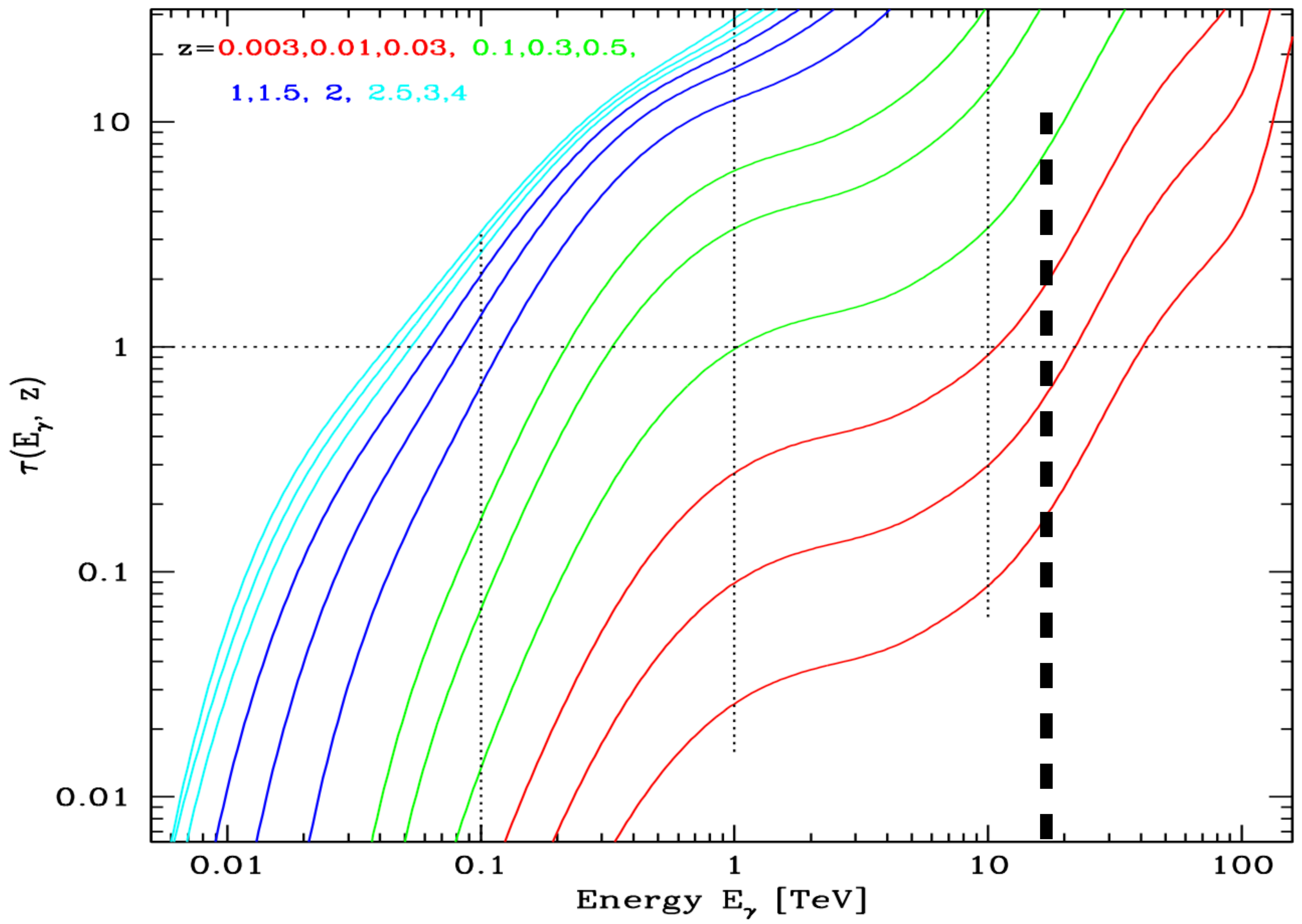
From: Zhao et al., 2022

New Physics from 18 TeV? 🤔

Based on the analysis of Zhao et al., 2022

- The error in the energy estimate of the LHASSO 18 TeV photon is 40%.
- At 18-6=11 TeV EBL absorption is insignificant. At 18+6=25 TeV it implies “new physics”.

  =>18±40% TeV from z=0/151 is insufficient evidence for new physics.



Not Yet 🙁

221009a vs 190114c

- Unfortunately the critical $E_{TeV,iso}$ /$E_{x,iso}$ ratio for 221009a is not clear. Swift couldn't observe 221009a for the first 3000 sec.

- An estimate suggests that both GRBs have $E_{TeV,iso} \sim E_{x,iso}$ during the early afterglow phase.

- Higher energy photons are observed in 221009a. This is expected in view of the much lower redshift.

- A flat spectrum in the GeV range (Fermi) may hints of KN corrections to SSC spectrum?

- Can we exclude in 221009a SSC with Γ ~ a few hundred @ a few hundred seconds and $\gamma \sim 10^{4-5}$, on the edge of Klein- Nishina?

Summary

- Klein-Nishina (KN) suppression makes SSC much reacher and more complicated than expected.

- KN can influence the low energy synchrotron spectrum (and lightcurve) even in cases that it seems (at first sight) that the peak flux is not in the KN regime.

- TeV observations of both early (90 sec) and late (145 sec) phases of 190114c seems to require modification of the simple afterglow model (constant equipartition parameters and $\gamma_{\rm m} \propto \Gamma$) .

- A model independent fits for both early and late 190114c observations lead to parameters and evolutionary behavior that are (surprisingly) consistent with the "Pair Balance model".

- 221009a seems similar to (but stronger than) 190114c. Can it be explained by SSC (Awaiting LHASSO data and predicting that the 18 TeV photon wasn't late)?

Open positions for PhD/postdocs with ERC “MultiJets” starting Oct 2023