Multimessenger Emission from GRBs

Tsvi Piran

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CDY Sept 1 2021

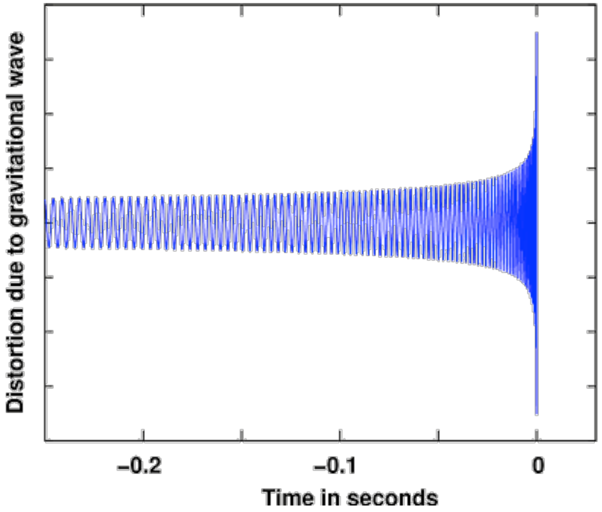
Outline

- GW from GRBs
- Jet-GWs from Jets: Birnholtz & TP PRD, 2013; Leiderschneider & TP arXiv:2107.12418
- Hidden Jets: TP + arXiv 1704.08298; ApJ, 2019
- TeV emission from GRBs Afterglows : Derishev & TP ApJL, 2019, arXiv: 2021.12035

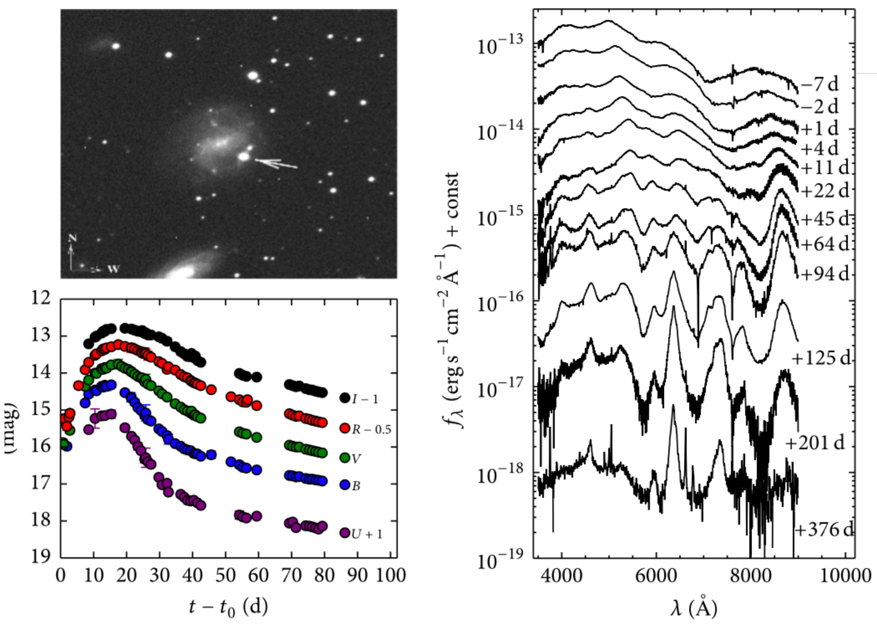
Binary Neutron Stars
Gravitational Waves

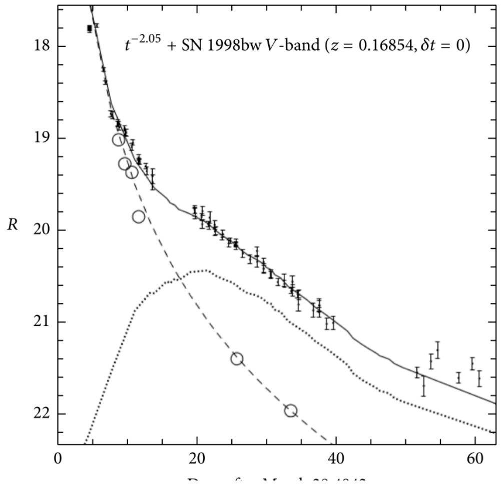
$$P = \frac{dE}{dt} = -\frac{32}{5}\,\frac{G^4}{c^5}\,\frac{(m_1 m_2)^2 (m_1 + m_2)}{r^5}$$

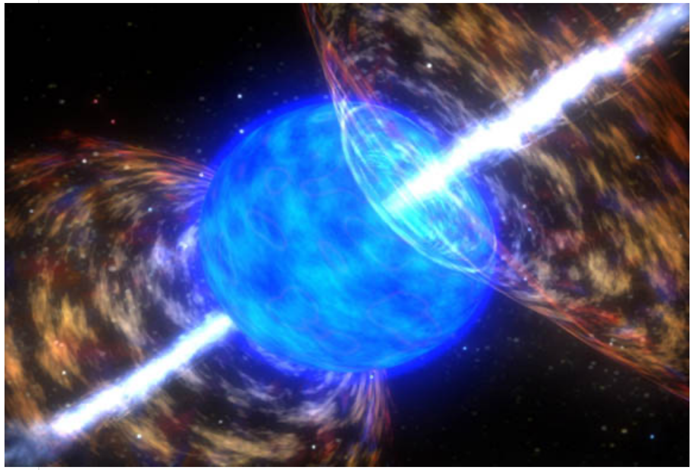
$$t_{merge} \simeq 30\,\mathrm{sec}\,(P/30)^{-8/3}(M/M_{sun})^{-5/3}$$



Supernova and Long GRBs







98bw GRB 980425

Collapsars

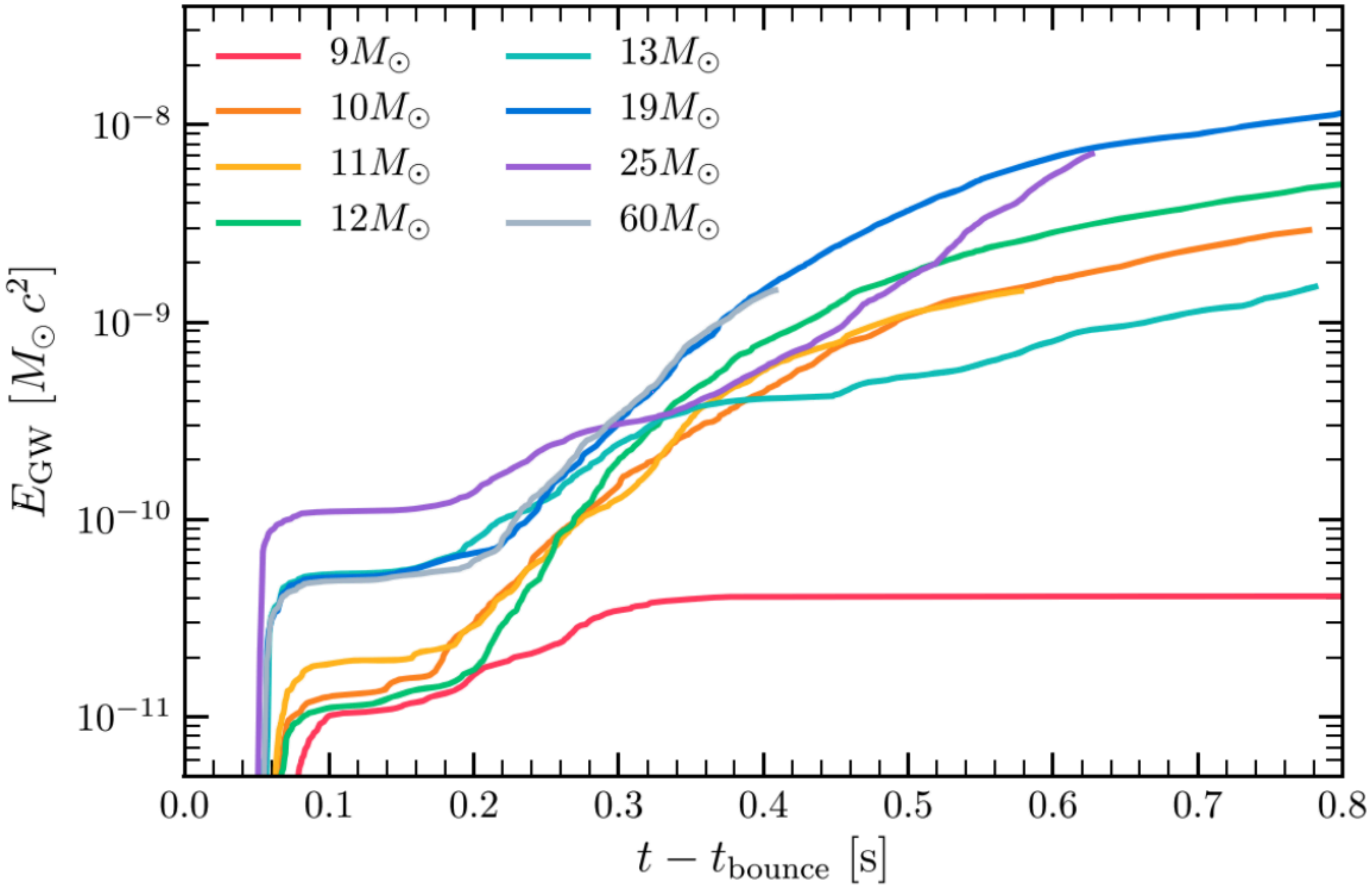
GW from Supernova

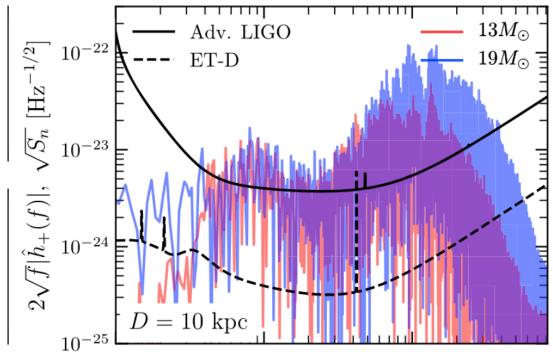
$$h = \epsilon \frac{GM}{c^2 d} = \epsilon \frac{r_g}{d} \qquad \nu = \sqrt{G\rho}$$

Once upon a time (late 70ies)

h=10^{-21} @ khZ <=> E_{gw}=10^{51} erg @ 10 Mpc

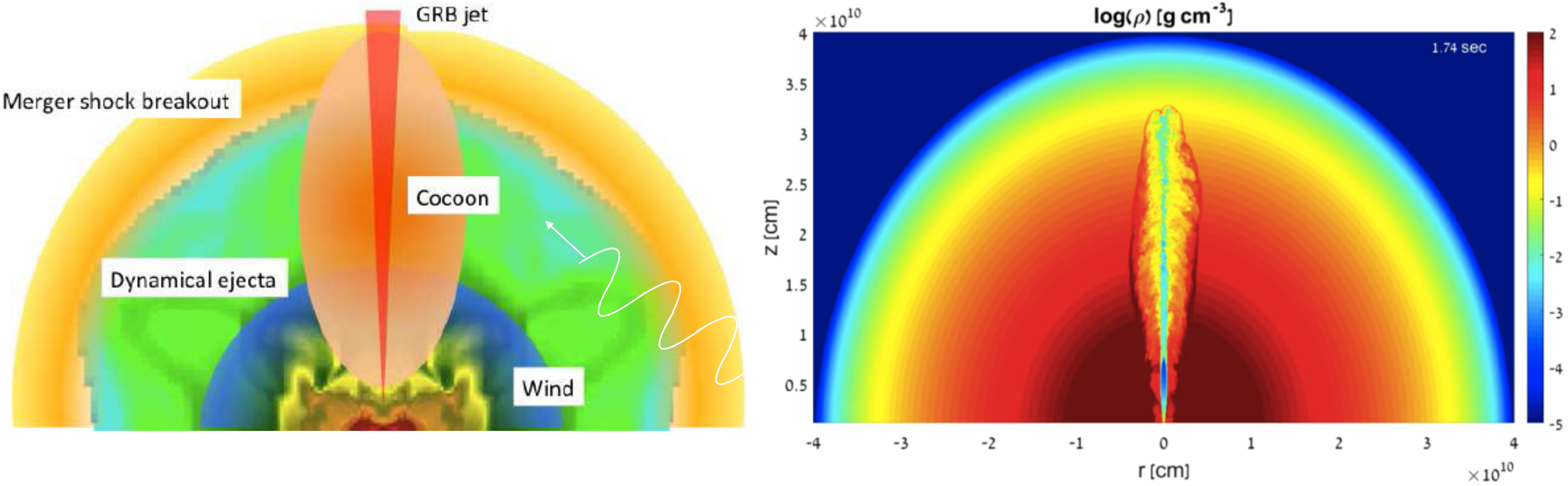
GW from Supernova



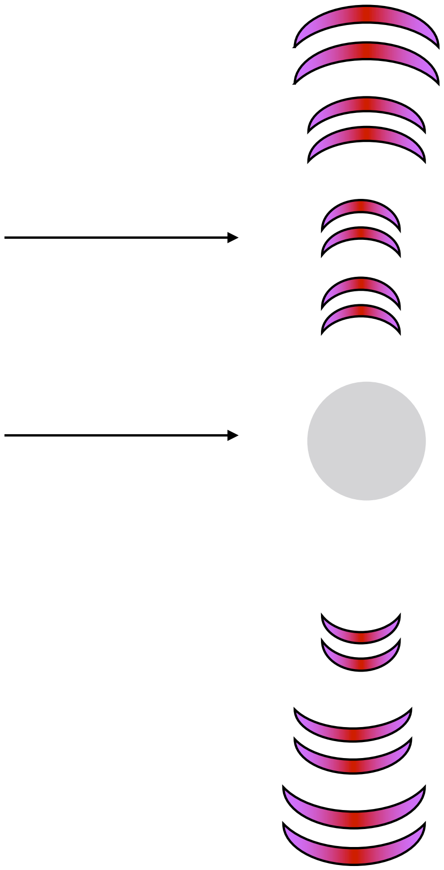


From ~10 kpc

More Gravitational Waves



Gravitational waves from the jet acceleration process
(TP 2002; Birnholtz & TP 2014; Liedershneider & TP 2021
Segalis & Ori 2001)

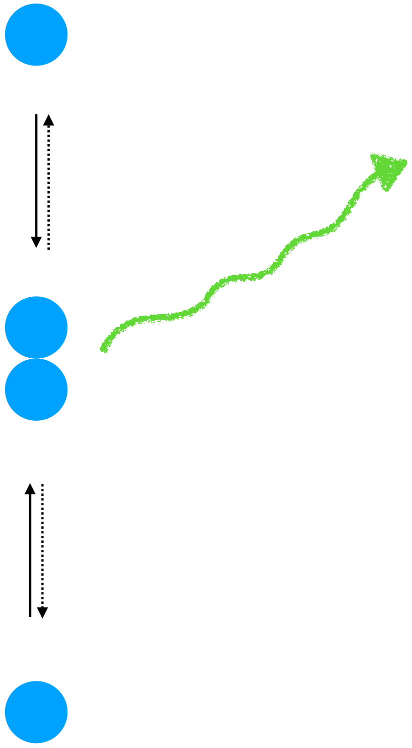


Jet
~10^{50} erg
Poynting flux or particles?
Opening angle ~5^{o}

Central Engine 10^{6} cm

10^{50} erg were standing still and then they suddenly they move at c
=> This must produce gravitational waves

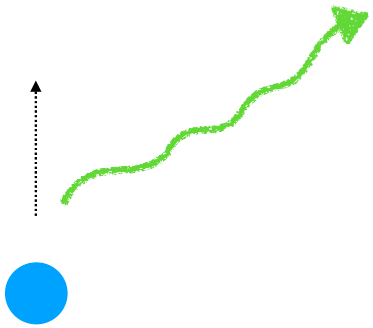
Weinberg - GW from particle collisions



The sun emits 10^{15} ergs/sec in GW (Weinberg)

The typical energy of the sun's gravitons is ~ keV with frequency of 10^{18} Hz

Only 1 in ~10^{25} scatterings produces a graviton

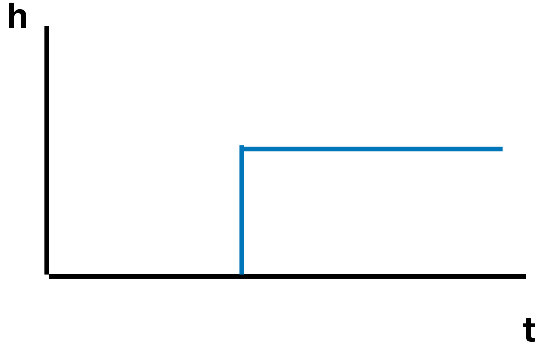


A “quarter” of the collision give us the results of an instantaneously accelerated particle.

The ZFL approximation

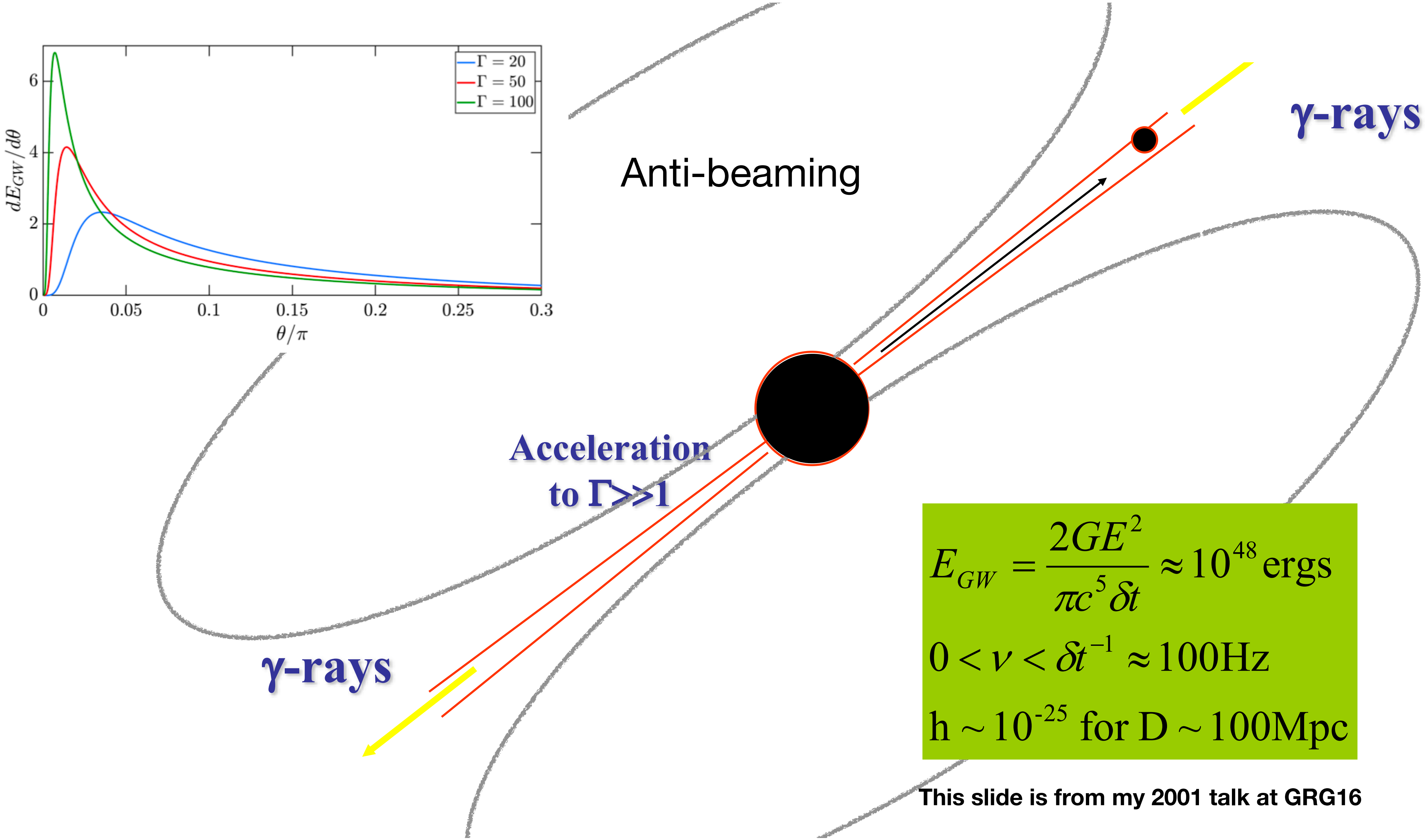
(Instantenous acceleration)

$$h^{TT}(\theta_{\rm v}) = h_+ + ih_{\rm x} = \frac{2\mathcal{E}\beta^2}{r}\frac{\sin^2\theta_{\rm v}}{1-\beta\cos\theta_{\rm v}}e^{2i\phi}.$$



$$h_{\rm max} = \frac{4\mathcal{E}}{r}, \quad \text{at} \quad \theta_{\rm max} = \sqrt{2/\Gamma}\,.$$

Anti-beaming



γ-rays

Acceleration to Γ>>1

γ-rays

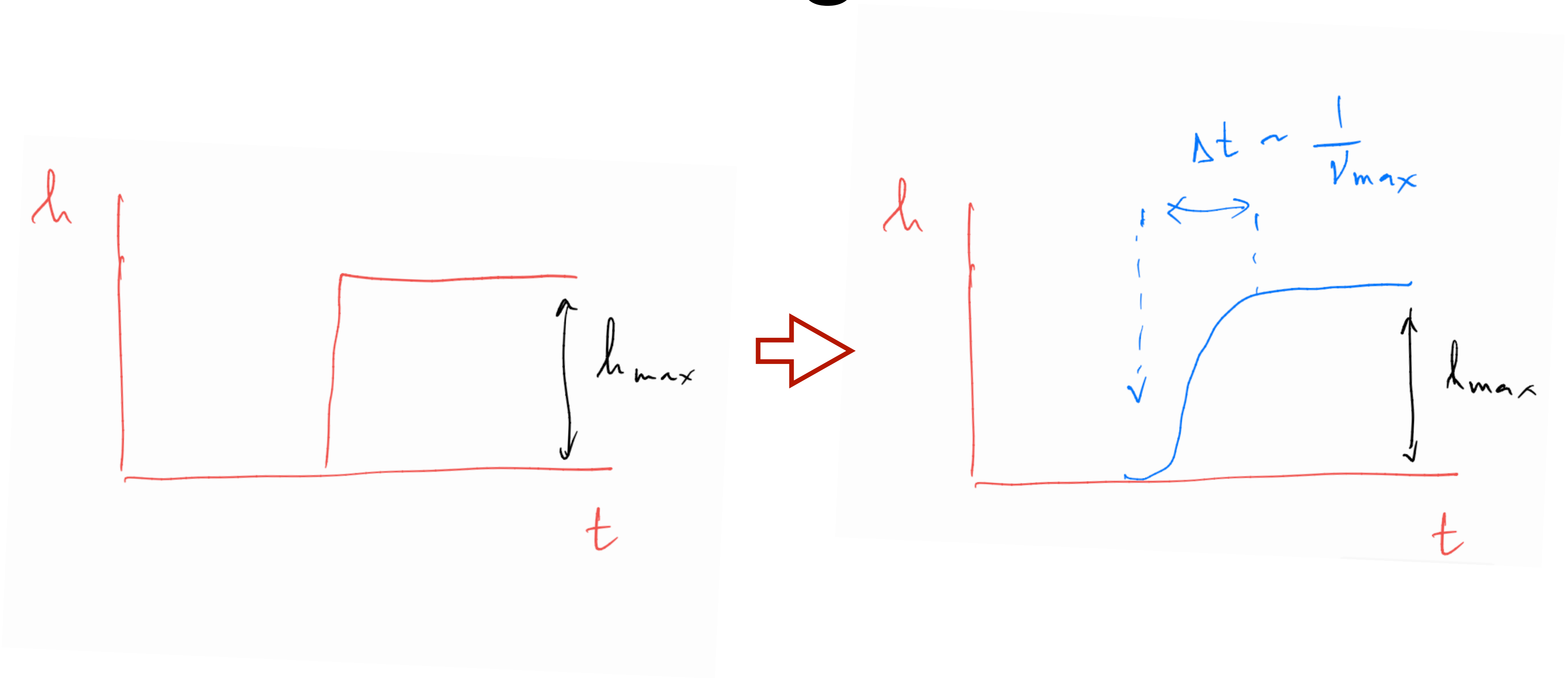
$$E_{GW} = \frac{2GE^2}{\pi c^5 \delta t} \approx 10^{48}\,\text{ergs}$$

$$0 < \nu < \delta t^{-1} \approx 100\,\text{Hz}$$

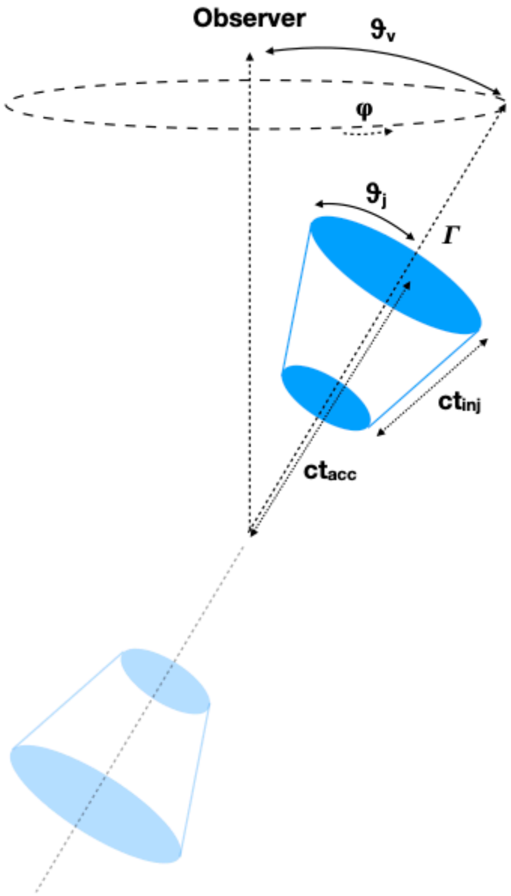
$$\text{h} \sim 10^{-25} \text{ for D} \sim 100\,\text{Mpc}$$

This slide is from my 2001 talk at GRG16

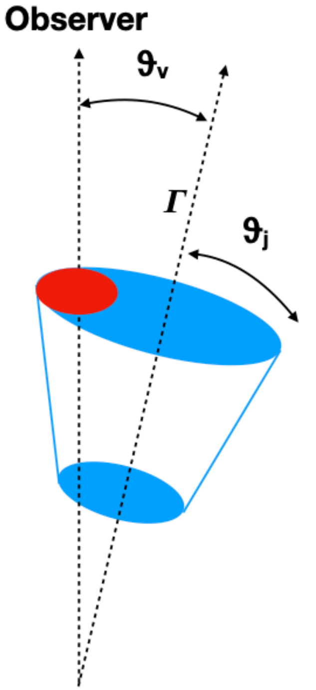
Realistic light curve

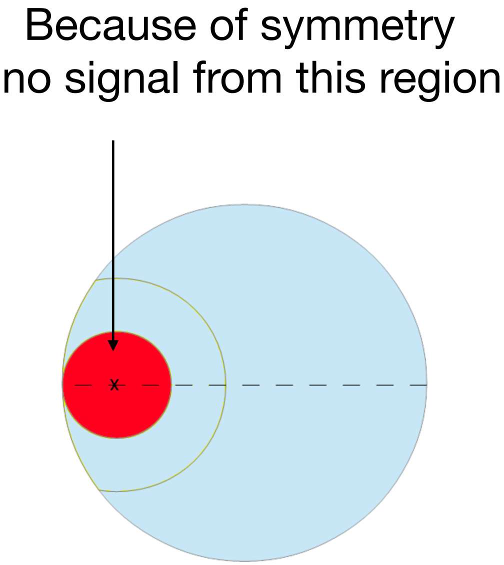


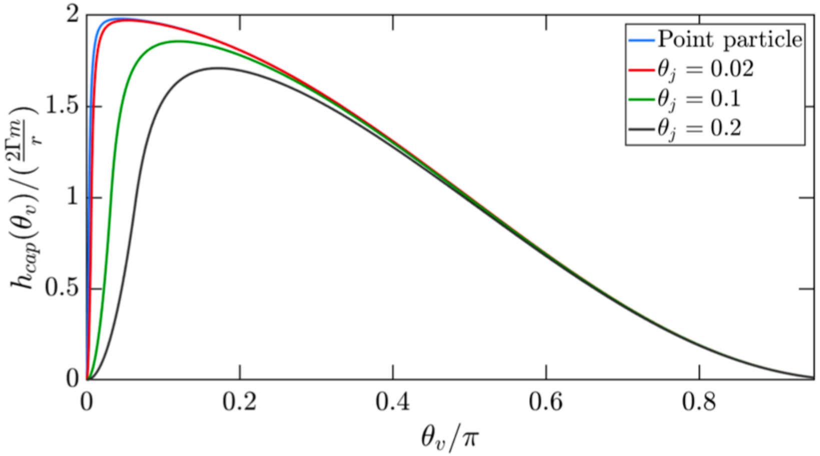
A more realistic configuration

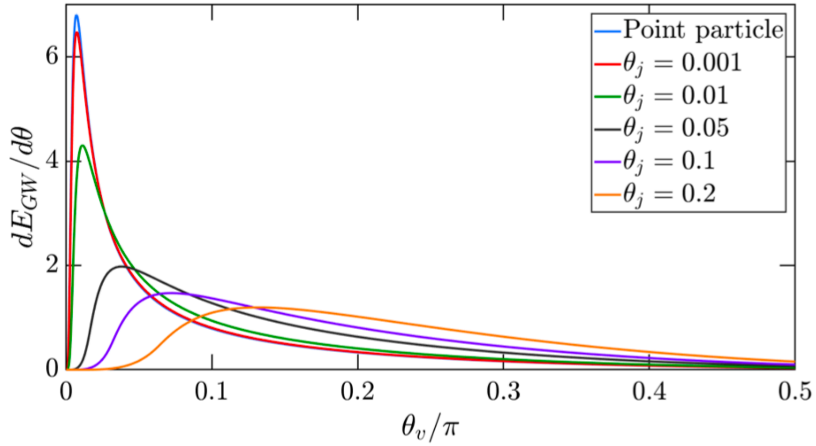


A jet



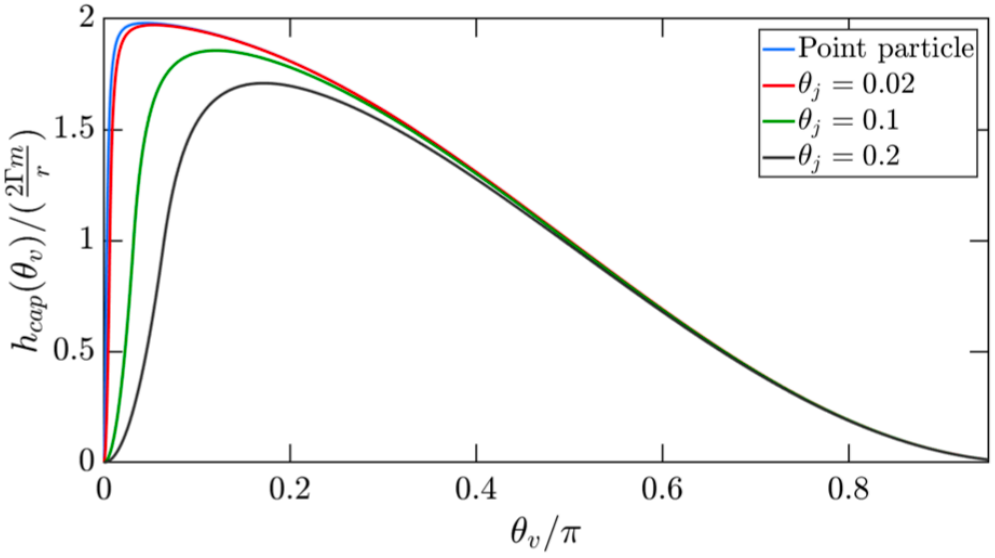

Because of symmetry
no signal from this region

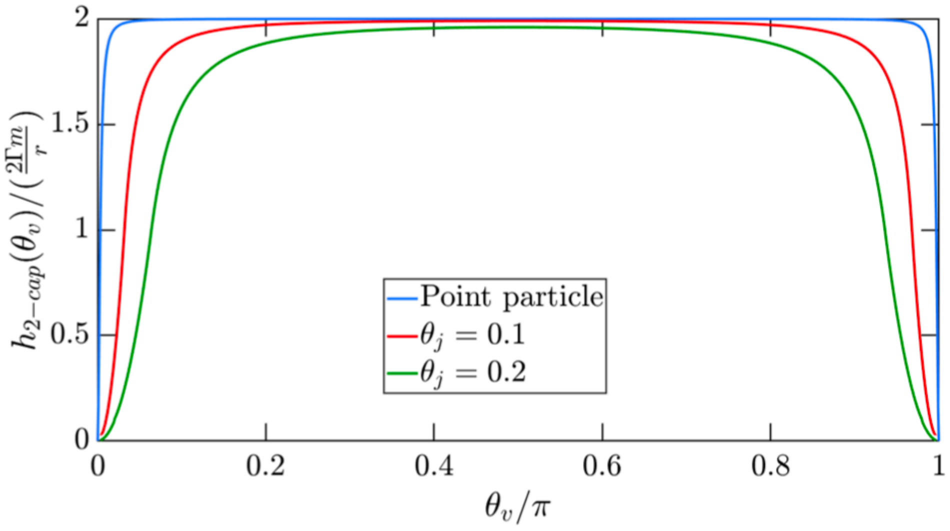




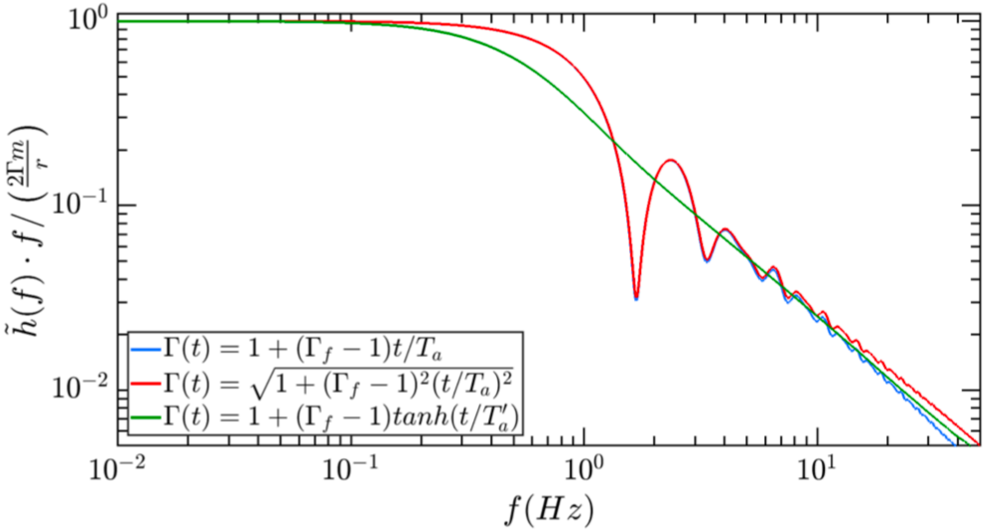
Antibeaming is defined by ϑj

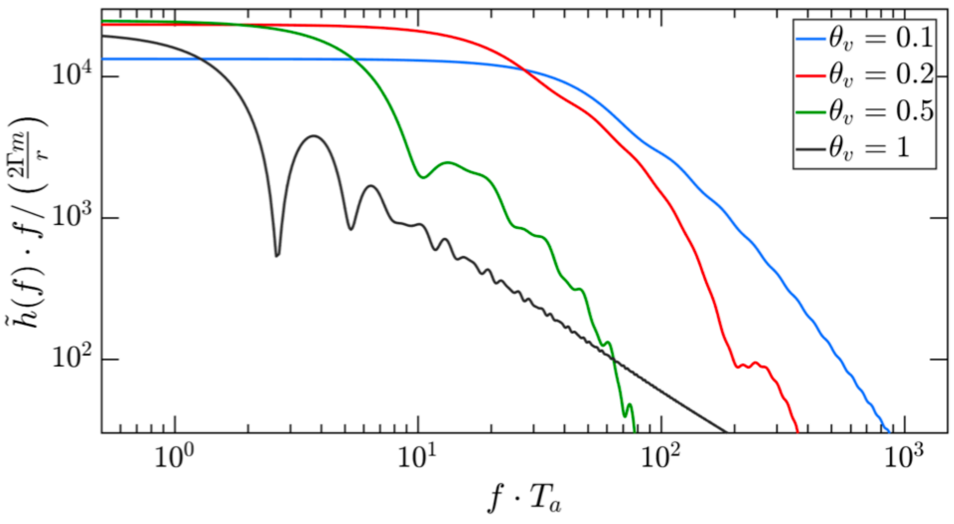
Two sided jets



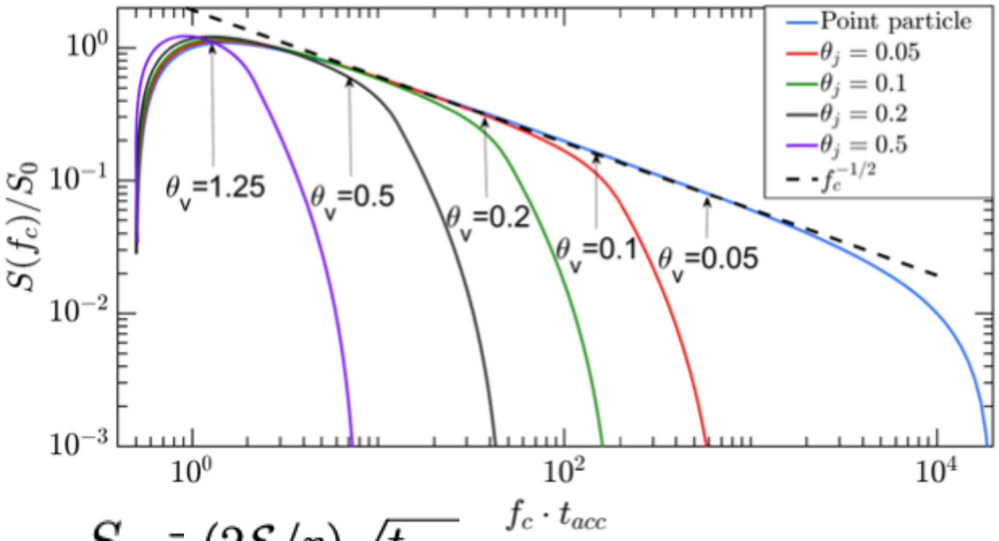


Different acceleration models

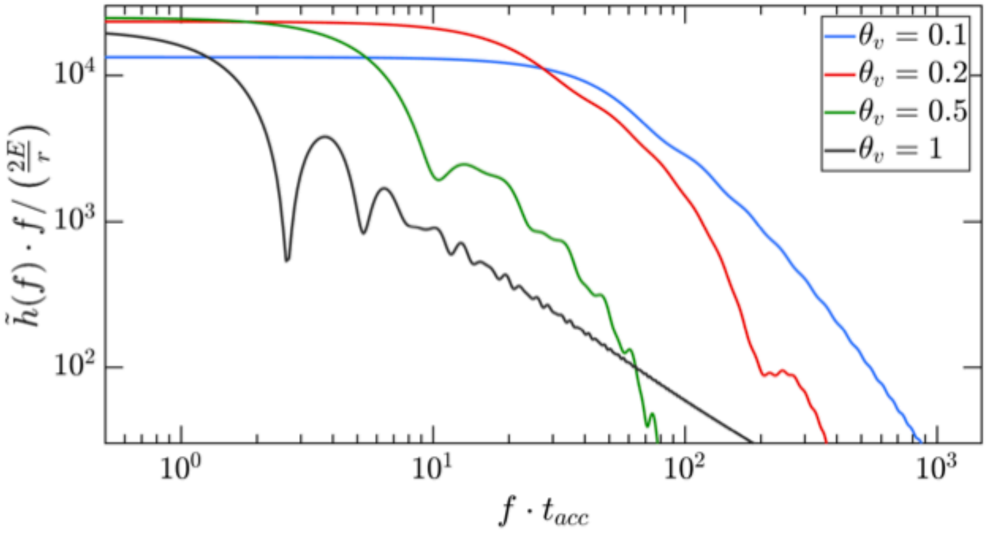




The crossover frequency

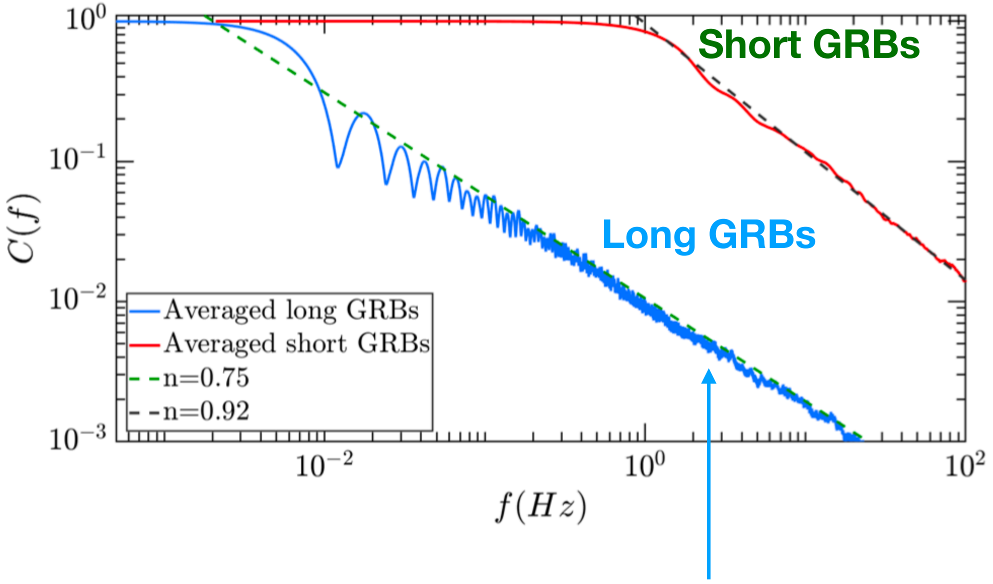


$$S_0 \equiv (2\mathcal{E}/r)\sqrt{t_{\rm acc}}$$

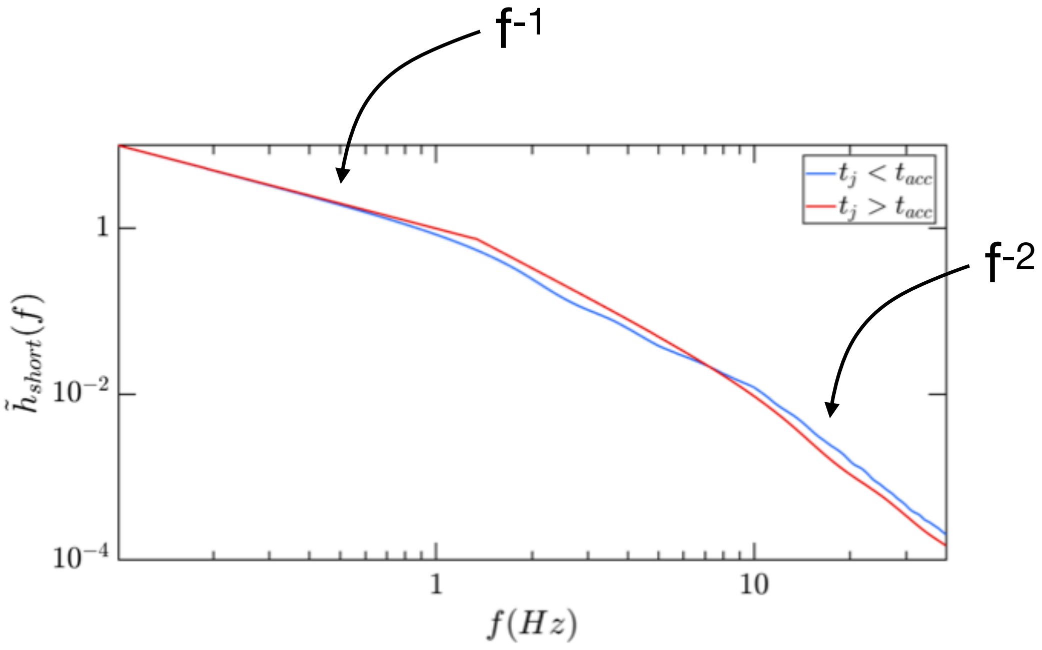


A transition frequency from f^{-1} at low frequency to $f^{-\alpha}$ with α>3/2 at higher frequencies

GW from GRB jets



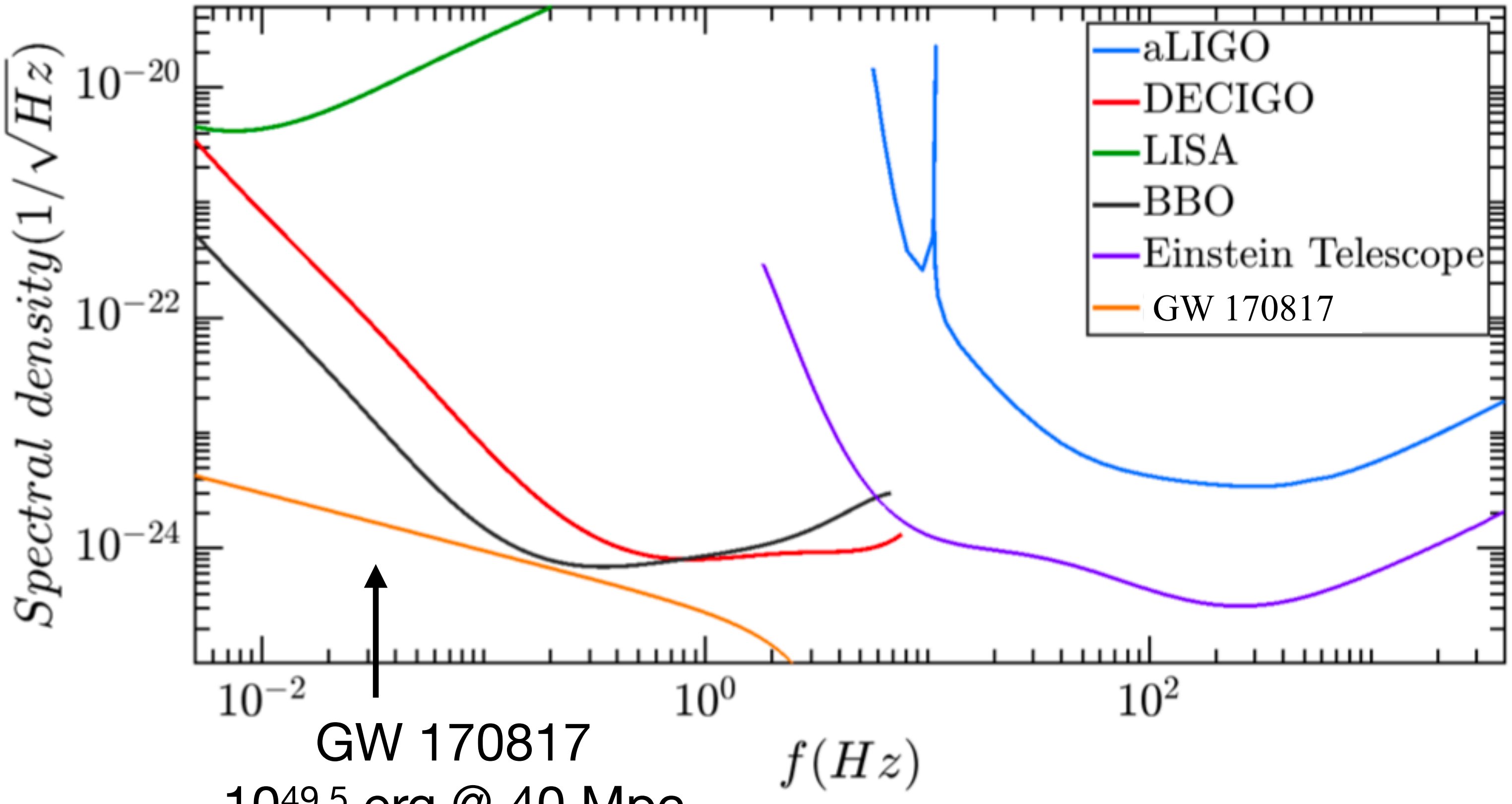
Beloborodov 2000



H for short GRBs

Assuming that the observed GRB power spectrum reflects the jet output

GW from the jet of GRB 170817



GW 170817

$10^{49.5}$ erg @ 40 Mpc

Low frequency $\lesssim$1Hz and weak $<10^{-24}$ but possibly detectable with BBO, and DECIGO

Are there better sources?

SN 1997ef

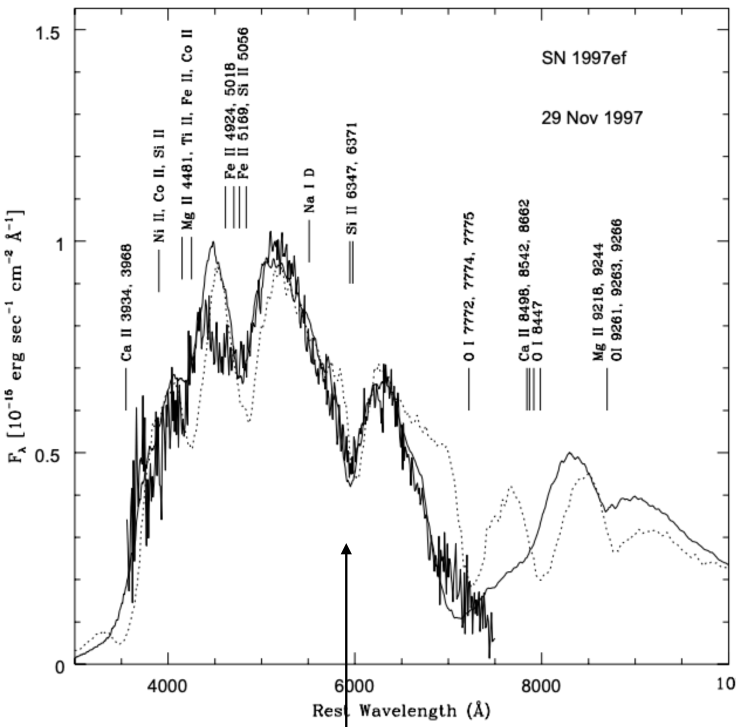


FIG. 2.— The observed, smoothed spectrum of SN 1997ef on Nov 29, 1997 (thick line), compared to two synthetic spectra computed fo $t = 9$ days. The dashed line is a spectrum computed with the original model CO100, while the fully drawn thin line is a spectrum compute with the modified outer density described in the text.

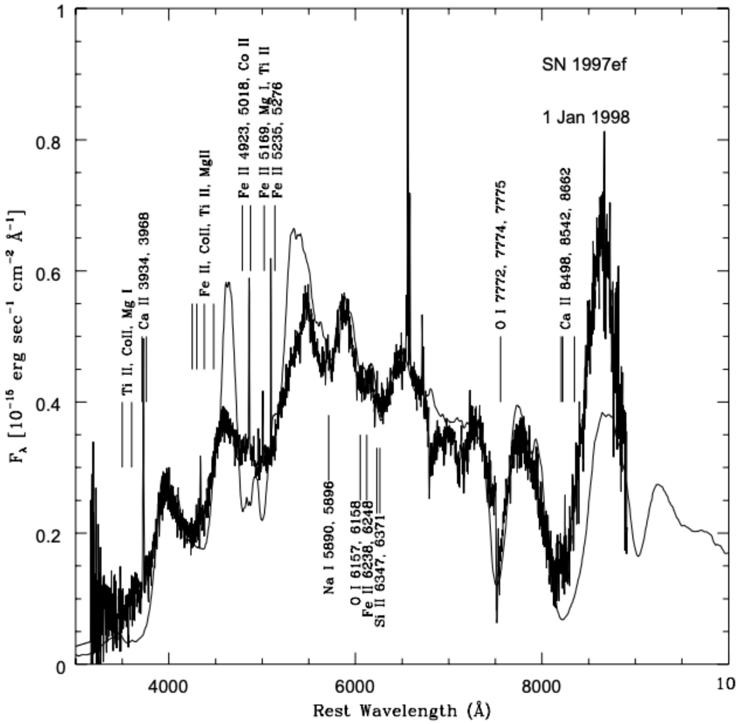


FIG. 6.— The observed spectrum of SN 1997ef on Jan 1, 1998 (thick line), compared to a synthetic spectra computed for $t = 42$ days using the modified density described in the text (thin line).

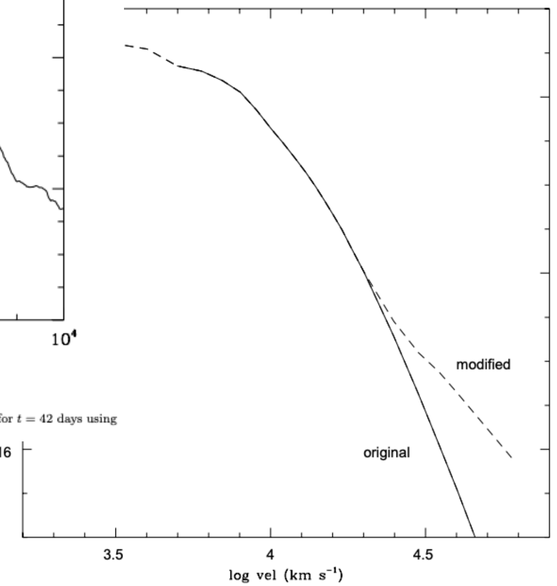
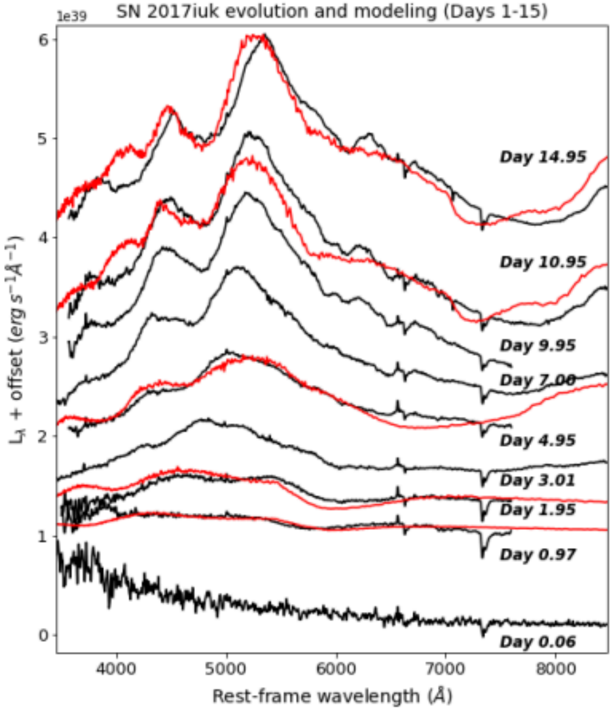


FIG. 8.— The original density structure of the hydrodynamical model CO100 (continuous line) and the modifications introduces to improved the spectral fits (dashed line). The outer part of the modified density structure has a power law index $n - \quad 4$, while the inner extension has $n = 1$ between $v = 3000$ and $v = 5000$ km s^{-1}and $n = -1$ below $v = 3000$ km s^{-1}.

Mazzali et al., 2000

Very broad absorption lines disappear at later spectrum

SN 2017iuk (GRB 171205A)



epoch spectroscopic observations of SN 2017iuk, associated with GRB 171205A which display features at extremely high expansion velocities of $\sim$ 100,000 km s^{-1} within the first day after the burst[4,5]. These high-velocity components are characterized by chemical abundances different from those observed in the ejecta of SN 2017iuk at later times. Using spectral synthesis models

Very broad absorption lines disappear at later spectrum

Figure 2. The spectral evolution of SN 2017iuk during the first 15 days after the GRB. All spectra are shown as black curves, and they have been de-reddened for Galactic extinction, with the GRB afterglow contribution being subtracted. The simulated emission (red curves) obtained from our synthesis model for some selected spectra are shown as red curves. For the spectral simulation at Day 0.957 an arbitrary constant has been considered, due to the uncertainty in the afterglow component continuum, to match the observed data.

Izzo et al., 2019

From density distribution
to energy distribution => v^5

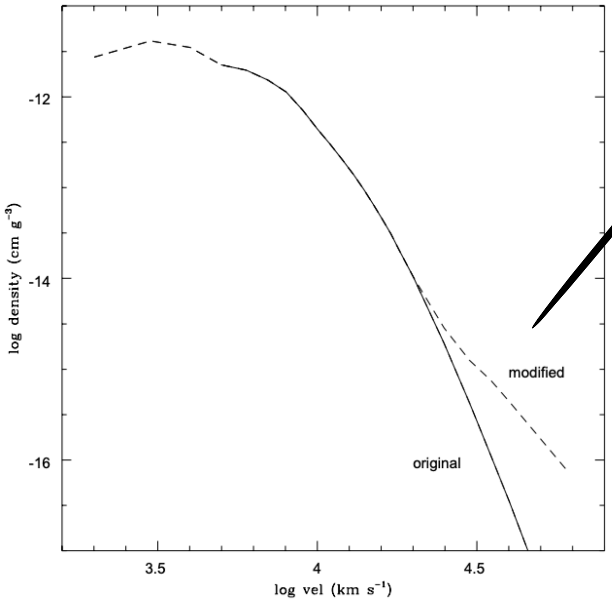
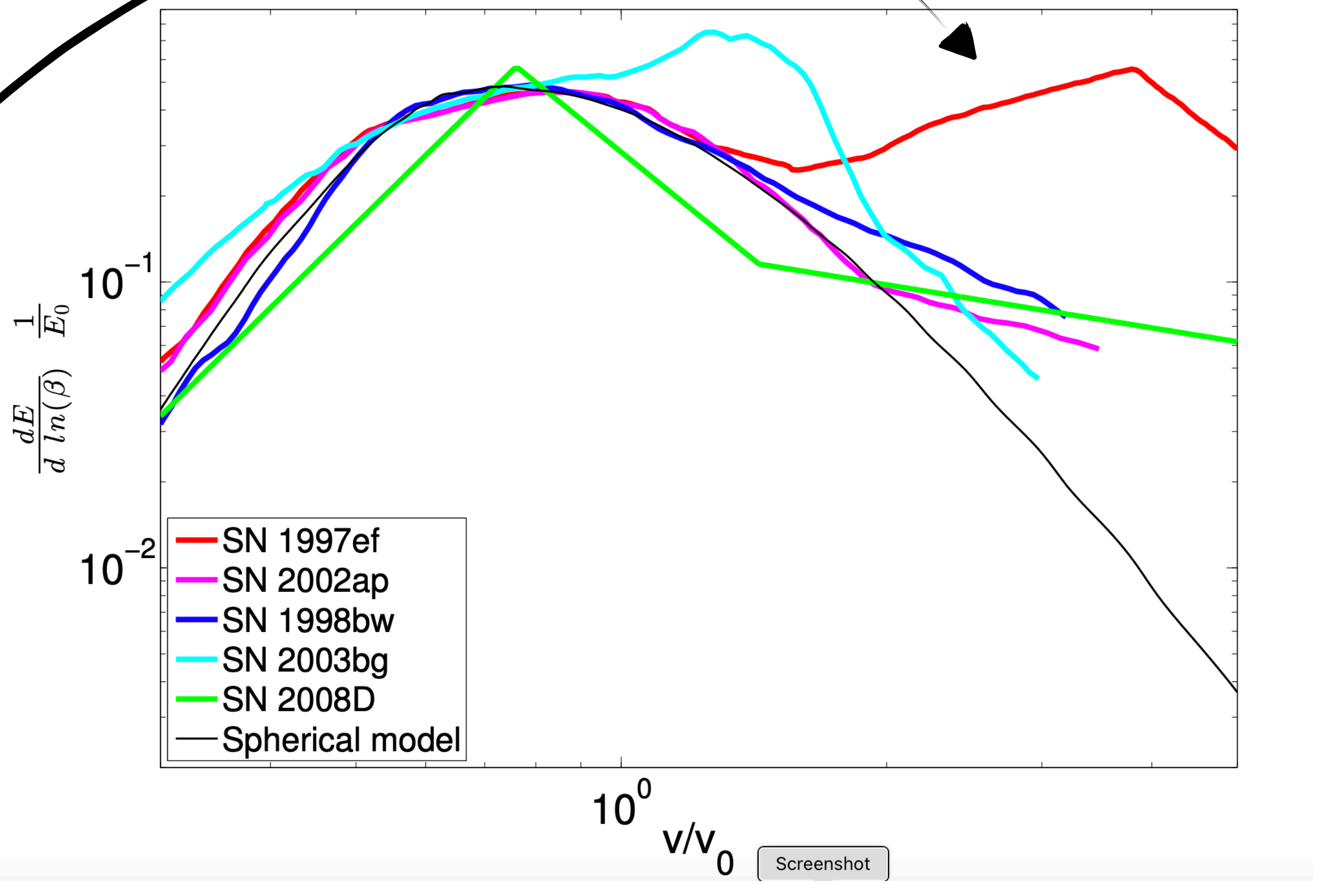


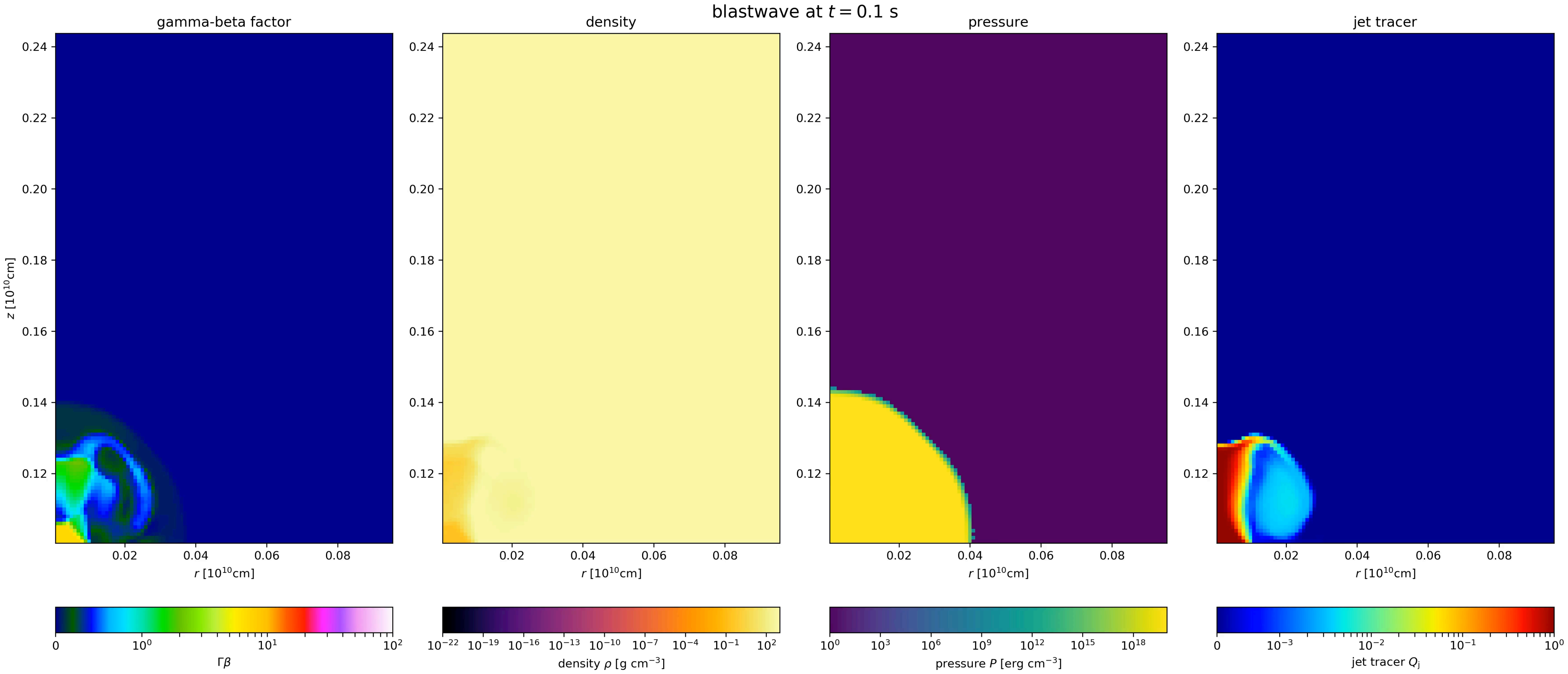
FIG. 8.— The original density structure of the hydrodynamical model CO100 (continuous line) and the modifications introduces to improved the spectral fits (dashed line). The outer part of the modified density structure has a power law index $n - -4$, while the inner extension has $n = 1$ between $v = 3000$ and $v = 5000$ km s^{-1}and $n = -1$ below $v = 3000$ km s^{-1}.



Mazzali et al., 2000

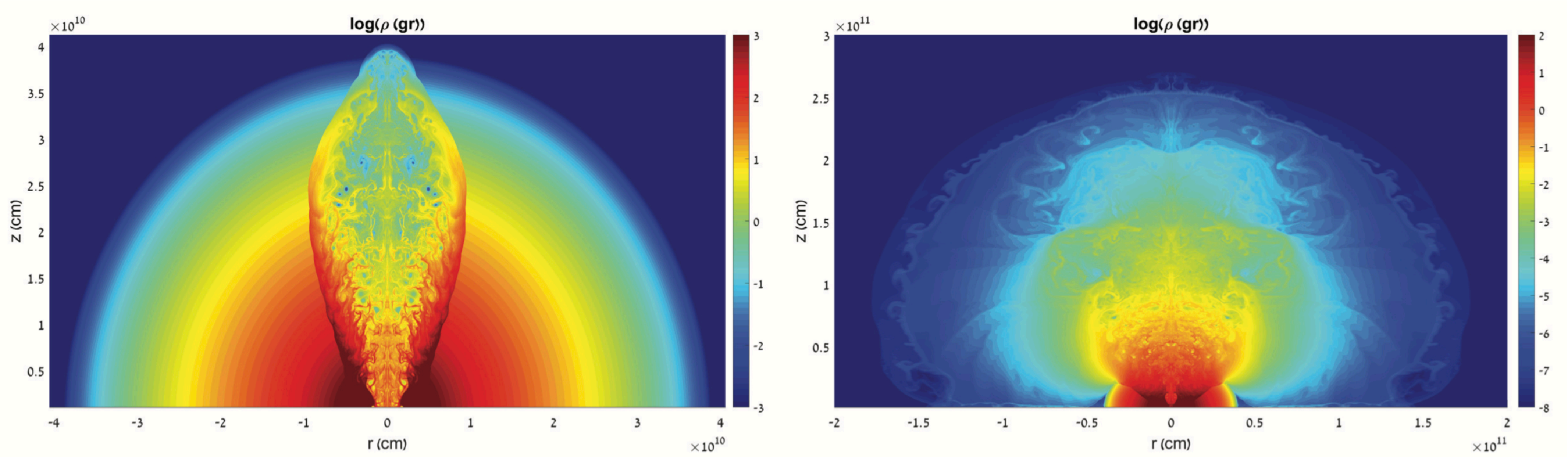
TP, Nakar, Mazzali & TP 2017,2019

Choked jet within a Star

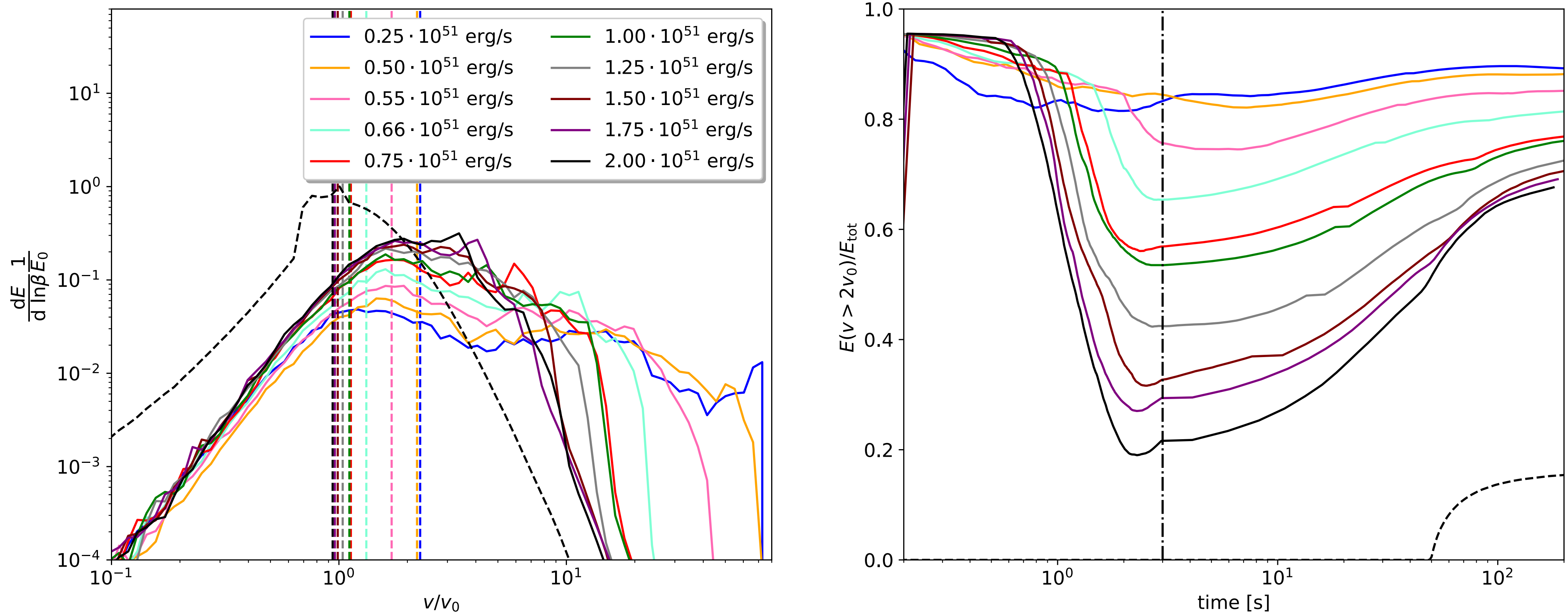


Credit: Matteo Pais

SNe harbor energetic jets

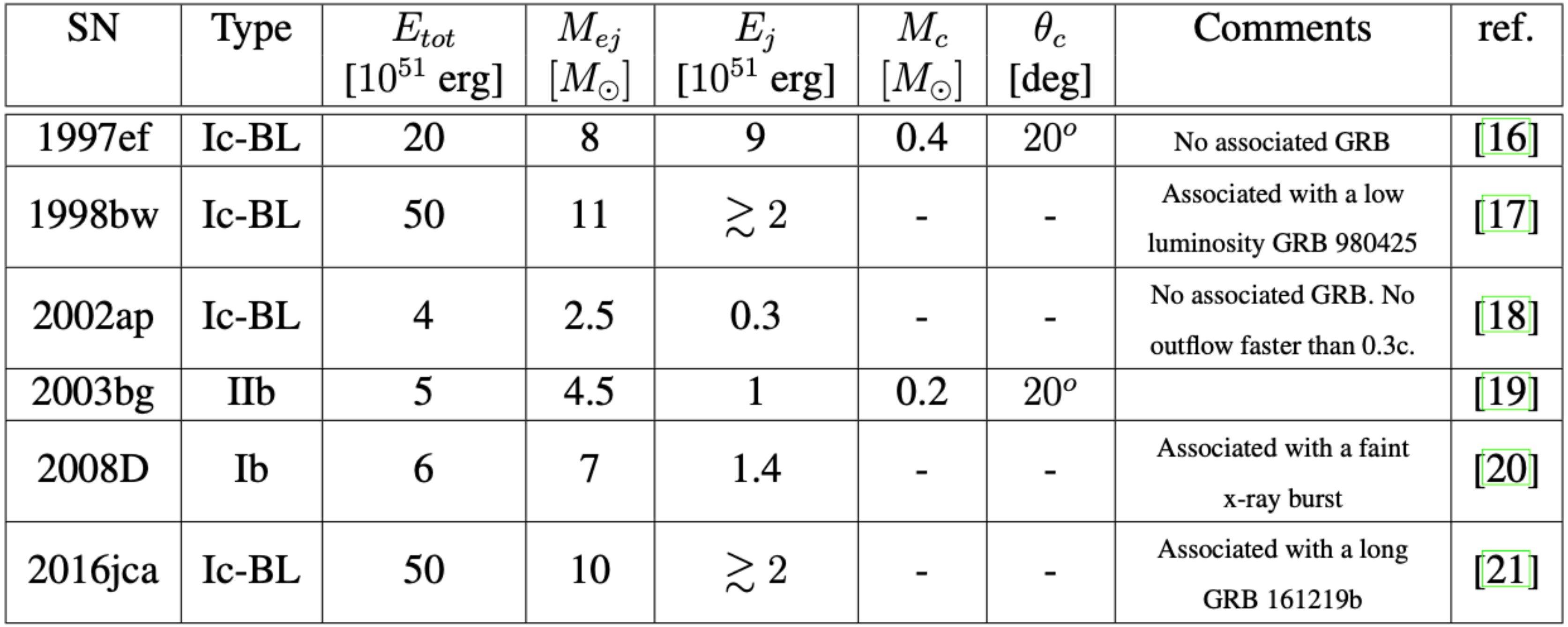


The energy distribution



Credit: Matteo Pais

Some SNe and their Jets

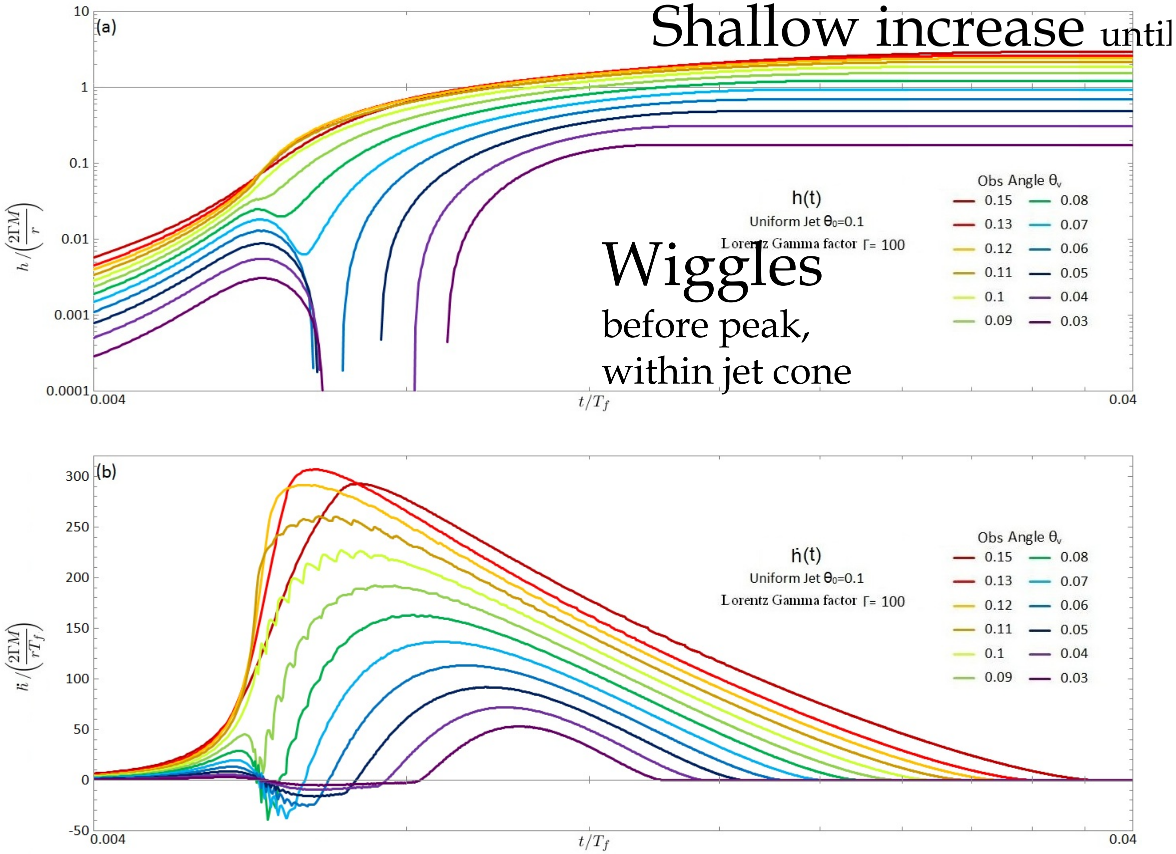


SN	Type	E_{tot} $[10^{51}$ erg]	M_{ej} $[M_\odot]$	E_j $[10^{51}$ erg]	M_c $[M_\odot]$	θ_c [deg]	Comments	ref.
1997ef	Ic-BL	20	8	9	0.4	20^o	No associated GRB	[16]
1998bw	Ic-BL	50	11	$\gtrsim 2$	-	-	Associated with a low luminosity GRB 980425	[17]
2002ap	Ic-BL	4	2.5	0.3	-	-	No associated GRB. No outflow faster than 0.3c.	[18]
2003bg	IIb	5	4.5	1	0.2	20^o		[19]
2008D	Ib	6	7	1.4	-	-	Associated with a faint x-ray burst	[20]
2016jca	Ic-BL	50	10	$\gtrsim 2$	-	-	Associated with a long GRB 161219b	[21]

All the SNe are stripped, some associated with llGRBs

GW from the jet

(Birnholtz & TP, 14)

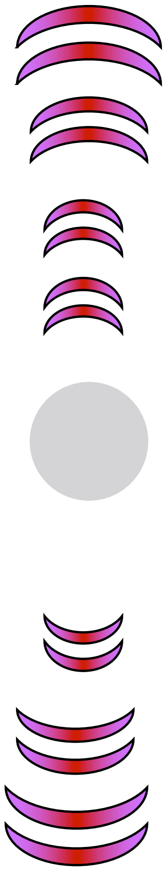


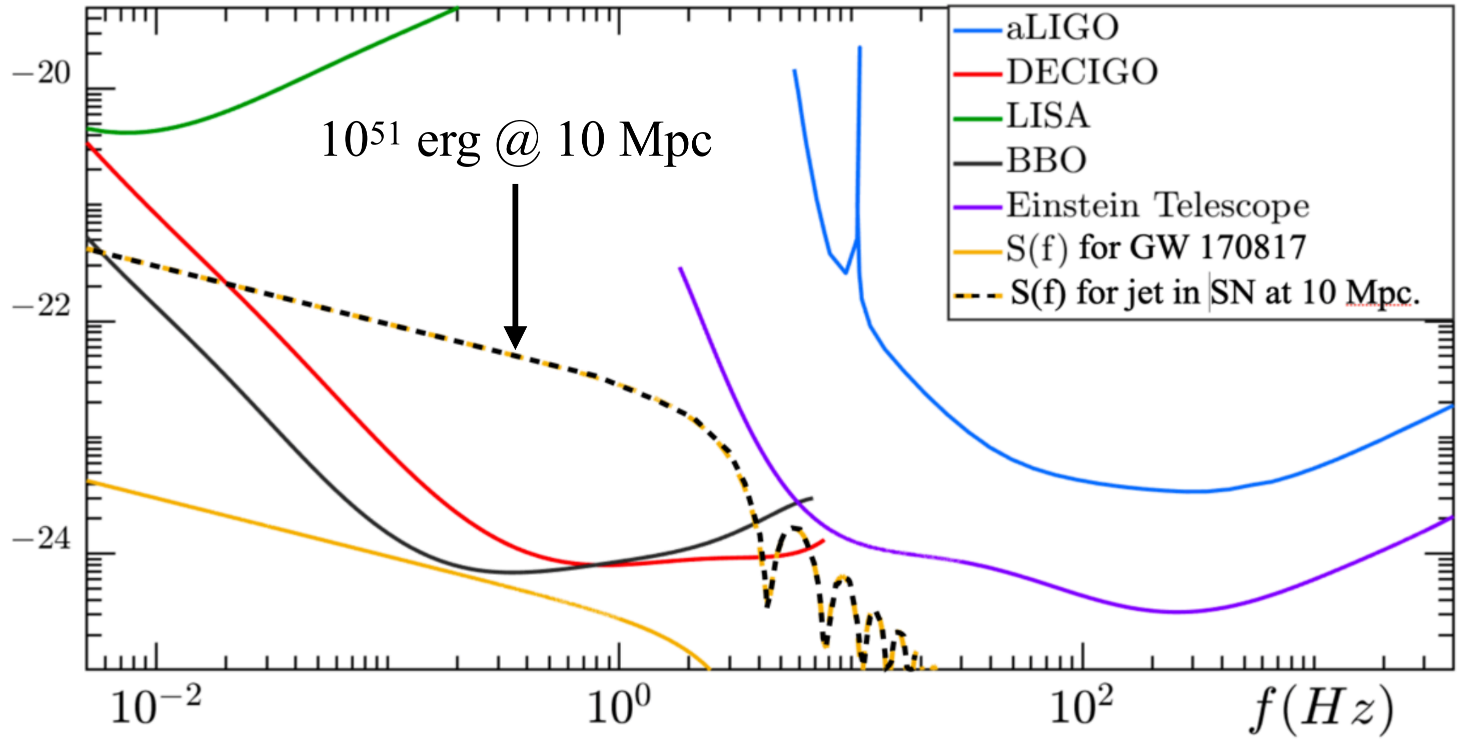
Shallow increase until

Wiggles

before peak,

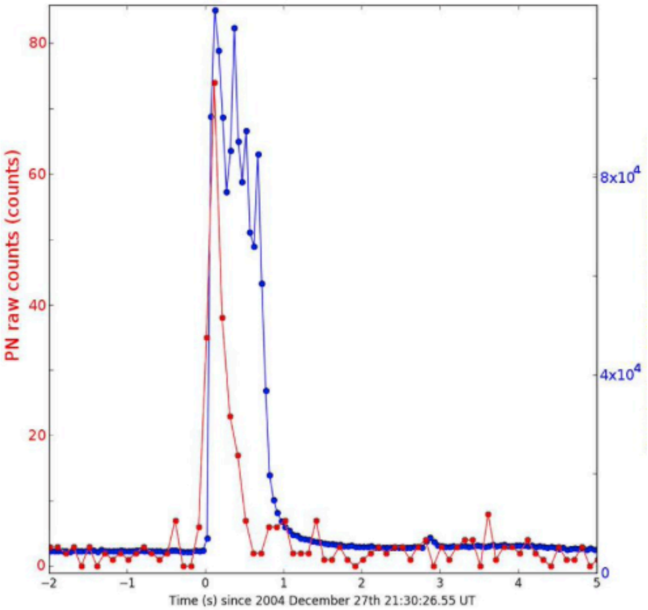
within jet cone

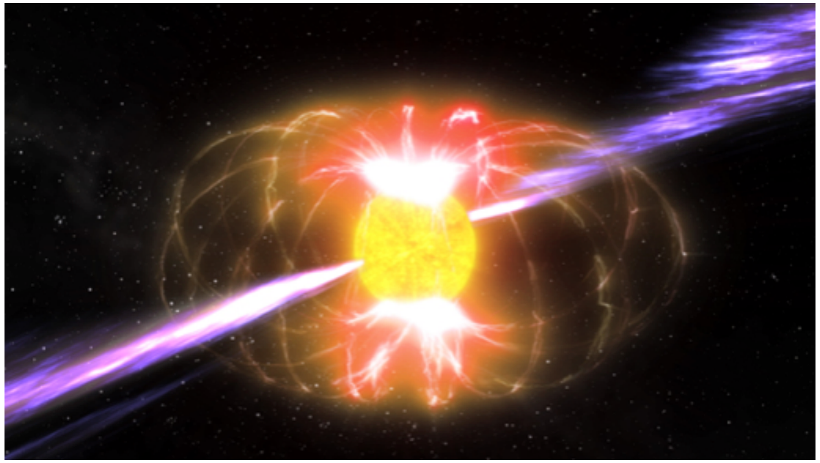




Low frequency ≲1Hz and mild $<10^{-23}$ but detectable with BBO, DECIGO and marginally Einstein Telescope

SGR giant flares?



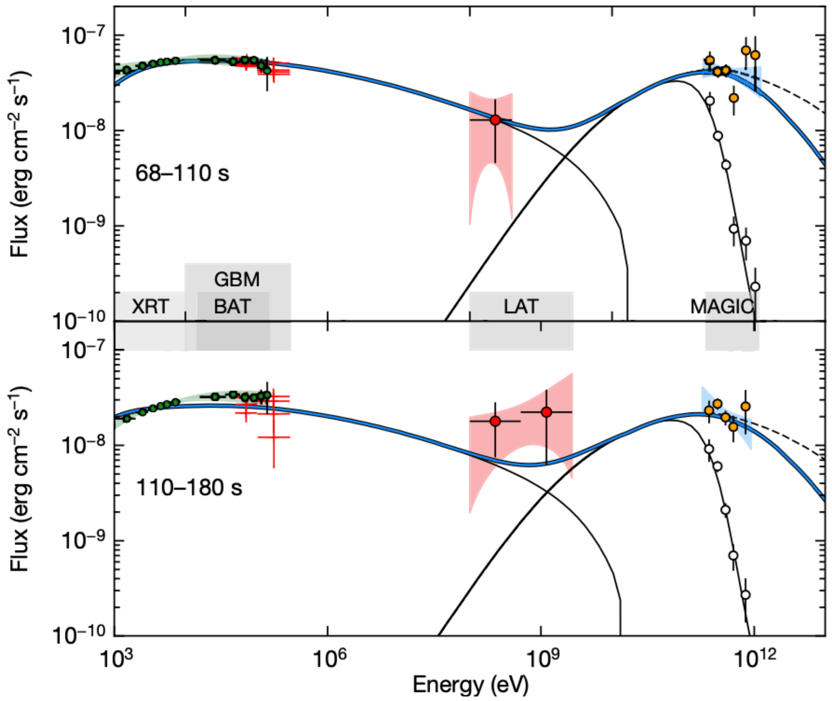


10^{47} erg in a few millisecond. Is this good enough ?

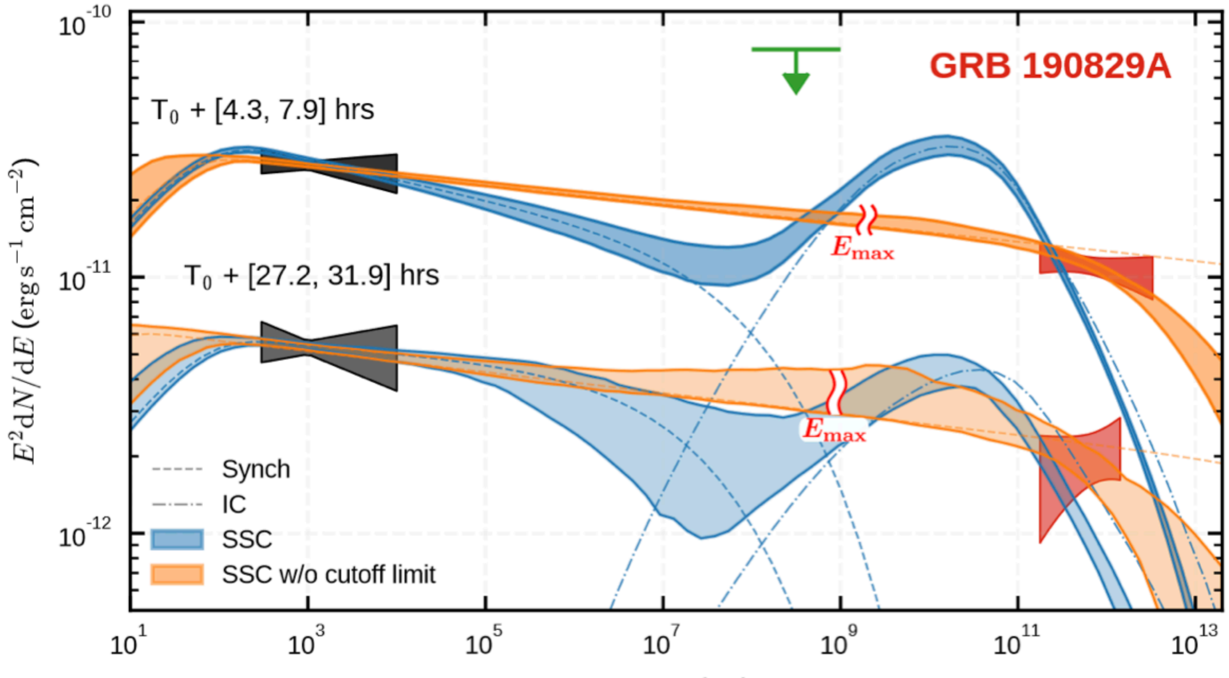
Summary

- Jet are sources of GW
- The GW could provide excellent diagnostic of the acceleration process
- However, GRBs are most likely too distant to detect their jets even with planned detectors.
- However, hidden jets in SNe might bring us back to detection of SNe from ~10 Mpc

TeV



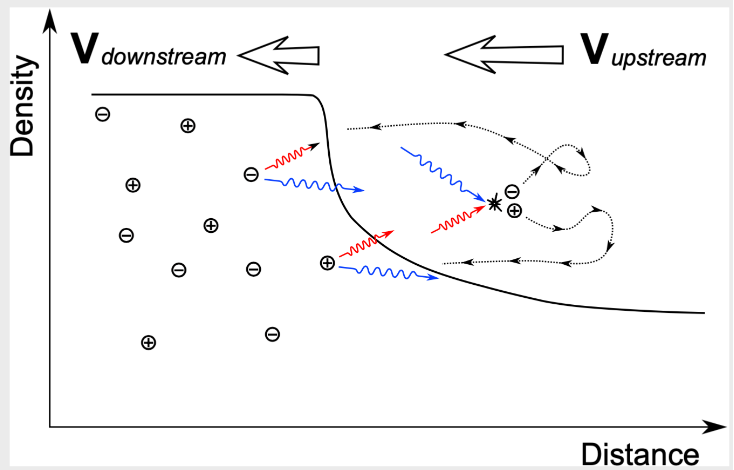
190114C-Magic

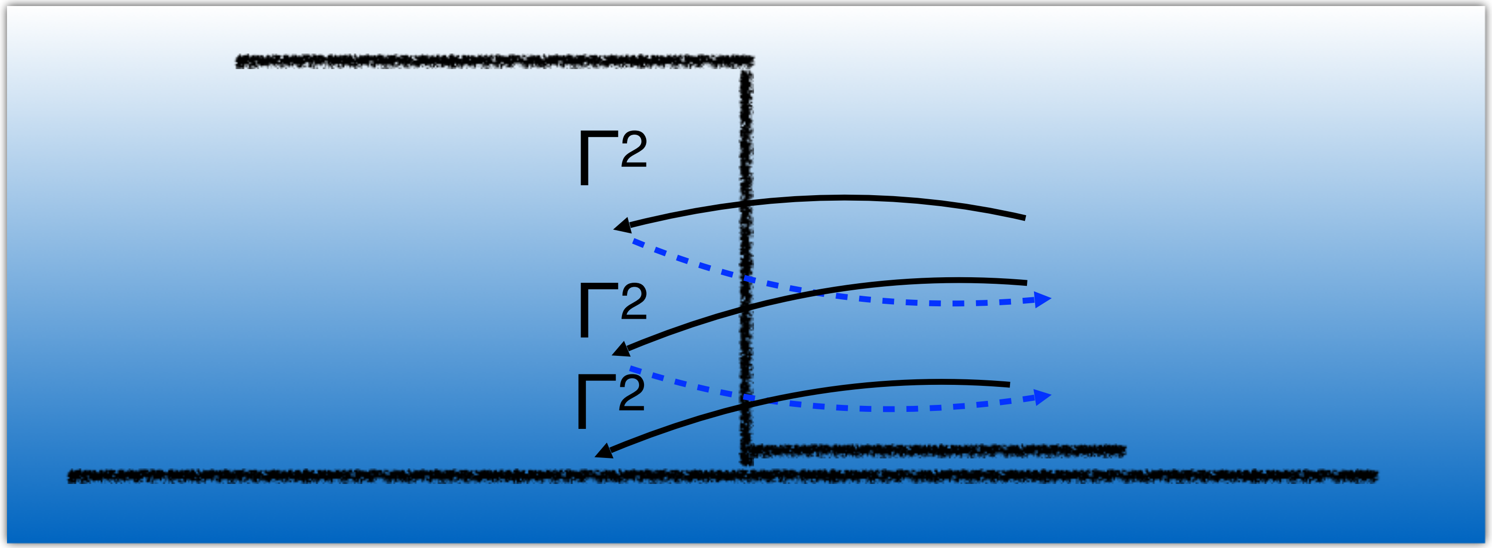


1900829A-H.E.S.S.

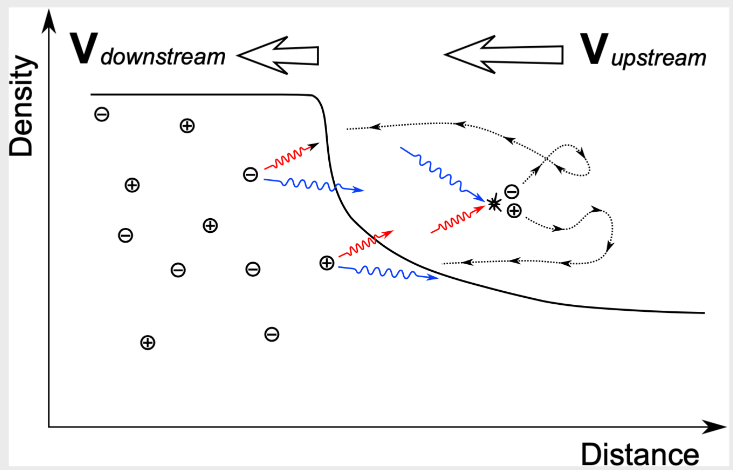
The Pair Balance model

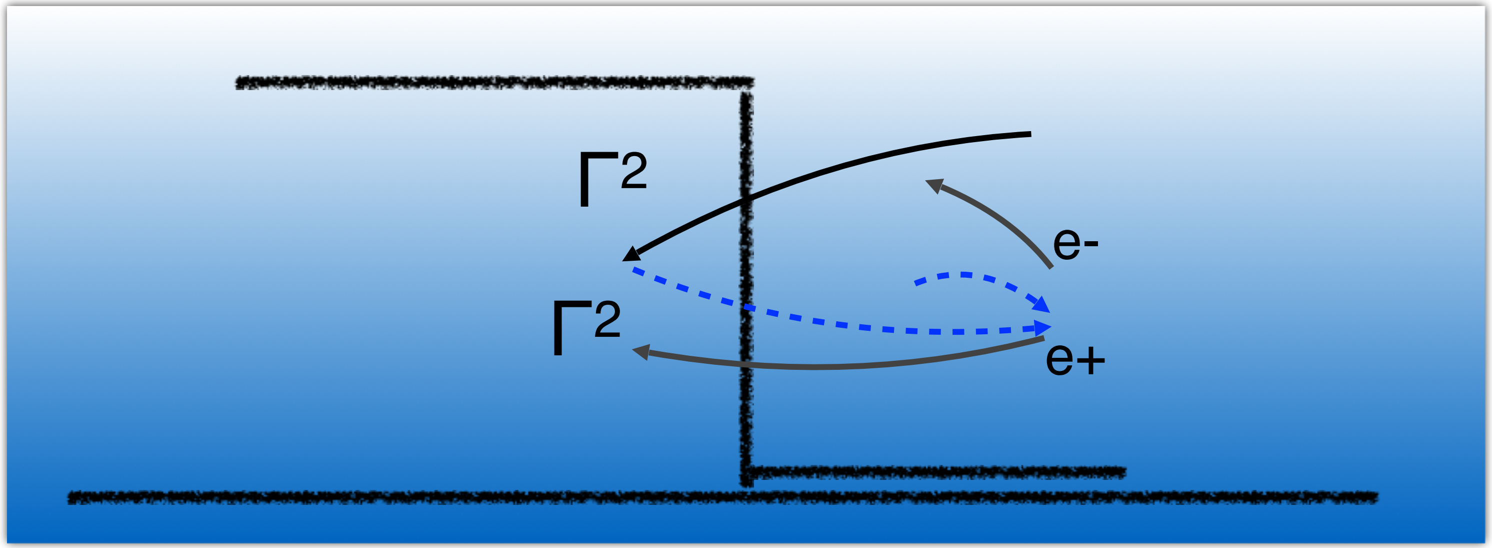
Derishev & TP 2016



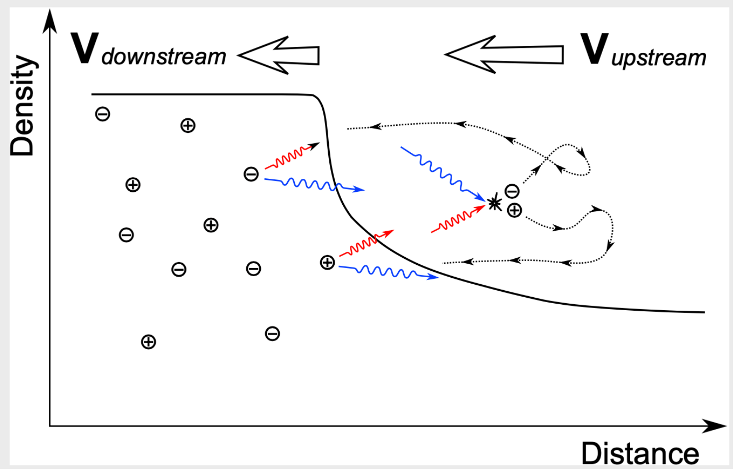


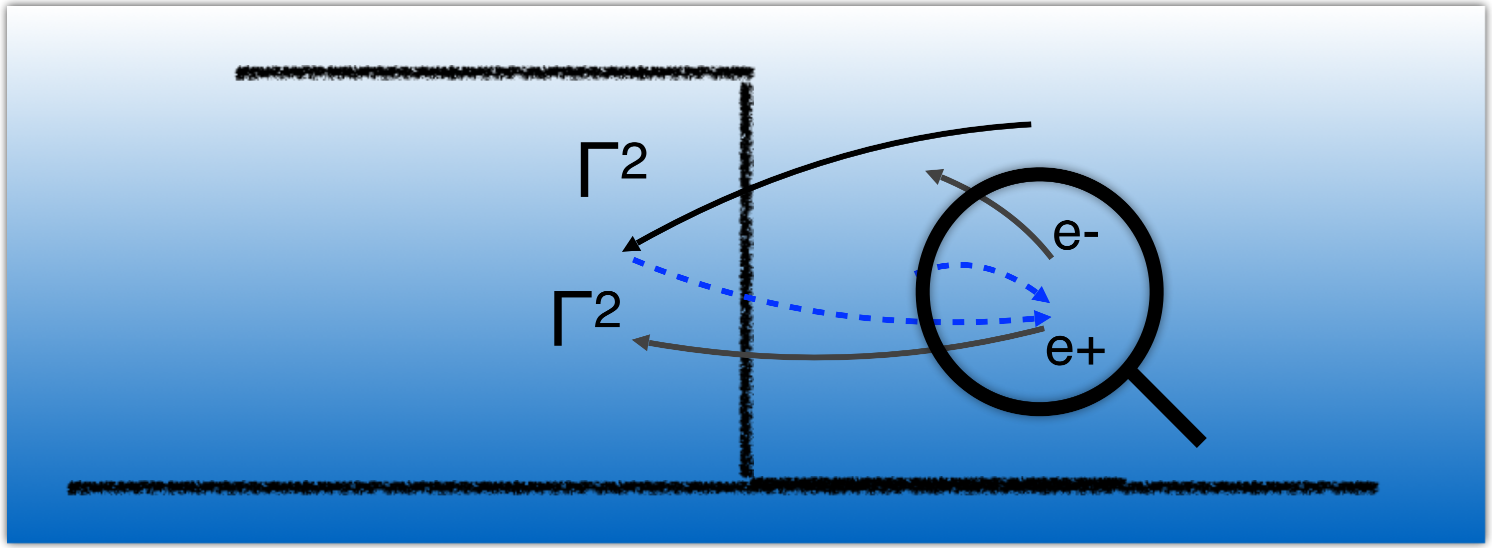
1) Pairs produced in the upstream
2) They are strongly accelerated once crossing the shock



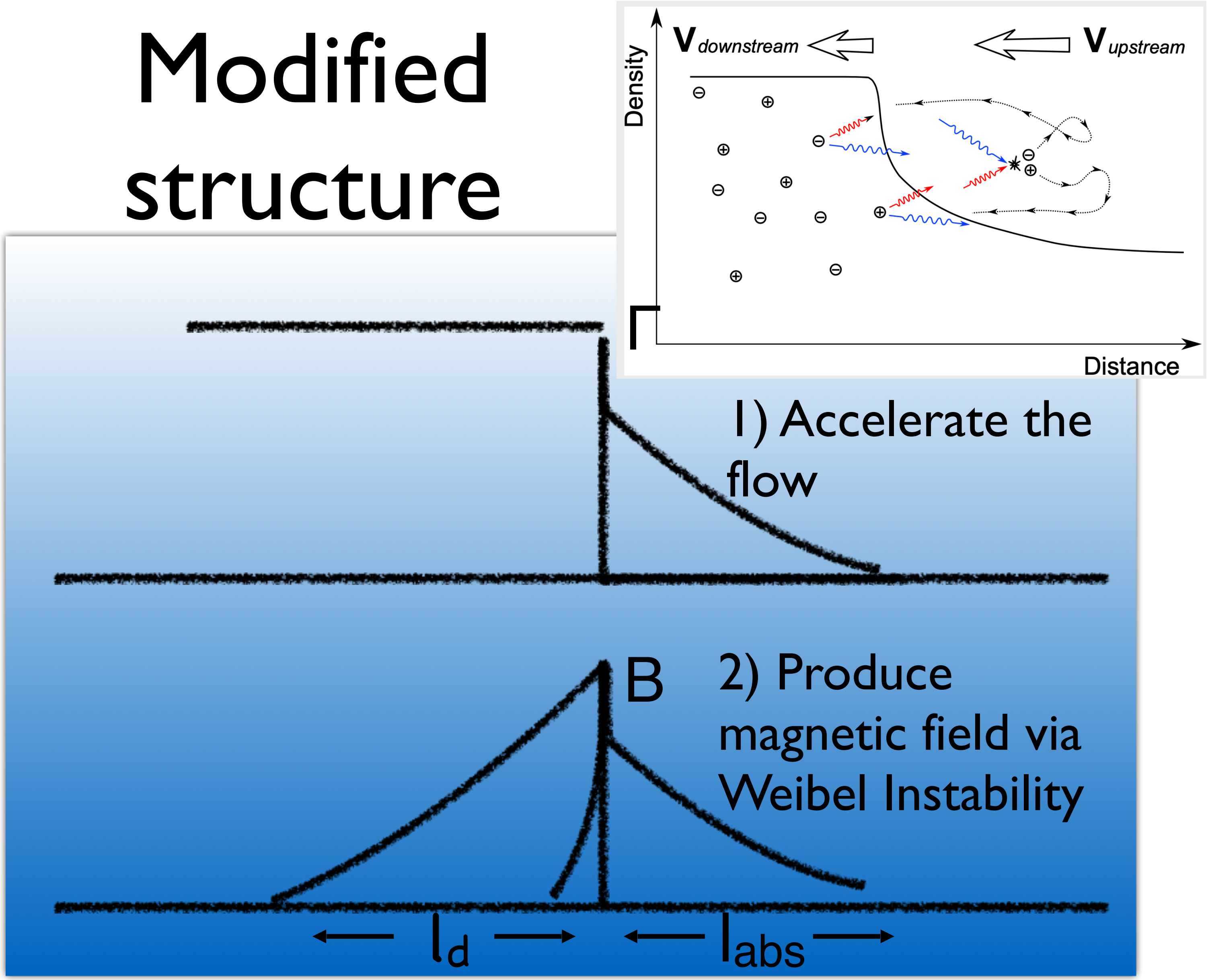


1) Accelerate the flow
2) Produce magnetic field via Weibel Instability





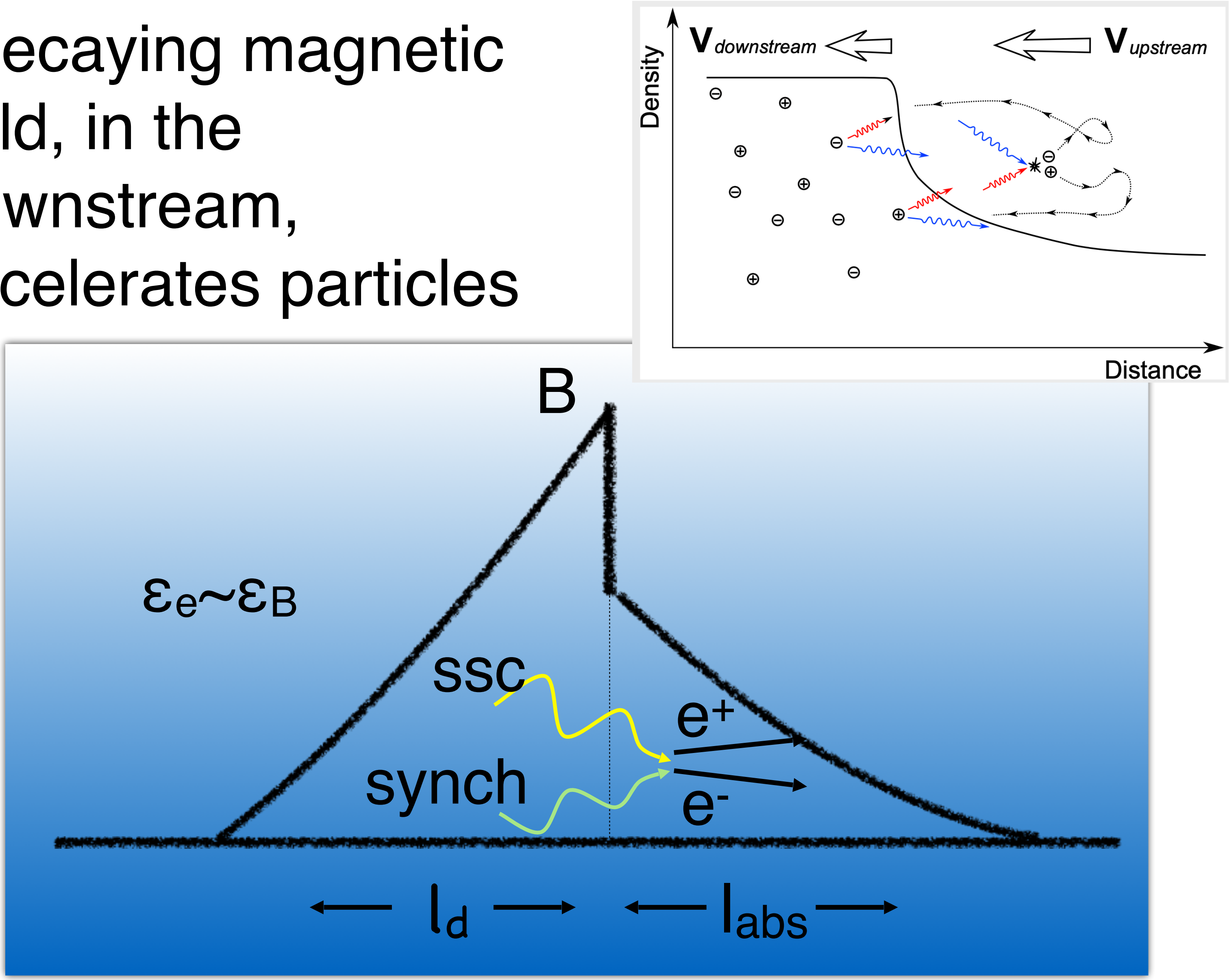
Modified structure



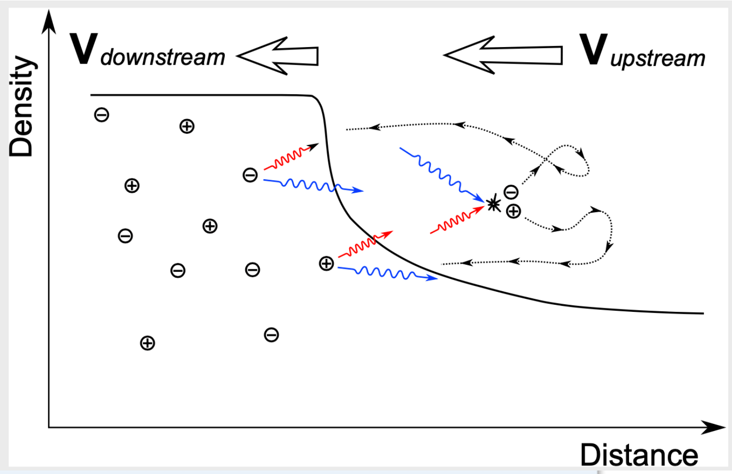
1) Accelerate the flow

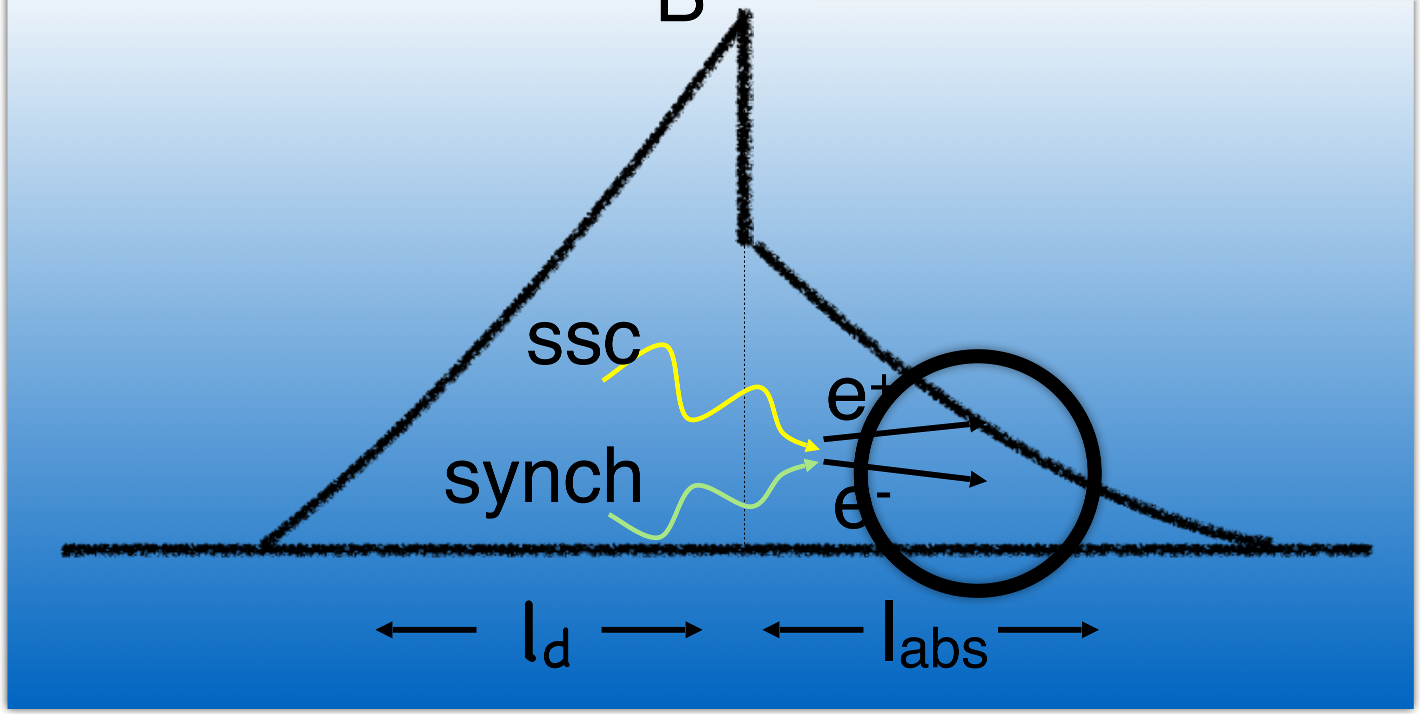
2) Produce magnetic field via Weibel Instability

Decaying magnetic field, in the downstream, accelerates particles



Pairs from the upstream increase the multiplicity of the downstream





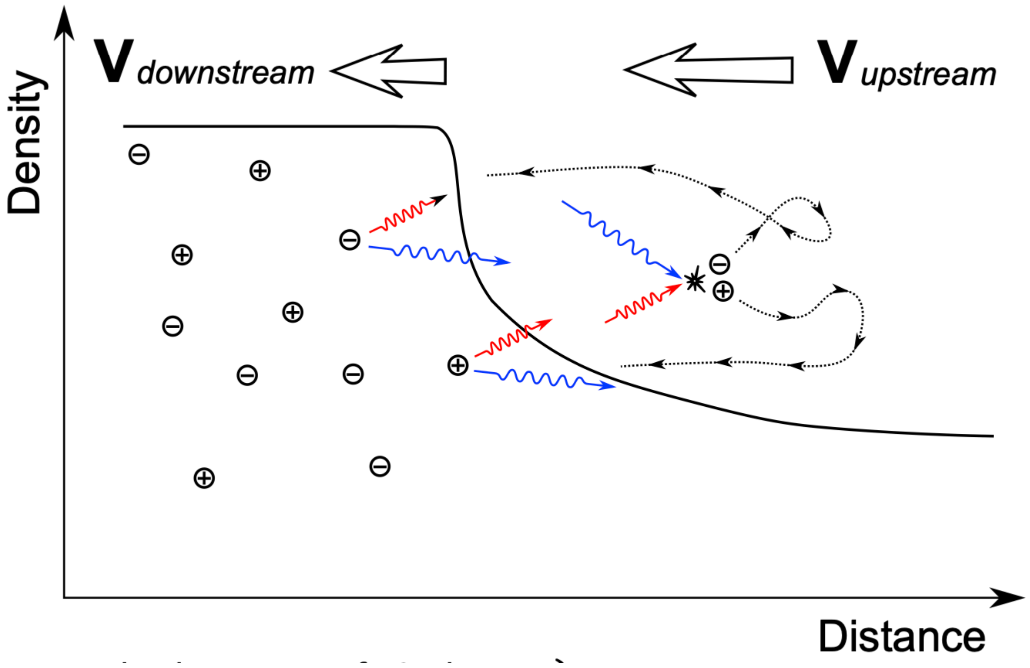
Some basic features of the Pair-Balance model

Derishev & TP 2016

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

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

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



One zone modeling

Sari, TP, Narayan 98

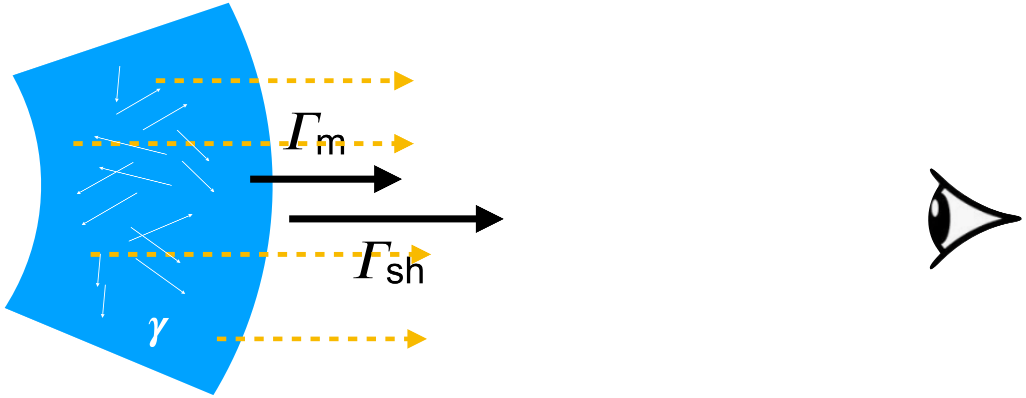
$$R = C_{\rm R}\Gamma^2 c t_{\rm obs}/(1+z)$$

$$E_{\rm kin} = C_{\rm E}\Gamma^2 M c^2$$

$$t_{\rm eff} = C_{\rm t}\Gamma t_{\rm obs}/(1+z)$$

$$h\nu_{\rm obs} = C_{\Gamma}\Gamma h\nu/(1+z)$$

$$L = C_{\rm L}\epsilon_r\ (1+z)E_{\rm kin}/t_{\rm obs}\ ,$$



	density profile	
Reference	Wind	ISM
Sari et al. (1998), "SPN98 coefficients" hereafter		$C_{\rm R} = 2,\ C_{\rm t} = 1/\sqrt{2},\ C_{\Gamma} = 1/\sqrt{2},\ C_{\rm L} = 17/12^*$
Panaitescu & Mészáros (1998b)	$C_{\rm R} \approx 3.1$	$C_{\rm R} \approx 6.5$
Nava et al. (2013)	$C_{\rm R} = 4/5$	$C_{\rm R} = 8/9$
Dai & Lu (1998)	$C_{\rm R} = 4,\ C_{\rm t} = 8\sqrt{2}/3$	$C_{\rm R} = 8,\ C_{\rm t} = 16\sqrt{2}/5$
Derishev & Piran (2019)	$C_{\rm R} = 4,\ C_{\rm E} = 1,\ C_{\rm t} = 4,\ C_{\Gamma} = 1$	$C_{\rm R} = 8,\ C_{\rm E} = 1,\ C_{\rm t} = 8,\ C_{\Gamma} = 1$
Current work (from Derishev 2021), "effective coefficients" hereafter	$C_{\rm R} \approx 2.45,\ C_{\rm E} = 2/9,\ C_{\rm t} \approx 1.16,$ $C_{\Gamma} \approx 0.64,\ C_{\rm L} = 9/8$	$C_{\rm R} \approx 5.55,\ C_{\rm E} = 6/17,\ C_{\rm t} \approx 0.96,$ $C_{\Gamma} \approx 0.87,\ C_{\rm L} = 17/16$

One Zone Coefficients

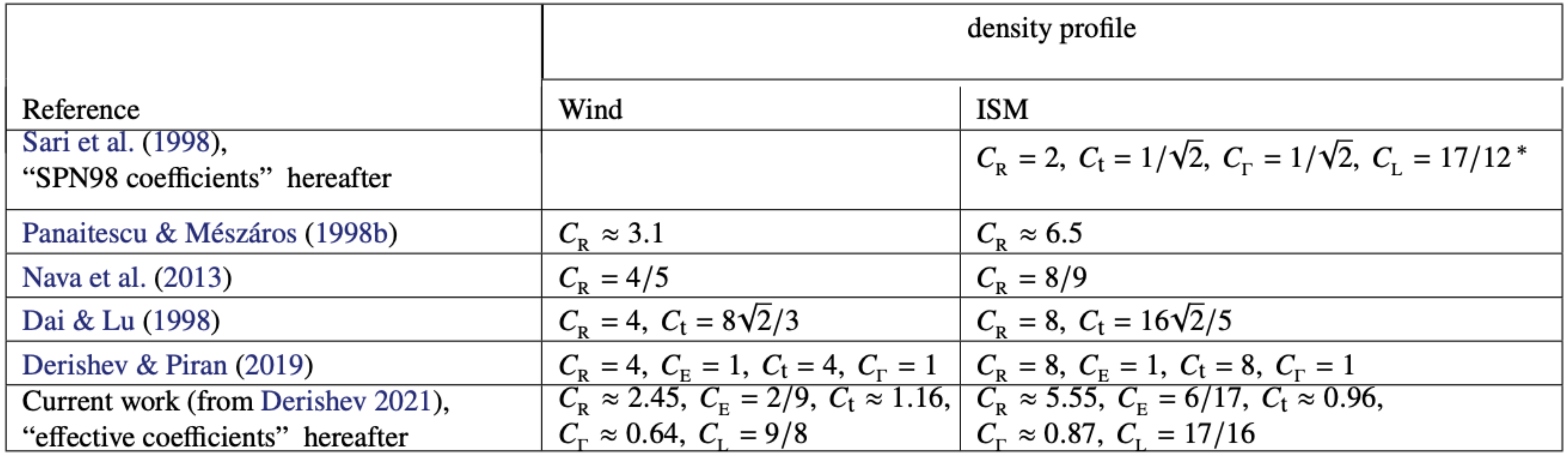
$$R = C_{\mathrm{R}}\Gamma^2 c t_{\mathrm{obs}}/(1+z)$$

$$E_{\mathrm{kin}} = C_{\mathrm{E}}\Gamma^2 M c^2$$

$$t_{\mathrm{eff}} = C_{\mathrm{t}}\Gamma t_{\mathrm{obs}}/(1+z)$$

$$h\nu_{\mathrm{obs}} = C_{\Gamma}\Gamma h\nu/(1+z)$$

$$L = C_{\mathrm{L}}\epsilon_r\ (1+z)E_{\mathrm{kin}}/t_{\mathrm{obs}}$$



	density profile	
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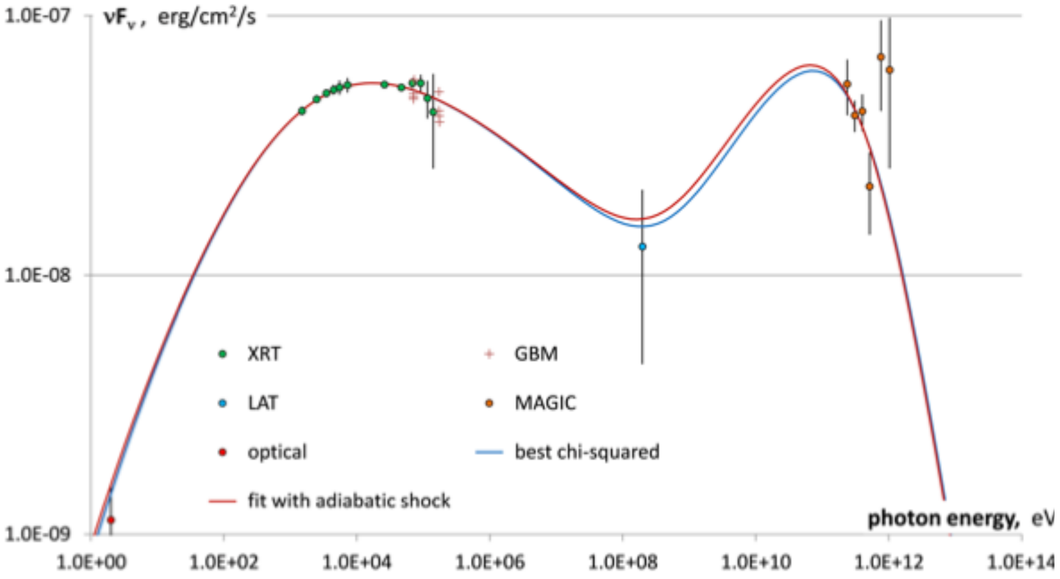
First Guesses 190114c

- $\gamma\Gamma\ m_e c^2 > E_{IC} \Rightarrow \gamma\Gamma \simeq 10^6$
- @ 70 sec and longer Γ cannot be too large $\Rightarrow \gamma \gtrsim 10^4$
- => Tev is Inverse Compton of X-rays (Consistent with a comparable X-ray luminosity)

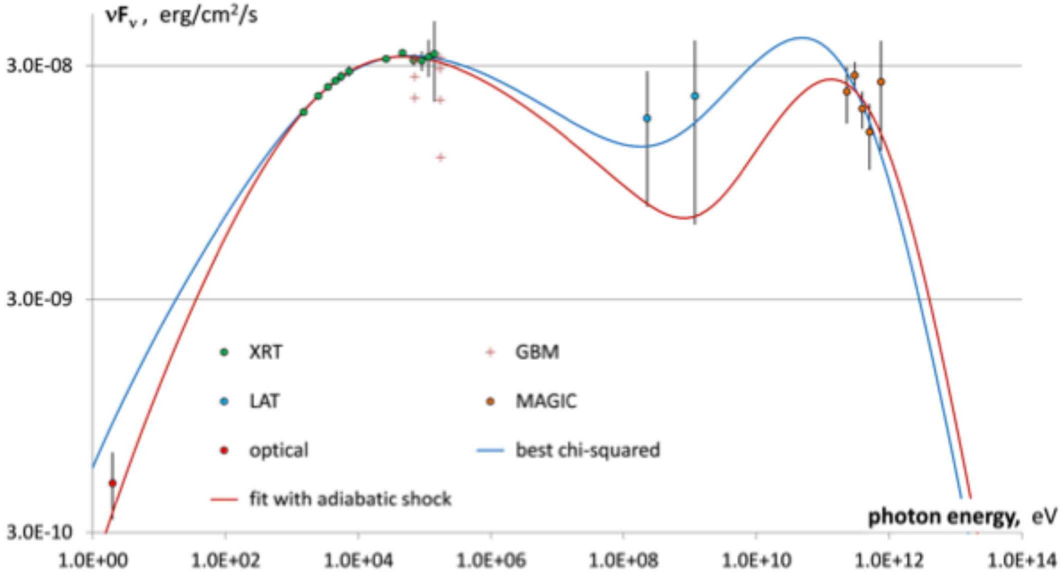
Detailed modeling

(Derishev & TP 2021)

- Conditions at the emitting region are determined by Γ, B, γ_{m}, $\epsilon_{\mathrm{e}}/\epsilon_{\mathrm{B}}$



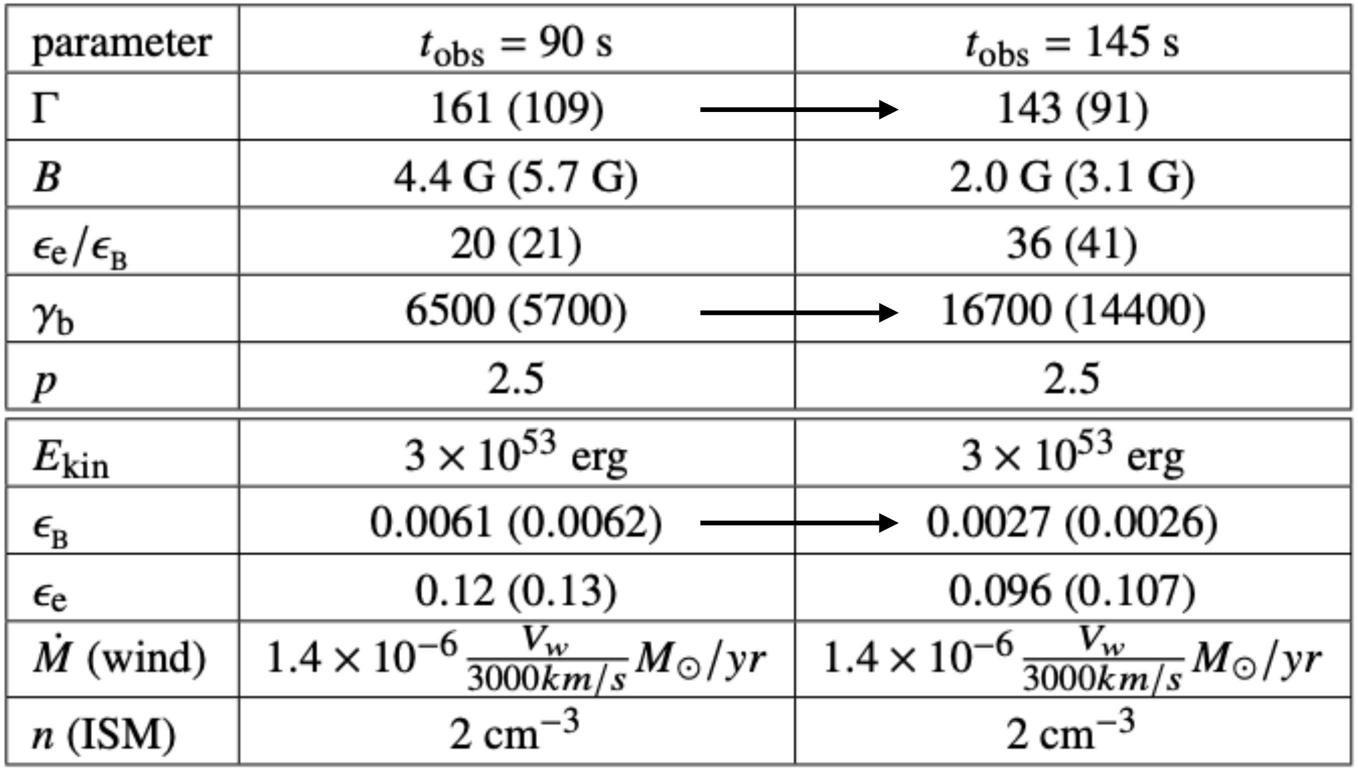
Early - 90 sec



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



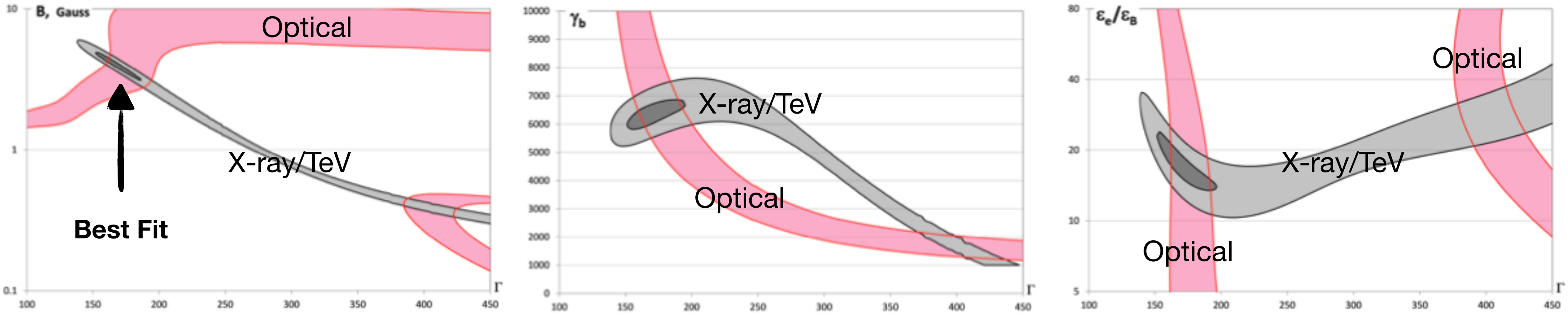
parameter	$t_{\rm obs} = 90$ s	$t_{\rm obs} = 145$ s
Γ	161 (109)	143 (91)
B	4.4 G (5.7 G)	2.0 G (3.1 G)
$\epsilon_{\rm e}/\epsilon_{\rm B}$	20 (21)	36 (41)
$\gamma_{\rm b}$	6500 (5700)	16700 (14400)
p	2.5	2.5
$E_{\rm kin}$	3×10^{53} erg	3×10^{53} erg
$\epsilon_{\rm B}$	0.0061 (0.0062)	0.0027 (0.0026)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

- 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)
- ϵ_B = 0.006 -> 0.003 (Varies)
- Somewhat surprisingly large Γ (large energy, low external density)

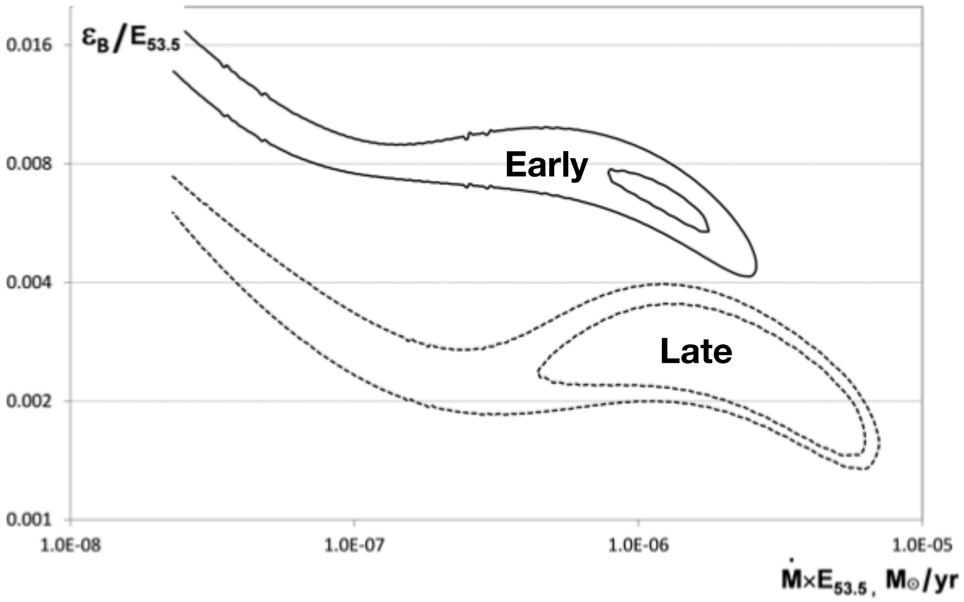
Detailed modeling

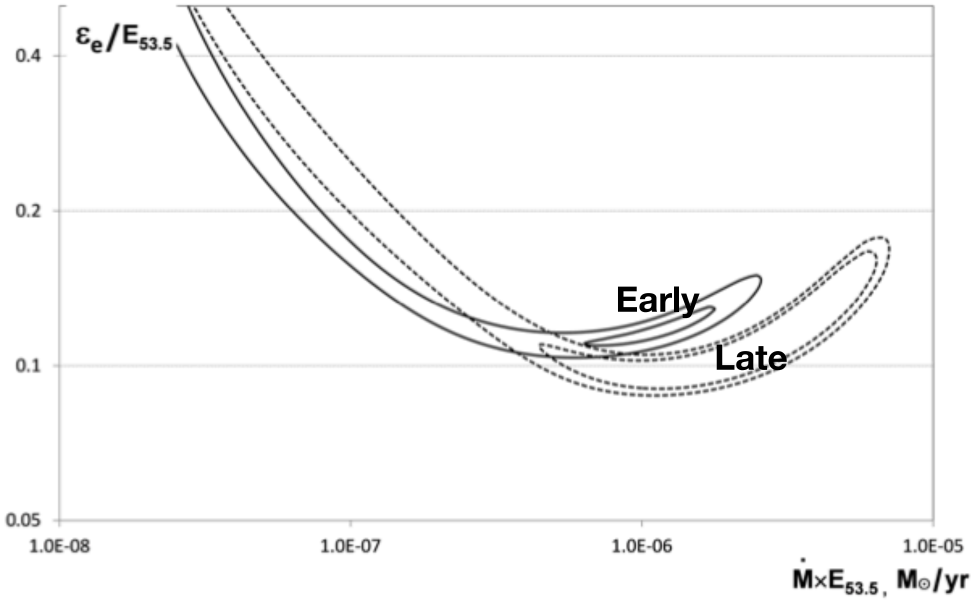
- Conditions at the emitting region are determined by Γ, B, γ_m, ϵ_e/ϵ_B



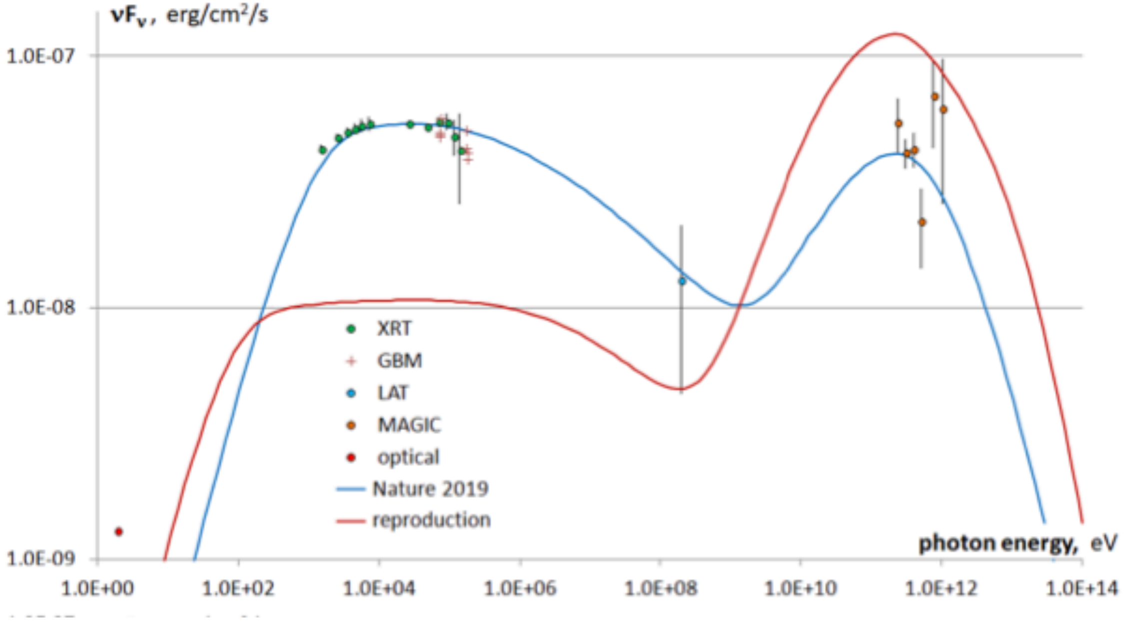
<- Fast cooling | slow cooling ->

ϵ_B must vary with time



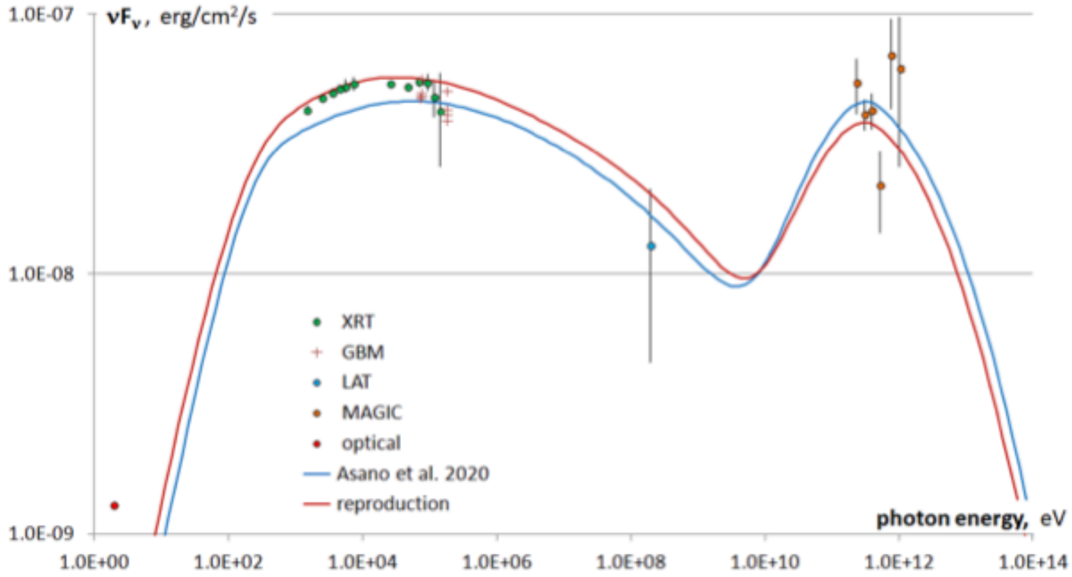


Comparison with other work

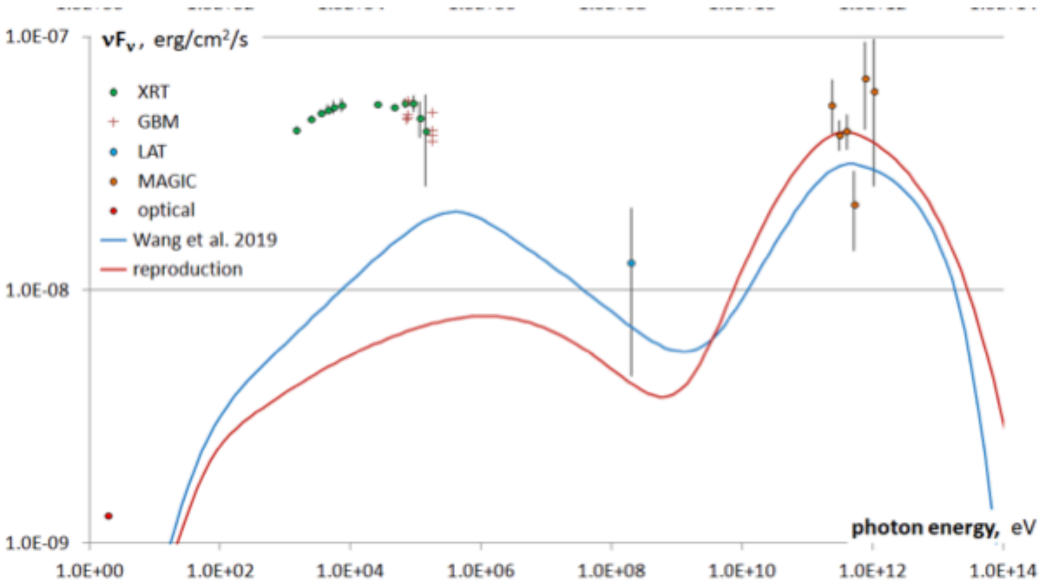


Magic 2019 ???

Comparison with other work



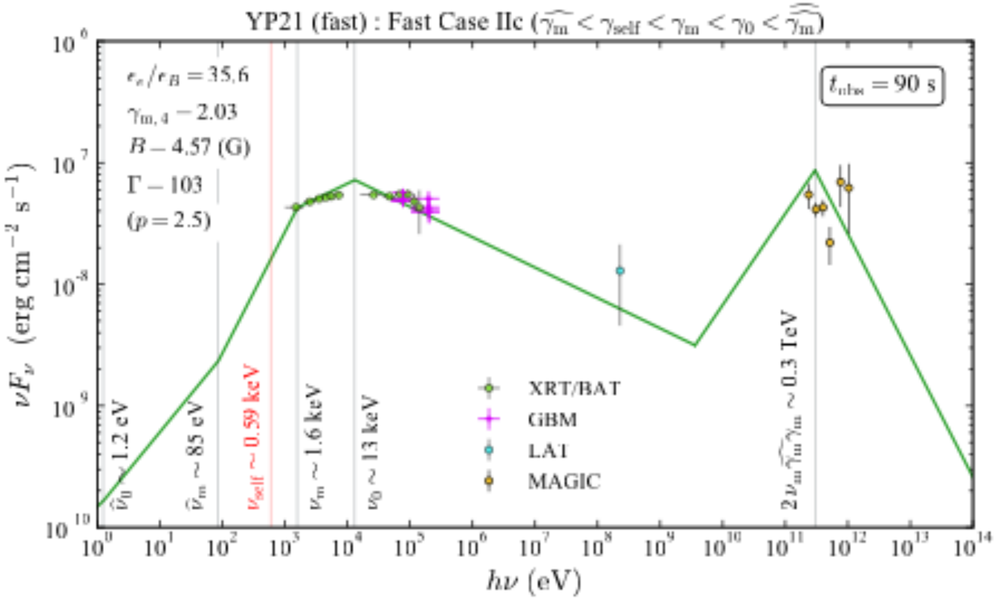
Asano & Murase 2020

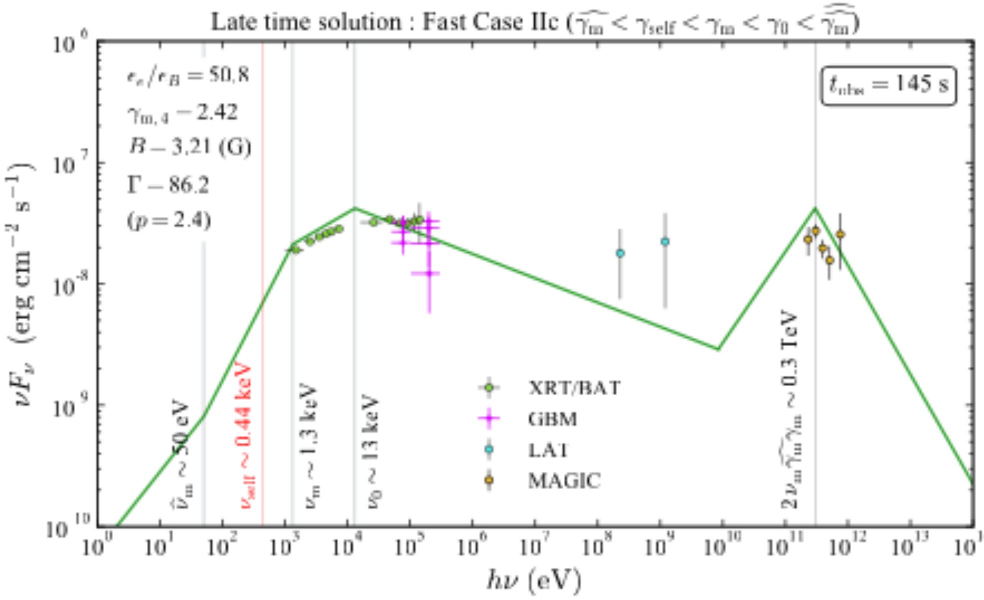


Wang et al., 2019

Analytic

Yamasaki & Piran 2021 following Nakar et al., 2009*

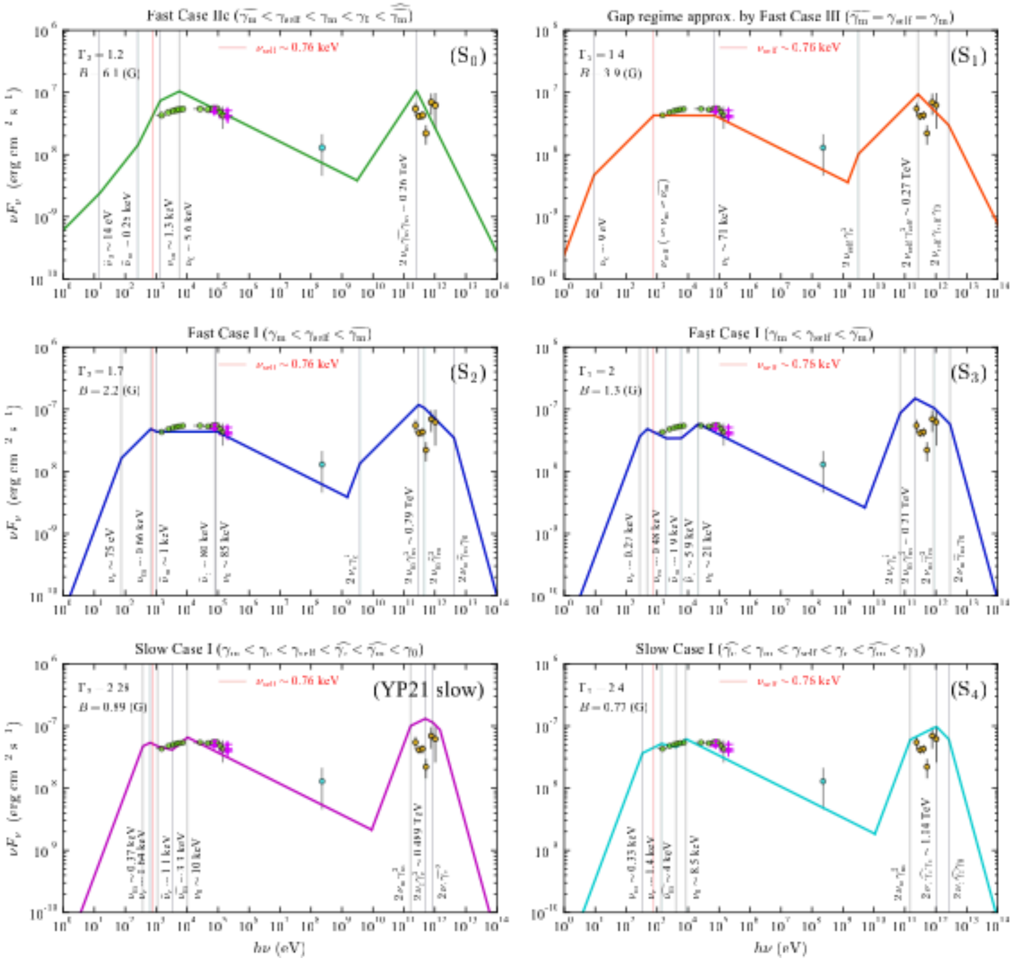

YP21 (fast) : Fast Case IIc ($\widetilde{\gamma_m} < \gamma_{self} < \gamma_m < \gamma_0 < \widetilde{\widetilde{\gamma_m}}$)

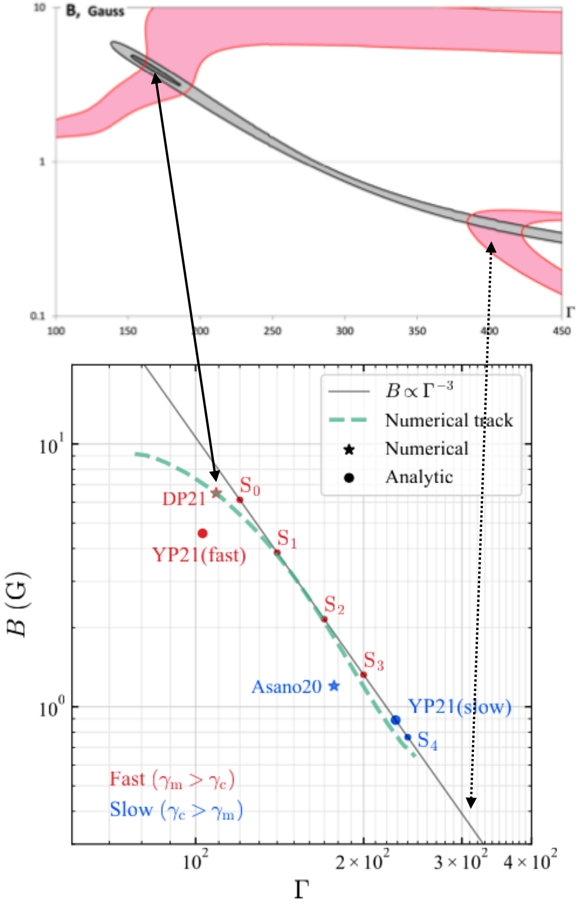

Late time solution : Fast Case IIc ($\widetilde{\gamma_m} < \gamma_{self} < \gamma_m < \gamma_0 < \widetilde{\widetilde{\gamma_m}}$)

* Sharp threshold for KN effect must be modified to start at ~100 keV

Analytic

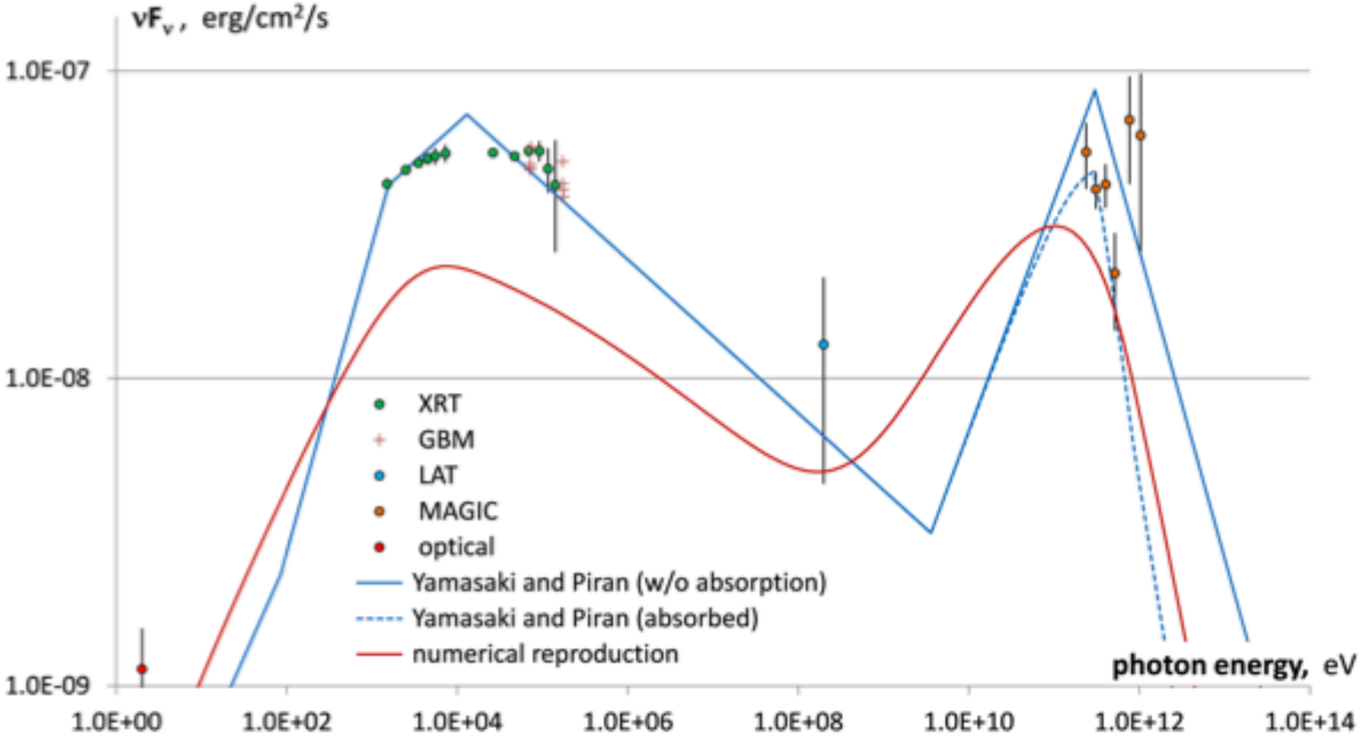
Yamasaki & Piran 2021 following Nakar et al., 2009



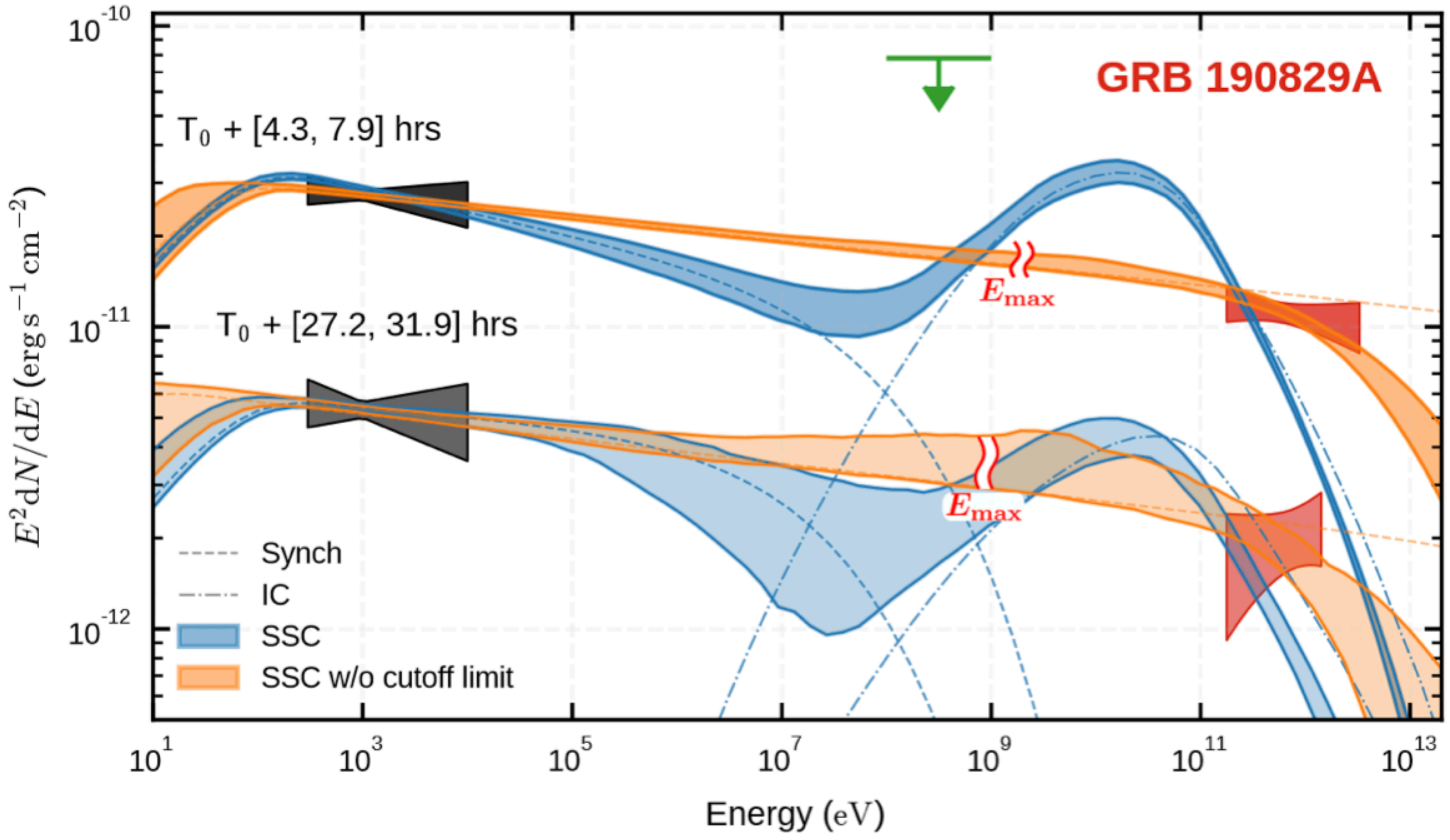


Analytic

Yamasaki & Piran 2021 following Nakar et al., 2009

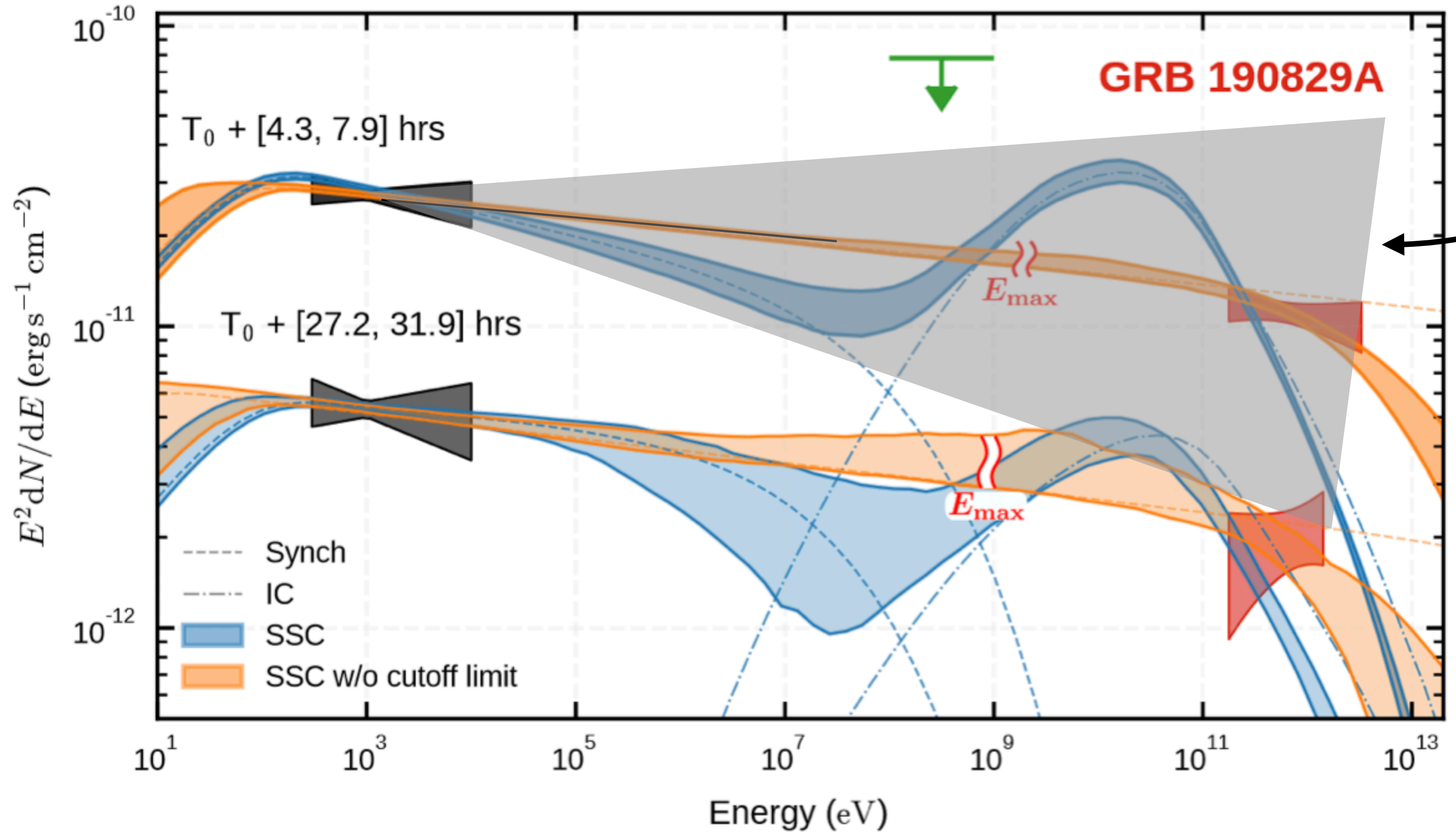


190829A

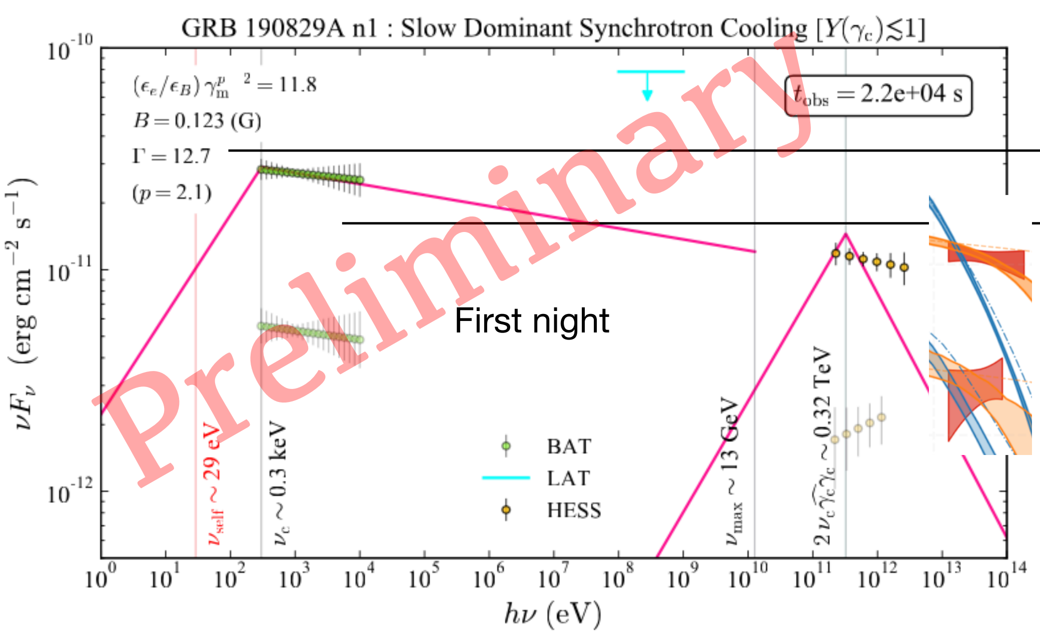

GRB 190829A
T$_0$ + [4.3, 7.9] hrs
T$_0$ + [27.2, 31.9] hrs
$E_{\rm max}$
$E_{\rm max}$
Synch
IC
SSC
SSC w/o cutoff limit
$E^2 dN/dE$ (erg s^{-1} cm^{-2})
Energy (eV)
10^{-10}
10^{-11}
10^{-12}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}

A strange claim of a single power-law fit

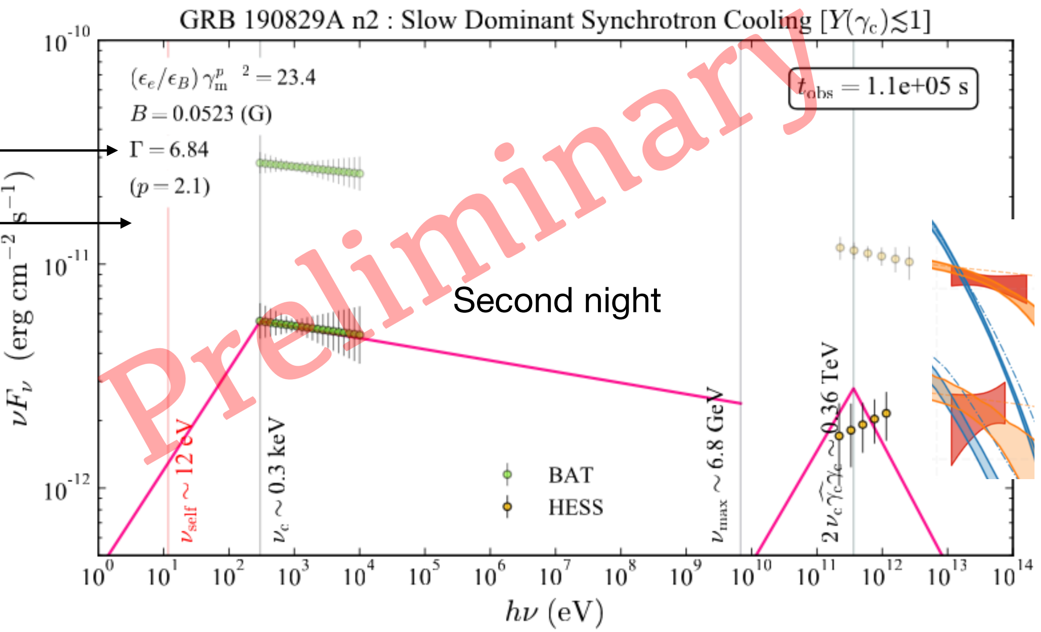
With the error bars of the X-ray slope everything can fit a single power low to the TeV



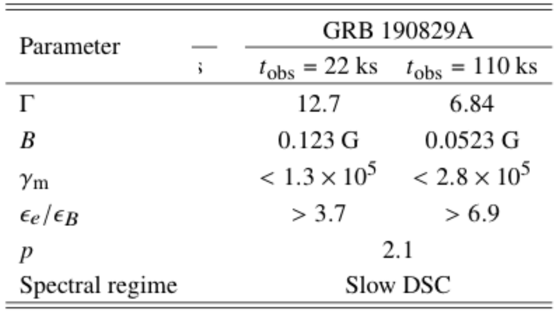
190829A analytic modeling



First night



Second night



Parameter	GRB 190829A	
	t_{obs} = 22 ks	t_{obs} = 110 ks
Γ	12.7	6.84
B	0.123 G	0.0523 G
γ_m	$< 1.3 \times 10^5$	$< 2.8 \times 10^5$
ϵ_e/ϵ_B	> 3.7	> 6.9
p	2.1	
Spectral regime	Slow DSC	

- $\gamma^3 B \lesssim 10^{14}$

Yamasaki & TP 2021

Summary

- TeV observations of both 190114c and 190829A seems to require modification of the simple afterglow model.

- A model independent fits for both bursts lead to parameters and evolutionary behavior that are (surprisingly) consistent with the Pair Balance model.

Thanks for the attention