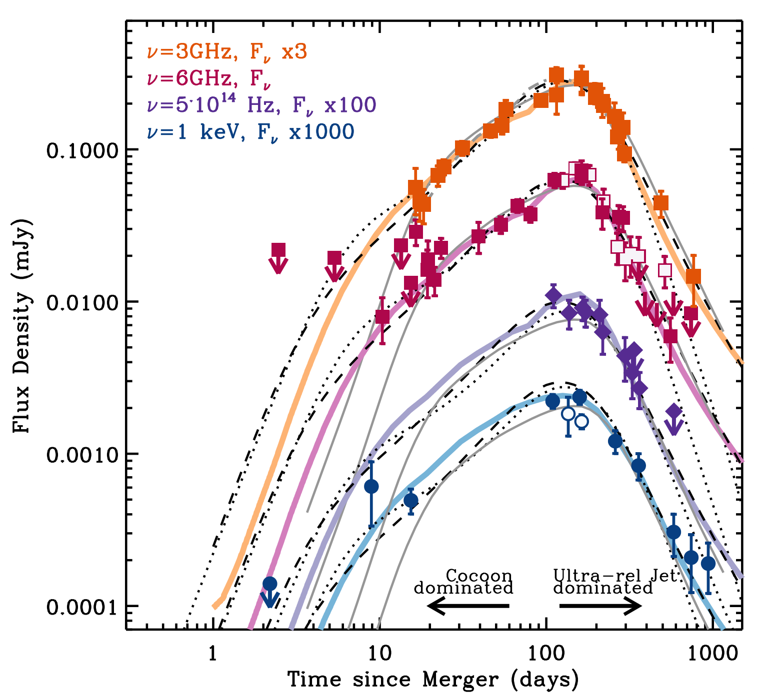
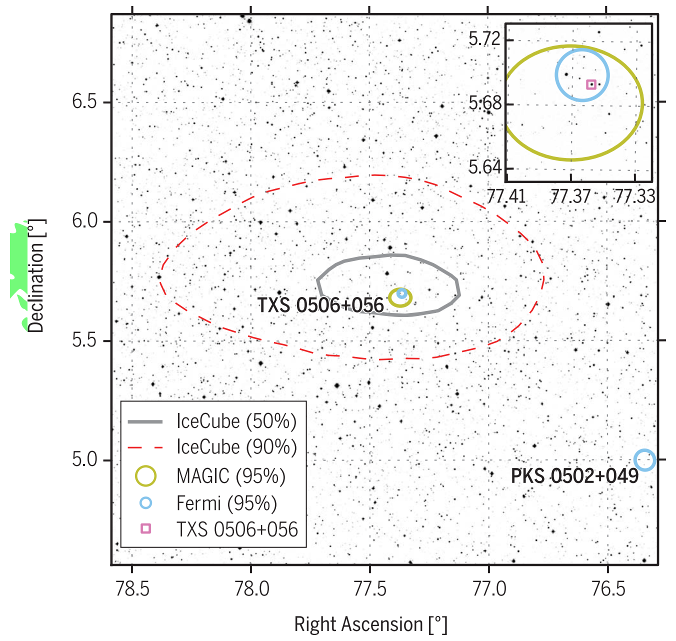
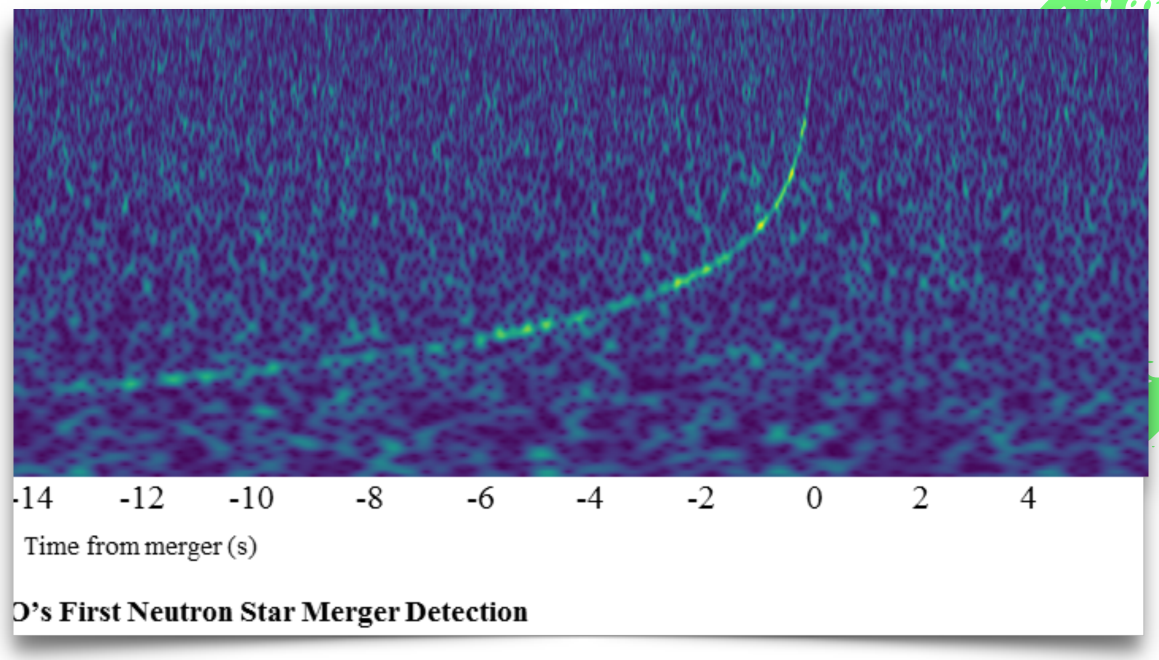
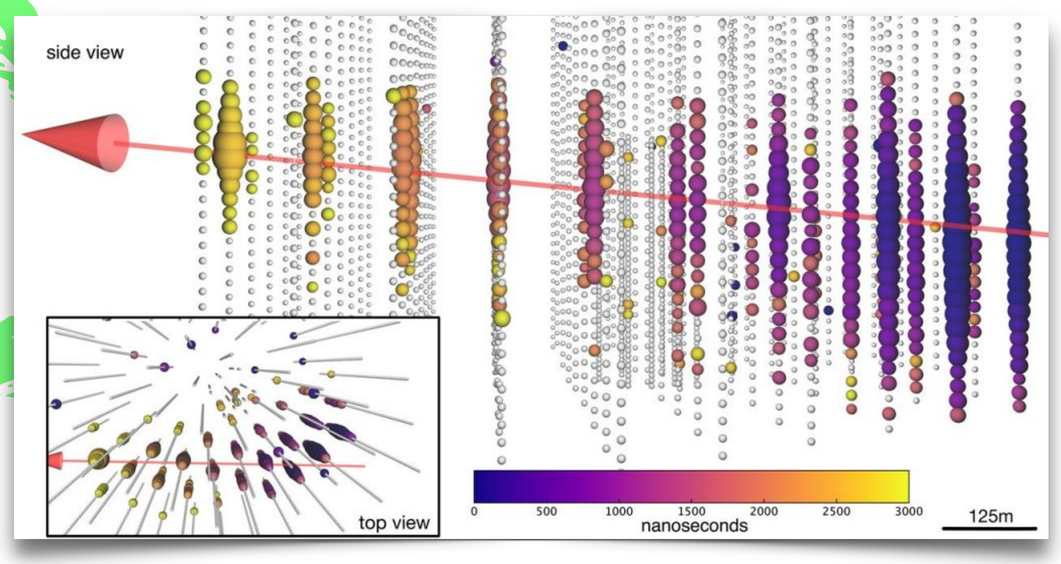
Multi-messenger astrophysics

THE TRIANGLE OF MULTI-MESSENGER ASTROPHY.: MM3





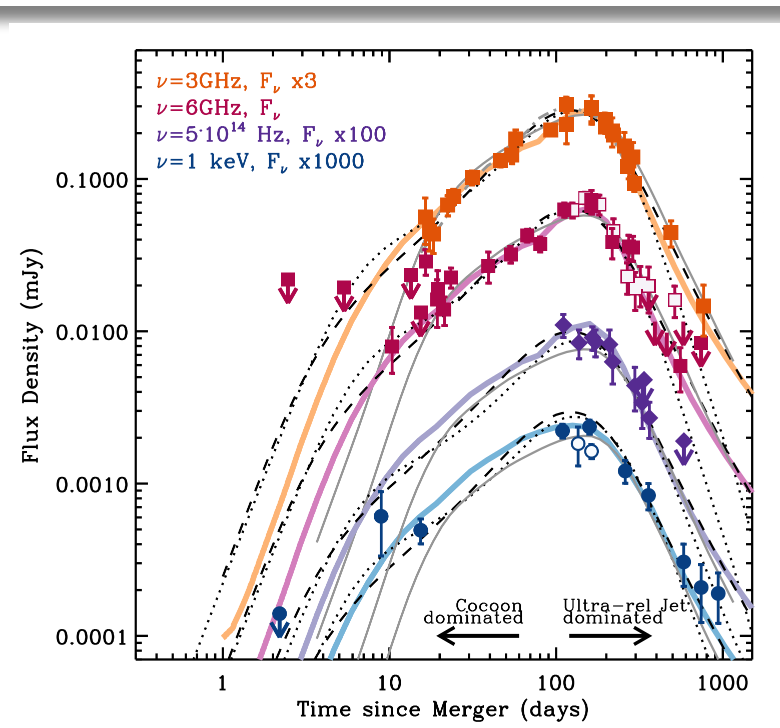


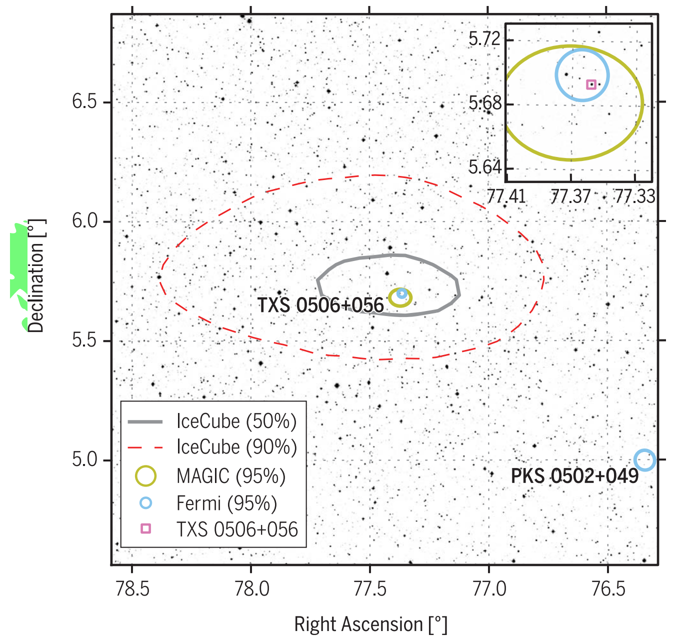


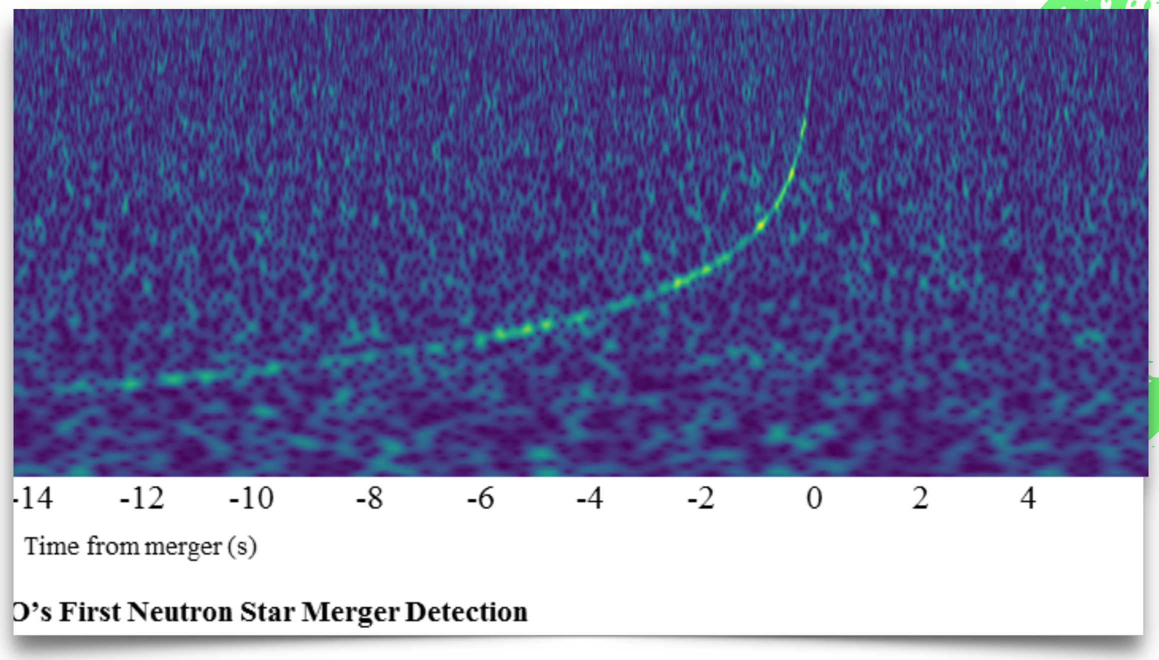
MM3

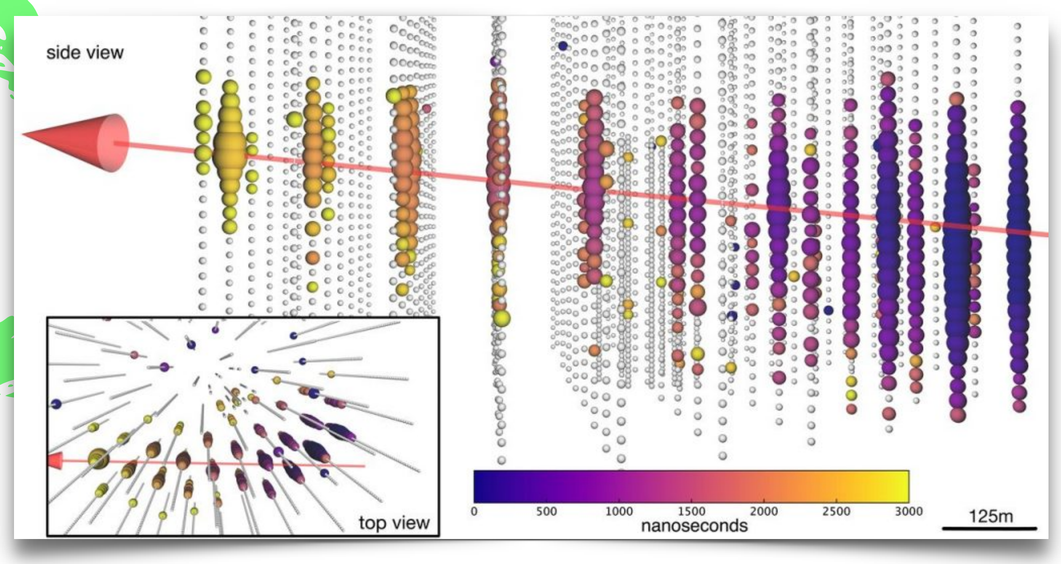
1. First GW signal BNS
2. Short Gamma Burst (1.7 s after)
3. Fast Opt/NIR (Kilonova)
4. Long lasting (>1yr) (non thermal)

1. NS physical prop.
2. BNS = short GRB progenitors
3. BNS contribute r-processes
4. A relativistic jet emerged









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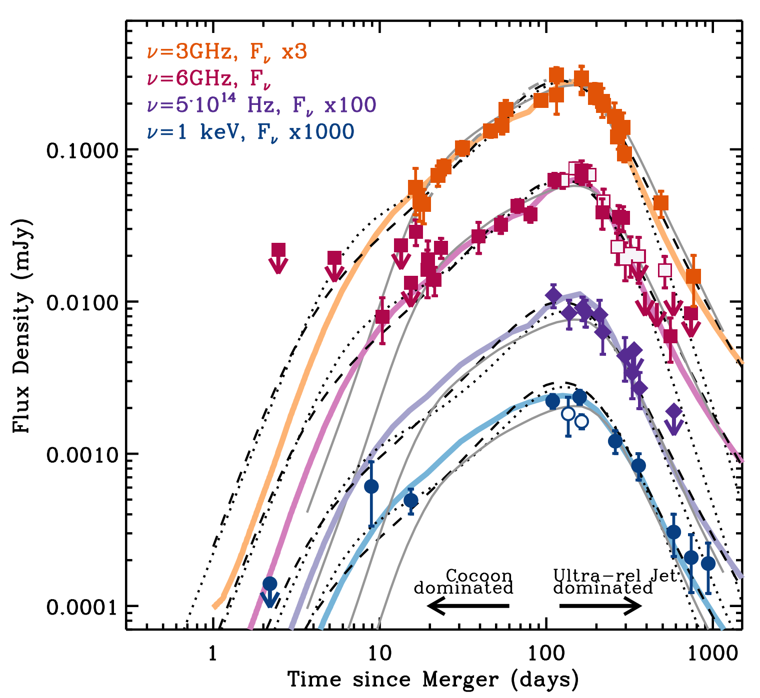
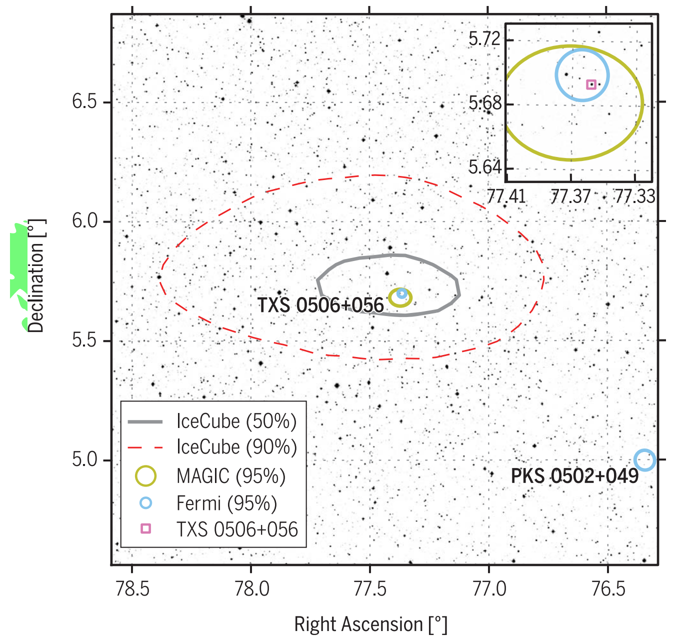
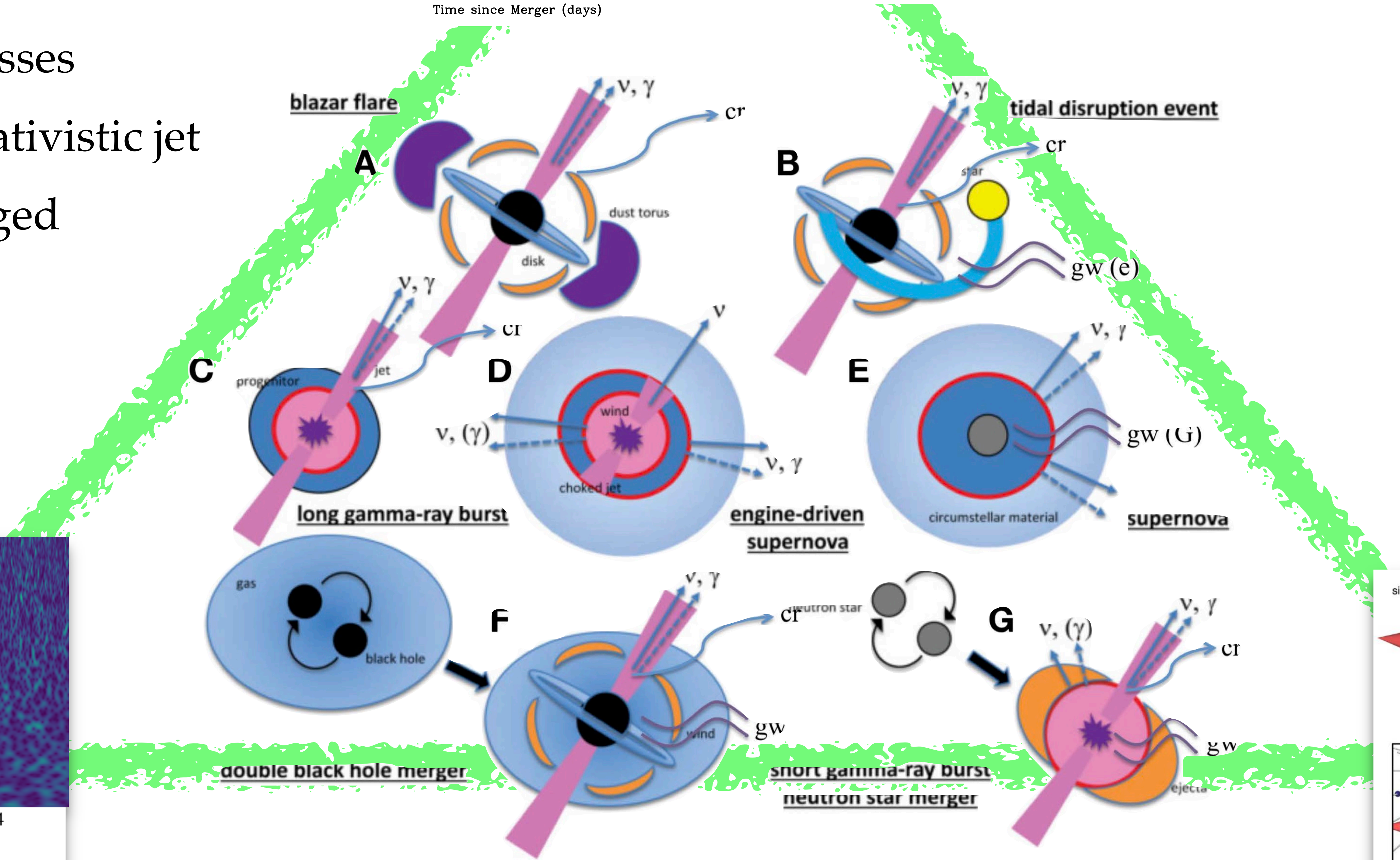
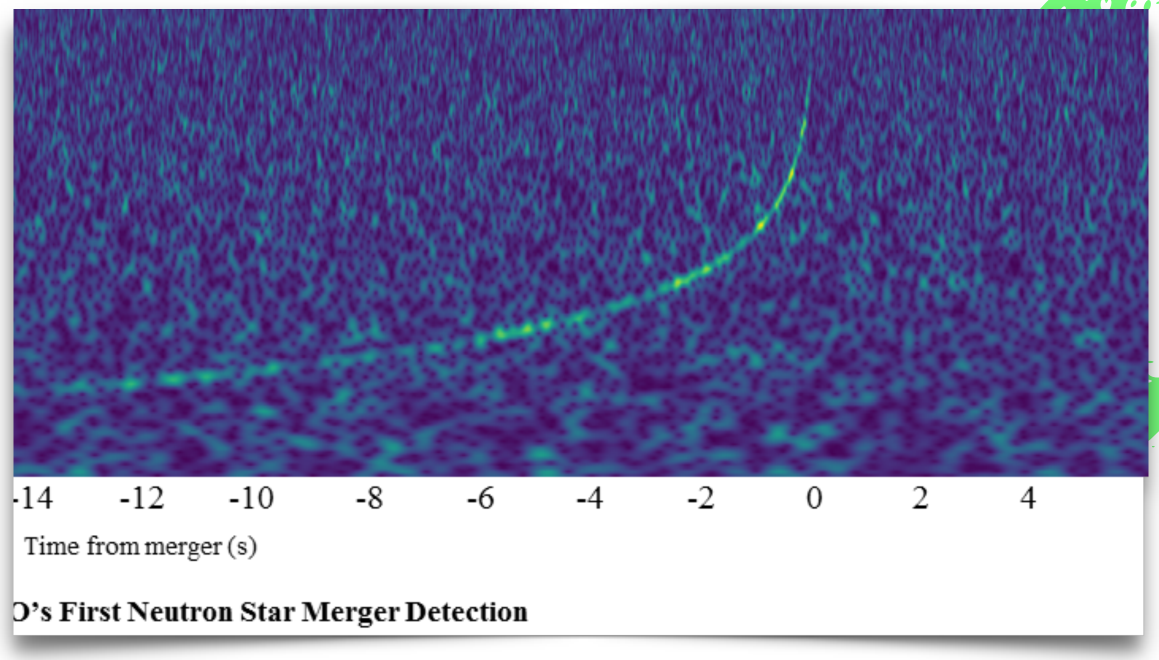


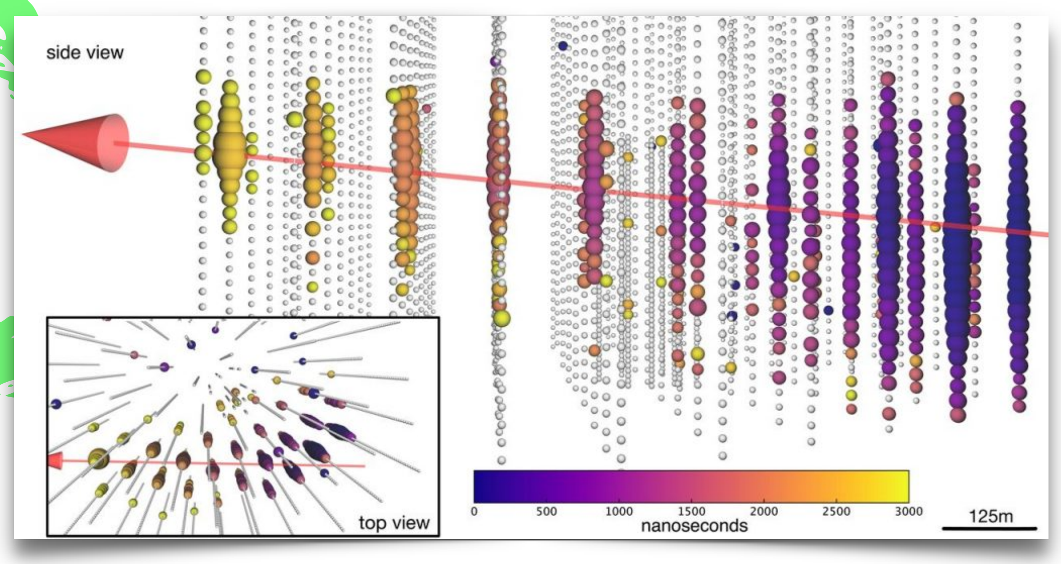


1. 170922 - 290 TeV
2. Blazar TXS 0506+056
3. Possible excess before

1. Physics of acceletators
2. Origin of HECR







Establishing connections between different research fields (across astrophysics and fundamental physics)

PLAN OF THE LECTURES

Legend:
1) L1/L2
2) Title
3) Take home message
4) *References*

L1 — Gamma Ray Bursts

L2 — GRB170817
KN2017gfo

Simplified observational picture and simplified physical model

Hundreds of papers on the subjects: apologise for the incomplete view and for any missing valuable reference

1) Observational picture (short vs long): Berger et al. 2013
2) GRB theoretical picture: Piran 1999; Kumar & Zhang 2015
3) Compact binary mergers: Ruiz et al. 2021
4) 170817 multi-messenger: Nakar 2020; Margutti & Chornok 2020
5) Kilonova: Metzger 2020

Scope of the lectures: acquire basic tools to face the MM2 challenges

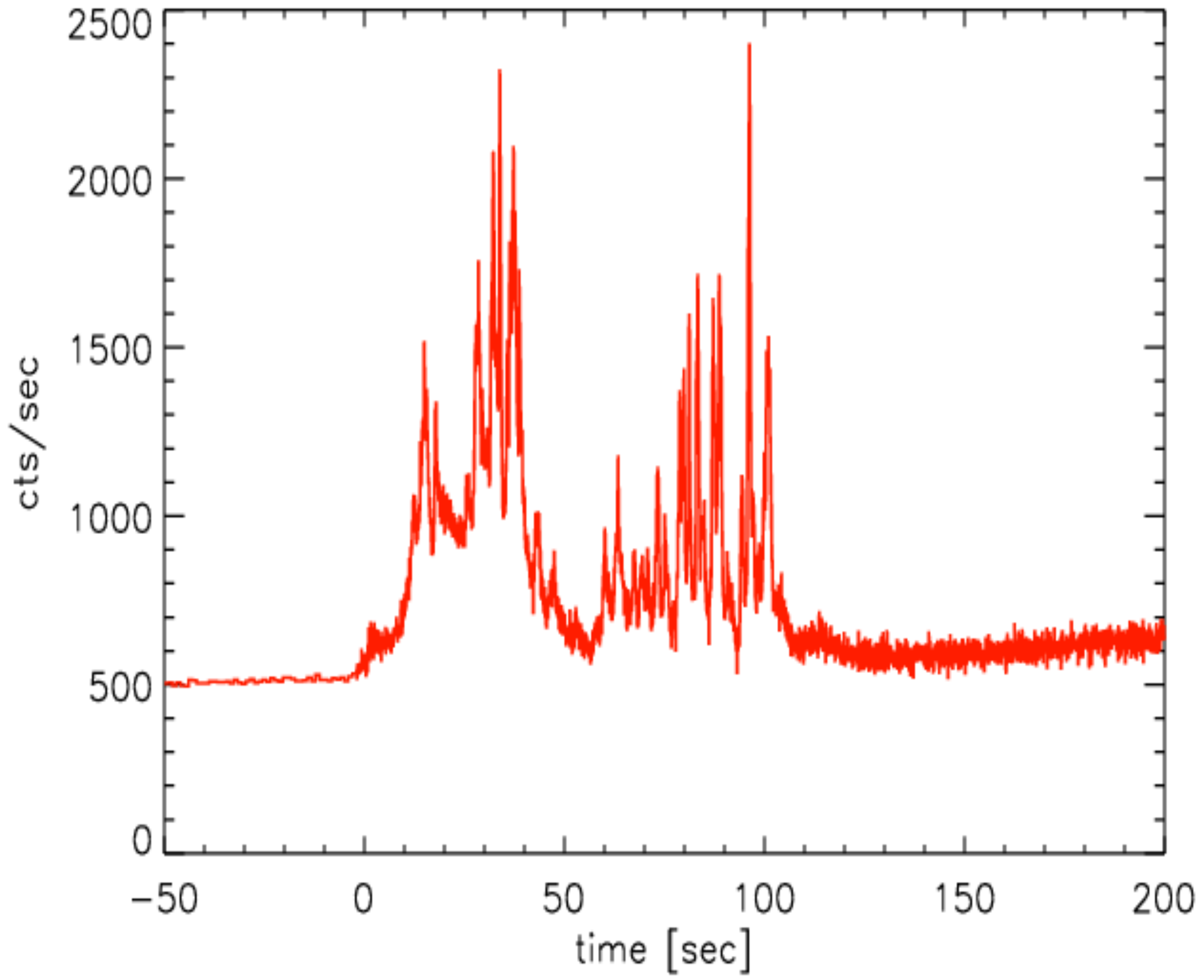
Gamma Ray Bursts*

* Unless explicitly stated what I will descibe is in general (and in fist approximation) valid for both long and short GRBs

Gamma Ray Bursts (GRB)

>1973

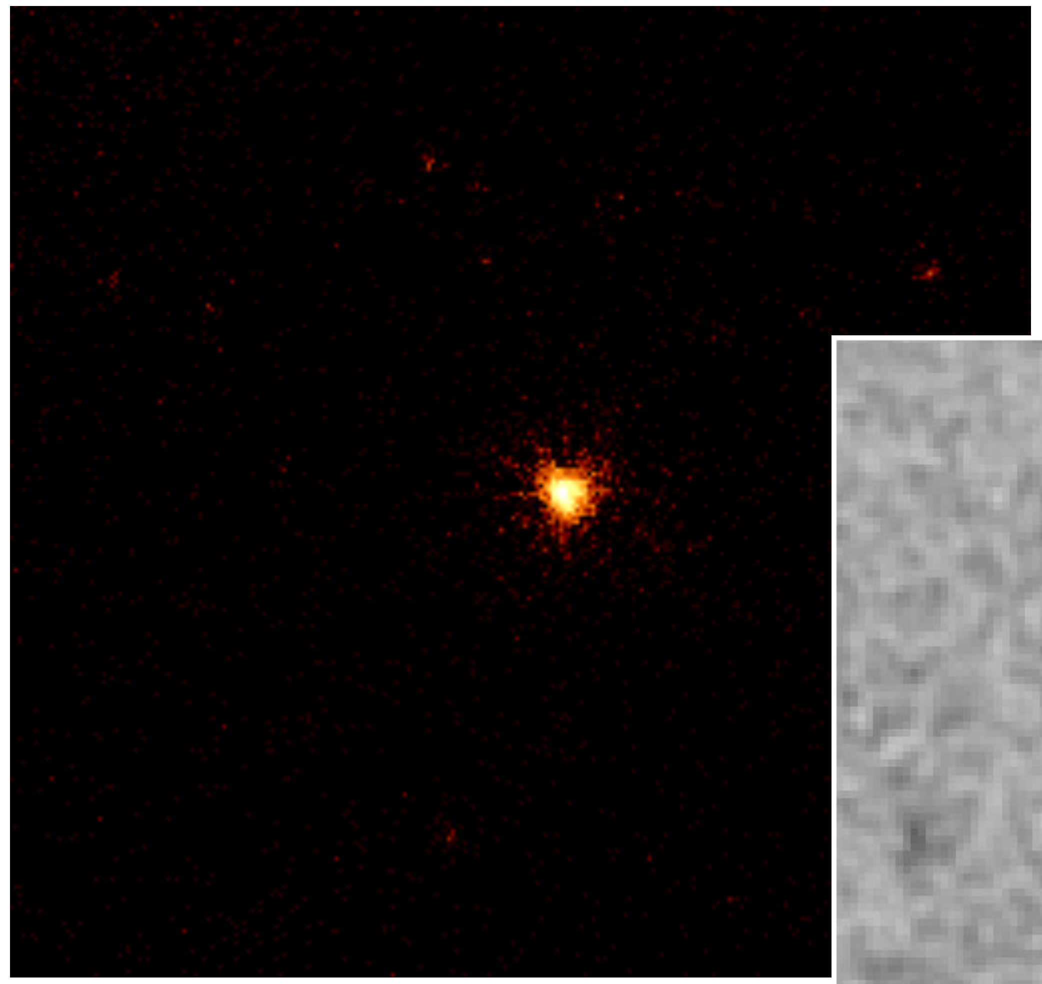
Short flashes of keV photons



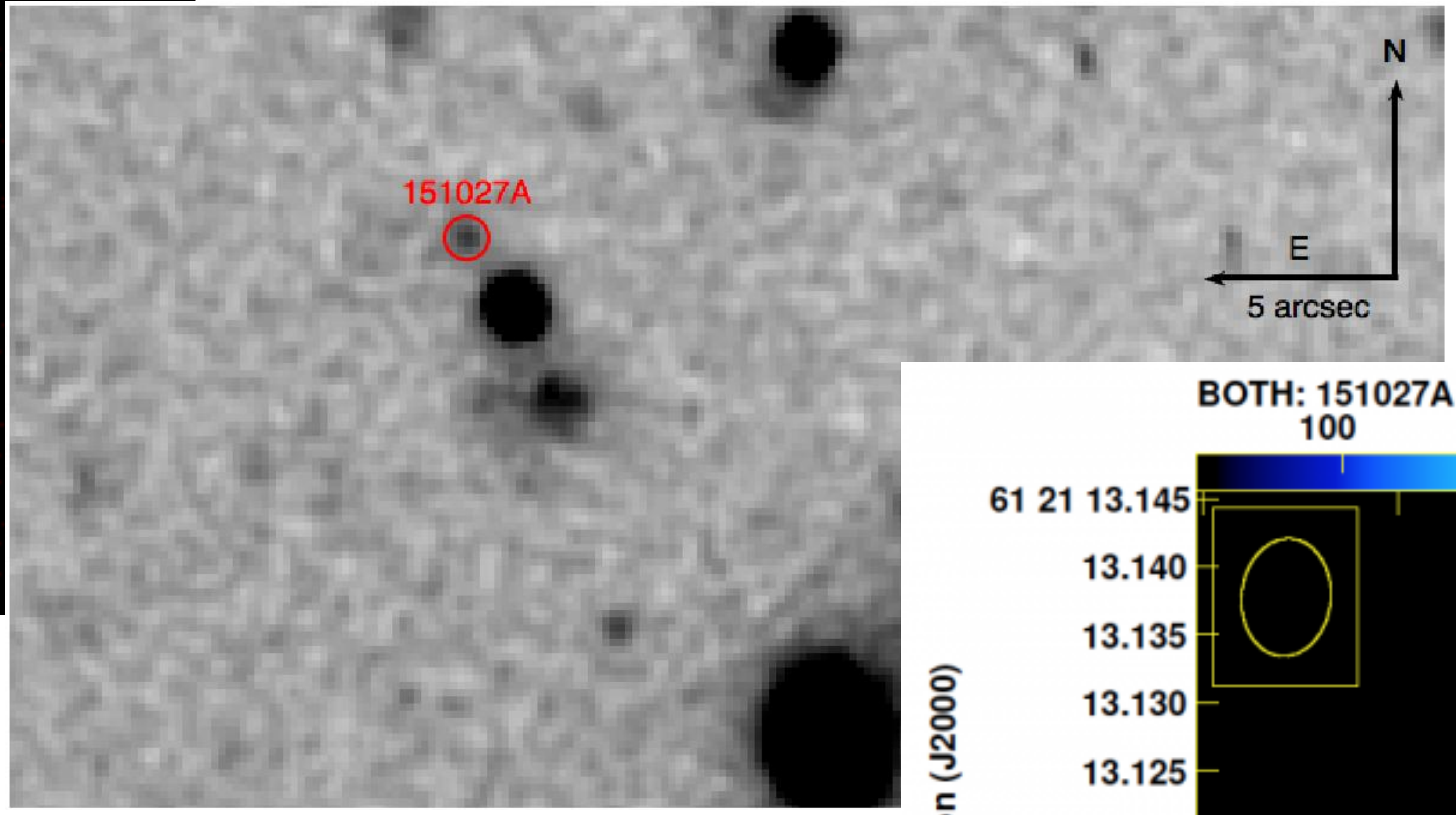
Prompt

>1997

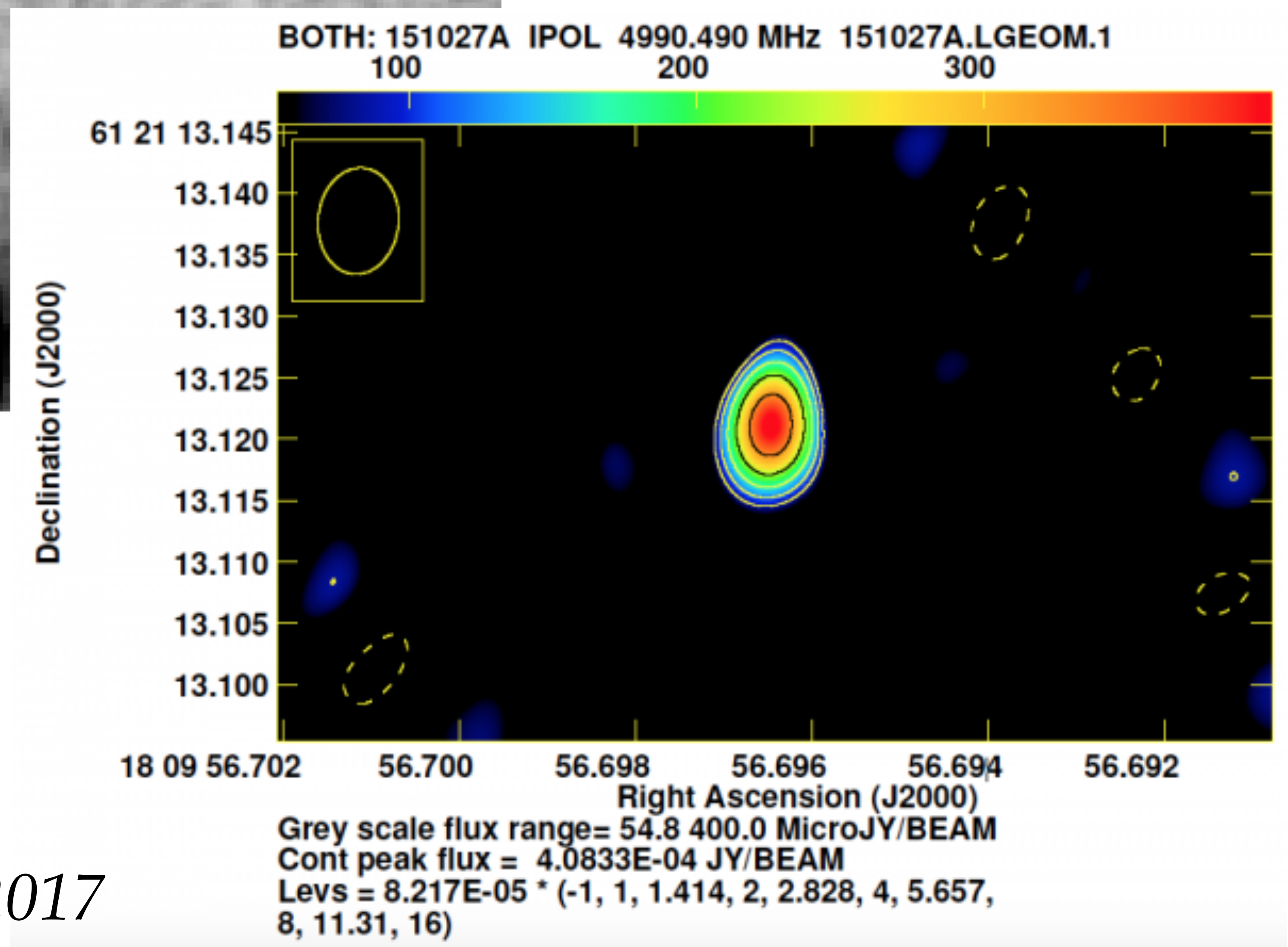
X-ray



Optical



Radio



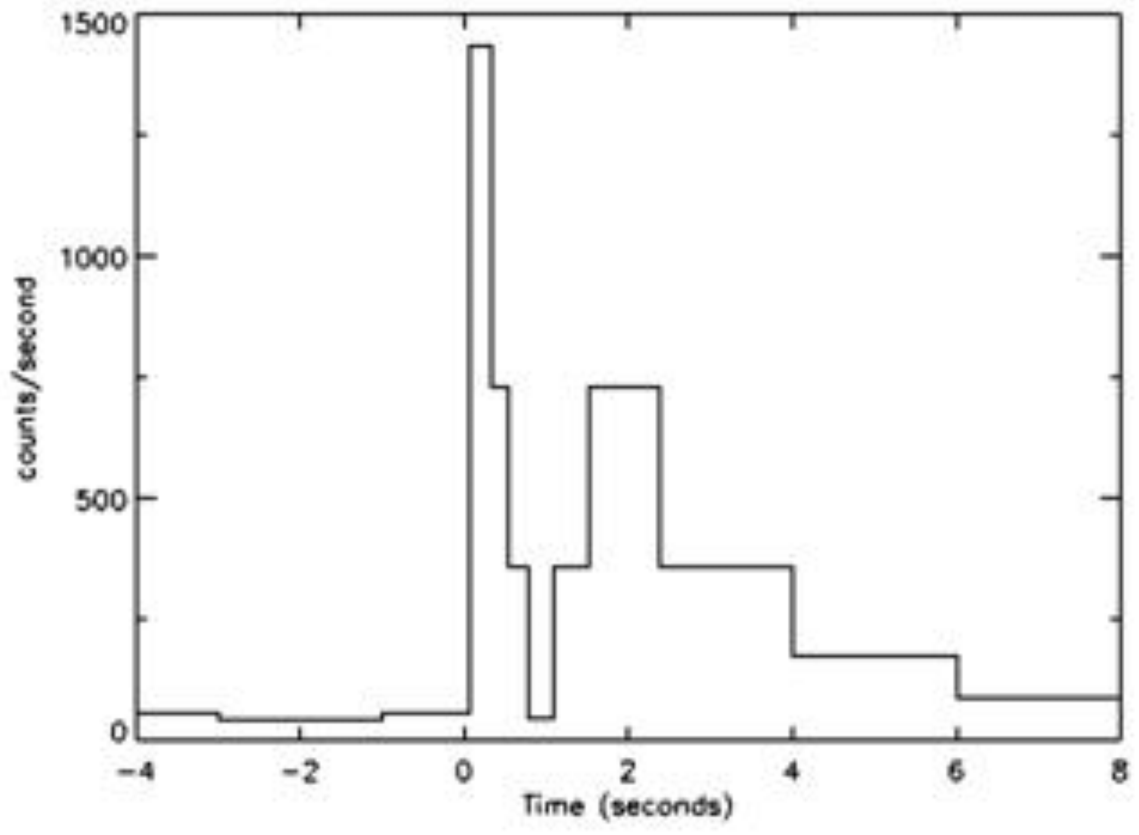
Afterglow

e.g. GRB 151027A: Nappo+2017

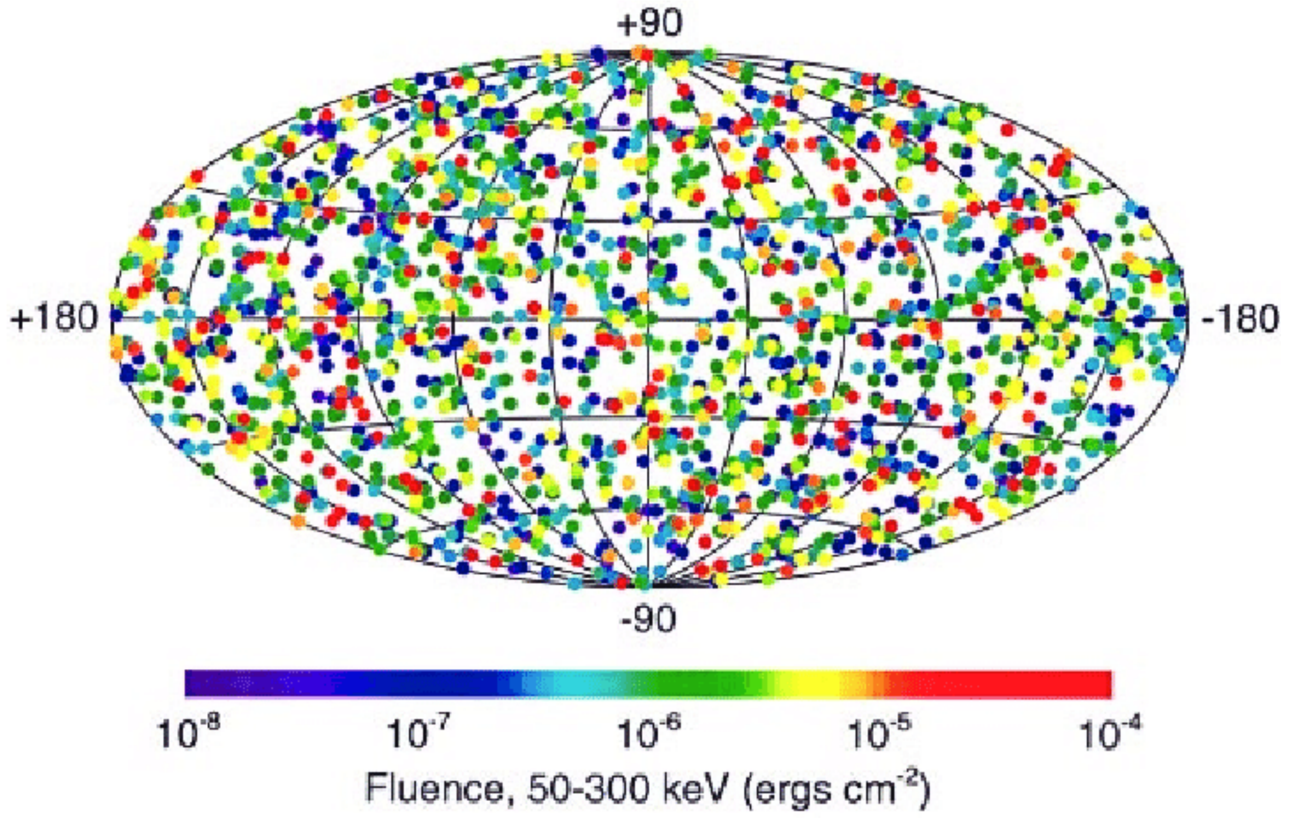
GRBs are multi-wavelength emitters

KEY DISCOVERIES

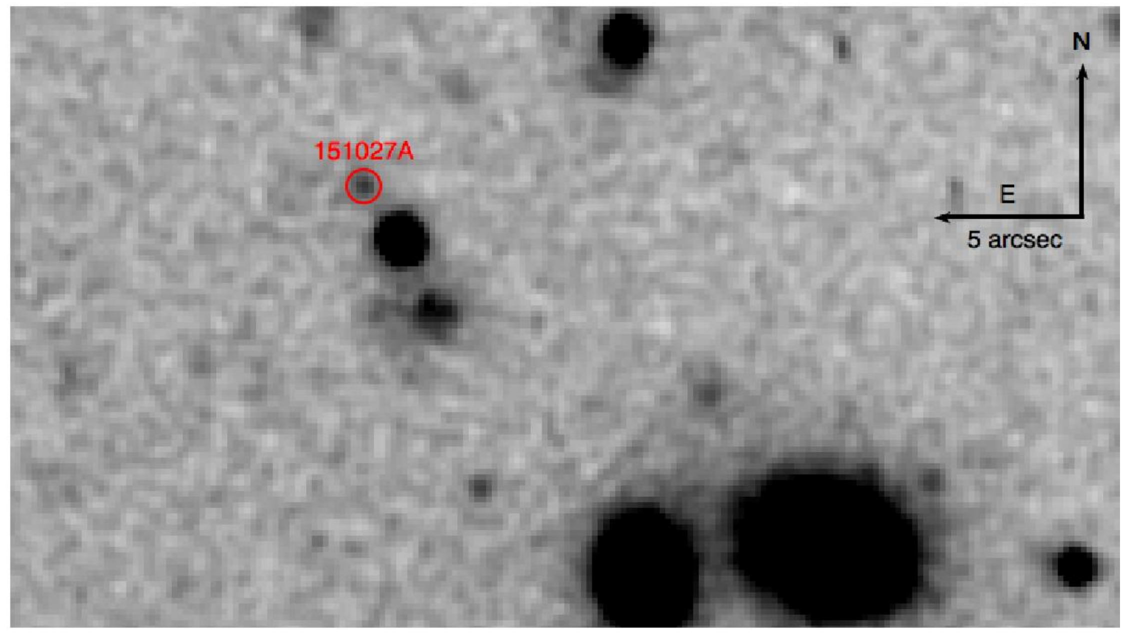
Vela Satellites



CGRO

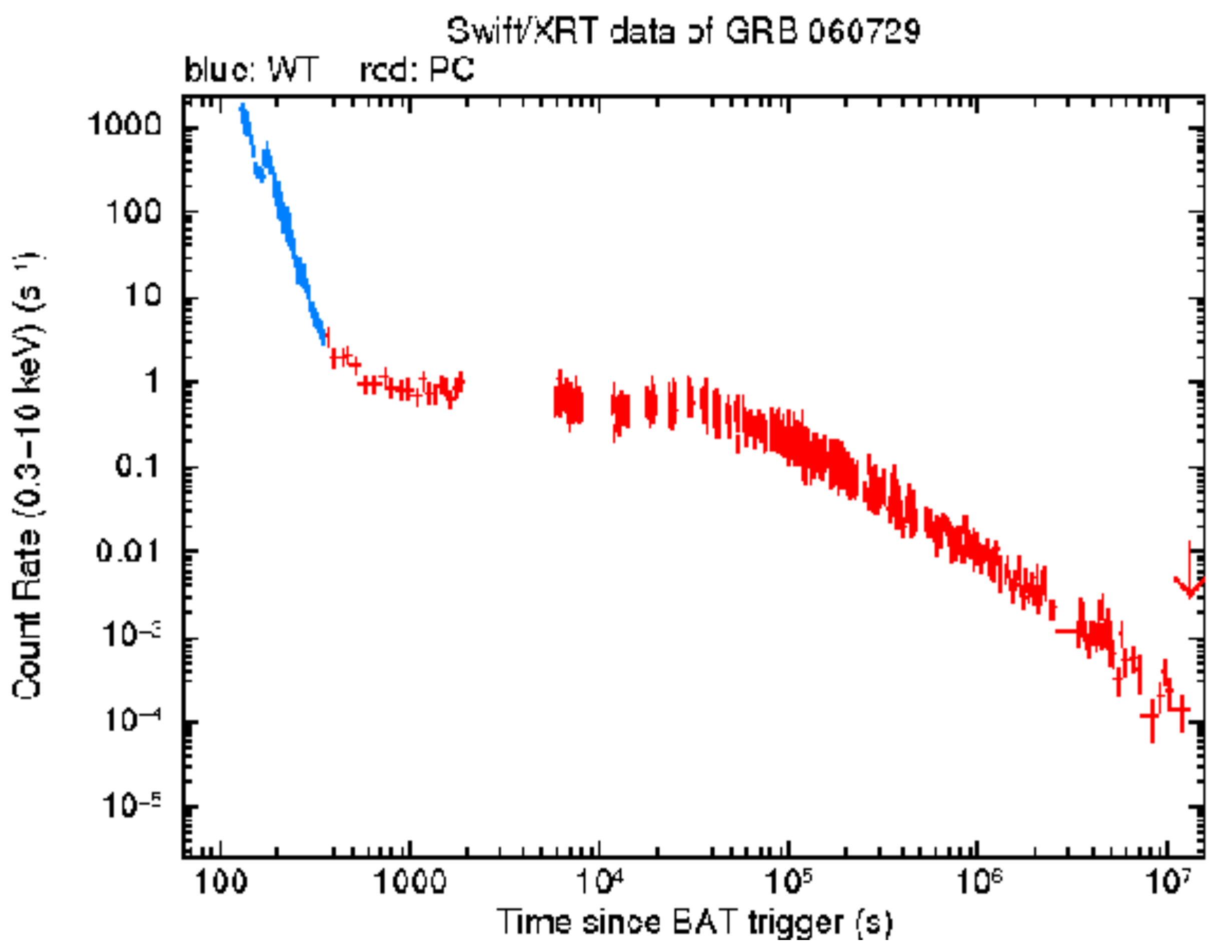


BeppoSAX+Ground

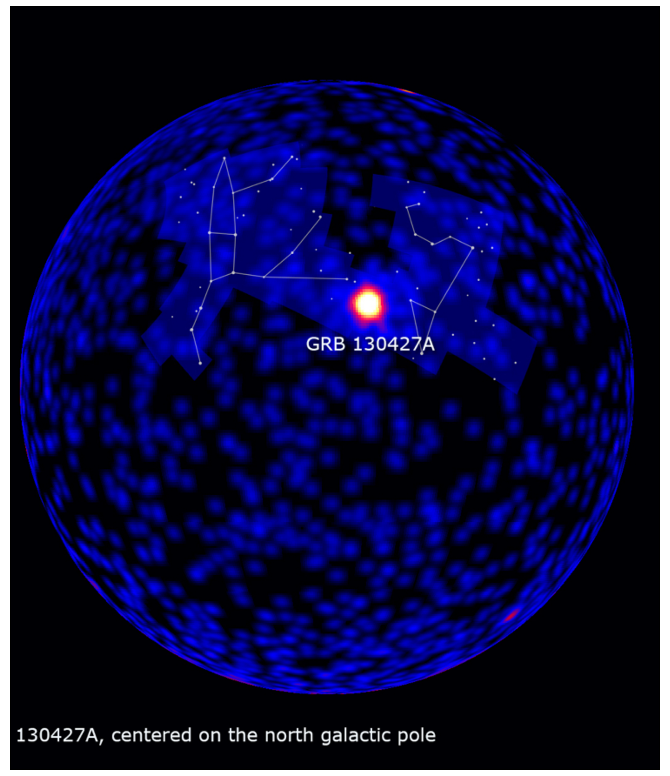


1973 — 1992 — 1997 — 1998

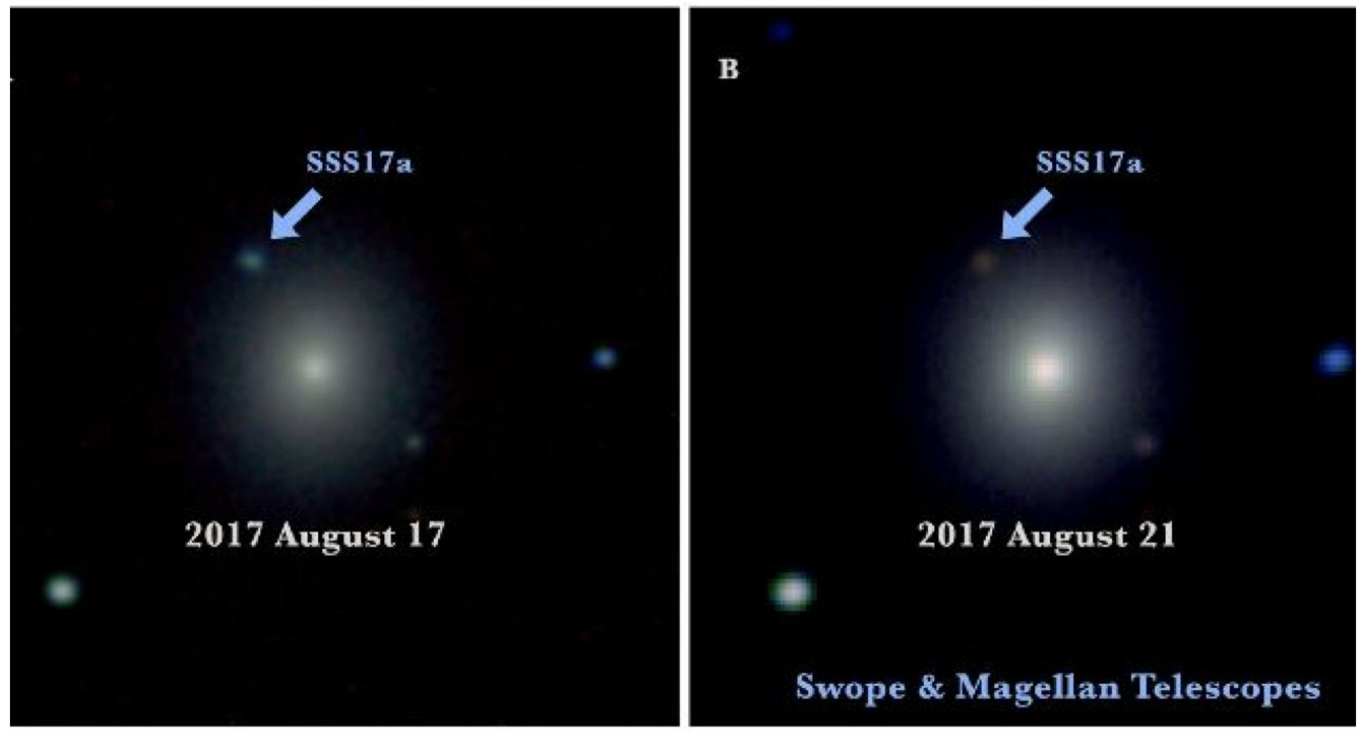
Swift



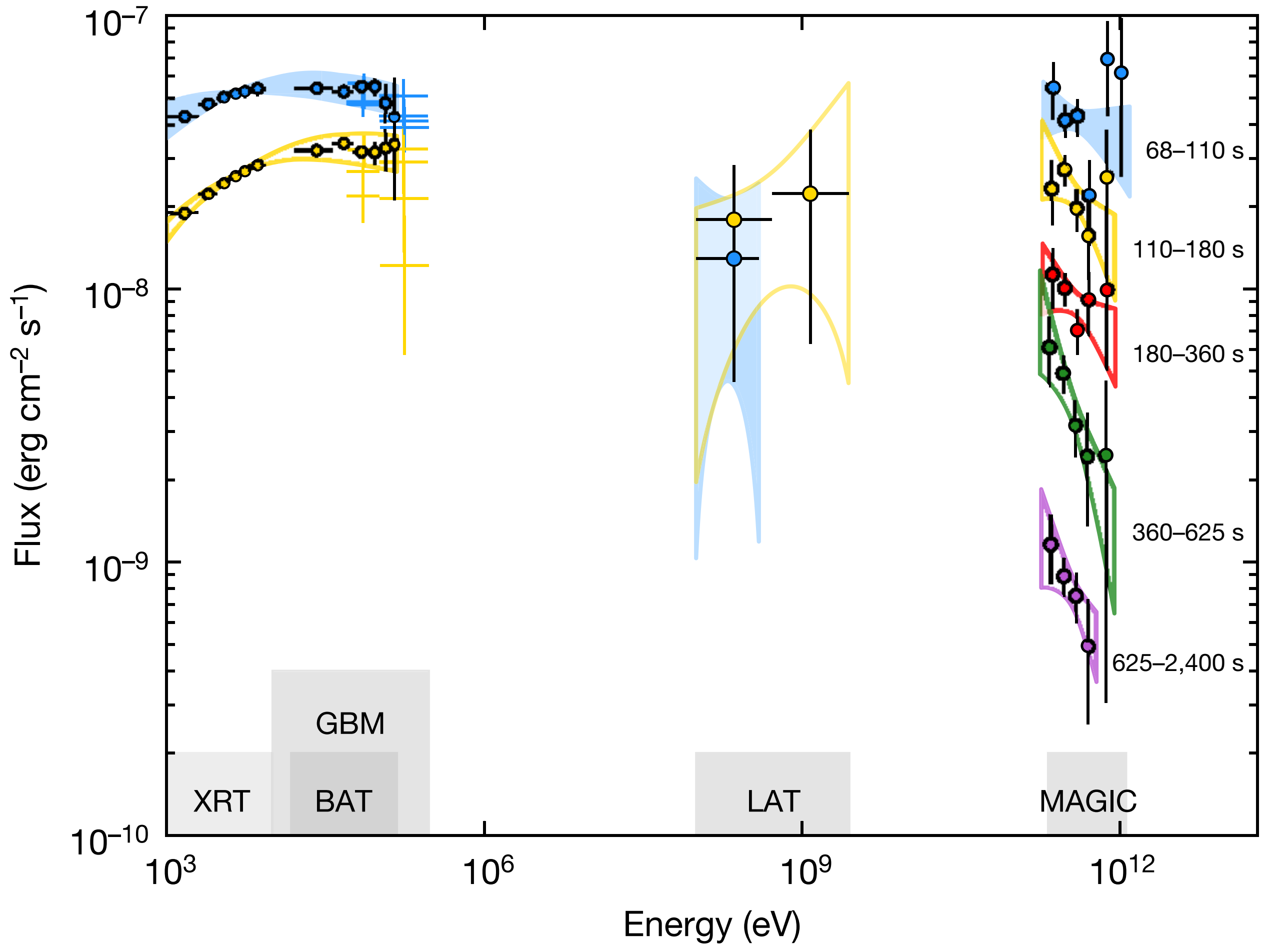
Fermi



LVC+Space+Ground

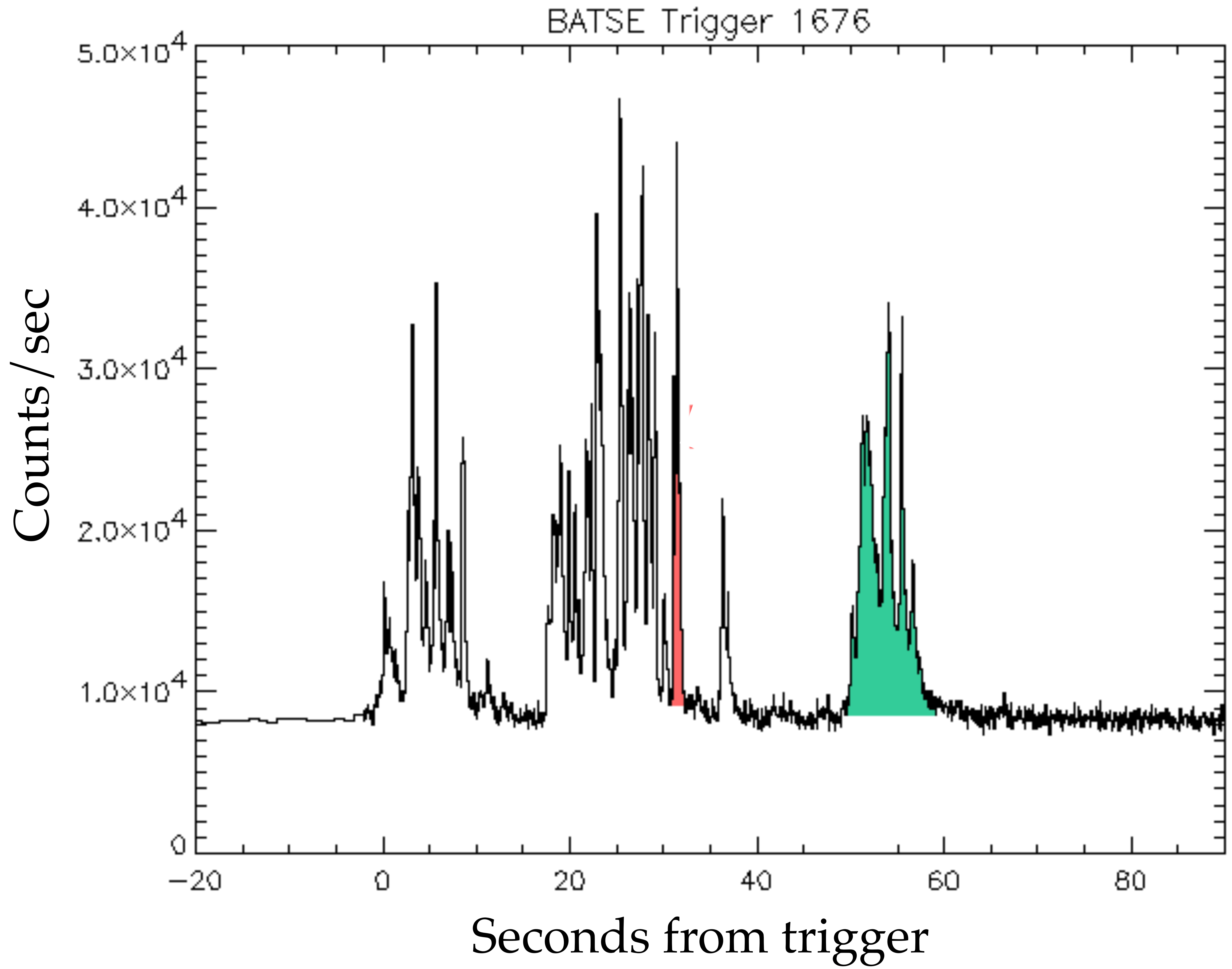


Magic



2005 — 2008 — 2017 — 2019

Fundamental steps often coincide with advent of new instruments / satellites



Total duration (including quiescence)

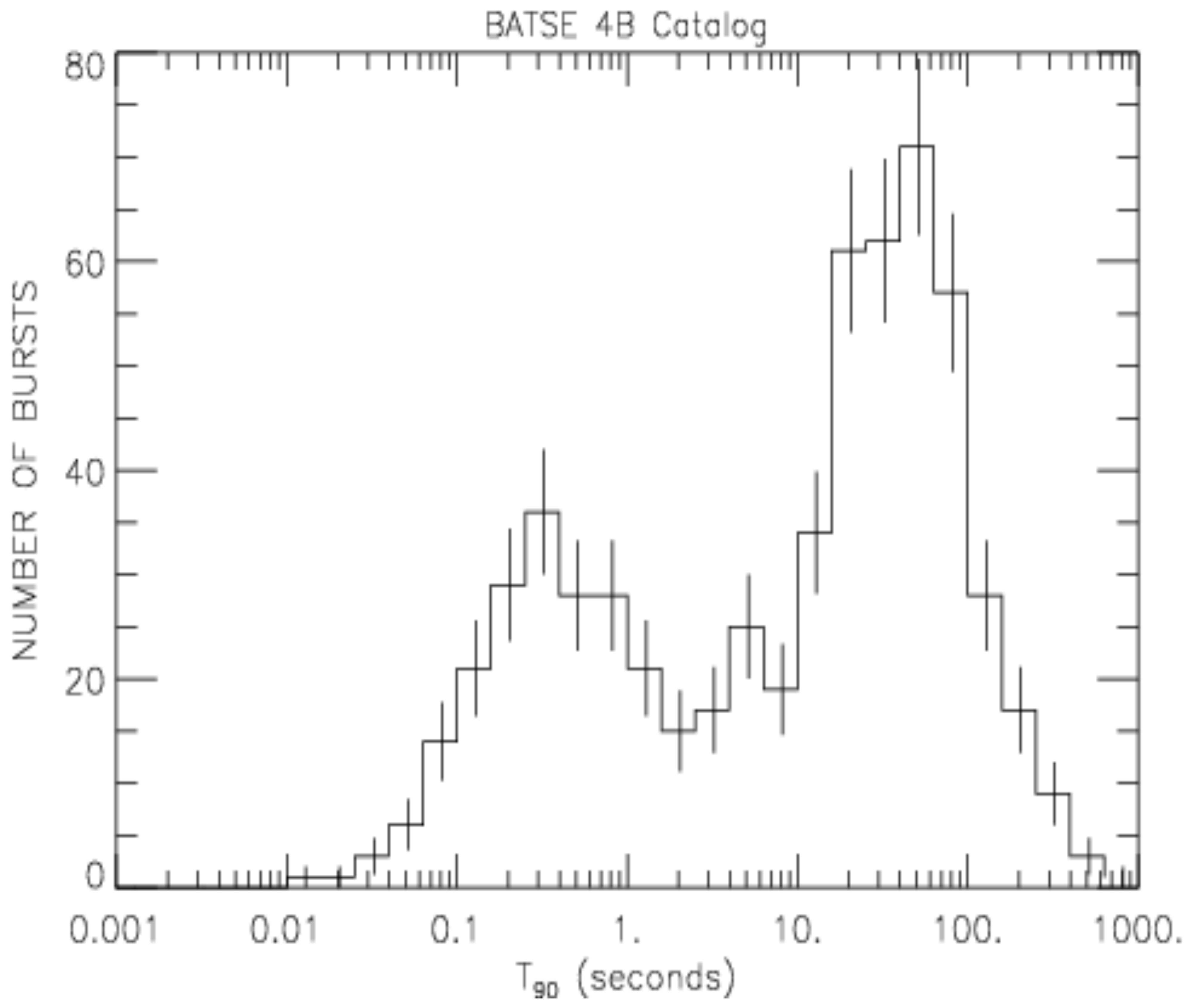
Pulses

Quiescent phases

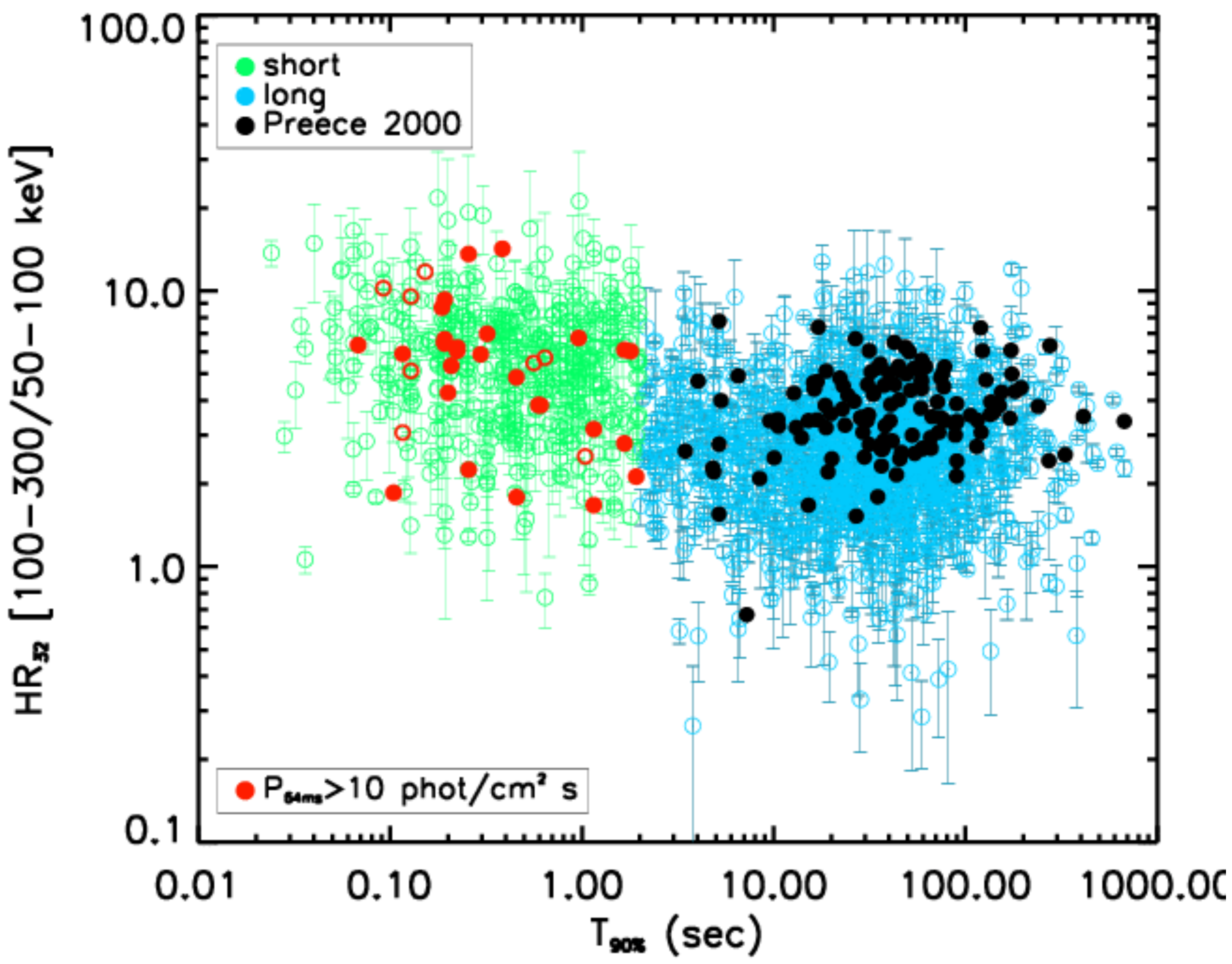
Shortest spikes ~few milliseconds

GRBs as fast transients (ms-hundreds of seconds) at gamma-rays

DURATION: TWO CLASSES

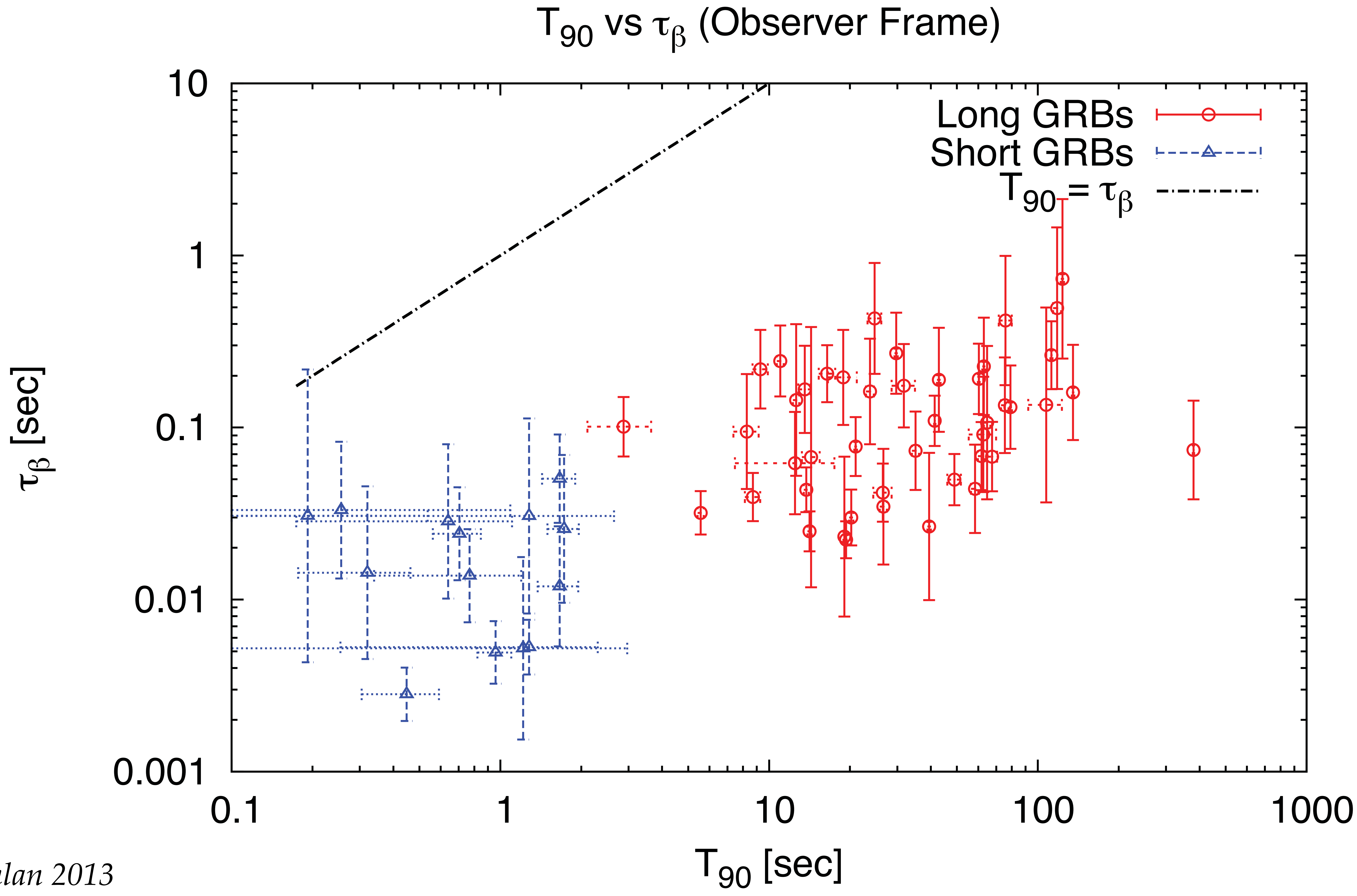


Kouveliotou+1994



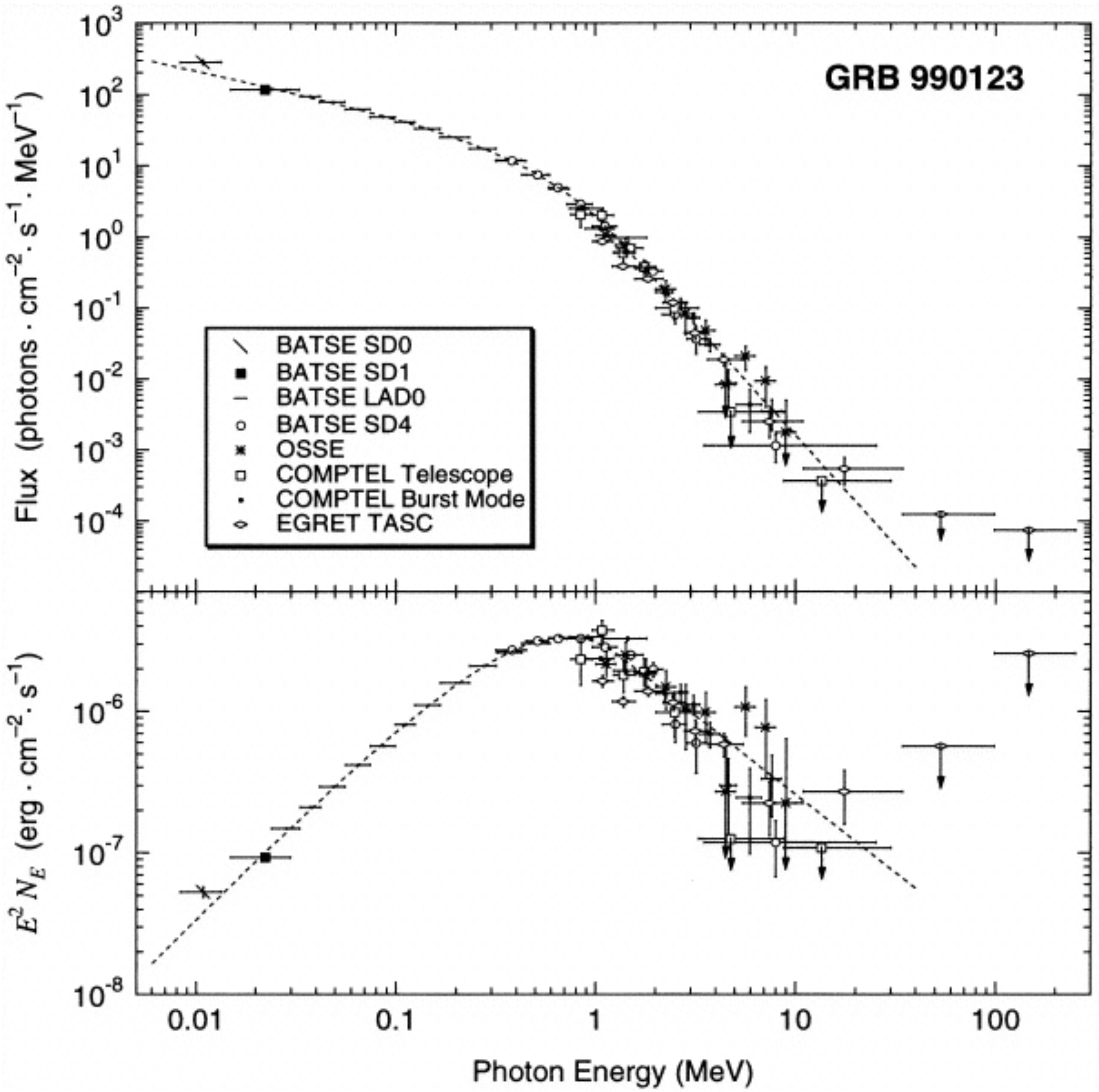
Bimodal duration distribution + Hardness-Duration = possible different origin

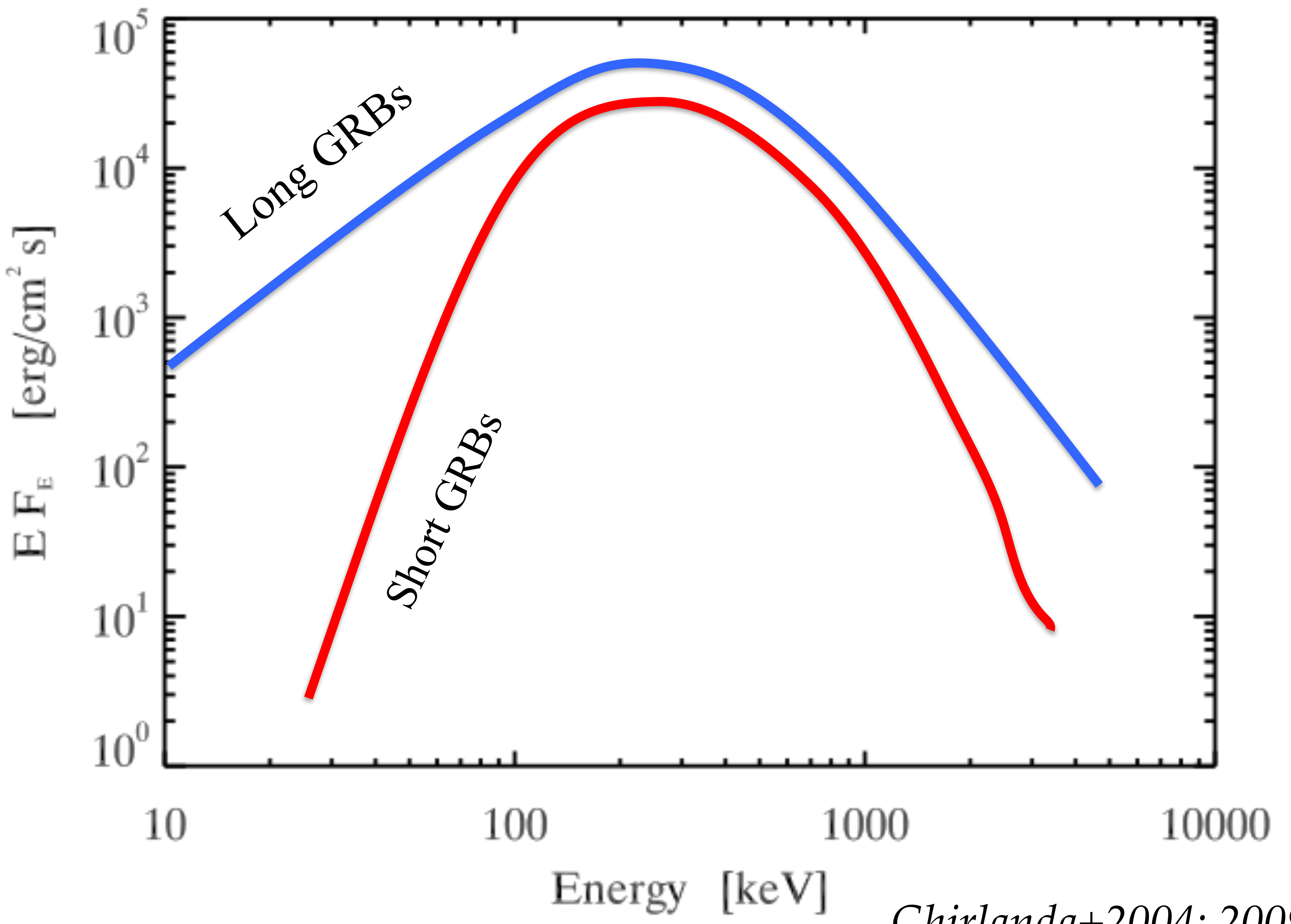
DURATION: VARIABILITY



E.g. MacLachlan 2013

Variability 1-10 ms → $R \simeq 10^7 - 10^8$ cm



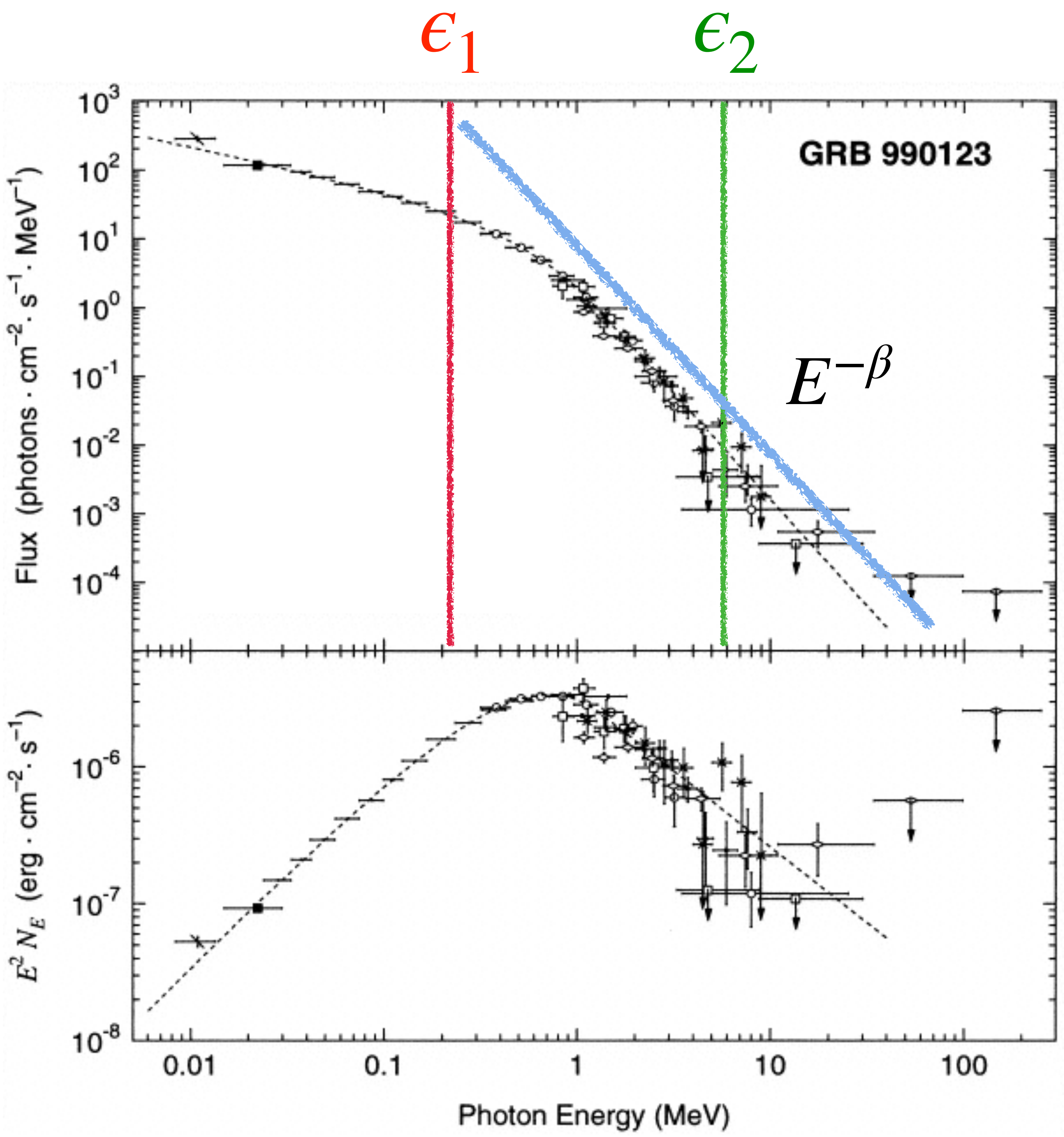


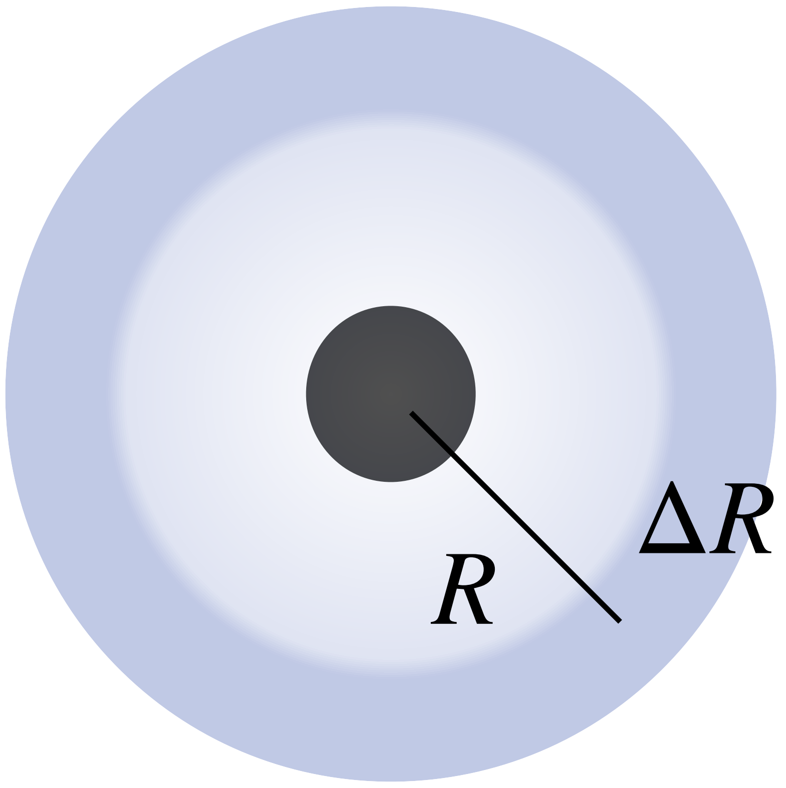
Ghirlanda+2004; 2009

Non-thermal (few keV up tp several MeV)

Short harder than long (in the low energy component)

GRBs are relativistic (I)





$$\tau_{\gamma\gamma} \sim \sigma_T n_{ph} \Delta R$$

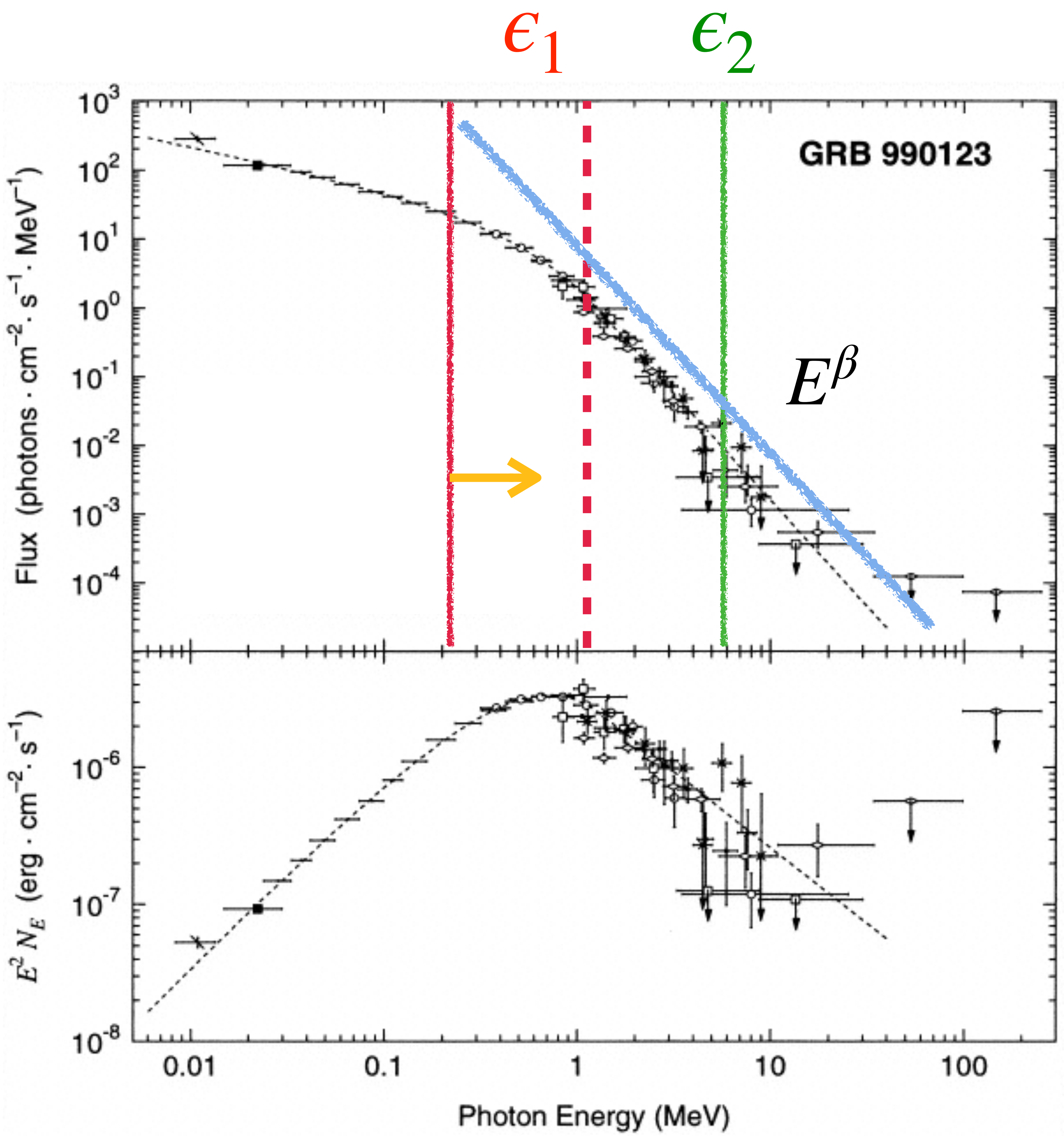
$$\tau_{\gamma\gamma} \sim \sigma_T \frac{E\xi}{\frac{4}{3}\pi R^2 \Delta R \epsilon_1} \Delta R \approx 3 \times 10^{16} \xi E_{52} \delta t_{-2}^{-2}$$

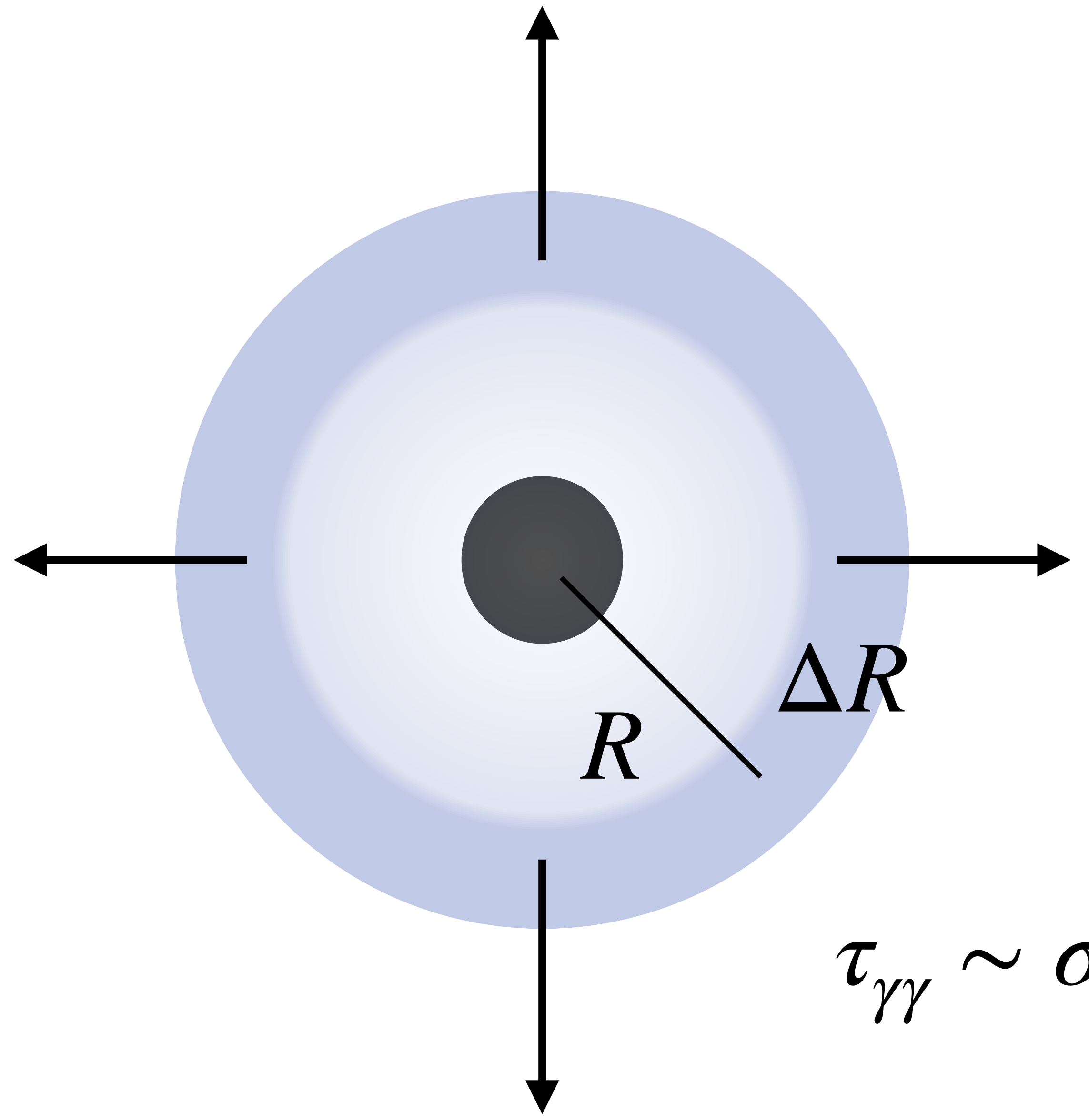
$$\epsilon_1 \epsilon_2 \geq (m_e c^2)^2$$

$$R = c\delta t$$

Should see a sharp cutoff in the high energy spectrum

GRBs ARE RELATIVISTIC (I)





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$$\epsilon_1 \epsilon_2 \geq (m_e c^2)^2 \longrightarrow \epsilon_1 \epsilon_2 \geq \Gamma^2 (m_e c^2)^2$$

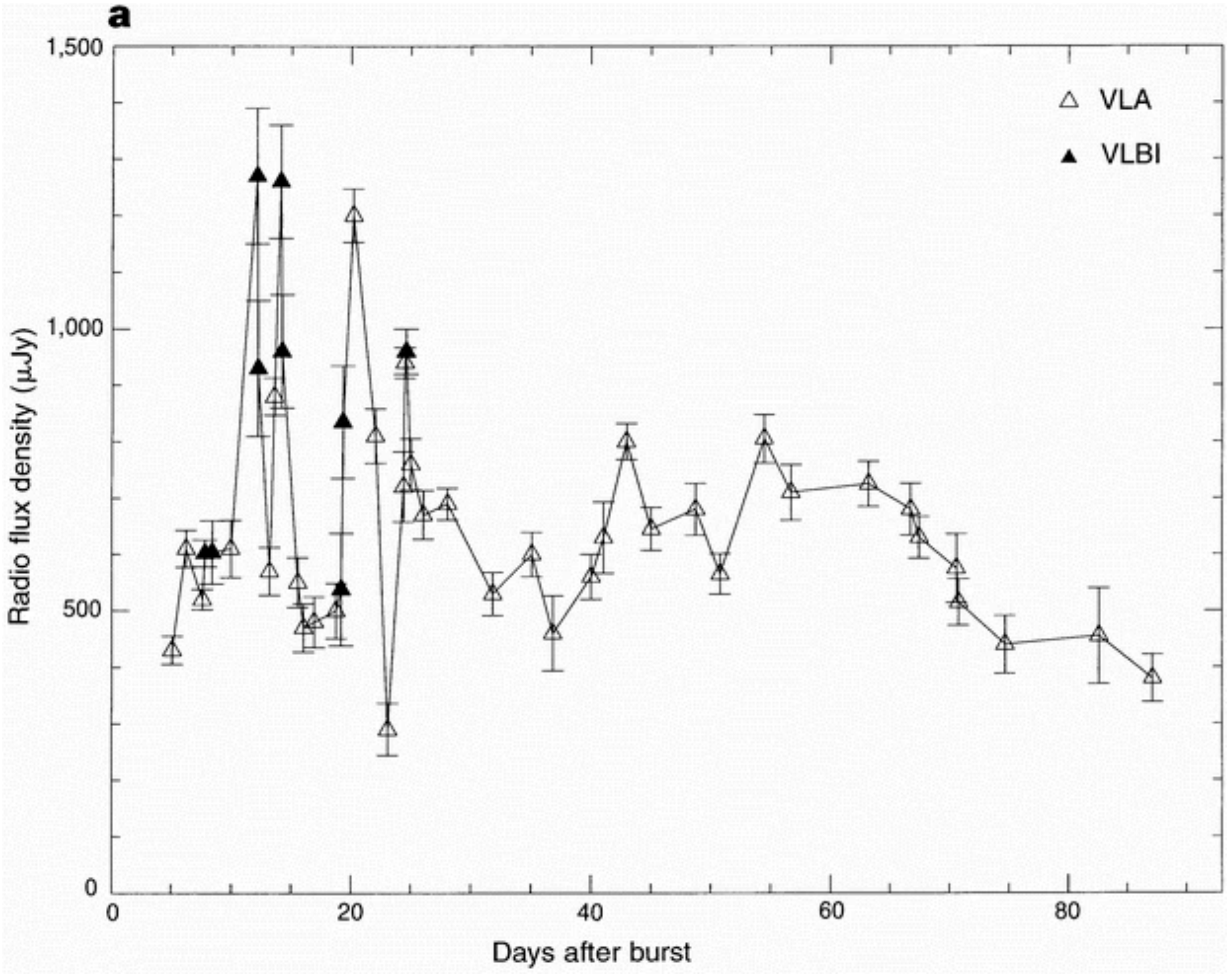
$$R = c\delta t \longrightarrow R = c\delta t \Gamma^2$$

$$\tau_{\gamma\gamma,R} \sim \Gamma^{2\beta-2} \tau_{\gamma\gamma,NR}$$

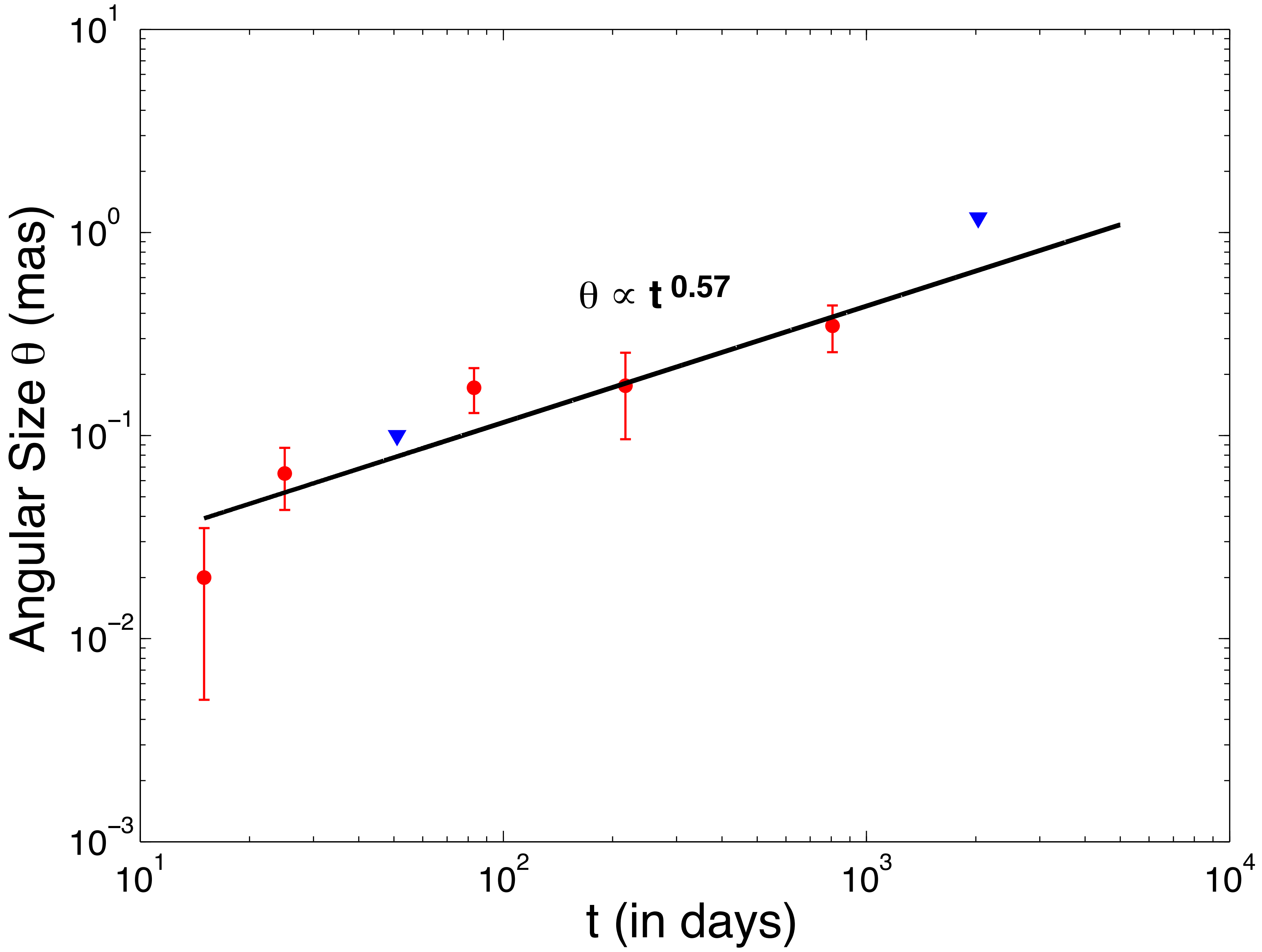
Source internal opacity is overcome if emitting region is moving at ultra relativistic speed

GRBs are relativistic (II)

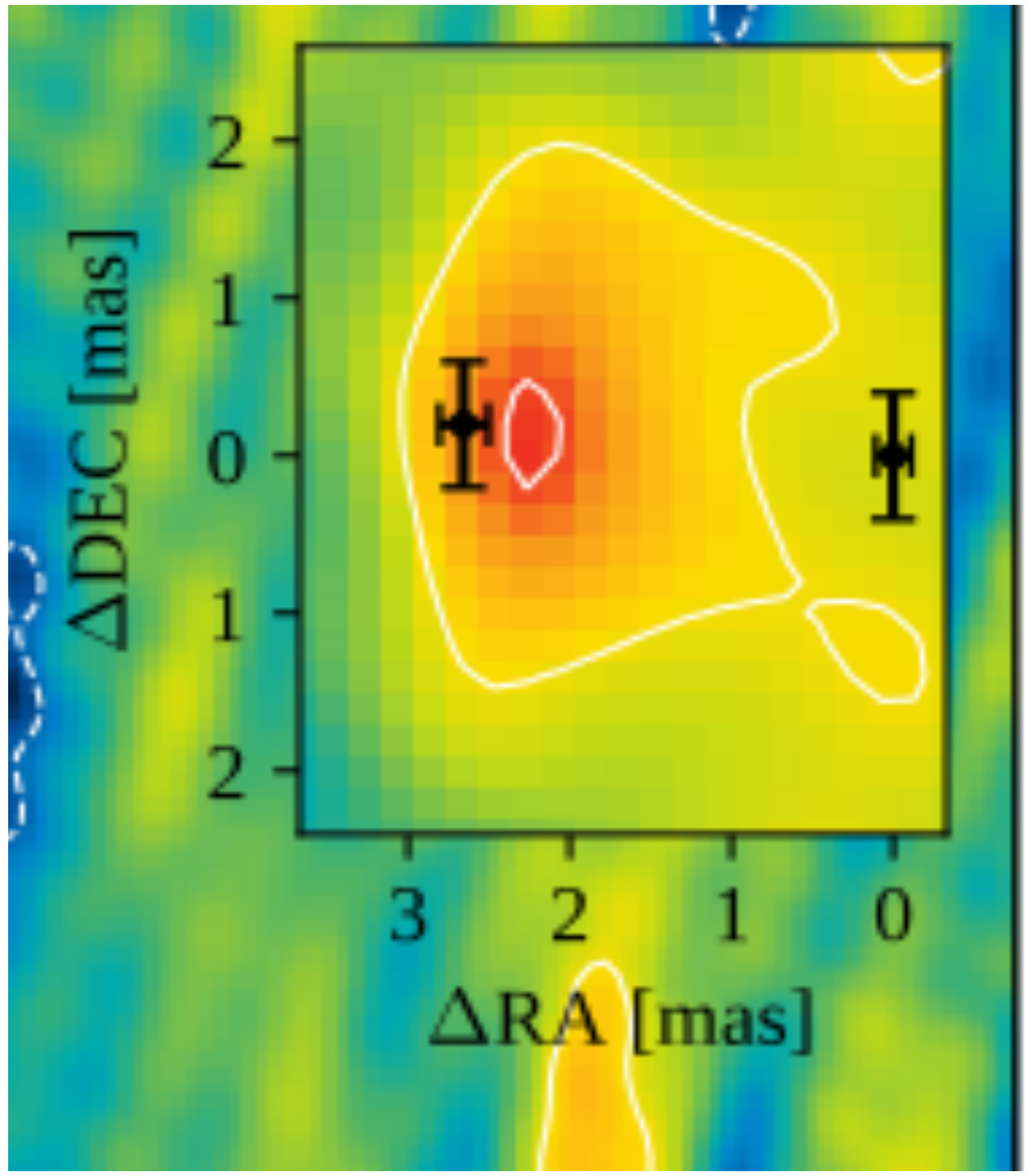
Radio scintillation	Source size expansion	Proper motion
GRB 970508 - 5.2 Gpc	GRB 030329 - 800 Mpc	GRB 170817 - 40 Mpc



Frail et al. 1997

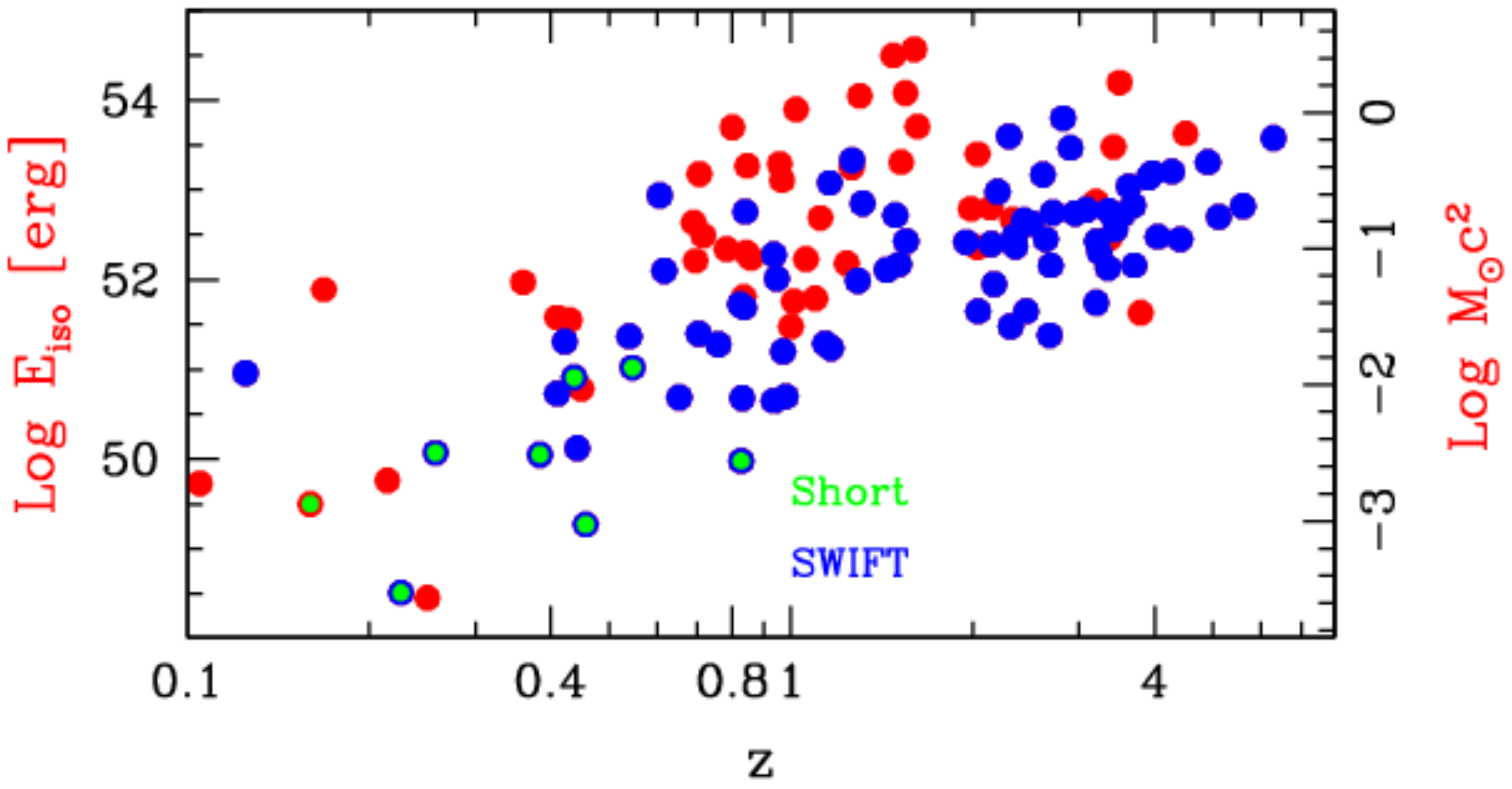


Philstrom et al 2012

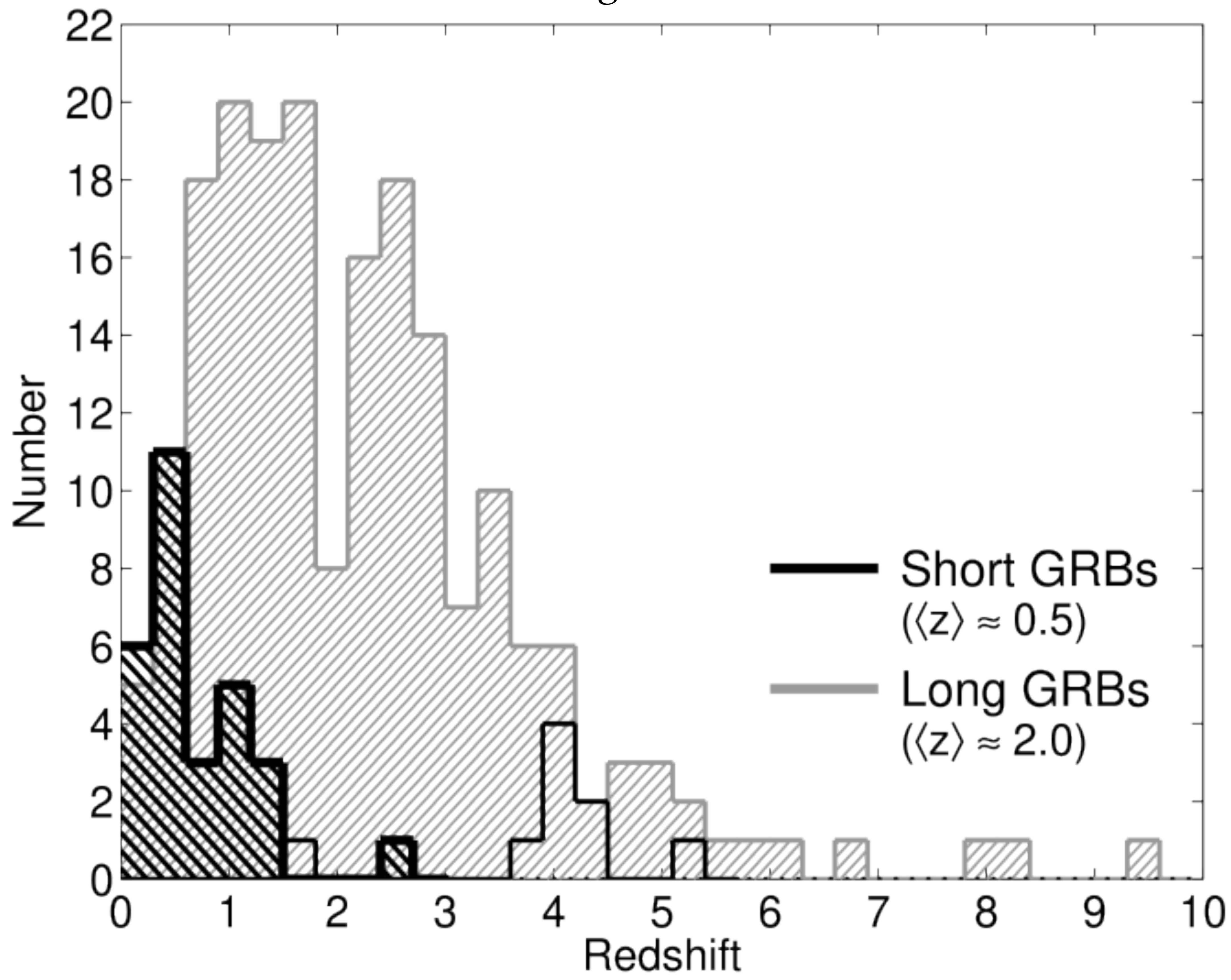


Mooley+2018

Scintillation (indirect) and high resolution imaging (direct) at different epochs (VLBI)

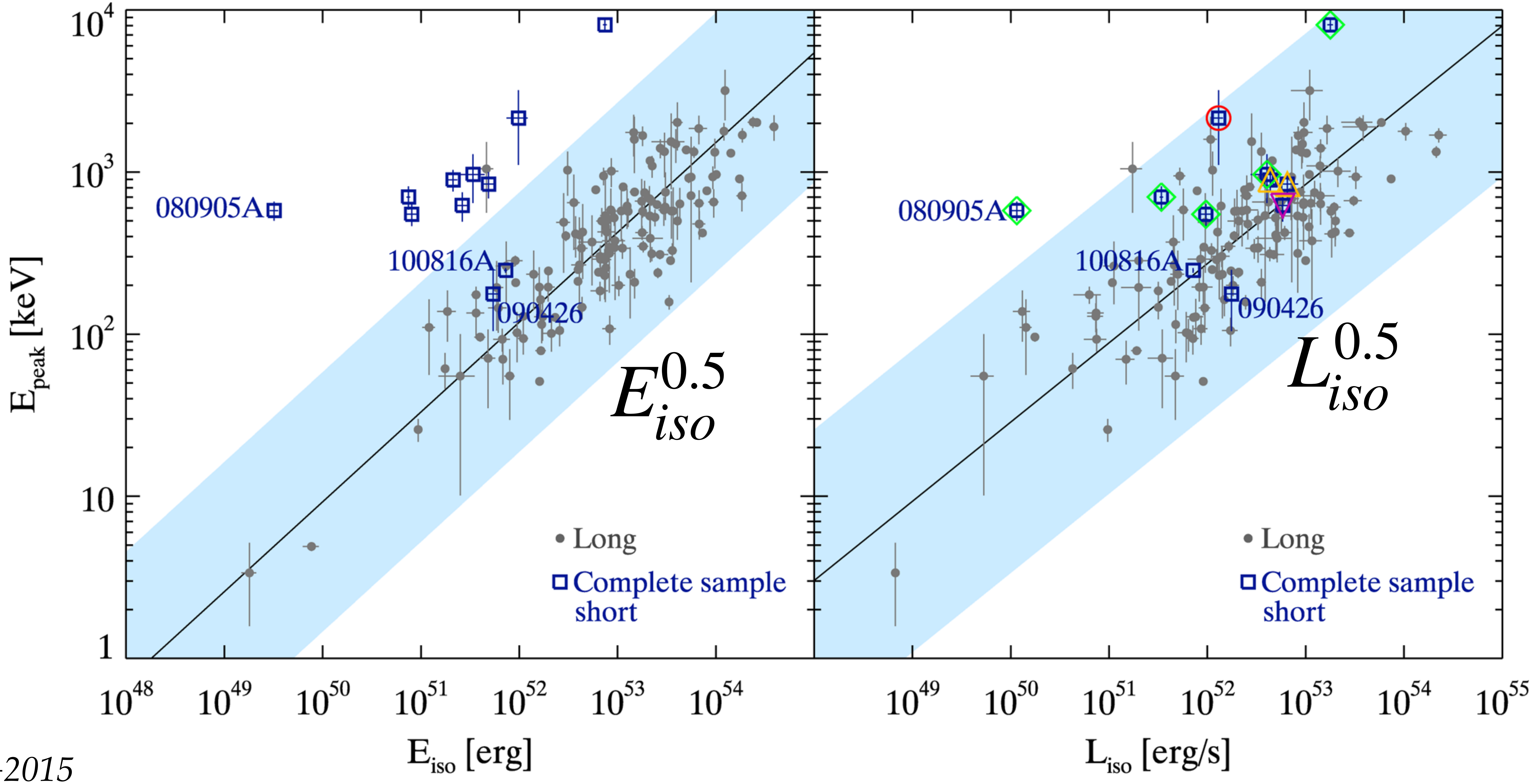


Berger 2013



Short are less energetic and closer than long events

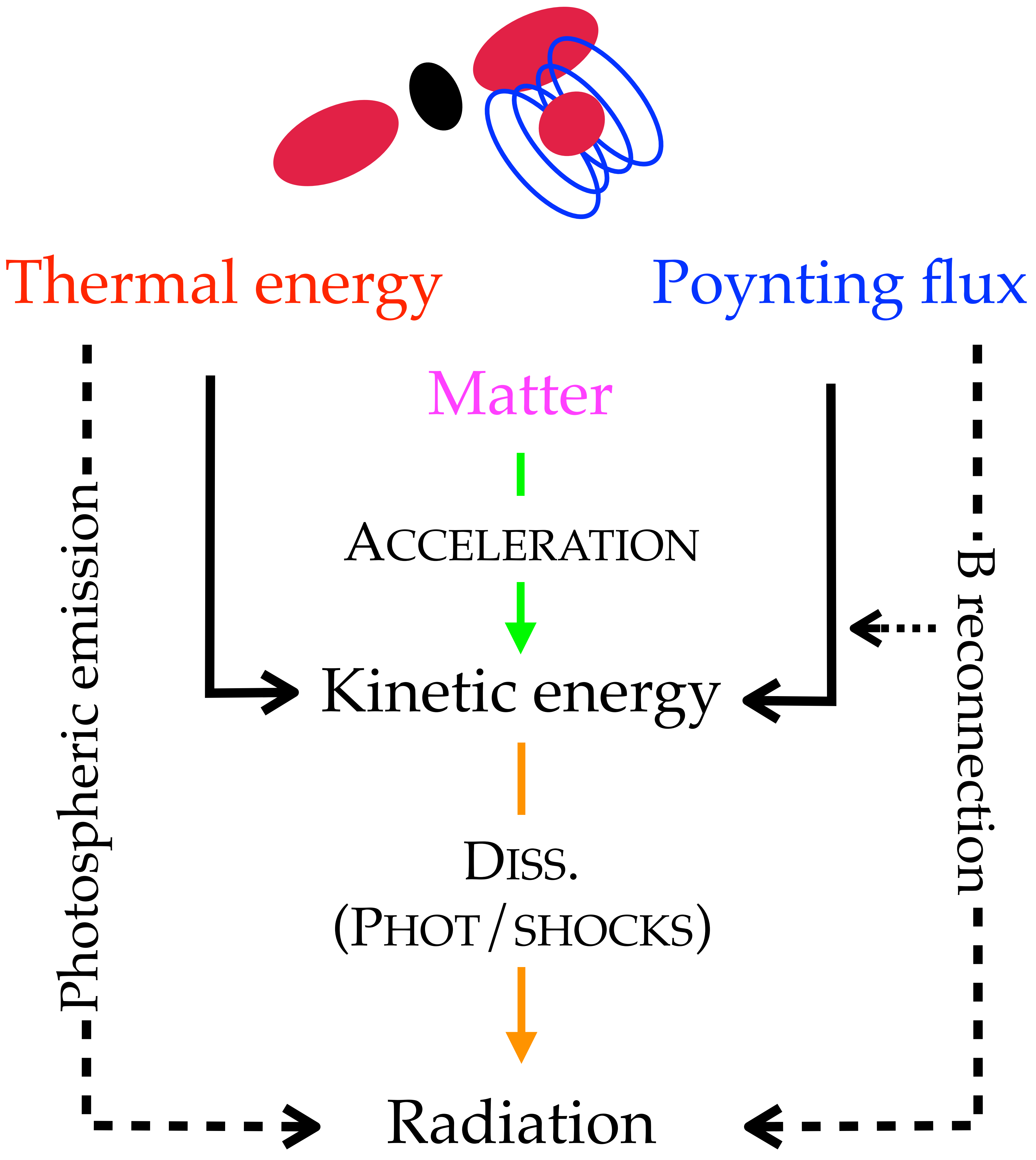
Parallel correlations with energy ~similar correlation with luminosity



D'Avanzo+2015

The harder the more energetic

OUTFLOW ENERGY CONTENT



$$\mu_0 = \frac{Mc^2 + E_{th,0} + E_{B,0}}{Mc^2}$$

$$\eta = \frac{Mc^2 + E_{th,0}}{Mc^2} = 1 + \frac{U_{th,0}}{nm_pc^2} \qquad \sigma_0 = \frac{E_{B,0}}{\eta Mc^2} = \frac{B_0^2}{4\pi\eta\rho_0 c^2}$$

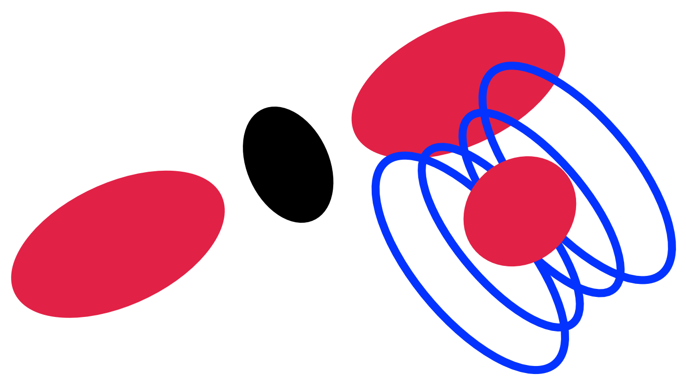
$$\mu_0 = \eta(1+\sigma_0)$$

$$\mu(r) = \Gamma(r)\eta(r)[1+\sigma(r)]$$

Fireball ("hot" outflow): $\sigma_0 \ll \eta$

I will consider the fireball case for the ease of description

BASIC FIREBALL DYNAMICS



Thermal energy

Matter

ACCELERATION

Kinetic energy

DISS.
(PHOT / SHOCKS)

Radiation

Photospheric emission

R

Obs lum $\qquad \dot{E}_0$

$$L \leq 4\pi R_0 \sigma_B T_0^4$$

$$kT_0 \gtrsim 1.7 L_{52} R_{0,7}^{-1/2} \ \mathrm{MeV}$$

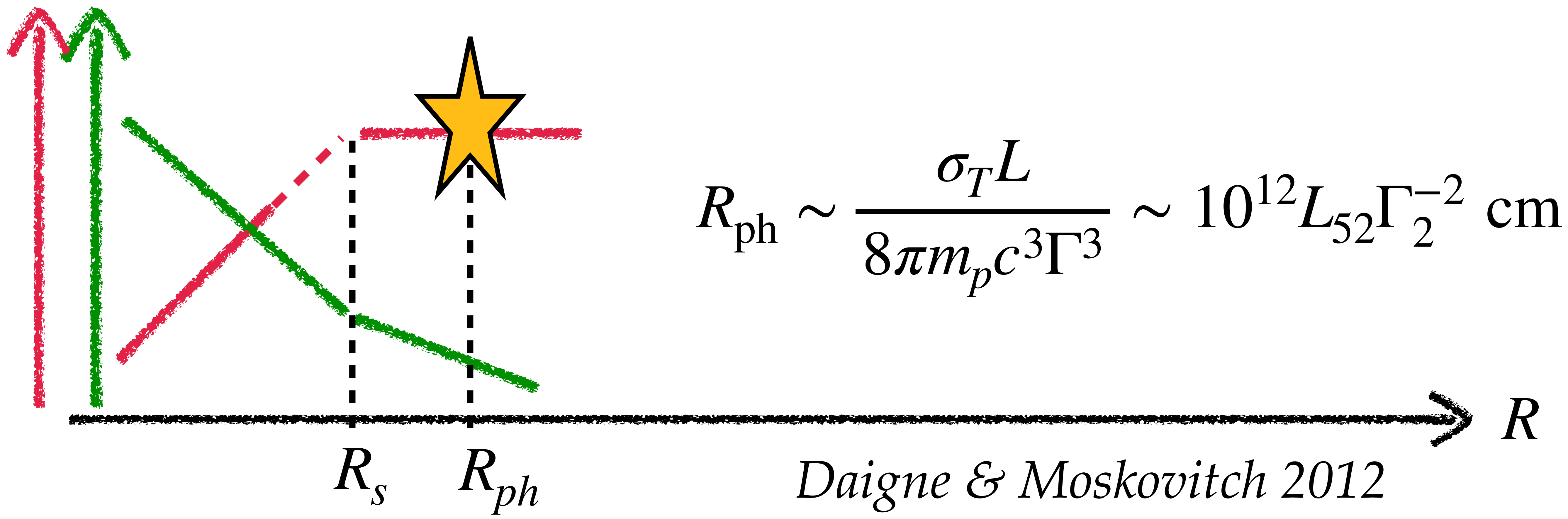
Relativistic adiabatic expansion

$$L \sim \Gamma^2 4\pi R^2 \sigma_B T'^4$$

$$s \sim \Gamma 4\pi R^2 \Delta R T'^3$$

$$\Gamma = \frac{R}{R_0}$$

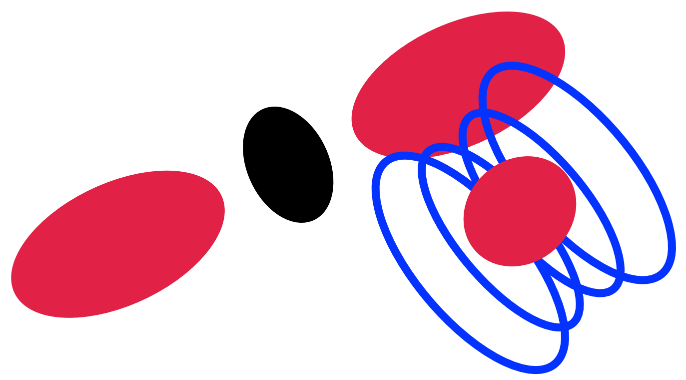
$$T' = T_0 \frac{R_0}{R}$$



$$R_{\rm ph} \sim \frac{\sigma_T L}{8\pi m_p c^3 \Gamma^3} \sim 10^{12} L_{52} \Gamma_2^{-2} \ \mathrm{cm}$$

Daigne & Moskovitch 2012

Transparency (first light) should have thermal like spectrum



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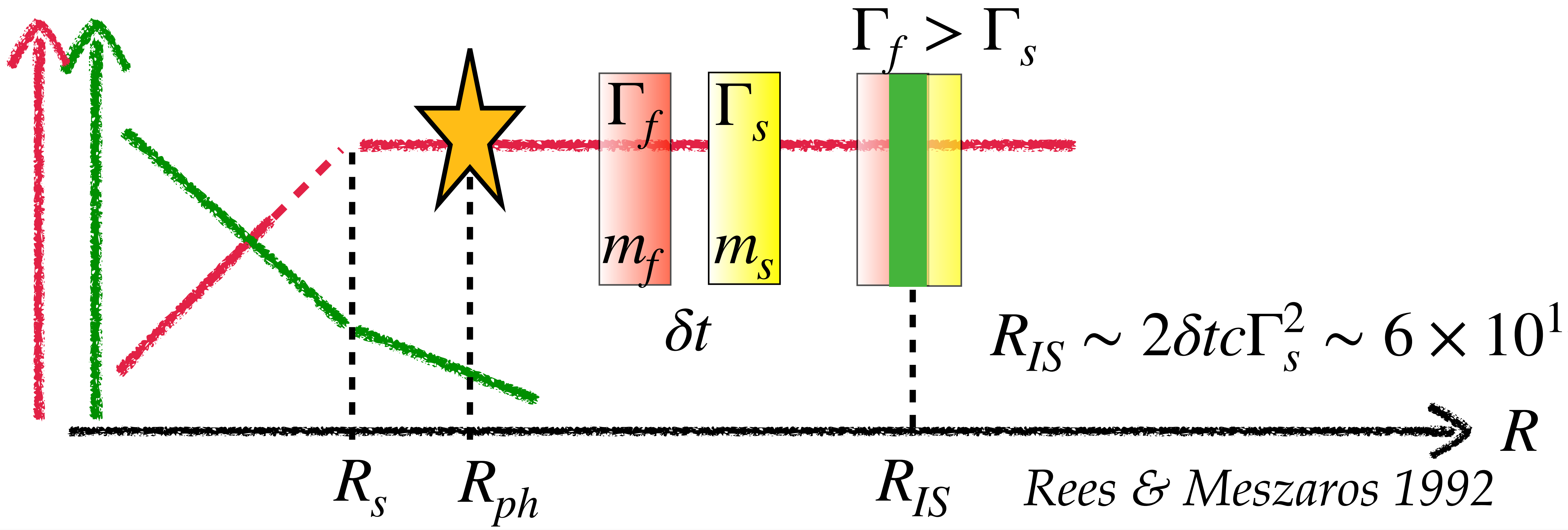
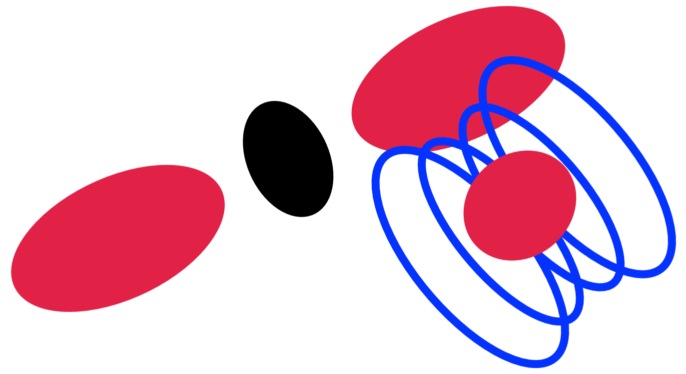


$$R_{IS} \sim 2\delta t c \Gamma_s^2 \sim 6 \times 10^{12} \delta t_{-2} \Gamma_{s,2}^2 \text{ cm}$$

Rees & Meszaros 1992

Internal dissipation through shocks

BASIC FIREBALL EMISSION



Thermal energy

Photospheric emission

Matter

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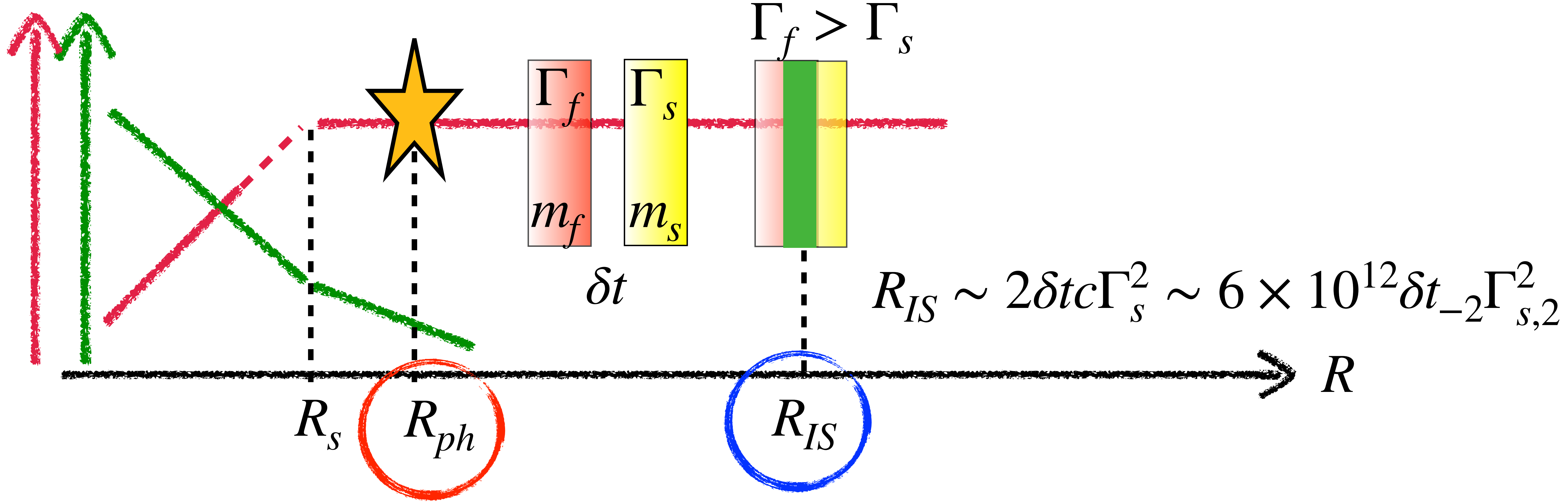
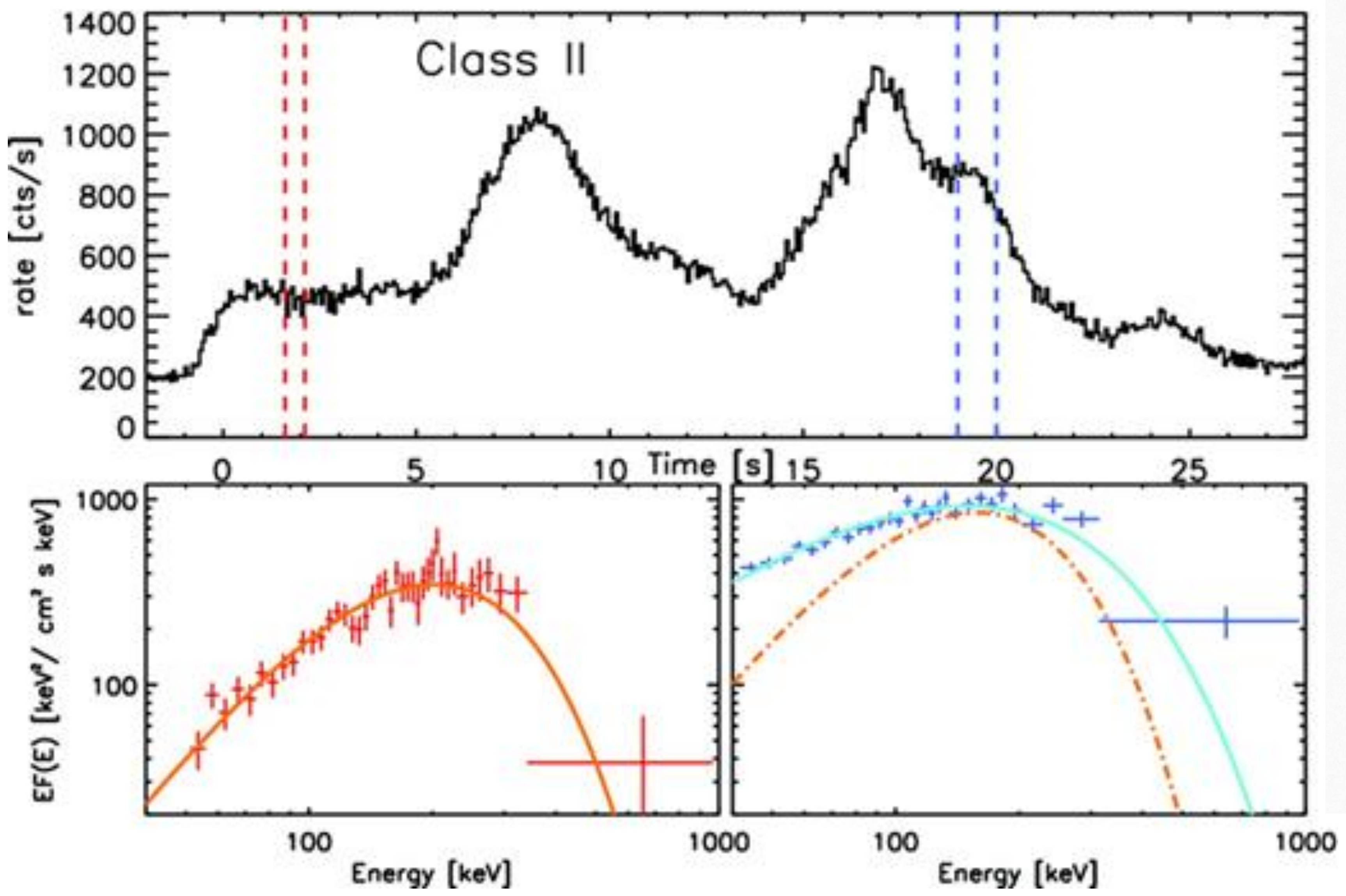
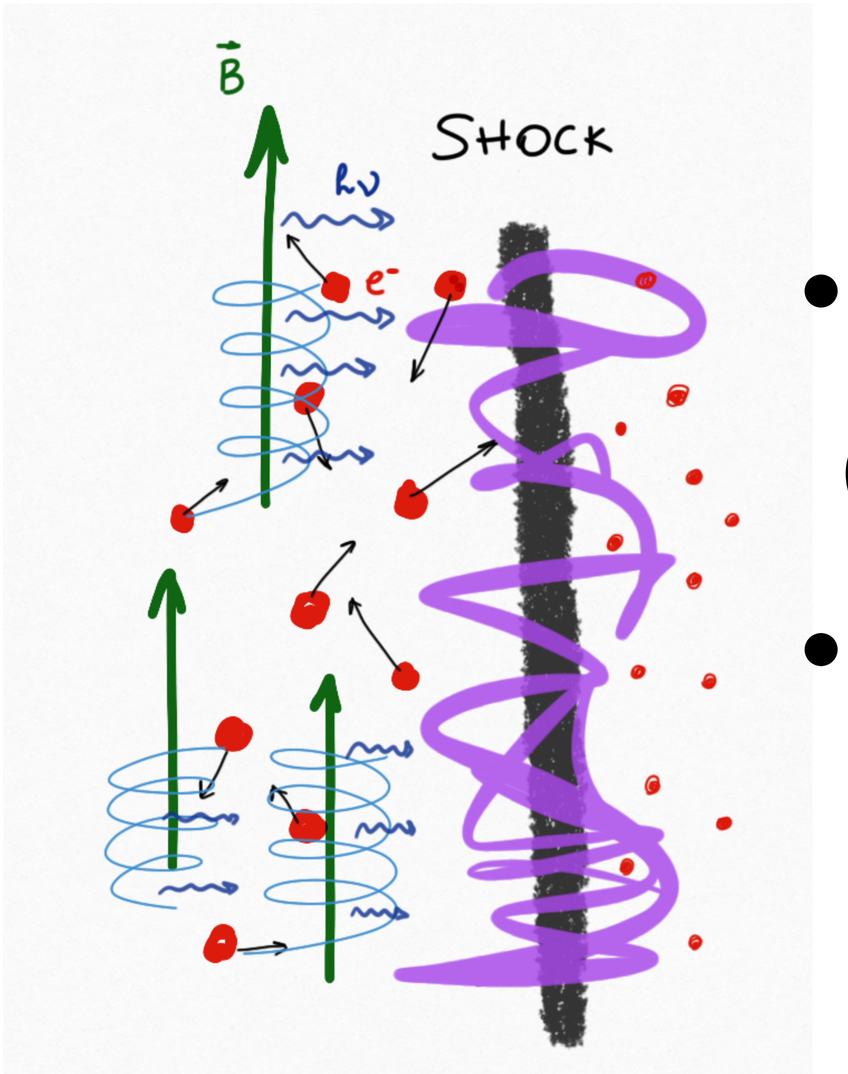
DISS.
(PHOT / SHOCKS)

Radiation



Ghirlanda+2013



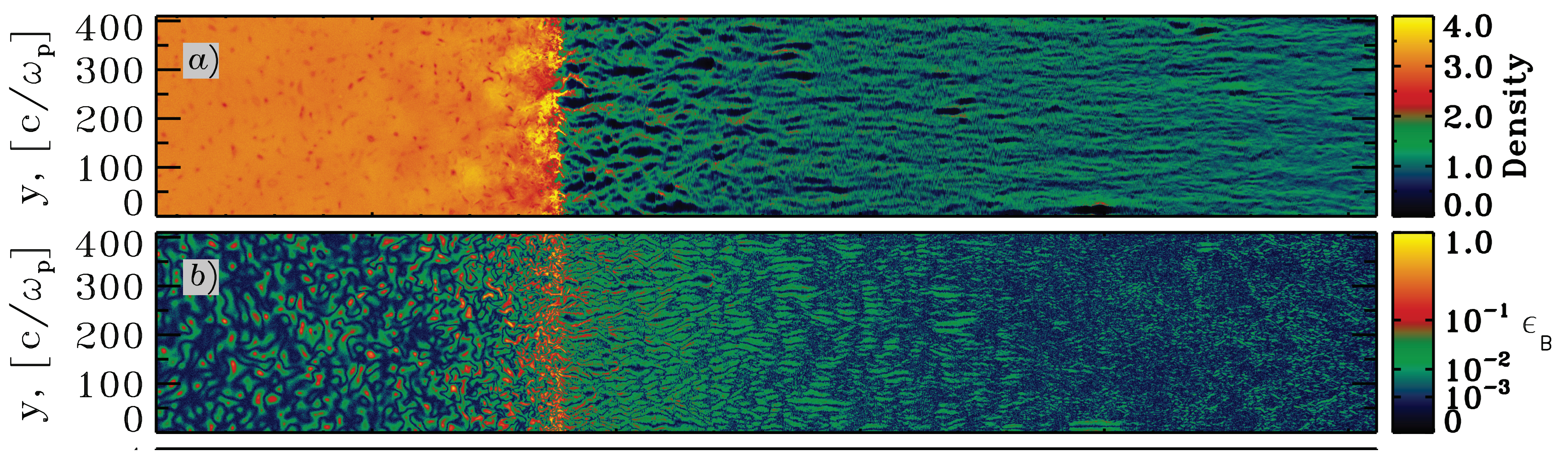


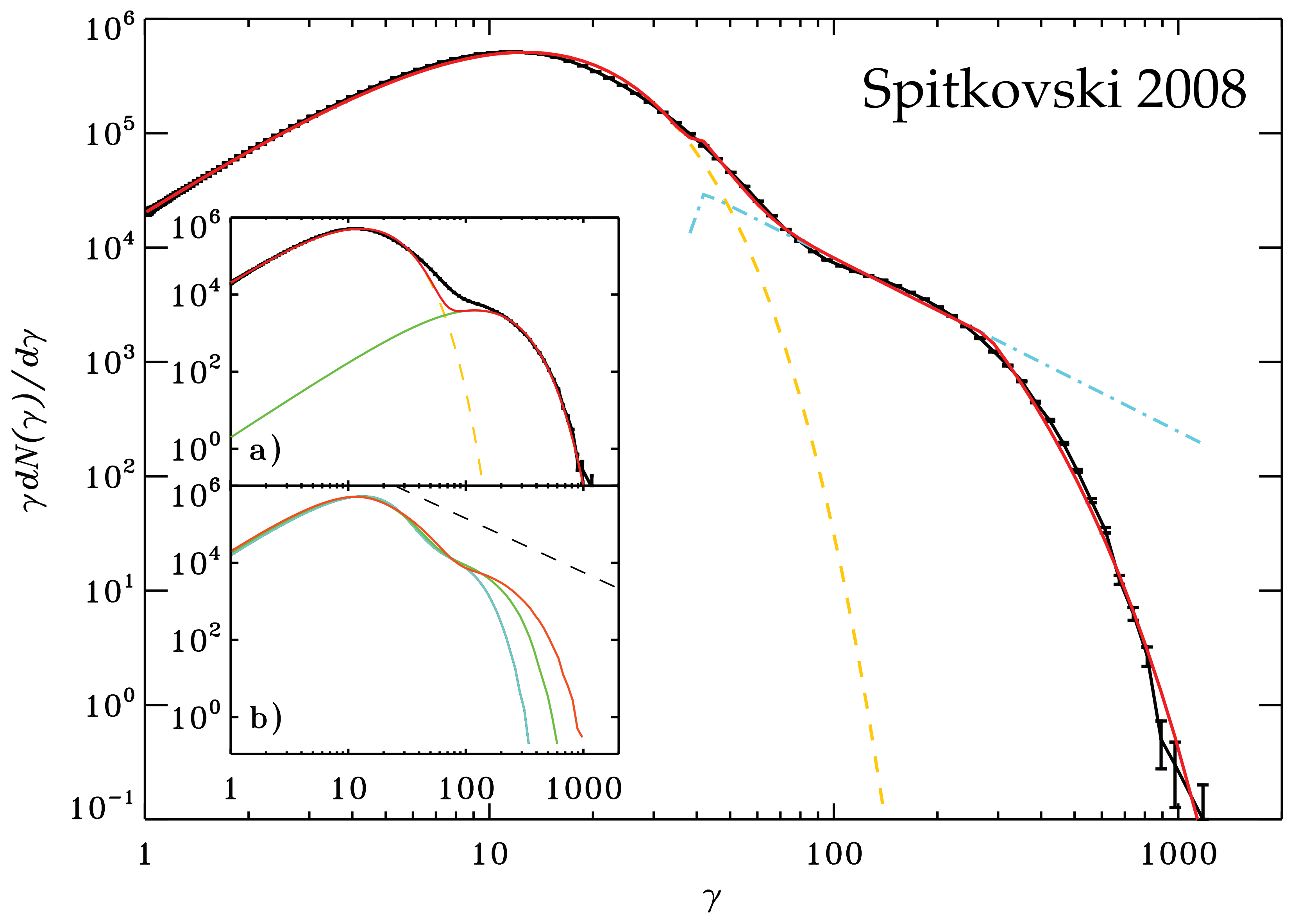
- Non-thermal spectrum (synchrotron?)
- Fast variability

Prompt emission spectrum

PIC Unmagnetized relativistic collisionless shocks:

1. develop downstream magnetic field via instability
2. accelerate electrons to Maxwellian + Powerlaw tail
3. Powerlaw slope ~ 2.4
4. Can extend x100 kT
5. >10% of energy in the non-thermal tail





High energy tail

$$dN(\gamma) \propto \gamma^{-p} d\gamma$$

Internal shocks large electron energy and magnetic field

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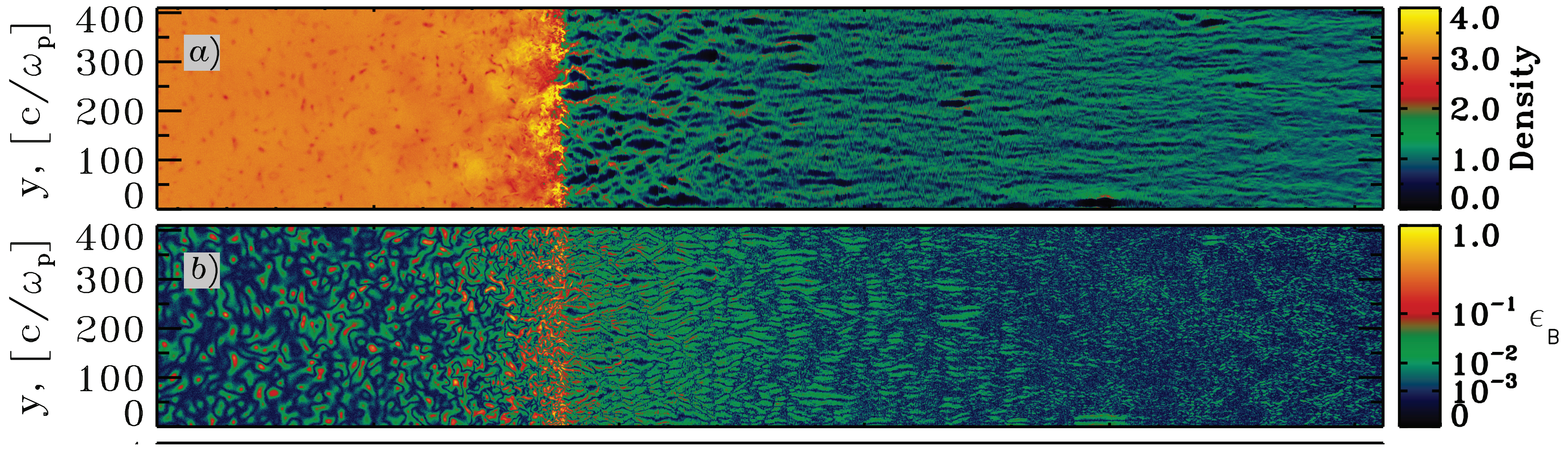
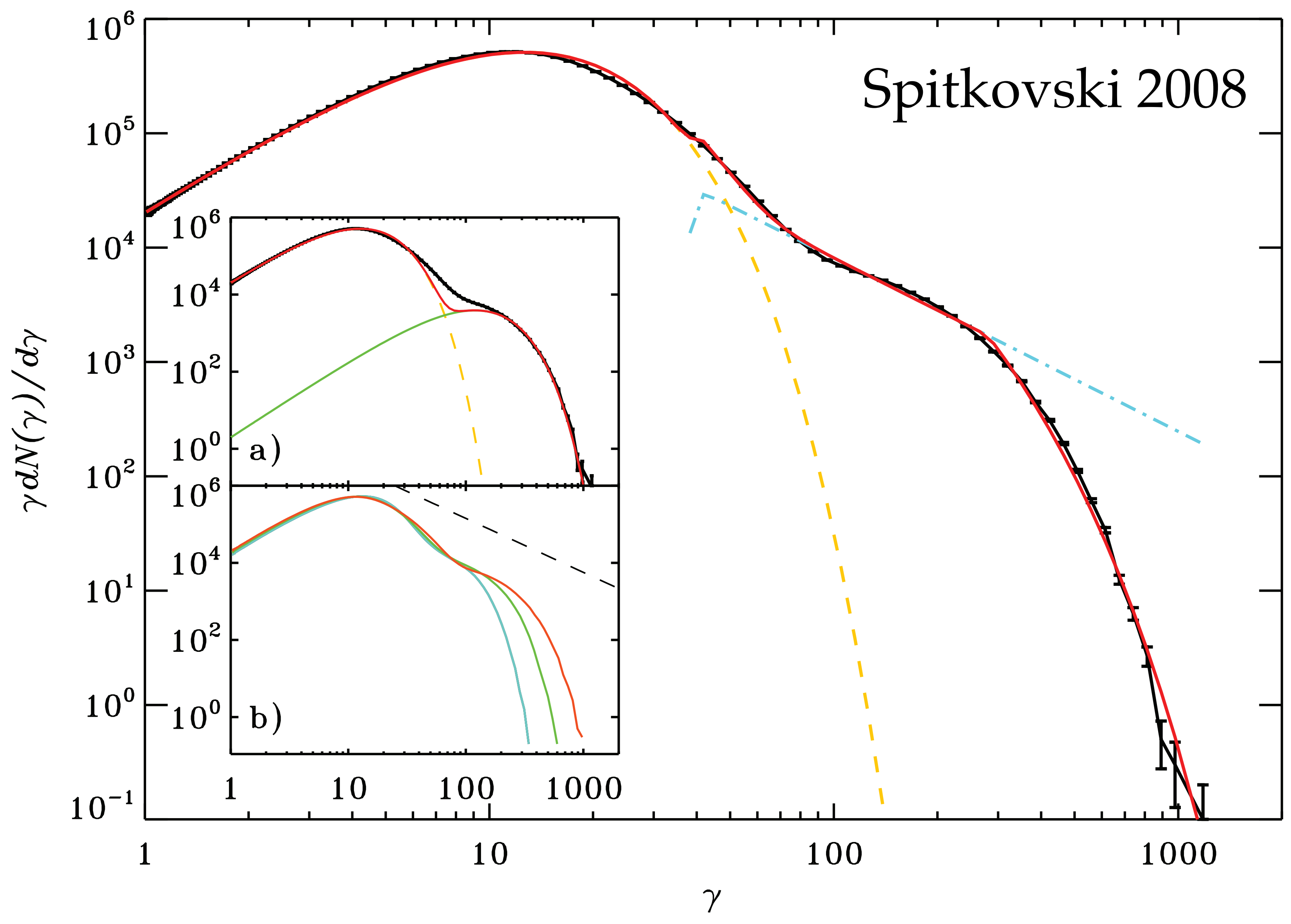
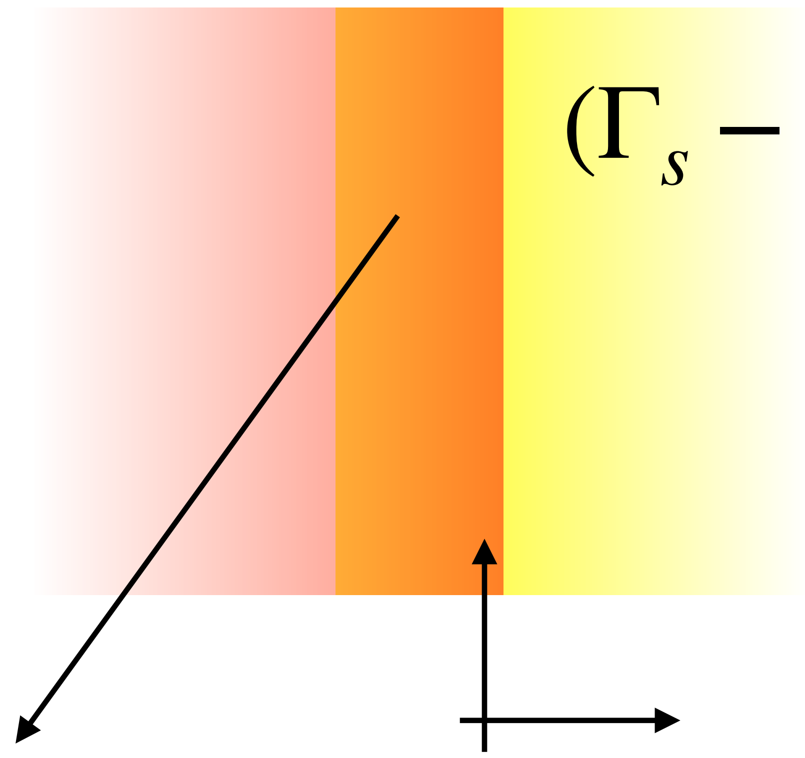






$(\Gamma_s - 1)n_p m_p c^2$

High energy tail

$$dN(\gamma) \propto \gamma^{-p} d\gamma$$

$$\gamma_e n_e m_e c^2 \simeq \epsilon_e(\Gamma_s - 1)n_p m_p c^2$$

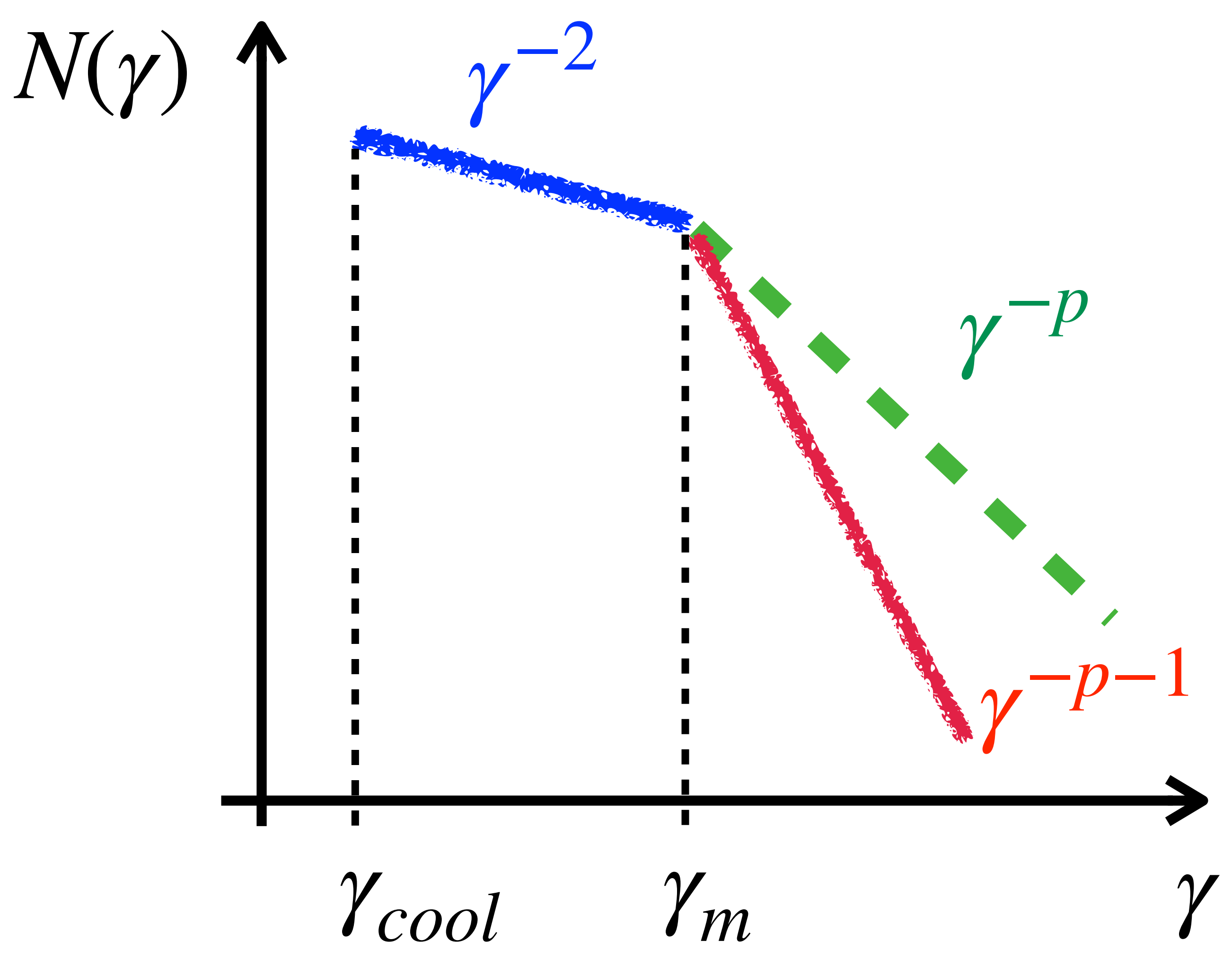
$$\gamma_e = \frac{p-2}{p-1}\epsilon_e(\Gamma_s - 1)\frac{n_p}{n_e}\frac{m_p}{m_e}$$

$$L_B = \Gamma_s^2 \frac{R^2 B'^2 c}{2} = \epsilon_B L$$

$$B' = \epsilon_B^{1/2}\left(\frac{2L}{c}\right)^{1/2}\frac{1}{R\Gamma_s}$$

Internal shocks large electron energy and magnetic field

$$t_{cool,syn} = \frac{6\pi m_e c}{\sigma_T \gamma_e B'^2} \frac{1+z}{\Gamma} \quad << \quad t_{dyn} = \frac{R}{2c\Gamma^2}(1+z)$$ Fast cooling

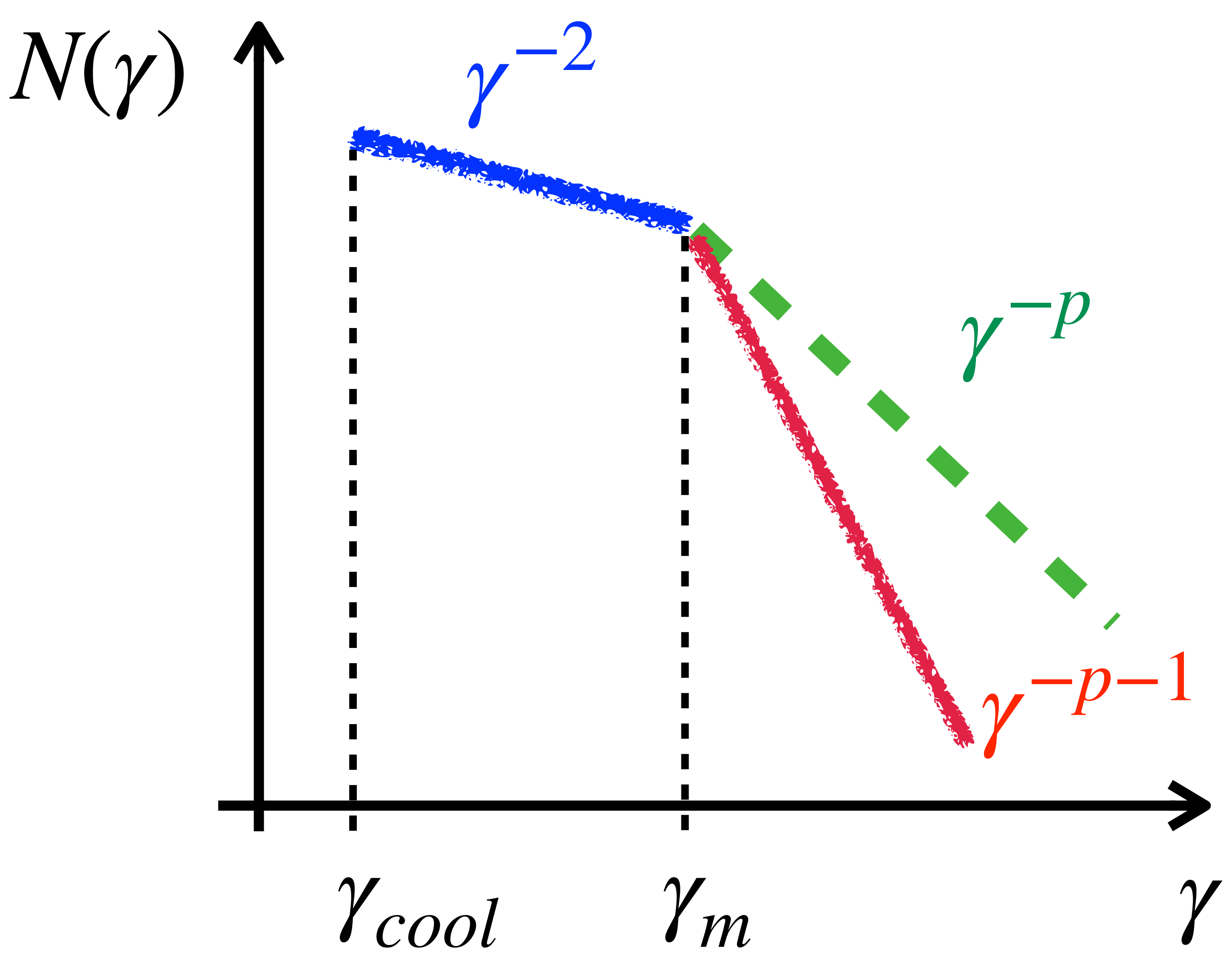


For typical parameters fast cooling emission

SYNCHROTRON PROMPT EMISSION

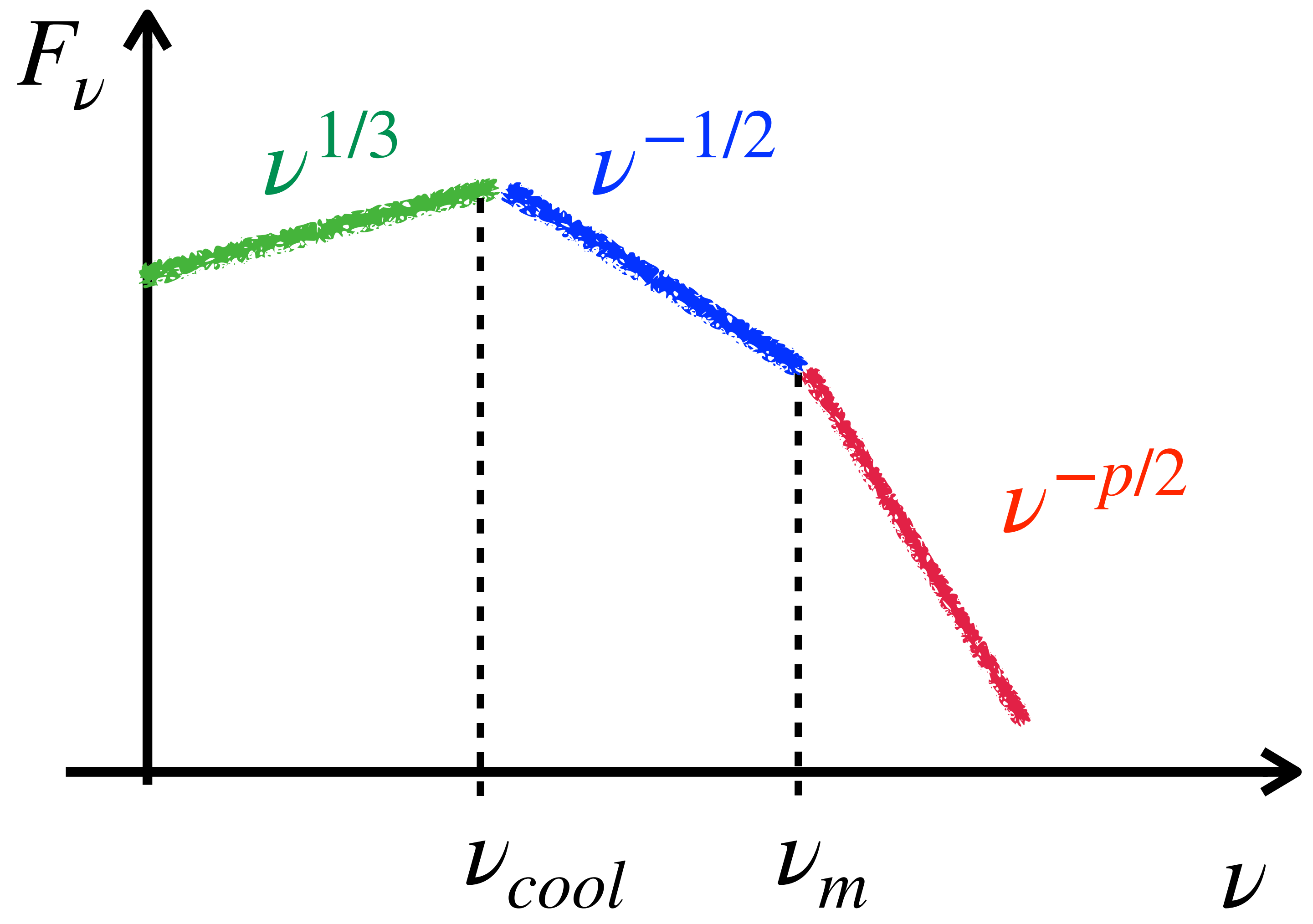
$$t_{cool,syn} = \frac{6\pi m_e c}{\sigma_T \gamma_e B'^2} \frac{1+z}{\Gamma} \quad << \quad t_{dyn} = \frac{R}{2c\Gamma^2}(1+z)$$

Fast cooling



$$\nu \propto \gamma^2$$

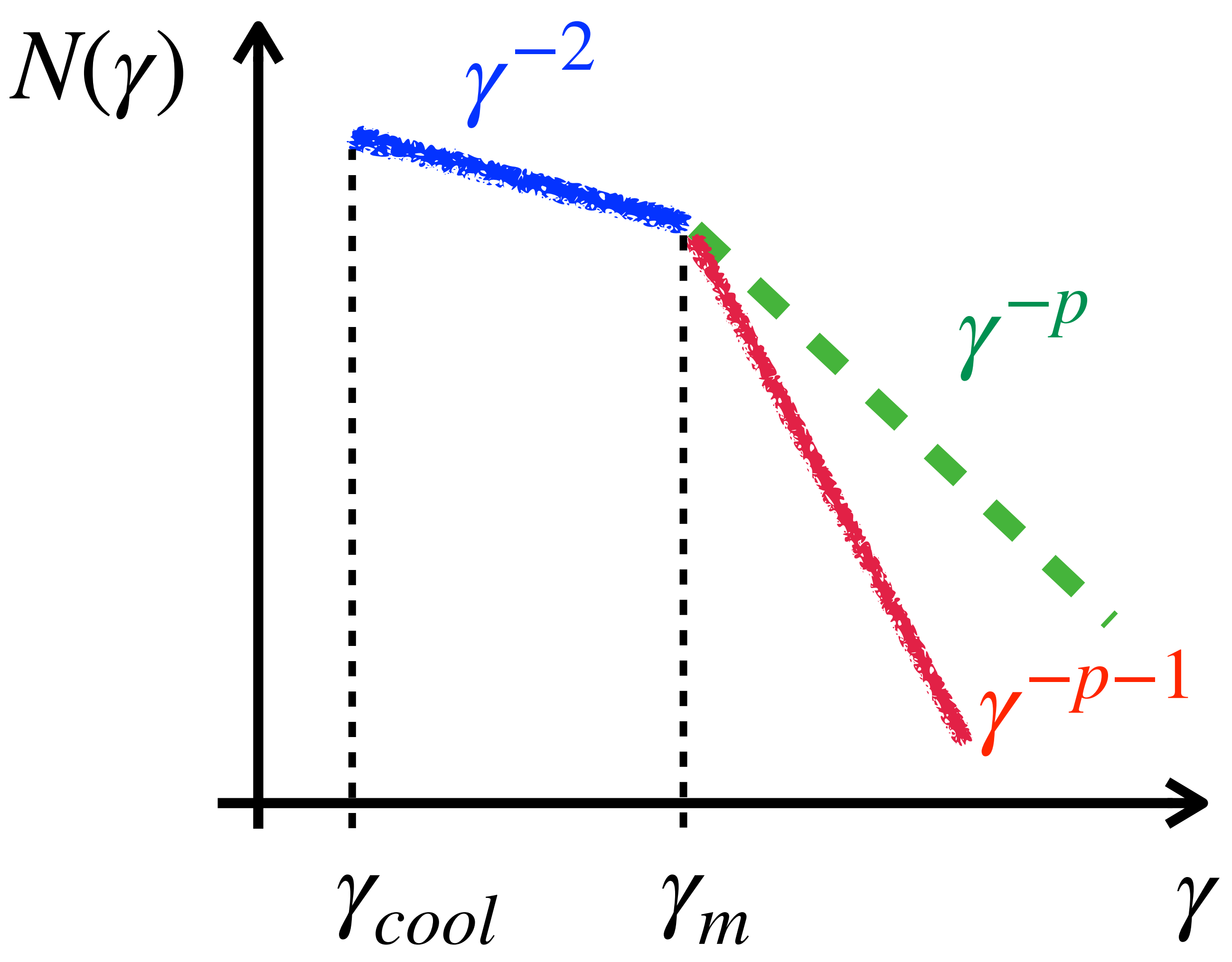
$$n(\gamma) \propto \gamma^{-s} \longrightarrow F_\nu \propto \nu^{-\frac{s-1}{2}}$$



For typical parameters fast cooling emission

$$t_{cool,syn} = \frac{6\pi m_e c}{\sigma_T \gamma_e B'^2} \frac{1+z}{\Gamma} \quad << \quad t_{dyn} = \frac{R}{2c\Gamma^2}(1+z)$$

Fast cooling



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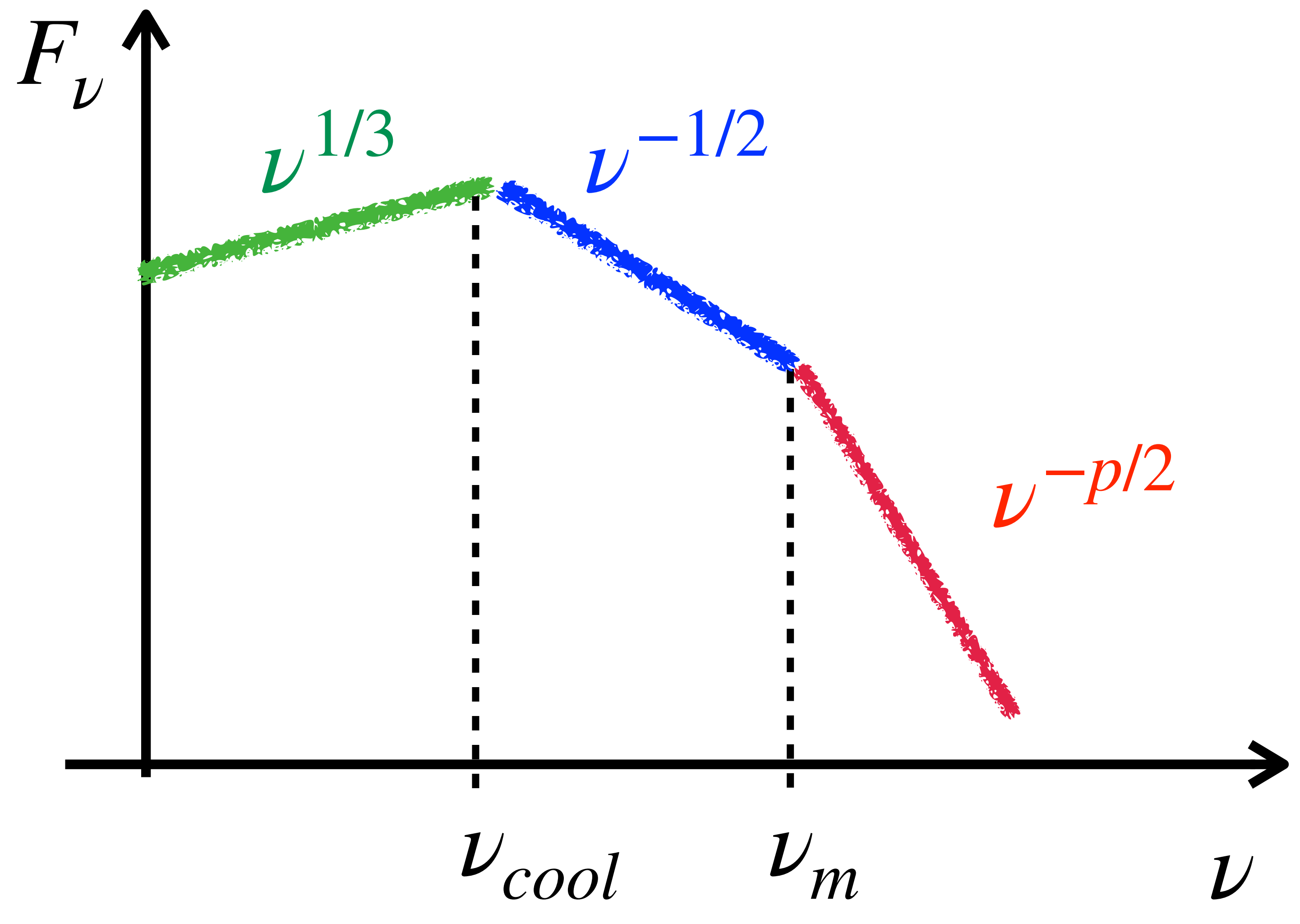
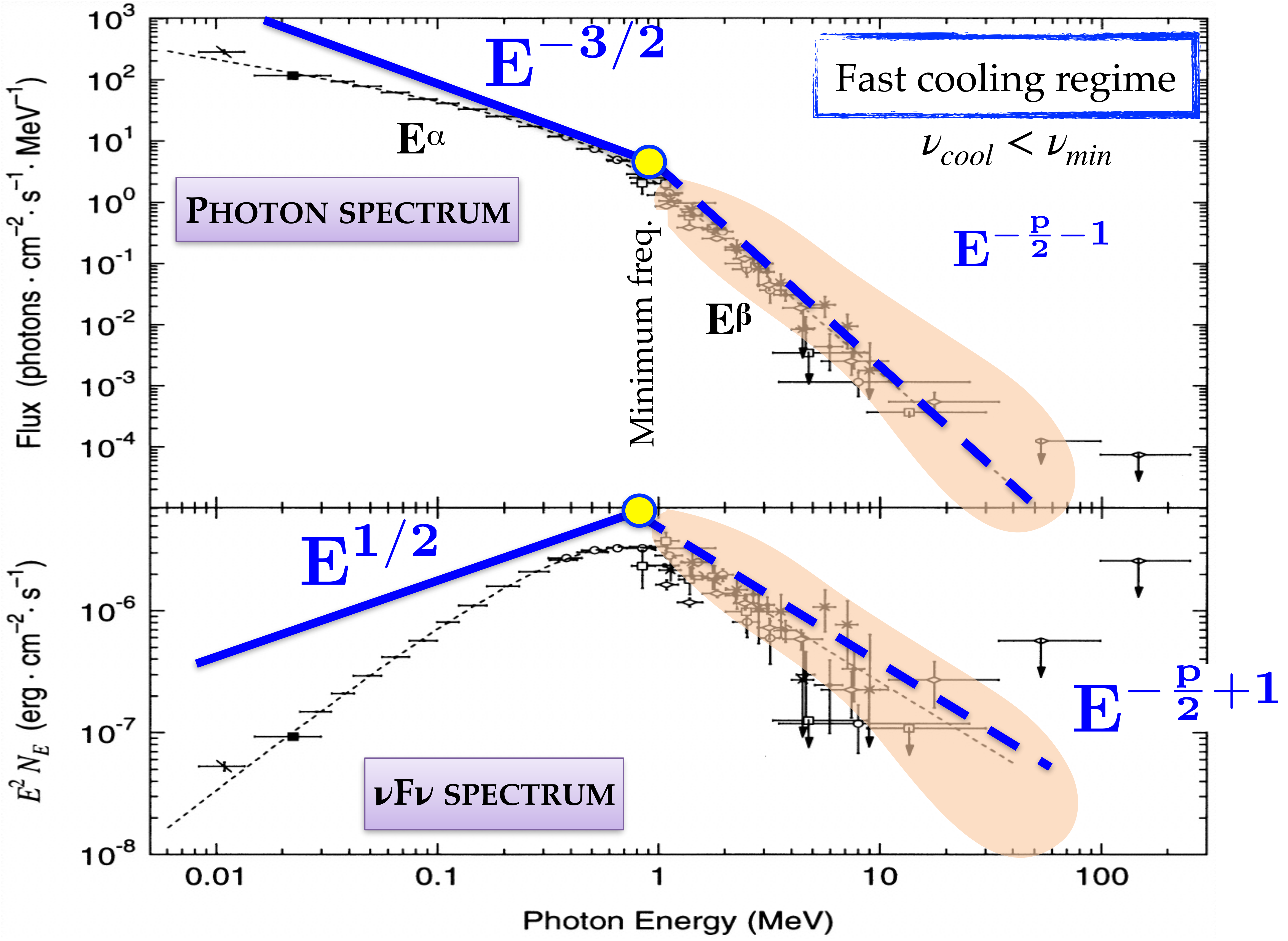


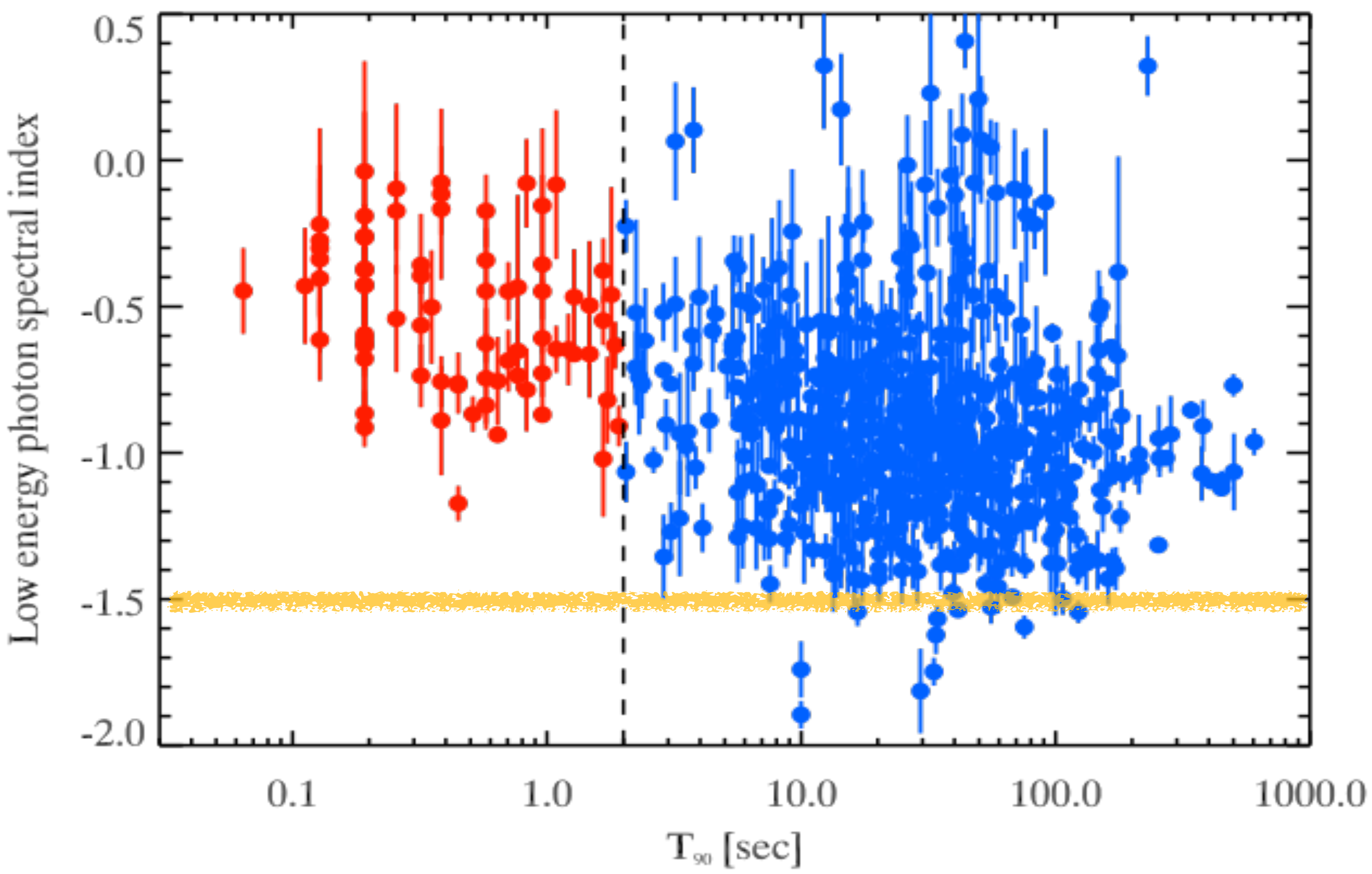
$$h\nu_{p,syn} = \frac{2eh}{3\pi m_e c}\gamma_e^2 B' \frac{\Gamma_s}{1+z} \approx 40\ \mathrm{keV}\,\epsilon_B^{1/2}\epsilon_e^2(\Gamma_s - 1)^2\left(\frac{n_p}{n_e}\right)^2 L_{52}^{1/2}\frac{1}{R_{13}(1+z)}$$

Synchrotron can reproduce the typical peak spectral energy

For typical parameters fast cooling emission

SYNCHROTRON PROMPT EMISSION (?)

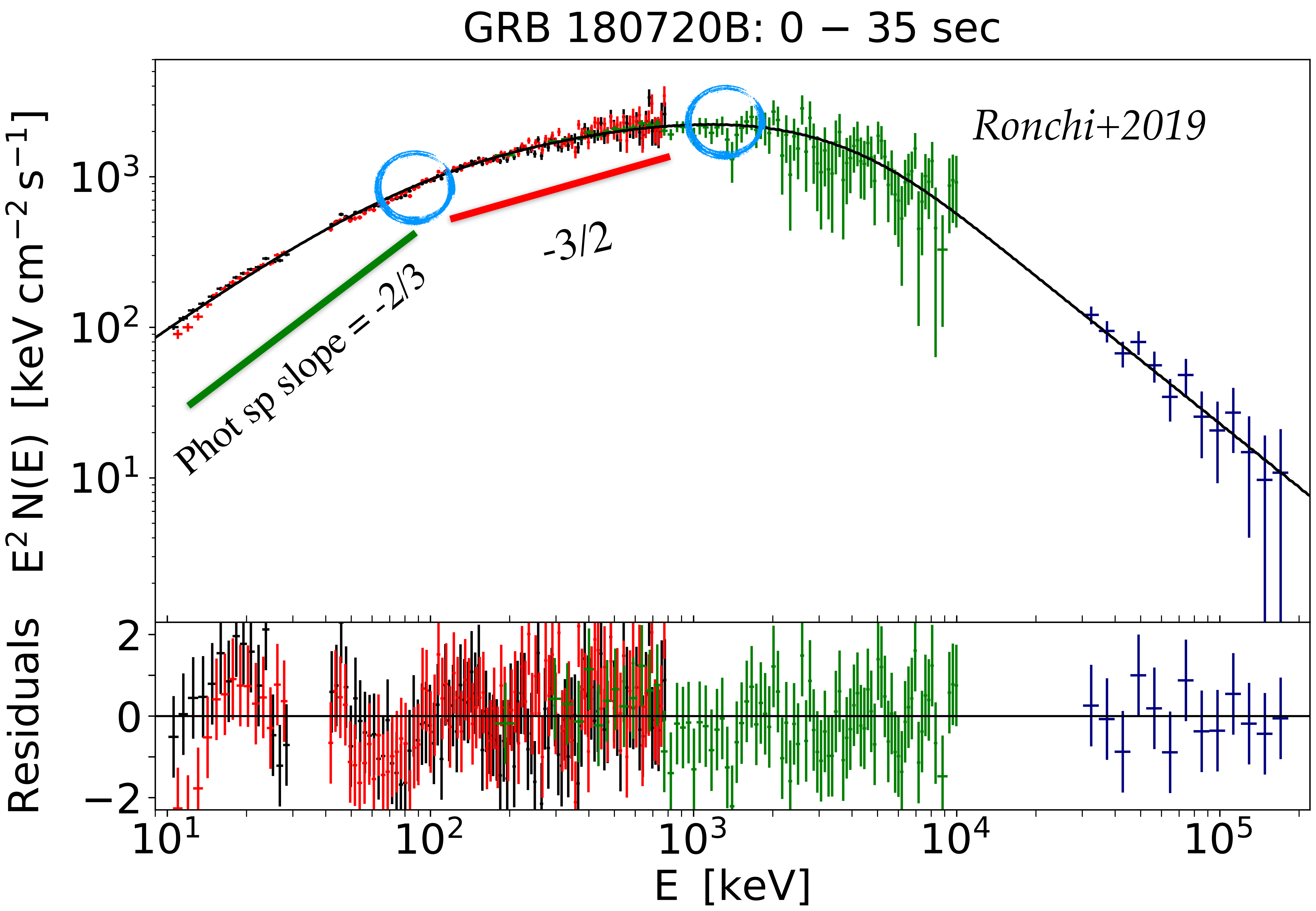




Observations: *Preece et al. 1998; Ghirlanda et al. 2002; Kaneko et al. 2006; Frontera et al. 2006; Vianello et al. 2008; Gruber et al. 2014 …….*

Theory: *Sari, Narayan & Piran 1996; Ghisellini et al. 2000; Daigne et al. 2012*

Most of long and all short GRBs are harder than synchrotron spectrum



Oganesyan et al. 2017: 14 bright GRBs detected by Swift

Oganesyan et al. 2017a: 34 GRBs detected by Swift

62% of GRBs
- ✓ Show two spectral breaks (new: low energy break 3-20 keV) which significantly improves the fit sigma
- ✓ The average photon indices below and above the break are -2/3 and -3/2

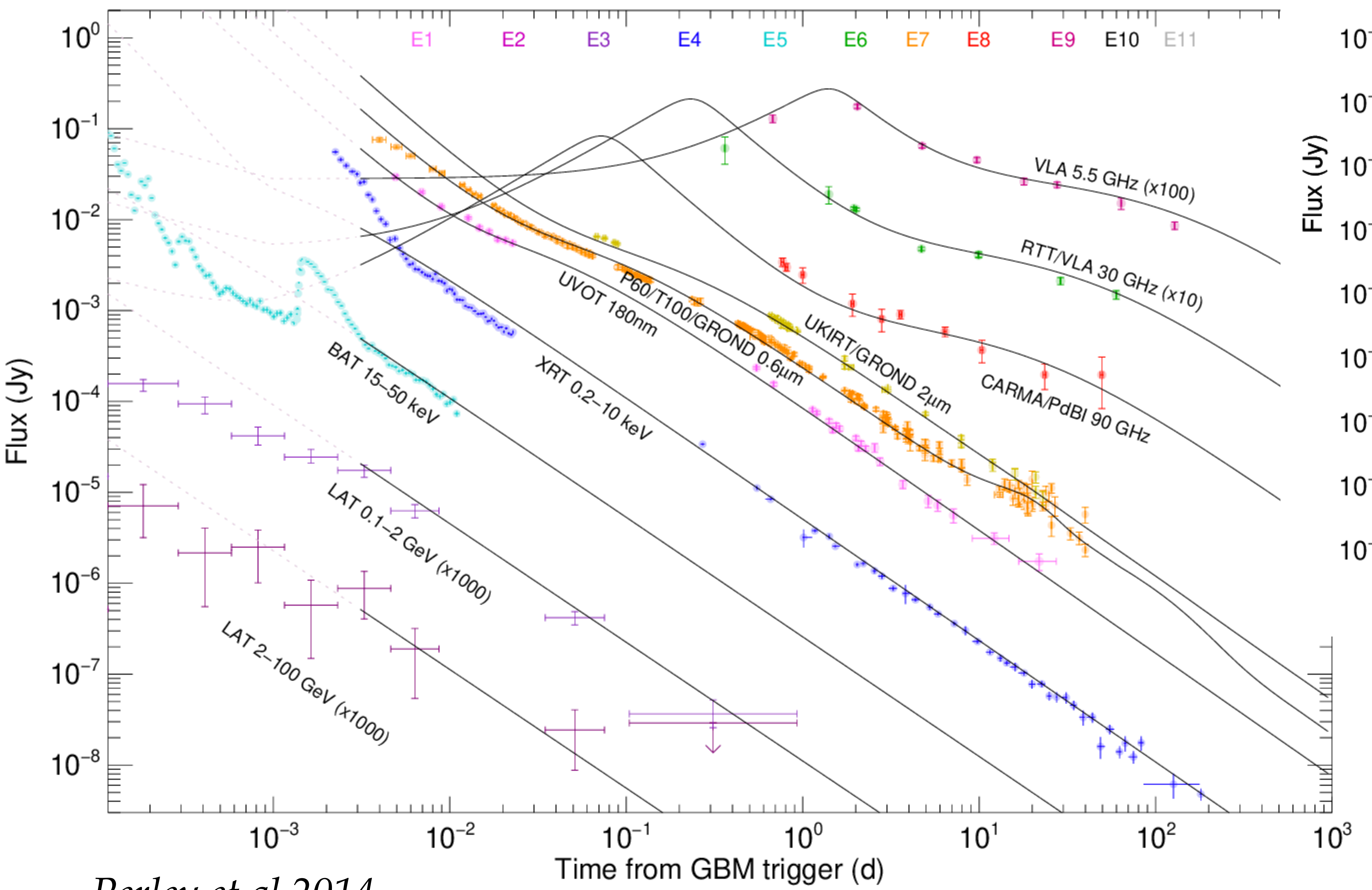
Fermi/GBM:
- Short and long Fermi GRBs (*Ravasio+2019*)
  Short Ep ~ Eb
- Bayesian analysis (*Burgess+2019*)

But quite extreme physical parameters of the emission region (see Ghisellini 2020)

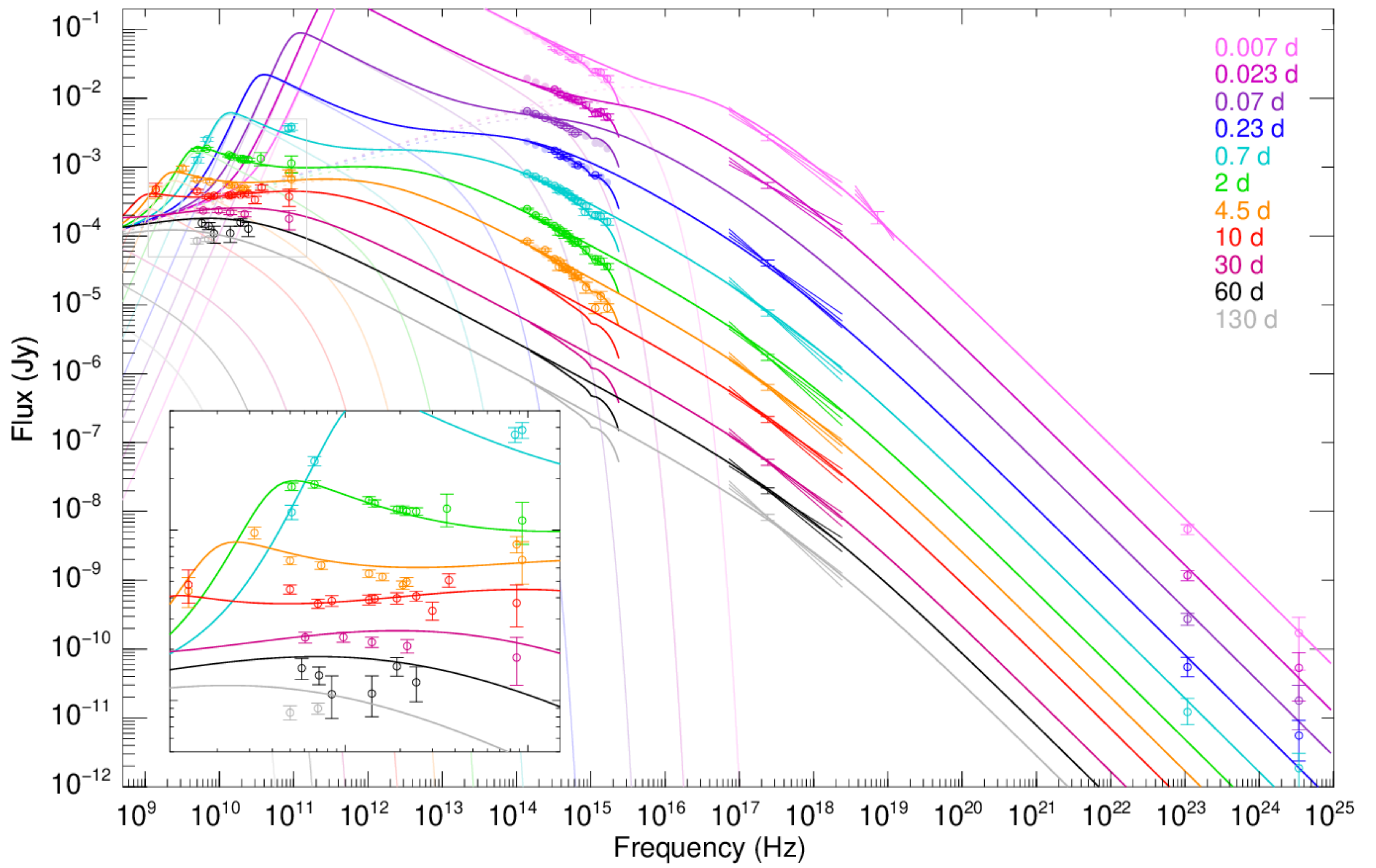
Starting to shed light on a long standing issue

Afterglow

GRB 130427A (z=0.34)



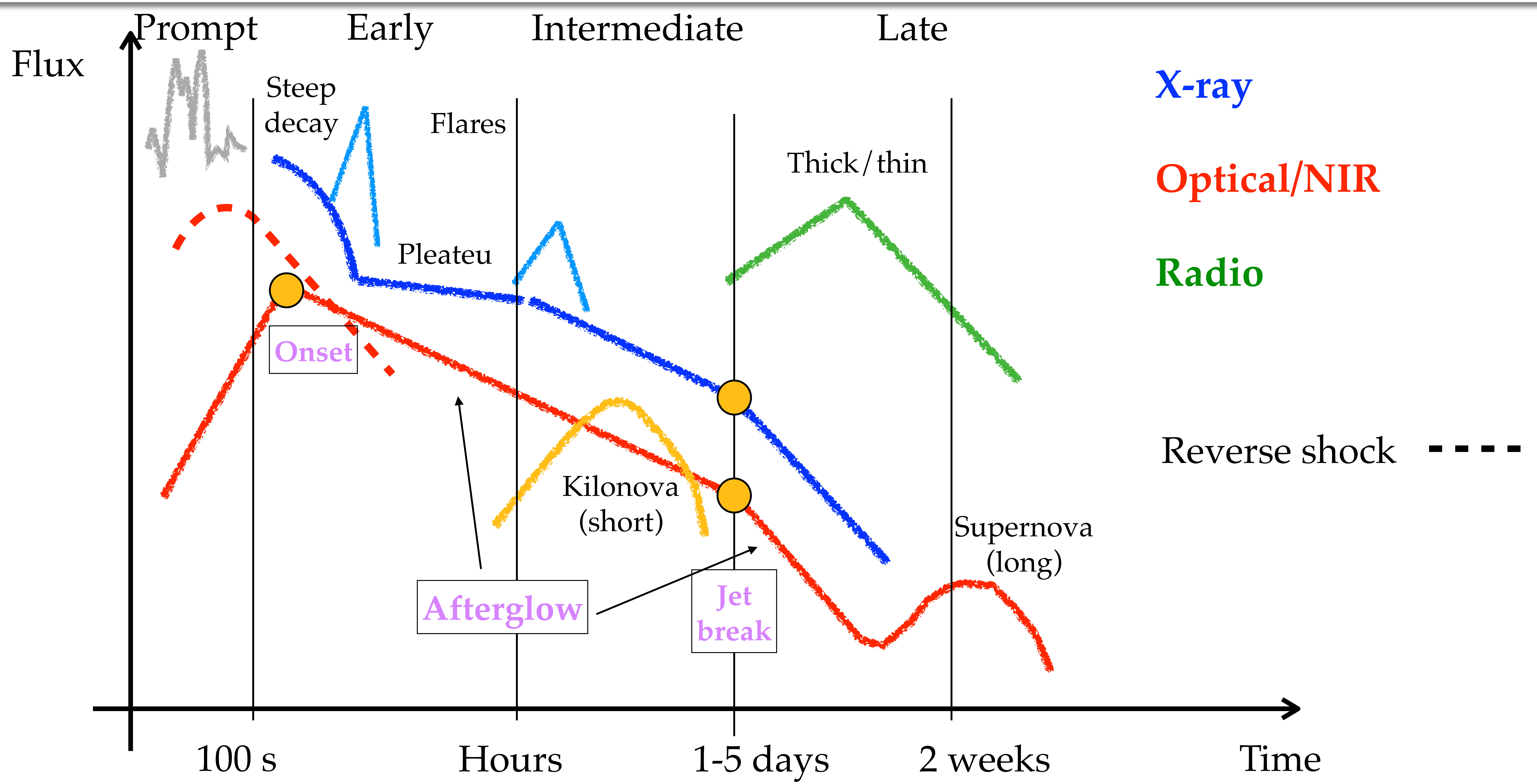
Perley et al 2014



On the banks of the river

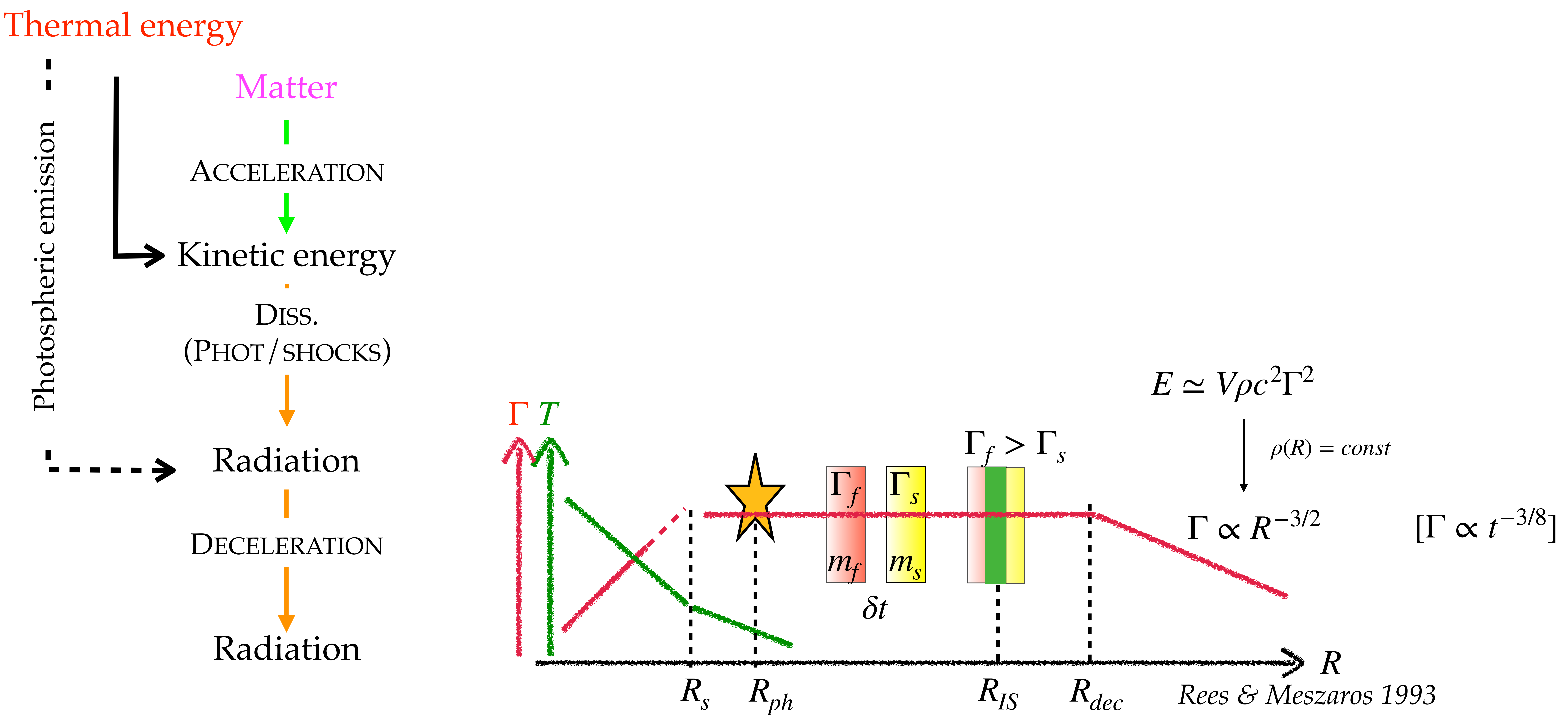
$$F(\nu, t) \propto \nu^{-\alpha} t^{-\beta}$$

AFTERGLOW PROPERTIES

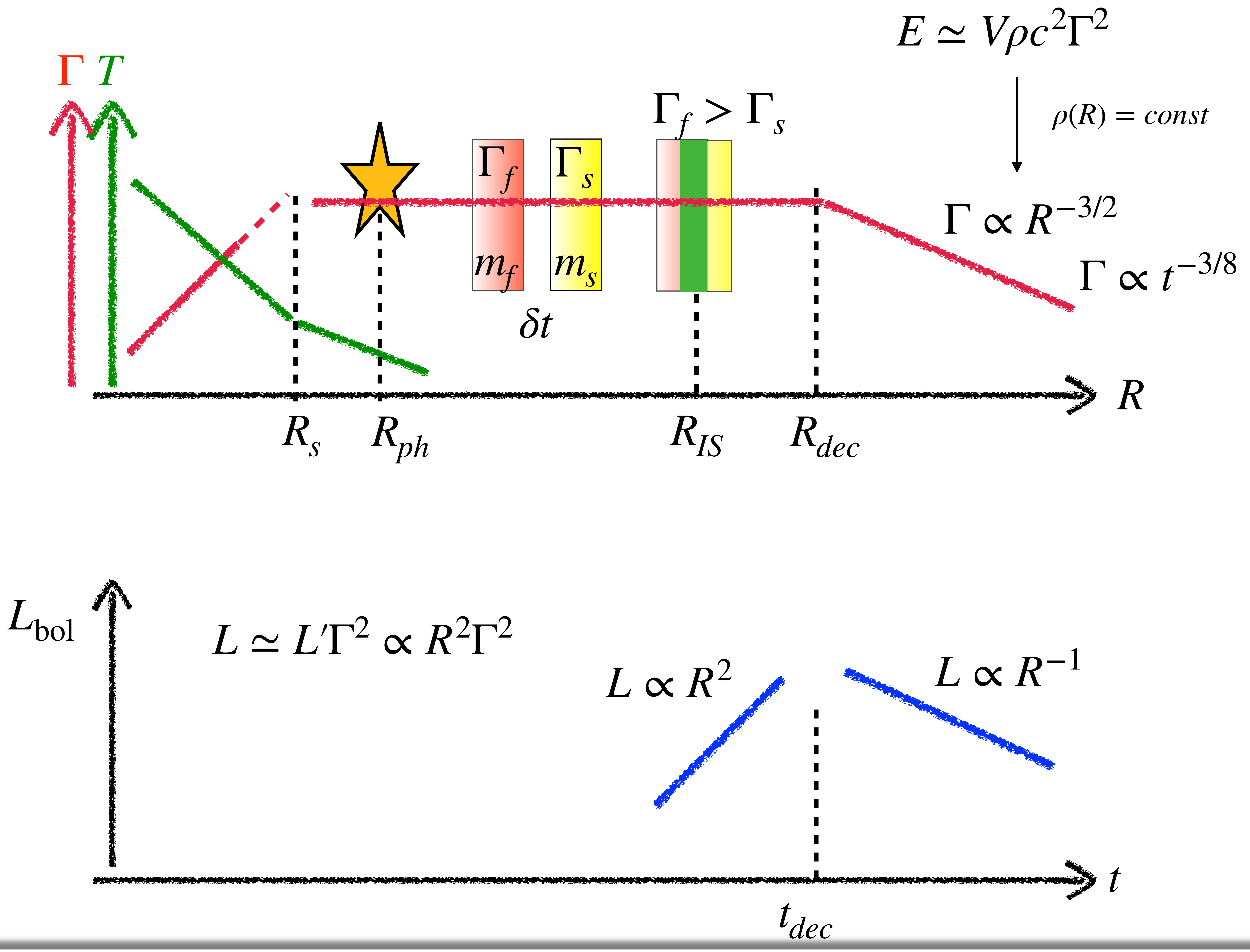


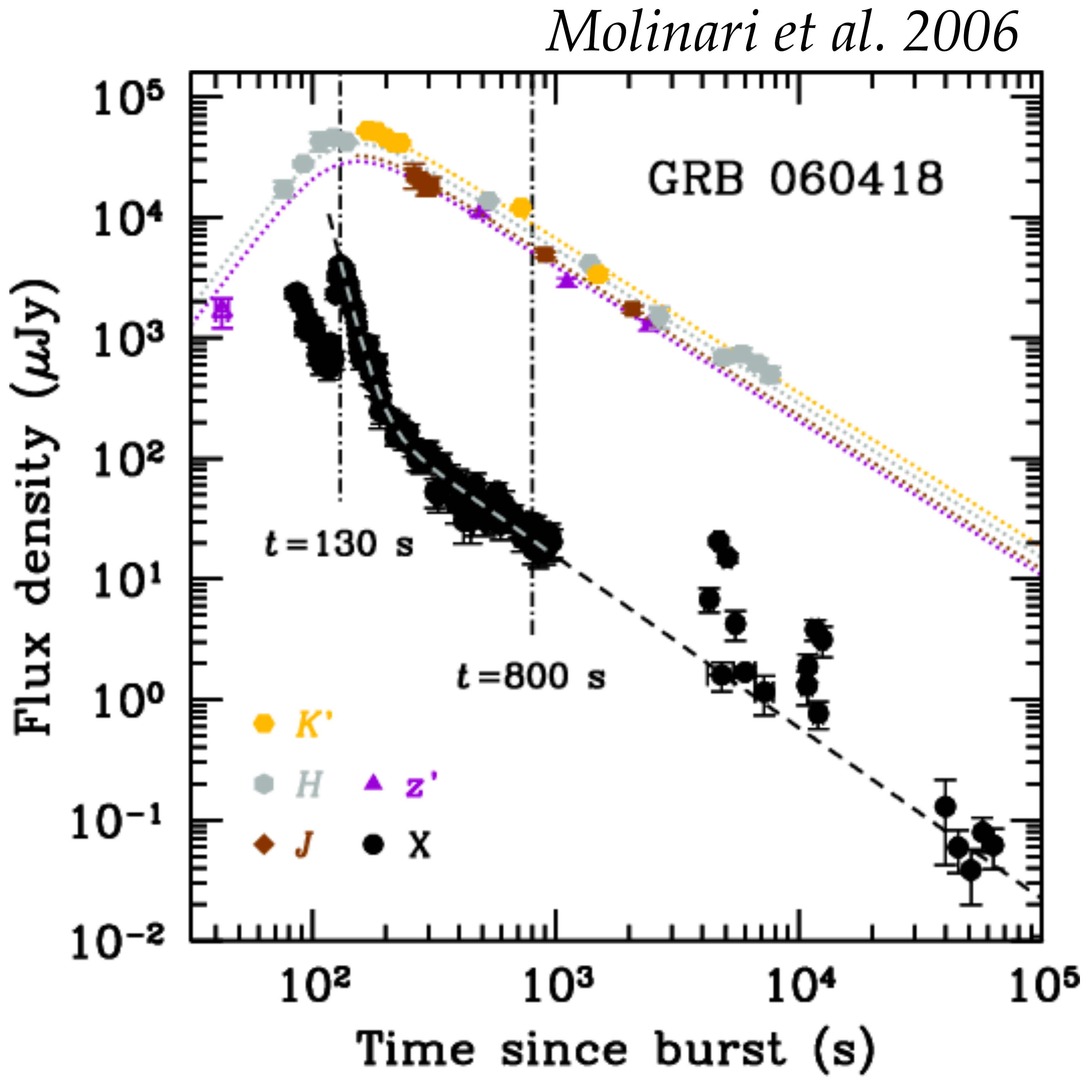
An oversimplified scheme

BASIC FIREBALL DYNAMICS: DECELERATION



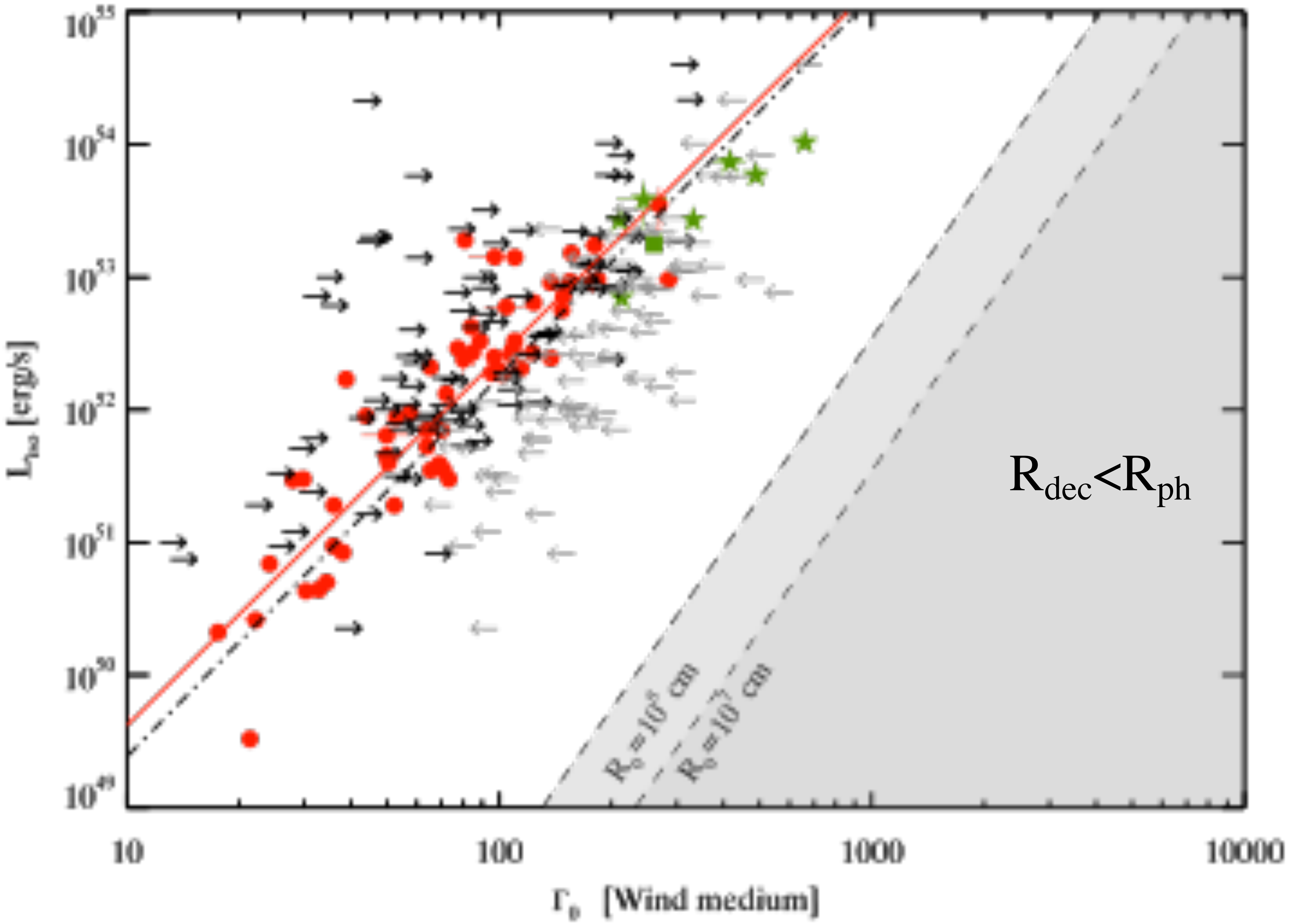
Deceleration dynamic scaling depends on the circumburst density

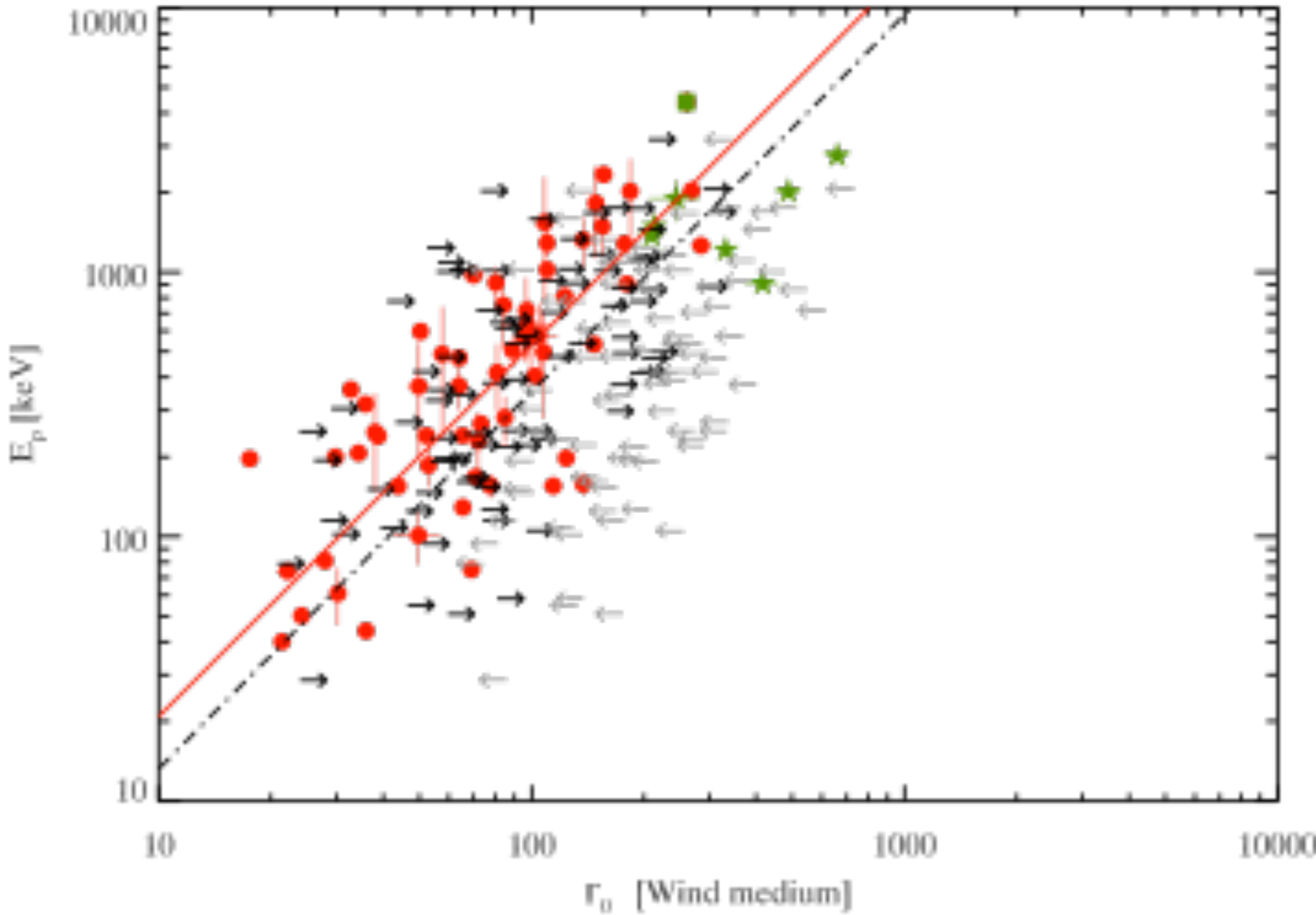




$$\Gamma_0 \approx 0.1 \left(\frac{E_k}{n_0 m_p c^5}\right)^{1/8} \left(\frac{t_{dec}}{1+z}\right)^{-3/8}$$

From the observable to the physical parameter (Γ_0)



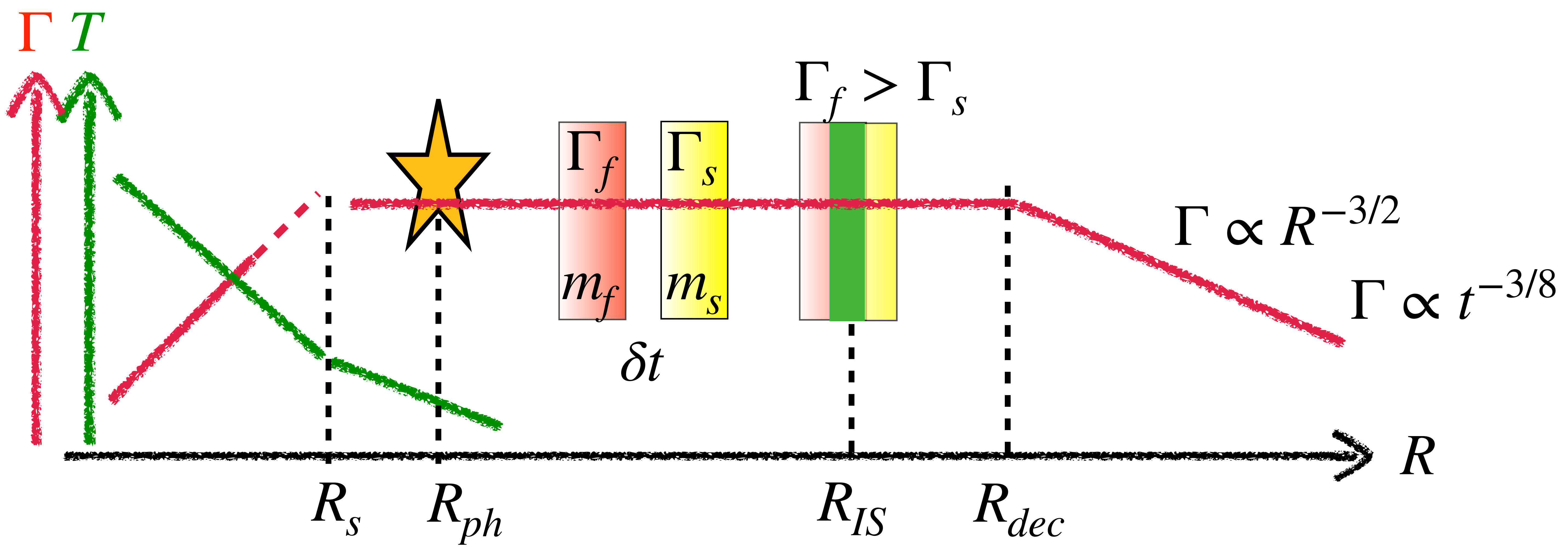


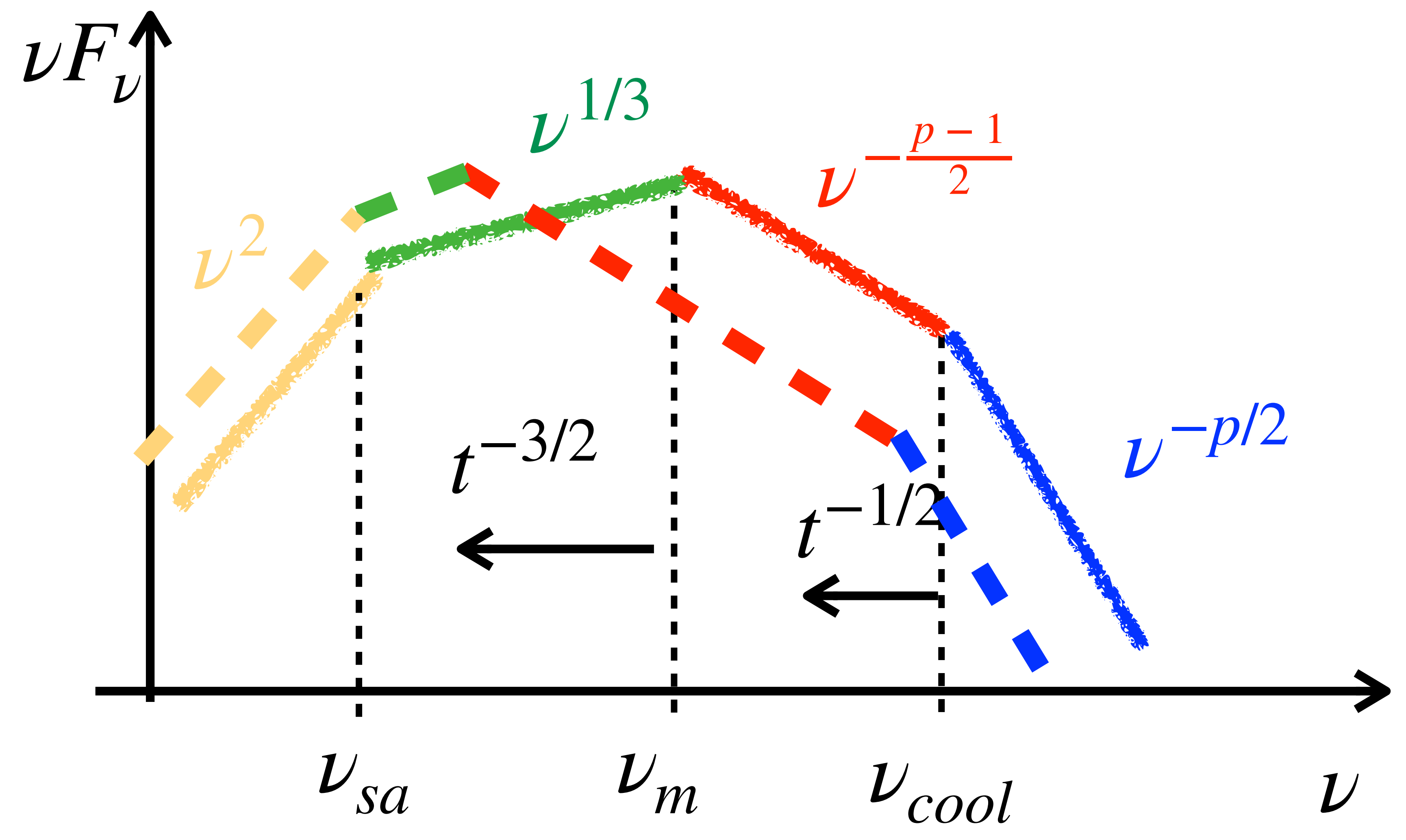
Ghirlanda+2010, 2018

$$L_{\rm iso} \propto \Gamma_0^2 \qquad E_{\rm peak} \propto \Gamma_0$$

$$E_{\rm peak} \propto L_{\rm iso}^{0.5}$$ (Similarly for E_{iso})

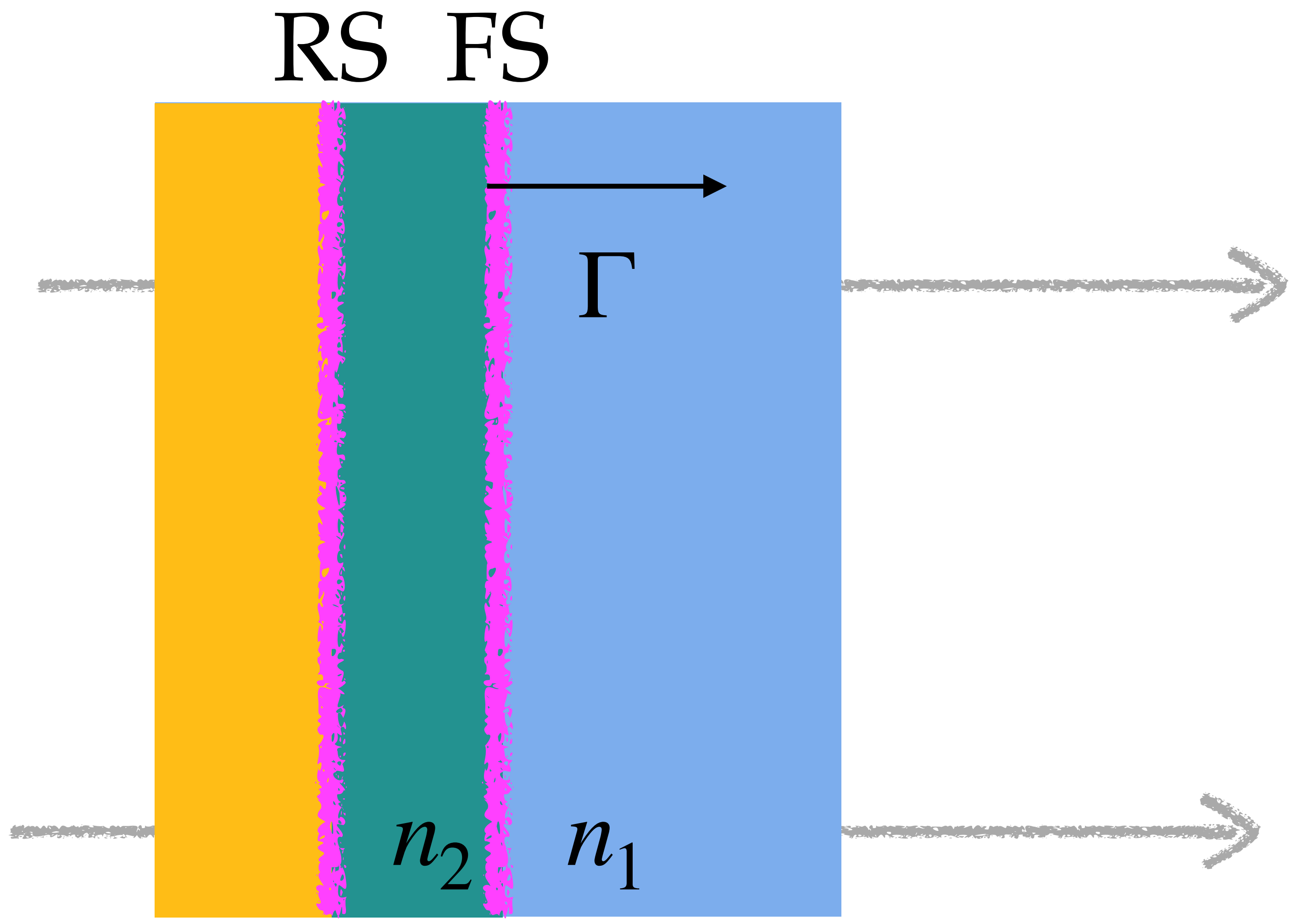
Larger luminosity (energy), larger bulk velocity





$$\gamma_m = \frac{p-2}{p-1}\epsilon_e(\Gamma-1)\frac{n_p}{n_e}\frac{m_p}{m_e}$$

$\gamma_m \propto \Gamma$



$\nu_m \propto t^{-3/2}$

$$\frac{B'^2}{8\pi} = \epsilon_B(\Gamma-1)n_2 m_p c^2$$

$B' \propto \Gamma$

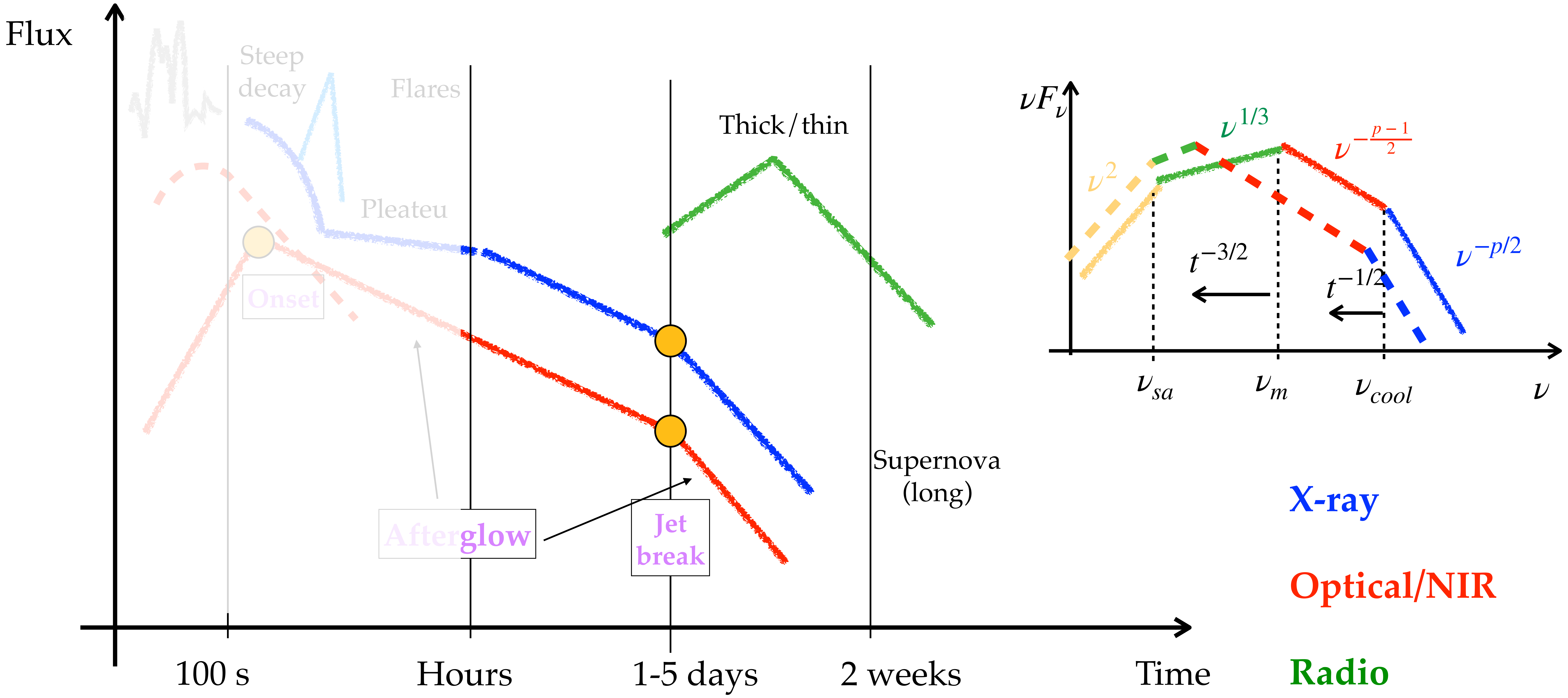
$F_m \propto NP_{syn} \propto R^3 B'\Gamma = t^0$

$$t'_{cool,syn} = \frac{6\pi m_e c}{\sigma_T \gamma_e B'^2 \Gamma}$$

$\gamma_{cool} \propto \Gamma^{-1} t'^{-1} B'^{-2}$

$\nu_{cool} \propto t^{-1/2}$

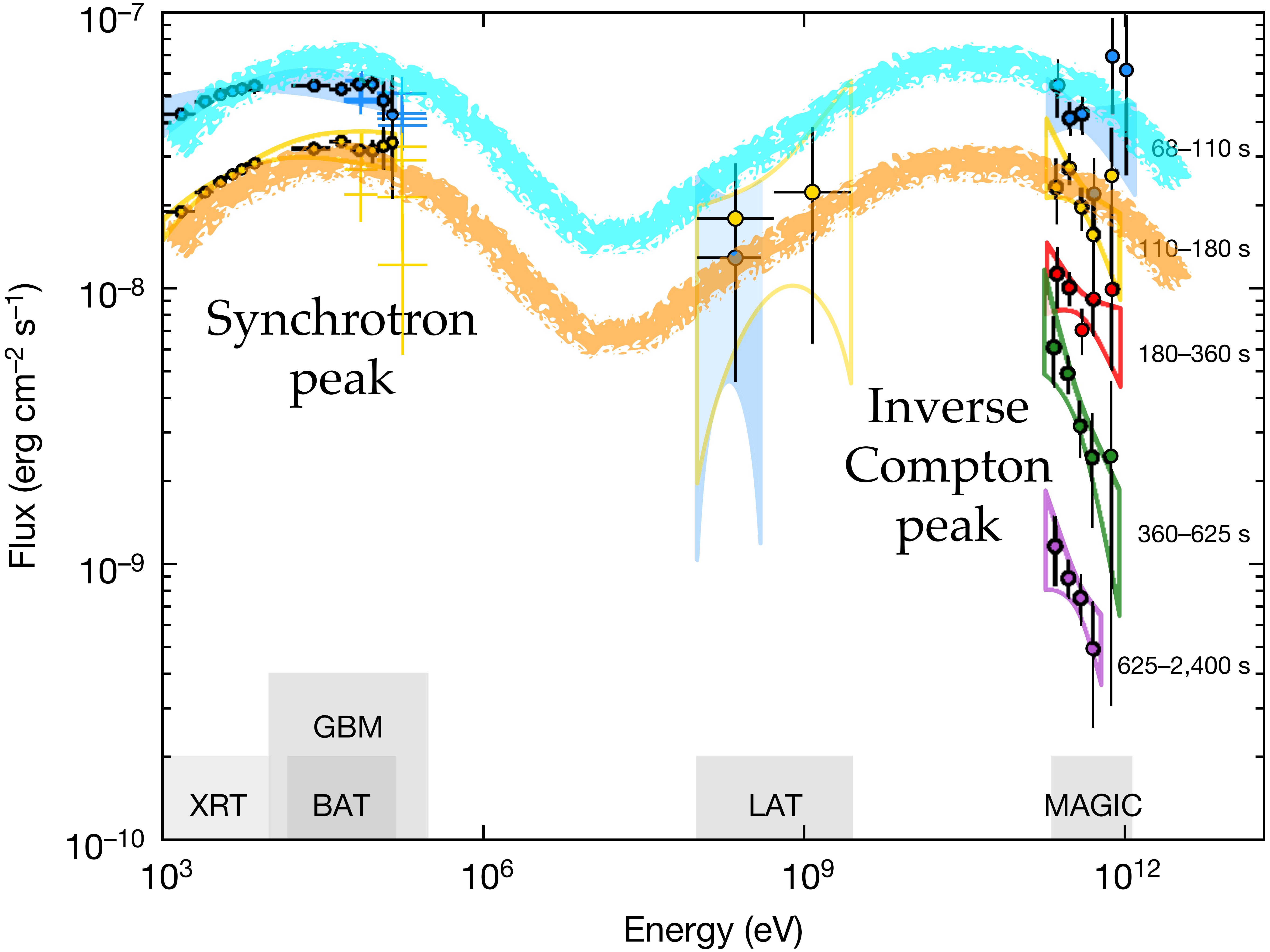
Linking shock microphysical parameters to shock dynamics



Spectral evolution is the key to understand the light curves at different frequencies

AFTERGLOW SSC

GRB190114C *MAGIC collaboration 2020*



$L_{SCC} \sim L_{Syn}$

- Spectral slope of Magic spectrum $\nu_{p,SSC} \leq 100$ GeV
- Spectral evolution of Magic spectrum $\nu_{p,SSC} \downarrow$ with time
- If sub-MeV is synchrotron $\nu_{p,syn} \simeq 10$ keV

$$\nu_{p,SSC} \simeq 2\gamma_e^2 \nu_{p,syn} \quad \text{(Th)}$$

$$\nu_{p,SSC} \simeq 2\gamma_e m_e c^2 \frac{\Gamma}{1+z} \quad \text{(KN)}$$

$\gamma_m \leq 10^3$

$\Gamma B \geq 10^5$

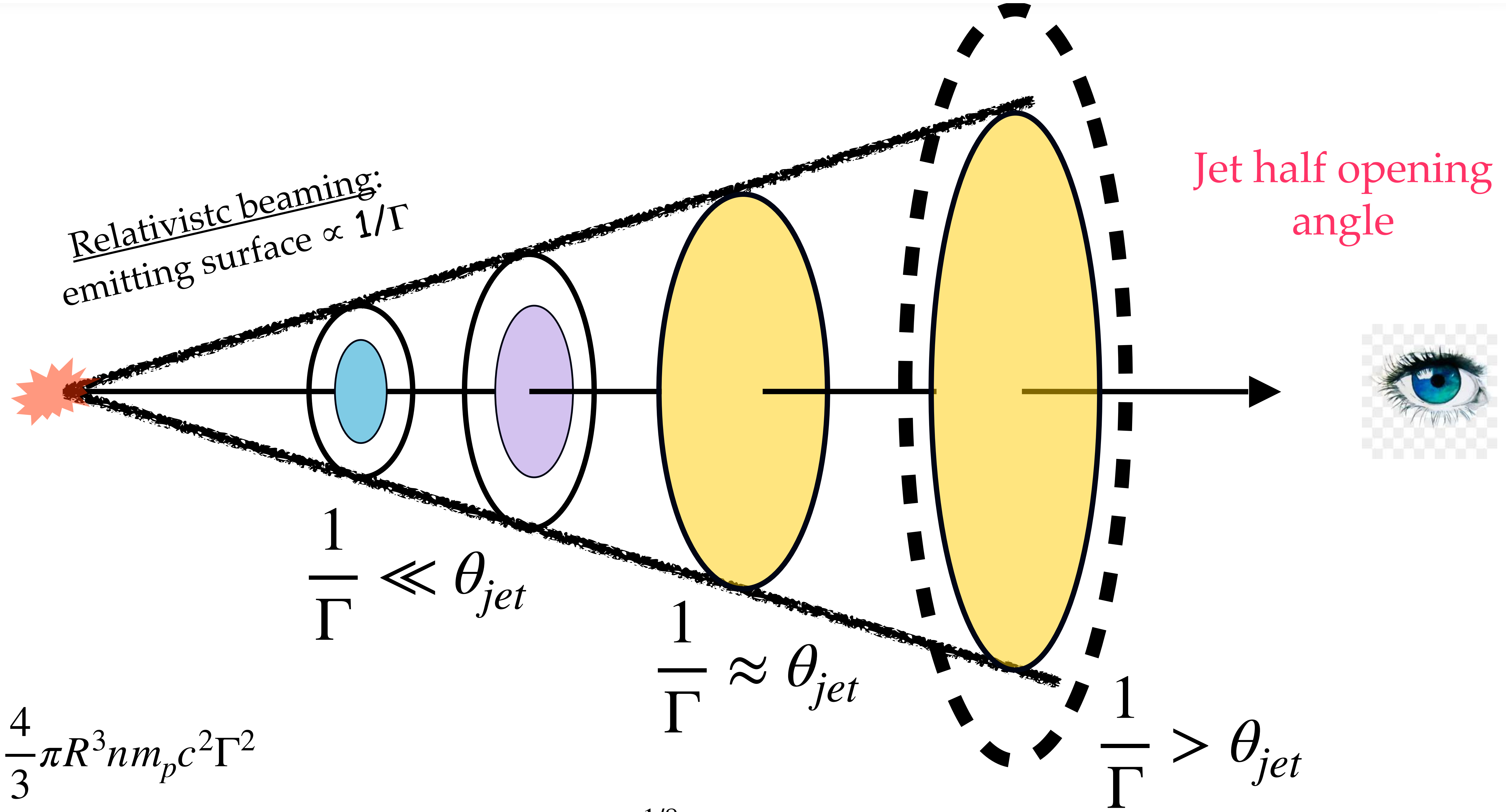
$\epsilon_e \leq 0.1 - 0.01$

Possible role of pairs

SSC << SYN

The VHE emission component started to be explored only recently

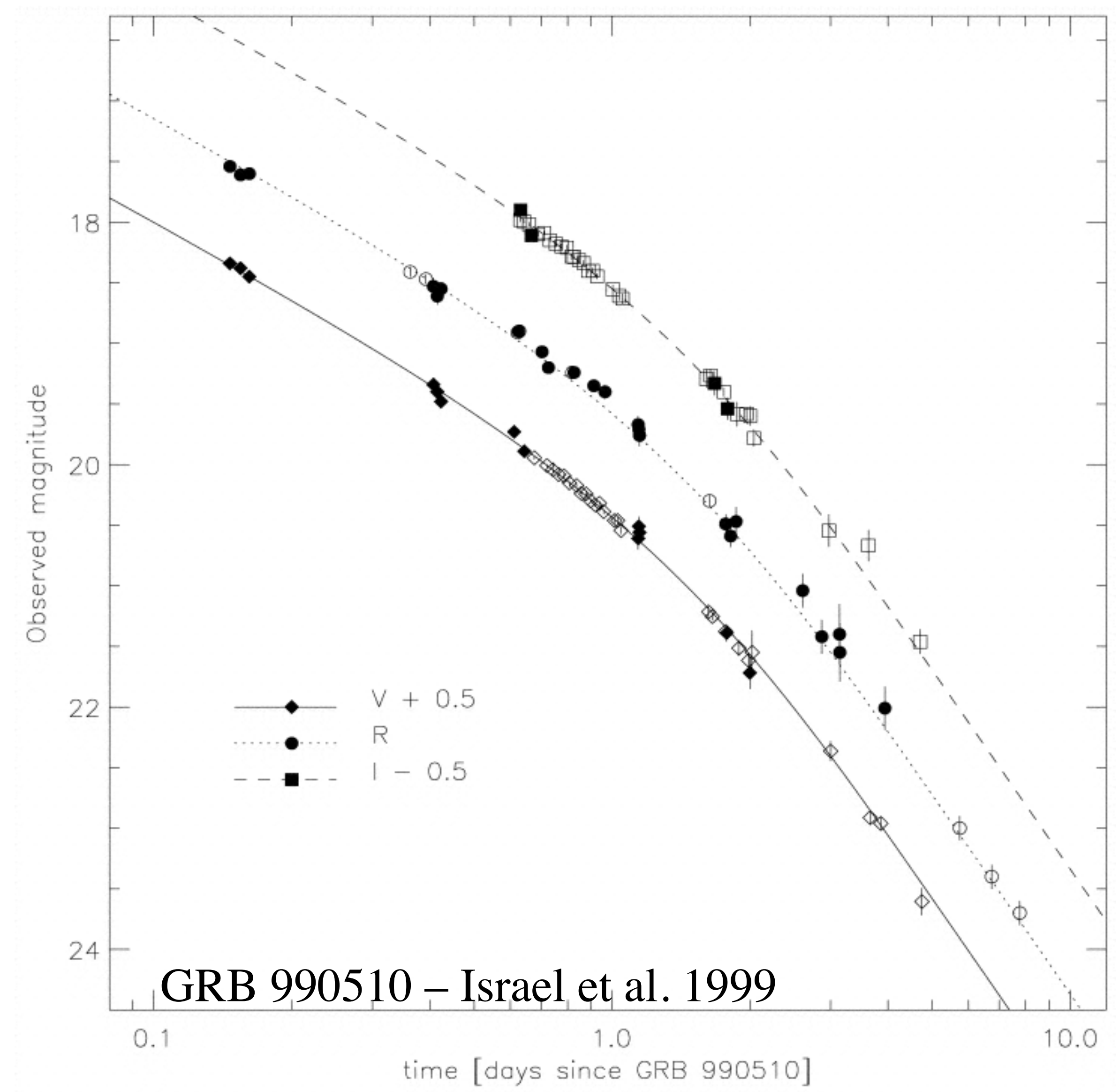
JET EFFECT

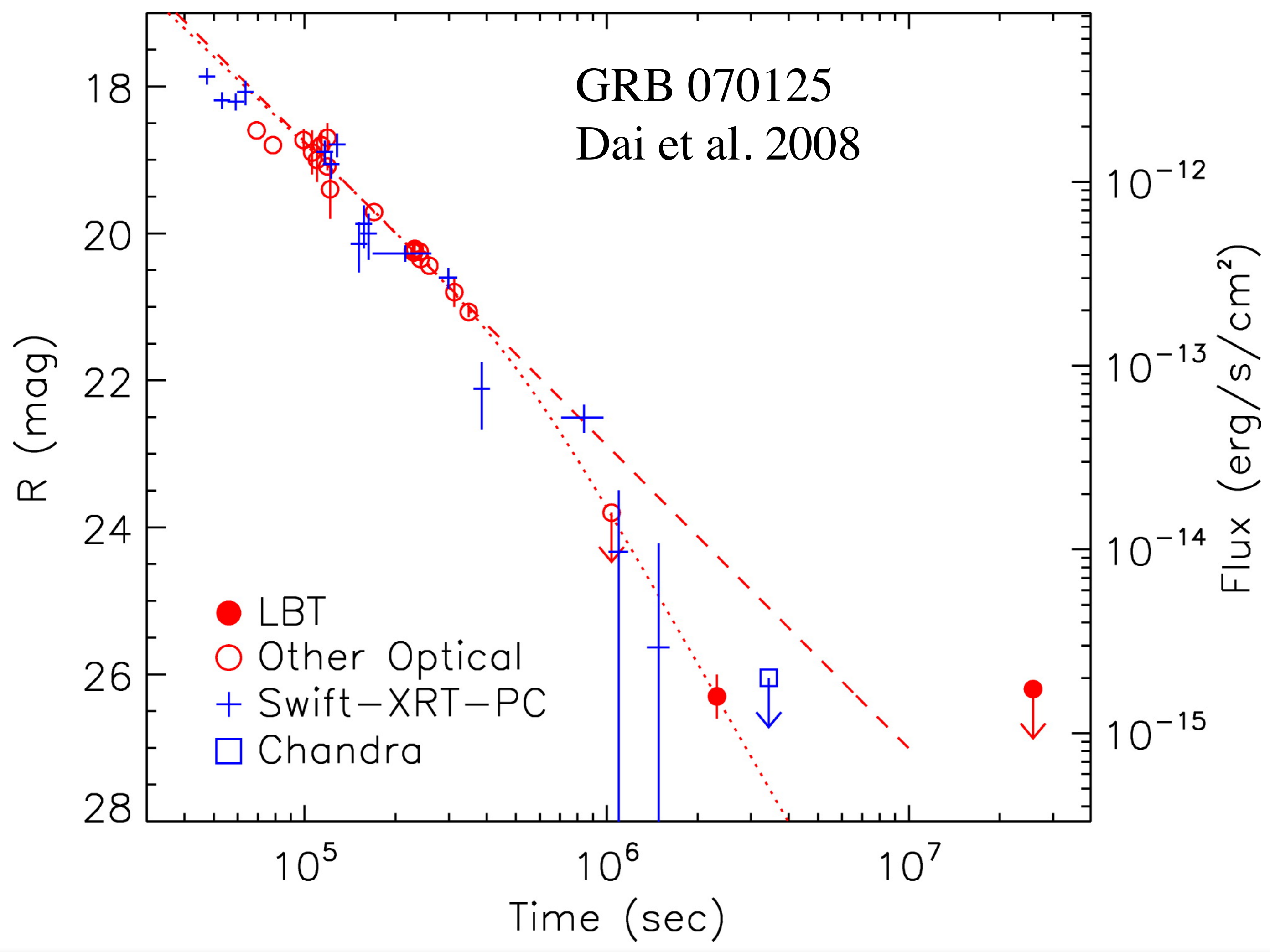


$$E = \frac{4}{3}\pi R^3 n m_p c^2 \Gamma^2$$

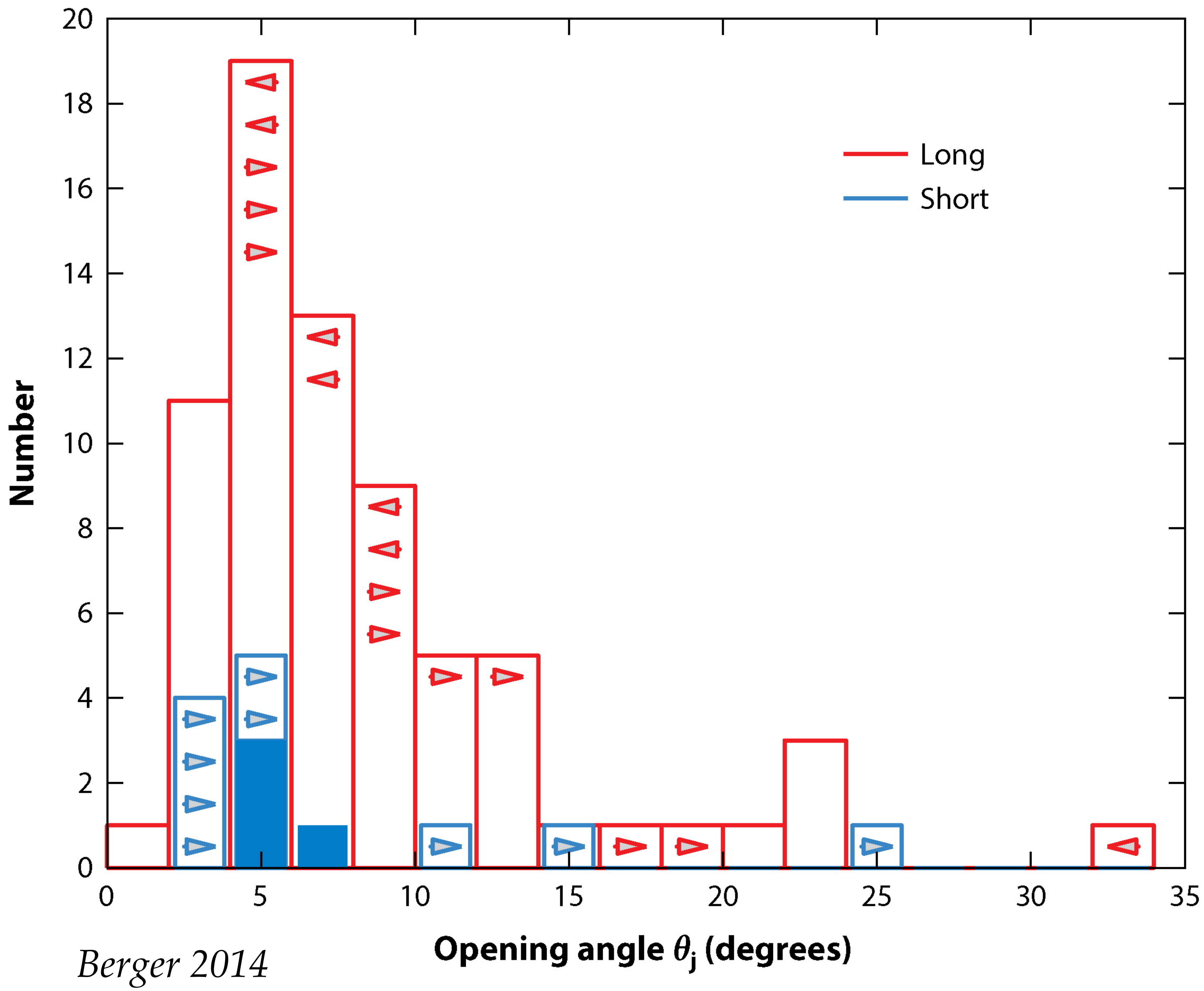
$$R \sim 2ct\Gamma^2 \qquad \Gamma = \left(\frac{3E}{256\pi n m_p c^5}\right)^{1/8} t^{-3/8} \qquad \theta_{jet} = \frac{1}{\Gamma} \sim \left(\frac{256\pi n m_p c^5}{3E}\right)^{1/8} t_{break}^{3/8}$$

$$\boxed{\theta_{jet} = 0.61 \left(\frac{n}{E_{52}}\right)^{1/8} \left(\frac{t_{break}}{1+z}\right)^{3/8}}$$

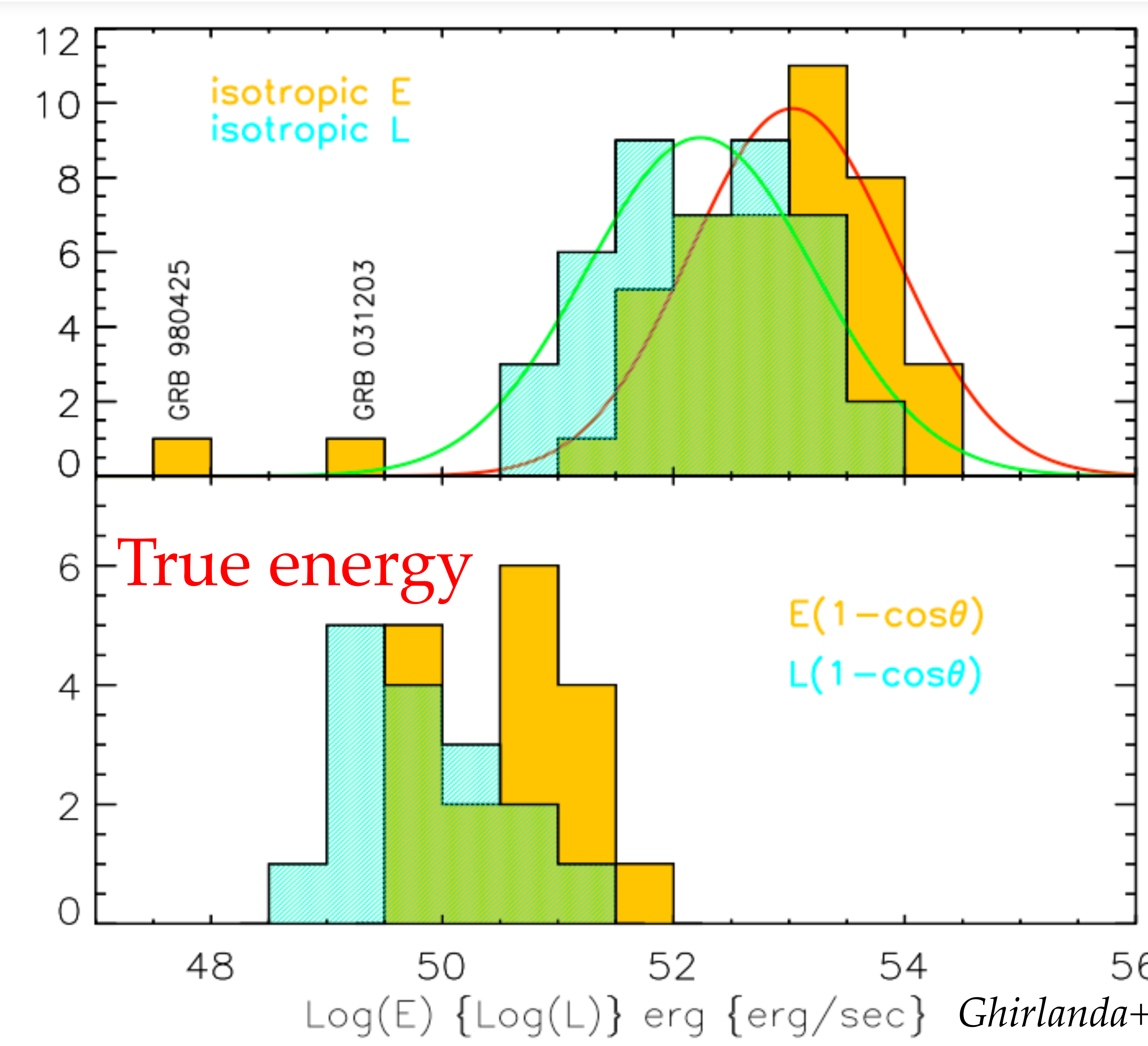




From the observable to the physical parameter (θ_{jet})



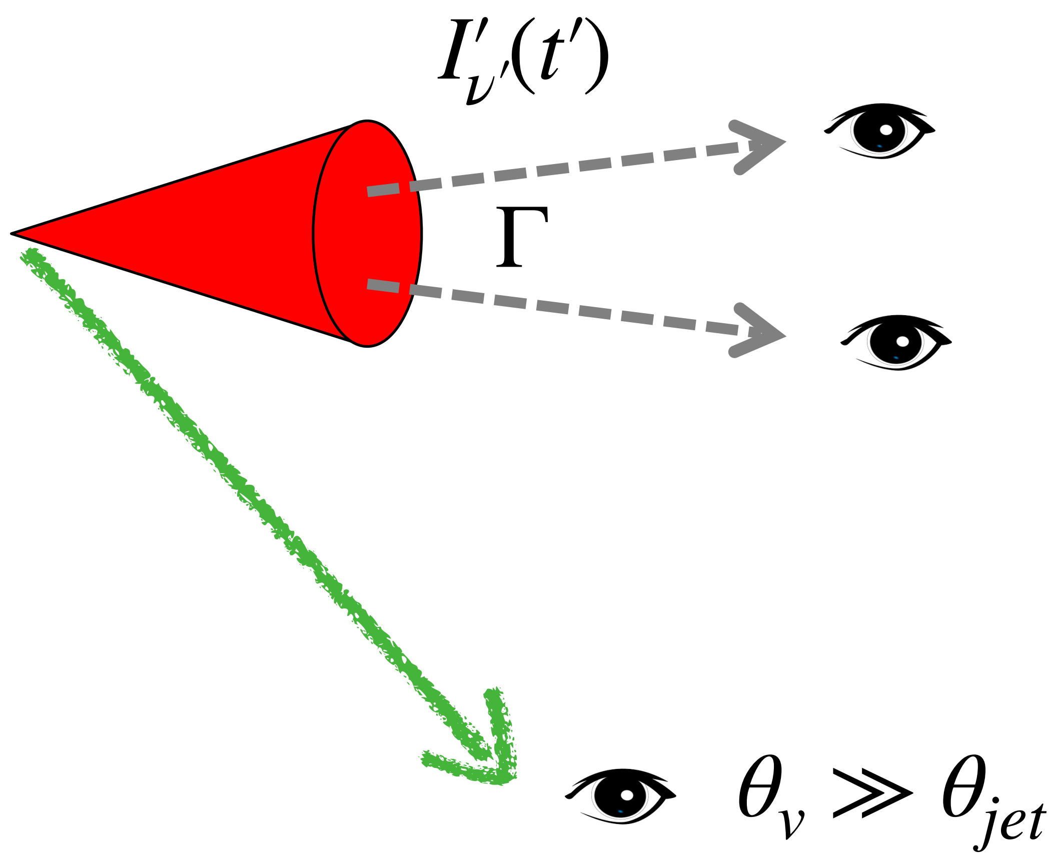
Berger 2014



Ghirlanda+2007

The presence of a jet reduces the GRB energy budget

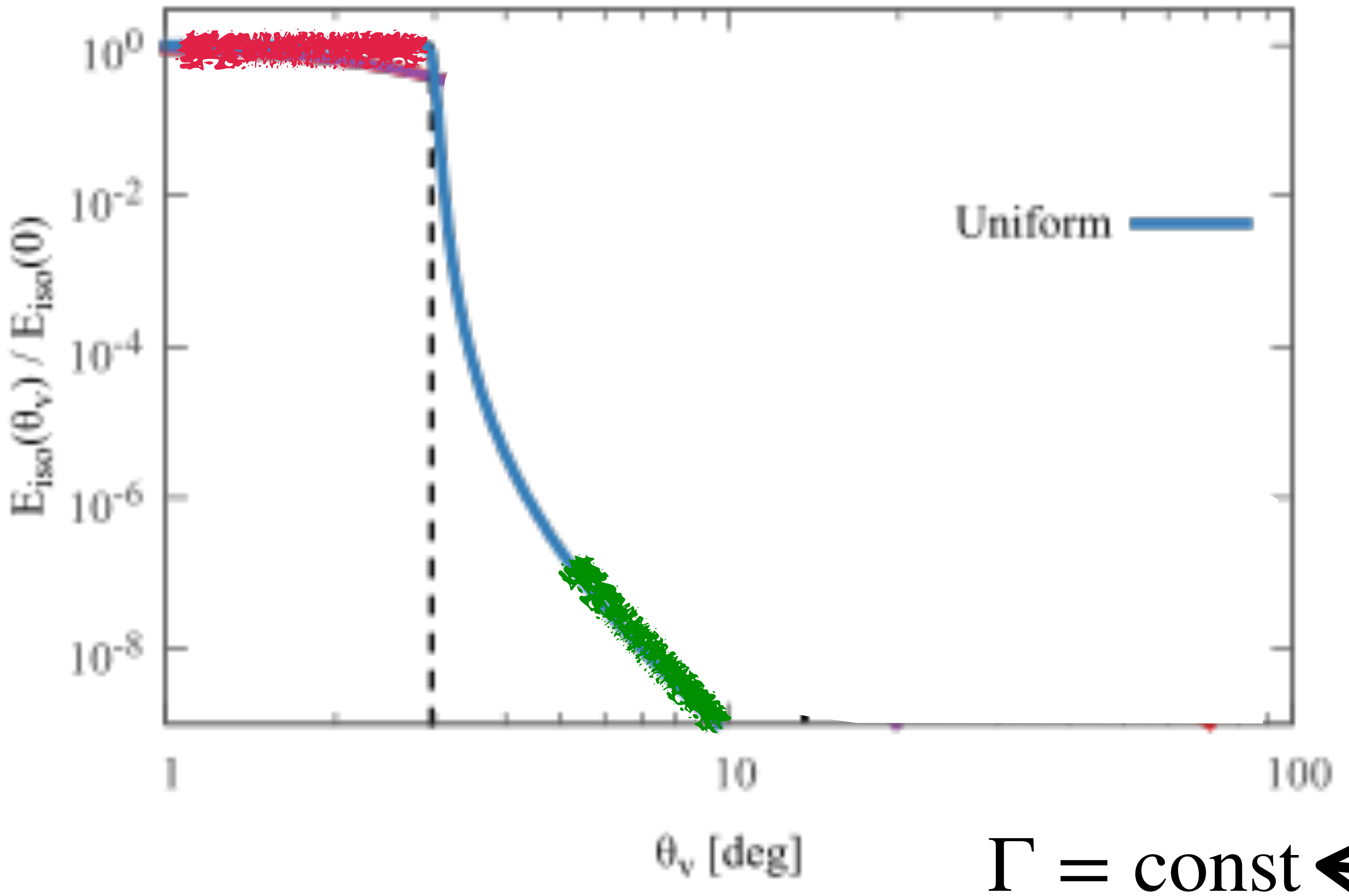
VIEWING ANGLE EFFECTS



$$\delta_{on} \simeq \frac{1}{\Gamma(1-\beta)}$$

$$\frac{\delta_{off}}{\delta_{on}} = \frac{\Gamma(1-\beta)}{\Gamma(1-\beta\cos\theta_v)} \simeq \frac{1}{1+\Gamma^2\theta_v^2}$$

$$\delta_{off} = \frac{1}{\Gamma(1-\beta\cos\theta_v)}$$



$$I_\nu(t) = I_{\nu'}(t')\delta^3$$

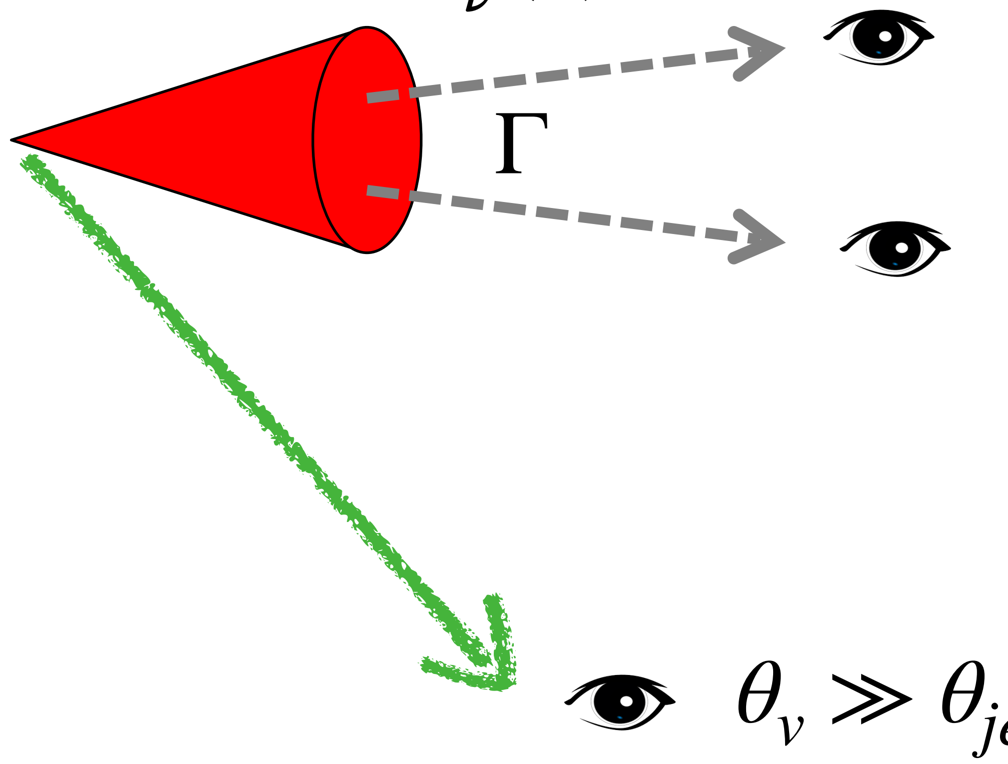
$$L_\nu(t,\theta_v) = L(t,0)\left(\frac{\delta_{off}}{\delta_{on}}\right)^3$$

Prompt

$\Gamma = \text{const}$

Given the large values of Gamma the "debeaming" effect is dramatic already for slightly off axis angles

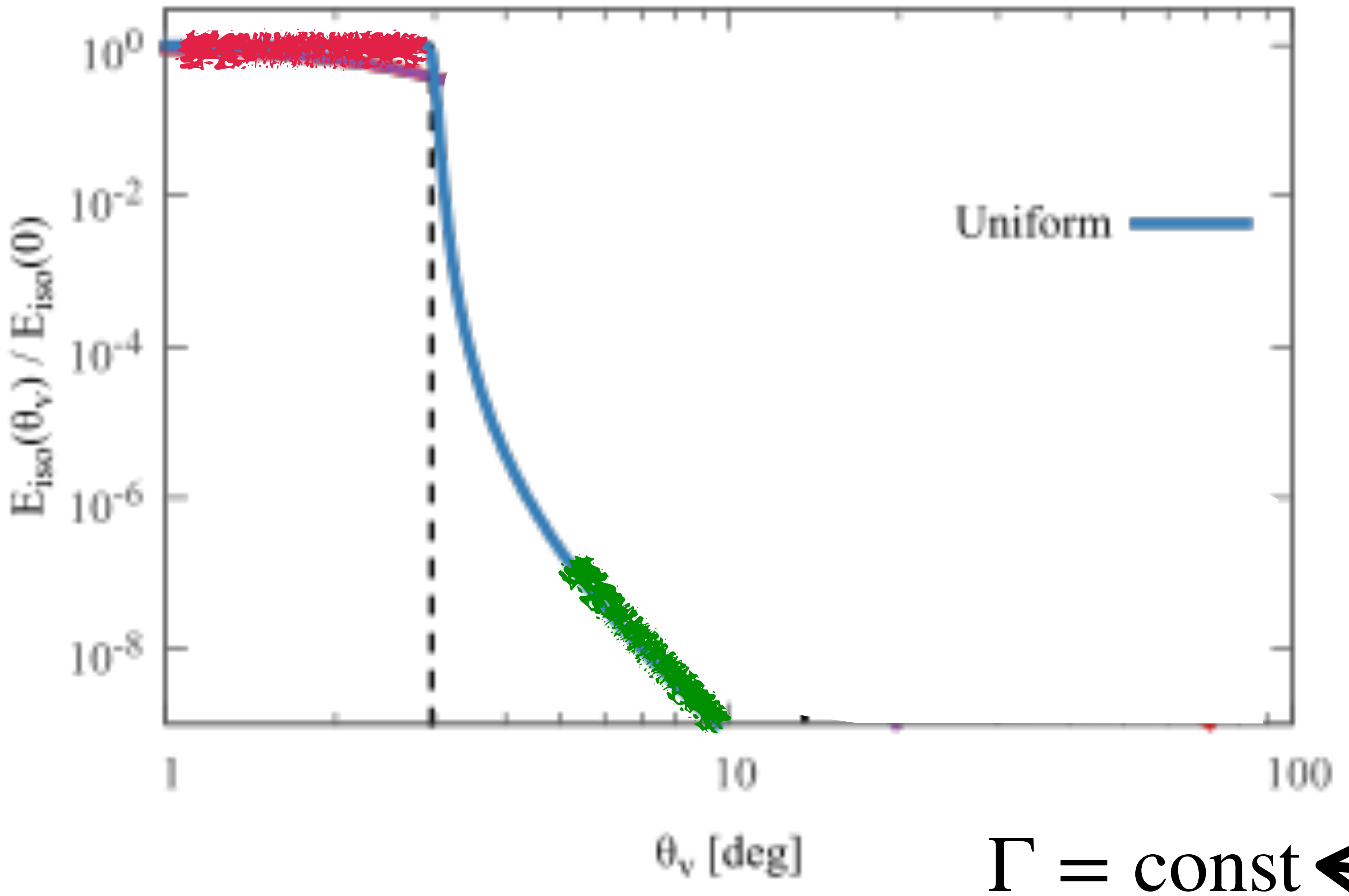
VIEWING ANGLE EFFECTS



$$\delta_{on} \simeq \frac{1}{\Gamma(1-\beta)}$$

$$\delta_{off} = \frac{1}{\Gamma(1-\beta\cos\theta_v)}$$

$$\frac{\delta_{off}}{\delta_{on}} = \frac{\Gamma(1-\beta)}{\Gamma(1-\beta\cos\theta_v)} \simeq \frac{1}{1+\Gamma^2\theta_v^2}$$



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$$L_\nu(t,\theta_v) = L(t,0)\left(\frac{\delta_{off}}{\delta_{on}}\right)^3$$

Prompt

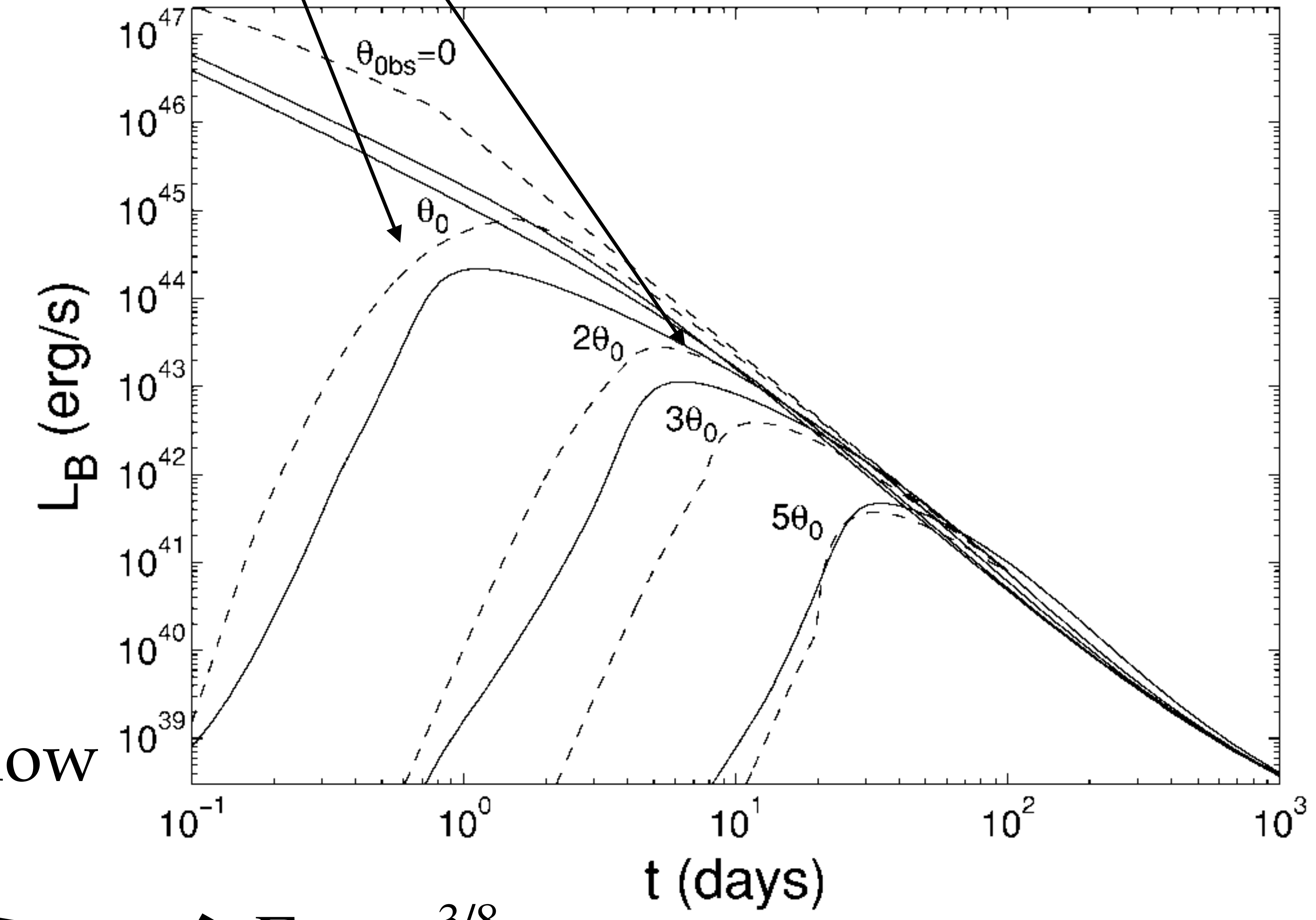
$\Gamma = \text{const}$

Afterglow

$\Gamma = t^{-3/8}$

Peak when $\Gamma \sim \frac{1}{\theta_v}$

$$t_p \approx 60 \text{ days } E_{52}^{1/3} n_0^{-1/3} \left(\frac{\theta_v - \theta_{jet}}{15^\circ}\right)^2$$



Granot 2002

Given the large values of Gamma the “debeaming” effect is dramatic already for slightly off axis angles

Uniform jet
Top hat jet

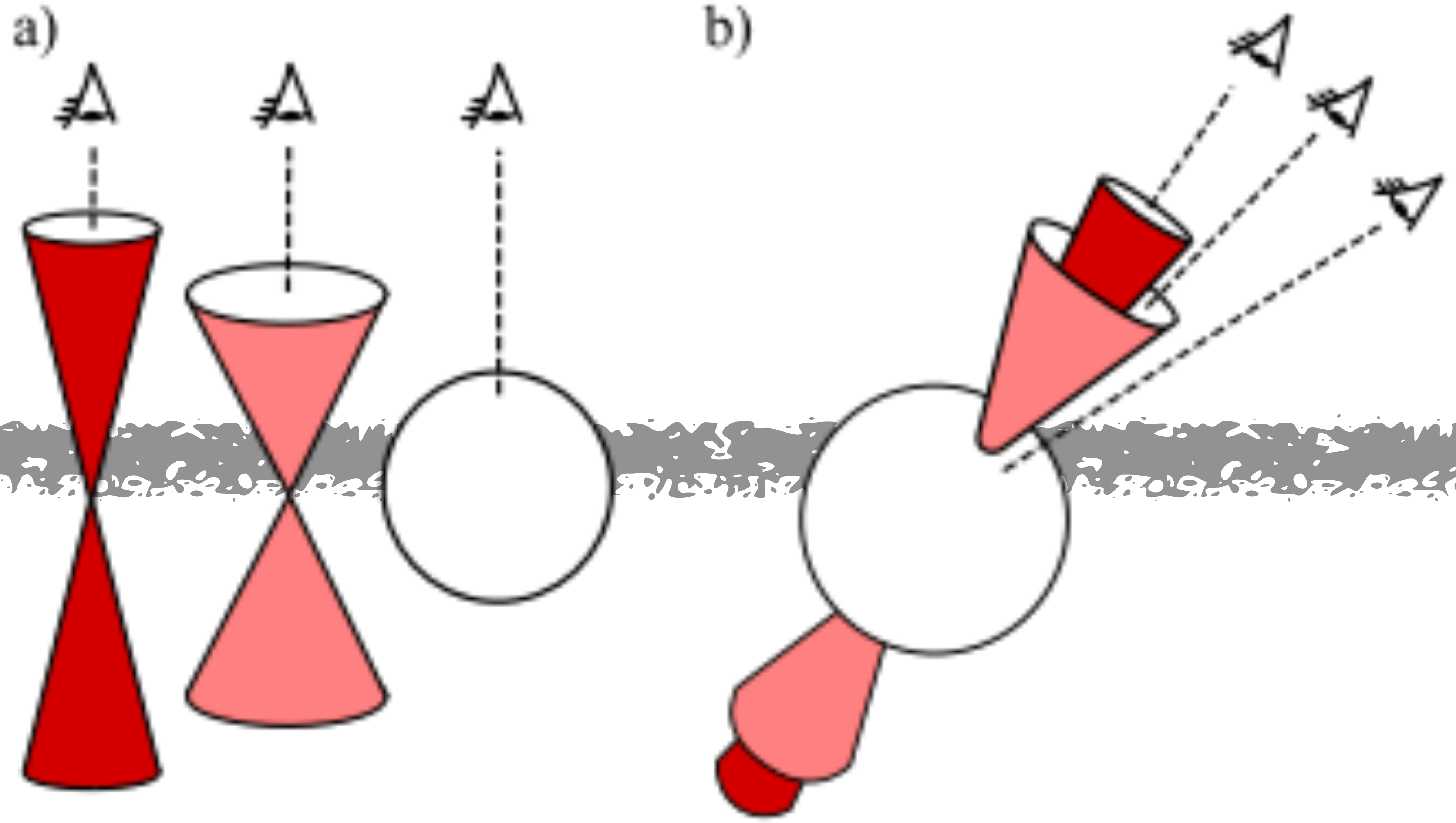
Structured jet
Universal jet

GRB diversity —> different θ_{jet}

GRB diversity —> different θ_v

$E_{\rm true} \simeq E_{\rm iso}\theta_{jet}^2 \sim$ const

$E_{\rm iso} \simeq \theta_{jet}^{-2}$



Strctured jet + cocoon
Uniform jet + cocoon
Structured cocoon
…

Lipunov et al. 2001

Rossi + 2002; Zhang+ 2002

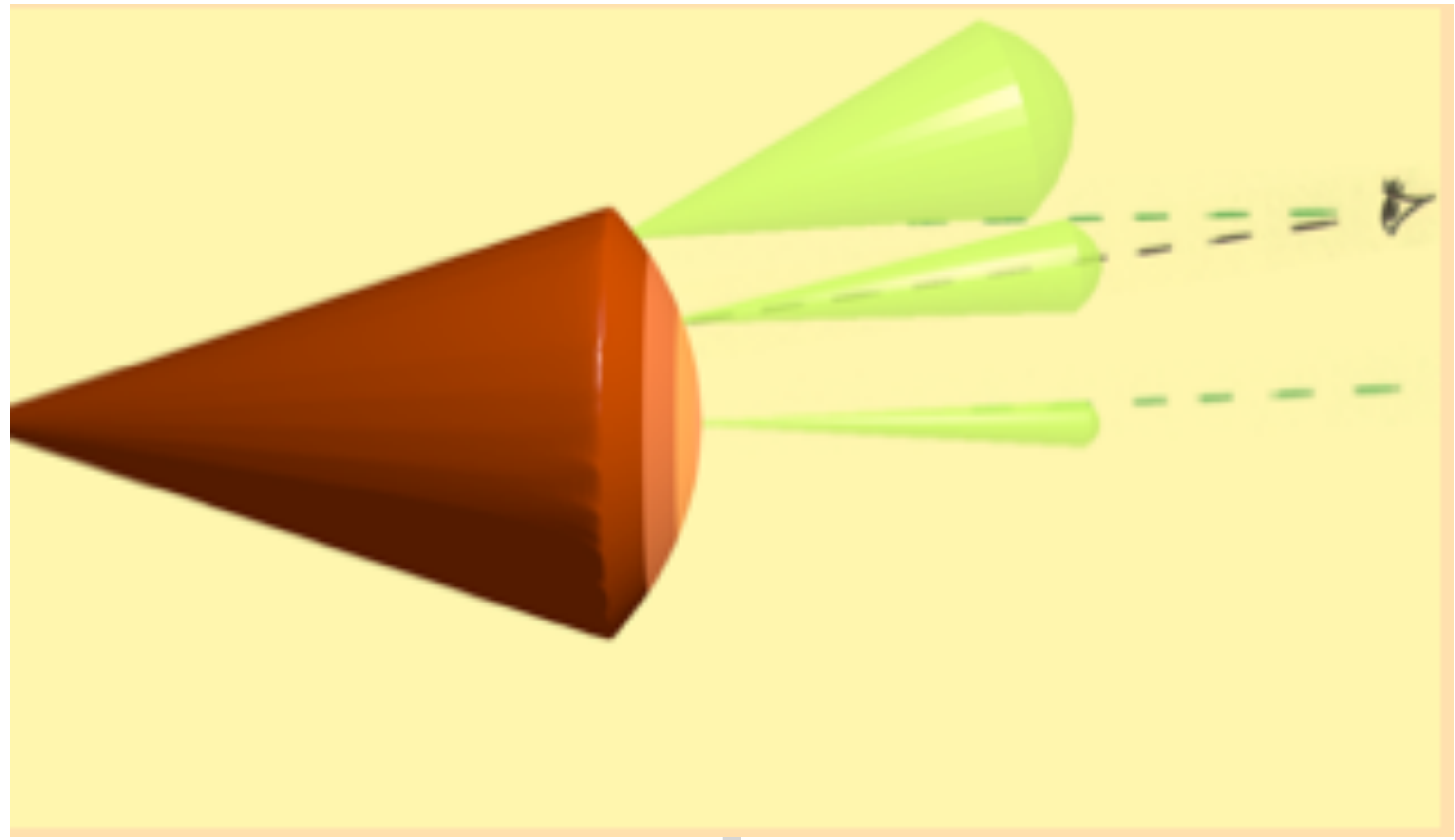
2017 Aug → Many …

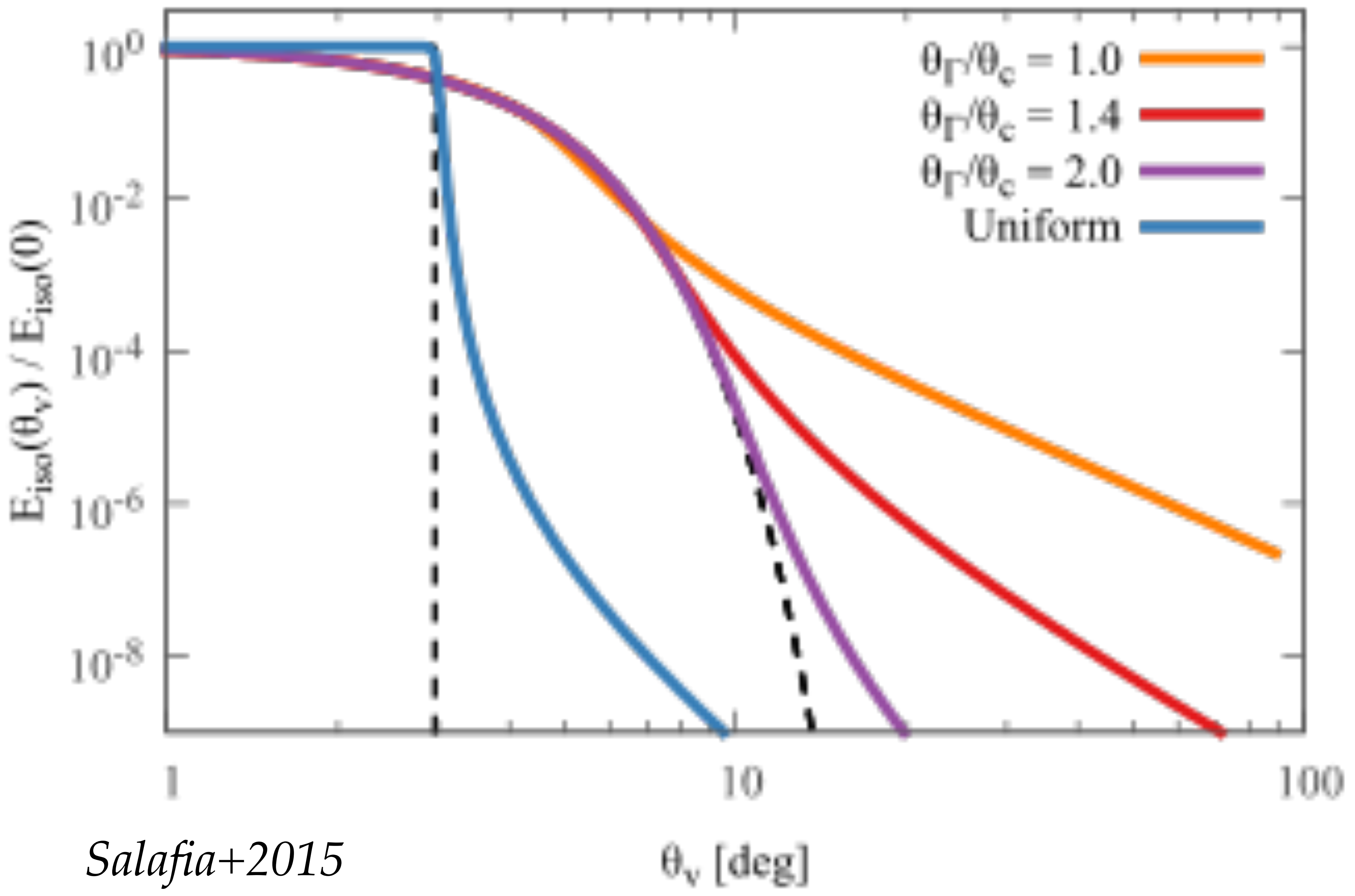
Evolution of structured jet concept

STRUCTURED JET

$$E_{\rm k,iso}(\theta) = \frac{E_{\rm core}}{1-(\theta/\theta_{\rm core})^{s_1}}$$

$$\Gamma(\theta) = 1 + \frac{\Gamma_{\rm core}-1}{1+(\theta/\theta_{\rm core})^{s_2}}$$



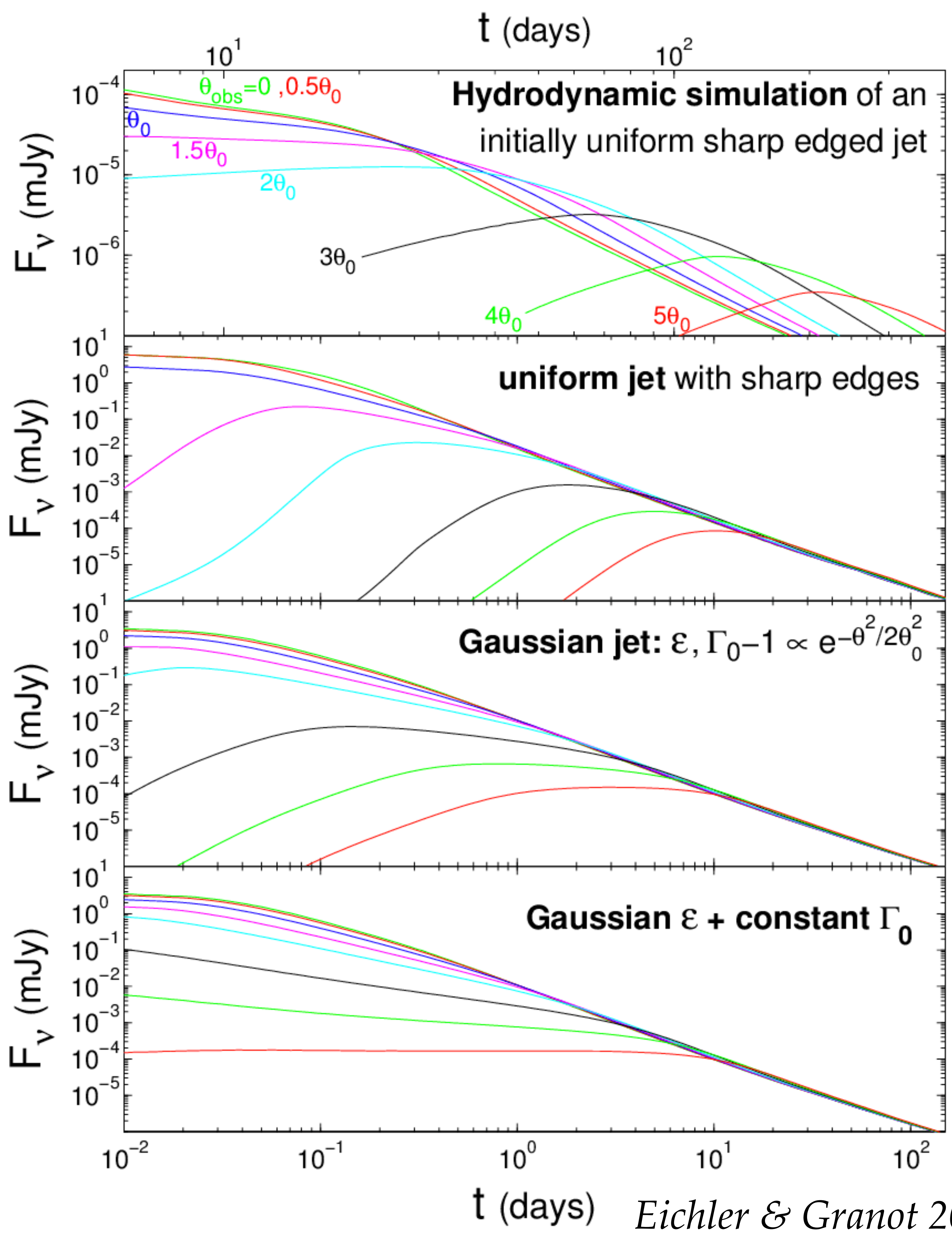


Salafia+2015

Prompt

Afterglow

$E(\theta, t)$ $\Gamma(\theta, t)$

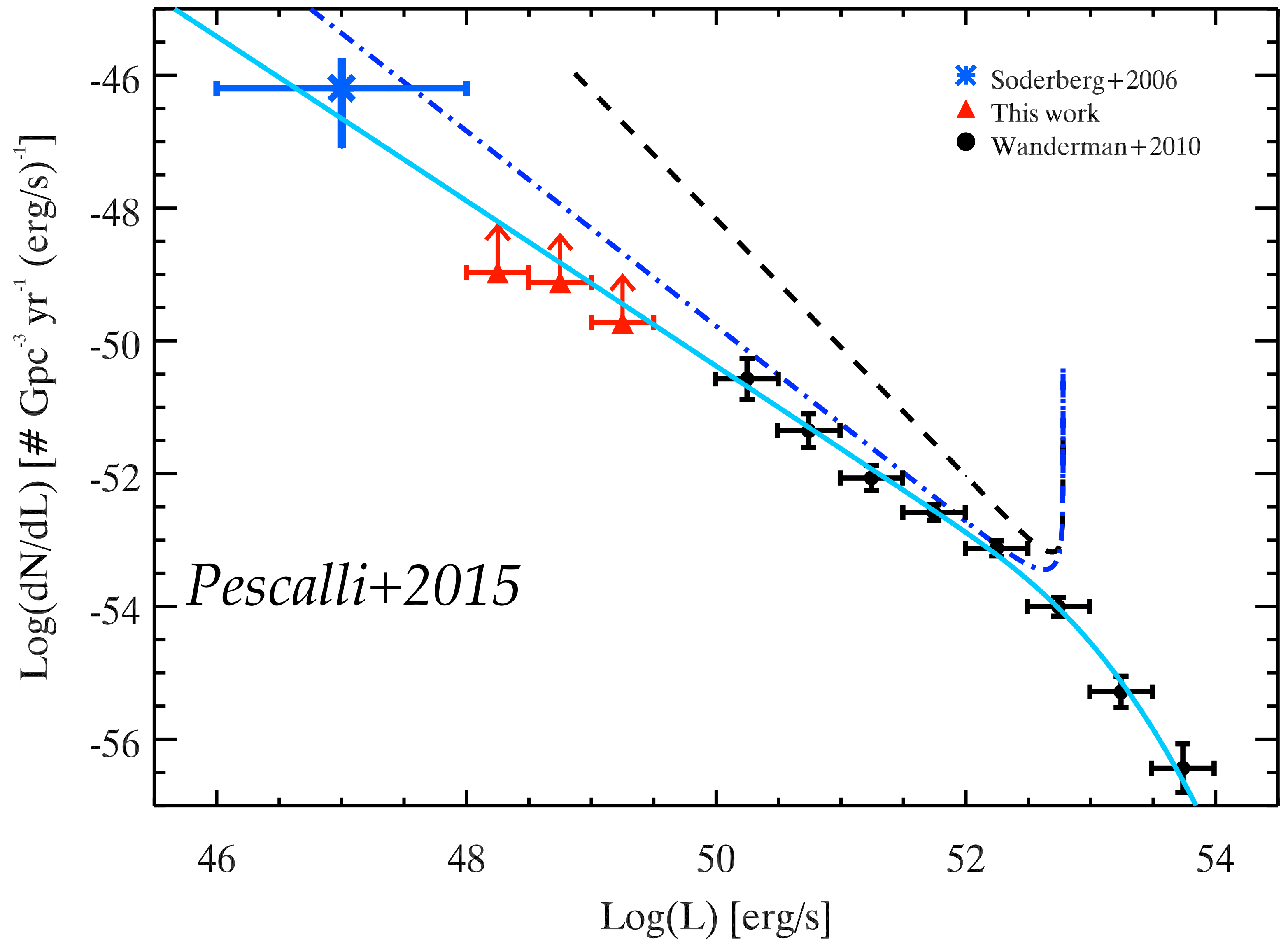


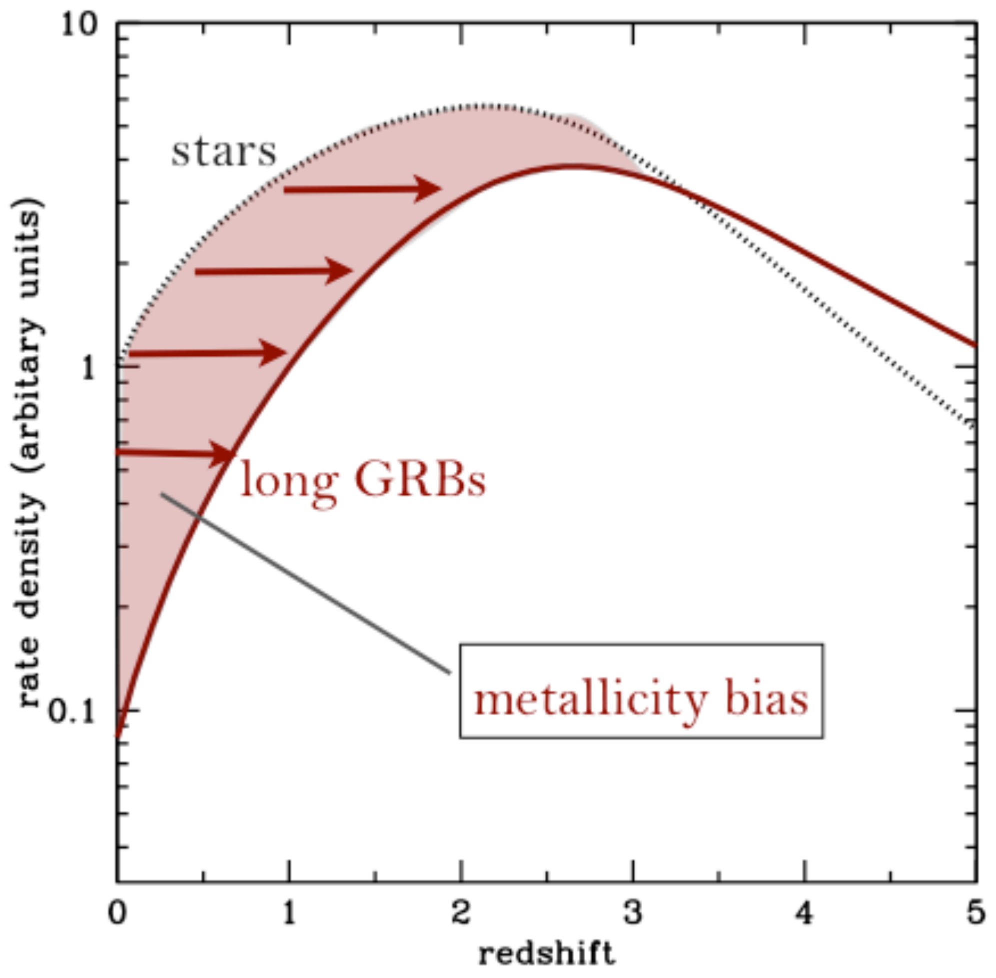
Eichler & Granot 2006

Different prompt and afterglow observed for different parameter combination

GRB RATES

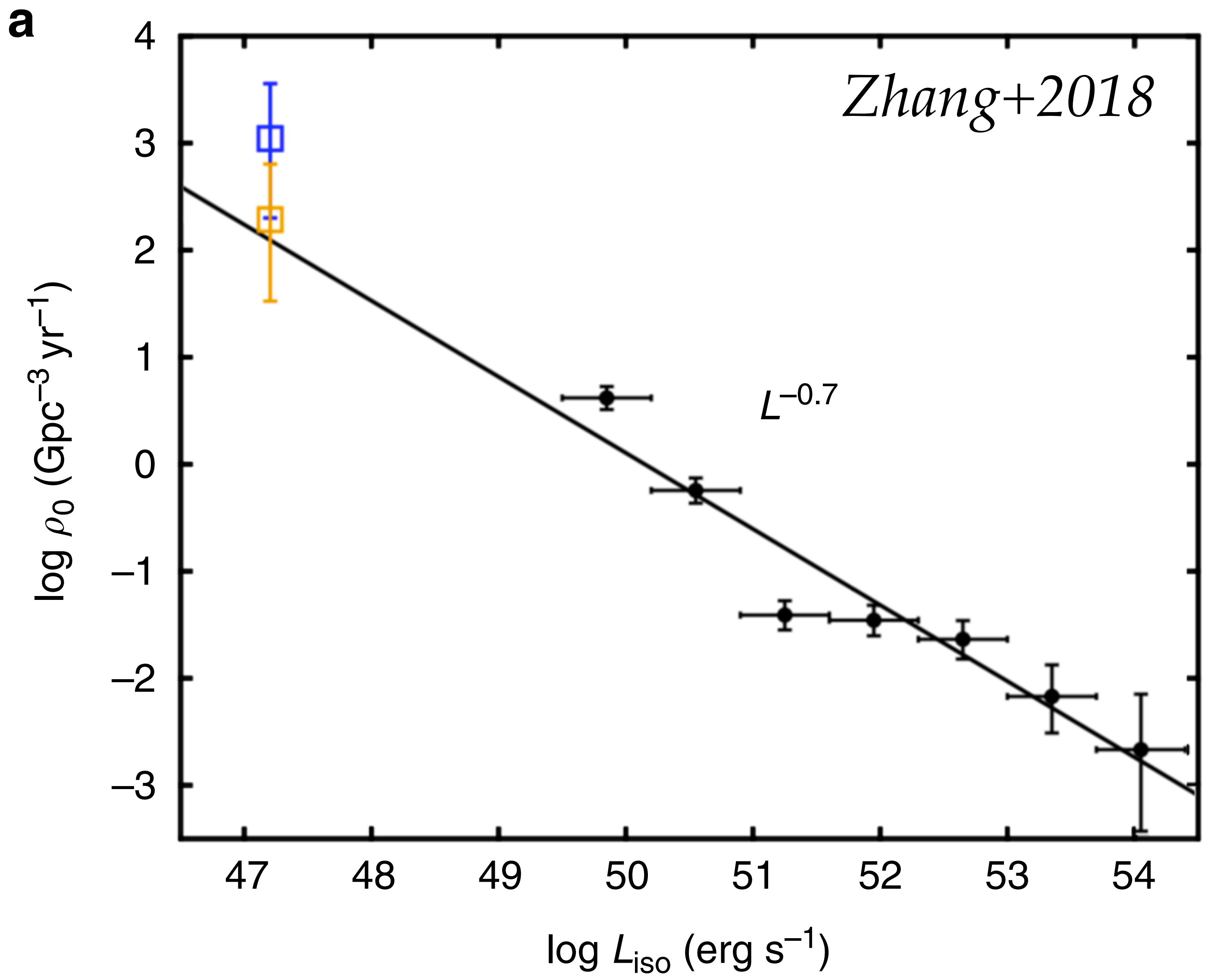
Long GRBs



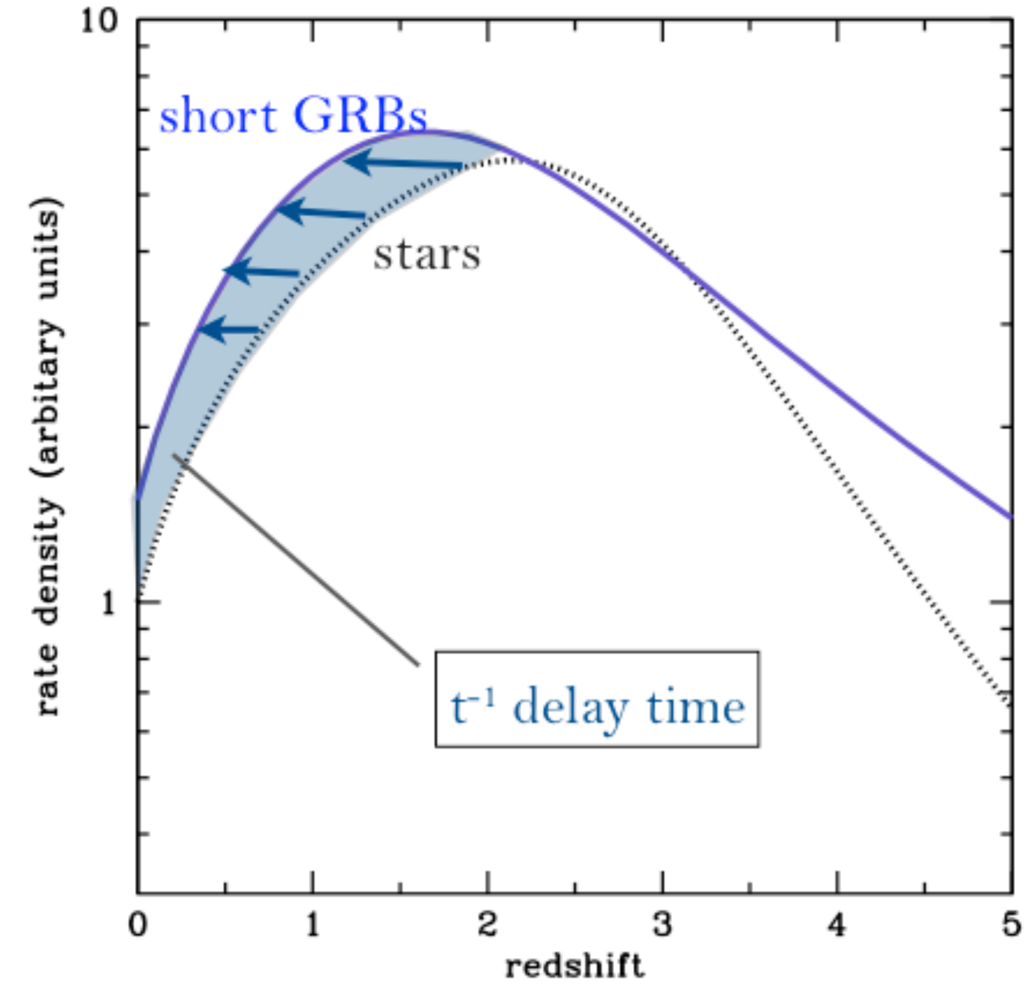


$\rho_{HL}(> 10^{50} erg cm^{-2}) \sim 0.5 - 1 \mathrm{Gpc\,yr}^{-1}$

Short GRBs



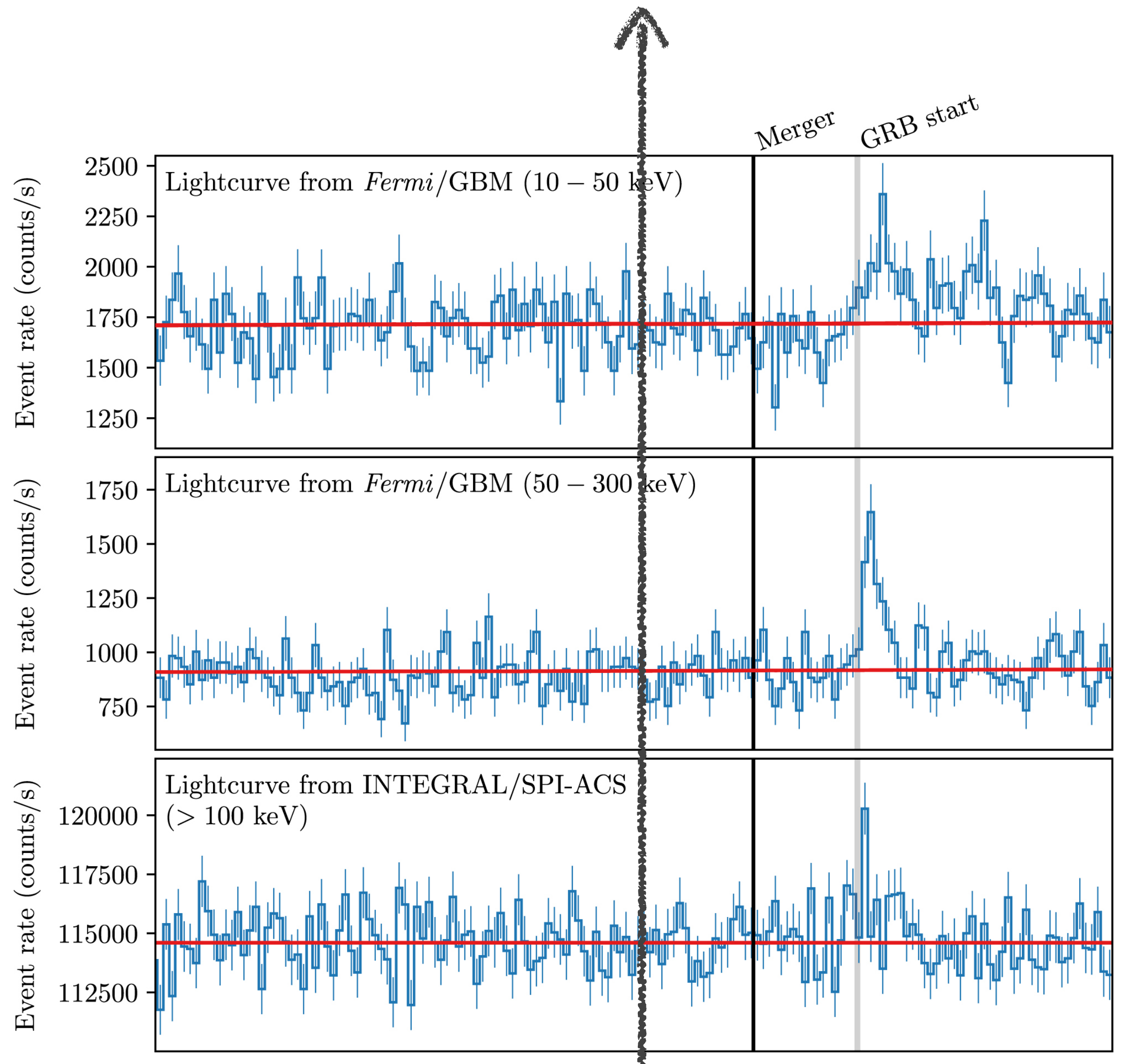
$\rho_{HL}(> 10^{50} erg cm^{-2}) \sim 0.1 - 3 \mathrm{Gpc\,yr}^{-1}$

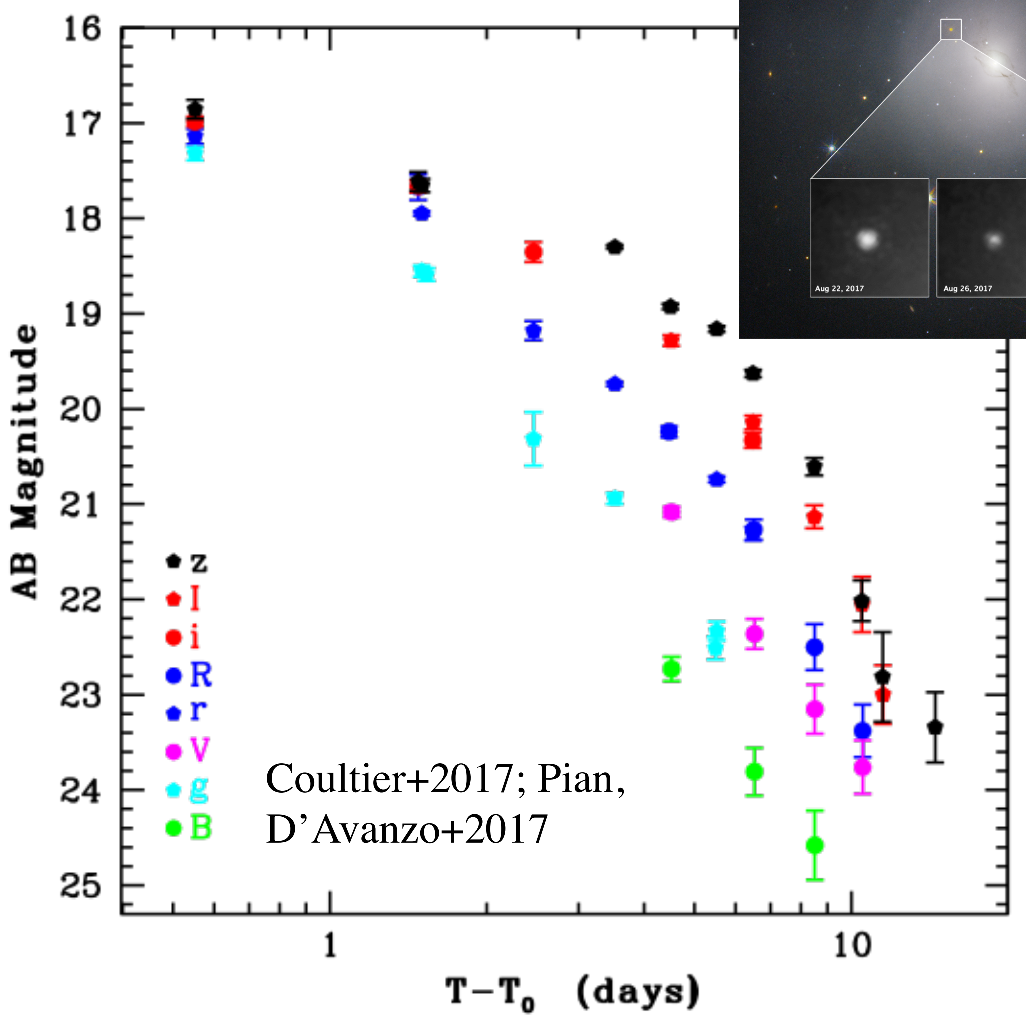


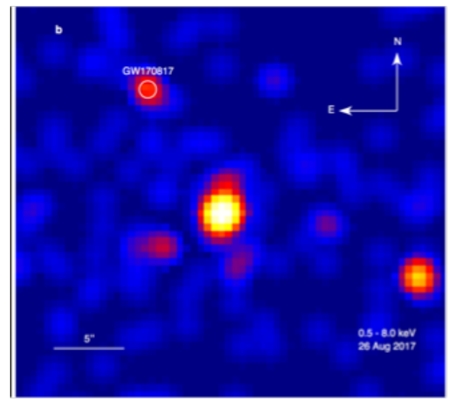
Observed rates:
Fermi (10keV -40 MeV) ~ 250/yr (1/4 short)
Swift (15keV - 150keV) ~ 70/yr (1/9 short)

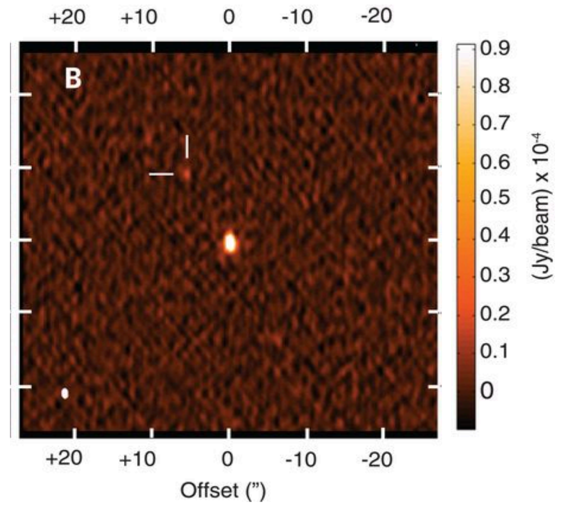
170817

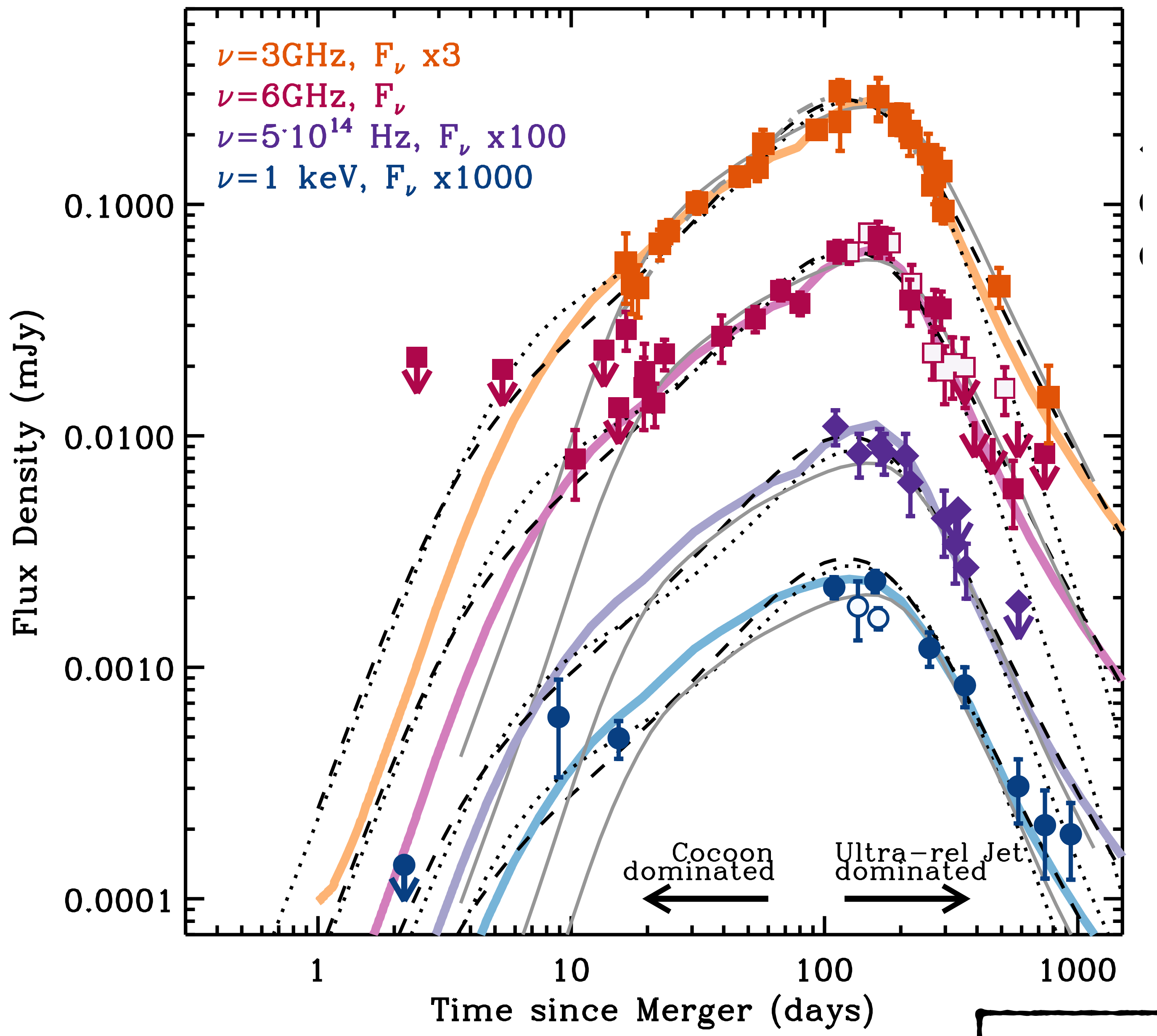
GW-sGRB-Kilonova-Afterglow



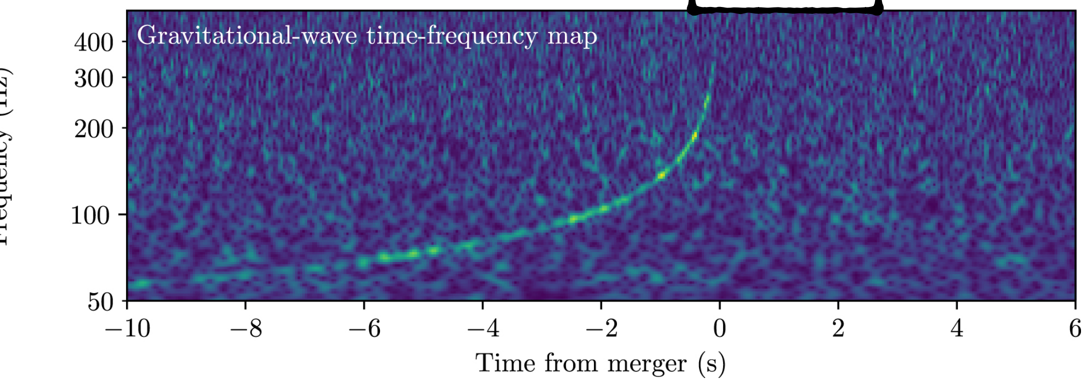








1.7 sec — 10.5 hours — 9 days — 16 days — 1000 days



Short GRB:

1.Delay ~ 1.7 s

2.Duration ~ 0.5 s

3.Hard spike L~1e47 erg/s

4.Softer (Thermal?) tail

Kilonova & Host

1.Fast color evolution

2.L~1e42 erg/s and $t^{-1/3}$

3.Massive old Stellar pop

4.2 kp off center

Afterglow

1.MW long lasting emission

2.Slowly rising phase

3.Peak @ 150 d

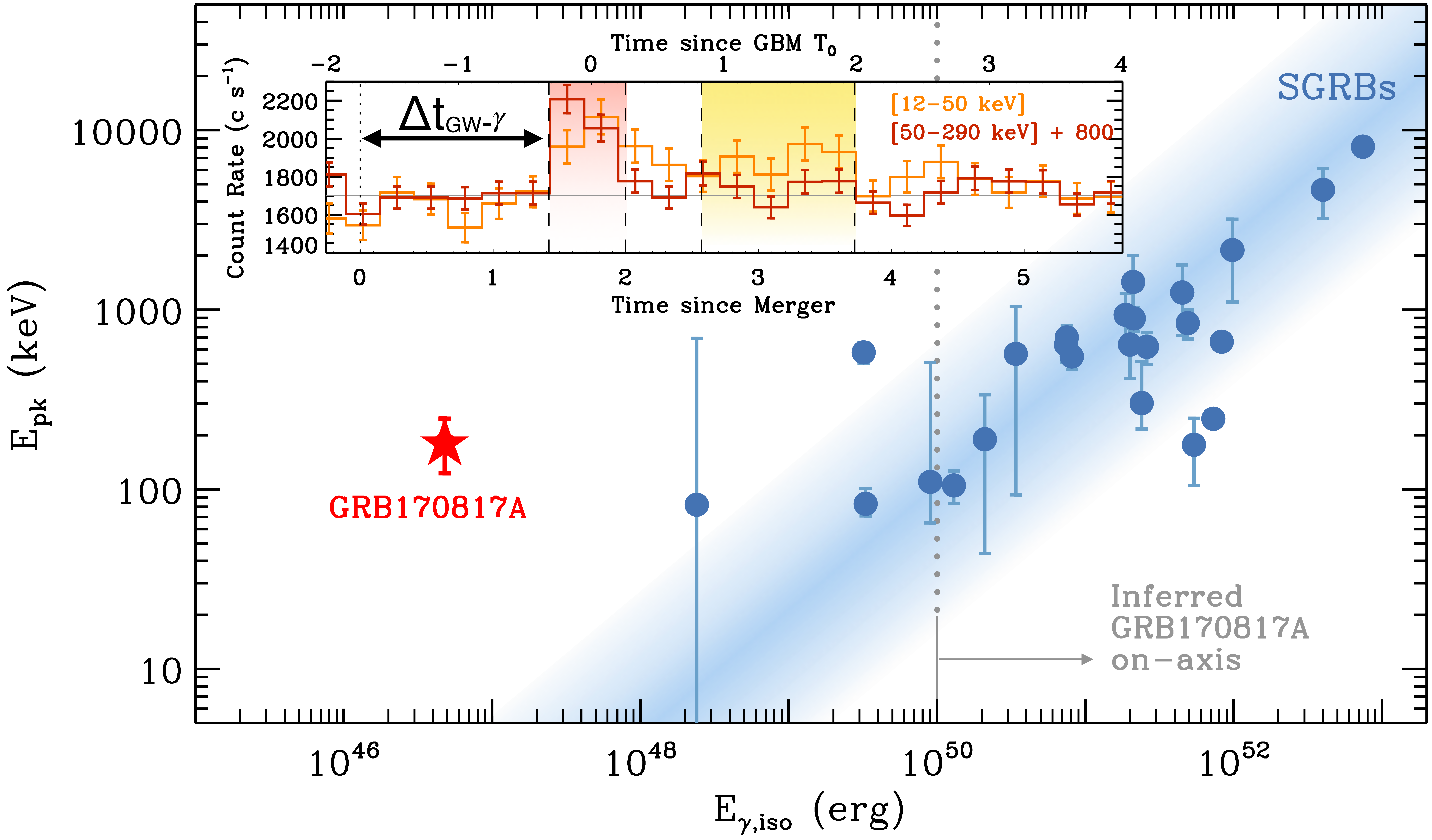
4.Proper motion at peak

5.Fast decay

6.…

Interpretation evolved with the source emission

GRB170817: A SHORT GRB?

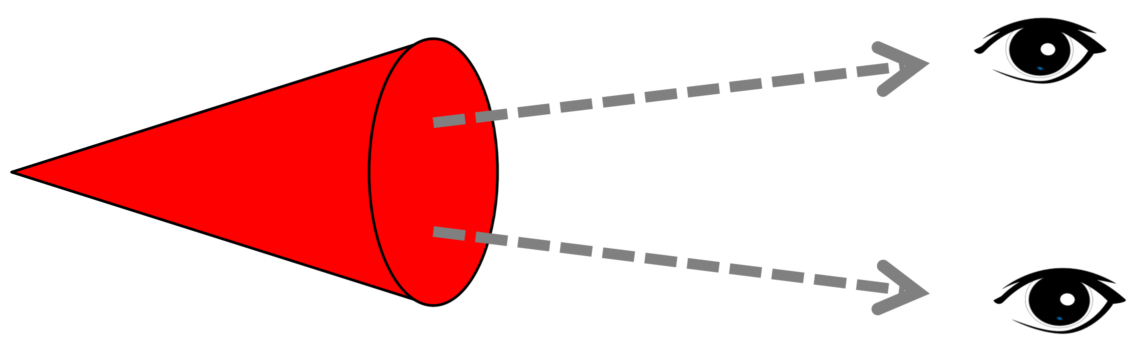


Low luminosity and slightly softer

VERY EARLY INTERPRETATION

L~10^{51} erg/s ✗

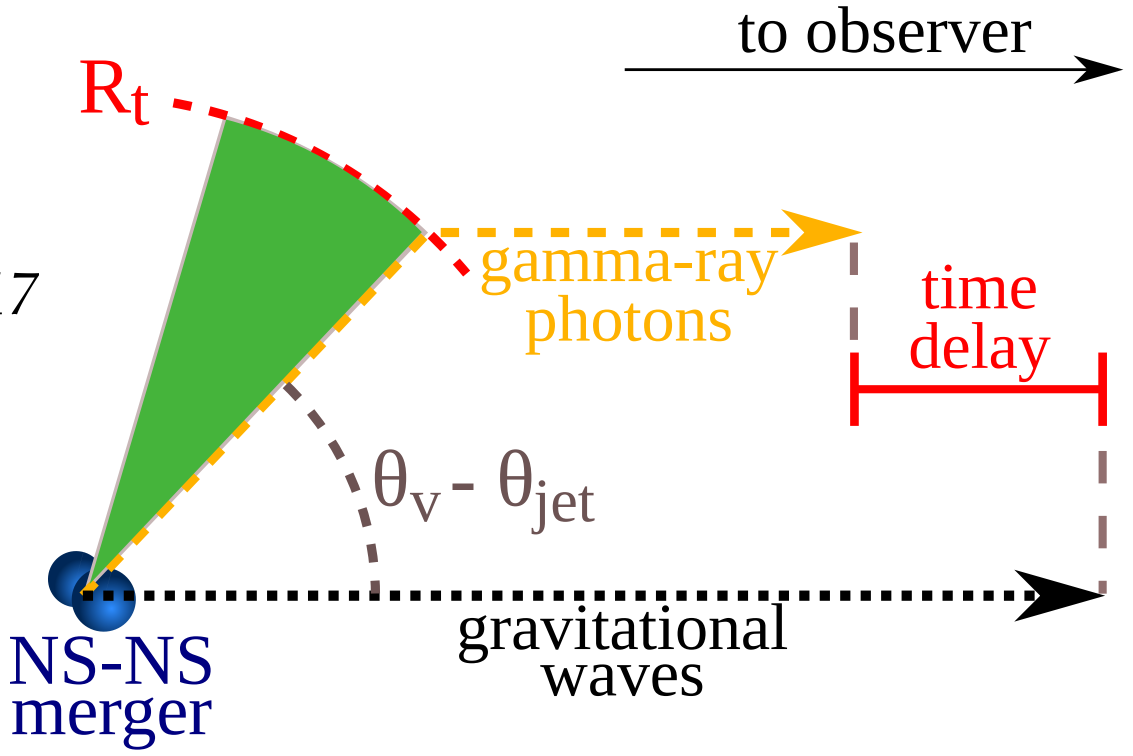
Afterglow t^{-1} ✗



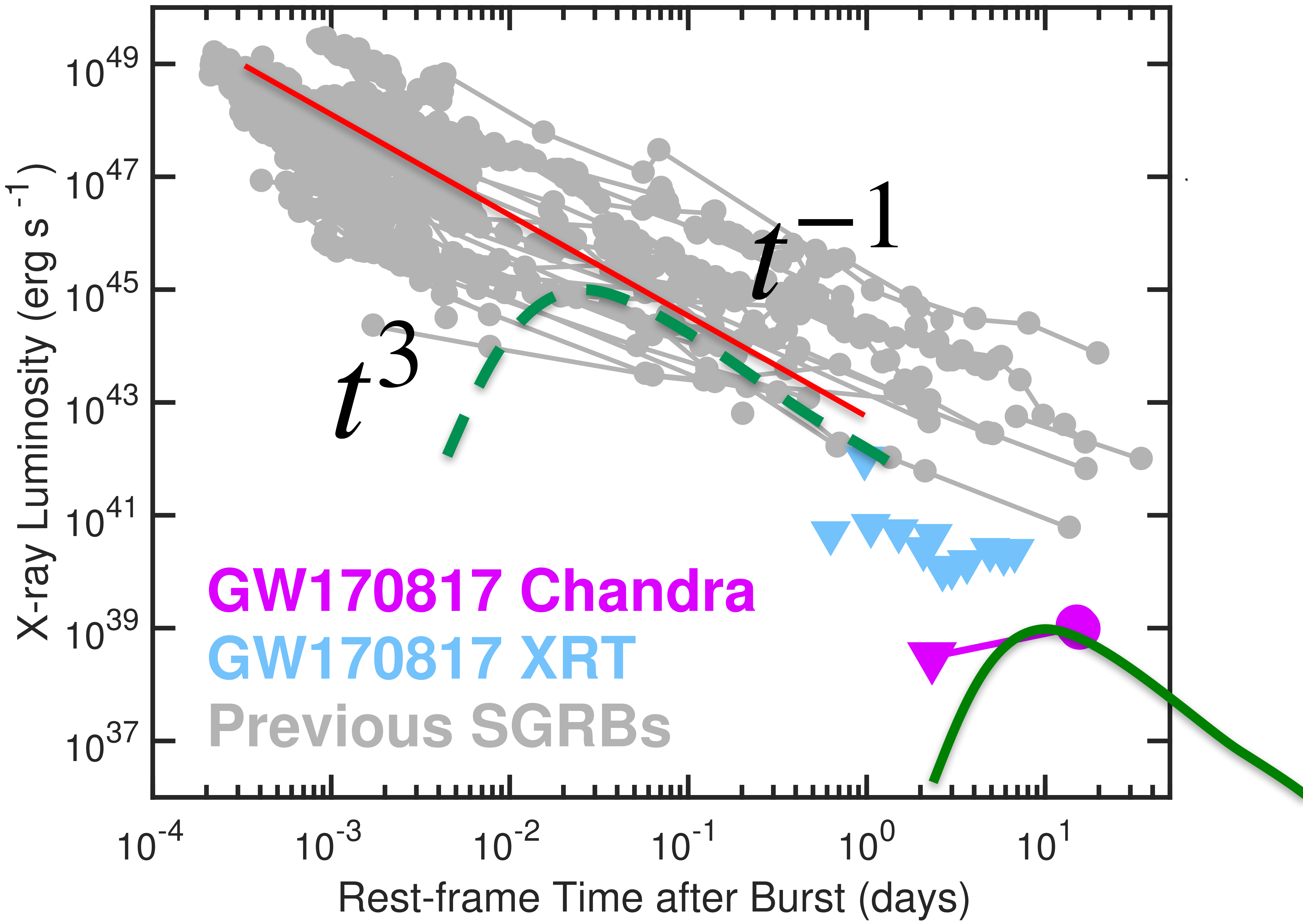
$$P(<\theta_{\rm jet}=10^\circ)=1.5\%$$

- ✓ L~10^{47} erg/s (debeaming)
- ✓ Afterglow appears when $\dfrac{1}{\Gamma(t)} \sim \theta_{\rm view}$
- ✓ Delay GW-EM

Salafia+2017



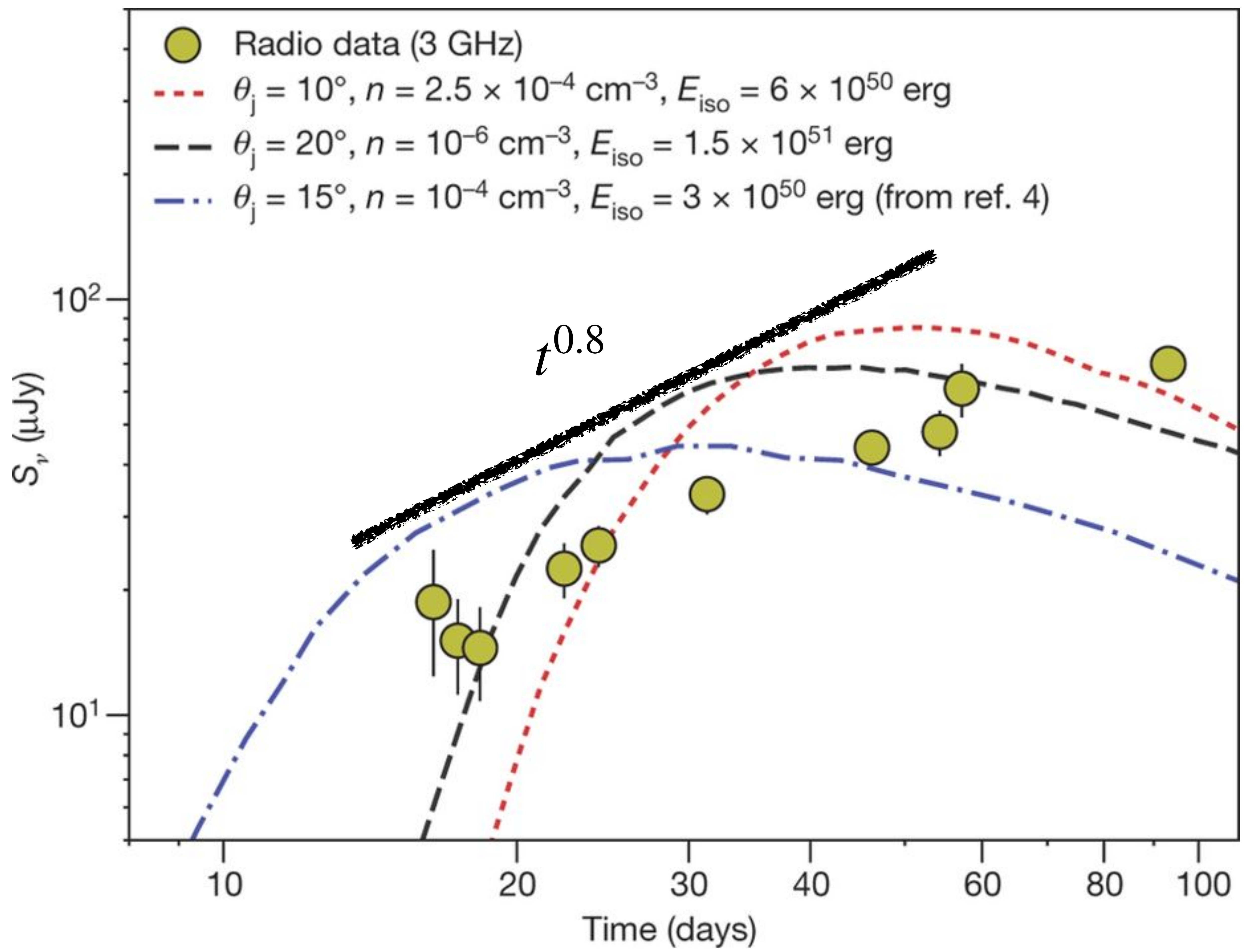
Fong+2020



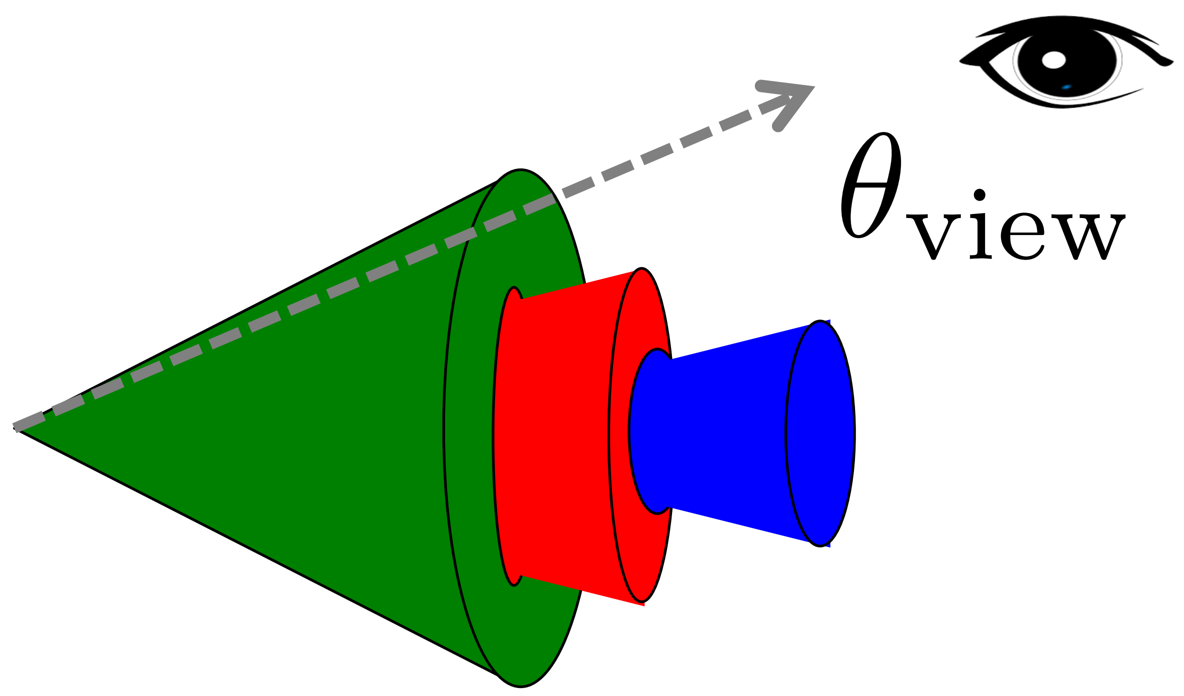
Pian et al. 2017; Margutti et al. 2017; Nakar et al. 2017; Granot et al. 2017 …

Standard GRB picture: first compelling evidence of off-axis jet

EVIDENCE OF STRUCTURED JET



Mooley et al. 2018



$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$

Discrete→continous structure

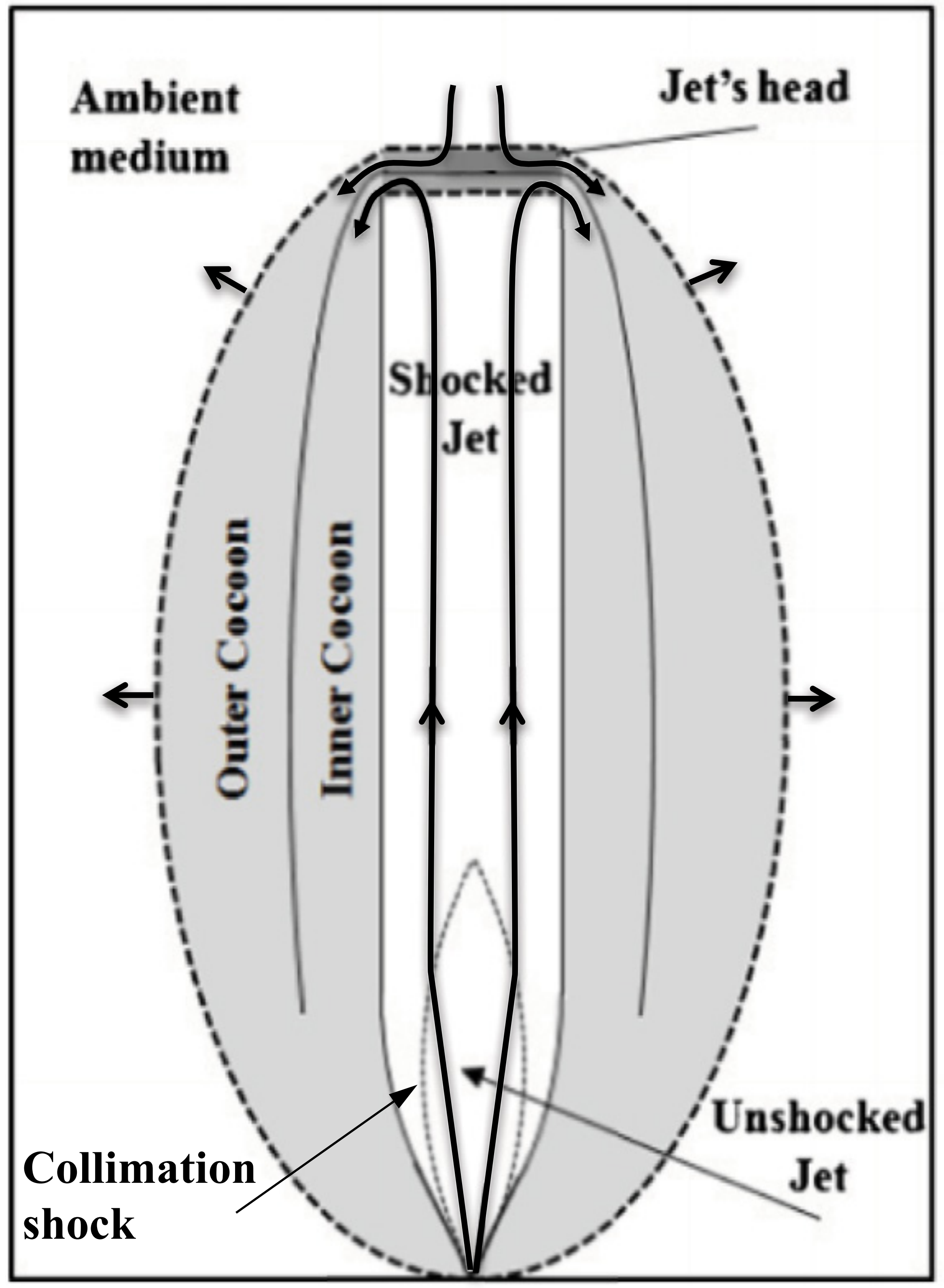
- ✔ L~10^{47} erg/s (δ^{-3})
- ✔ Afterglow appears when
- ✔ Delay GW-EM
- ✔ Shallow rise of the radio light curve

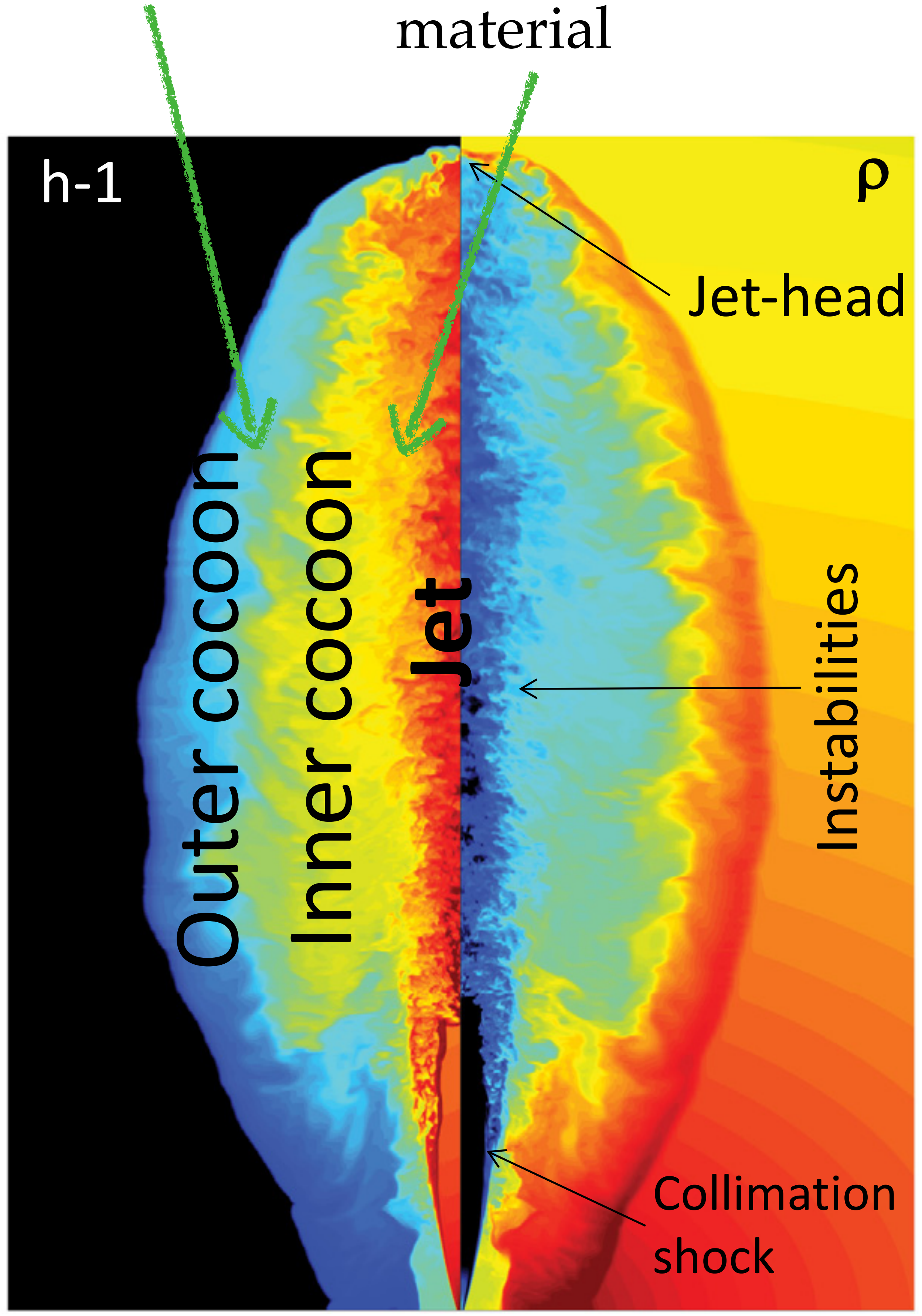
Temporal evolution of the afterglow implies non standard jet

PHYSICAL MOTIVATION

Jet - environment interaction

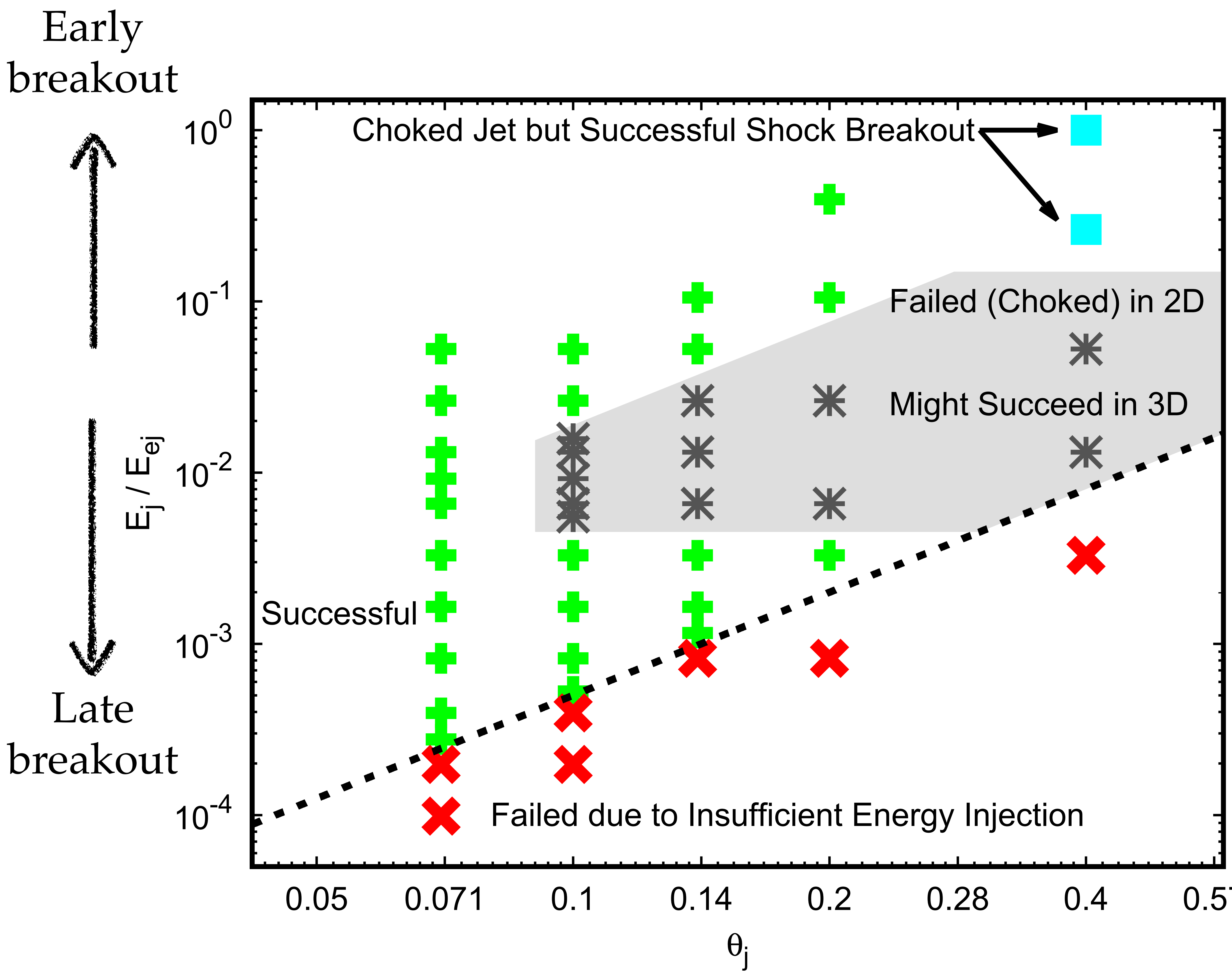
(stellar envelope - LGRB)
(merger ejecta - SGRB)





Akira 2013 … … Nakar 2020

Breakout condition $E_{\rm j} > E_{\rm crit} = kE_{\rm ej}\theta_j^2$

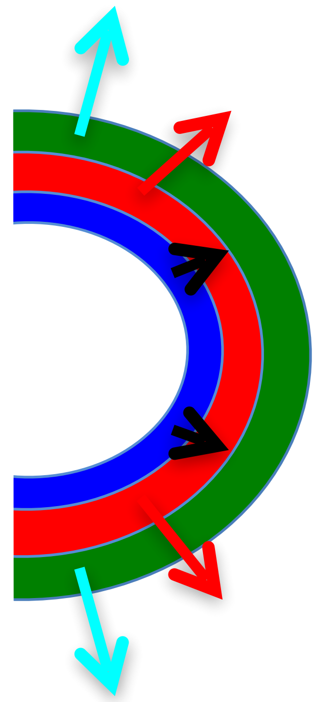


Duffel+2018

Jet+cocoon = jet structure; larger injected energy larger chances to breakout

SUCCESSFUL VS CHOKED JET

Choked jet
Radial structure



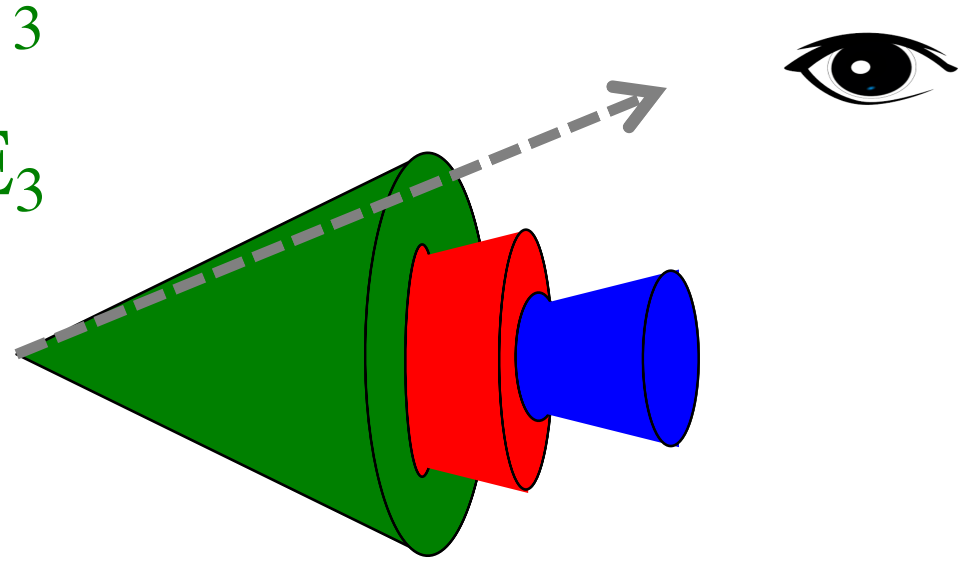
$\Gamma_1 < \Gamma_2 < \Gamma_3$

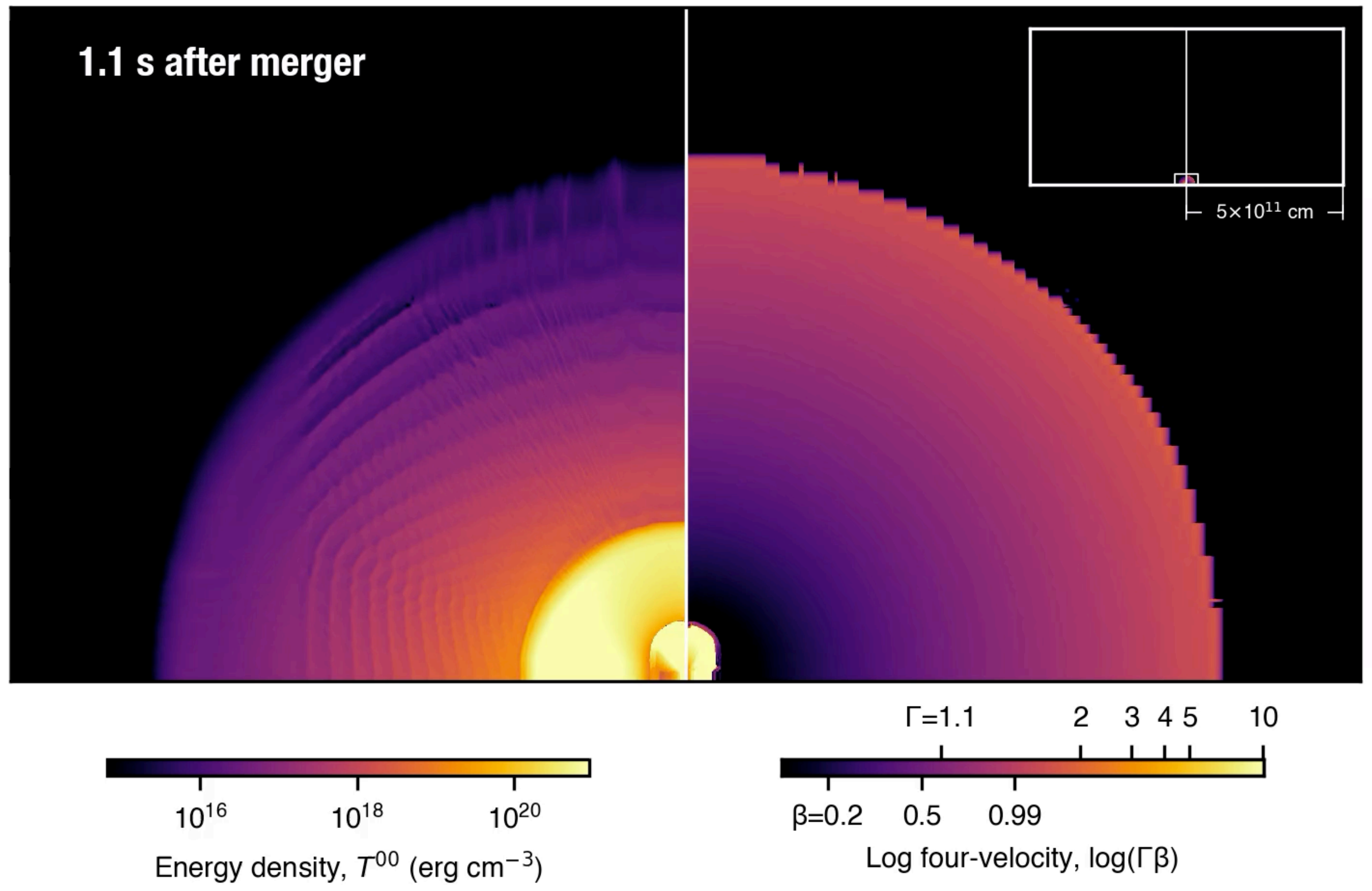
$E_1 > E_2 > E_3$

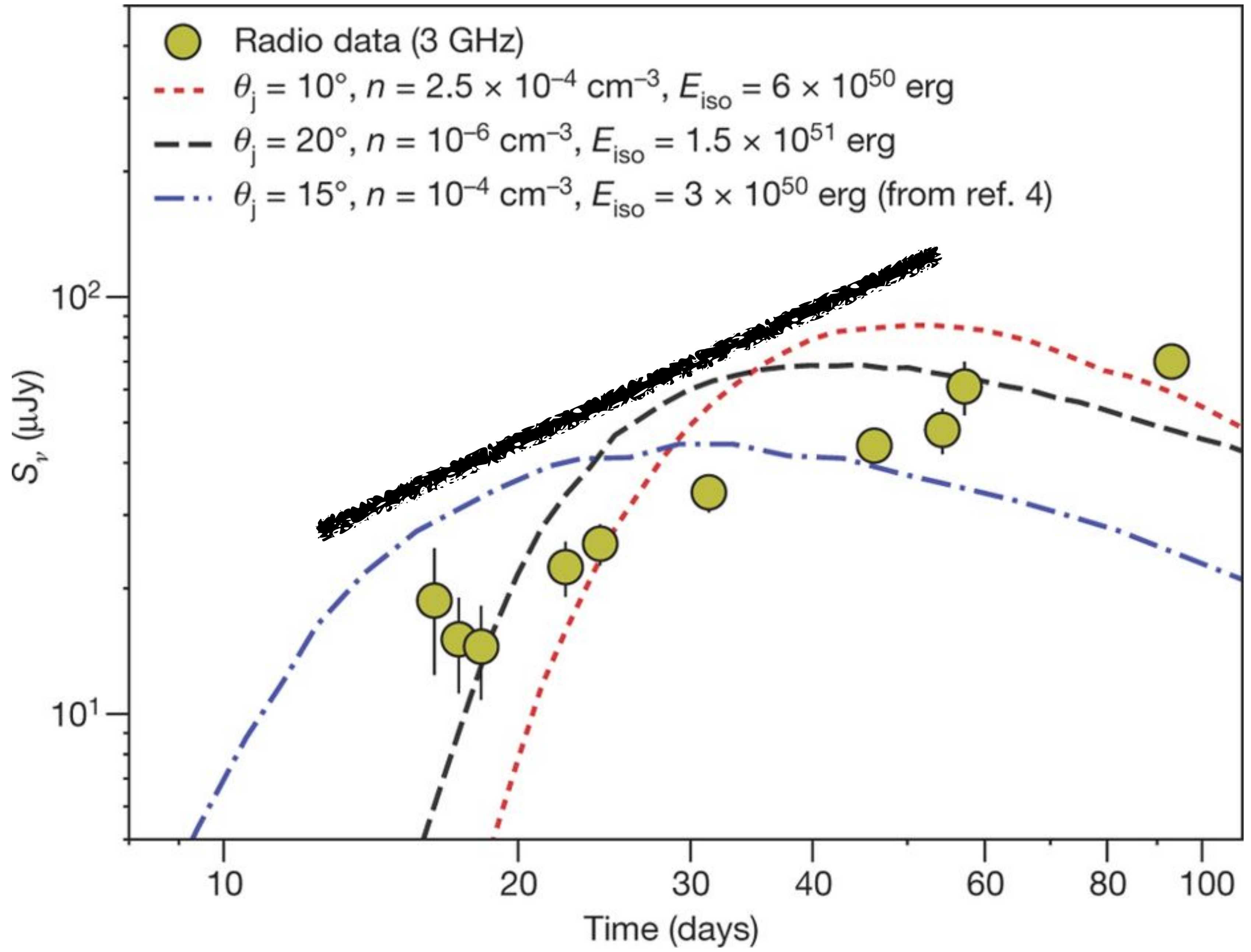
Succesfull jet
Angular structure

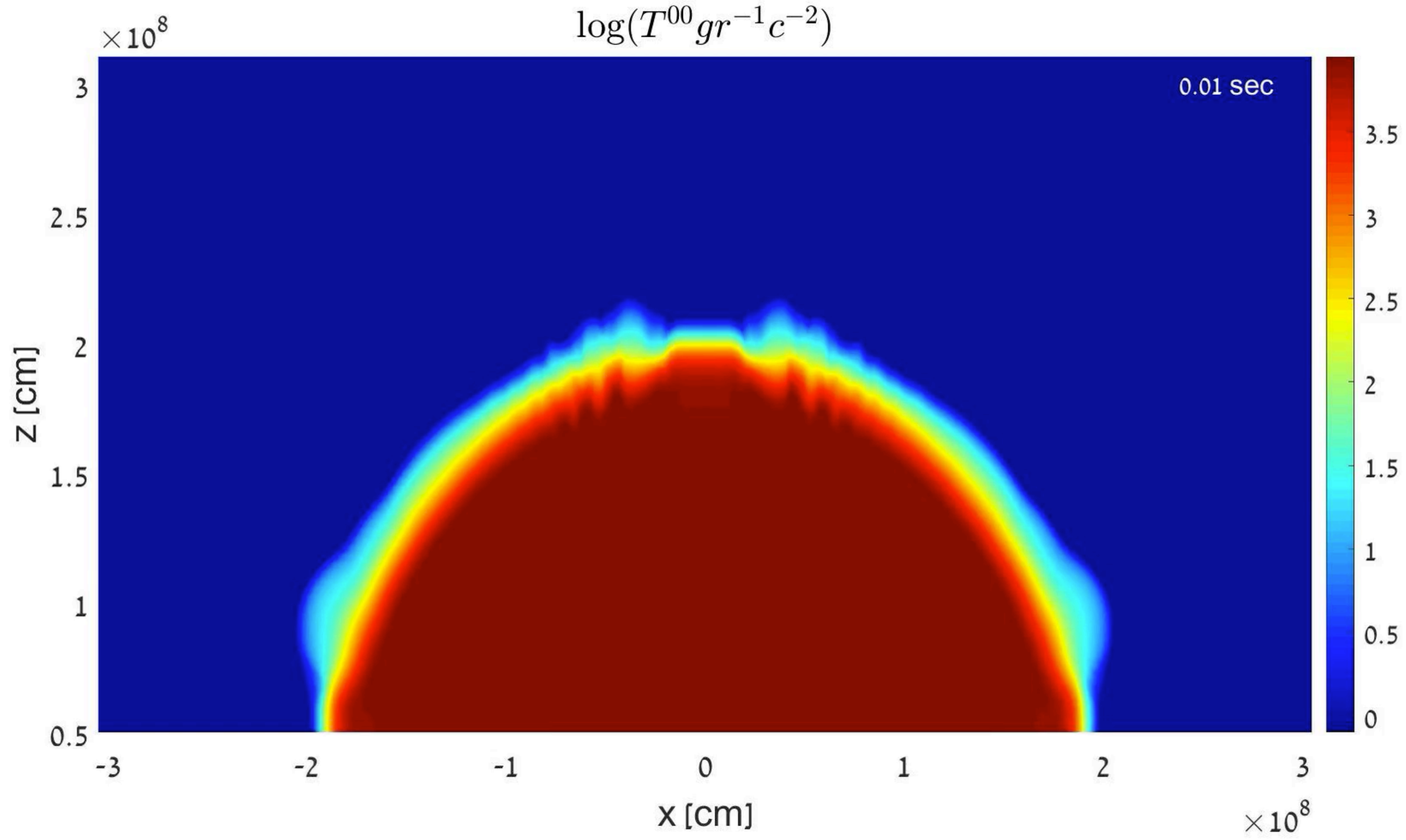
$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$





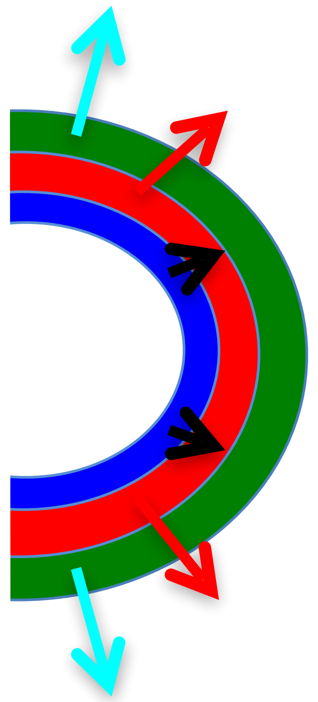




Gottlieb, Nakar et al. 2018

Can't tell if the jet successfully emerged from the ejecta

THE PEAK



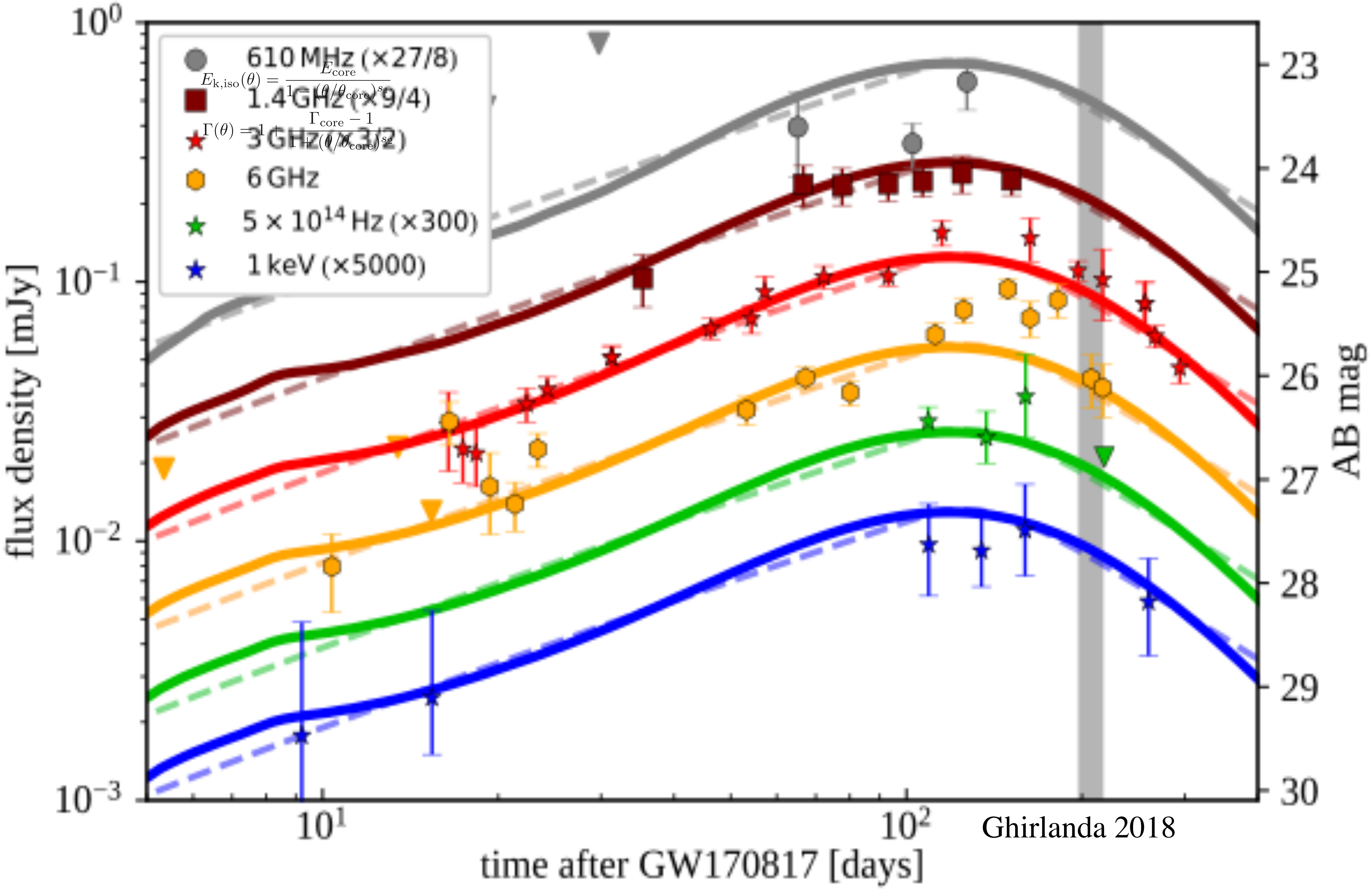
$E(>\Gamma\beta) = E_0(\Gamma\beta)^{-\alpha}$

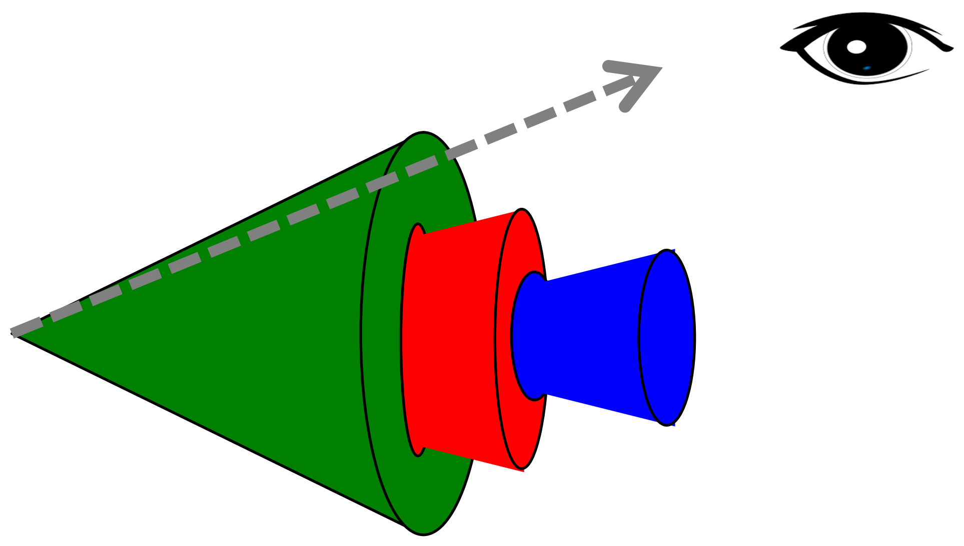
$E_0 = 1.5\text{x}10^{52}$ erg

$\alpha = 6$

$\Gamma_{max} = 6$

$\Theta = 30, 45, 60$ deg





Gaussian structure

$E_{core}=2.5\text{x}10^{52}$ erg ; $s_1=5.5$;

$\Gamma_c = 250$; $s_2=3.5$; $\vartheta_{core}=3.4$ deg

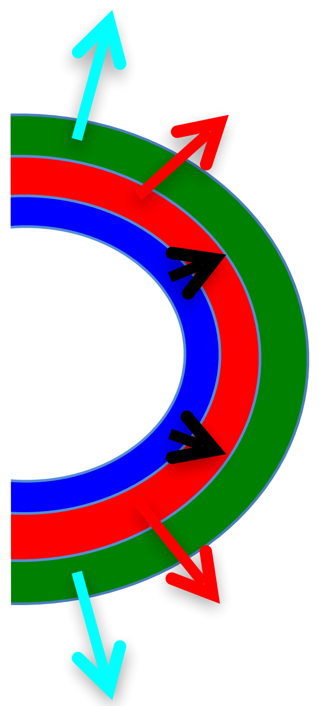
$n_{ism}=4\text{x}10^{-4}$ cm^{-3} ; $\vartheta_{view}=15$ deg

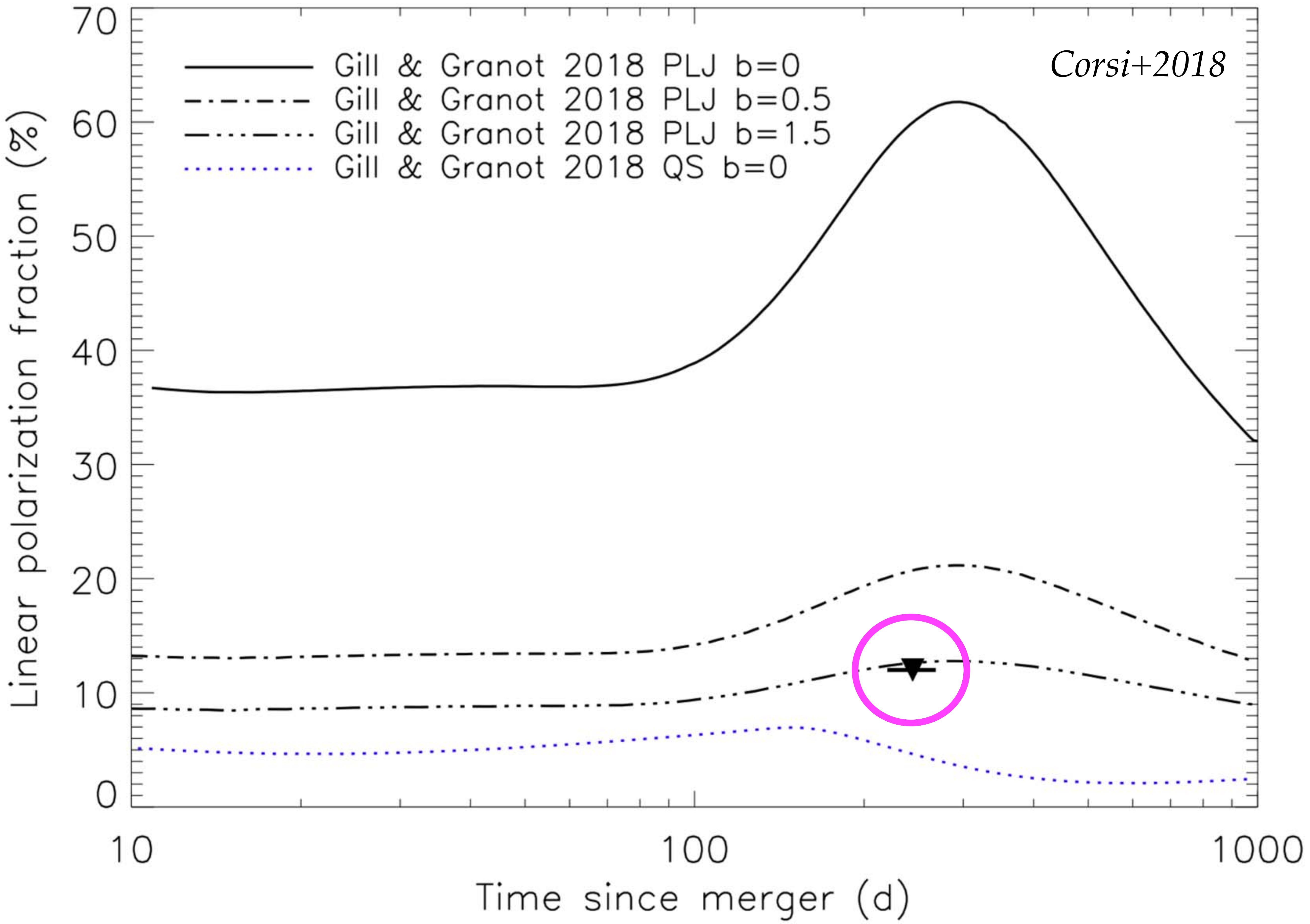
Rise and peak have dynamic or geometric origin in the two scenarios

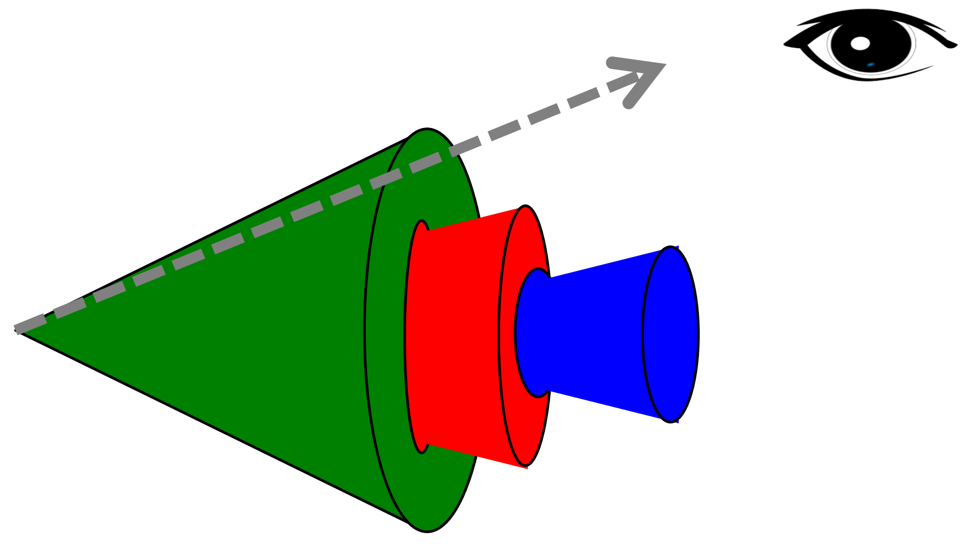
KILLING OBSERVATION I

[Rossi+2004 … Gill & Granot 2018; Nakar+2018; Lazzati+2018]

$$b = 2\frac{< B_\perp >}{< B_\parallel >}$$







JVLA @ 244d, 2.8 GHz

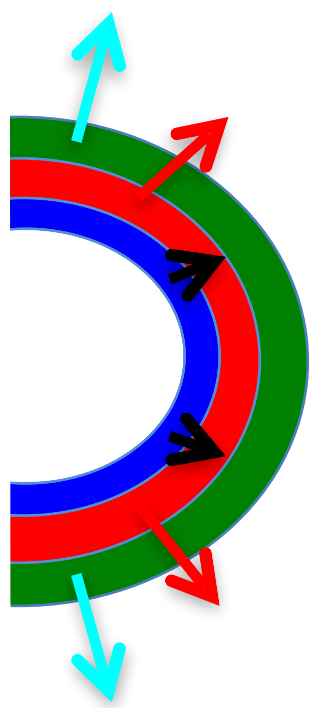
Π<12% (90%)

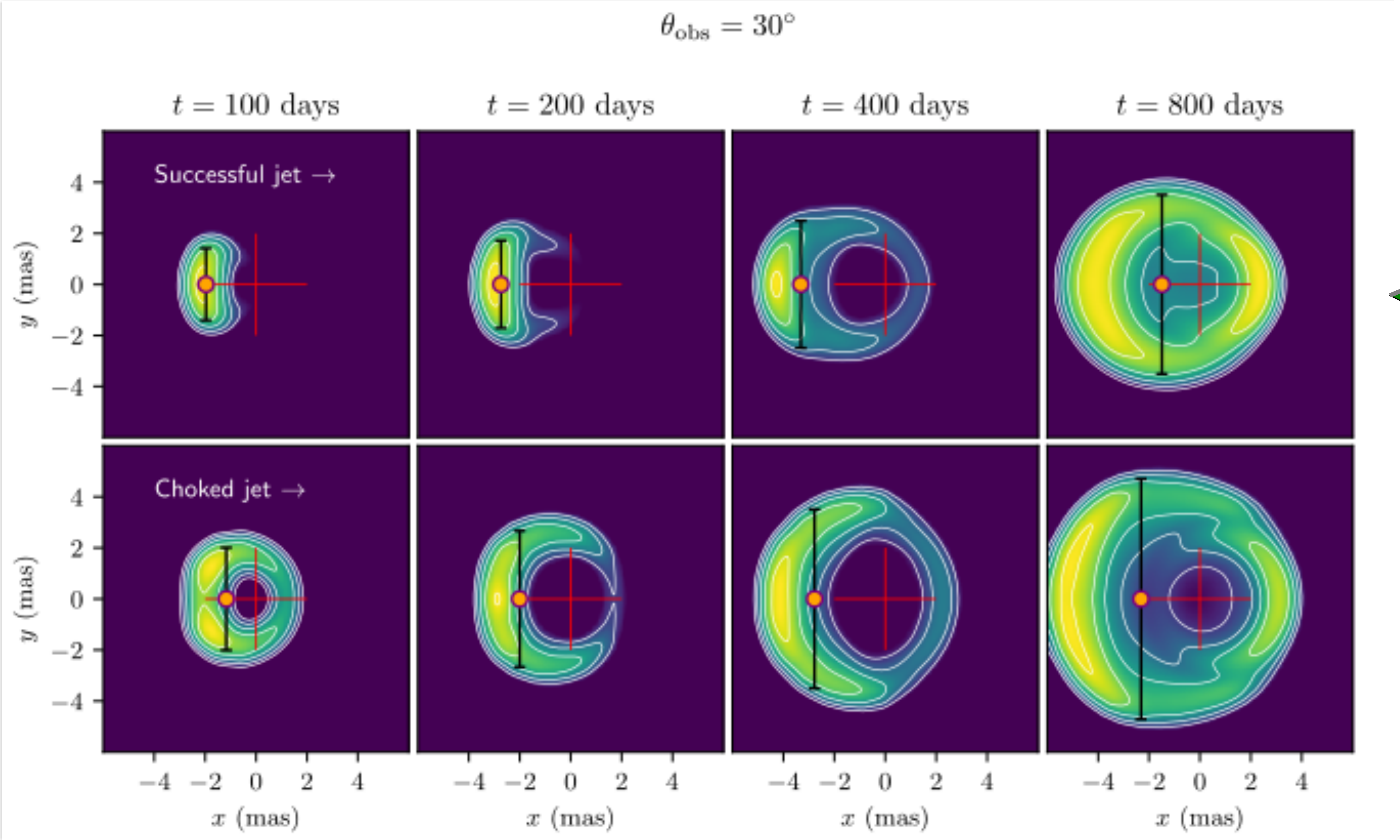
Still compatible with a structured jet with B component perp. shock

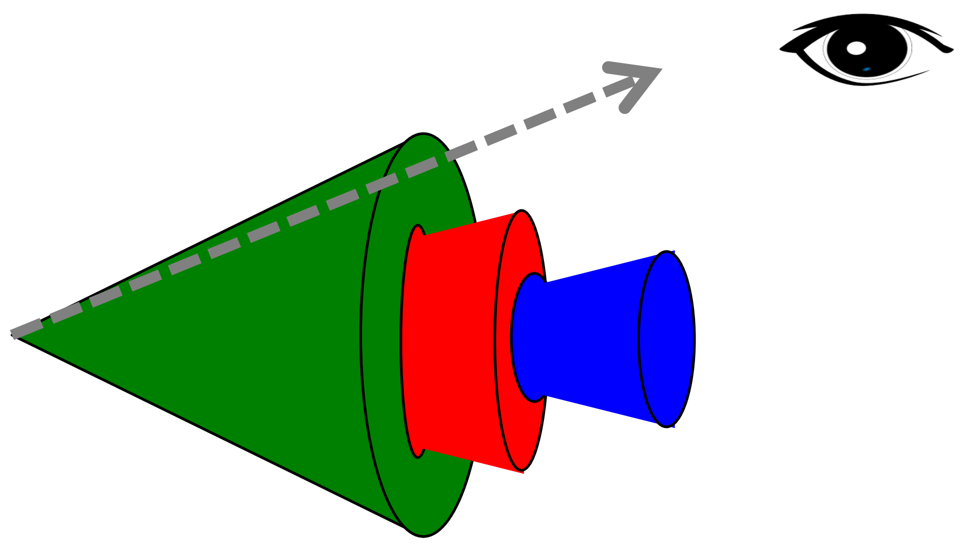
Contribute:

1) Magnetic field configuration (randomness & compression)
2) Γ
3) Geometry (ϑ_{jet} ; ϑ_{view})
4) Emission mechanism

Polarization not conclusive (several combined effects)





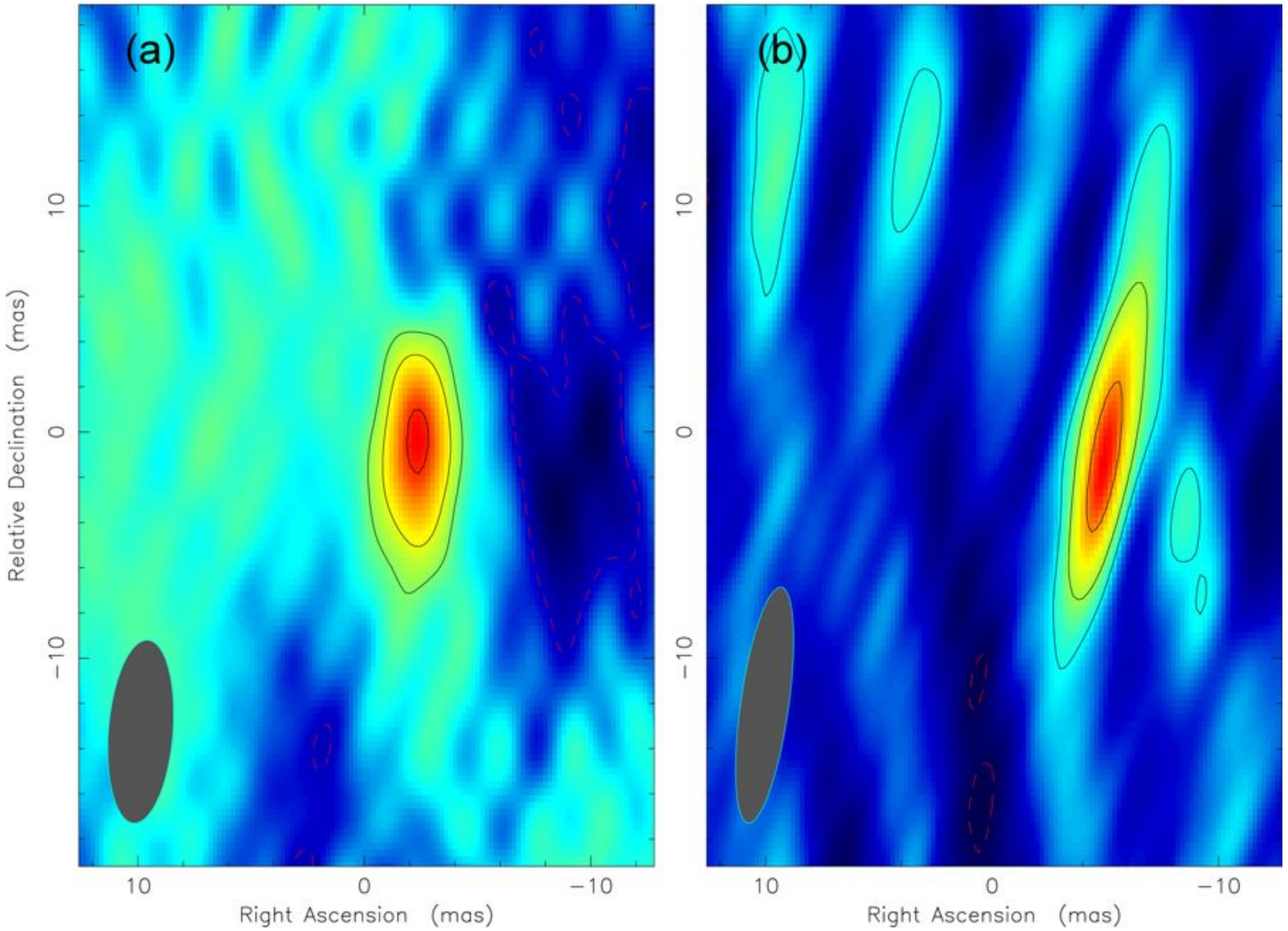


[Gill & Granot 2018; Nakar+2018; Zrake+2018]

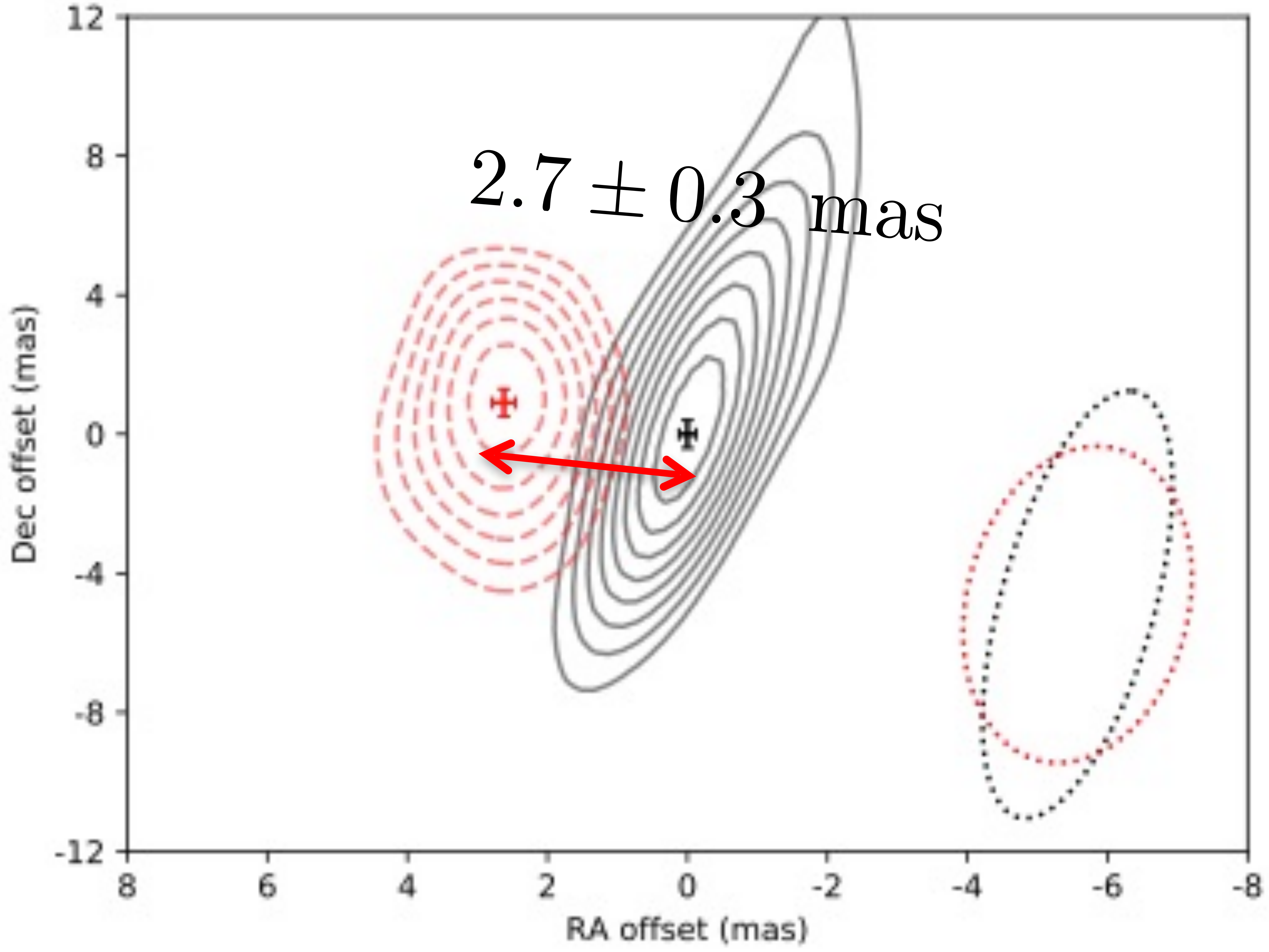
Radio Imaging holds the key: source size and displacement

VLBA + VLA + GBT: 2/4 epochs (Sept 2017 – Apr. 2018, L,S,C,C) @ <75d> and <230d> (4.5 GHz)

230 days 75 days



$\beta_{\rm app} \sim \Gamma$ $\theta_{\rm obs} - \theta_{\rm view} \sim 1/\Gamma \sim 0.25$



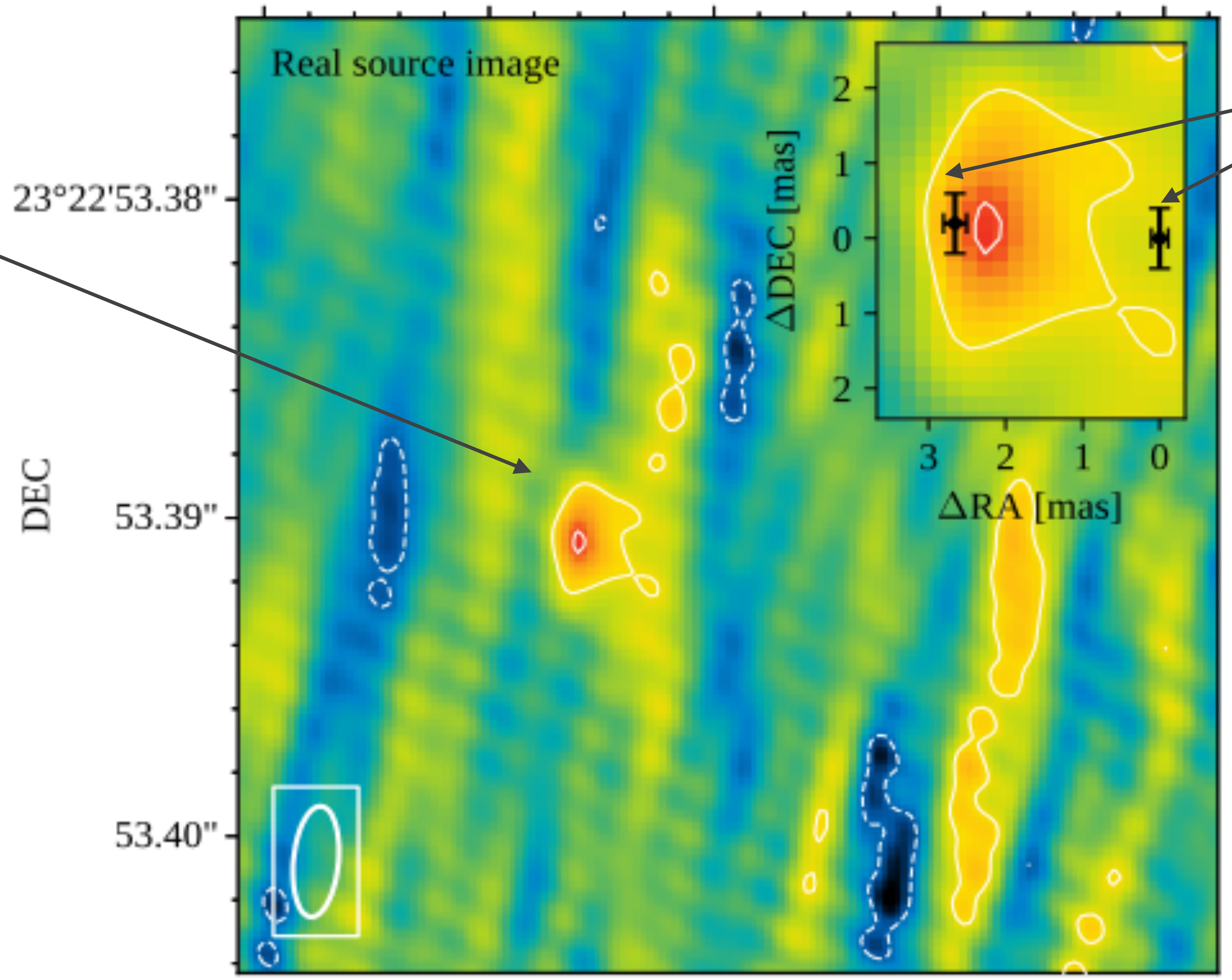
Mooley+2018

There is relativistic jet and it is 20 deg off the los

SIZE CONSTRAINT

12-13 March 2018 = 204.7 days @ 5 GHz (32 ant. but VLA)

Peak brightness 42 ± 8 μJy/beam



HSA 75d & 230d positions
Mooley+, Nat. 2018
PROPER MOTION

G.Ghirlanda. O. S. Salafia+2019

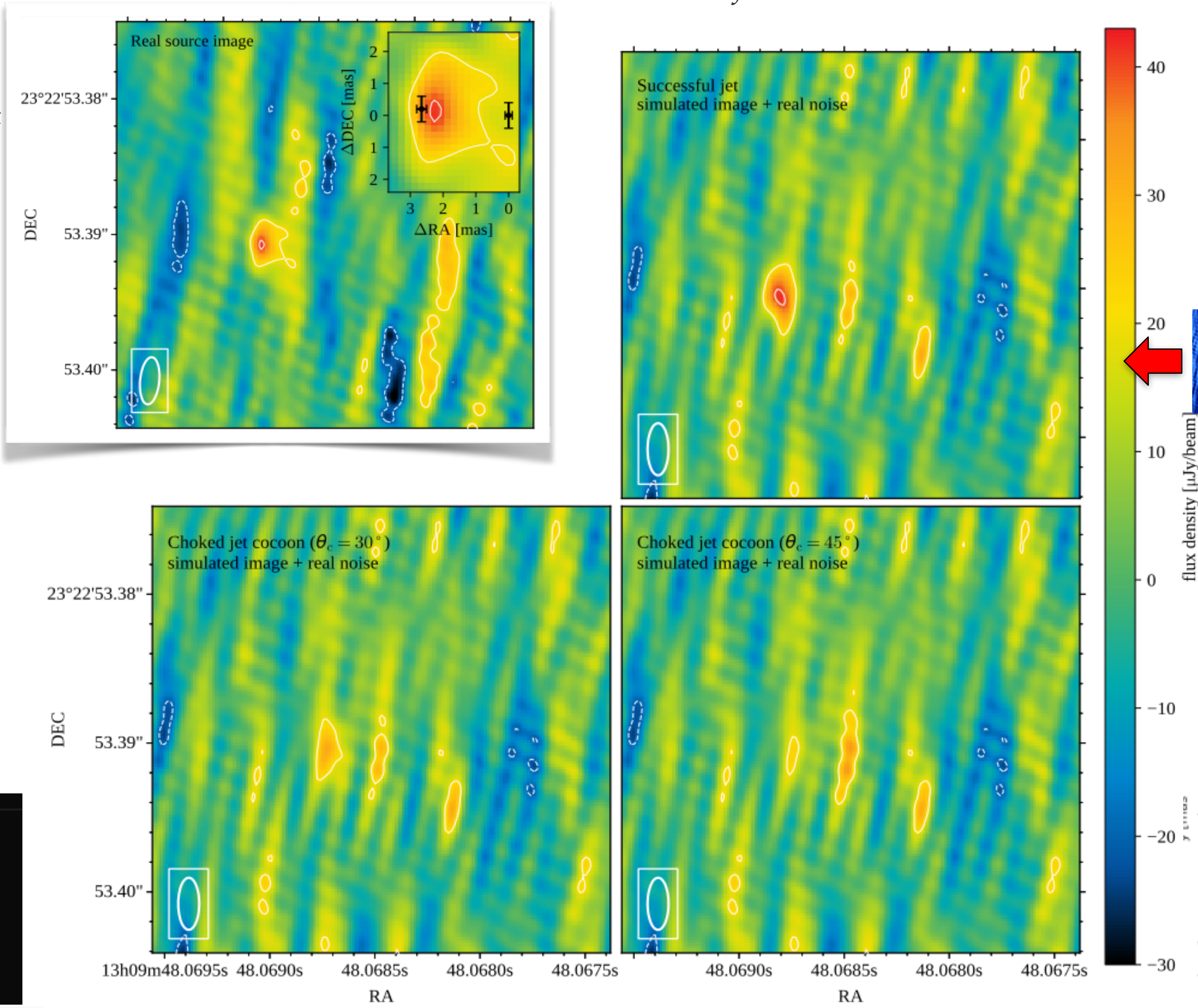
Source is compact and unresolved on the beam size

SIZE CONSTRAINT

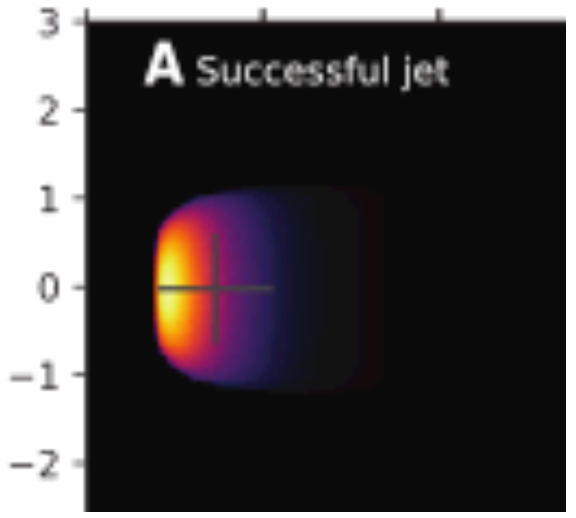
G.Ghirlanda. O. S. Salafia+2019

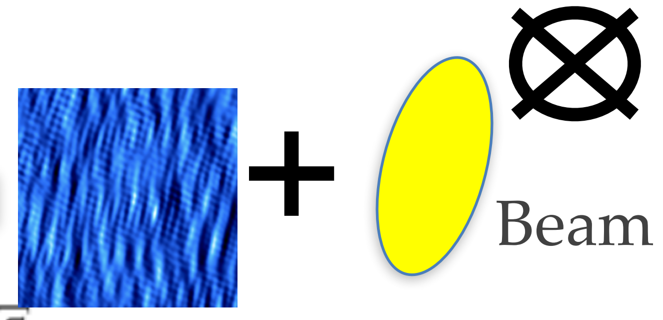
Source size< 2.5 mas at 90% confidence level

Jet parameters from:
1. light curve
2. Proper motion
3. Source size constraint

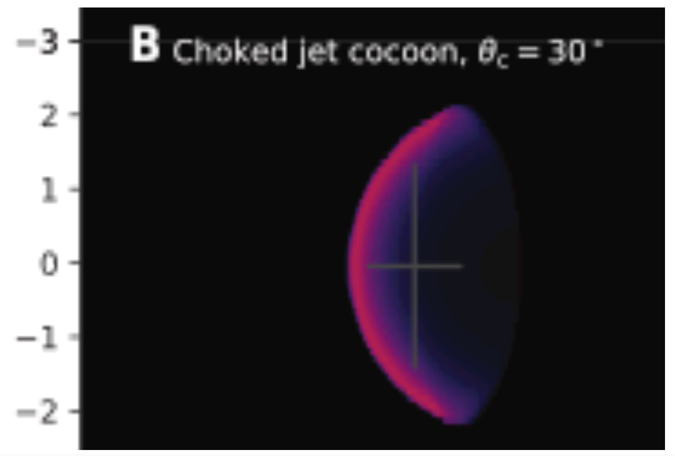


Successful jet

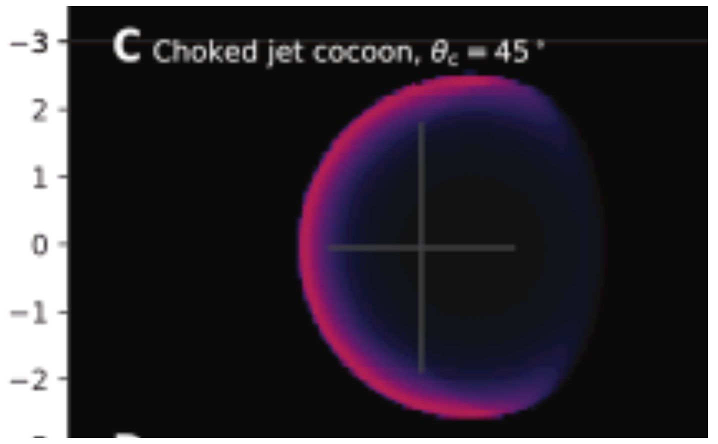




Choked jet (30 deg)



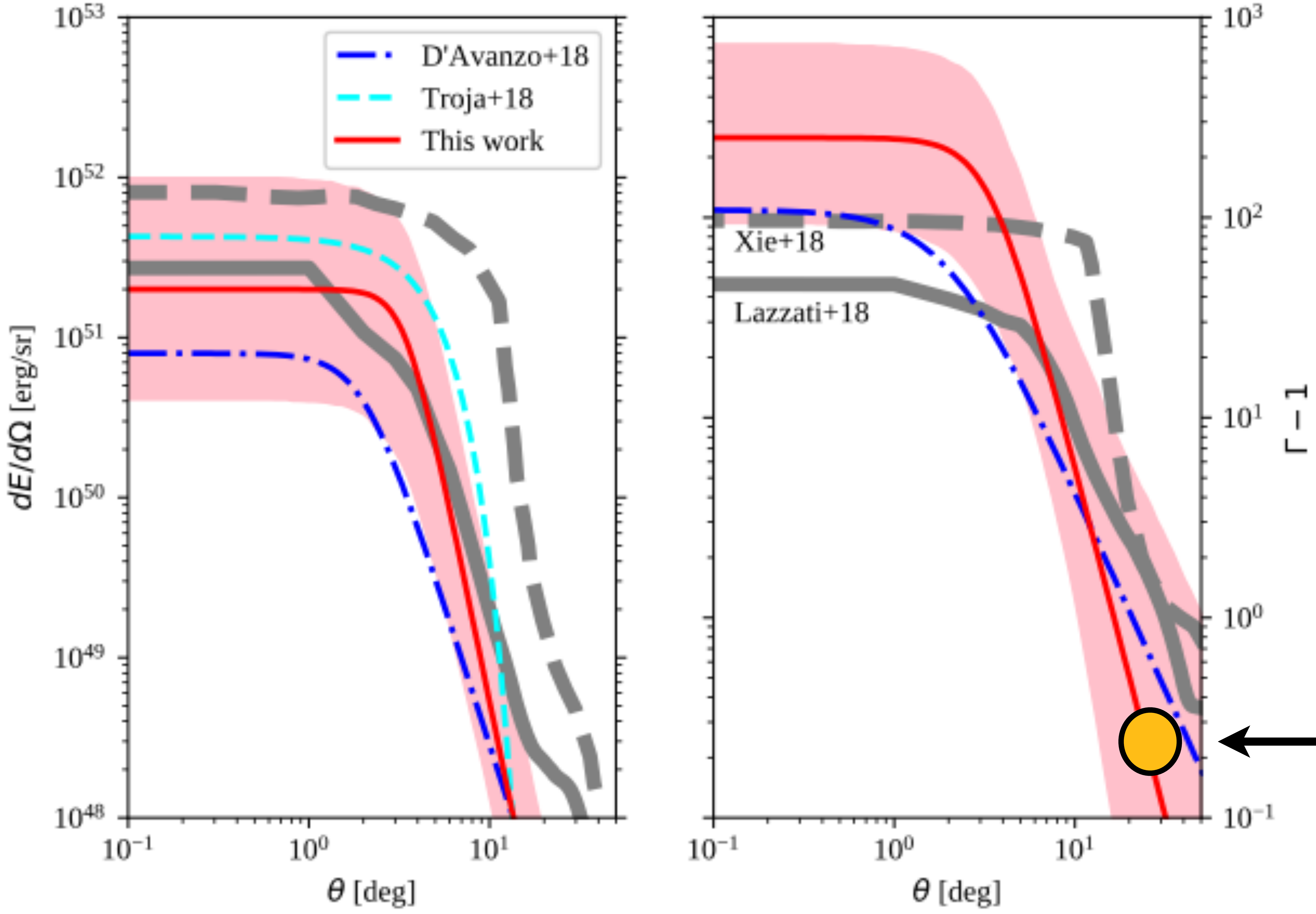
Choked jet (45 deg)



Collimated relativistic jet emerged from the ejecta

$$E_{\mathrm{k,iso}}(\theta) = \frac{E_{\mathrm{core}}}{1-(\theta/\theta_{\mathrm{core}})^{s_1}} \qquad \Gamma(\theta) = 1 + \frac{\Gamma_{\mathrm{core}}-1}{1+(\theta/\theta_{\mathrm{core}})^{s_2}}$$

$E_{c,kin} \sim 10^{52}$ erg

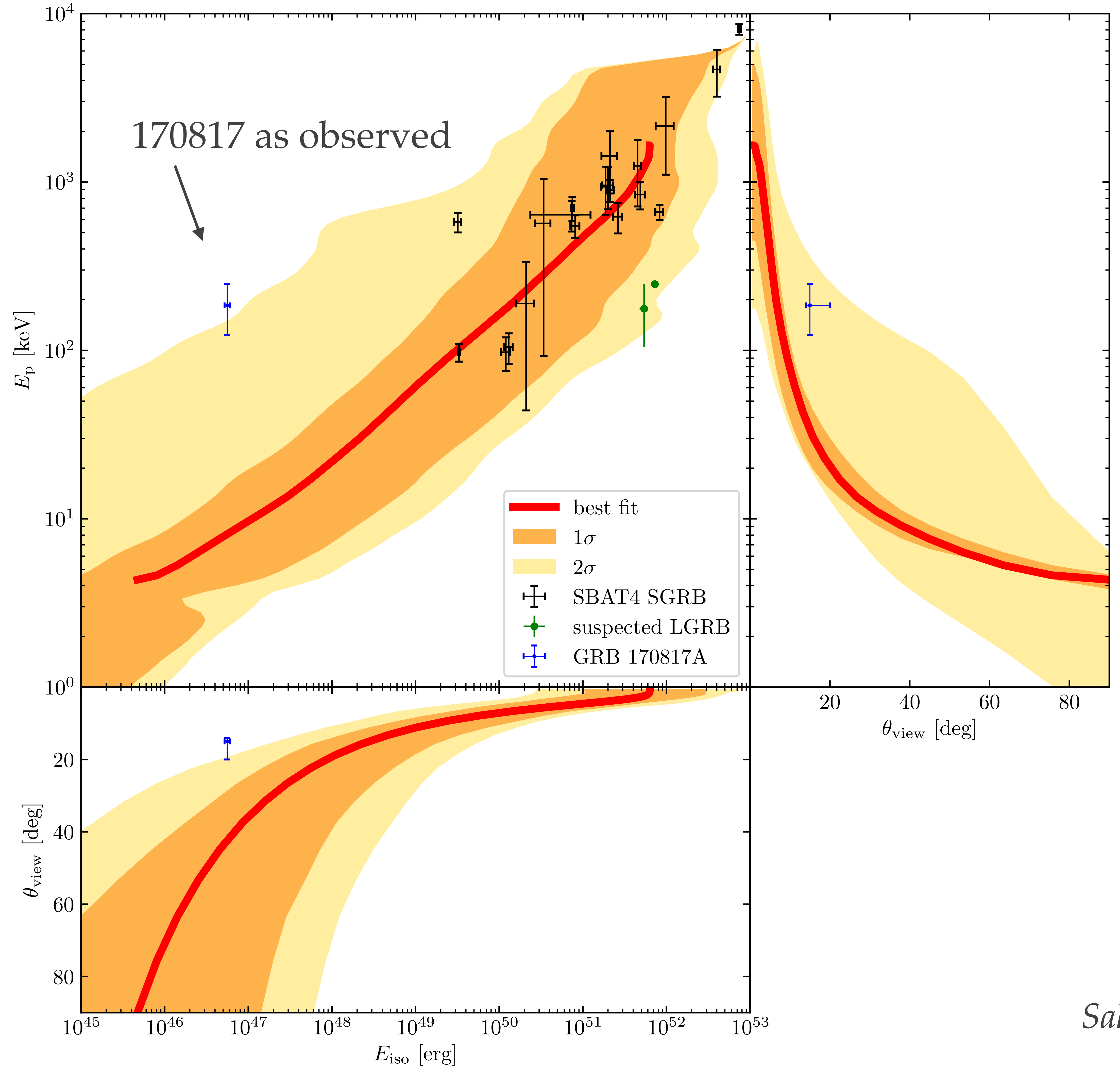


$\theta_{view} \sim 20^{\circ}$

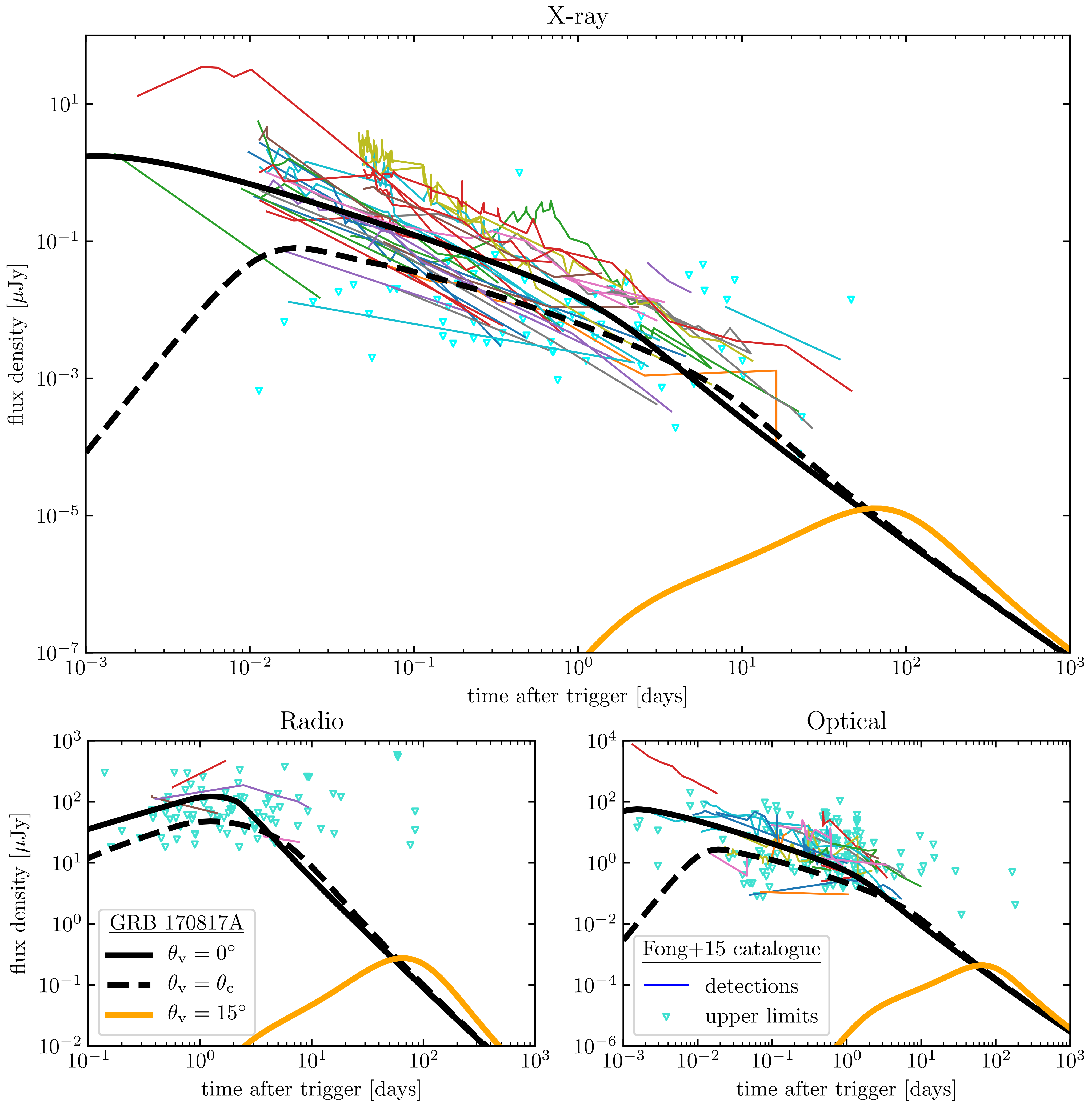
Combined observations

GRB 170817 IN THE CONTEXT OF SHORT GRB POPULATION

Prompt emission



Afterglow emission



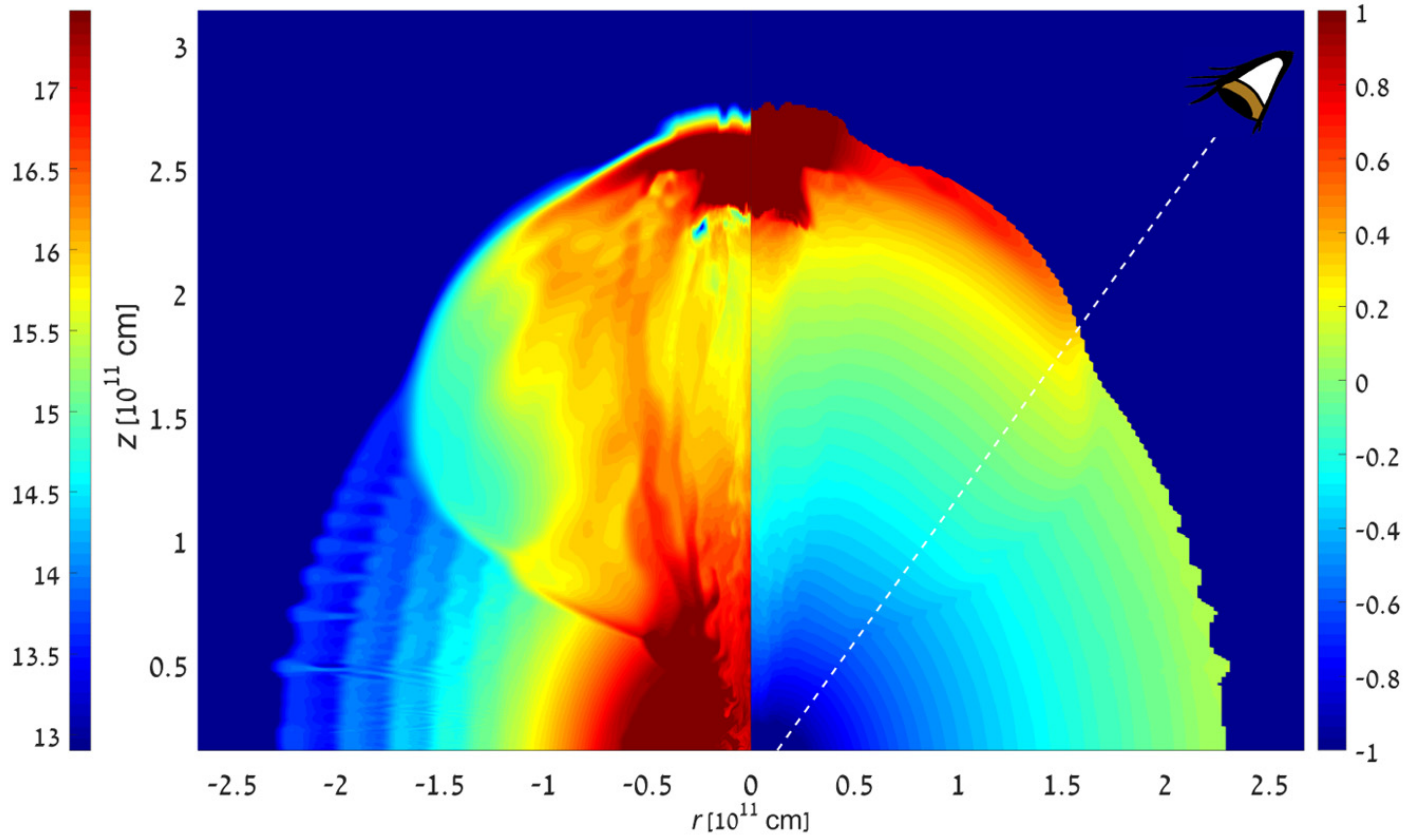
Salafia+2019

Ok for the afterglow, marginally consistent for the prompt

Cocoon emission and jet wings emission

Cocoon shock breakout

- Low energy
- Small variability
- Hard to soft spectral ev.
- Dealy GW-EM
- Wide angle emission



Gottlieb+2018

Structured jet wings

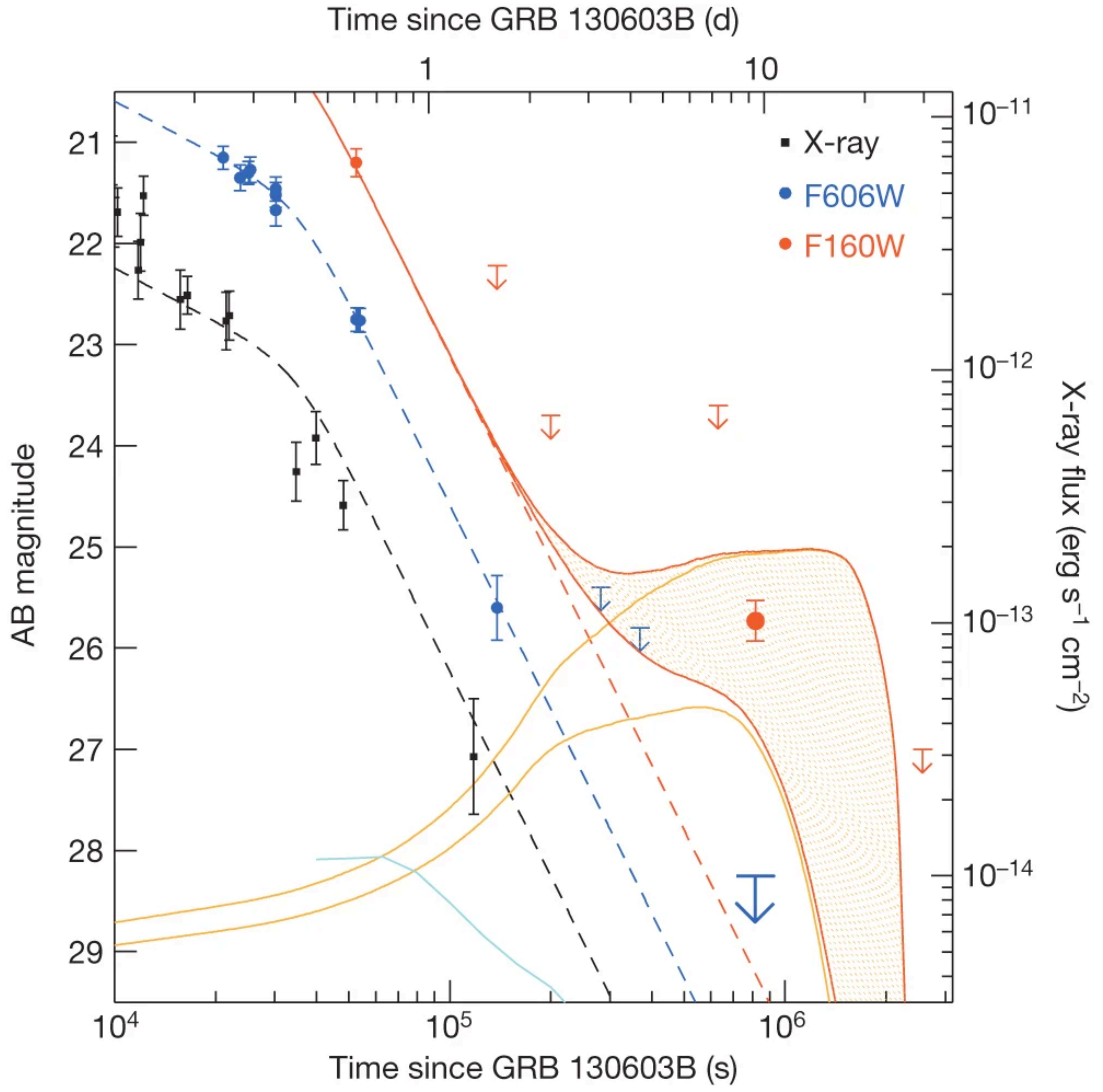
- $E(\theta) \,|\, \Gamma(\theta); E_{jet}(\theta); \eta(\theta)$
- High variability
- Hard to soft spectral ev.
- Dealy GW-EM
- Efficiency

$$t_{\rm bo} \sim 1 \left(\frac{E_{\rm bo}}{10^{46}{\rm erg}}\right)^{1/2} \left(\frac{T_{\rm bo}}{100{\rm keV}}\right)^{5/2} \quad sec$$

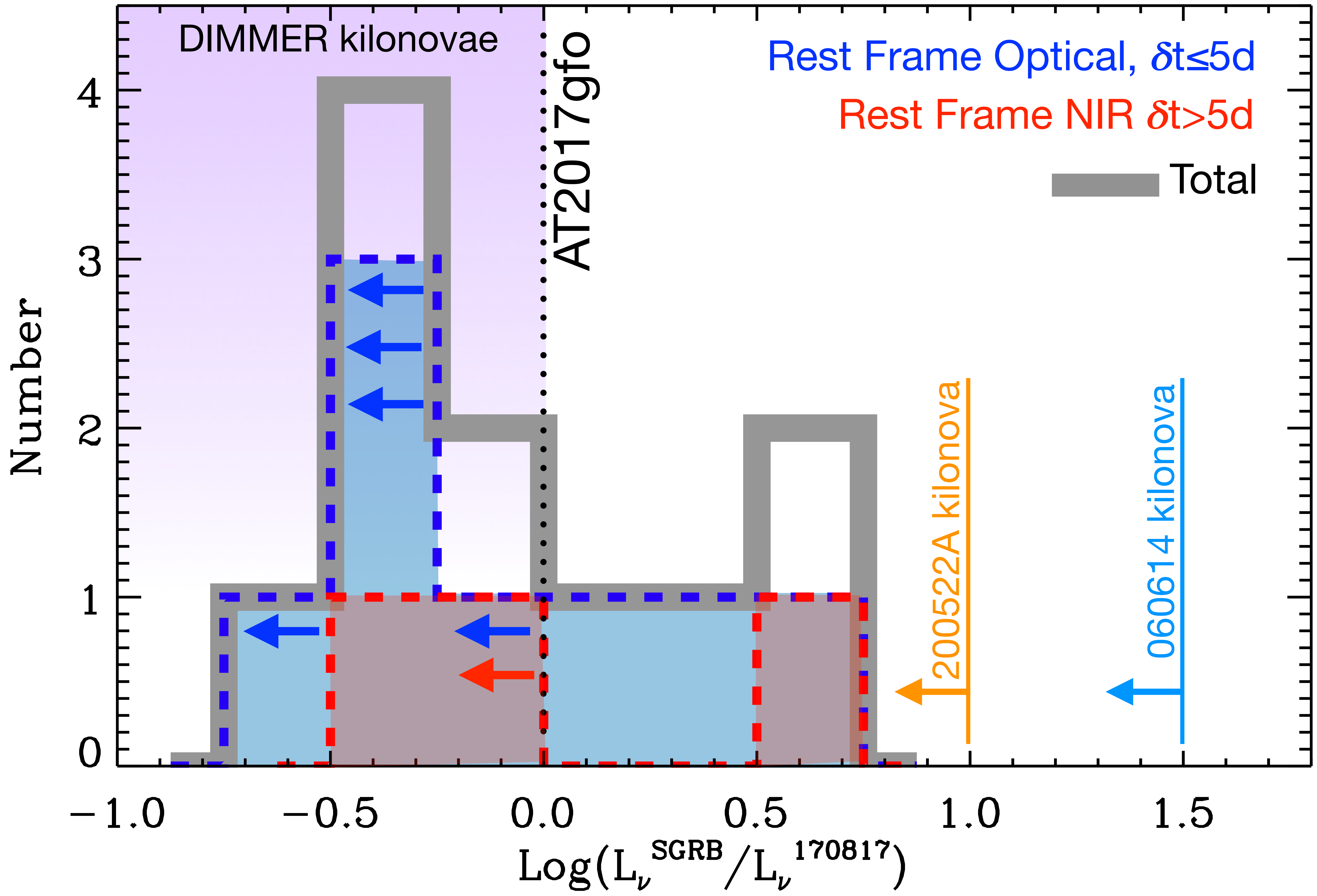
For a successful jet (as 170817 AG proves) both SJ and CC are present.
emission: internal dissipation (SJ), shock breakout (CC)

Kilonova AT2017gfo

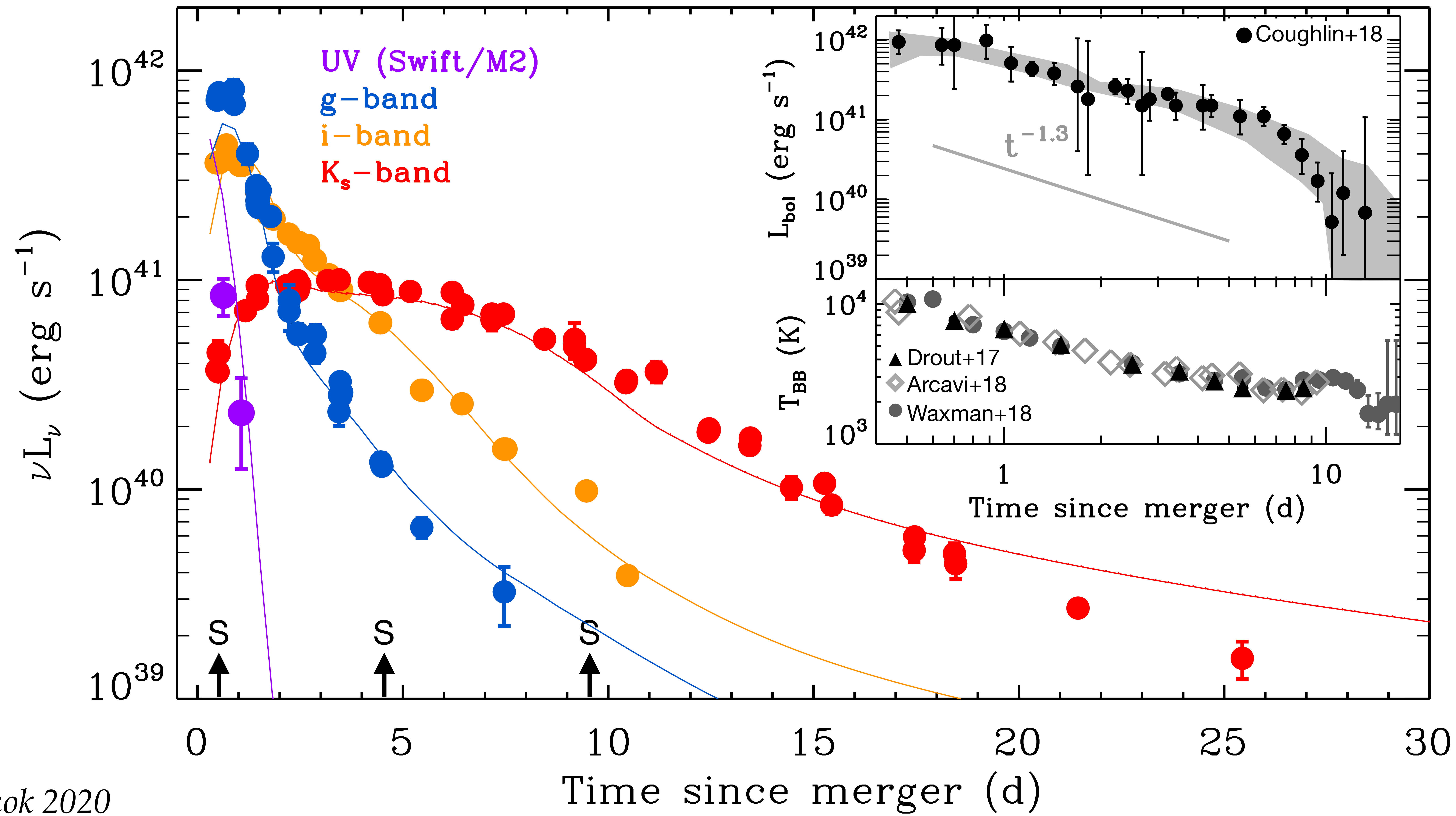
KILONOVAE



Tanvir et al. 2013



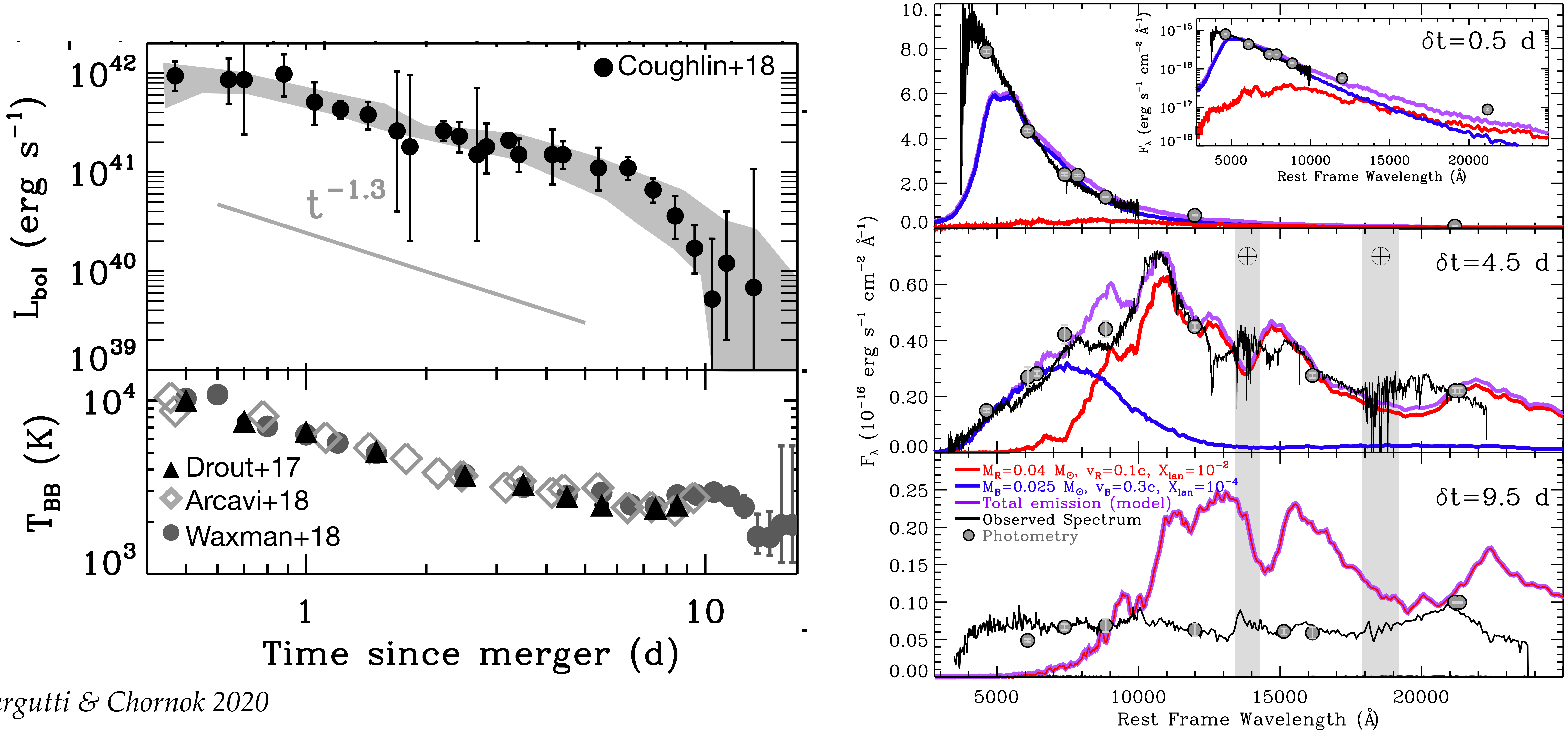
Large diversity of KN emission <—> intrinsic & extrinsic



Margutti & Chornok 2020

Richest and only dataset to date

KILONOVA OBSERVATIONAL FACTS



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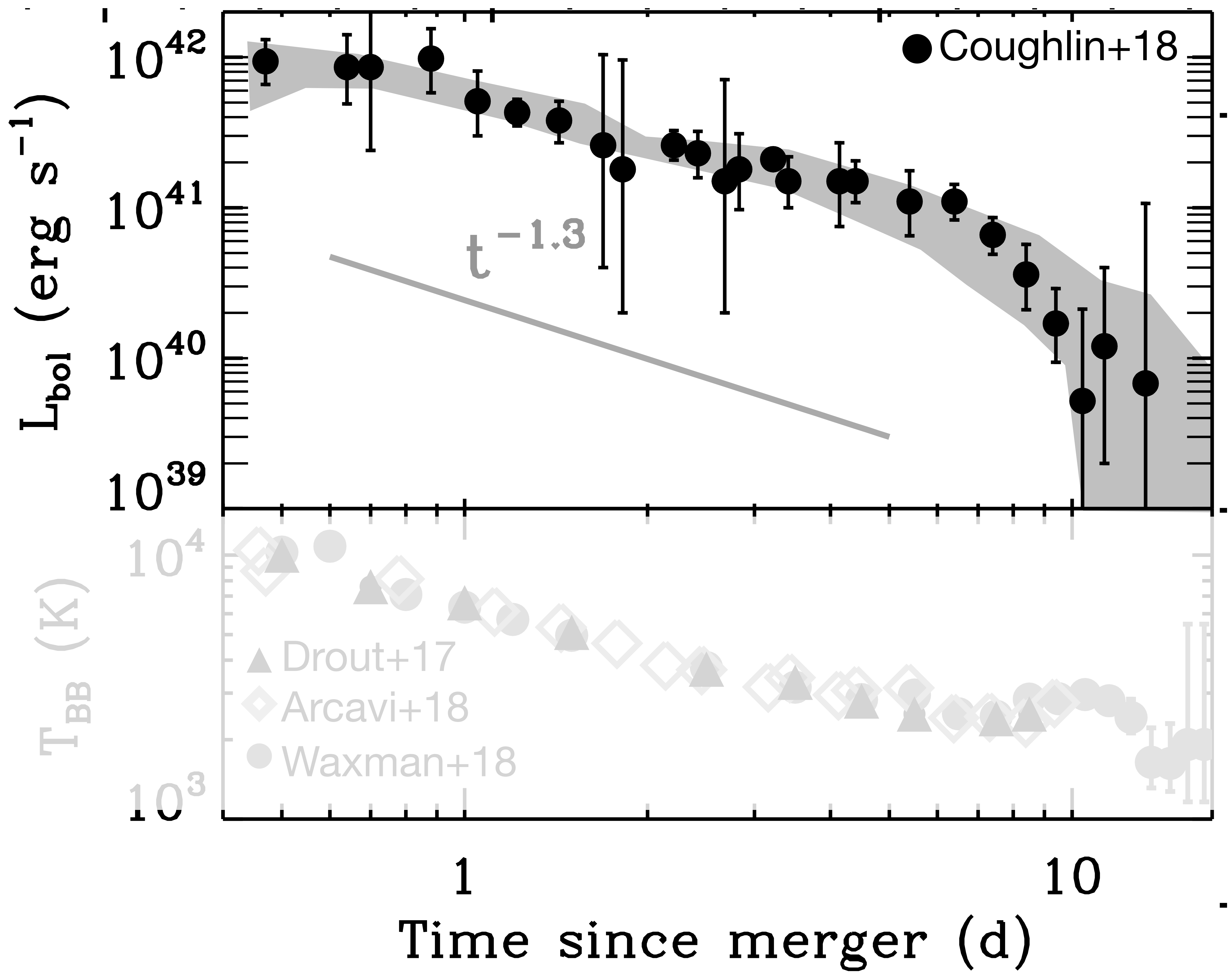
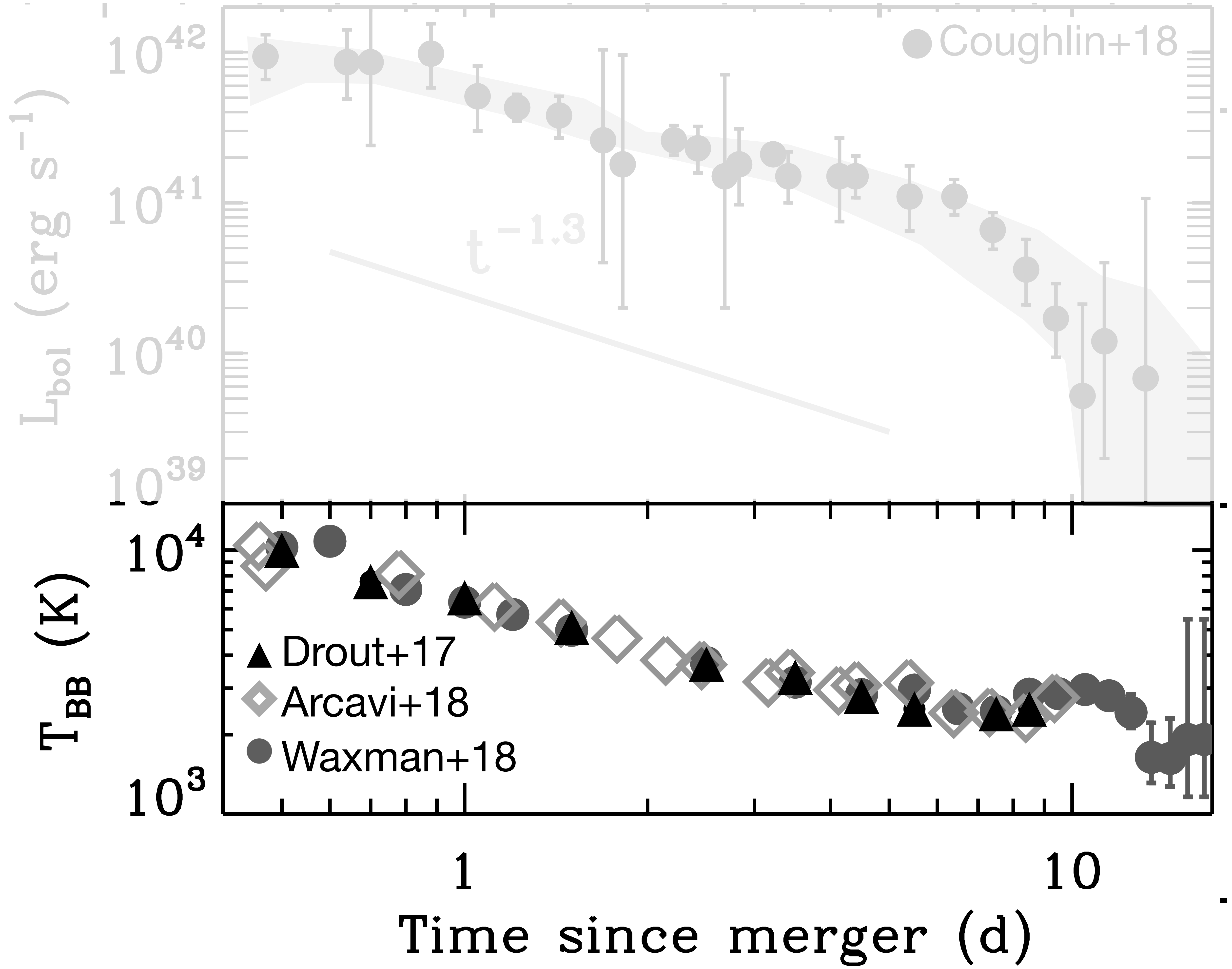
KILONOVA OBSERVATIONAL FACTS

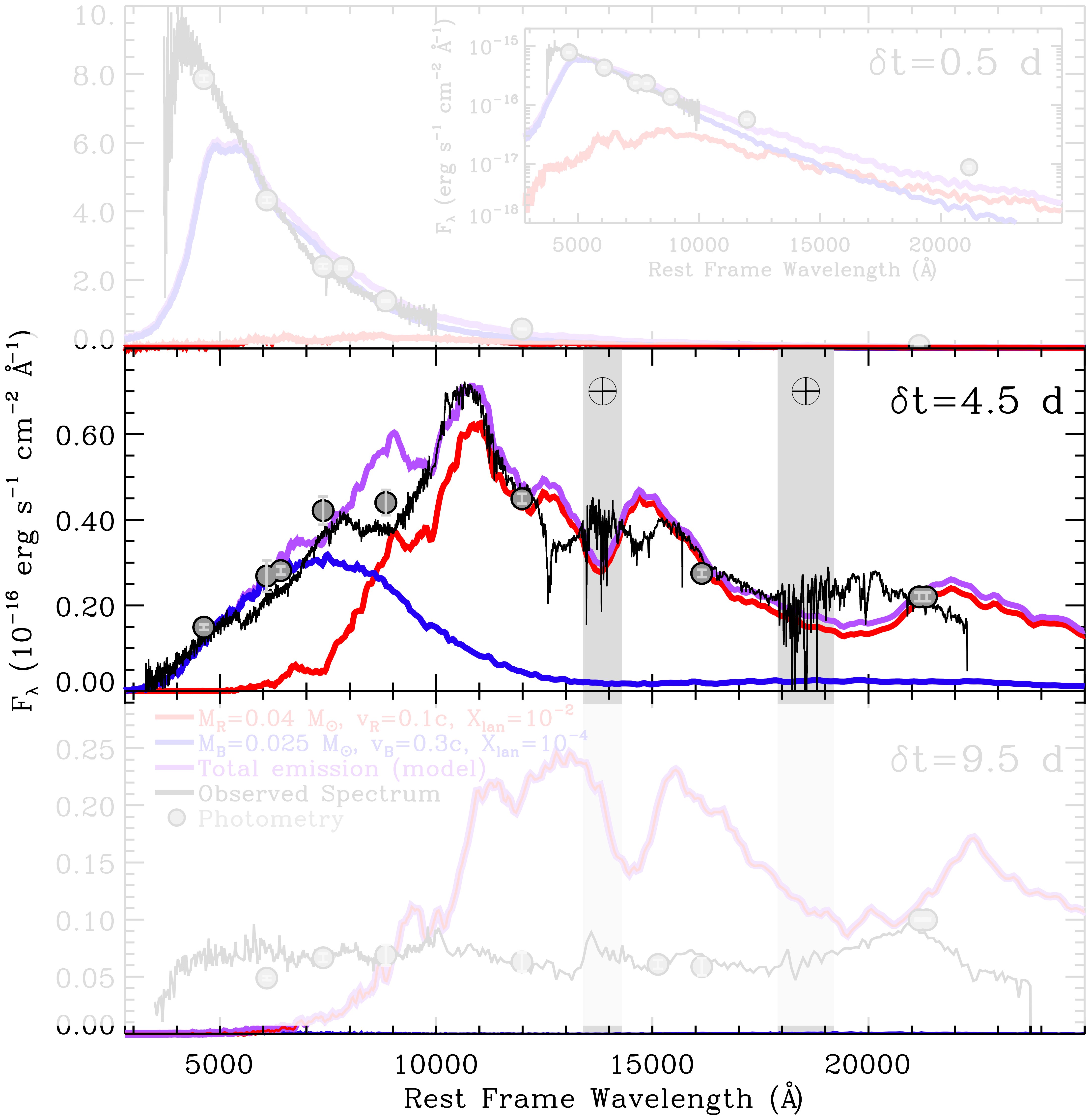


Margutti & Chornok 2020

Large luminosity and t^-1/3 —> r-process powered transient

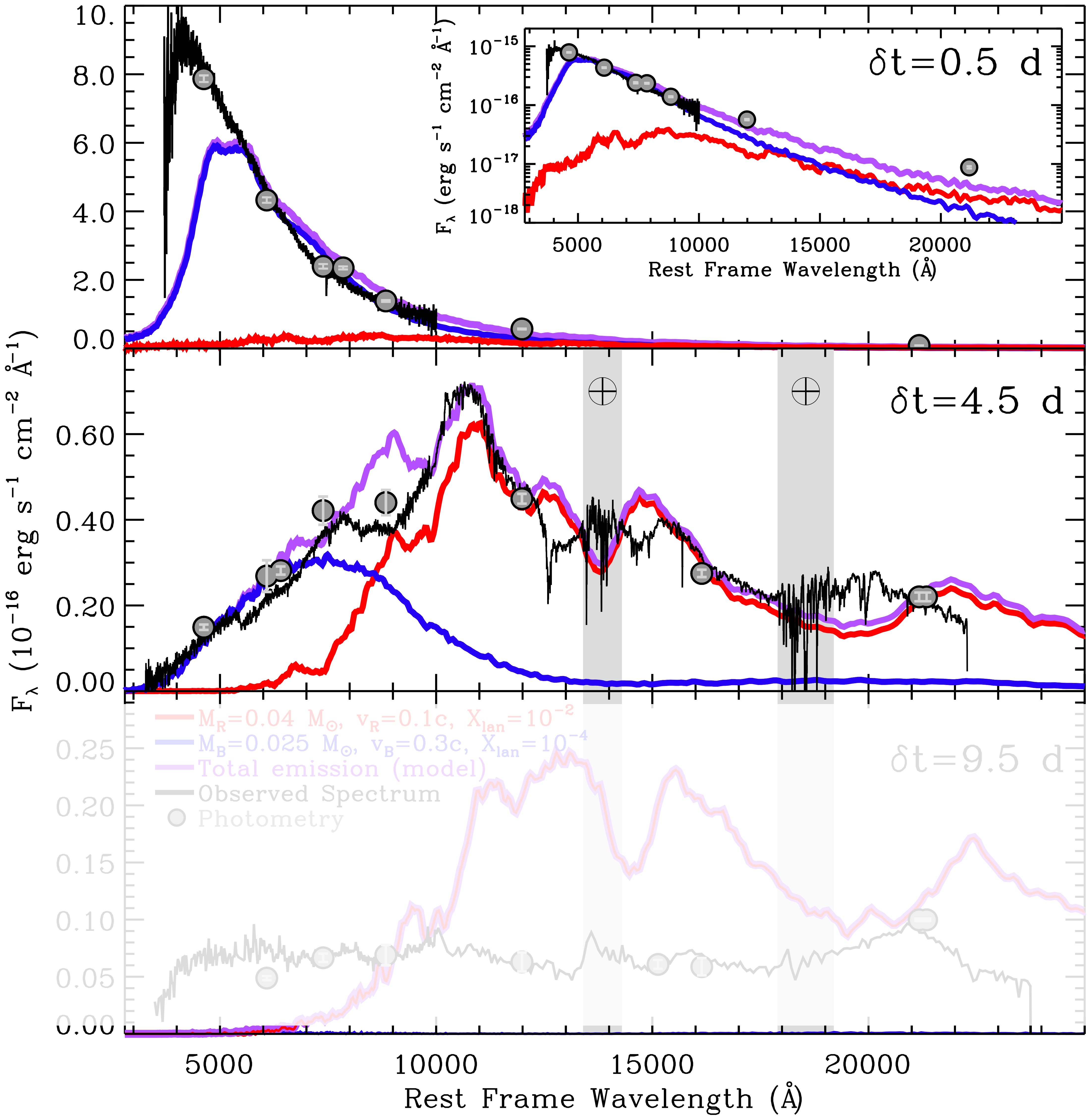
KILONOVA OBSERVATIONAL FACTS





Margutti & Chornok 2020

$T_{BB} \sim 10^4 K$ —> R~1e14 cm & blended large lines ==> $\beta \sim 0.3$



Margutti & Chornok 2020

Early emission: additional energy source

A SIMPLE KILONOVA MODEL: INGREDIENTS

Kilonova (1000x Nova - Metzger et al. 2010)

r-process nuclear decay powered transient in sub relativistic expanding ejecta

Lattimer & Schramm 1974
Symbalisty &Schramm 1982
Eichler + 1989
Li & Paczynski 1998
Kulkarni+2005
Metzger 2010
Tanaka+2013
Barnes+2013
….

Radioactive decay → Energy into expanding material → Opacity → Emission

$\dot{\epsilon}_{nuc}$ | $m_{ej}(v_{ej})$ | k

Blue KN $L \sim 10^{41}$ erg/s $t_p \sim 1$ day Lanthanide free ejecta

Red KN $L \sim 10^{40}$ erg/s $t_p \sim 1$ week Lanthanide rich ejecta

Can become extremely complicated (from analytical to fully numerical)

A SIMPLE KILONOVA MODEL: INGREDIENTS

L2

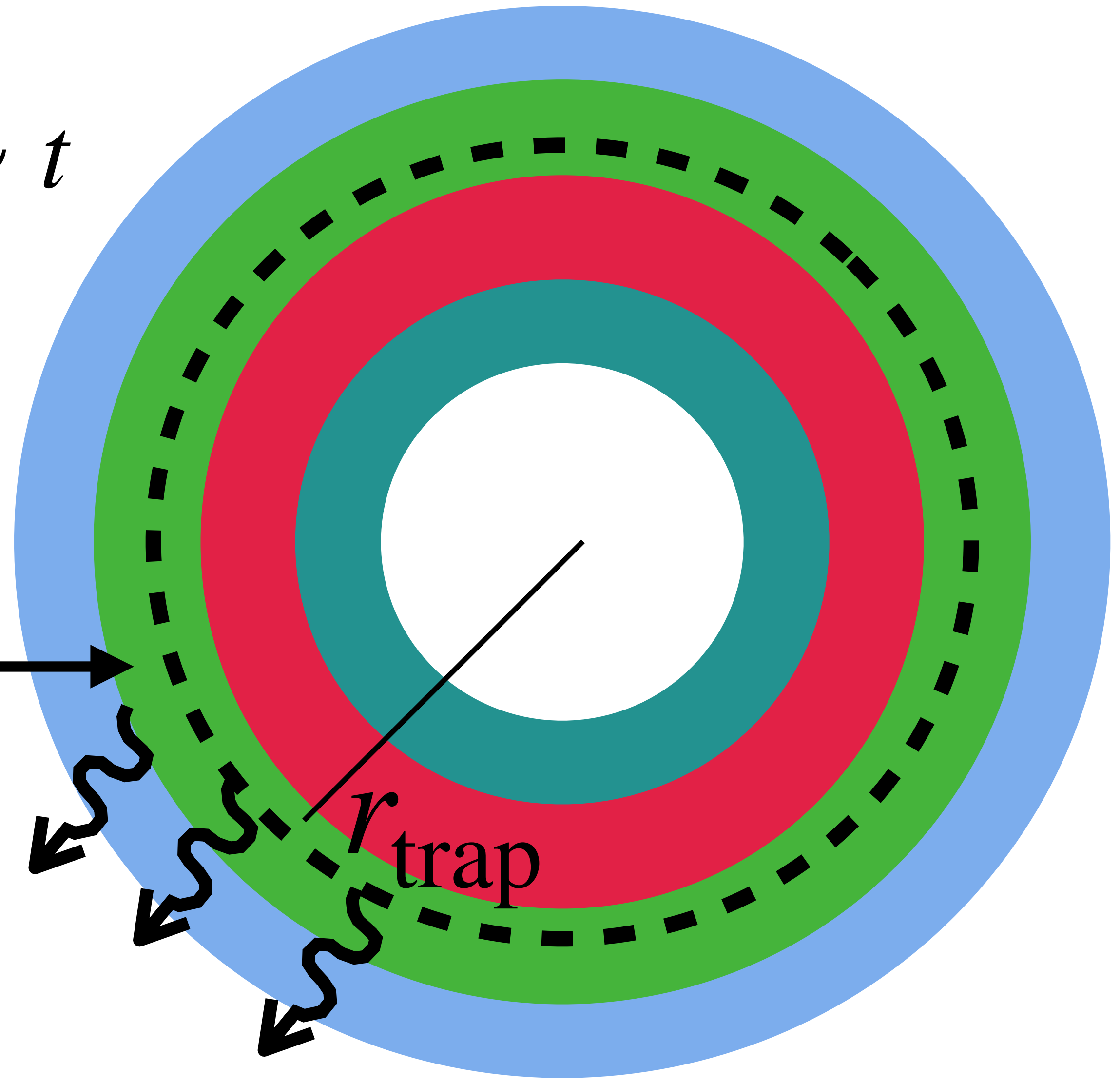
Radioactive decay	Energy into expanding material	Opacity	Emission
$\dot{\epsilon}_{nuc}$	$m_{ej}(v_{ej})$	k	Nuclear decay deposited @ r>r_{trap}

$r_{\rm trap} \rightarrow t_{\rm diff} \sim t_{\rm dyn} \sim t$

$t_{\rm diff} \simeq \tau r/c$

$$\tau(m) = \int_{vt}^{\infty} k\rho(r)dr \simeq k\frac{m(r)}{4\pi r^2} = k\frac{m(r)}{4\pi v^2 t^2}$$

$$\tau = \frac{c}{v} = \frac{1}{\beta}$$



Emission produced at r_{trap}

$$m_{EM} = \frac{4\pi\beta c^2 t^2}{k} \simeq 3\times 10^{-2} M_\odot\ \beta_{-1}\left(\frac{k}{0.1{\rm cm^2\,g^{-1}}}\right)^{-1} t_{\rm d}^2$$

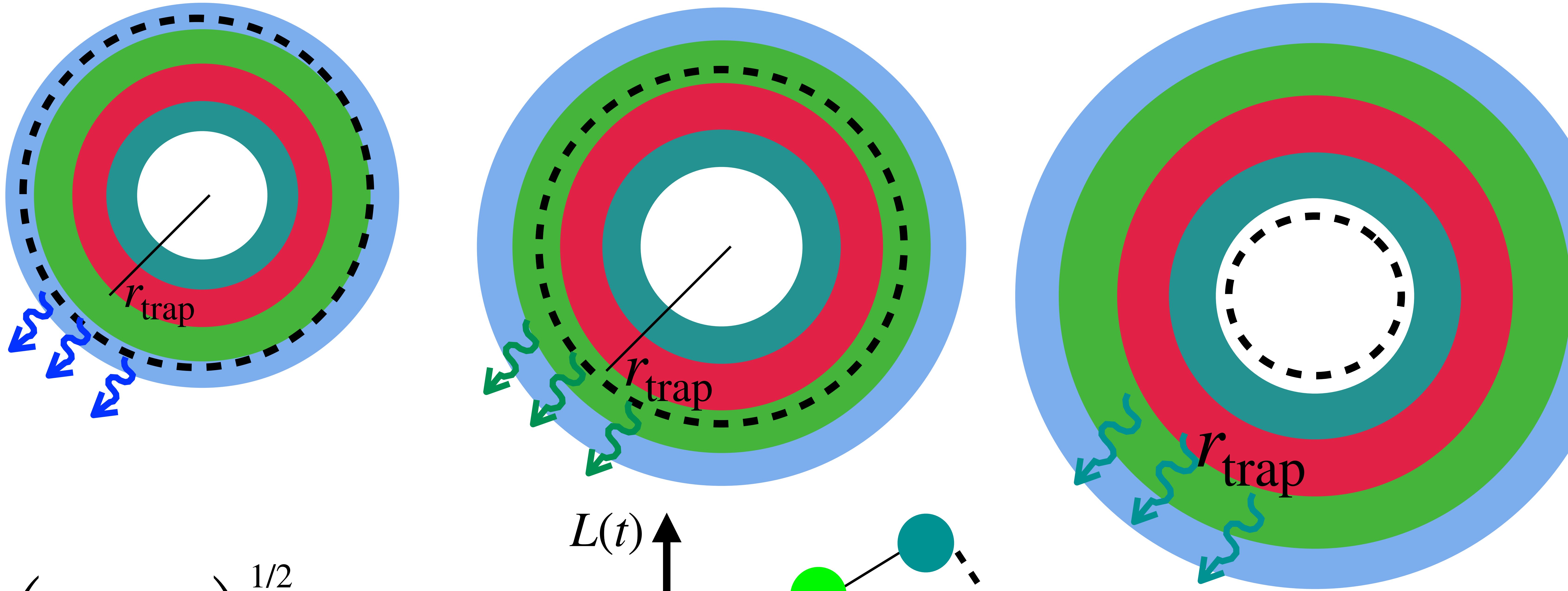
$$m(>v) = m(v)$$

Homol. Expansion $v(r) = r/t$

Mass responsible for the emission increases with time

A SIMPLE KILONOVA MODEL

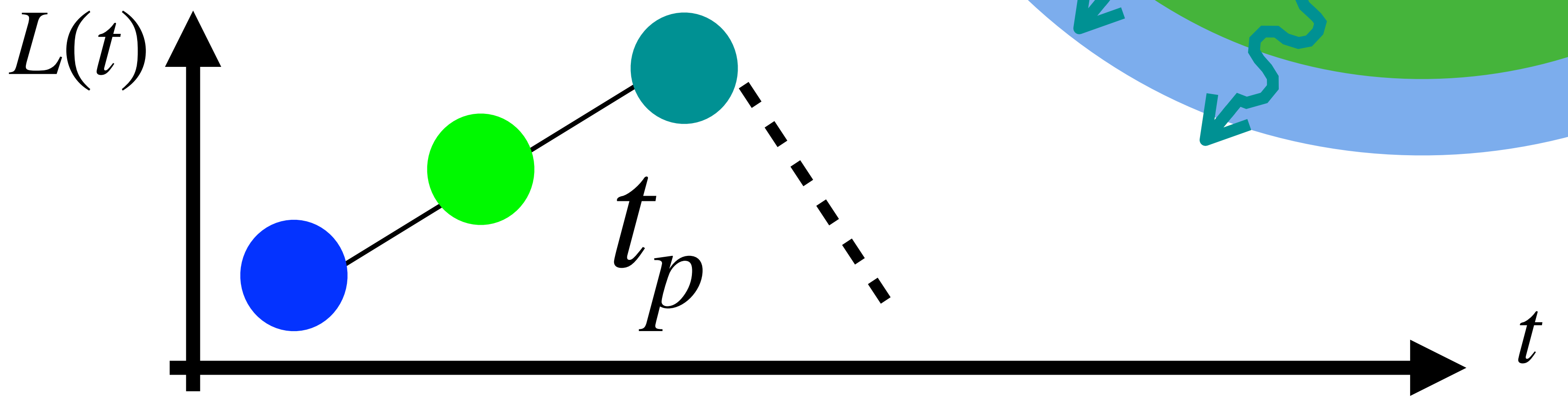
Radioactive decay	Energy into expanding material	Opacity	Emission
$\dot{\epsilon}_{nuc}$	$m_{ej}(v_{ej})$	k	Nuclear decay deposited @ $r>r_{trap}$



Emission produced at r_{trap}

$$m_{EM} = \frac{4\pi\beta c^2 t^2}{k}$$

Time of the peak $\quad t_p \approx 3.5\ \text{days} \left(\frac{m_{ej}}{0.05 M_\odot}\right)^{1/2} \beta_{-1,min}^{-1/2}\, k_0^{1/2}$



Peak time <—> mass, velocity and opacity ($0.5 - 30\,\text{cm}^2\text{g}^{-1}$)

A SIMPLE KILONOVA MODEL

Radioactive decay → Energy into expanding material → Opacity → Emission

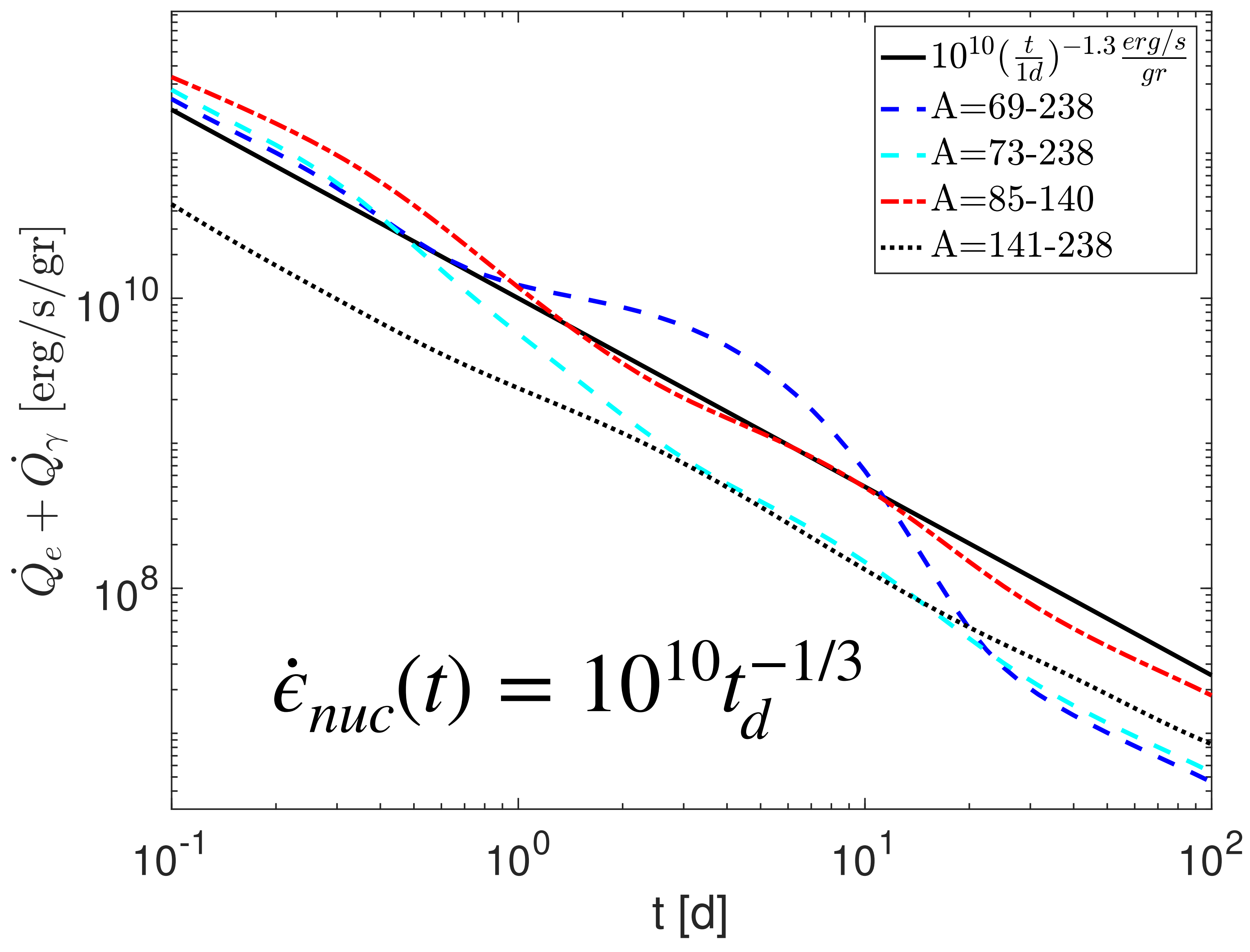
$\dot{\epsilon}_{nuc}$

$m_{ej}(v_{ej})$

k

Nuclear decay deposited @ r>r$_{trap}$

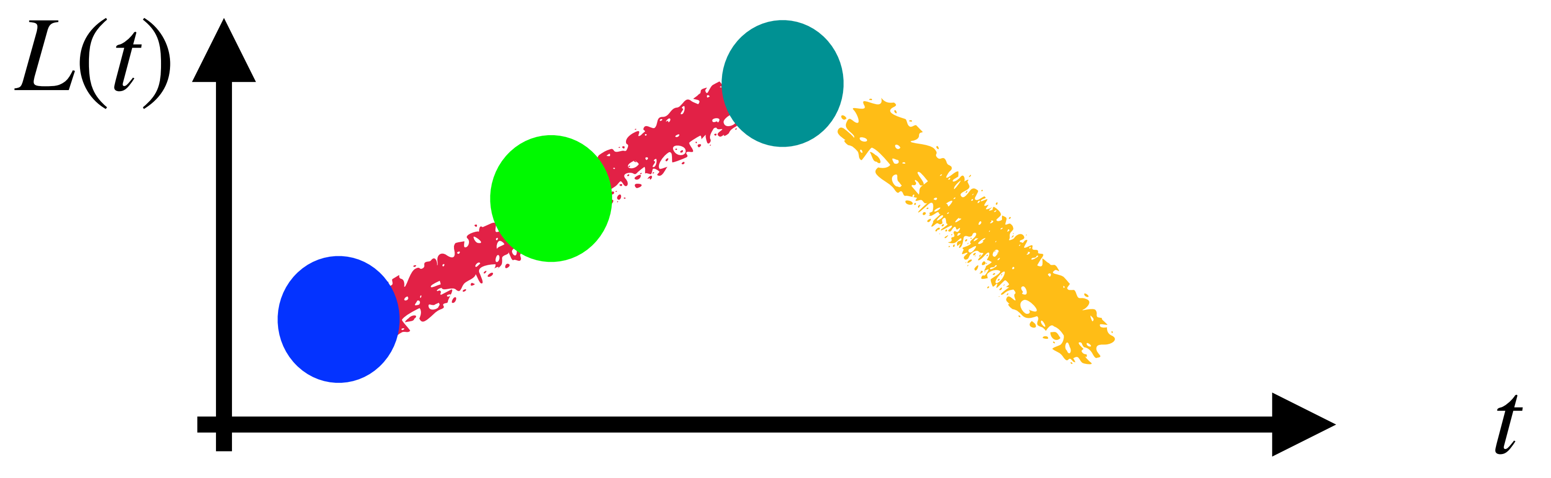
$$L(t) = \dot{\epsilon}(t)m(t)$$



Sneden 2008

$$L(t) = \dot{\epsilon}_{nuc}(t)m(t) \propto \xi_{ad}\beta_{-1}k_0^{-1}\left(\frac{\dot{\epsilon}_{nuc}}{10^{10}t_d^{-1/3}}\right)t_d^{0.7}$$

$$t_p \approx 3.5 \text{ days} \left(\frac{\mathrm{m_{ej}}}{0.05\mathrm{M_\odot}}\right)^{1/2} \beta_{-1,\mathrm{min}}^{-1/2}\,\mathrm{k}_0^{1/2}$$

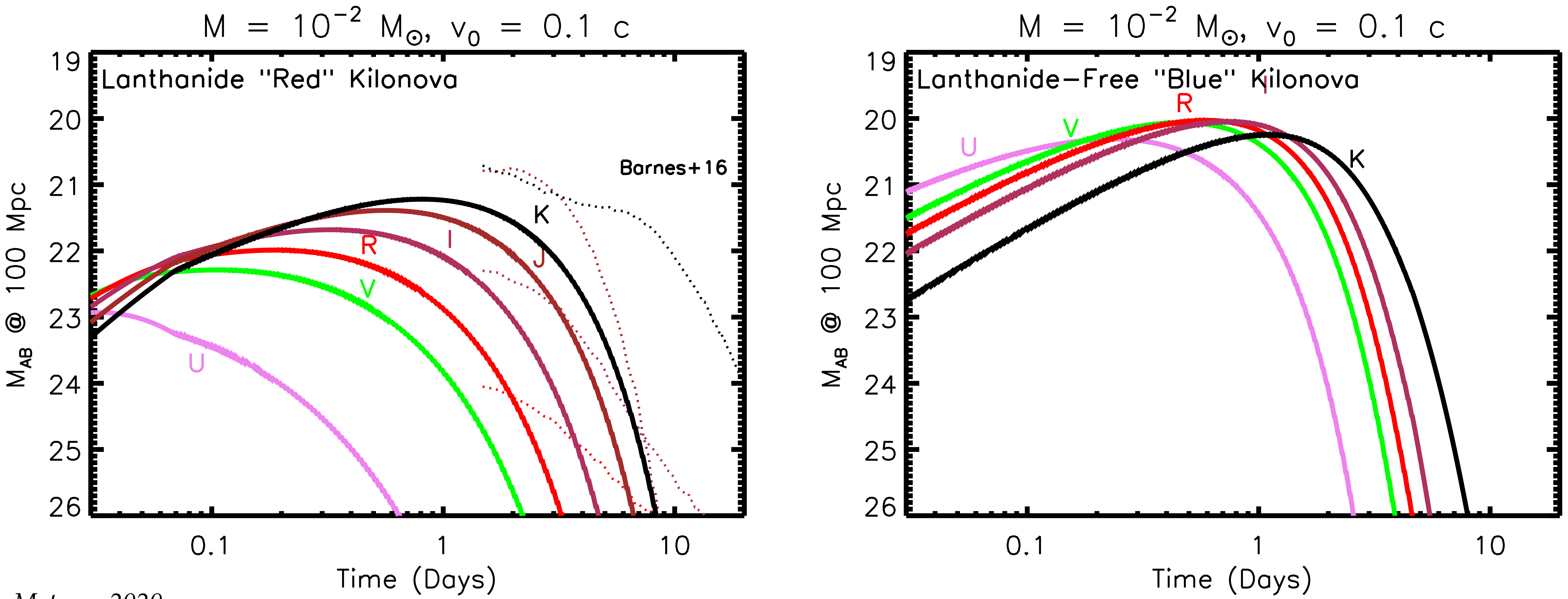


$$L(t) = \dot{\epsilon}_{nuc}(t)m = 8\times 10^{40}\,\mathrm{erg\ s^{-1}}\left(\frac{\mathrm{m_{ej}}}{0.05\ \mathrm{M_\odot}}\right)\left(\frac{\dot{\epsilon}_{\mathrm{nuc}}}{10^{10}\mathrm{t_d^{-1/3}}}\right)\mathrm{t_d^{-1.3}}$$

If $m(v) \propto t^{-a}$: $\quad L(t < t_p) \propto t^{\frac{0.7(a-1.86)}{1+a}}$

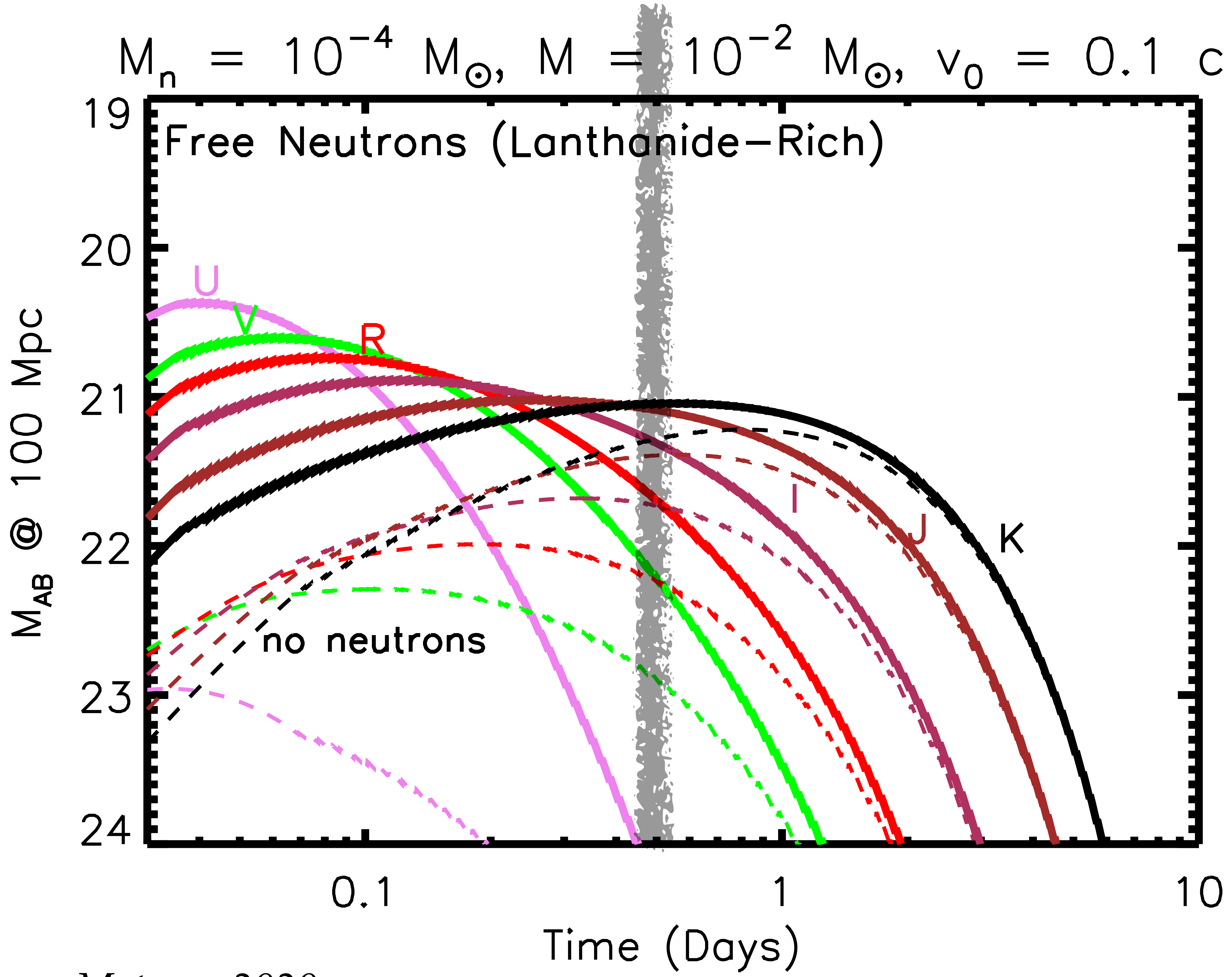
Kilonova light curve scaling

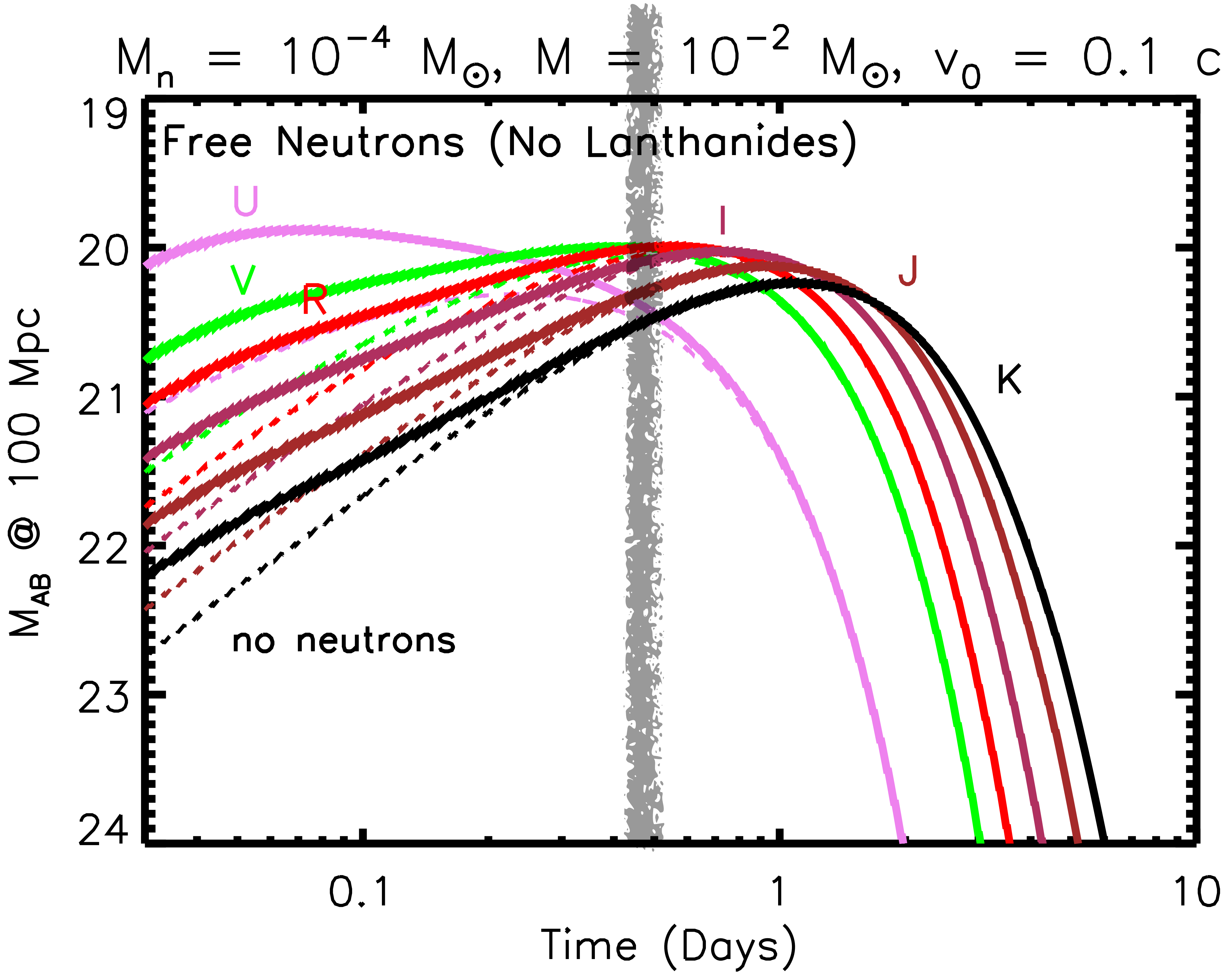
A SIMPLE KILONOVA MODEL



Metzger 2020

Kilonova light curves





Metzger 2020

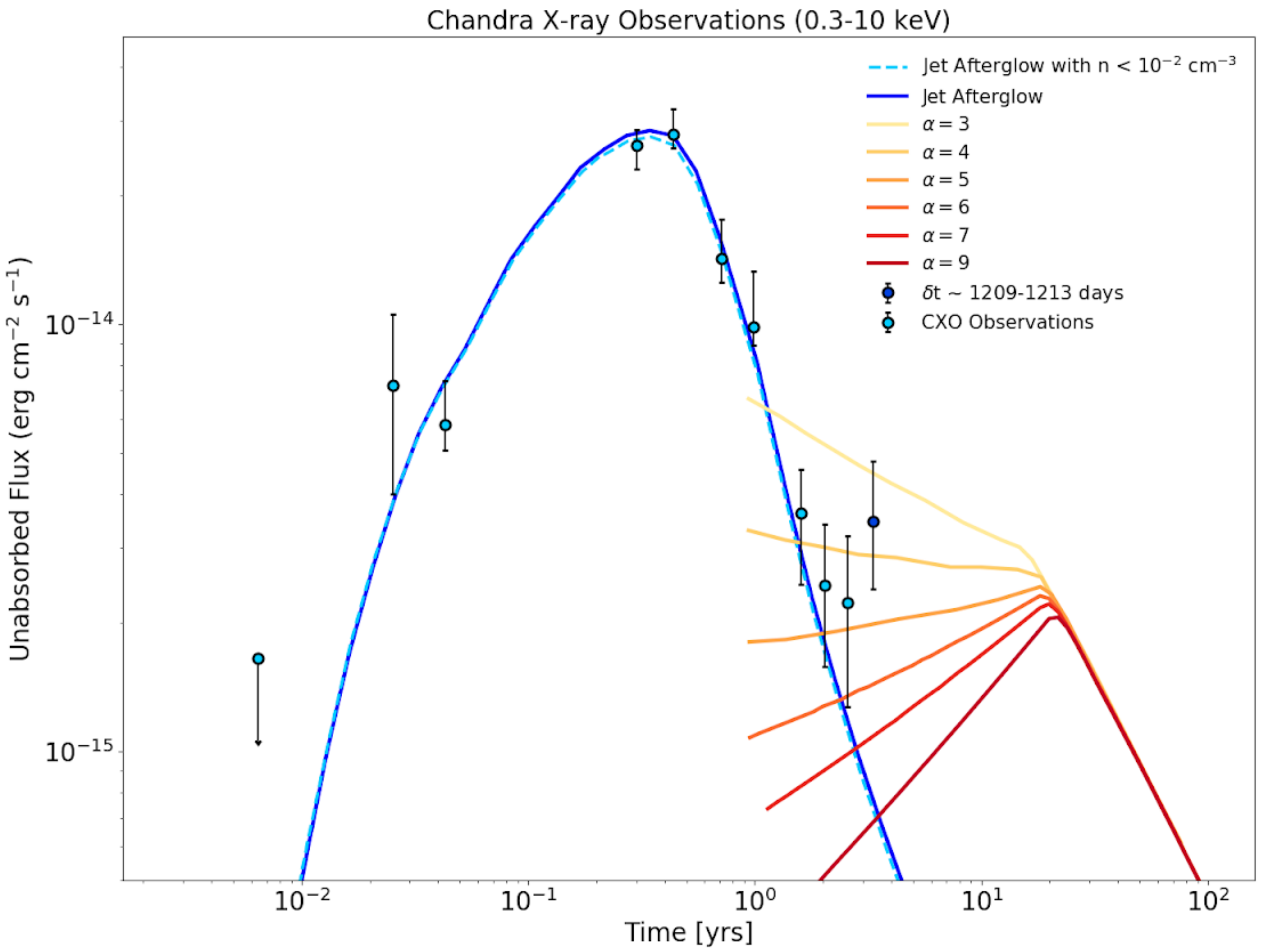
Neutron precursor

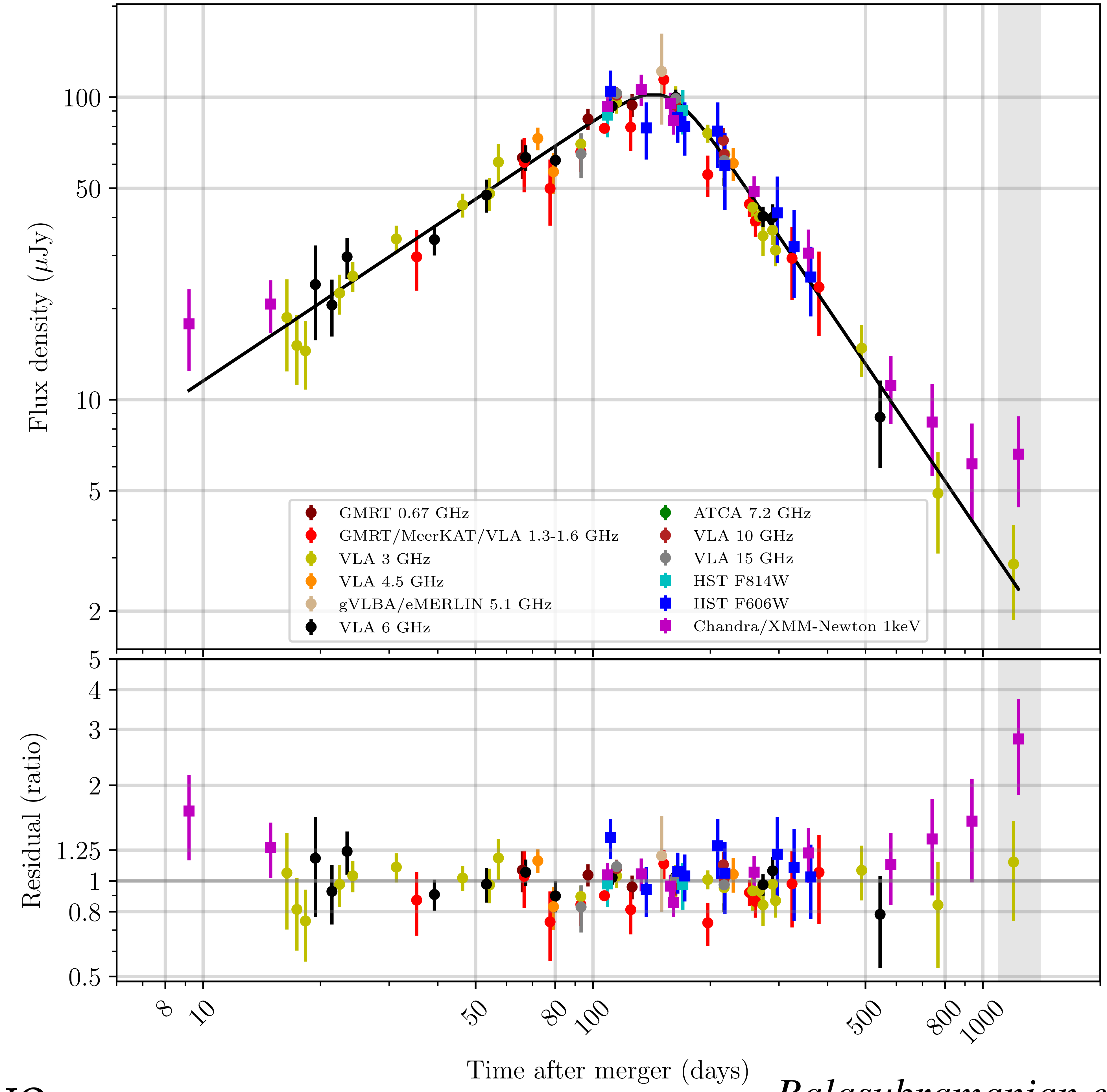
KILONOVA AFTERGLOW

Ejecta deceleration by the interstellar medium —> very late time afterglow

e.g. Piran+2013

Hajiela+2020 GCN 29041



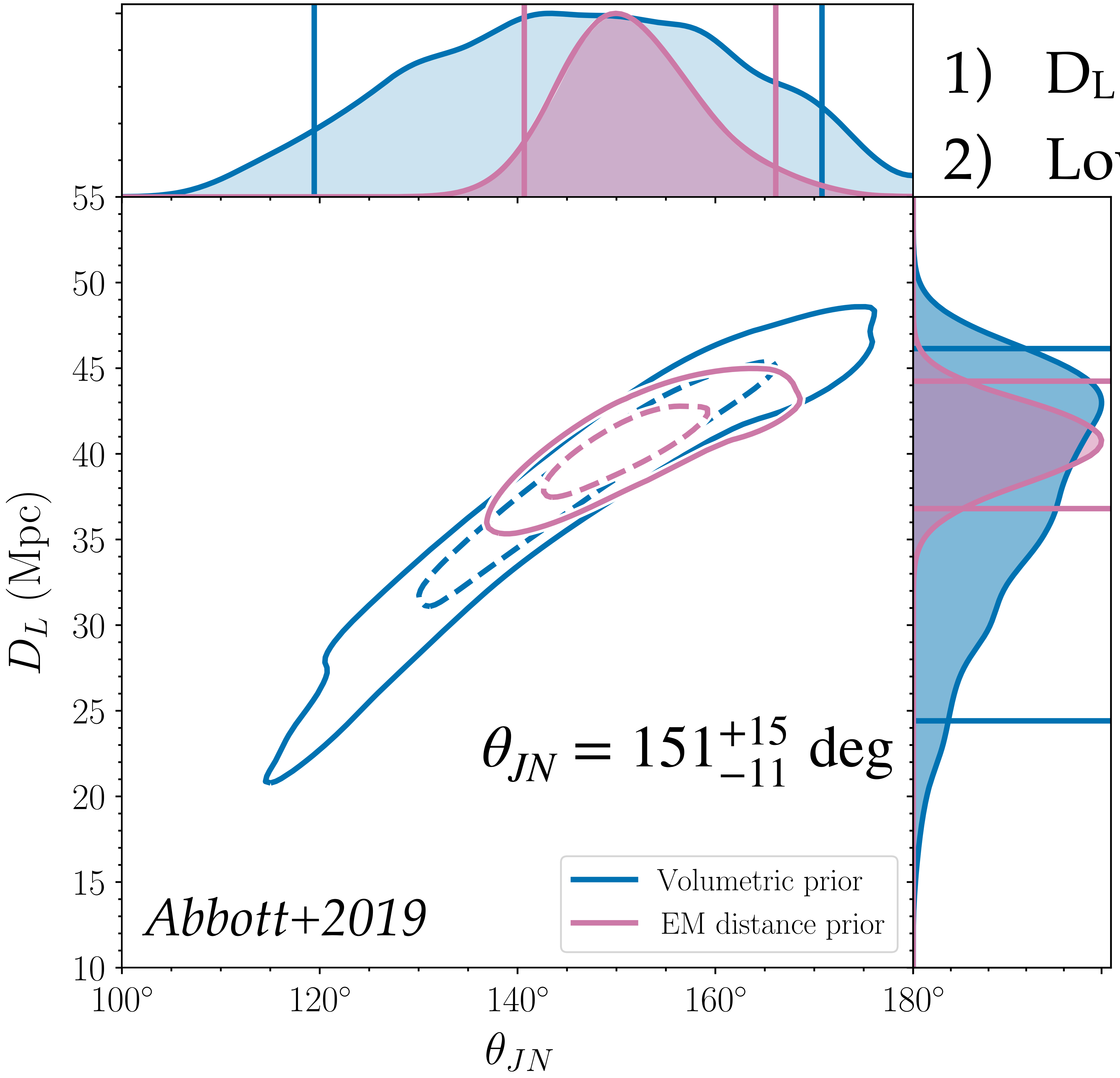


Possible deviation from jet decay but not yet conclusive

Balasubramanian et a. 2021

Rising phase can constrain the mass-velocity stratification of the outflow

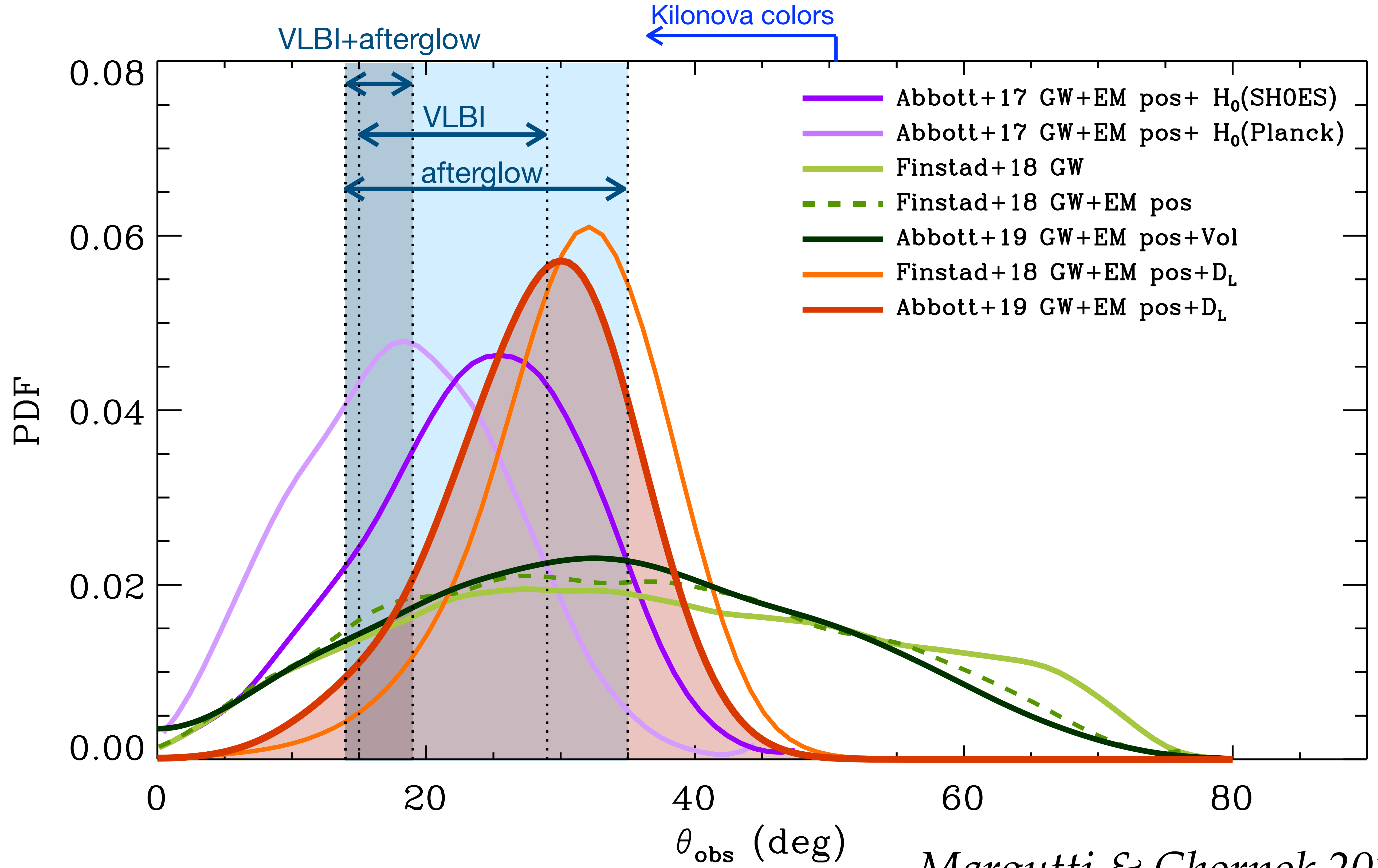
MM2: IMPROVEMENT OF GW PARAMETER SPACE



1) D_L from EM counterpart
2) Low spin prior (<0.05)

Afterglow: peak time

VLBI: $\theta_{obs} - \theta_{jet} \sim 1/\Gamma \sim 0.25$



Margutti & Chornok 2020

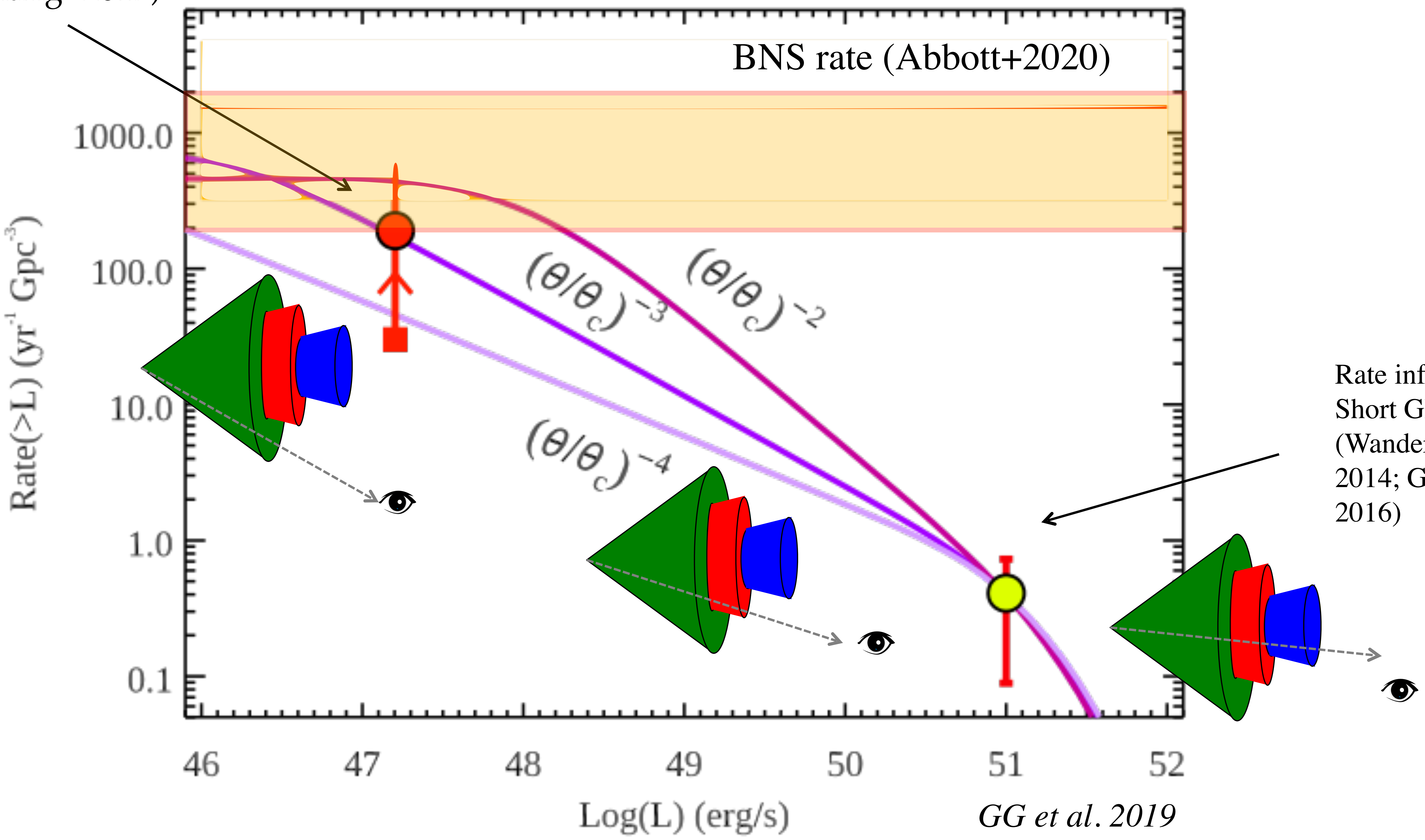
Other constraints (R, Λ …) with additional astrophysically informed priors (*Abbott+2018*)

Combined MM reduce parameter degeneracy

MM2: POPULATION & RATES

Structured jet model (universal structure) Luminosity function (Pescalli et al. 2015; Salafia et al. 2015)

Rate infered from
Fermi (Zhang+2017)

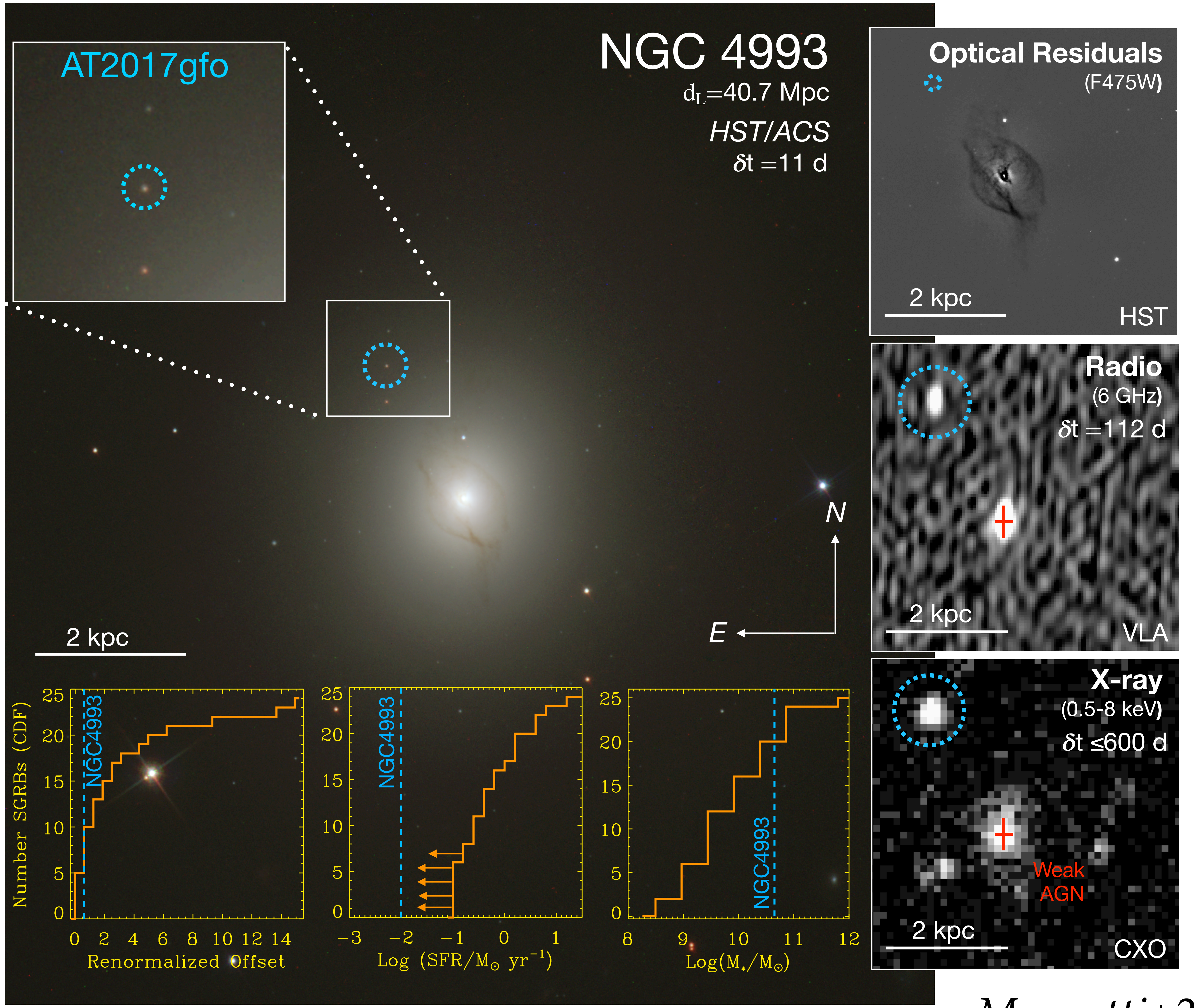


Rate infered from
Short GRBs
(Wanderman & Piran
2014; Ghiralnda et al.
2016)

At least 10% of BNS launch a jet that successfully breaks out of the merger ejecta

$L(458\,d) \leq 3 \times 10^3 L_\odot$

BNS origin



Dust lanes

Compact active nucleus

Comparison with SGRB hosts:
Closer to the center
Lowest SFR
Massive host

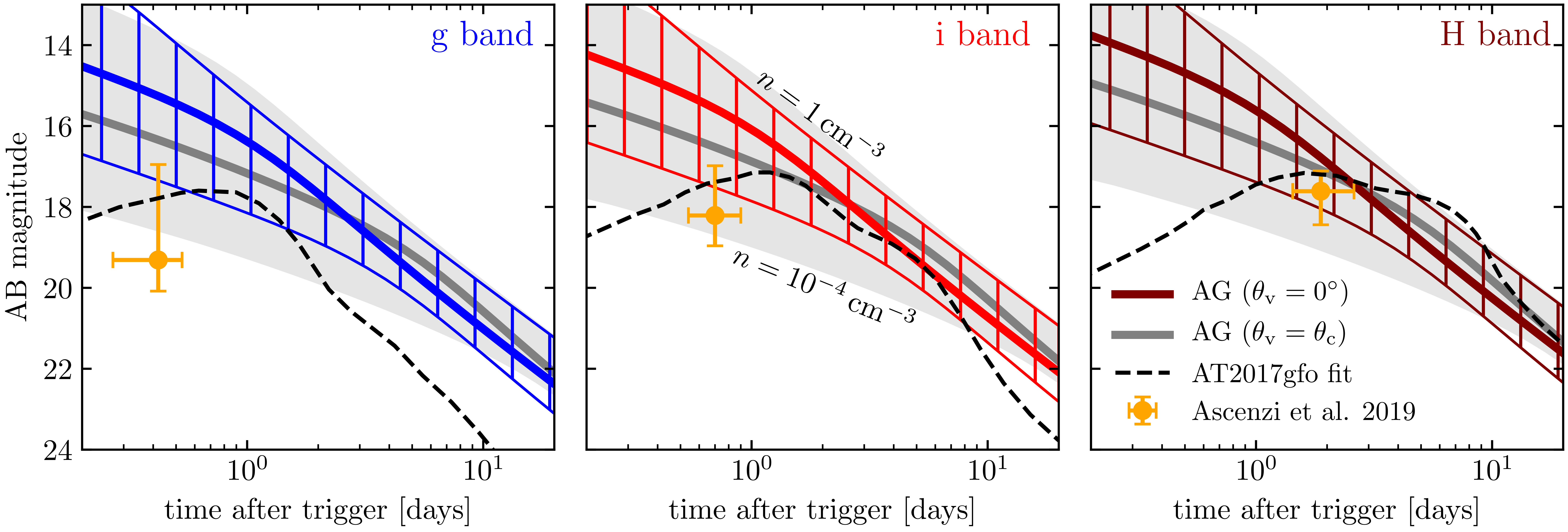
Margutti+2020

Inferences on the BNS origin from the close and large scale environment (cf sGRB host studies)

AFTERGLOW VS KILONOVA

At 40 Mpc
On axis or at the jet core border
$n \in (10^{-4}, 1)$ cm^{-3}

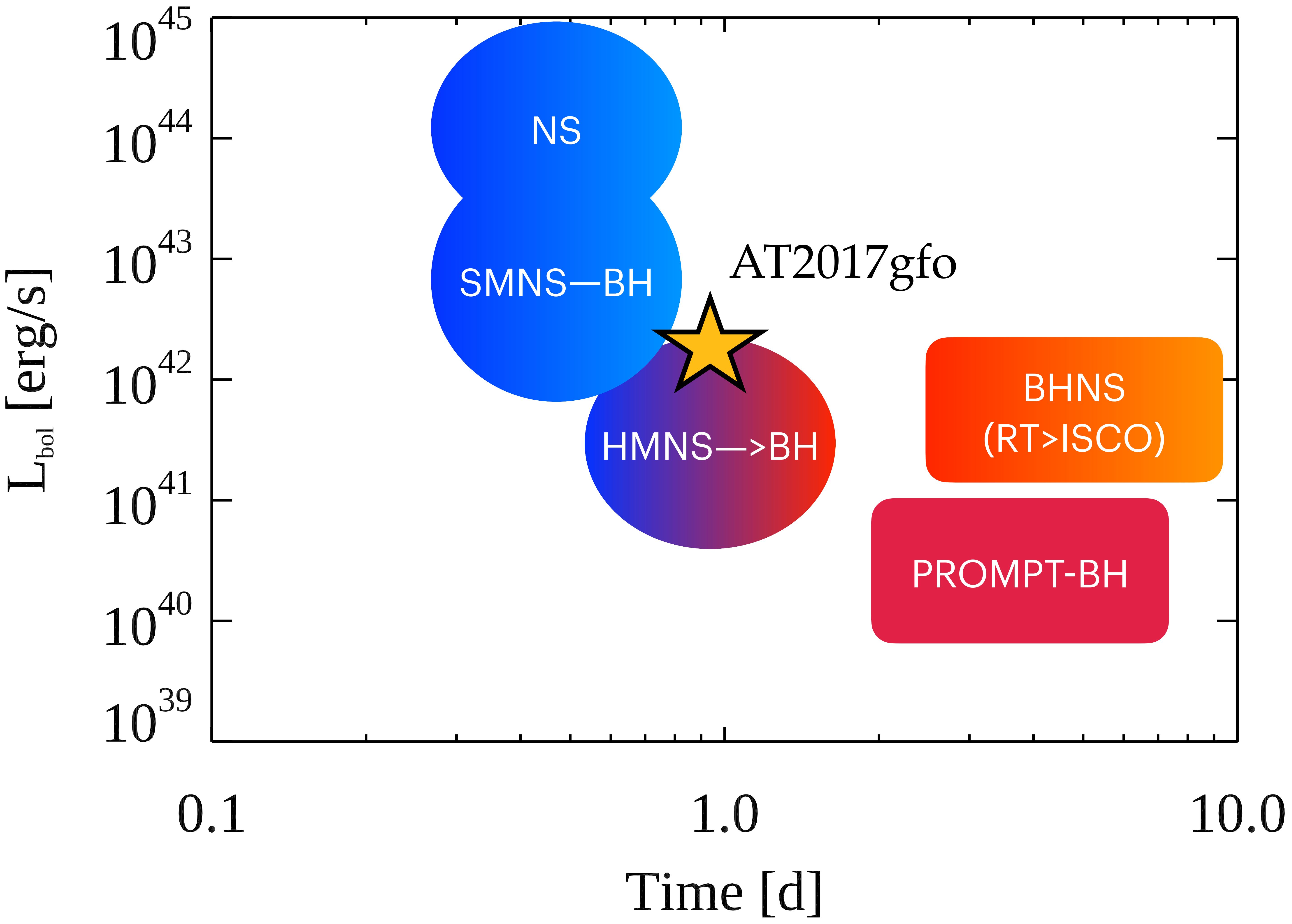
KN evidences/claims
[Tanvir+2013; Berger+2013; Jin+2016; Jin+2015; Yang+2015; Troja+2018; Rossi+2019]



Salafia+2019

IR bands more promising (e.g. 130613B - Tanvir+2013; Berger+2013)

On axis jet would over shine the KN component unless in a very low density environment



On axis jet would over shine the KN component unless in a very low density environment

Conclusions

GW170817+GRB170817+ AG170817: first direct connection short GRBs—BNS:
BNS —> relativistic jet —> core with properties similar to those of cosmological short GRBs + structure (first ever event in the realm of GRBs).

AT2017gfo —> r-process nuclear heating powered transient and BNS are sites of r-process nucleosynthesis.

Multi-messenger (I): GW+EM can constrain extrinsic (e.g. inclination) or intrinsic (e.g. EoS)

Multi-messenger (II): GW+EM —> standard sirens