Short Gamma-Ray Bursts in the Era of Multi-Messenger Astrophysics

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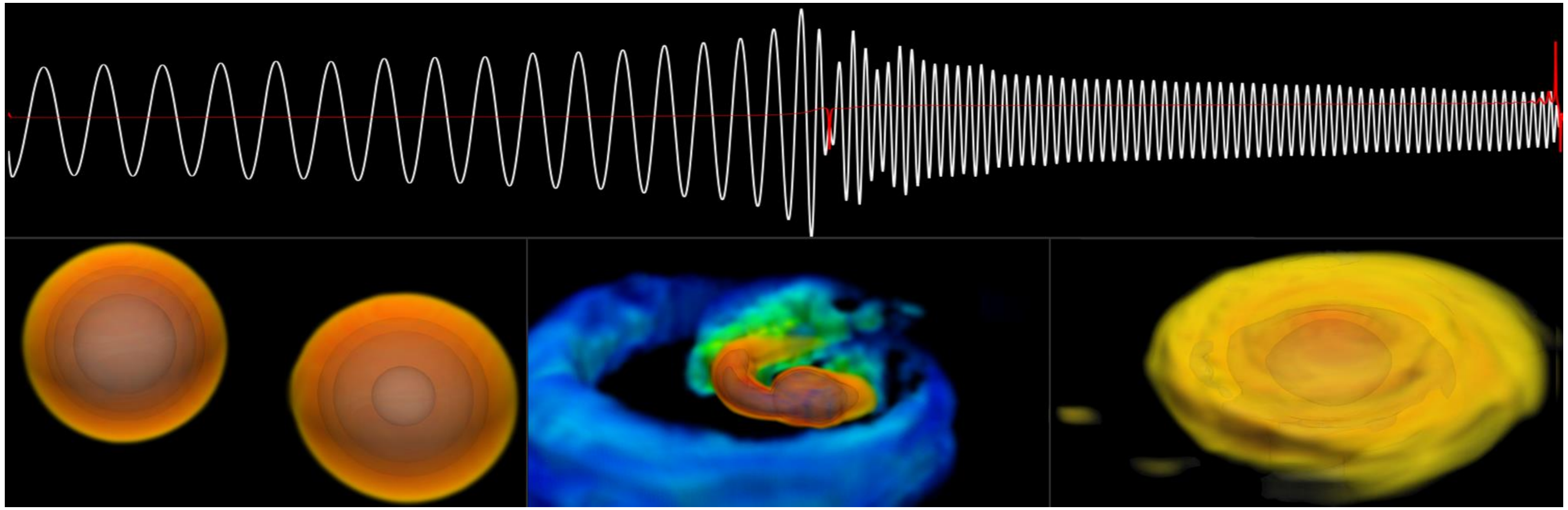
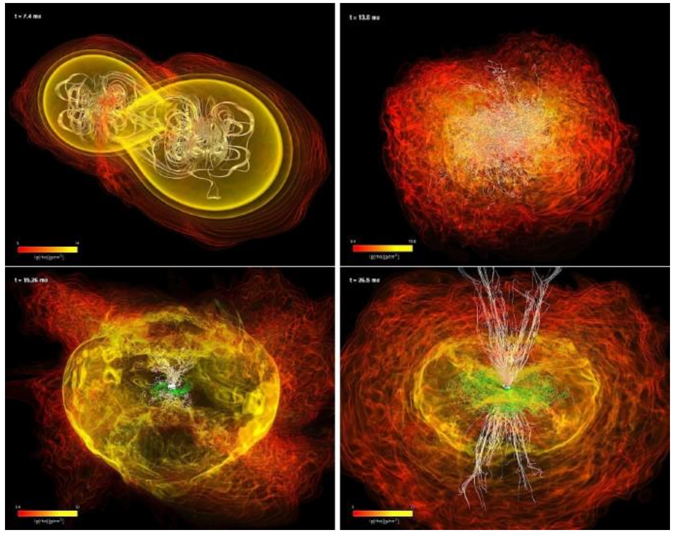




JGRG34: The 34th Workshop on General Relativity and Gravitation in Japan

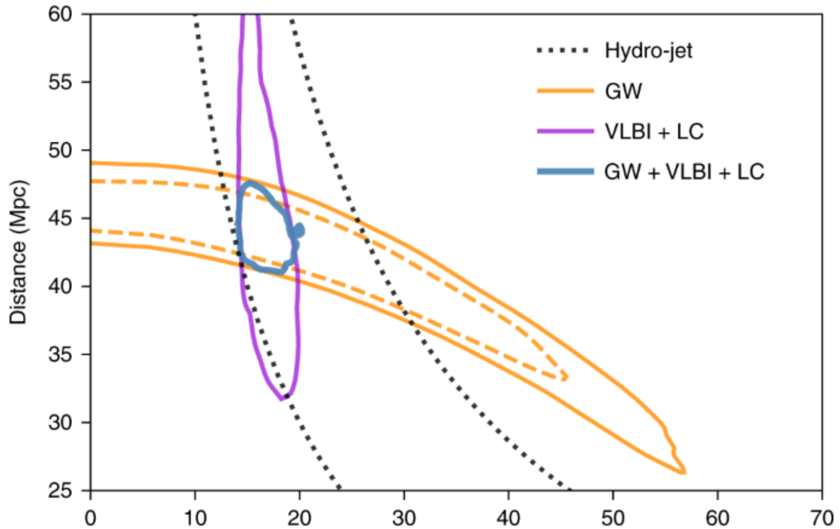
Kyoto University, Kyoto, Japan, 22 January 2026

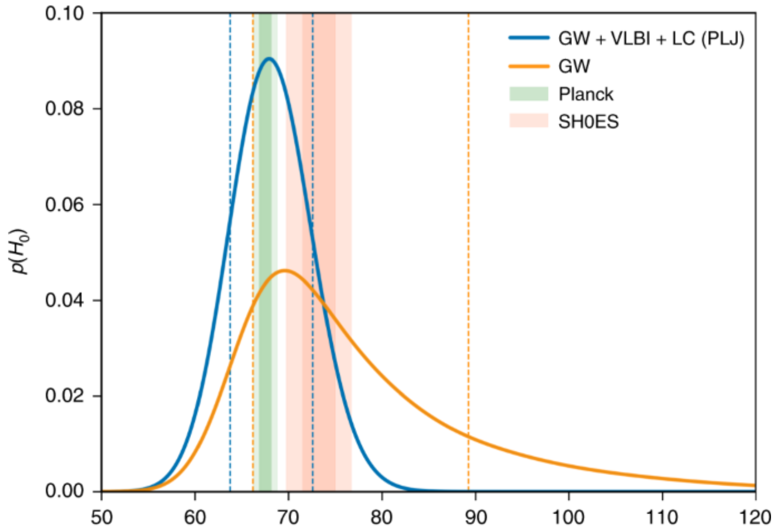
Importance of Gravitational Wave EM Counterparts

- **Combining the two** teaches us much more about the **astrophysical objects**
- Enables measuring the **redshift**, and constrains the **speed of gravity waves**
- Also constrains the **Hubble constant** (expansion rate of the Universe; **GW170817**):
  - Using the **redshift + GW** data alone: $H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ (Abbott et al. 2017)
  - Adding **short GRB** jet modeling (afterglow LC + VLBI) constrains our viewing angle from the jet (angular momentum) axis giving: $H_0 = 70.3^{+5.3}_{-5.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ (Hotokezaka et al. 2019)

$$\begin{pmatrix} h_+ \\ h_\times \end{pmatrix} \propto \frac{[\mathcal{M}(1+z)]^{5/3} f^{2/3}}{d_L} \begin{pmatrix} 1+\cos^2\theta_{\rm obs} \\ 2\cos\theta_{\rm obs} \end{pmatrix}$$

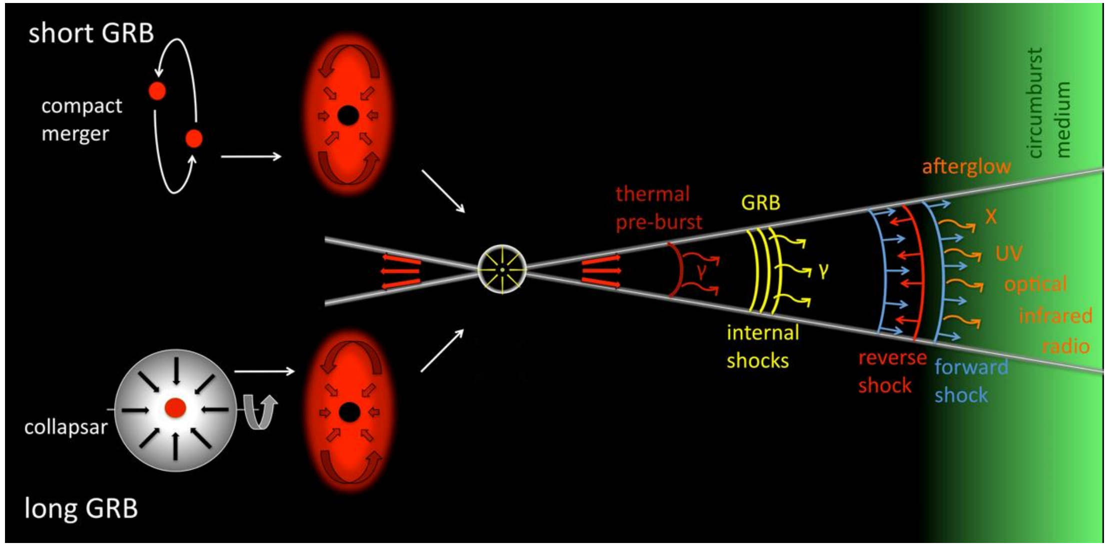
$$\mathcal{M} = \left(\frac{M_1^3 M_2^3}{M_1+M_2}\right)^{1/5}$$ (chirp mass)





(Hotokezaka et al. 2019)

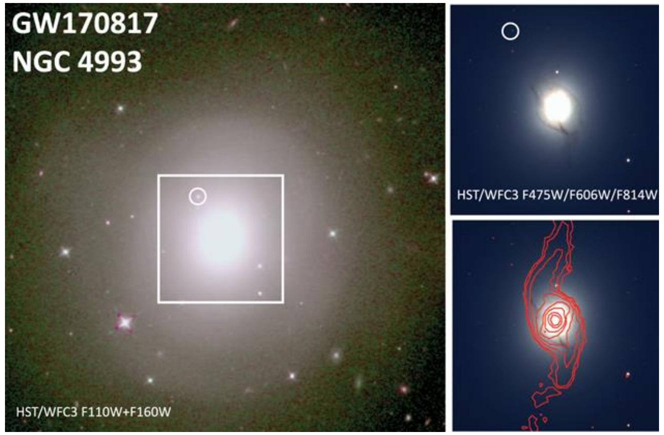
GRB Theoretical Framework:

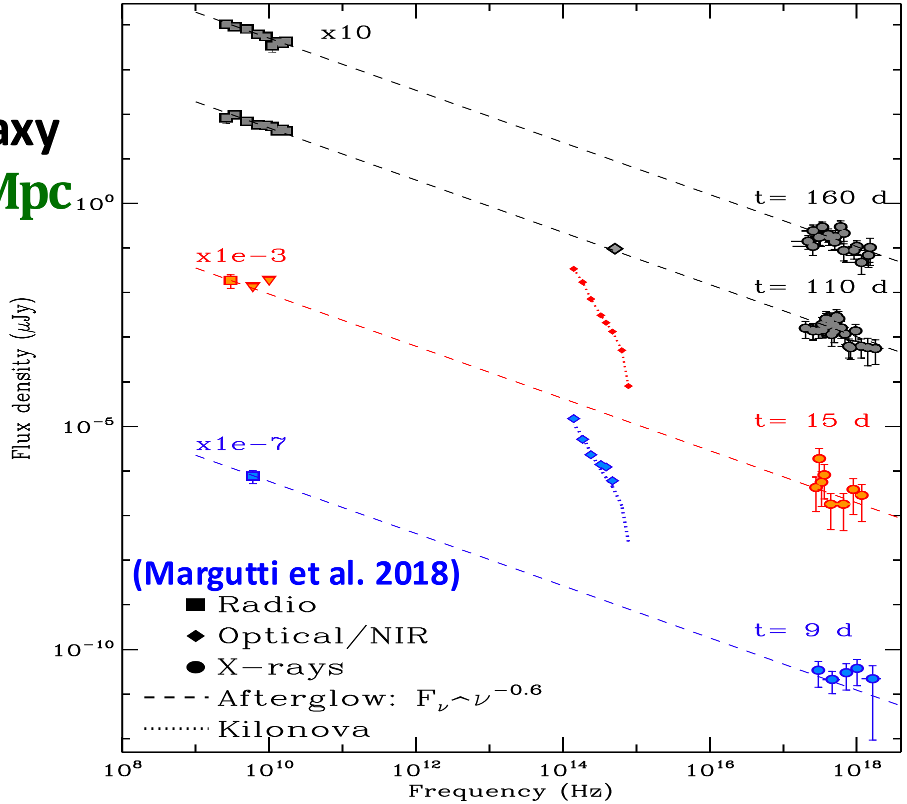


- **Progenitors**:
  - **Long**: massive stars
  - **Short**: binary mergers (NS-NS, BH-NS?)
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: **dissipation – internal shocks or magnetic reconnection?** Emission mechanism?
- **Deceleration**: the outflow decelerates (by a reverse shock for low magnetizations $\sigma = \frac{B^2}{4\pi h \rho c^2} \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long-lived forward shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

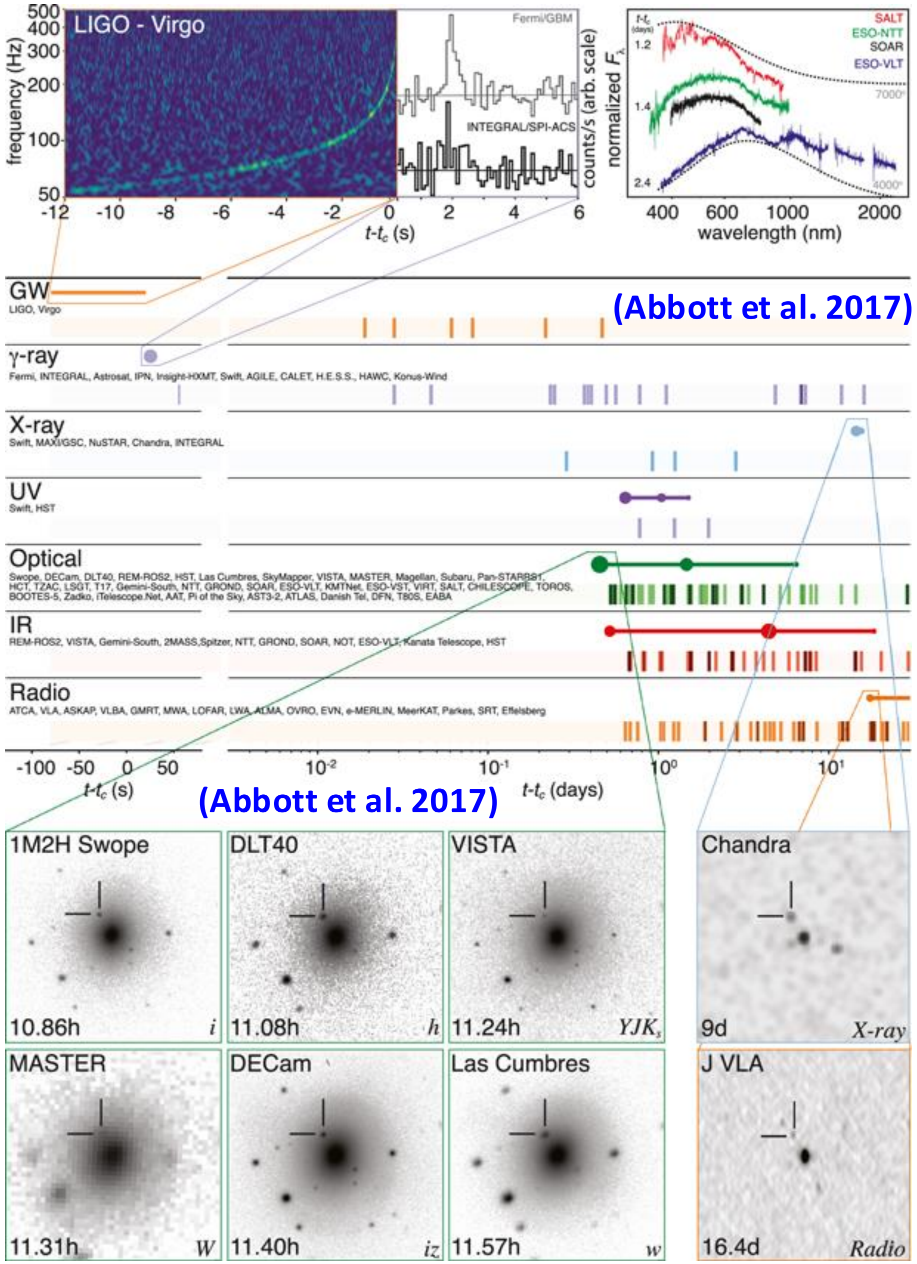
GW170817 / GRB170817A: NS-NS merger

- First NS-NS merger detected in gravitational waves (GW)
- First electromagnetic counterpart to a GW event
  - ❖ The short GRB 170817A (very under-luminous, 1.74 s γ-GW delay)
  - ❖ Optical (IR to UV) kilonova emission over a few weeks
  - ❖ X-ray (> 9 d; still barely detected) to radio (>16 d) afterglow
- First direct sGRB - NS-NS merger association (Eichler+ 1989)
- First clear-cut kilonova
- $D_{GW} = 43^{+2.9}_{-6.9}$ Mpc; host galaxy is elliptical: $D = 41.0 \pm 3.1$ Mpc ($z = 0.009783$) 2 kpc from host center in projection





(Margutti et al. 2018)

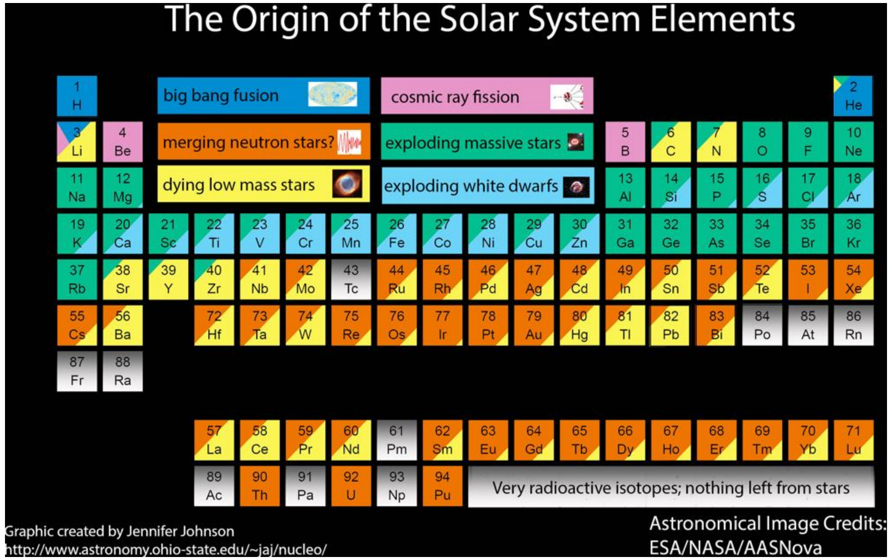


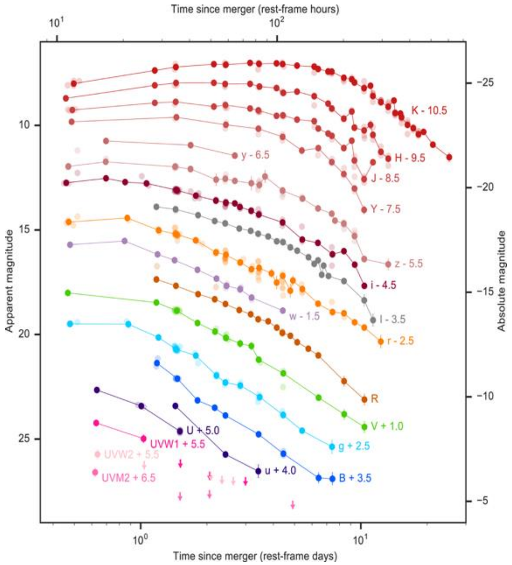
(Abbott et al. 2017)

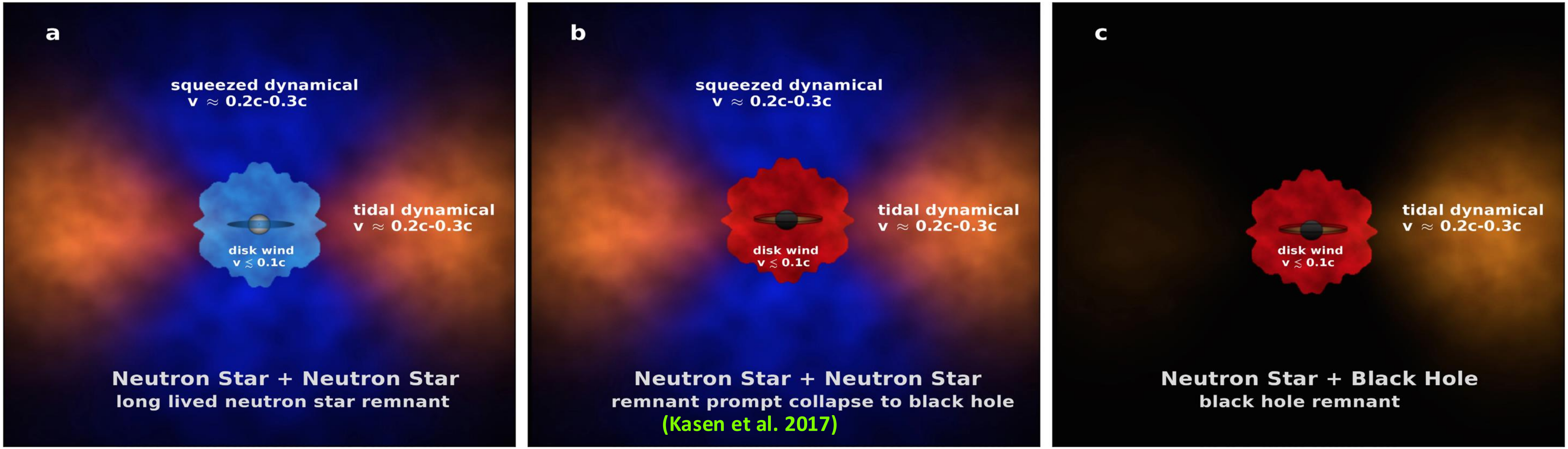
(Abbott et al. 2017)

GW170817 / GRB170817A: Kilonova

- **Observations require two components**:
  - First blue/fast, lanthanide-poor
    $M_{\rm ej} \approx (1\% - 2\%) M_\odot$, $v_{\rm ej} \approx (0.2 - 0.3)c$
  - Second red/slow, lanthanide-rich
    $M_{\rm ej} \approx (3\% - 5\%) M_\odot$, $v_{\rm ej} \approx (0.05 - 0.2)c$
- **Synthesized large amounts of heavy elements** (may dominate the cosmic r-process nucleosynthesis, heavy metals e.g. gold, platinum)



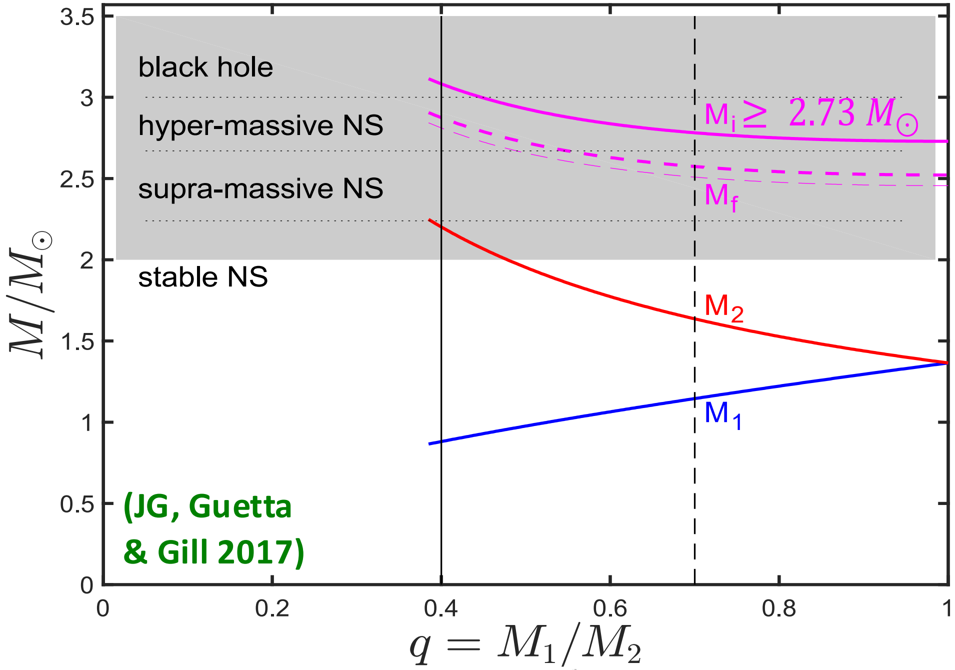




(Kasen et al. 2017)

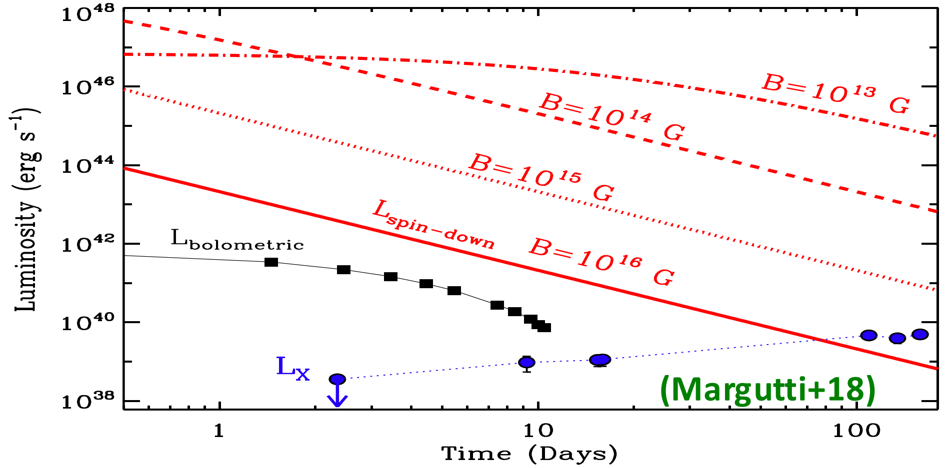
GW170817 / GRB170817A: Remnant Type

- $M_{1,2}$ = pre-merger NS $M_{gravitational}$
- post-merger total mass: $M_i = M_1 + M_2$
- Final mass $M_f \approx 0.93 M_i$ due to:
  - ❖ GW & neutrino energy losses
  - ❖ Mass ejection during the merger
- A stable NS or SMNS $\Rightarrow P_0 \approx 1$ ms $\Rightarrow E_{rot} \gtrsim 10^{52.5}$ erg, $\tau_{sd} \approx 20 B_{13}^{-2}$ days $\Rightarrow$ would contradict afterglow observations (also what produces the GRB/afterglow?)
- The argument can be reversed to constrain NS EoS & $M_{max} \lesssim 2.17 M_\odot$ (Margalit & Metzger 2017; Rezzolla et al. 2018)



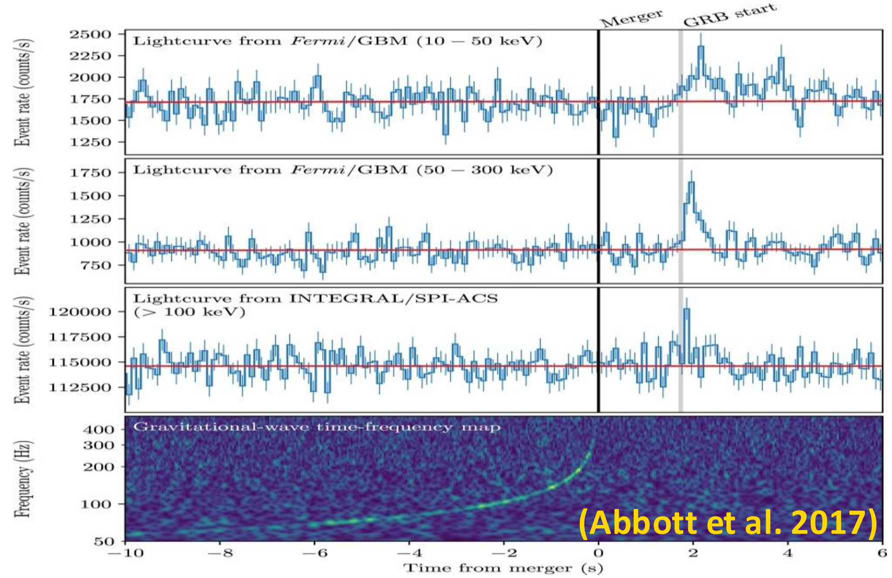
$$\text{Chirp mass: } \mathcal{M} = \left(\frac{M_1^3 M_2^3}{M_1 + M_2}\right)^{1/5} = 1.188^{+0.004}_{-0.002} M_\odot$$

(Abbott+ 2017)

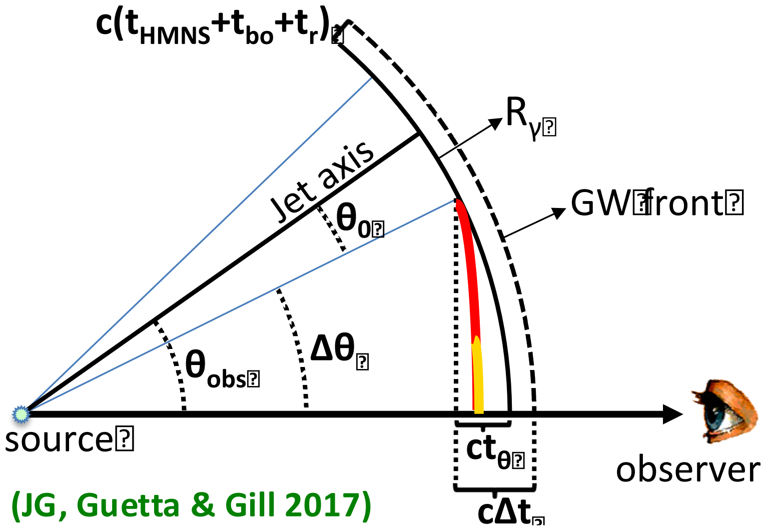


GW170817 / GRB170817A: The Time Delay

- The $\Delta t \approx 1.74$ s delay between the GW chirp signal & the sGRB onset $\Rightarrow \left|\frac{v_{GW}}{c} - 1\right| \lesssim 4 \cdot 10^{-16}$
- A HMNS may explain $\Delta t \approx 1.74$ s by $t_{\rm HMNS} \lesssim 0.5$ s & $t_{\rm bo} \sim 1$ s
  (Moharana & Piran 2017 find $t_{\rm bo} \sim 0.5$ s for SGRBs, from a plateau in their duration distribution, $dN_{\rm GRB}/dT_{\rm GRB}$)
- Direct BH formation ⇒ a shorter jet breakout time $t_{\rm bo}$ ⇒ the jet is less likely to be chocked
- If the prompt **γ**-rays are beamed away from us (large $\Gamma\Delta\theta$), the implied on-axis $L_{\gamma,\rm iso}$ & $E_{\rm peak}$ are very high – inconsistent with their observed correlation (JG+ 2017) & implying large compactness (Matsumoto+ 2019) ⇒ they must arise from $\Gamma\Delta\theta < 1$ ⇒ a jet with angular structure

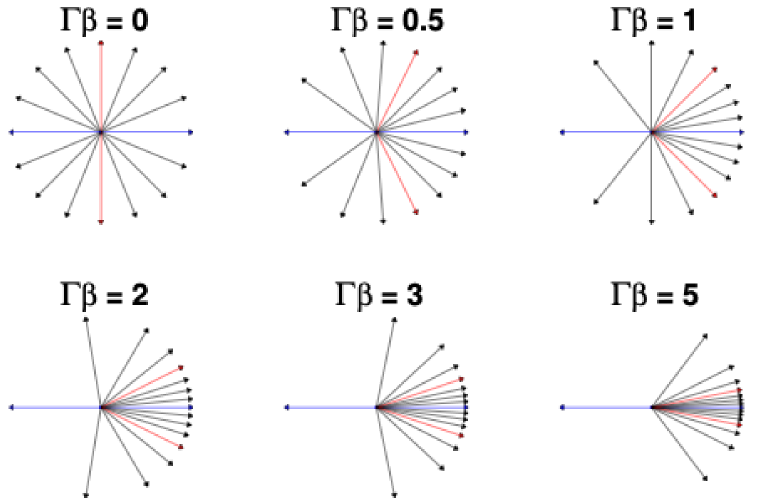


(Abbott et al. 2017)

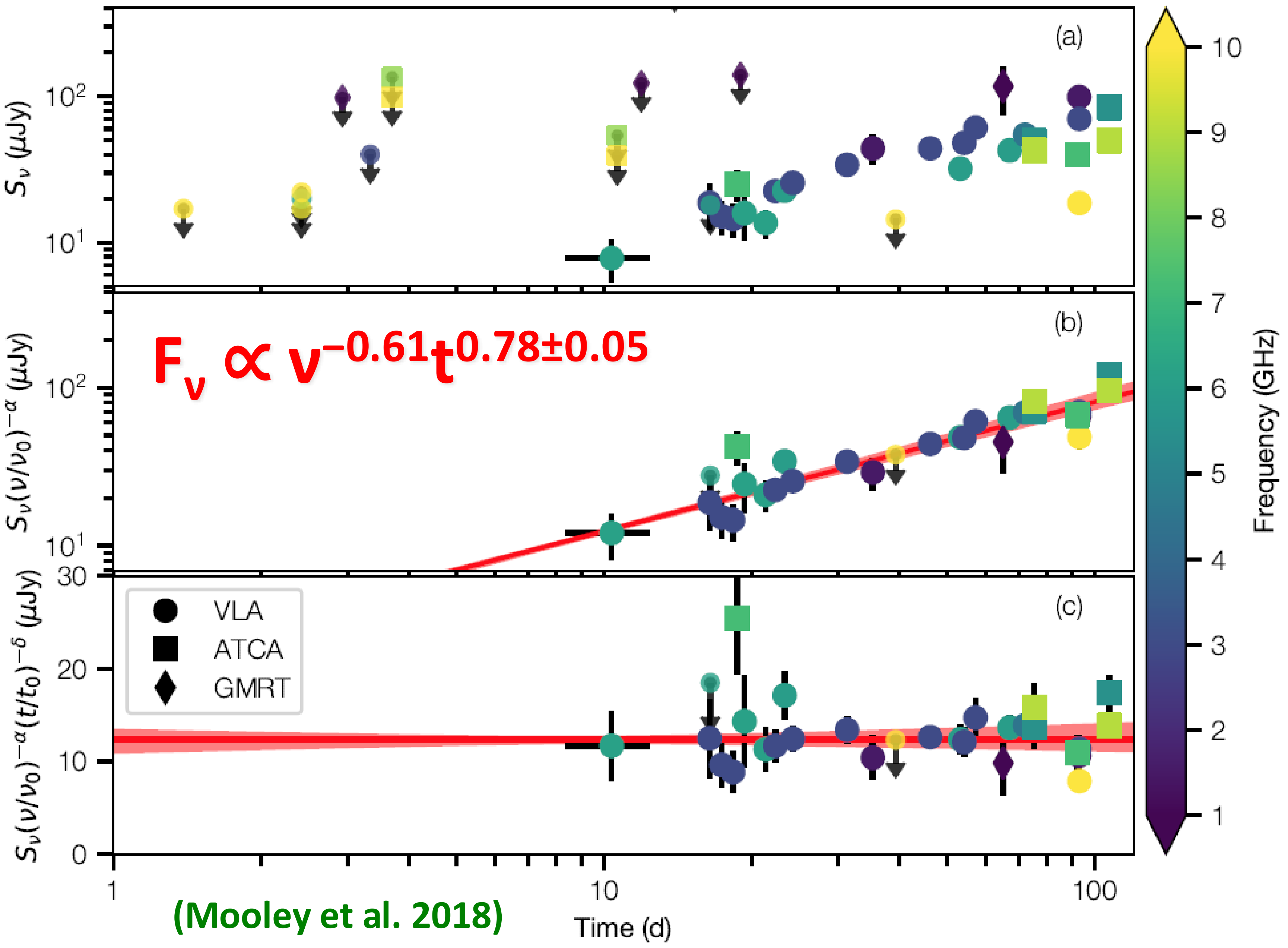


(JG, Guetta & Gill 2017)

Relativistic beming (abberation of light)

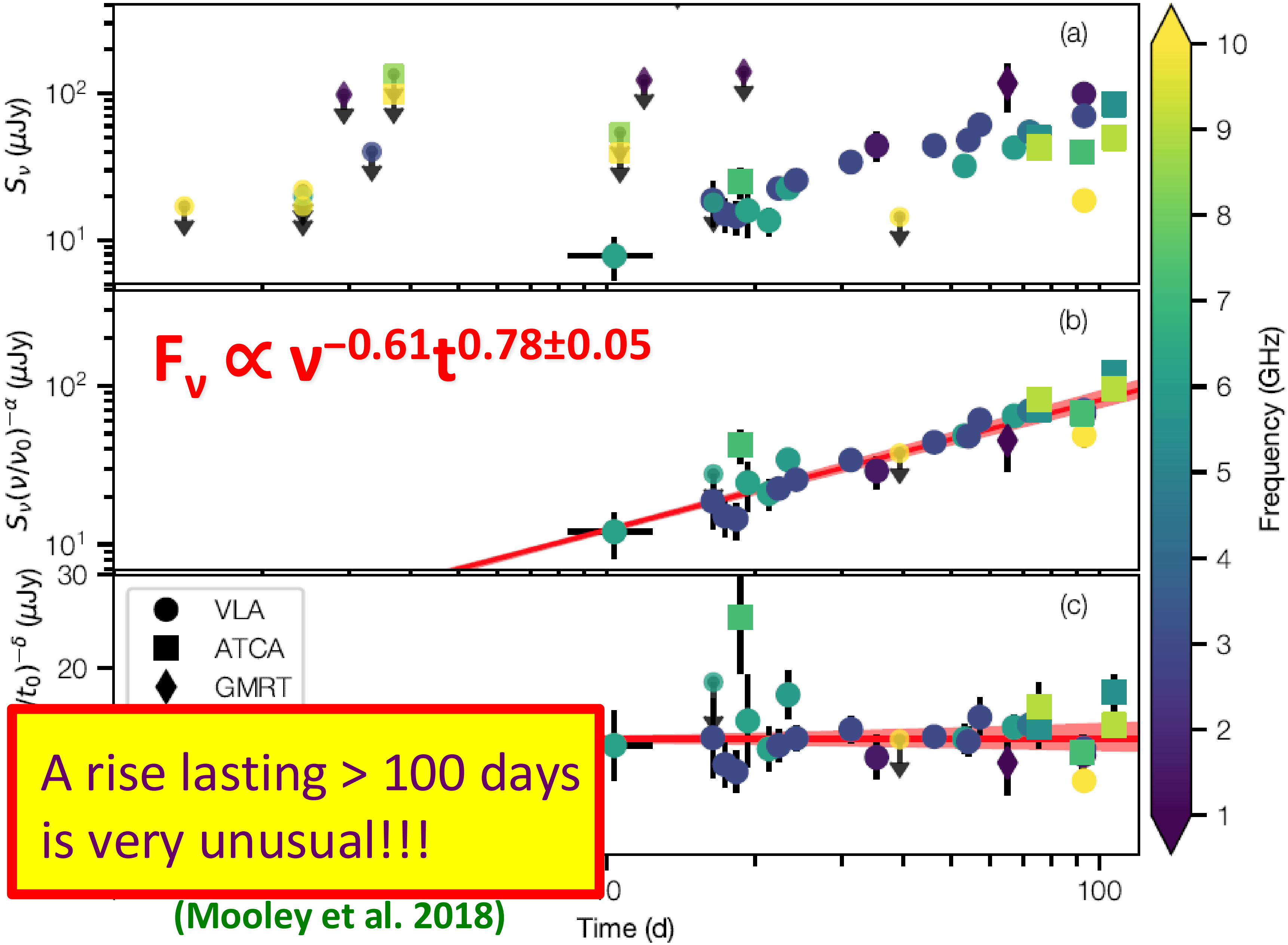


GRB170817A: Afterglow Observations



(Mooley et al. 2018)

GRB170817A: Afterglow Observations



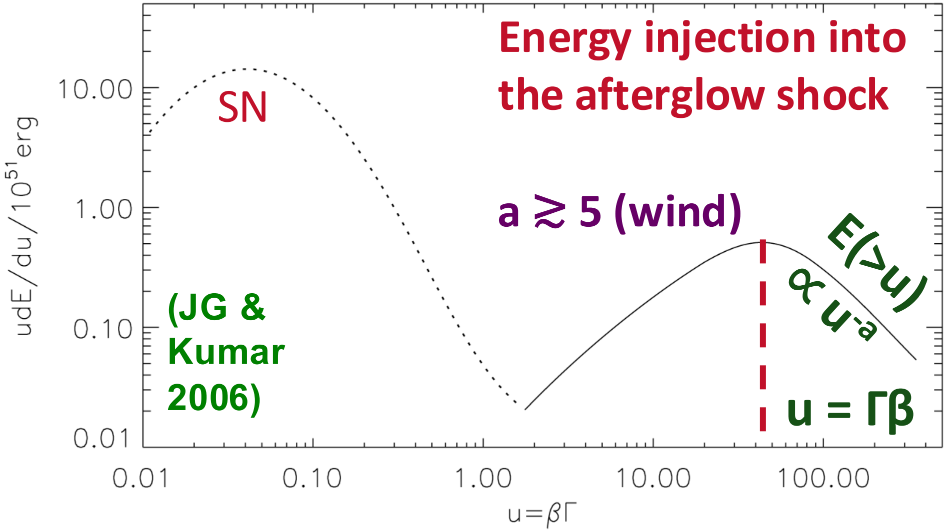
$F_\nu \propto \nu^{-0.61} t^{0.78\pm0.05}$

A rise lasting > 100 days is very unusual!!!

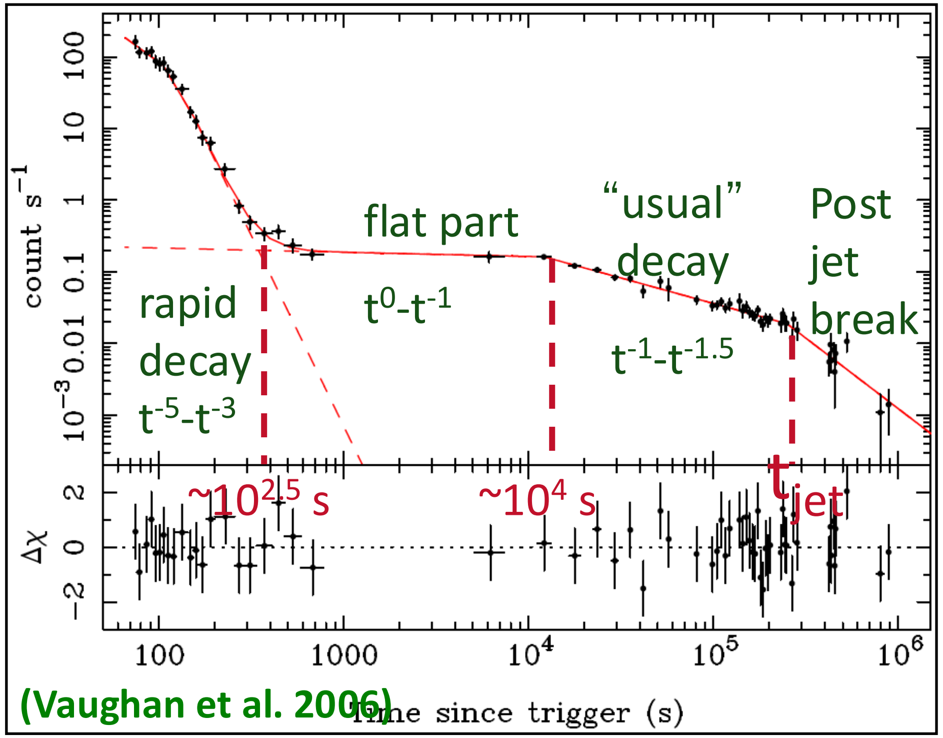
(Mooley et al. 2018)

Analogy to rising F_ν : X-ray Plateaus

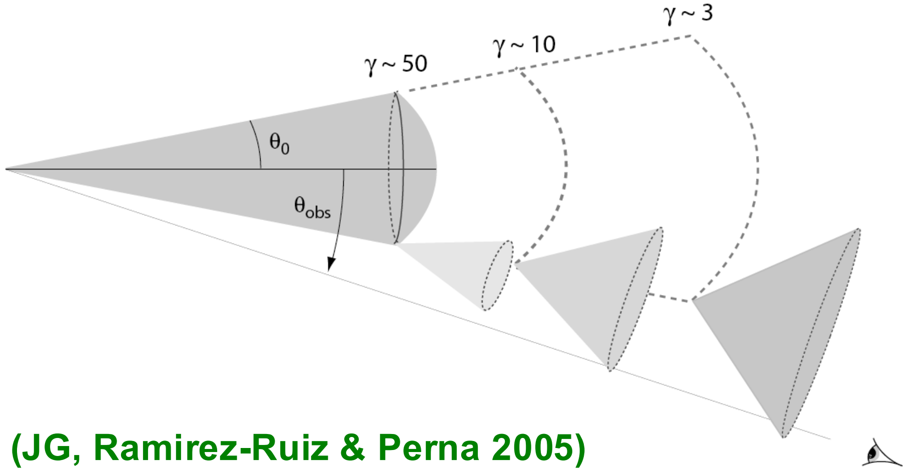
- Possible solutions:
- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
- Energy injection into external shock:
  1. long-lived relativistic wind
  2. slower ejecta catching up
  (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)



- Viewing angle effects **angular**



(Vaughan et al. 2006)



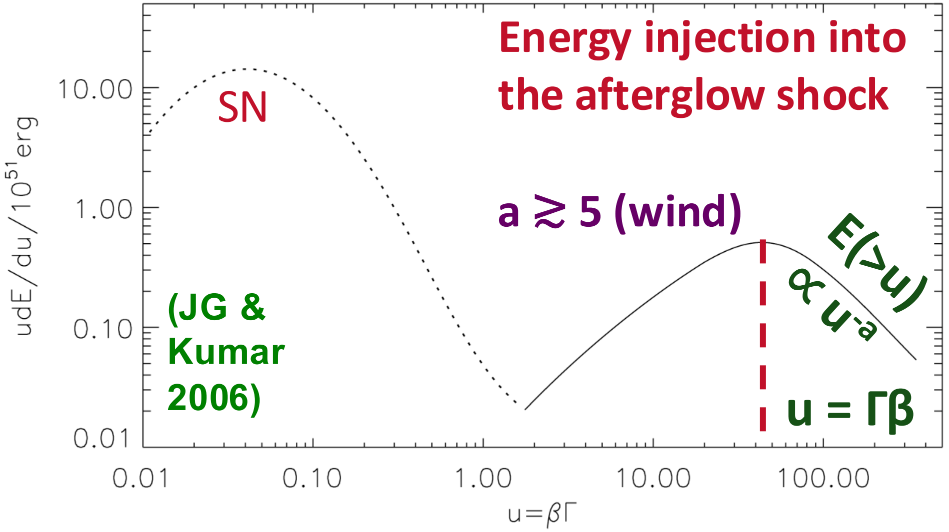
(JG, Ramirez-Ruiz & Perna 2005)

Analogy to rising F_ν : X-ray Plateaus

- Possible solutions:
- Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
- Energy injection into external shock:

1. long-lived relativistic wind
2. slower ejecta catching up **radial**

(Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)



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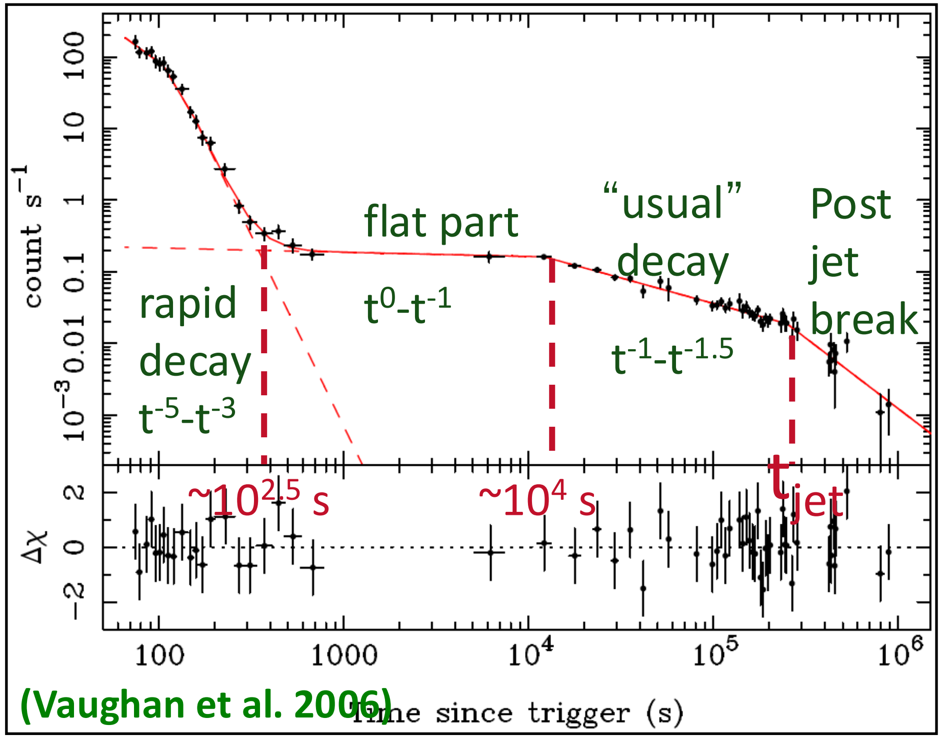

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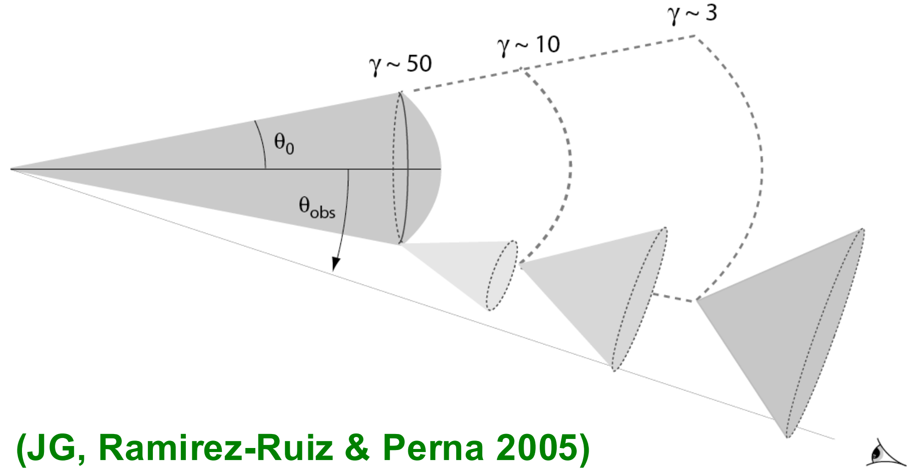
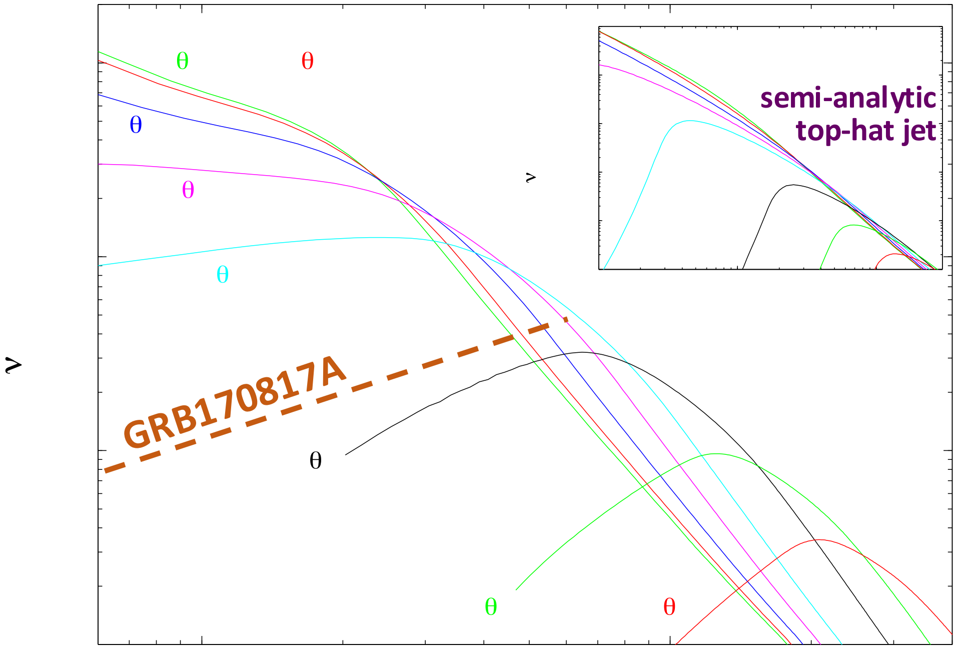


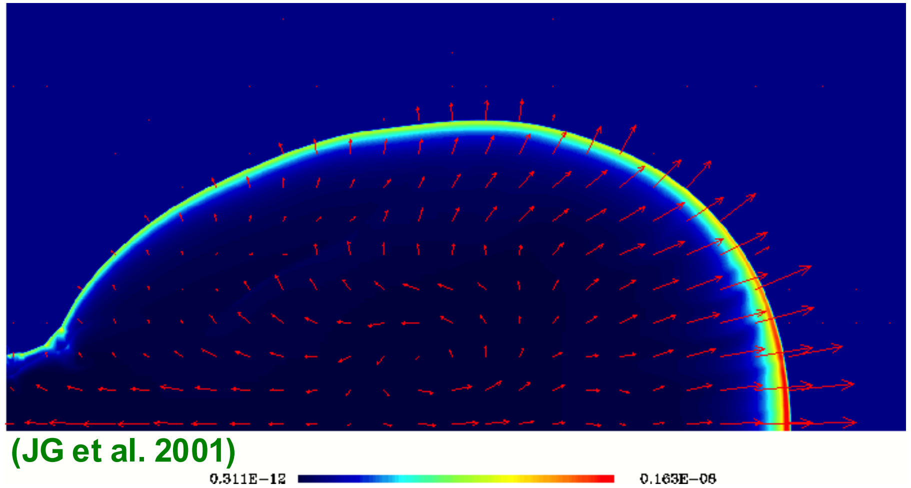
(JG, Ramirez-Ruiz & Perna 2005)

Analogy to rising F_ν : Off-Axis Viewing

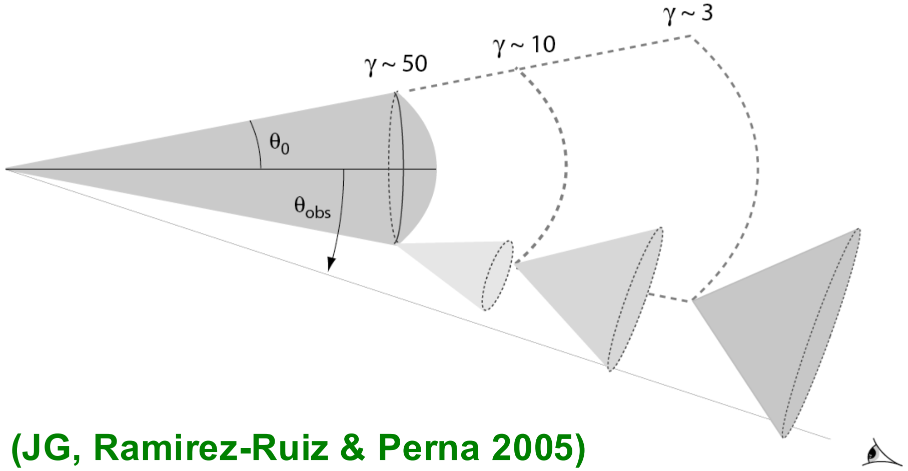
- The emission is initially strongly beamed away from our L.o.S
- F_ν rises as beaming cone widens
- When beaming cone reaches LoS F_ν peaks & approaches on-axis F_ν
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet's sides with non-radial velocities



(JG et al. 2002)



(JG et al. 2001)

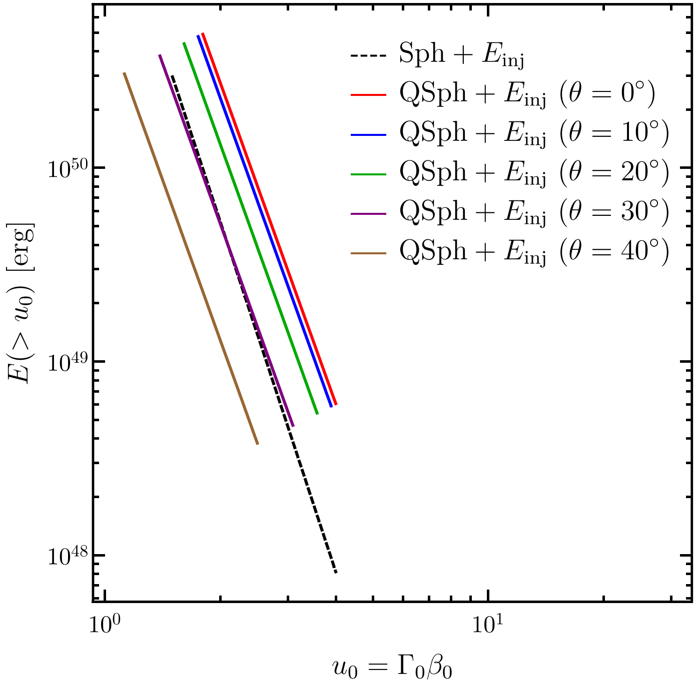


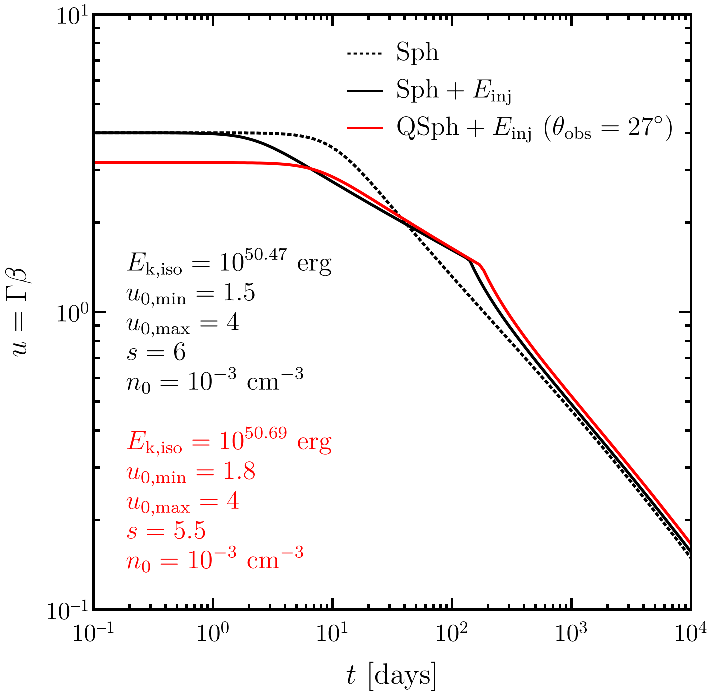
(JG, Ramirez-Ruiz & Perna 2005)

Outflow Structure: Breaking the Degeneracy (Gill & JG 18)

- The lightcurves leave a lot of degeneracy between models
- The degeneracy may be lifted by calculation the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018)
- We considered 4 different models including both main types
  - Sph+E_{inj}: Spherical with energy injection $E(>u=\Gamma\beta)\propto u^{-6}$, $1.5<u<4$
  - QSph+E_{inj}: Quasi-Spherical + energy injection $E(>u)\propto u^{-s}$, $u_{min,0}=1.8$ $u_{max,0}=4$, $s = 5.5$, $\zeta = 0.1$

$$\frac{\epsilon(\theta)}{\epsilon_0}=\frac{u_{0,\min}(\theta)}{u_{\min,0}}=\frac{u_{0,\max}(\theta)}{u_{\max,0}}=\frac{\zeta+\cos^2\theta}{\zeta+1}$$





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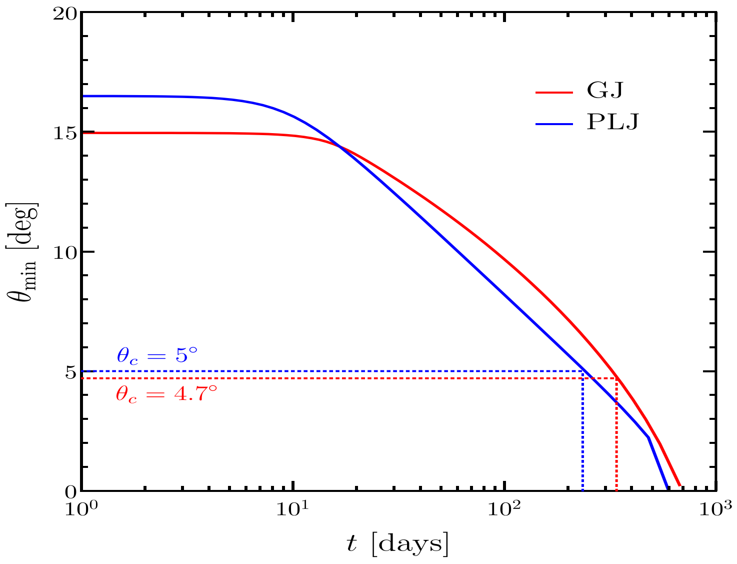
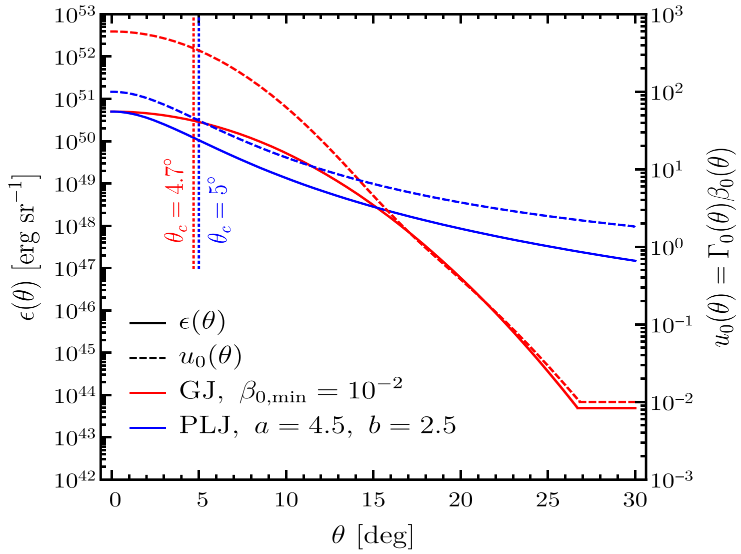
- The degeneracy may be lifted by calculation the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018)
- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, Γ_0-1) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c\Theta^{-a}$, $\Gamma_0-1 = (\Gamma_c-1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$, $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$
- As there is a lot of freedom we fixed: $p = 2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{obs} = 27°$

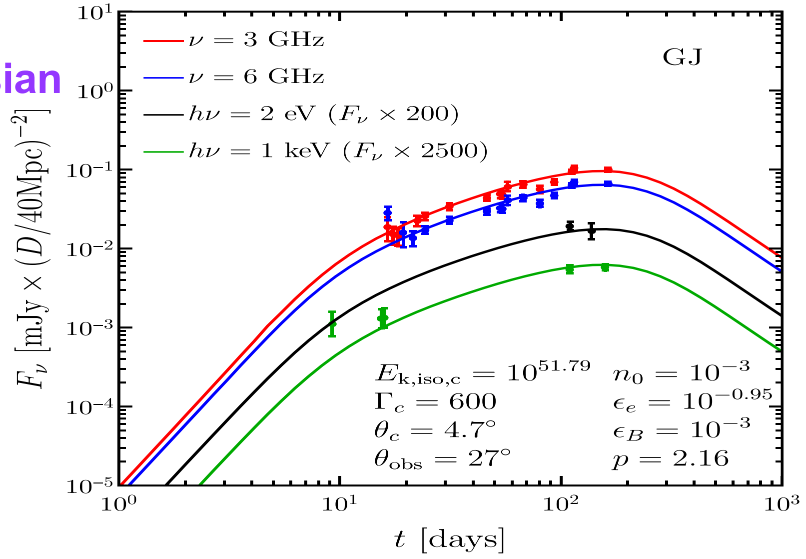


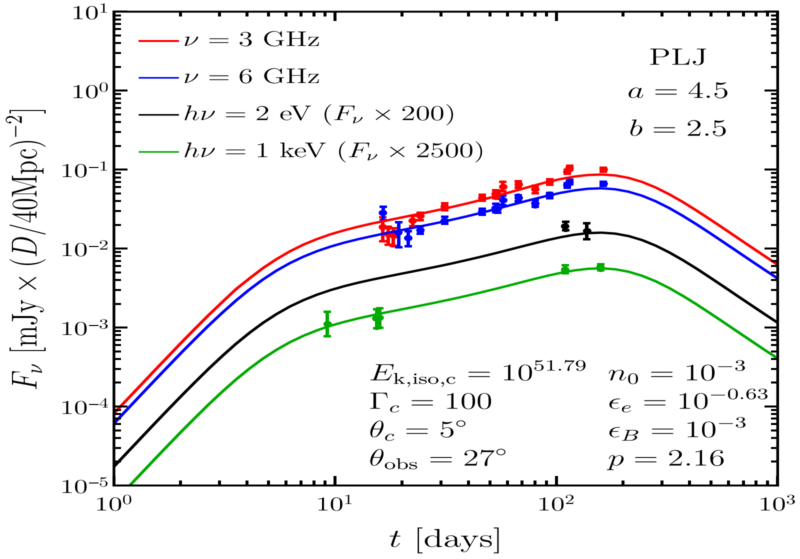


Outflow Structure: Breaking the Degeneracy (Gill & JG 18)

- Tentative fit to GRB170817A afterglow data (radio to X-ray)

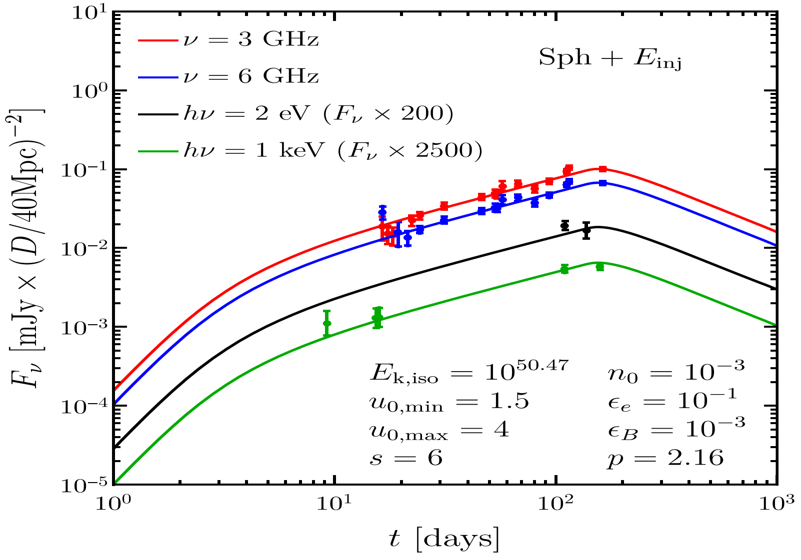
Gaussian Jet

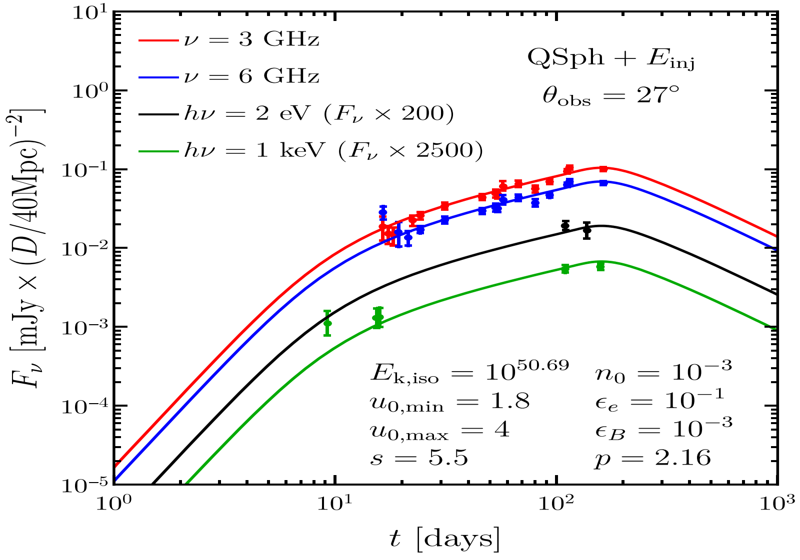




Power Law Jet

Spherical + Energy Injection



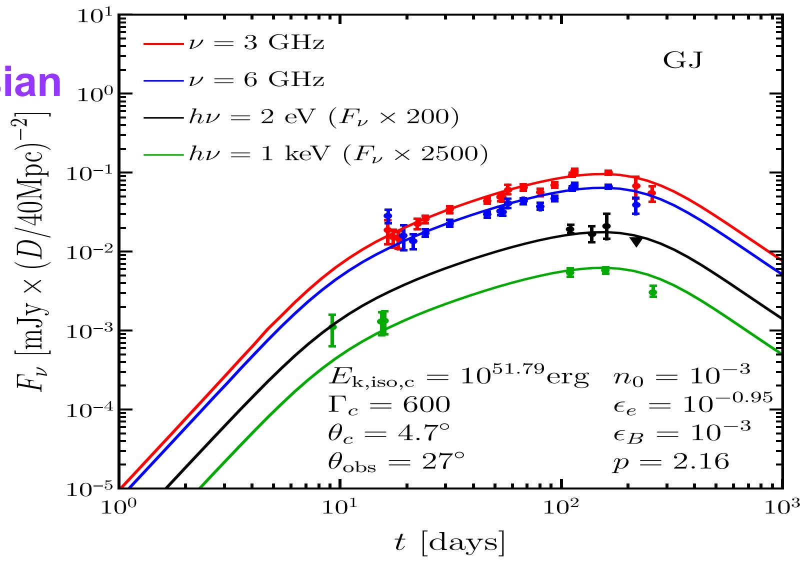


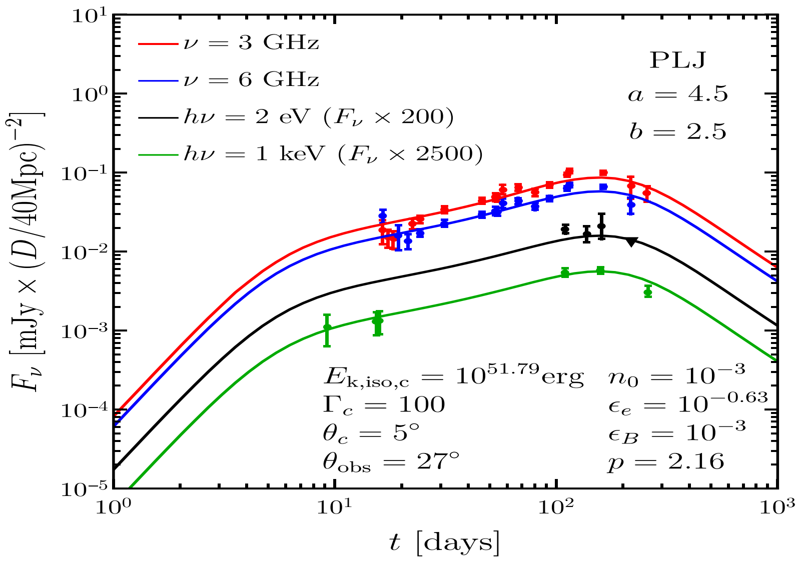
Quasi Spherical + Energy Injection

Outflow Structure: Breaking the Degeneracy (Gill & JG 18)

- New data that came out established a peak at $t_{\text{peak}} \sim 150$ days

Gaussian Jet





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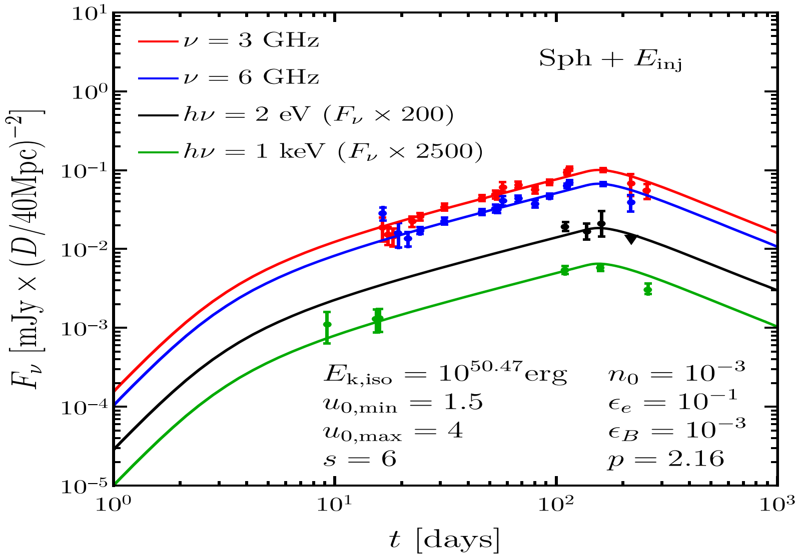
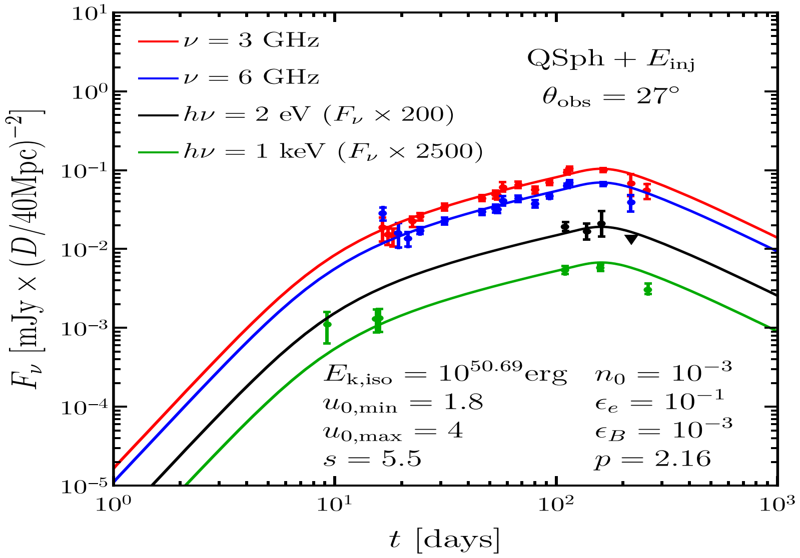


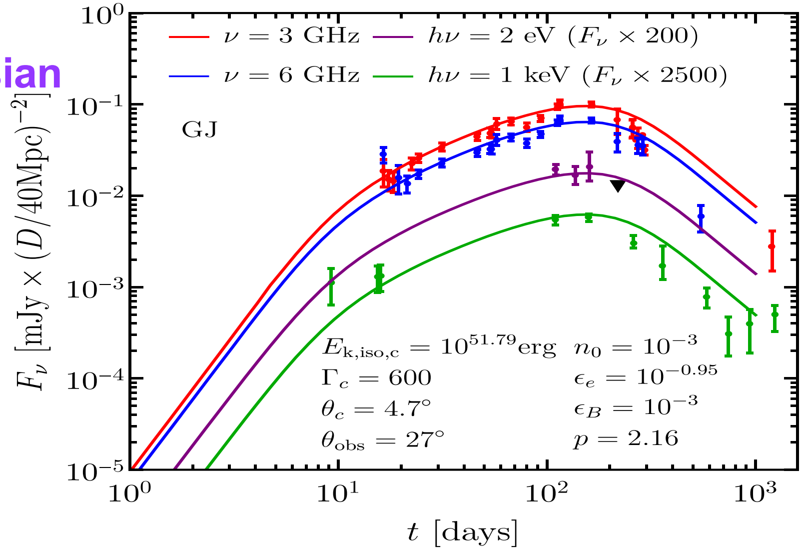


Quasi Spherical + Energy Injection

Outflow Structure: Breaking the Degeneracy (Gill & JG 18)

- The jet models decay faster (closer to post-peak data: $F_\nu \propto t^{-2.2}$)

Gaussian Jet



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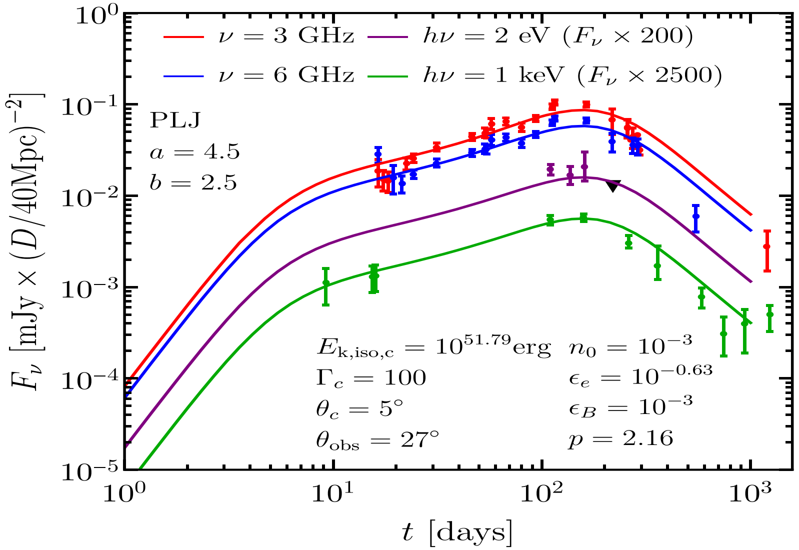
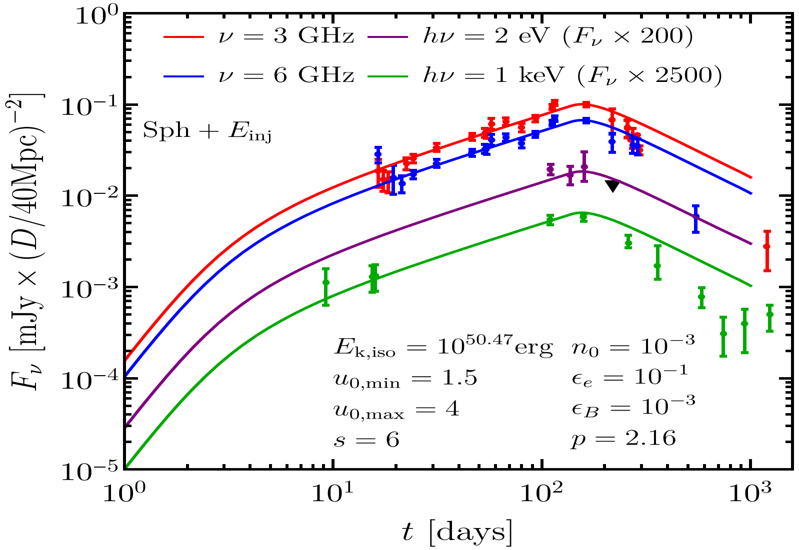


Spherical + Energy Injection



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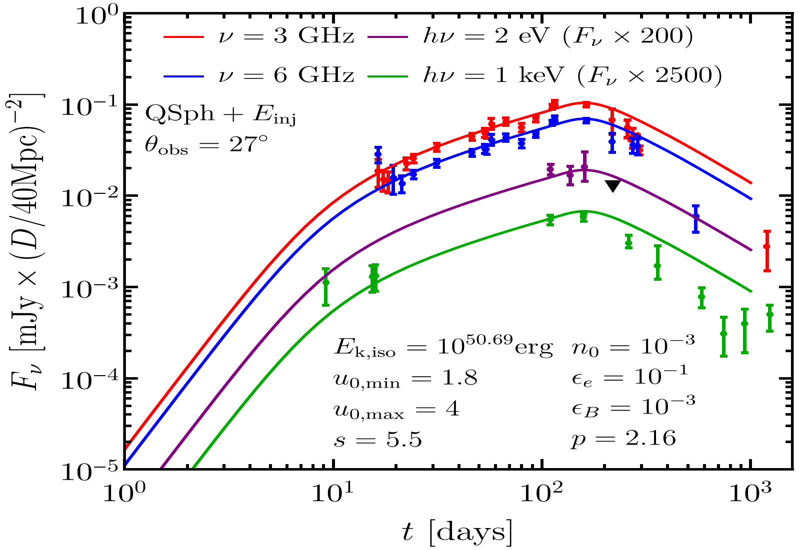
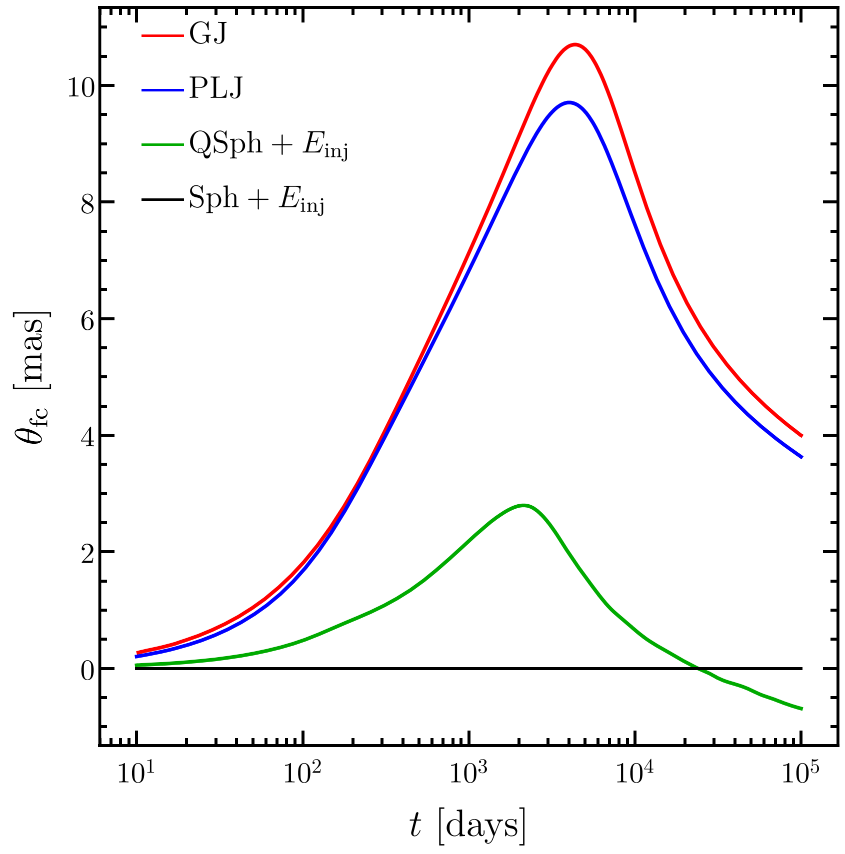
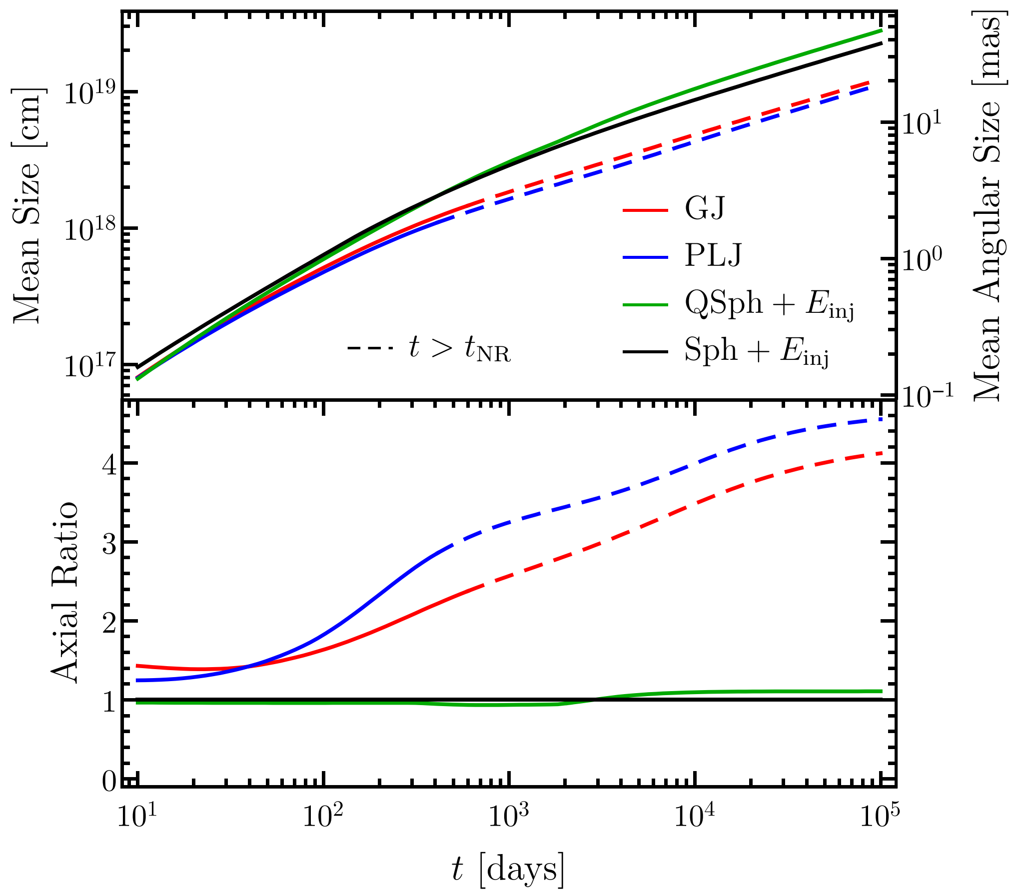


Afterglow Images: Flux Centroid, Size, Shape

- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models





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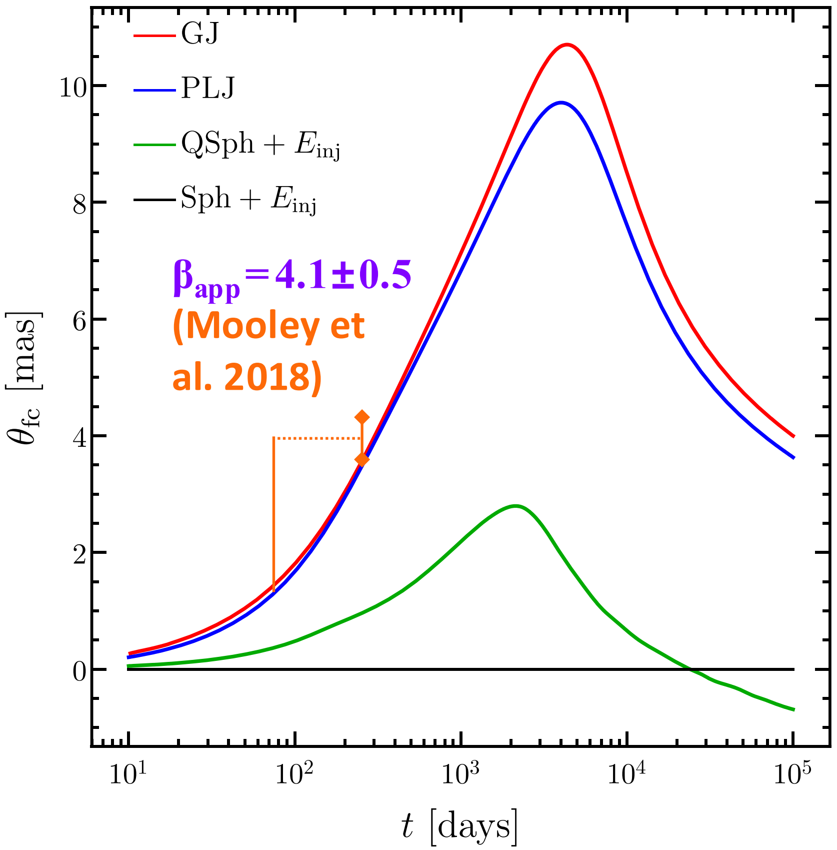

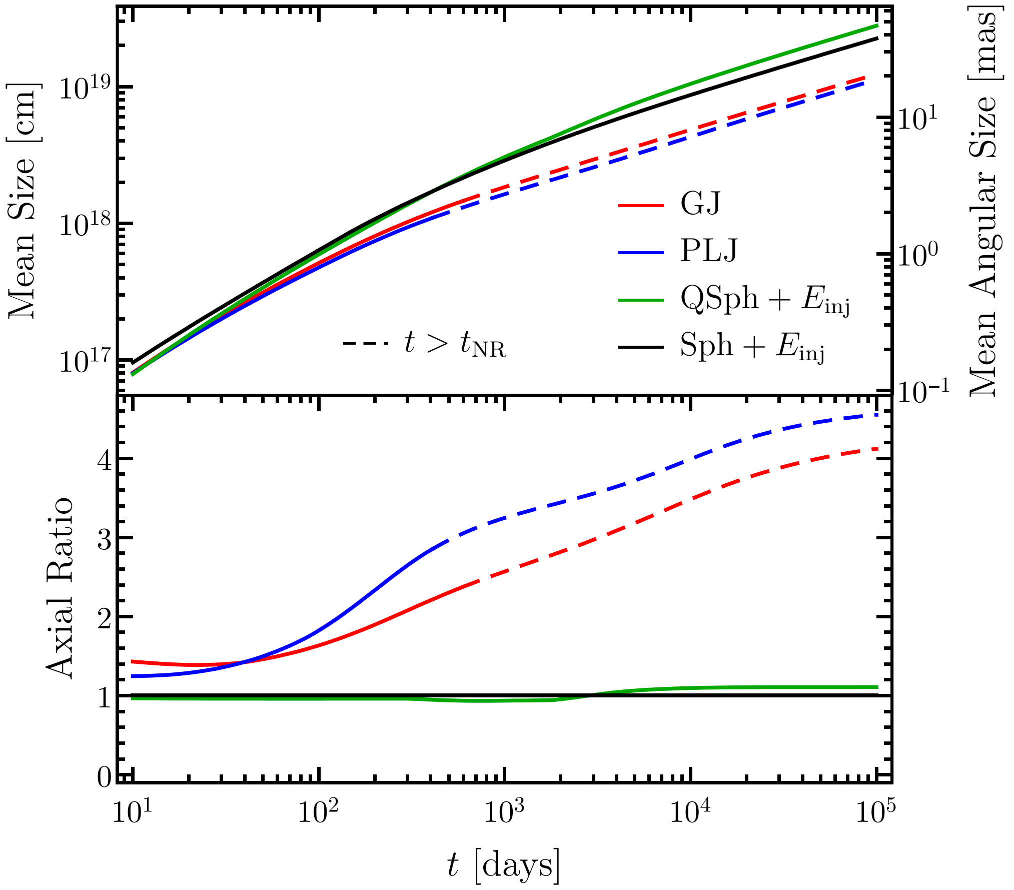

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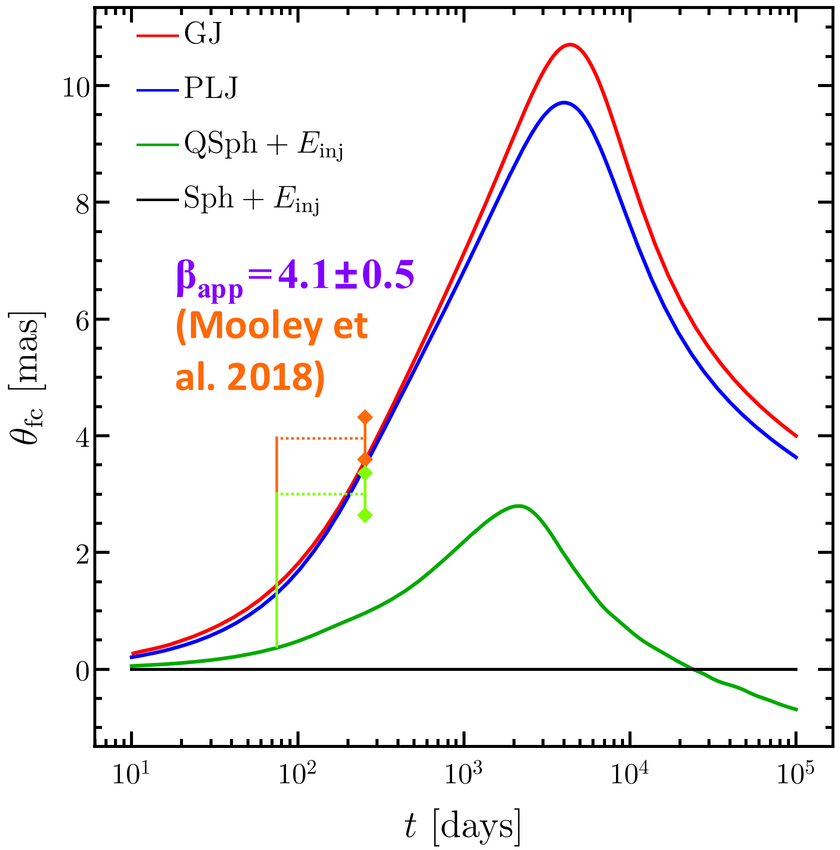
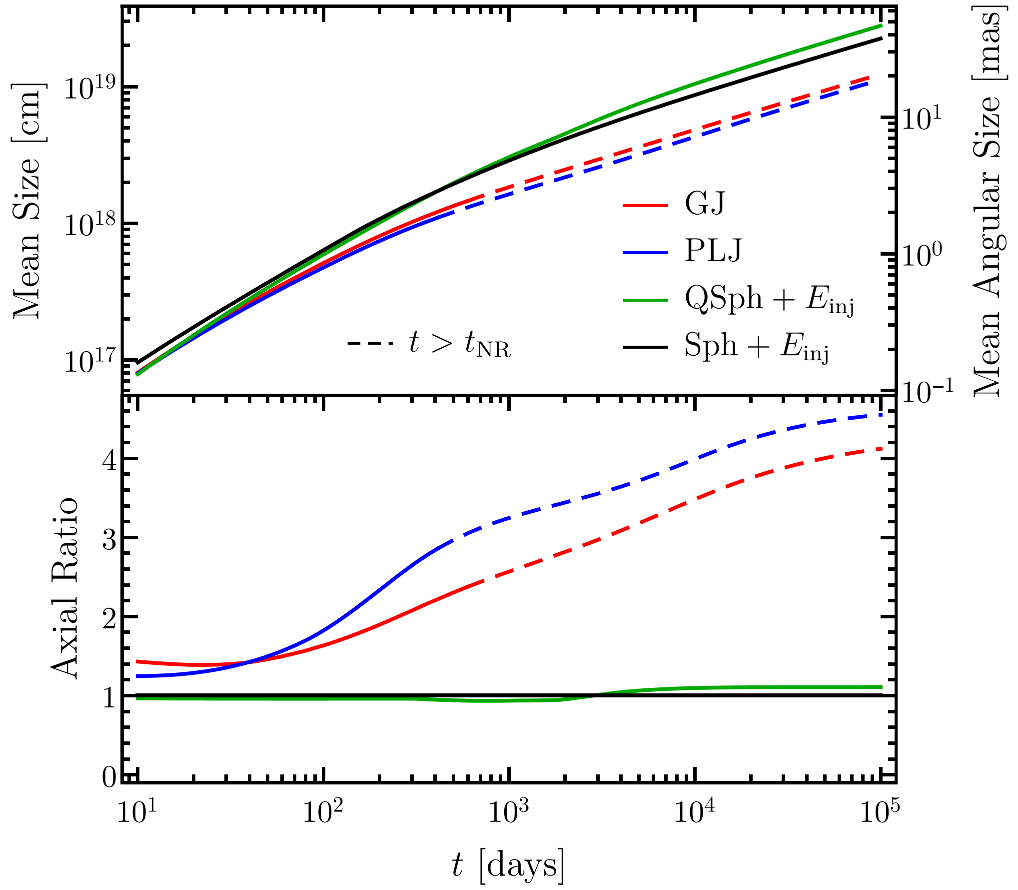
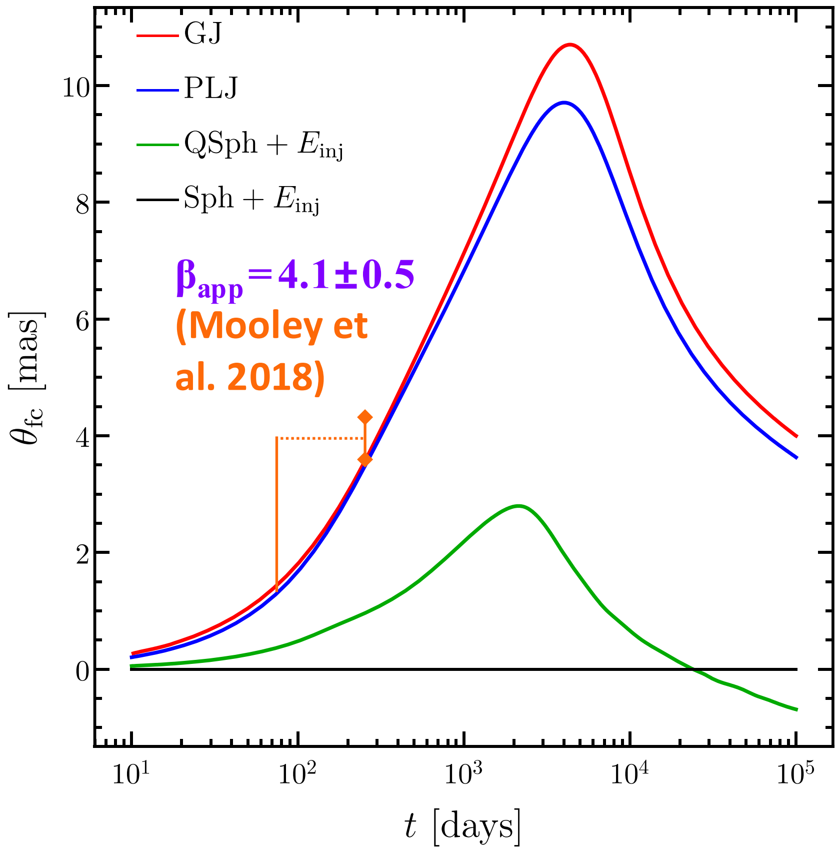
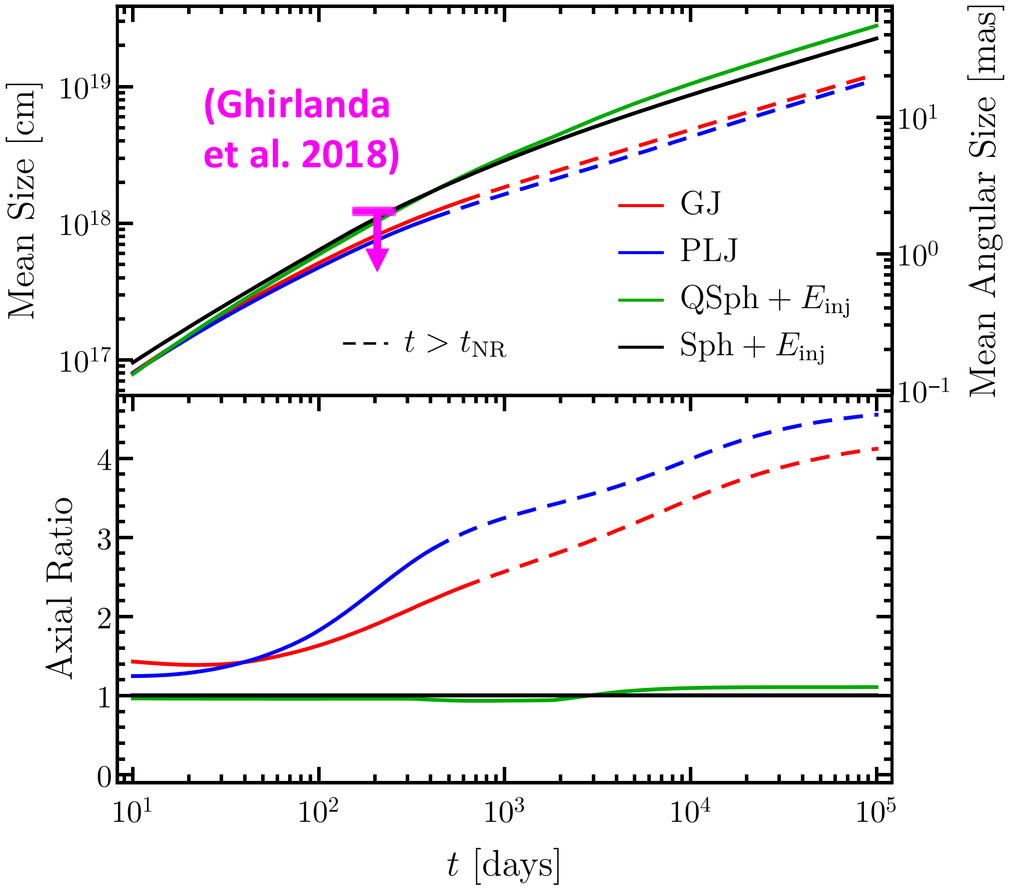




Afterglow Images: Flux Centroid, Size, Shape

- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models





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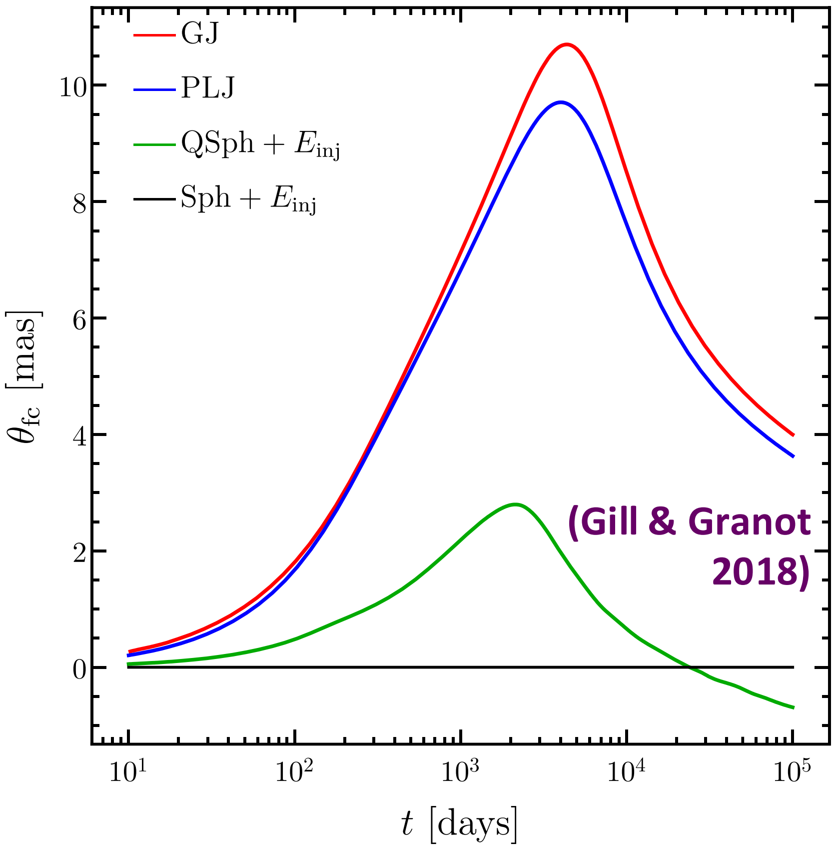
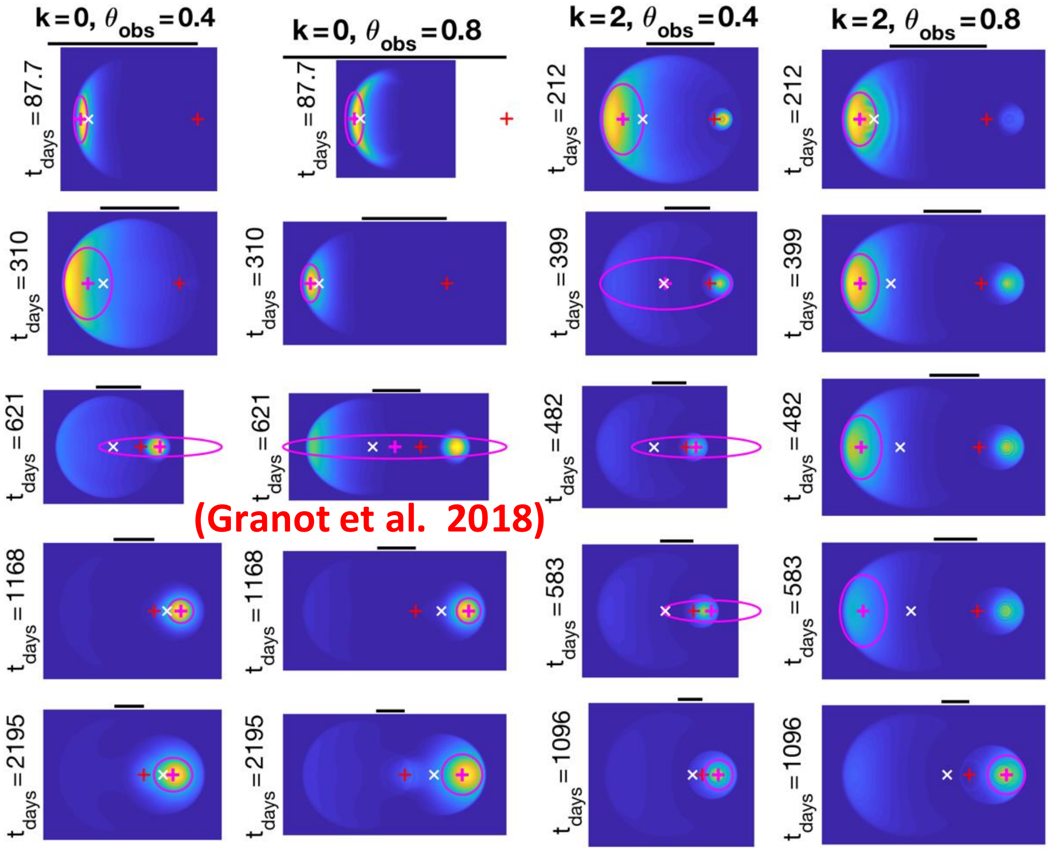
Radio flux centroid motion: semi-analytic



(Gill & JG 2018)

Agree with radio afterglow images from simulations

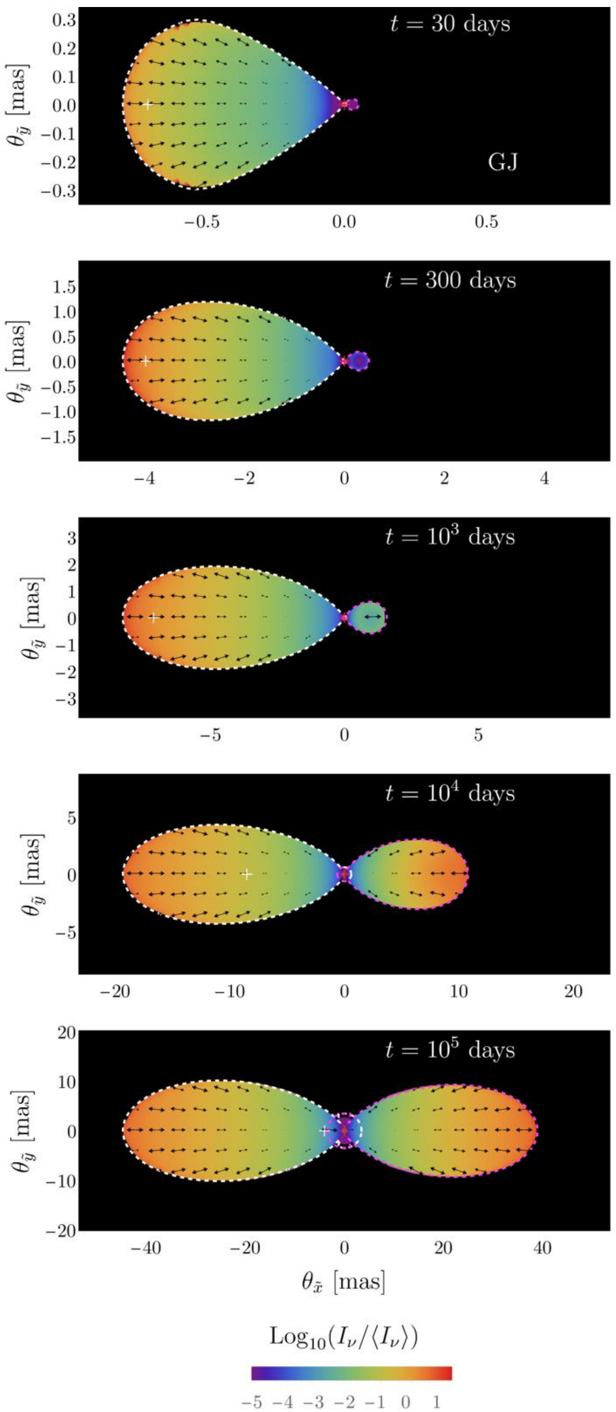


(JG, De Colle & Ramirez-Ruiz 2018)

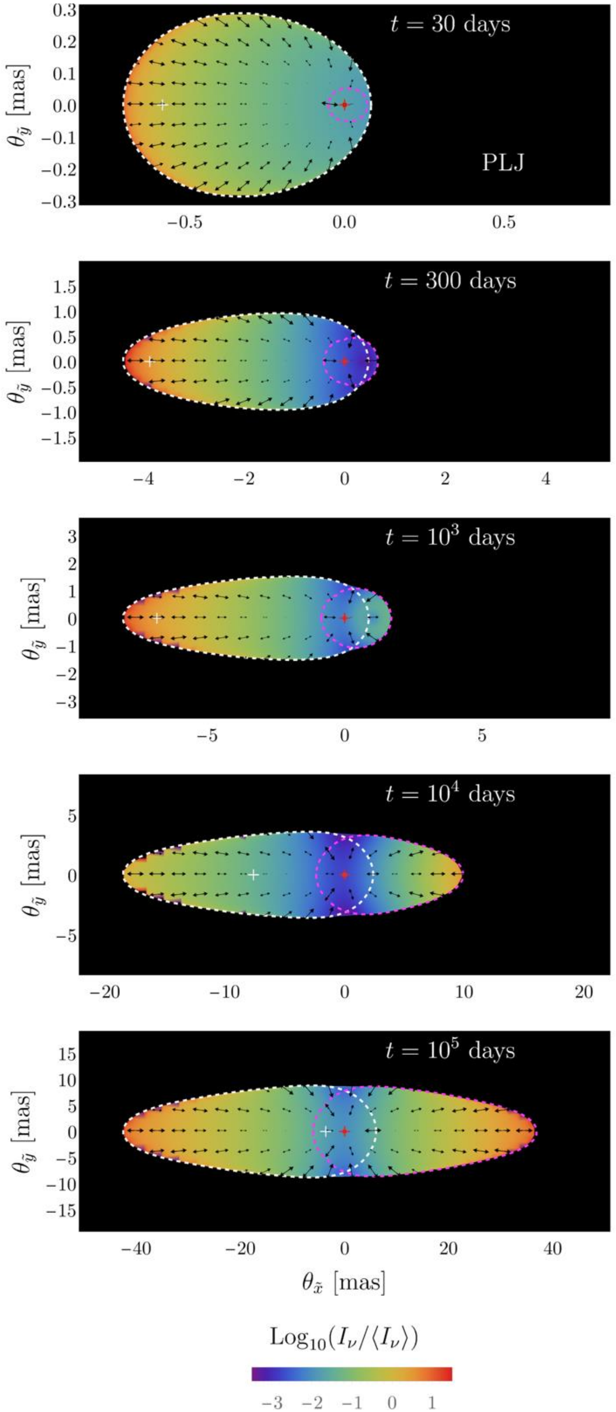
Afterglow Images:

with a polarization map

Gaussian Jet

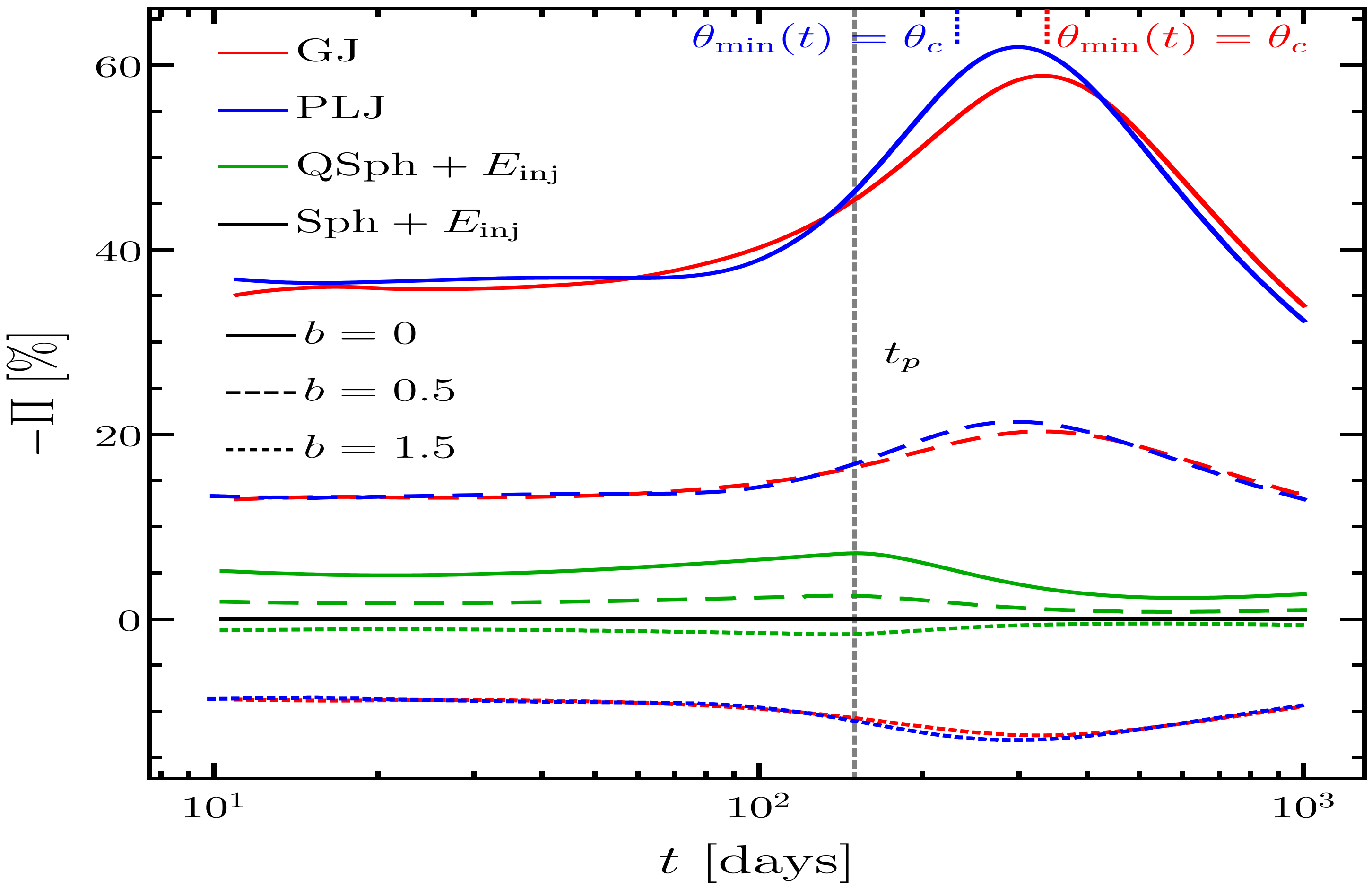


Power-Law Jet



GRB 170817A: polarization UL ⇒ post-shock B-field

- Jet angular structure & $\theta_{\rm obs}$ well constrained ⇒ breaks degeneracies
- Assuming a shock-produce B-field with $b \equiv 2\langle B_\parallel^2\rangle/\langle B_\perp^2\rangle$ (JG & königl 03; Gill & JG 18)



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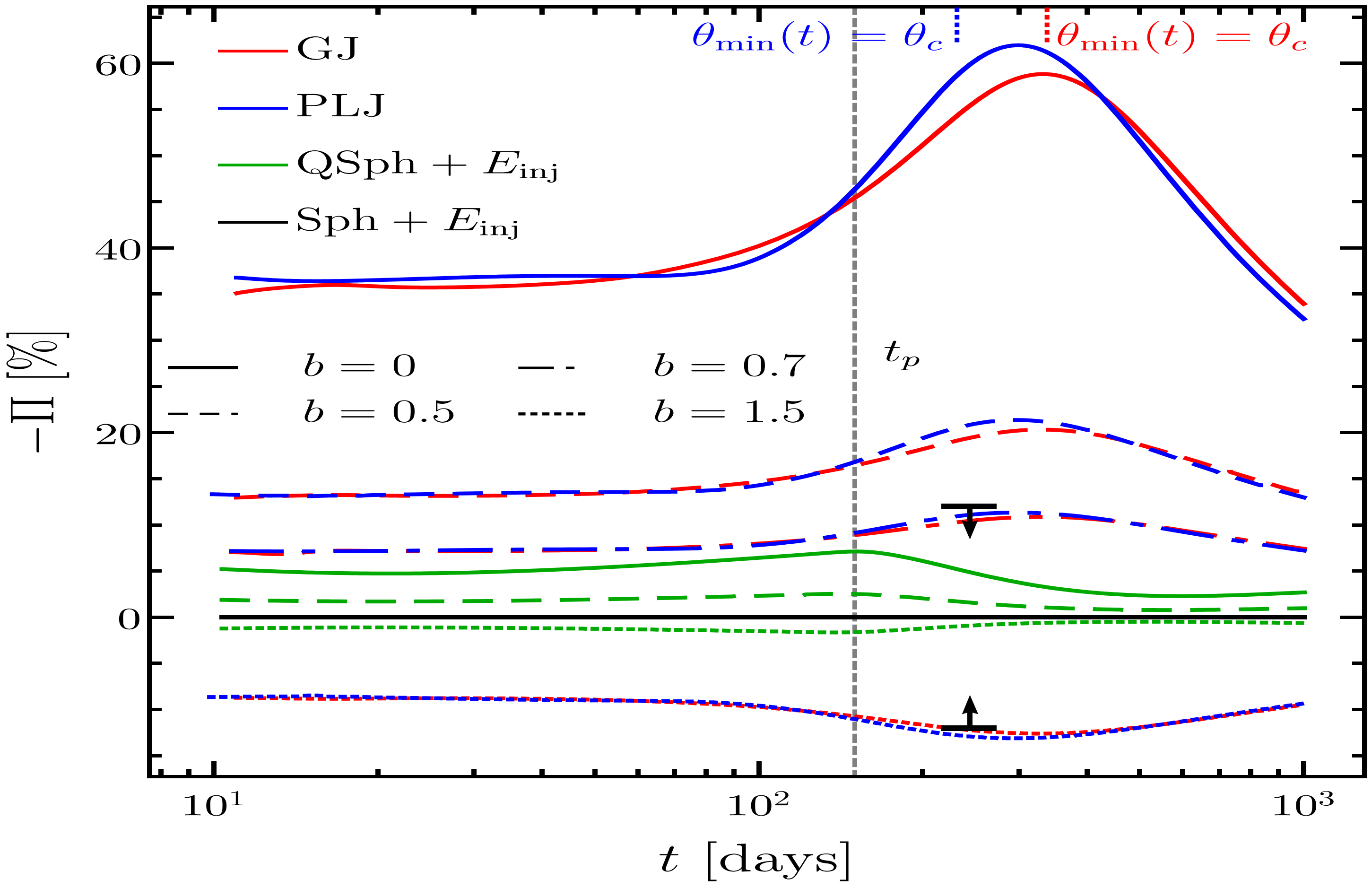

Later: upper limit $P_{\rm lin} < 12\%$ @ $\nu = 2.8$ GHz, t = 244 days (Corsi + 2018)

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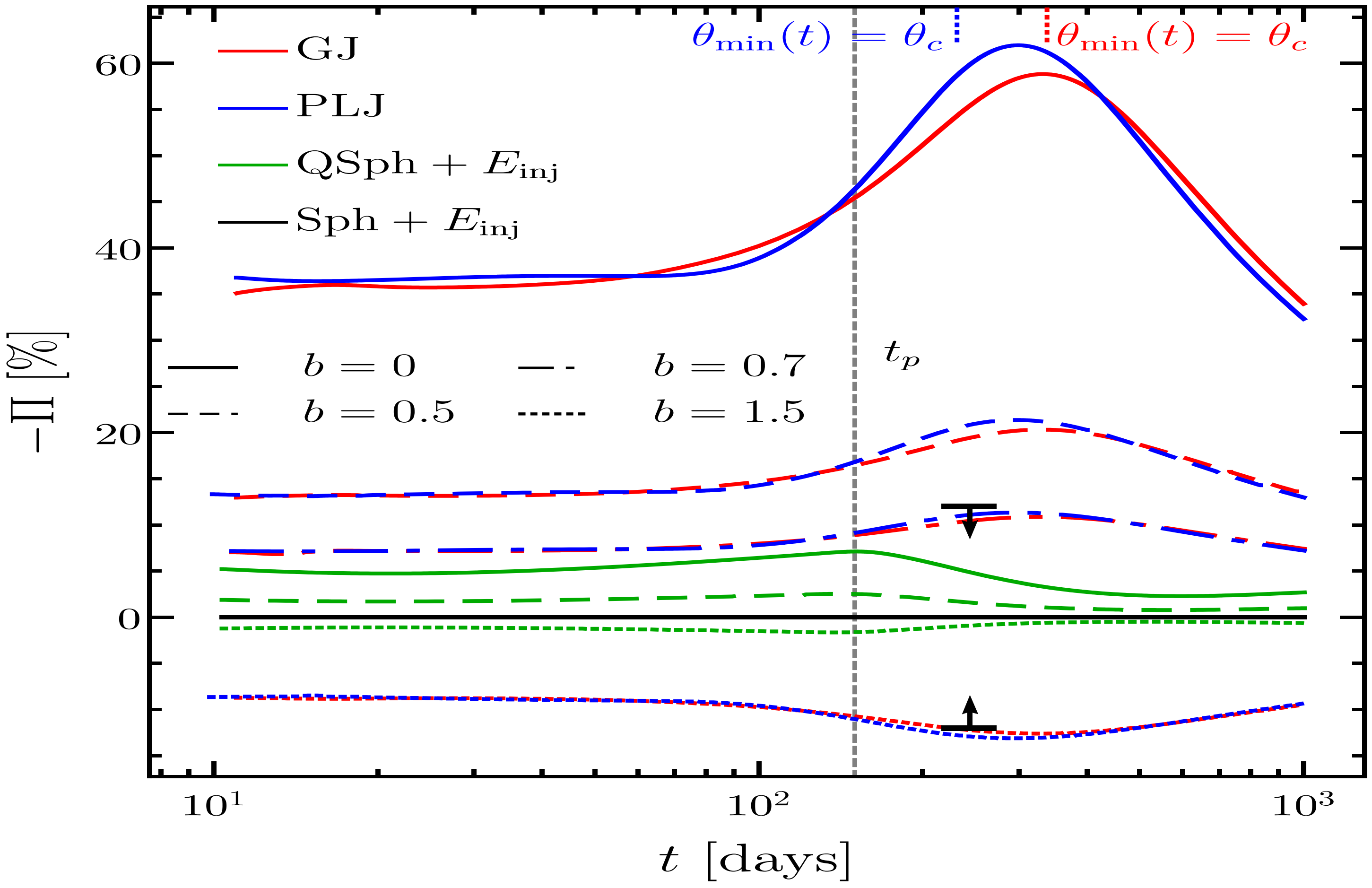


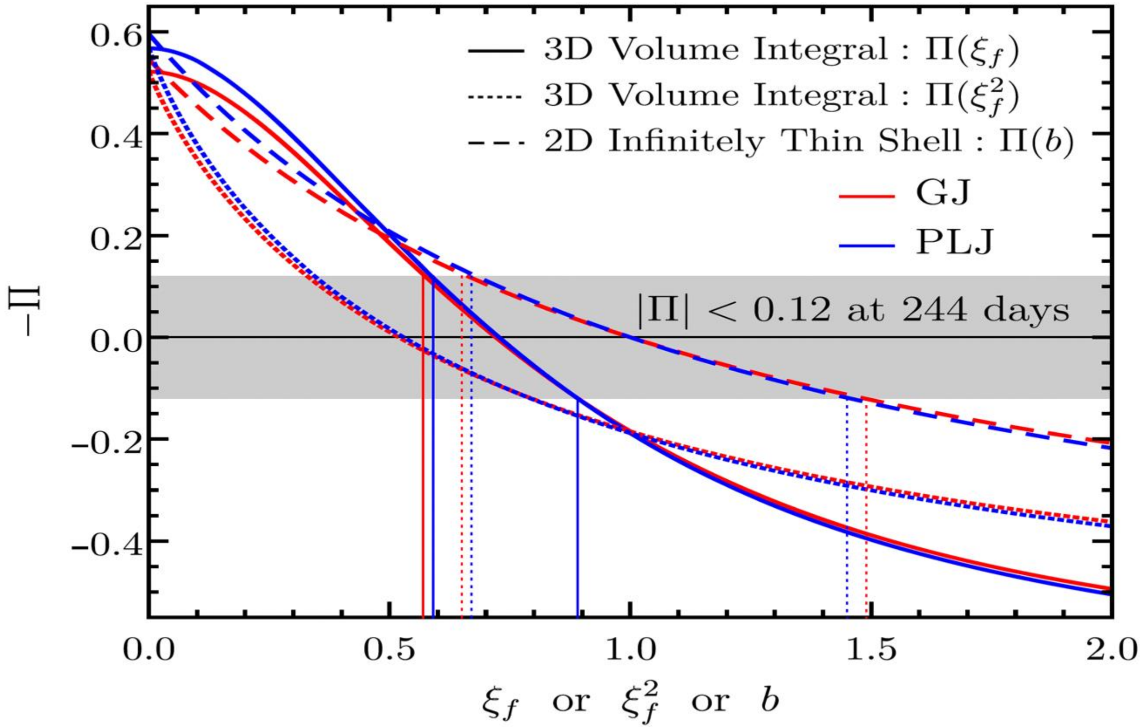
0.7 ≲ b ≲ 1.5 for jet models

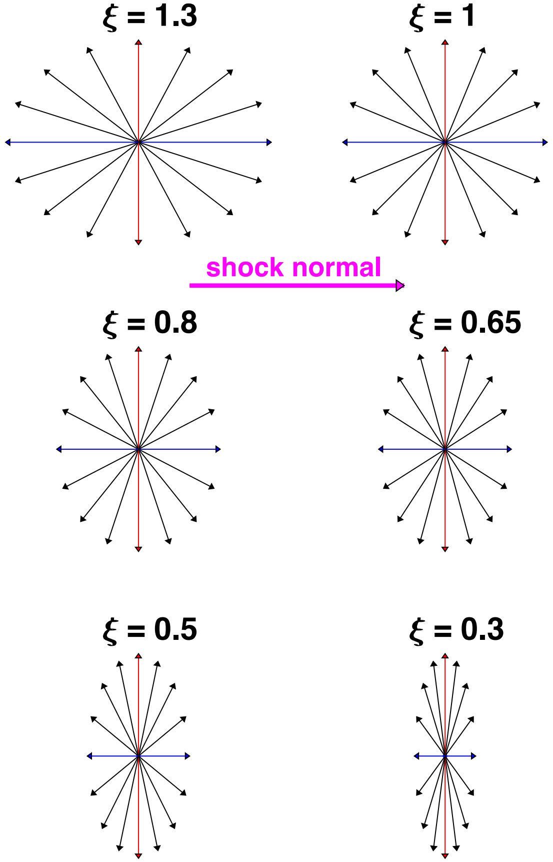
Later: upper limit $P_{\rm lin}$ < 12% @ ν = 2.8 GHz, t = 244 days (Corsi + 2018)

GRB 170817A: polarization UL ⇒ post-shock B-field

More realistic assumptions ⇒ B-field in collisionless shocks: (Gill & JG 2020)

- 2D emitting shell → 3D emitting volume (local BM76 radial profile)
- B-field evolution by faster radial expansion: $L'_r / L'_{\theta,\phi} \propto \chi^{(7-2k)/(8-2k)}$
- B-field isotropic in 3D with $B'_r \rightarrow \xi B'_r$ (Sari 1999); $\xi = \xi_f \chi^{(7-2k)/(8-2k)}$

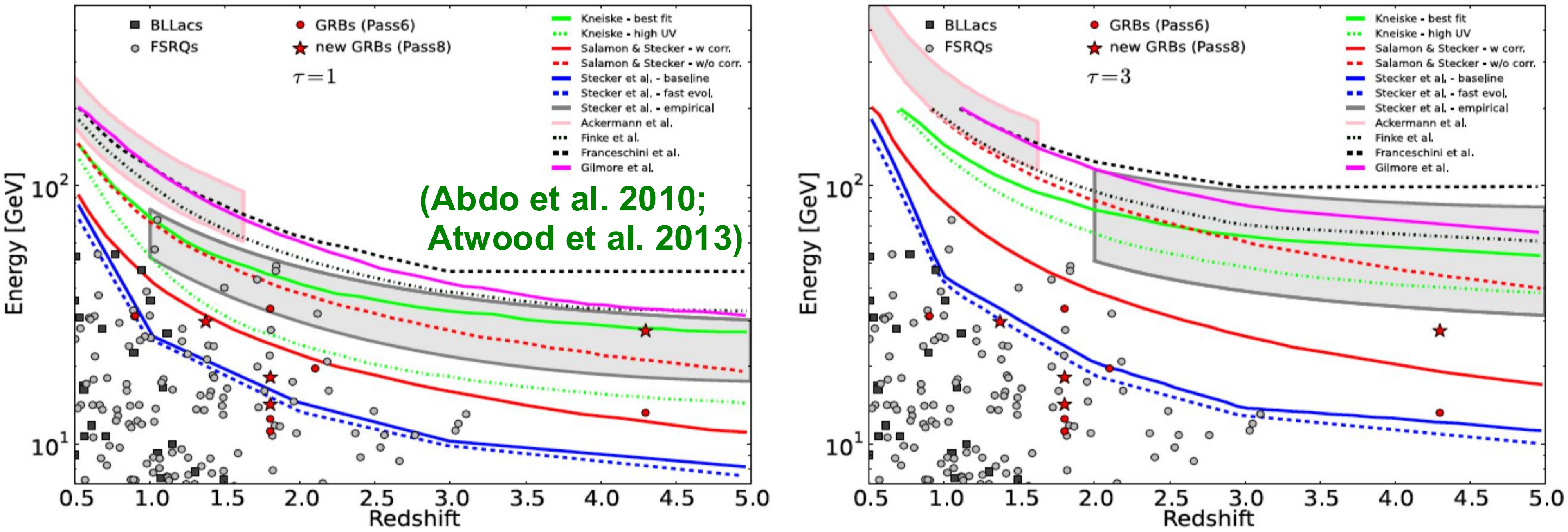




$0.57 \lesssim \xi_f \lesssim 0.89$

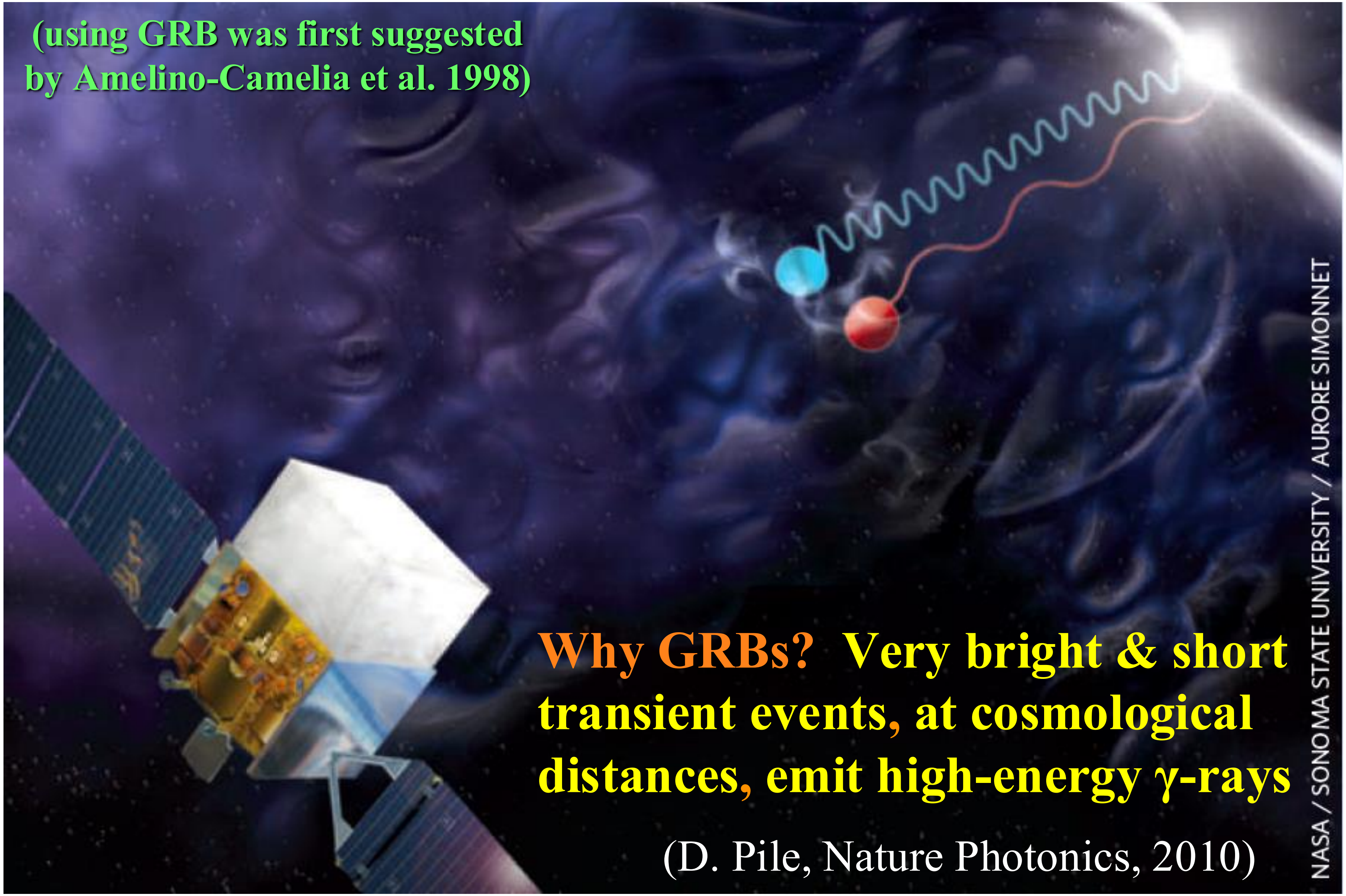
Constraining the Opacity of the Universe

- γ-rays from distant sources can pair produce ($\gamma\gamma \rightarrow e^{+}e^{-}$) on the way to us with the extragalactic background light (EBL)
- This can test the transparency of the Universe and constrain EBL models (or the massive star formation rate at z $\gtrsim$ 1)
- GRBs are already competitive with AGN, & probe higher z
- EBL likely detected (with blazars: LAT+IACTs; Dominguez+2013; Acciari+2019)



(Abdo et al. 2010; Atwood et al. 2013)

Testing for Lorentz Invariance Violation



(using GRB was first suggested by Amelino-Camelia et al. 1998)

Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

(D. Pile, Nature Photonics, 2010)

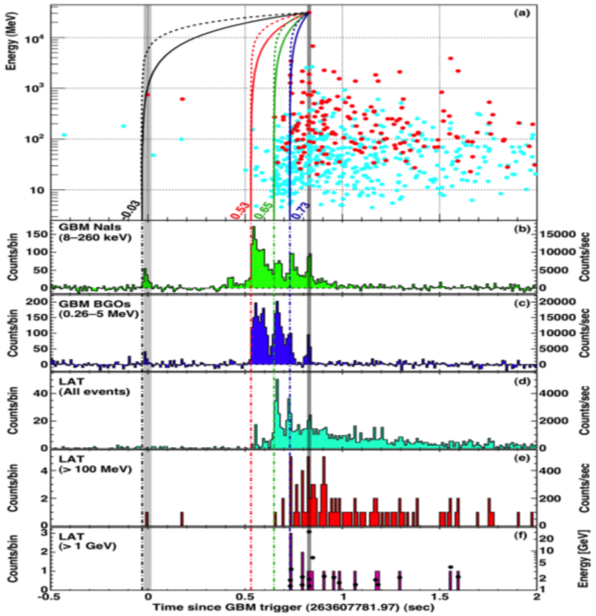
Testing for Lorentz Invariance Violation

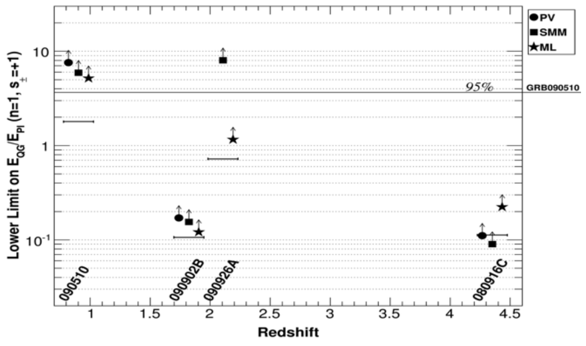
- GRB 090510 is much better than the rest (short, hard, very fine time structure)
- Abdo+ 2009, Nature, 462, 331: 1st direct time-of-flight limit beyond Plank scale on linear (n = 1) energy dispersion:

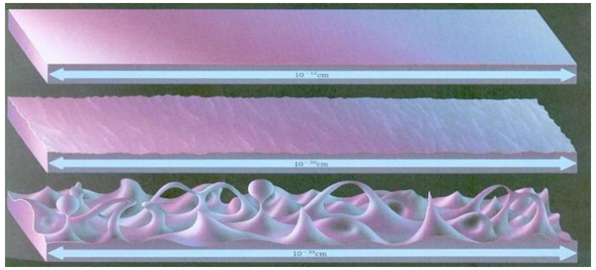
$$v_{\rm ph}/c \approx 1 \pm \tfrac{1}{2}(1+n)\left(E_{\rm ph}/E_{\rm QG,n}\right)^n \qquad E_{\rm QG,1} > 1.2E_{\rm Planck}$$

(robust, conservative, 2 independent methods)

- Vasileiou+ 2013: 3 different methods, 4 GRBs (090510 is still the best by far), the limits improved by factors of a few
- Vasileiou+ 2015, Nature Phys., 11, 344: stochastic LIV – motivation: space-time foam (1st Planck-scale limit of its kind)







Conclusions: Short GRBs & Multimessenger Astrophysics

- GW170817 is unique with a wide range of implications
- GW speed: $\left|\frac{v_{GW}}{c} - 1\right| \lesssim 4 \cdot 10^{-16}$; Kilonova: r-process elements
- Merger Remnant: BH or HMNS ➞ BH ⇒ $M_{TOV} \lesssim 2.17 M_\odot$
- Two main types of explanations for the rising afterglow flux energy distribution with proper velocity (r) or with angle (θ)
- Possible diagnostics to distinguish between them
  - The post-peak flux decay slope
  - Flux centroid motion or image axis ratio
- Later flux centroid motion observations: $\beta_{app} = 4.1 \pm 0.5$
- Polarization UL: shock-produced B-field $0.57 \lesssim \xi_0 \lesssim 0.89$
- GRBs can also constrain Lorentz Invariance Violation or the EBL

The End