Lessons from GW170817 / GRB170817A

Jonathan Granot

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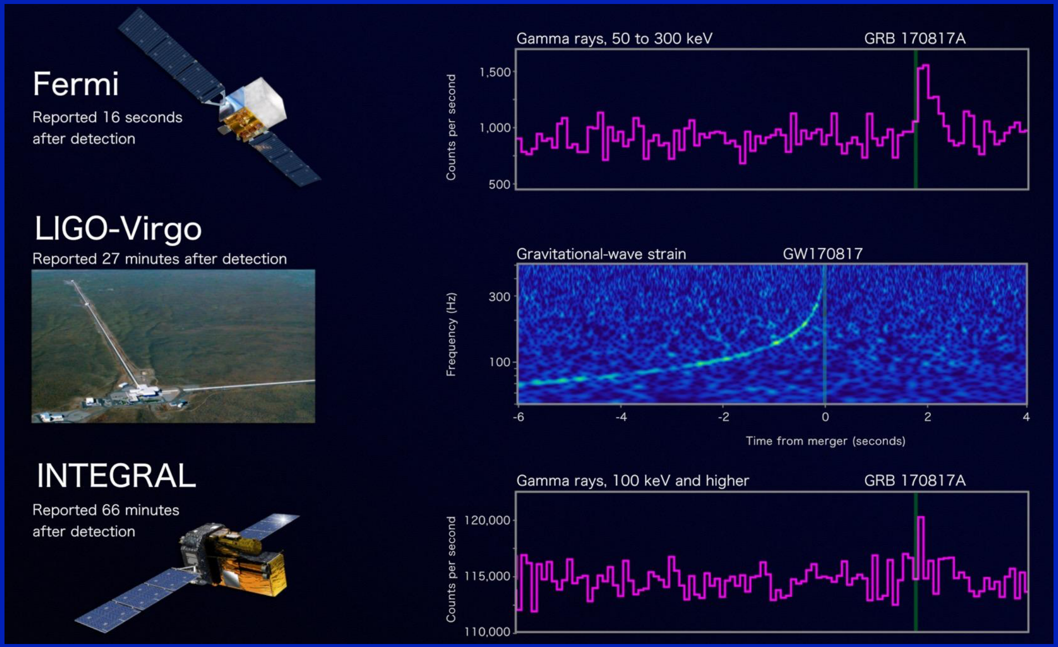

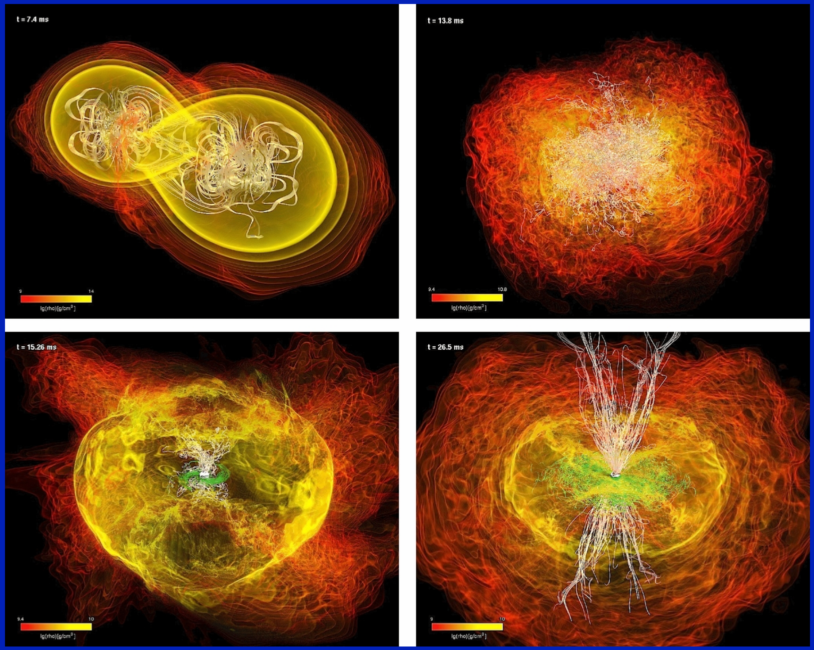

Exploring the Universe: Near Earth Space Science to Extra-Galactic Astronomy (tribute to S. N. Bose's 125th birth anniv.); **Kolkata, 15 Nov. 2018**

Outline of the Talk:

- The dawn of a new Era: **Gravitational-Wave Astronomy**
- **The Extraordinary event GW170817/GRB170817A**
- **The merger remnant: Black Hole or a massive NS?**
- The afterglow emission:
  - **Two main options for the early flux rise: r vs. θ dependence**
  - **Breaking the degeneracy: lightcurves? Images, Polarization**
  - **New observations imply: dominant θ dependence (off-axis jet)**
- **Conclusions**

Gravitational Wave Astronomy:

- Einstein **predicted** Gravitational Waves in 1916
- **1st indirect evidence:** Hulse-Taylor binary pulsar (1974; ⇒1993 Nobel prize)
- **1st direct detection:** LIGO detected a **BH-BH merger,** GW150914; announced 11 Feb. 2016 ⇒ 2017 Nobel prize

The Nobel Prize in Physics 2017

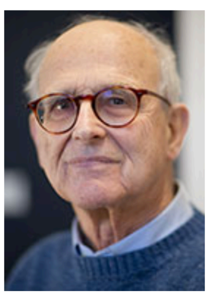

Photo: Bryce Vickmark

Rainer Weiss

Prize share: 1/2

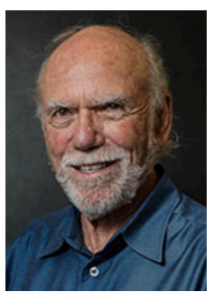

Photo: Caltech

Barry C. Barish

Prize share: 1/4

Photo: Caltech Alumni Association

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

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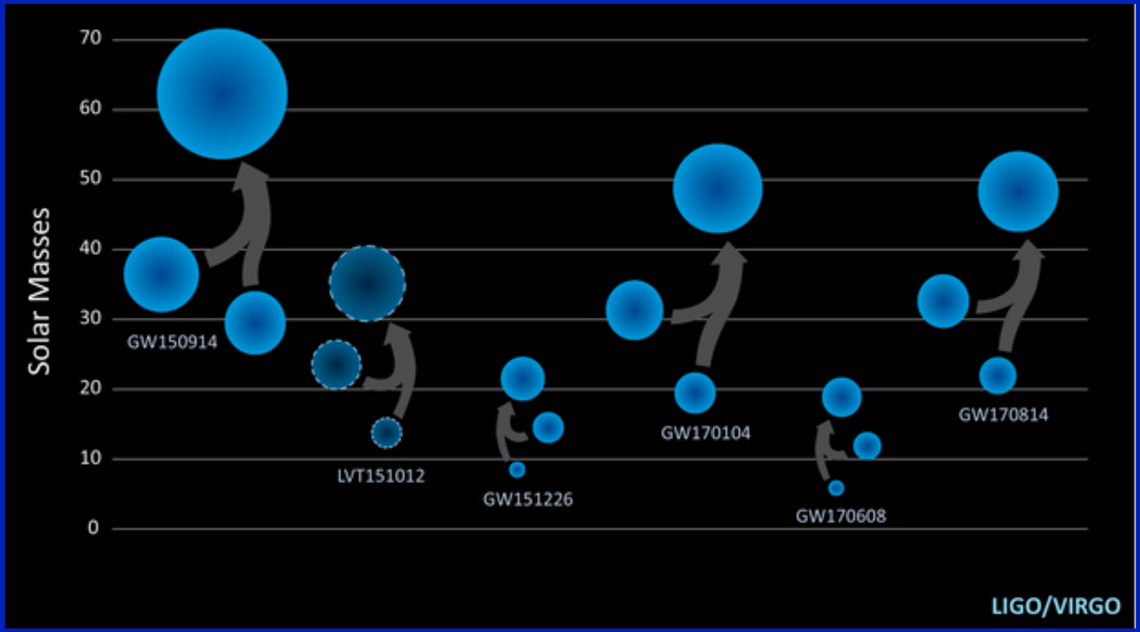
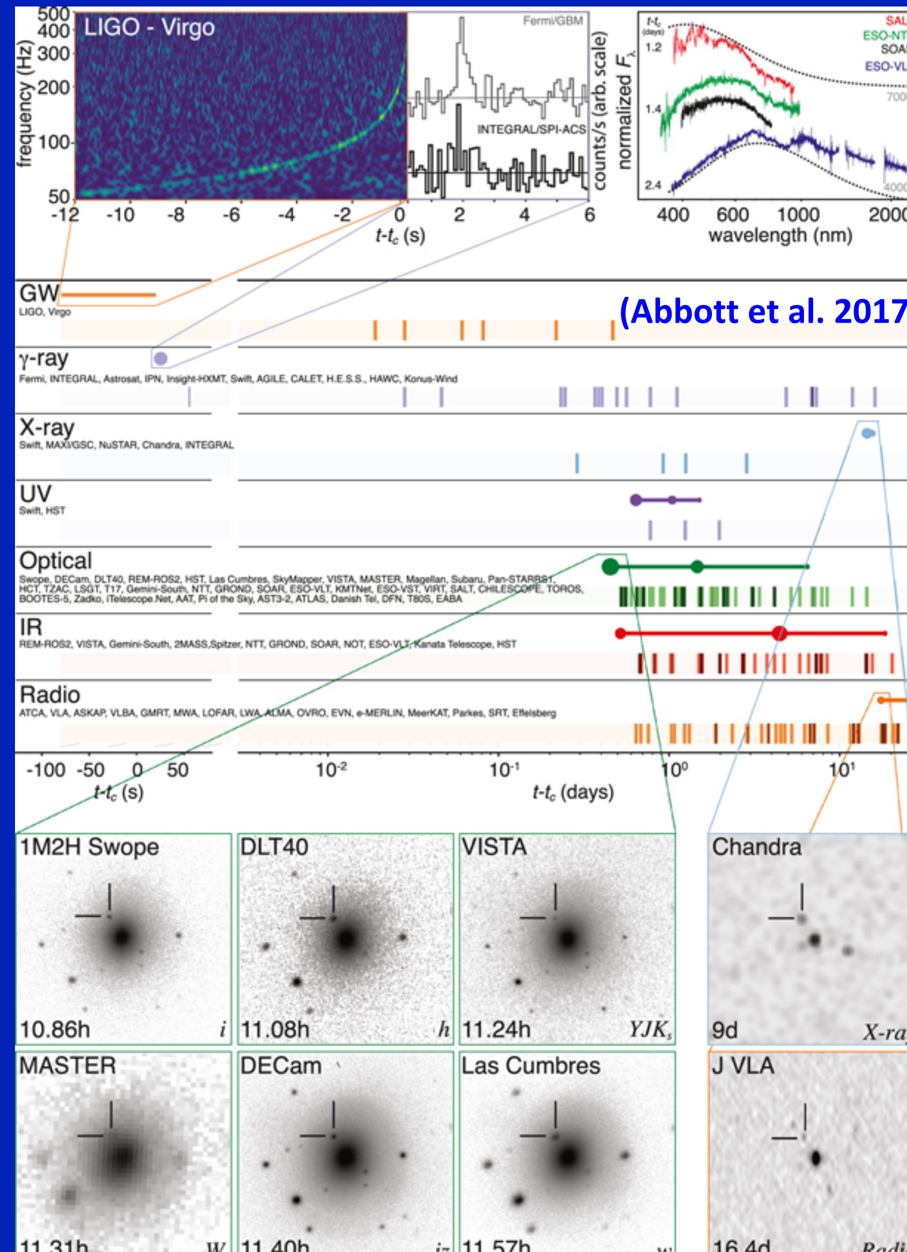
- **1st direct detection:** LIGO detected a **BH-BH merger,** GW150914; announced 11 Feb. 2016 ⇒ 2017 Nobel prize
- **5** BH-BH mergers detected so far, but no EM counterpart



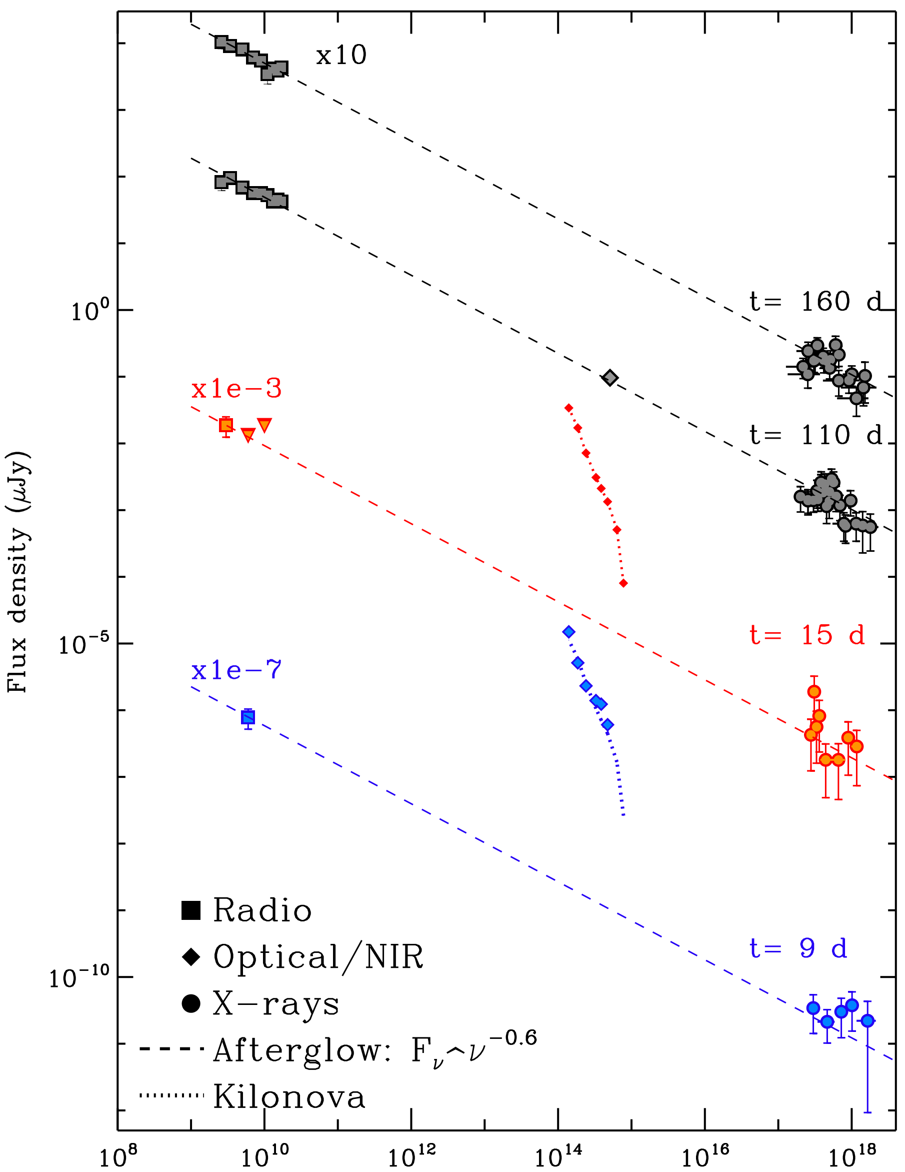
GW 170817 / GRB 170817A:

- **First GW detection** of a **NS-NS merger**
- **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) to radio (>16 d) afterglow (still detected)
- **First direct association of a sGRB & NS-NS merger*** (Eichler+ 1989; Narayan+ 1992)
- **First clear-cut kilonova**

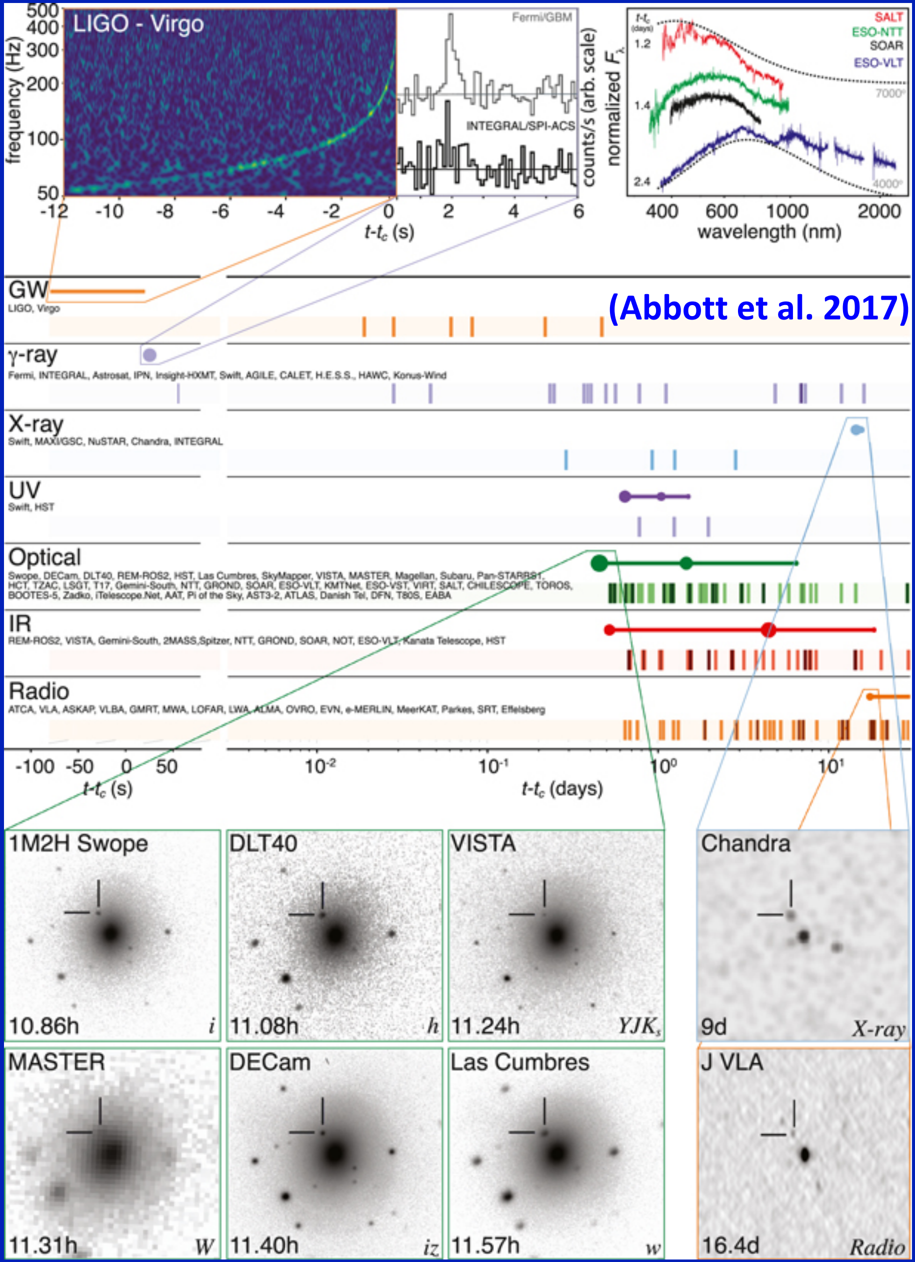


(Abbott et al. 2017)

GW 170817 / GRB 170817A:



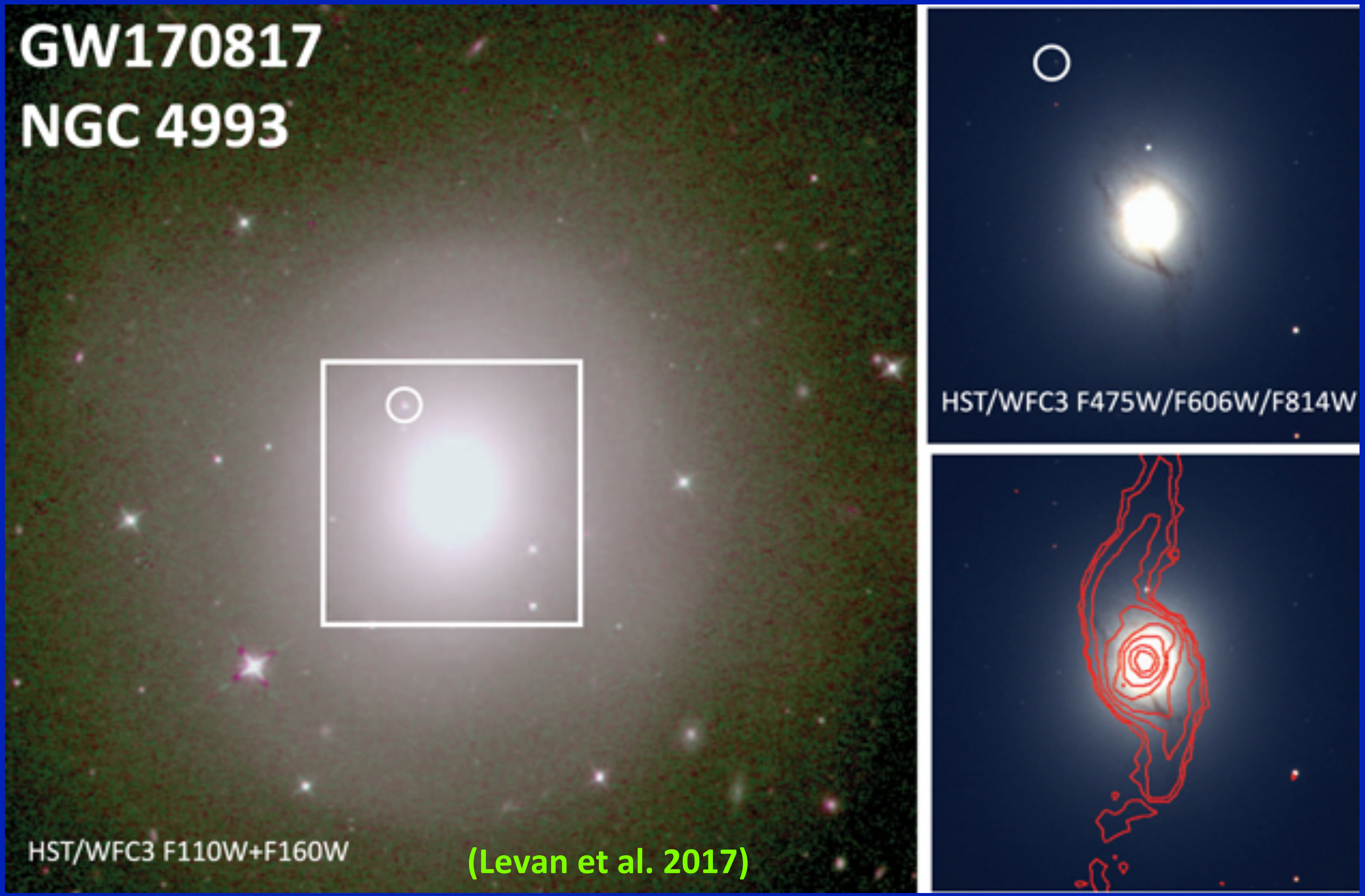
(Margutti et al. 2018)



(Abbott et al. 2017)

GW 170817: distance and host galaxy

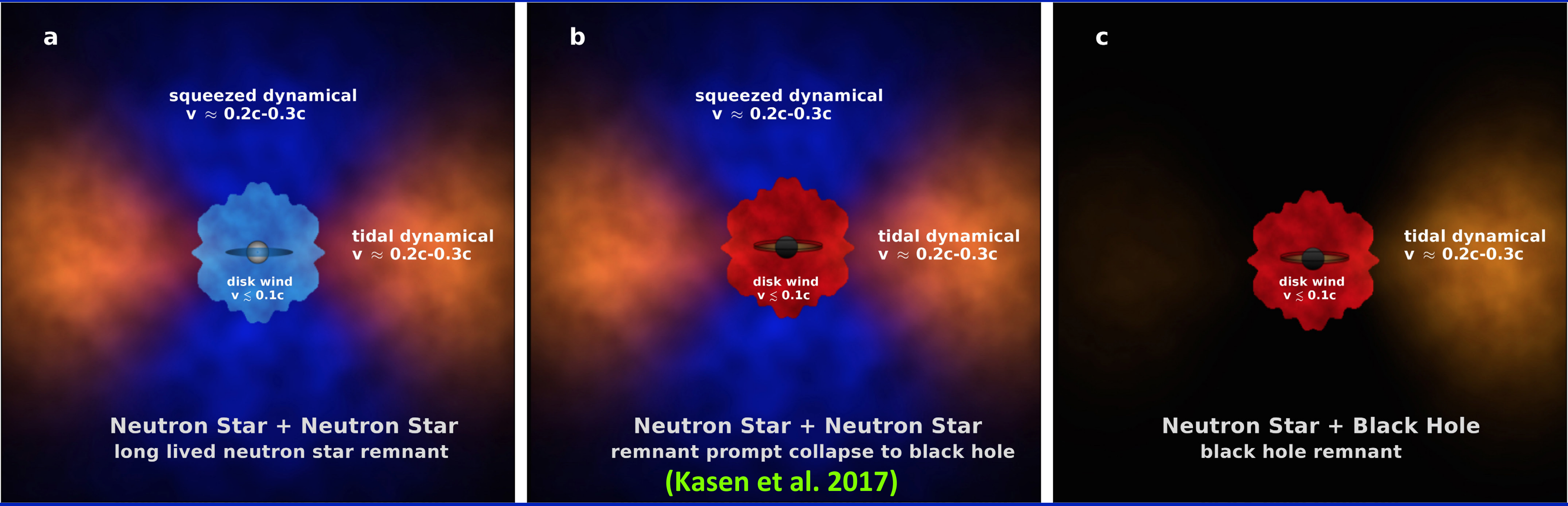
- Distance from the GW signal: $D_{GW} = 43.8^{+2.9}_{-6.9}$ Mpc
- Elliptical host galaxy: NGC 4993 at D = 41.0 ± 3.1 Mpc
  (Hjorth+17; z=0.009783; located 2 kpc in projection from its center)



(Levan et al. 2017)

GW 170817: the associated **kilonova**

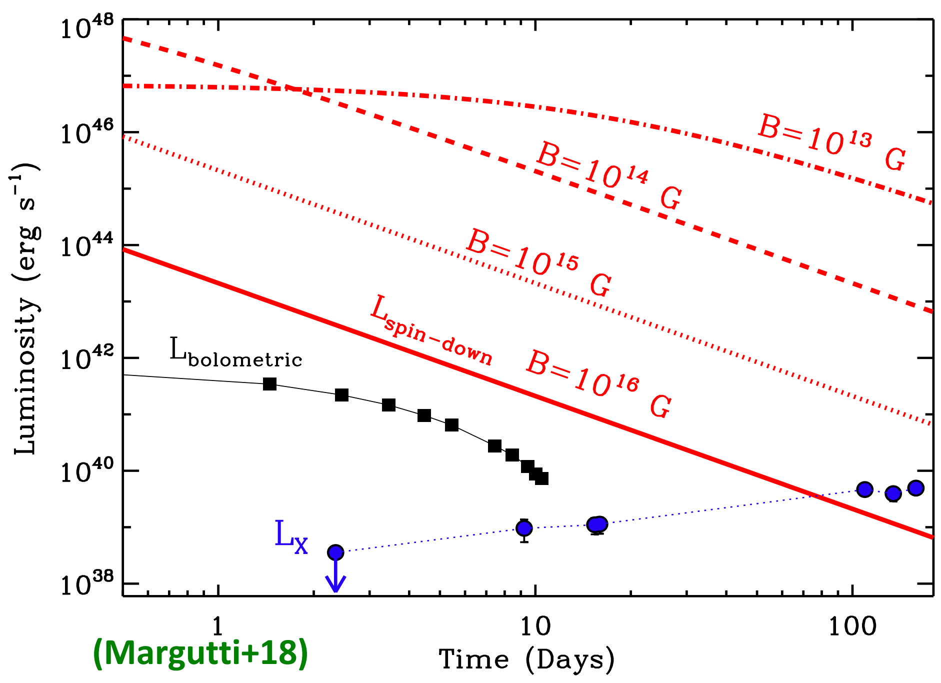
- The observations require **two components:**
  - blue/fast, lanthanide-poor **M_{ej} ~ 1–2% $M_{\odot}$, v_{ej} ~ 0.2–0.3c**
  - red/slow, lanthanide-rich **M_{ej} ~ 3–5% $M_{\odot}$, v_{ej} ~ 0.05–0.2c**
- Synthesized large amounts of heavy elements (may dominate the cosmic r-process nucleosynthesis)



(Kasen et al. 2017)

GW 170817: the type of remnant

- $M_{1,2}$ = pre-merger NS $M_{\text{gravitational}}$ 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



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)

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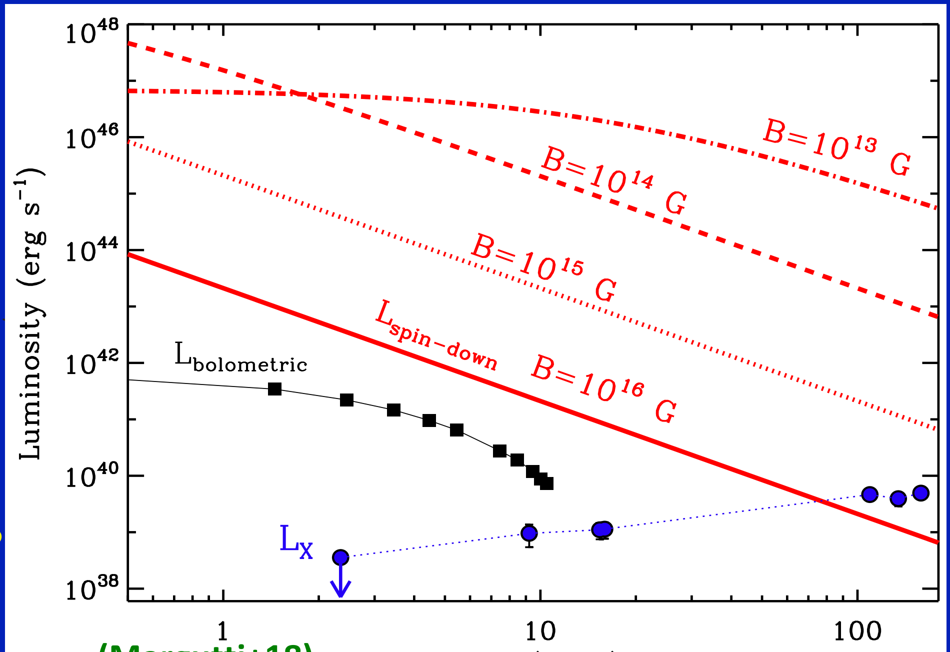
- Final mass $M_f \approx 0.93 M_i$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger
- A stable NS or SMNS $\Rightarrow P_0 \approx 1$ ms

$\Rightarrow E_{rot} \gtrsim 10^{52.5}$ erg, $\tau_{sd} \approx 20 B_{13}^{-2}$ days

$\Rightarrow$ would contradict afterglow obs.

(also what produces the GRB/afterglow?)



(Margutti+18)

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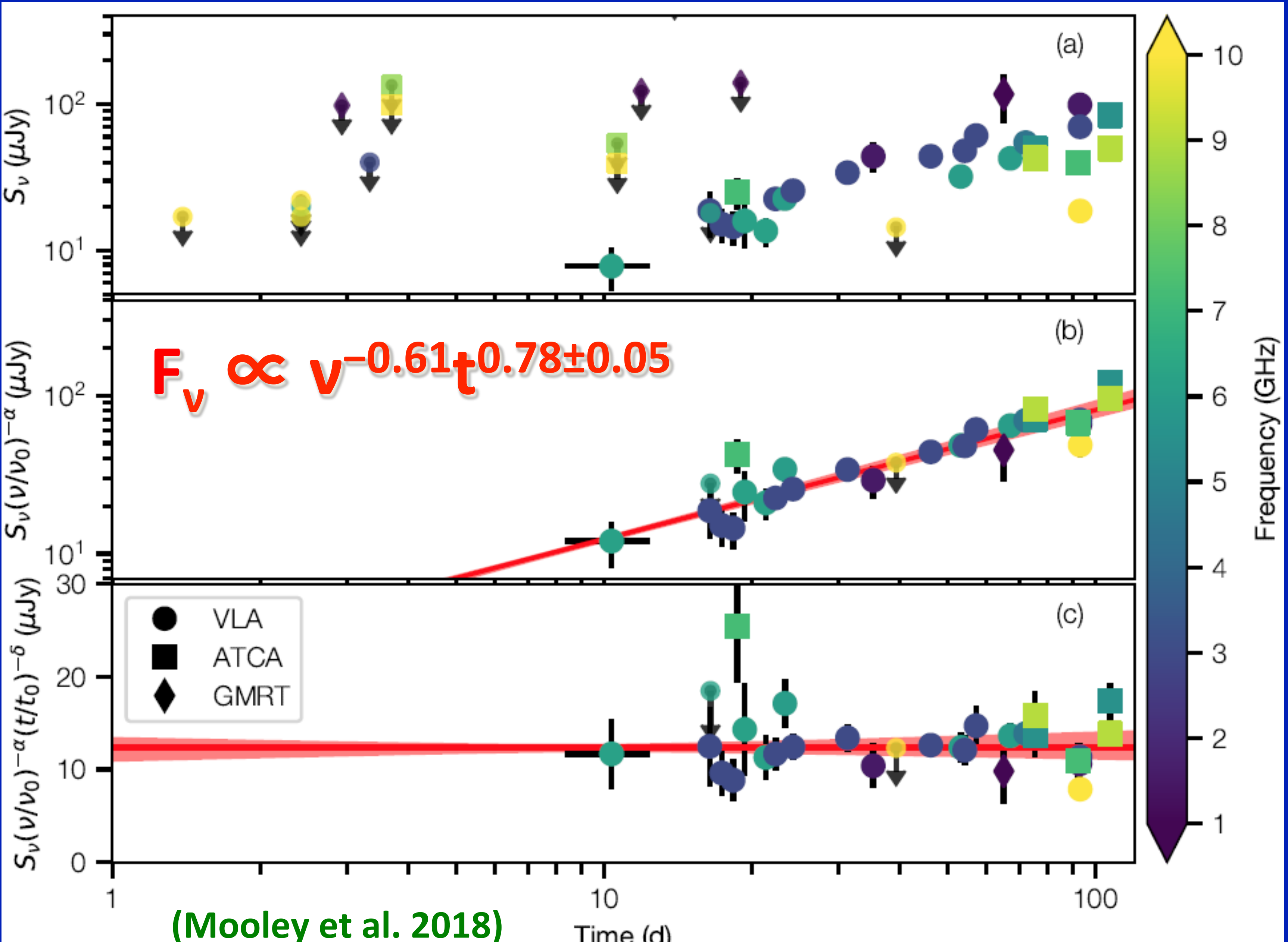
- The argument can be reversed to constrain NS EoS & $M_{max} \lesssim 2.17 M_\odot$

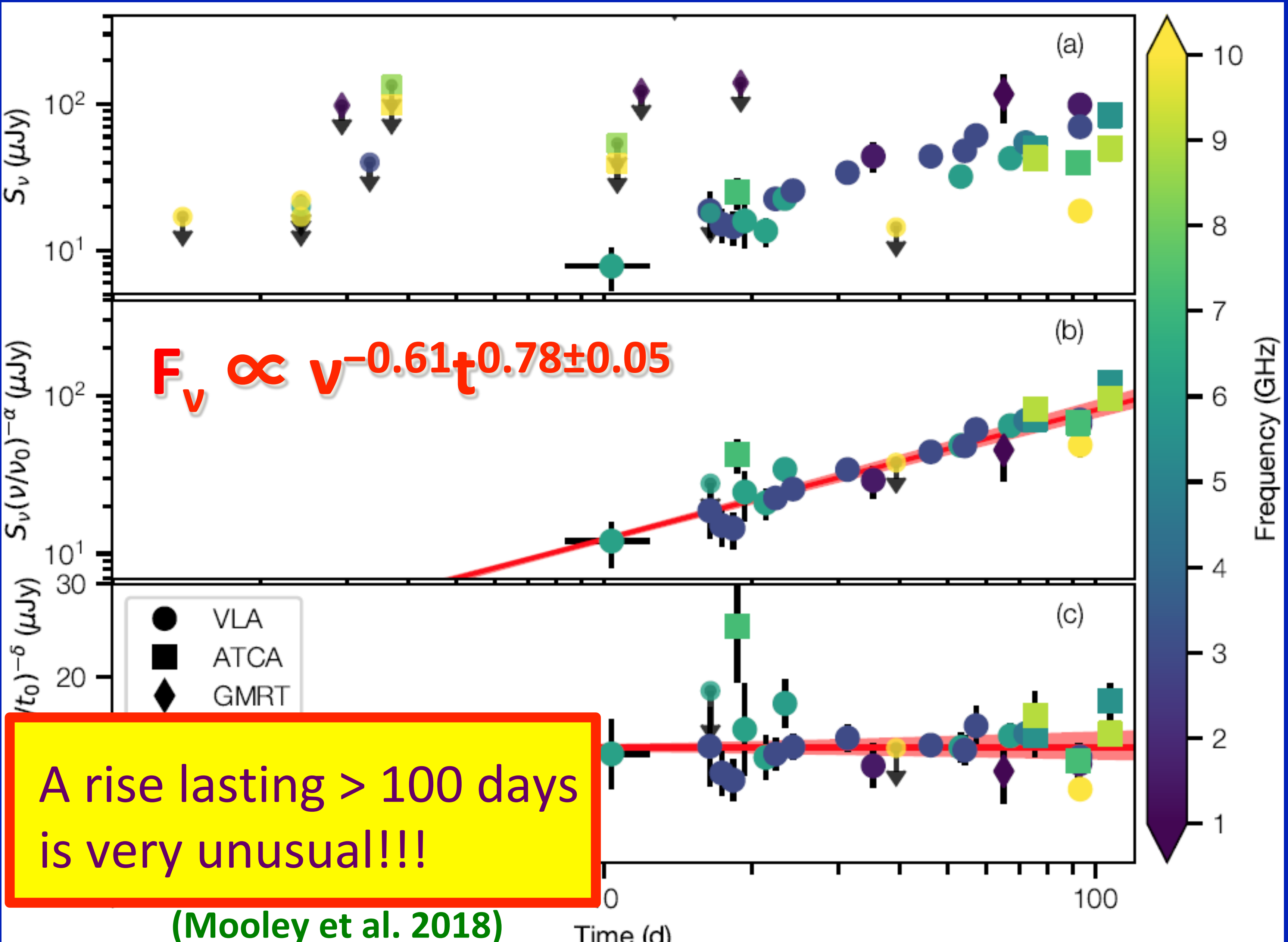
(Margalit & Metzger 2017; Rezzolla et al. 2018)

GRB 170817A: afterglow observations



(Mooley et al. 2018)

GRB 170817A: afterglow observations



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

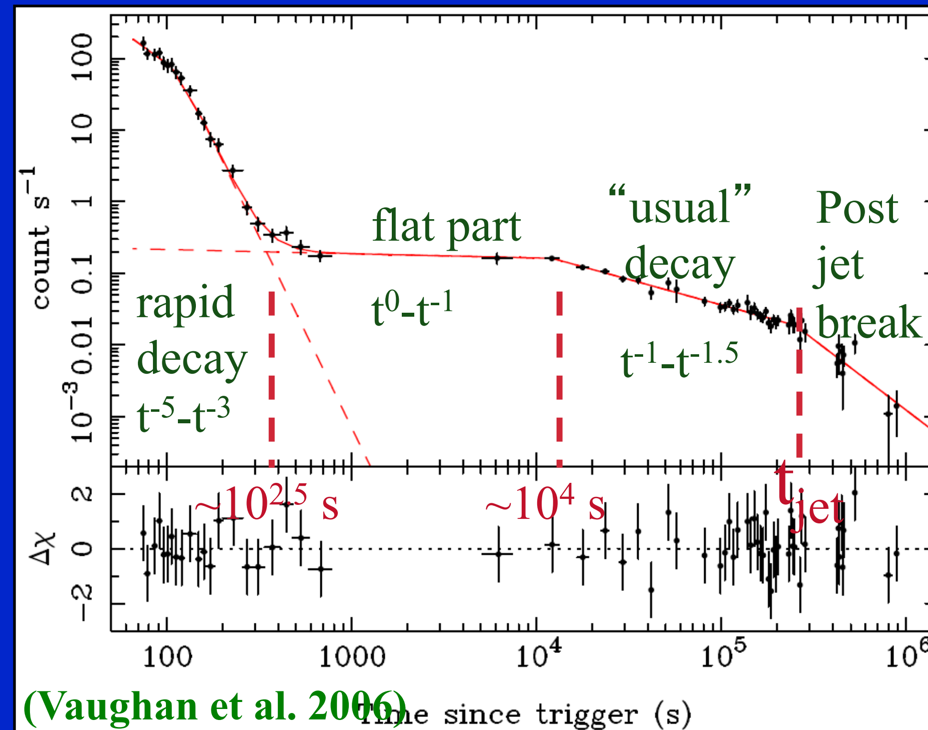
A rise lasting > 100 days is very unusual!!!

(Mooley et al. 2018)

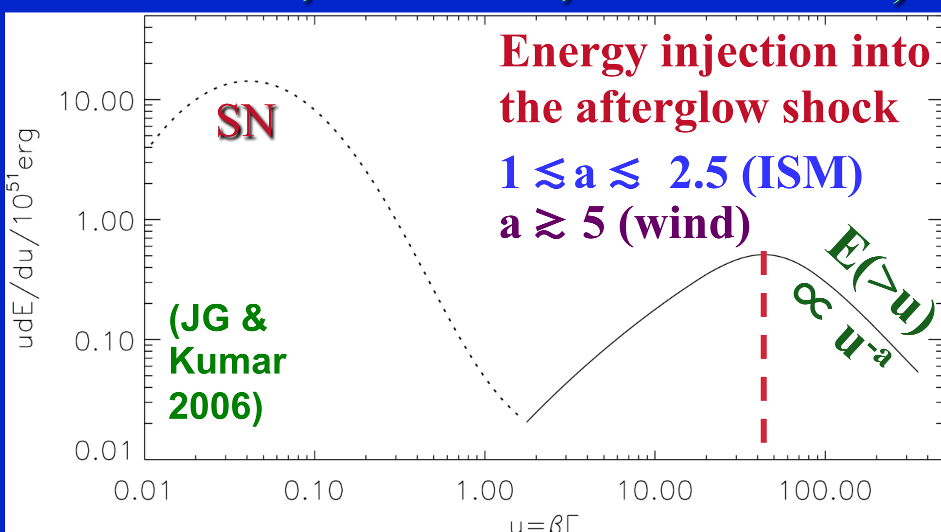
Analogy to rising F_ν: X-ray Plateaus

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

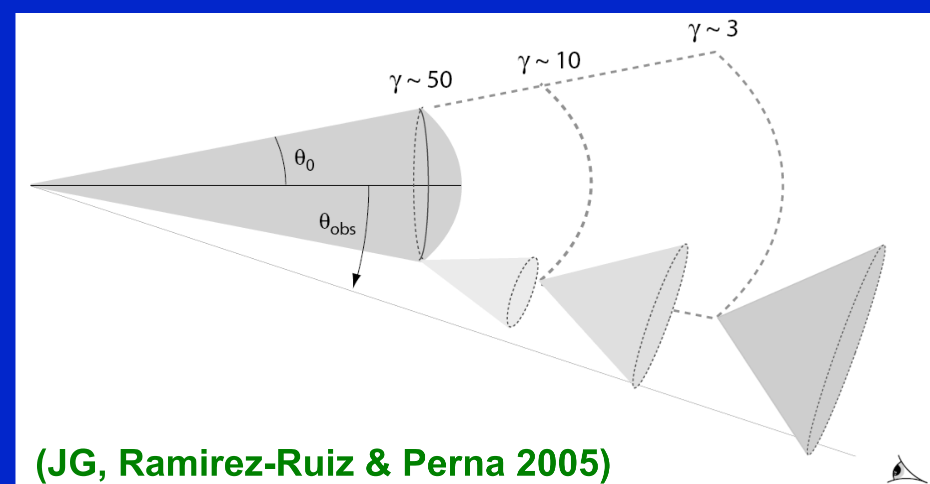
1. long-lived relativistic wind
2. slower ejecta catching up (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)



(Vaughan et al. 2006)



(JG & Kumar 2006)



(JG, Ramirez-Ruiz & Perna 2005)

- Viewing angle effects

Analogy to rising F_ν: X-ray Plateaus

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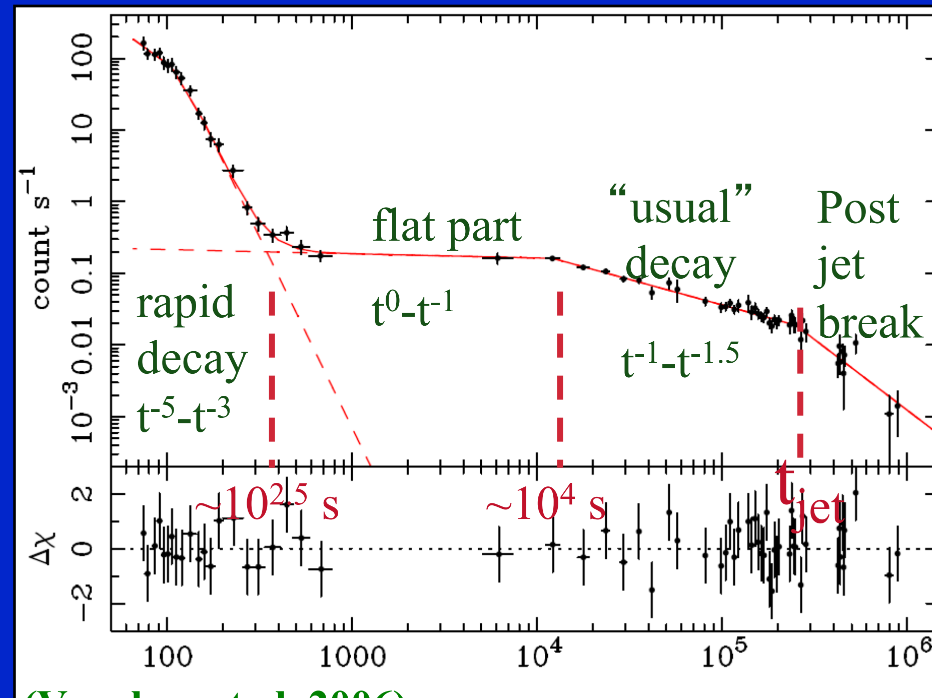
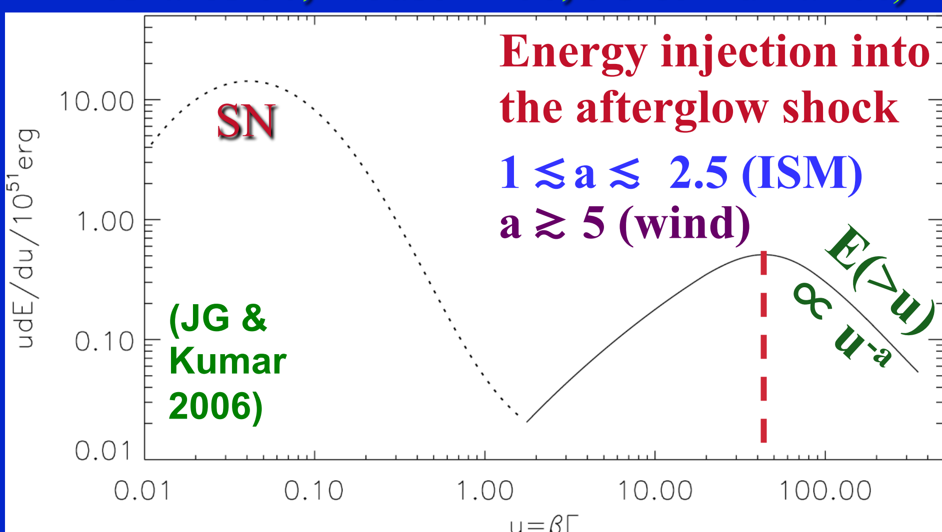


(Vaughan et al. 2006)



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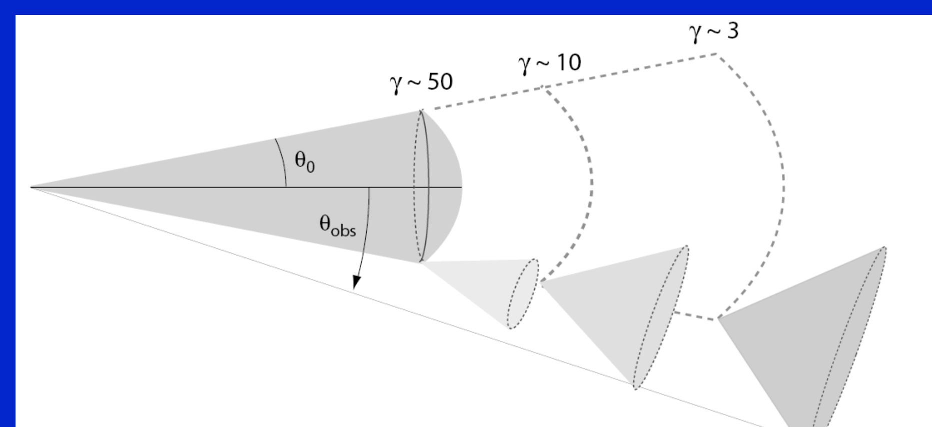
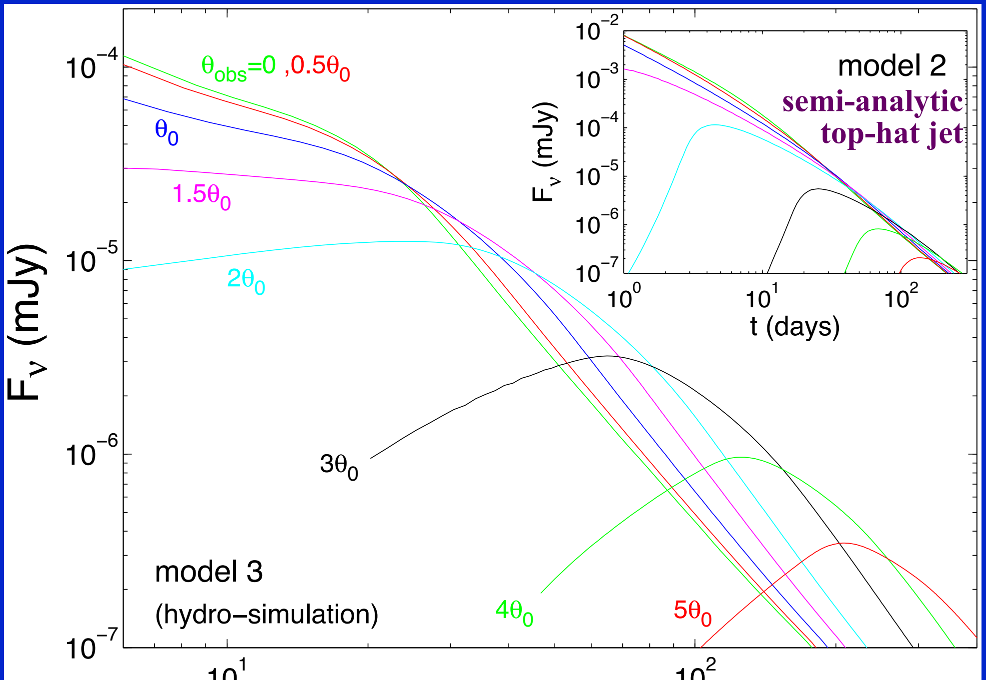


(JG, Ramirez-Ruiz & Perna 2005)

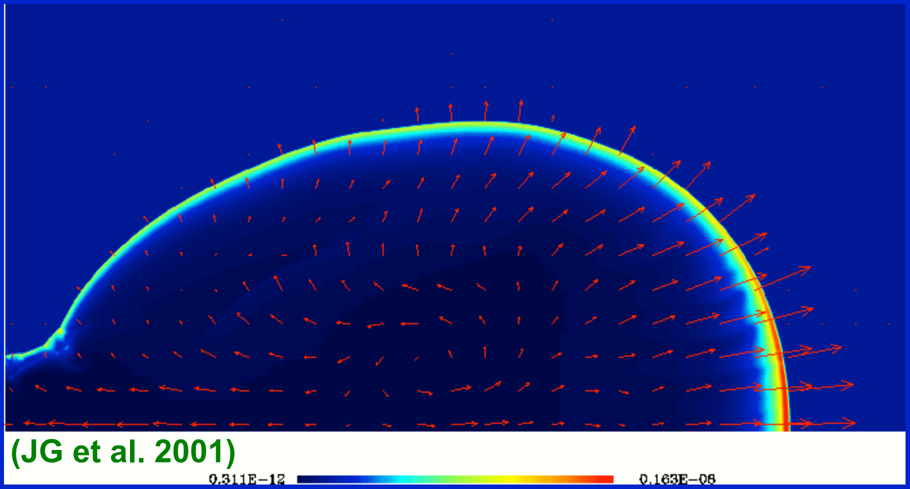
- Viewing angle effects **angular**

Off-Axis Afterglow Lightcurves

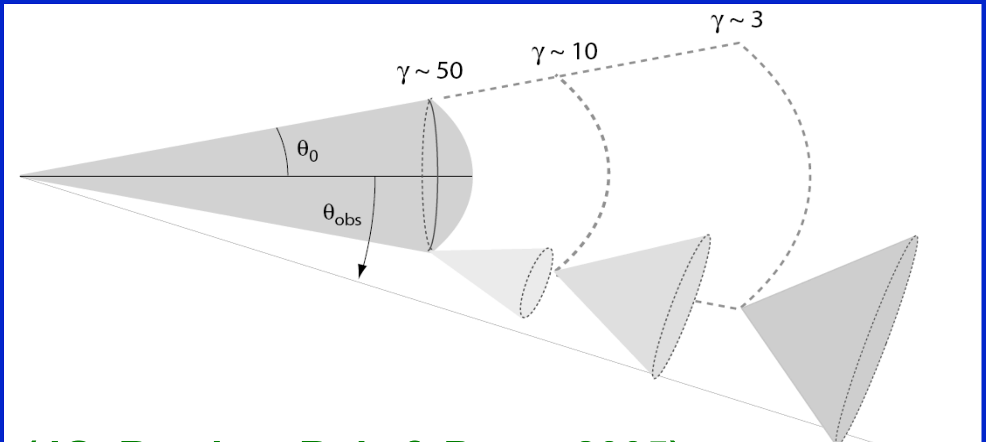
- The emission is initially strongly beamed away from our L.o.S
- F_ν rises as beaming cone widens
- When beaming cone reaches LoS F_ν peaks & approaches on-axis F_ν
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet's sides with non-radial velocities



(JG et al. 2002)



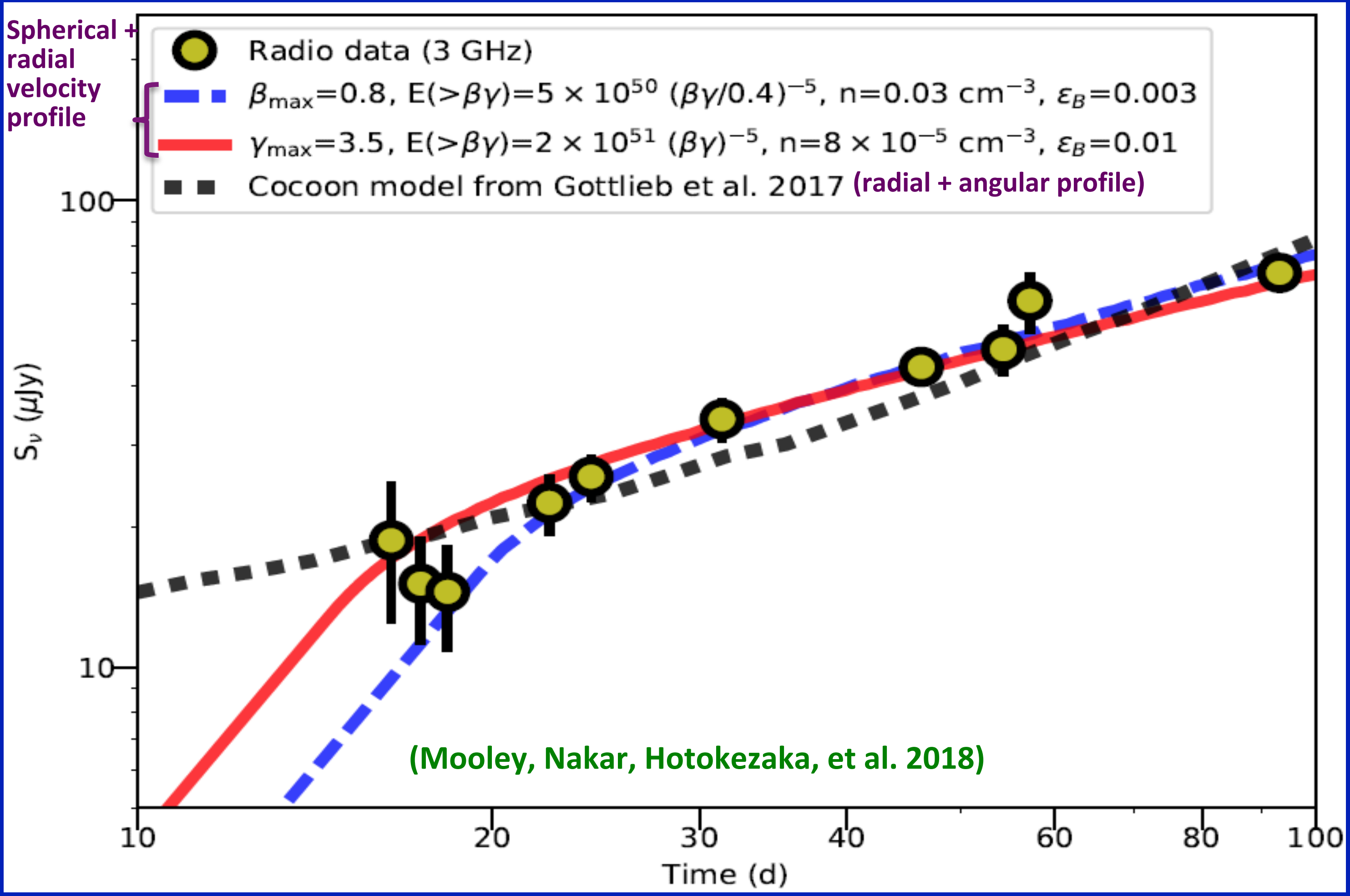
(JG et al. 2001)



(JG, Ramirez-Ruiz & Perna 2005)

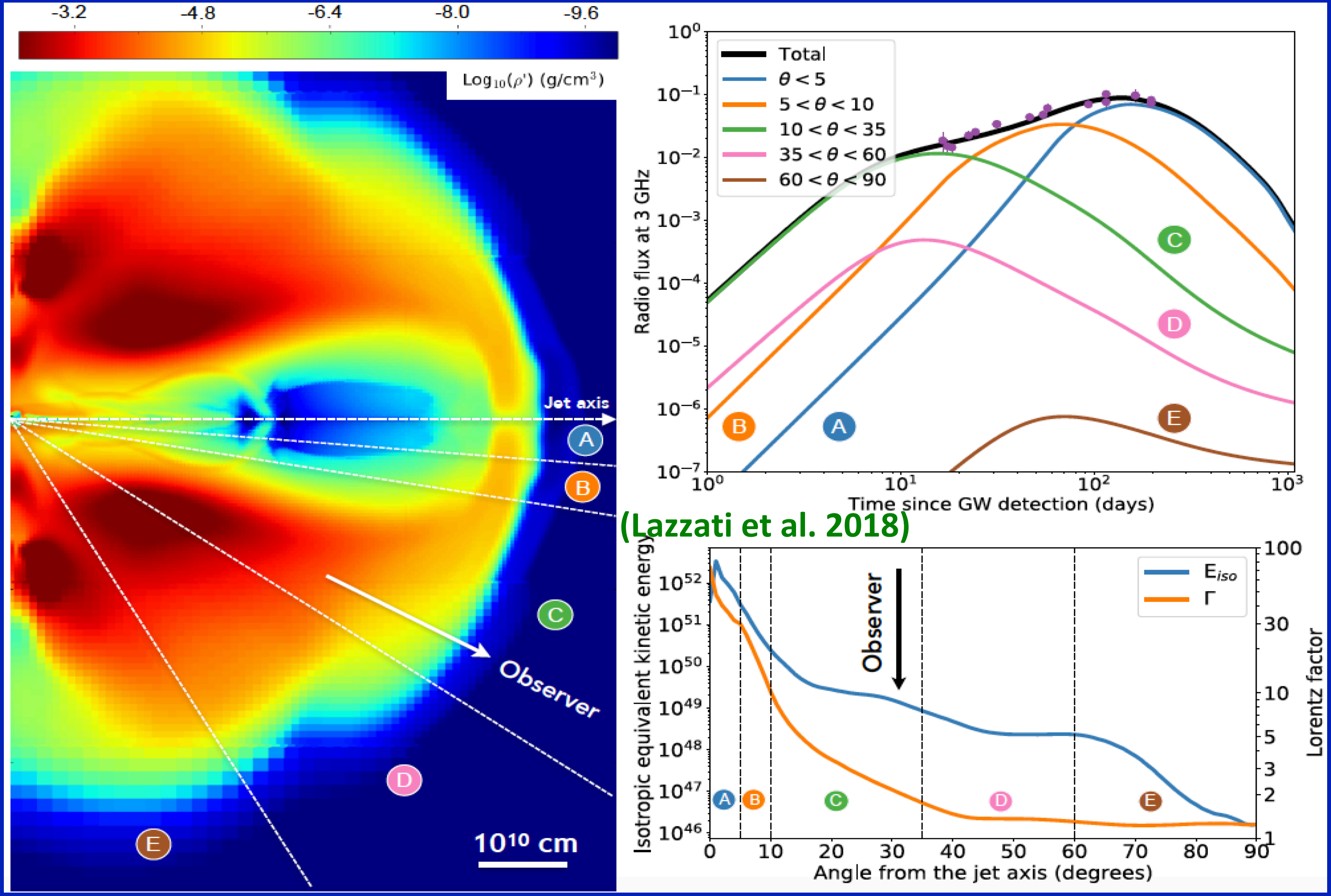
GRB170817 outflow structure: prompt, afterglow

- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): **r** & **θ** profile
- Cocoon-driven shock breakout can naturally produce the γ-rays (Kasliwal+17; Gottlieb+17; Bromberg+18; Nakar & Piran 18; Nakar+18)



GRB170817 outflow structure: the afterglow

- A structured jet explanation (Lazzati+17; Margutti+18; Gill & JG 18;…):
  - Simulation of jet breaking out of the Newtonian ejecta near a NS-NS merger site: the cocoon energizes the jet's sides/wings
  - Afterglow dominated by θ profile

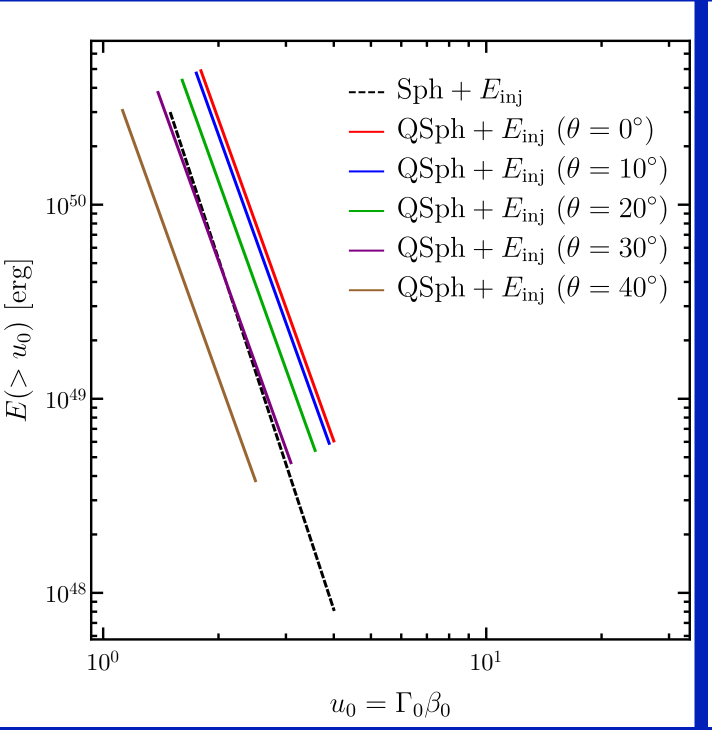


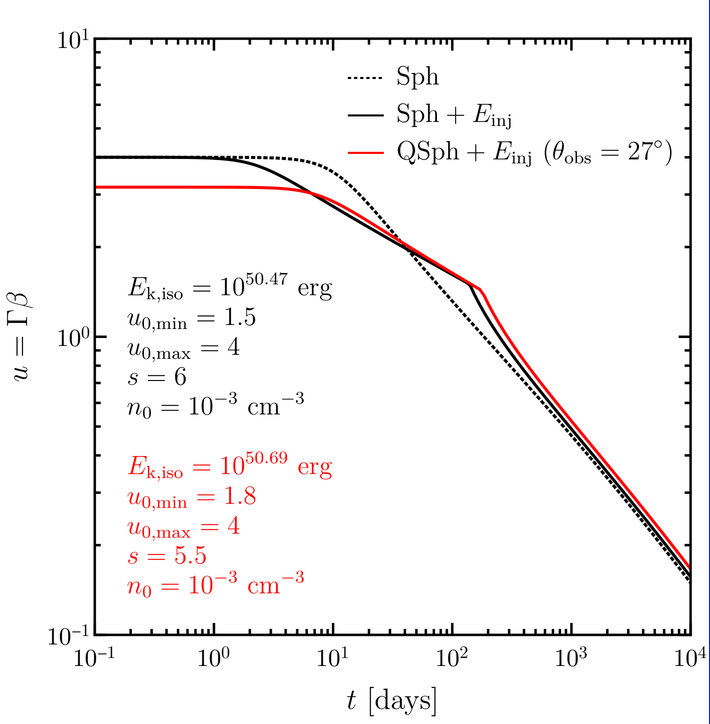
(Lazzati et al. 2018)

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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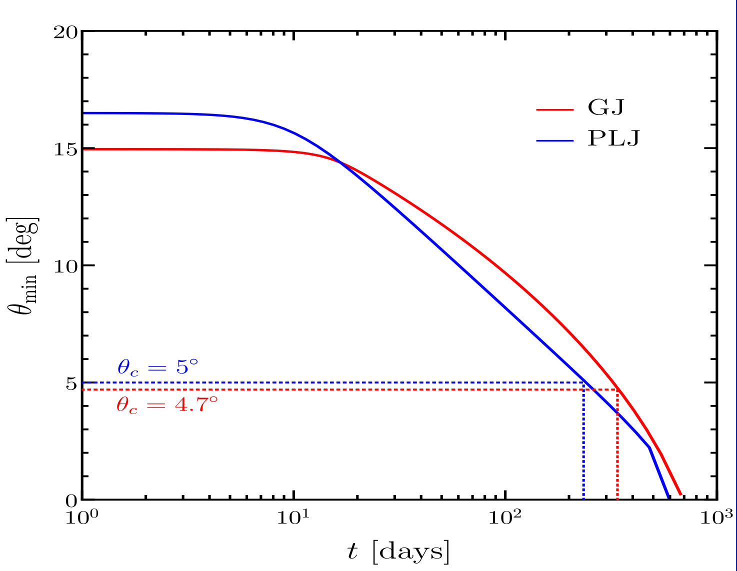
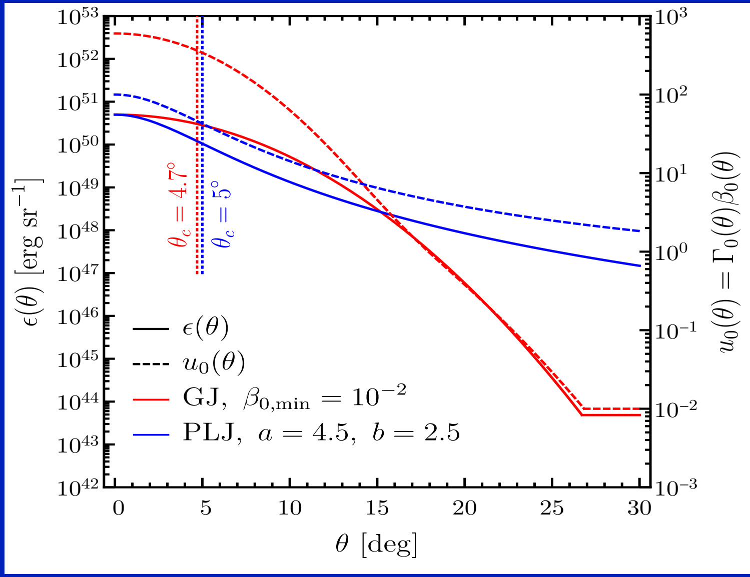
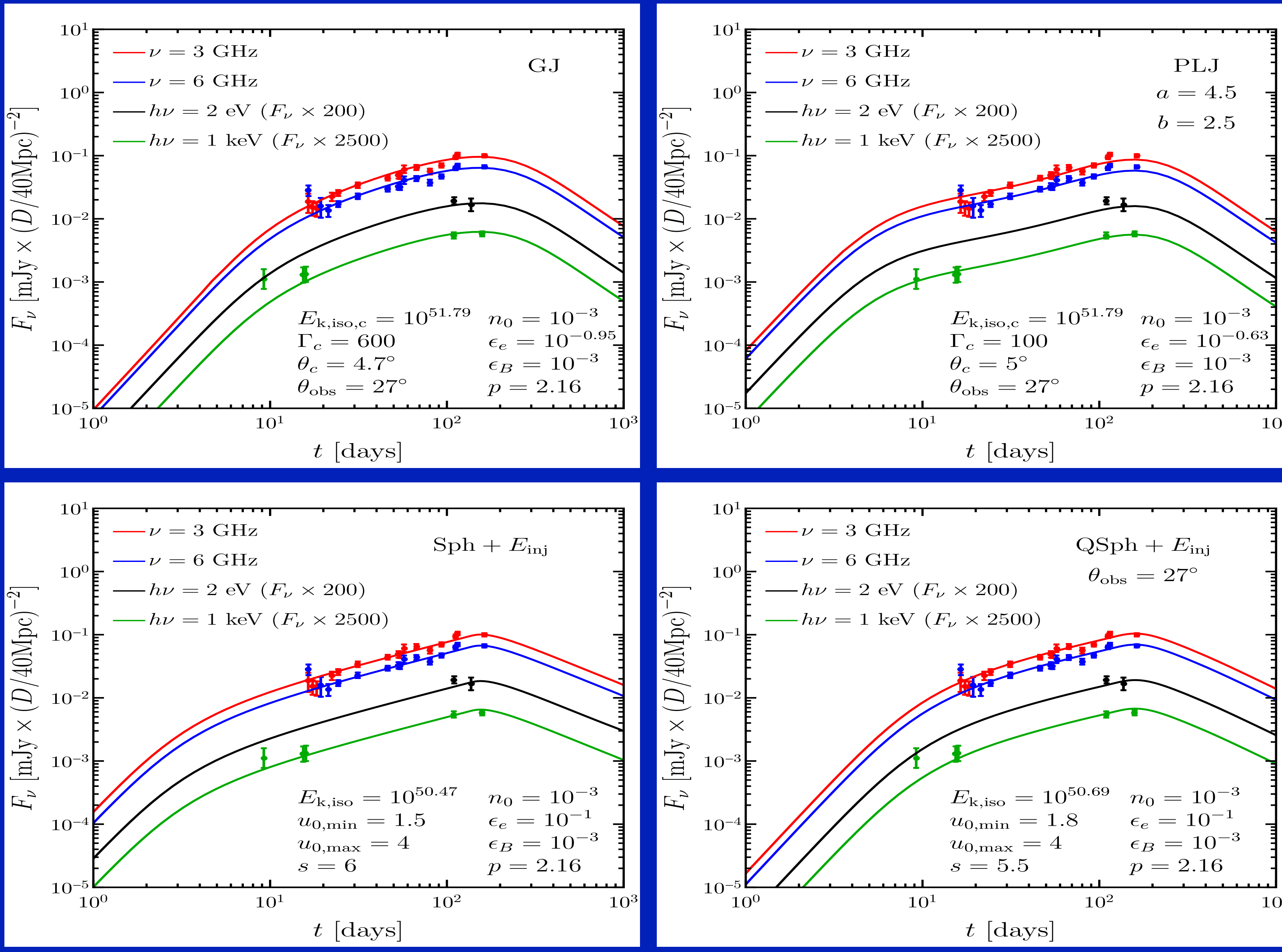
- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = dE/d\Omega$, Γ_0-1) $\Gamma_c = 600$, $\theta_c = 4.7°$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c\Theta^{-a}$, $\Gamma_0-1 = (\Gamma_c-1)\Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$ $\Gamma_c = 100$, $\theta_c = 5°$, $a = 4.5$, $b = 2.5$
- As there is a lot of freedom we fixed: $p = 2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{obs} = 27°$





The outflow structure: breaking the degeneracy

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



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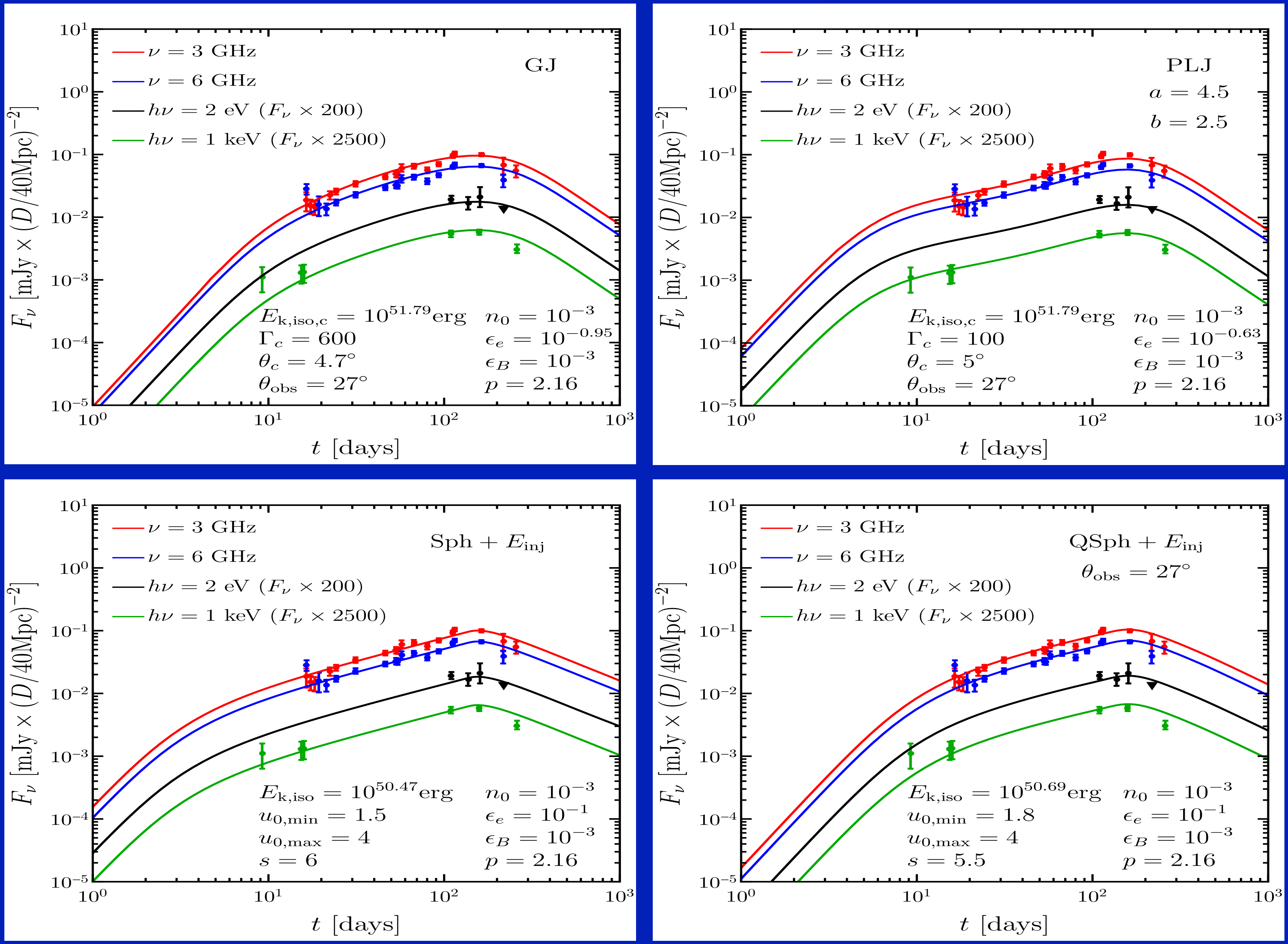
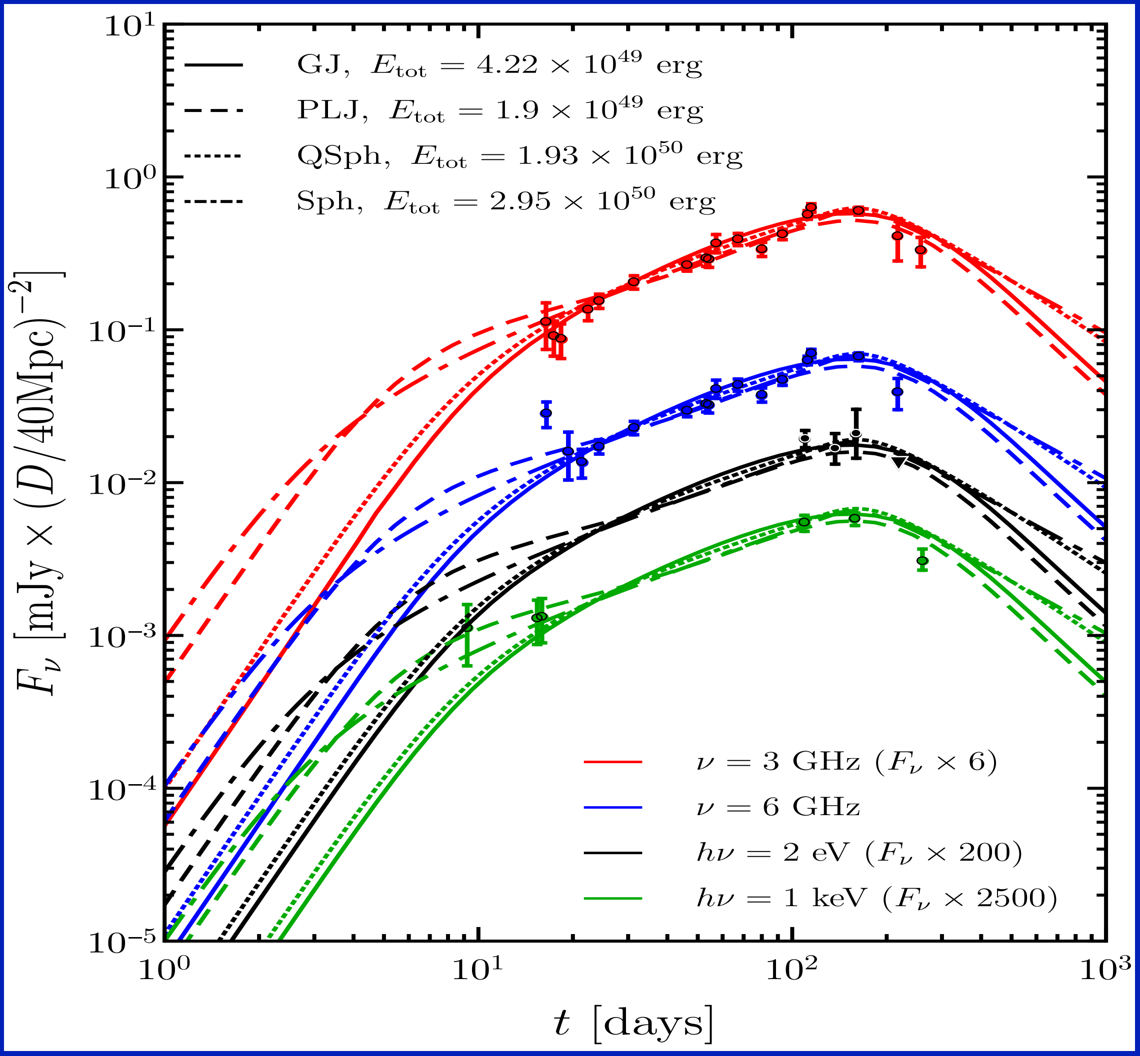


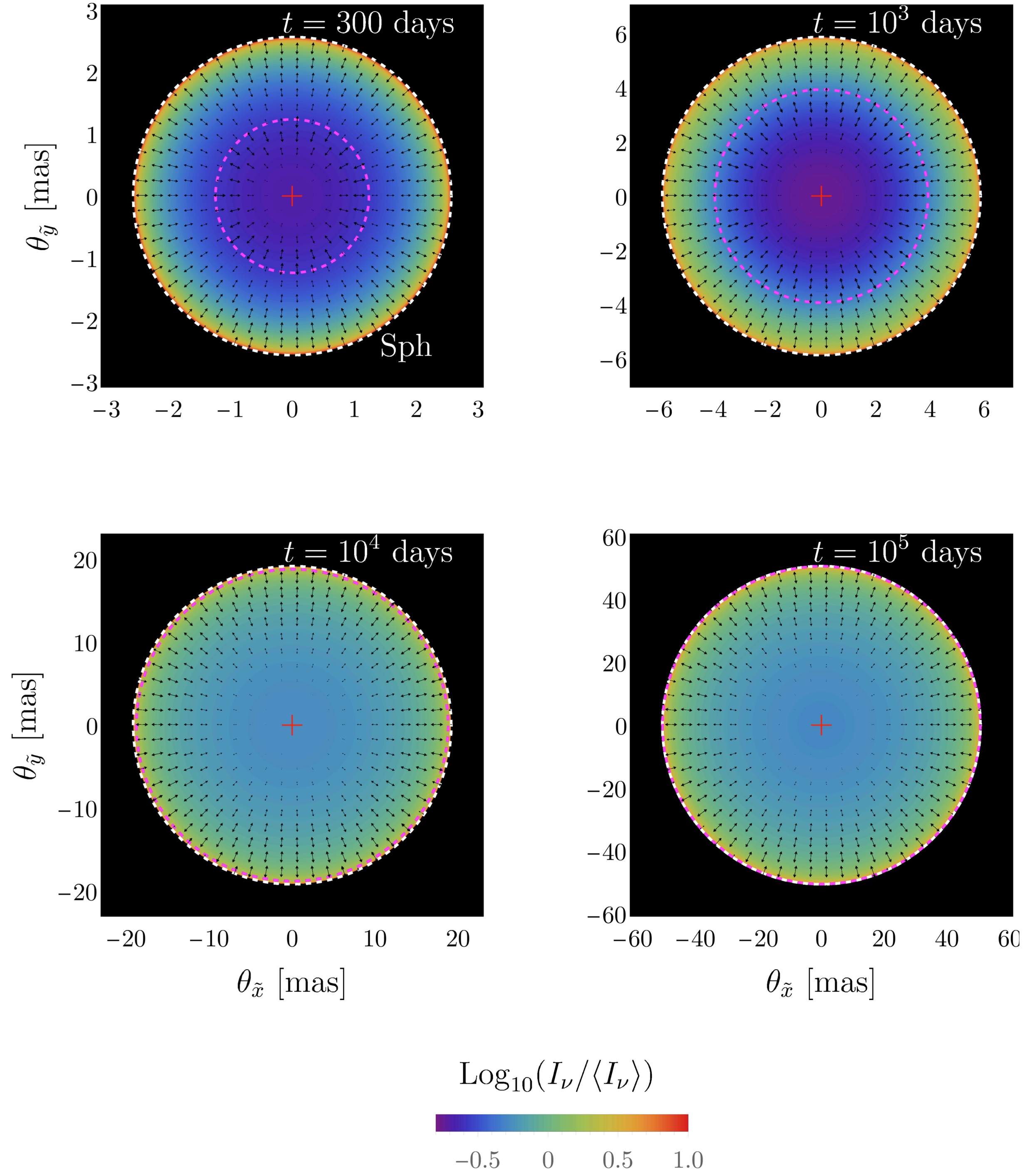
The outflow structure: breaking the degeneracy

- New data that came out established a peak at t_p ~150 days
- The jet models decay faster (slightly preferred by the latest data)

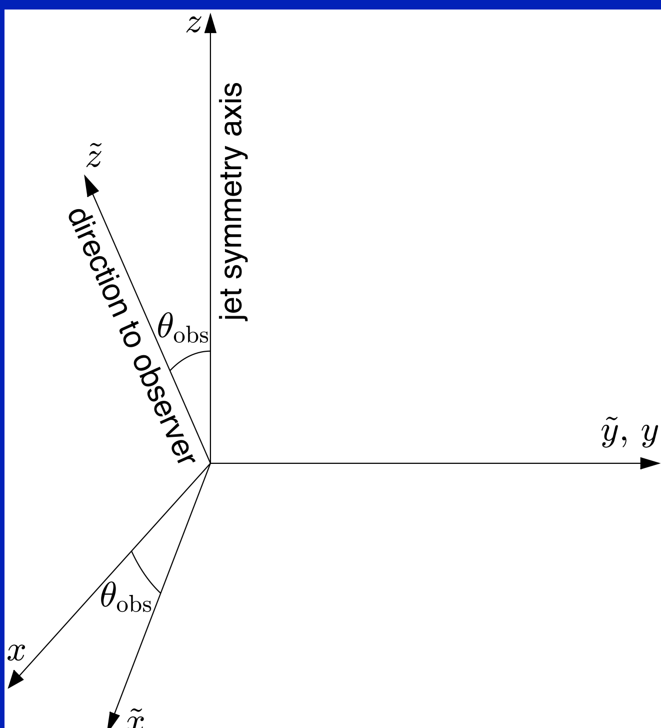


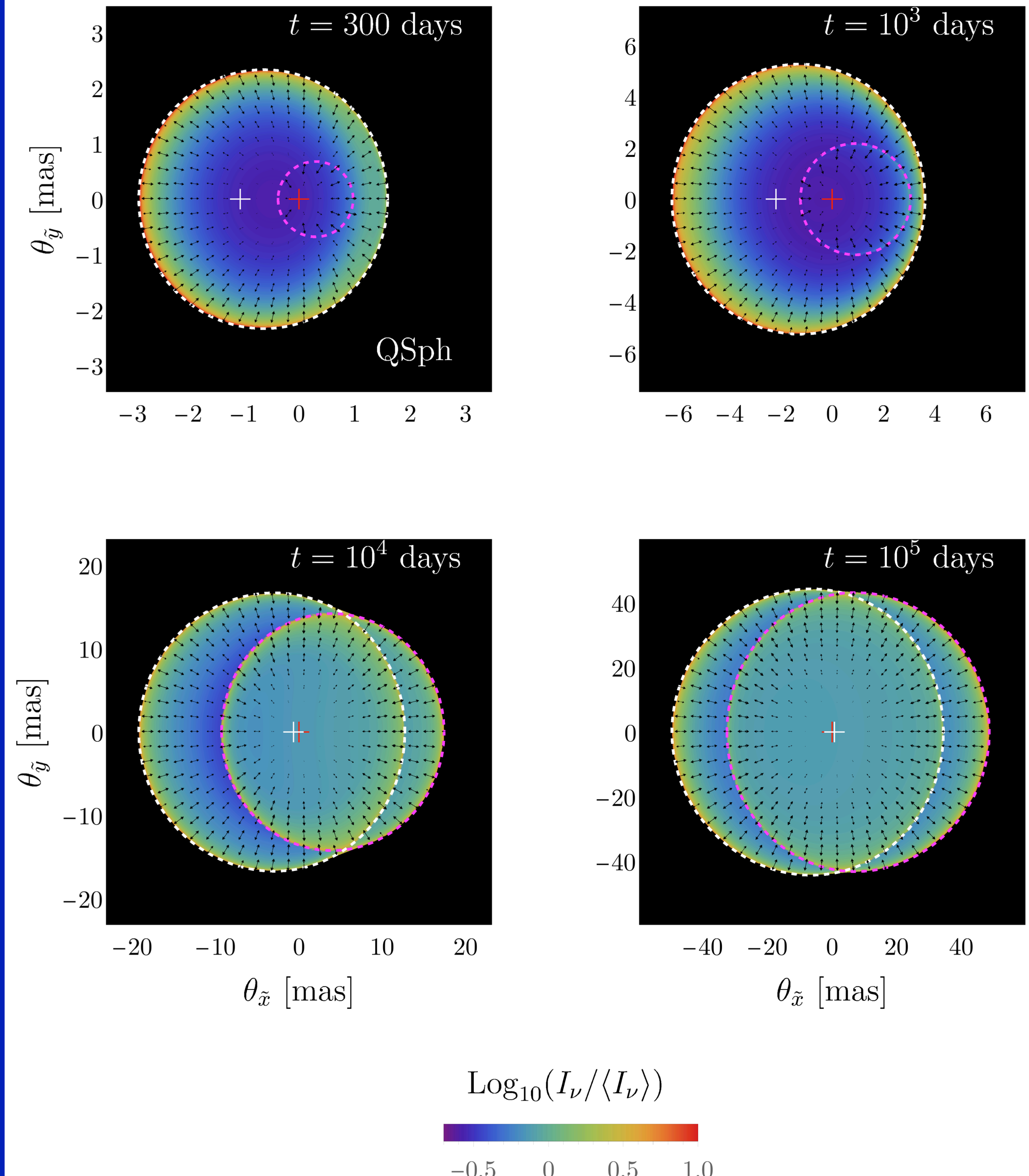
Decay: ~$t^{-2.2}$
(Mooley+18)

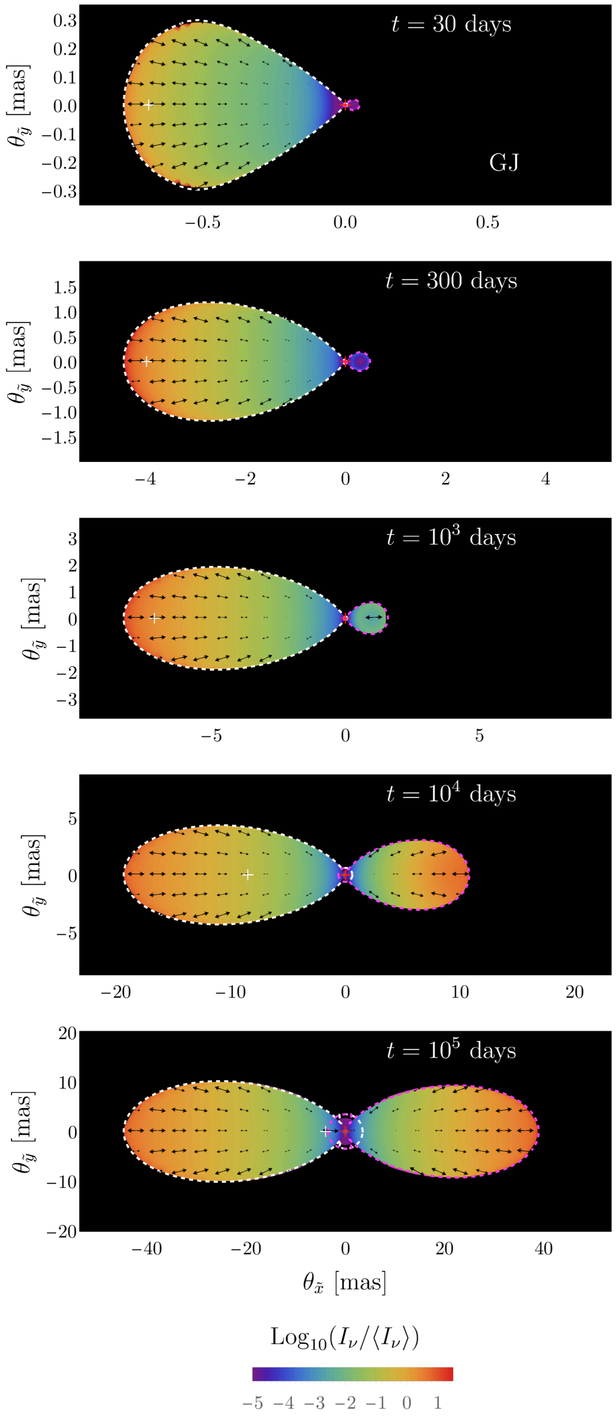
Afterglow Images: Sph + E_{inj}



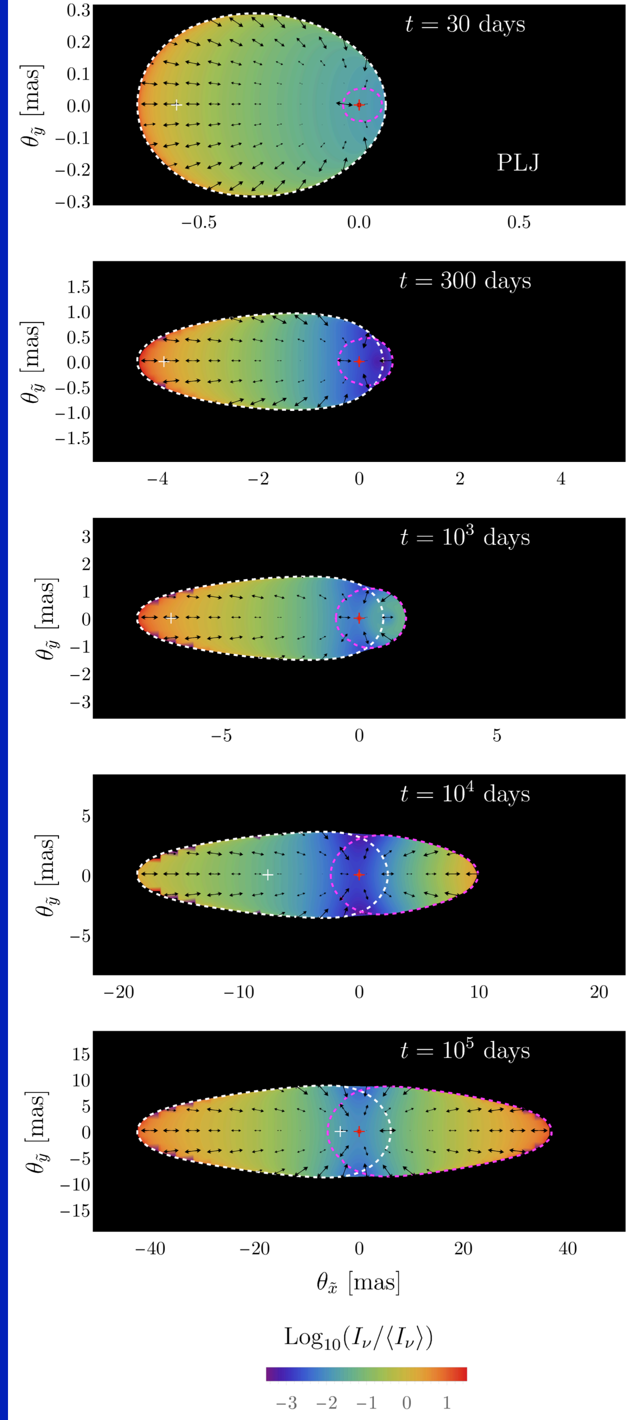
Afterglow Images: QSph + E_{inj}





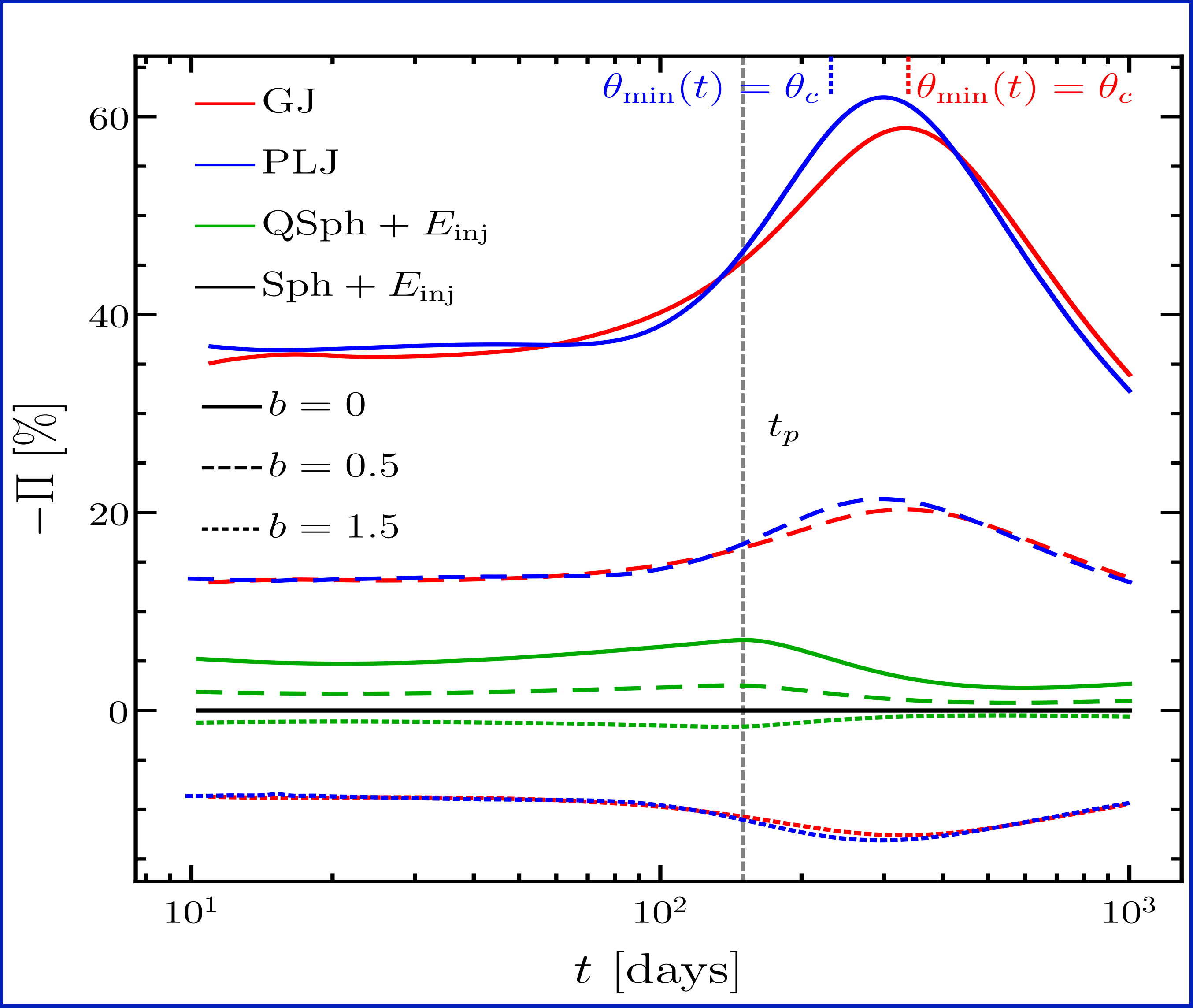


Afterglow Images: GJ, PLJ



Linear Polarization

- Assuming a shock-produce B-field with $b \equiv 2\langle B_{\parallel}^2\rangle / \langle B_{\perp}^2\rangle$



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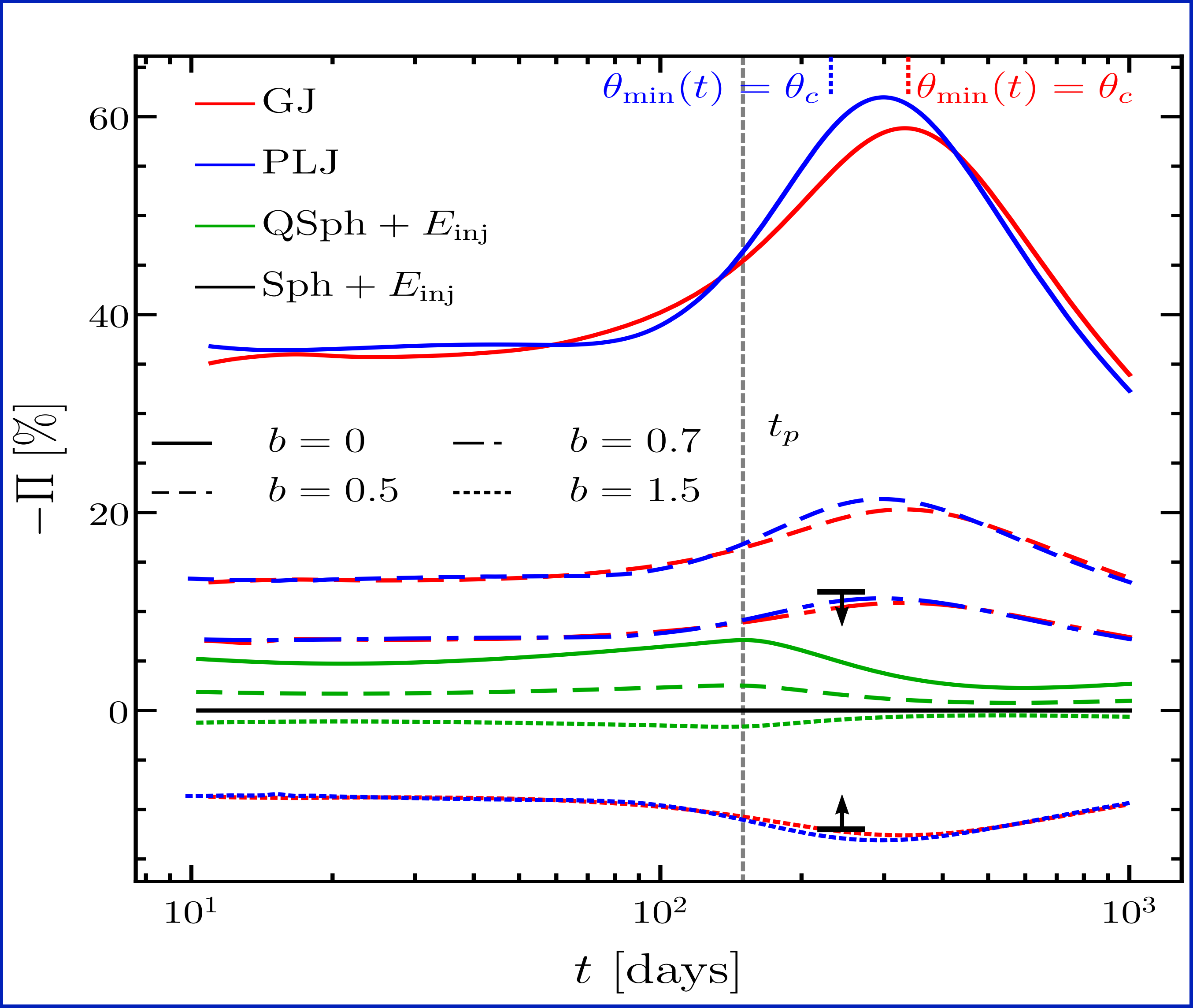
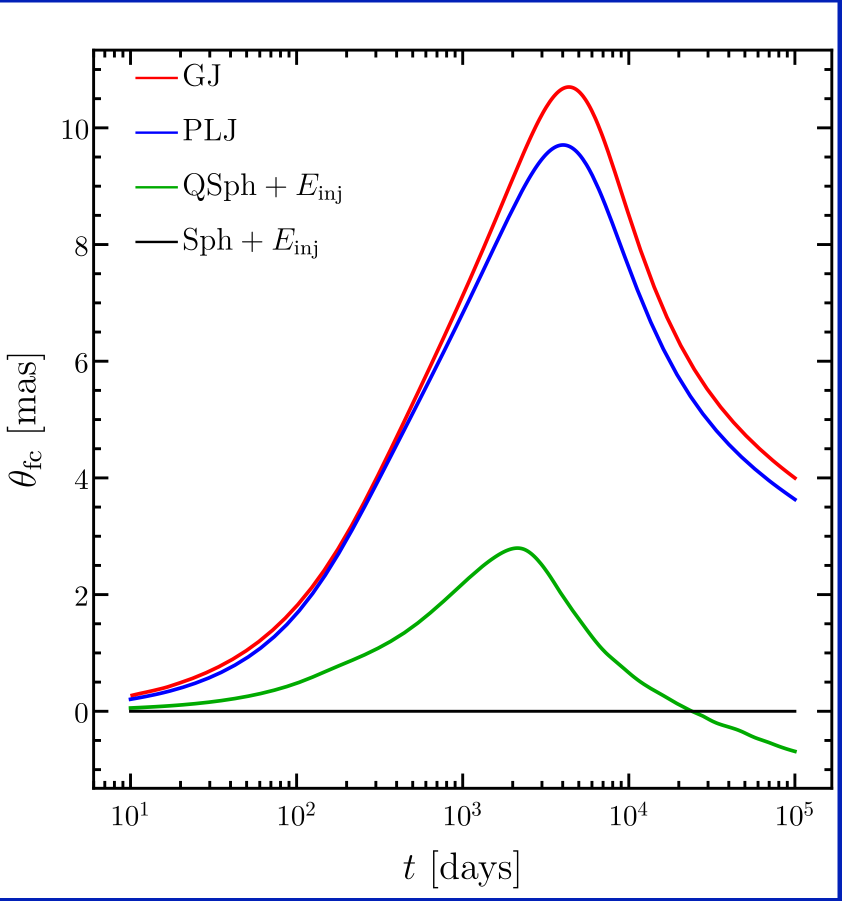


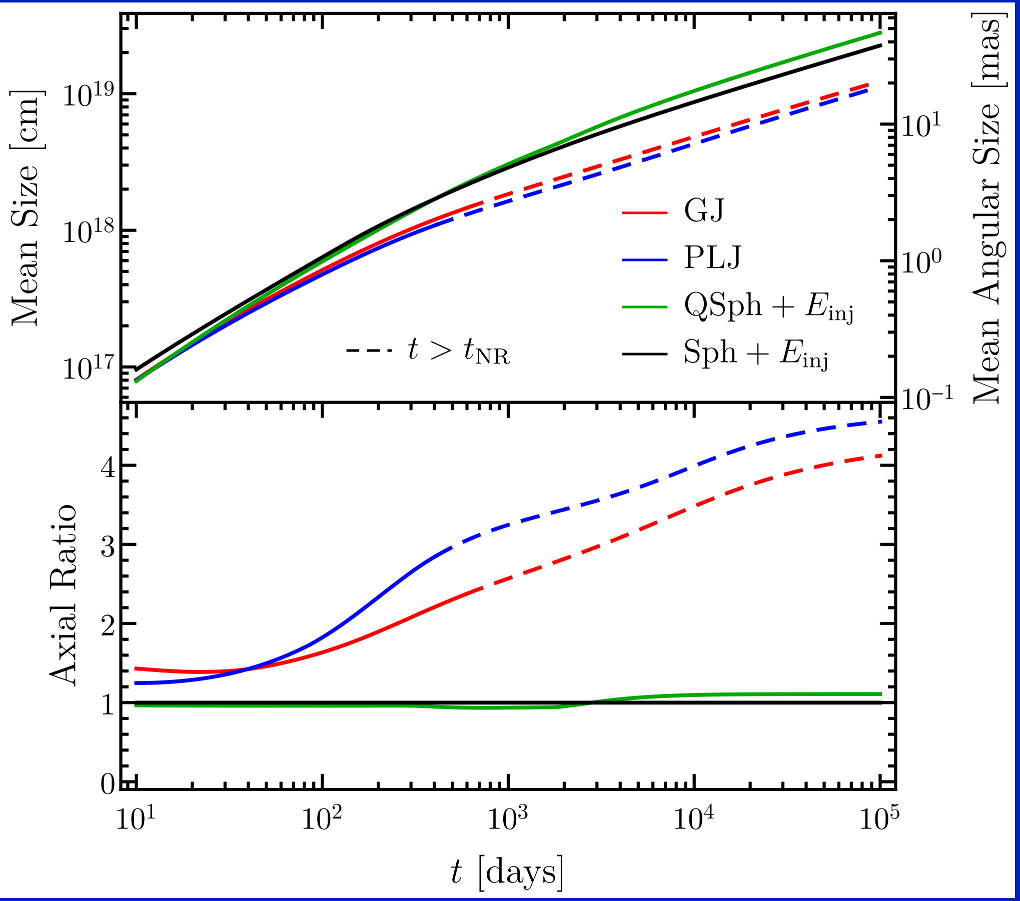
$0.7 \lesssim b \lesssim 1.5$ for jet models

New: upper limit on linear pol. @ 2.8 GHz (Corsi + 2018)

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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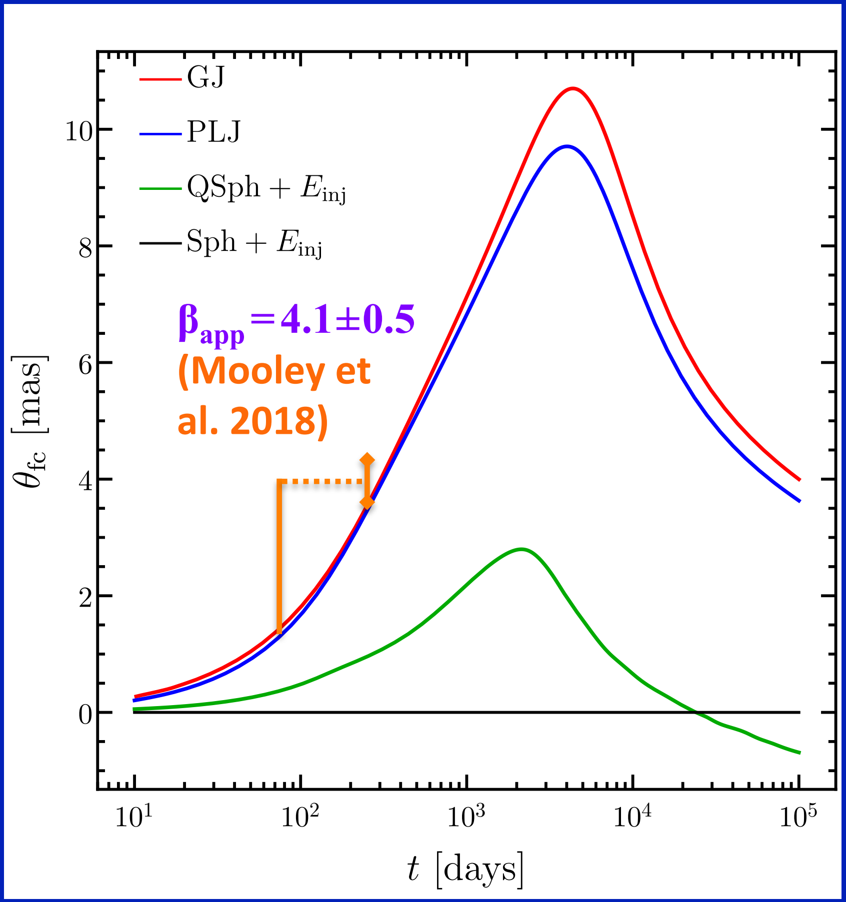

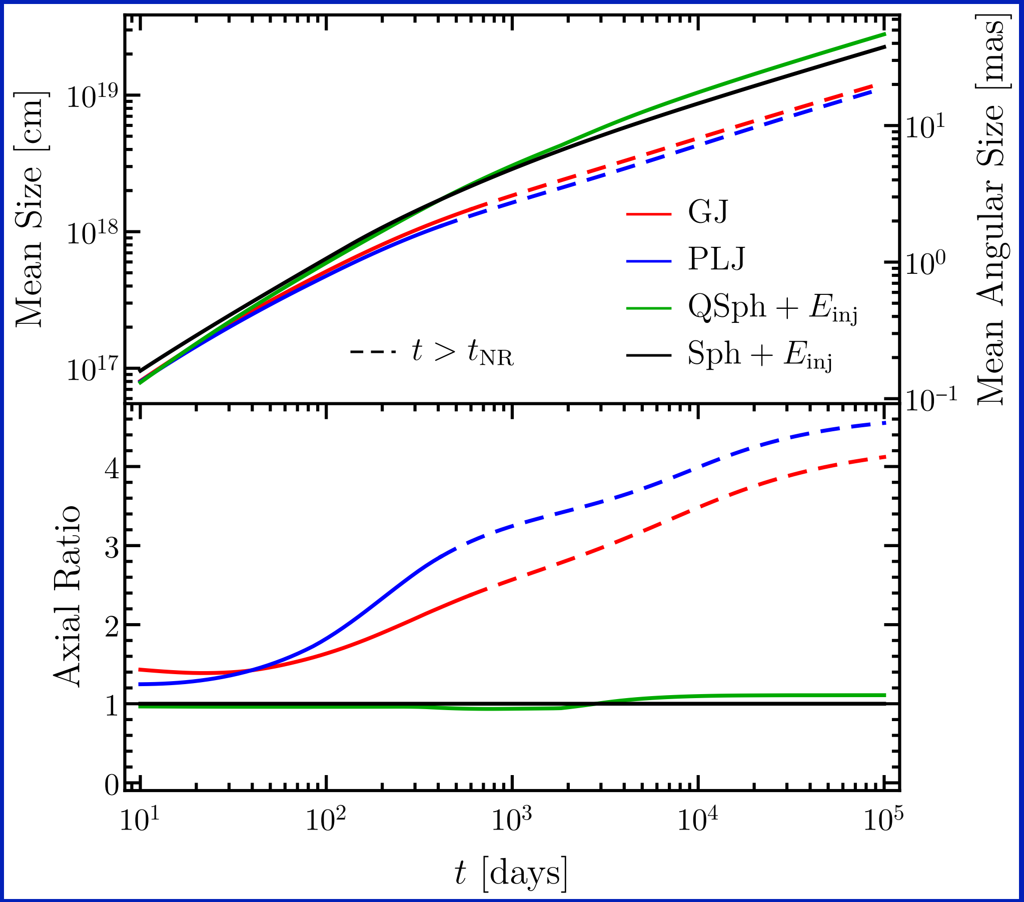

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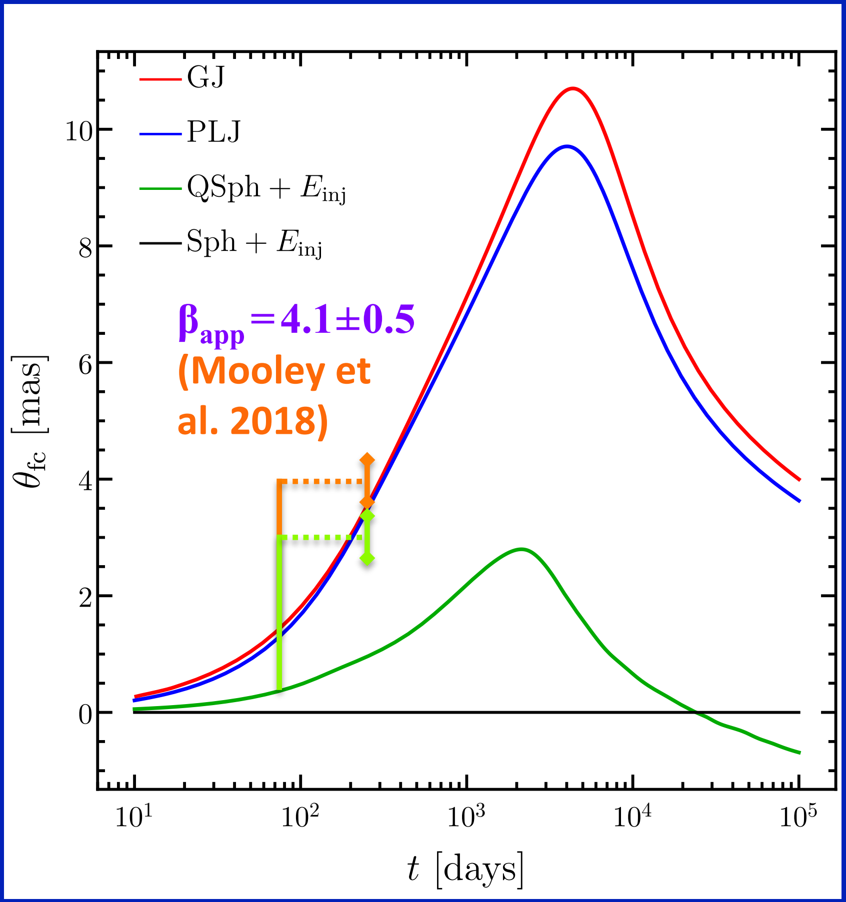

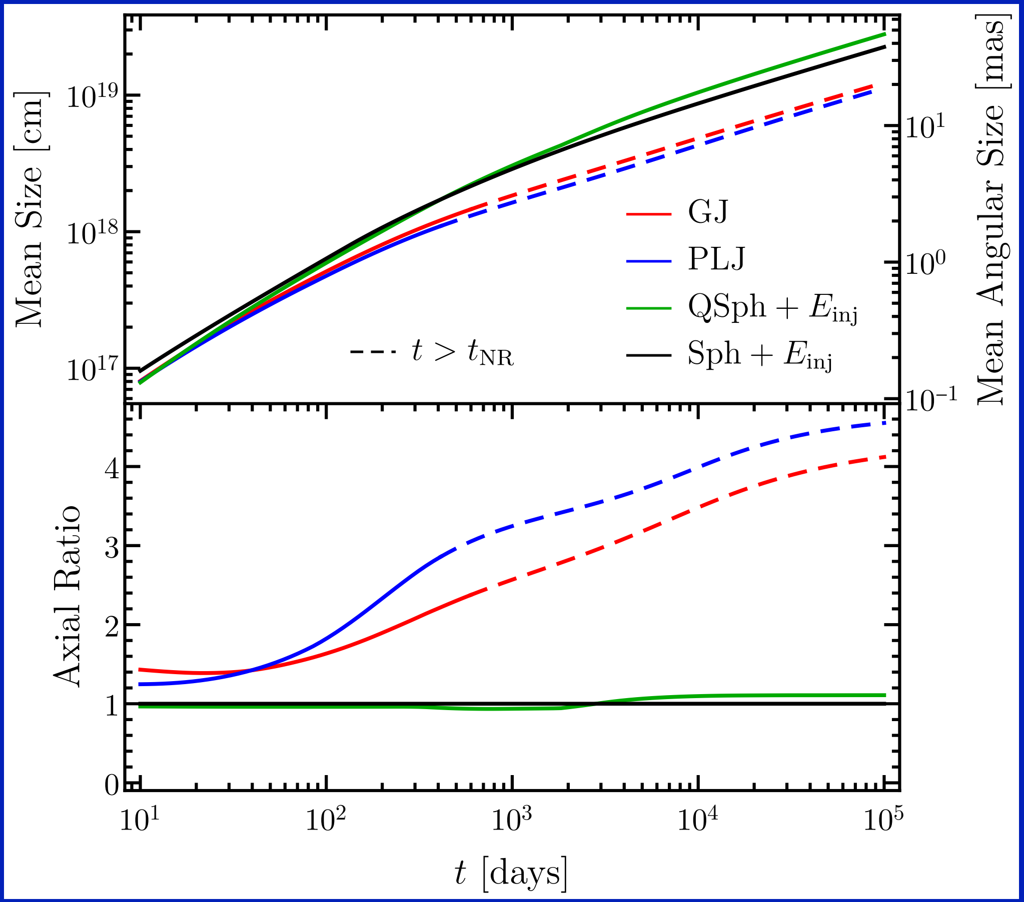

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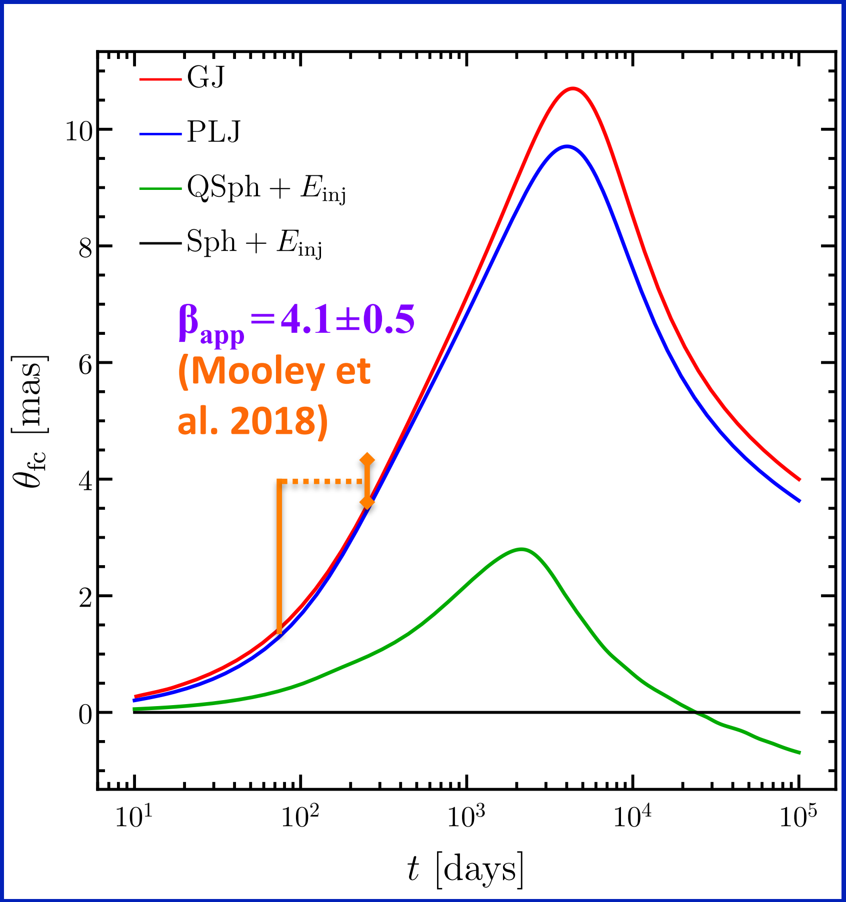
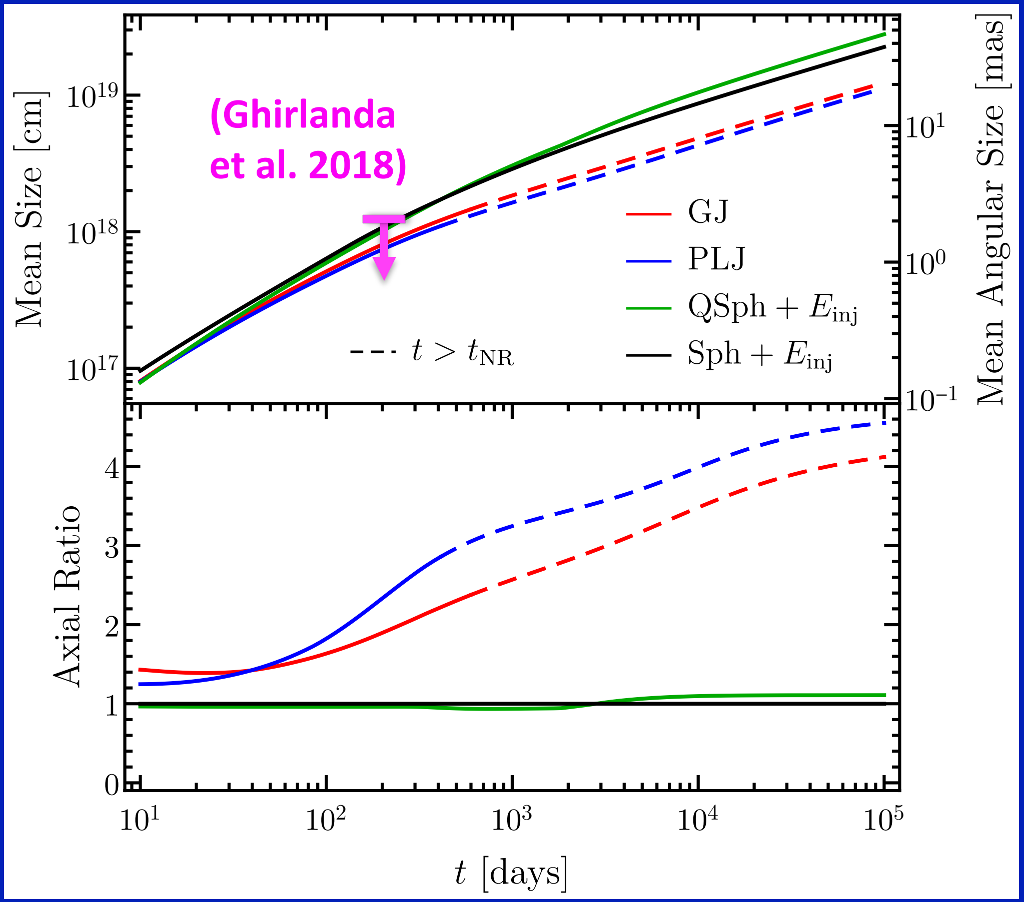
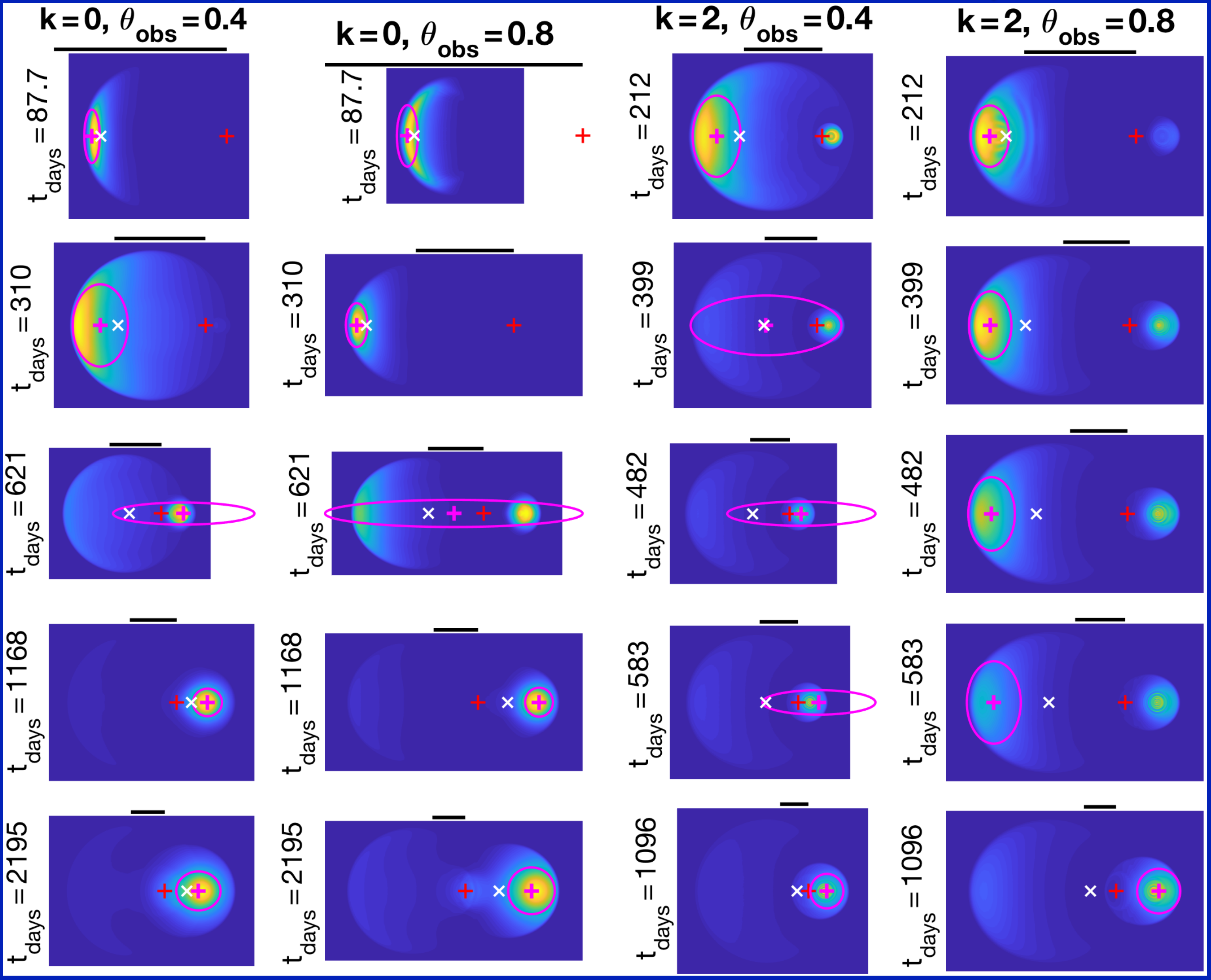




Afterglow Images: uniform jet simulations

(JG, De Colle & Remirez-Ruiz 2018)



Conclusions:

- GW170817/GRB170817A is a unique event with a wide range of implications
- First secure association of a sGRB with a NS-NS merger, but the sGRB is atypical (its afterglow, very low $E_{\gamma,iso}$)
- Merger Remnant: BH or HMNS → BH ⇒ $M_{max} \lesssim 2.17 M_{\odot}$
- 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 (challenging with image size or polarization alone)

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- New flux centroid motion observations: $\beta_{app} = 4.1 \pm 0.5$