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X-ray emission from gravitational wave sources

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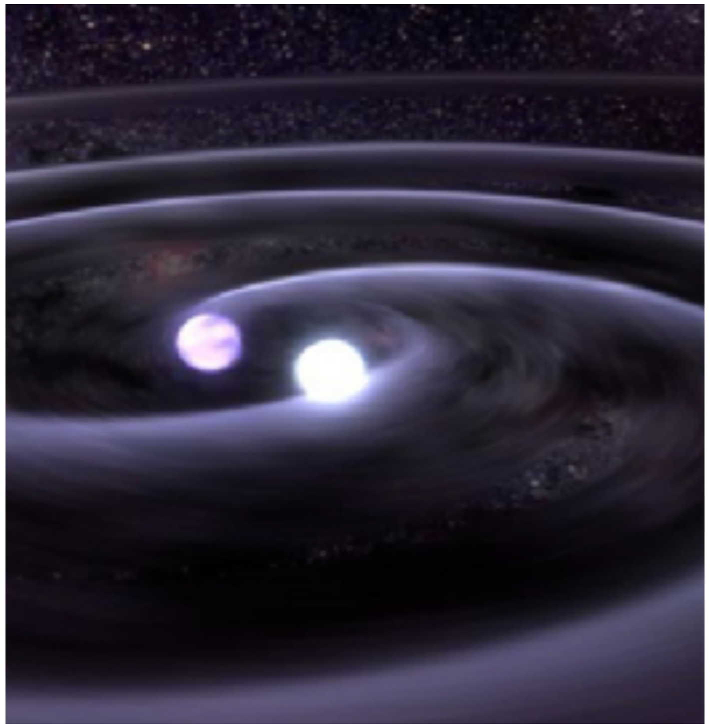
THESEUS Workshop - Napoli 5th October 2017

BNS mergers and EM counterparts



binary neutron star (BNS) mergers and neutron star-black hole (NS-BH) binary mergers

⇩

among the **most promising gravitational wave sources** for advanced LIGO and Virgo

	detection rate	best expectation
BNS	~(0.4-400)/yr	~40/yr
NS-BH	~(0.2-300)/yr	~10/yr

Abadie et al. 2010

rewards of a combined GW-EM detection:

- observed EM signals would incredibly enhance the chances of GW detection
- EM follow-up observations of a detected GW source is the ultimate way to unravel the nature of the system, by providing crucial and complementary information
- luminosity distance form GWs and redshift from EM signals will allow to measure H_0
- joint GW-EM signals can confirm the astrophysical origin of short gamma-ray bursts

EM counterparts to BNS mergers

	BRIGHT	ISOTROPIC	LONG-LASTING	HIGH OCCURRENCE	DISTINGUISH BNS AND NS-BH
SGRB (prompt)	✓	✗	✗	✓ / ✗	✗
SGRB (off-axis)	✓ / ✗	✓ / ✗	✓	✓ / ✗	✗
SGRB (jet afterglows)	✓ / ✗	✓ / ✗	✓	✓ / ✗	✗
KILONOVA	✓ / ✗	✓	✓	✓	✗
RADIO TRANSIENTS	✗	✓	✓	✓	✗
NS SPINDOWN	✓	✓	✓ / ✗	✓ / ✗	✓

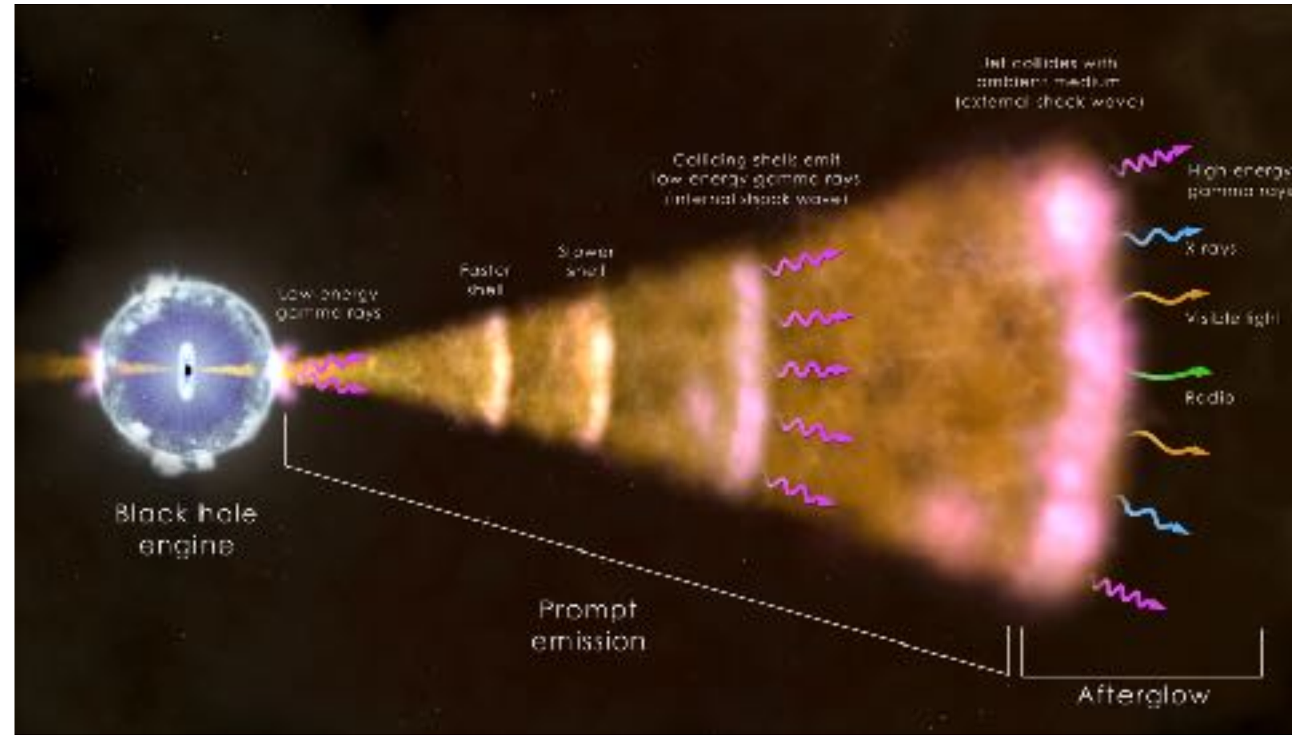
EM counterparts to BNS mergers

	BRIGHT	ISOTROPIC	LONG-LASTING	HIGH OCCURRENCE	DISTINGUISH BNS AND NS-BH
SGRB (prompt)	✓	✗	✗	✓/✗	✗
SGRB (off-axis)	✓/✗	✓/✗	✓	✓/✗	✗
SGRB (jet afterglows)	✓/✗	✓/✗	✓	✓/✗	✗
KILONOVA	✓/✗	✓	✓	✓	✗
RADIO TRANSIENTS	✗	✓	✓	✓	✗
NS SPINDOWN	✓	✓	✓/✗	✓/✗	✓

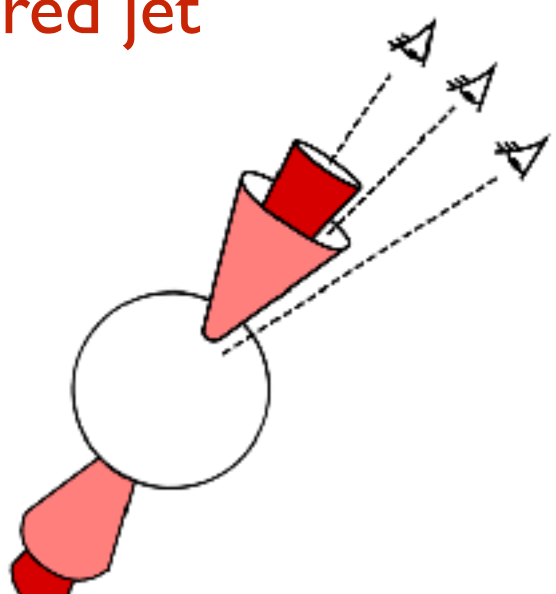
Off-axis SGRB and jet afterglows

- forward shock emission
  (canonical afterglow)

  - well studied for long GRBs
  - X-rays, but also optical and radio

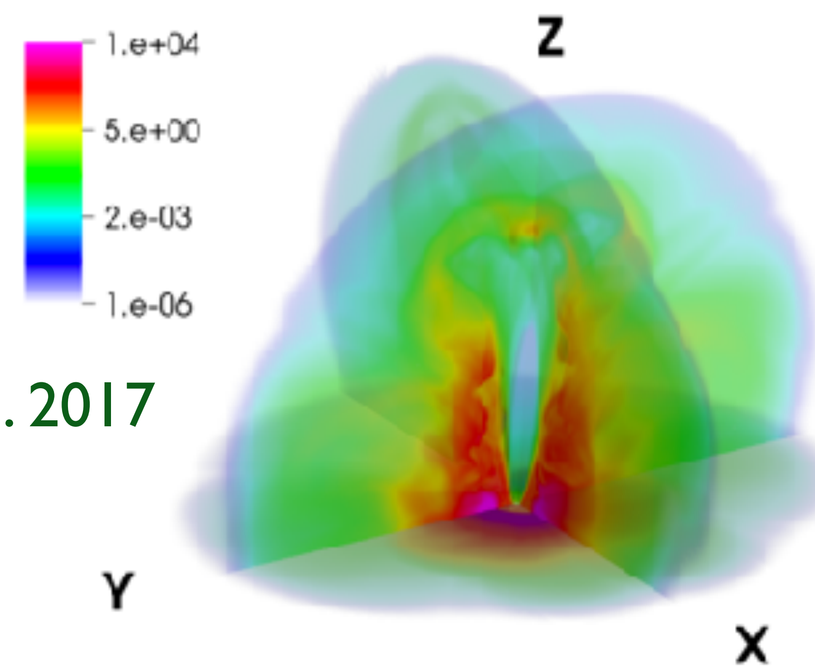


- off-axis emission: structured jet



Salafia et al. 2015

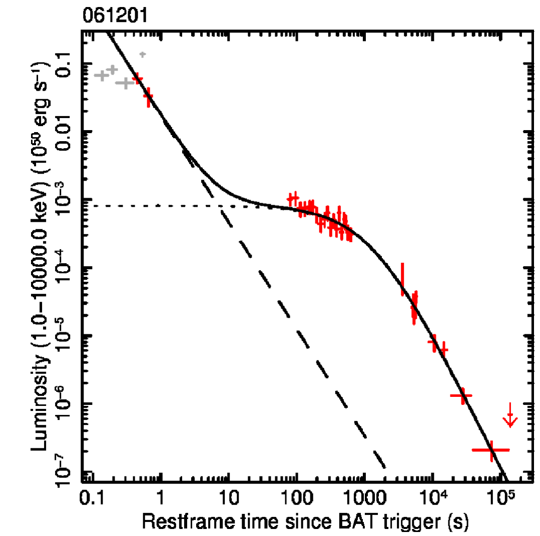
- off-axis emission: cocoon emission

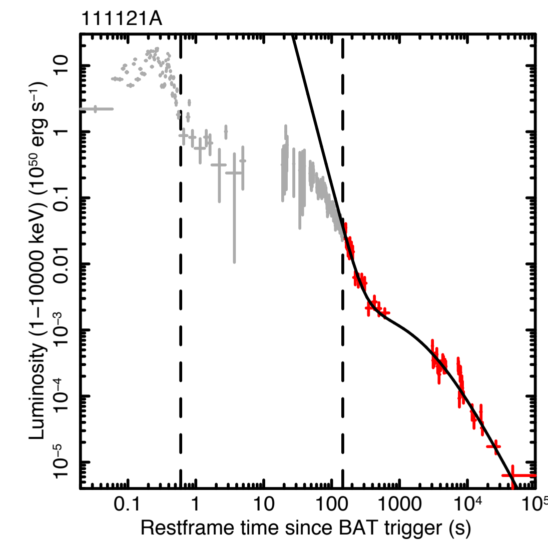


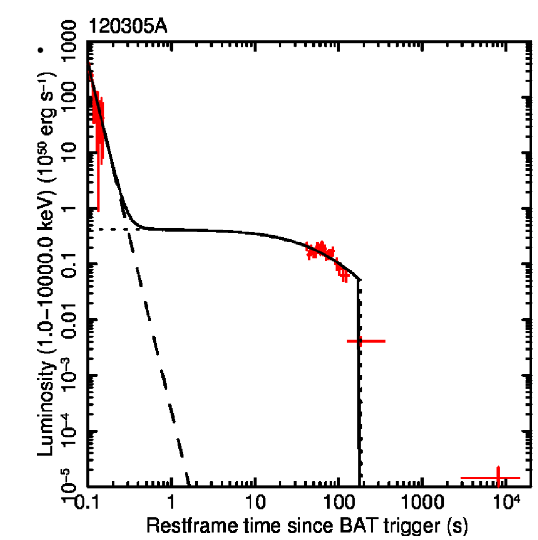
Lazzati et al. 2017

X-ray afterglows of SGRBs

- Swift revealed that most SGRBs are accompanied by long-duration $(\sim 10^2 - 10^5\ \mathrm{s})$ and high-luminosity $(10^{46} - 10^{51}\ \mathrm{erg/s})$ X-ray afterglows
- total energy can be higher than the SGRB itself
- hardly produced by BH-torus system - they suggest ongoing energy injection from a long-lived NS







Gompertz et al. 2013
Rowlinson et al. 2013

MAGNETAR MODEL

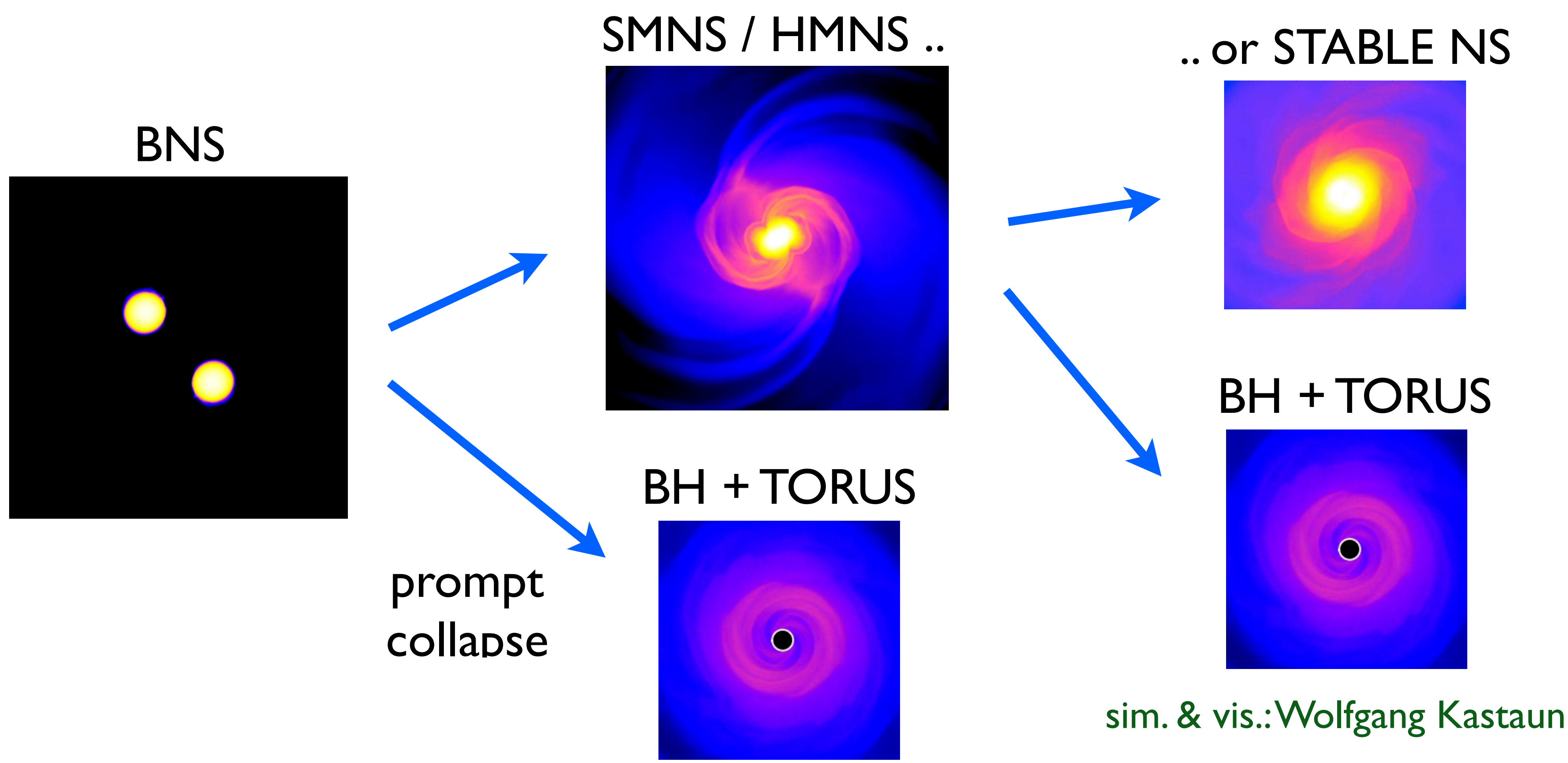
Zhang & Meszaros 2001
Metzger et al. 2008

X-ray emission ⟶ spindown of a uniformly rotating NS with a strong surface magnetic field $\gtrsim 10^{14} - 10^{15}\,\mathrm{G}$

dipole spindown

$$L_{\mathrm{sd}}(t) \sim B^2 R^6 \Omega_0^4 \left(1 + \frac{t}{t_{\mathrm{sd}}}\right)^{-2}$$

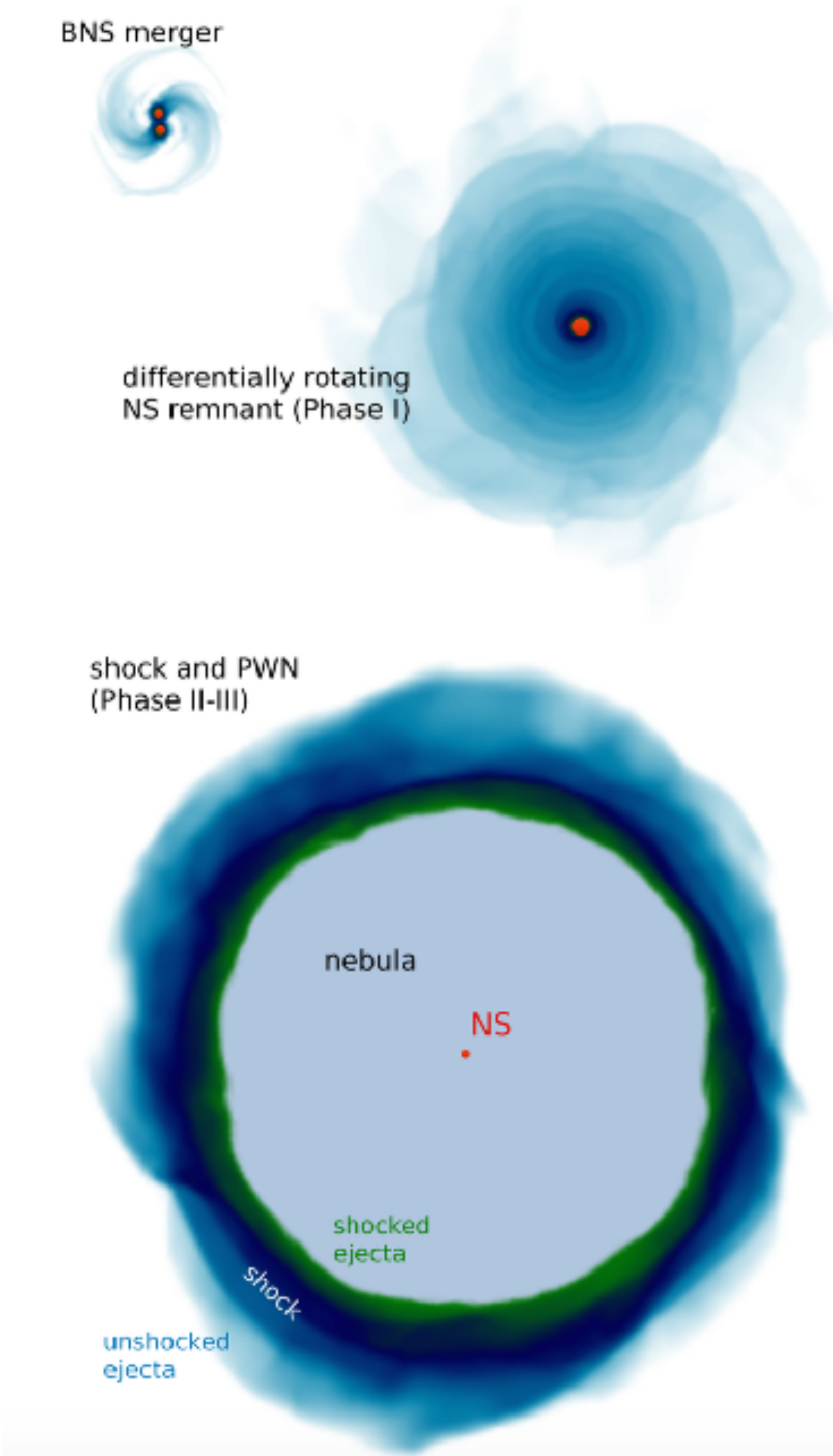
Product of BNS mergers



- observation of $\sim 2\ \mathrm{M}_\odot$ NSs Demorest et al. 2010, Antoniadis et al. 2013
- rotation allows to support higher masses $M_{\rm supra} \sim 1.2\ M_{\rm TOV} \gtrsim 2.4\ \mathrm{M}_\odot$ Lasota et al. 1996
- progenitor masses peak around $1.3 - 1.4\ \mathrm{M}_\odot$ ➔ BMP mass likely $< 2.5\ \mathrm{M}_\odot$
  Lattimer 2012 Belczynski et al. 2008

LONG-LIVED NS IS A VERY LIKELY OUTCOME OF A BNS MERGER!

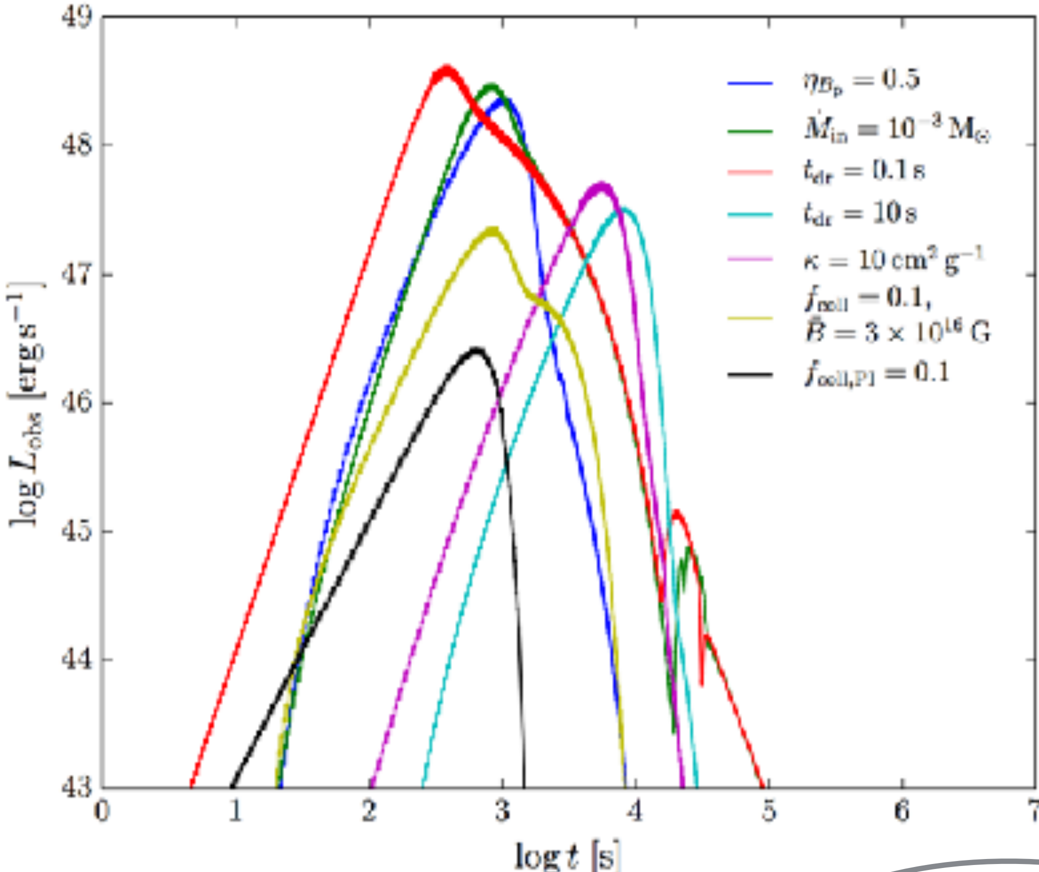
EM emission from the long-lived NS remnant



- spindown-powered transients studied only recently
  e.g. Yu et al. 2013
  Metzger & Piro 2014
  Siegel & Ciolfi 2016a,b
- differentially rotating NS remnant
  matter ejection as baryon-loaded wind (neutrino- and/or magnetically-induced)
- uniformly rotating NS
  dipole spindown radiation inflates a photon-pair plasma nebula inside ejecta cavity
- radiation reprocessed by the ejecta, finally escaping
- along the evolution, NS can collapse to BH (if supramassive)

EM emission from the long-lived NS remnant

Siegel & Ciolfi 2016a,b

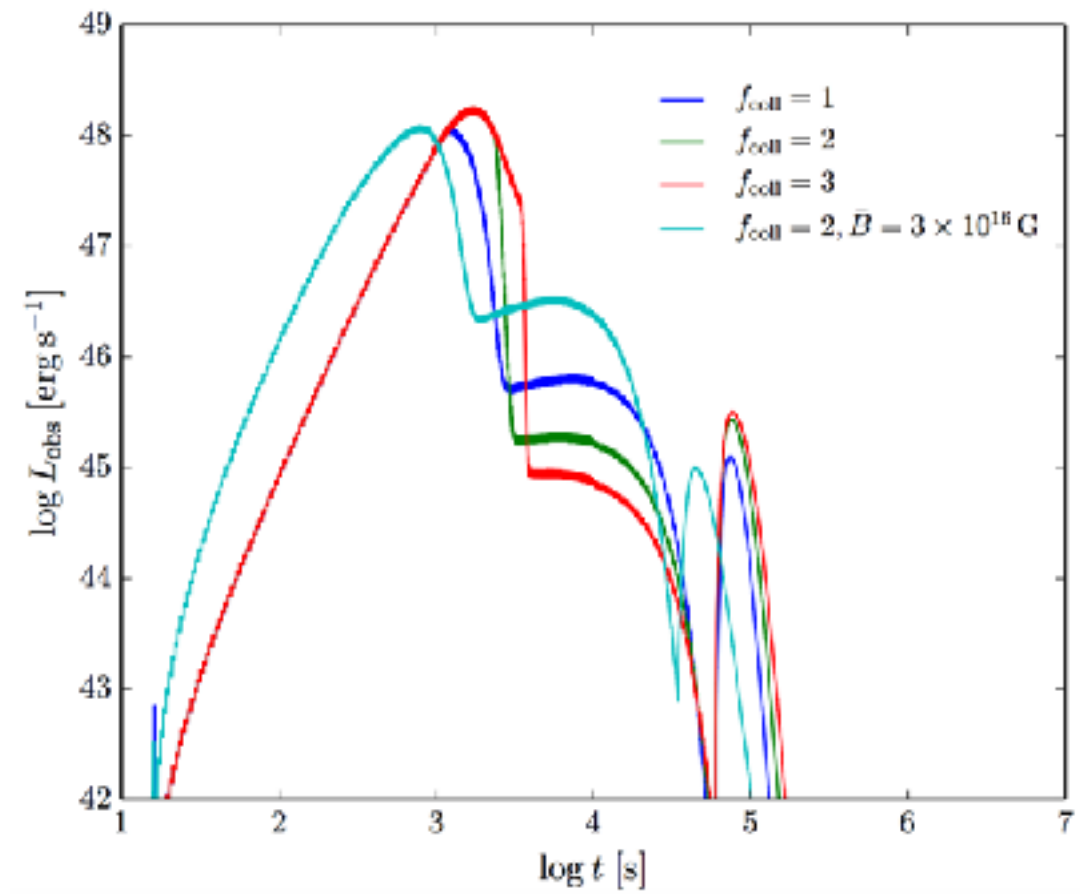


- signal peaks at 10^2-10^4 s (similar range for duration), with ~10-100 s delayed onset
- luminosities 10^{46}-10^{48} erg/s
- mostly in the soft X-rays

non-collapsing models

Luminosity in soft X-ray band (0.3-10 KeV)

collapsing models



Conclusions

X-ray emission from BNS mergers include

- signals closely related to SGRB jet evolution (side emission, cocoon, forward shock afterglows..)
- spindown-powered transients from long-lived merger remnant (massive NS)

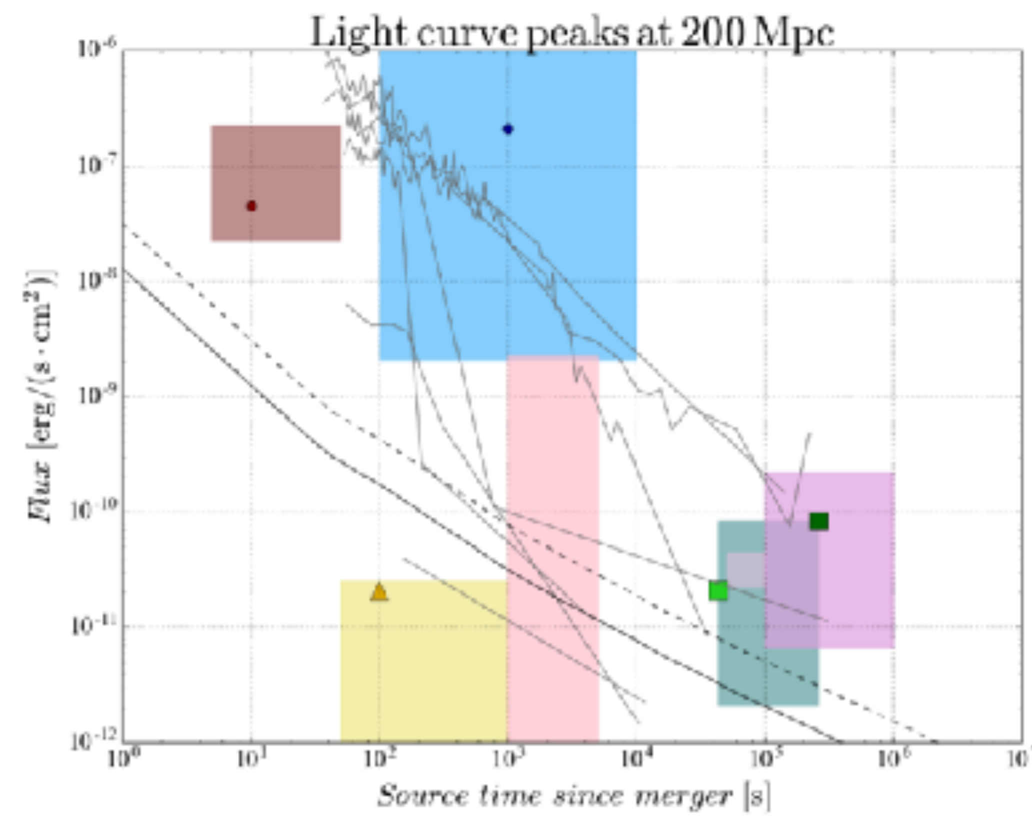
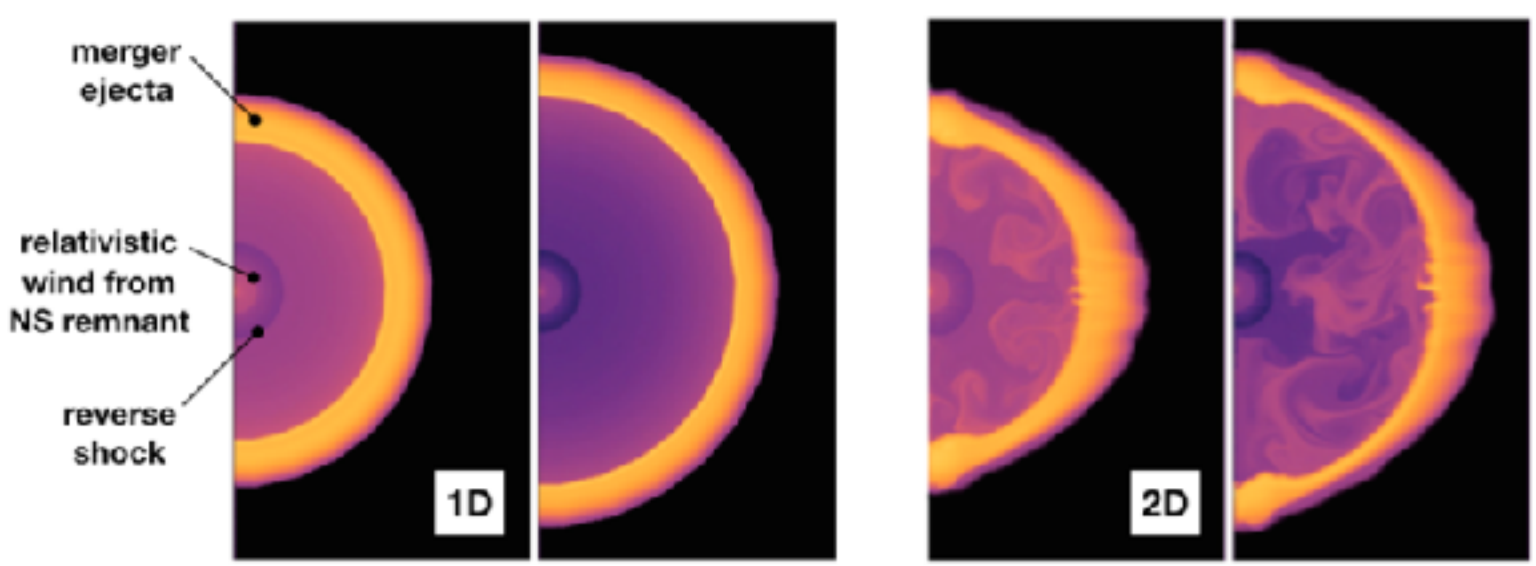


figure by S. Vinciguerra

next step:

from semi-analytical 1D models to 2D hydro simulations



in collaboration with S. Ascenzi

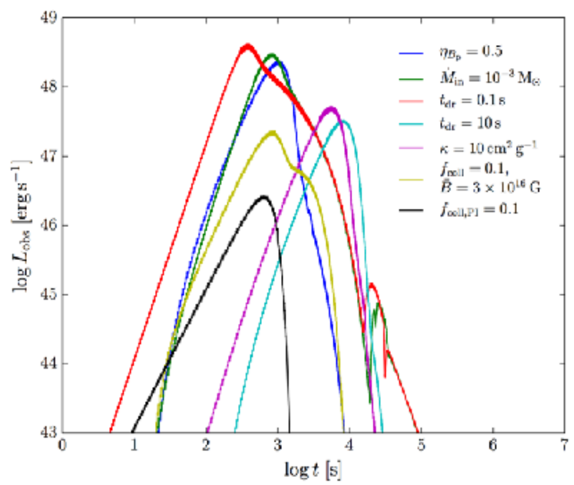
← PRELIMINARY!

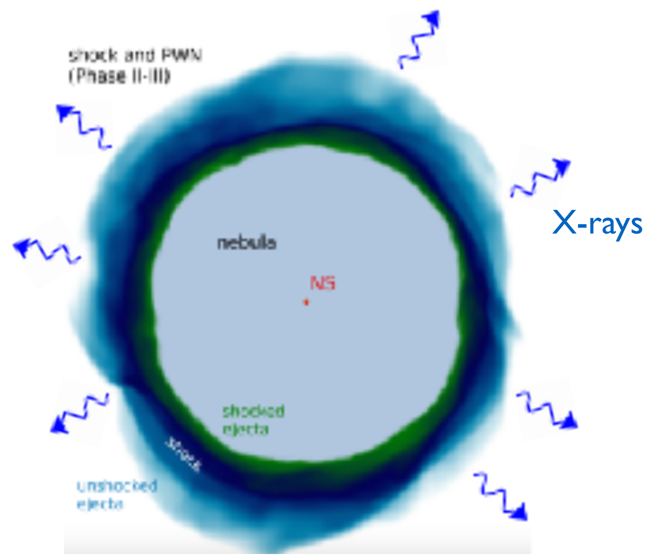
BACKUP SLIDES

X-ray flashes powered by NS spindown

Ciolfi 2016

- are all XRFs really a subclass of long GRBs?

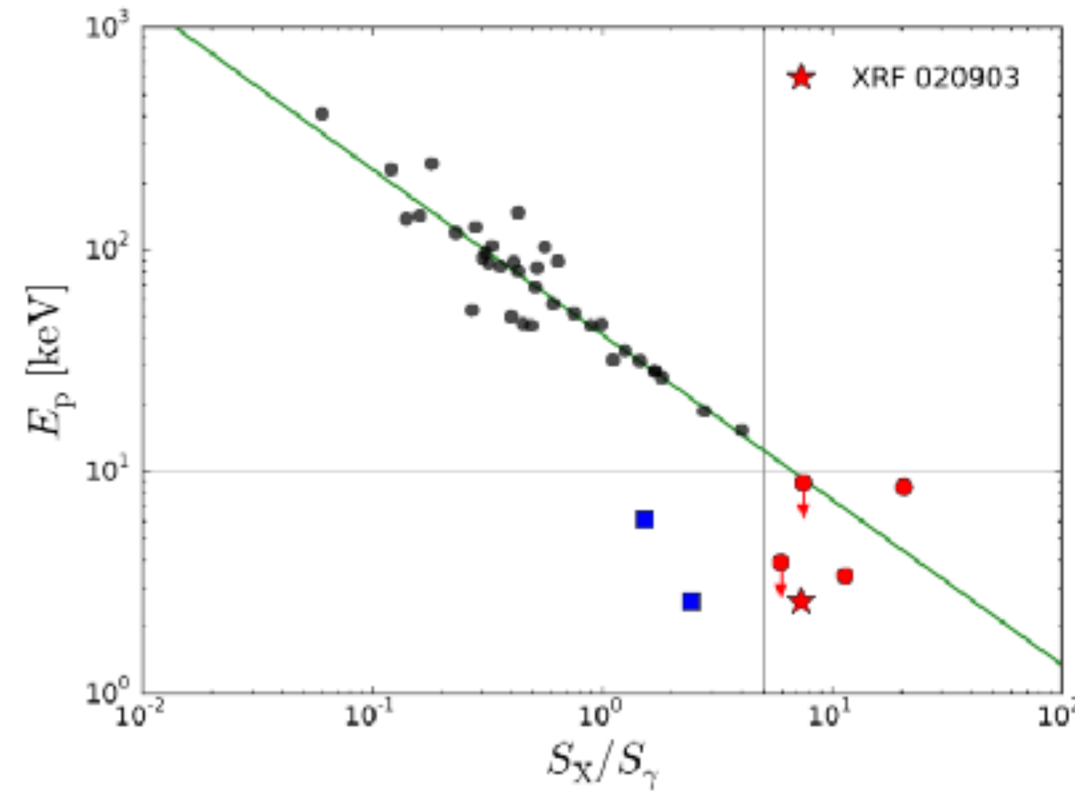


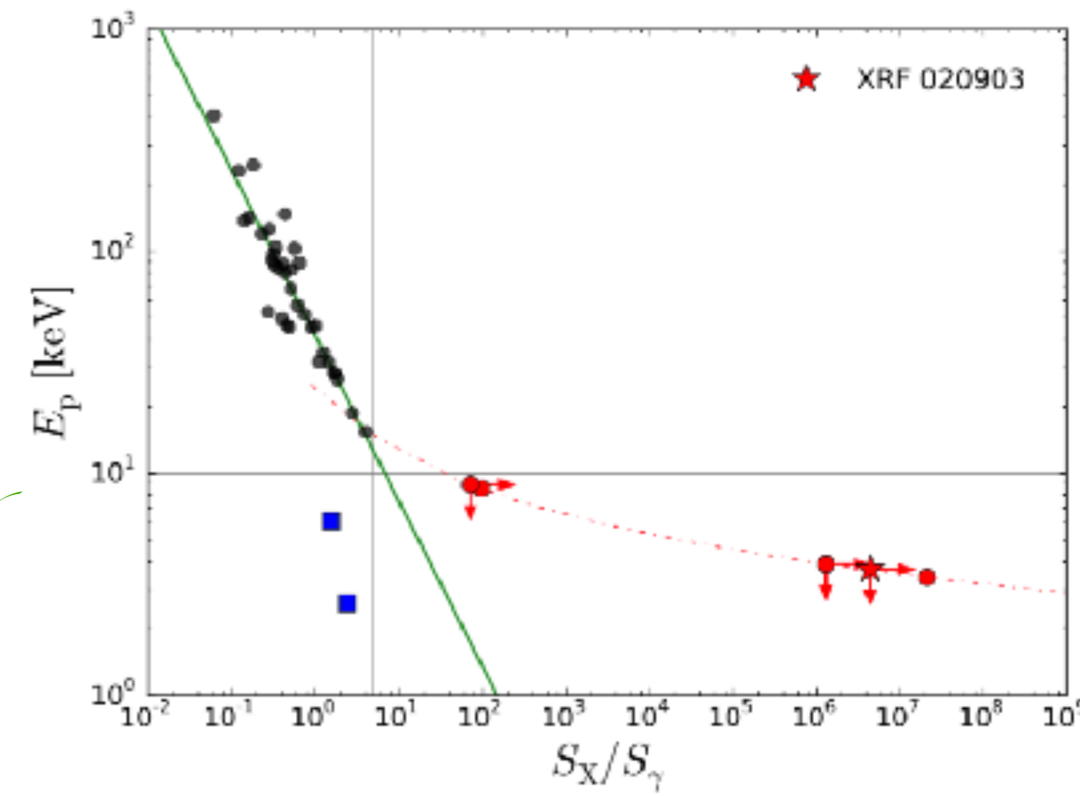


- spindown-powered X-ray emission from long-lived NSs matches the high-energy emission of soft XRFs (those emitting no gamma-rays)

spectral properties
- lack of gamma-rays ✓
- mainly thermal ✓
- black body T and its evolution ✓

lightcurve properties
- luminosity ✓
- duration ✓





EM emission from the long-lived NS remnant

Siegel & Ciolfi 2016a, 2016b

isotropy → 1D model

set of coupled ODEs for the evolution

I

$$\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} = v_{\mathrm{w}}(R_{\mathrm{ej}}(t), t)$$

$$\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} = L_{\mathrm{EM}}(t) + \frac{\mathrm{d}E_{\mathrm{th,NS}}}{\mathrm{d}t} - L_{\mathrm{rad}}(t)$$

II

$$\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} = v_{\mathrm{w}}(R_{\mathrm{ej}}(t), t)$$

$$\frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t} = v_{\mathrm{sh}}(t)$$

$$\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} = \frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t} - \frac{\mathrm{d}\Delta_{\mathrm{sh}}}{\mathrm{d}t}$$

$$\frac{\mathrm{d}E_{\mathrm{th,sh}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\mathrm{sh}}}{\mathrm{d}t} + \frac{\mathrm{d}E_{\mathrm{th,vol}}}{\mathrm{d}t} + \frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t} - L_{\mathrm{rad,in}}(t)$$

$$\frac{\mathrm{d}E_{\mathrm{th,ush}}}{\mathrm{d}t} = -\frac{\mathrm{d}E_{\mathrm{th,vol}}}{\mathrm{d}t} - L_{\mathrm{rad}}(t)$$

$$\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\mathrm{th,sh}}}{\mathrm{d}t} + \frac{\mathrm{d}E_{\mathrm{th,ush}}}{\mathrm{d}t}$$

$$\frac{\mathrm{d}E_{\mathrm{nth}}}{\mathrm{d}t} = -\frac{E_{\mathrm{nth}}}{R_{\mathrm{n}}}\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} - \frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t} + L_{\mathrm{rad,in}}(t) + \eta_{\mathrm{TS}}[L_{\mathrm{sd}}(t) + L_{\mathrm{rad,pul}}(t)]$$

$$\frac{\mathrm{d}E_{B}}{\mathrm{d}t} = \eta_{B_*}[L_{\mathrm{sd}}(t) + L_{\mathrm{rad,pul}}(t)]$$

III

$$\frac{\mathrm{d}v_{\mathrm{ej}}}{\mathrm{d}t} = a_{\mathrm{ej}}(t)$$

$$\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} = v_{\mathrm{ej}}(t) + \frac{1}{2}a_{\mathrm{ej}}(t)\mathrm{d}t$$

$$\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} = \frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t}$$

$$\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} = [1 - f_{\mathrm{ej}}(t)]\frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t} - L_{\mathrm{rad}}(t) - L_{\mathrm{rad,in}}(t)$$

$$\frac{\mathrm{d}E_{B}}{\mathrm{d}t} = \eta_{B_*}[L_{\mathrm{sd}}(t) + L_{\mathrm{rad,pul}}(t)]$$

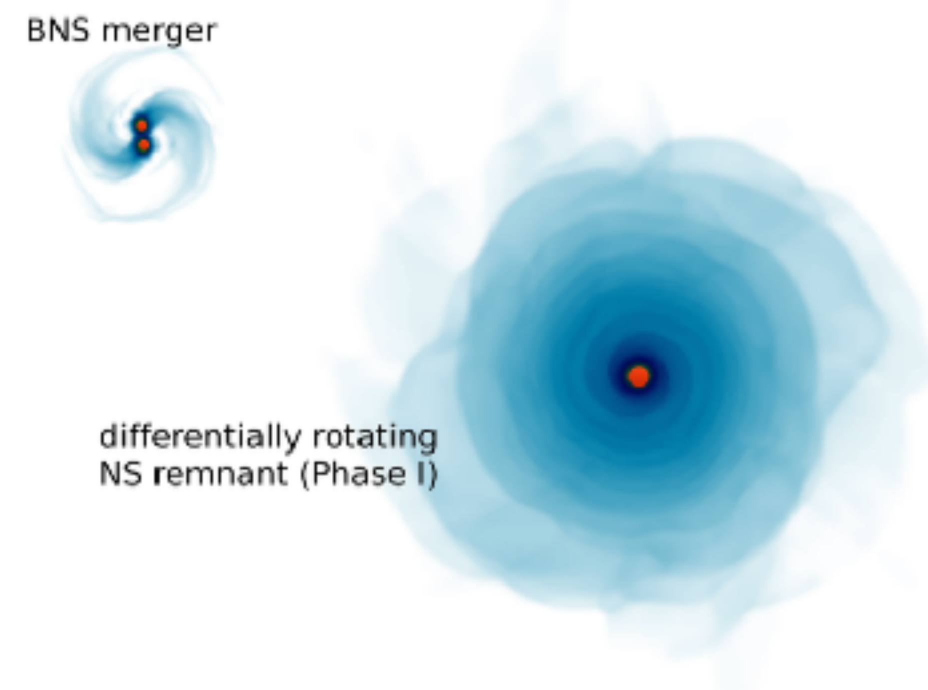
+

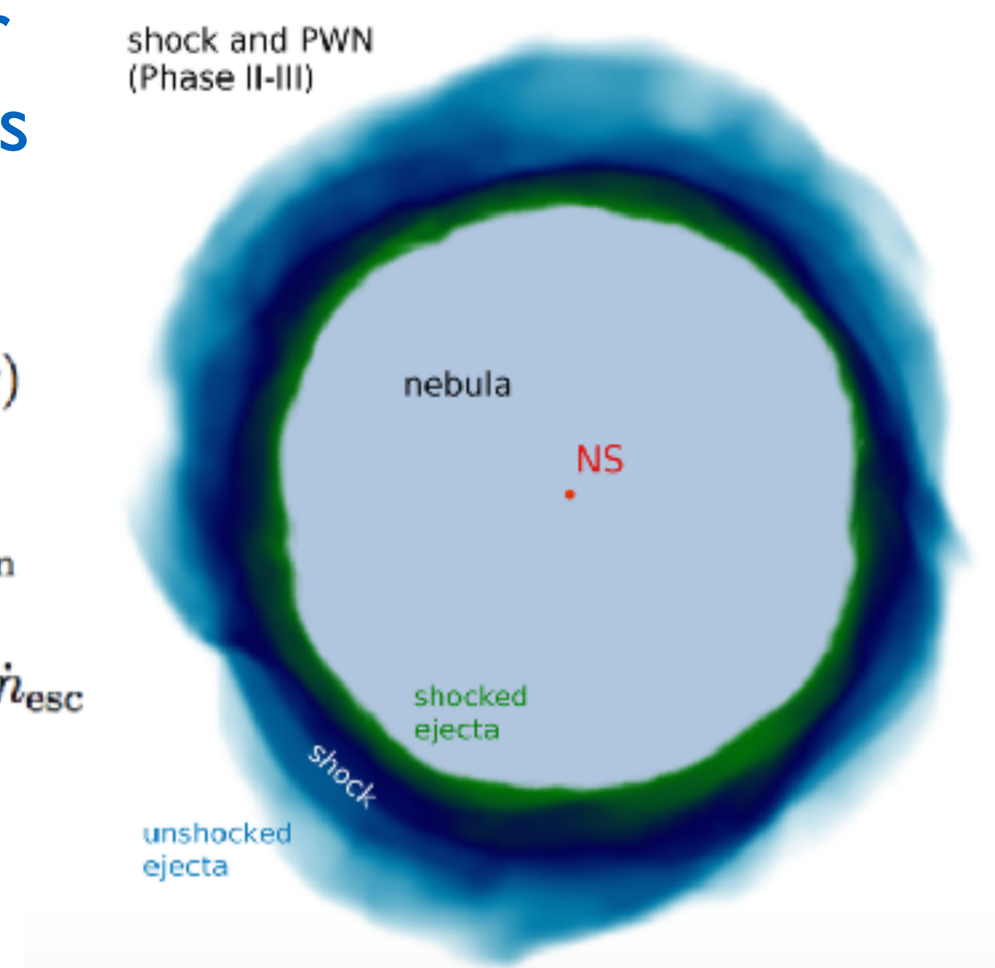
balance equation for photons and particles

↓

$$0 = Q(\gamma) + P(\gamma) + \dot{N}_{\mathrm{C,syn}}(\gamma)$$

$$0 = \dot{n}_0 + \dot{n}_{\mathrm{A}} + \dot{n}_{\mathrm{C}}^{\mathrm{NT}} + \dot{n}_{\mathrm{C}}^{\mathrm{T}} + \dot{n}_{\mathrm{syn}} - \frac{c}{R_{\mathrm{n}}} n(\Delta\tau_{\mathrm{C}}^{\mathrm{NT}} + \Delta\tau_{\gamma\gamma}) - \dot{n}_{\mathrm{esc}}$$



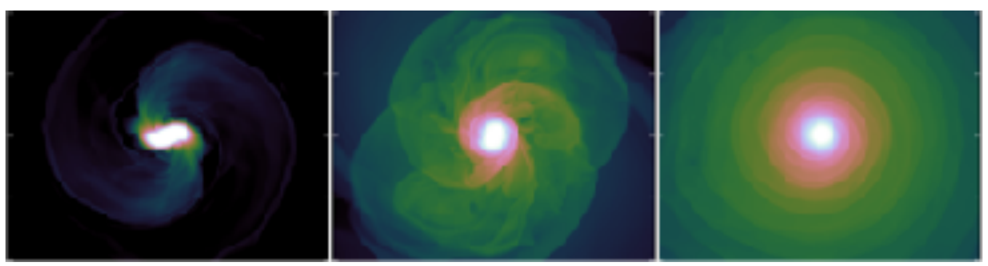


PROBLEM OF THE MAGNETAR MODEL:

strong baryon pollution can choke the formation of a relativistic jet

→ HARD TO EXPLAIN THE SGRB PROMPT EMISSION

e.g., Dessart et al. 2009, Hotokezaka et al. 2013, Siegel et al. 2014
Nagakura et al. 2014, Murguia-Berthier et al. 2016



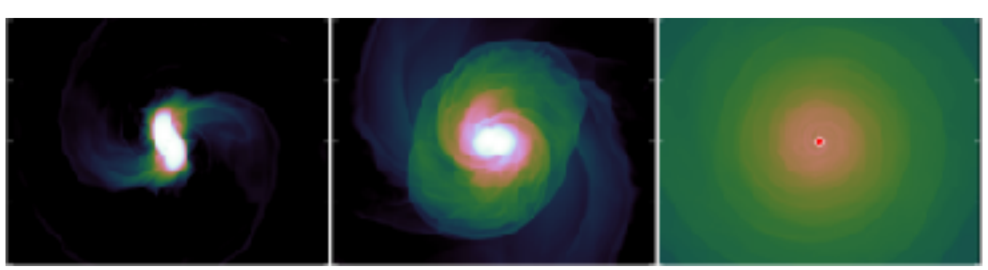
long-lived NS

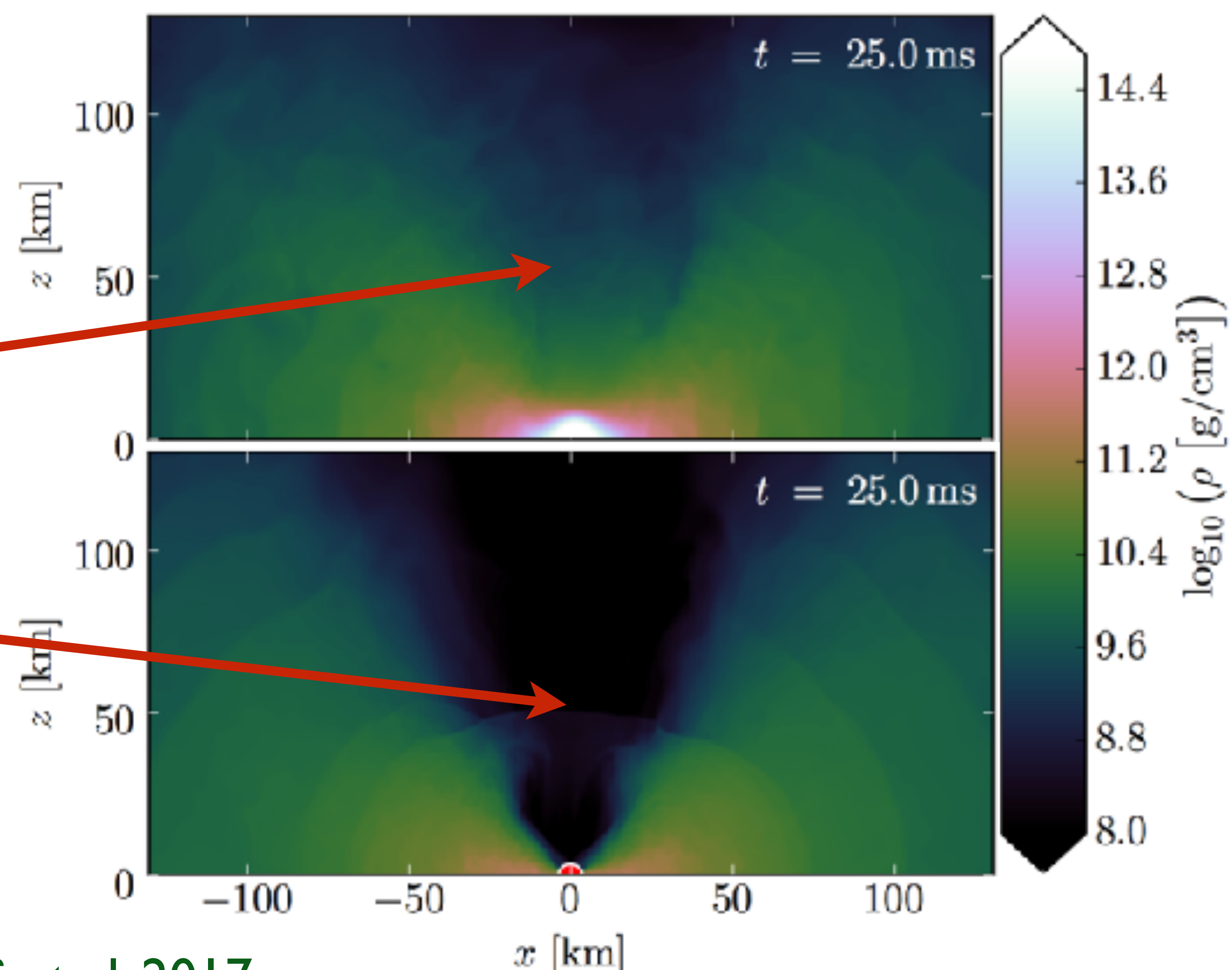
baryon-loaded funnel

vs

BH-disk

baryon-free funnel

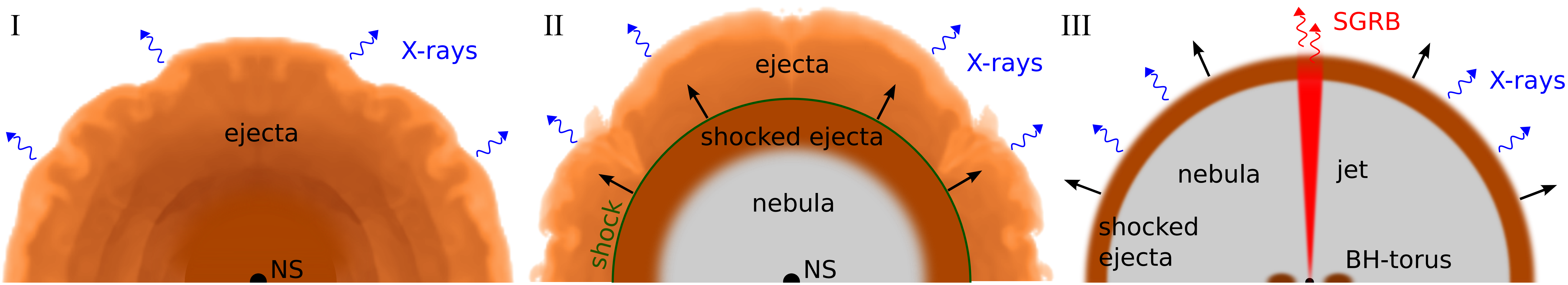




Ciolfi et al. 2017

"Time-reversal" scenario for SGRBs

Ciolfi & Siegel 2015a, ApJ Letters 798, L36

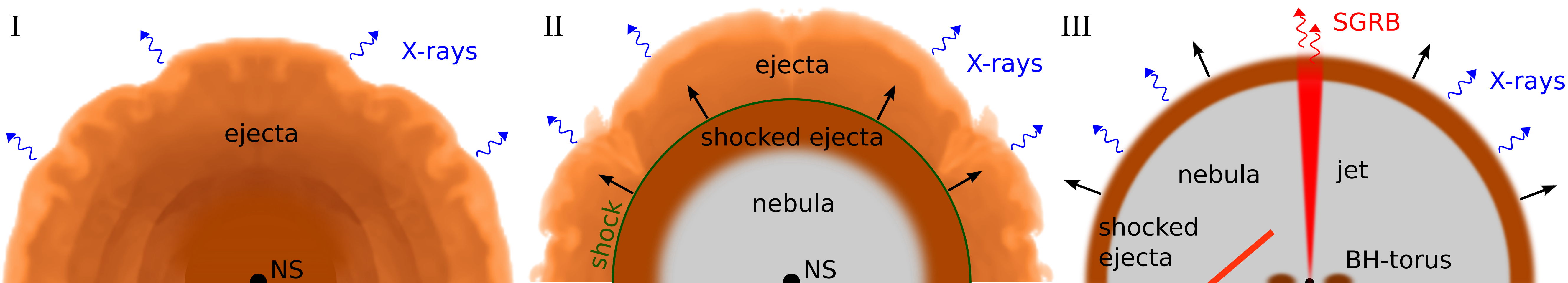


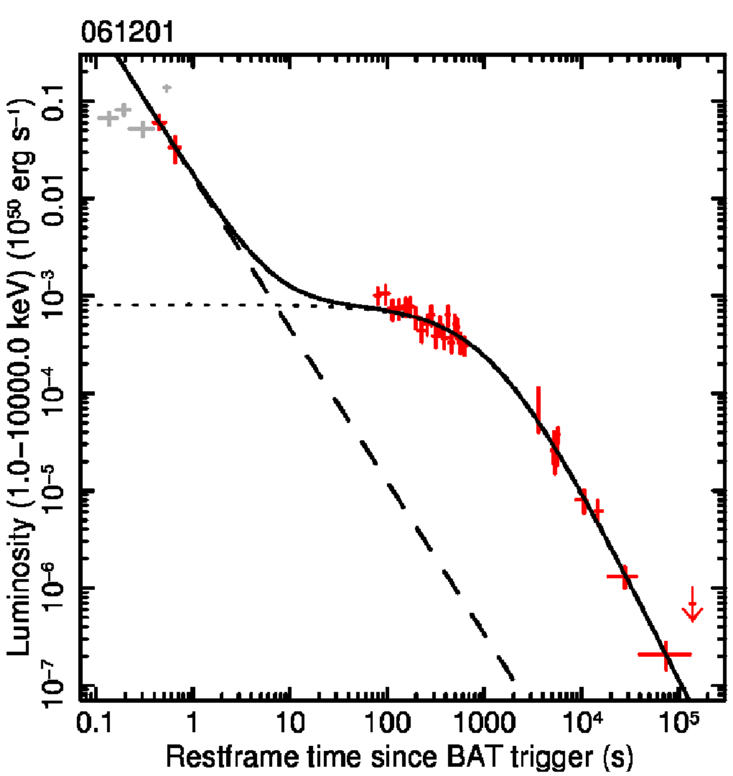
(I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

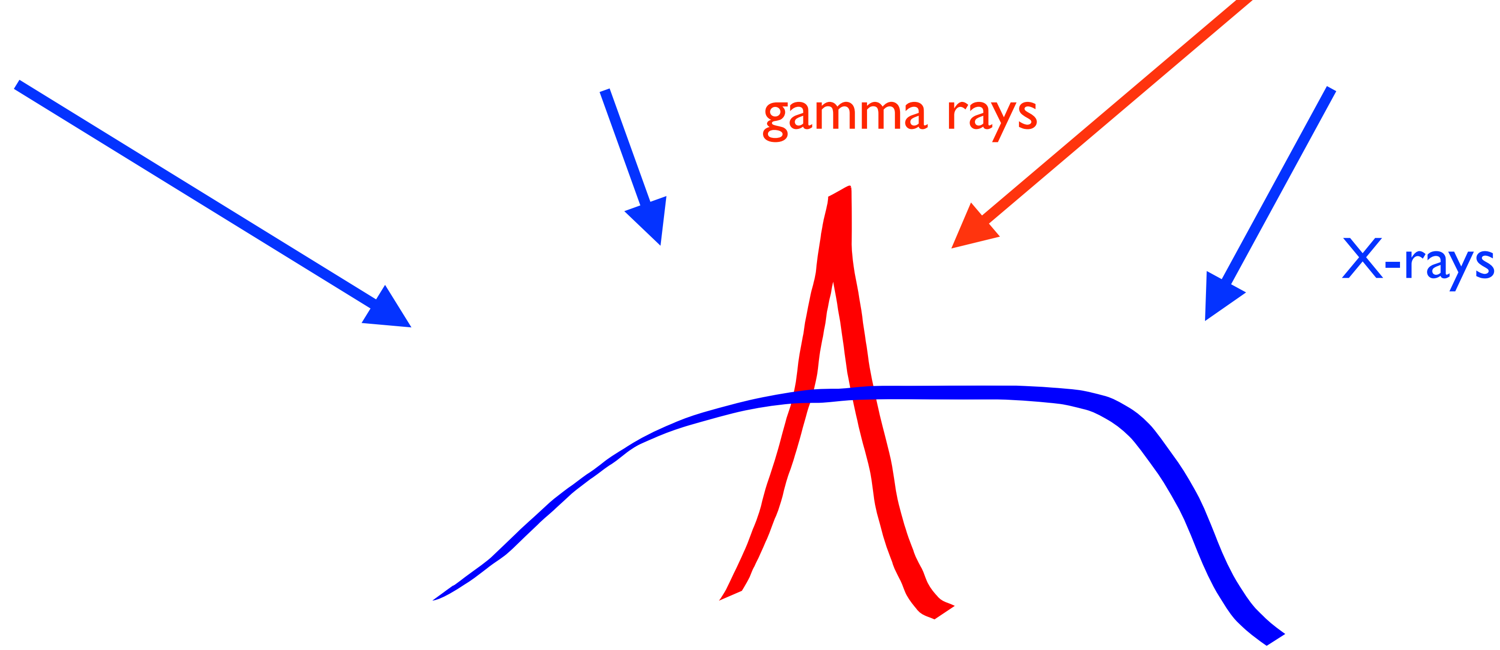
(II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta

(III) The NS collapses to a black hole (BH), a relativistic jet drills through the nebula and the ejecta shell and produces the prompt SGRB, while spin-down emission diffuses outwards on a much longer timescale, producing the X-ray afterglow

Electromagnetic emission in the TR scenario





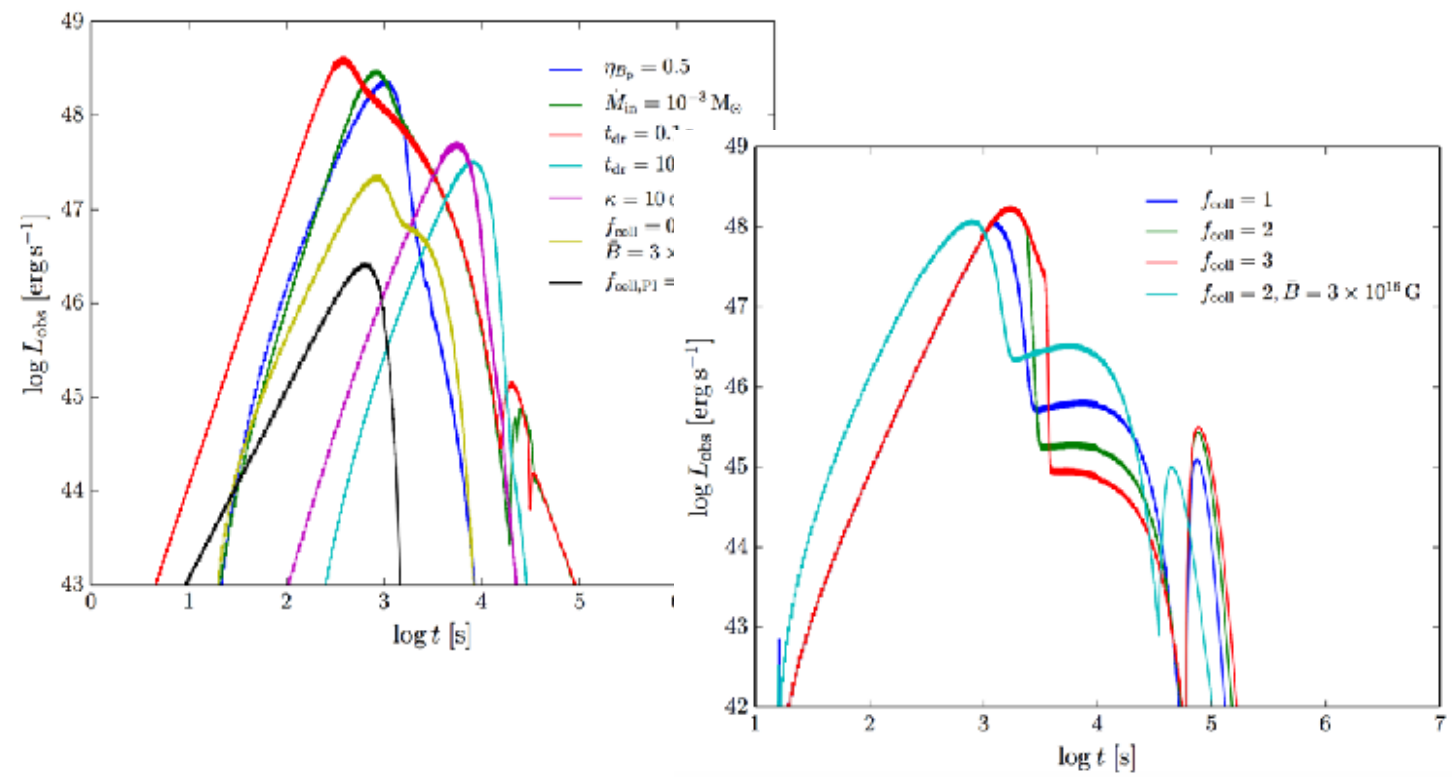


The spin-down emission is given off before but (in part) observed after the prompt SGRB radiation

Comparison with SGRB afterglows

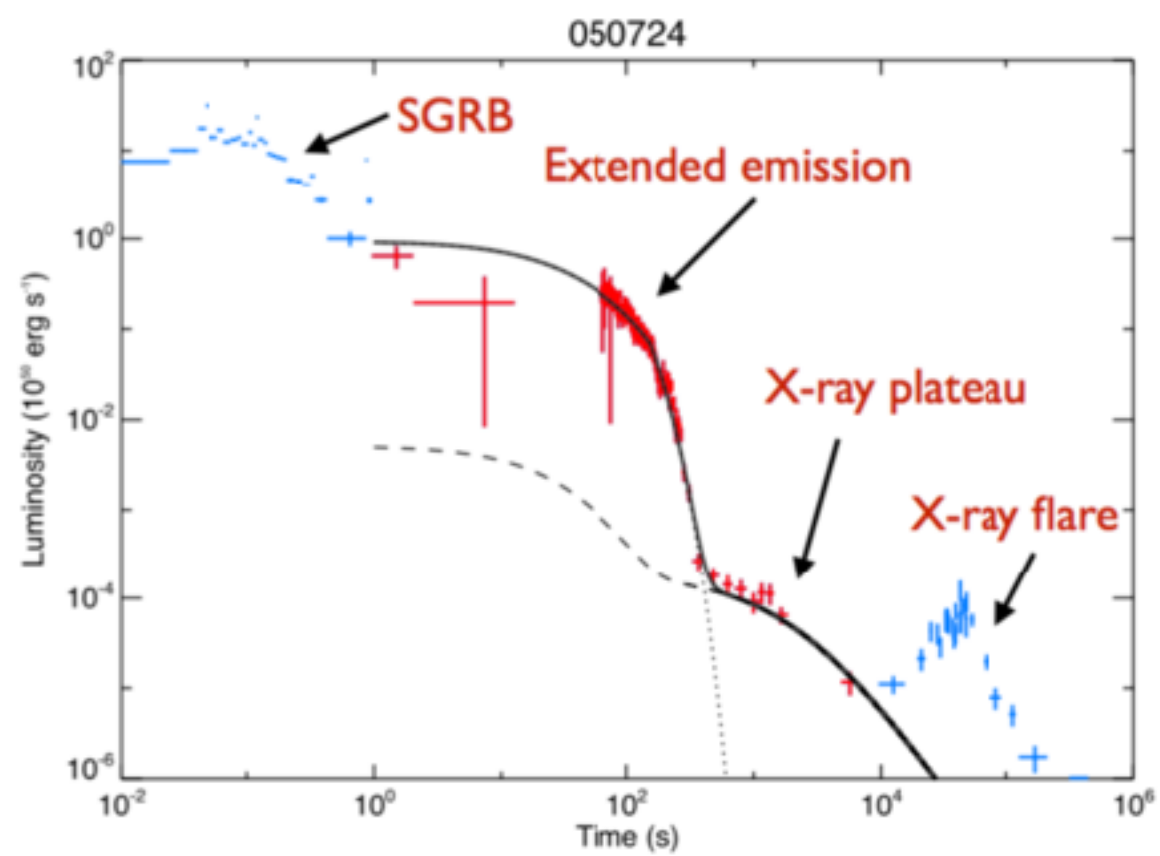
broad characteristics
in good agreement

- signals cover the right band (soft X-rays)
- very nice match with range of durations and luminosities

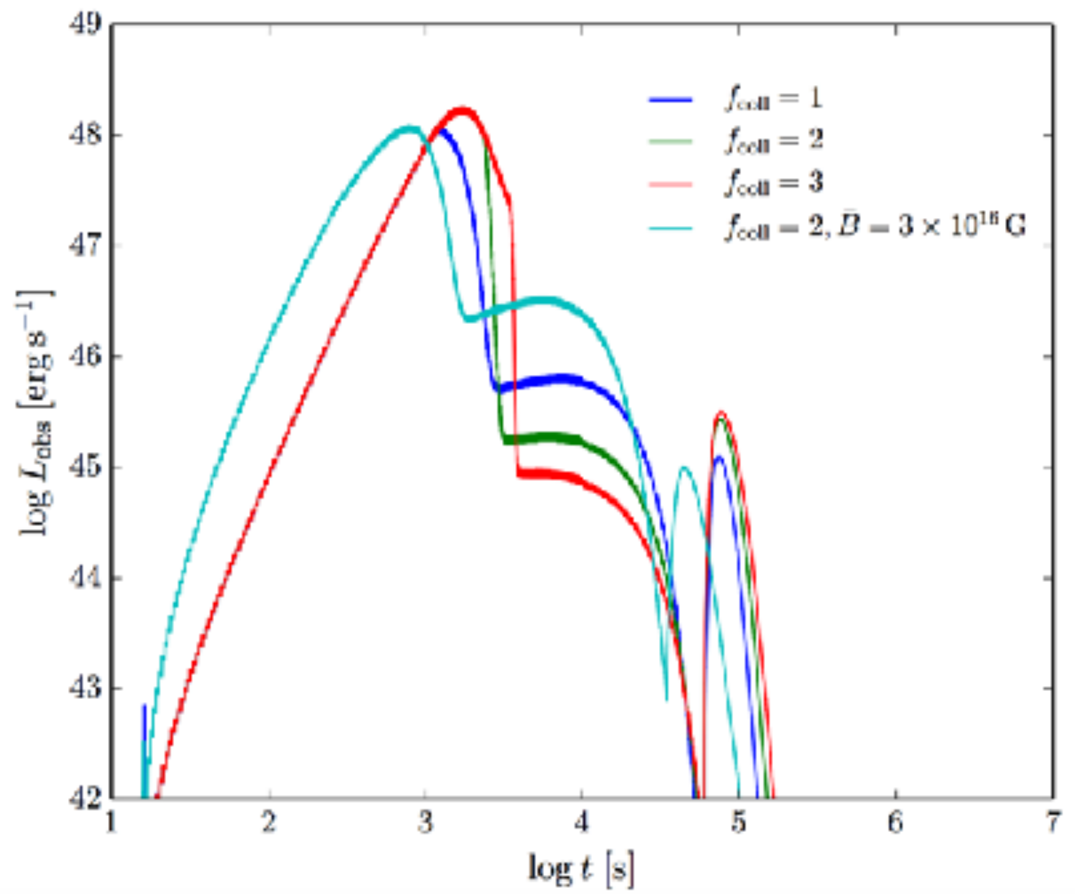


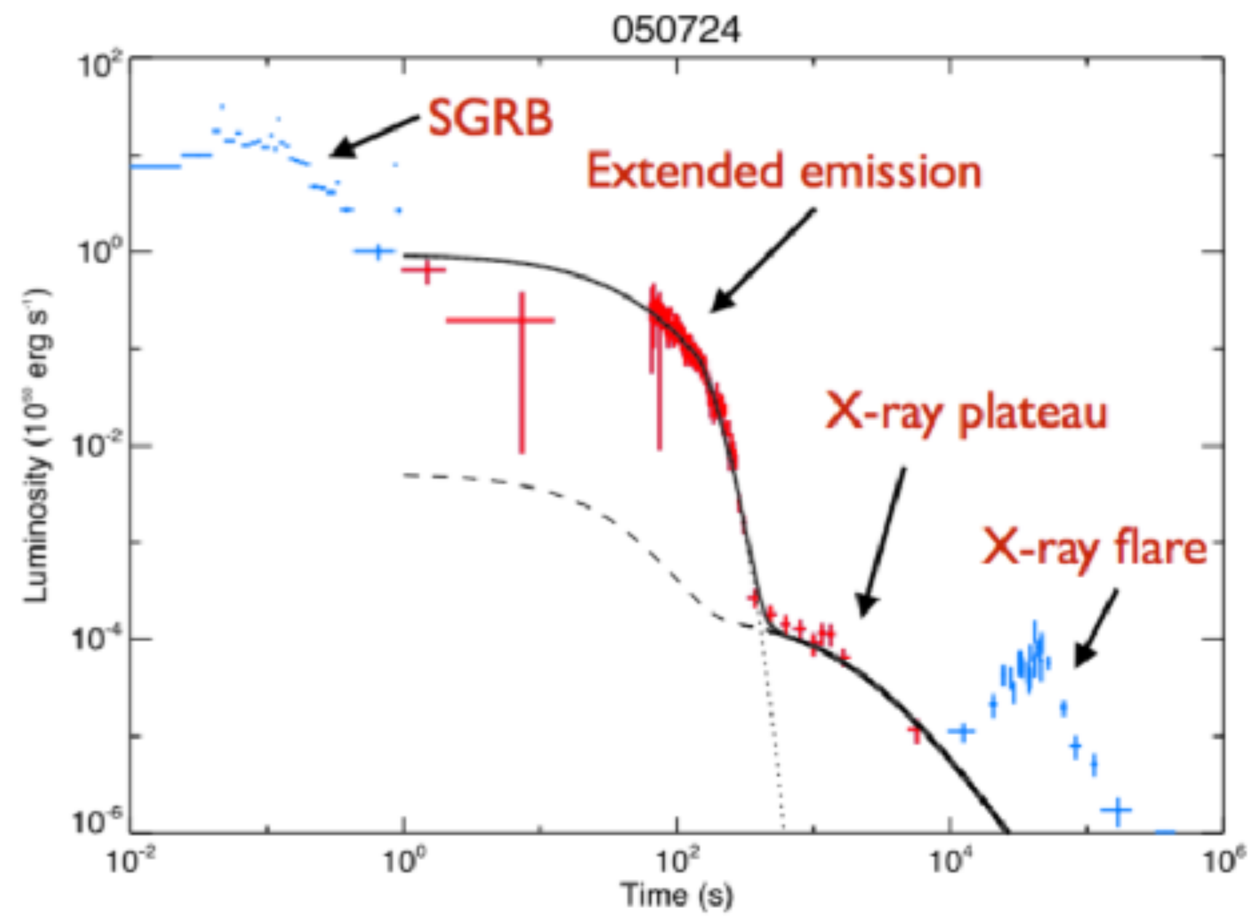
but with a closer look..

- no observations of early rising
- second plateau explained only for collapsing models
- flares explained as transition to optically thin ejecta?



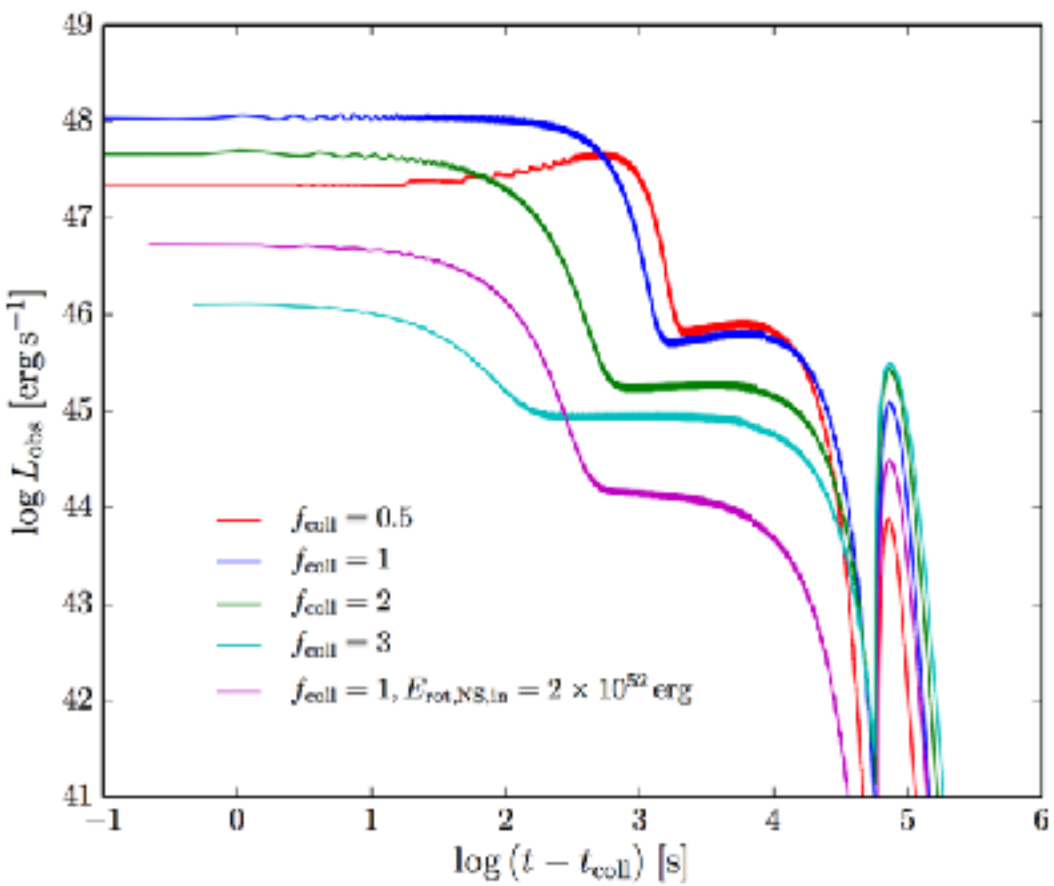
TR scenario - implications

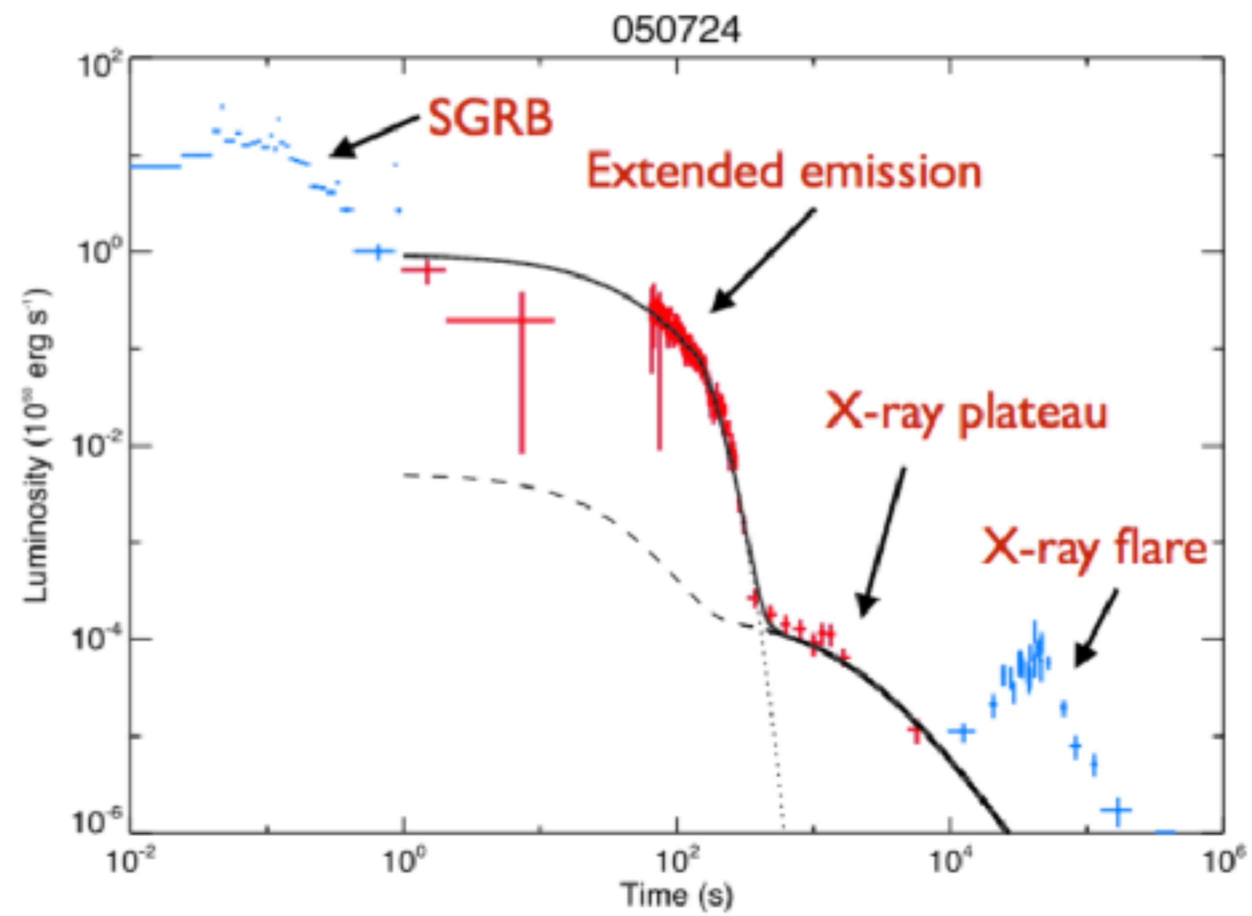




afterglows as seen by the observer assuming **SGRB** (trigger) **at merger**

TR scenario - implications

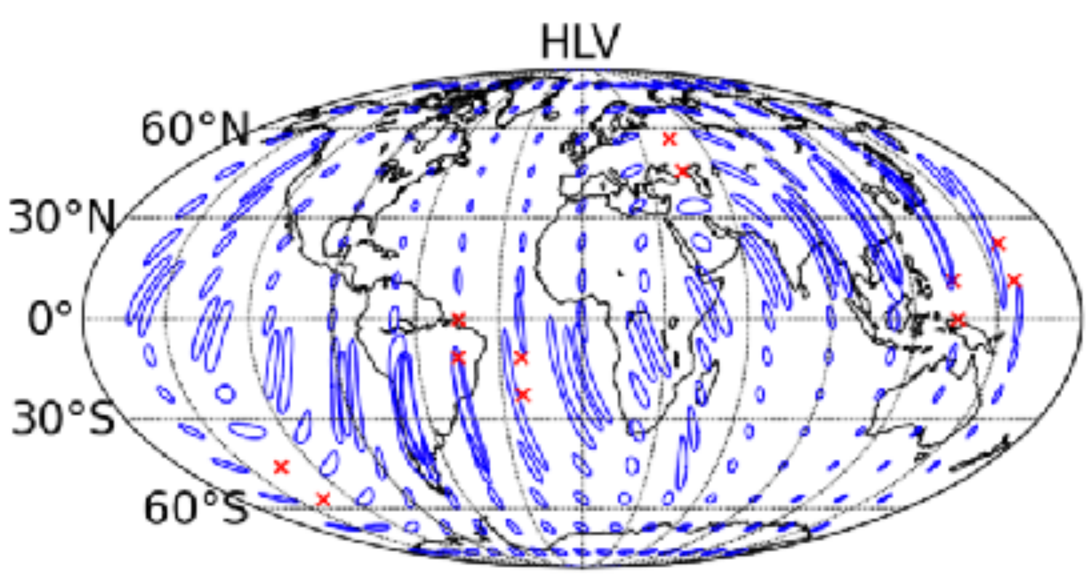


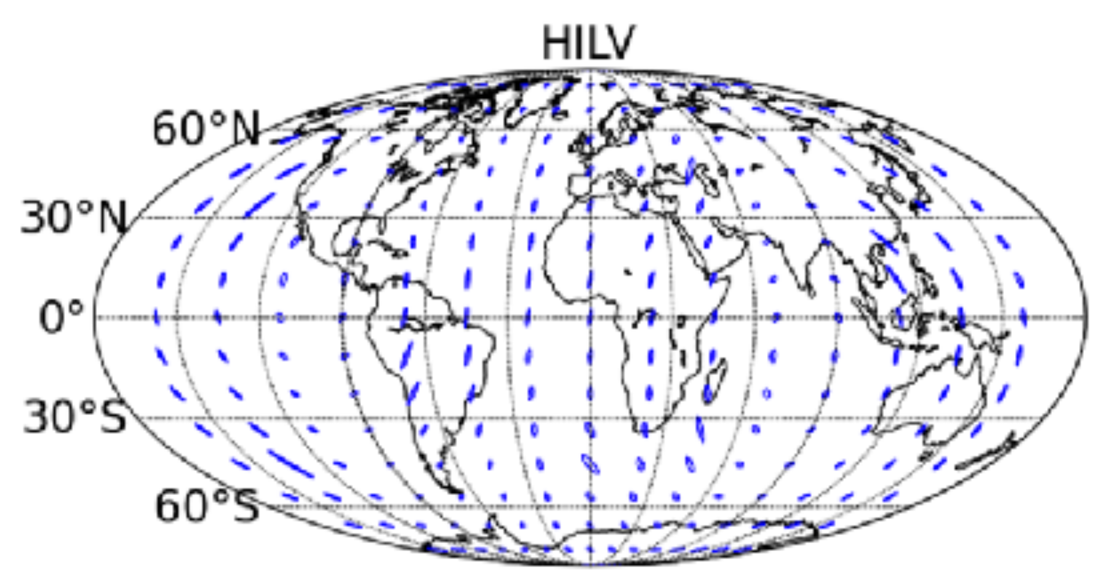


afterglows as seen by the observer assuming **SGRB** (trigger) **at collapse**

improved match assuming the time-reversal scenario!

GW detector network





3 detectors **4 detectors**

sky localization (90% confidence level)