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Short gamma-ray bursts from binary neutron star mergers: the “time-reversal” scenario

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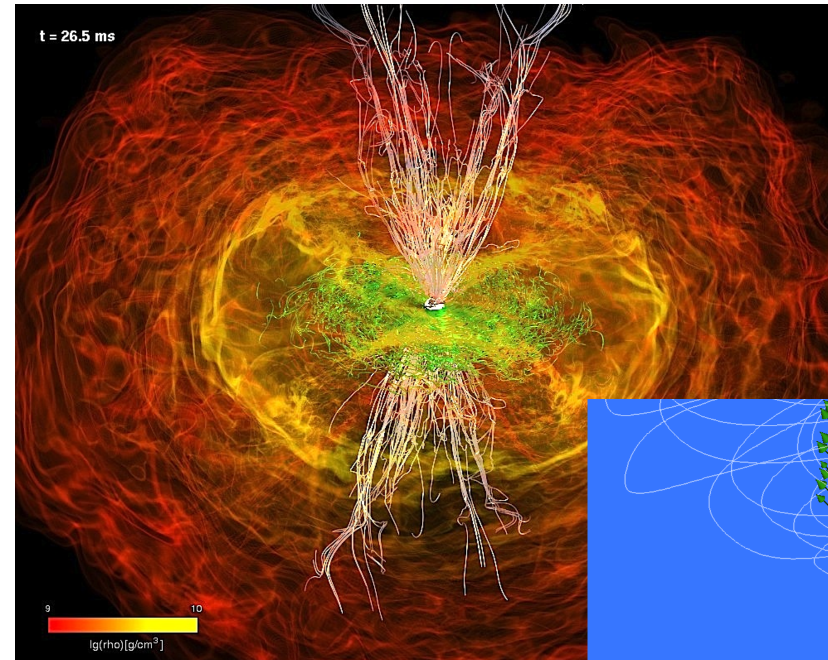
Introduction: SGRBs

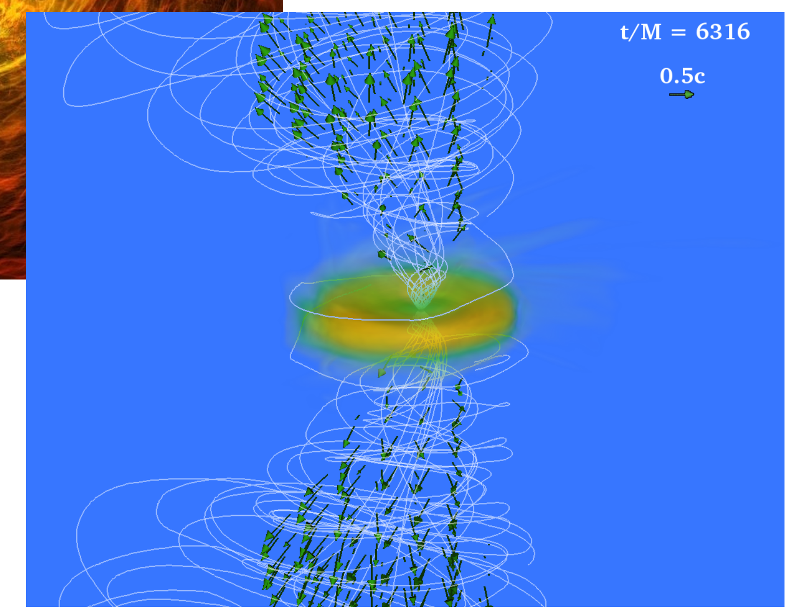
leading model of short gamma-ray bursts (SGRBs)

central engine is a black hole surrounded by hot thick torus
⟶ end result of a binary neutron star (BNS) or mixed binary (NS-BH) merger

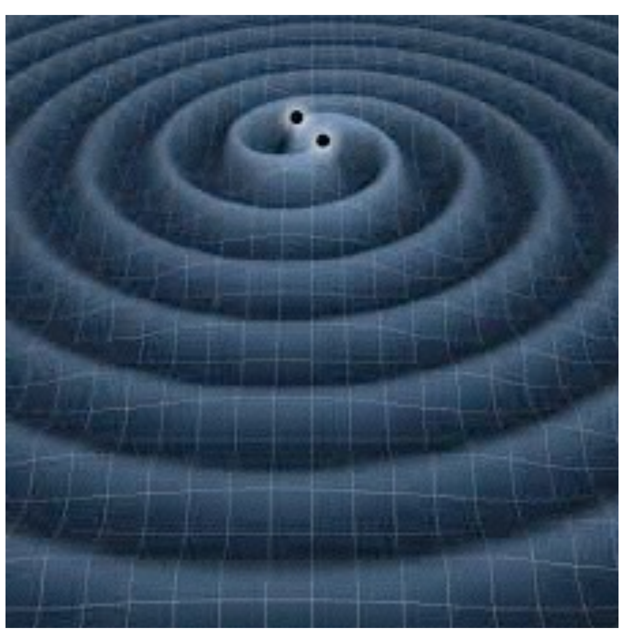
Paczynski 1986, Eichler et al. 1989
Narayan et al. 1992, Barthelmy et al. 2005,
Fox et al. 2005, Gehrels et al. 2005, …



Rezzolla et al. 2011



Paschalidis et al. 2014



BNS and NS-BH binary mergers are among the most promising sources of gravitational waves

likely of rate ~40/yr for Advanced LIGO and Virgo
possibility of combined GW-EM detection!

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

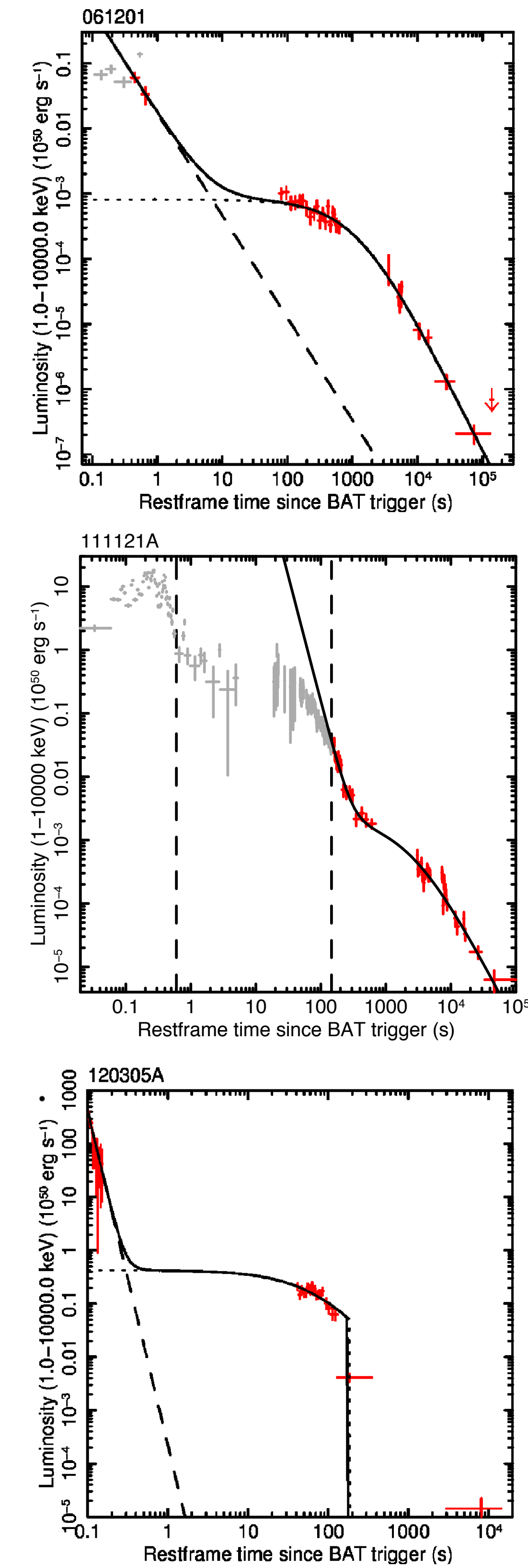
MAGNETAR MODEL

Zhang & Meszaros 2001
Metzger et al. 2008

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

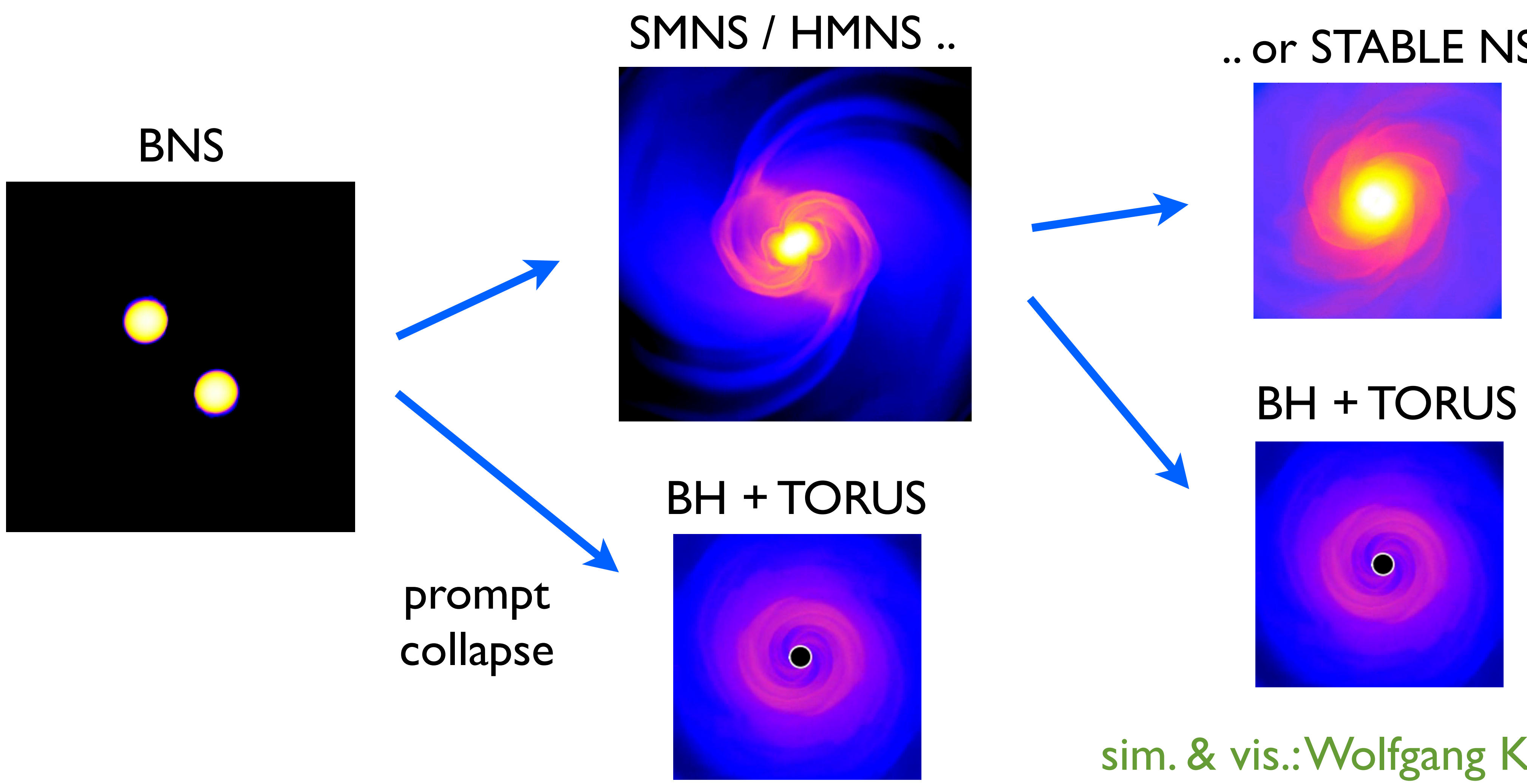
dipole spindown

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



Gompertz et al. 2013
Rowlinson et al. 2013

Product of BNS mergers

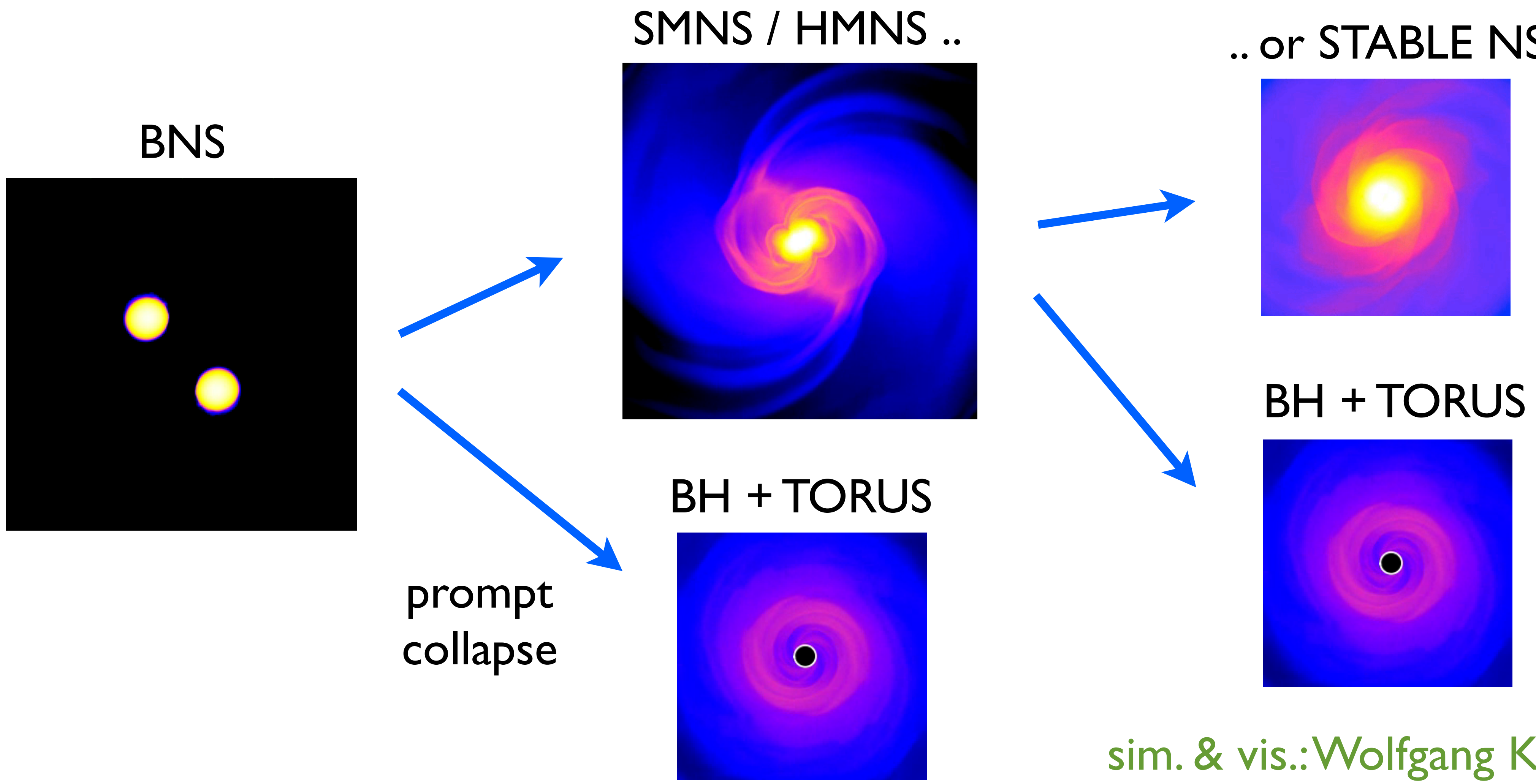


sim. & vis.: Wolfgang Kastaun

LONG-LIVED NS IS A LIKELY OUTCOME OF THE MERGER

- observation of $\sim 2\ \mathrm{M}_\odot$ NSs — Demorest et al. 2010, Antoniadis et al. 2013
- progenitor masses peak around $1.3 - 1.4\ \mathrm{M}_\odot$ ➔ BMP mass likely $< 2.5\ \mathrm{M}_\odot$ — Belczynski et al. 2008
- stable NS obtained in GR BNS merger simulations — Giacomazzo & Perna 2013

Product of BNS mergers



sim. & vis.: Wolfgang Kastaun

PROBLEM OF THE LONG-LIVED NS MODEL :

strong baryon pollution can choke the formation of a relativistic jet

→ **HARD TO EXPLAIN THE SGRB PROMPT EMISSION**

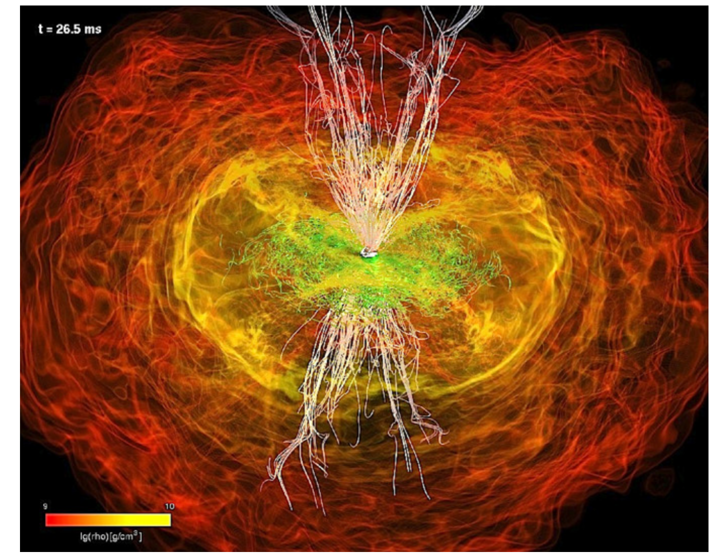
e.g., Dessart et al. 2009, Hotokezaka et al. 2013, Siegel et al. 2014

The SGRB dichotomy

- Numerical relativity picture: prompt BH-torus formation

  → can explain prompt SGRB emission

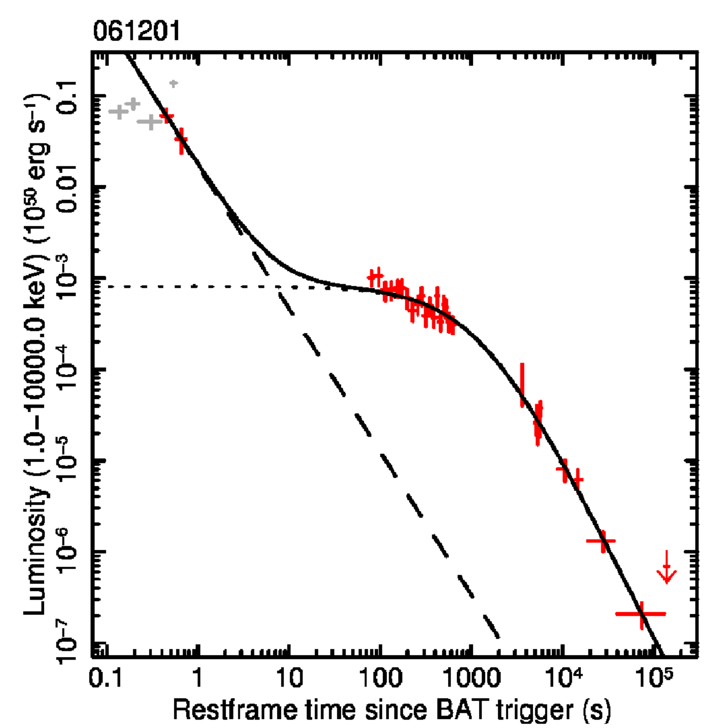
  → cannot explain X-ray afterglows



- Observational picture: magnetar model

  → cannot explain prompt SGRB emission

  → can explain X-ray afterglows

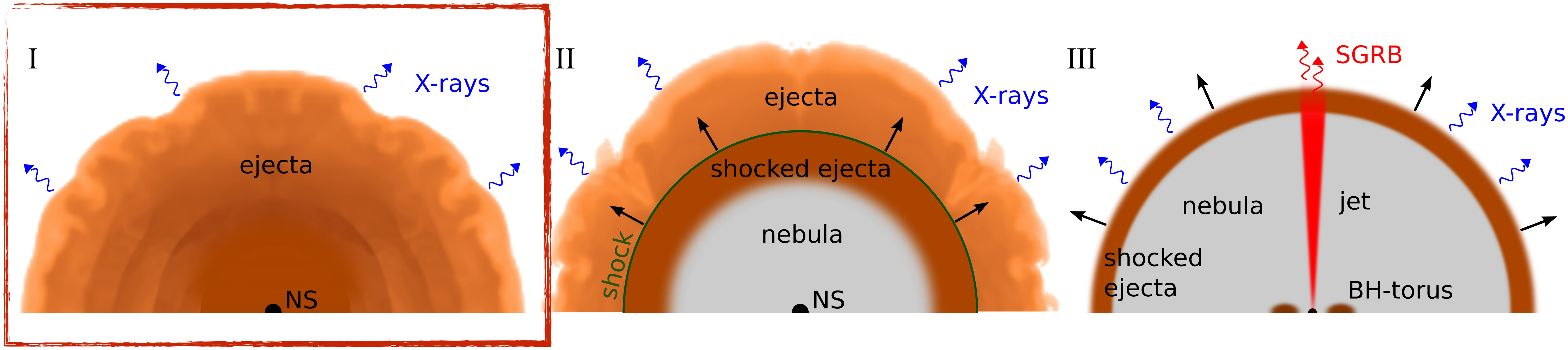


Possible solution: "time-reversal" scenario

Ciolfi & Siegel 2015a

"Time-reversal" phenomenology

Ciolfi & Siegel 2015a, ApJ Letters 798, L36



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

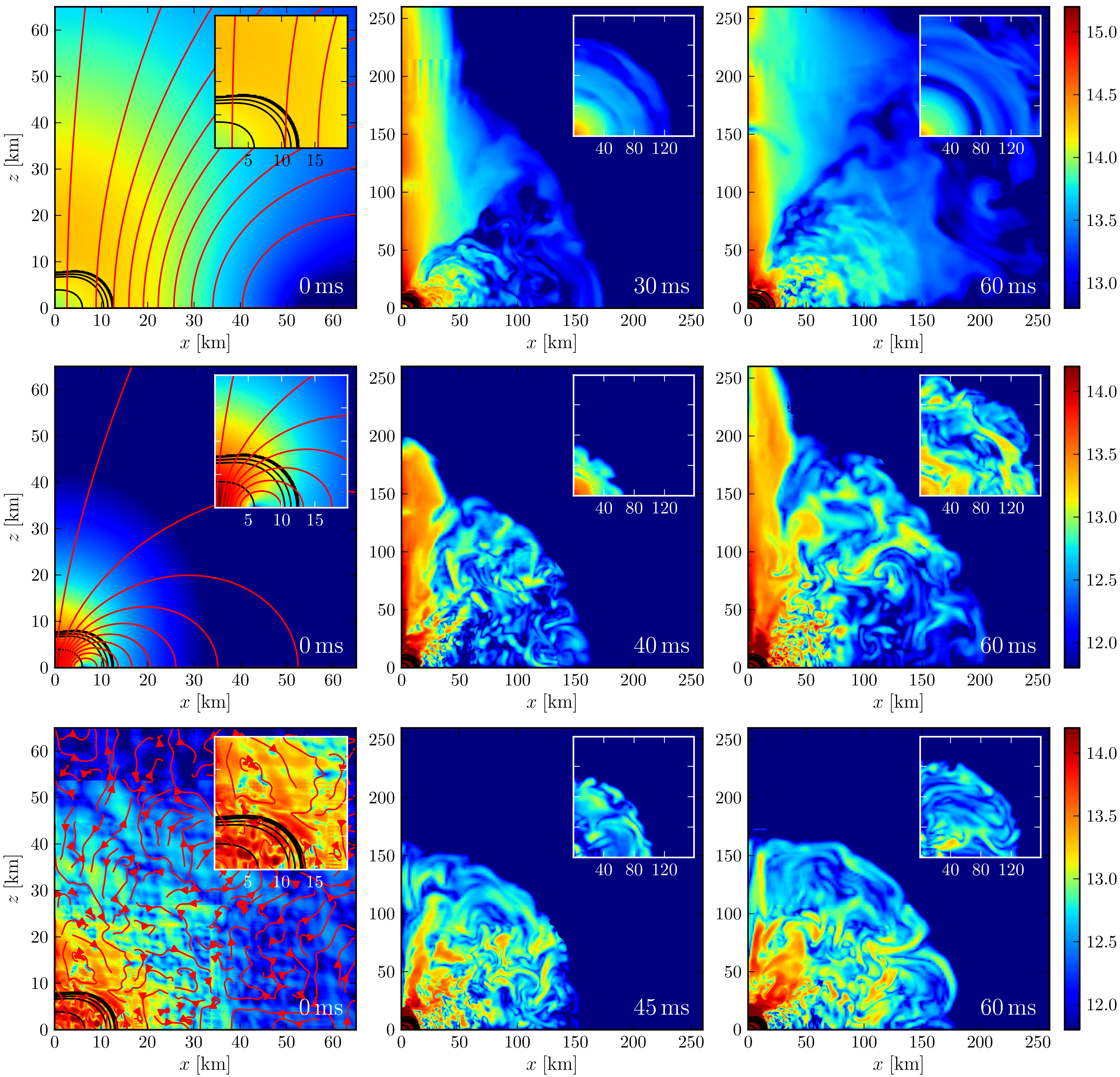
Siegel et al. 2014

(see also Siegel & Ciolfi 2015a)

Dessart et al. 2009

"Time-reversal" phenomenology I

Siegel et al. 2014
Siegel & Ciolfi 2015a



60 ms evolution
for 3 geometries

dipole 60
dipole 6
random

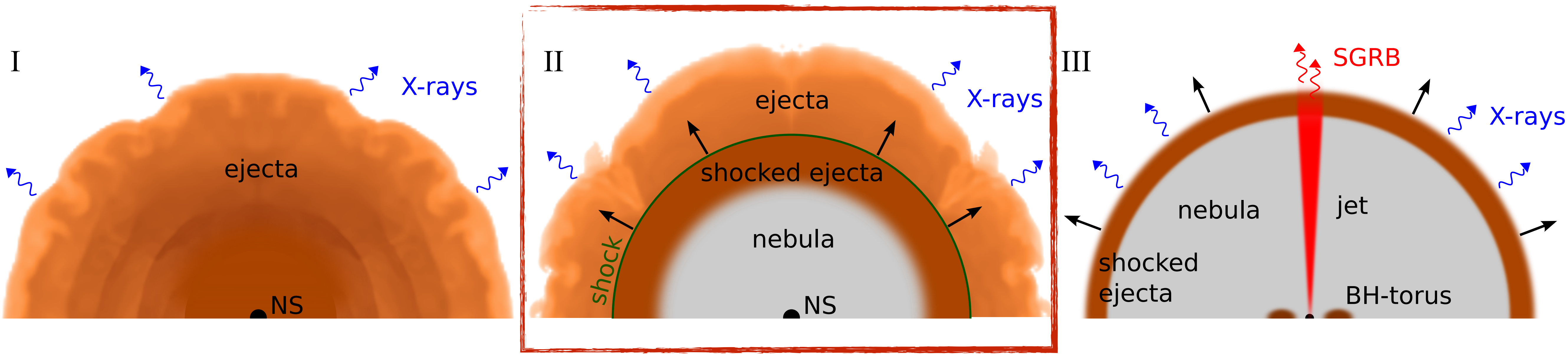
differential rotation powers baryon-loaded and magnetized outflow

for all MF geometries the outflow has an isotropic component

collimation depends strongly on MF geometry

“Time-reversal” phenomenology

Ciolfi & Siegel 2015a, ApJ Letters 798, L36



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

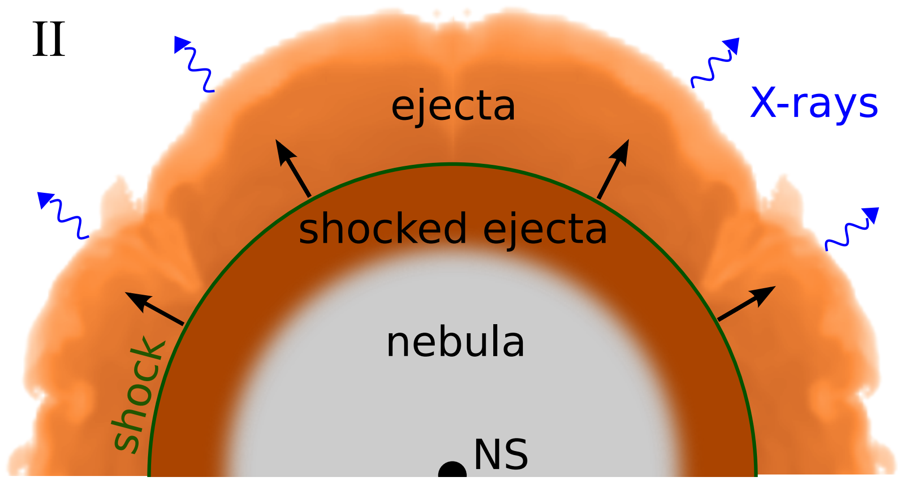
(II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta

"Time-reversal" phenomenology II

- uniformly rotating NS emits spin-down radiation and inflates a photon-pair nebula

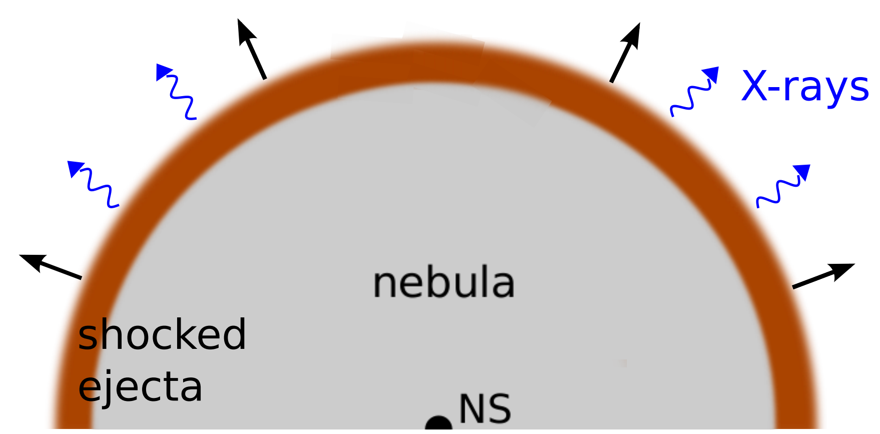
$$L_{\rm sd} \simeq 1.5 \times 10^{49} B_{\rm p,15}^2 R_6^3 P_{\rm in,-3}^{-4} (1 + t/t_{\rm sd})^{-2}\,{\rm erg\ s}^{-1}$$

$$t_{\rm sd} \simeq 2.7 \times 10^3 B_{\rm p,15}^{-2} R_6^{-3} P_{\rm in,-3}^2\,{\rm s}$$



- high photon pressure drives a strong shock through the ejecta, sweeps up material into a thin shell
- nebula energy rapidly heats up and accelerates the ejecta shell (up to mildly relativistic speeds)

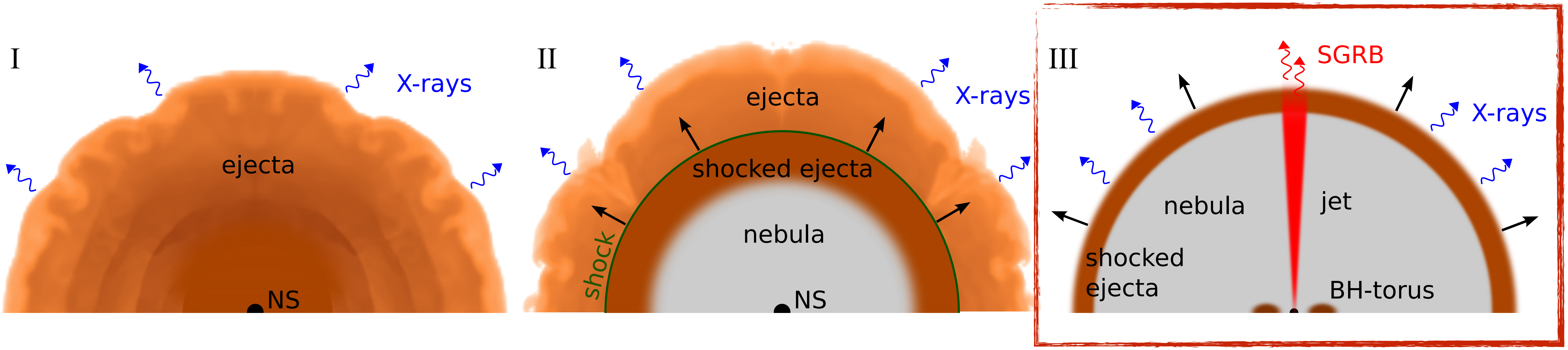
Metzger & Piro 2014



analogies with PWNe
(see talk by D. Siegel)

“Time-reversal” phenomenology

Ciolfi & Siegel 2015a, ApJ Letters 798, L36

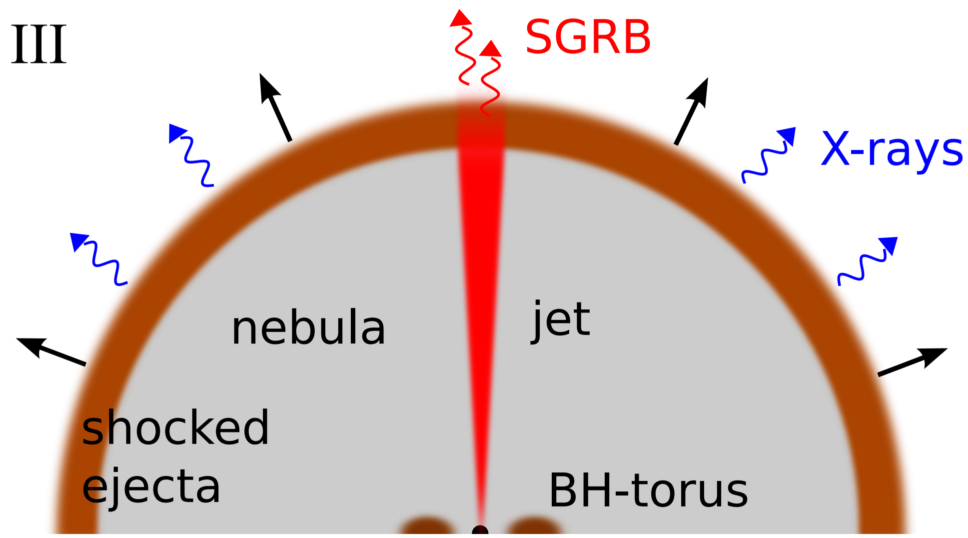


(I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

(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

"Time-reversal" phenomenology III



- at $t_{\rm coll} \sim t_{\rm sd}$ the NS collapses to a BH-torus system

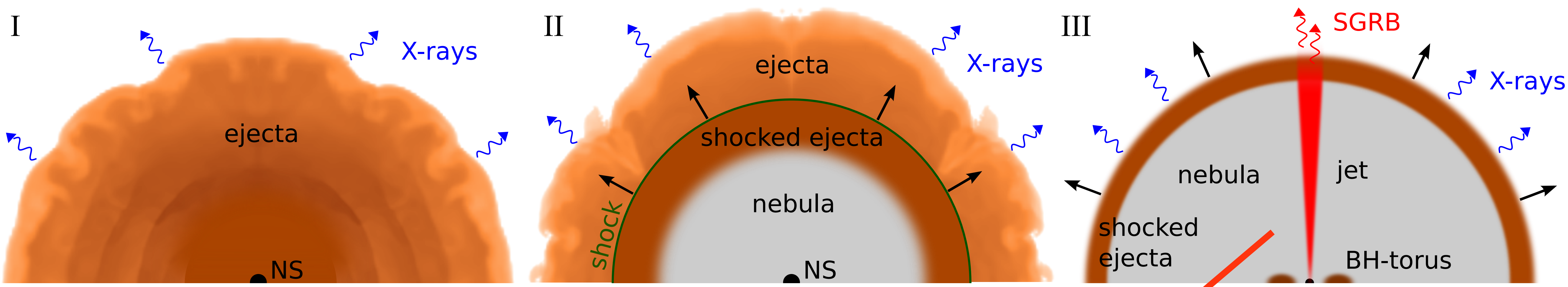
  ⟶ transient jet is formed in $\lesssim 0.01 - 1\,{\rm s}$ drills through the ejecta and generates the SGRB

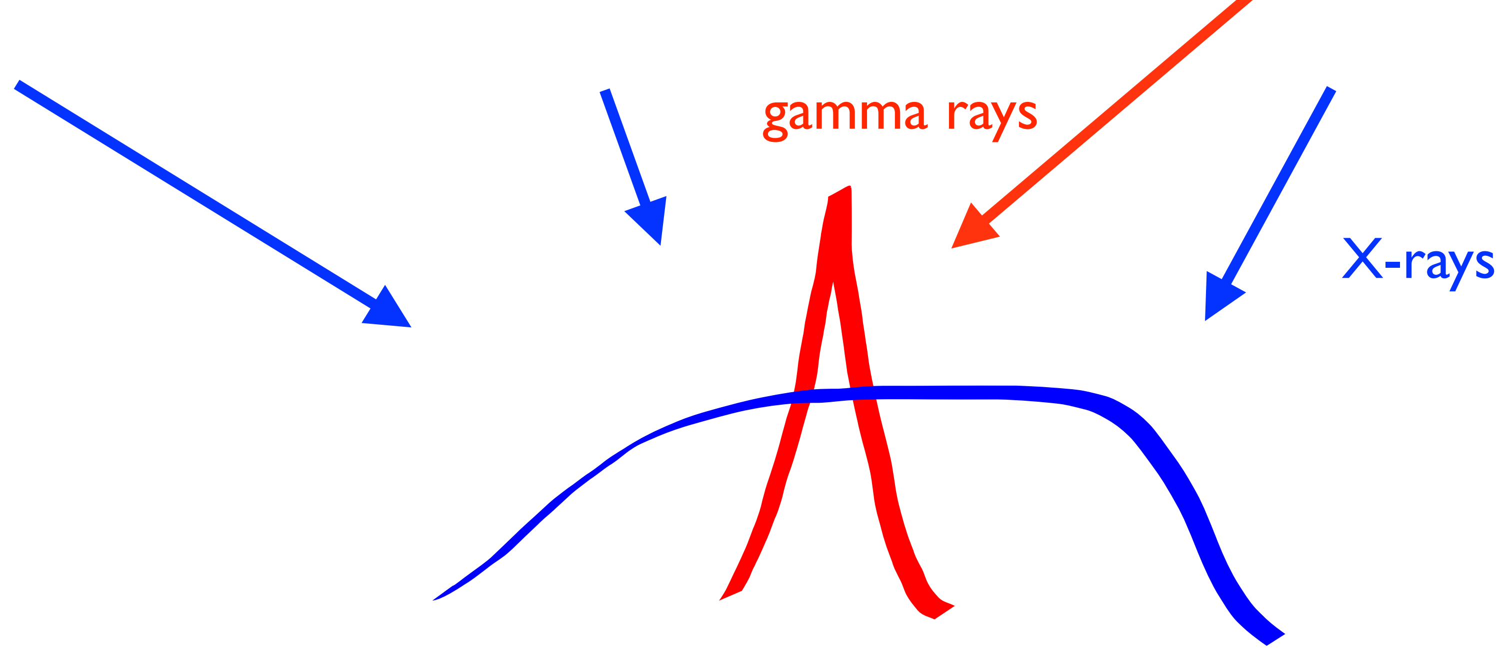
- nebula and ejecta represent an optically thick environment

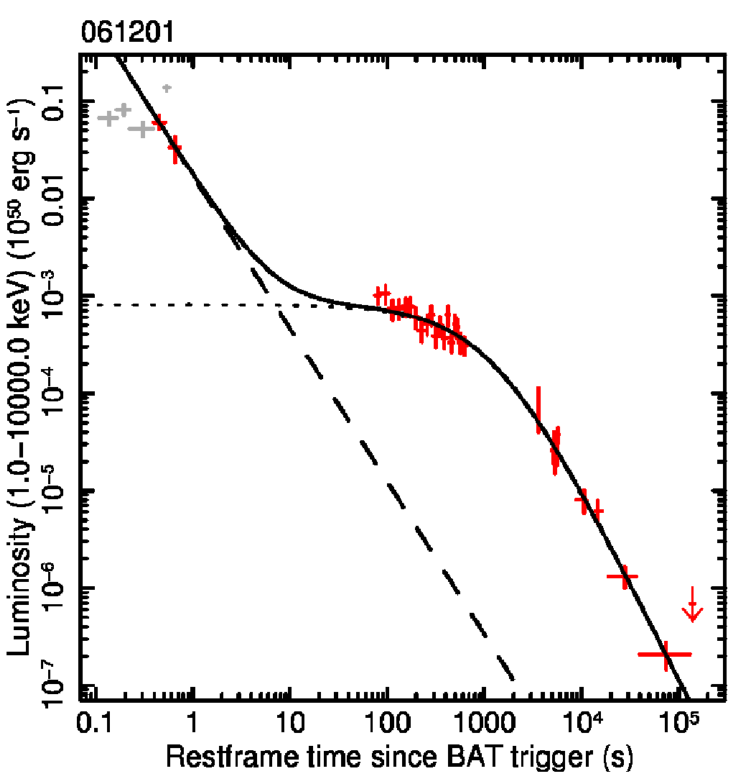
  ⟶ large fraction of spin-down energy is still trapped and diffuses outwards on much longer timescale

  ⟶ spin-down energy acquires substantial delay before emerging and producing the X-rays

Electromagnetic emission







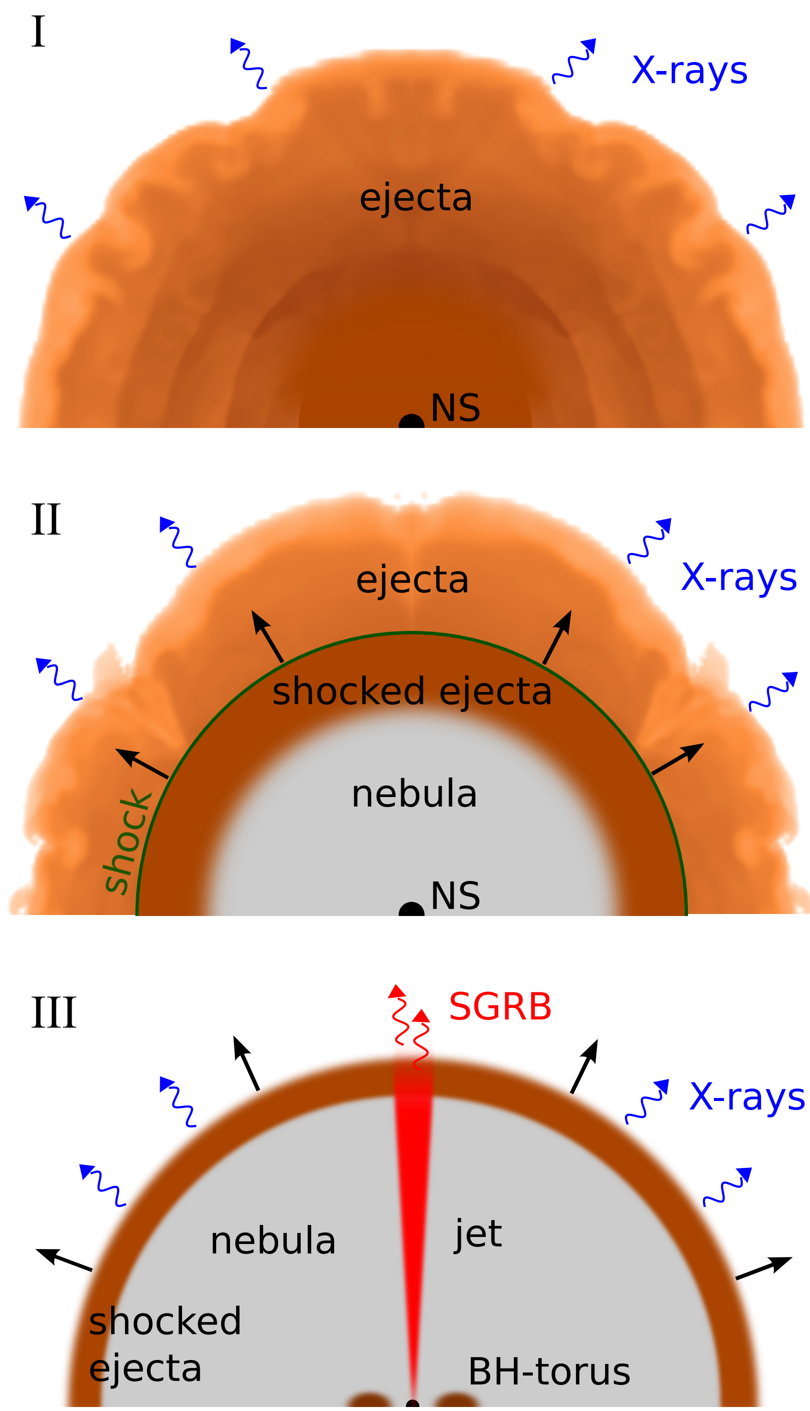
The spin-down emission is given off before but (in part) observed after the prompt SGRB radiation

Discussion: evidence

- proposed new scenario to solve SGRB-X-ray afterglow dichotomy → "time-reversal" scenario

- delay times can explain observed X-ray afterglow durations

  → attractive alternative to current models



Evidence:

- potential observation of X-ray plateau with SGRB in between

  → indication of time reversal

- potential observation of an orphan event without SGRB

  → isotropy of afterglow

Discussion: implications

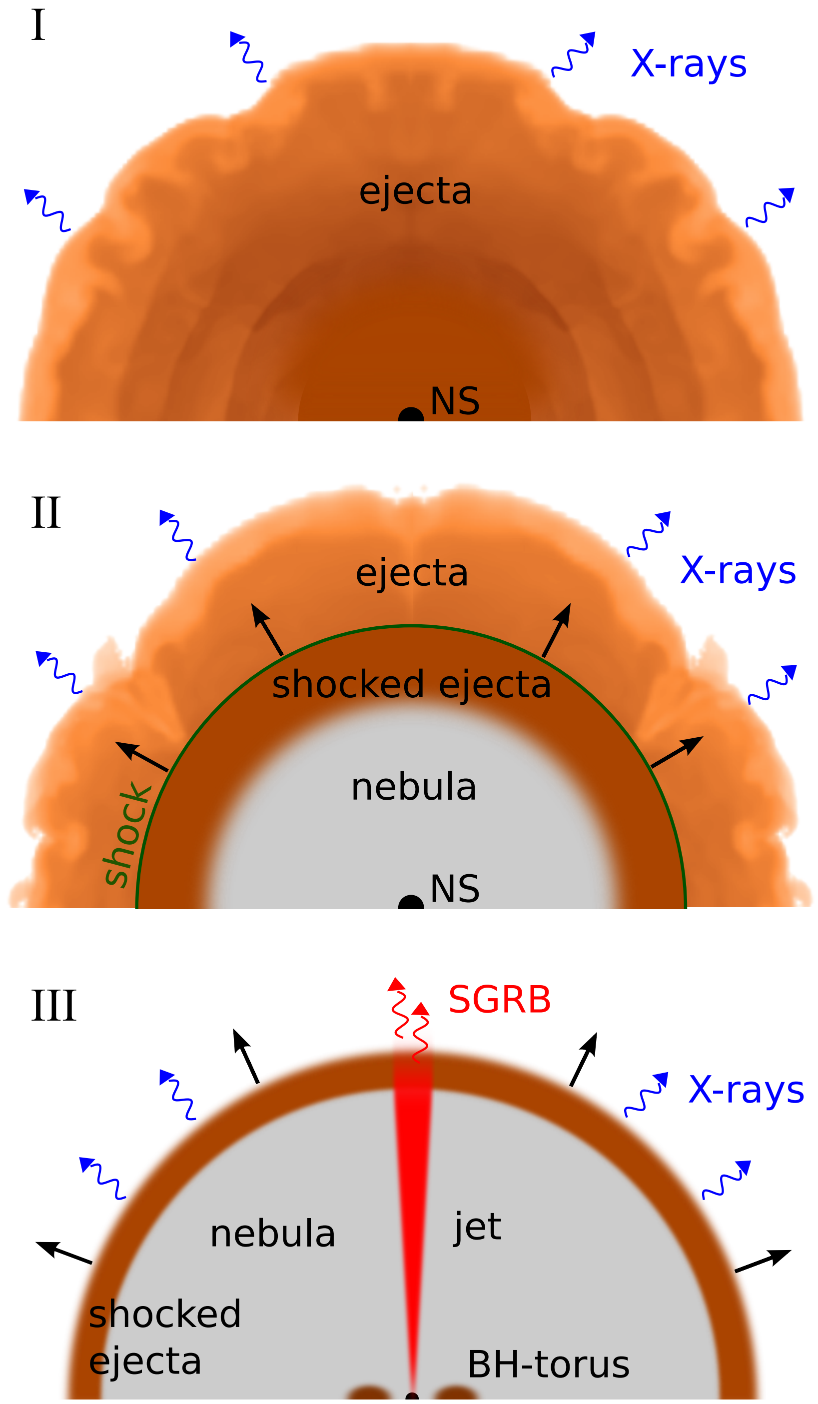
Implications:

- SGRBs with X-ray afterglows (majority of observed events) originate from BNS mergers ⟶ no BH-NS progenitors

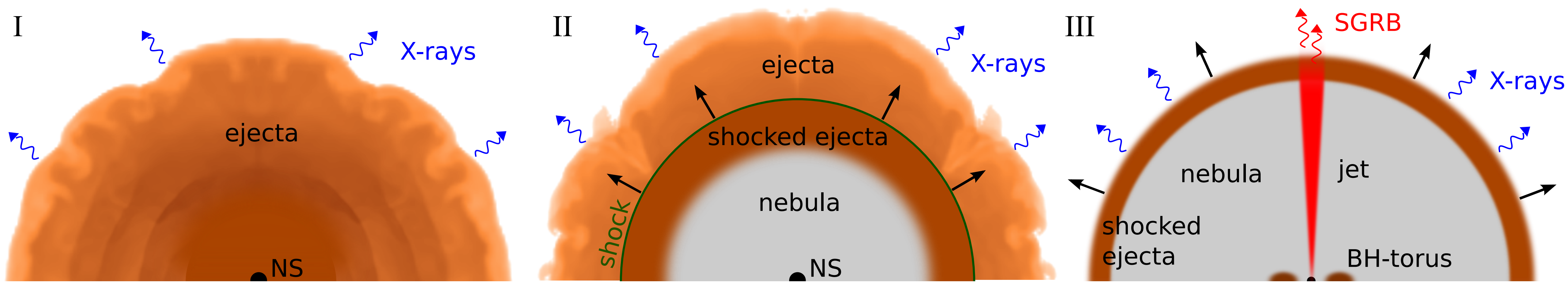
- SMNS constraints on EOS in combination with a mass estimate

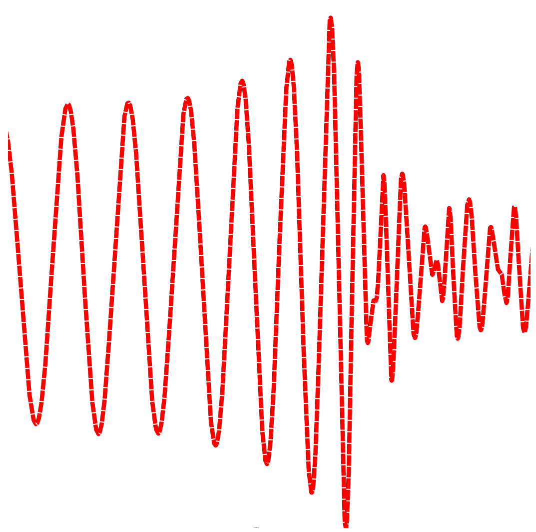
Ciolfi & Siegel 2015b

- peak amplitude of GW emission separated from SGRB by lifetime of the NS



GW and EM observations

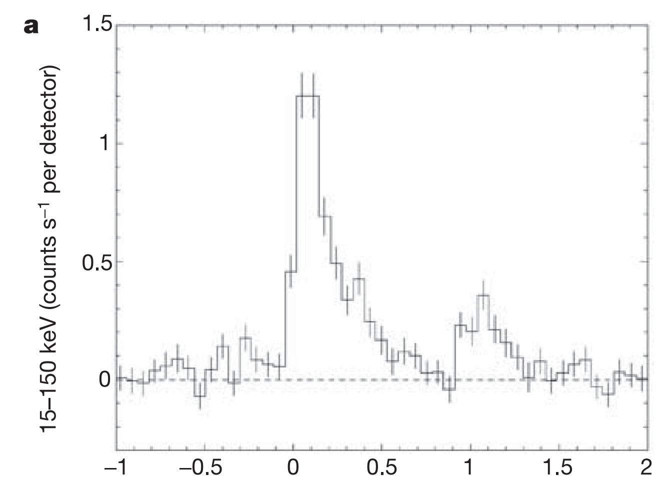




peak amplitude GW signal

$$t_{\rm coll} \sim t_{\rm sd} \sim 10^3\ {\rm s}$$

lifetime of the NS



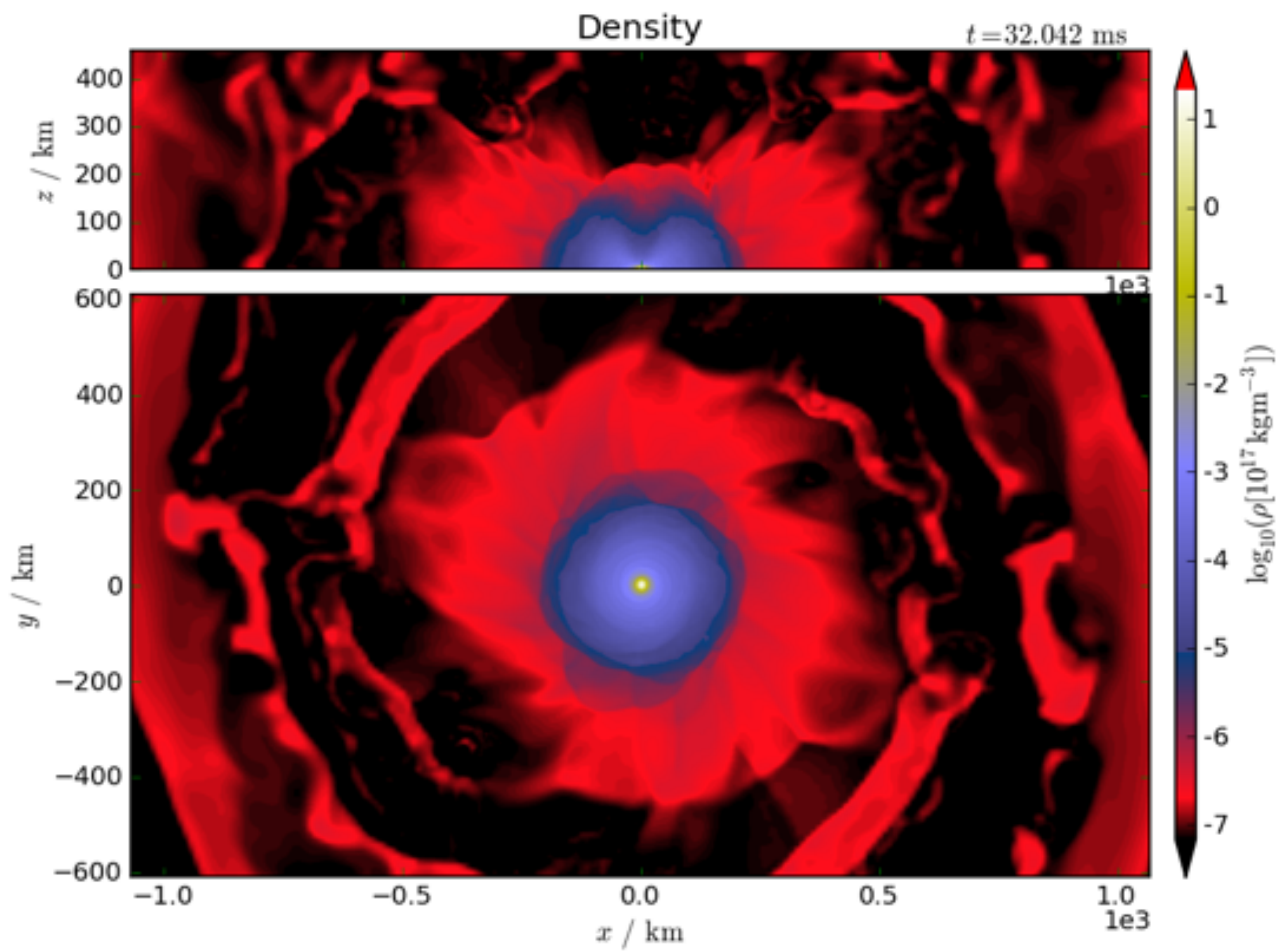
EM SGRB signal

- GW observations ideal trigger for EM observations
- peak amplitude of GW emission separated from SGRB by lifetime of the NS

$\longrightarrow$ very precise measurement of the NS lifetime!

Following steps

- GRMHD simulations of BNS mergers



long post-merger evolution

SMNS properties

mass ejection, winds

(Ciolfi, Kastaun, Giacomazzo, Siegel)

- 1D dynamical model to describe phase II and phase III → realistic light curves and spectra

(see talk by D. Siegel)

much larger spatial scales and time scales NOT covered by GRMHD simulations

Siegel & Ciolfi 2015b, 2015c
arXiv:1508.07911 arXiv1508.07939

References

Ciolfi R. & Siegel D.M. (2015a) ApJ Letters 798, L36
Short gamma-ray bursts in the 'time-reversal' scenario

Ciolfi R. & Siegel D.M. (2015b), in "*Swift: 10 Years of Discovery*", PoS(SWIFT 10)108
Short gamma-ray bursts from binary neutron star mergers: the time-reversal scenario

Siegel D.M., Ciolfi R., Rezzolla L. (2014) ApJ Letters 785, L6
Magnetically driven winds from differentially rotating neutron stars and X-ray afterglows of short gamma-ray bursts

Siegel D.M. & Ciolfi R. (2015a), in "*Swift: 10 Years of Discovery*", PoS(SWIFT 10)169
Magnetically-induced outflows from binary neutron star merger remnants

Siegel D.M. & Ciolfi R. (2015b), arXiv:1508.07911
Electromagnetic emission from long-lived binary neutron star merger remnants I: formulation of the problem

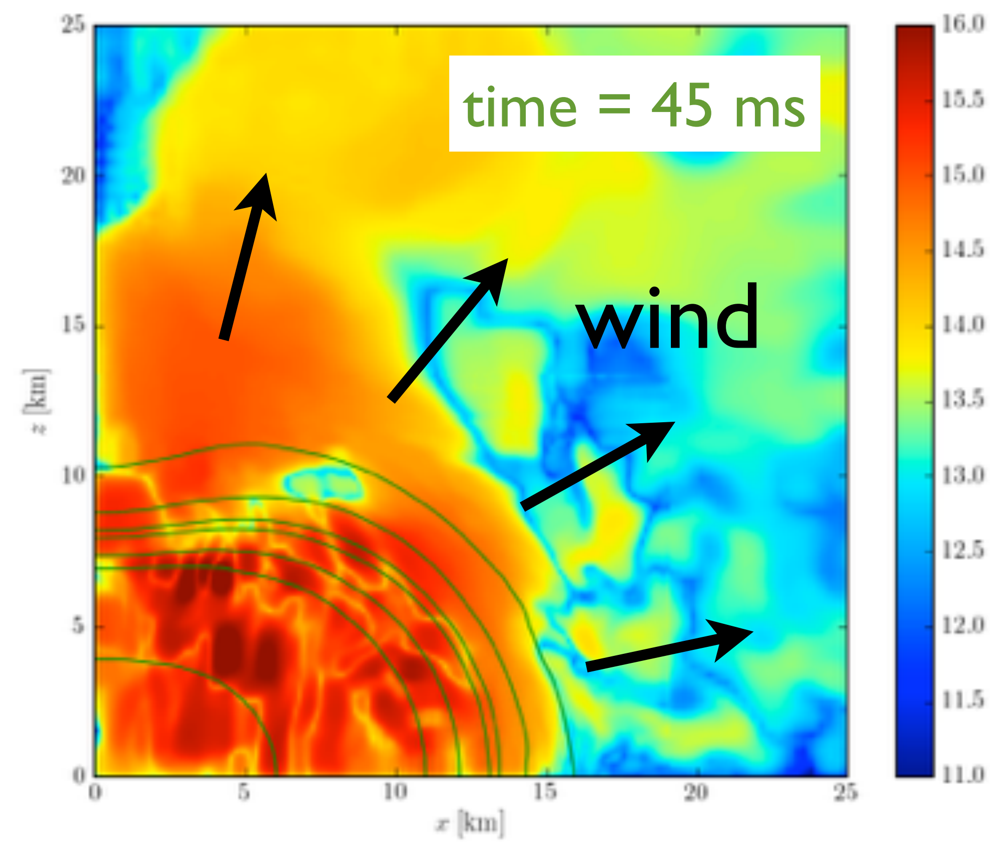
Siegel D.M. & Ciolfi R. (2015c), arXiv:1508.07939
Electromagnetic emission from long-lived binary neutron star merger remnants II: light curves and spectra

BACKUP SLIDES

Baryon-loaded wind

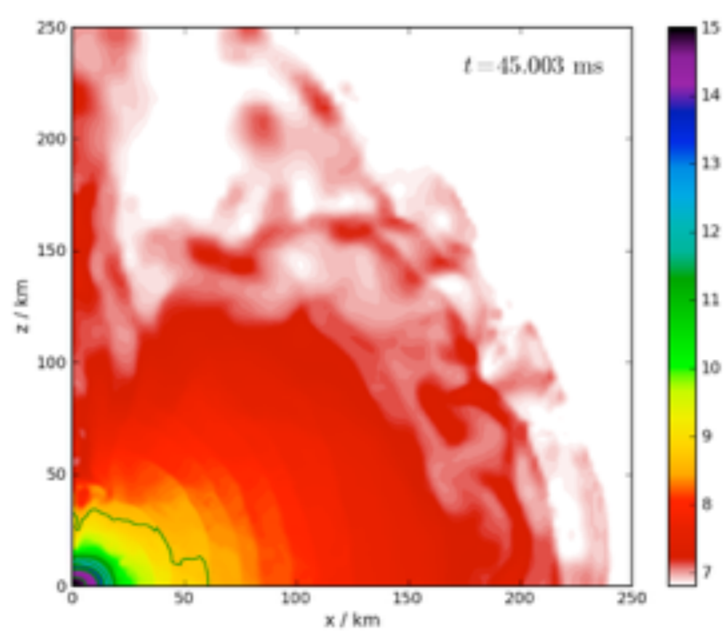
- rest-mass density of the wind $\rho \sim 10^8 \ \mathrm{g/cm}^3$
- ejection speed $v \lesssim 0.1 \ \mathrm{c}$
- mass loss rate $\dot{M} \sim 10^{-3} \ \mathrm{M}_\odot/\mathrm{s}$
- mostly isotropic!

rand

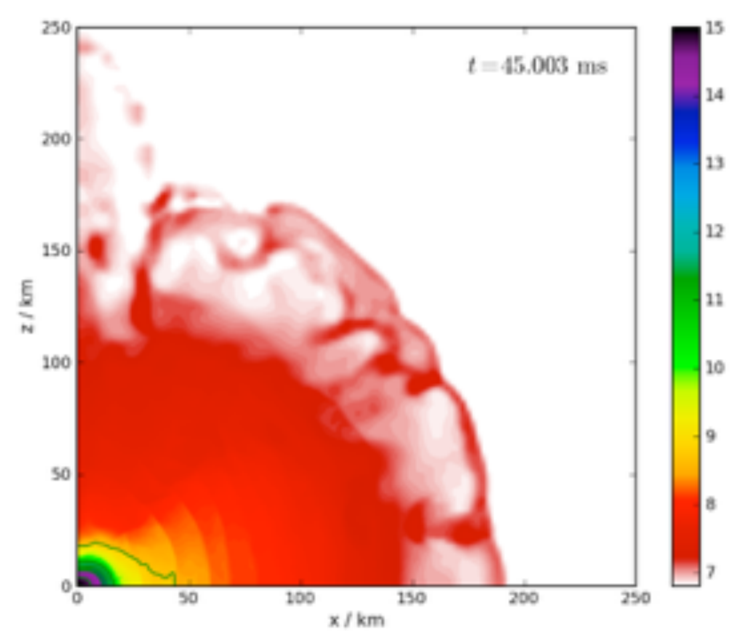


rest-mass density evolution ↓

dipole 60



dipole 6



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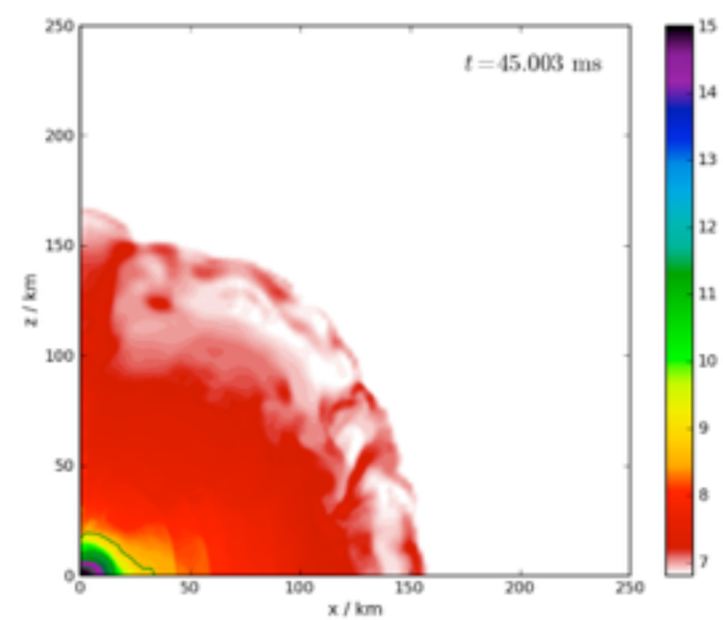
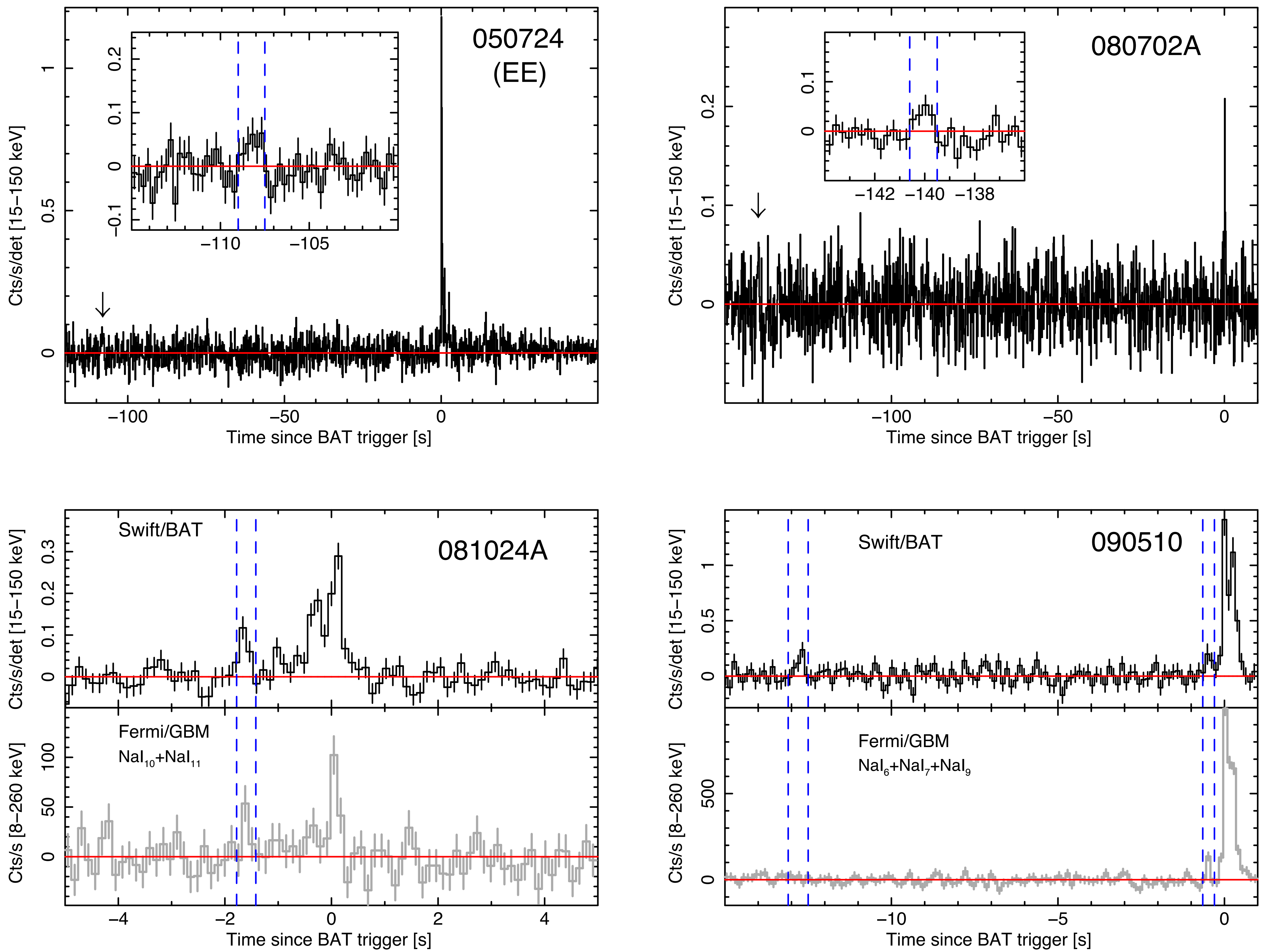


SGRB precursors

Troja et al. 2010

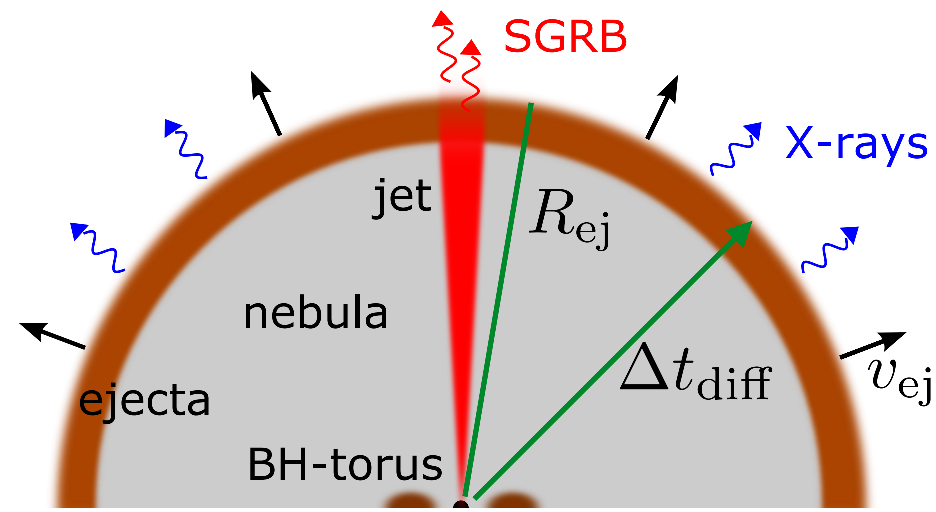


Timing argument

The scenario cannot hold unless the maximum delay is at least as large as the observed afterglow duration

- from observations: $t_{\rm coll} \gtrsim t_{\rm sd}$
- typically: $t_{\rm sd} \gg t_{\rm dr} + \Delta t_{\rm shock}$

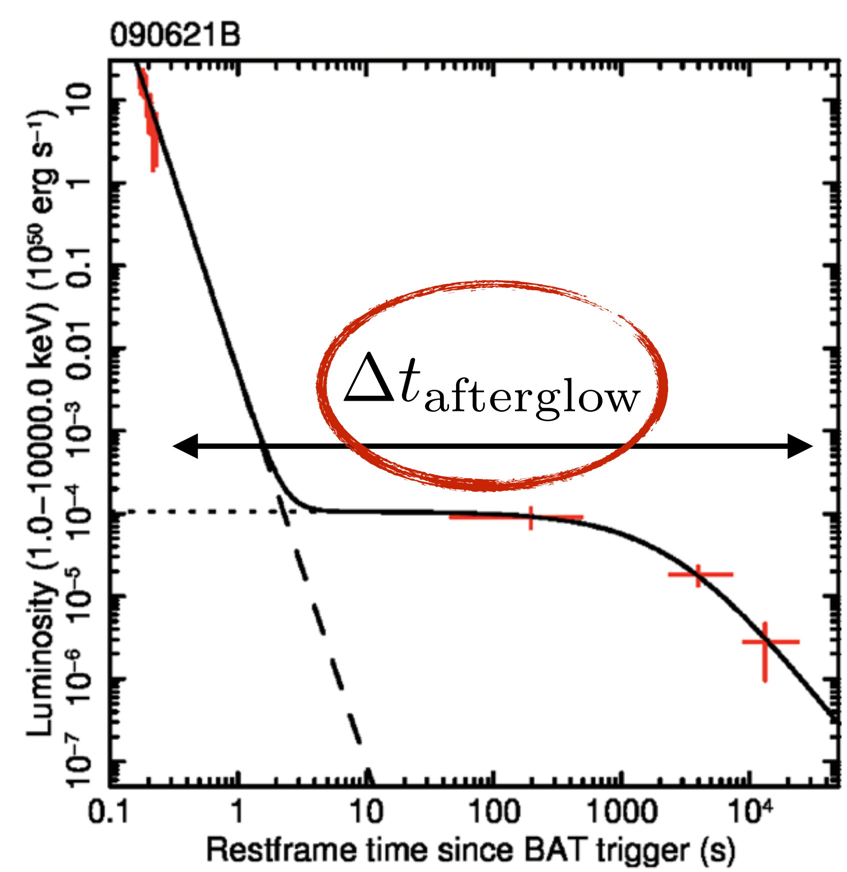
  $\longrightarrow$ at $t_{\rm coll}$ ejecta matter is swept up into thin shell



- delay for a photon emitted just before collapse ("last spin-down photon"):

$$t_{\rm NS}^{\rm delay} = \Delta t_{\rm diff} - \frac{R_{\rm ej}(t_{\rm coll} + \Delta t_{\rm diff})}{c}$$

- Delay of jet is negligible (very low densities at $t_{\rm coll}$)



Timing criterion

$$t_{\rm NS}^{\rm delay} \simeq t_{\rm NS}^{\rm delay} - t_{\rm jet}^{\rm delay} \gtrsim \Delta t_{\rm afterglow}$$

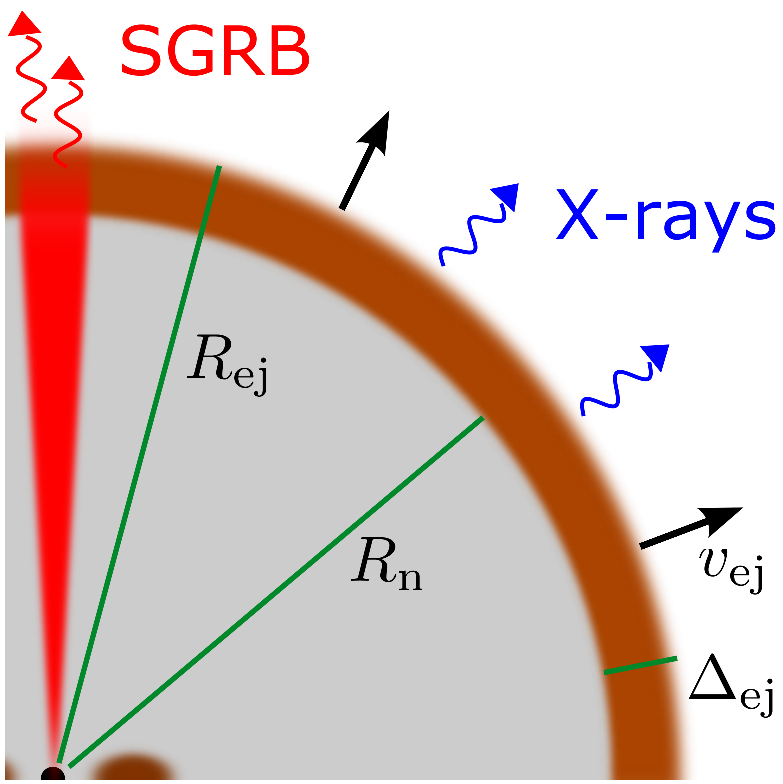
Diffusion timescales

- for static ejecta:

$$t_{\rm diff}^{\rm ej,\ stat}(t) = \frac{\Delta_{\rm ej}}{c}(1+\kappa\rho_{\rm ej}(t)\Delta_{\rm ej}) \propto t^{-2}$$

- for static nebula:

$$t_{\rm diff}^{\rm n,stat}(t) = \frac{R_{\rm n}(t)}{c}\left(1+\sqrt{\frac{4Y\sigma_{\rm T}L_{\rm sd}(t)}{\pi R_{\rm n}(t) m_{\rm e} c^3}}\right) \propto t^{-1/2}$$



$$t_{\rm NS}^{\rm delay} \lesssim t_{\rm diff}^{\rm ej,stat}(t_{\rm coll}) + t_{\rm diff}^{\rm n,stat}(t_{\rm coll}) - R_{\rm ej}(t_{\rm coll})/c$$

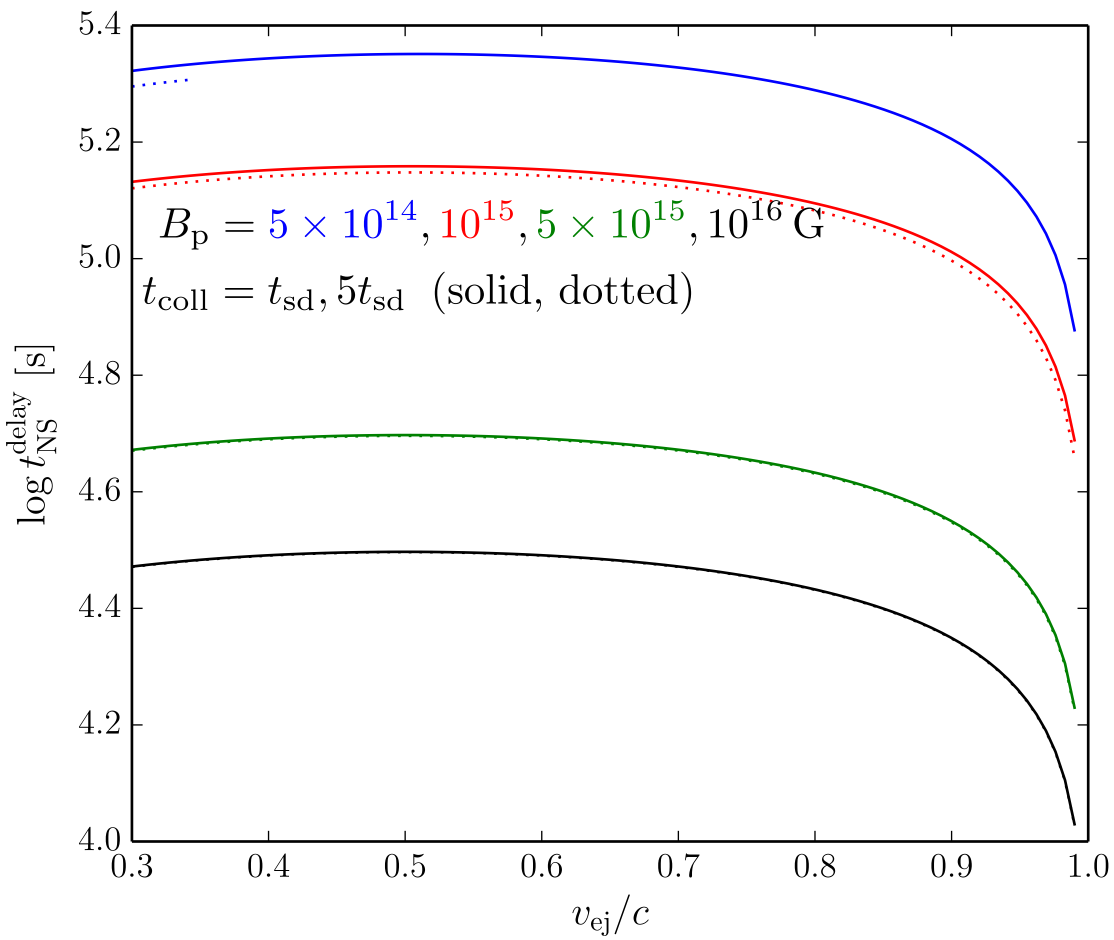
$$t_{\rm NS}^{\rm delay} \gtrsim t_{\rm diff}^{\rm ej,stat}(t^*_{\rm coll}) + t_{\rm diff}^{\rm n,stat}(t^*_{\rm coll}) - R_{\rm ej}(t^*_{\rm coll})/c$$

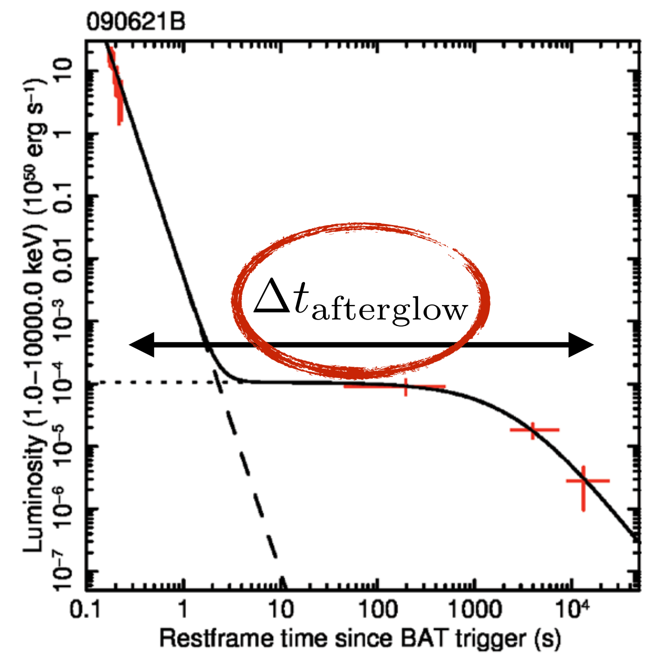
solve iteratively for $t^*_{\rm coll}$:

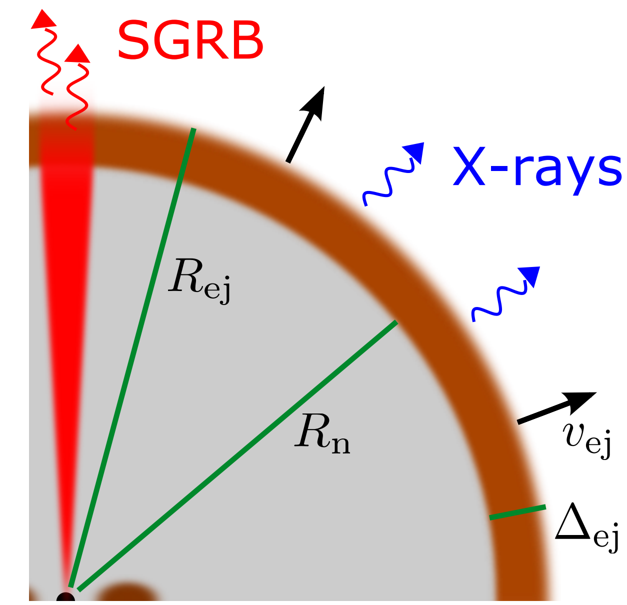
$$t^*_{\rm coll} = t_{\rm coll} + t_{\rm diff}^{\rm ej,\ stat}(t^*_{\rm coll}) + t_{\rm diff}^{\rm n,stat}(t^*_{\rm coll})$$

⟶ use lower limit to check the timing criterion

Results on delay estimation







- for parameter ranges considered:

$$t_{NS}^{delay} > 3\times10^4\,\mathrm{s}$$
$$t_{NS}^{delay} \gtrsim 10^5\,\mathrm{s} \quad (B_p \lesssim 10^{15}\,\mathrm{G})$$

parameter ranges:

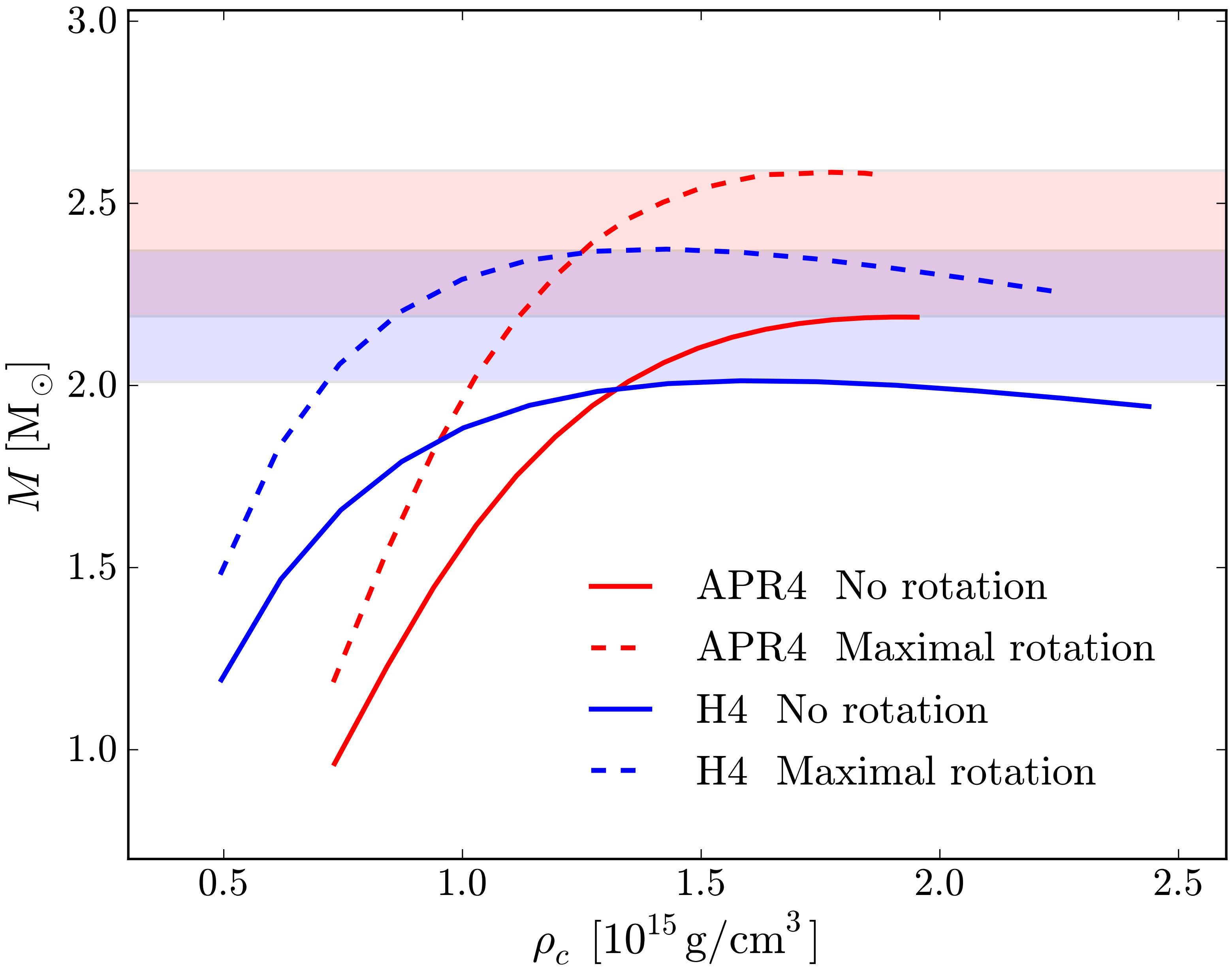
$$B_p \sim 10^{14} - 10^{16}\,\mathrm{G}$$
$$P_{in} \sim 0.5 - 5\,\mathrm{ms}$$
$$t_{dr} \sim 0.1 - 10\,\mathrm{s}$$
$$\dot{M} \sim 10^{-4} - 10^{-2} M_\odot\,\mathrm{s}^{-1}$$
$$\Delta t_{shock} \sim 0 - 100\,t_{dr}$$
$$v_{ej}^0 \sim 0.01 - 0.1\,c$$

generally: $t_{NS}^{delay} \gtrsim \Delta t_{afterglow}$

→ "time-reversal" scenario compatible with observations

EOS constraint for a SMNS

Ciolfi & Siegel 2015b



most likely progenitor mass combination

$1.3 - 1.4\ M_\odot$

Belczynski et al. 2008

↓

$M \sim 0.9(M_1 + M_2 - 0.1)$

↓

$M \sim 2.34\ M_\odot$

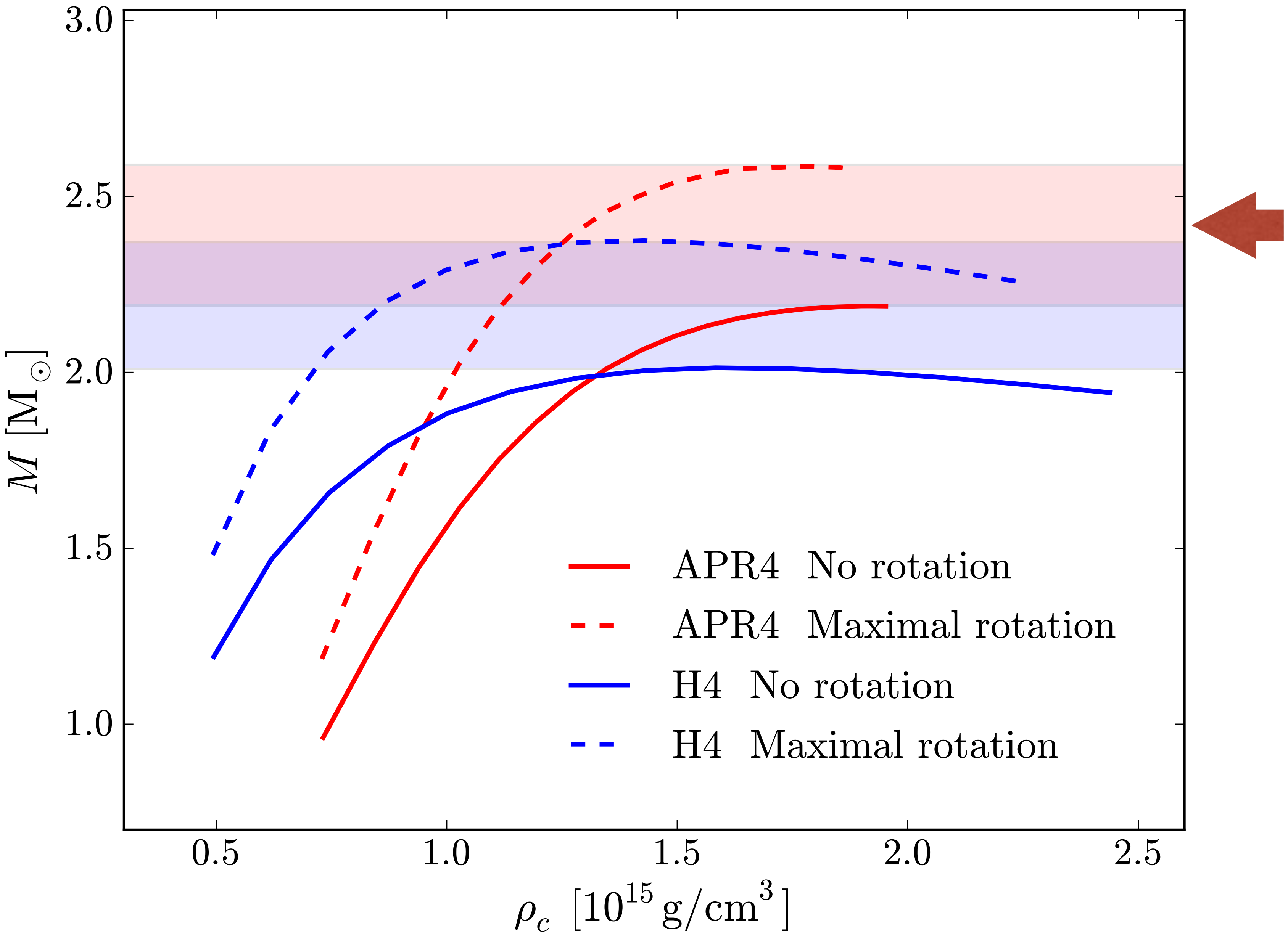
$(\ M_b \sim 2.87\ M_\odot\ )$

APR4 ✓

H4 ✓

EOS constraint for a SMNS

Ciolfi & Siegel 2015b



progenitor
mass combination

$$1.4 - 1.4 \ \mathrm{M}_\odot$$

↓

$$M \sim 0.9(M_1 + M_2 - 0.1)$$

↓

$$M \sim 2.43 \ \mathrm{M}_\odot$$

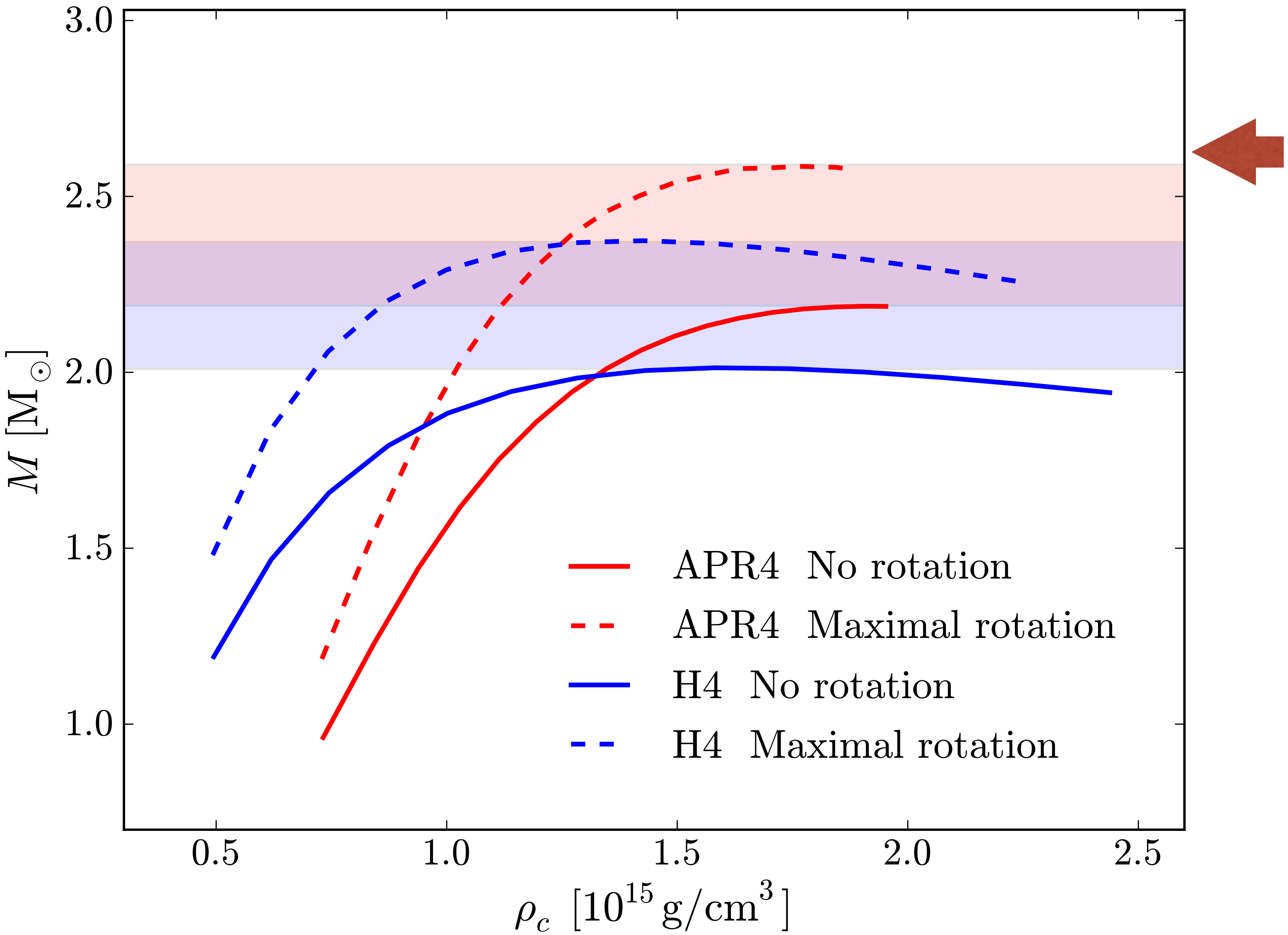
$$(\ M_b \sim 2.98 \ \mathrm{M}_\odot \ )$$

APR4 ✓

H4 ✗

EOS constraint for a SMNS

Ciolfi & Siegel 2015b



progenitor
mass combination

$$1.5 - 1.5\ \mathrm{M}_\odot$$

↓

$$M \sim 0.9(M_1 + M_2 - 0.1)$$

↓

$$M \sim 2.61\ \mathrm{M}_\odot$$

$$(\ M_b \sim 3.2\ \mathrm{M}_\odot\ )$$

APR4 ✗

H4 ✗

EM emission from long-lived BNS merger remnants

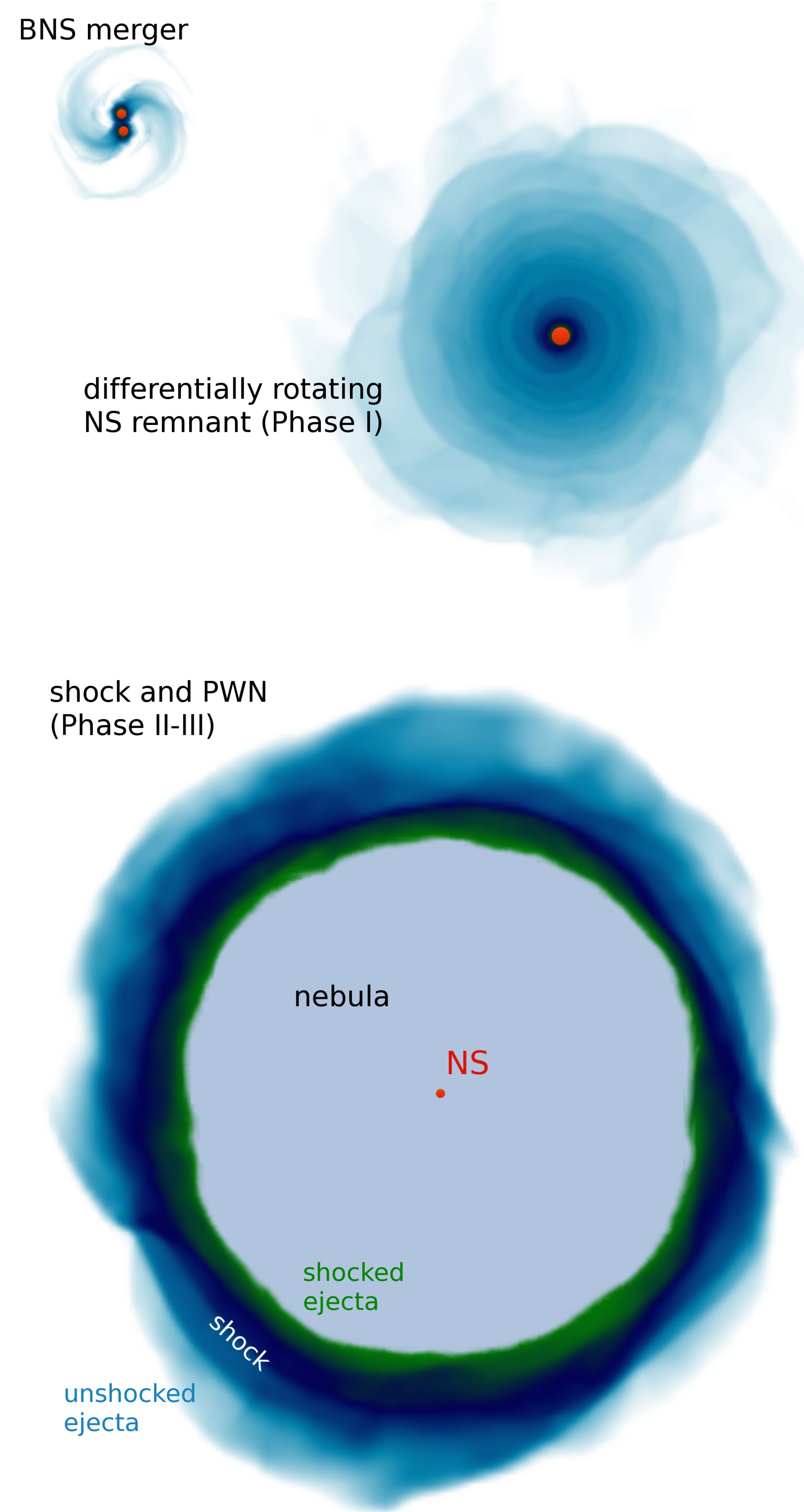
Siegel & Ciolfi 2015b, 2015c

- 1D dynamical model to describe phase II and phase III on large time and spatial scales

↓

ideal EM counterpart to the GW signal

- bright (up to $L_X \sim 10^{48}$ erg/s)
- long-lasting (typically 10^4 s)
- isotropic
- associated with a large fraction of BNS merger events
- clear distinction NS-NS vs NS-BH



EM emission from long-lived BNS merger remnants

Siegel & Ciolfi 2015b, 2015c

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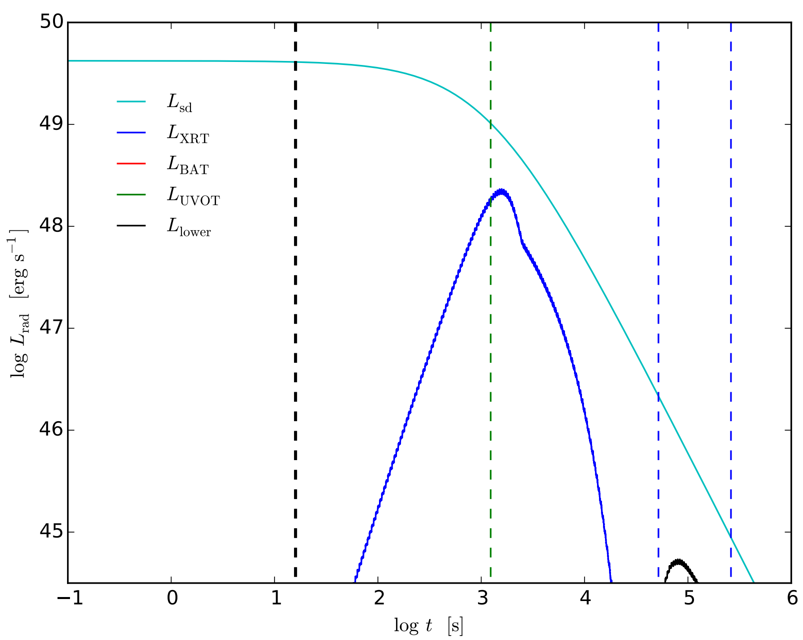
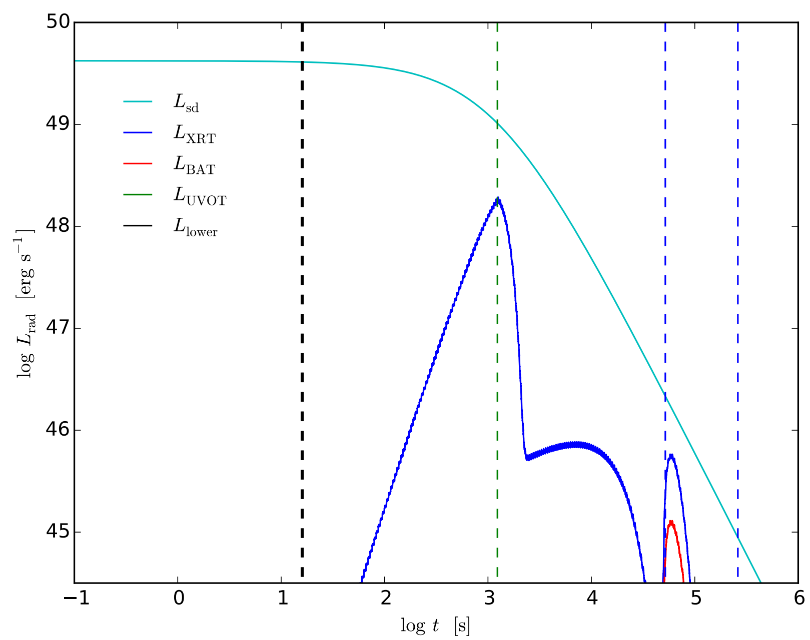
light curves and spectra



NO SMNS collapse

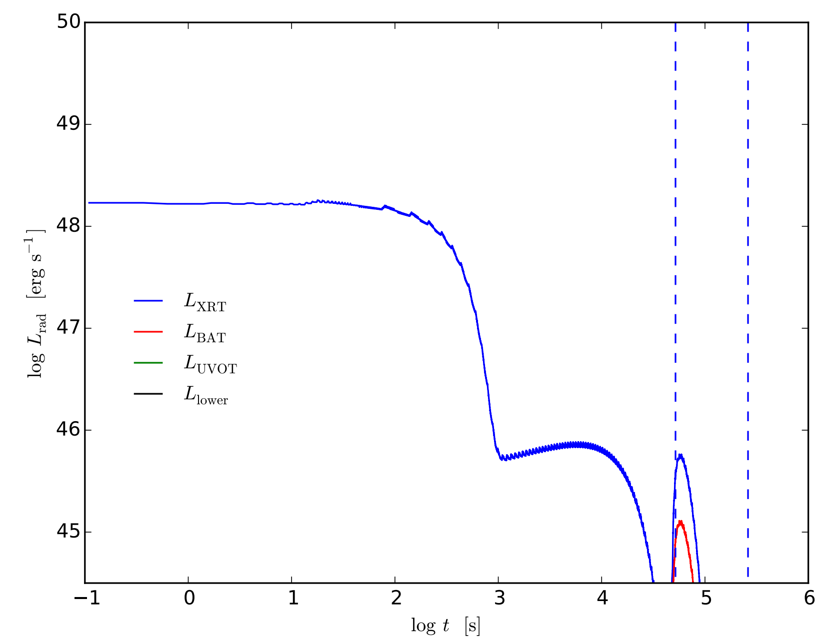
SGRB prompt emission @ merger



SMNS collapse

$t_{\rm coll} = t_{\rm spin-down}$

SGRB prompt emission @ merger



SMNS collapse

$t_{\rm coll} = t_{\rm spin-down}$

SGRB prompt emission @ SMNS collapse (time-reversal scenario)

EM emission from long-lived BNS merger remnants

Siegel & Ciolfi 2015b, 2015c