



UNIVERSITY OF TRENTO - Italy



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

RICCARDO CIOLFI

Ciolfi R. & Siegel D.M. (2015a) *ApJ Letters* 798, L36

Ciolfi R. & Siegel D.M. (2015b), in “*Swift: 10 Years of Discovery*”,
PoS(SWIFT 10)108

Siegel D.M. & Ciolfi R. (2015b), arXiv:1508.07911

Siegel D.M. & Ciolfi R. (2015c), arXiv:1508.07939

Società Italiana di Fisica, 101° Congresso Nazionale
Rome - September 25th 2015

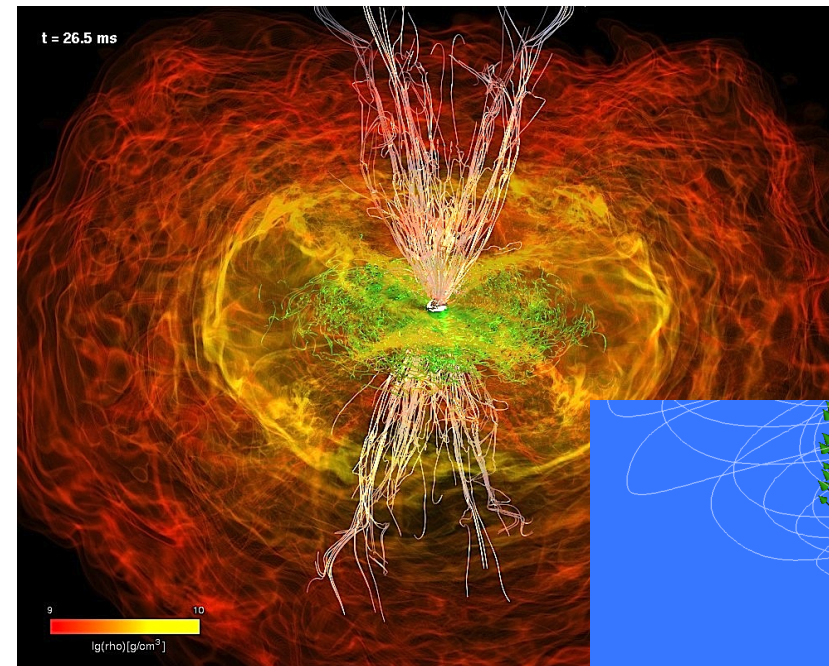
Introduction: SGRBs

leading model of short gamma-ray bursts (SGRBs)

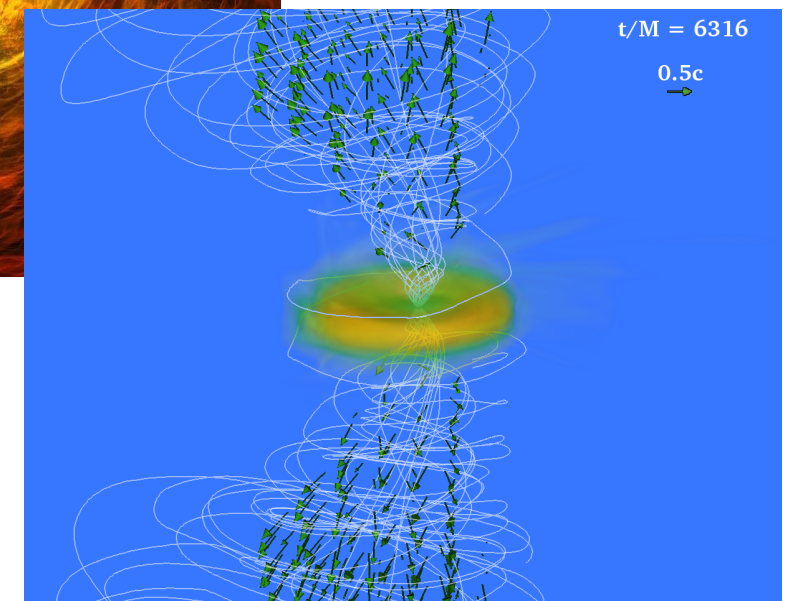
central engine is a black hole surrounded by hot thick torus
→ end result of a binary neutron star (BNS) or mixed binary (NS-BH) merger

Paczynski 1986, Eichler et al. 1989

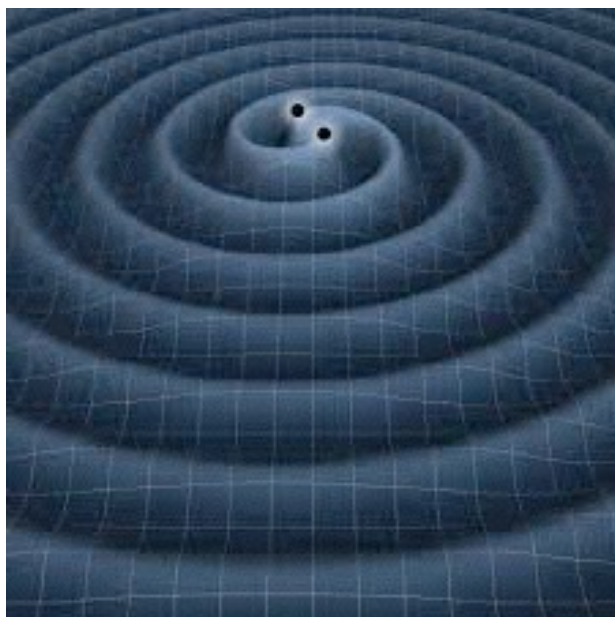
Narayan et al. 1992, Barthelmy et al. 2005, Fox et al. 2005, Gehrels et al. 2005, ...



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 $\sim 40/\text{yr}$ for Advanced Virgo and LIGO
possibility of combined GW-EM detection!

X-ray afterglows of SGRBs

- SWIFT revealed that most SGRBs are accompanied by long-duration ($\sim 10^2 - 10^5$ s) and high-luminosity ($10^{46} - 10^{51}$ 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

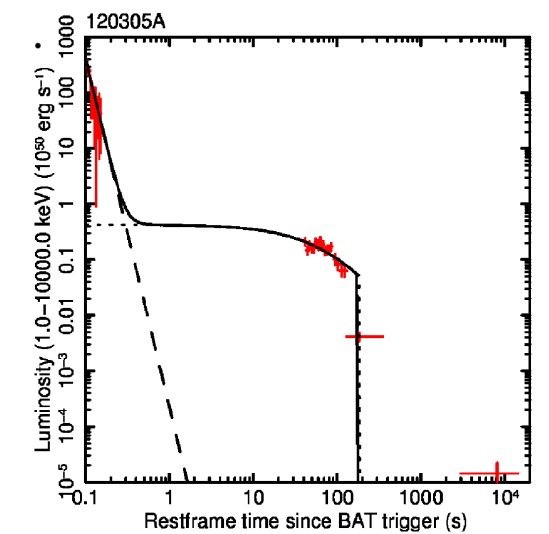
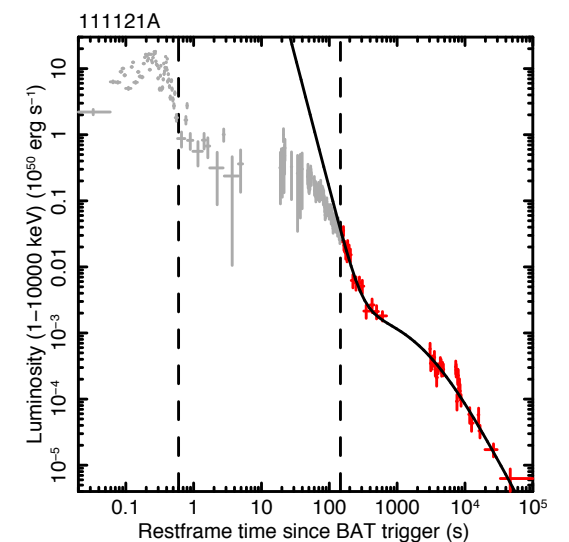
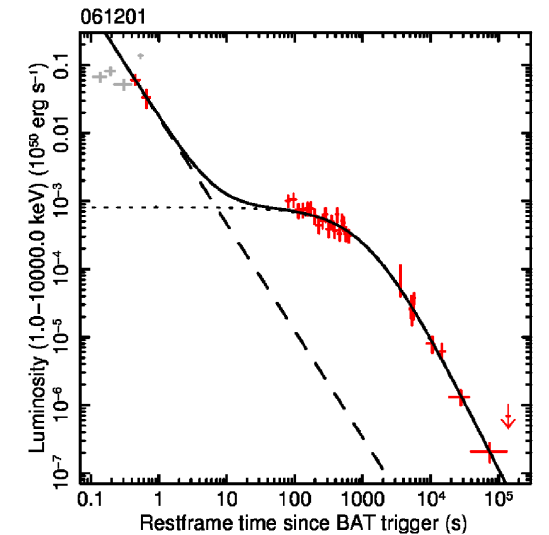
Metzger et al. 2008

X-ray emission \rightarrow spindown of a **uniformly rotating NS** with a strong surface magnetic field

$$\gtrsim 10^{14} - 10^{15} \text{ G}$$

**dipole
spindown**

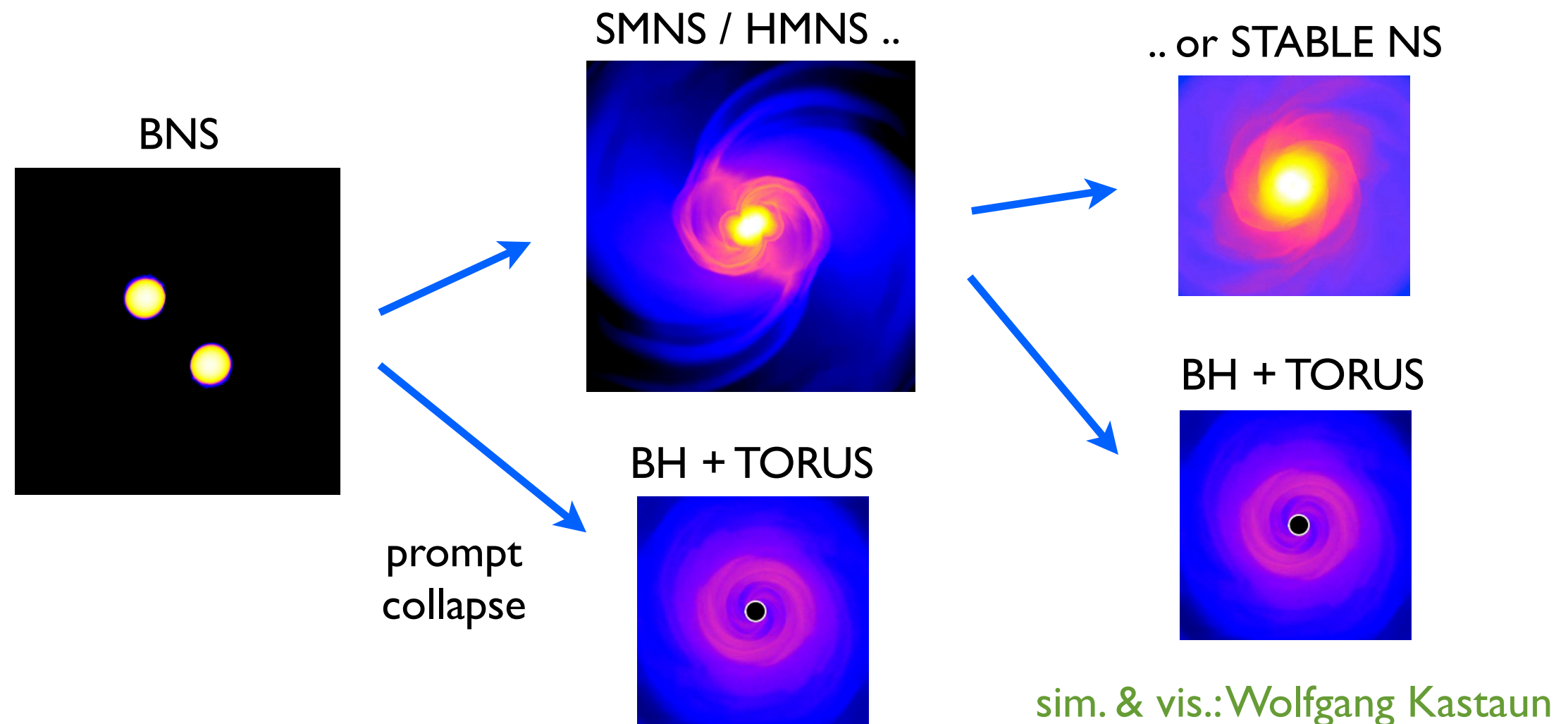
$$L_{\text{sd}}(t) \sim B^2 R^6 \Omega_0^4 \left(1 + \frac{t}{t_{\text{sd}}} \right)^{-2}$$



Gompertz et al. 2013

Rowlinson et al. 2013

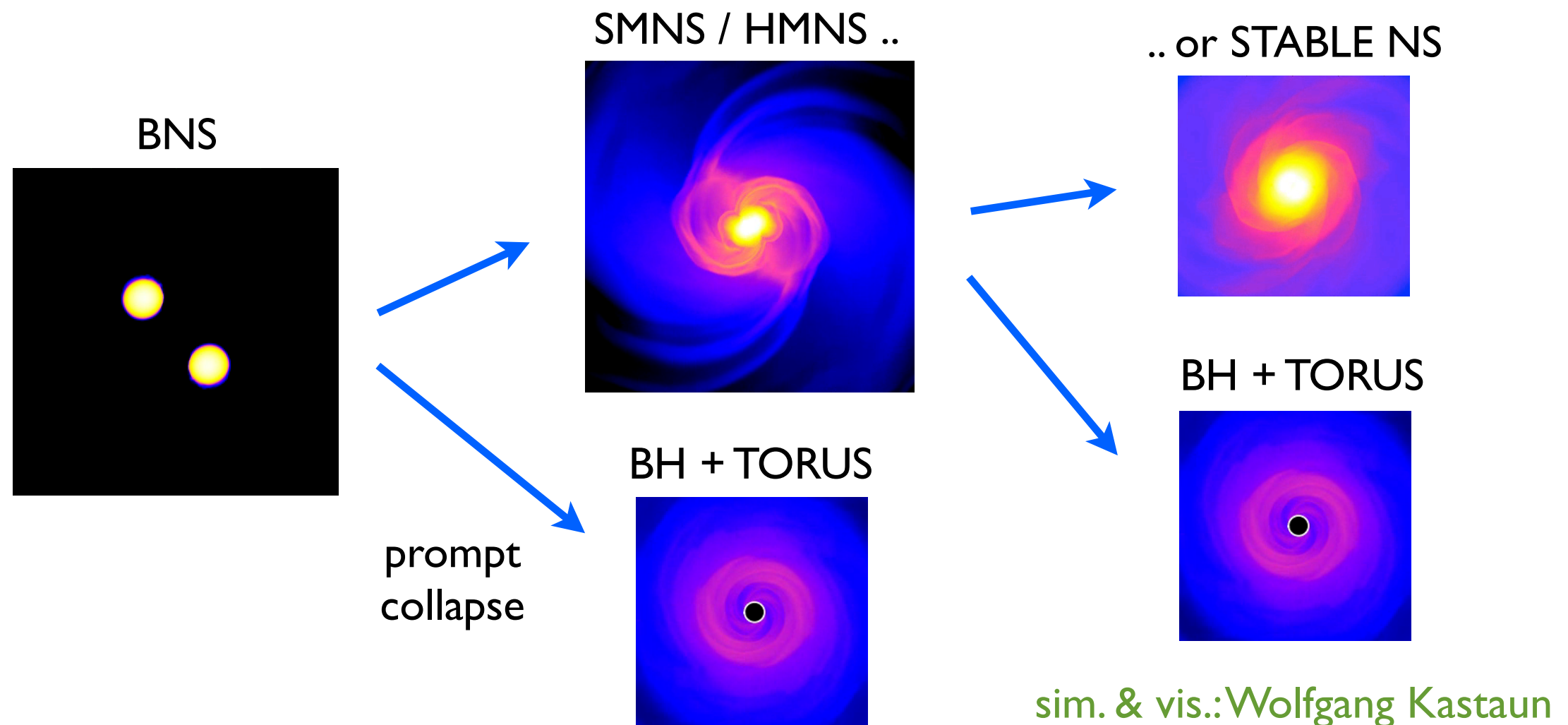
Product of BNS mergers



LONG-LIVED NS IS A LIKELY OUTCOME OF THE MERGER

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

Product of BNS mergers



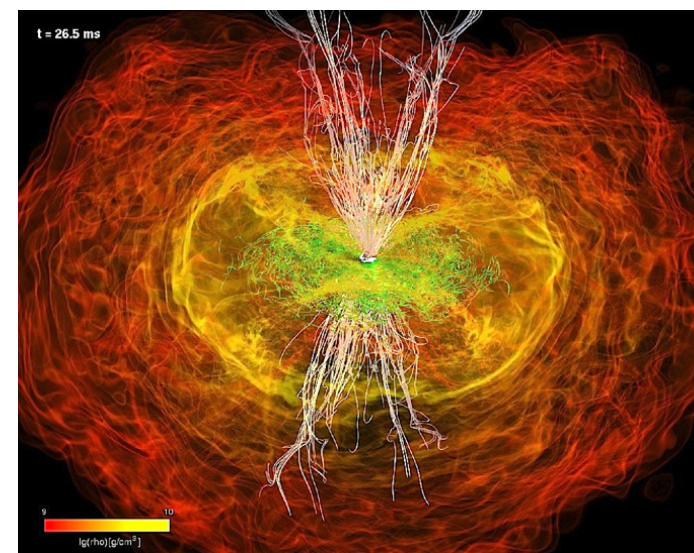
**PROBLEM OF THE LONG-LIVED NS MODEL :
HOW CAN A RELATIVISTIC JET BE
LAUNCHED AT MERGER?**

e.g., [Giacomazzo & Perna 2013](#), ..

The SGRB dichotomy

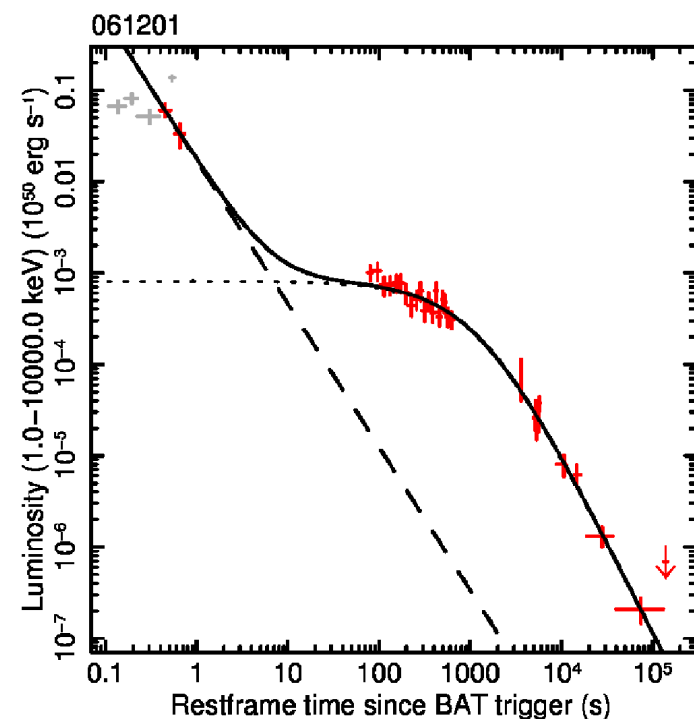
- Numerical relativity picture: prompt BH-torus formation

- can explain prompt SGRB emission ✓
- cannot explain X-ray afterglows ✗



- Observational picture: magnetar model

- cannot explain prompt SGRB emission ✗
- can explain X-ray afterglows ✓

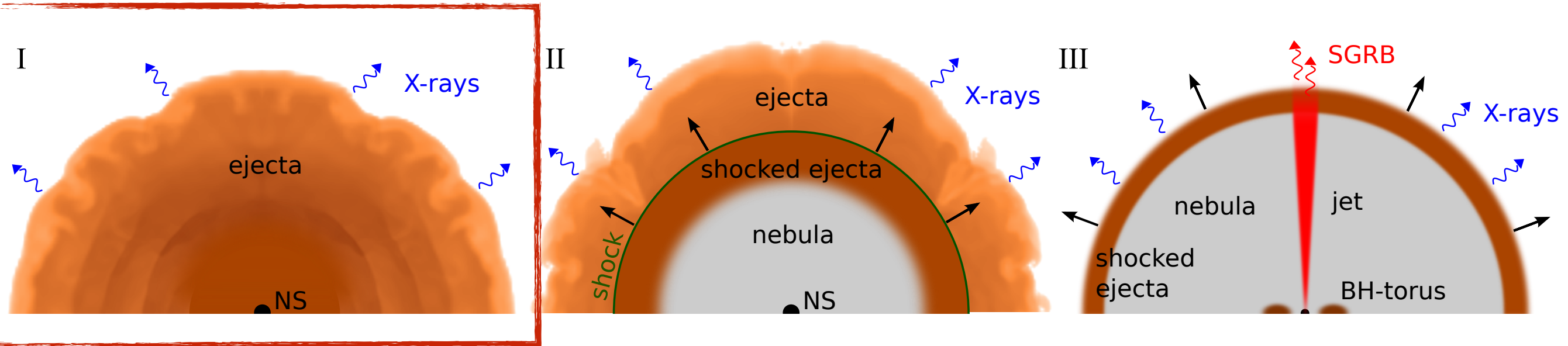


Possible solution: “time-reversal” scenario

Ciolfi & Siegel 2015a

“Time-reversal” phenomenology

Ciolfi & Siegel 2015a



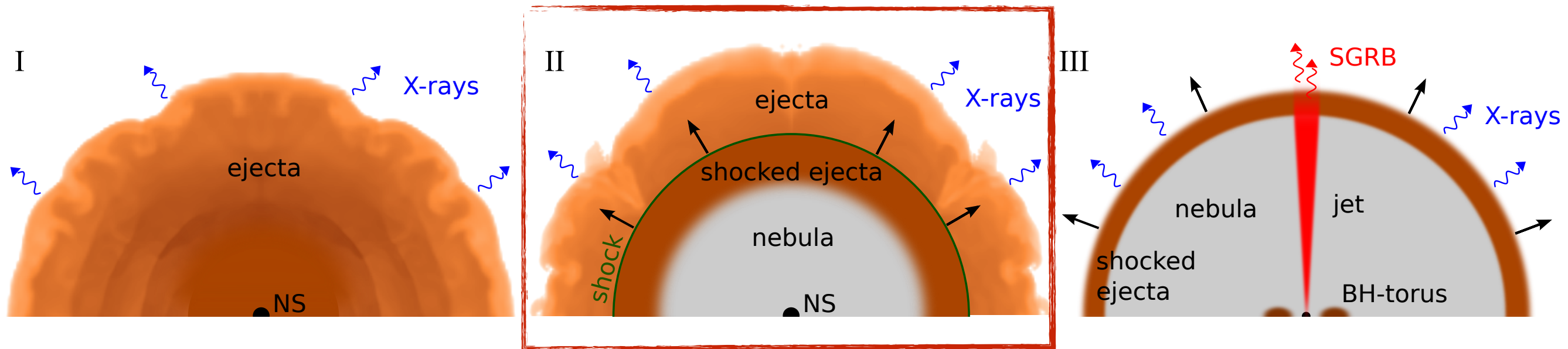
- ➔ (I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

Siegel et al. 2014

Siegel & Ciolfi 2015a

“Time-reversal” phenomenology

Ciolfi & Siegel 2015a



(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

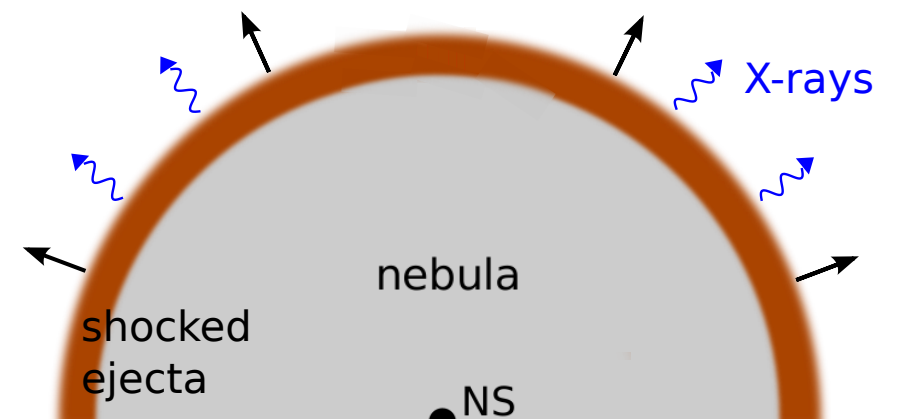
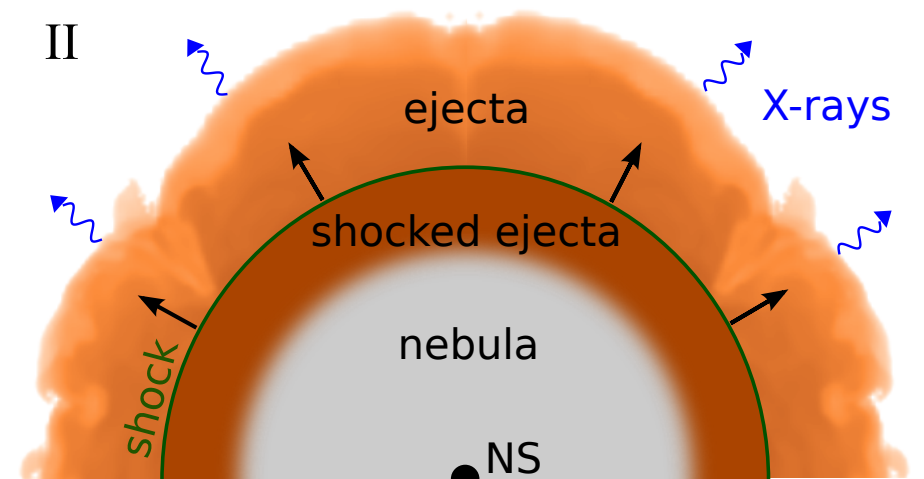
- uniformly rotating NS emits spin-down radiation and inflates a photon-pair nebula

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

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

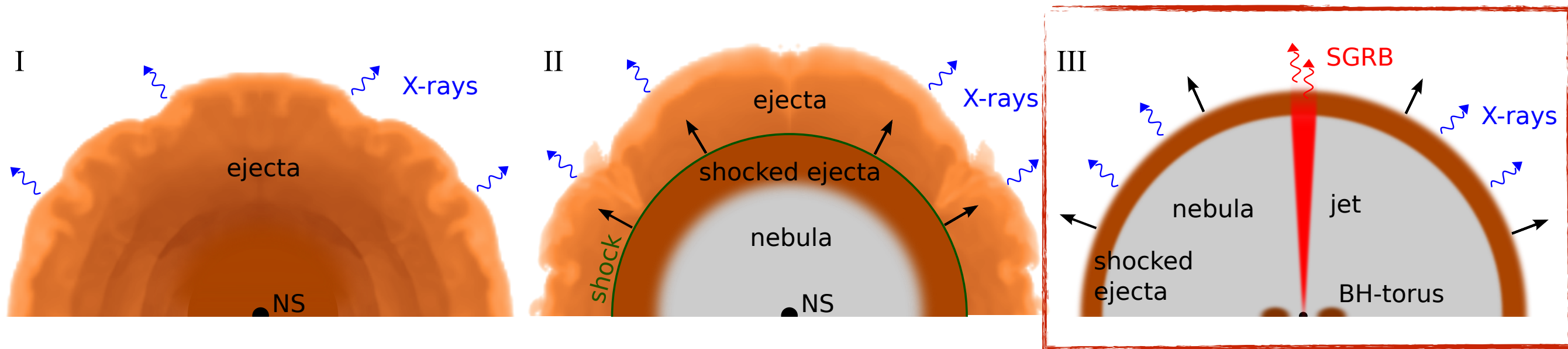
- high photon pressure drives a strong shock through the ejecta, sweeps up material into a thin shell
- nebula energy rapidly heats up and accelerates the ejecta shell (up to mildly relativistic speeds)

Metzger & Piro 2014



“Time-reversal” phenomenology

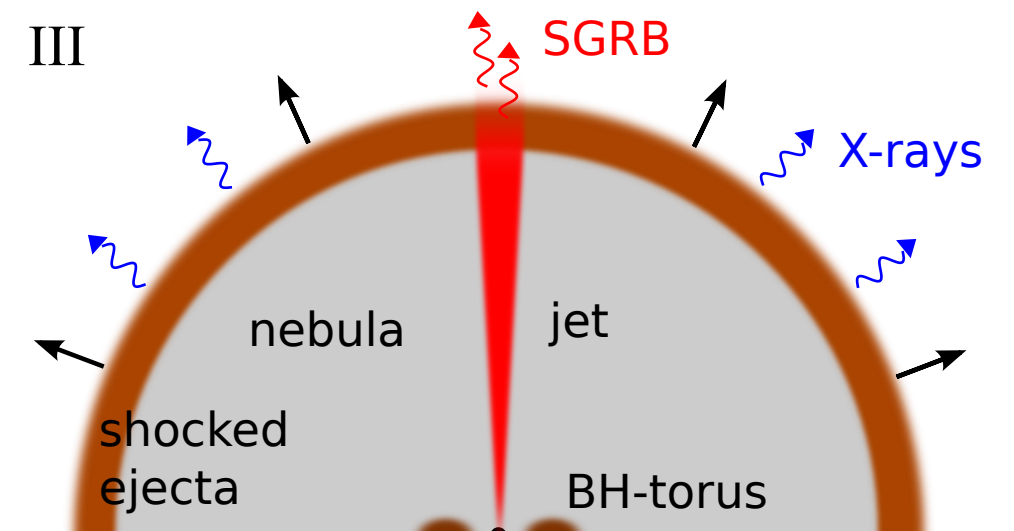
Ciolfi & Siegel 2015a



- (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

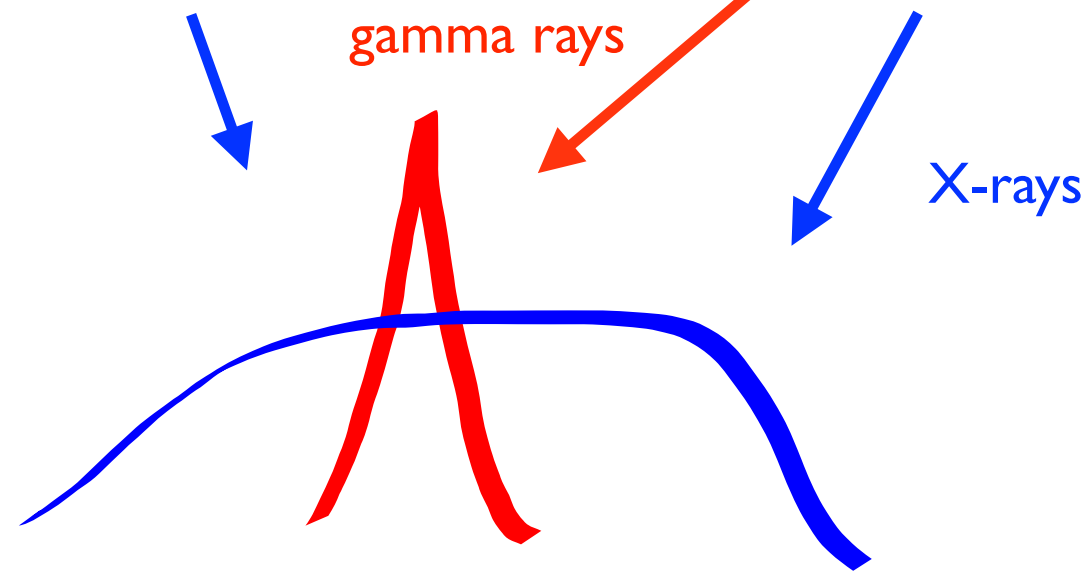
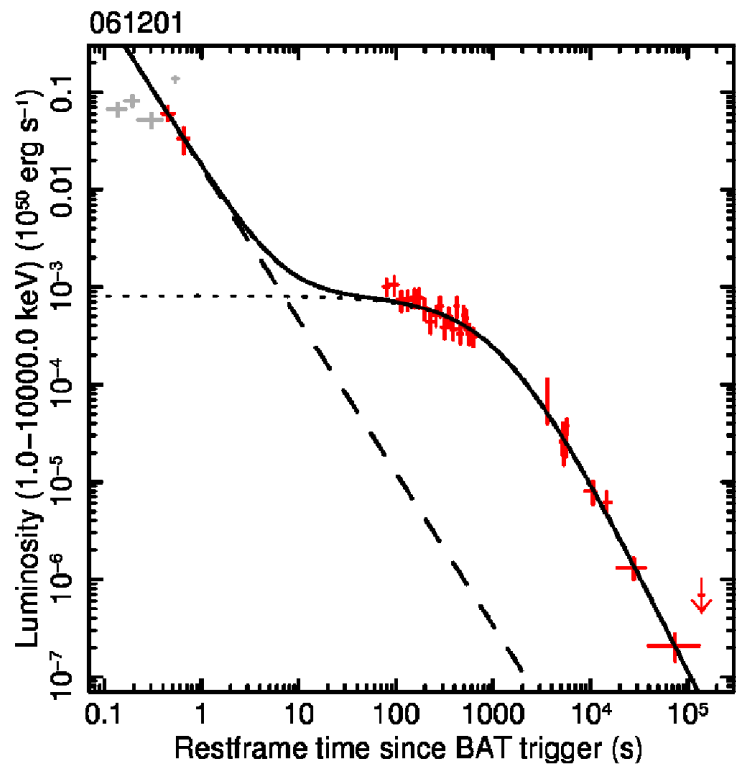
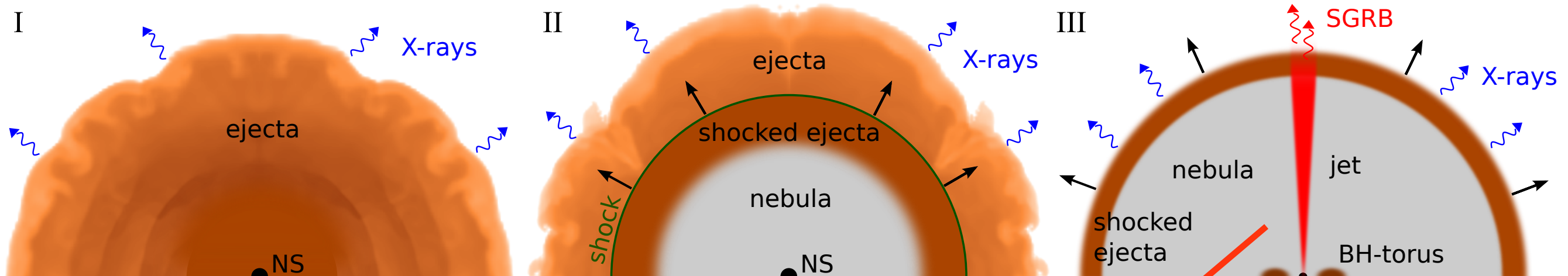
“Time-reversal” phenomenology III

- at $t_{\text{coll}} \sim t_{\text{sd}}$ the NS collapses to a **BH-torus system**
 - **transient jet** is formed in $\lesssim 0.01 - 1$ 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



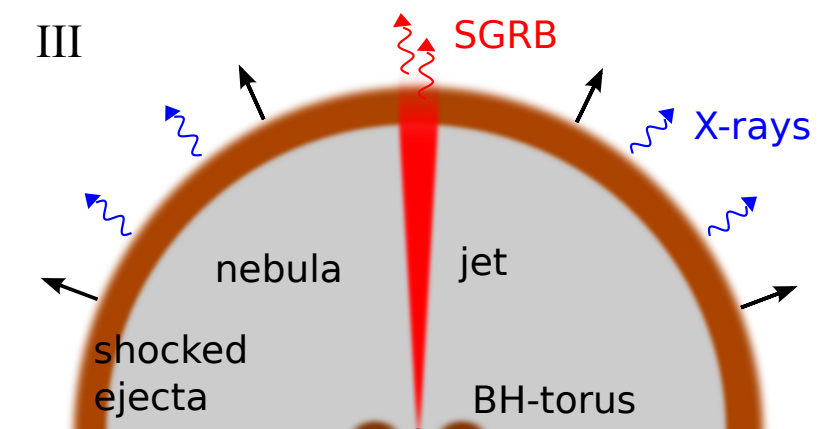
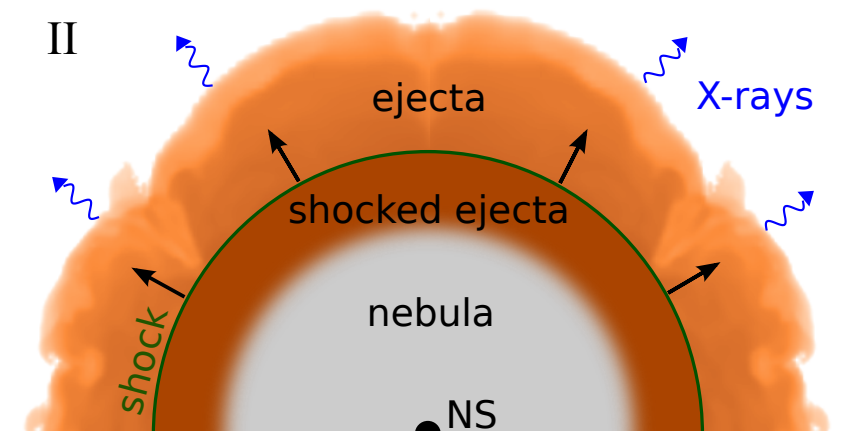
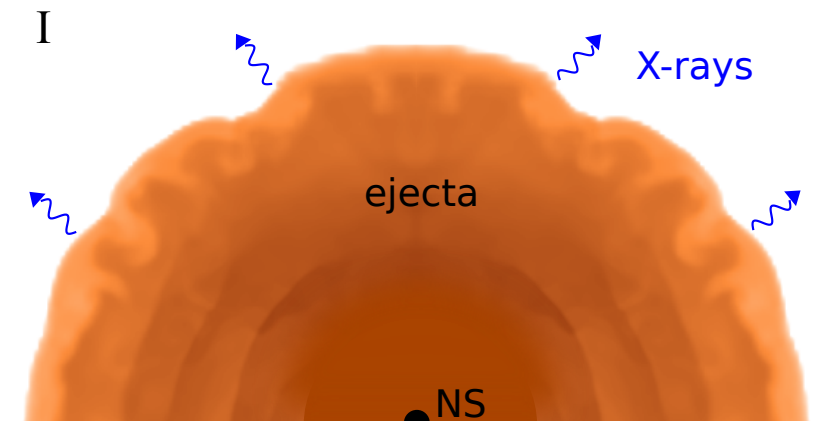
The spin-down emission is **given off before** but (in part) **observed after** the prompt SGRB radiation

Concluding remarks

- 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:

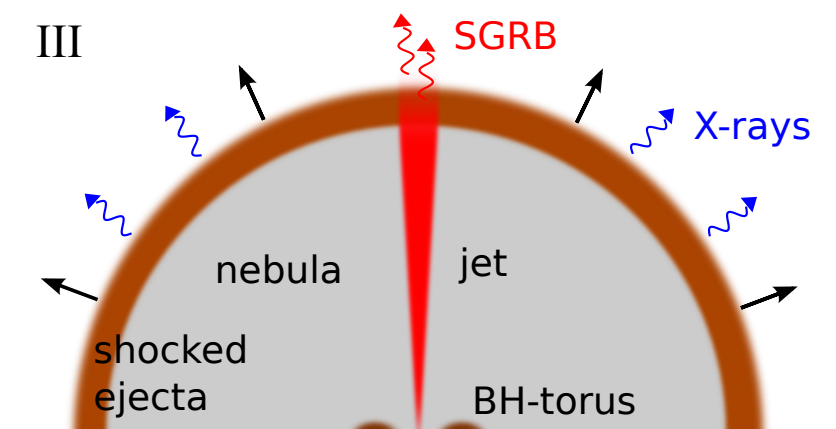
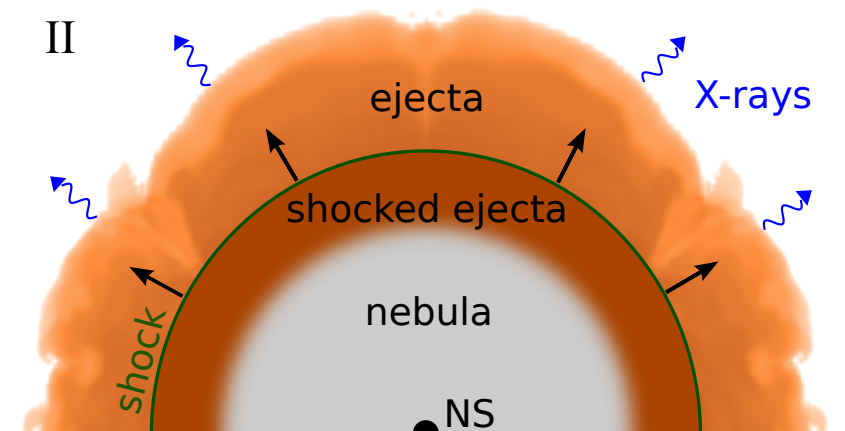
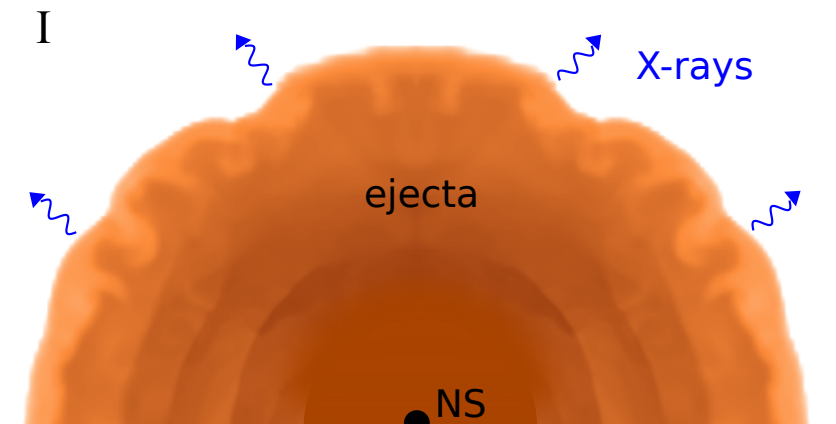
- potential observation of X-ray plateau with SGRB in between
→ indication of time reversal
- potential observation of an orphan event without SGRB
→ isotropy of afterglow



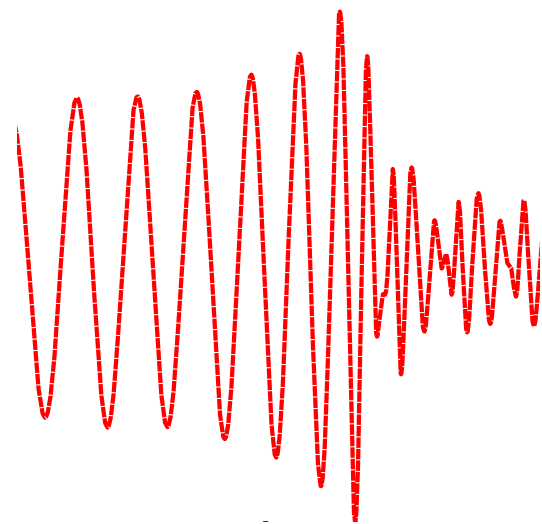
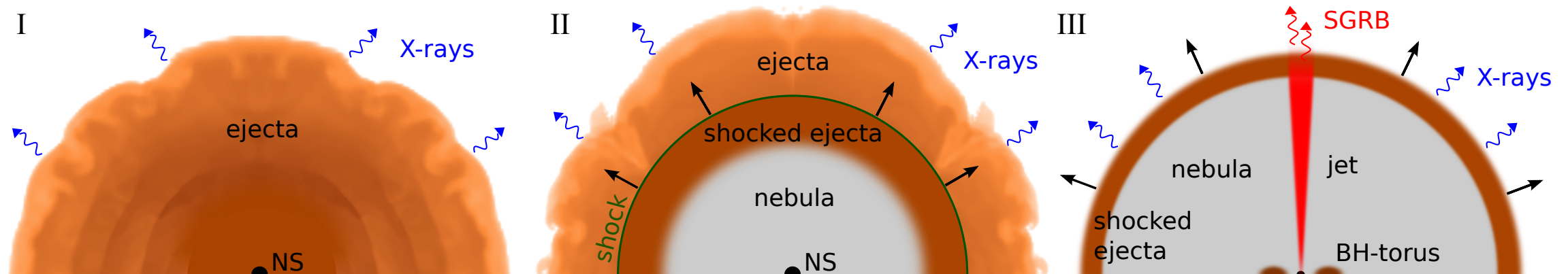
Concluding remarks

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**



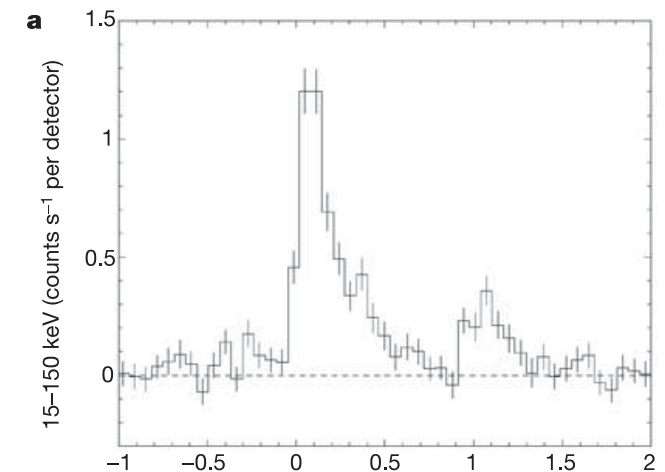
GW and EM observations



peak amplitude GW signal

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

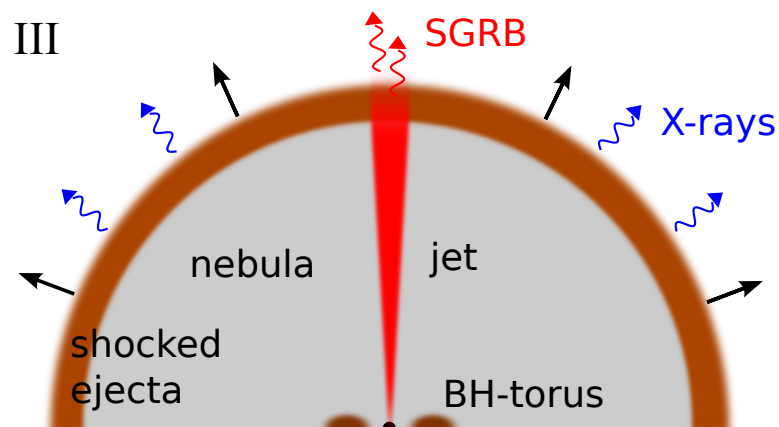
lifetime of the NS



EM SGRB signal

- GW observations ideal trigger for EM observations
- peak amplitude of **GW emission separated from SGRB** by **lifetime of the NS**
→ **very precise measurement of the NS lifetime!**

Next steps



- Investigation on SMNS collapse to establish the conditions of **jet formation**

Margalit et al. 2015

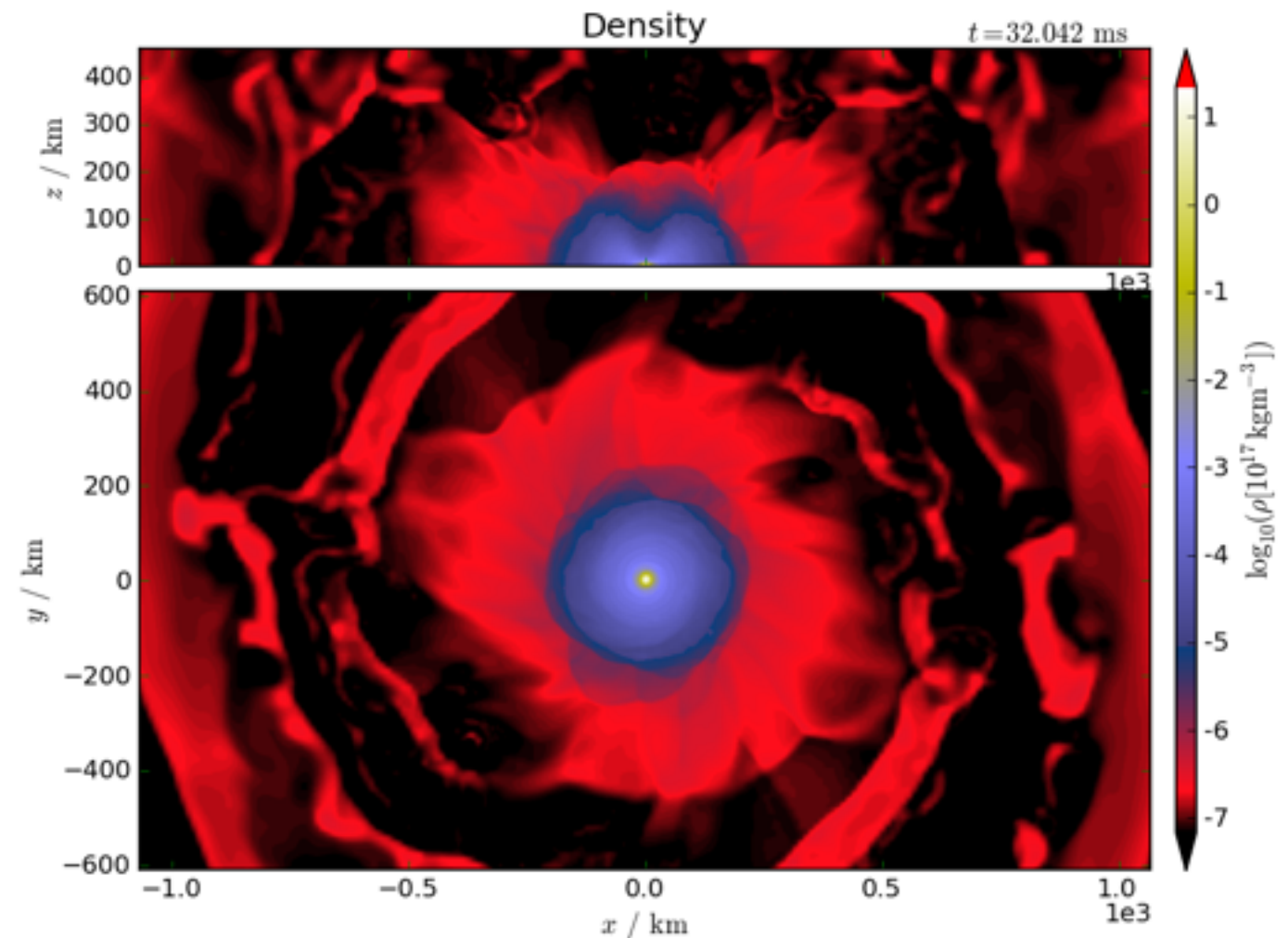
- GRMHD simulations of BNS mergers with long post-merger evolution

(Ciolfi, Kastaun, Giacomazzo, Siegel)

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

→ realistic light curves and spectra

Siegel & Ciolfi 2015b, 2015c



BACKUP SLIDES

“Time-reversal” phenomenology I

Siegel et al. 2014

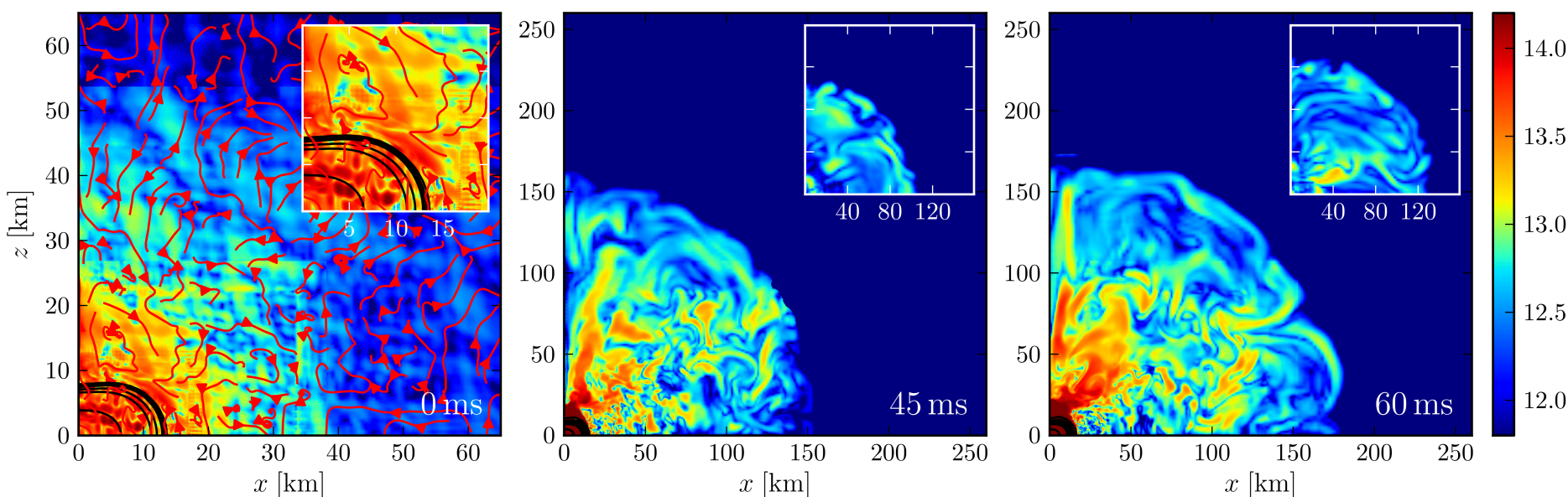
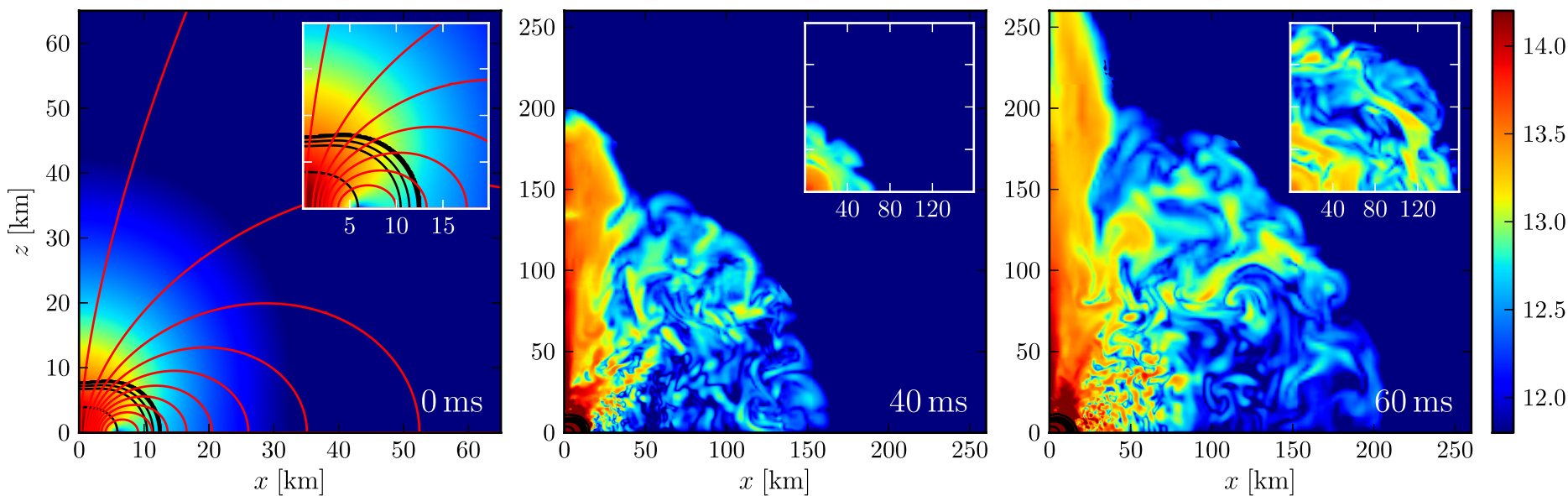
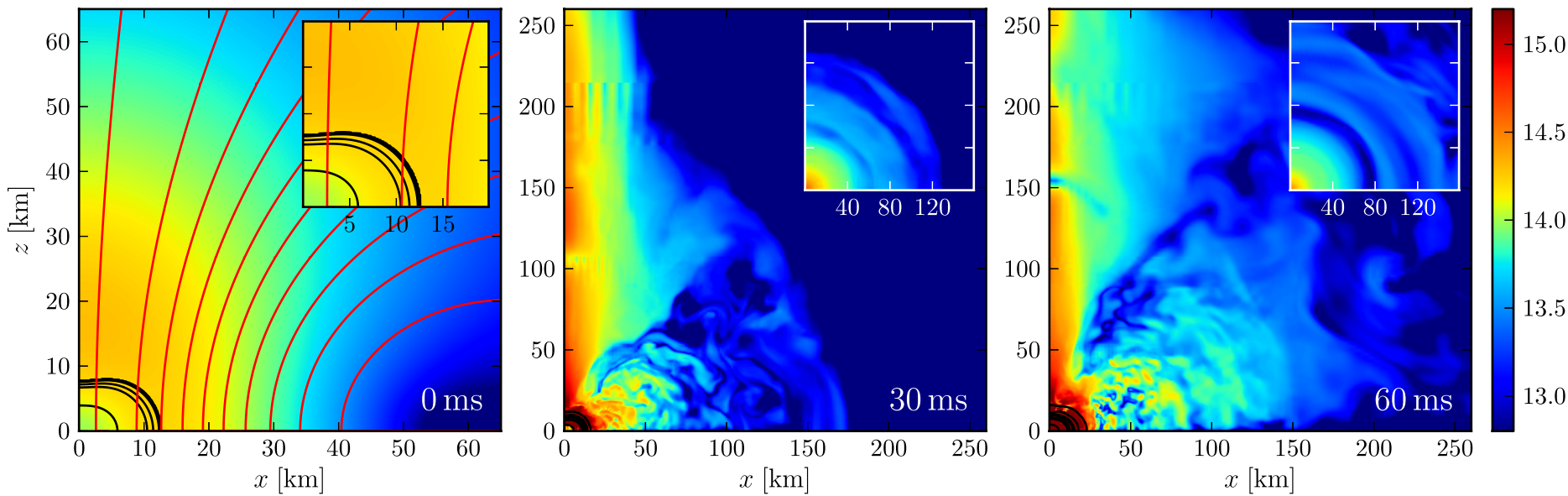
Siegel & Ciolfi 2015a

60 ms evolution
for 3 geometries

dipole 60

dipole 6

random



differential rotation
powers baryon-loaded
and magnetized outflow

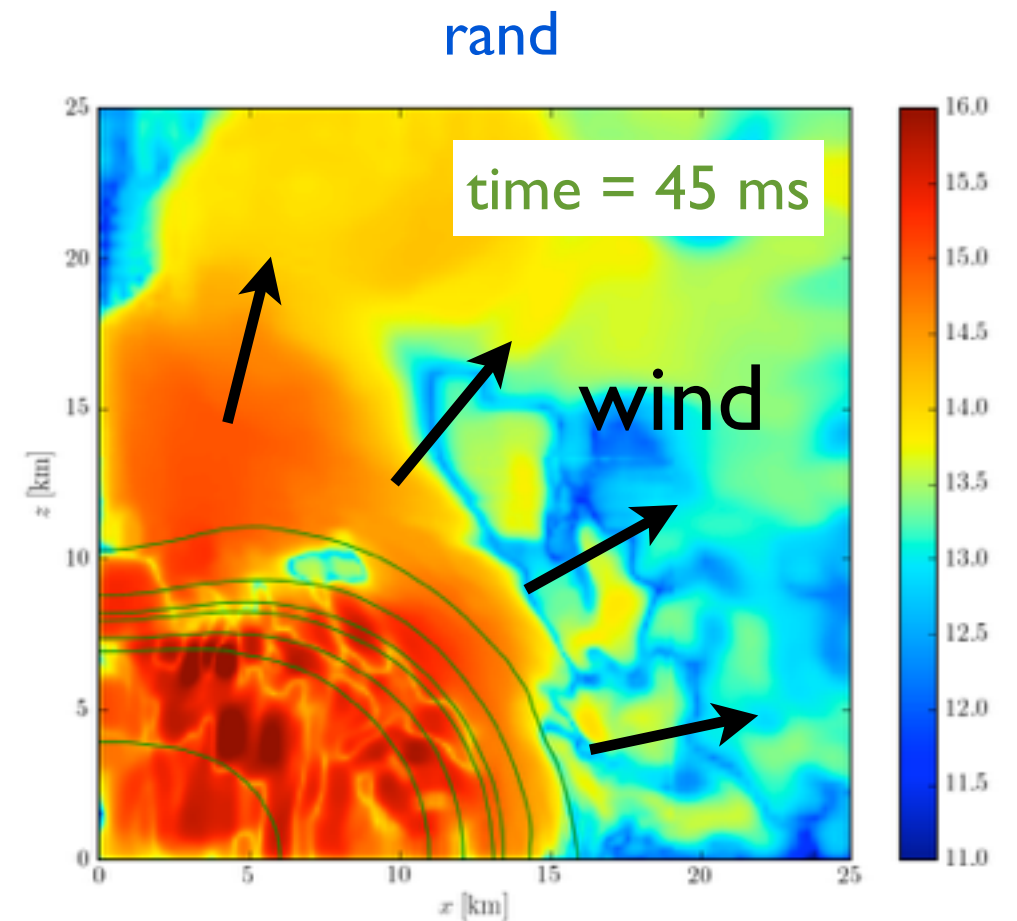
for all MF geometries
the outflow has an
isotropic component

collimation depends
strongly on MF
geometry

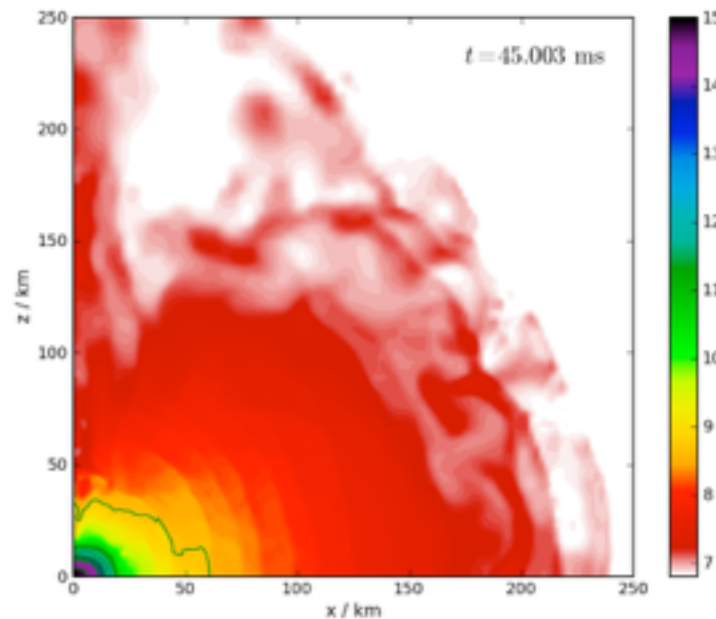
Baryon-loaded wind

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

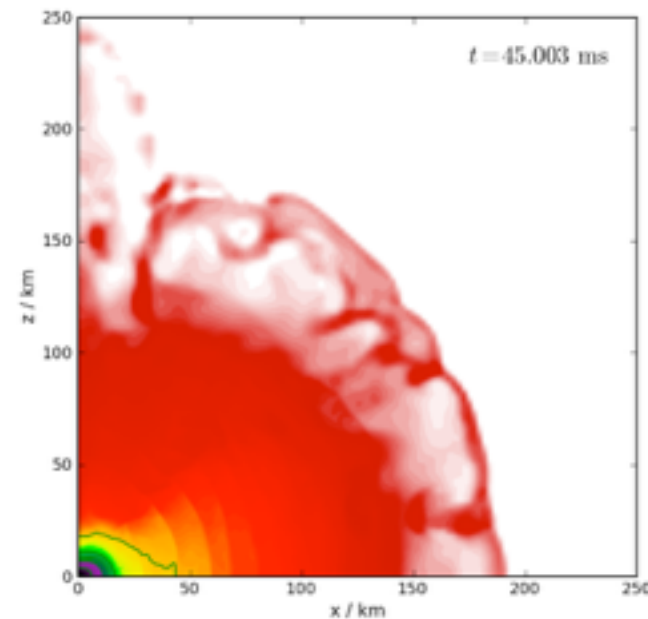
rest-mass density evolution ↓



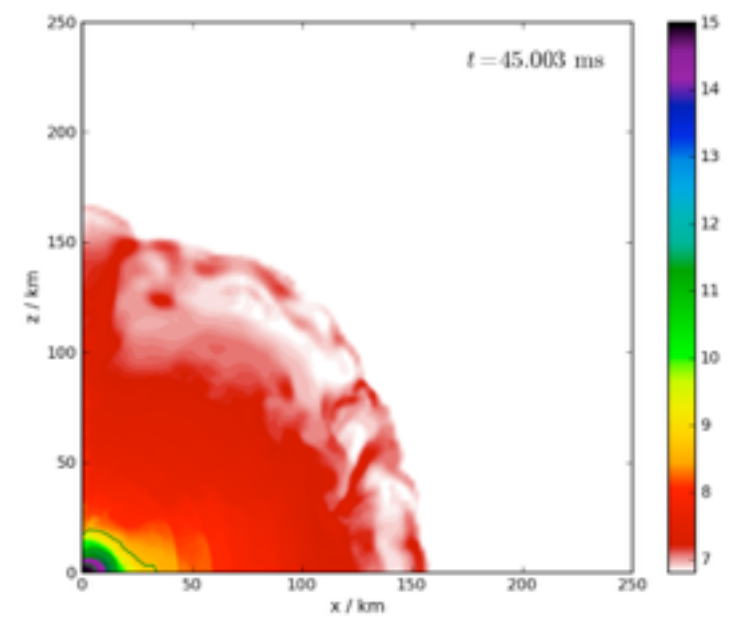
dipole 60



dipole 6

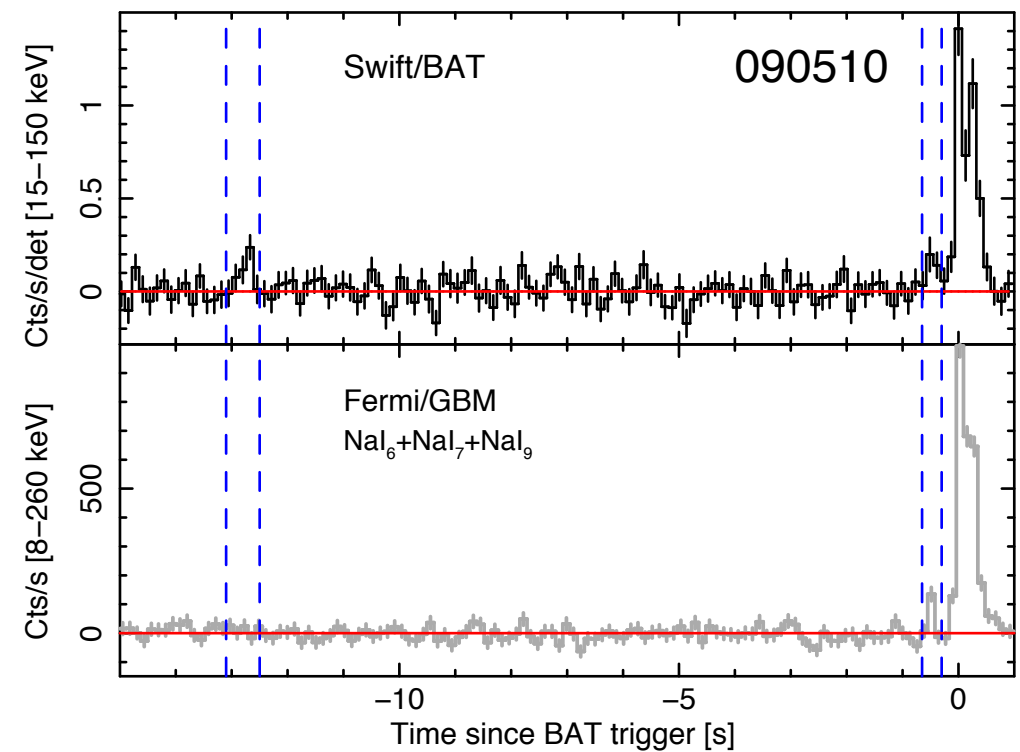
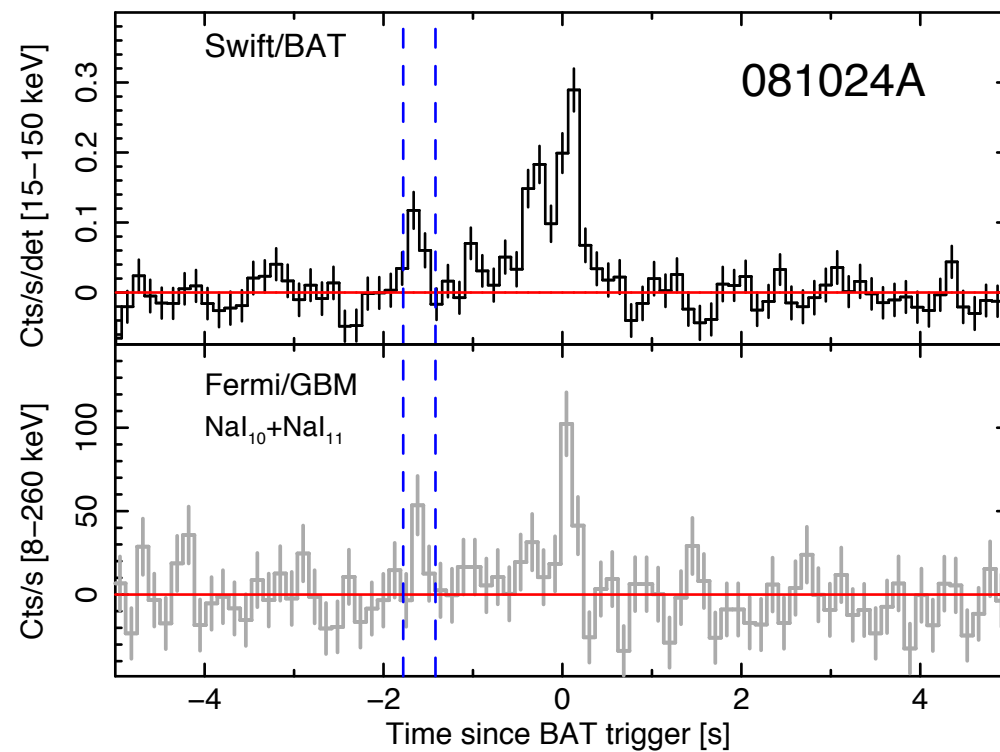
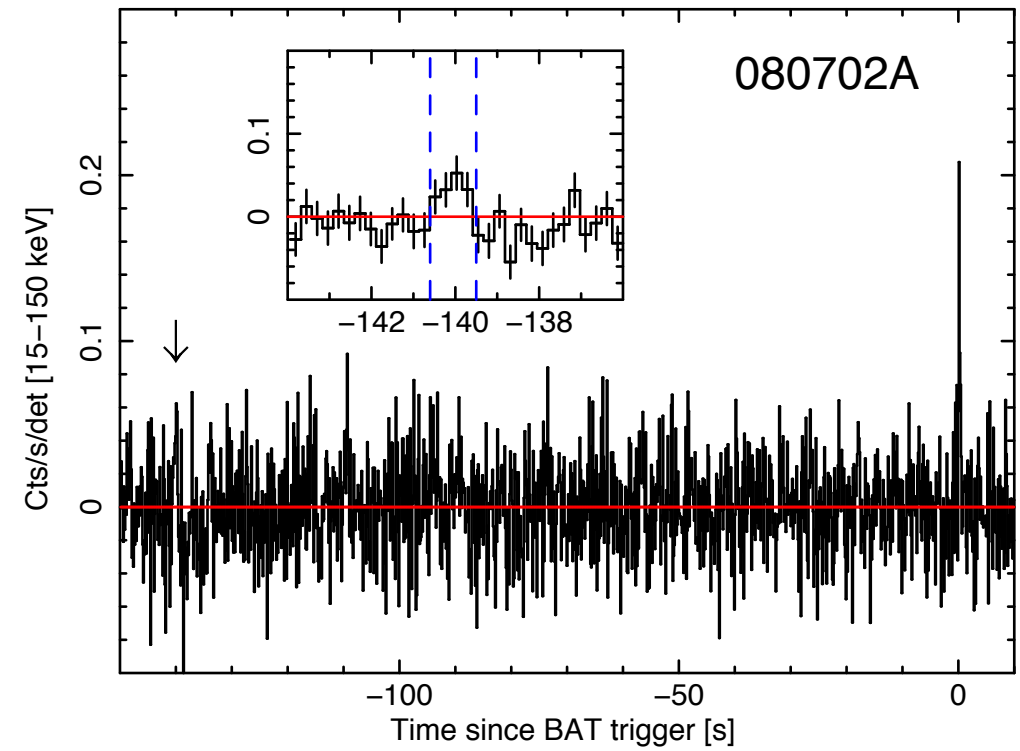
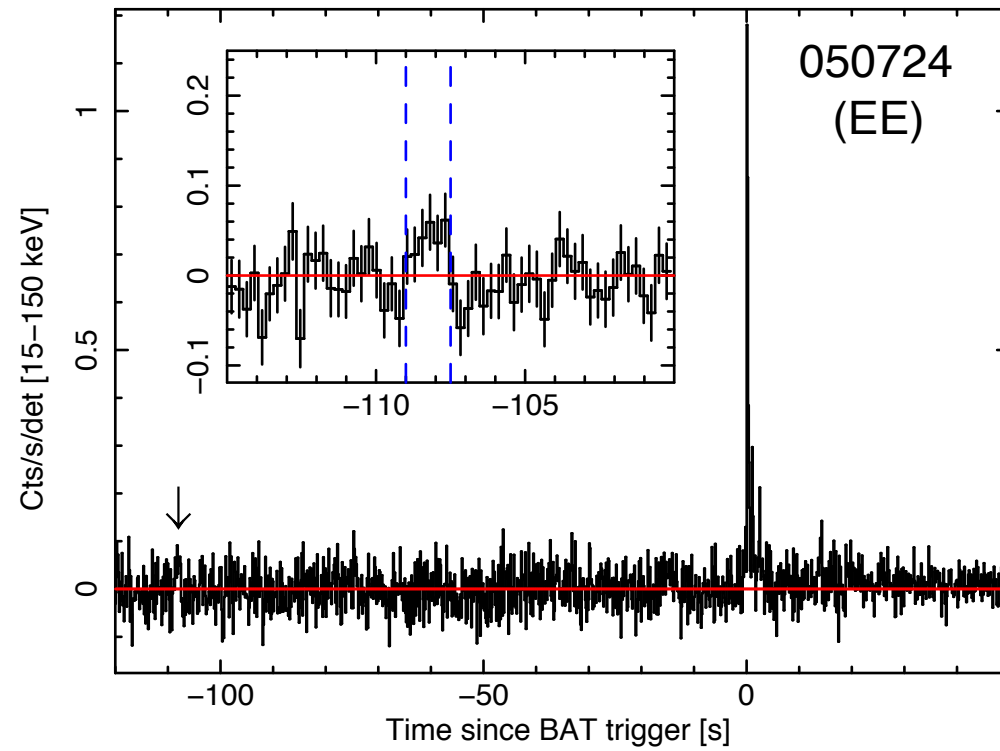


rand



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: $t_{\text{coll}} \gtrsim t_{\text{sd}}$
- typically: $t_{\text{sd}} \gg t_{\text{dr}} + \Delta t_{\text{shock}}$
 \rightarrow at t_{coll} ejecta matter is swept up into thin shell

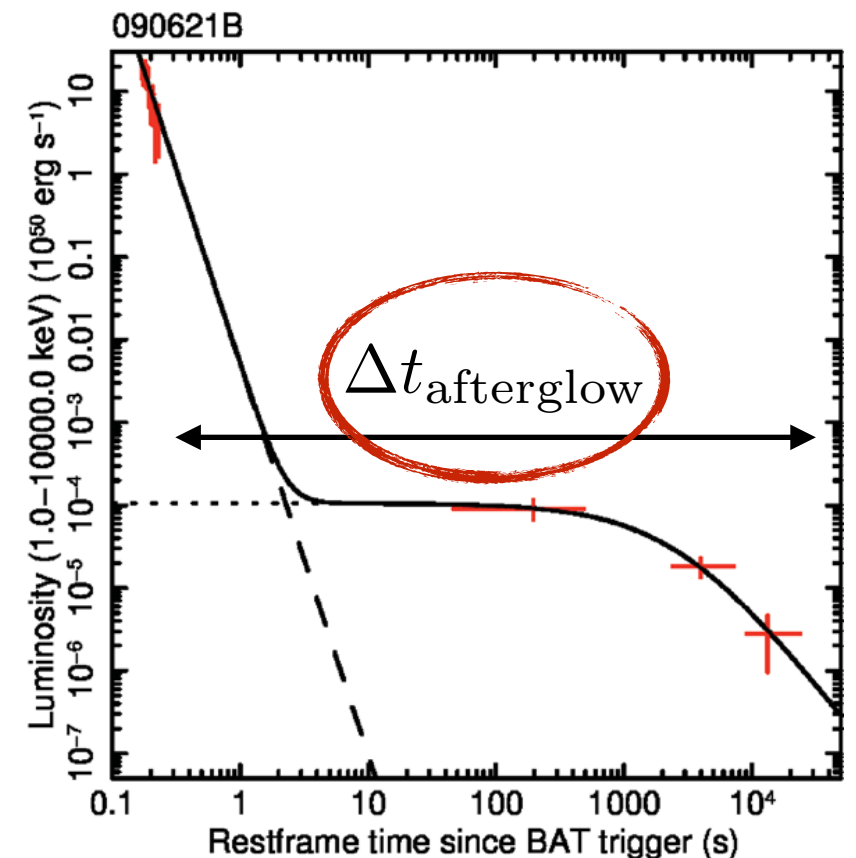
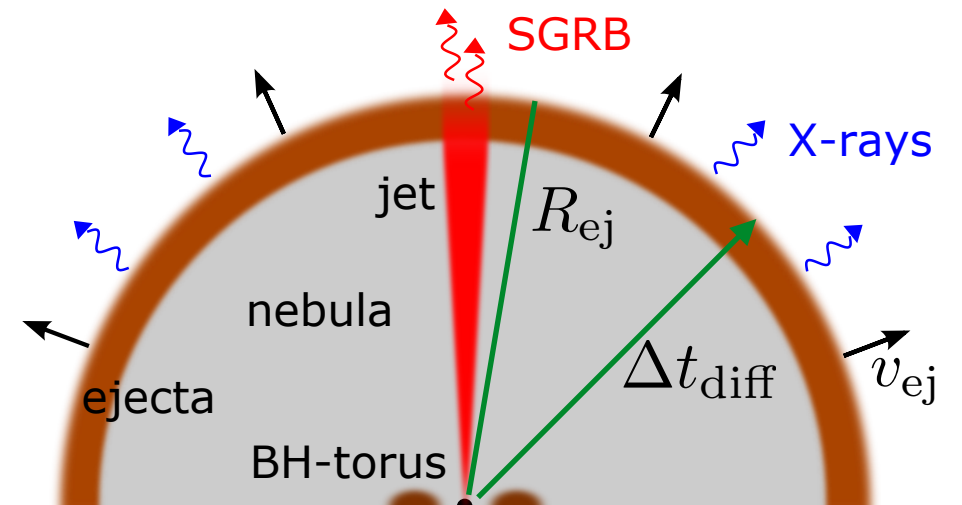
- delay for a photon emitted just before collapse (“last spin-down photon”):

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

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

Timing criterion

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



Diffusion timescales

- for static ejecta:

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

- for static nebula:

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

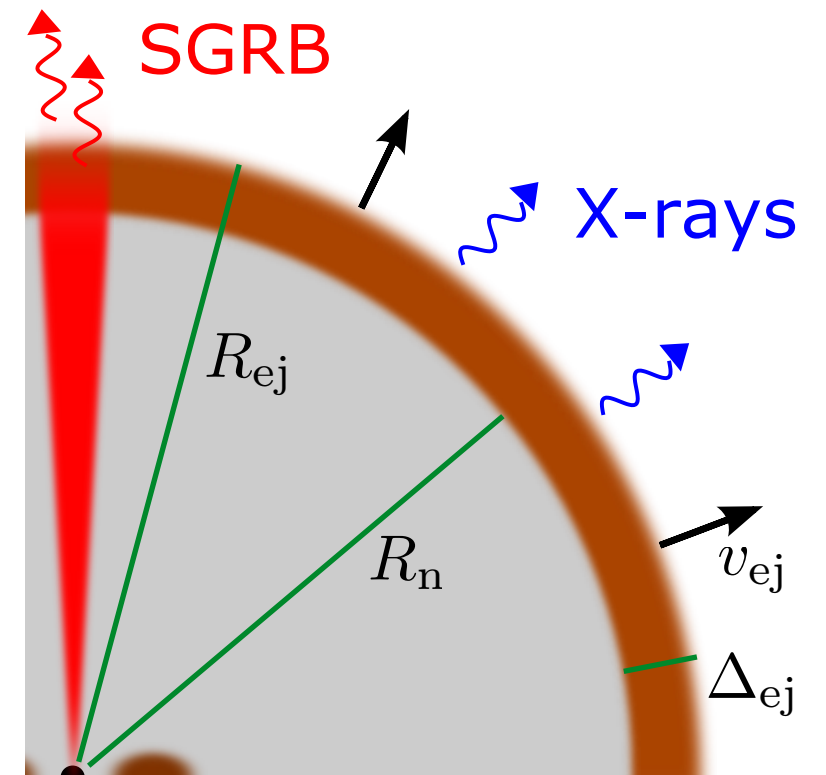
$$t_{\text{NS}}^{\text{delay}} \lesssim t_{\text{diff}}^{\text{ej, stat}}(t_{\text{coll}}) + t_{\text{diff}}^{\text{n, stat}}(t_{\text{coll}}) - R_{\text{ej}}(t_{\text{coll}})/c$$

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

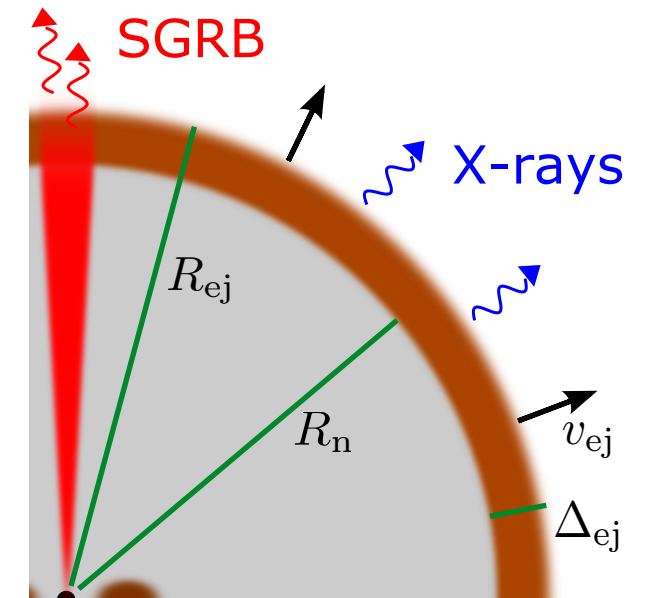
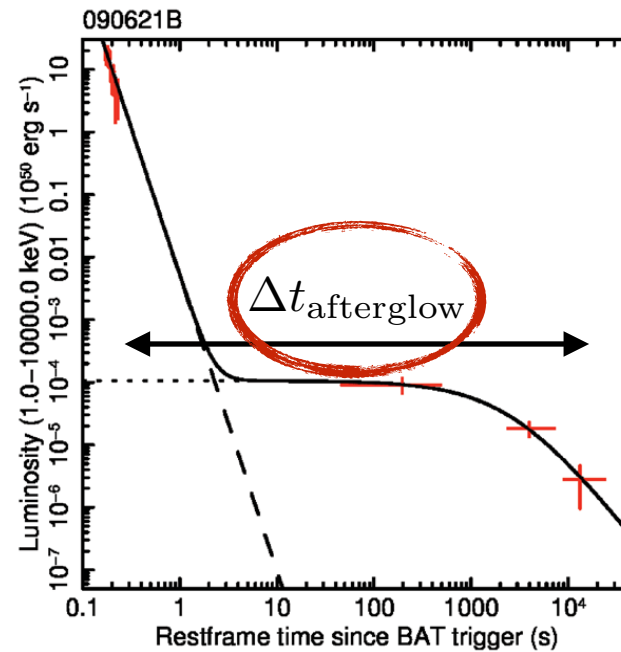
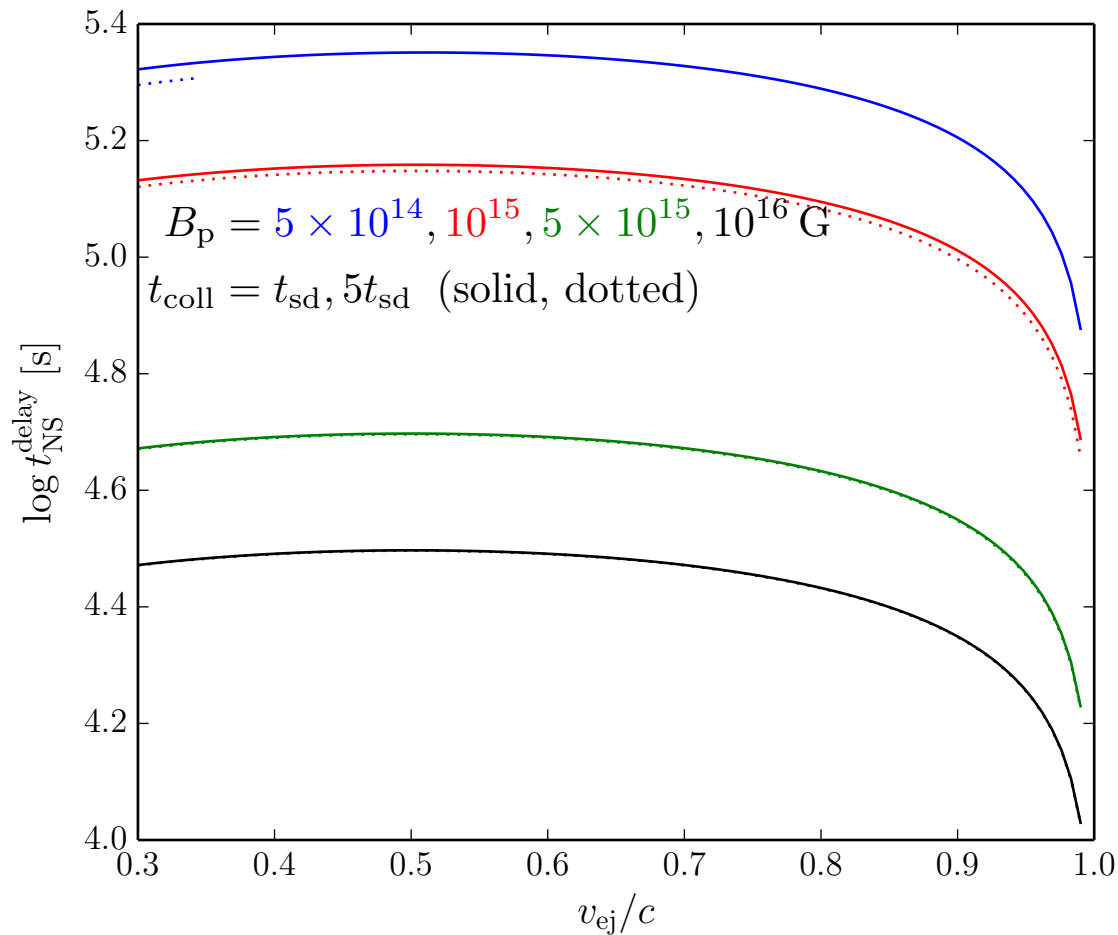
solve iteratively for t_{coll}^* :

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

→ use lower limit to check the timing criterion



Results on delay estimation



parameter ranges:

$$B_p \sim 10^{14} - 10^{16} \text{ G}$$

$$P_{\text{in}} \sim 0.5 - 5 \text{ ms}$$

$$t_{\text{dr}} \sim 0.1 - 10 \text{ s}$$

$$\dot{M} \sim 10^{-4} - 10^{-2} M_{\odot} \text{ s}^{-1}$$

$$\Delta t_{\text{shock}} \sim 0 - 100 t_{\text{dr}}$$

$$v_{\text{ej}}^0 \sim 0.01 - 0.1 c$$

- for parameter ranges considered:

$$t_{\text{NS}}^{\text{delay}} > 3 \times 10^4 \text{ s}$$

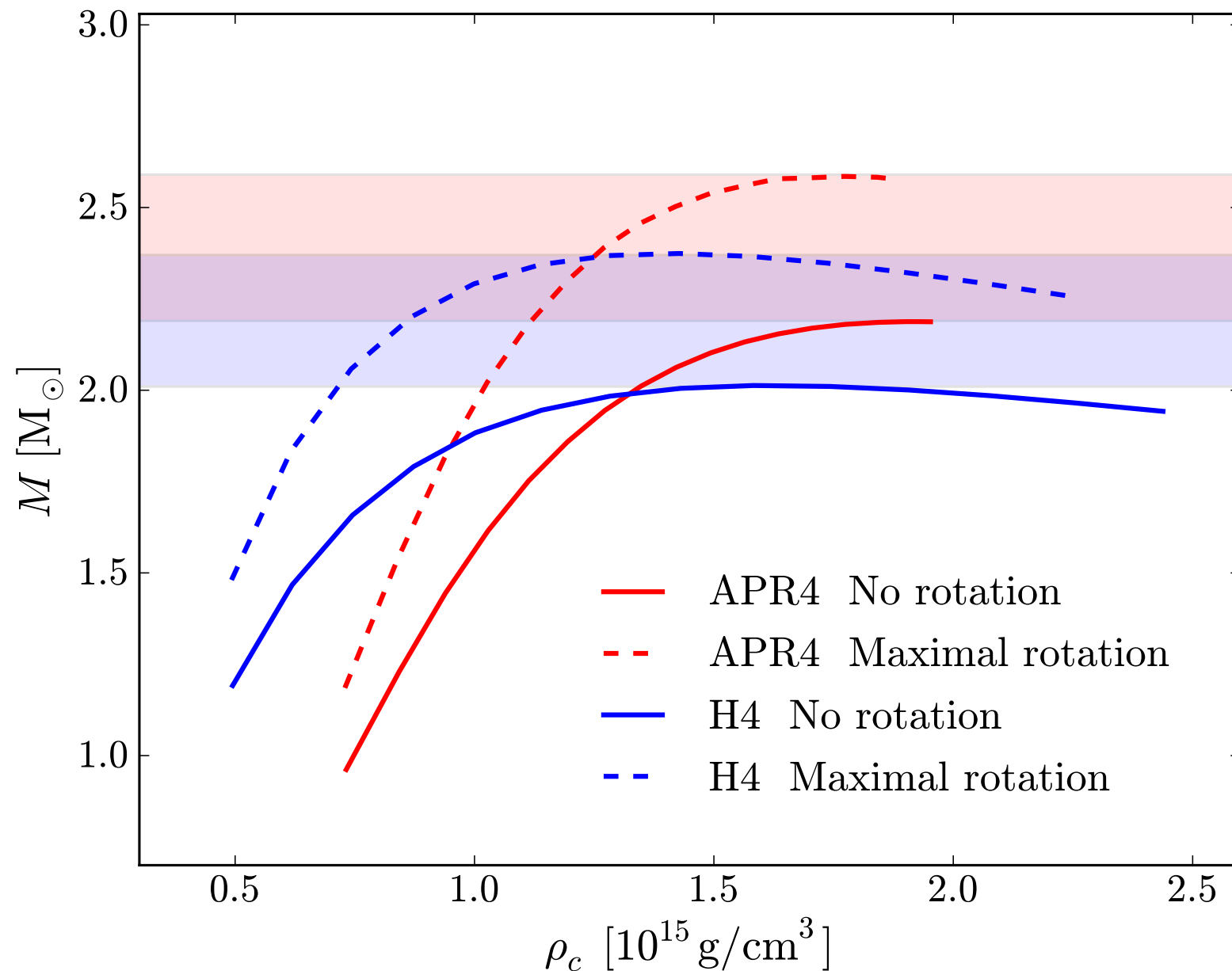
$$t_{\text{NS}}^{\text{delay}} \gtrsim 10^5 \text{ s} \quad (B_p \lesssim 10^{15} \text{ G})$$

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

→ “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



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



$$M \sim 2.34 M_{\odot}$$

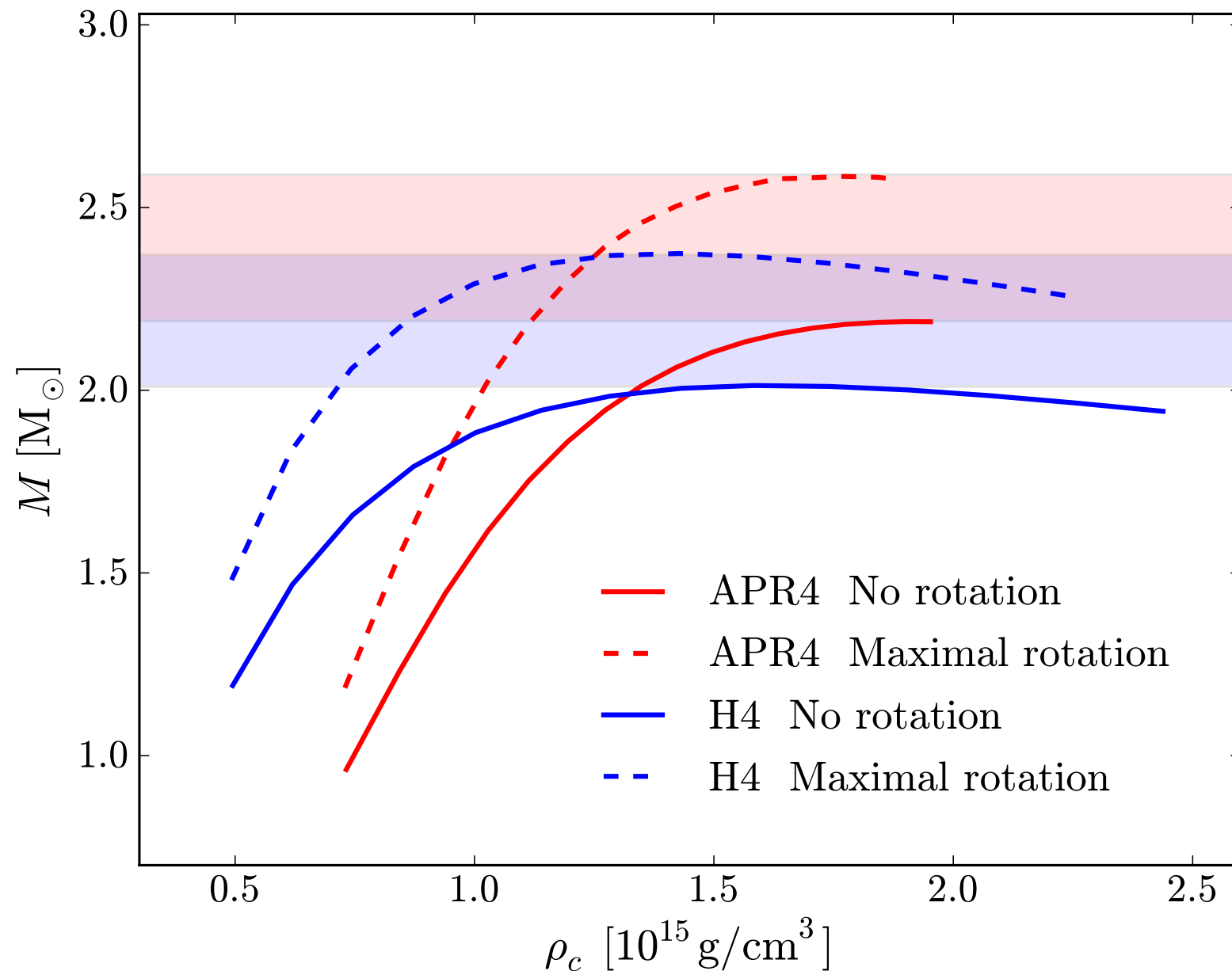
$$(M_b \sim 2.87 M_{\odot})$$

APR4 ✓

H4 ✓

EOS constraint for a SMNS

Ciolfi & Siegel 2015b



progenitor
mass combination

$$1.4 - 1.4 M_{\odot}$$



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



$$M \sim 2.43 M_{\odot}$$

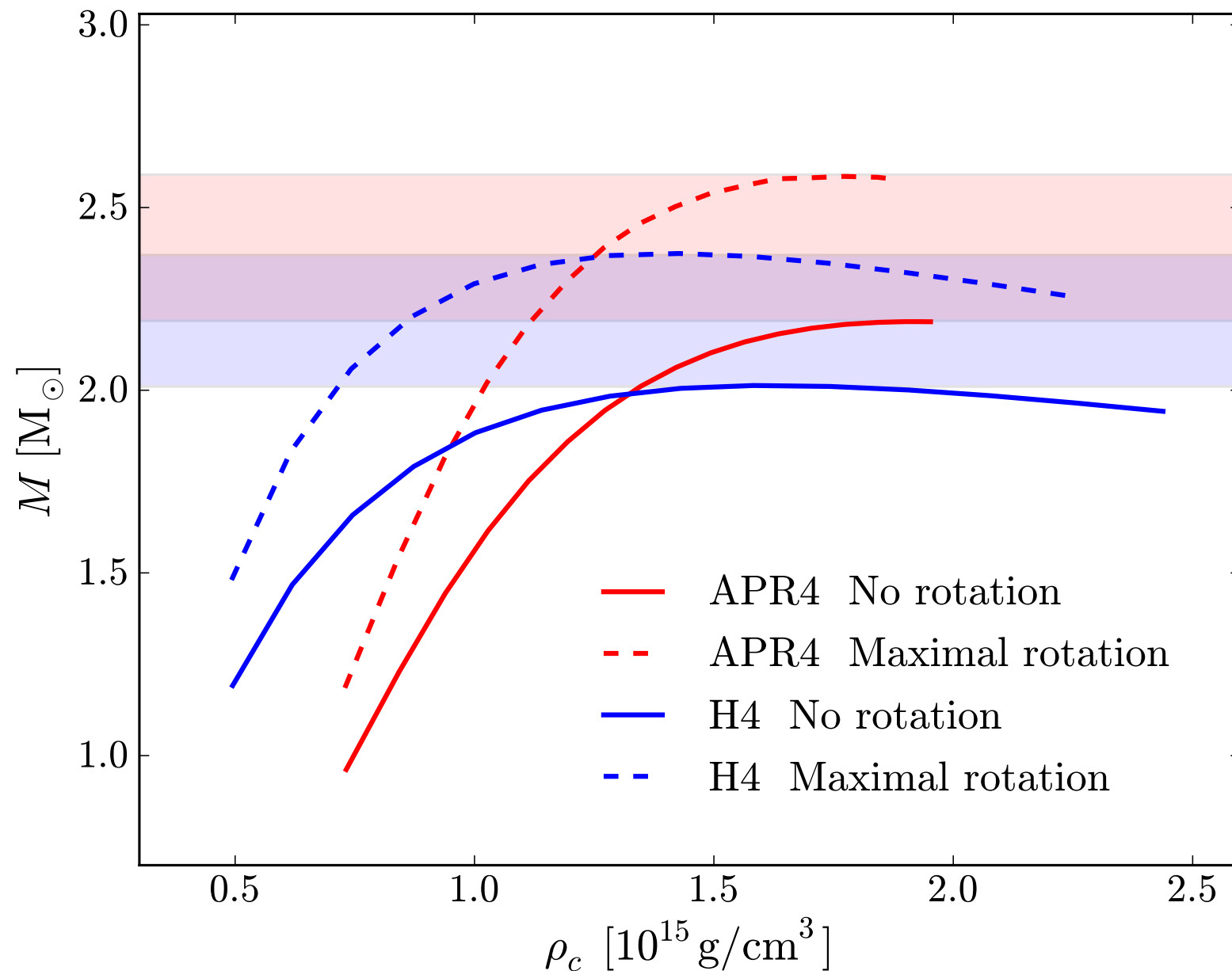
$$(M_b \sim 2.98 M_{\odot})$$

APR4 ✓

H4 ✗

EOS constraint for a SMNS

Ciolfi & Siegel 2015b



progenitor
mass combination

$$1.5 - 1.5 M_{\odot}$$



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



$$M \sim 2.61 M_{\odot}$$

$$(M_b \sim 3.2 M_{\odot})$$

APR4 ✗

H4 ✗

EM emission from long-lived BNS merger remnants

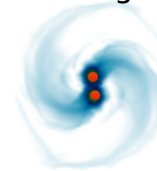
- **1D dynamical model** to describe phase II and phase III on large time and spatial scales

Siegel & Ciolfi 2015b, 2015c

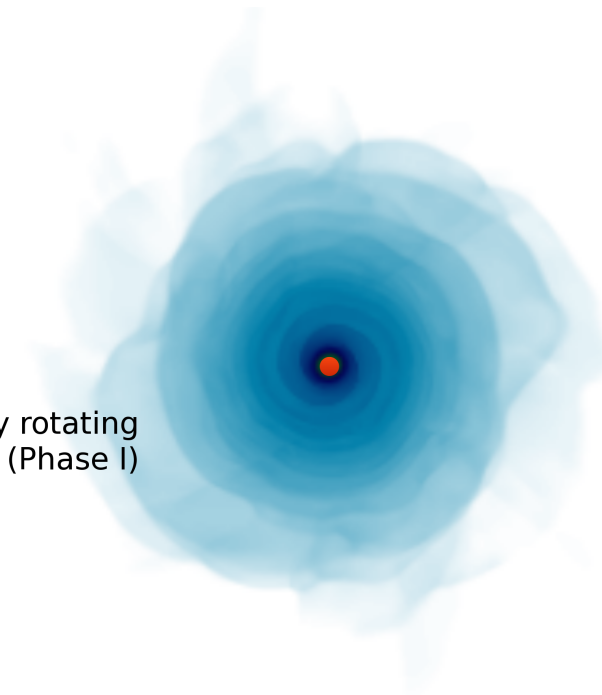


realistic light curves
and spectra

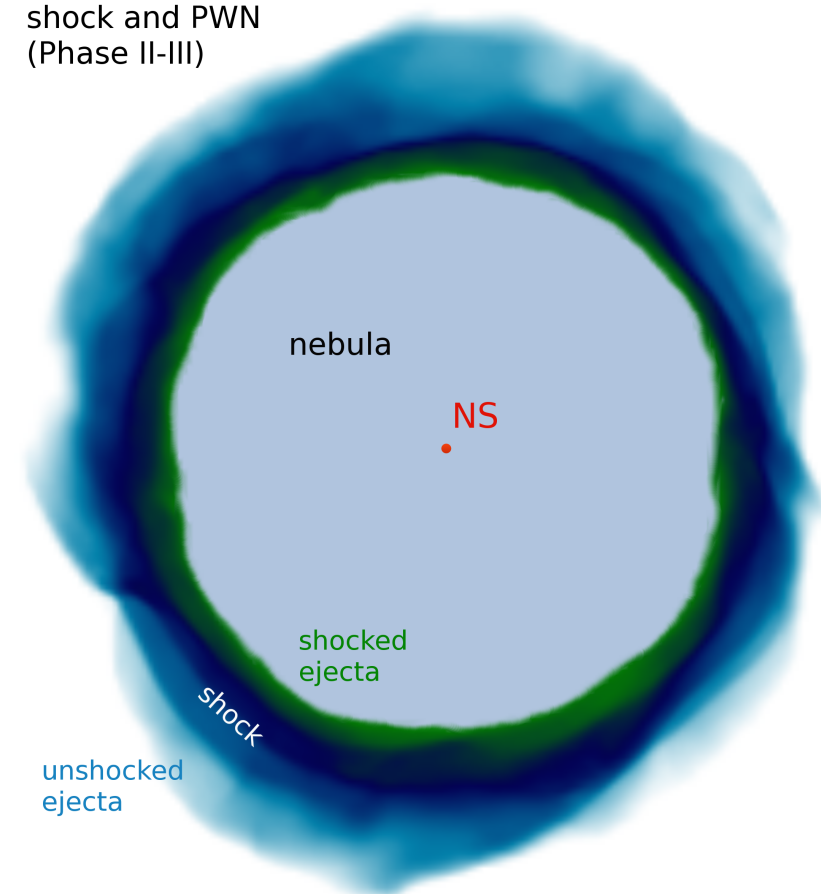
BNS merger



differentially rotating
NS remnant (Phase I)

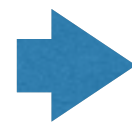


shock and PWN
(Phase II-III)



EM emission from long-lived BNS merger remnants

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

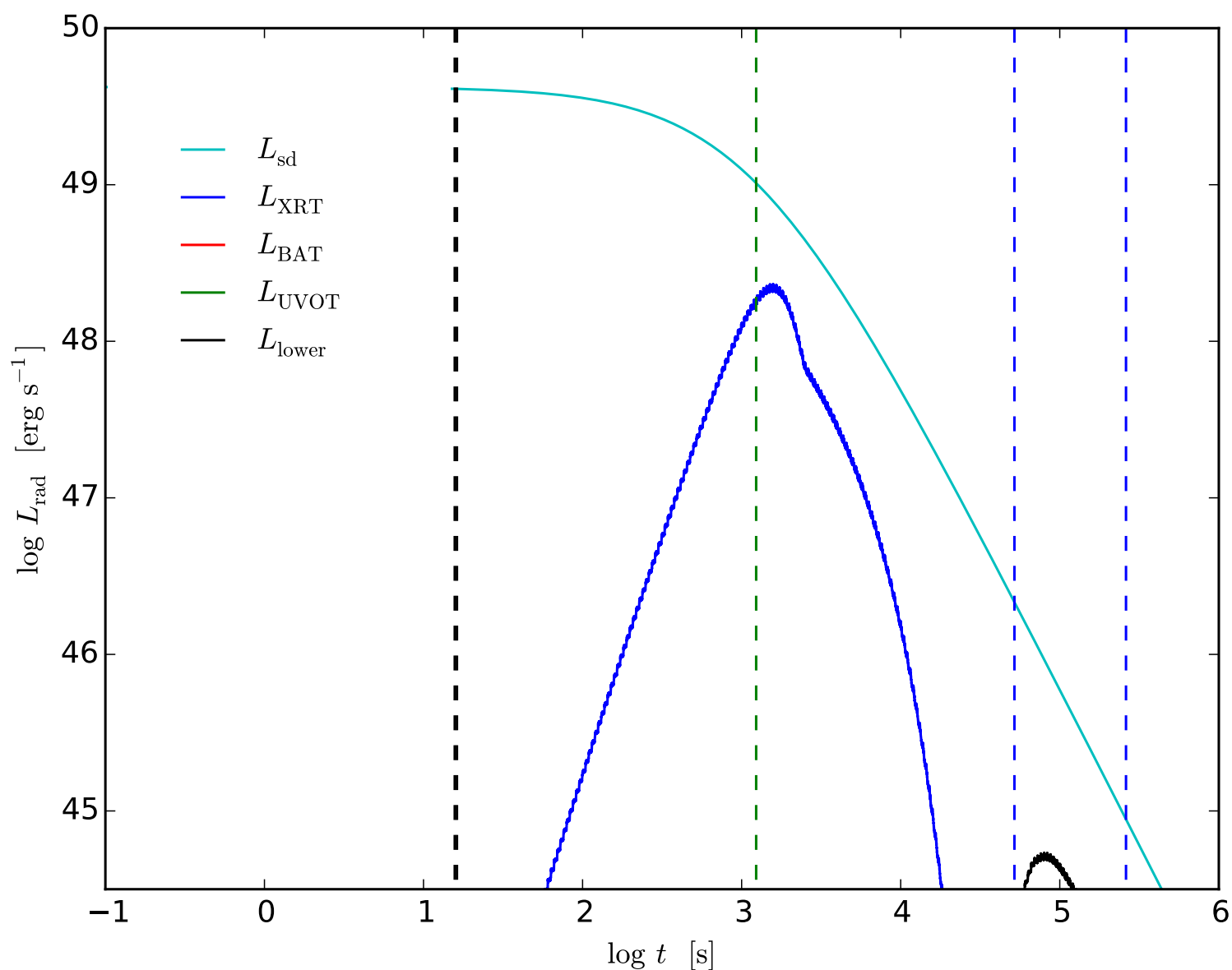


realistic light curves and spectra

Siegel & Ciolfi 2015b, 2015c

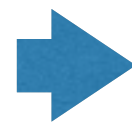
NO SMNS collapse

SGRB prompt emission @ merger



EM emission from long-lived BNS merger remnants

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



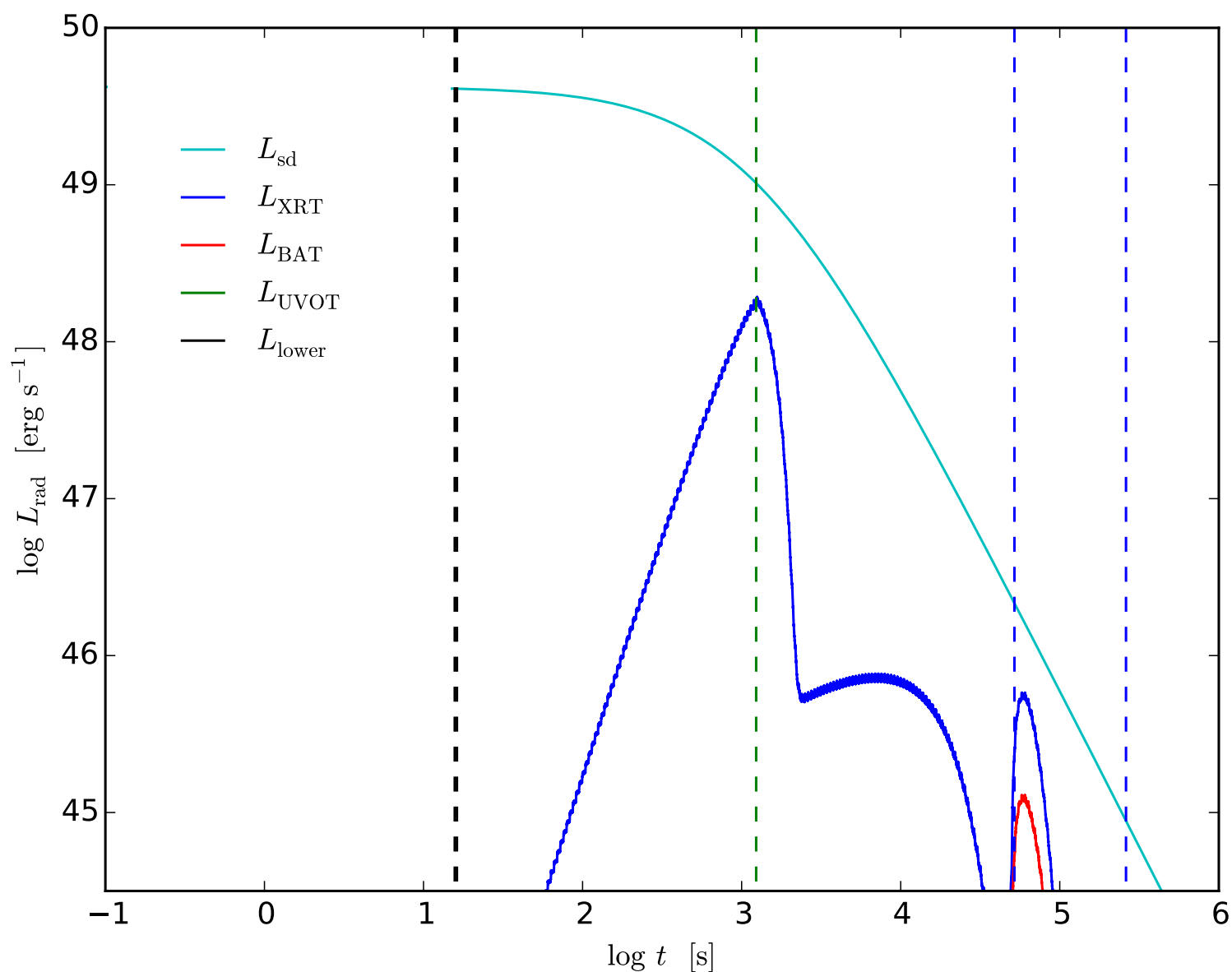
realistic light curves
and spectra

Siegel & Ciolfi 2015b, 2015c

SMNS collapse

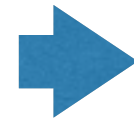
$$t_{\text{coll}} = t_{\text{spin-down}}$$

SGRB prompt emission @ merger



EM emission from long-lived BNS merger remnants

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



realistic light curves
and spectra

Siegel & Ciolfi 2015b, 2015c

SMNS collapse

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

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

