Columbia University
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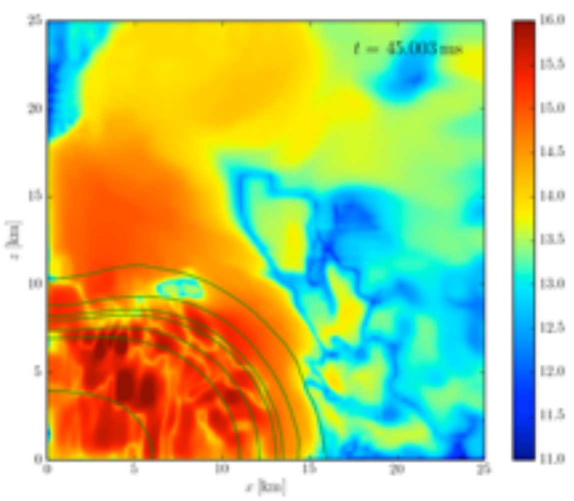
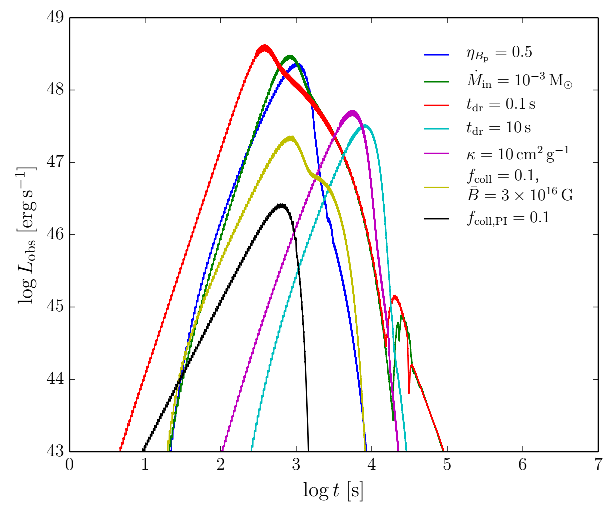
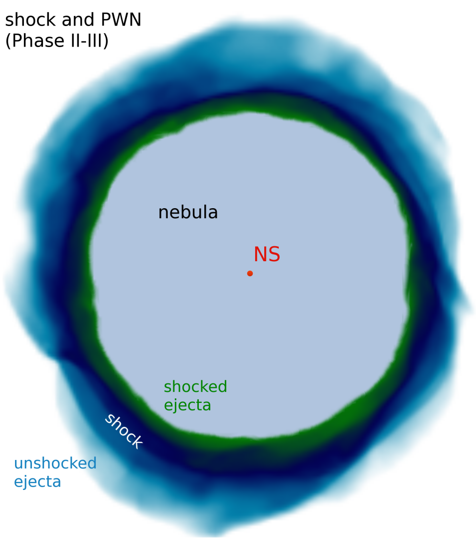
EM counterparts from long-lived BNS merger remnants







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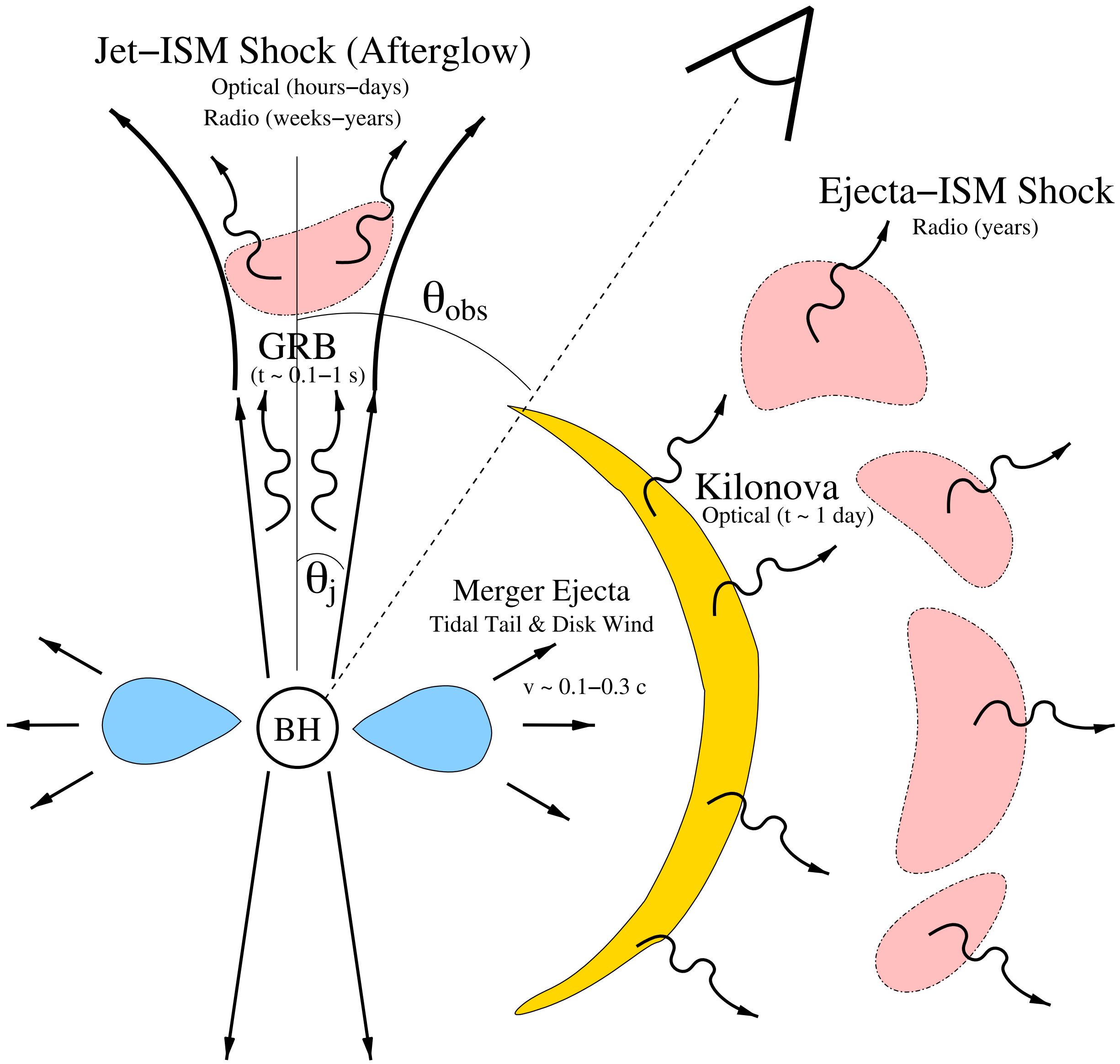
GR21@Columbia University, NYC, 14th July 2016

EM counterparts to NS mergers



Metzger & Berger 2012

- Short gamma-ray bursts (SGRBs)

  "Standard" afterglows:
  - X-ray
  - UV/optical
  - radio

  Berger 2014, Kumar & Zhang 2015

  "Non-standard" X-ray afterglows:
  (revealed by *Swift*)
  - Extended Emission
  - X-ray plateaus
  - X-ray flares

  Rowlinson+ 2013, Gompertz+ 2013,2014, Lue+ 2015

- Interaction of dynamical ejecta with ISM (radio)

  Hotokezaka & Piran 2015

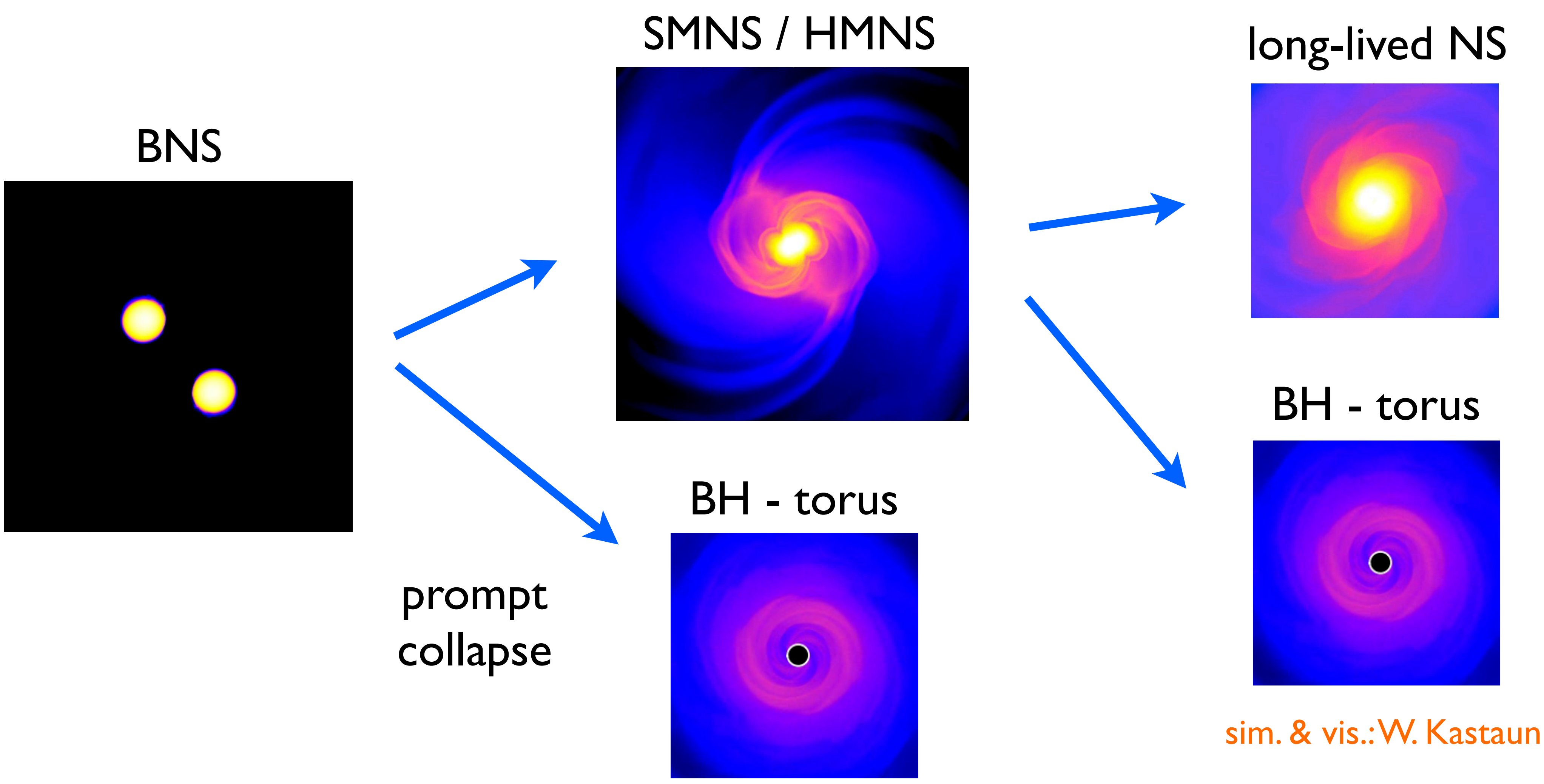
- radioactively powered kilonova (macronova)

  Li & Paczynski 1998, Rosswog 2005, Metzger+ 2010, Barnes & Kasen 2013, Piran+ 2013, Tanaka & Hotokezaka 2013

What is a promising EM counterpart?

	bright	isotropic	long lasting	high fraction	smoking gun for BNS
SGRBs	✓	✗	✗	✗	✗
standard afterglows	✗	✗	✓	✗	✗
BNS post-merger transients (this talk)	…	…	…	…	…
dynamical ejecta, ISM	✗	✓	✓	✓	✗
kilonovae	✓	✓	✓	✓	✗

Product of BNS mergers



- observationally: $\mathrm{M}_{\mathrm{TOV}} \gtrsim 2\,\mathrm{M}_\odot$ Demorest+ 2010, Antoniadis+ 2013
- progenitor masses peak around $1.3 - 1.4\ \mathrm{M}_\odot$

  $\longrightarrow$ remnant NS mass typically $\approx 2.3\,\mathrm{M}_\odot - 2.4\,\mathrm{M}_\odot$ Belczynski+ 2008
- supramassive to hypermassive limit at $\approx 1.2\,\mathrm{M}_{\mathrm{TOV}} \gtrsim 2.4\,\mathrm{M}_\odot$ Lasota+ 1996

$\longrightarrow$ the most likely outcome should be a long-lived (supramassive) NS

Post-merger evolution

General Phenomenology for BNS mergers leading to a long-lived (>100ms) remnant NS:

Phase I (baryonic wind phase, ~1s):

- hot, differentially rotating NS
- baryon pollution due to dynamical ejecta, neutrino and magnetically driven winds

Phase II (Pulsar 'ignition' and pulsar wind shock ~sec-min):

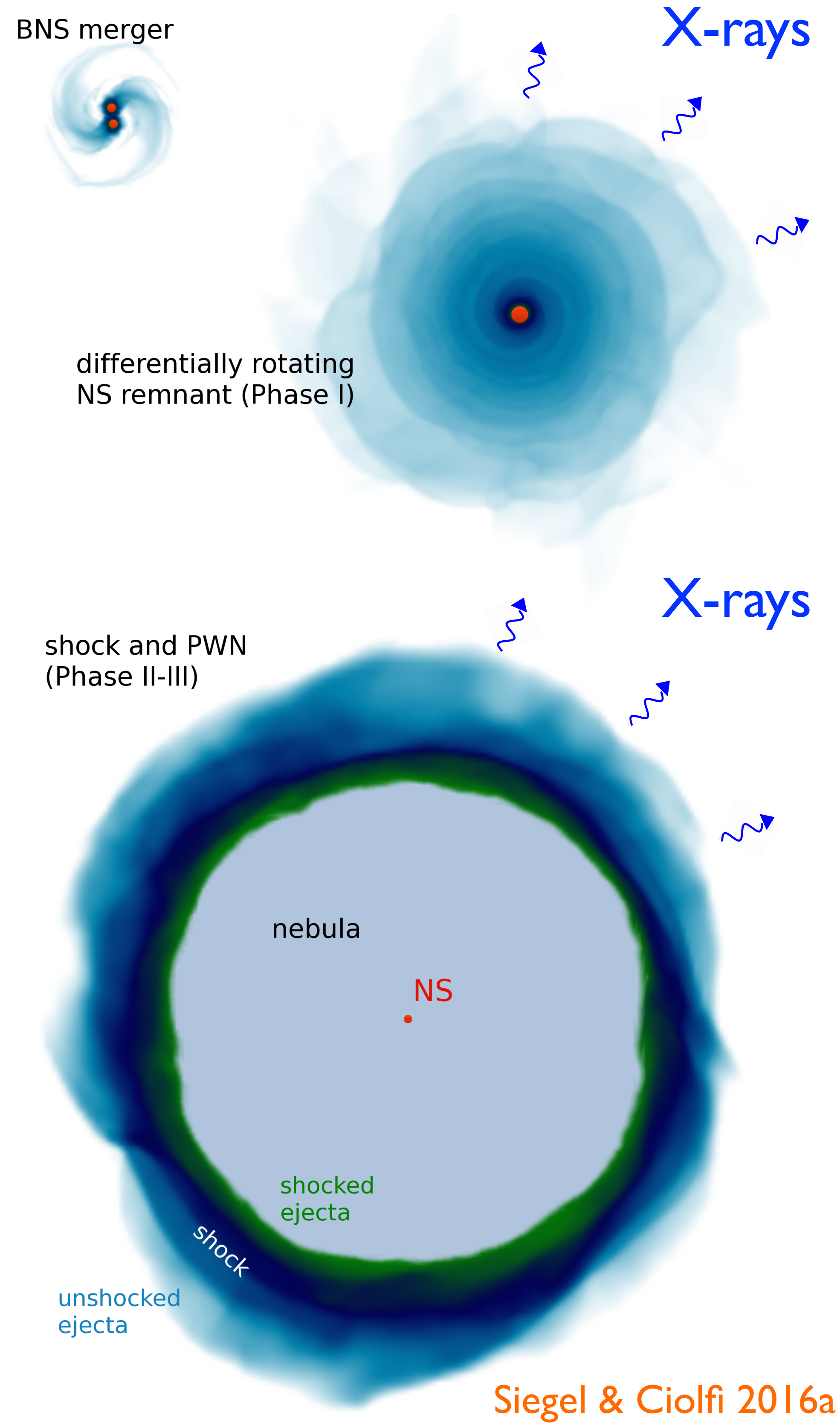
- cold, uniformly rotating NS
- baryon pollution suppressed ⟶ spin-down emission, pulsar wind inflates nebula, drives shock through ejecta

Phase III (Pulsar wind nebula phase ~min-days):

- swept-up material provides cavity for a pulsar wind nebula (PWN) in analogy to CCSNe

- NS may collapse to a BH at any time
- EM emission: reprocessed spin-down energy

⟶ model predicts broad-band spectrum from radio to gamma rays



Siegel & Ciolfi 2016a

Post-merger evolution: evolution equations

Phase I:

$$\begin{aligned}
\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} &= v_{\mathrm{w}}(R_{\mathrm{ej}}(t),t)\\
\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} &= L_{\mathrm{EM}}(t)+\frac{\mathrm{d}E_{\mathrm{th,NS}}}{\mathrm{d}t}-L_{\mathrm{rad}}(t)
\end{aligned}$$

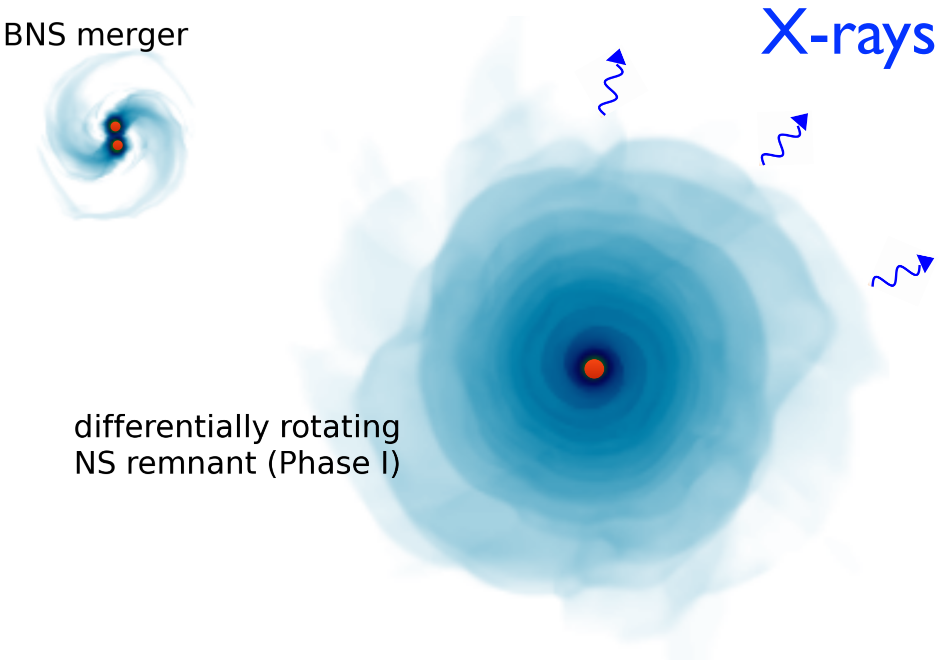
Phase II:

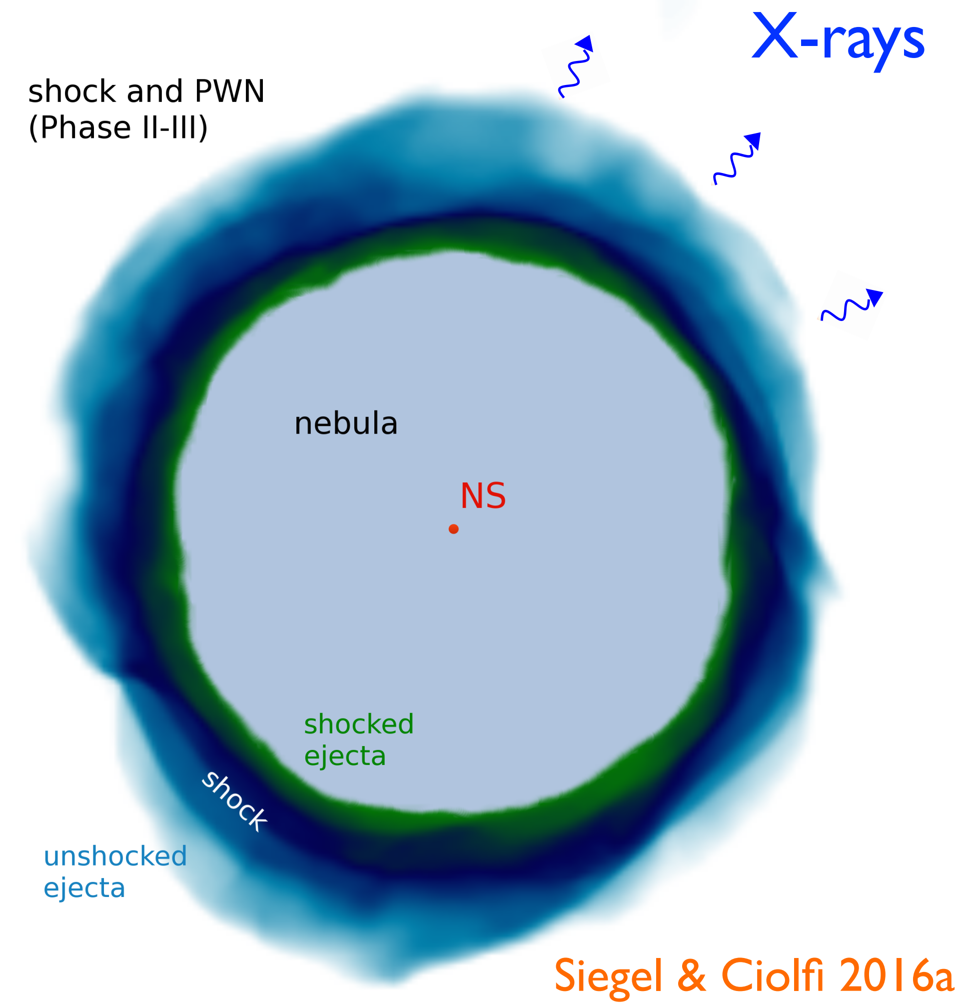
$$\begin{aligned}
\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} &= v_{\mathrm{w}}(R_{\mathrm{ej}}(t),t)\\
\frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t} &= v_{\mathrm{sh}}(t)\\
\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} &= \frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t}-\frac{\mathrm{d}\Delta_{\mathrm{sh}}}{\mathrm{d}t}\\
\frac{\mathrm{d}E_{\mathrm{th,sh}}}{\mathrm{d}t} &= \frac{\mathrm{d}E_{\mathrm{sh}}}{\mathrm{d}t}+\frac{\mathrm{d}E_{\mathrm{th,vol}}}{\mathrm{d}t}+\frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t}-L_{\mathrm{rad,in}}(t)\\
\frac{\mathrm{d}E_{\mathrm{th,ush}}}{\mathrm{d}t} &= -\frac{\mathrm{d}E_{\mathrm{th,vol}}}{\mathrm{d}t}-L_{\mathrm{rad}}(t)\\
\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} &= \frac{\mathrm{d}E_{\mathrm{th,sh}}}{\mathrm{d}t}+\frac{\mathrm{d}E_{\mathrm{th,ush}}}{\mathrm{d}t}\\
\frac{\mathrm{d}E_{\mathrm{nth}}}{\mathrm{d}t} &= -\frac{E_{\mathrm{nth}}}{R_{\mathrm{n}}}\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t}-\frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t}+L_{\mathrm{rad,in}}(t)+\eta_{\mathrm{TS}}[L_{\mathrm{sd}}(t)+L_{\mathrm{rad,pul}}(t)]\\
\frac{\mathrm{d}E_{B}}{\mathrm{d}t} &= \eta_{B_{\mathrm{n}}}[L_{\mathrm{sd}}(t)+L_{\mathrm{rad,pul}}(t)]
\end{aligned}$$

set of coupled ODEs

Phase III:

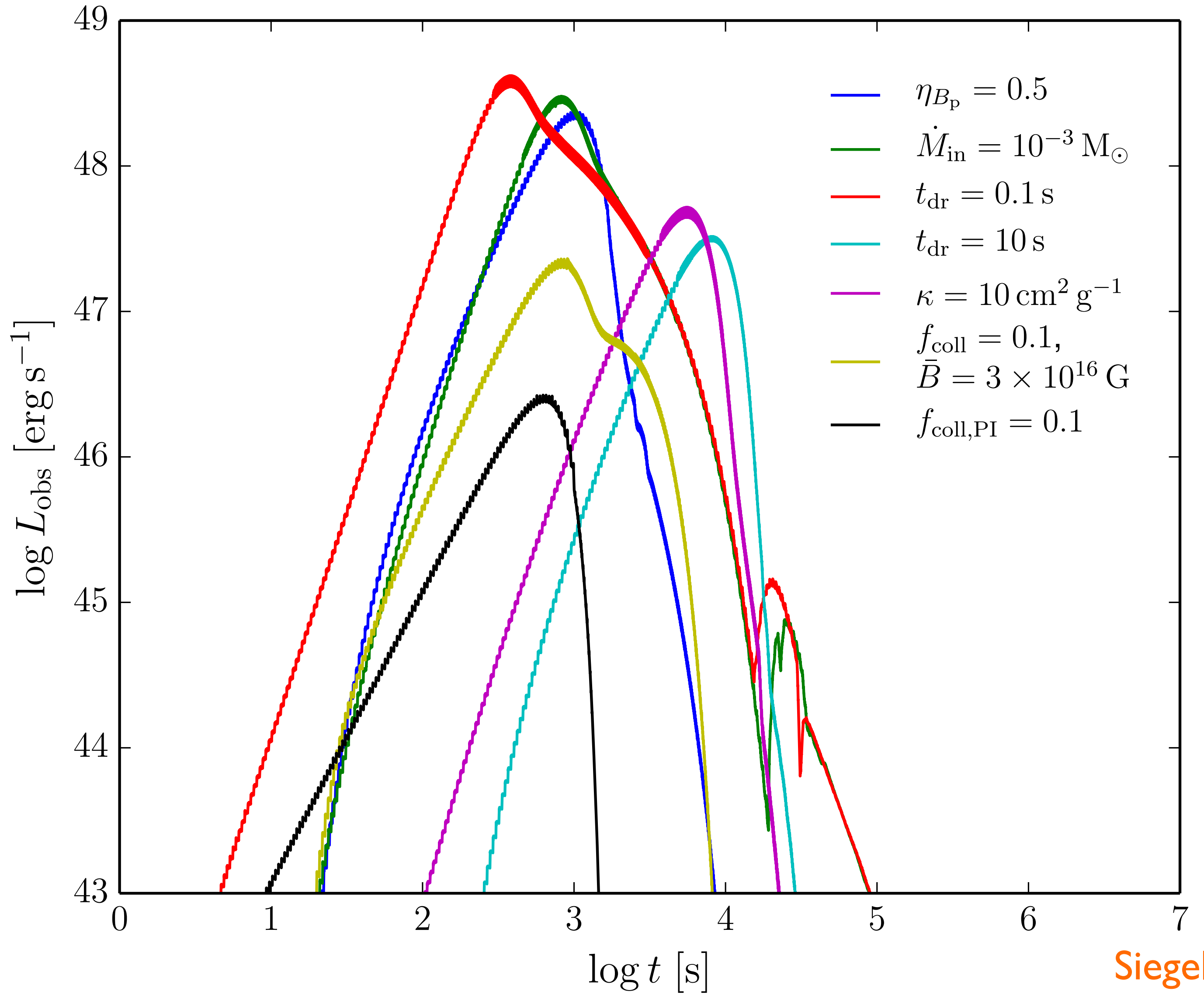
$$\begin{aligned}
\frac{\mathrm{d}v_{\mathrm{ej}}}{\mathrm{d}t} &= a_{\mathrm{ej}}(t)\\
\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} &= v_{\mathrm{ej}}(t)+\frac{1}{2}a_{\mathrm{ej}}(t)\mathrm{d}t\\
\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} &= \frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t}\\
\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t} &= [1-f_{\mathrm{ej}}(t)]\frac{\mathrm{d}E_{\mathrm{PWN}}}{\mathrm{d}t}-L_{\mathrm{rad}}(t)-L_{\mathrm{rad,in}}(t)\\
\frac{\mathrm{d}E_{B}}{\mathrm{d}t} &= \eta_{B_{\mathrm{n}}}[L_{\mathrm{sd}}(t)+L_{\mathrm{rad,pul}}(t)]
\end{aligned}$$





Siegel & Ciolfi 2016a

Post-merger EM emission



Siegel & Ciolfi 2016b

Fig.: Reconstructed X-ray lightcurves (0.3-10 keV)

- hot ejecta (continuous heating by nebula): emission is in the X-rays
- delayed onset of strong X-ray radiation ~1-10s after merger (high optical depth at early times)
- bright, isotropic, long-lasting X-ray signal peaking at ~10^2-10^4s after merger (L~10^{46}-10^{48}erg s^{-1})

Post-merger EM emission

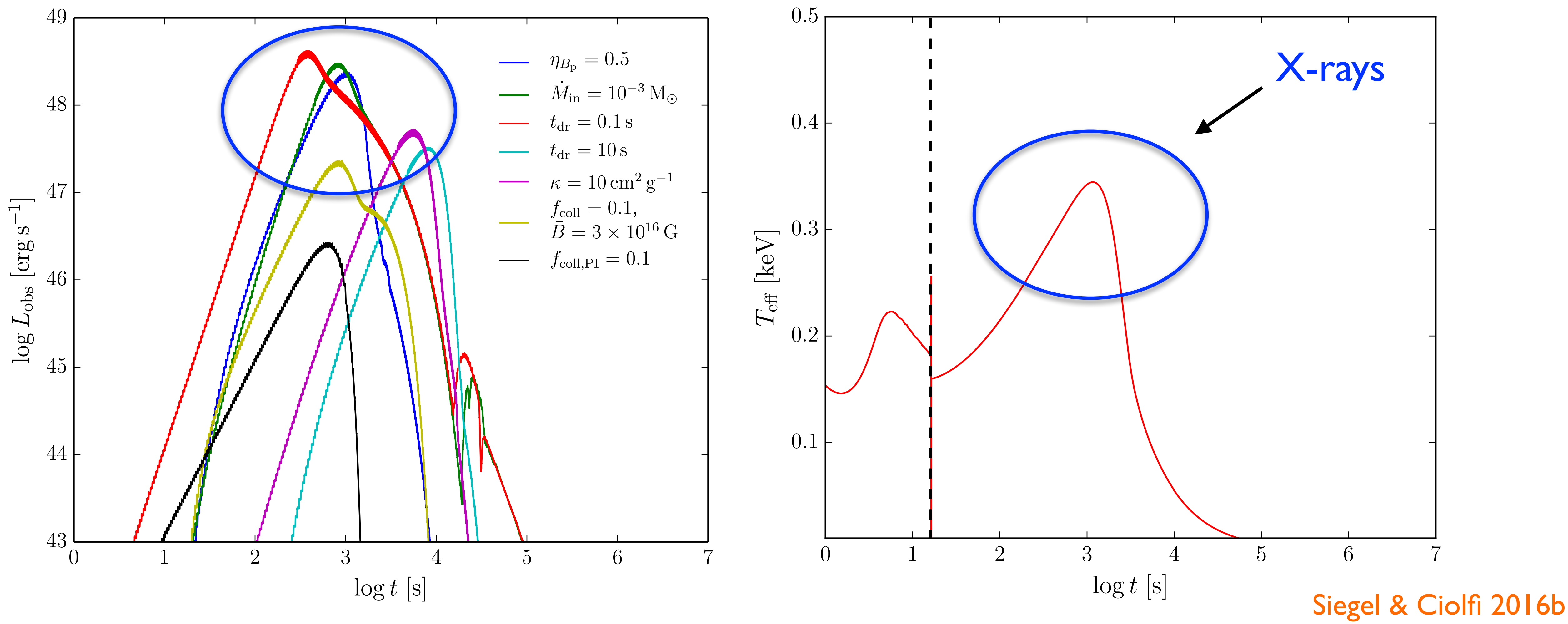
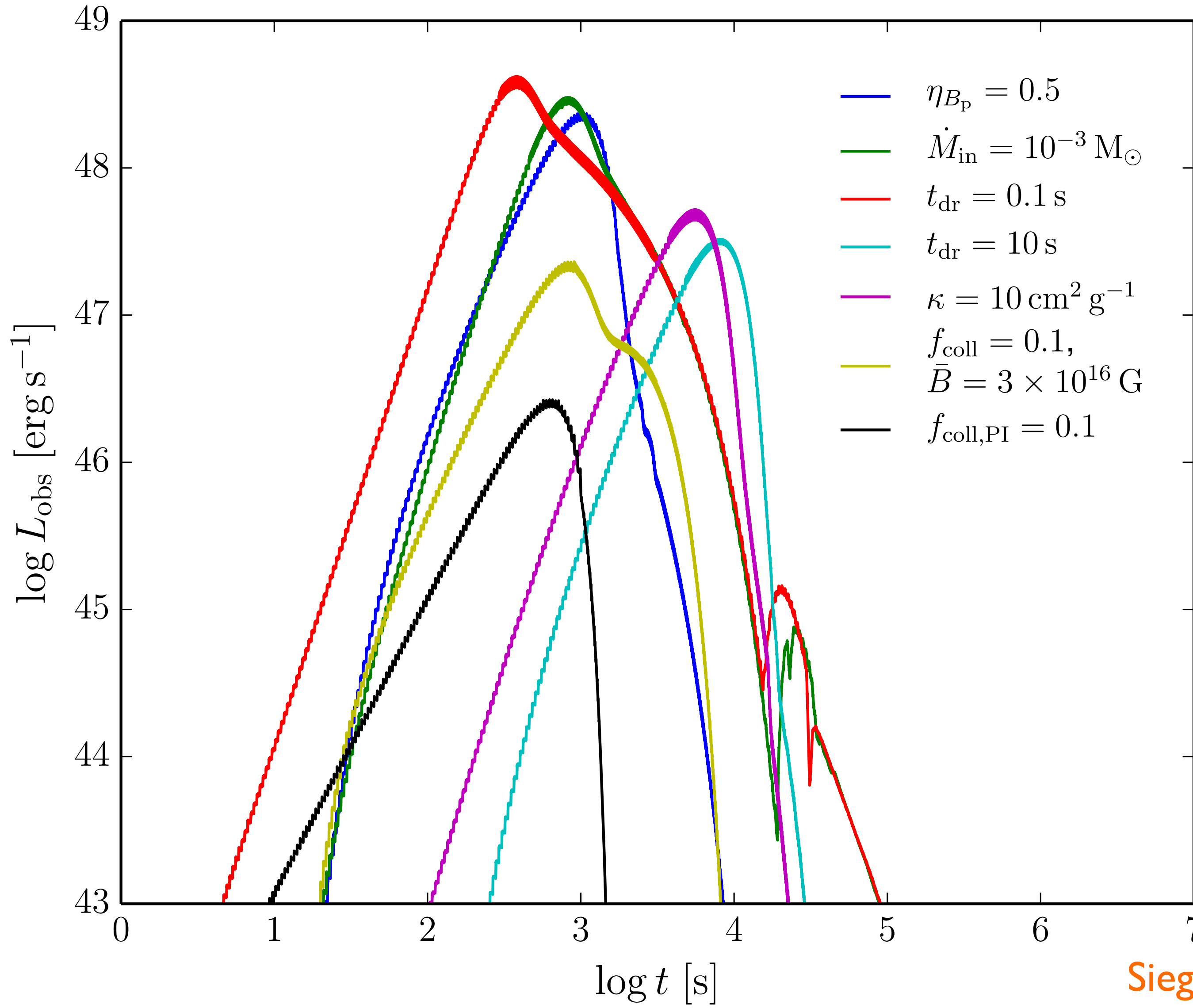


Fig.: X-ray light curves and effective temperature evolution (example)

- at timescale of peak brightness, predominantly thermal emission in the X-rays (continuous heating by the nebula)
- heating by r-process nucleosynthesis typically subdominant up to t ~1h - 1d
- degree of ionization of ejecta matter important

Post-merger EM emission: EM counterpart to GWs



Siegel & Ciolfi 2016b

Fig.: Reconstructed X-ray lightcurves (0.3-10 keV)

- bright, isotropic, long-lasting X-ray signal peaking at ~10^2-10^4s after merger (L~10^{46}-10^{48}erg s^{-1})

→ smoking gun for BNS merger event → timescale well suited for EM follow up of GW event

→ X-ray signal represents ideal EM counterpart

What is a promising EM counterpart?

	bright	isotropic	long lasting	high fraction	smoking gun for BNS	
SGRBs	✓	✗	✗	✗	✗	
standard afterglows	✗	✗	✓	✗	✗	
BNS post-merger X-ray transients (this talk)	✓	✓	✓	✓	✓	!!!
dynamical ejecta, ISM	✗	✓	✓	✓	✗	
kilonovae	✓	✓	✓	✓	✗	

according to the model:
BNS post-merger X-ray transients represent ideal EM counterpart

Conclusions

- majority of BNS mergers should lead to long-lived NSs
- proposed post-merger phenomenology and detailed numerical model for those events

→ general model to compute broad band EM emission (radio to gamma rays)

→ bridges the gap between numerical relativity simulations and the observational timescales of EM transients

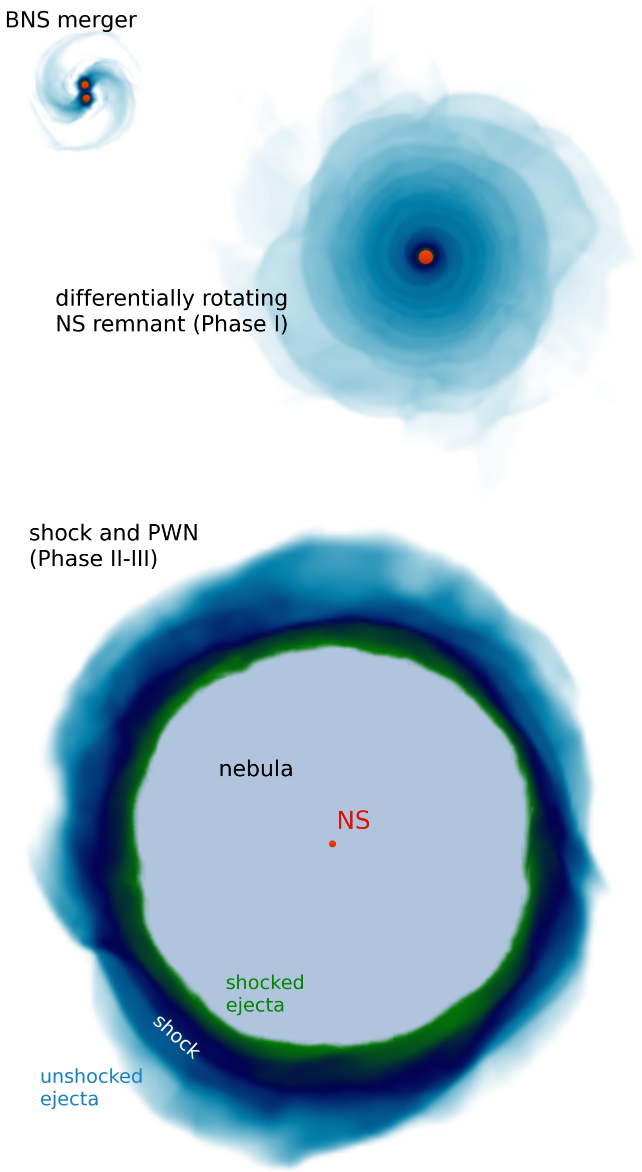
→ reveals strong X-ray transient (also UV and optical counterparts at later times), promising counterpart for GW astronomy

⇝ magnetar powered kilonova

→ together with NS component masses from GW signal can tightly constrain EOS (using supramassive NS assumption)

→ makes very specific predictions that can be tested observationally

⇝ see also "time-reversal" scenario
Ciolfi & Siegel (2015), *ApJL* **798**, L36



Siegel D.M. & Ciolfi R. (2016a), *ApJ* **819**, 14

Siegel D.M. & Ciolfi R. (2016b), *ApJ* **819**, 15

Appendix

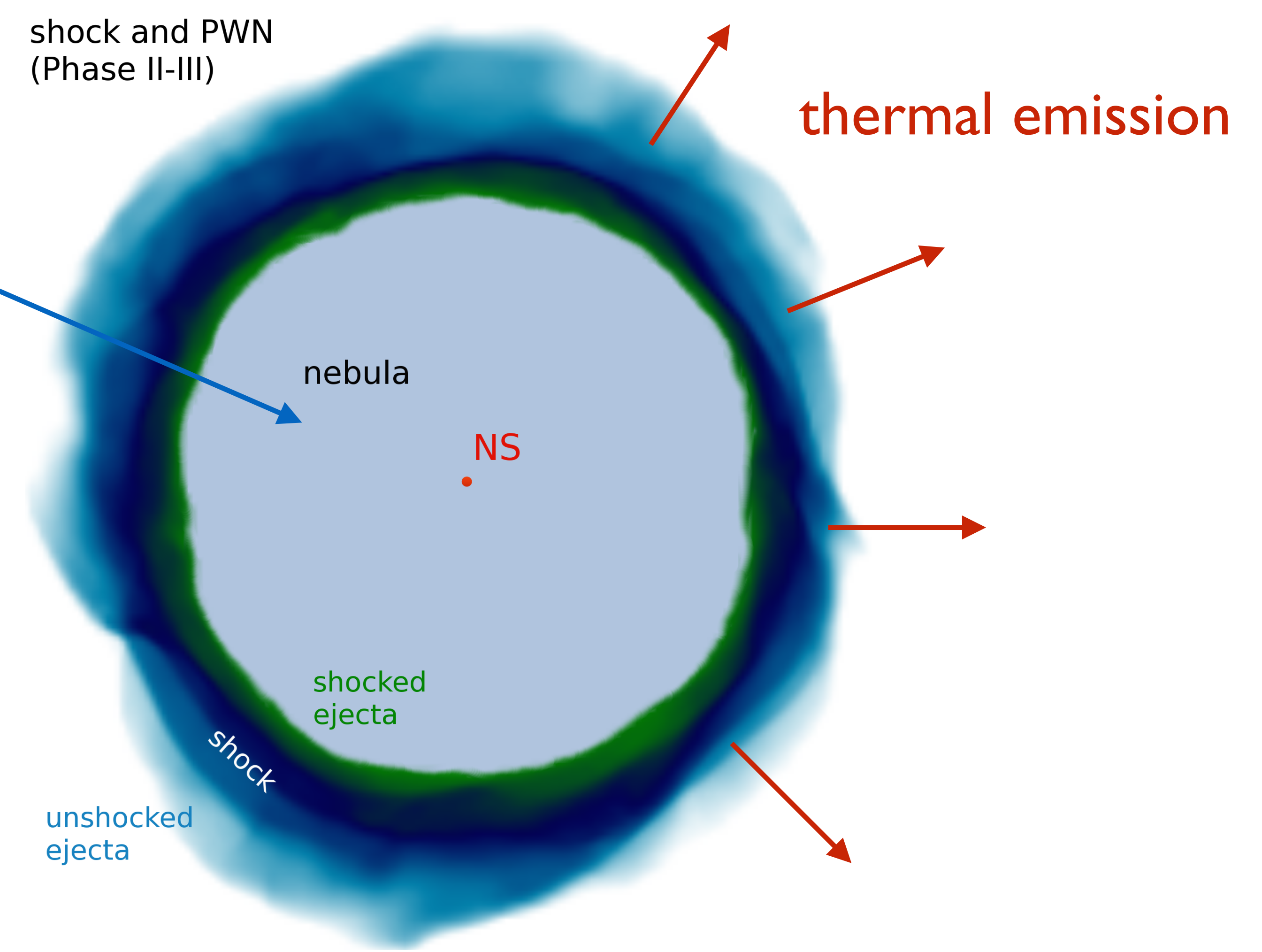
Post-merger evolution: the pulsar wind nebula

Pulsar wind nebula:

gas of electrons, positrons, photons

complicated radiative interactions,
non-thermal photon and particle spectra

- synchrotron cooling and self-absorption
- (inverse) Compton scattering
- pair production and annihilation
- Thomson scattering
- Photon escape



Siegel & Ciolfi 2016a

Particle balance equation:

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

Photon balance equation:

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

Coupled set of integro-differential equations to be solved at every time step

Post-merger evolution: methodology

Phase I (baryonic wind phase): ~1s

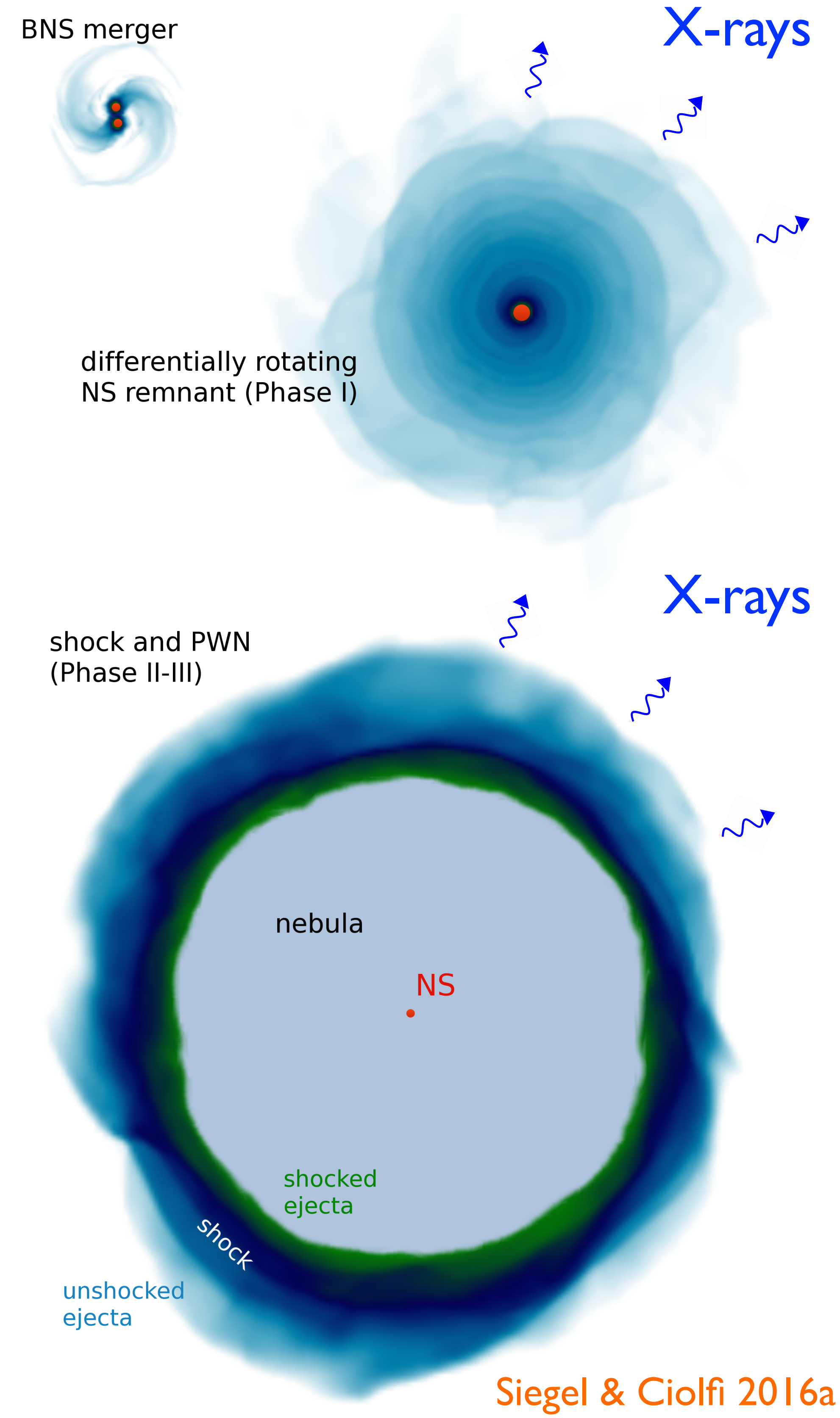
Phase II (Pulsar 'ignition', pulsar wind shock): ~ sec - min

Phase III (Pulsar wind nebula phase): ~ min - days

- time and length scales far beyond what GRMHD simulations can do
- complicated radiative interactions in the nebula

⟶ formulate simpler evolution equations that capture the main physics

⟶ use GRMHD simulations of the early post-merger phase as 'initial data' (e.g., Siegel+ 2014)

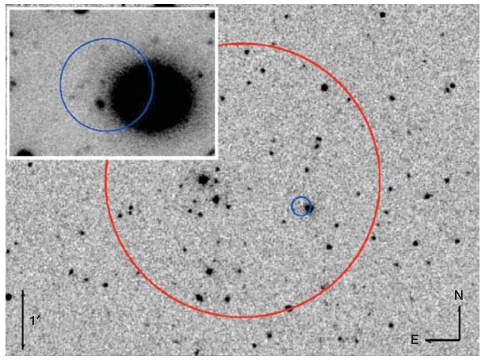


Siegel & Ciolfi 2016a

Multimessenger Astronomy

Joint EM and GW observations

- EM signals provide temporal and positional information, enhance GW search sensitivity
  Abadie+ 2012b, Aasi+ 2014, Williamson+ 2014, Clark+ 2014
- EM signals to confirm astrophysical origin of GW event
  Evans+ 2012, Abadie+ 2012a, Singer+ 2012
- EM signals carry information on the merger and post-merger process and the astrophysical environment of the GW event
  Siegel & Ciolfi 2015b,c, Metzger & Berger 2012
- EM signals improve sky localization, enable identification of host galaxy
  ⟶ two independent redshift measurements
  Schutz 1986, Metzger & Berger 2012, Berger 2014



Gehrels+ 2005

- Investigate association of BNS mergers with short gamma-ray bursts (SGRBs)
  ⟶ reveal when and how SGRBs are produced Ciolfi & Siegel 2015a,b

⟶ GW astronomy requires EM counterparts

SGRBs as EM counterparts

- prompt emission bright, but collimated
- standard afterglows too dim
- low fraction of events, e.g., for NS-NS:

$$r_{\mathrm{SGRB}} = f_{\mathrm{beam}} f_{\mathrm{jet}} r_{\mathrm{BNS}}$$

$$r_{\mathrm{BNS}} = 10^{-6} \mathrm{Mpc}^{-3} \mathrm{yr}^{-1}$$ Abadie+ 2010

$$r_{\mathrm{SGRB}} = 3 \times 10^{-9} \mathrm{Mpc}^{-3} \mathrm{yr}^{-1}$$ Wanderman & Piran 2015

collimation baryon pollution, …

$$f_{\mathrm{beam}} f_{\mathrm{jet}} \lesssim 0.3\%$$

likely rate of coincident detections: ~0.3 yr^{-1}
(but only for all sky EM coverage!)

Metzger & Berger 2012

So far no SGRB with known redshift within sensitivity volume of aLIGO for NS-NS (200 Mpc)

- details of generation remain unclear, coincidence could be "missed" (cf. "*time-reversal scenario*") Ciolfi & Siegel 2015 a,b

⟶ potentially rewarding counterpart, but unlikely

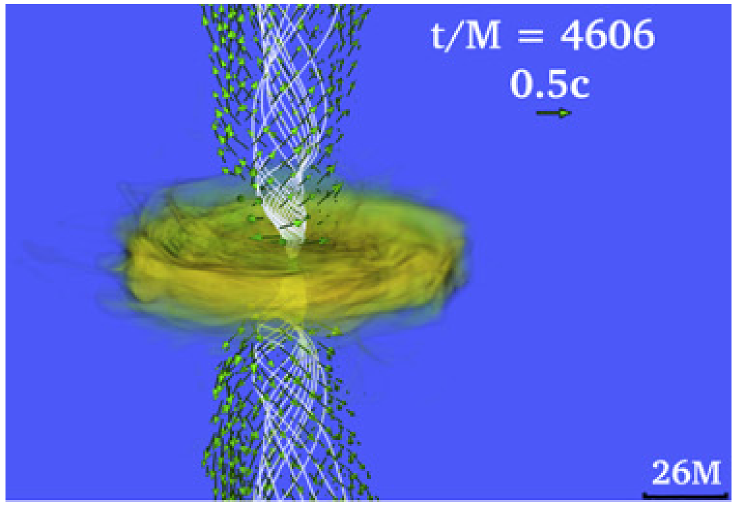


Fig.: Magnetic funnel emerging from a BH-torus system (BNS merger)
Ruiz+ 2016

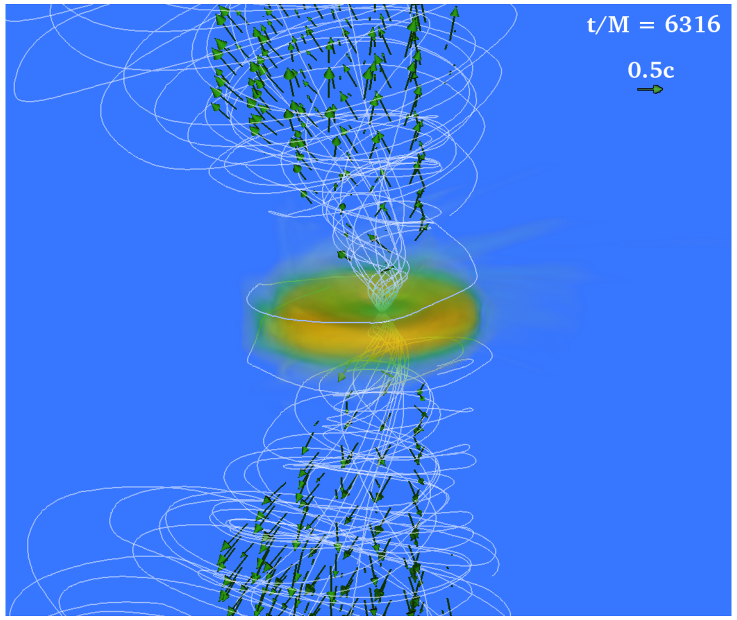
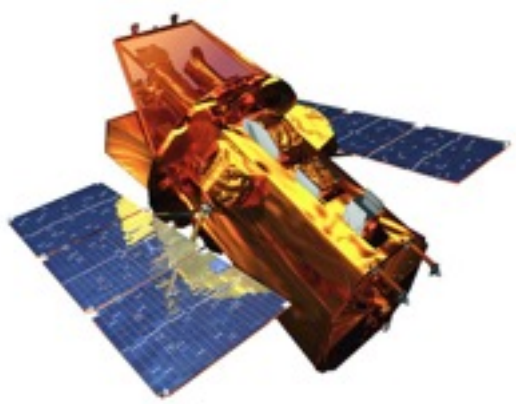
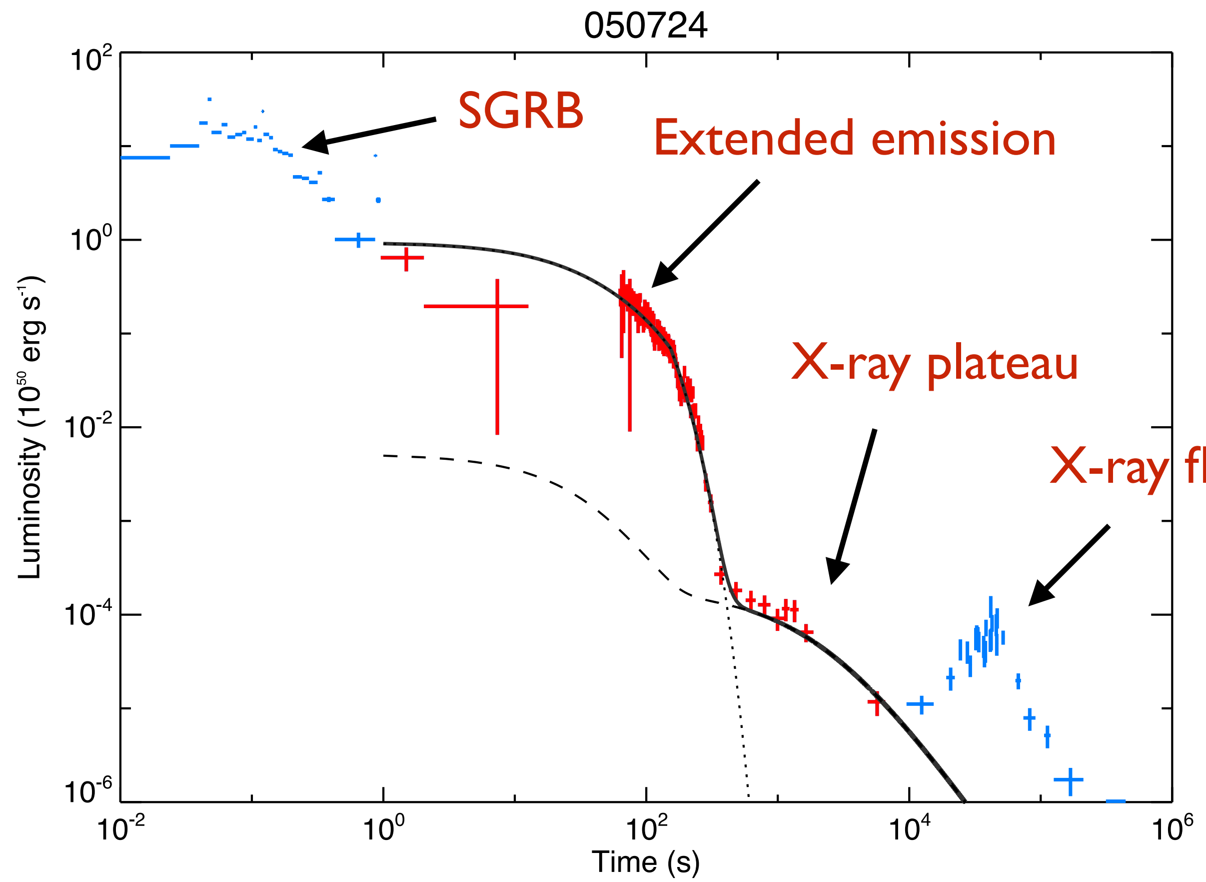


Fig.: Magnetic funnel emerging from a BH-torus system (NS-BH merger)
Paschalidis et al. 2015

Non-standard X-ray afterglows of SGRBs



Swift



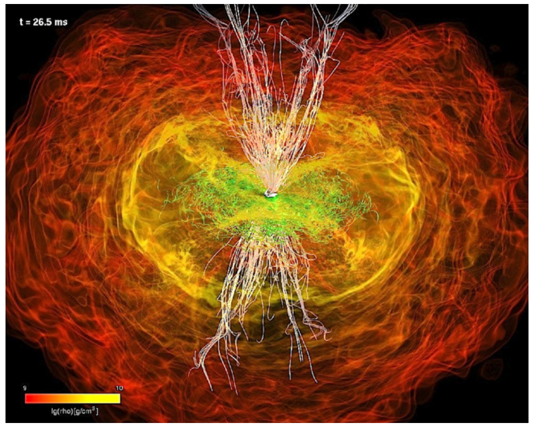
Gompertz+ 2014

- *Swift* revealed that a large fraction of SGRBs are accompanied by long-duration (~10^2-10^5s) and high-luminosity (~10^{46}-10^{51}erg/s) X-ray afterglows
- total energy can be higher than that of the SGRB
- unlikely produced by BH-torus system - indicative of ongoing energy injection ("long-lived engine")

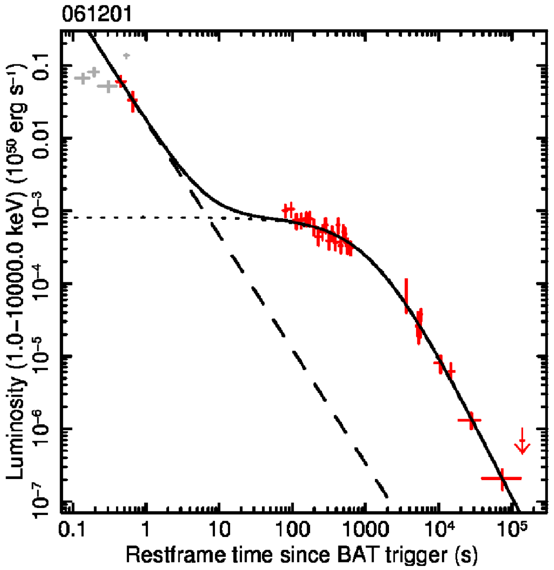
→ challenges BH-torus paradigm for SGRBs

The SGRB dichotomy

- Numerical relativity picture: prompt BH-torus formation
  - → can explain prompt SGRB emission ✓
  - → cannot explain X-ray afterglows ✗

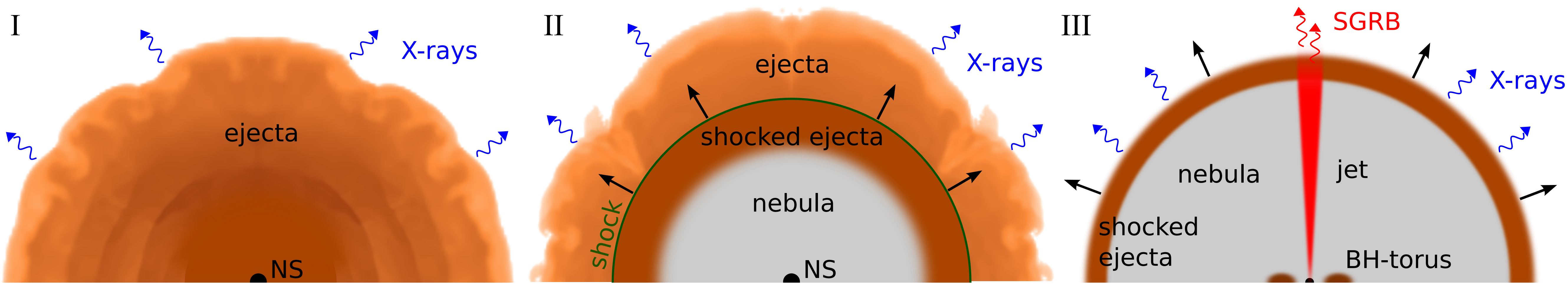


- Observational picture: magnetar model
  - → cannot explain prompt SGRB emission ✗
  - → can explain X-ray afterglows of SGRBs ✓



Possible solution: "time-reversal" scenario (Ciolfi & Siegel 2015a,b)

“Time-reversal” phenomenology



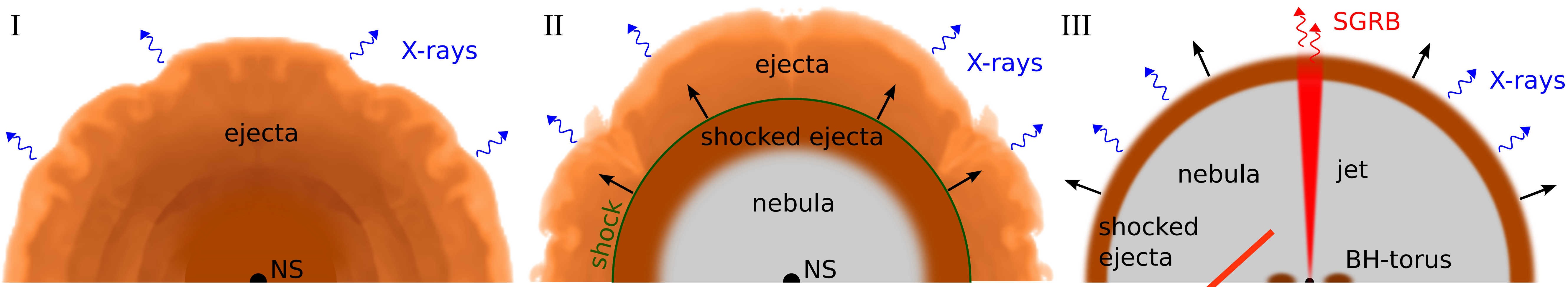
Ciolfi & Siegel 2015a

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

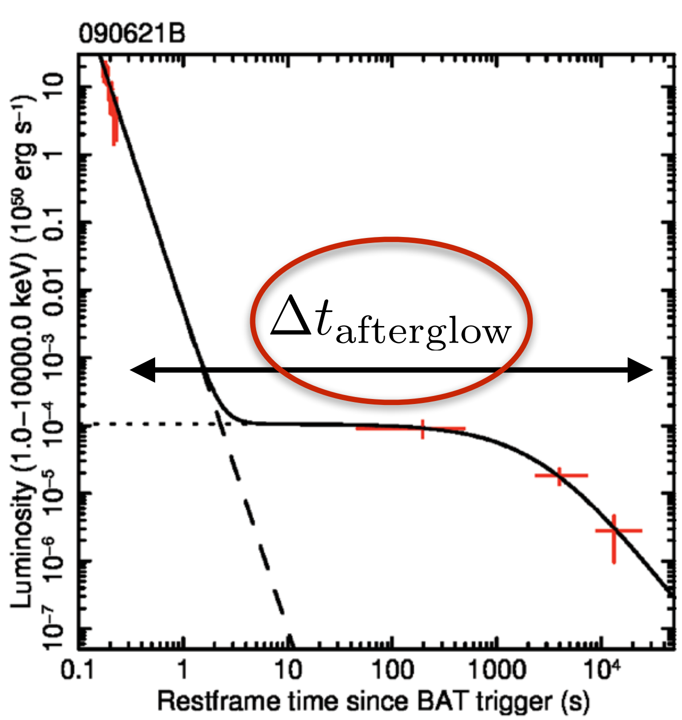
(II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta

(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

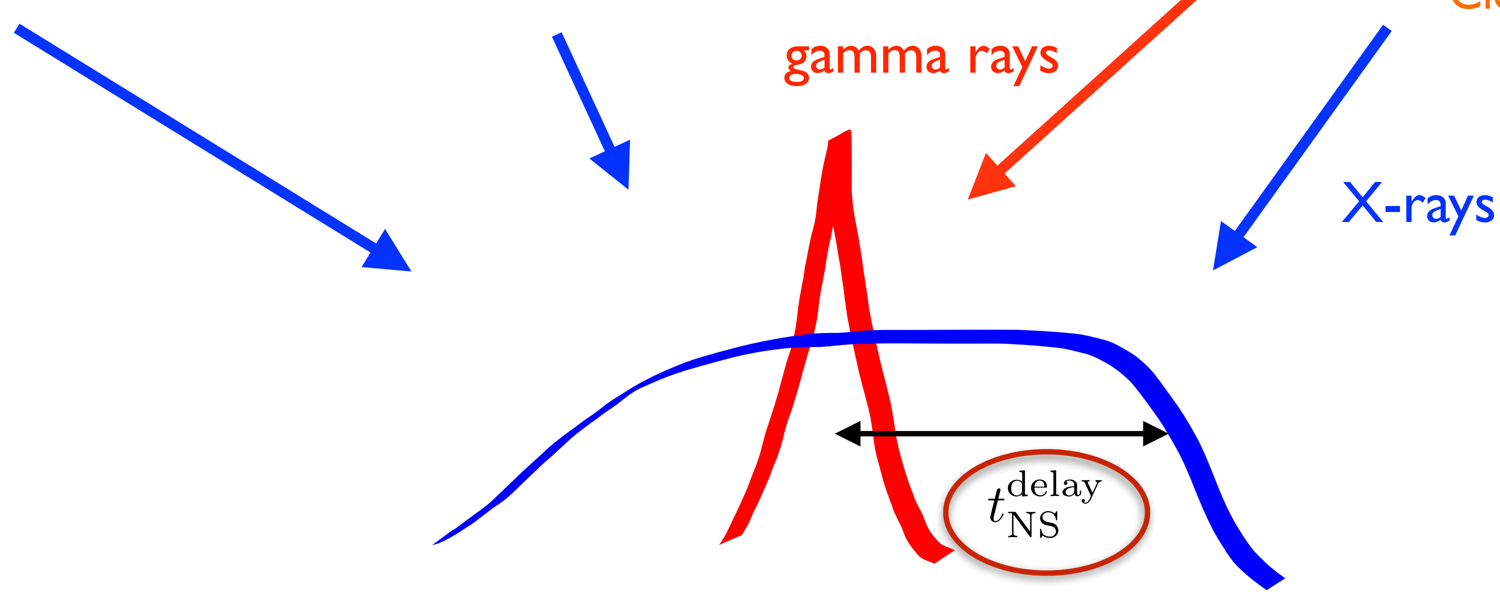
‘Time-reversal’ scenario



Ciolfi & Siegel 2015a



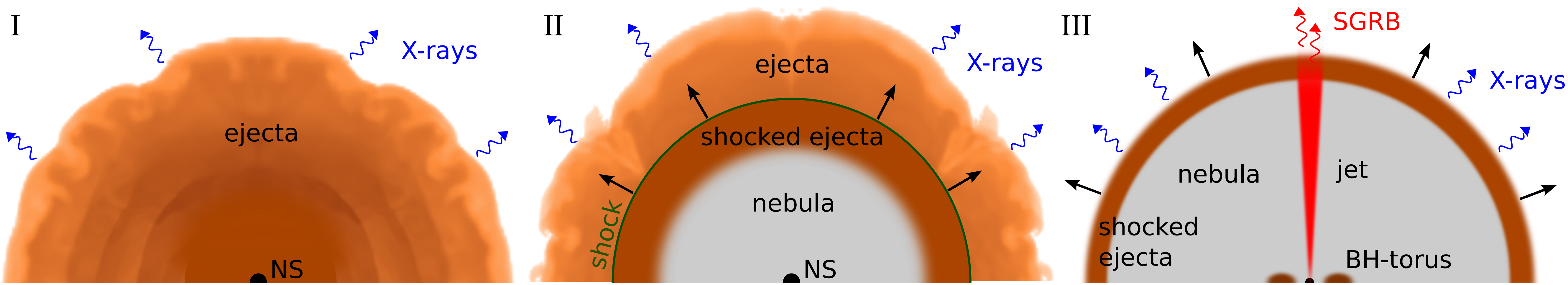
Rowlinson+2013



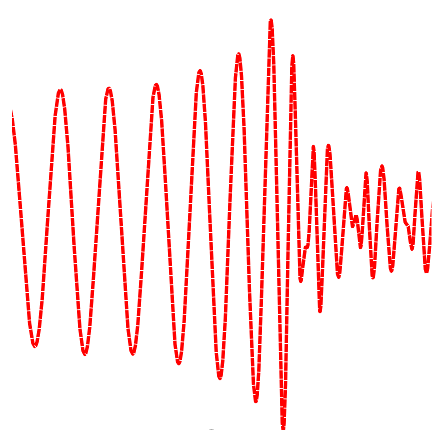
Model calculation: generally: $t_{\rm NS}^{\rm delay} \gtrsim \Delta t_{\rm afterglow}$

→ “time-reversal” scenario compatible with observations

'Time-reversal' scenario



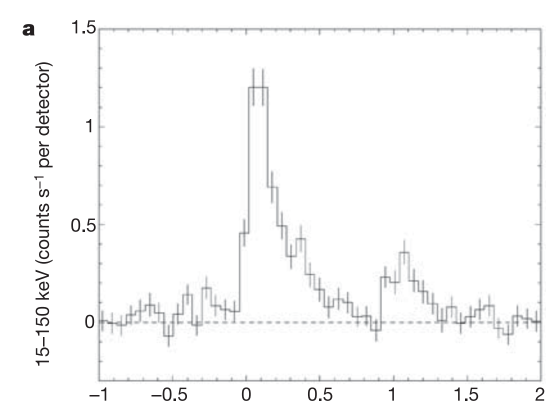
Ciolfi & Siegel 2015a



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

In the time-reversal scenario… Ciolfi & Siegel 2015a

1[st] plateau:

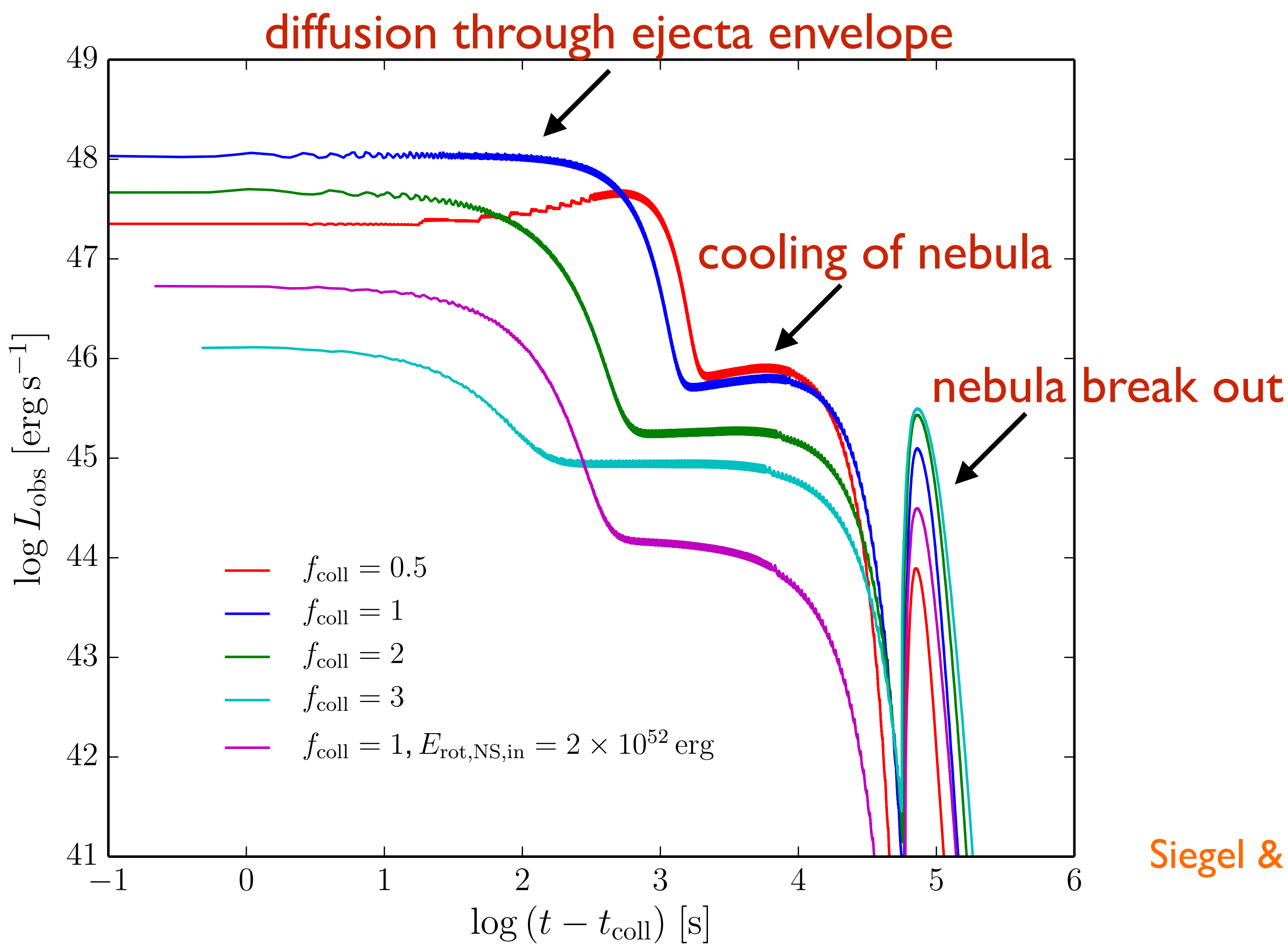
~10^2s

L_X ~ 10^{46}–10^{48} erg/s

2[nd] plateau:

~10^3–10^4 s

L_X ~ 10^{44}–10^{46} erg/s



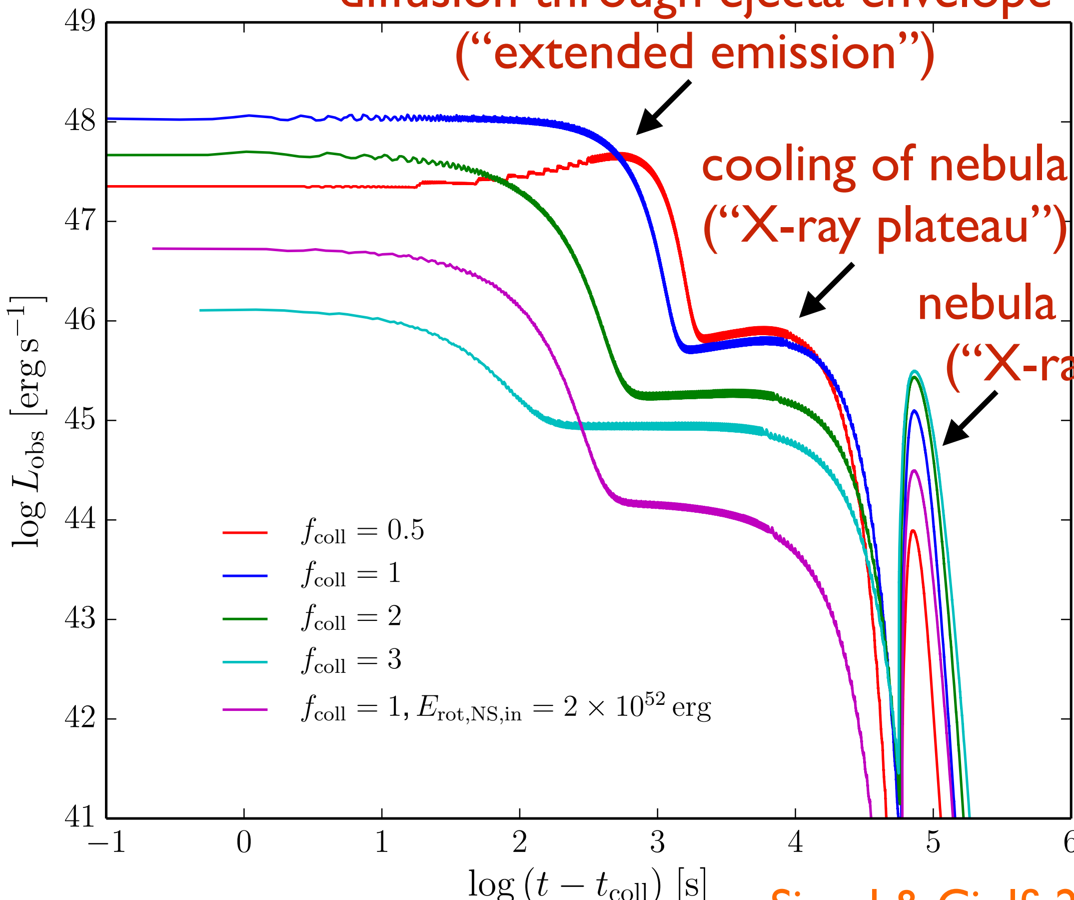
Siegel & Ciolfi 2015c

Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for time-reversal scenario (SGRB at collapse of NS)

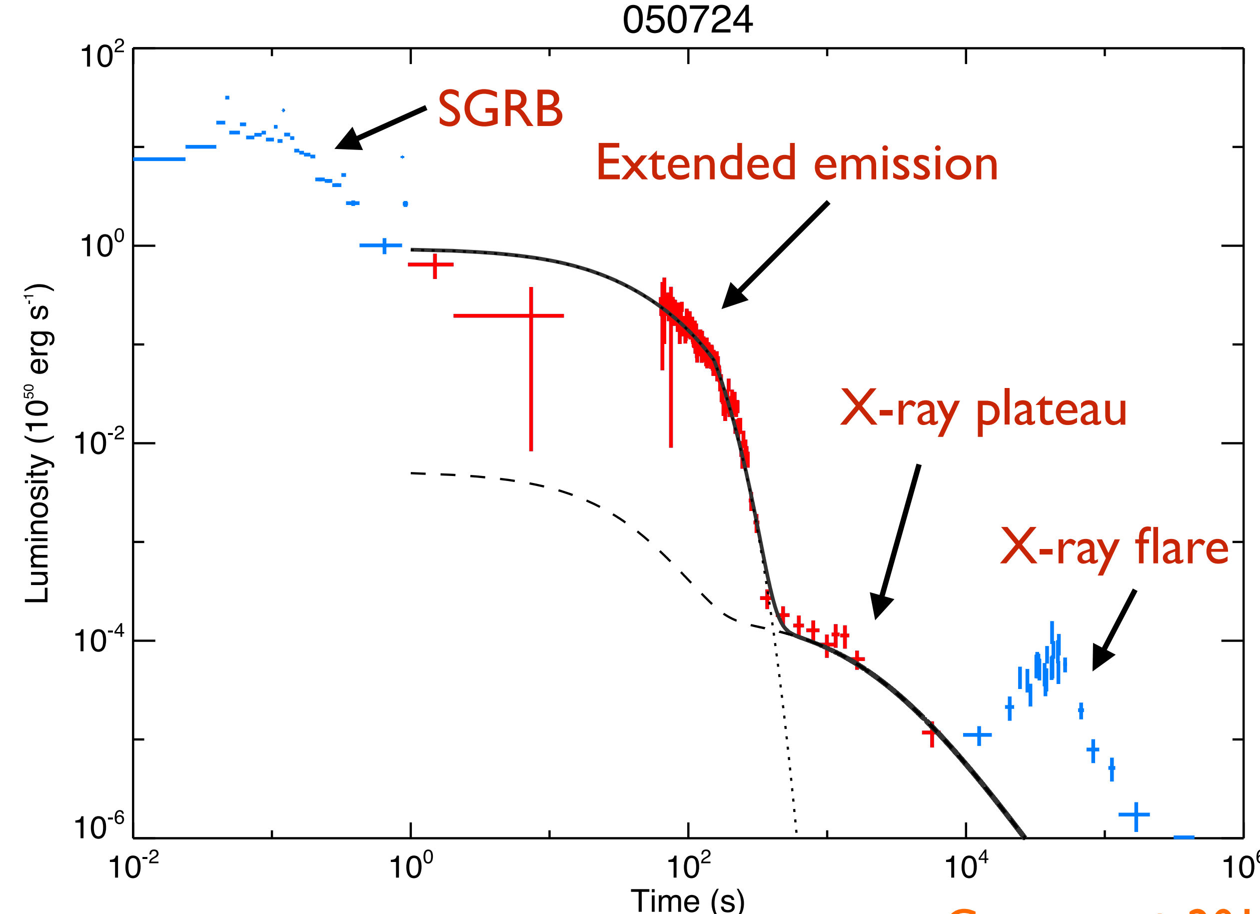
- two-plateau structures, late-time flares

In the *time-reversal* scenario…

Ciolfi & Siegel 2015a



Siegel & Ciolfi 2015c



Gompertz+ 2014

Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for *time-reversal* scenario (SGRB at collapse of NS)

- two-plateau structures, late-time flares
- Luminosity levels and time-scales for two-plateau structures are in agreement with SGRBs showing extended emission and X-ray plateaus

⟶ natural explanation for combined phenomenology of *Swift* X-ray lightcurves