COLUMBIA UNIVERSITY
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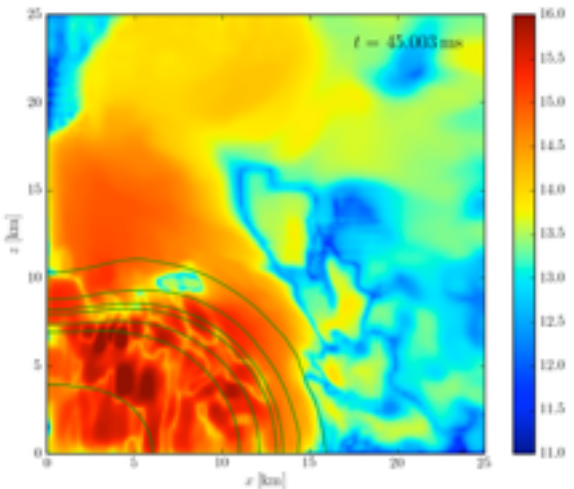
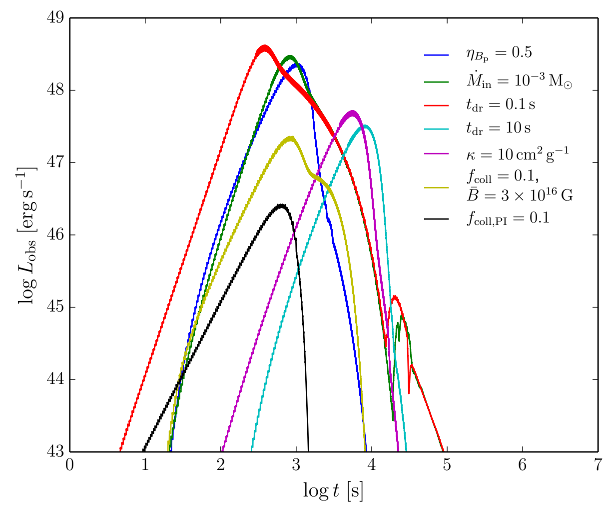
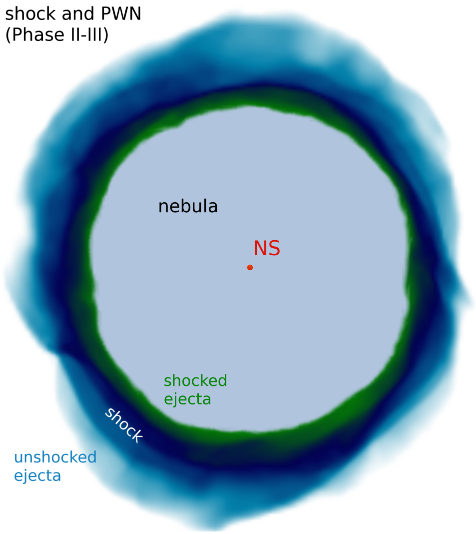
EM counterparts from long-lived BNS merger remnants







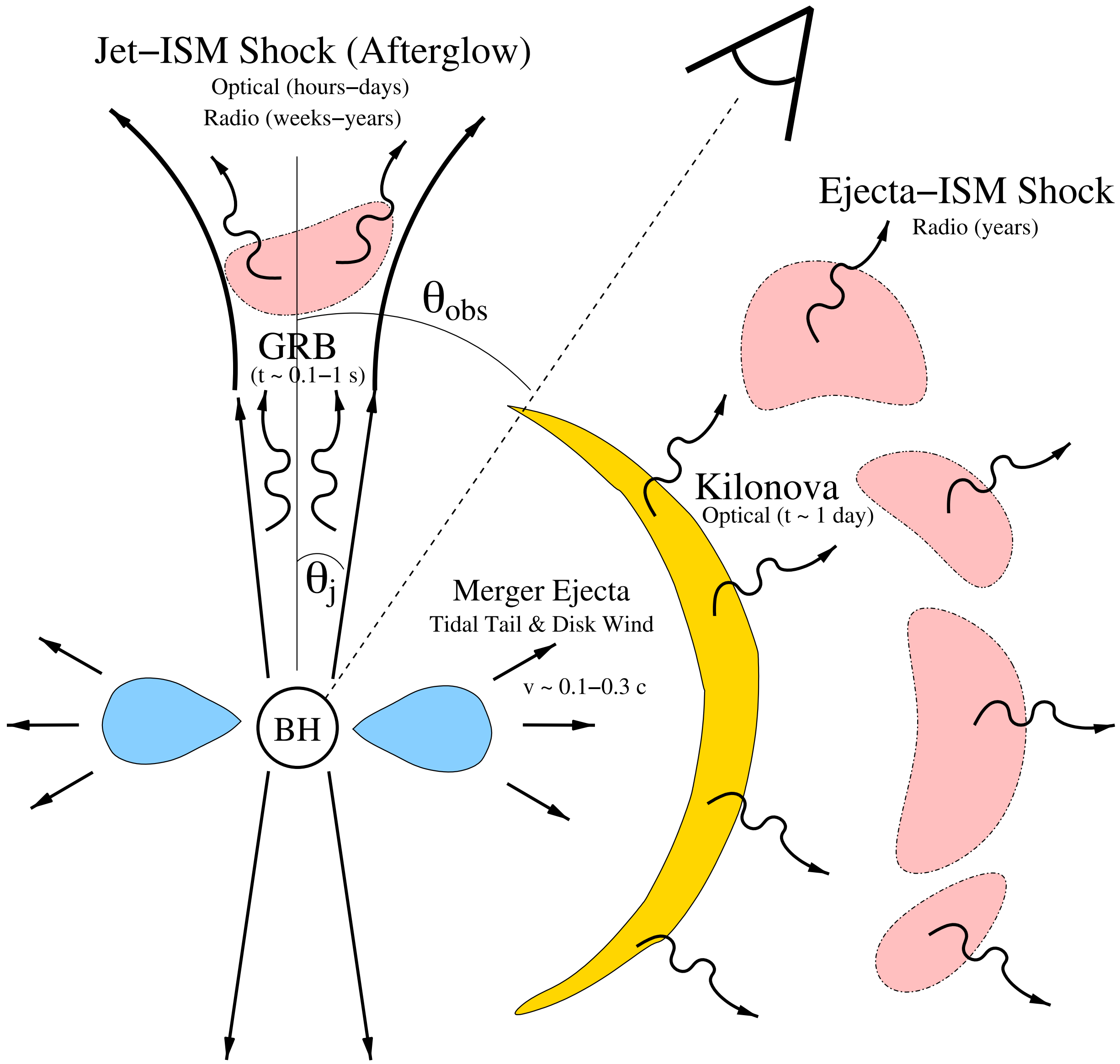
Daniel M. Siegel

Center for Theoretical Physics & Columbia Astrophysics Laboratory

Columbia University

Einstein Fellows Symposium, Harvard-Smithsonian Center for Astrophysics, Oct 19, 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

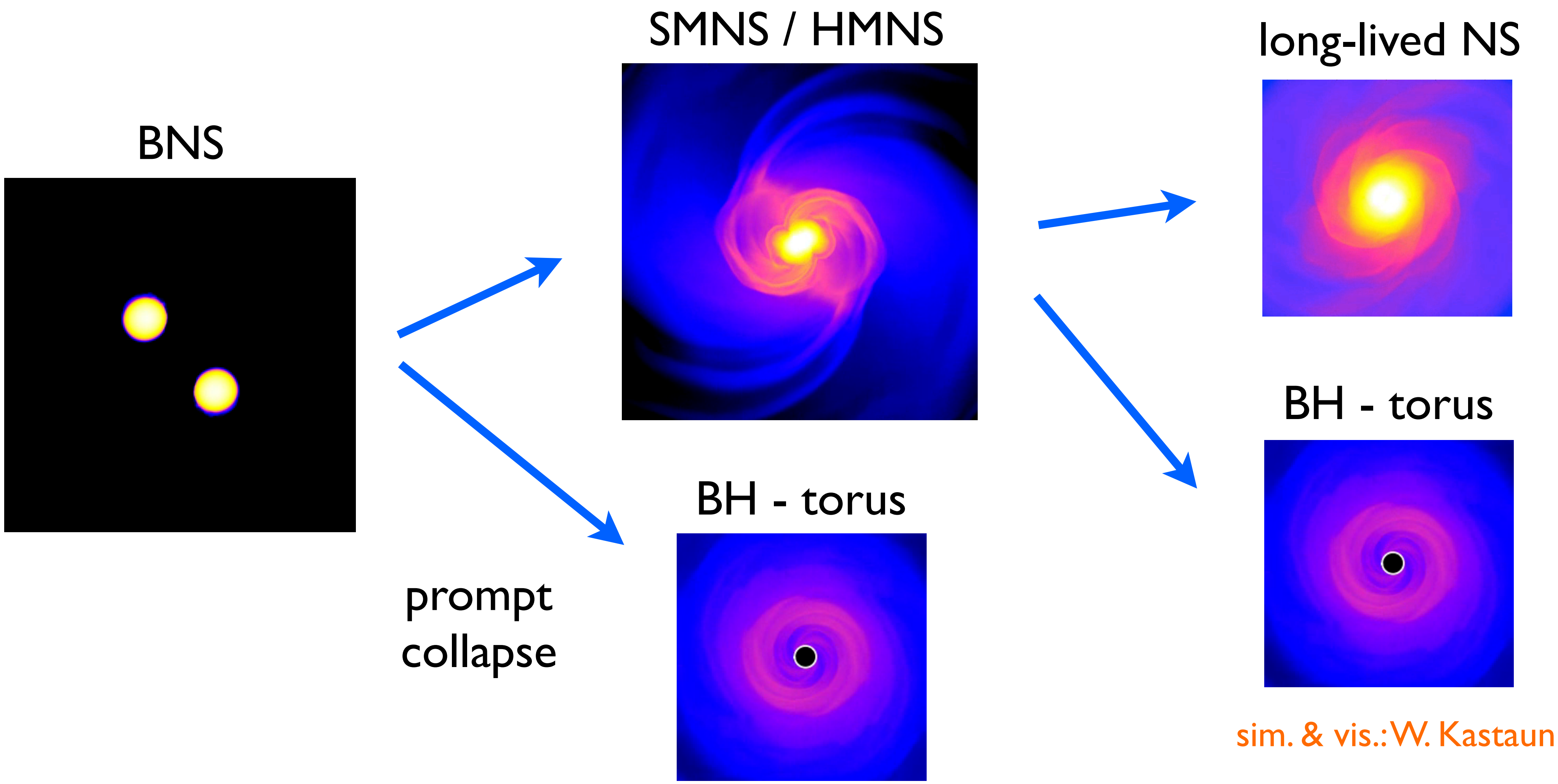
- radioactively powered kilonova/macronova

  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: $\mathrm{M_{TOV}} \gtrsim 2\,\mathrm{M_\odot}$ 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 $\approx 1.2\,\mathrm{M_{TOV}} \gtrsim 2.4\,\mathrm{M_\odot}$ 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):

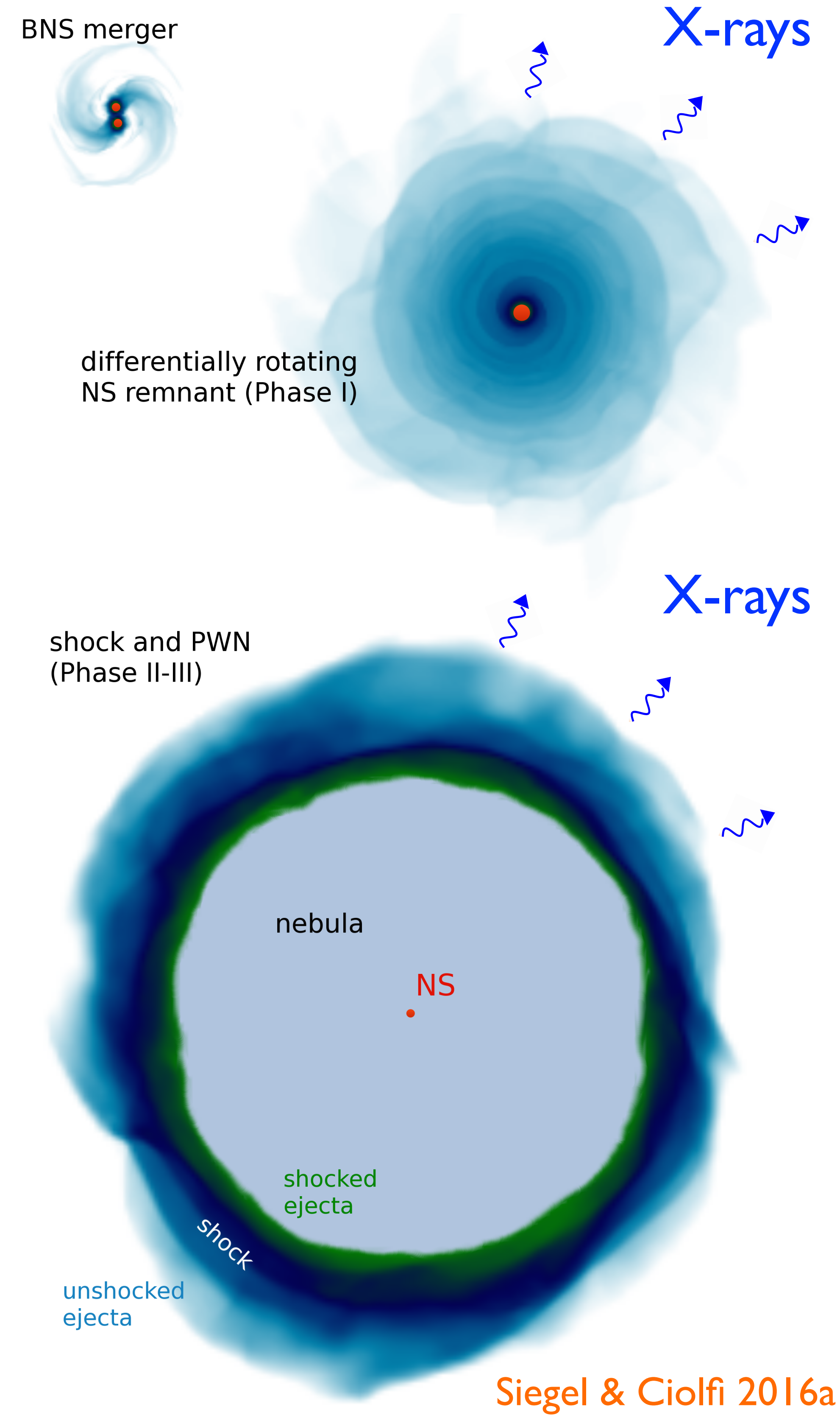
- cold, uniformly rotating NS
- baryon pollution suppressed ⟶ spin-down emission, pulsar wind inflates nebula, drives shock through ejecta

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

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

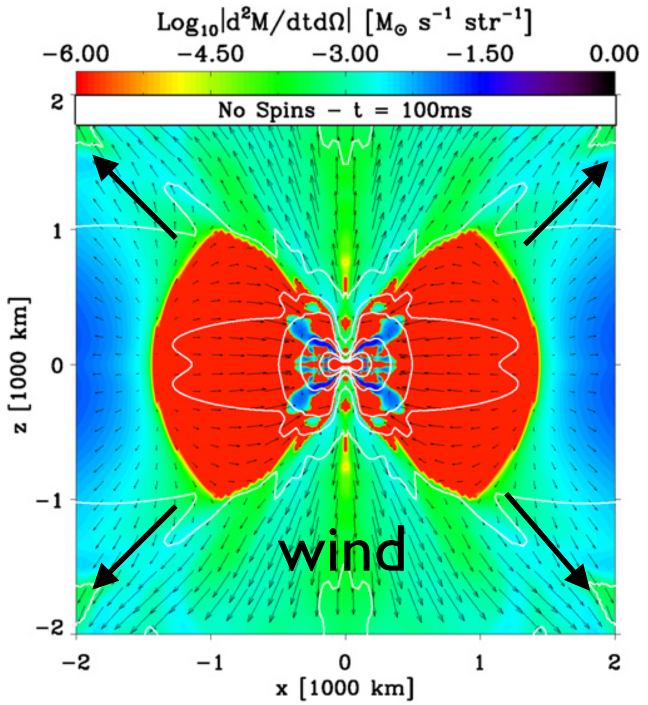
- NS may collapse to a BH at any time
- EM emission: reprocessed spin-down energy

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

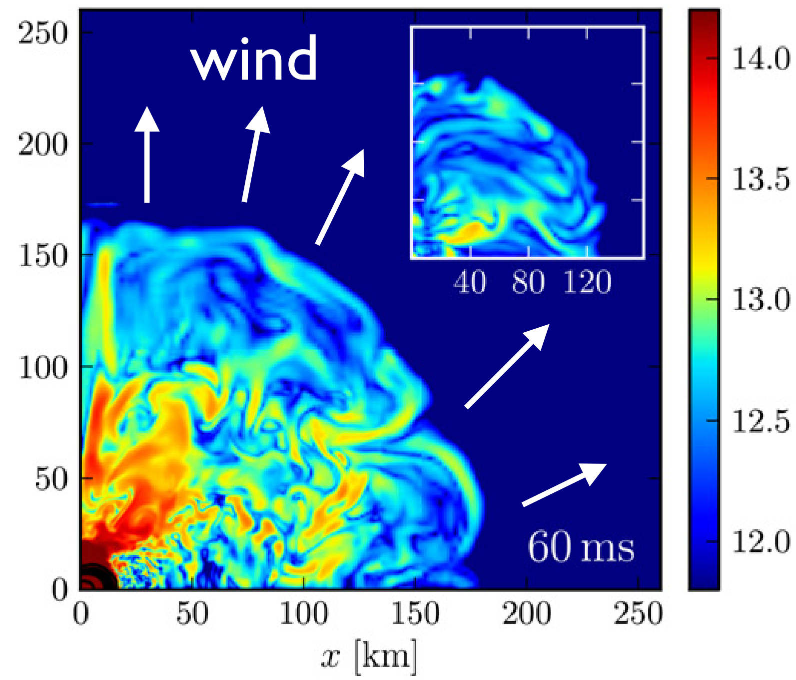


Siegel & Ciolfi 2016a

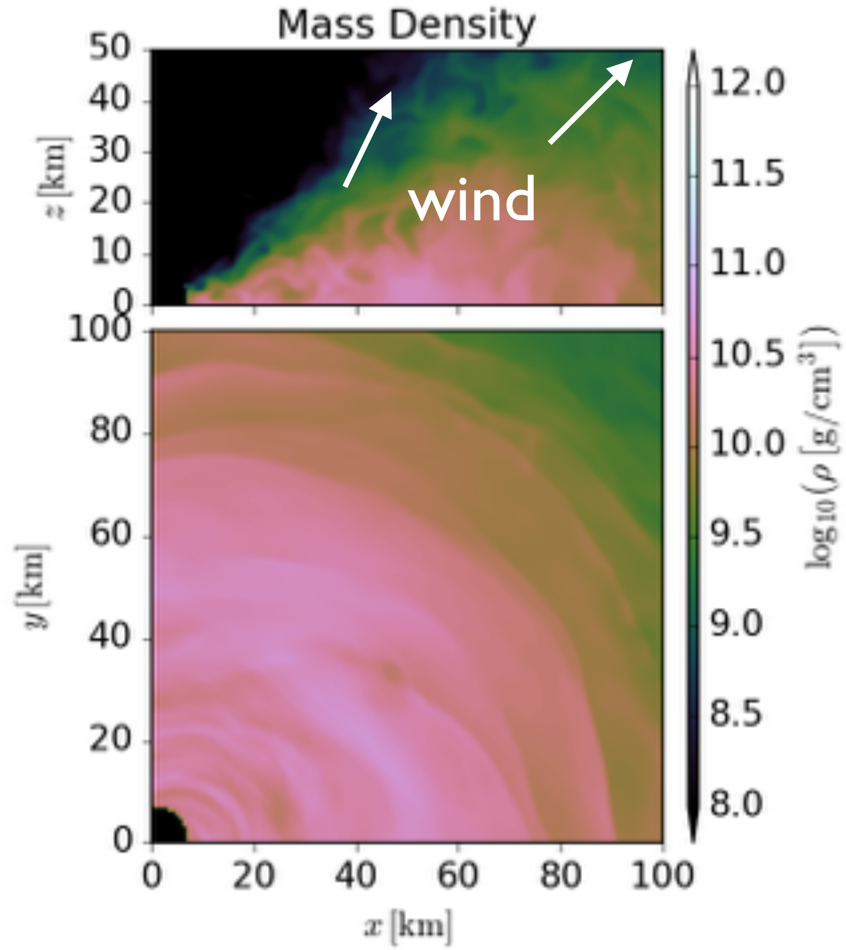
Outflows from BNS merger remnants



Dessart+ 2009



Siegel+ 2014



Siegel+ 2017

Fernández & Metzger 2013, Just+ 2015

neutrino-driven wind (from hot remnant NS)

(~ms-1s)

$$\dot{M}_{\rm in} \sim (10^{-4} - 10^{-3}) {\rm M}_\odot {\rm s}^{-1}$$

magnetically driven wind (from remnant NS)

(~ms-1s)

$$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$$

delayed outflows (from accretion disks)

(~1s)

$$M_{\rm tot} \lesssim 10^{-3} - 10^{-2} {\rm M}_\odot$$

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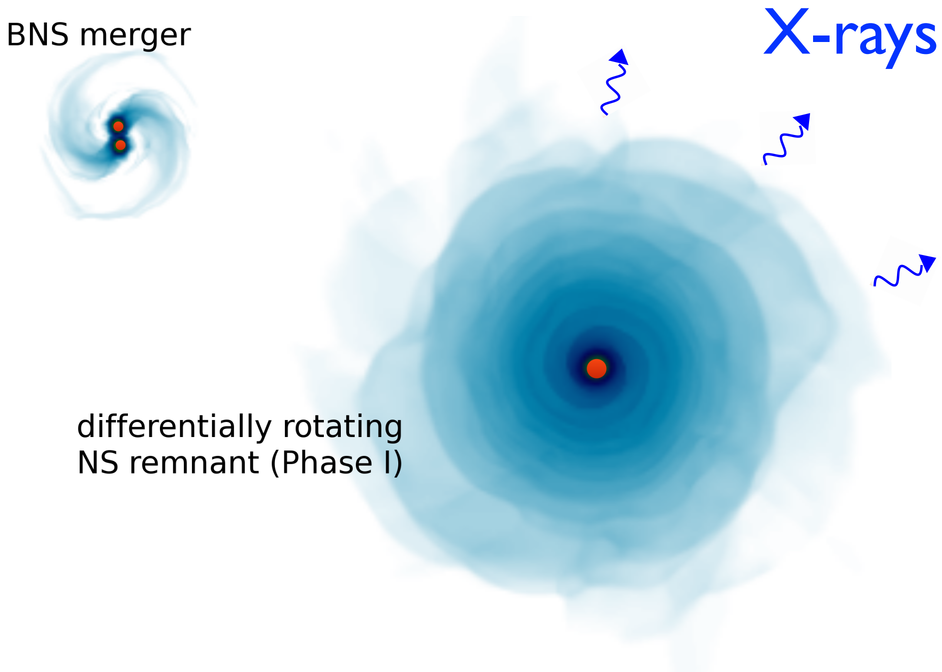
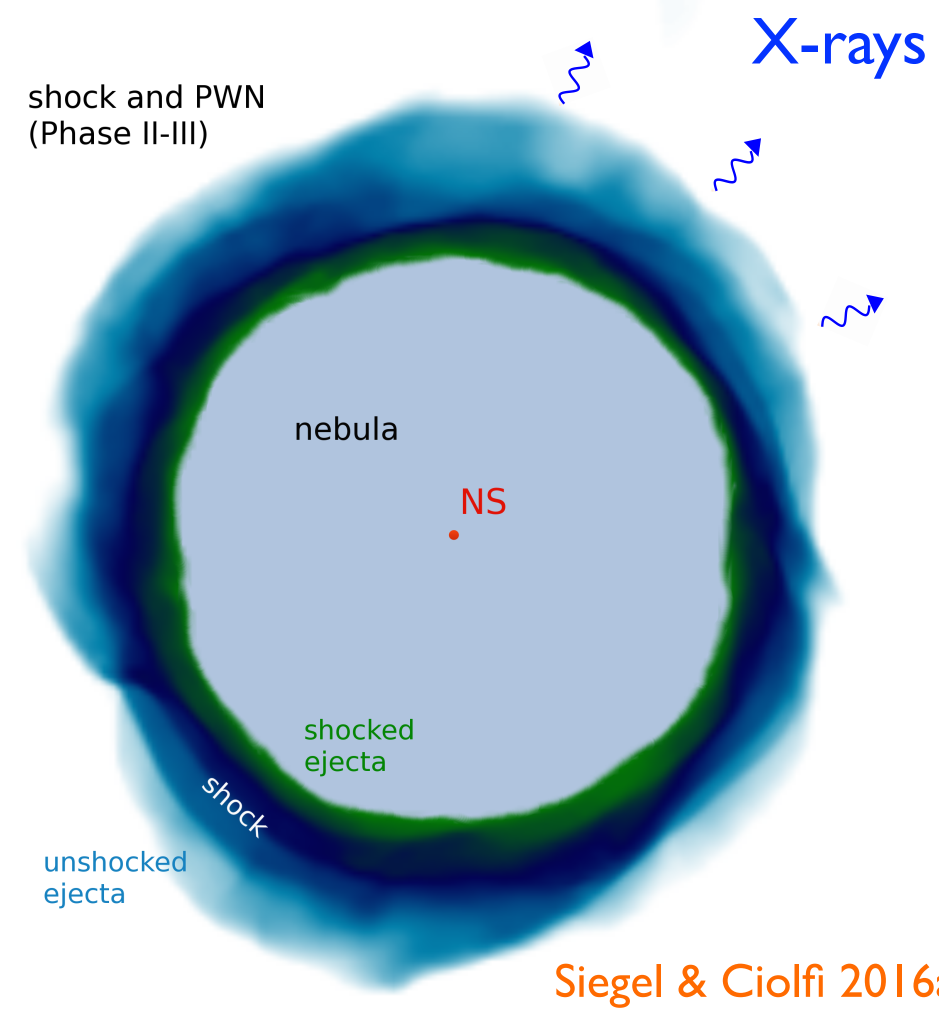




Siegel & Ciolfi 2016a

Post-merger evolution: evolution equations

Phase I:

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

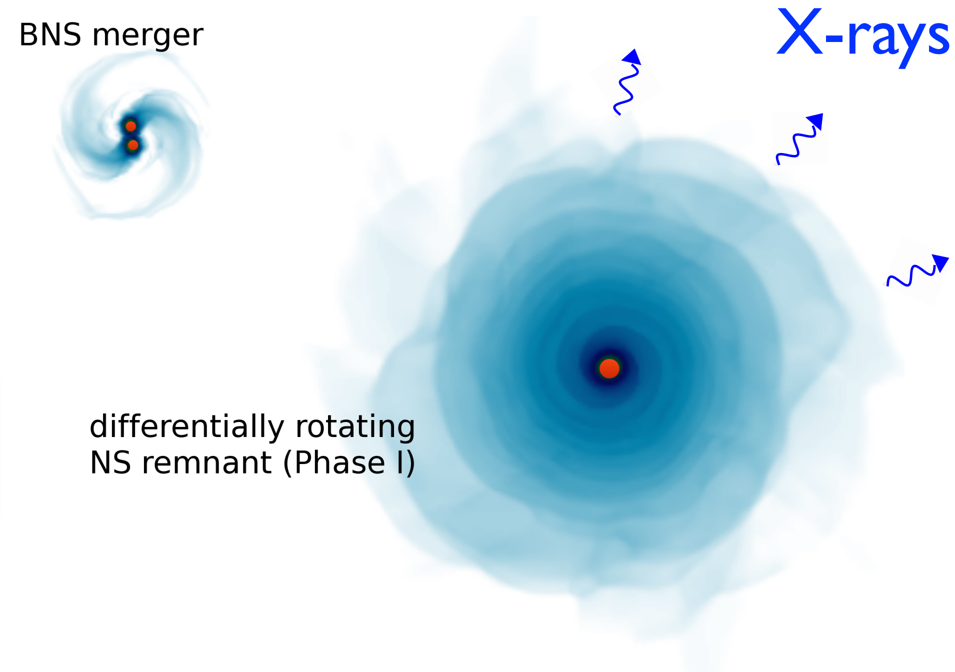
Phase II:

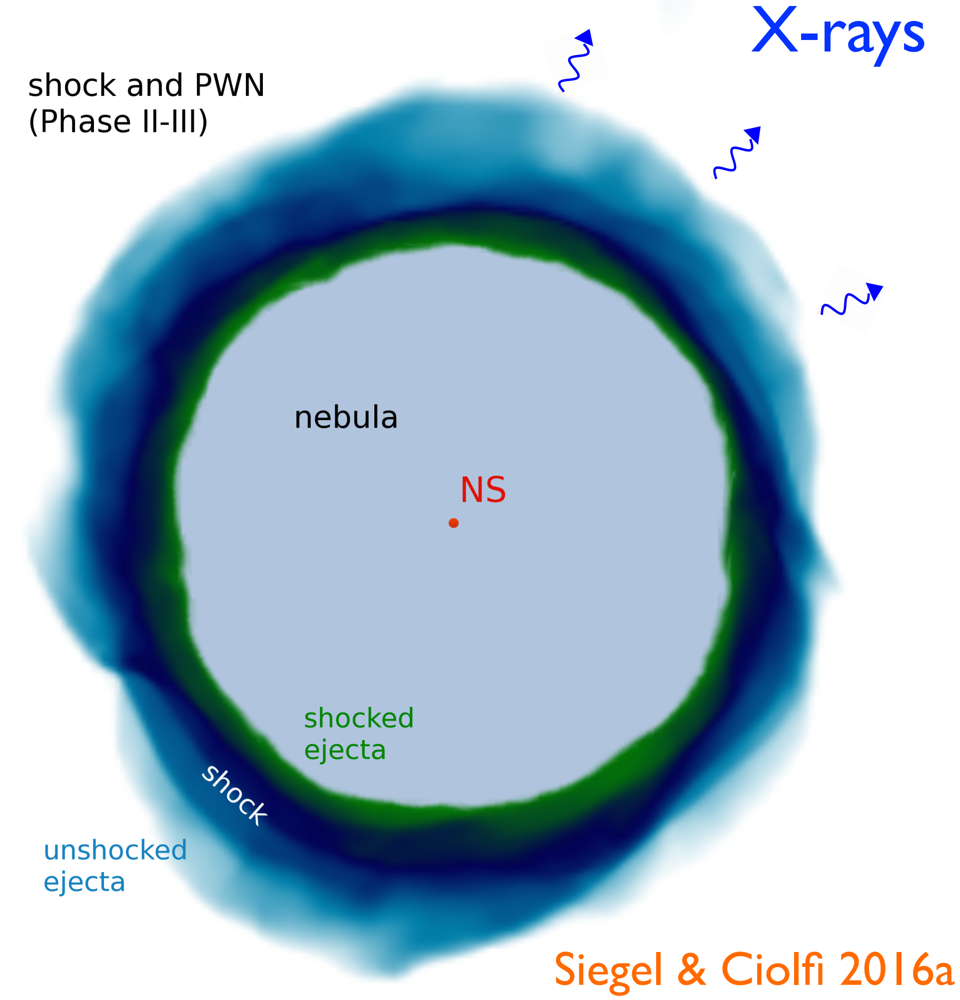
$$
\begin{aligned}
\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} &= v_{\mathrm{w}}(R_{\mathrm{ej}}(t),t)\\
\frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t} &= v_{\mathrm{sh}}(t)\\
\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} &= \frac{\mathrm{d}R_{\mathrm{sh}}}{\mathrm{d}t} - \frac{\mathrm{d}\Delta_{\mathrm{sh}}}{\mathrm{d}t}\\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

set of coupled ODEs

Phase III:

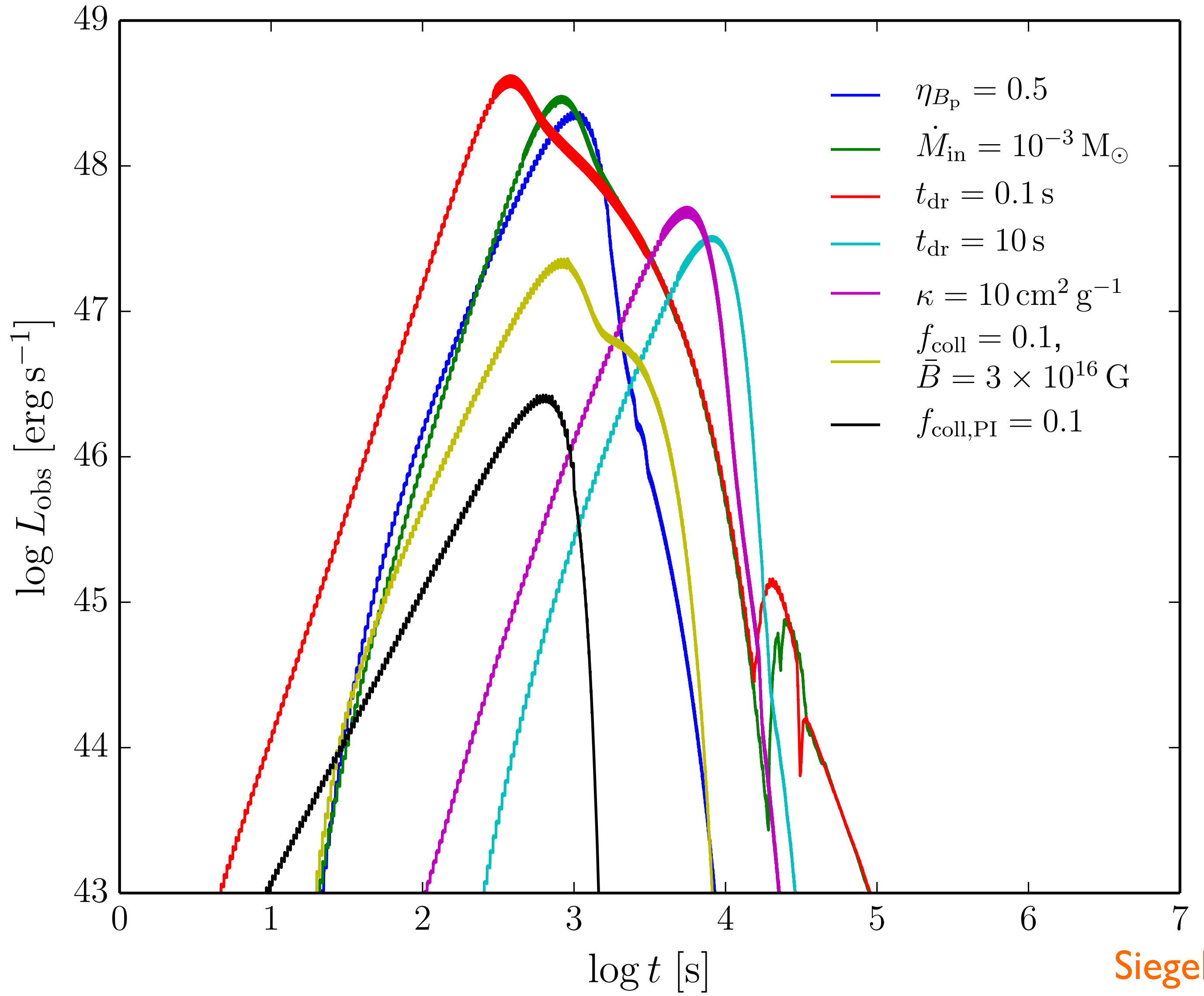
$$
\begin{aligned}
\frac{\mathrm{d}v_{\mathrm{ej}}}{\mathrm{d}t} &= a_{\mathrm{ej}}(t)\\
\frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t} &= v_{\mathrm{ej}}(t) + \frac{1}{2}a_{\mathrm{ej}}(t)\mathrm{d}t\\
\frac{\mathrm{d}R_{\mathrm{n}}}{\mathrm{d}t} &= \frac{\mathrm{d}R_{\mathrm{ej}}}{\mathrm{d}t}\\
\frac{\mathrm{d}E_{\mathrm{th}}}{\mathrm{d}t}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





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

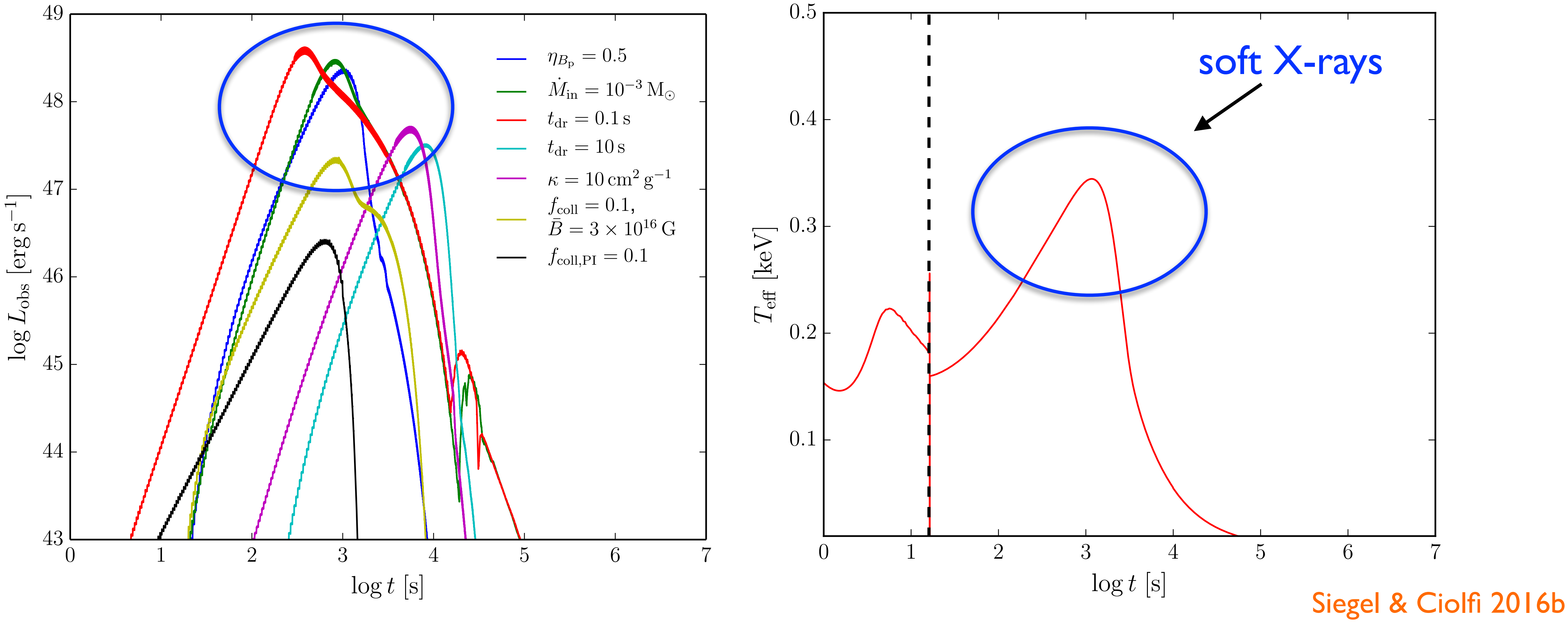
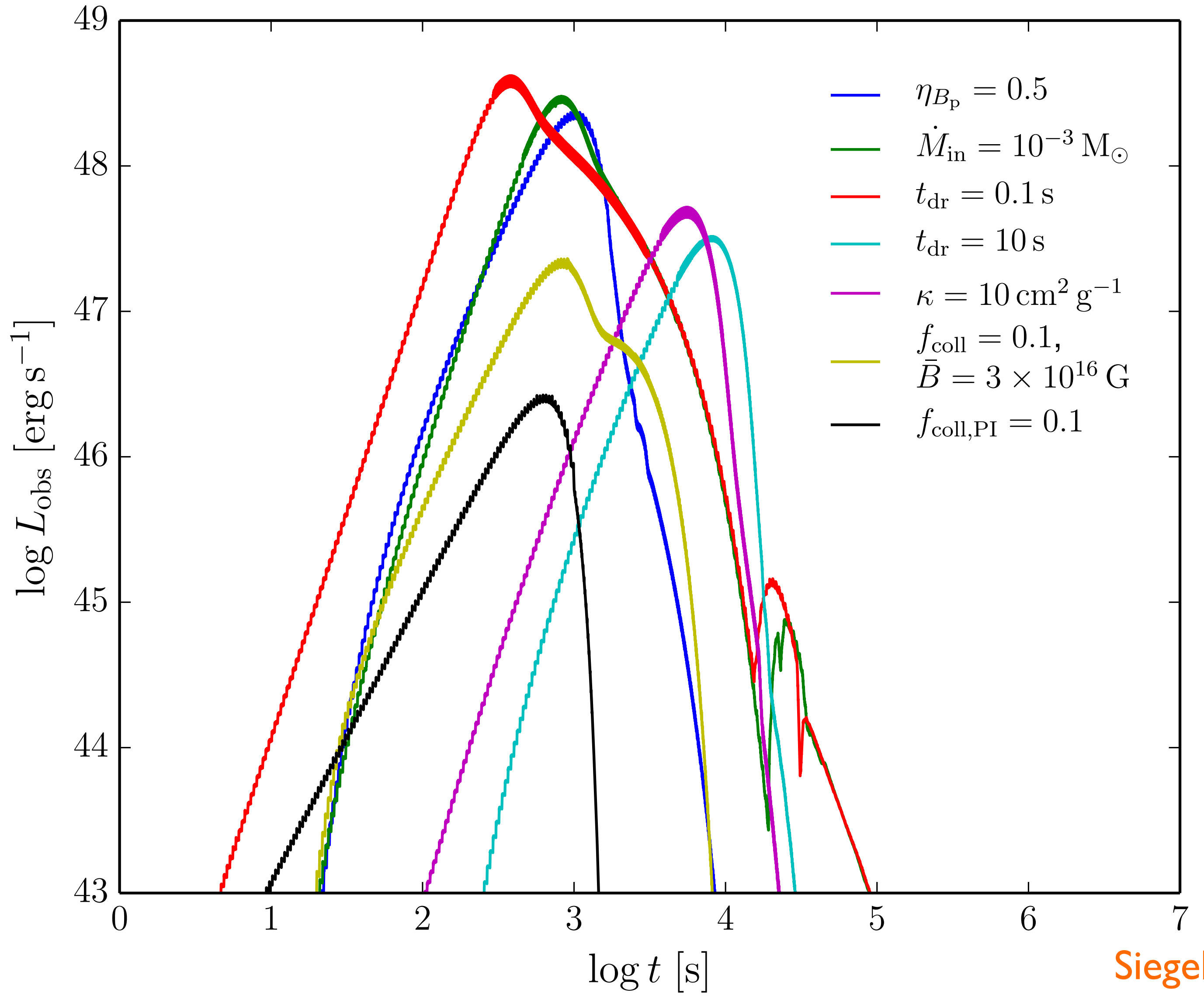


Fig.: X-ray light curves and effective temperature evolution (example)

- 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 ~ 1d
- degree of ionization of ejecta matter important: if low, peak might be shifted toward lower frequencies

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

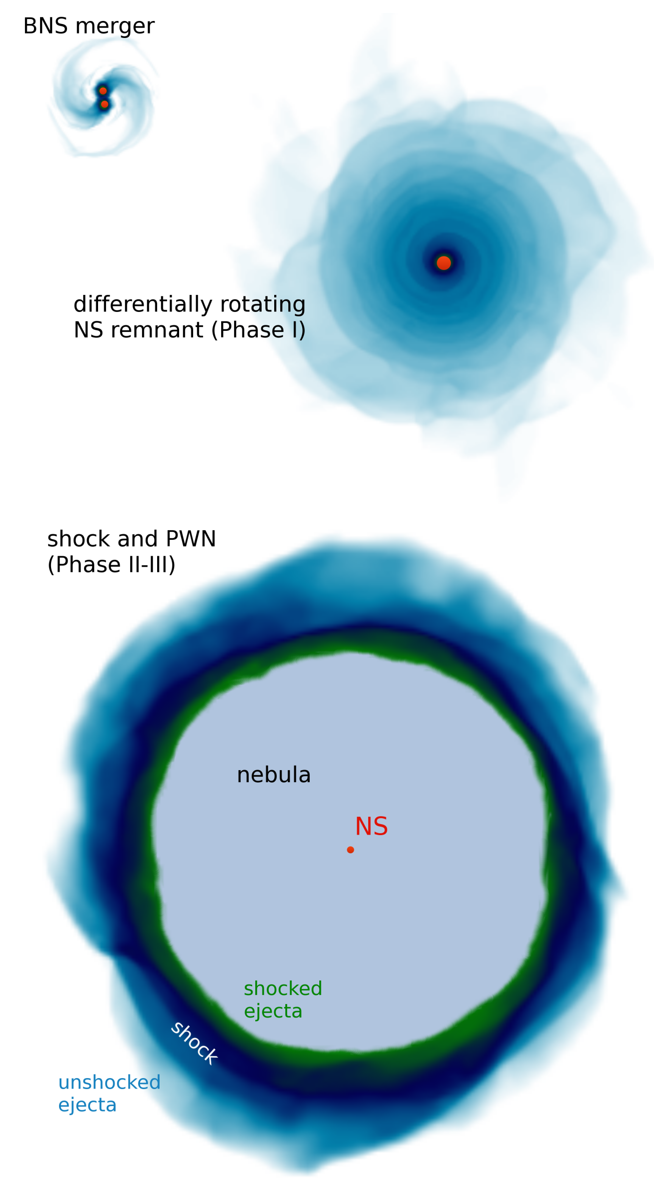
What is a promising EM counterpart?

	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 thermal transient (peaking in the X-rays, but also UV and optical counterparts at later times), promising counterpart for GW astronomy
  - → together with NS component masses from GW signal can tightly constrain EOS (using supramassive NS assumption)
    Ciolfi & Siegel (2015), *ProcSci* (SWIFT 10)108
  - → natural explanation for combined phenomenology of *Swift* X-ray lightcurves (not this talk), and late-time kilonova emission
  - → 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