Electromagnetic emission from long-lived binary neutron star merger remnants

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

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

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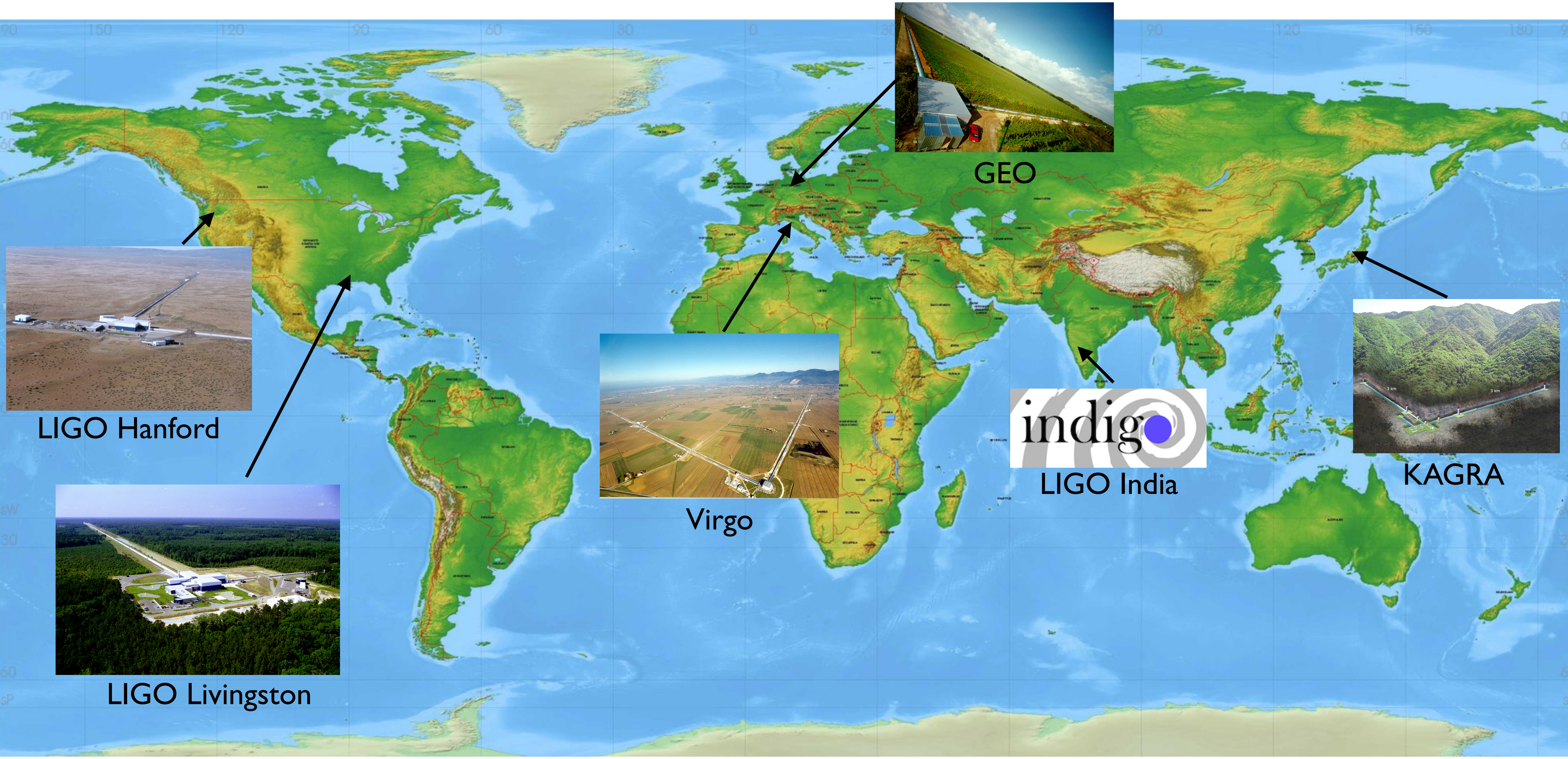
Ground-based Gravitational Wave Detector Network



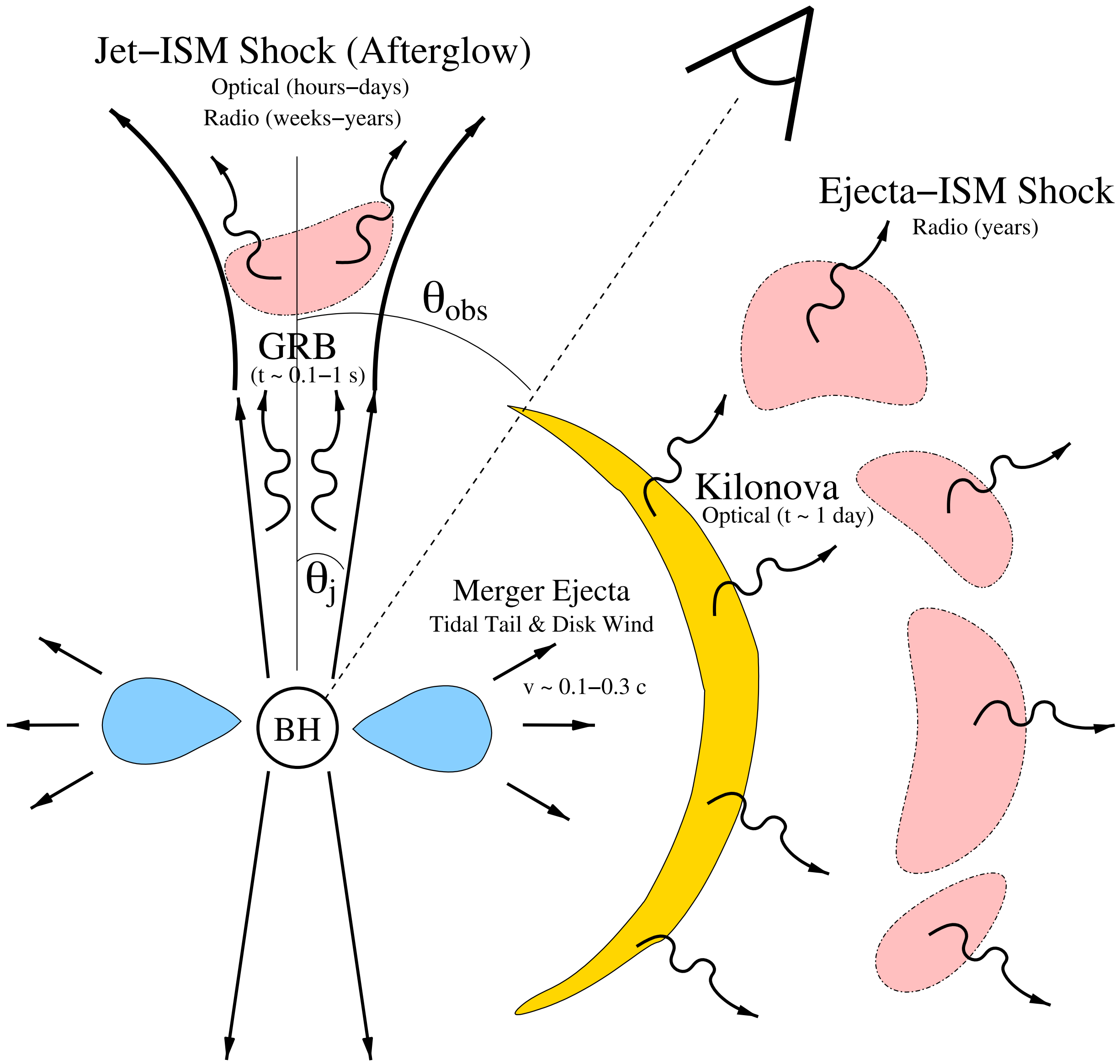
- BNS mergers most promising source of GWs for advanced LIGO/Virgo, routine detections expected in the next years

⟶ Multimessenger astronomy

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}
	NS–NS	0.4	40	400
	NS–BH	0.2	10	300
Advanced	BH–BH	0.4	20	1000
	IMRI into IMBH			10[b]
	IMBH-IMBH			0.1[d]

Abadie et al. 2010

EM counterparts to BNS 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

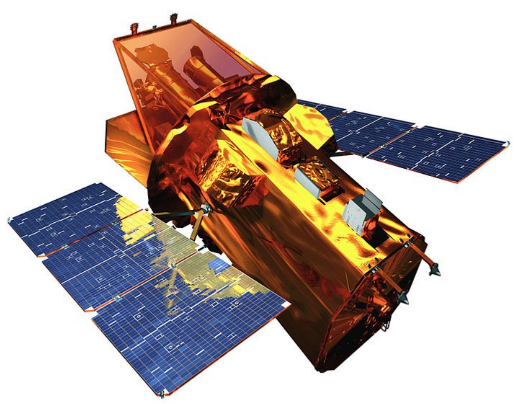
- Interaction of dynamical ejecta with ISM (radio)

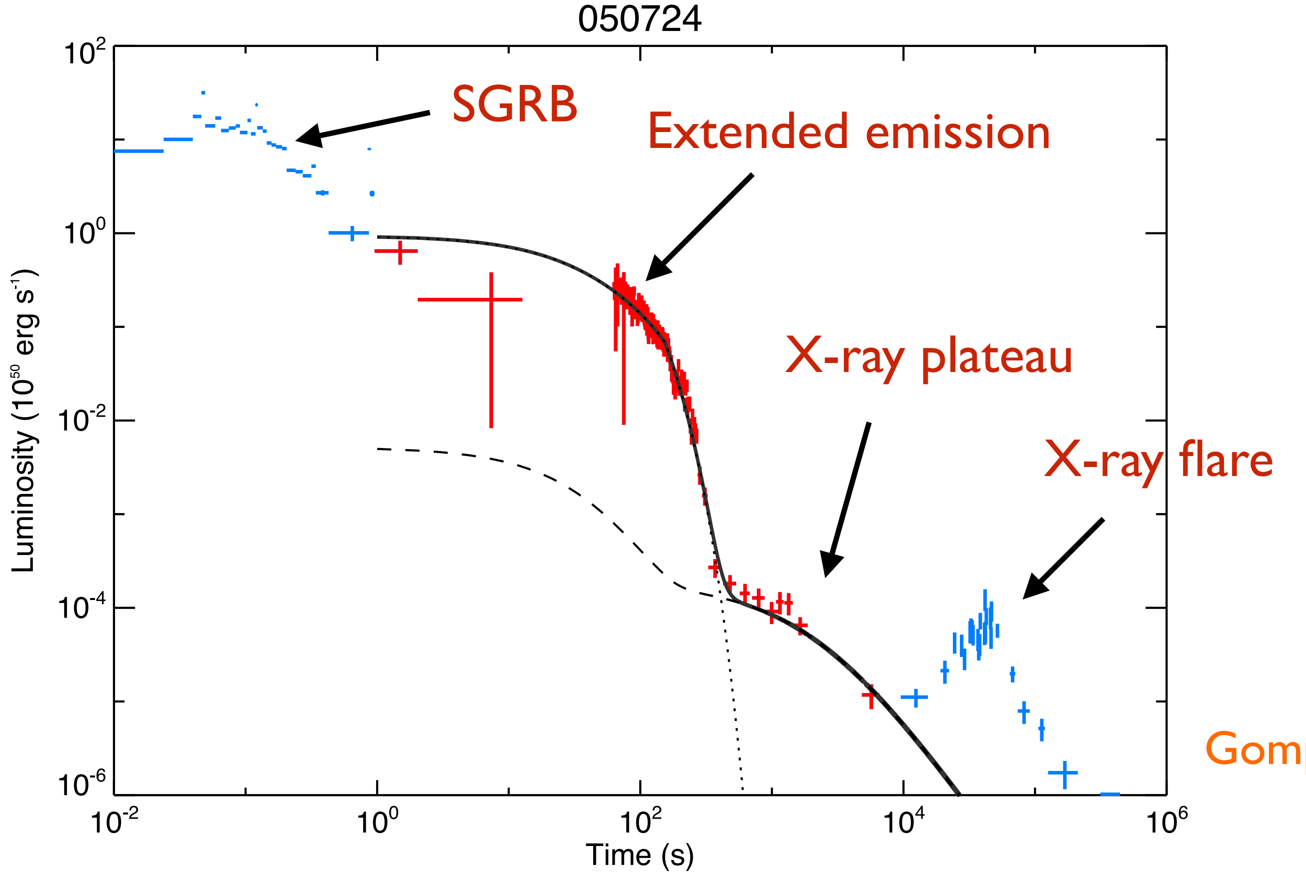
  Hotokezaka & Piran 2015

- radioactively powered kilonova (macronova)

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

Non-standard X-ray afterglows of SGRBs



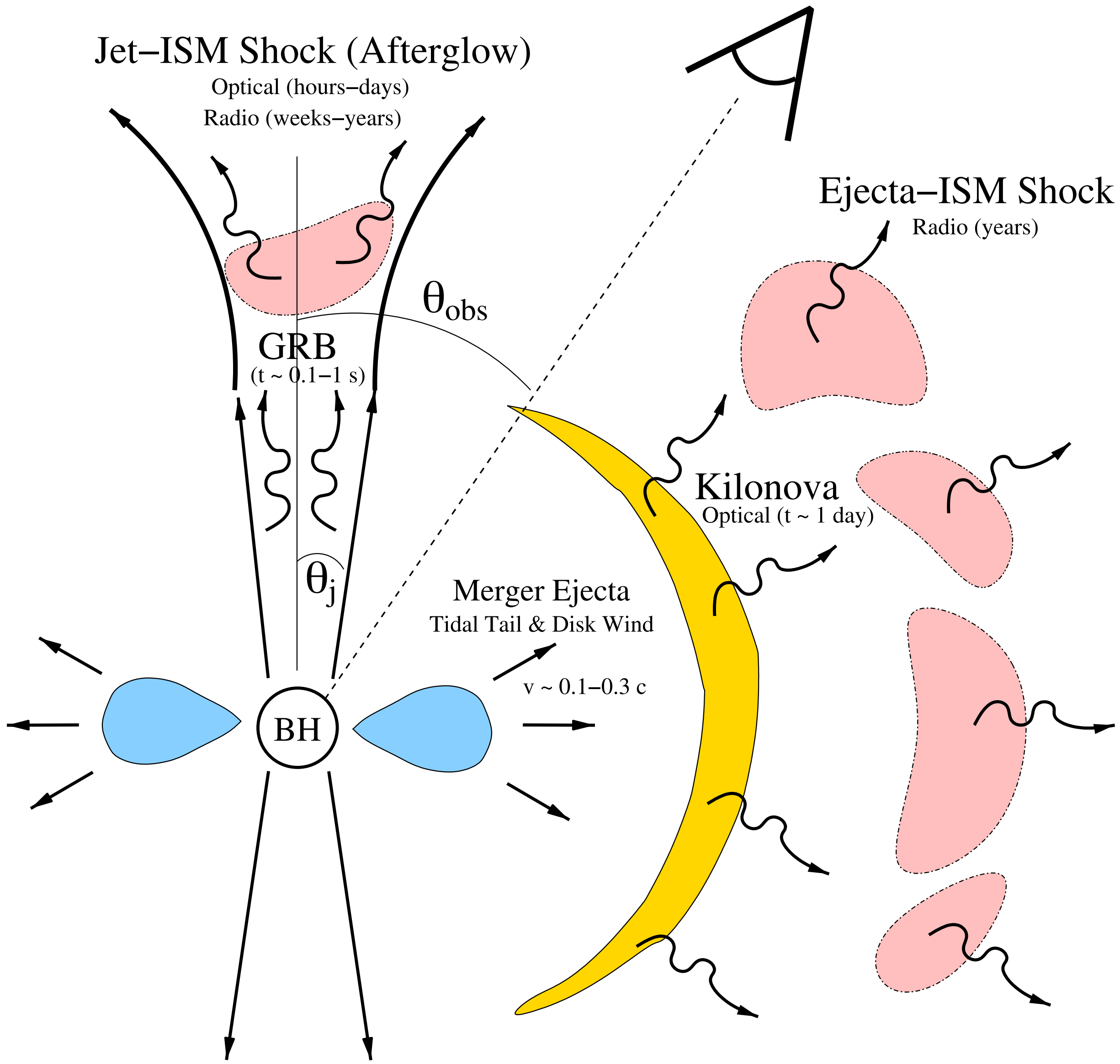


Gompertz+ 2014

- *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

EM counterparts to BNS mergers



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What is a promising EM counterpart?

	bright	isotropic	long lasting	high fraction	smoking gun for BNS
SGRBs	✓	✗	✗	✗	✗
standard afterglows	✗	✗	✓	✗	✗
non-standard X-ray afterglows	✓	✓	✓	?	?
dynamical ejecta, ISM	✗	✗	✓	✓	✗
kilonovae	✓	✓	✓	✓	✗

EM counterparts from BNS merger remnants

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

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

baryon pollution due to dynamical ejecta, neutrino and magnetically driven winds

Phase II (Pulsar 'ignition' and pulsar wind shock):

once baryon pollution suppressed positronic pulsar wind drives strong shock through ejecta

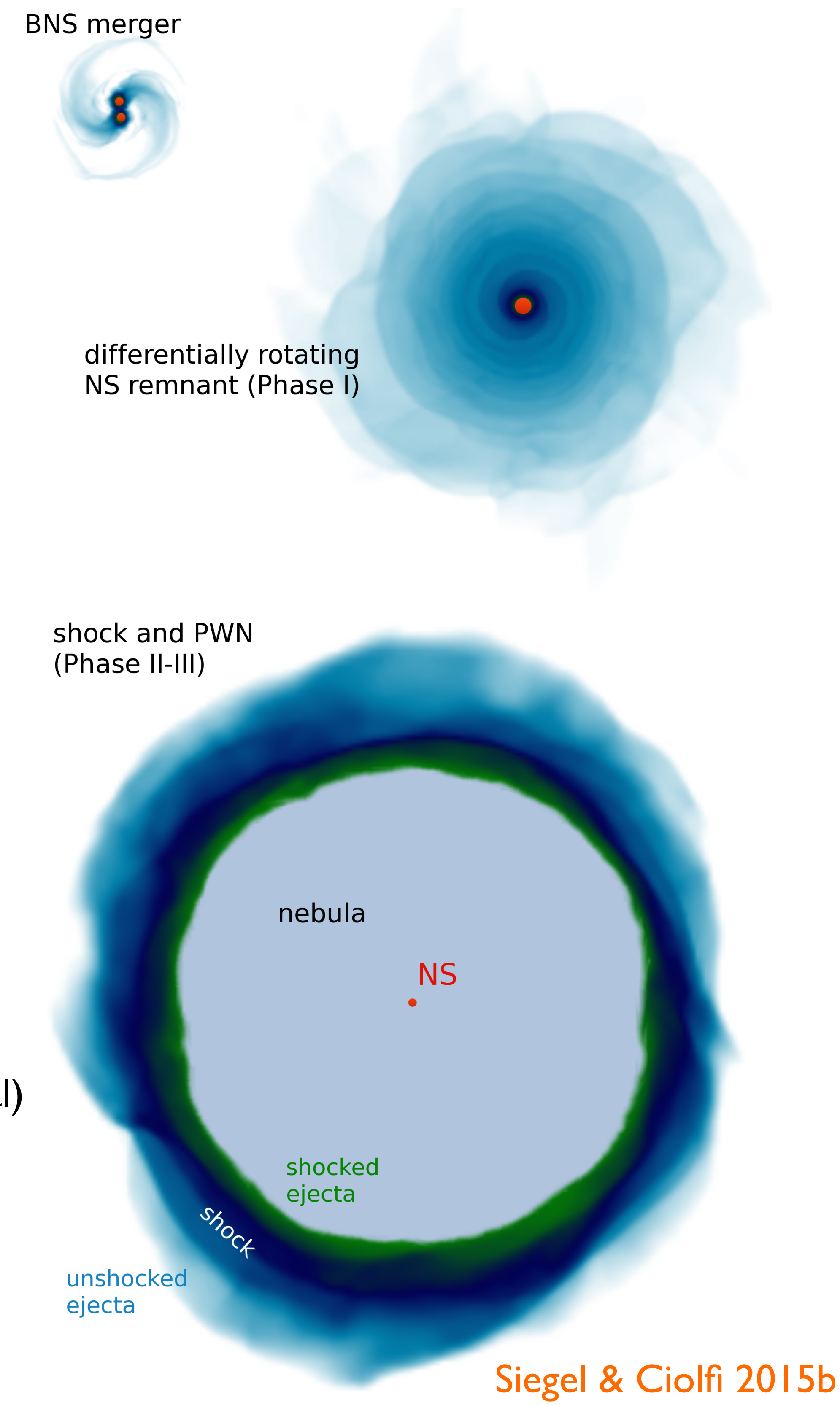
Phase III (Pulsar wind nebula phase):

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

Crab nebula (optical)

- NS can collapse to a BH at any time
- can accommodate standard and time-reversal scenario
- EM emission: reprocessed spin-down energy

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



Siegel & Ciolfi 2015b

EM counterparts from BNS merger remnants

Phase I:

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

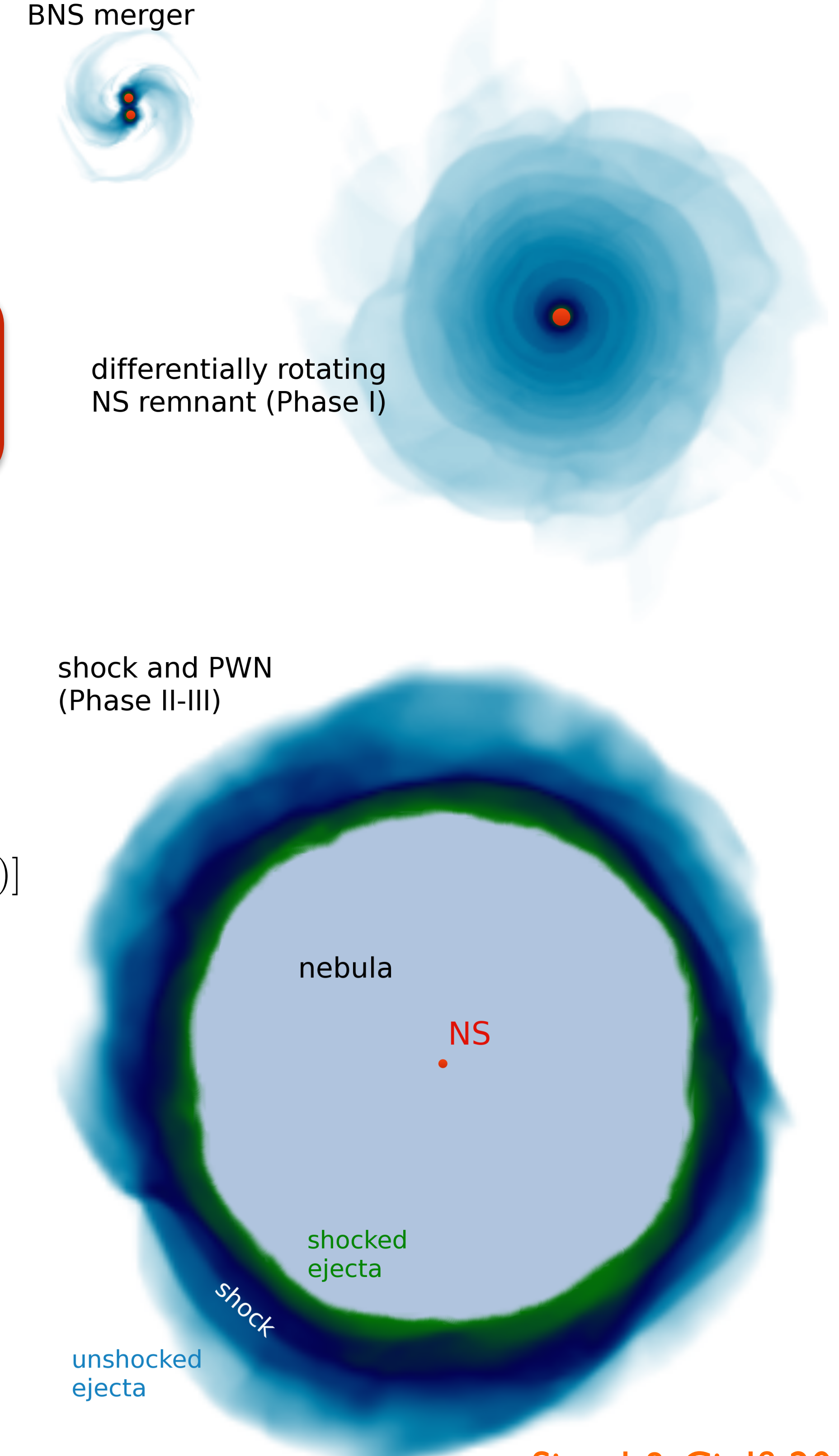
Phase II:

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

Phase III:

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

set of coupled ODEs



Siegel & Ciolfi 2015b

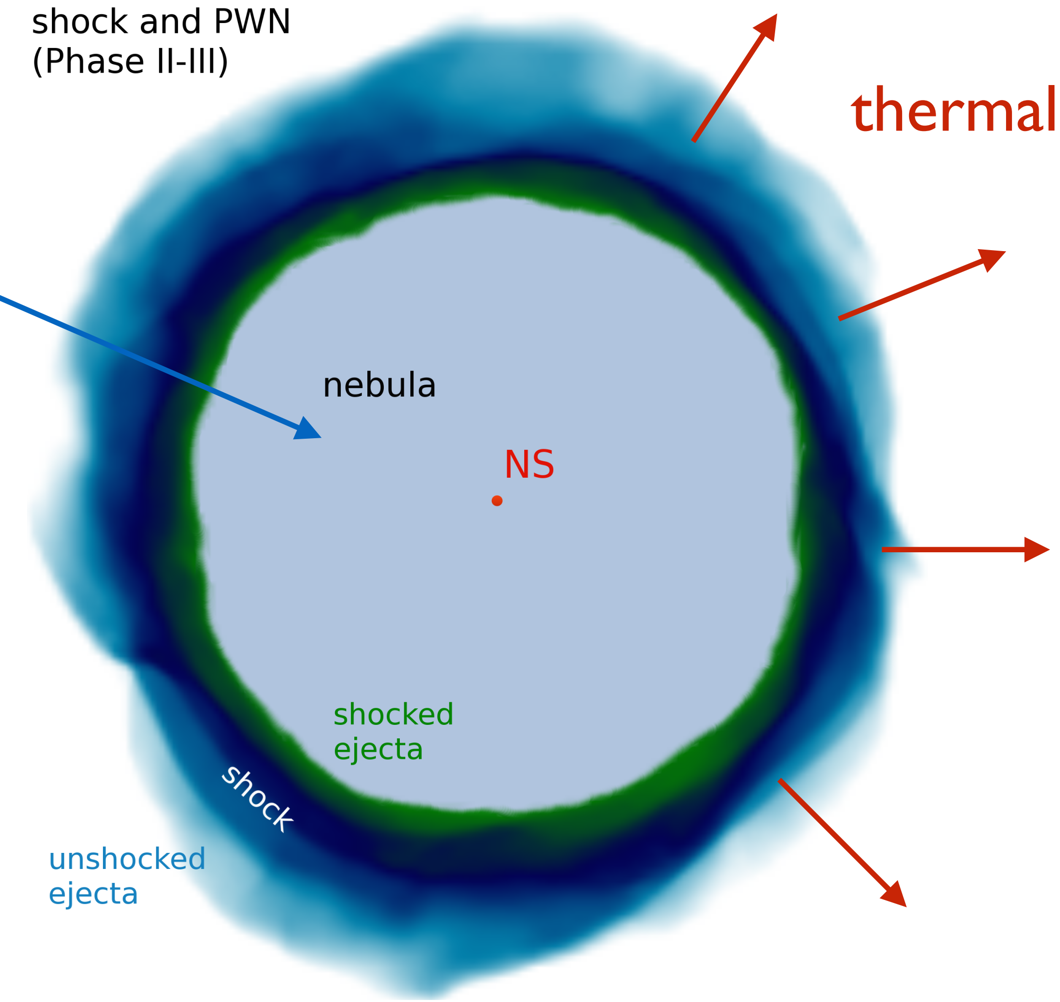
EM counterparts from BNS merger remnants

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 2015b

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

EM counterparts from BNS merger remnants

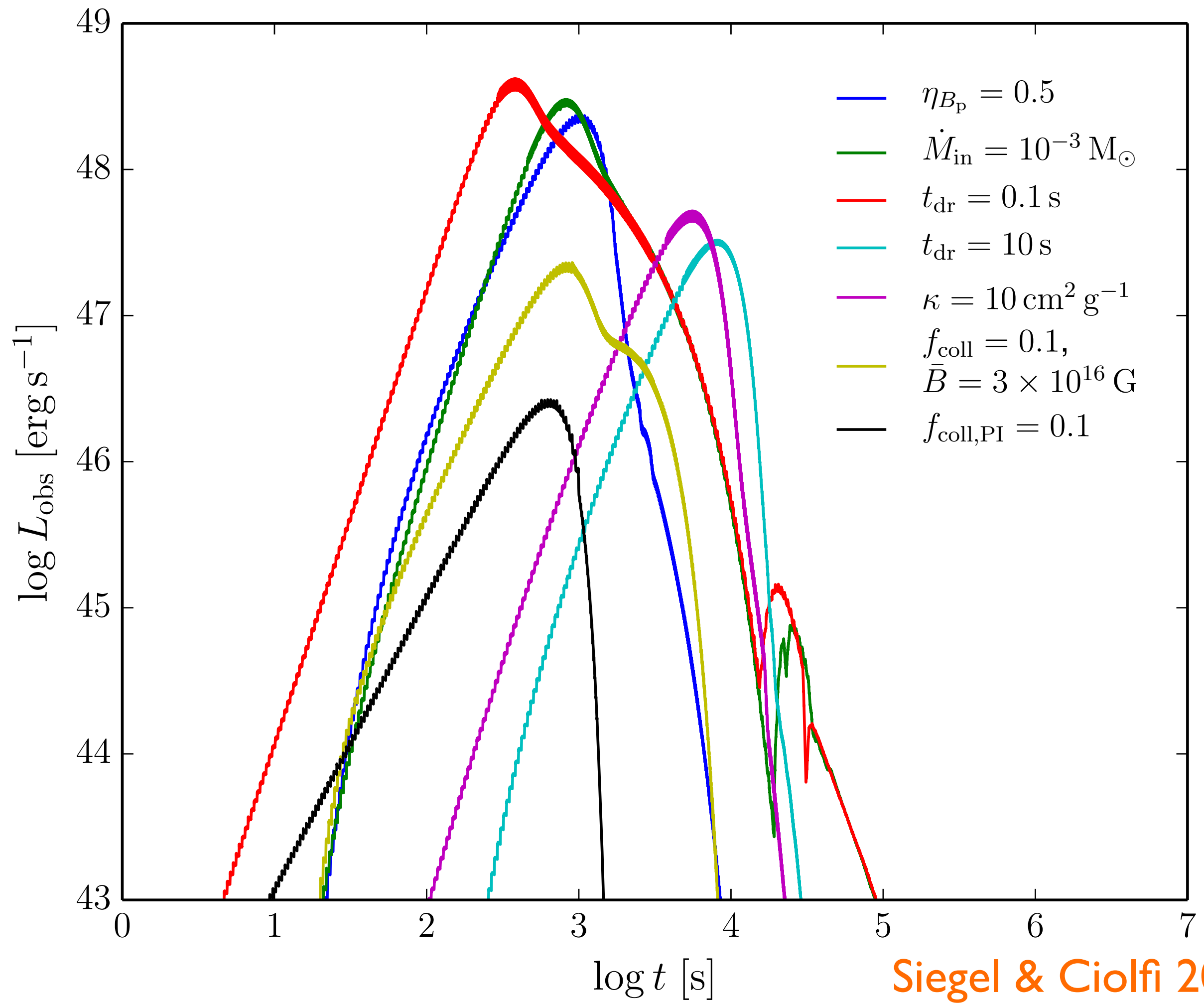


Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for standard scenario (SGRB at merger)

- 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})

→ 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	✗	✗	✓	✗	✗
non-standard X-ray afterglows	✓	✓	✓	✓ !	✓ !
dynamical ejecta, ISM	✗	✗	✓	✓	✗
kilonovae	✓	✓	✓	✓	✗

⟶ according to the model: non-standard X-ray afterglows represent ideal EM counterpart

In the time-reversal scenario…

Ciolfi & Siegel 2015a

1st plateau:

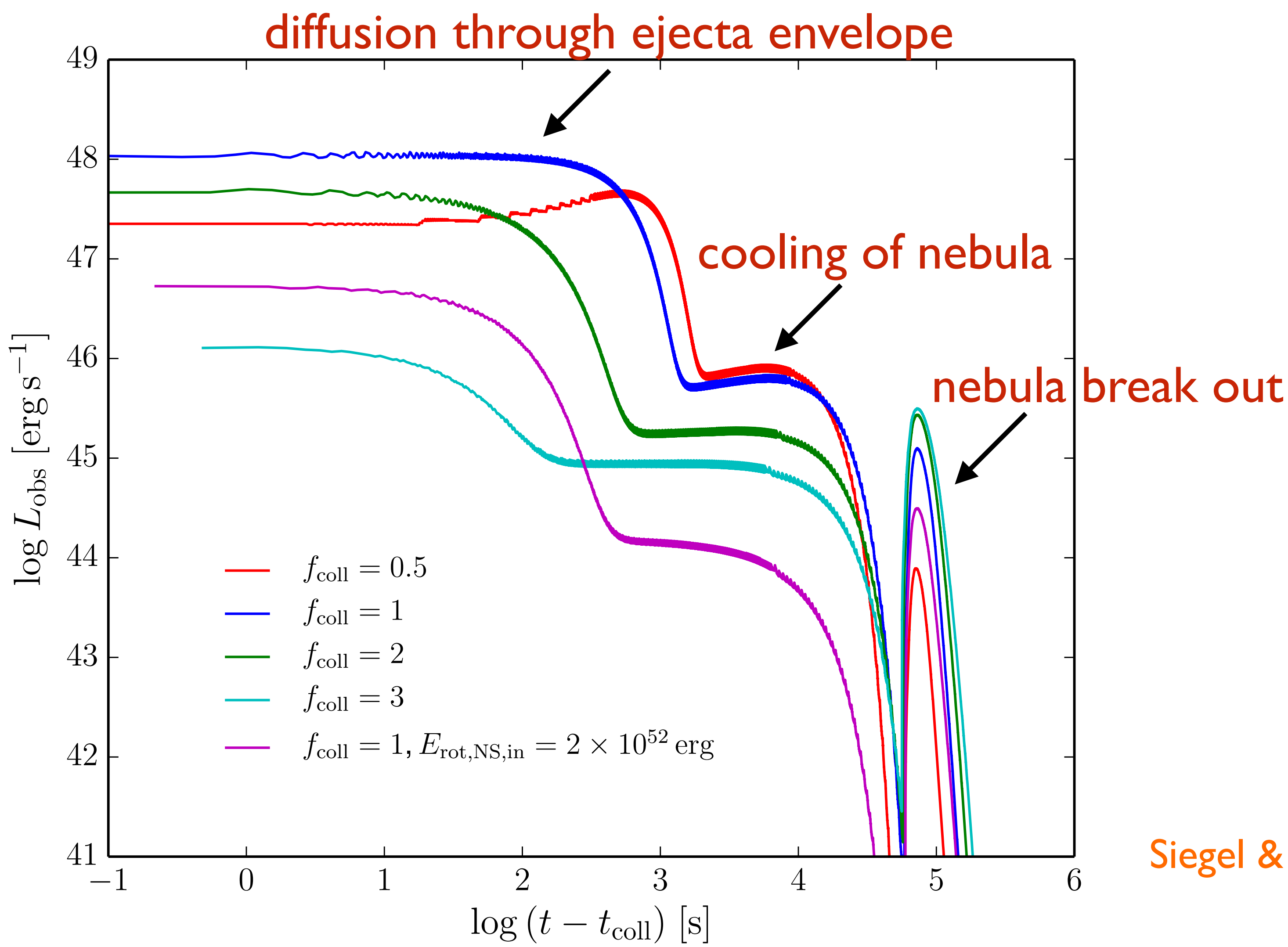
~10^2s

$L_X \sim 10^{46}$–10^{48} erg/s

2nd plateau:

~10^3–10^4 s

$L_X \sim 10^{44}$–10^{46} erg/s

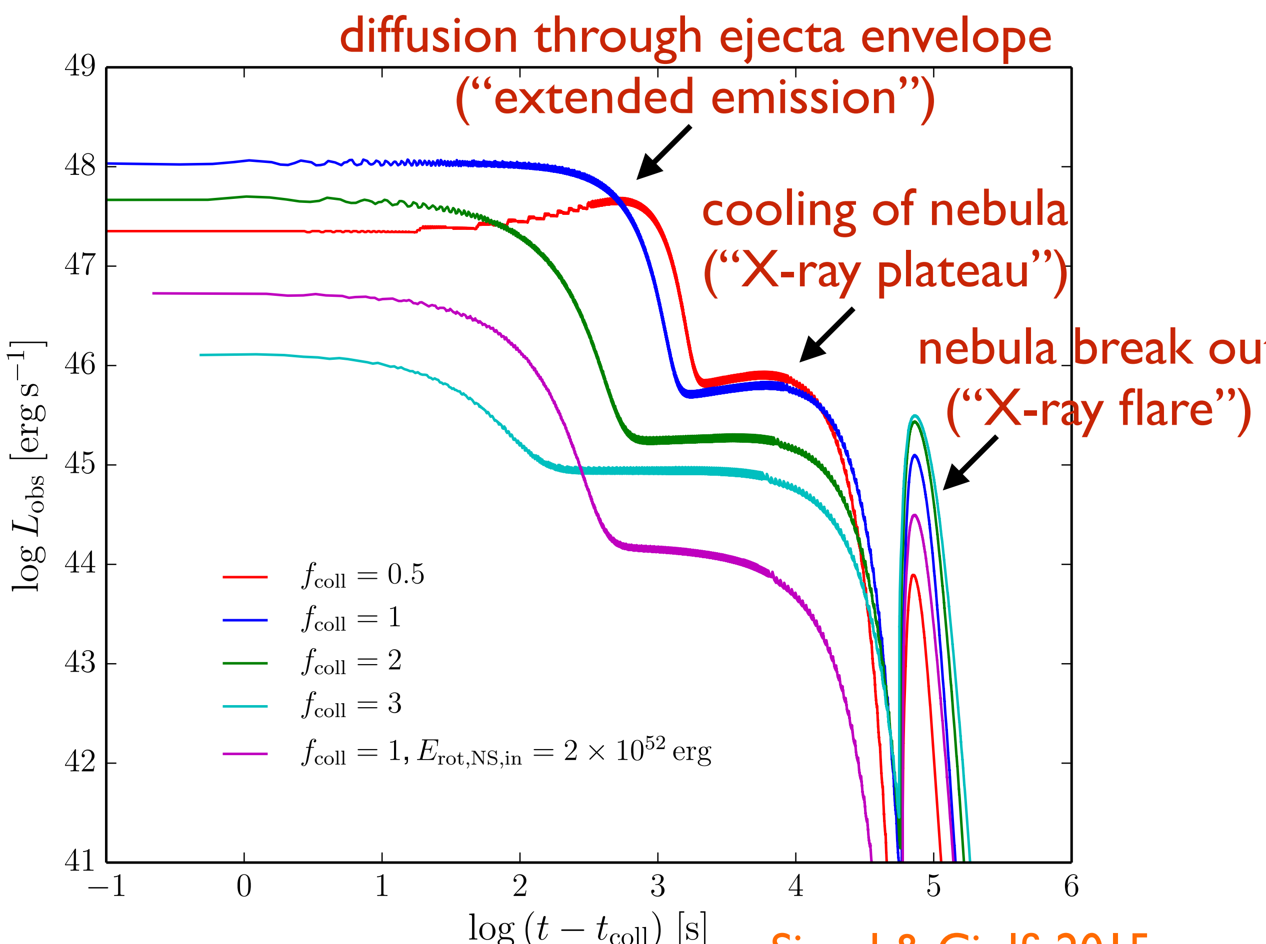


Siegel & Ciolfi 2015c

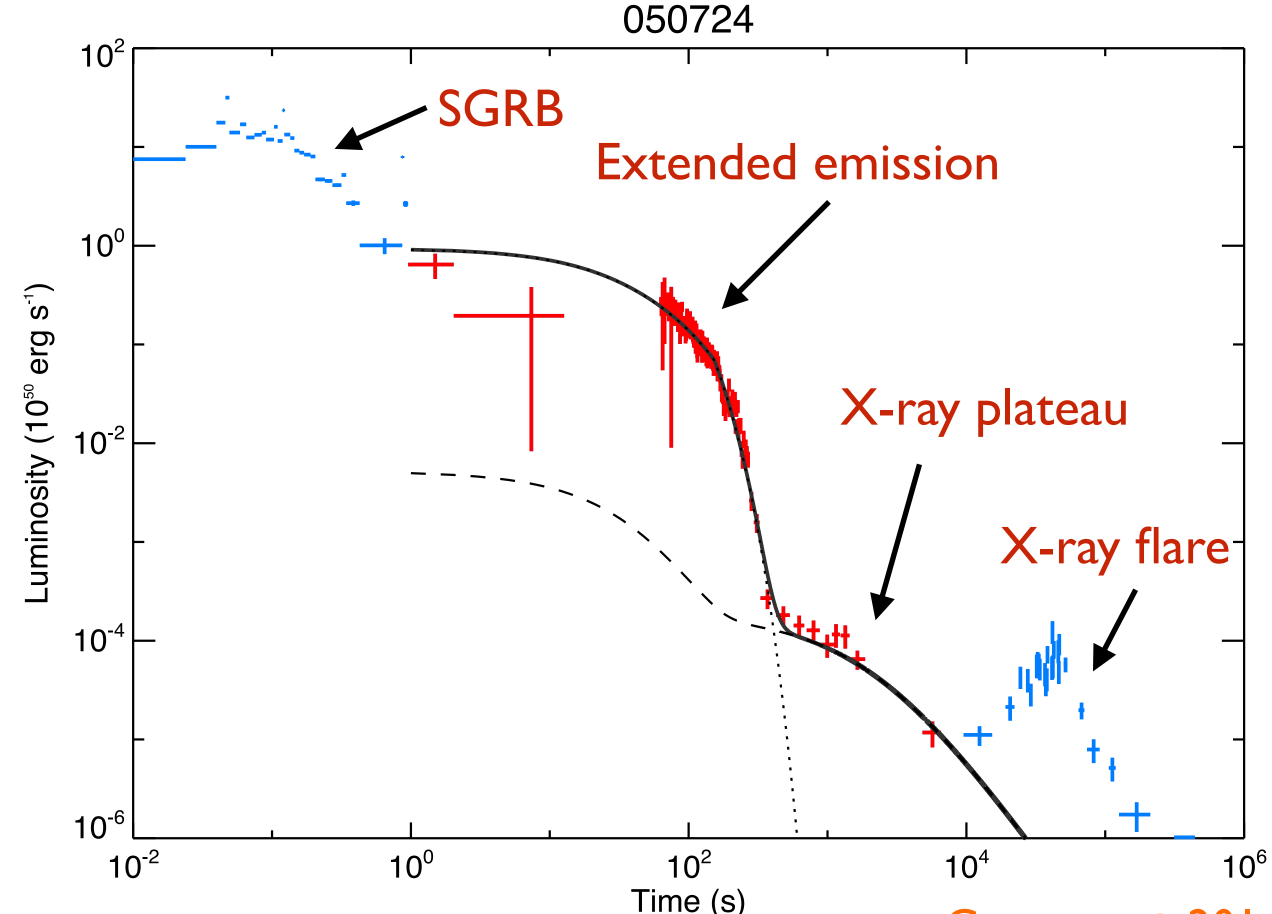
Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for time-reversal scenario (SGRB at collapse of NS)

- 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

Conclusions

- Proposed phenomenology and detailed numerical model for a large fraction of BNS mergers
  - ⟶ general model to compute broad band EM emission (radio to gamma rays) from post-merger system
  - ⟶ bridges the gap between numerical relativity simulations and the observational timescales of afterglows
  - ⟶ reveals a promising counterpart for GW astronomy
  - ⟶ combined with time-reversal scenario yields natural explanation for X-ray afterglows of SGRBs in a common phenomenology
  - ⟶ makes very specific predictions that can be tested observationally

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

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