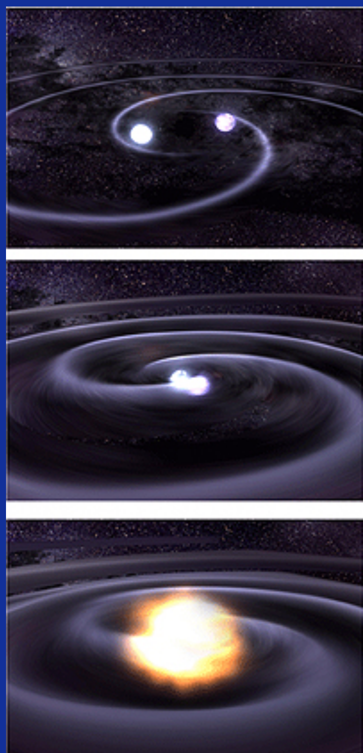
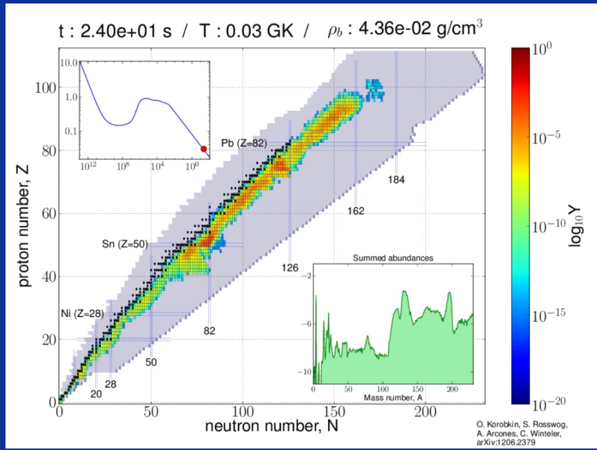
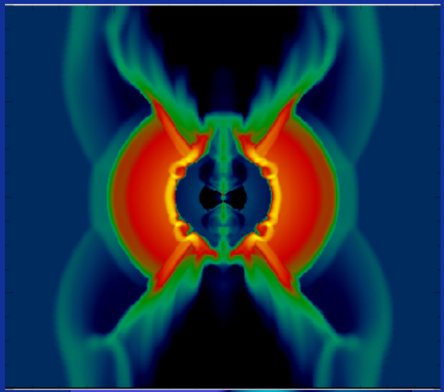
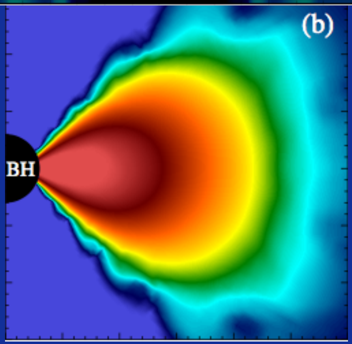
Multi-Messenger Signatures of the R-Process









Brian Metzger

Columbia University

In Collaboration with

Rodrigo Fernandez, Eliot Quataert, Geoff Bower, Dan Kasen (UC Berkeley)
Andrey Vlasov (Columbia), Almudena Arcones, Gabriel Martinez-Pinedo (Darmstadt)
Edo Berger, Wen-Fai Fong (Harvard), Tony Piro, Dan Perley (Caltech)
Dimitrios Giannios (Purdue), Shunsaku Horiuchi (VA Tech)

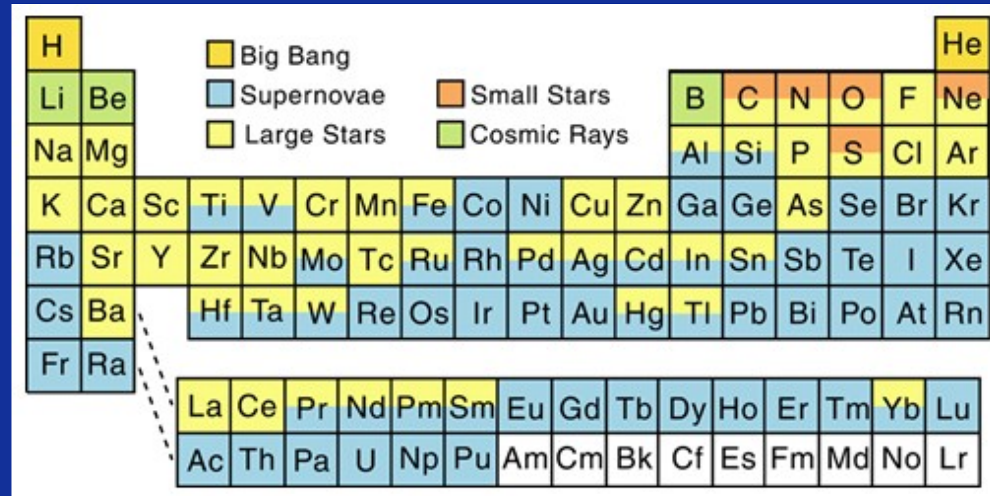
Institute for Nuclear Theory R-Process Workshop, August 1, 2014

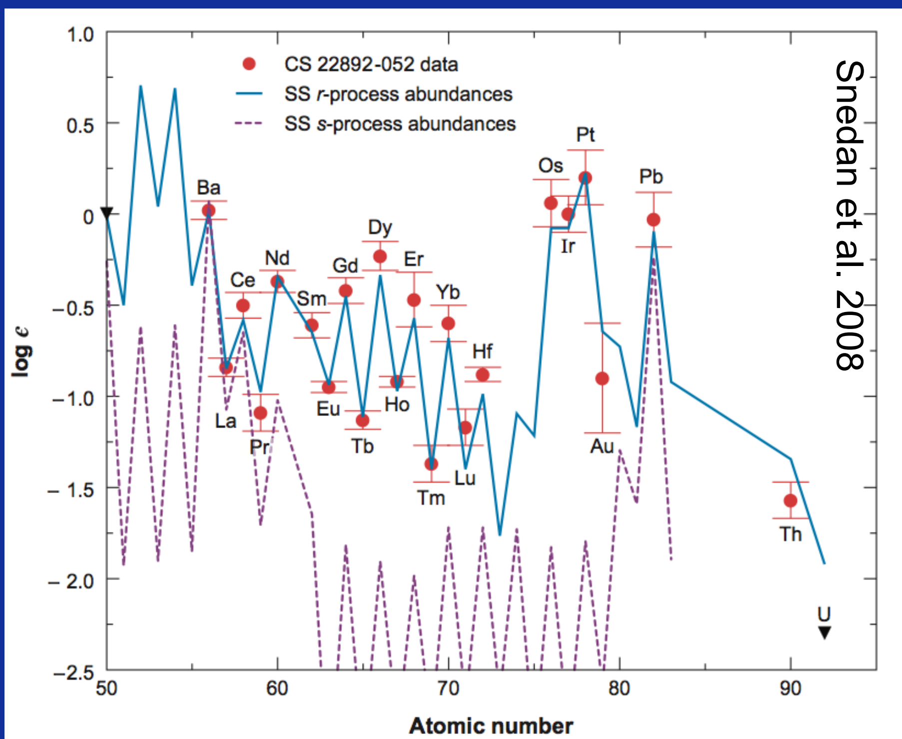
Where, Oh Where Has the R-Process Gone?

Galactic r-process rate:

$$\dot{M}_{A>130} \sim 5 \times 10^{-7}\, M_{\odot}\ \mathrm{yr}^{-1}$$

(Qian 2000)





fractional contribution to the r-process

Mergers

$$f_{\mathrm{NSM}} \sim \left(\frac{\dot{N}_{\mathrm{NSM}}}{10^{-4}\ \mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-2}\ M_{\odot}}\right)$$

SNe

$$f_{\mathrm{SN}} \sim \left(\frac{\dot{N}_{\mathrm{SN}}}{10^{-2}\ \mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-4}\ M_{\odot}}\right)$$

Hypernovae (MHD SNe?)

$$f_{\mathrm{HNe}} \sim \left(\frac{\dot{N}_{\mathrm{HNe}}}{10^{-4}\ \mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-2}\ M_{\odot}}\right)$$

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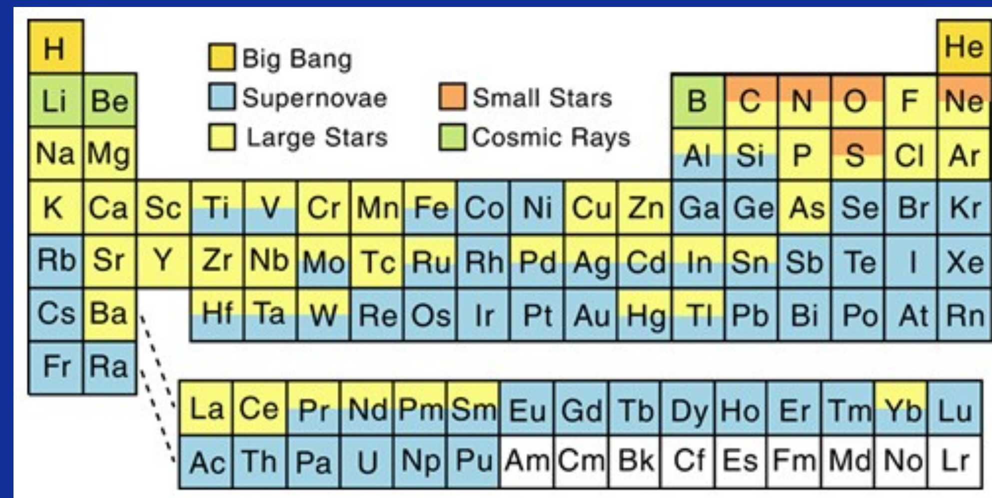

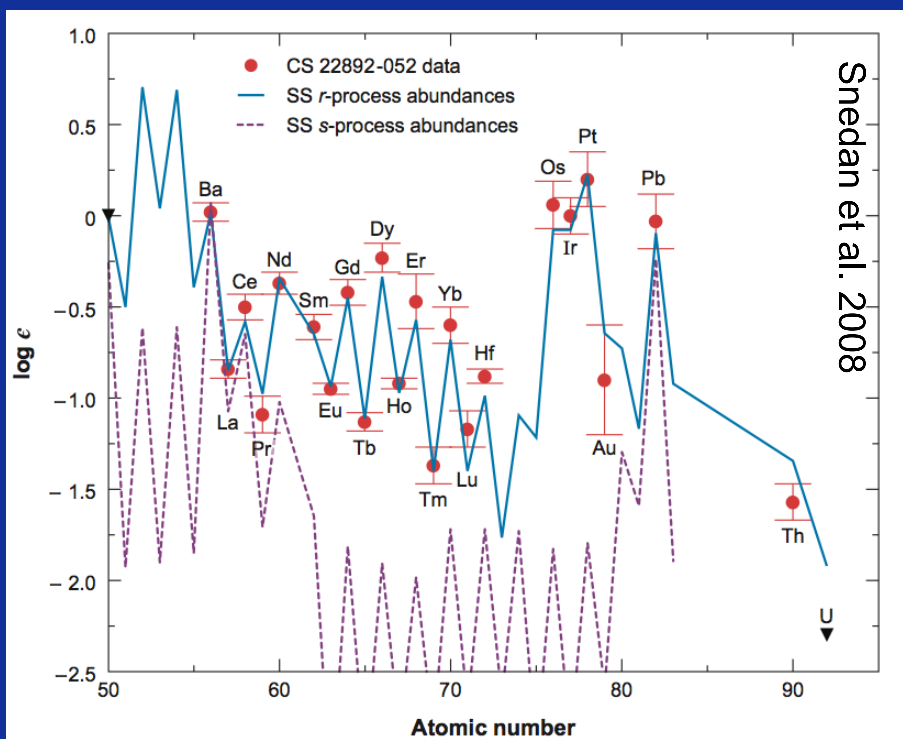

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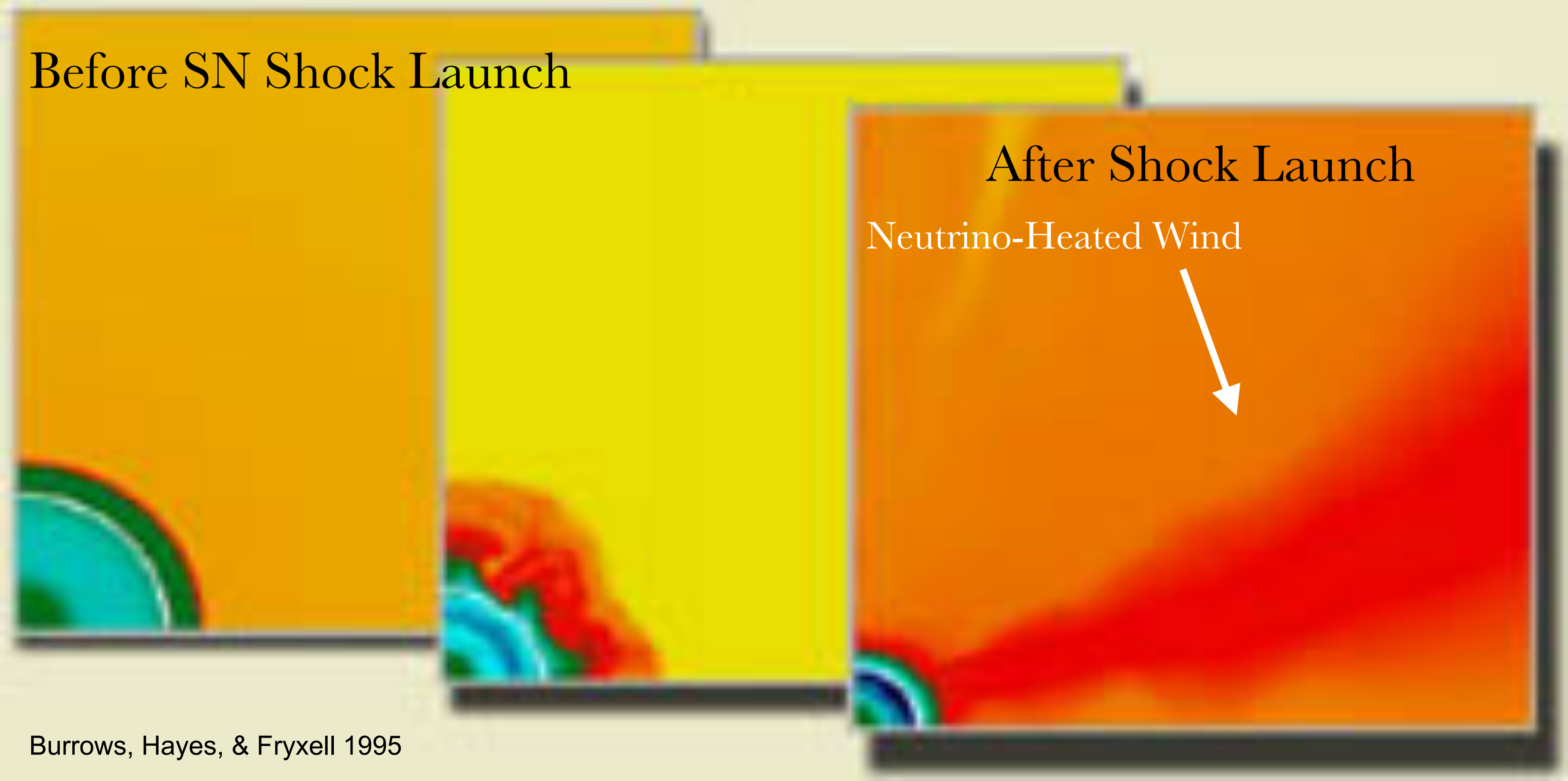
$$f_{\mathrm{HNe}} \sim \left(\frac{\dot{N}_{\mathrm{HNe}}}{10^{-4}\ \mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-2}\ M_{\odot}}\right)$$

Neutrino Driven Wind

Neutrinos heat proto-NS atmosphere (e.g. $\nu_e + n \Rightarrow p + e^-$)

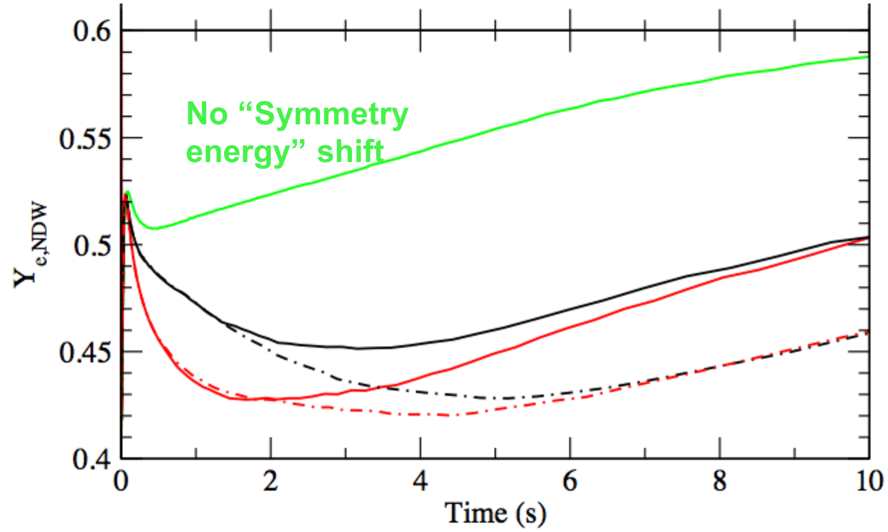
$\Rightarrow$ **drives outflow behind outgoing supernova shock** **(e.g. Qian & Woosley 96)**



Burrows, Hayes, & Fryxell 1995

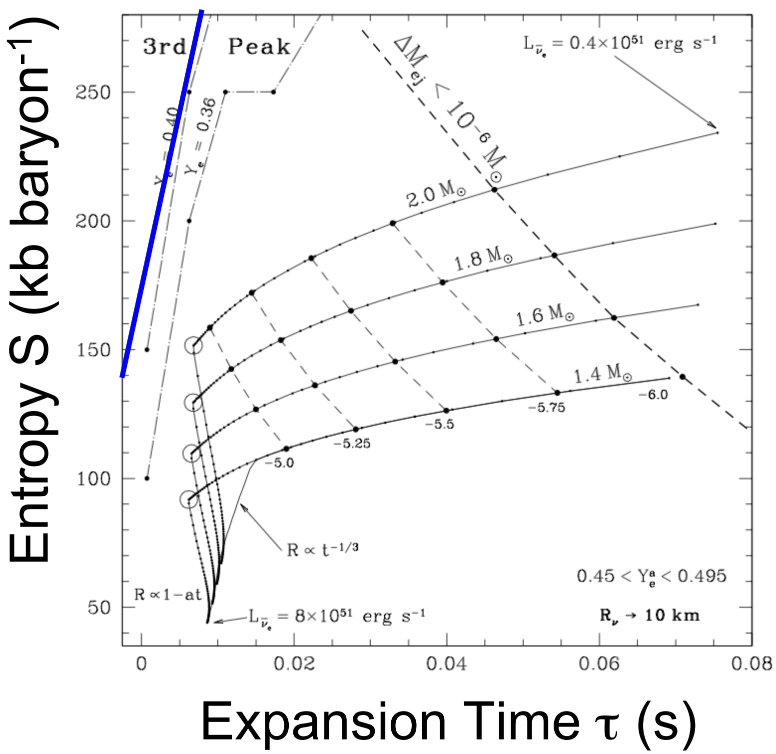
Conditions for Third Peak R-Process

$$Y_{e,\mathrm{NDW}} \approx \left[1 + \frac{\dot{N}_{\bar{\nu}_e} \langle \sigma(\epsilon)_{p,\bar{\nu}_e} \rangle}{\dot{N}_{\nu_e} \langle \sigma(\epsilon)_{n,\nu_e} \rangle}\right]^{-1}$$



Roberts et al. 2012 (see also Martinez-Pinedo et al. 2012)

1) need $Y_e < 0.5$



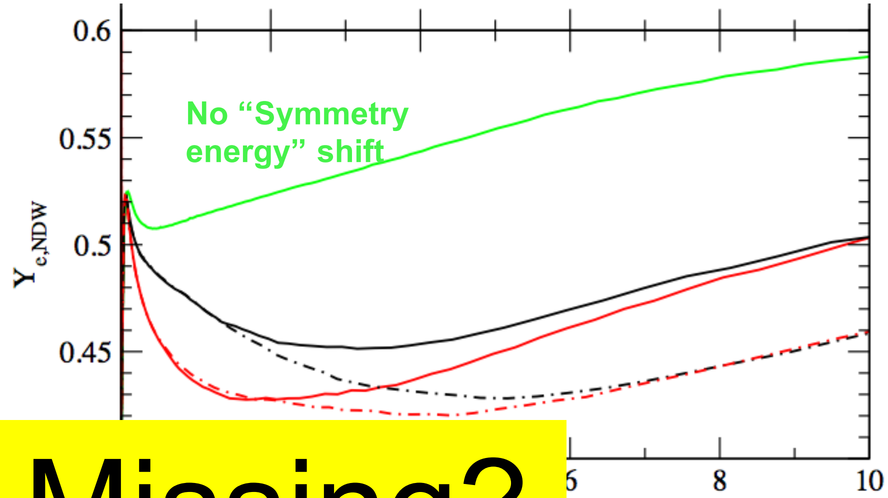
2) α-rich freeze-out of

$$^4\mathrm{He}(\alpha n,\gamma)^9\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$$

$$\frac{S^3}{Y_e^3 t_{\mathrm{exp}}} \gtrsim \eta_{\mathrm{thr}} \approx 8 \cdot 10^9 \left(k_B \mathrm{n}^{-1}\right)^3 s^{-1}$$

Conditions for Third Peak R-Process

$$Y_{e,\mathrm{NDW}} \approx \left[1 + \frac{\dot{N}_{\bar{\nu}_e}\langle\sigma(\epsilon)_{p,\bar{\nu}_e}\rangle}{\dot{N}_{\nu_e}\langle\sigma(\epsilon)_{n,\nu_e}\rangle}\right]^{-1}$$



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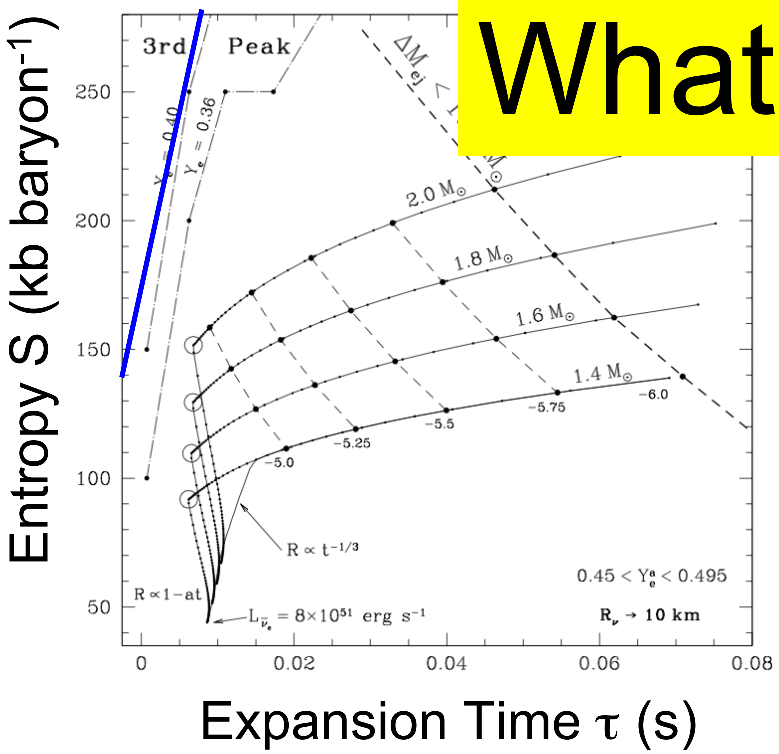


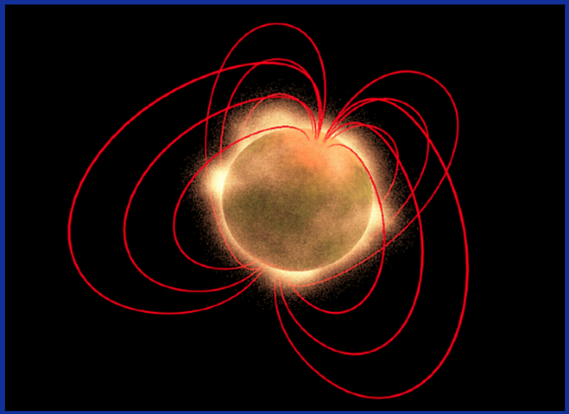
What is Missing?

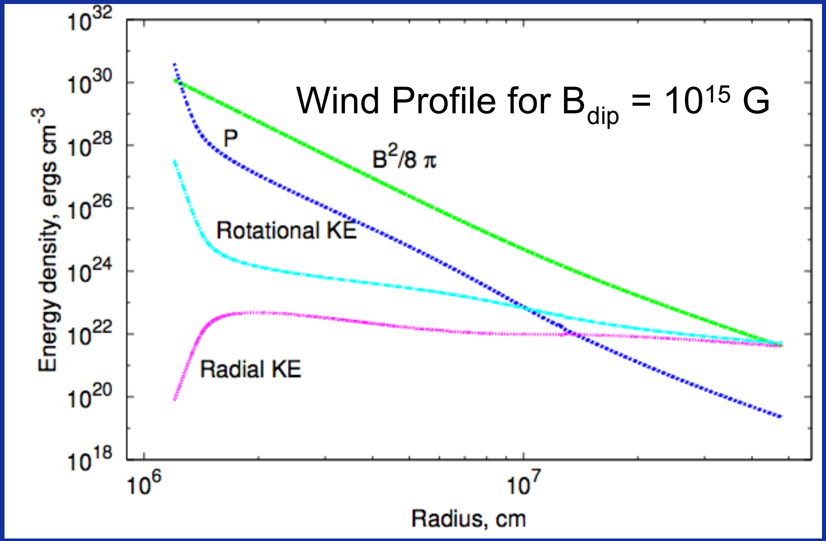
2) α-rich freeze-out of

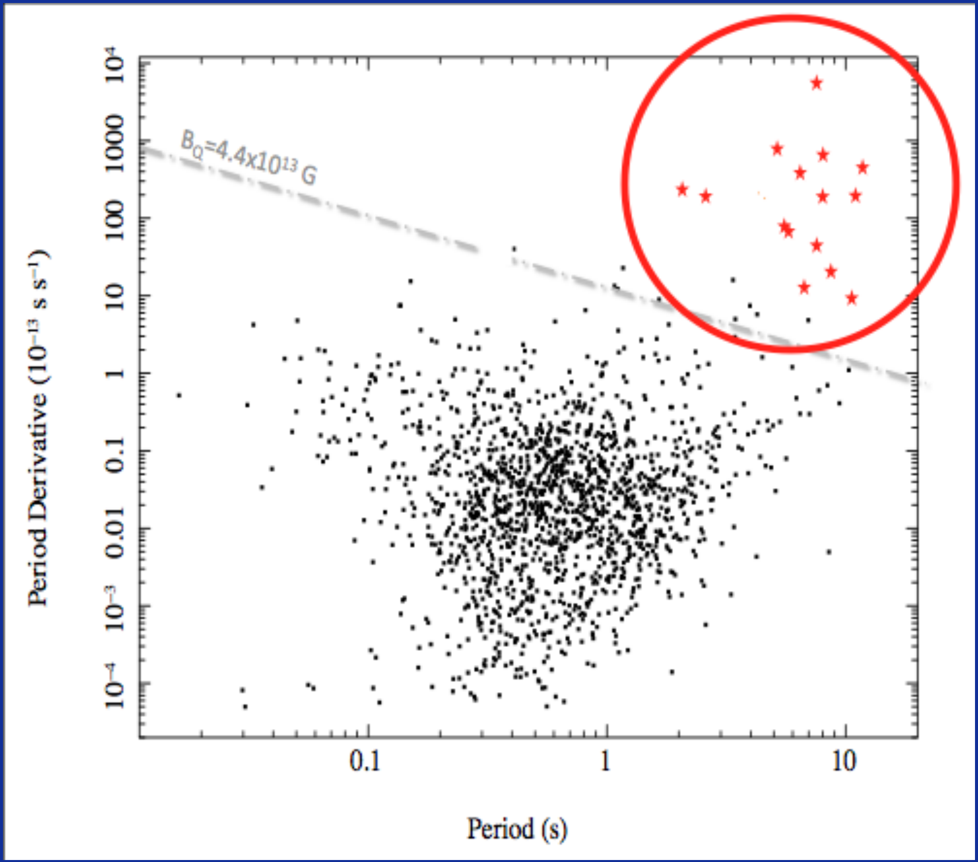
$$^{4}\mathrm{He}(\alpha n,\gamma)^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$$

$$\frac{S^3}{Y_e^3 t_{\mathrm{exp}}} \gtrsim \eta_{\mathrm{thr}} \approx 8\cdot 10^9 \left(k_B \mathrm{n}^{-1}\right)^3 s^{-1}$$

Magnetars







- Dipole field B ~ 10^{14}-10^{15} G
- Spin periods ~ 3-10 s (birth periods unconstrained)
- Birthrate ~10% CC-SNe (massive progenitors > 40 $M_{\odot}$)

Are Magnetars Born Rapidly Spinning?

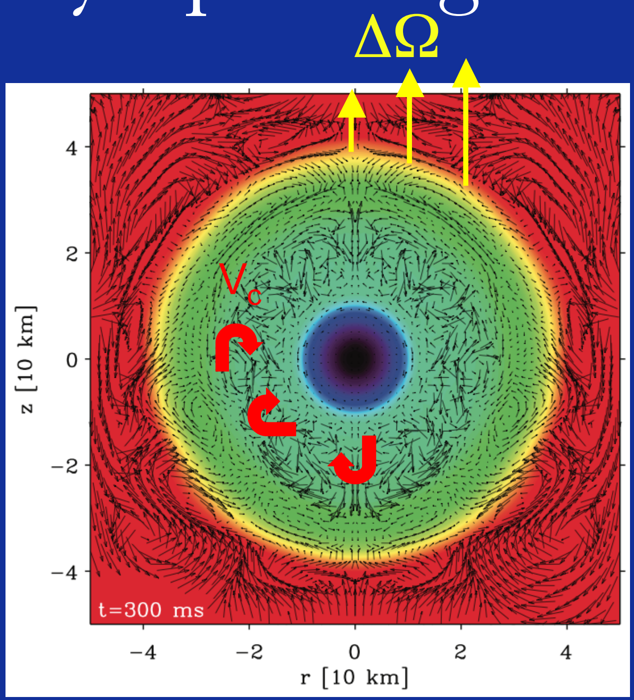
rotational energy

$$E_{rot} = \frac{1}{2} I\Omega^2 \sim 3\times 10^{51} \left(\frac{P}{3\ \mathrm{ms}}\right)^{-2} \mathrm{ergs}$$

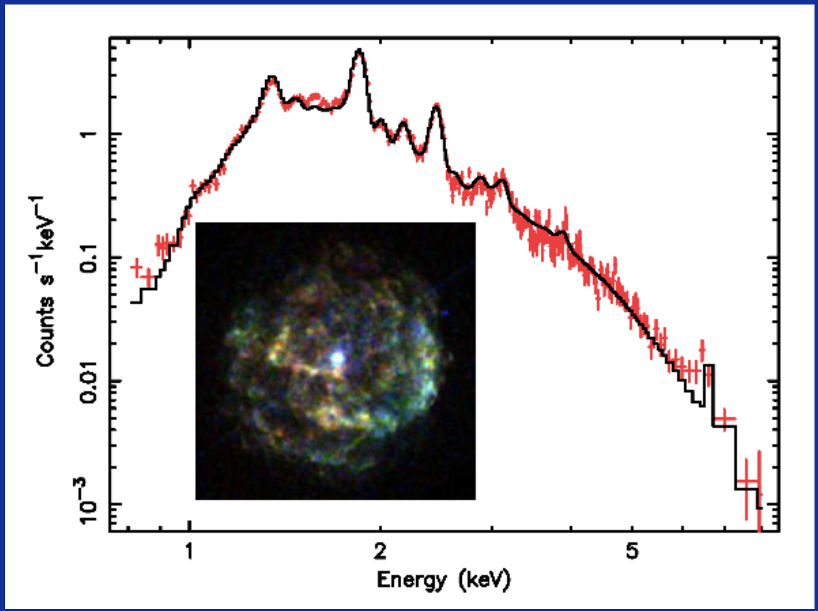
$$\Delta E_{rot} = \frac{B^2}{8\pi} \times \frac{4\pi}{3} R_{ns}^3 \quad \Rightarrow \quad B_{eq} \sim 10^{16} \left(\frac{\Delta\Omega}{\Omega/2}\right)^2 \left(\frac{P}{3\ \mathrm{ms}}\right)^{-2} \mathrm{G}$$

Field amplification via MRI or convective dynamo

(Thompson & Duncan 1993)



Dessart et al. 2006



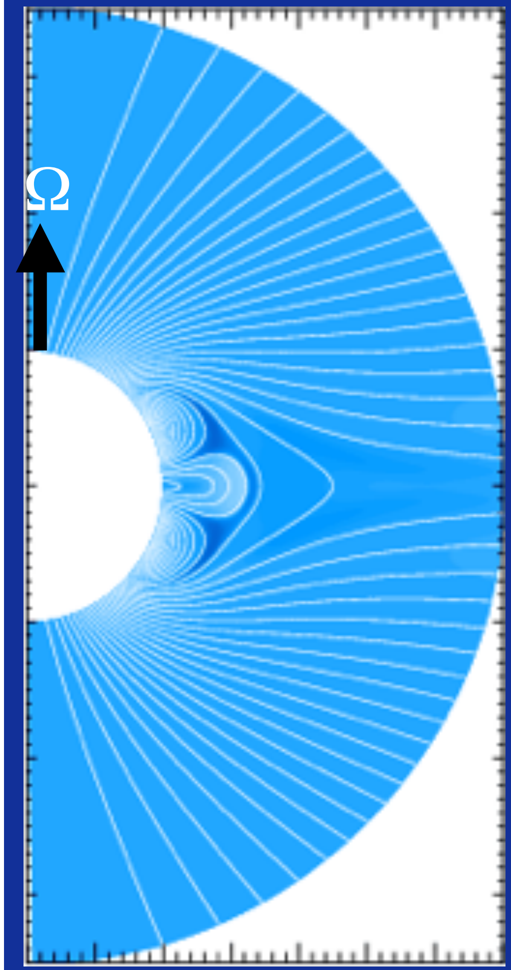
Vink & Kuiper 2006

SNR/Pulsar	Distance (kpc)	radius (pc)	E (10^{51} erg)
Kes 73/1E1841−045	7.0	4.3	0.5 ± 0.3
CTB109/1E2259+586	3.0	10	0.7 ± 0.3
N49/SGR 0526−66	50	9.3	1.3 ± 0.3

$\Rightarrow P_0 > 4$ ms

Effects of Strong Magnetic Fields

“Helmet - Streamer”



- Microphysics (EOS, ν Heating & Cooling)
  - Important for $B \geq 10^{16}$ G (Duan & Qian 2005)

Effects of Strong Magnetic Fields

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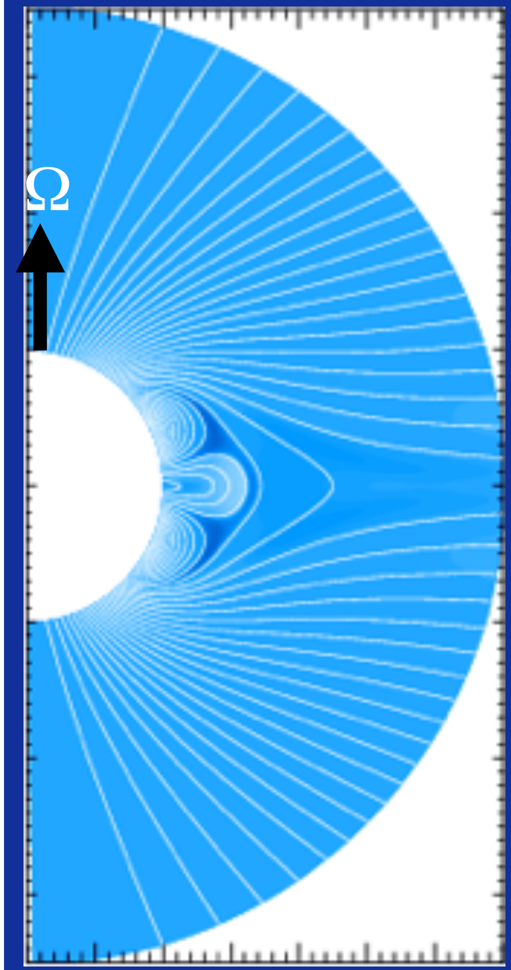


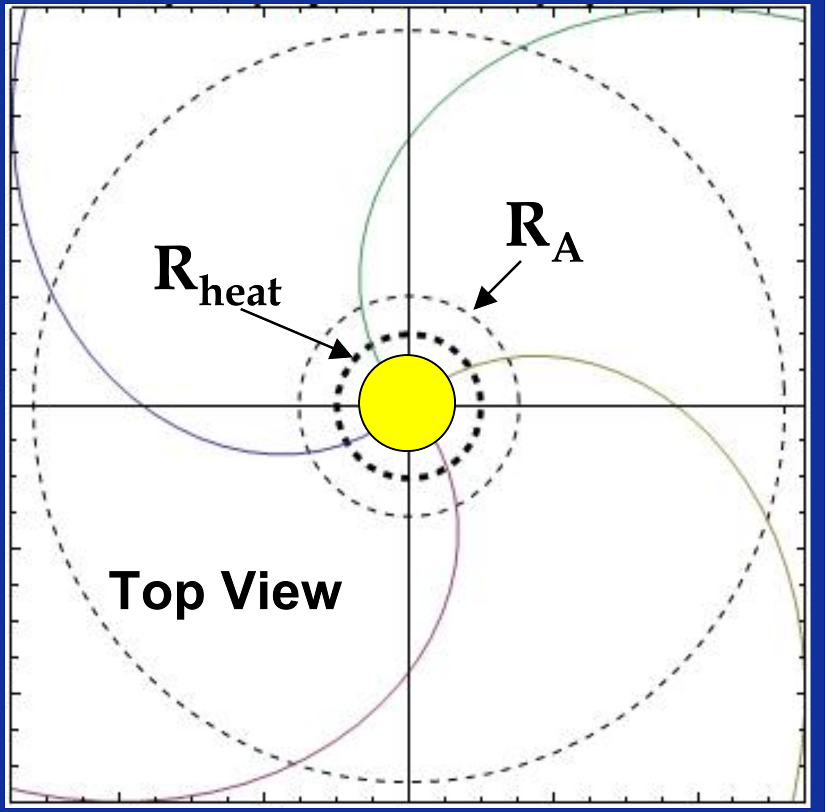
- Microphysics (EOS, ν Heating & Cooling)
  - Important for $B \geq 10^{16}$ G (Duan & Qian 2005)
- Magneto-Centrifugal Slinging
  (Weber & Davis 1967; Thompson, Chang & Quataert 2004)

Outflow Co-Rotates with Neutron Star when

$$B^2/8\pi > 1/2\,\rho\, v_r^2$$

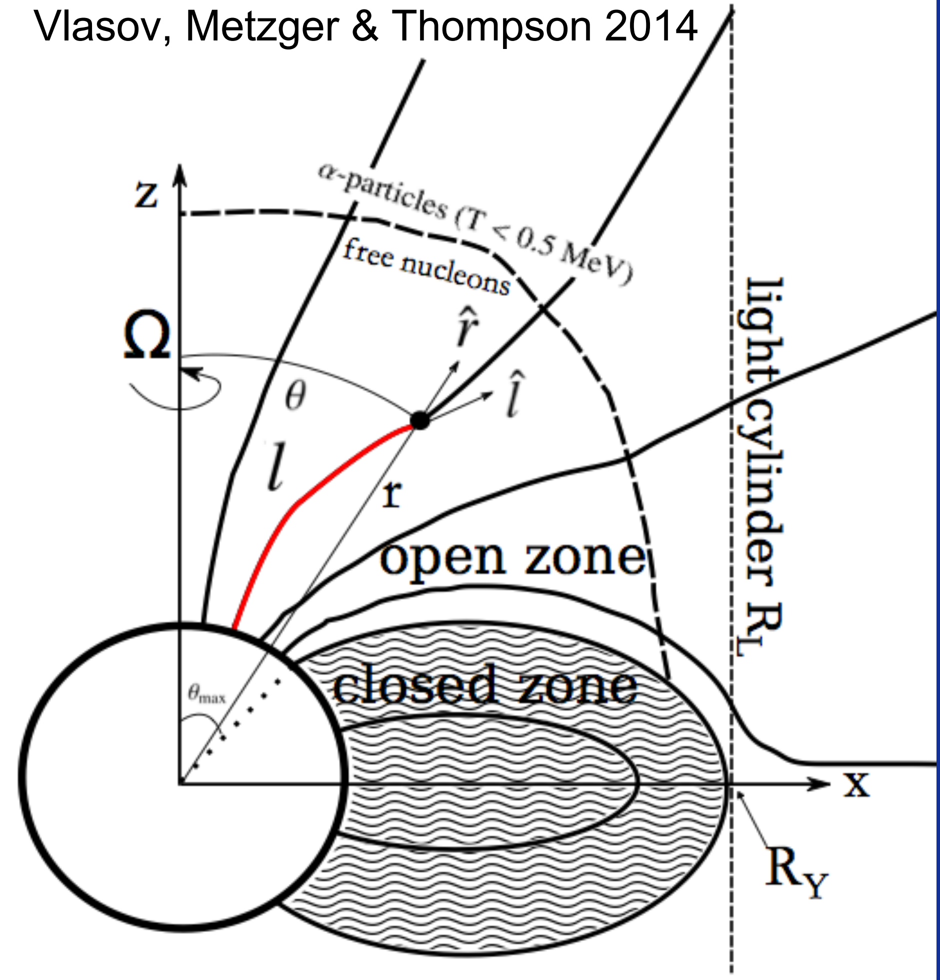
⇒

Magneto-Centrifugal Acceleration ("Beads on a Wire")

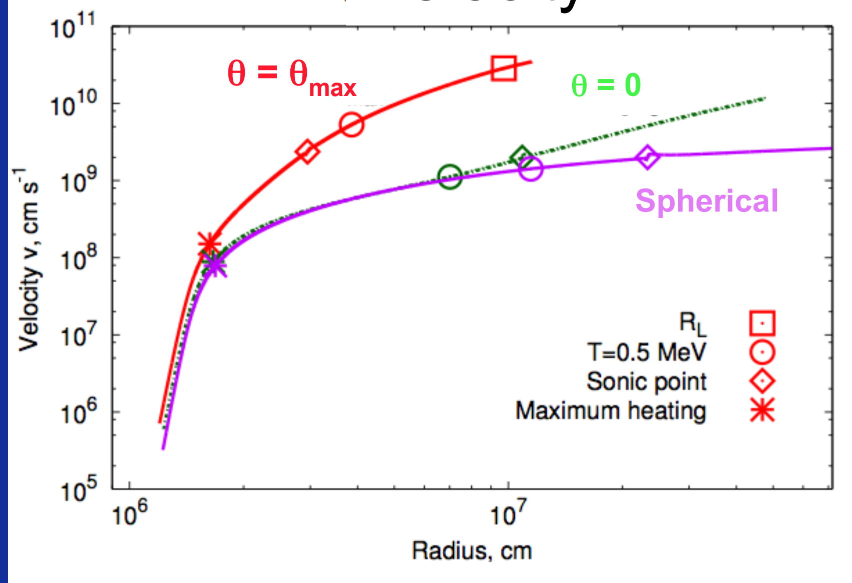


Neutrino Winds from Rotating Proto-Magnetars

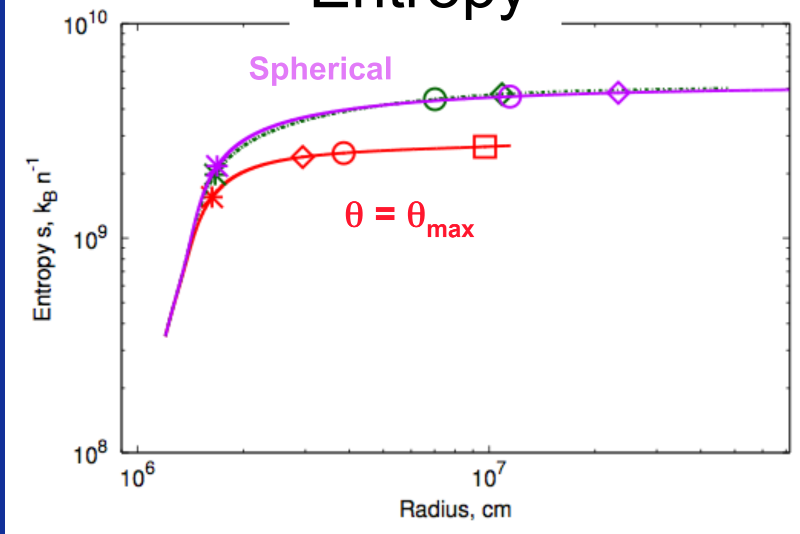
Vlasov, Metzger & Thompson 2014



Velocity

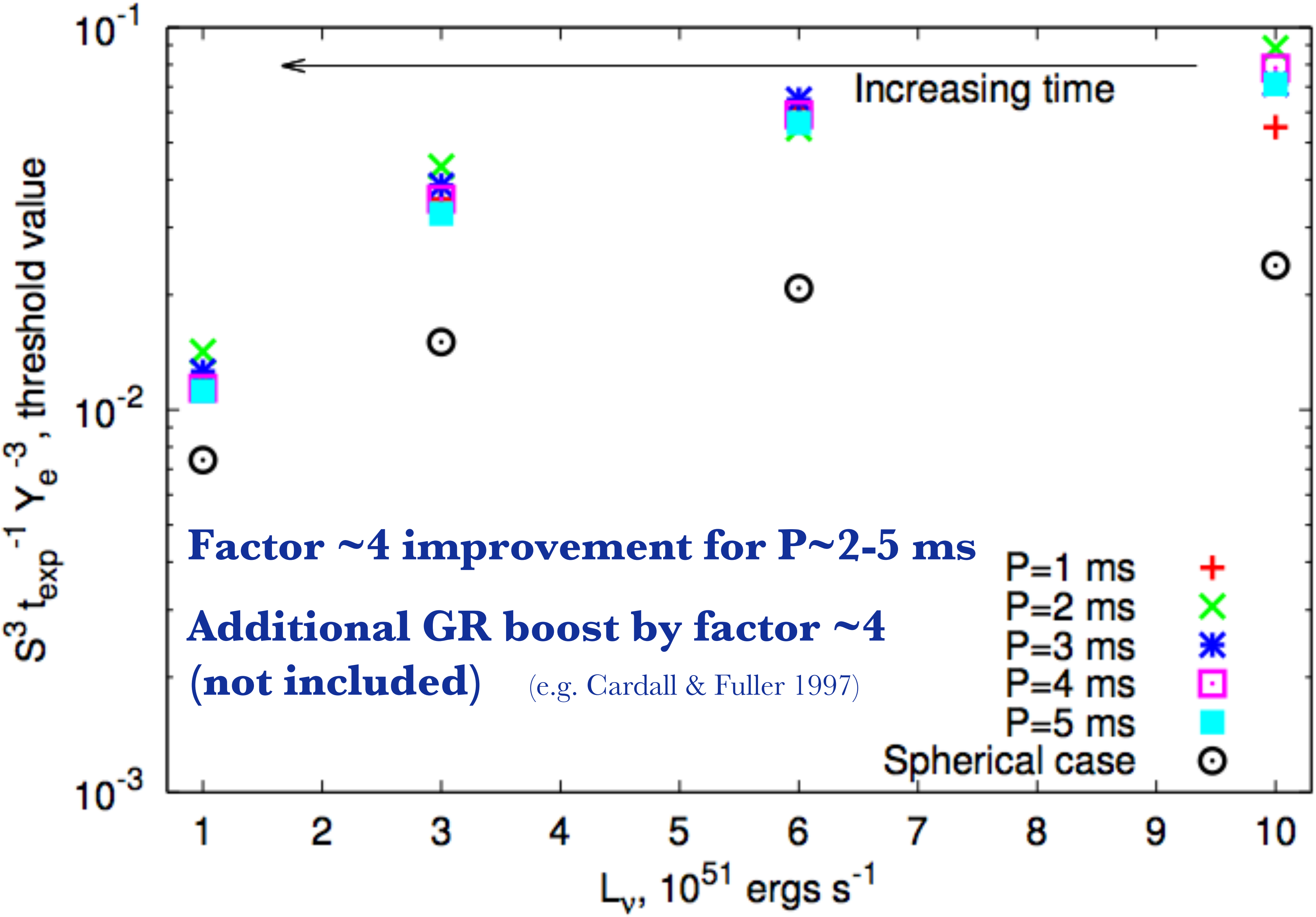


Entropy



Force-free magnetosphere: geometry depends on spin period P, but not on B-field strength

M = 1.4 $M_{\odot}$, R = 12 km



Factor ~4 improvement for P~2-5 ms

Additional GR boost by factor ~4 (not included) (e.g. Cardall & Fuller 1997)

Vlasov, BDM, Thompson

Moderately-Rapidly Rotating Proto-Magnetars as R-Process Source

- Required ejecta mass per event

$$\bar{M}_{\rm ej} = \frac{\dot{M}_{\rm r}}{f_{\rm r}\mathcal{R}} \approx 1.5\times 10^{-3} M_{\odot}\left(\frac{f_{\rm r}}{0.1}\right)^{-1}\left(\frac{\mathcal{R}}{0.1\mathcal{R}_{\rm CC}}\right)^{-1}$$

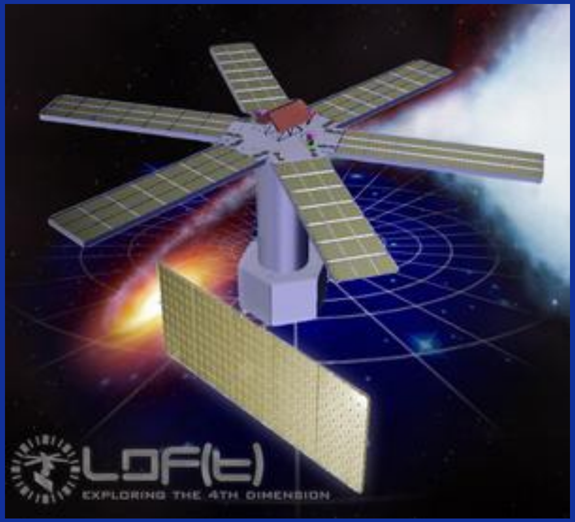
- Magnetars have massive progenitor stars
  $\Rightarrow$ more massive proto-NS $\Rightarrow$ higher S^3/τ.
- Birth periods P > 4 ms consistent with energetics of magnetar supernova remnants.
- Rapidly rotating stars more prevalent early in chemical evolution of galaxy.
  - Growing evidence for super-luminous SNe powered by magnetars in low metallicity galaxies (e.g. Kasen & Bildsten 2010)
- Even if not dominant source, can nucleosynthesis constrain the birth periods of magnetars?

X-ray Decay Lines from R-Nuclei in SN Remnants

Ripley, BDM, Arcones & Martinez-Pinedo 2014 (see also Qian et al. 1998, 1999)

Supernova Remnants

Source	Parent[(a)]	ϵ_X[(b)]	$\langle \dot{N}_X \rangle A_X$[(c)]	$\nu_X A_X$[(d)]	$\mathcal{O}_X$[(e)]	$\mathcal{O}$[(f)]
		(keV)	(s^{-1})	(s^{-1})		
Vela Jr						27
	^{126}Sn	3.7*	1.64×10^{-4}	16.0	84	
	^{126}Sn	4.5*	2.51×10^{-5}	22.1	4.9×10^{2}	
	^{126}Sn	4.1*	2.12×10^{-5}	24.4	6.1×10^{2}	
Cas A						1.5×10^{2}
	^{126}Sn	3.7*	2.42×10^{-6}	0.111	3.6×10^{2}	
	^{126}Sn	4.5*	3.69×10^{-7}	0.154	2.8×10^{3}	
	^{126}Sn	4.1*	3.12×10^{-7}	0.170	3.5×10^{3}	
SN 1987A						1.4×10^{2}
	^{194}Os	10.7*	3.28×10^{-6}	6.48×10^{-2}	2.0×10^{2}	
	^{194}Os	9.2*	2.56×10^{-6}	7.58×10^{-2}	2.8×10^{2}	
	^{194}Os	10.9*	5.82×10^{-7}	6.35×10^{-2}	1.1×10^{3}	
SN 1006						2.1×10^{2}
	^{126}Sn	3.7*	1.03×10^{-5}	4.00	5.1×10^{2}	
	^{126}Sn	4.5*	1.57×10^{-6}	5.53	3.9×10^{3}	
	^{126}Sn	4.1*	1.32×10^{-6}	6.10	4.9×10^{3}	
3yrs, 10kpc						0.2
	^{194}Os	10.7*	3.95×10^{-3}	6.48×10^{-2}	0.20	
	^{194}Os	9.2*	3.08×10^{-3}	7.58×10^{-2}	0.20	
	^{194}Os	10.9*	6.99×10^{-4}	6.35×10^{-2}	1.0	



$$\mathcal{O} \equiv M^r / \langle M^r \rangle$$

Ave. mass per event

$$\langle M^r \rangle \approx \frac{X_\odot M_G \chi}{\mathcal{R} \tau_G}$$

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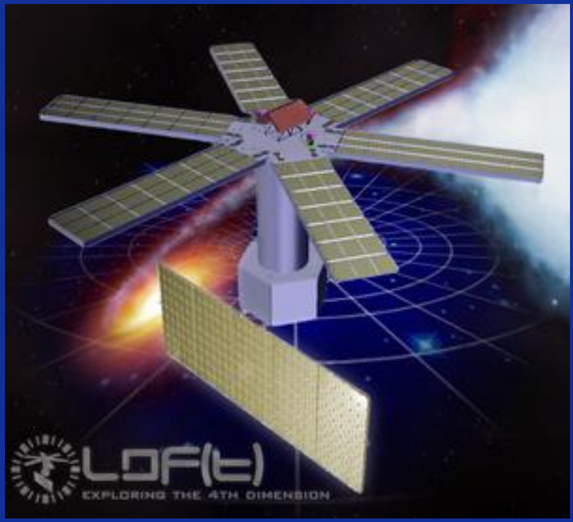
Ripley, BDM, Arcones & Martinez-Pinedo 2014 (see also Qian et al. 1998, 1999)

Magnetars Remnants (assume $M_{ej} = 10^{-2}\ M_\odot$)

Source	Parent[(a)]	ϵ_X[(b)] (keV)	$\langle \dot{N}_X \rangle A_X$[(c)] ($s^{-1}$)	$\nu_X A_X$[(d)] (s^{-1})	$\mathcal{O}_X$[(e)]	$\mathcal{O}$[(f)]
1E 2259+586						0.50
	^{126}Sn	3.7*	8.50×10^{-4}	0.111	1.0	
	^{126}Sn	4.5*	1.30×10^{-4}	0.154	7.9	
	^{126}Sn	4.1*	1.10×10^{-4}	0.170	9.8	
SGR 0501+4516						1.5
	^{126}Sn	3.7*	3.01×10^{-3}	16.0	3.5	
	^{126}Sn	4.5*	4.60×10^{-4}	22.1	27	
	^{126}Sn	4.1*	3.89×10^{-4}	24.4	34	
1E 1841-045						2.3
	^{126}Sn	3.7*	1.61×10^{-4}	0.111	5.4	
	^{126}Sn	4.5*	2.45×10^{-5}	0.154	42	
	^{126}Sn	4.1*	2.07×10^{-5}	0.170	53	
1E 1547.0-5408						0.70
	^{126}Sn	3.7*	5.75×10^{-4}	0.111	1.5	
	^{126}Sn	4.5*	8.77×10^{-5}	0.154	12	
	^{126}Sn	4.1*	7.41×10^{-5}	0.170	15	
AX J1845-0258						4.8
	^{126}Sn	3.7*	7.75×10^{-5}	0.111	12	
	^{126}Sn	4.5*	1.18×10^{-5}	0.154	87	
	^{126}Sn	4.1*	9.99×10^{-6}	0.170	1.1×10^{2}	



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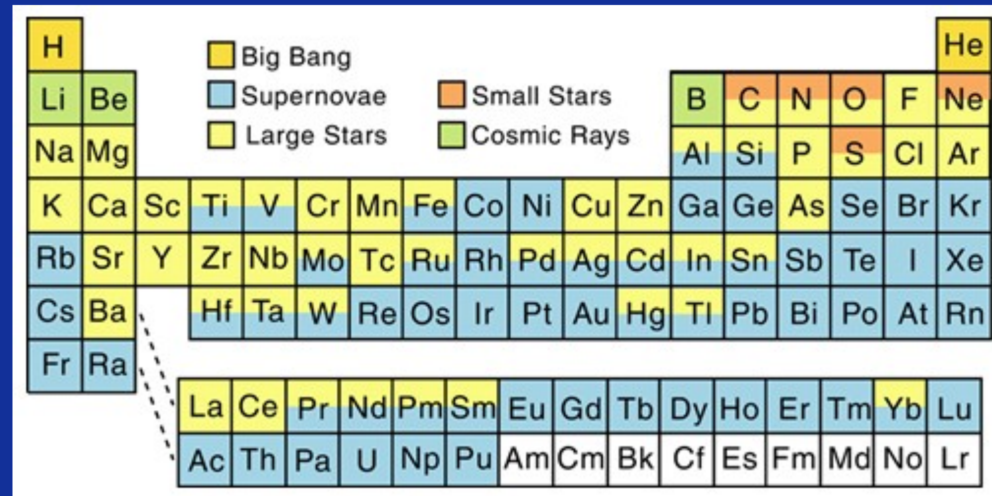

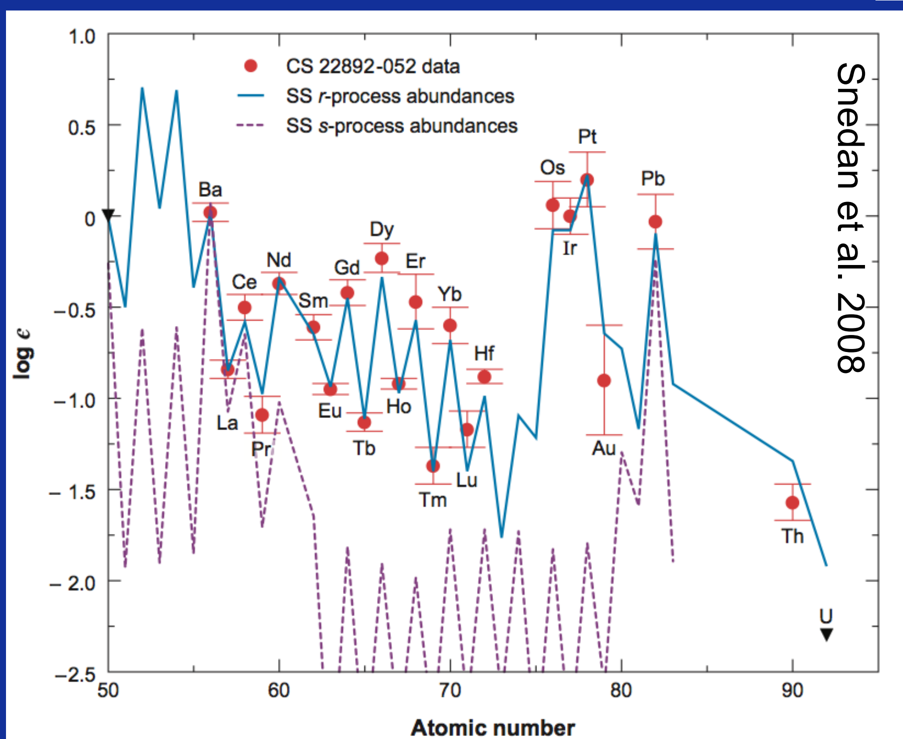

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SNe

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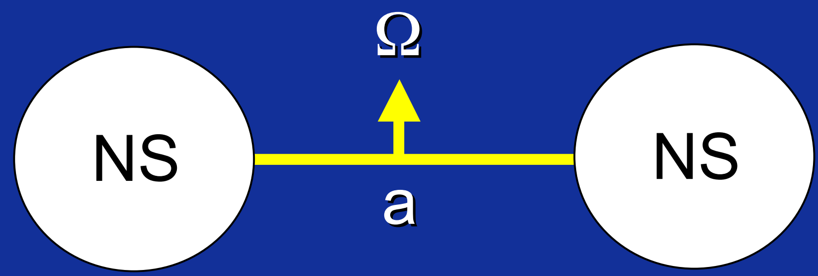
Hypernovae (MHD SNe?)

$$f_{\mathrm{HNe}} \sim \left(\frac{\dot{N}_{\mathrm{HNe}}}{10^{-4}\,\mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-2}\,M_{\odot}}\right)$$

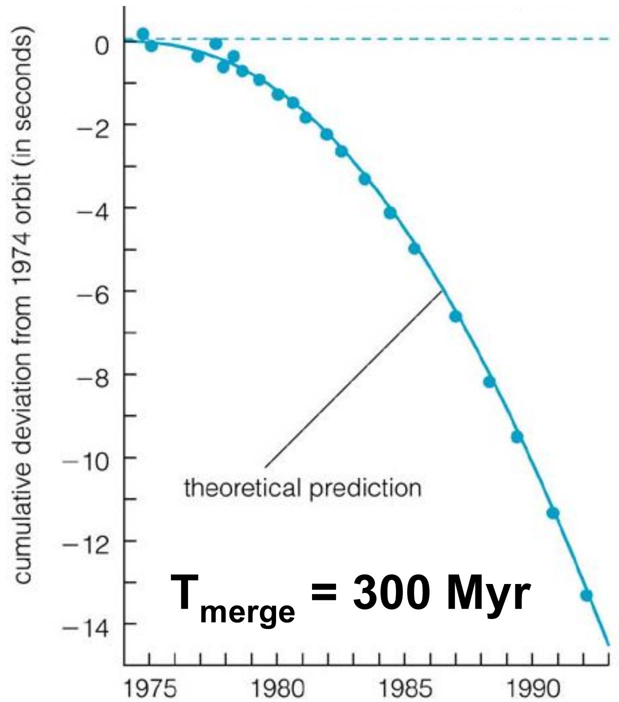
Binary Neutron Star Mergers

Gravitational Waves

$$-\frac{1}{P}\frac{dP}{dt} = \frac{48}{5}\frac{G^3}{c^5}\frac{M^2}{a^4}$$



Hulse-Taylor Pulsar



10 Known Galactic NS-NS Binaries

(Lorimer 2008)

	J0737−3039	J1518+4904	B1534+12	J1756−2251	J1811−1736
P [ms]	22.7/2770	40.9	37.9	28.5	104.2
P_b [d]	0.102	8.6	0.4	0.32	18.8
e	0.088	0.25	0.27	0.18	0.83
$\log_{10}(\tau_c/[\mathrm{yr}])$	8.3/7.7	10.3	8.4	8.6	9.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	7.9	12.4	9.4	10.2	13.0
Masses measured?	Yes	No	Yes	Yes	Yes

	B1820−11	J1829+2456	J1906+0746	B1913+16	B2127+11C
P [ms]	279.8	41.0	144.1	59.0	30.5
P_b [d]	357.8	1.18	0.17	0.3	0.3
e	0.79	0.14	0.085	0.62	0.68
$\log_{10}(\tau_c/[\mathrm{yr}])$	6.5	10.1	5.1	8.0	8.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	15.8	10.8	8.5	8.5	8.3
Masses measured?	No	No	Yes	Yes	Yes

$$\dot{N}_{\mathrm{merge}} \sim 10^{-5} - 10^{-4}\ \mathrm{yr}^{-1}$$

(e.g., Kalogera et al. 2004, Belczynski et al. 2002)

Binary Neutron Star Mergers

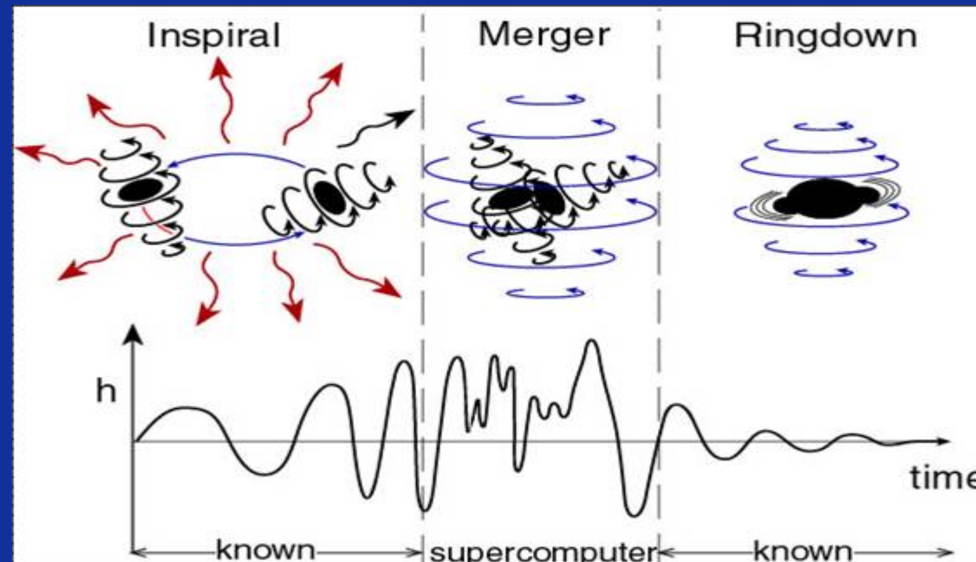
"Advanced" LIGO / Virgo

Range ~ 200-500 Mpc

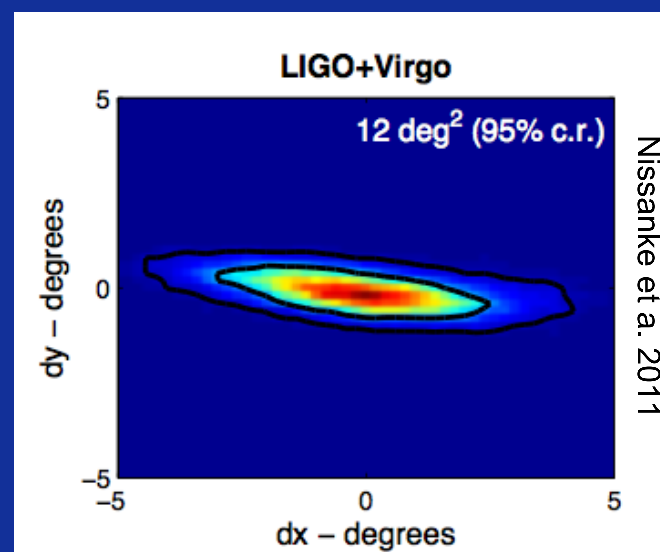
Detection Rate ~ 1-100 yr^{-1}

LIGO (North America)

Virgo (Europe)



Sky Error Regions ~ 10-100 deg^2



Gamma-Rays

Fermi Gamma-ray Space Telescope

GBM FOV ~ 60%

Radio

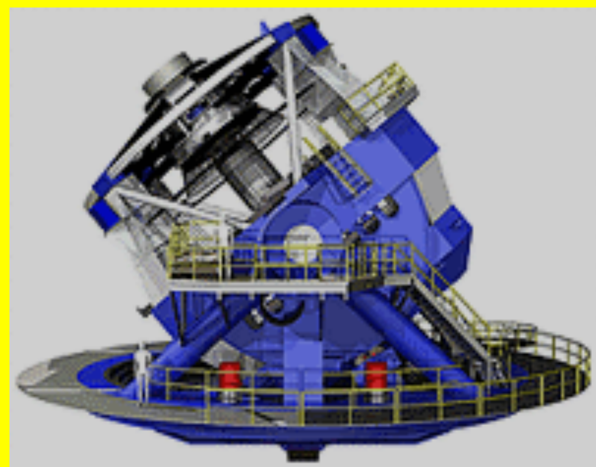
Expanded Very Large Array

Optical ("Now")

THE DARK ENERGY SURVEY

Optical (Future)

Large Synoptic Survey Telescope (LSST)



~All sky m_{AB}<24.5 every ~3 d - Online >~2020

Neutron Star Binary Mergers

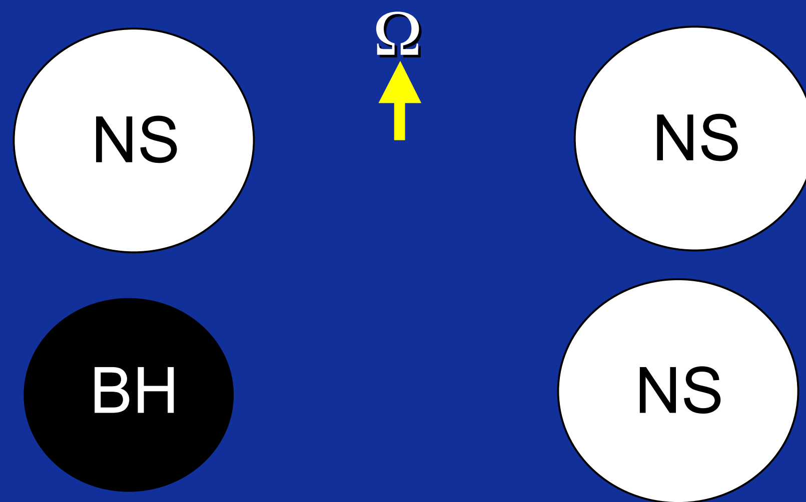
"Advanced" LIGO/Virgo (>2016)

Range ~ 200-500 Mpc

Detection Rate ~ 1-100 yr^{-1}

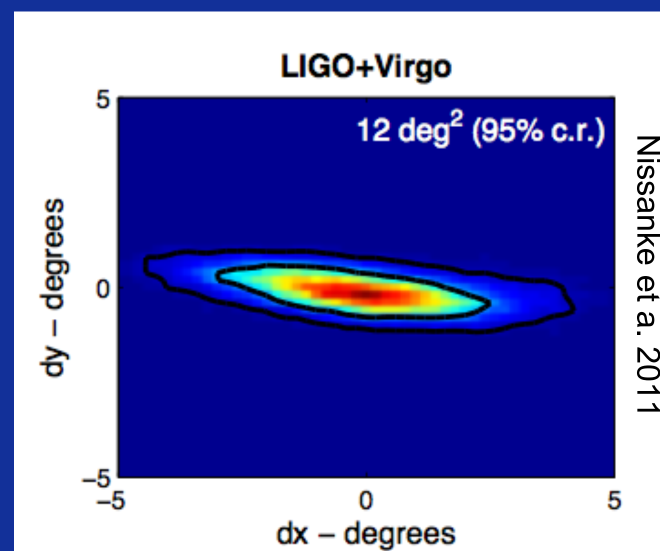
LIGO (North America)

Virgo (Europe)

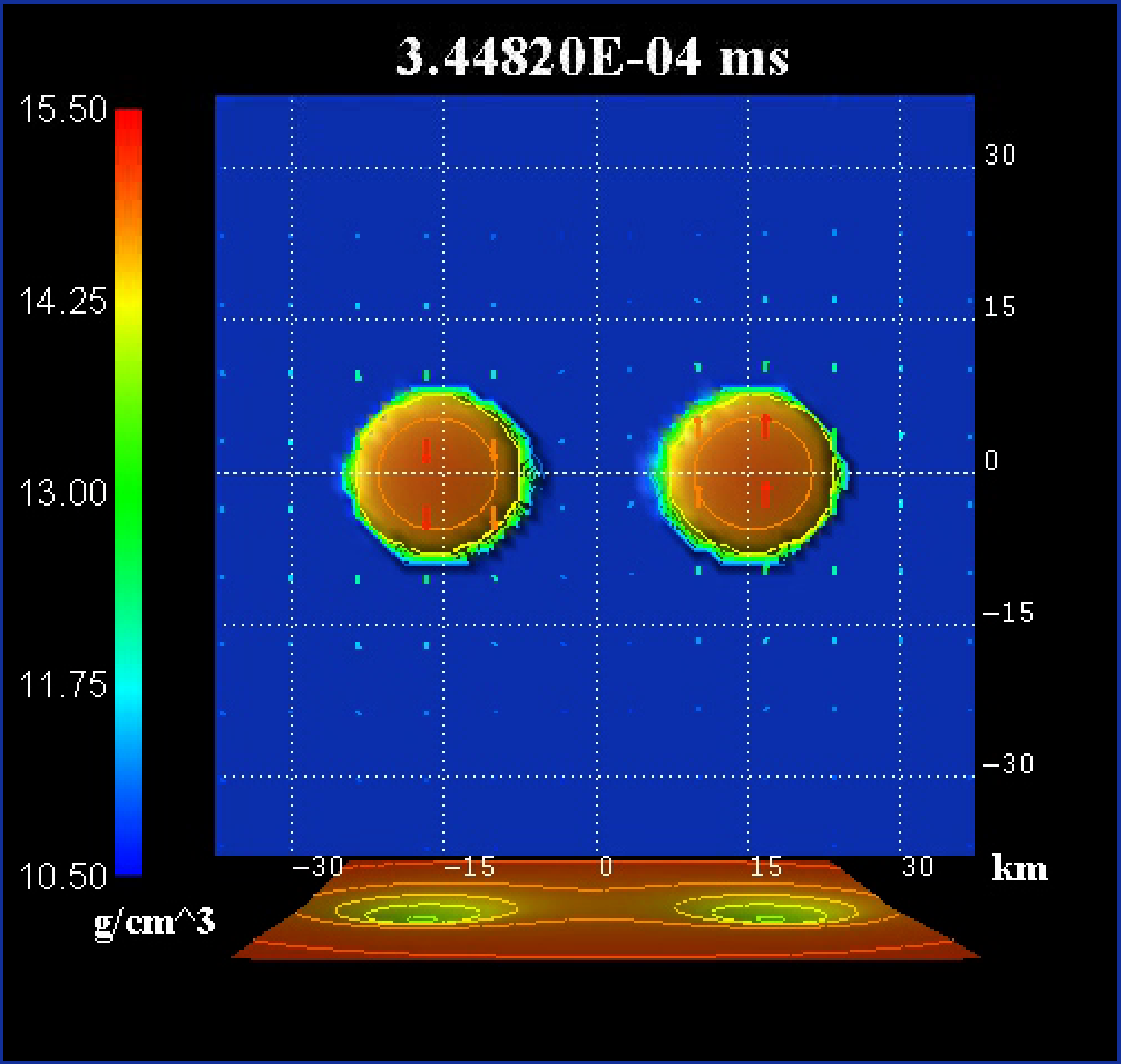


Sky Error Regions ~ 10-100 deg^2

⇒ ~ 10^3-10^4 galaxies

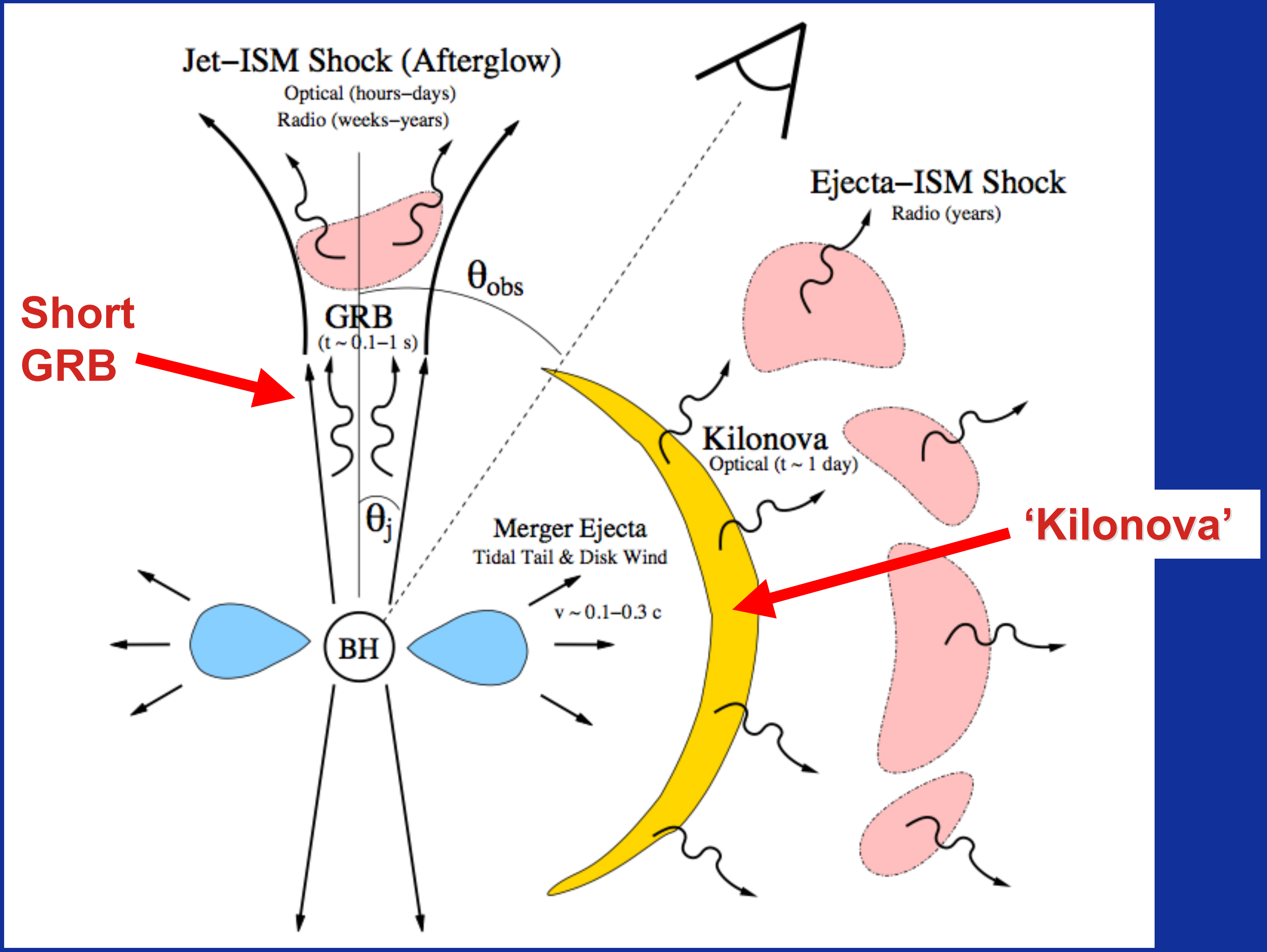


Numerical Simulation - Two 1.4 $M_\odot$ NSs



Courtesy M. Shibata (Kyoto)

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012

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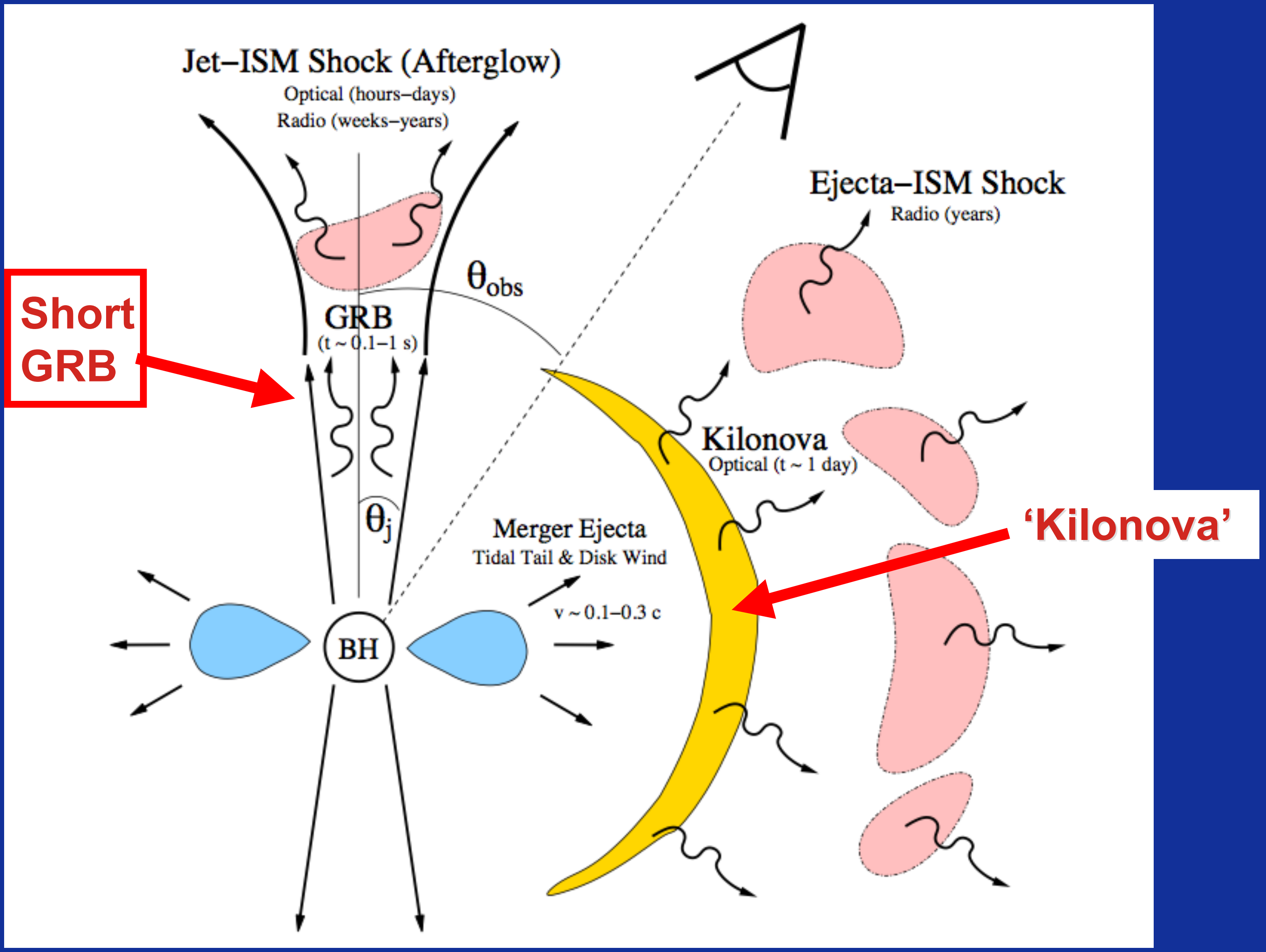
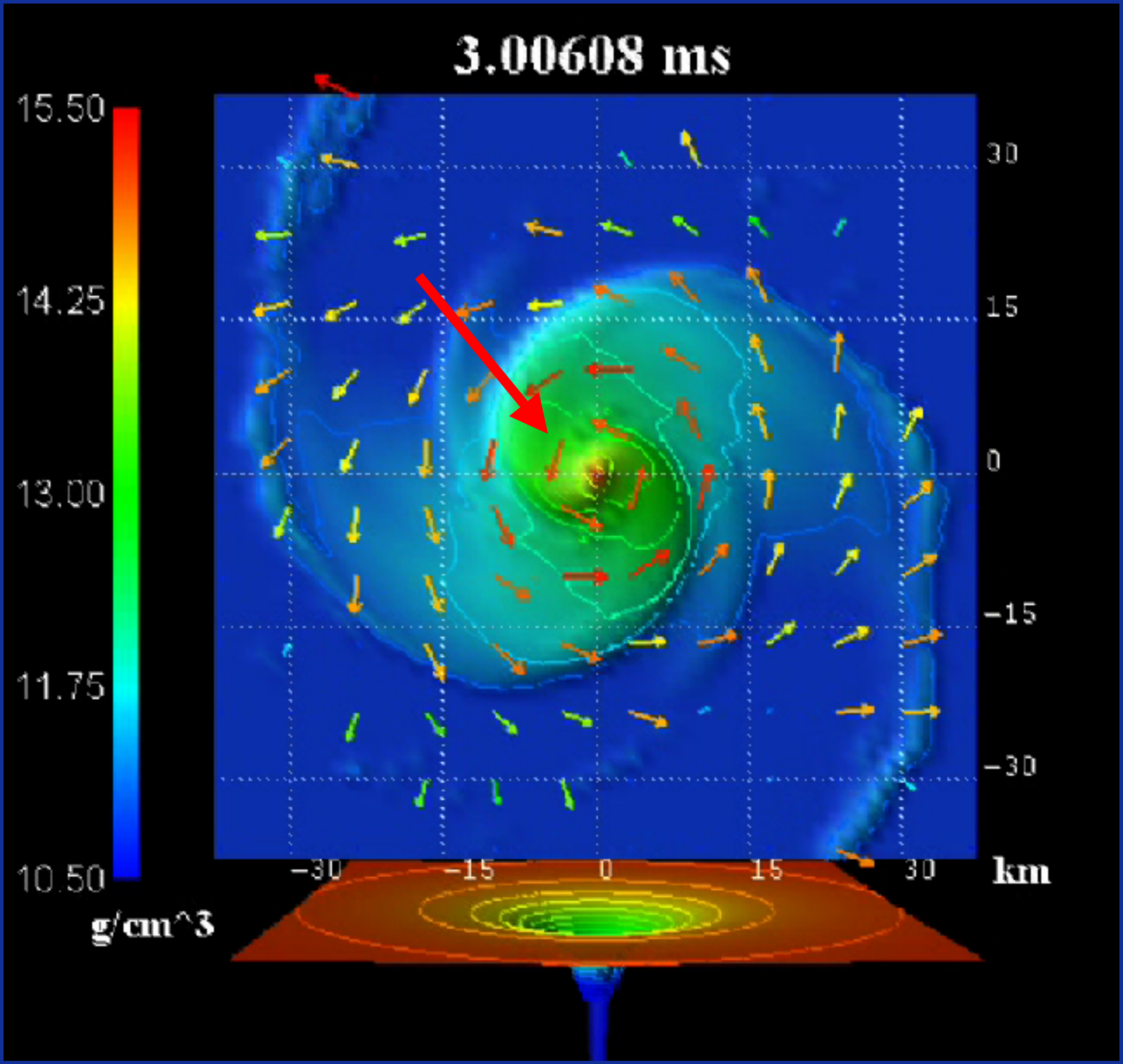


Metzger & Berger 2012

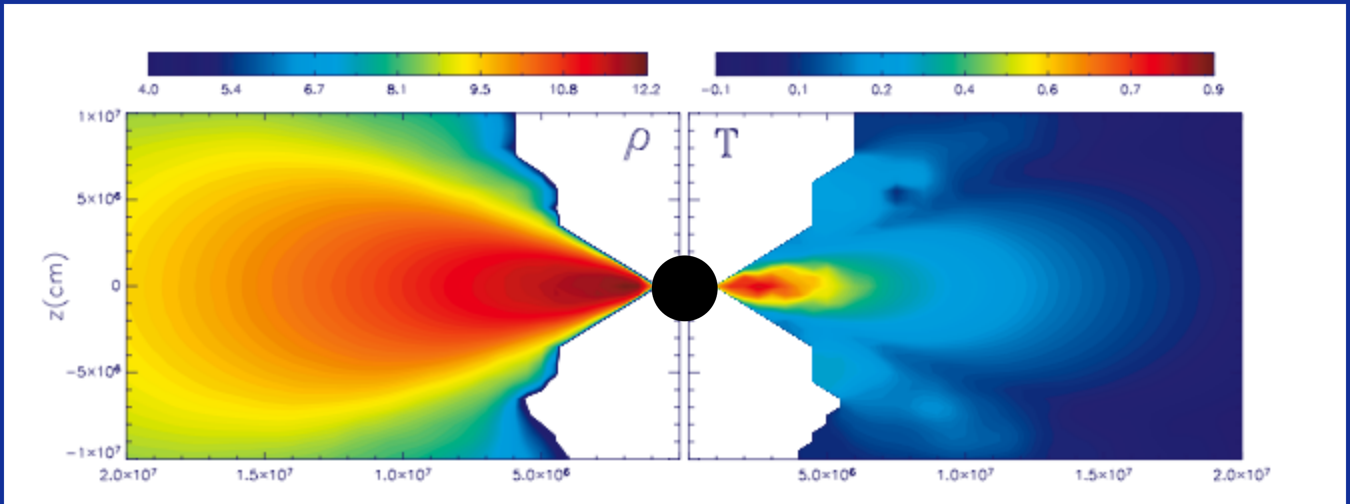
Numerical Simulation - Two 1.4 $M_\odot$ NSs



Courtesy M. Shibata (Tokyo U)

Remnant Accretion Disk

(e.g. Ruffert & Janka 1999; Shibata & Taniguchi 2006; Faber et al. 2006; Chawla et al. 2010; Duez et al. 2010; Foucart 2012; Deaton et al. 2013)



Lee et al. 2004

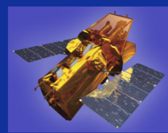
- Disk **Mass ~0.01 - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Hot (T > MeV) & Dense ($\rho \sim 10^8$-10^{12} g cm^{-3})
- Neutrino Cooled: ($\tau_\nu \sim$ 0.01-100)
- Equilibrium $e^+ + n \rightarrow \bar{\nu}_e + p$ vs. $e^- + p \rightarrow \nu_e + n$ $\Rightarrow Y_e \sim 0.1$

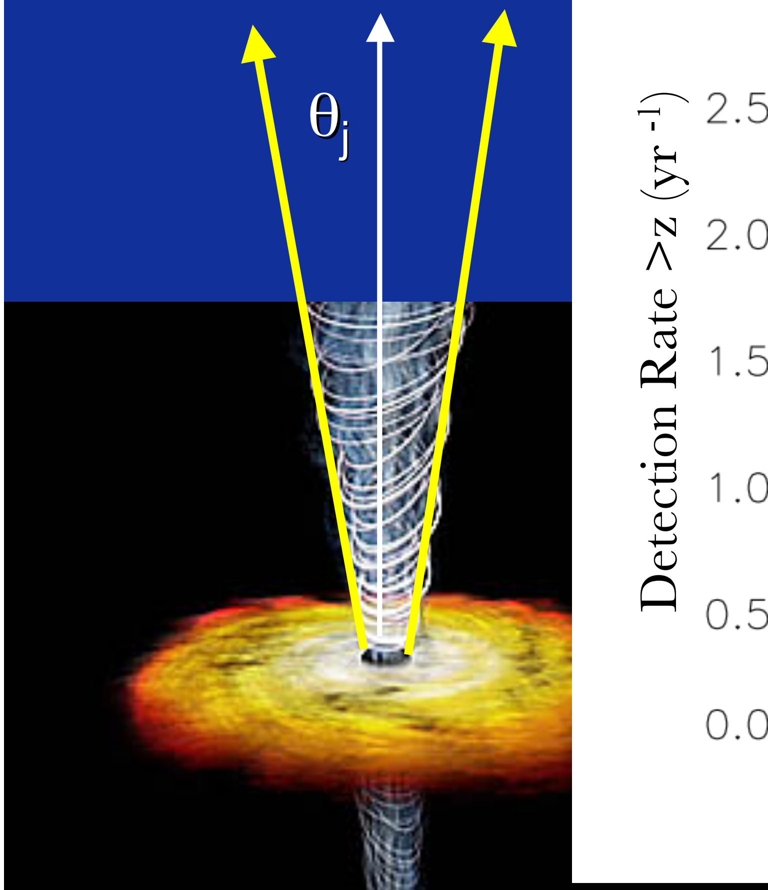
Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\ \mathrm{s}^{-1}$

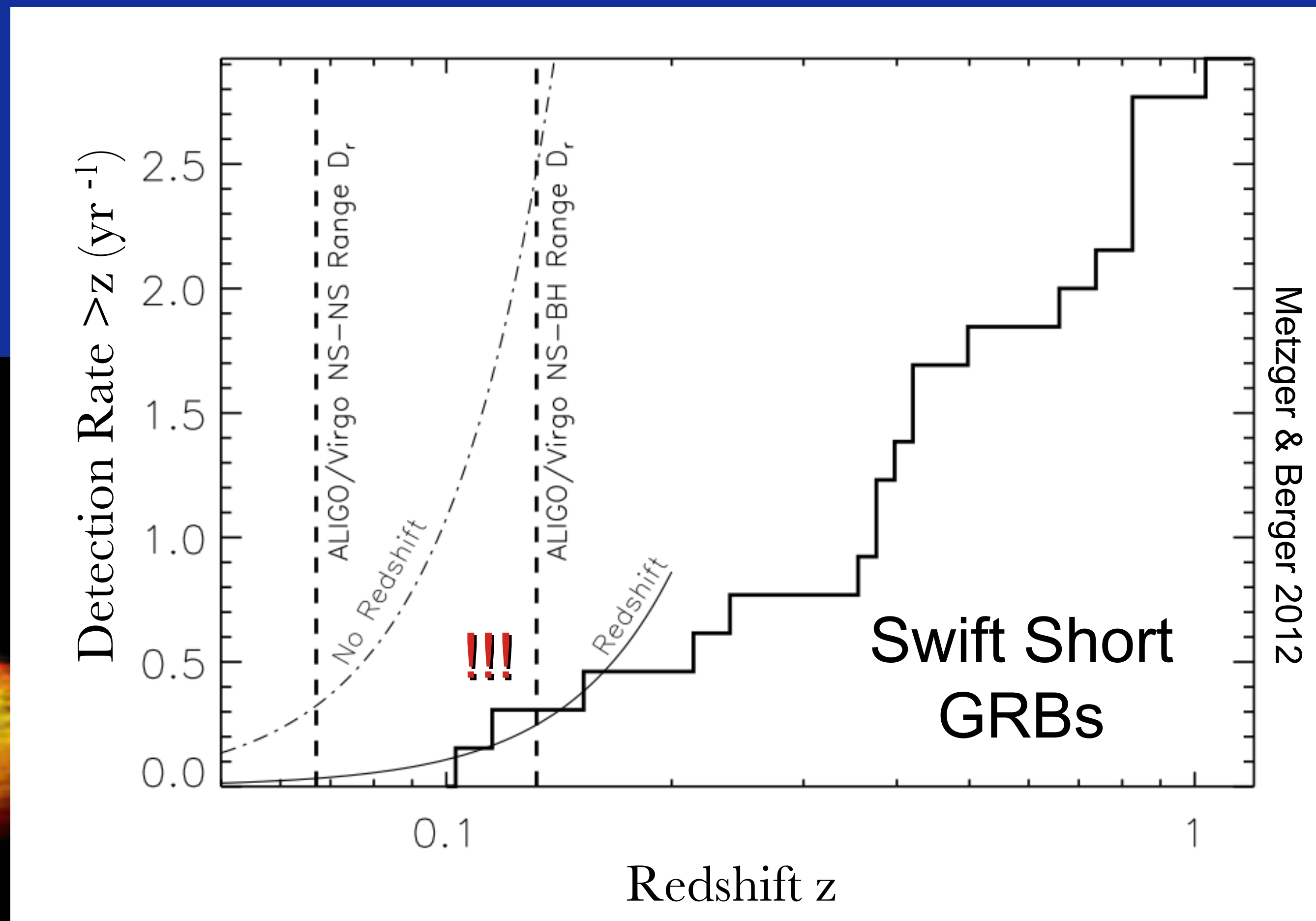
$$t_{\rm visc} \sim 0.1 \left(\frac{M_\bullet}{3M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_d}{100\ \mathrm{km}}\right)^{3/2} \left(\frac{H/R}{0.5}\right)^{-2} \mathrm{s}$$

Short GRB Engine?

Short GRBs are Rare in the LIGO Volume



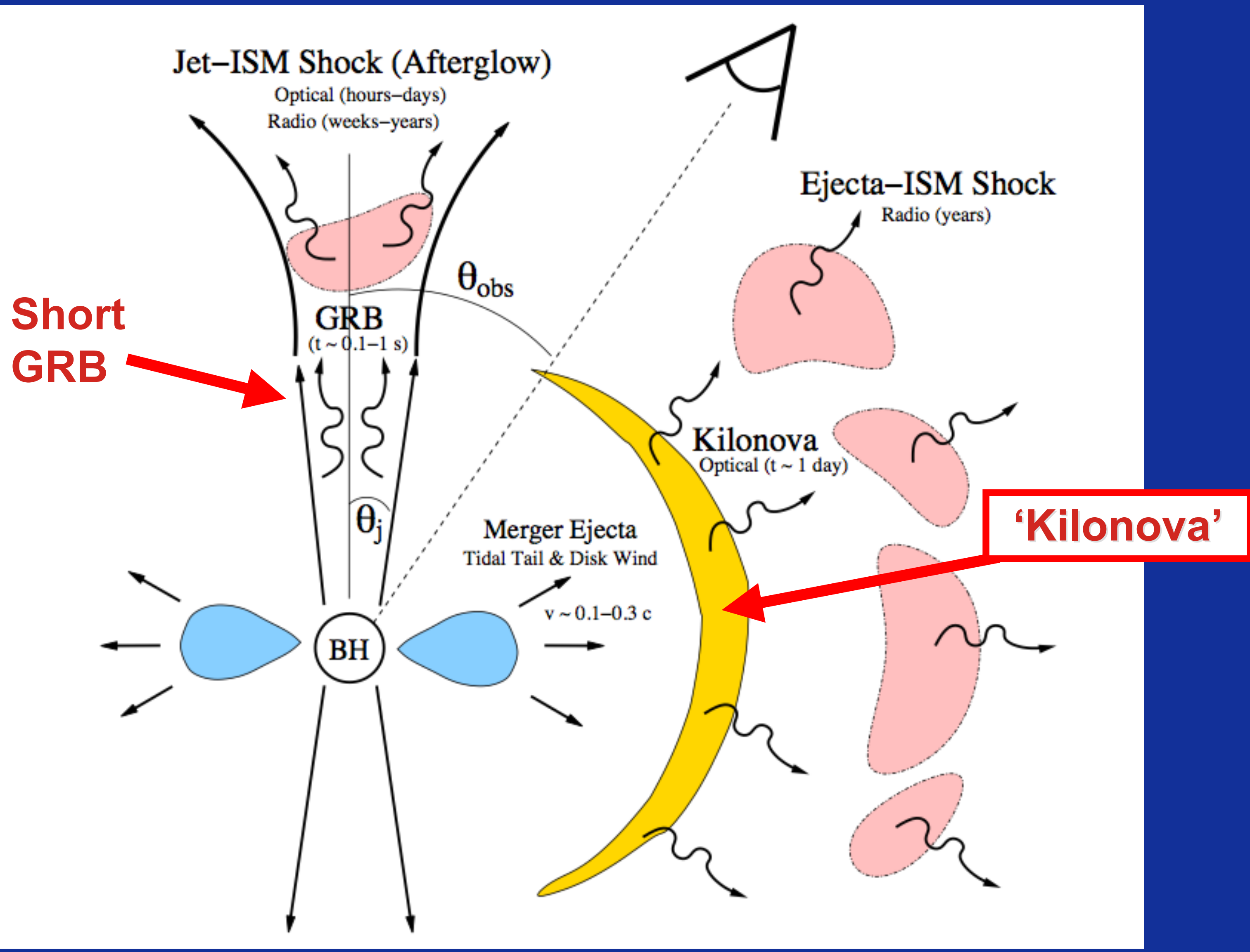




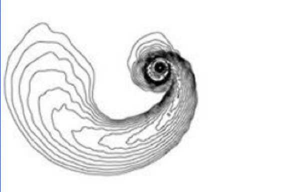
Detectable fraction by all sky γ-ray telescope

$$f_\gamma \sim 3.4 \times \theta_j^2/2 \sim 0.07\left(\frac{\theta_j}{0.2}\right)^2$$

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012



1.1 & 1.6 $M_\odot$ NS merger

Neutron-Rich Ejecta

Dynamical Tidal Tails

(e.g. Janka et al. 1999; Lee & Kluzniak 1999; Ruffert & Janka 2001; Rosswog et al. 2004; Rosswog 2005; Shibata & Taniguchi 2006; Giacomazzo et al. 2009; Duez et al. 2010; East et al. 2012; Hotokezaka et al. 2013)

Full GR / Simple EOS / Circular

$$M_{ej} \sim 10^{-4} - 0.1\ M_\odot$$

Newtonian / Realistic EOS / Eccentric

$$Y_e \equiv \frac{n_p}{n_p + n_n} < 0.1$$

Model			M_{ej} (10^{-3} $M_\odot$)
APR4-130160	1.8	BH	2.0
APR4-140150	1.8	BH	0.6
APR4-145145	1.8	BH	0.1
APR4-130150	1.8	HMNS→BH	12
APR4-140140	1.8	HMNS→BH	14
APR4-120150	1.6	HMNS	9
APR4-120150	1.8	HMNS	8
APR4-120150	2.0	HMNS	7.5
APR4-125145	1.8	HMNS	7
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APR4-135135	1.6	HMNS	11
APR4-135135	1.8	HMNS	7
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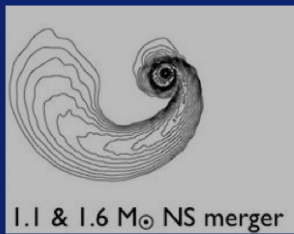
APR4-120140	1.8	HMNS	3
APR4-125135	1.8	HMNS	5
APR4-130130	1.8	HMNS	2
ALF2-140140	1.8	HMNS→BH	2.5
ALF2-120150	1.8	HMNS	5.5
ALF2-125145	1.8	HMNS	3
ALF2-130140	1.8	HMNS → BH	1.5
ALF2-135135	1.8	HMNS → BH	2.5
ALF2-130130	1.8	HMNS	2
H4-130150	1.8	HMNS→BH	3
H4-140140	1.8	HMNS→BH	0.3
H4-120150	1.6	HMNS	4.5
H4-120150	1.8	HMNS	3.5
H4-120150	2.0	HMNS	4
H4-125145	1.8	HMNS	2
H4-130140	1.8	HMNS	0.7
H4-135135	1.6	HMNS→BH	0.7
H4-135135	1.8	HMNS→BH	0.5
H4-135135	2.0	HMNS	0.4
H4-120140	1.8	HMNS	2.5
H4-125135	1.8	HMNS	0.6
H4-130130	1.8	HMNS	0.3
MS1-140140	1.8	MNS	0.6
MS1-120150	1.8	MNS	3.5
MS1-125145	1.8	MNS	1.5
MS1-130140	1.8	MNS	0.6
MS1-135135	1.8	MNS	1.5
MS1-130130	1.8	MNS	1.5

Hotokezaka et al. 2013



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ALF2-130130	1.8	HMNS	2
H4-130150	1.8	HMNS→BH	3
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H4-120150	1.6	HMNS	4.5
H4-120150	1.8	HMNS	3.5
H4-120150	2.0	HMNS	4
H4-125145	1.8	HMNS	2
H4-130140	1.8	HMNS	0.7
H4-135135	1.6	HMNS→BH	0.7
H4-135135	1.8	HMNS→BH	0.5
H4-135135	2.0	HMNS	0.4
H4-120140	1.8	HMNS	2.5
H4-125135	1.8	HMNS	0.6
H4-130130	1.8	HMNS	0.3
MS1-140140	1.8	MNS	0.6
MS1-120150	1.8	MNS	3.5
MS1-125145	1.8	MNS	1.5
MS1-130140	1.8	MNS	0.6
MS1-135135	1.8	MNS	1.5
MS1-130130	1.8	MNS	1.5

Hotokezaka et al. 2013

Disk Outflows

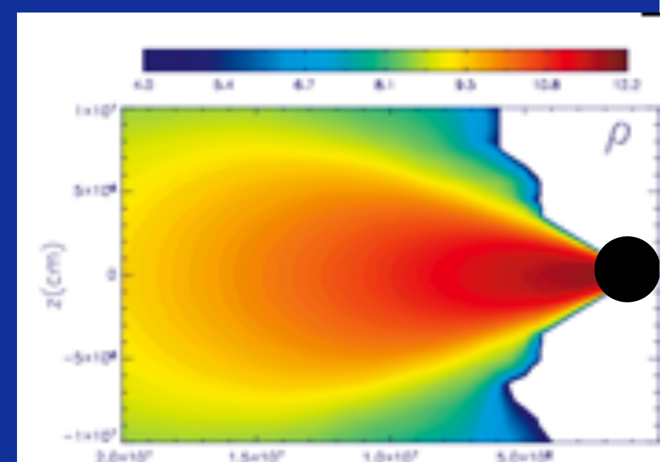
Neutrino-Powered (Early)

(e.g. McLaughlin & Surman 05; Surman+08; BDM+08; Dessart+09)

Recombination-Powered (Late)

(e.g. Beloborodov 08; BDM+08, 09; Lee+09; Fernandez & BDM 13)

$$Y_e \sim ???$$

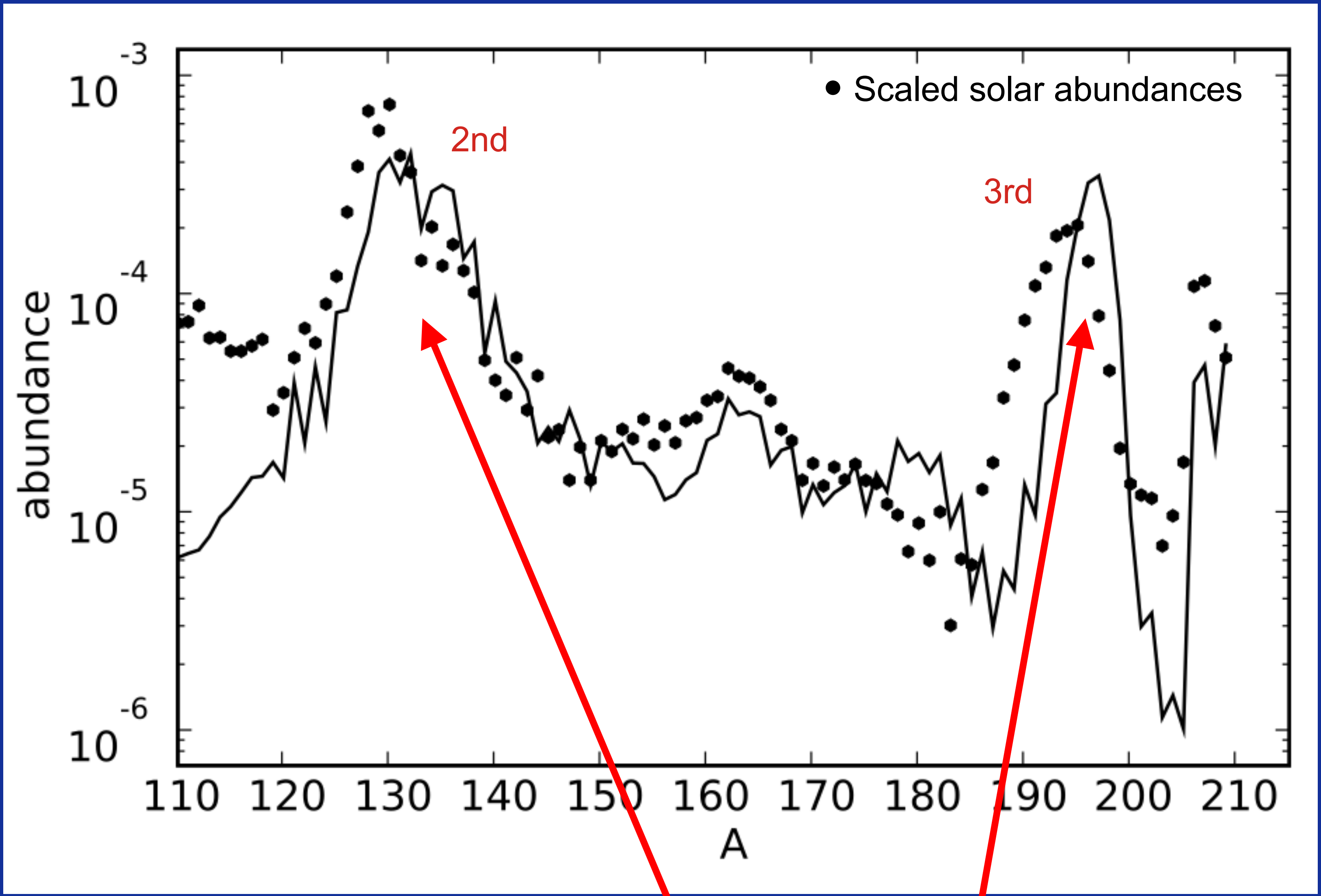


$$M_{ej} = f_w M_d \sim 10^{-3}\text{-}10^{-2}\ (f_w/0.1)\ M_\odot$$

R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)

as used in Metzger et al. 2010 (movie courtesy G. Martinez-Pinedo, A. Arcones)

Final Abundance Distribution

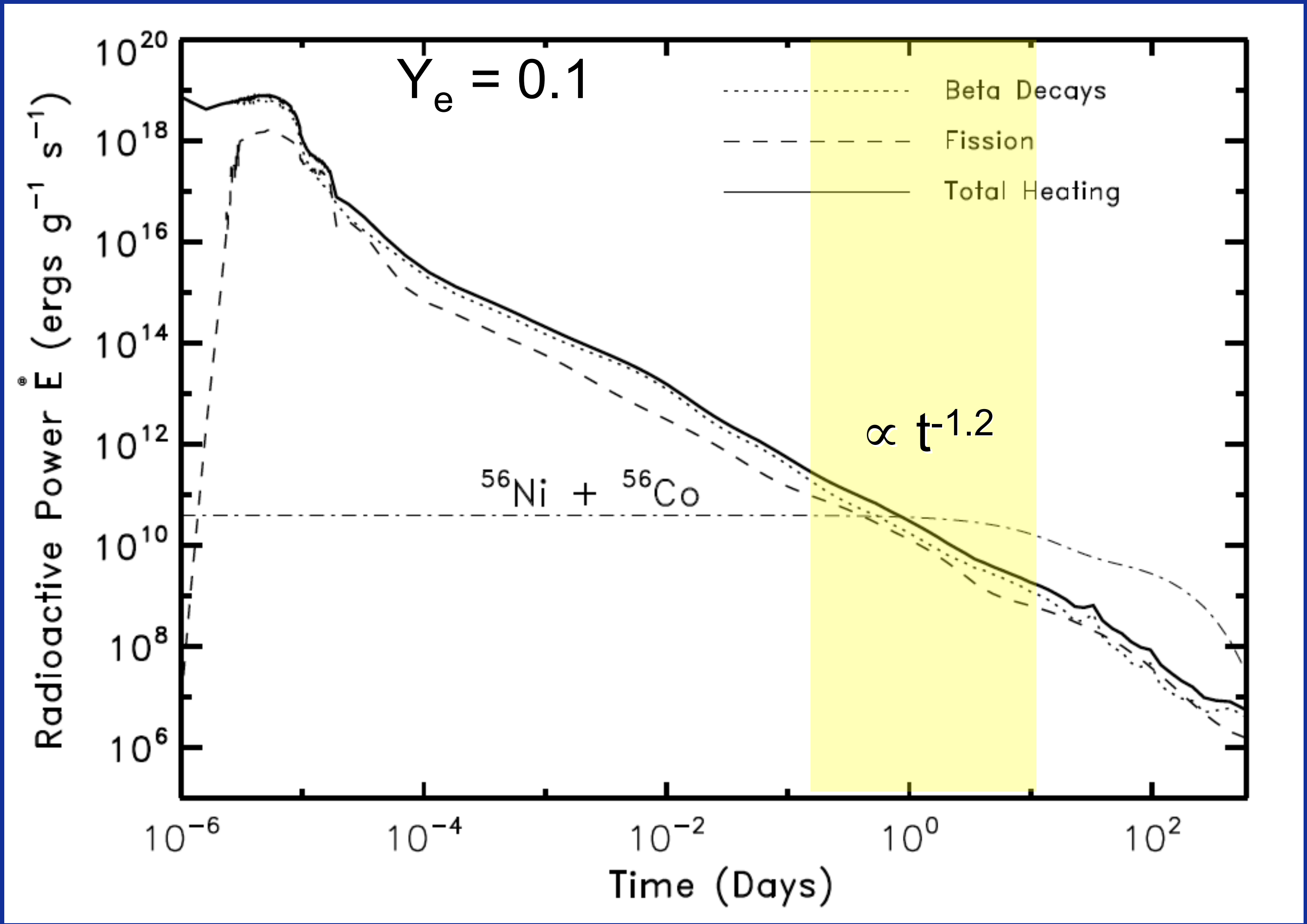


BDM et al. 2010

peaks at A ~ 130, 195

Radioactive Heating of Merger Ejecta

(BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013)



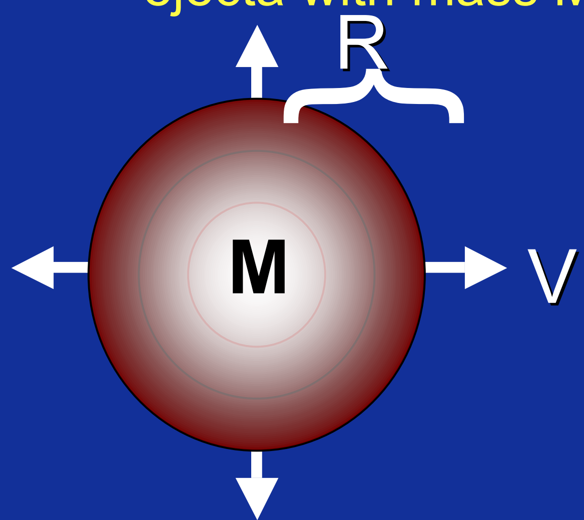
Metzger et al. 2010

Dominant β-Decays at t ~ 1 day: ^{132,134,135}I, ^{128,129}Sb, ^{129}Te, ^{135}Xe

Relatively insensitive to details (Y_e, expansion history, NSE or not)

How Supernovae Shine (Arnett 1982; Li & Paczynski 1998)

ejecta with mass M, velocity v, thermal energy $E = f\,Mc^2$, opacity κ



$$R = v\,t \qquad \rho = \frac{M}{\frac{4\pi}{3} R^3}$$

$$\tau \sim \kappa \rho R \qquad t_{diff} \sim \tau R / c$$

$$\text{Peak } (t = t_{diff}) \Rightarrow \quad t_{peak} \sim 2 \text{ weeks} \left(\frac{v}{10^4 \text{ km s}^{-1}} \right)^{-1/2} \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{\kappa}{\kappa_{Fe}} \right)^{1/2}$$

$$L_{peak} \sim \frac{E(t_{peak})}{t_{peak}} \sim 10^{43} \text{ ergs s}^{-1} \left(\frac{f}{10^{-5}} \right) \left(\frac{v}{10^4 \text{ km s}^{-1}} \right)^{1/2} \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{\kappa}{\kappa_{Fe}} \right)^{-1/2}$$

Type Ia Supernova:

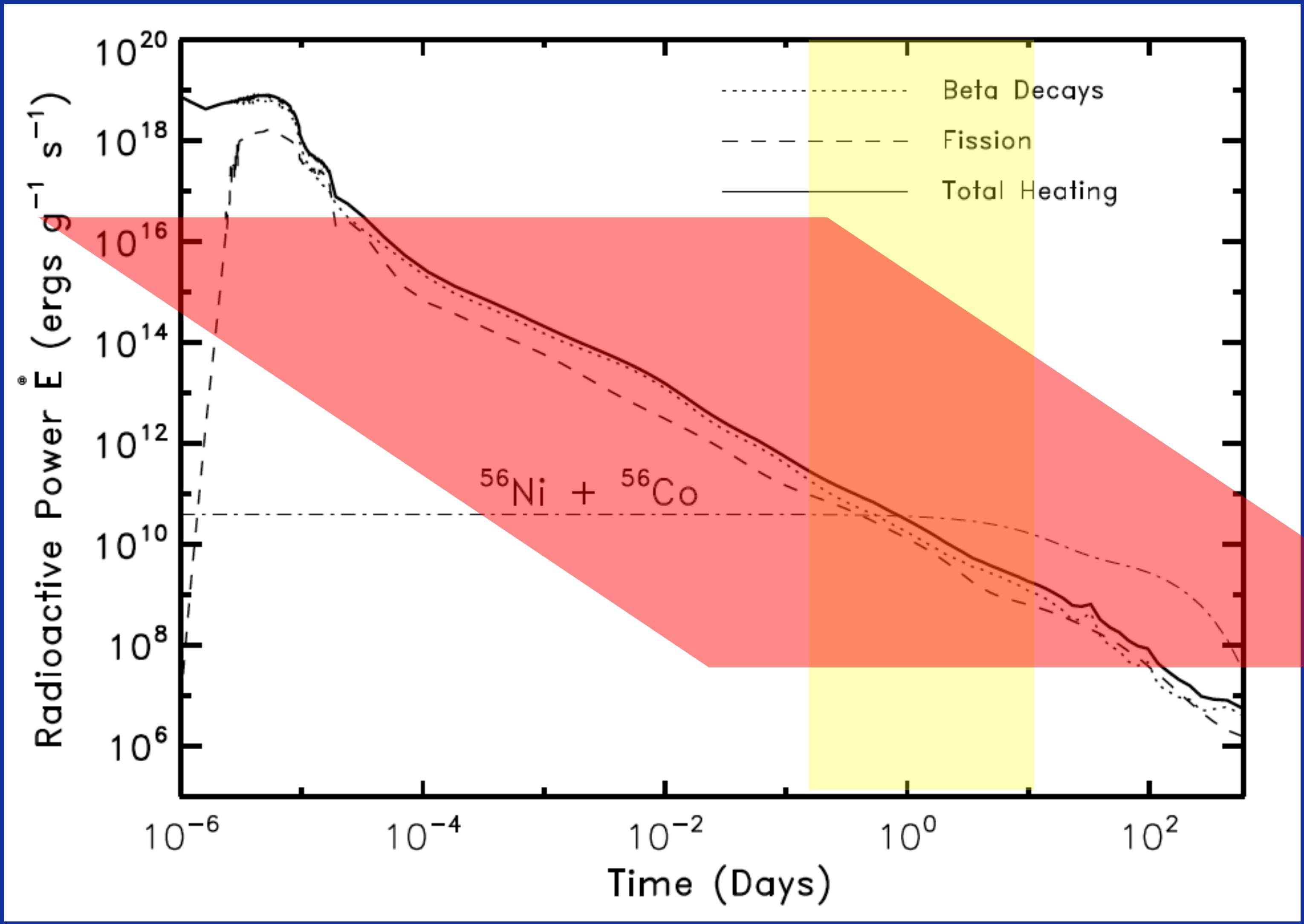
$v \sim 10^4$ km s^{-1}, $M_{ej} \sim M_\odot$, $f_{Ni \rightarrow Co} \sim 10^{-5} \Rightarrow t_{peak} \sim$ week, $L \sim 10^{43}$ erg s^{-1}

NS Merger:

$v \sim 0.1$ c, $M_{ej} \sim 10^{-2} M_\odot$, $f \sim 3\times10^{-6} \Rightarrow t_{peak} \sim 1$ day, $L \sim 10^{42}$ erg s^{-1}

Radioactive Heating of Merger Ejecta

(BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013)



Metzger et al. 2010

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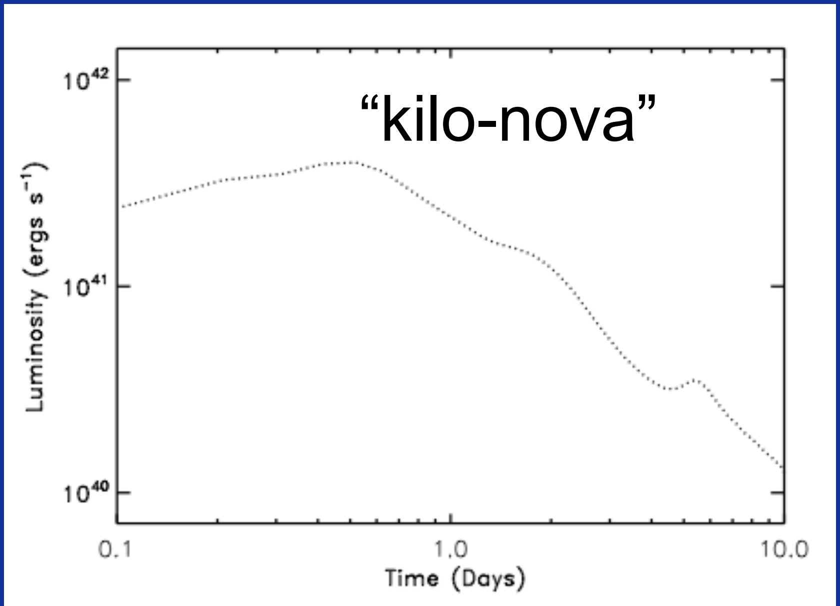
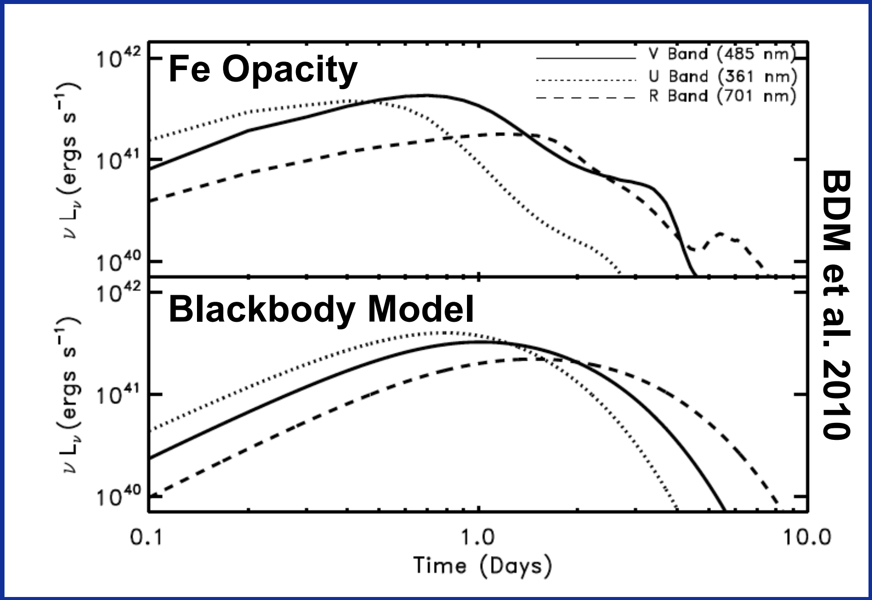
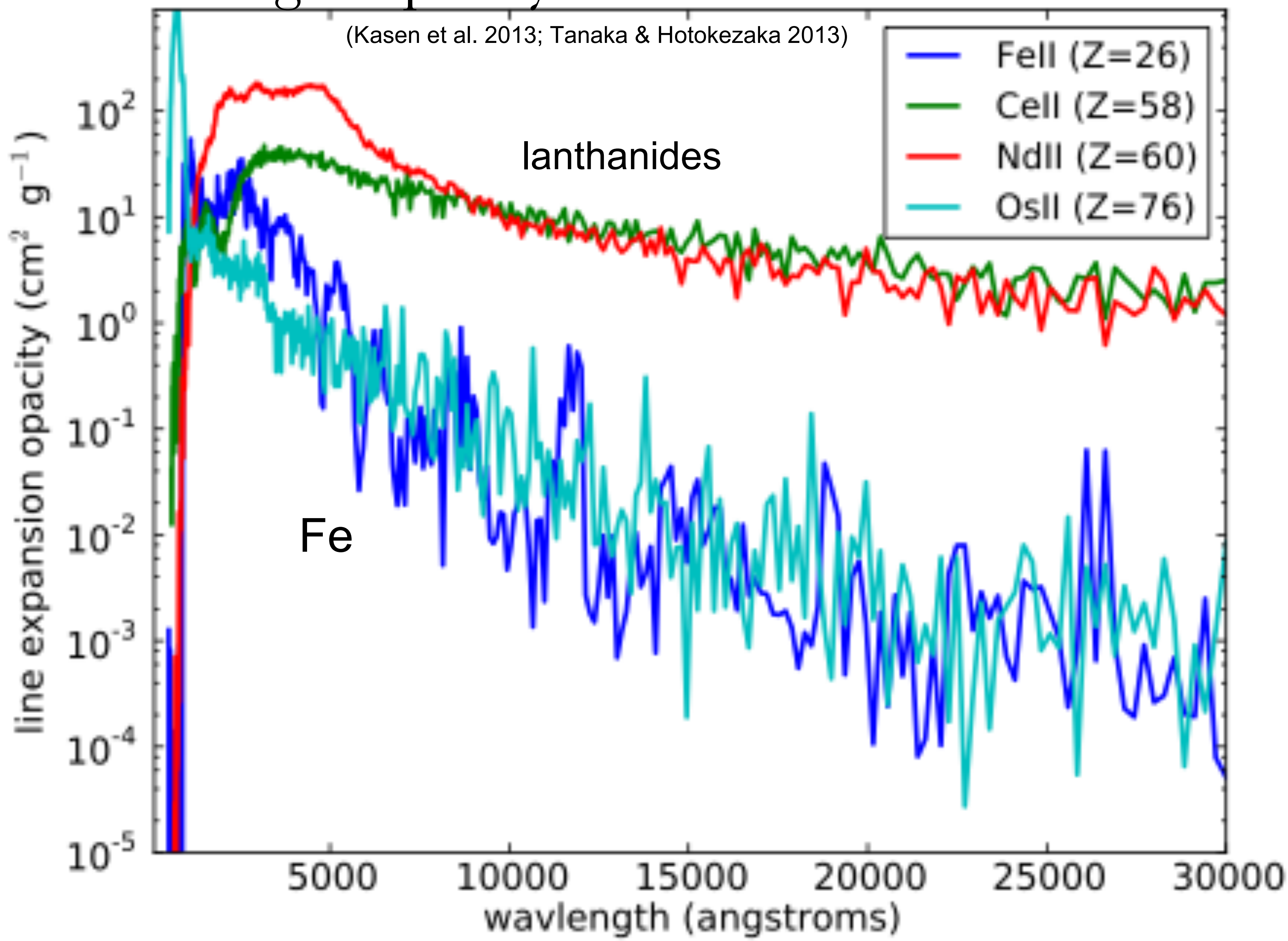
Bolometric Luminosity



Color Evolution



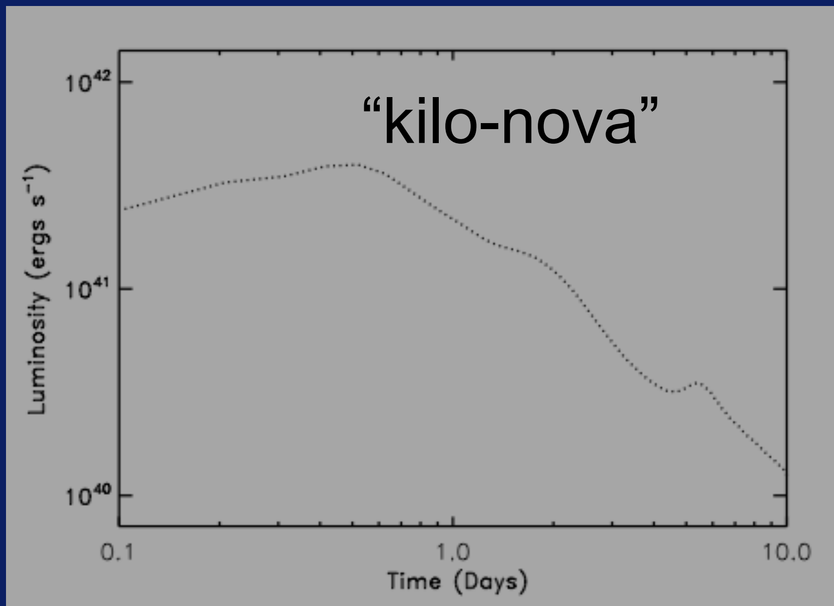
High Opacity of the Lanthanides

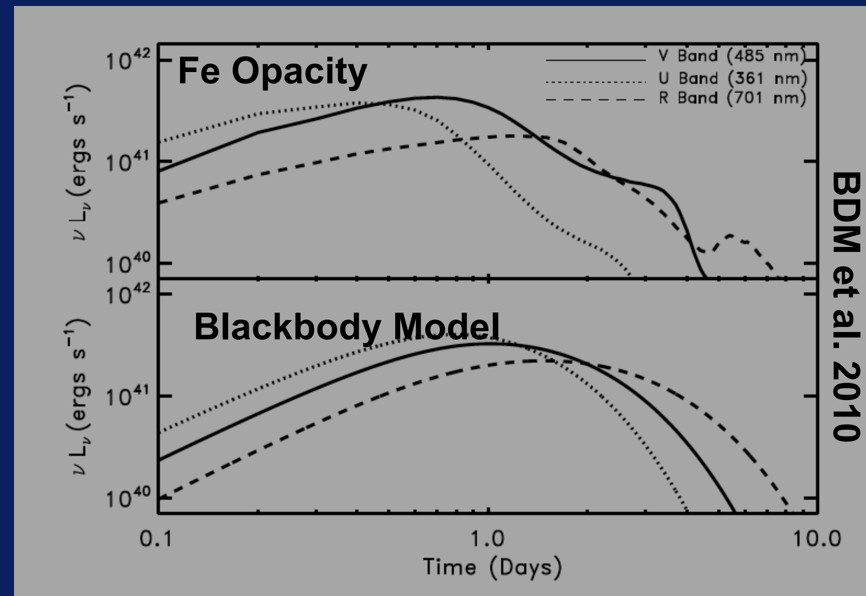


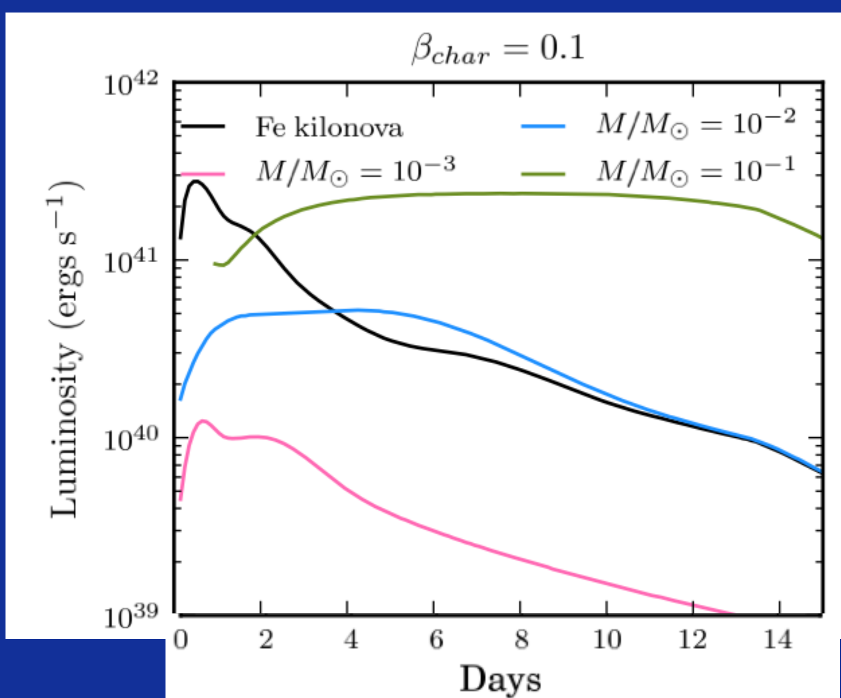
Kasen et al. 2013

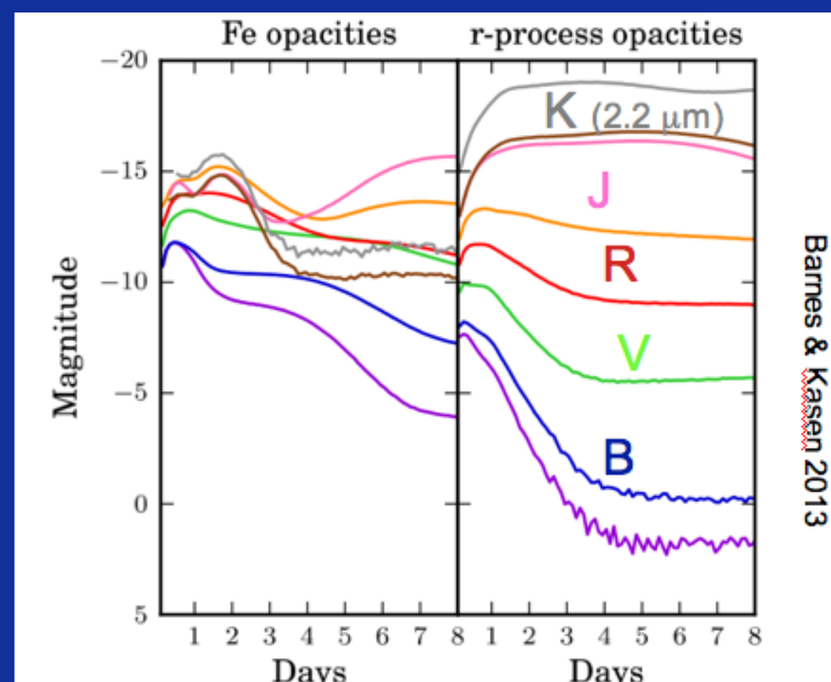
Bolometric Luminosity

Color Evolution

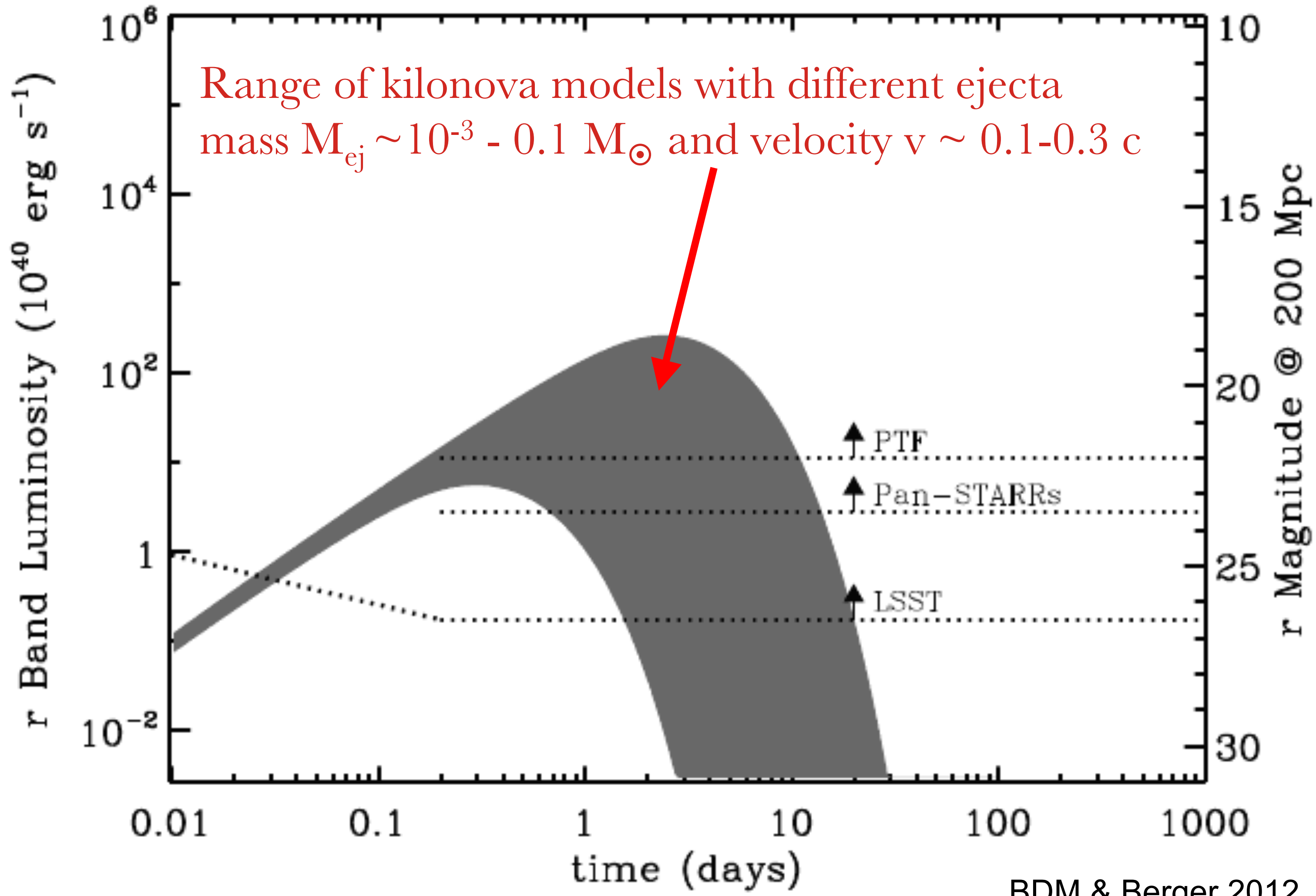








EM Counterpart Search following a GW Trigger

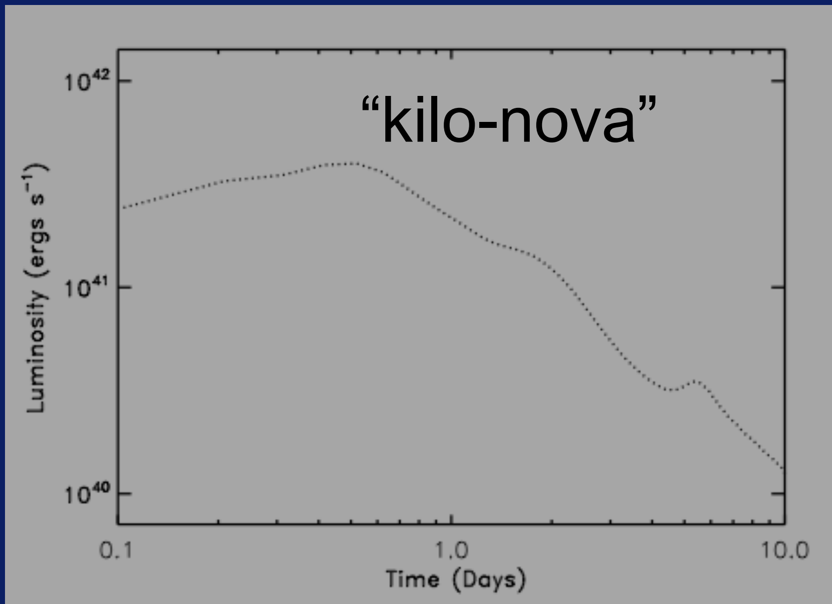


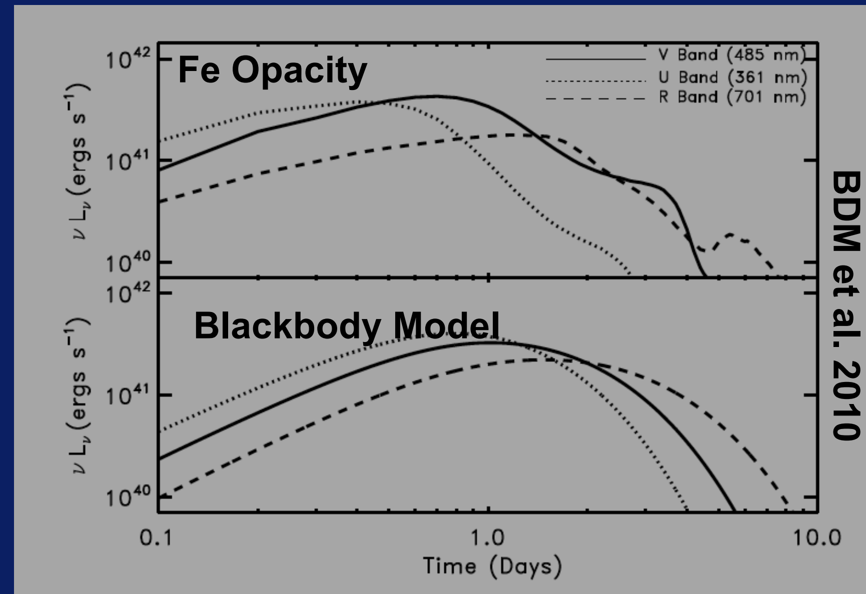
BDM & Berger 2012

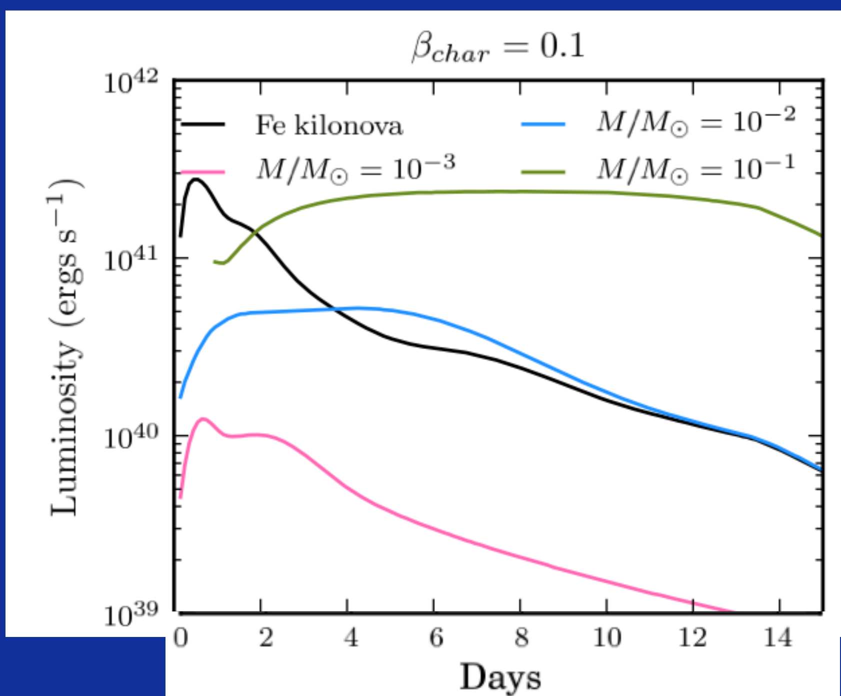
⇒ Requires depth J ~ 22-24 and short cadence

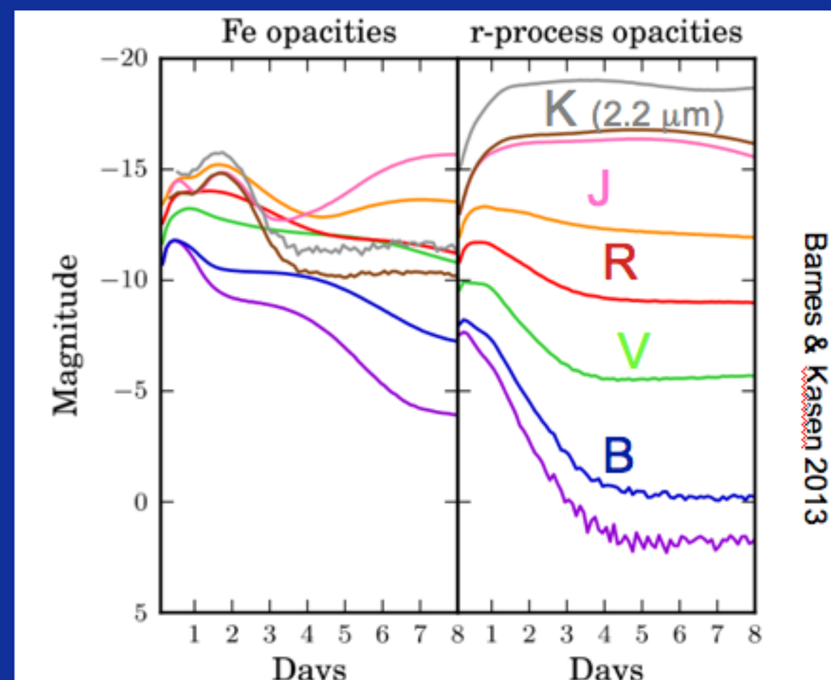
Bolometric Luminosity

Color Evolution









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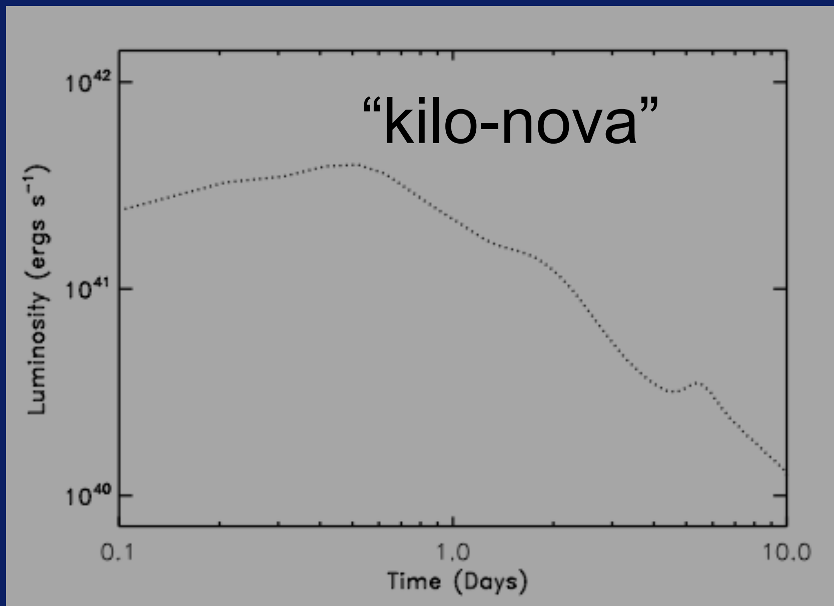

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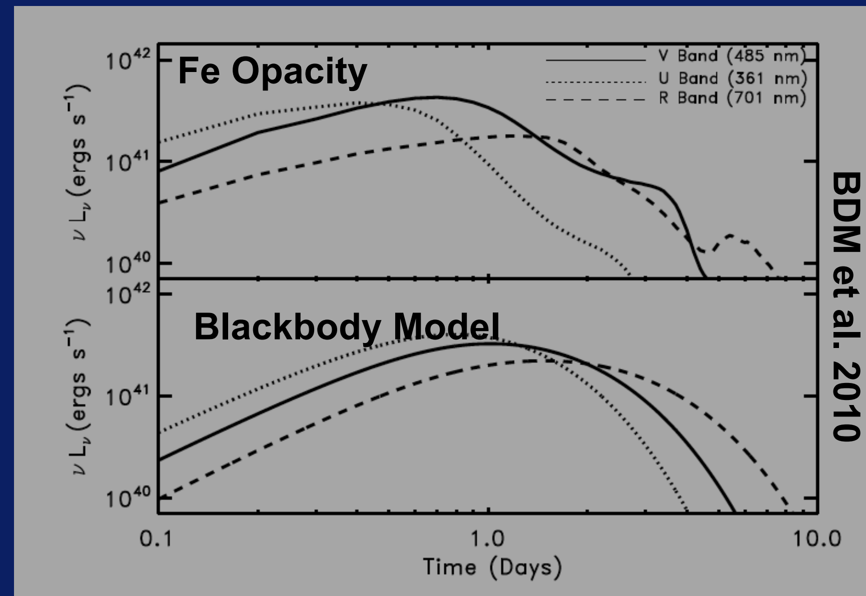

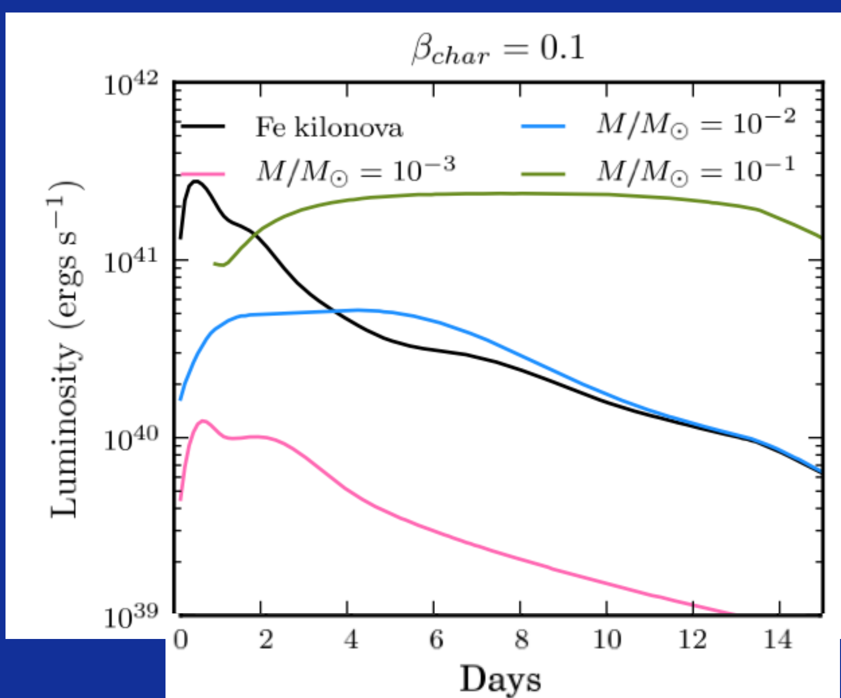

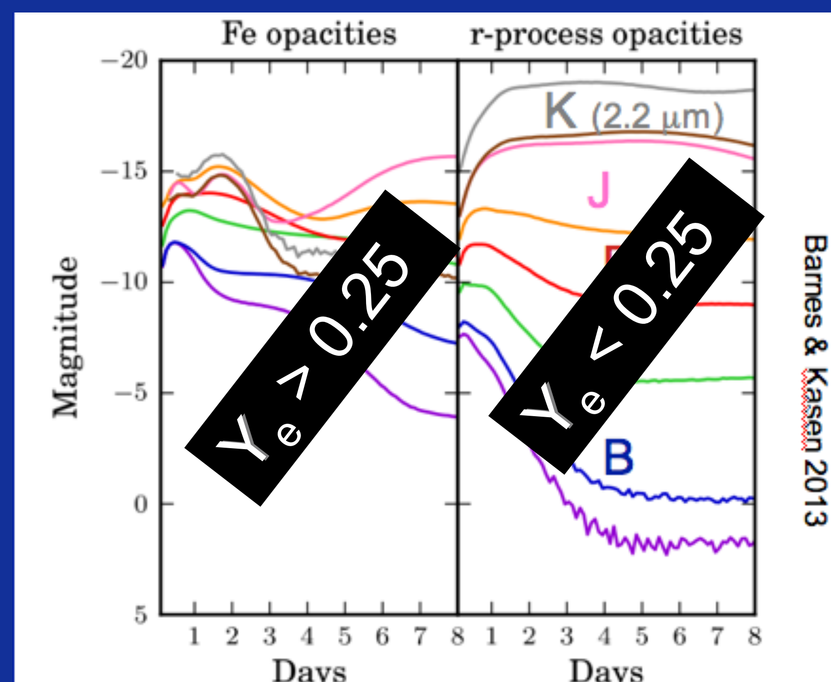

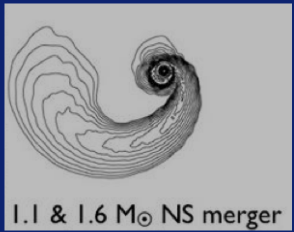

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H4-120140	1.8	HMNS	2.5
H4-125135	1.8	HMNS	0.6
H4-130130	1.8	HMNS	0.3
MS1-140140	1.8	MNS	0.6
MS1-120150	1.8	MNS	3.5
MS1-125145	1.8	MNS	1.5
MS1-130140	1.8	MNS	0.6
MS1-135135	1.8	MNS	1.5
MS1-130130	1.8	MNS	1.5

Hotokezaka et al. 2013

Disk Outflows

Neutrino-Powered (Early)

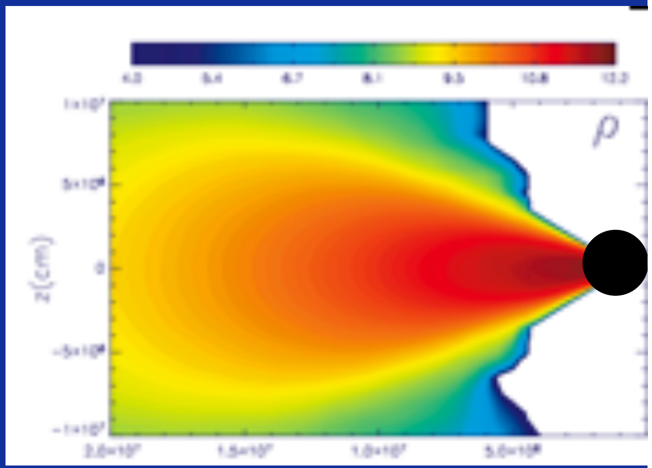
(e.g. McLaughlin & Surman 05; Surman+08; BDM+08; Dessart+09)

Recombination-Powered (Late)

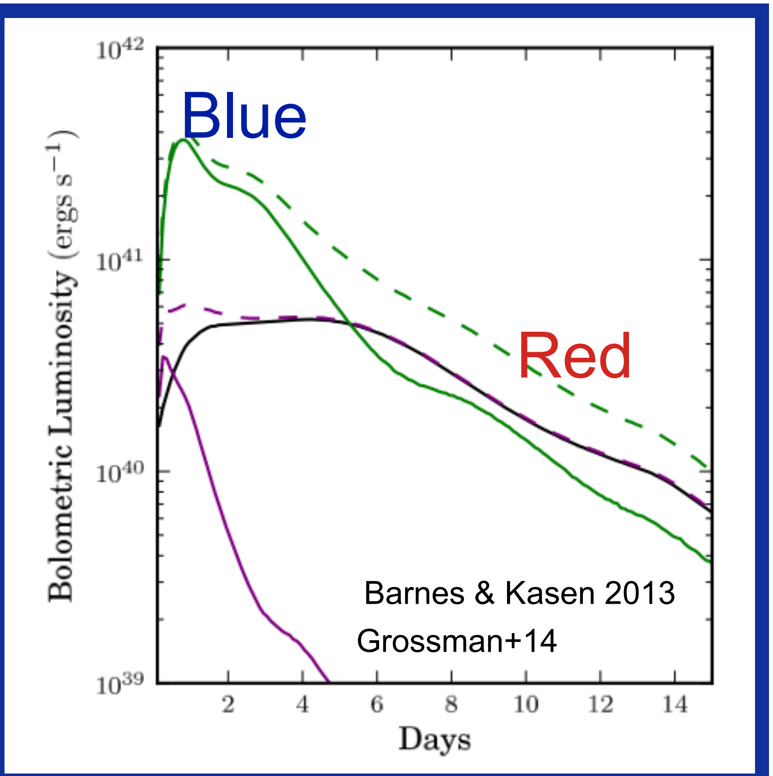
(e.g. Beloborodov 08; BDM+08, 09; Lee+09; Fernandez & BDM 13)

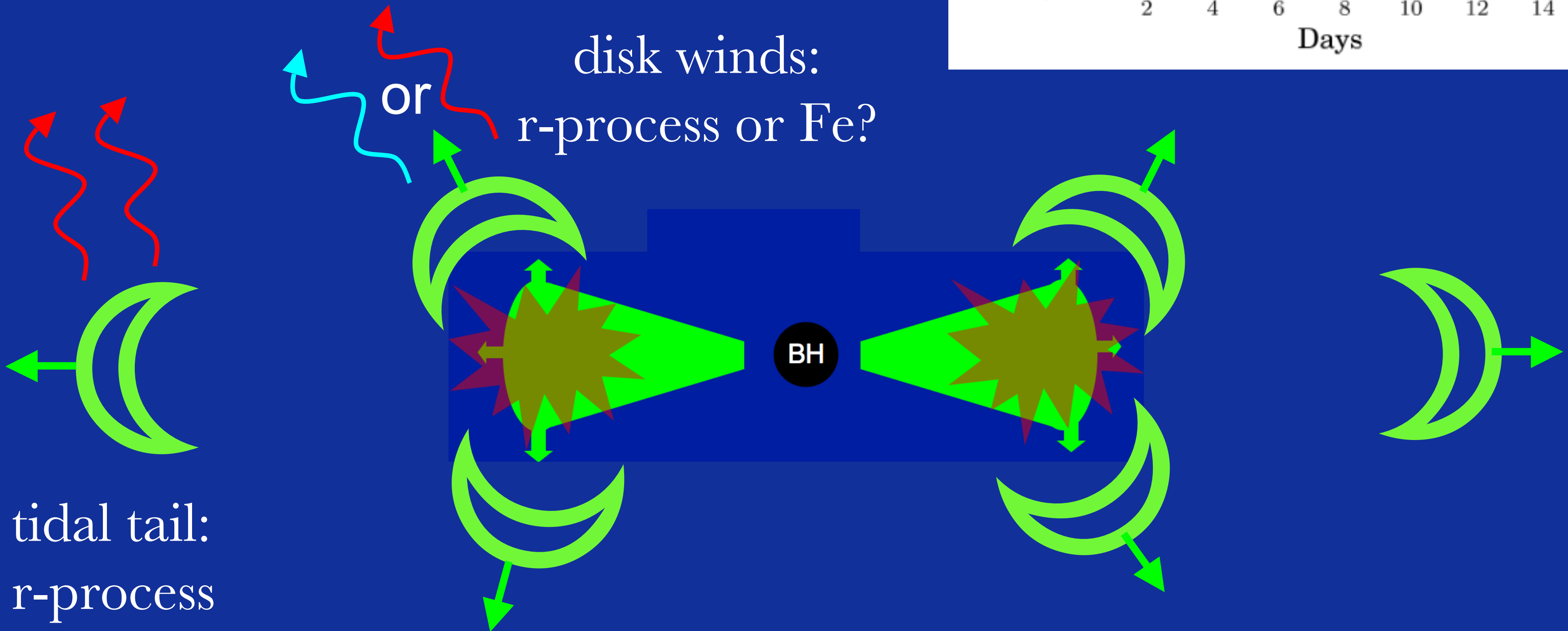
$$Y_e \sim ???$$

$$M_{ej} = f_w M_d \sim 10^{-3}\text{-}10^{-2}\ (f_w/0.1)\ M_{\odot}$$



Two Component Light Curve

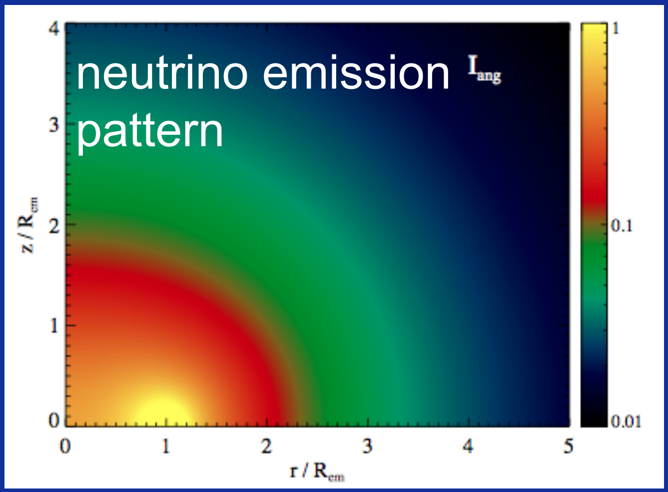


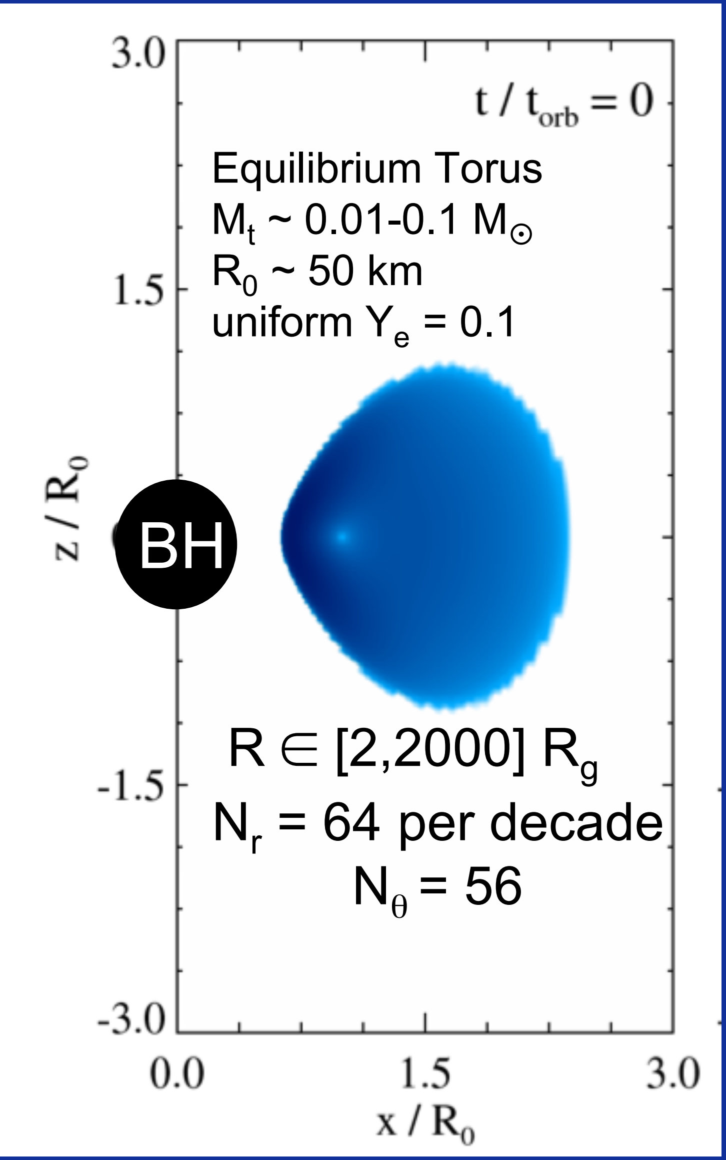


Remnant Torus Evolution

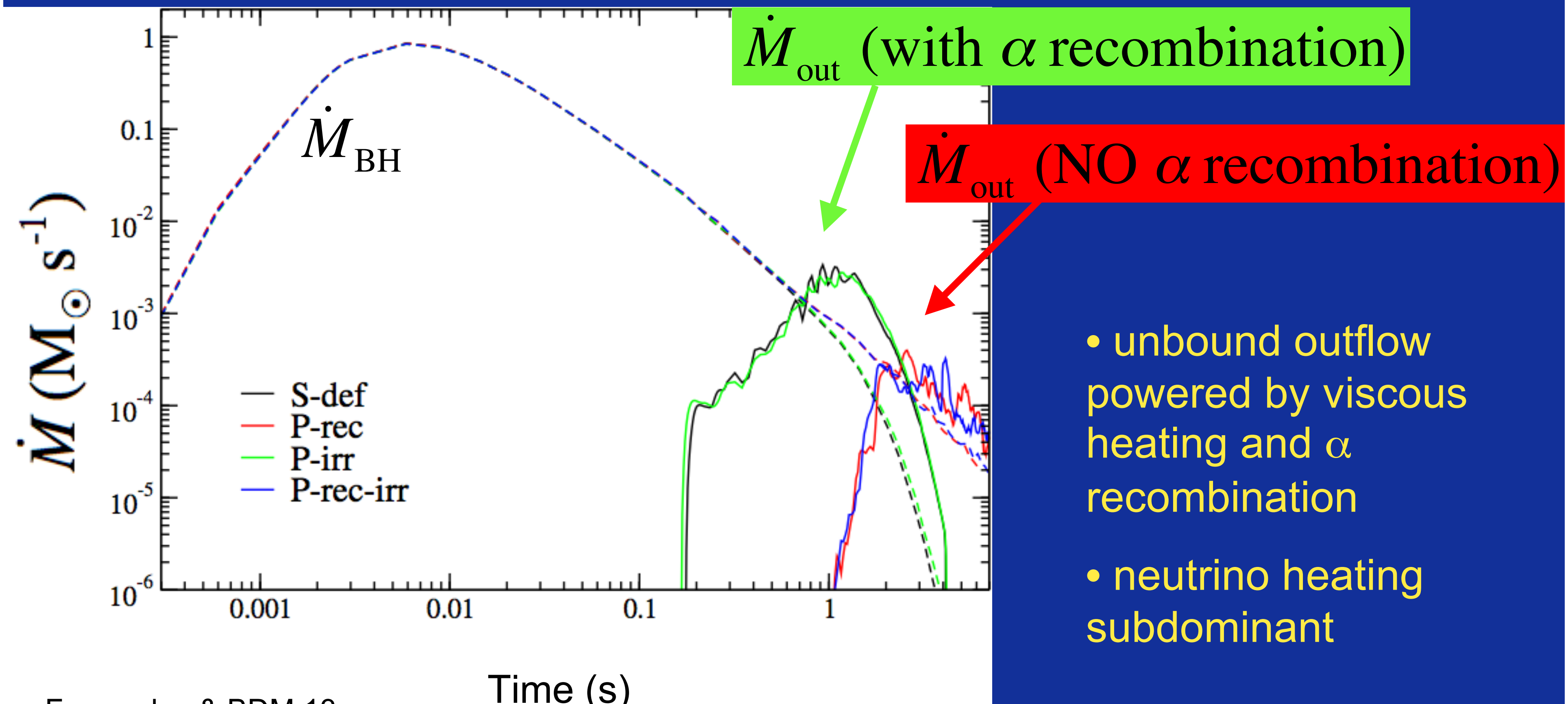
(Fernandez & Metzger 2012, 2013)

- P-W potential with $M_{BH} = 3{,}10\ M_{\odot}$
- hydrodynamic α viscosity
- NSE recombination 2n+2p ⇒ ^{4}He
- run-time $\Delta t \sim 1000\text{-}3000\ t_{orb}$
- neutrino self-irradiation: "light bulb" + optical depth corrections:





Delayed Disk Outflows



Fernandez & BDM 13

- unbound outflow powered by viscous heating and α recombination
- neutrino heating subdominant

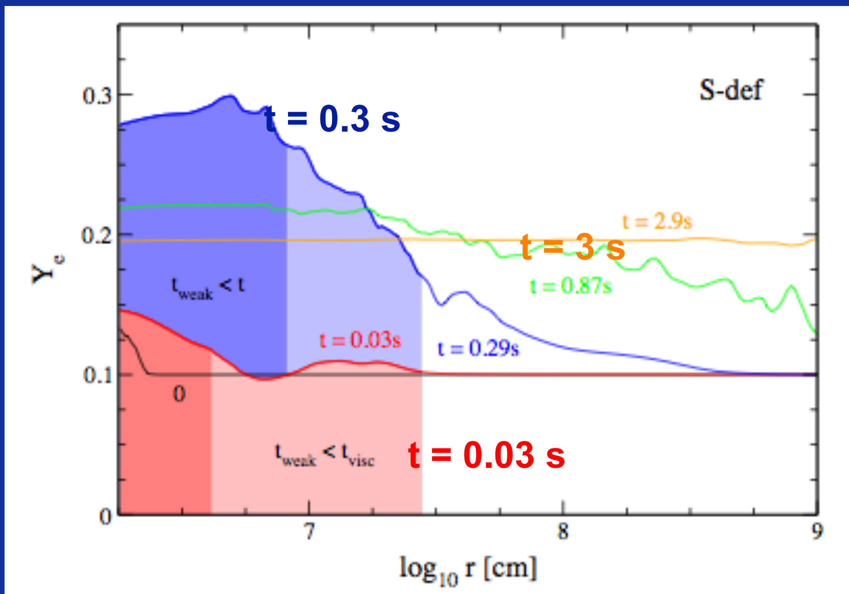
outflow robust

$$M_{ej} \sim 0.05\ M_t \quad V_{ej} \sim 0.1\ c$$

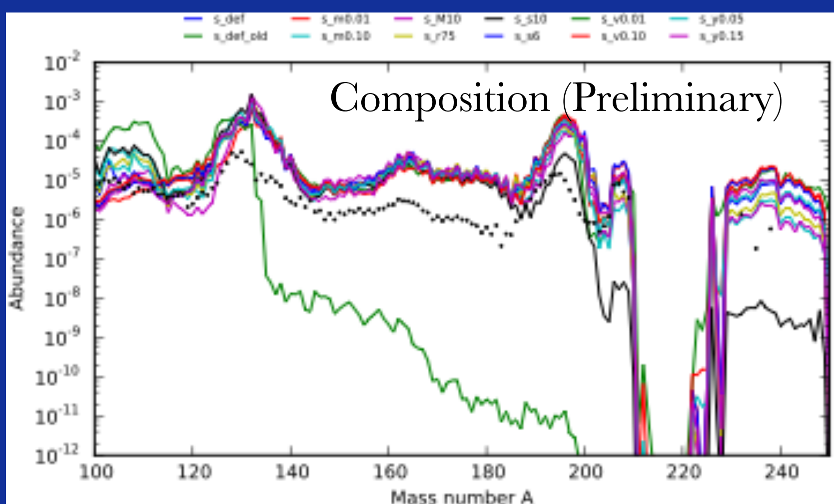
compare with Just et al. (2014), who find $M_{ej} \sim 0.2\ M_t$

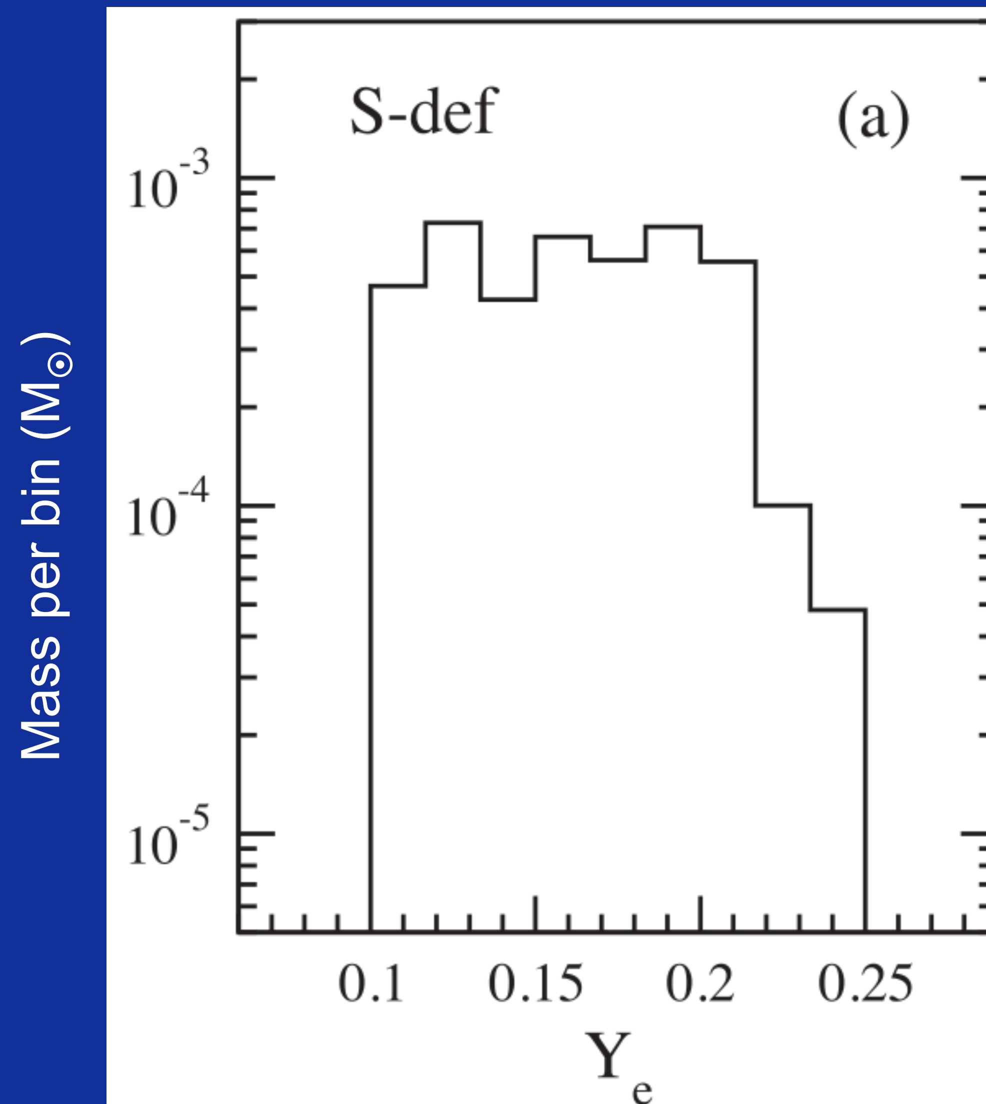
Outflow Composition

Y_e Freeze Out



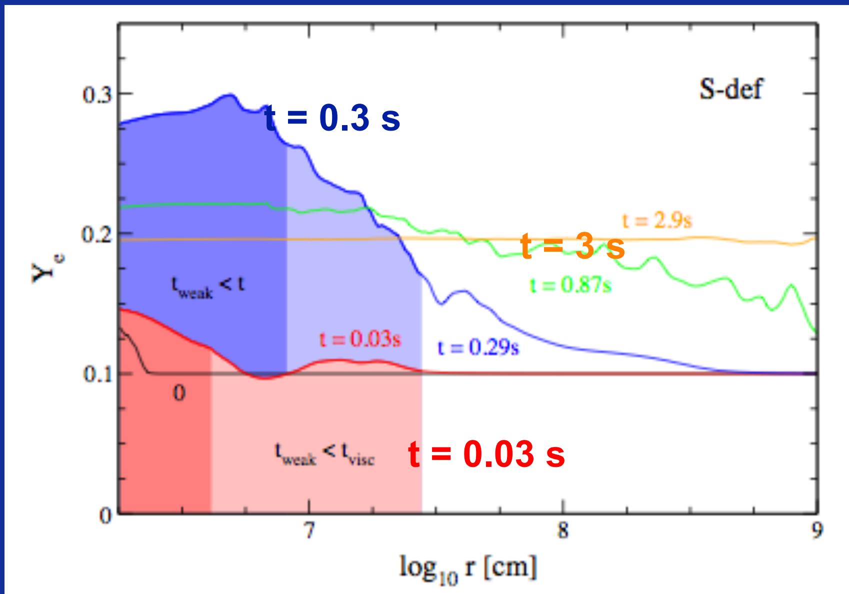
⇒ still produces lanthanides



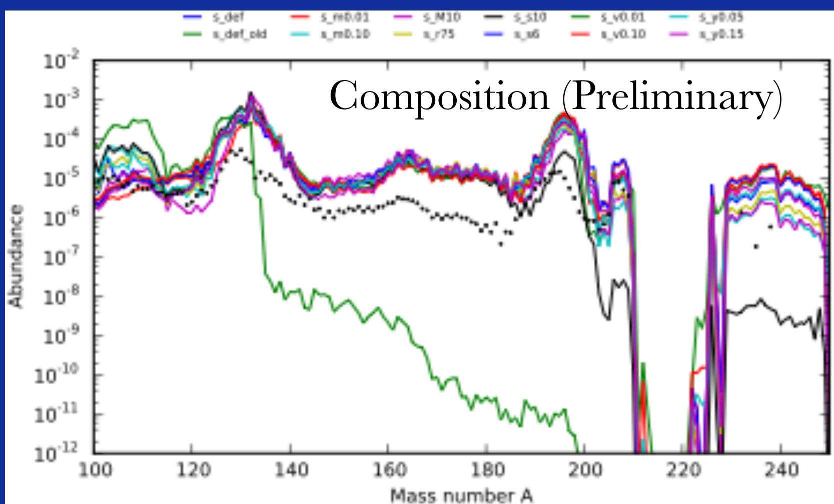


Outflow Composition

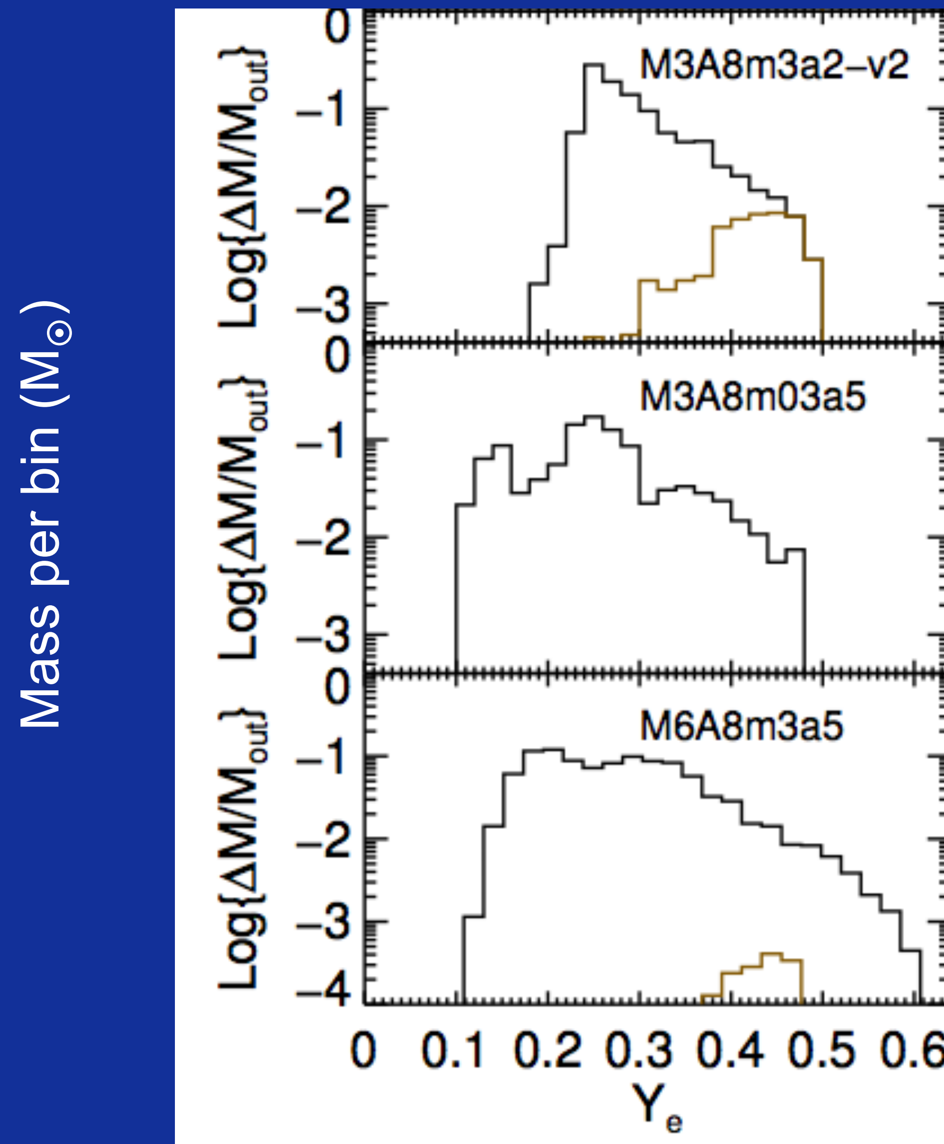
Y_e Freeze Out



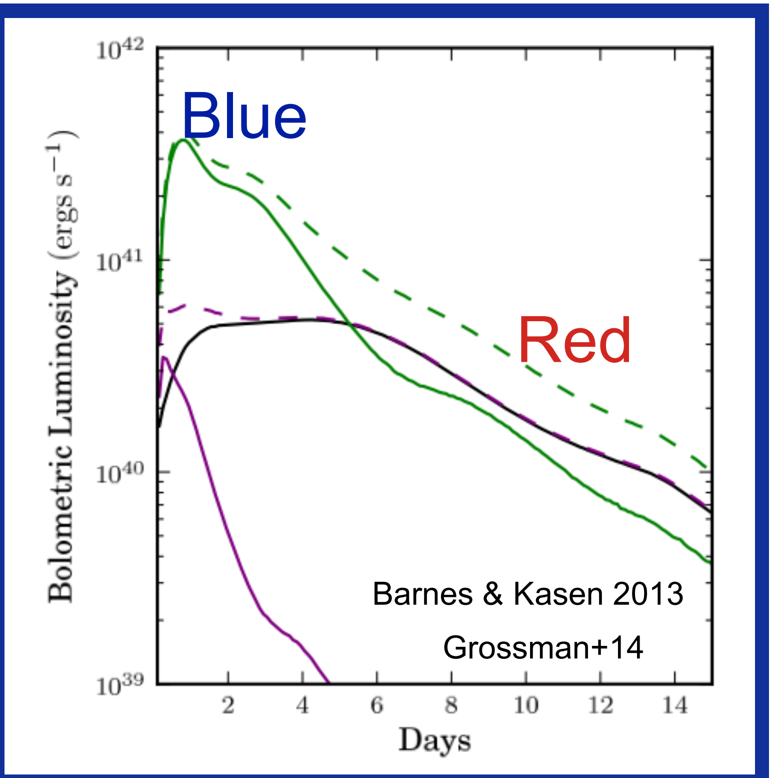
⇒ still produces lanthanides

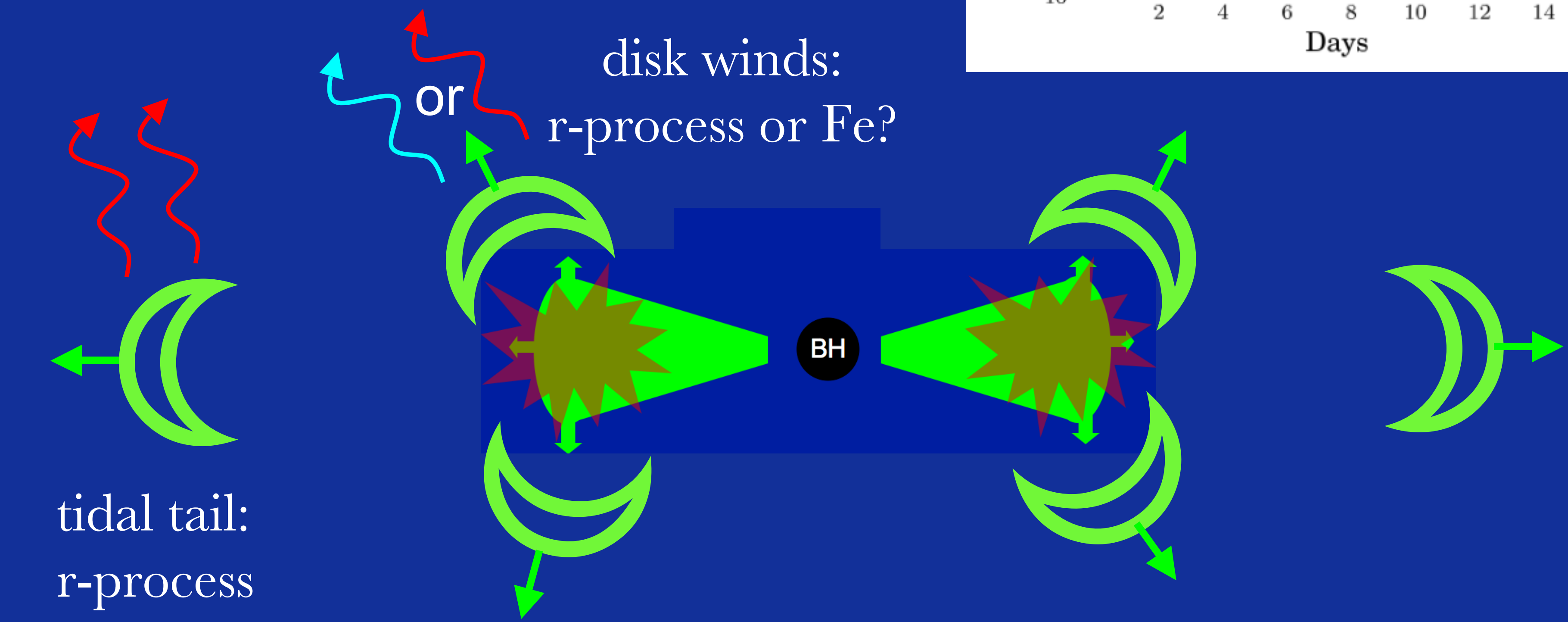


Compare with: Just et al. 2014

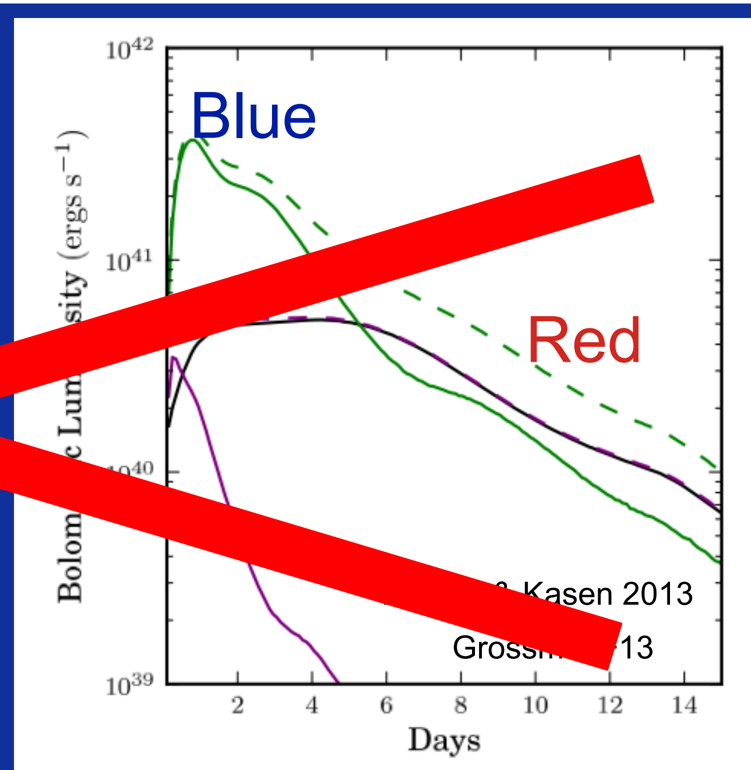


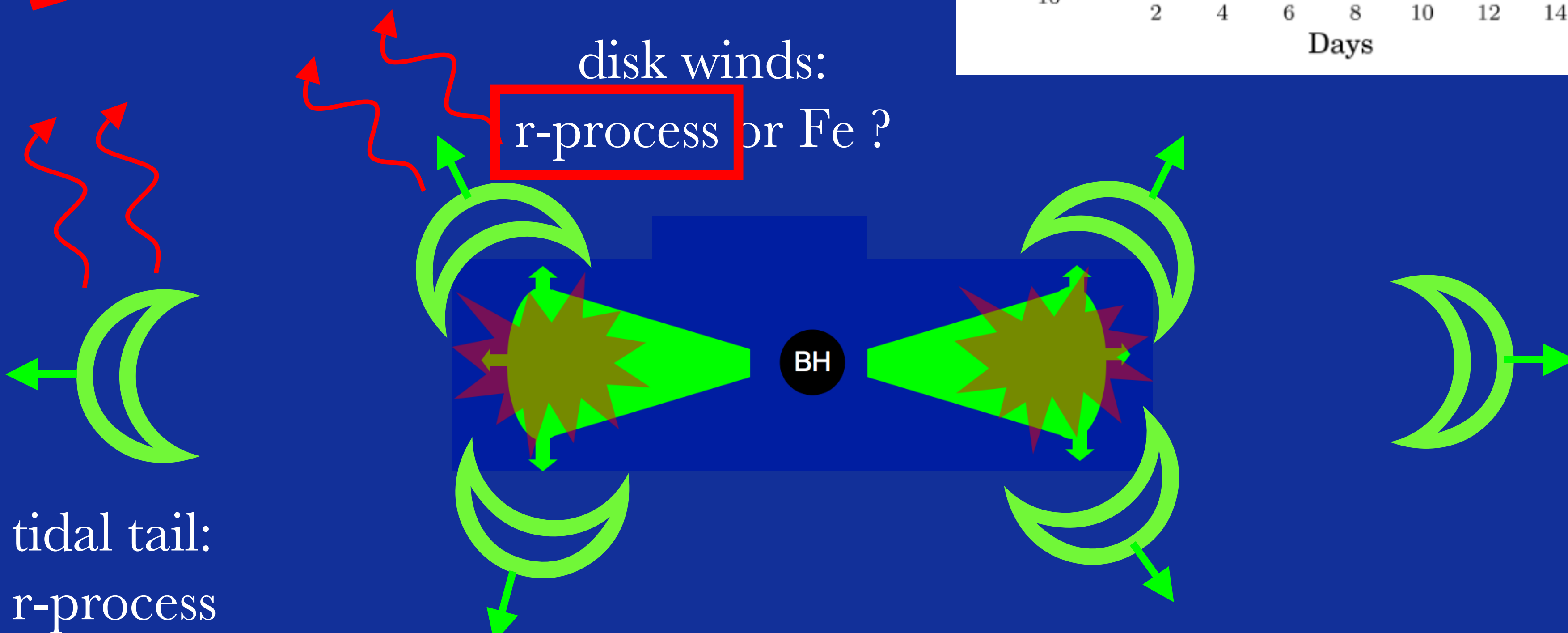
Two Component Light Curve





Two Component Light Curve





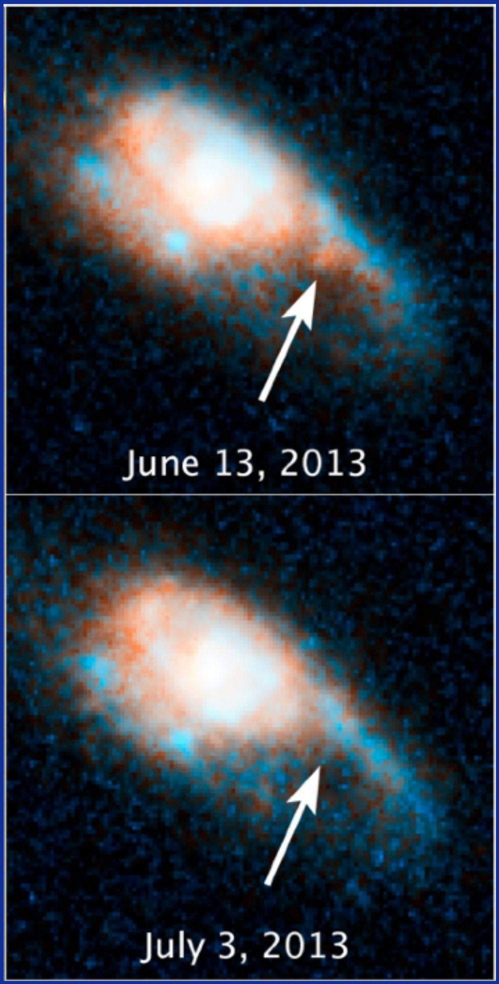
An r-Process Kilonova Associated with the Short-Hard GRB 130603B

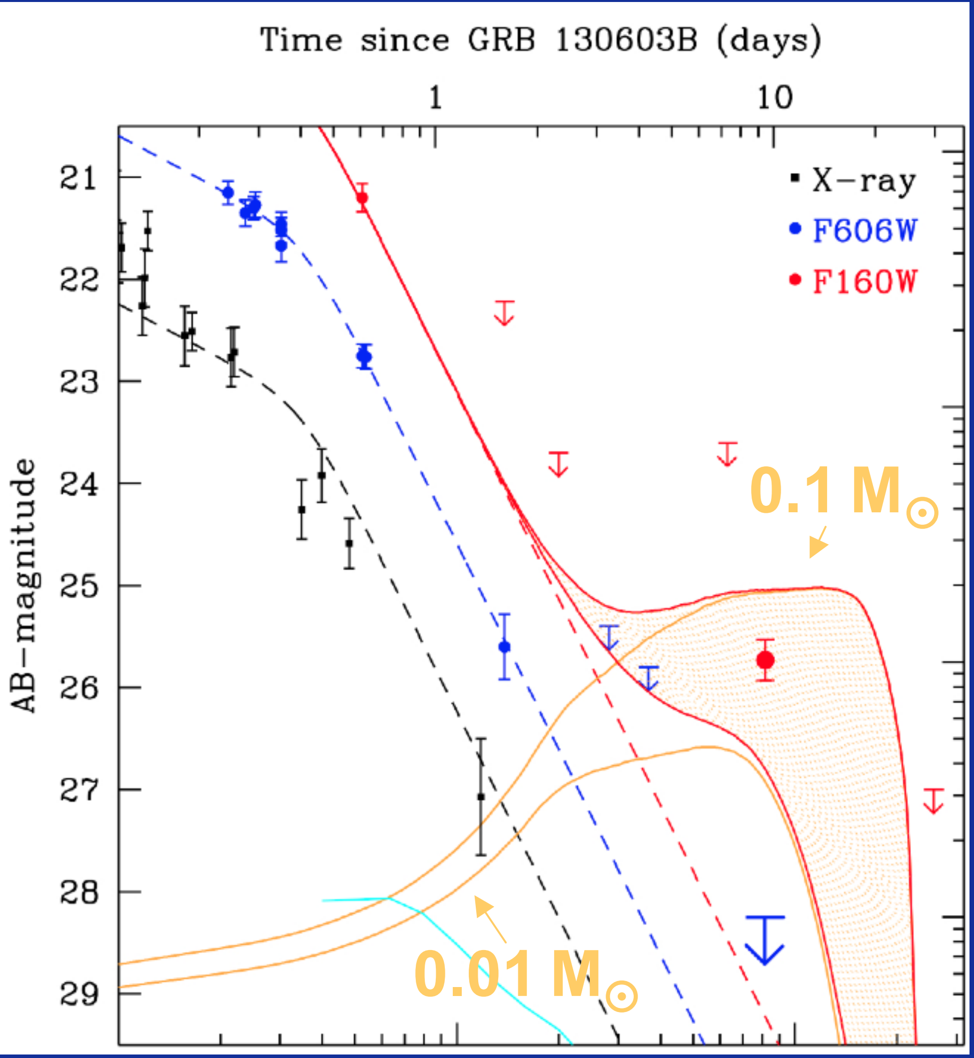
E. Berger[1], W. Fong[1], and R. Chornock[1]

A 'kilonova' associated with the short-duration γ- ray burst GRB 130603B

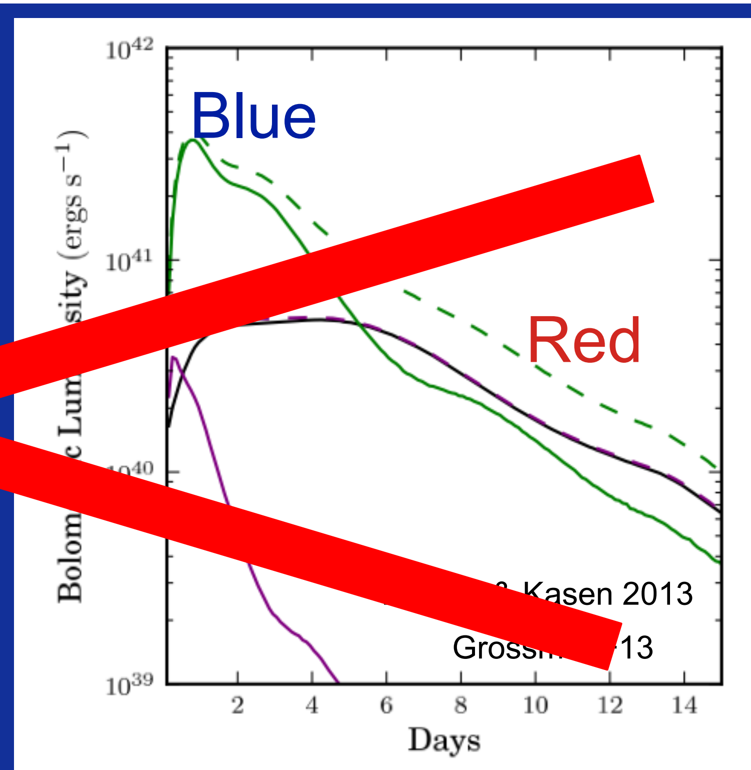
N. R. Tanvir, A. J. Levan, A. S. Fruchter, J. Hjorth, R. A. Hounsell, K. Wiersema & R. L. Tunnicliffe

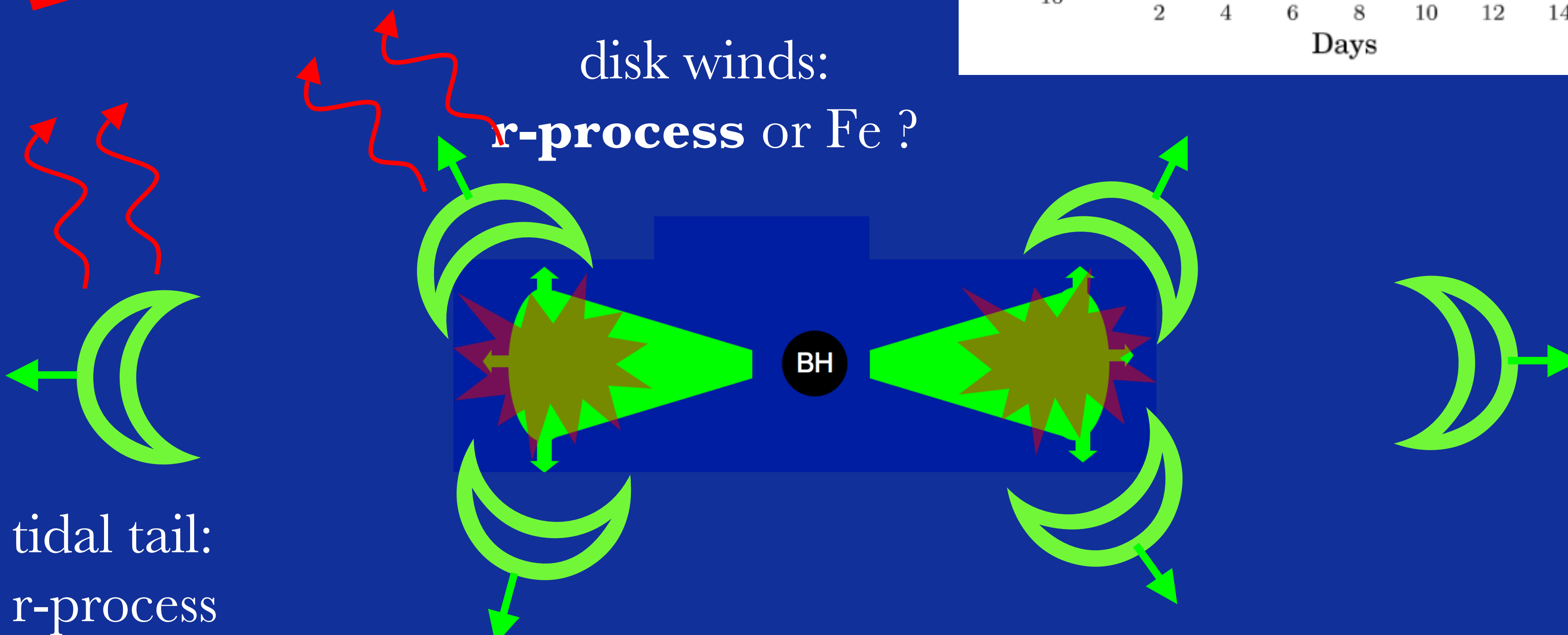
Tanvir et al. 2013



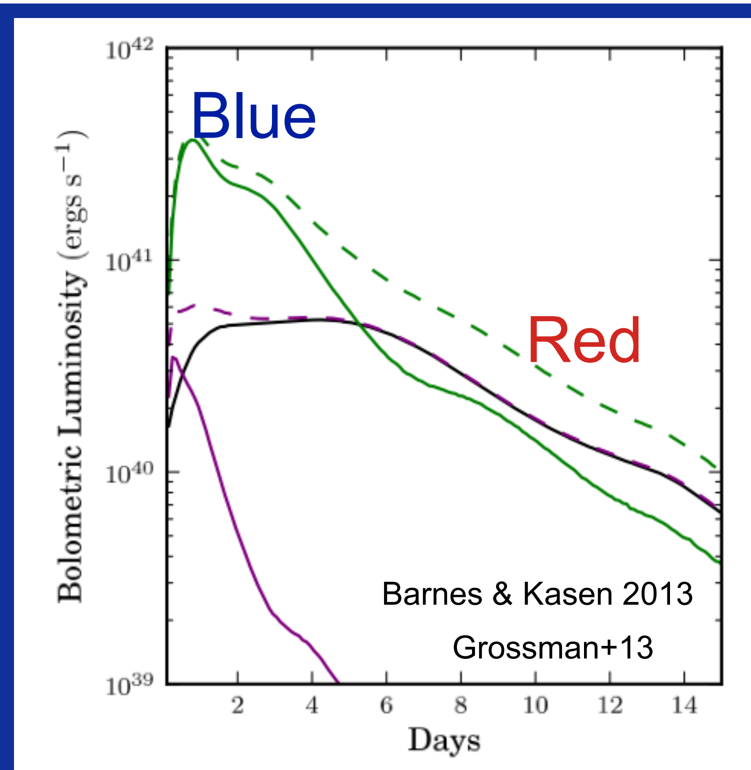


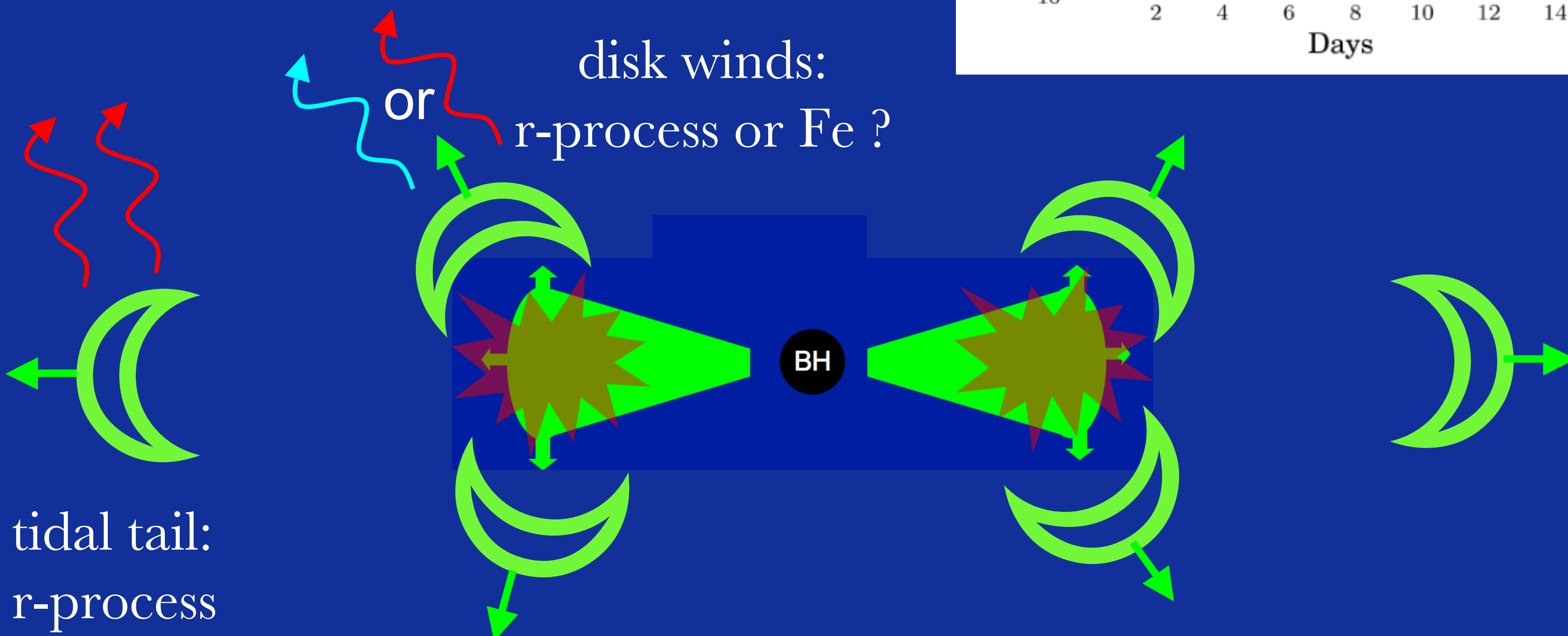
Two Component Light Curve



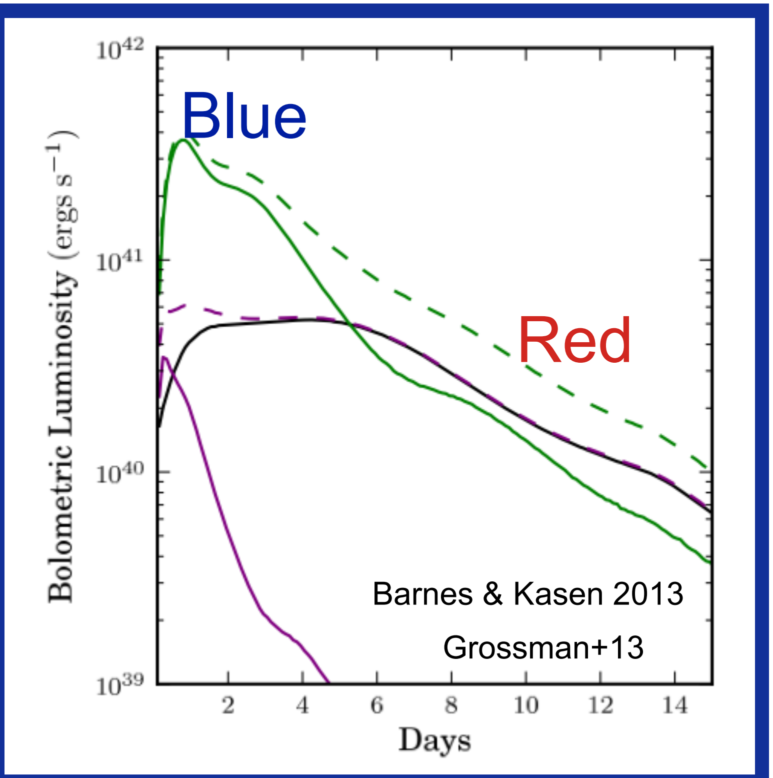


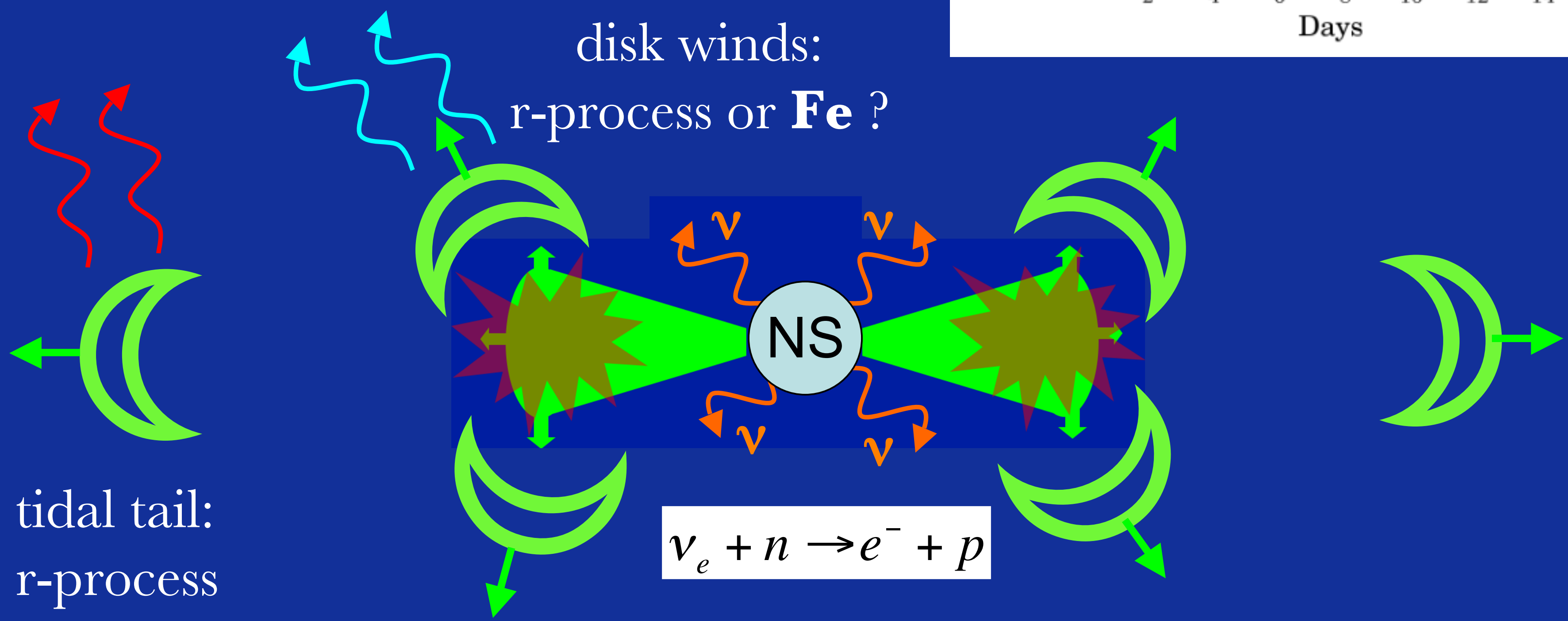
Two Component Light Curve





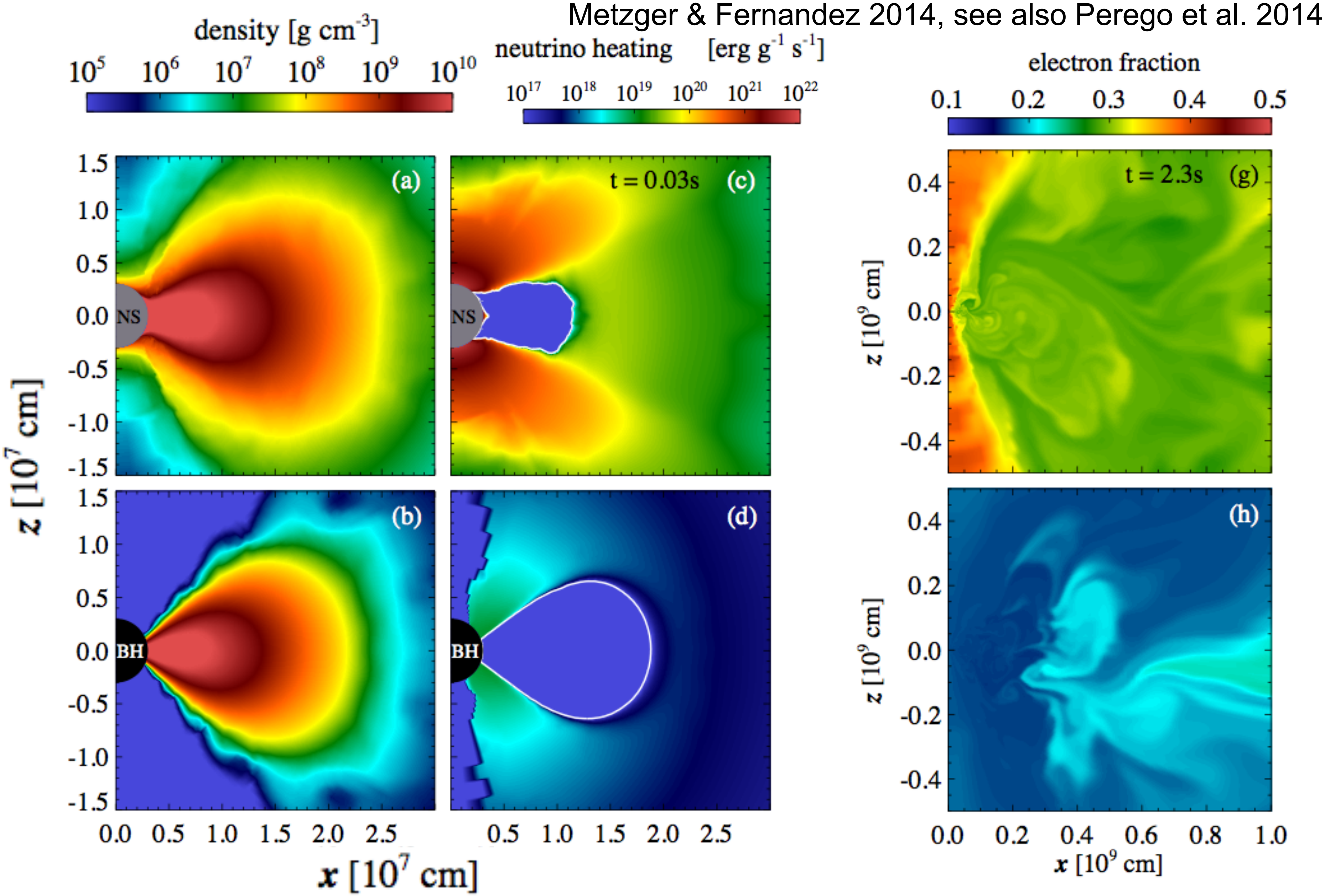
Two Component Light Curve



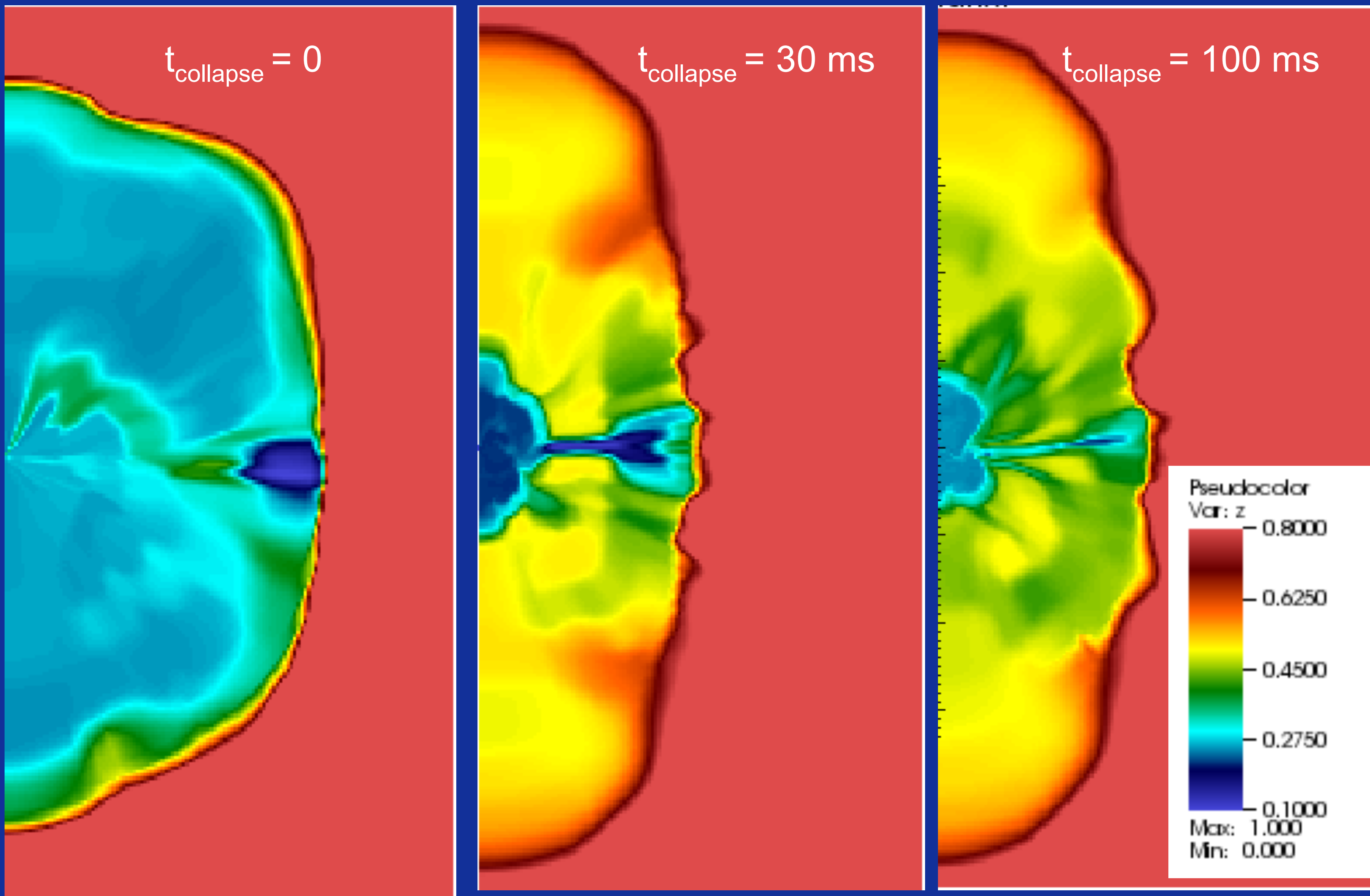


Effect of Hypermassive Neutron Star

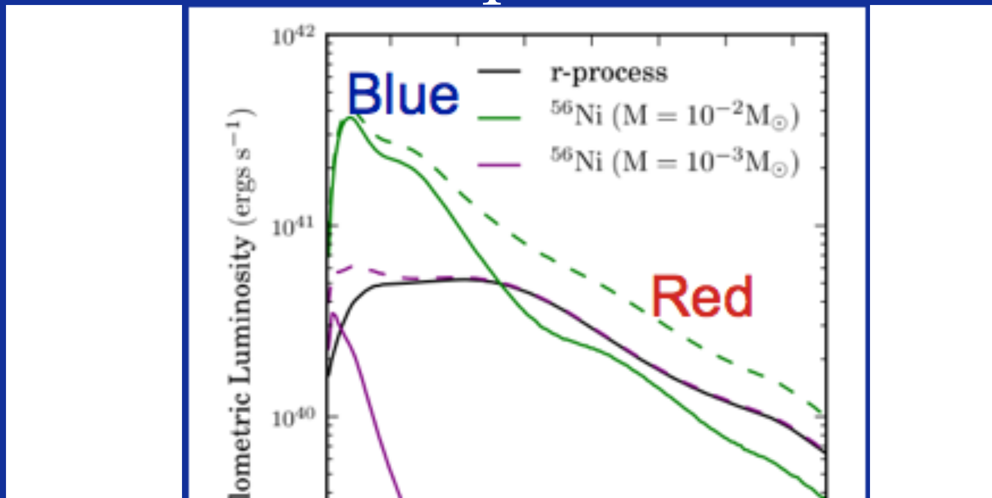
Metzger & Fernandez 2014, see also Perego et al. 2014

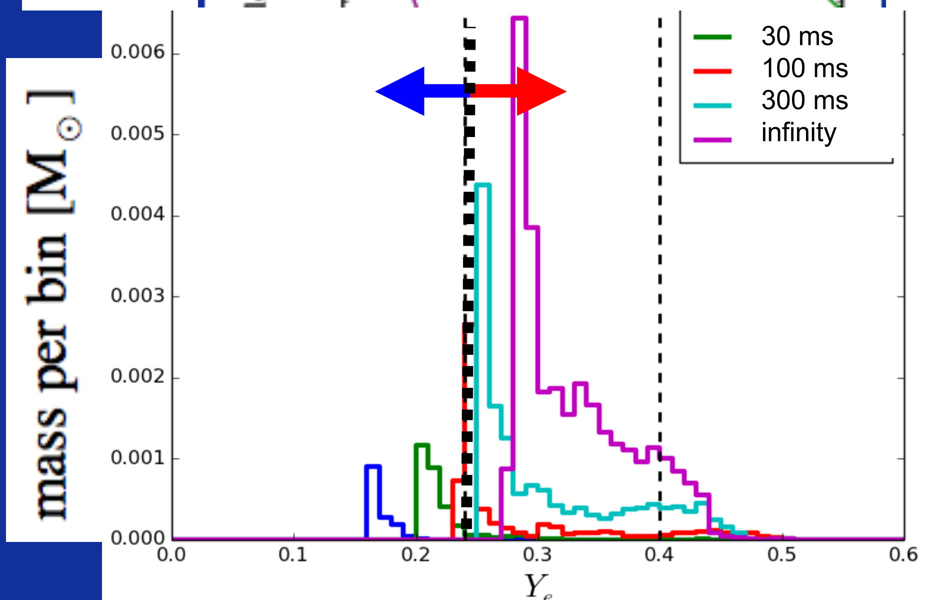


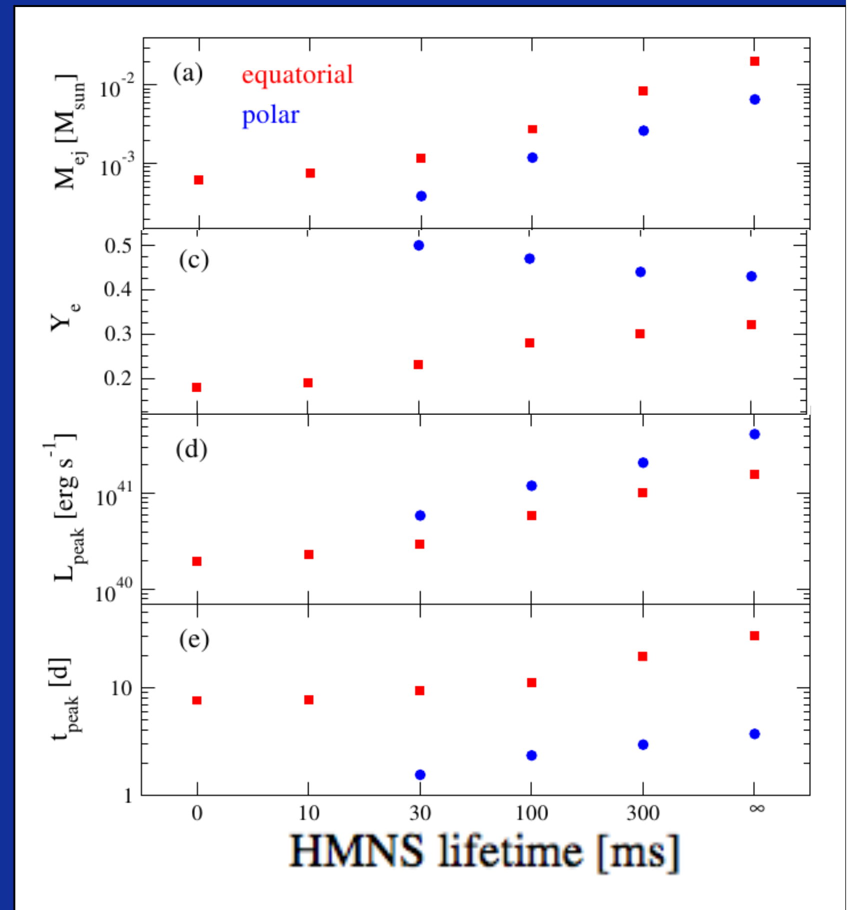
Distribution of Ejecta Y_e for Different Collapse Times



Imprint of the HMNS Lifetime







- **strength of 'blue bump' may encode HMNS lifetime**
- **ejecta mass up to ~10 times higher than prompt BH case**

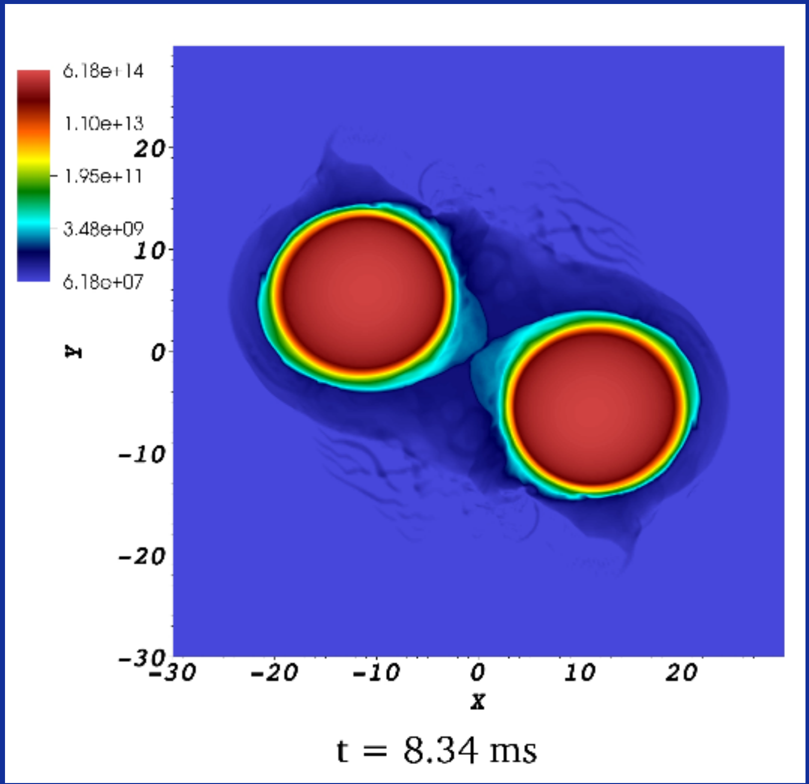
Stable Merger Remnant?

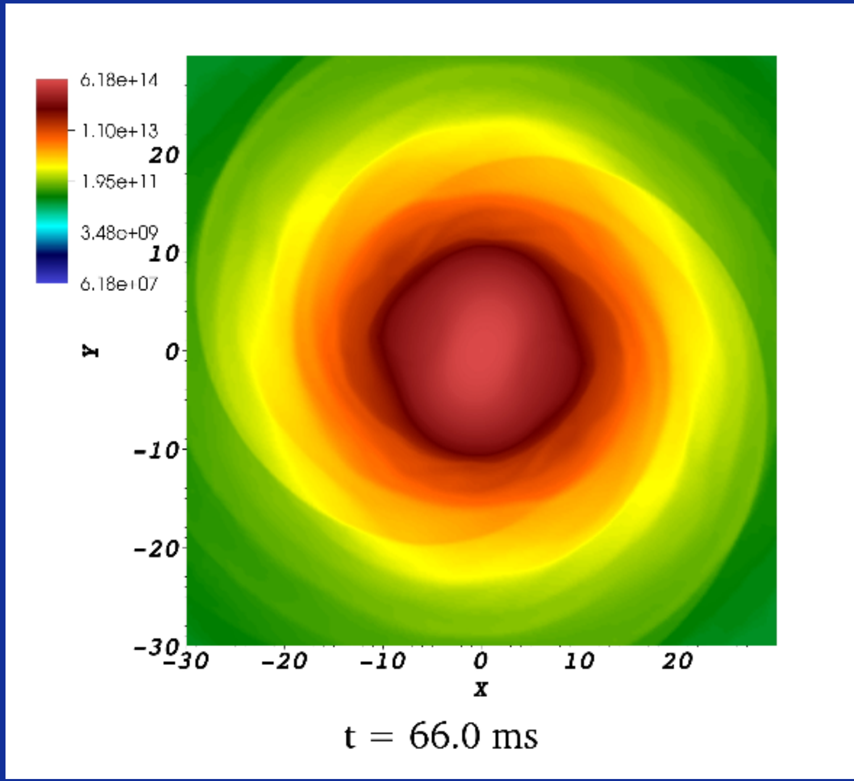
(e.g. BDM+08; Ozel et al. 2010; Bucciantini et al. 2012; Zhang 13; Yu et al. 2013; Giacomazzo & Perna 13; Siegel 2014)

- Requires: low total mass binary, stiff EOS*, and/or mass loss during merger

  *supported by recent discovery of $2M_\odot$ NS by Demorest et al. 2011

- Rotating at centrifugal break-up limit with spin period P ~ 1 ms
- Magnetic field amplified by rotational energy + convection ⇒ **“Magnetar” ?**

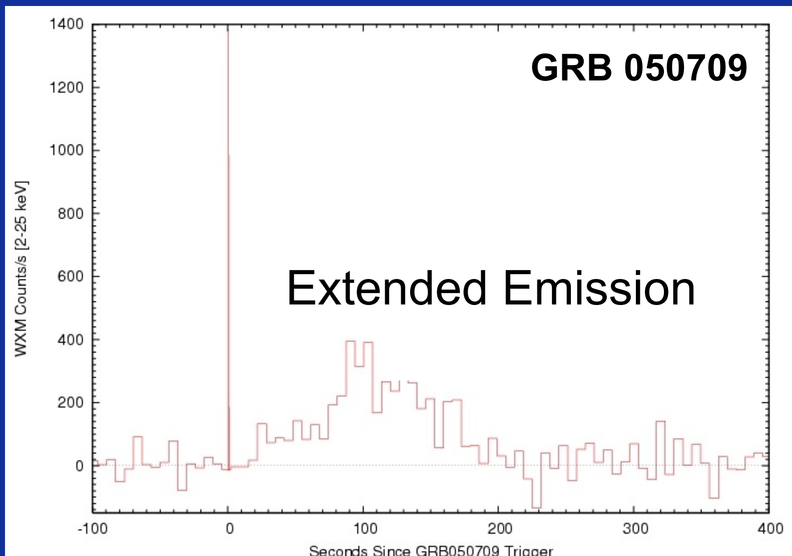


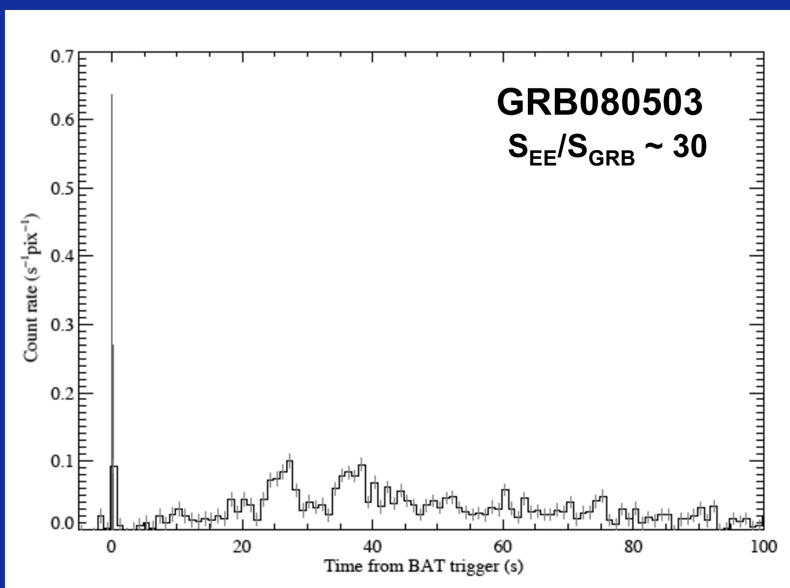


Giacomazzo & Perna 2013

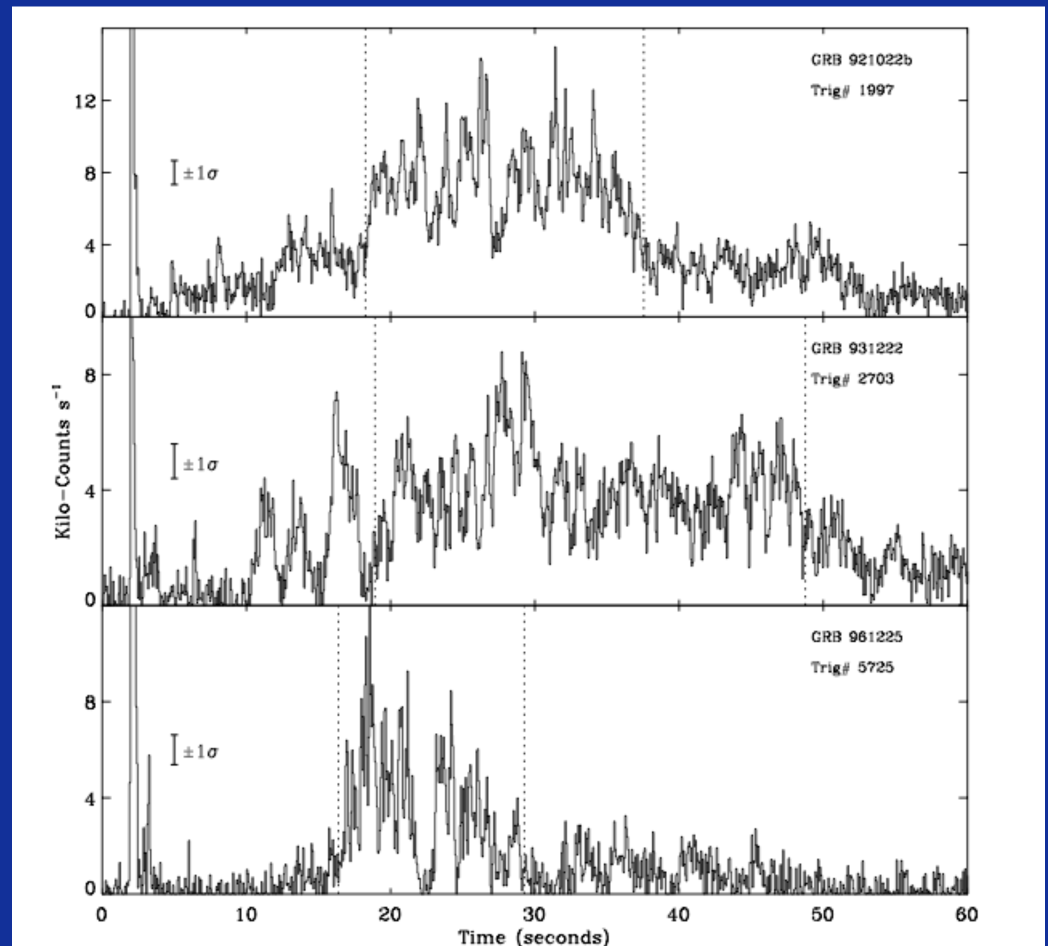
Short GRBs with Extended Emission

- 1/5 Swift Short Bursts have X-ray Tails
- Rapid Variability ⇒ Ongoing Engine Activity
- Energy up to ~30 times Burst Itself!





Perley, BDM et al. 2009



BATSE Examples (Norris & Bonnell 2006)

Stable Merger Remnant?

(e.g. BDM+08; Ozel et al. 2010; Bucciantini et al. 2012; Zhang 13; Yu et al. 2013; Giacomazzo & Perna 13; Siegel 2014)

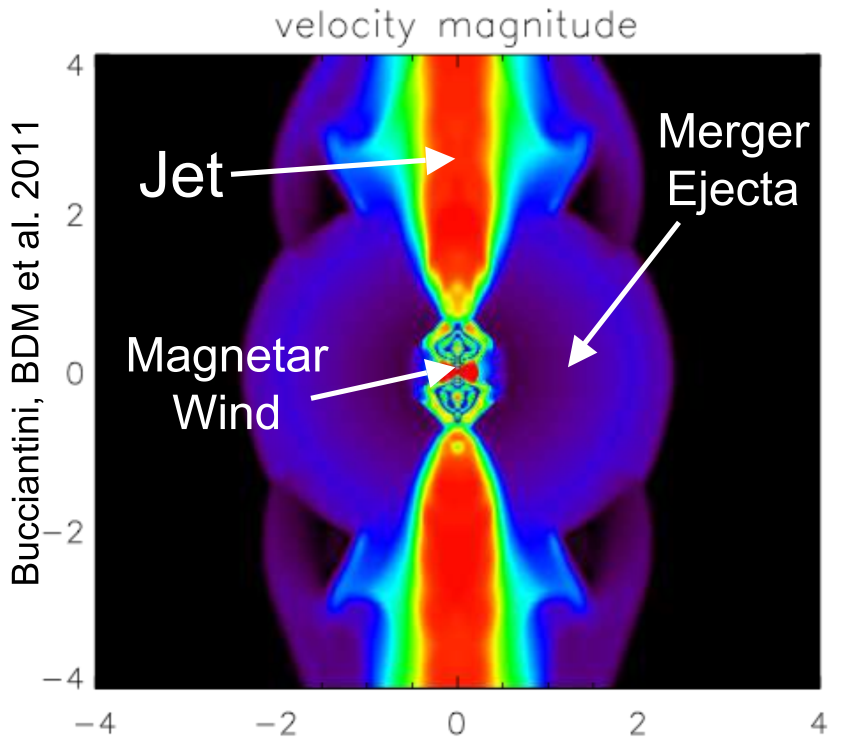
spin-down luminosity :

$$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{49} \left(\frac{P}{1\text{ ms}}\right)^{-4} \left(\frac{B_{dip}}{10^{15}\text{ G}}\right)^{2} \text{erg s}^{-1}$$

spin-down time :

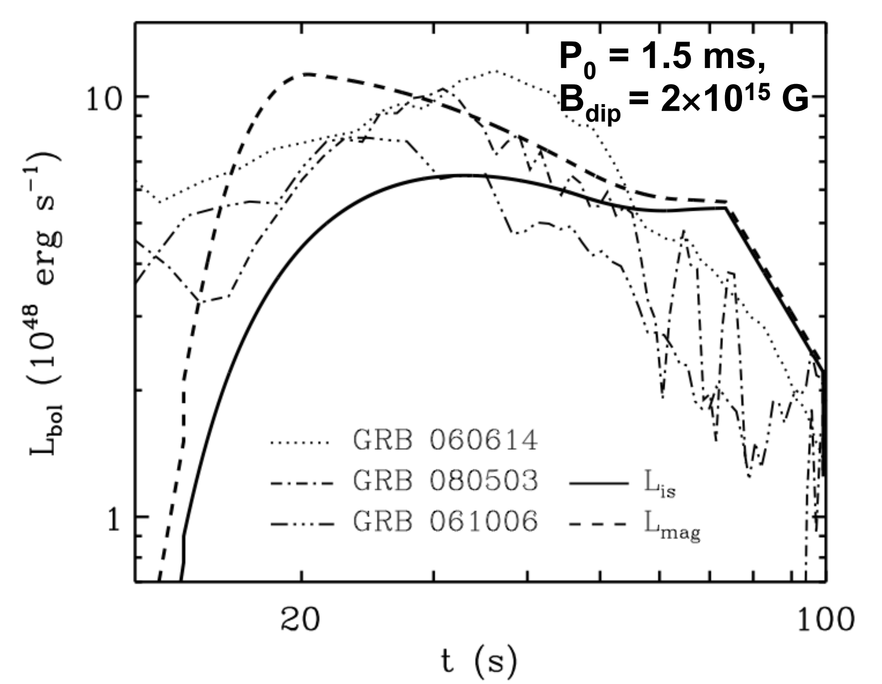
$$\tau_{sd} = \frac{E_{rot}}{L_{sd}} \approx 5 \left(\frac{P_0}{1\text{ ms}}\right)^{2} \left(\frac{B_{dip}}{10^{15}\text{ G}}\right)^{-2} \text{min}$$

Magnetar wind confined by merger ejecta



Theoretical Light Curves vs. Observed X-ray Tails

(magnetar wind model from Metzger et al. 2011)



Radio constraints on stable merger remnants

(BDM & Bower 2013)

- Rotational energy

$$E_{\rm rot} = \frac{1}{2}I\Omega^2 \simeq 3 \times 10^{52}{\rm ergs}\left(\frac{P}{1\ {\rm ms}}\right)^{-2}$$

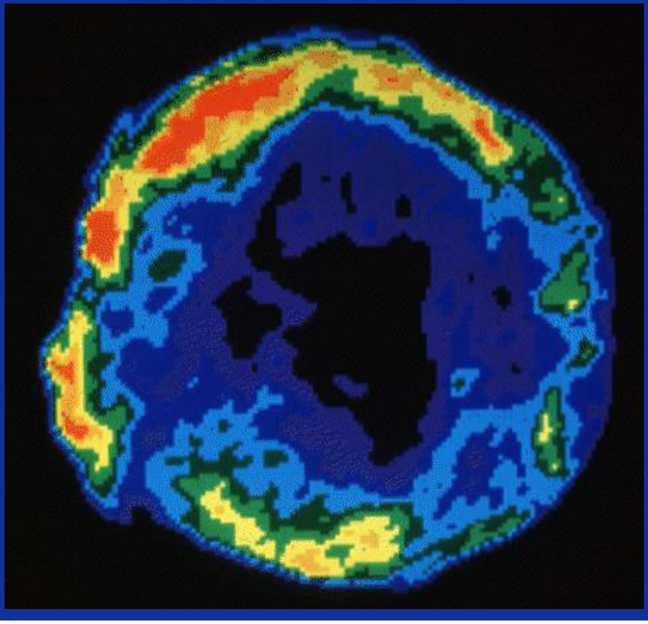
eventually transferred to ISM via relativistic shock ⇒ bright radio emission

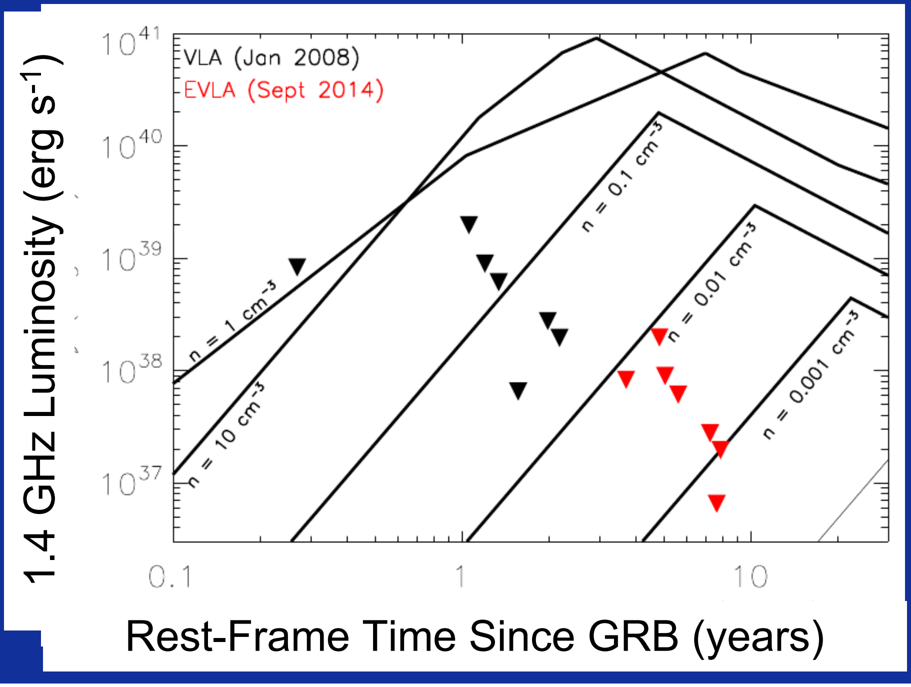
- We observed 7 short GRBs with VLA on timescales ~1-3 years after burst

- NO DETECTIONS
⇒ stable remnant disfavored in 2 GRBs with high ISM densities

- Additional JVLA observations now would be much more constraining

- Upcoming radio surveys (e.g. ASKAP) will strongly constrain stable NS merger remnants ⇒ indirectly probes EoS





Timeline of Binary NS Mergers

1. Chirp enters LIGO Bandpass	t (minus) ~ mins
2. Last Orbit, Plunge & Dynamical Ejecta	t ~ ms
3. BH Formation	~ ms - ∞
4. Accretion of Remnant Disk, Jet Formation (GRB)	~ 0.1-1 s
5. He-Recombination + Disk Evaporation ⇒ outflow Y_e depends on NS collapse time	~ 0.3-3 s
6. R-Process in Merger Ejecta	~ few s
7. Jet from Magnetar (**X-rays**)	~ min (or longer)
8. Disk Wind Kilonova	
⇒ prompt BH formation $Y_e < 0.25$ (NIR, $L \sim 10^{41}$ erg s^{-1})	~ week
⇒ delayed BH formation $Y_e > 0.25$ (Optical, $L \sim 10^{42}$ erg s^{-1})	~ day
⇒ stable magnetar (Optical, $L \sim 10^{44}$ erg s^{-1})	~ day
9. Tidal Tail Kilonova (**IR**)	~ week
10. Ejecta ISM Interaction (**Radio**) ⇒ Much brighter if stable magnetar	~ years

Conclusions

• Strong B fields and rapid rotation alter the properties of proto-neutron star winds due to magneto-centrifugal acceleration. Both the dynamical timescale and entropy increase, increasing S^3/t_{exp} by a factor ~4.

• Moderately rapidly rotating proto-magnetars thus represent a promising r-process site, consistent with observations.

• The first direct detection of gravitational waves will likely be a binary NS merger, within the next ~3 years. Identifying an EM counterpart will be essential to maximize the scientific impact of this discovery.

• The most promising isotropic counterpart is an optical/IR transient ("kilonova") powered by the radioactive decay of r-process nuclei.

• The radioactive heating of the ejecta is now well understood, but the photon opacity of r-process ejecta remains uncertain.

• The sensitive dependence of opacity on ejecta composition (lanthanide fraction) make kilonova colors a sensitive probe of physical processes at work during the merger, such as the delay until black hole formation.