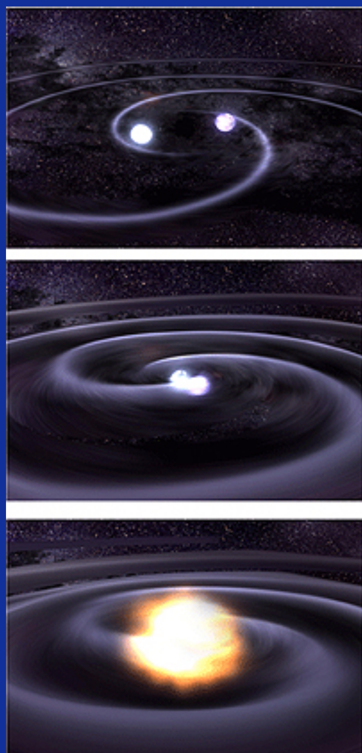
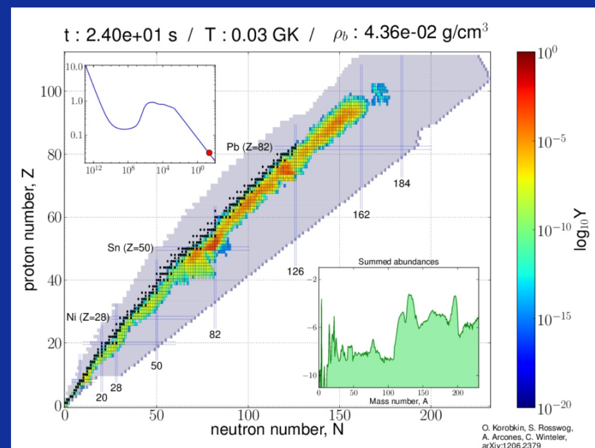
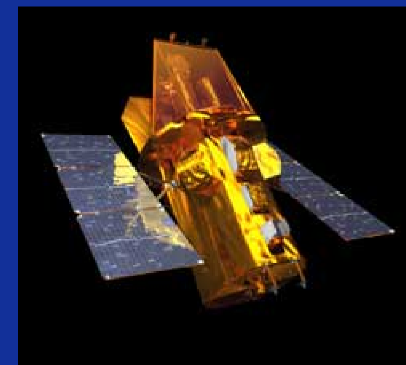
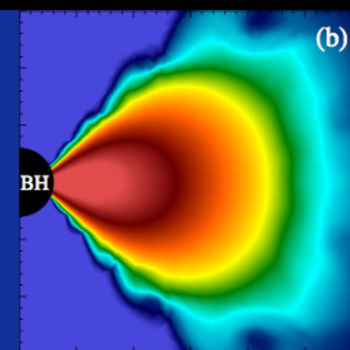
Signatures of Binary Neutron Star Mergers









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Edo Berger, Wen-Fai Fong (Harvard), Tony Piro, Dan Perley (Caltech)

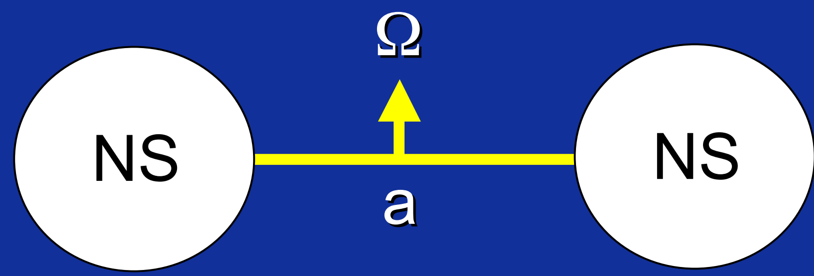
Almudena Arcones, Gabriel Martinez-Pinedo (GSI/TU Darmstadt)

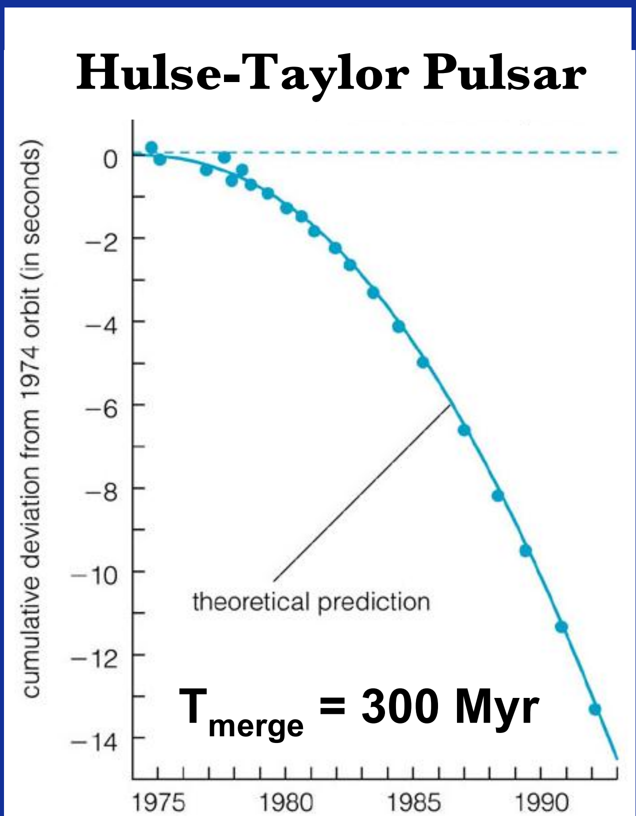
Institute for Nuclear Theory Colloquium, U Washington, July 21, 2014

Binary Neutron Star Mergers

Gravitational Waves

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





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)

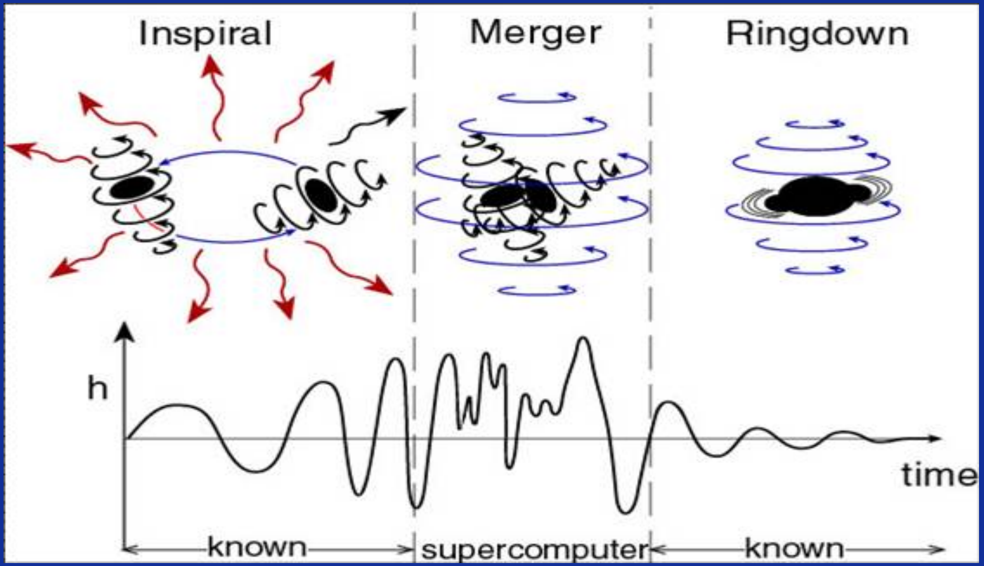
Gravitational Wave Sources

"Advanced" LIGO / Virgo

Range ~ 200-500 Mpc

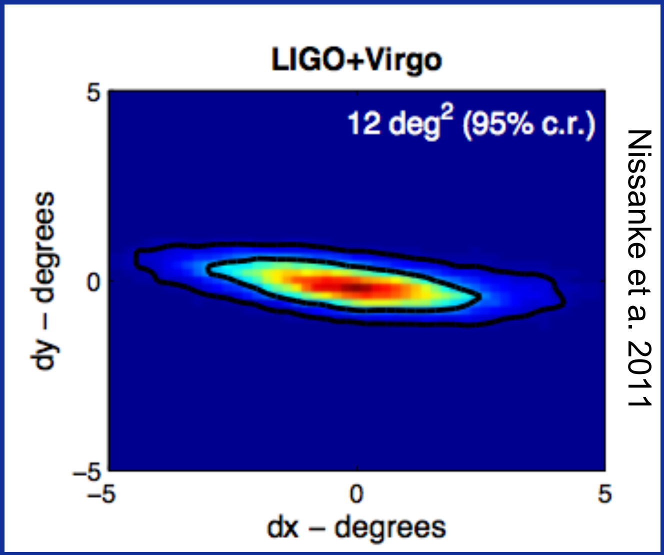
Detection Rate ~ 1-100 yr^{-1}

LIGO (North America)

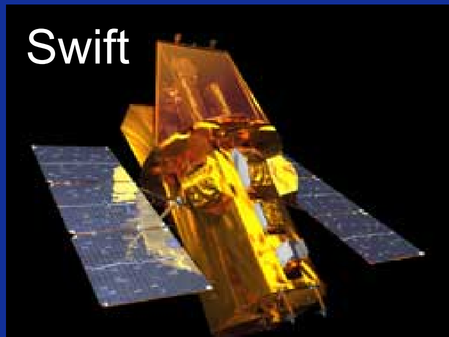


Sky Error Regions ~ 10-100 deg^2

Virgo (Europe)



Gamma-Rays



BAT FOV ~ 15%

XRT slews in ~min

Fermi Gamma-ray Space Telescope

GBM FOV ~ 60%

Radio

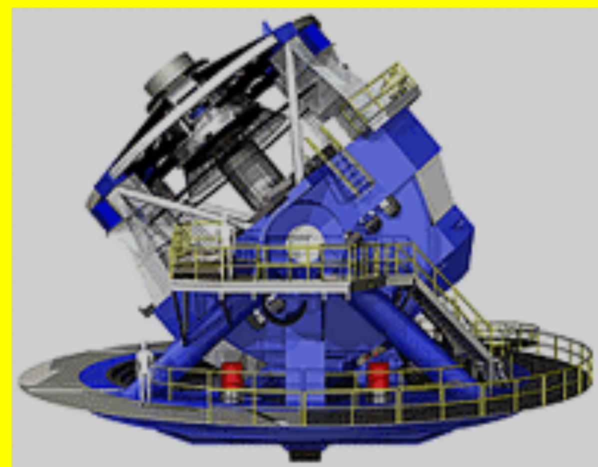
Expanded Very Large Array

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

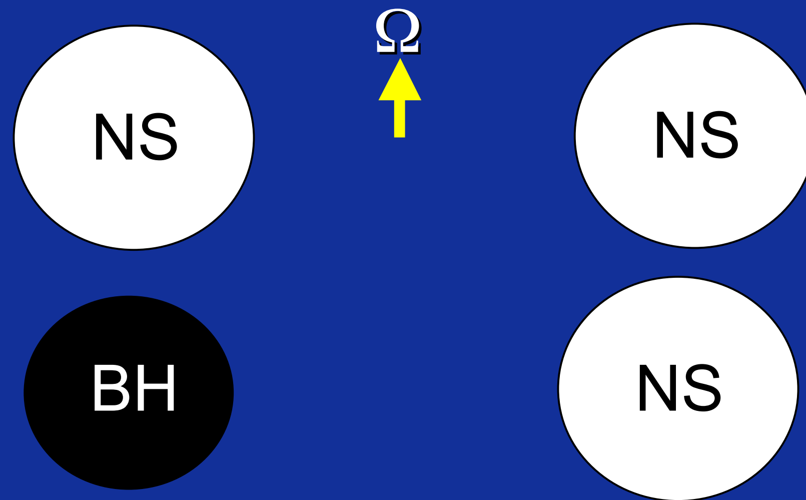
“Advanced” LIGO/Virgo (>2016)

Range ~ 200-500 Mpc

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

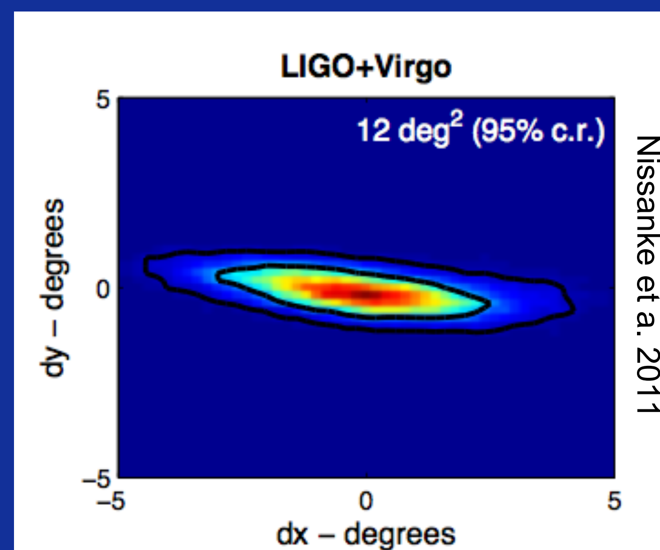
LIGO (North America)

Virgo (Europe)



Sky Error Regions ~ 10-100 deg^2

$\Rightarrow$ ~ 10^3-10^4 galaxies



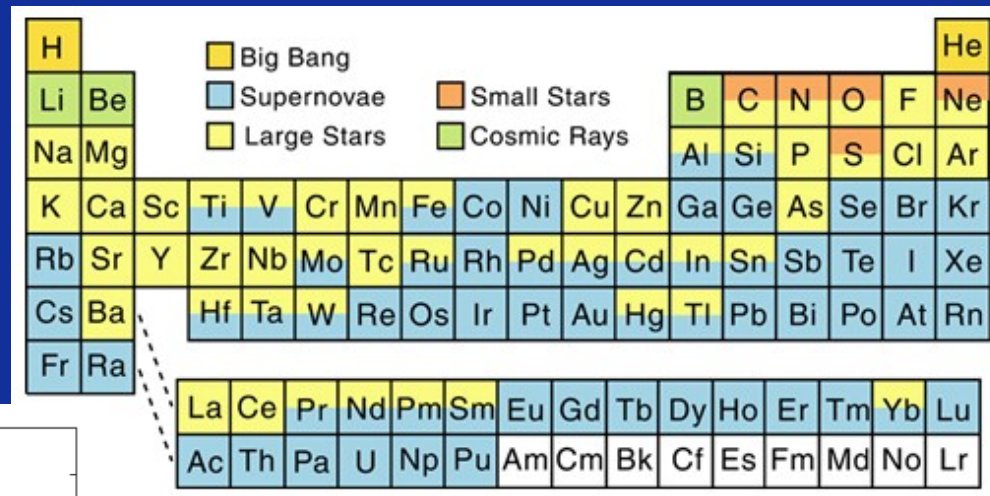
Origin of R-Process Nuclei

Core Collapse Supernovae or NS Binary Mergers?

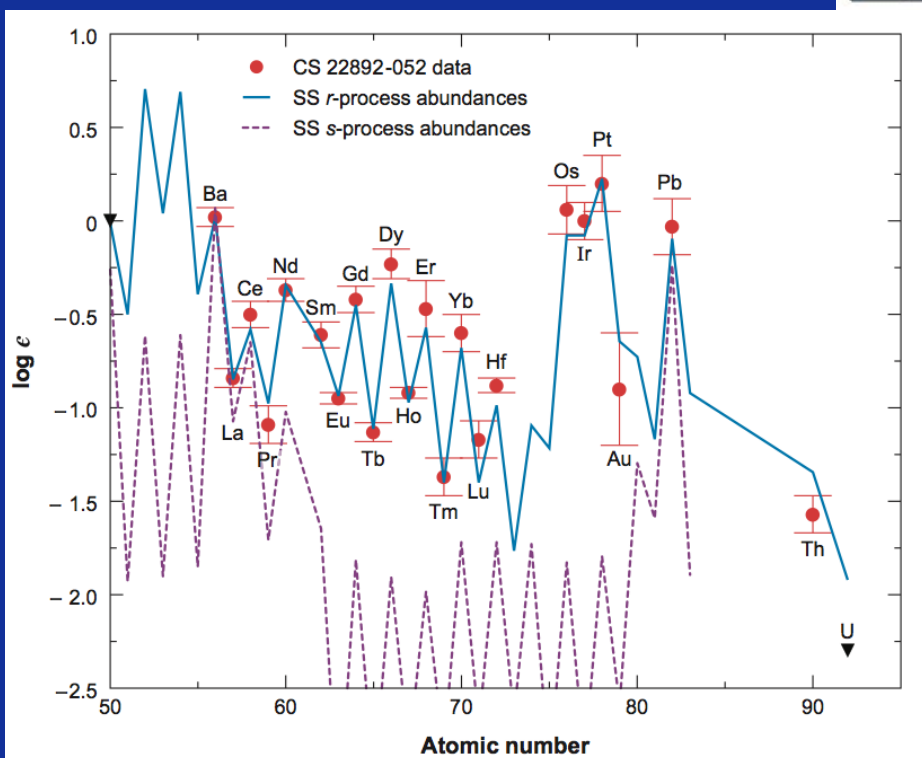
Galactic r-process rate:

$$\dot{M}_{A>130} \sim 5\times10^{-7}\, M_\odot\ \mathrm{yr}^{-1}$$

(Qian 2000)



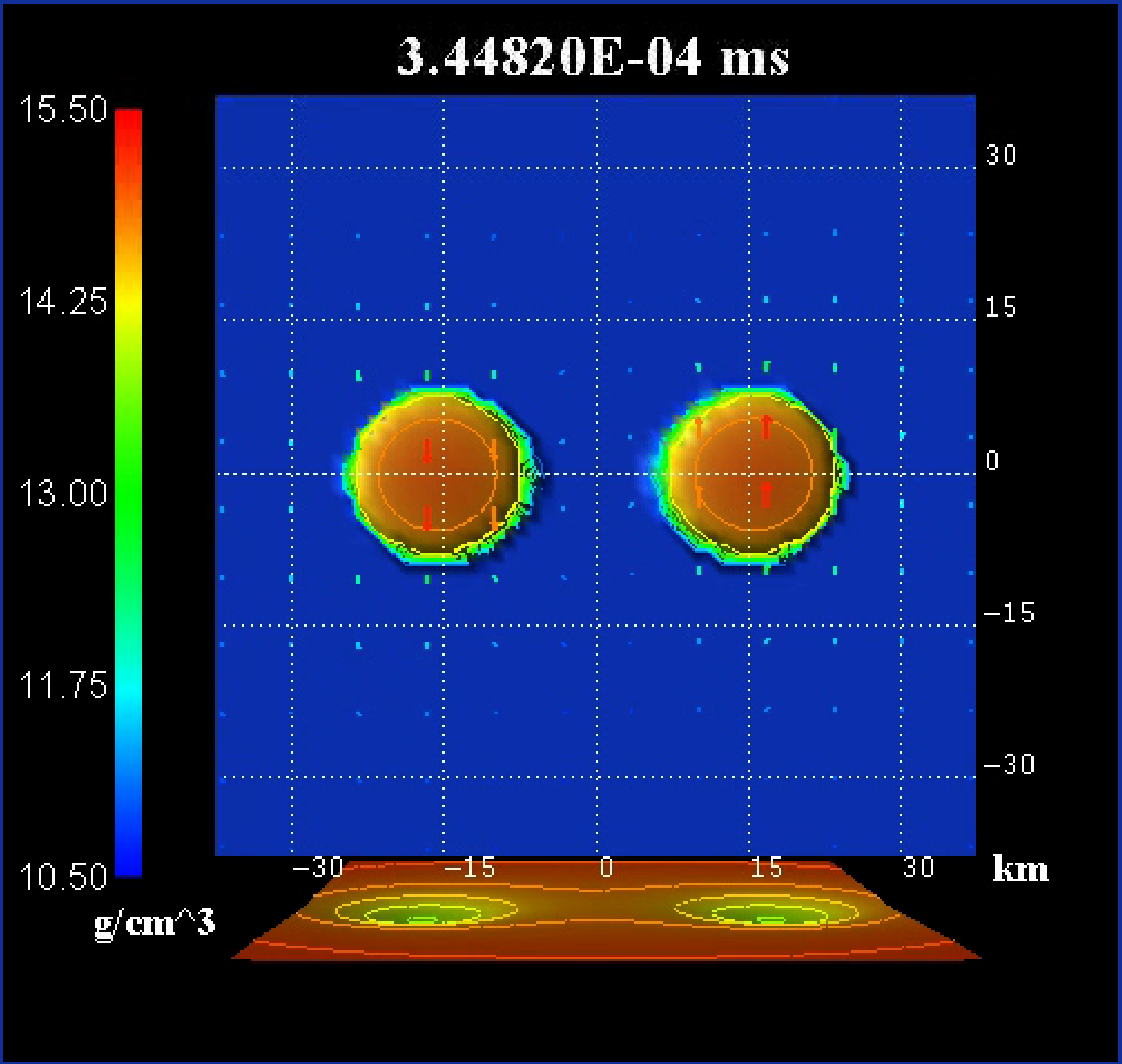
Snedan, Cowan & Gallino 2008



fraction of r-process contributed by NS Mergers:

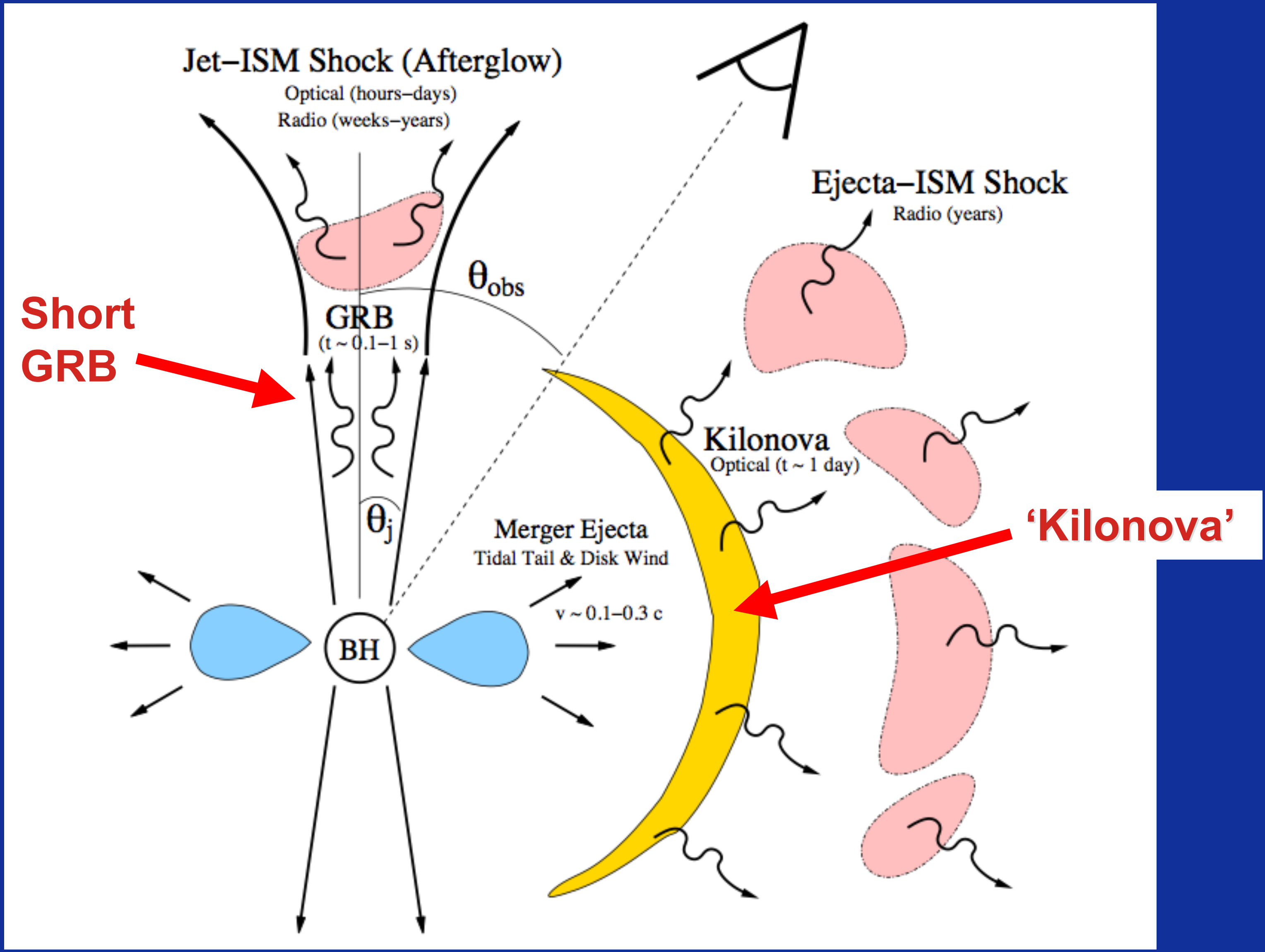
$$f_R \sim \left(\frac{\dot{N}_{\mathrm{merge}}}{10^{-4}\ \mathrm{yr}^{-1}}\right)\left(\frac{\overline{M}_{\mathrm{ej}}}{10^{-2}\, M_\odot}\right)$$

Numerical Simulation - Two 1.4 $M_\odot$ NSs



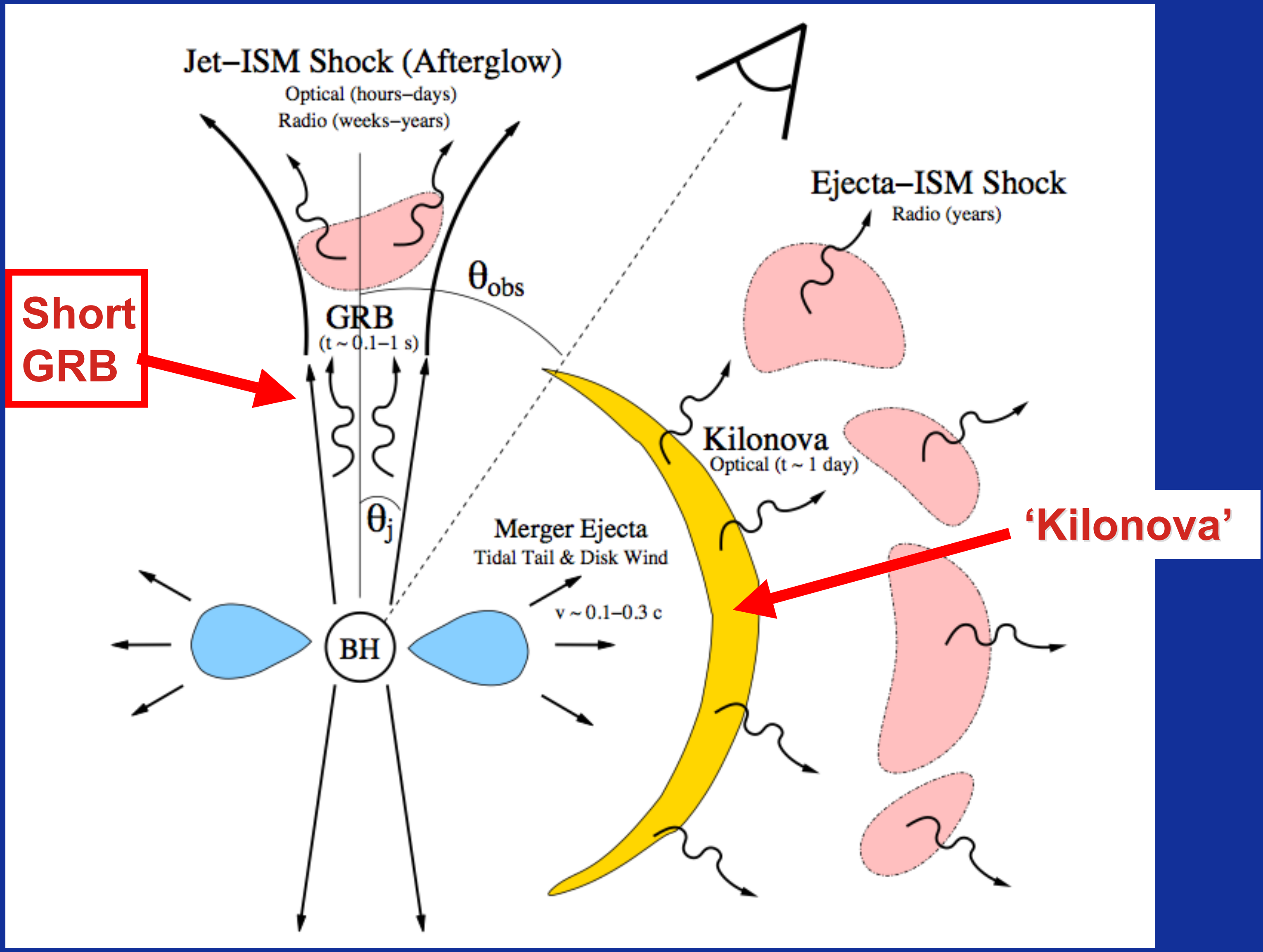
Courtesy M. Shibata (Kyoto)

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012

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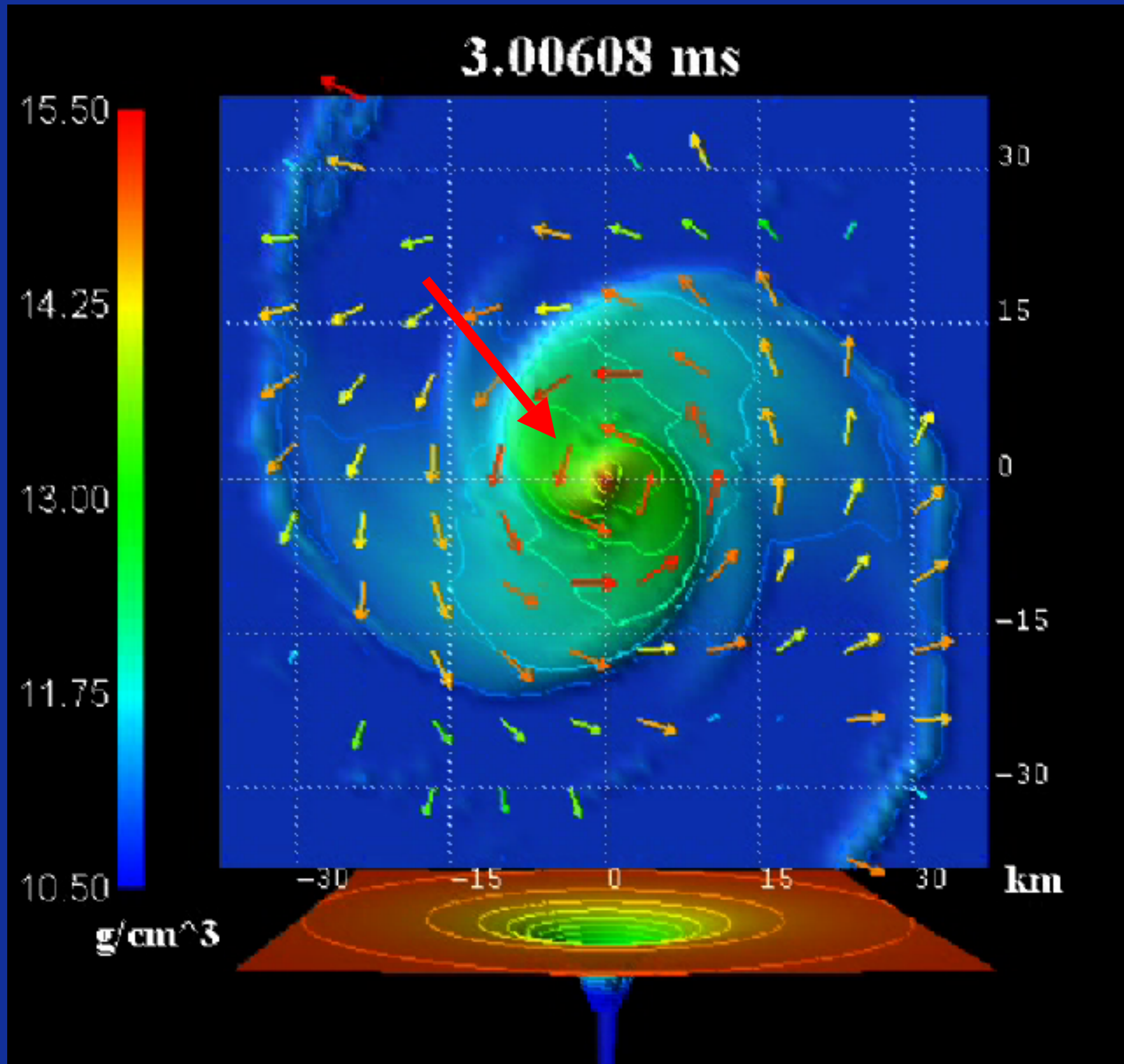
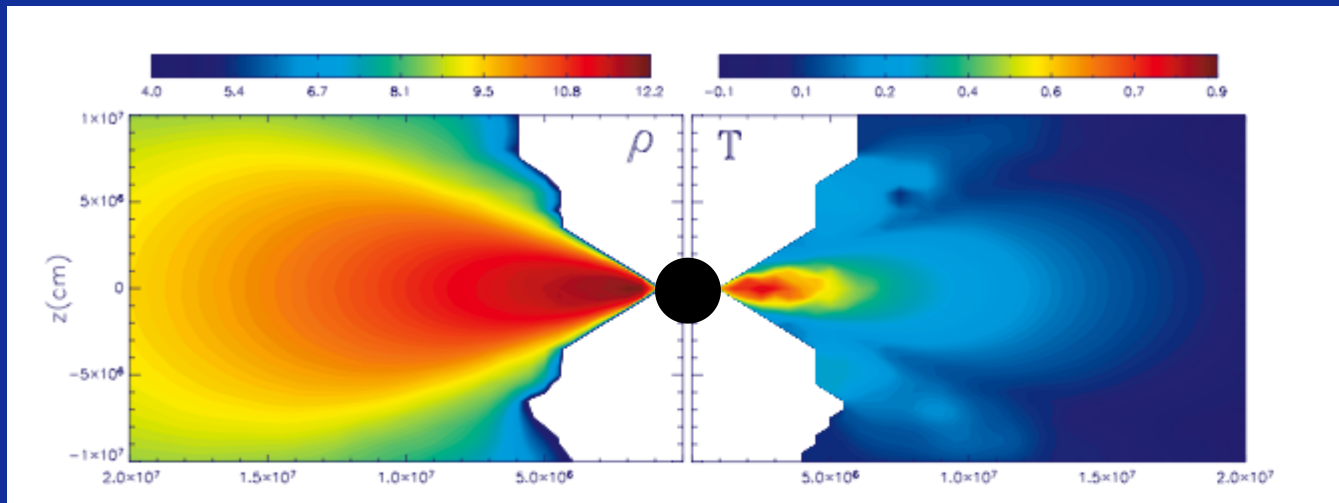


Courtesy M. Shibata (Tokyo U)

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. $e^- + p \rightarrow \nu_e + n$ $\Rightarrow Y_e \sim 0.1$

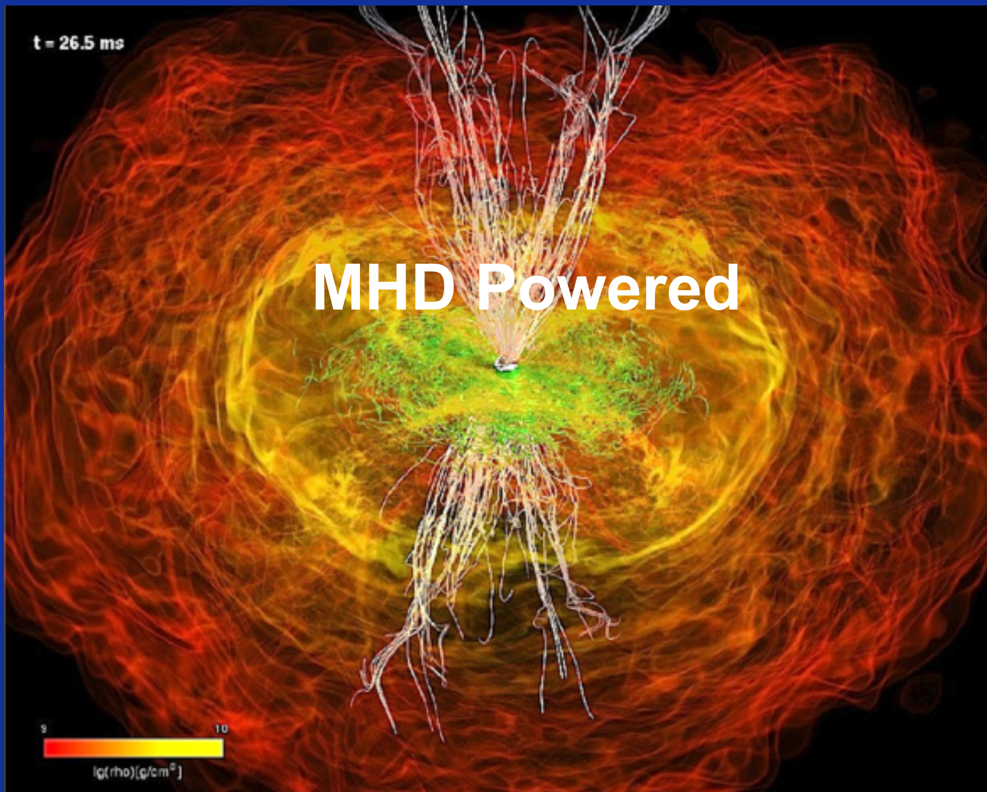
Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\ \mathrm{s}^{-1}$

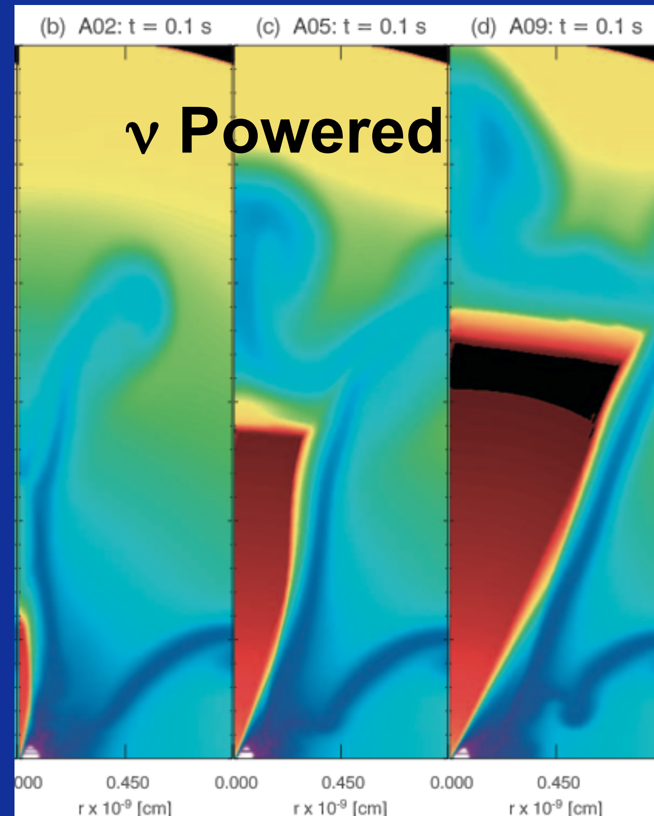
$$t_{\mathrm{visc}} \sim 0.1 \left(\frac{M_\bullet}{3M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_d}{100\ \mathrm{km}}\right)^{3/2} \left(\frac{H/R}{0.5}\right)^{-2}\ \mathrm{s}$$

Short GRB Engine?

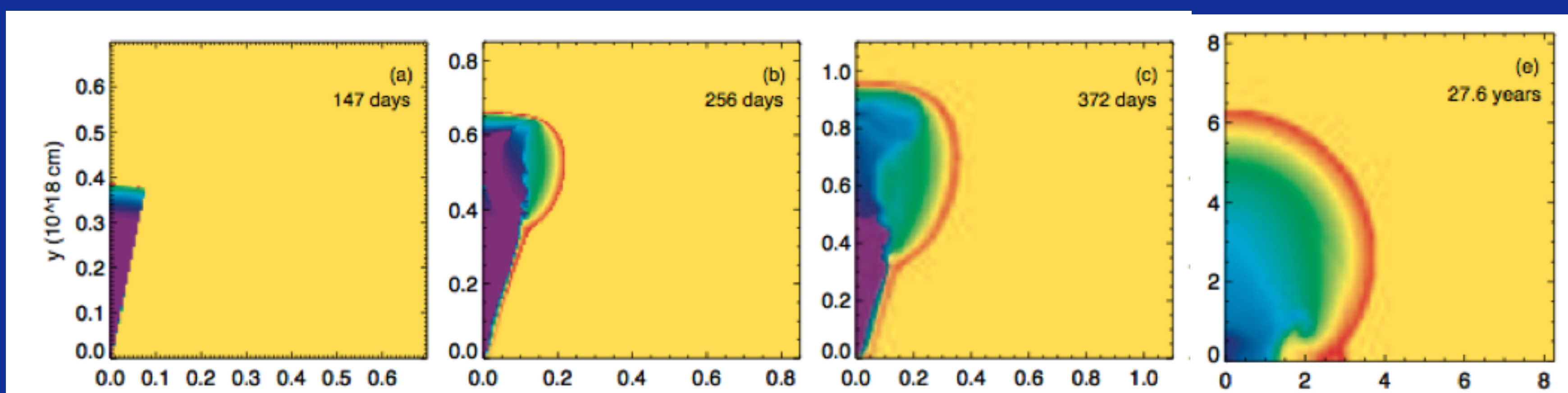
Relativistic Jets and Short GRBs

Rezzolla et al. 2010



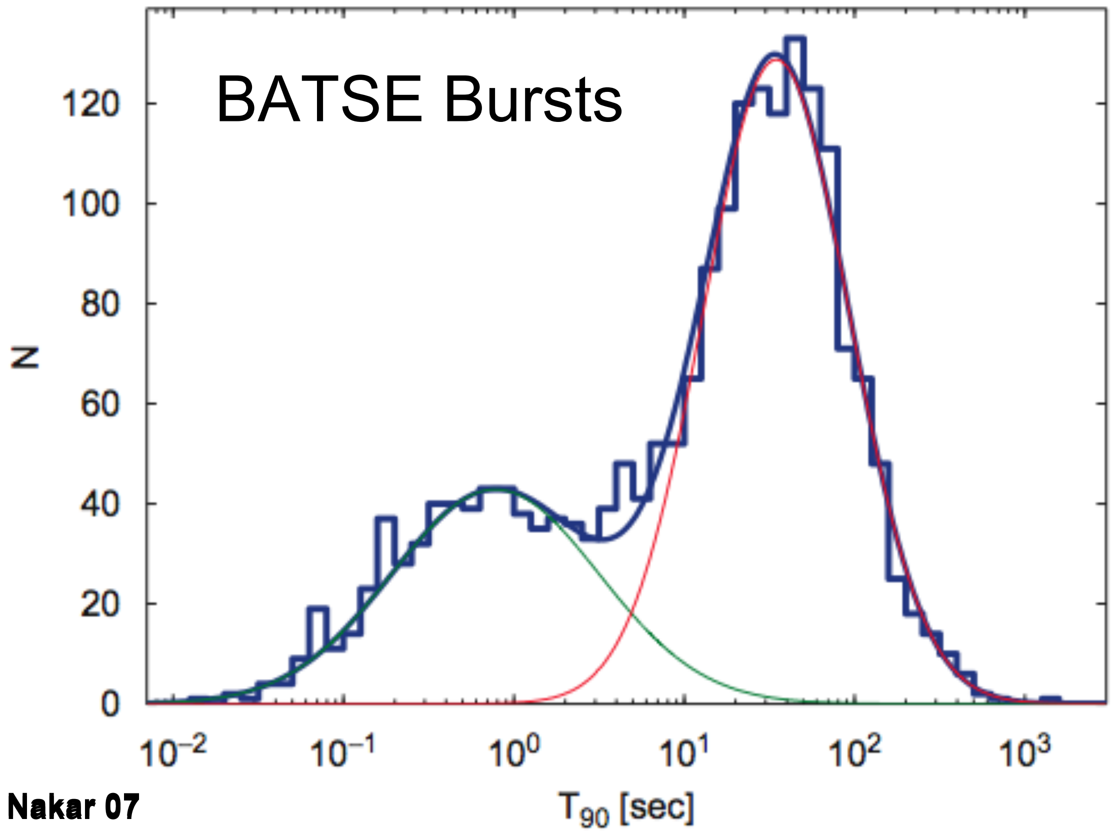


Aloy et al. 2005



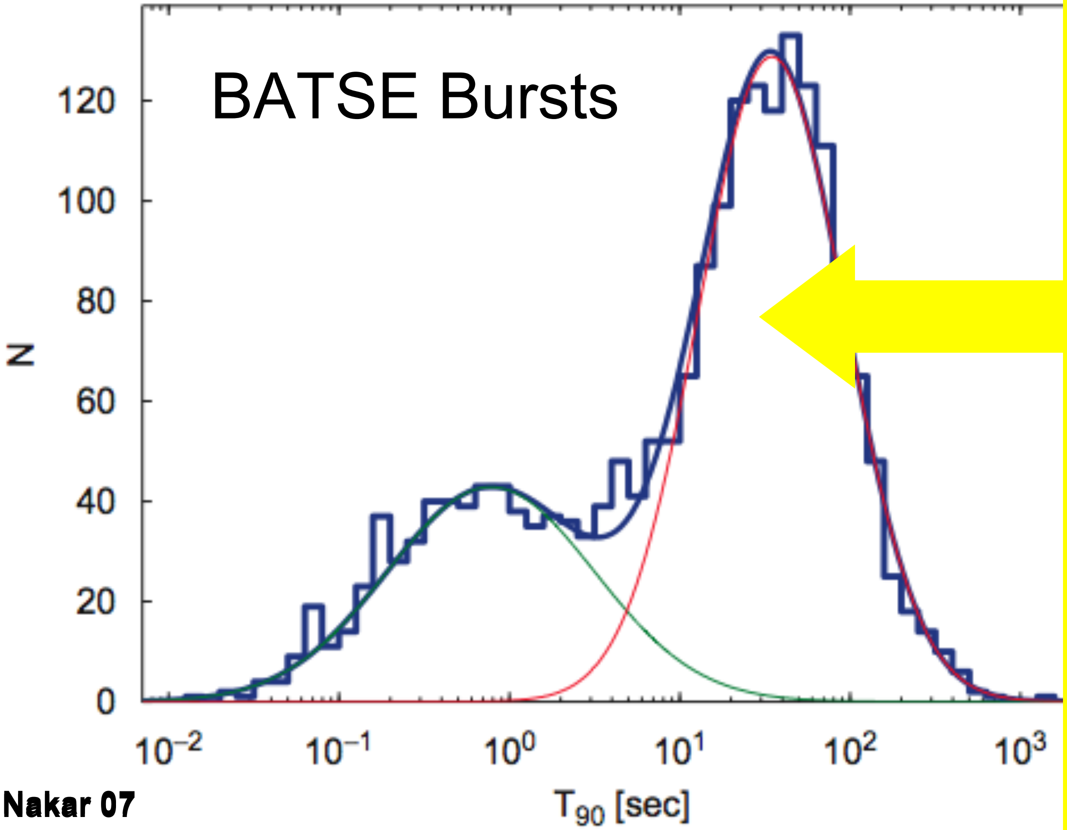
Zhang & MacFadyen 2009

Short & Long Gamma-Ray Bursts



Nakar 07

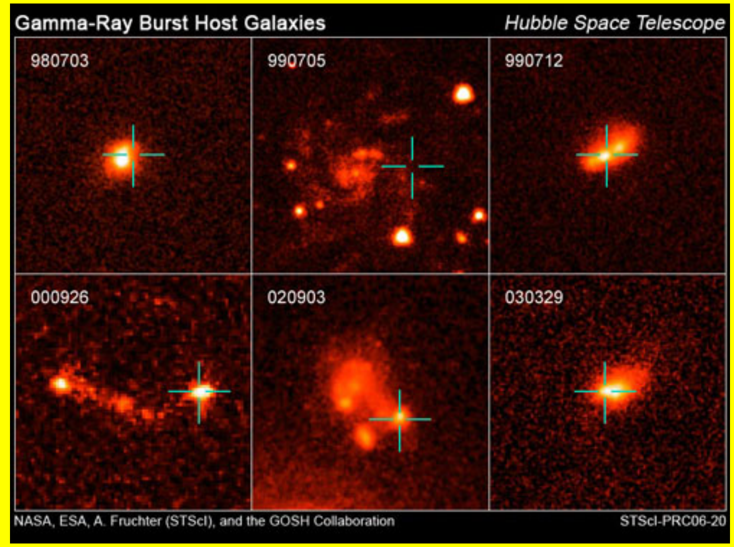
Short & Long Gamma-Ray Bursts



Nakar 07

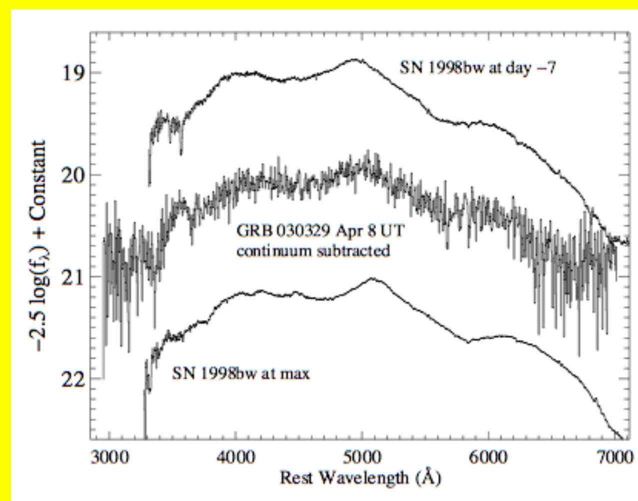
Long GRBs = Death of Massive Stars

Star-Forming Host Galaxies (z_{avg}~2-3)



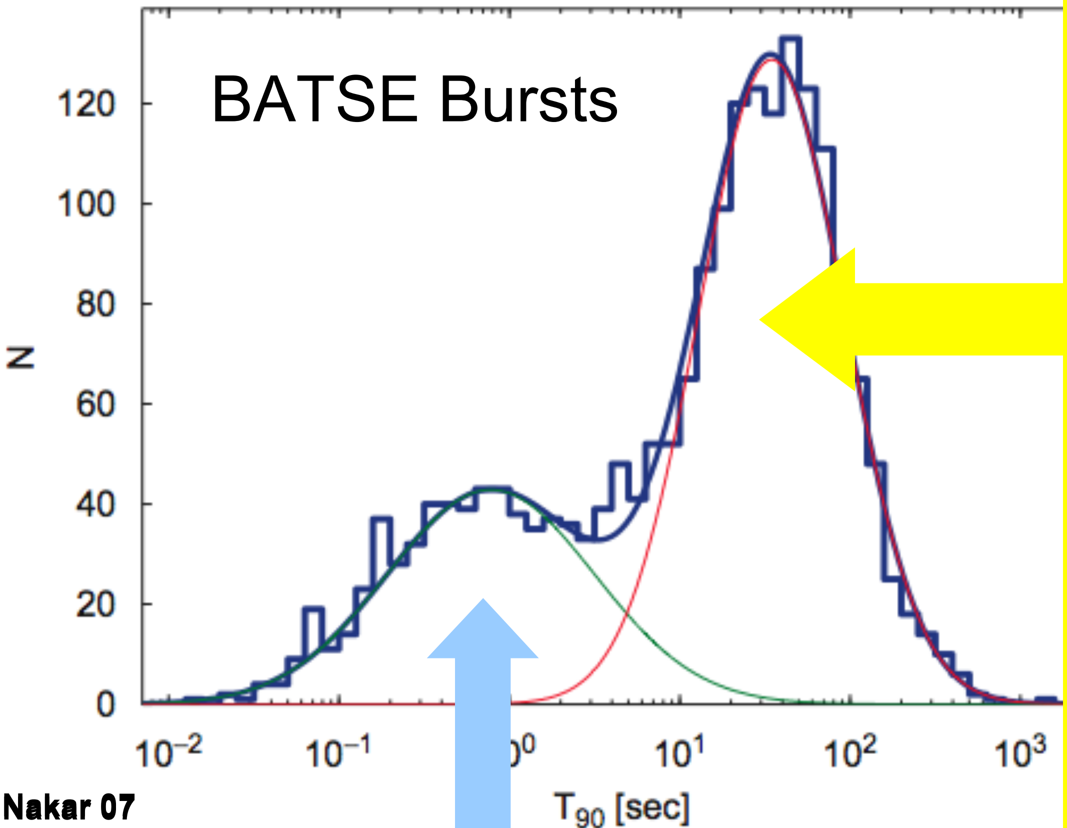
Supernova Connection

GRB 030329 ⇔ SN 2003dh

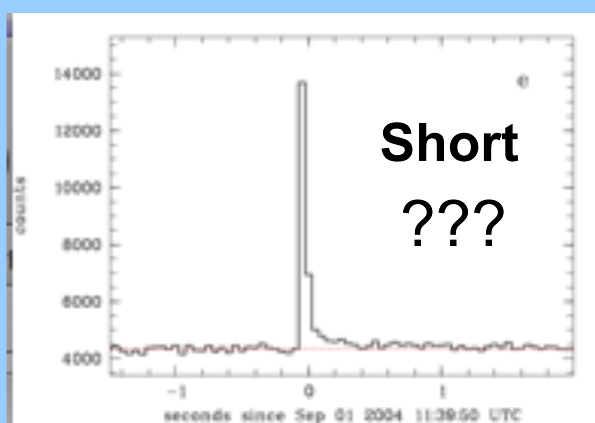


Stanek et al. 2003

Short & Long Gamma-Ray Bursts



Nakar 07



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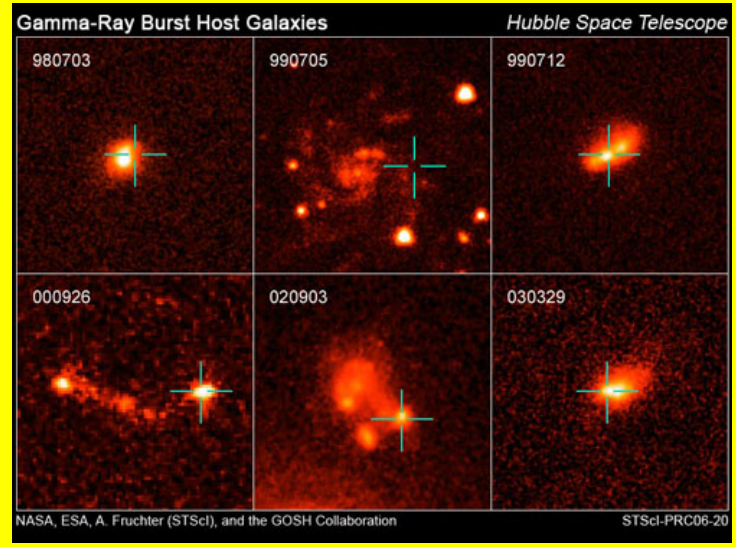
Star-Forming Host Galaxies (z_{avg}~2-3)



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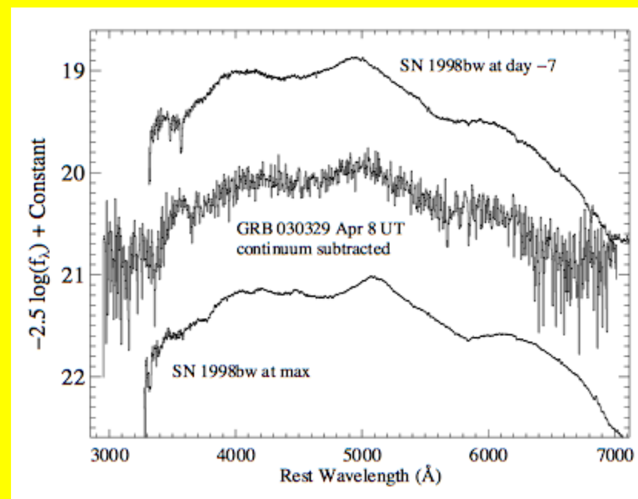
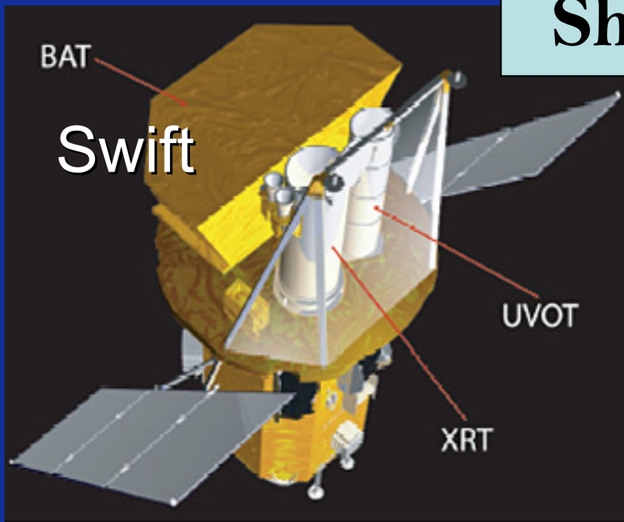
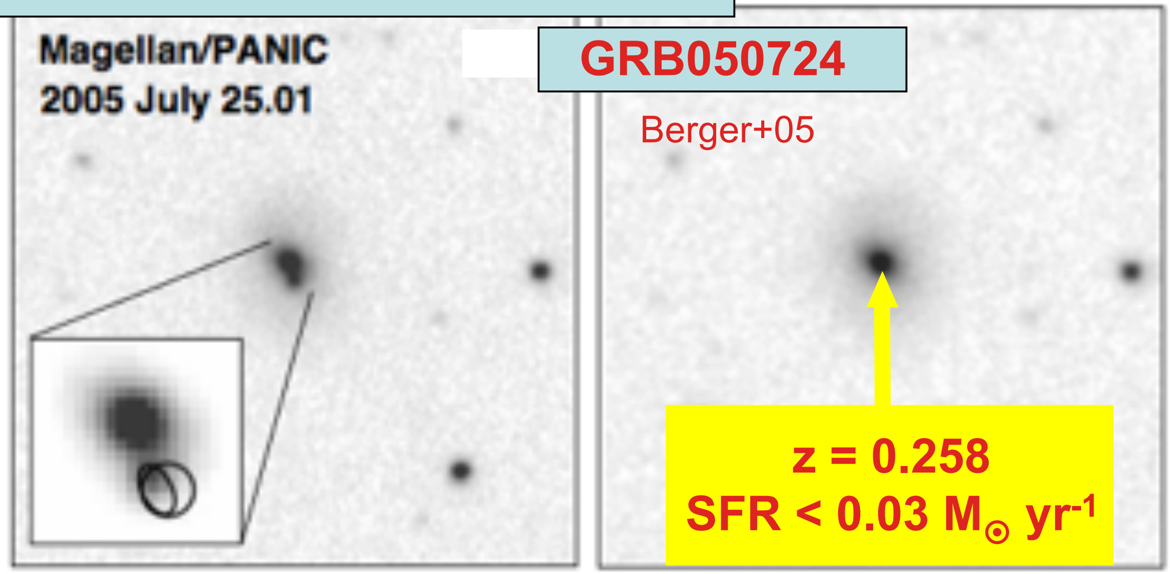
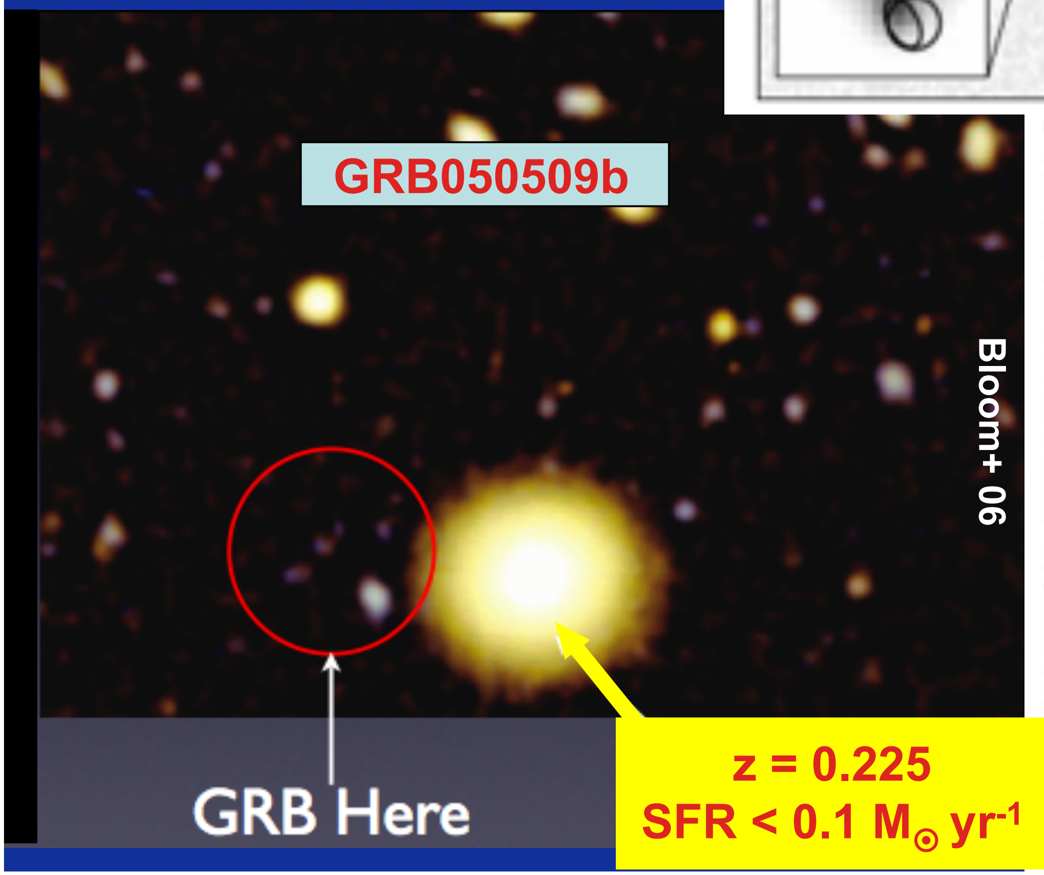


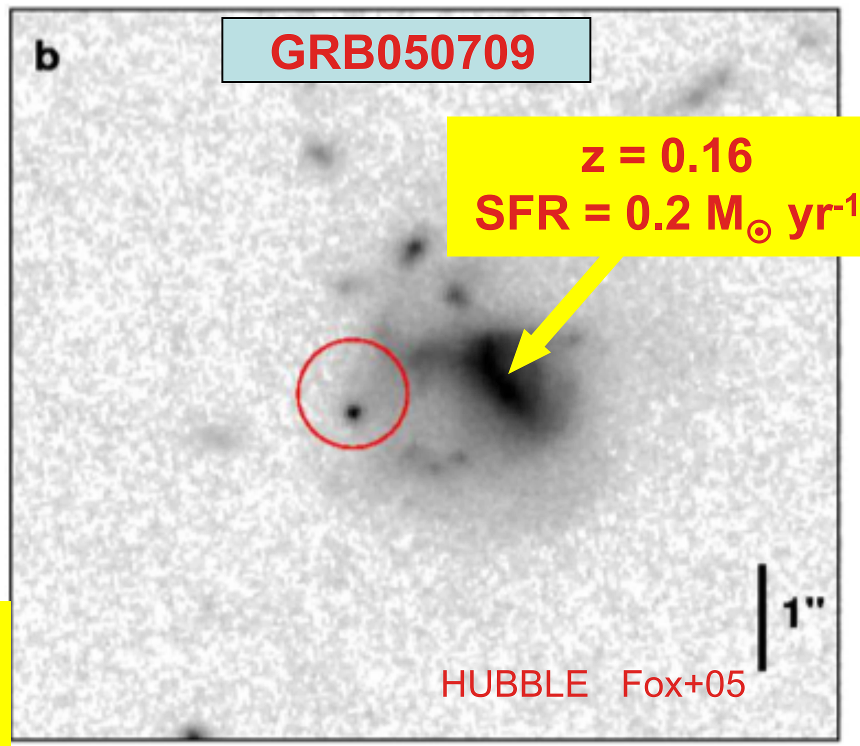
Stanek et al. 2003

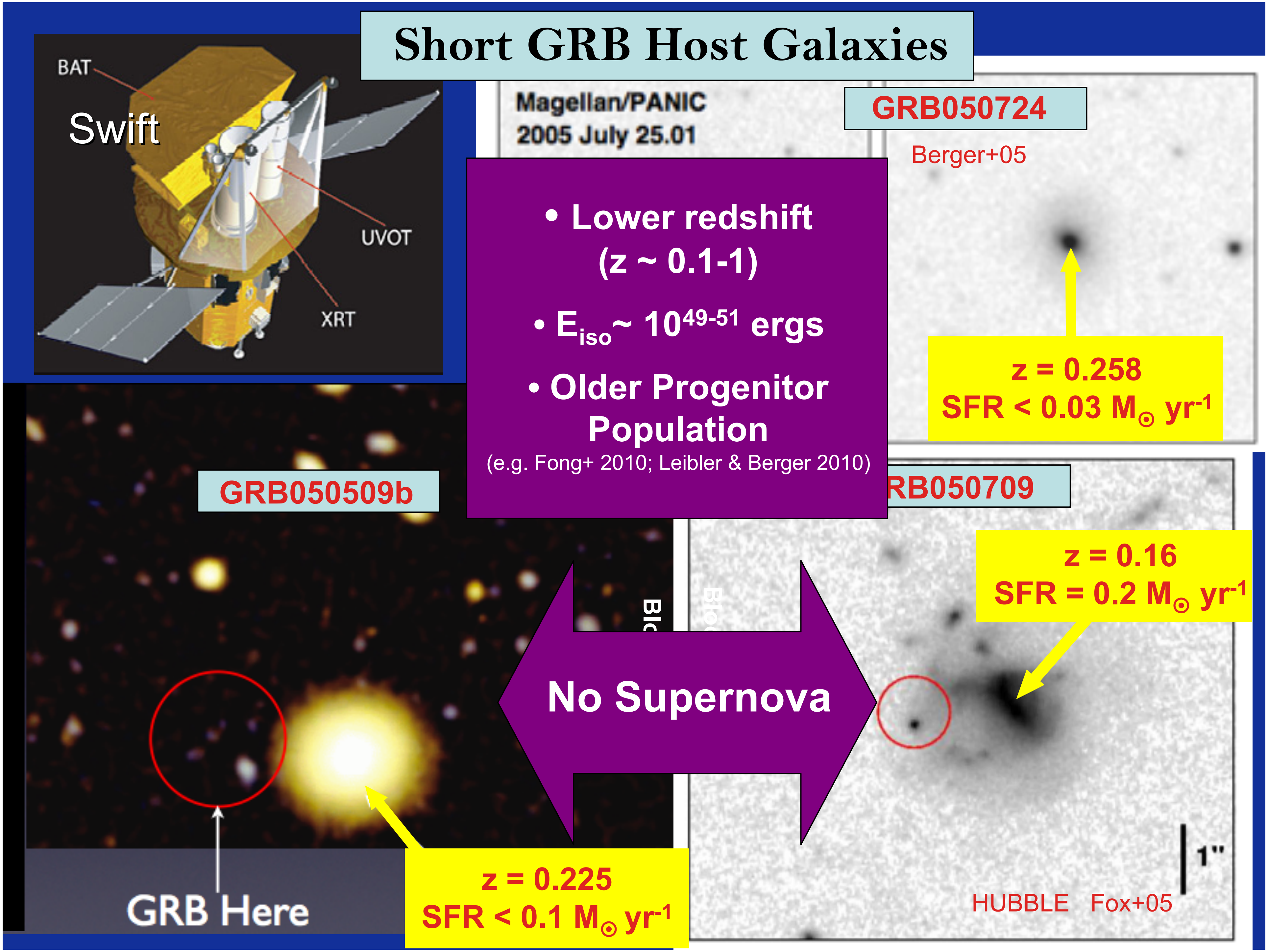
Short GRB Host Galaxies



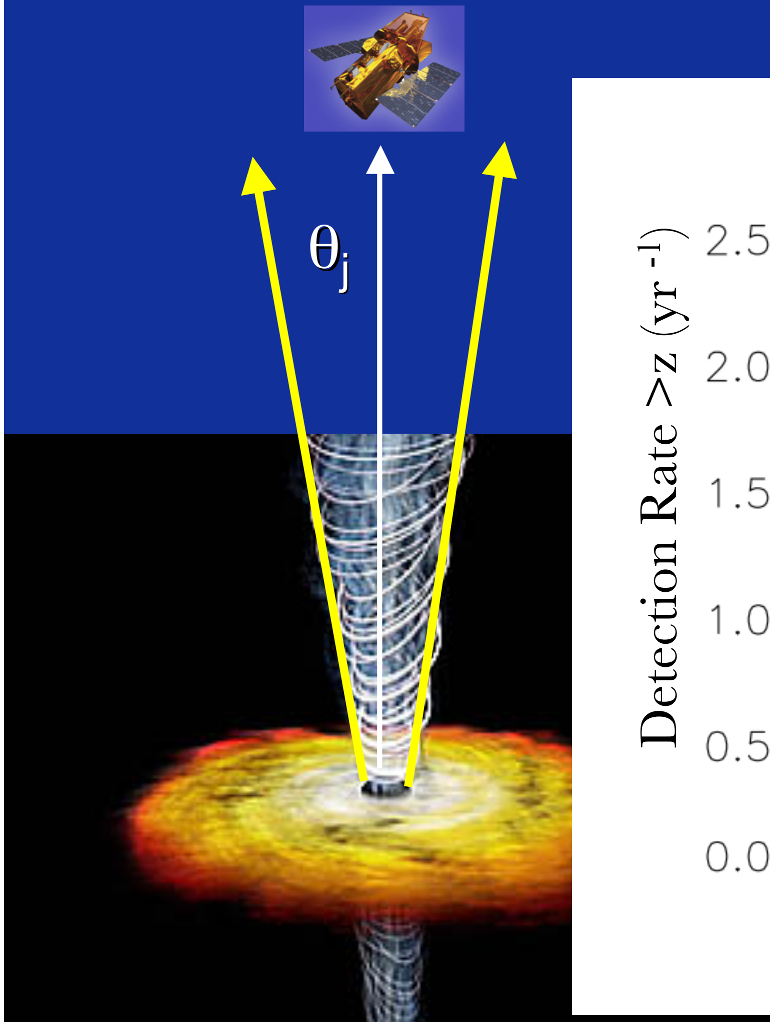


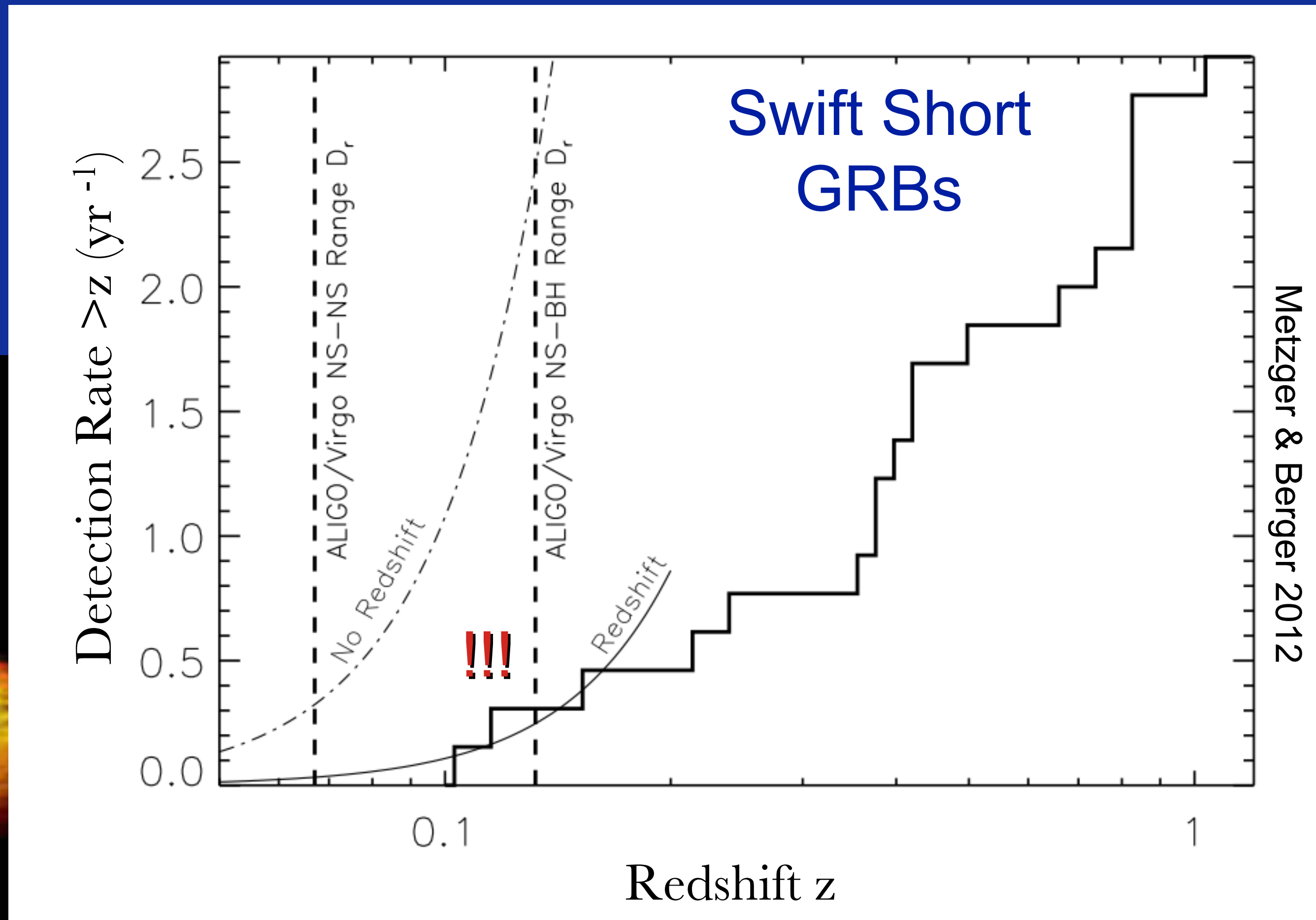





Short GRB Host Galaxies
BAT
Swift
UVOT
XRT
Magellan/PANIC
2005 July 25.01
GRB050724
Berger+05
• Lower redshift
(z ~ 0.1-1)
• E_{iso} ~ 10^{49-51} ergs
• Older Progenitor Population
(e.g. Fong+ 2010; Leibler & Berger 2010)
z = 0.258
SFR < 0.03 $M_{\odot}$ yr^{-1}
GRB050509b
RB050709
z = 0.16
SFR = 0.2 $M_{\odot}$ yr^{-1}
No Supernova
GRB Here
z = 0.225
SFR < 0.1 $M_{\odot}$ yr^{-1}
1"
HUBBLE
Fox+05

Short GRBs are Rare in the LIGO Volume

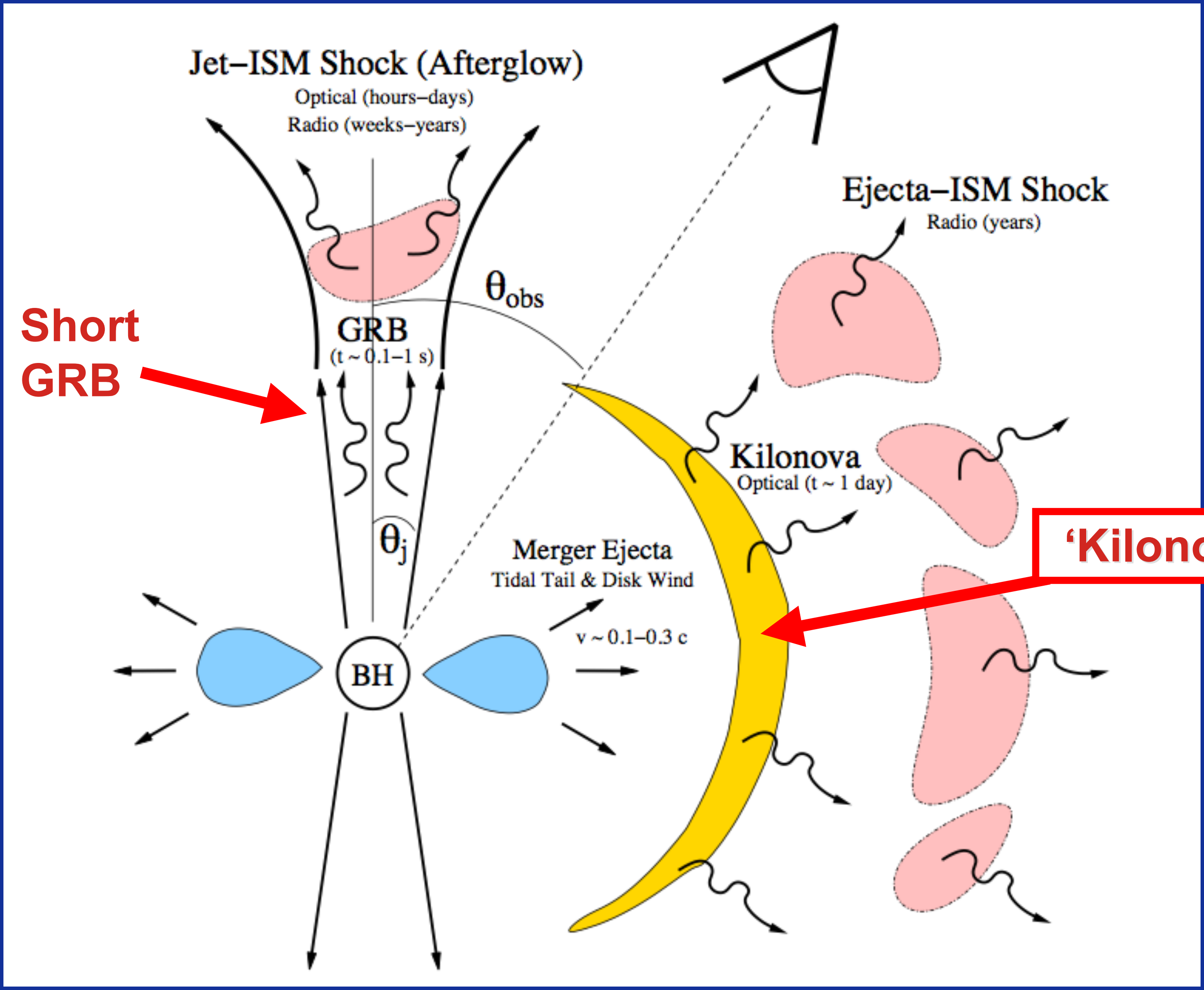




Detectable fraction by all sky γ-ray telescope

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

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012

Neutron-Rich Ejecta

1.1 & 1.6 $M_\odot$ NS merger

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

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

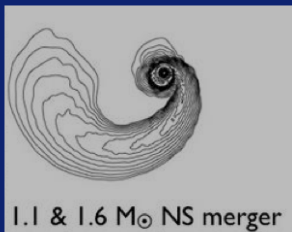
Newtonian / Realistic EOS / Eccentric

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

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
APR4-130140	1.8	HMNS	8
APR4-135135	1.6	HMNS	11
APR4-135135	1.8	HMNS	7
APR4-135135	2.0	HMNS	5
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

Neutron-Rich Ejecta



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(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)

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Model			M_{ej} (10^{-3} $M_{\odot}$)
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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
APR4-130140	1.8	HMNS	8
APR4-135135	1.6	HMNS	11
APR4-135135	1.8	HMNS	7
APR4-135135	2.0	HMNS	5
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

Disk Outflows

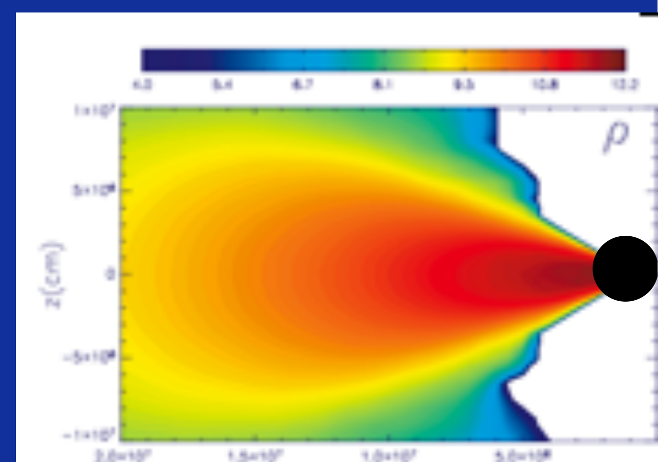
Neutrino-Powered (Early)

(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)

$$Y_e \sim ???$$

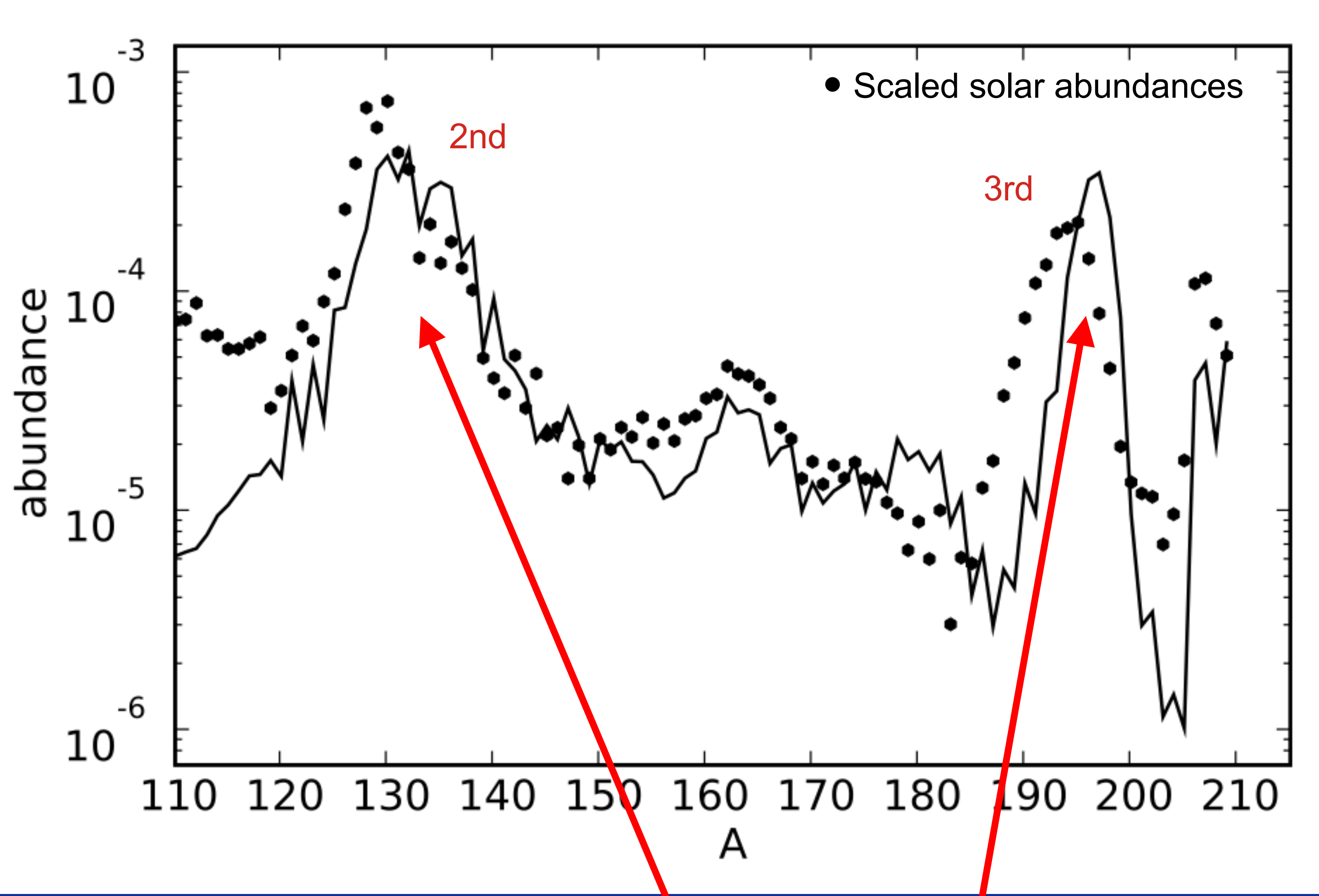


$$M_{ej} = f_w M_d \sim 10^{-3}\text{-}10^{-2}\ (f_w/0.1)\ M_{\odot}$$

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

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

Final Abundance Distribution

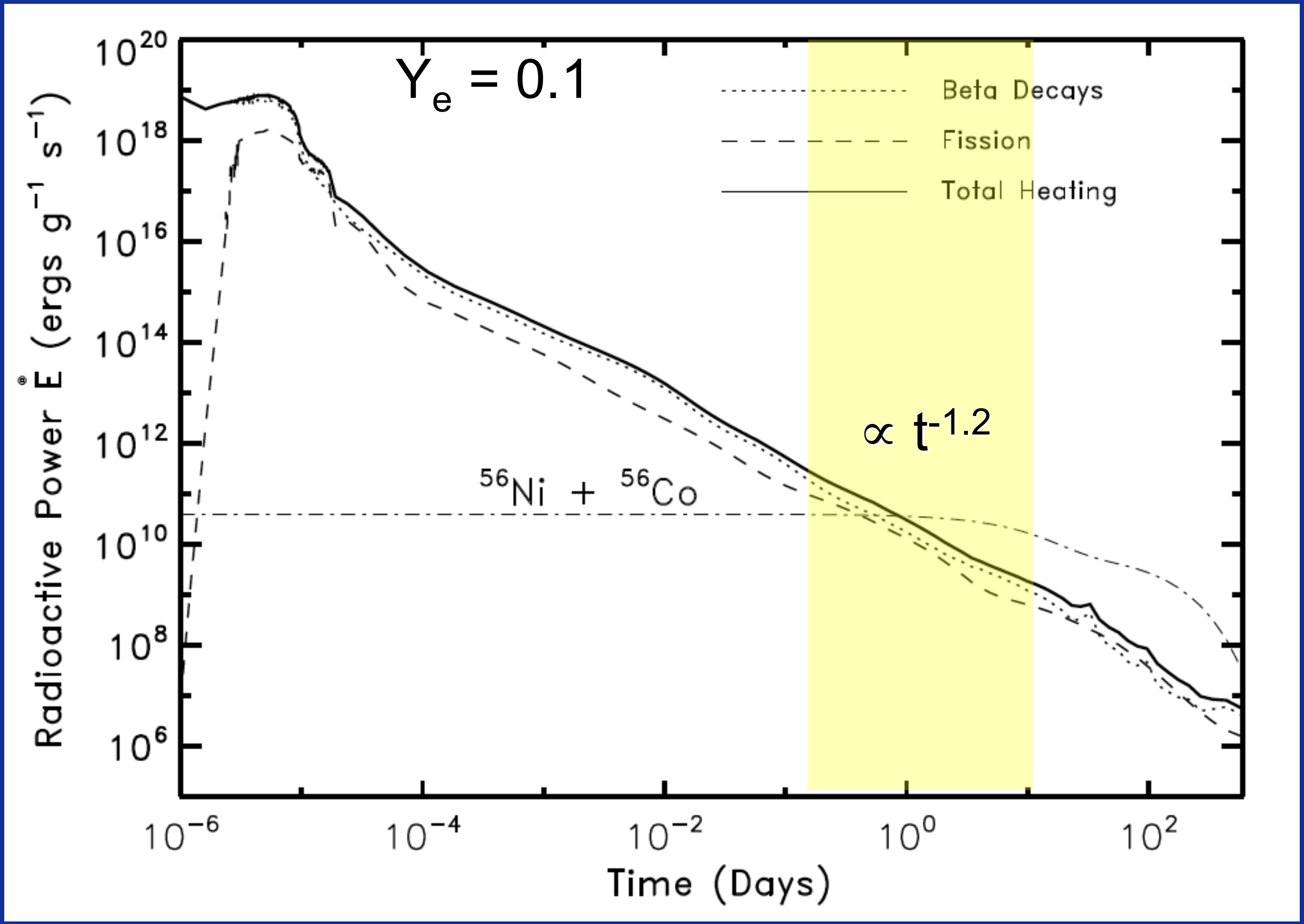


peaks at A ~ 130, 195

BDM et al. 2010

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)



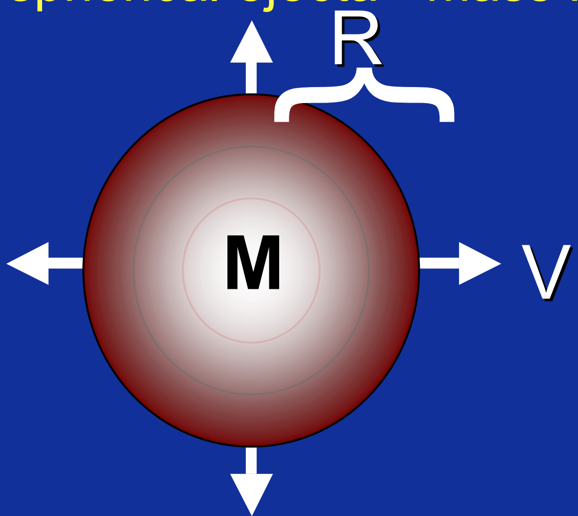
Metzger et al. 2010

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)

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



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

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

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

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

Type Ia Supernova:

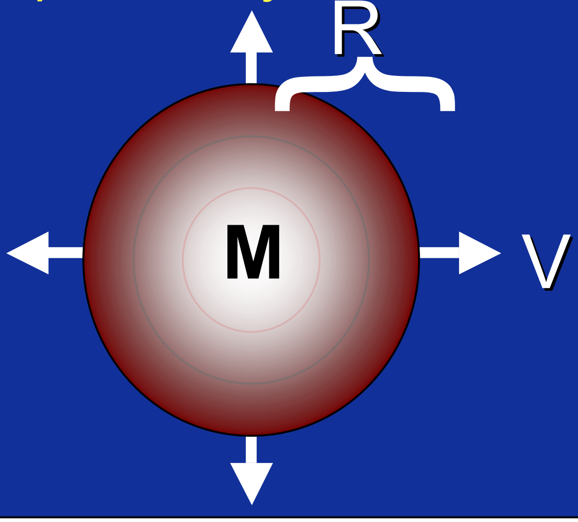
$v \sim 10^4$ km s^{-1}, $M_{ej} \sim M_\odot$, $f_{Ni \rightarrow Co} \sim 10^{-5} \Rightarrow t_{peak} \sim$ week, $L \sim 10^{43}$ erg s^{-1}

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}

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

spherical ejecta - 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:

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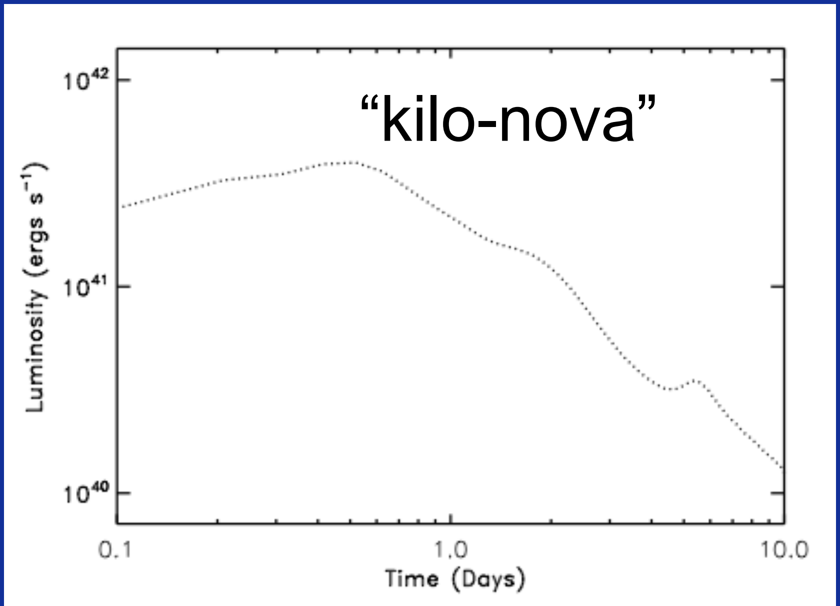
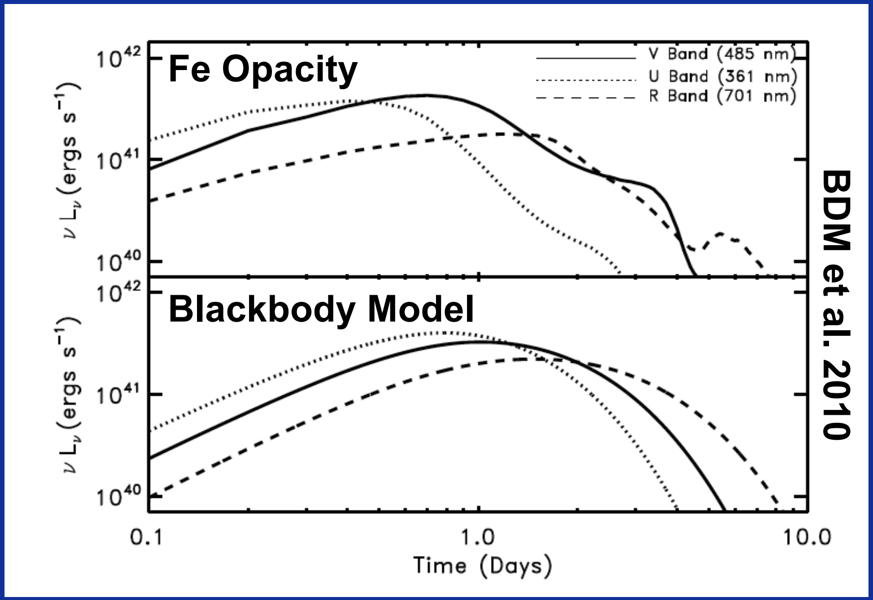
NS Merger:

$v \sim 0.1$ 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}

Bolometric Luminosity

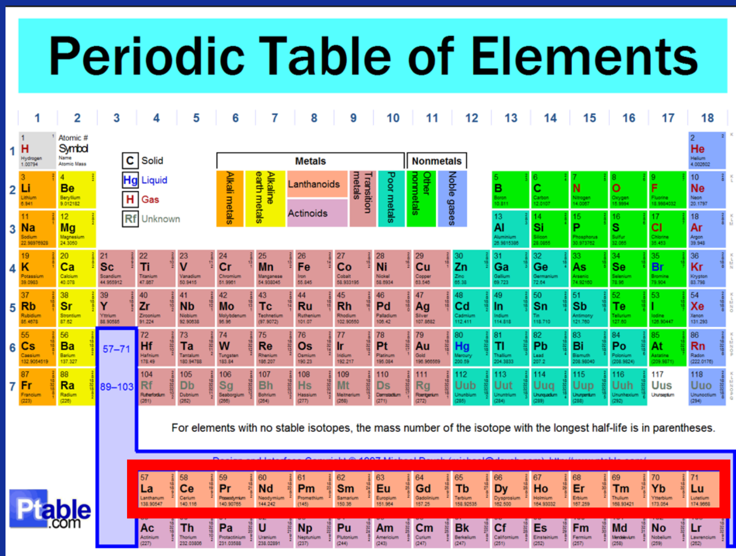


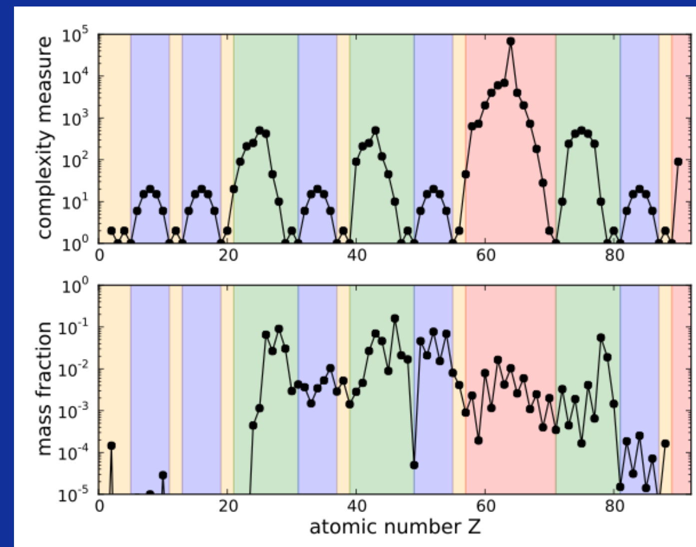
Color Evolution

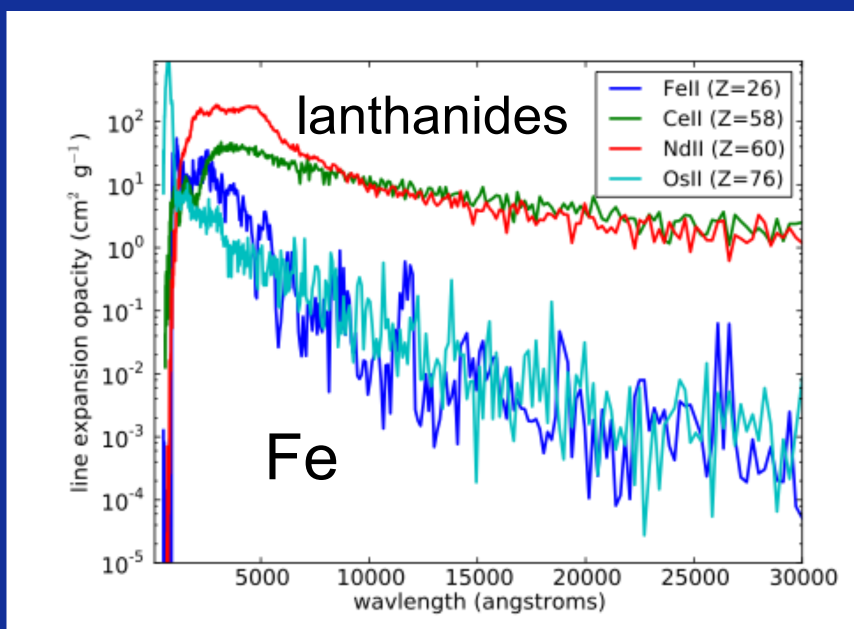


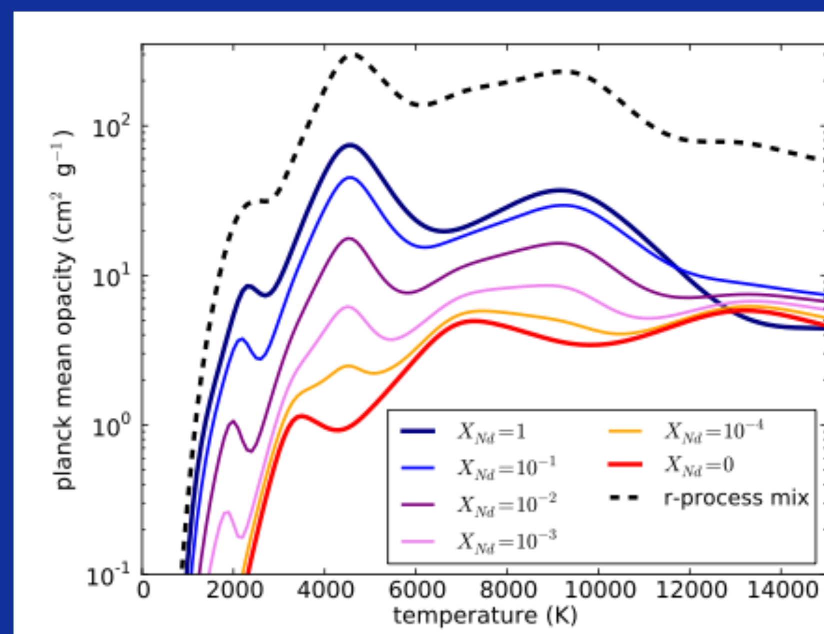
High Opacity of the Lanthanides

(Kasen et al. 2013; Tanaka & Hotokezaka 2013)



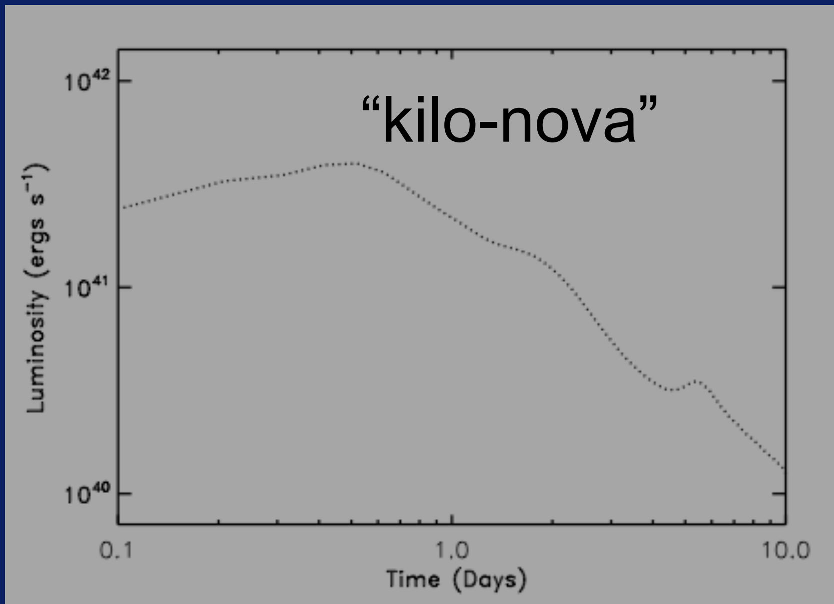




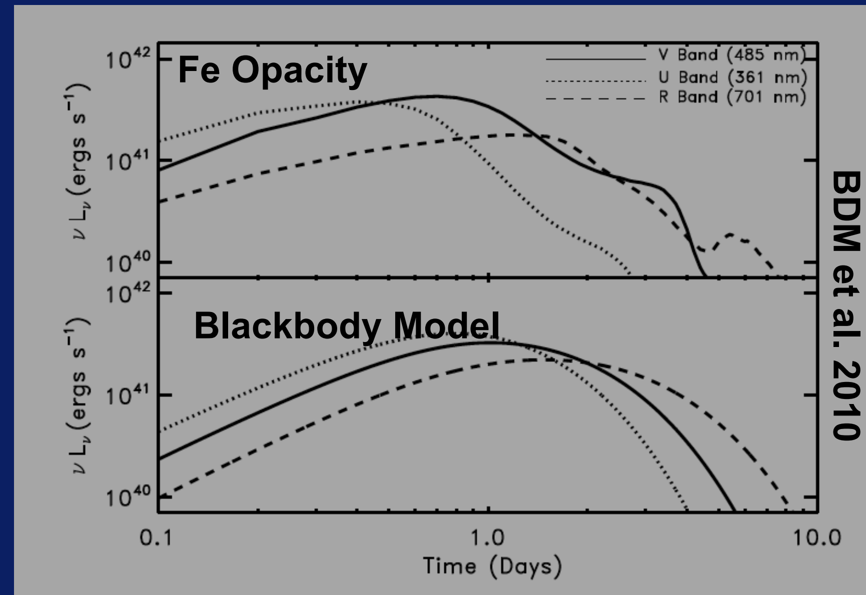


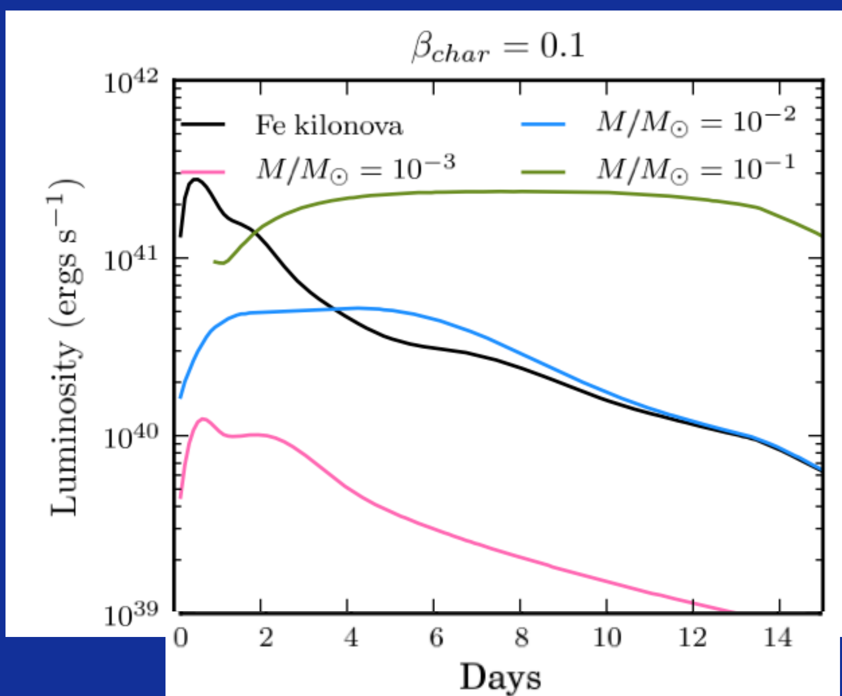
Kasen et al. 2013

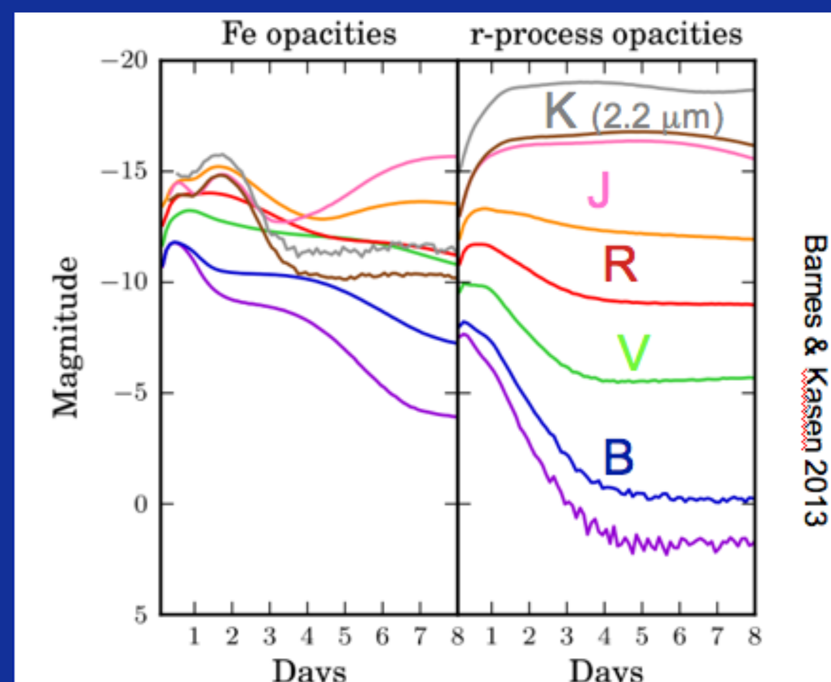
Bolometric Luminosity



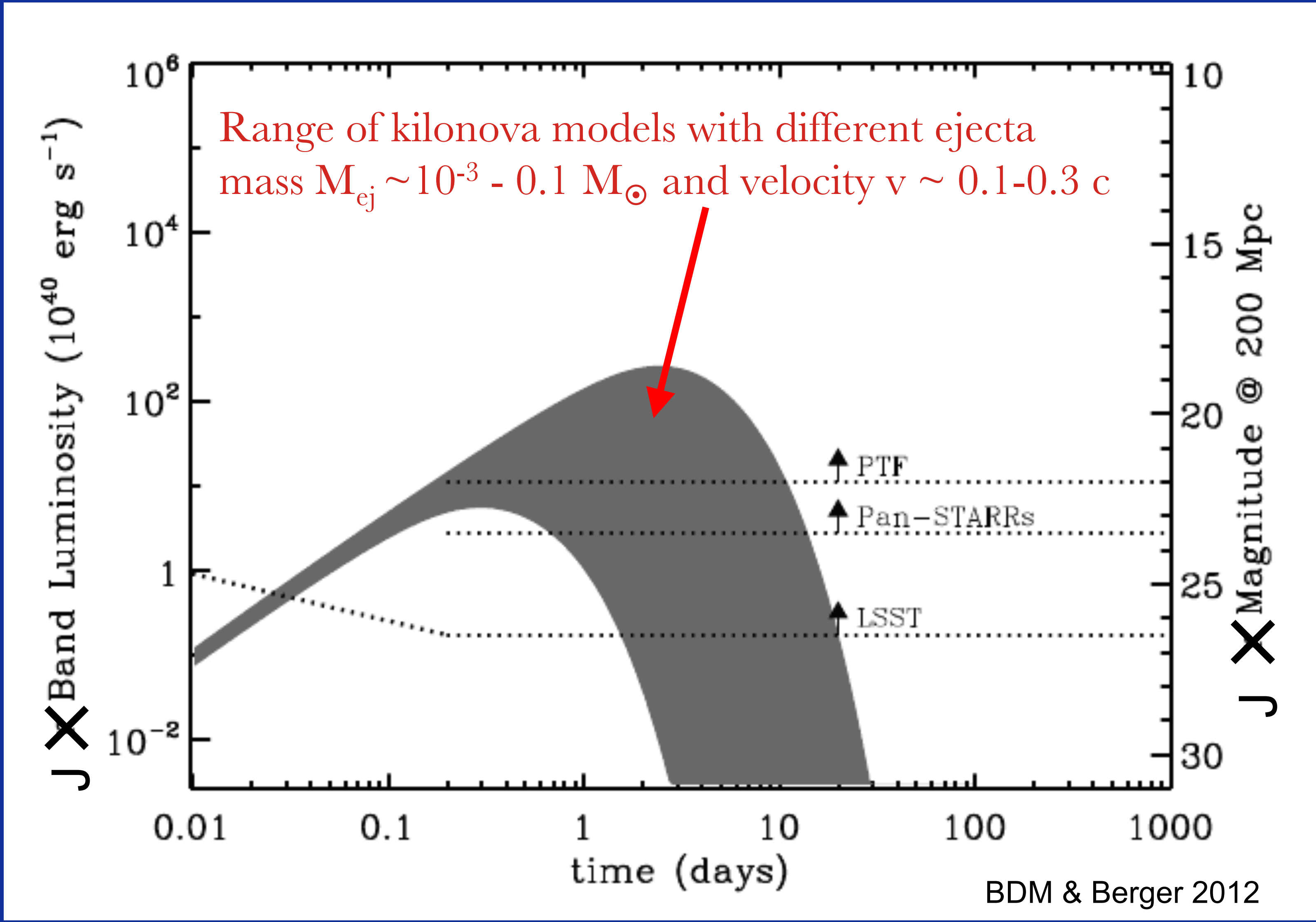
Color Evolution





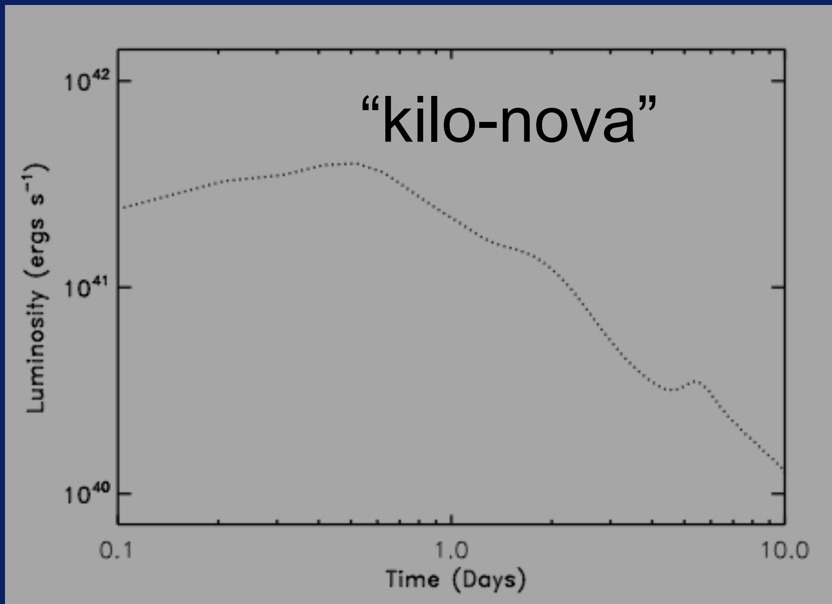


EM Counterpart Search following a GW Trigger

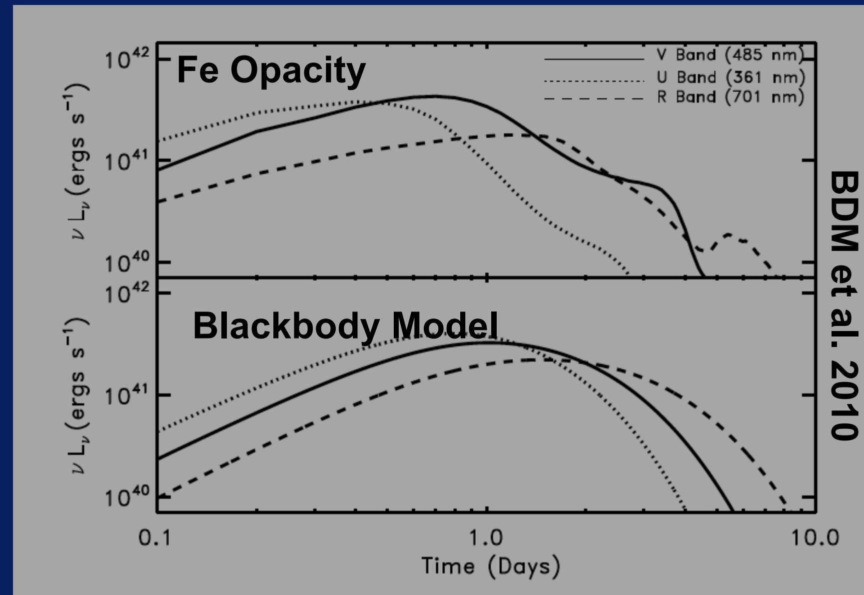


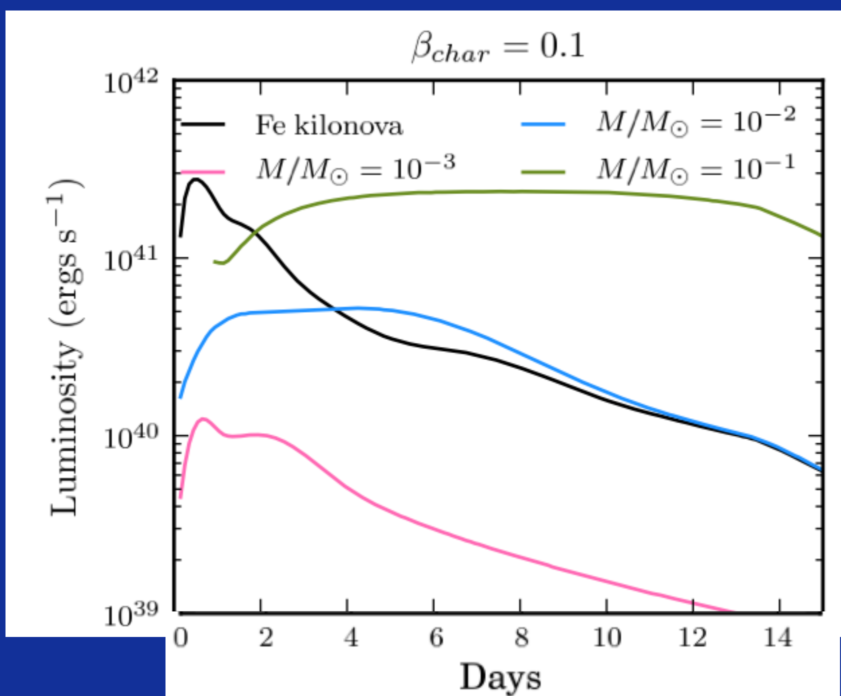
⇒ **Requires depth J ~ 22-24 and short cadence**

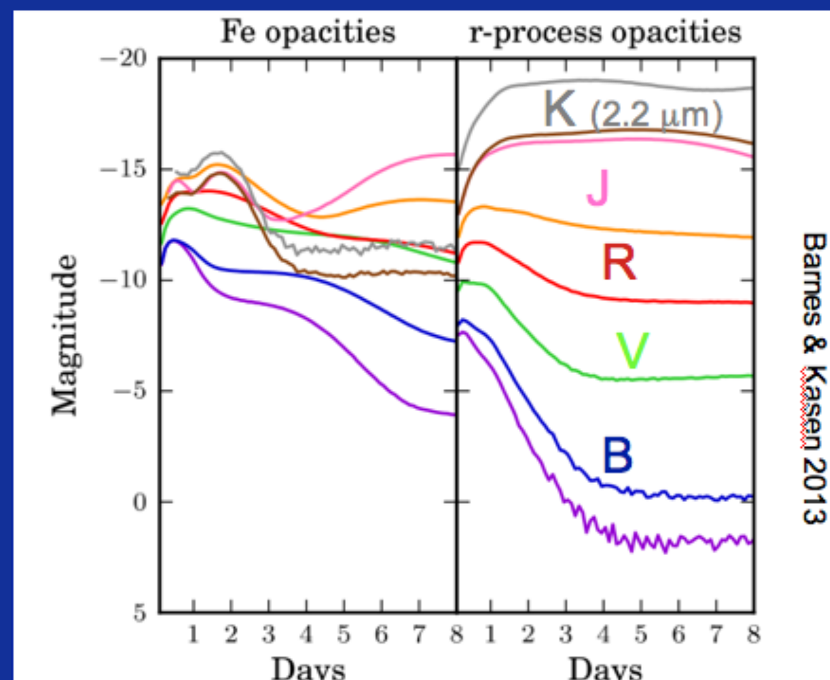
Bolometric Luminosity



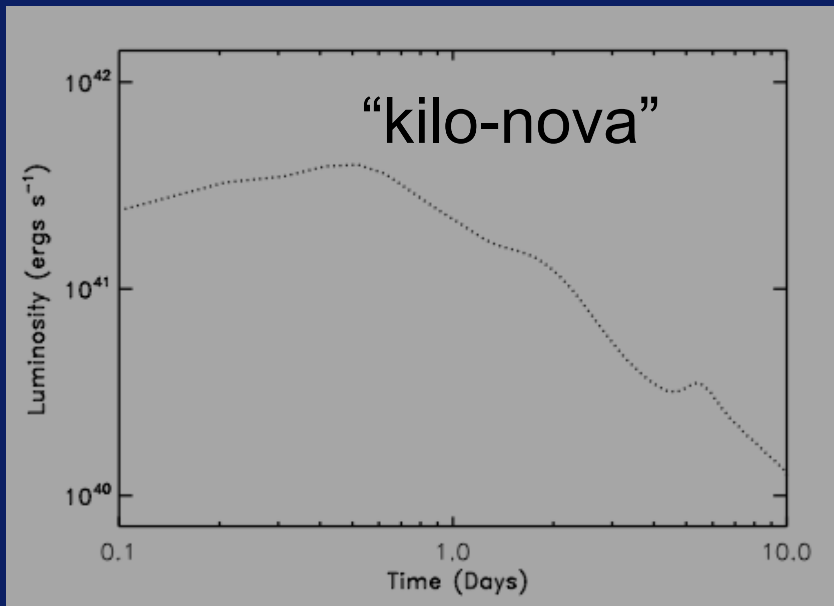
Color Evolution



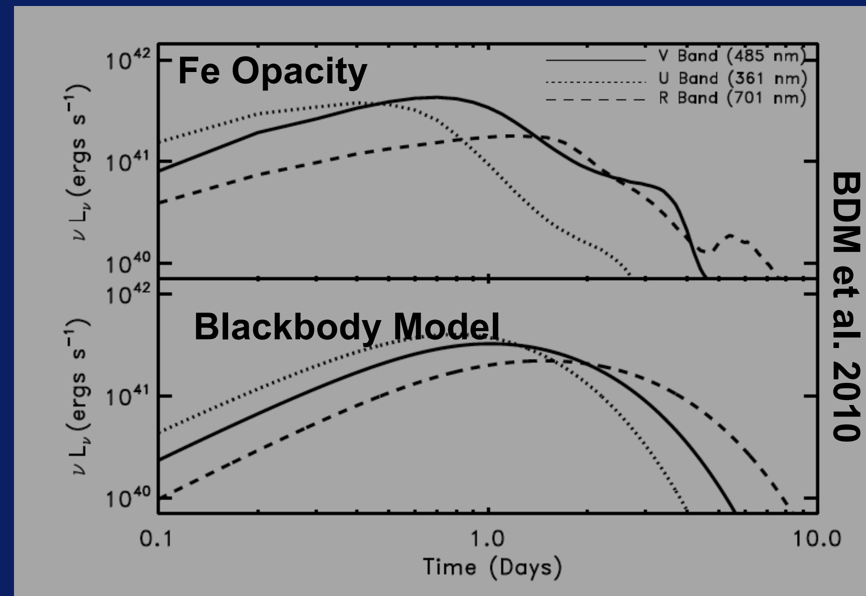


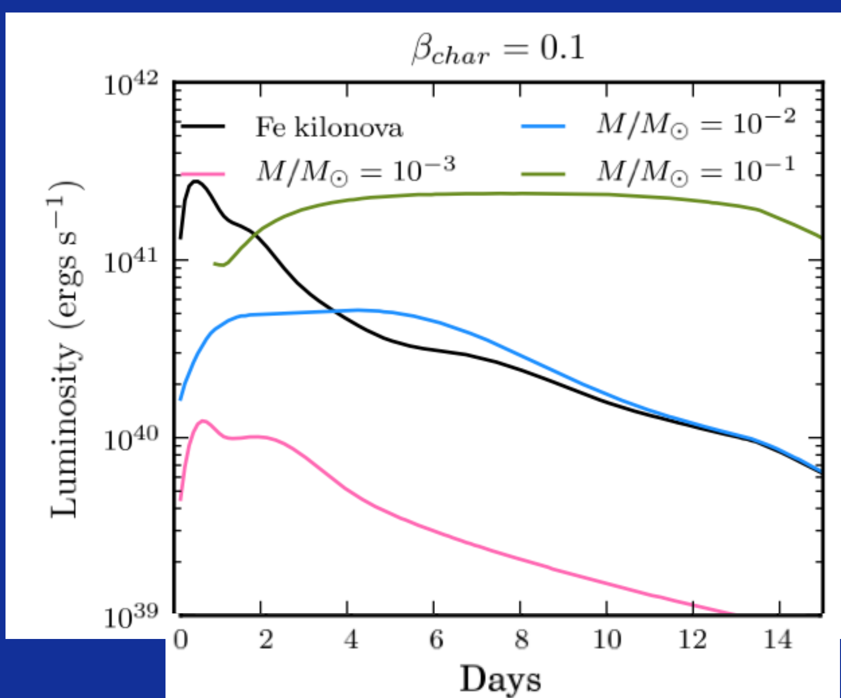


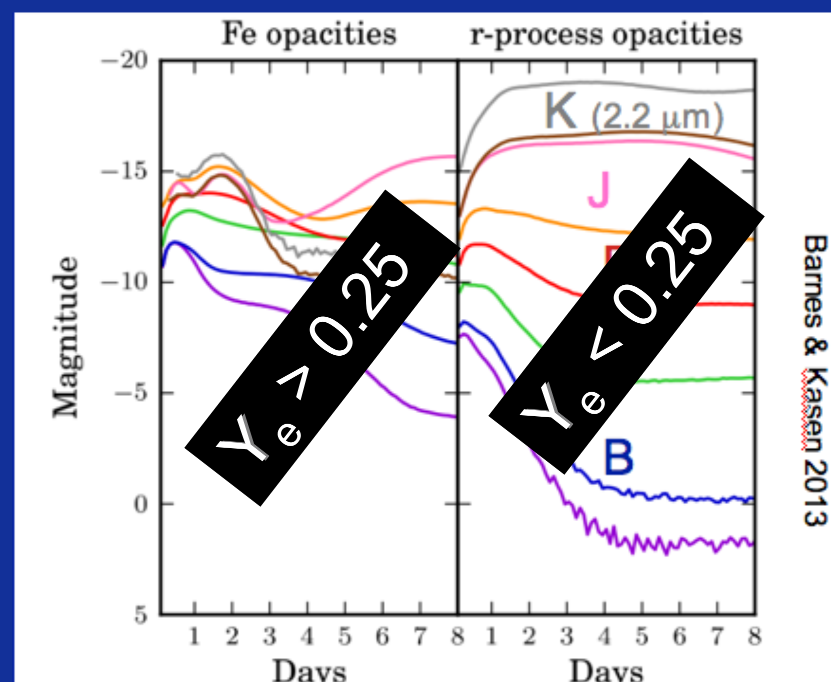
Bolometric Luminosity



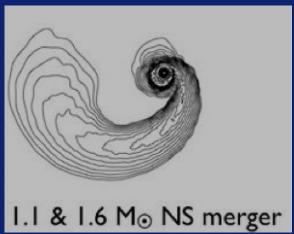
Color Evolution







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
APR4-130140	1.8	HMNS	8
APR4-135135	1.6	HMNS	11
APR4-135135	1.8	HMNS	7
APR4-135135	2.0	HMNS	5
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

Disk Outflows

Neutrino-Powered (Early)

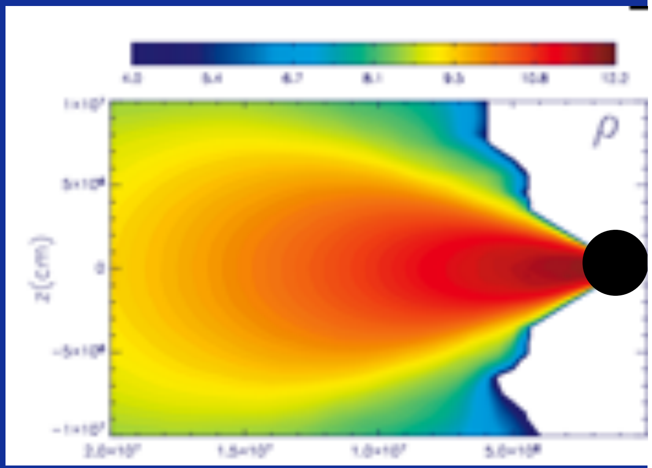
(e.g. McLaughlin & Surman 05; Surman+08; BDM+08; Dessart+09)

Recombination-Powered (Late)

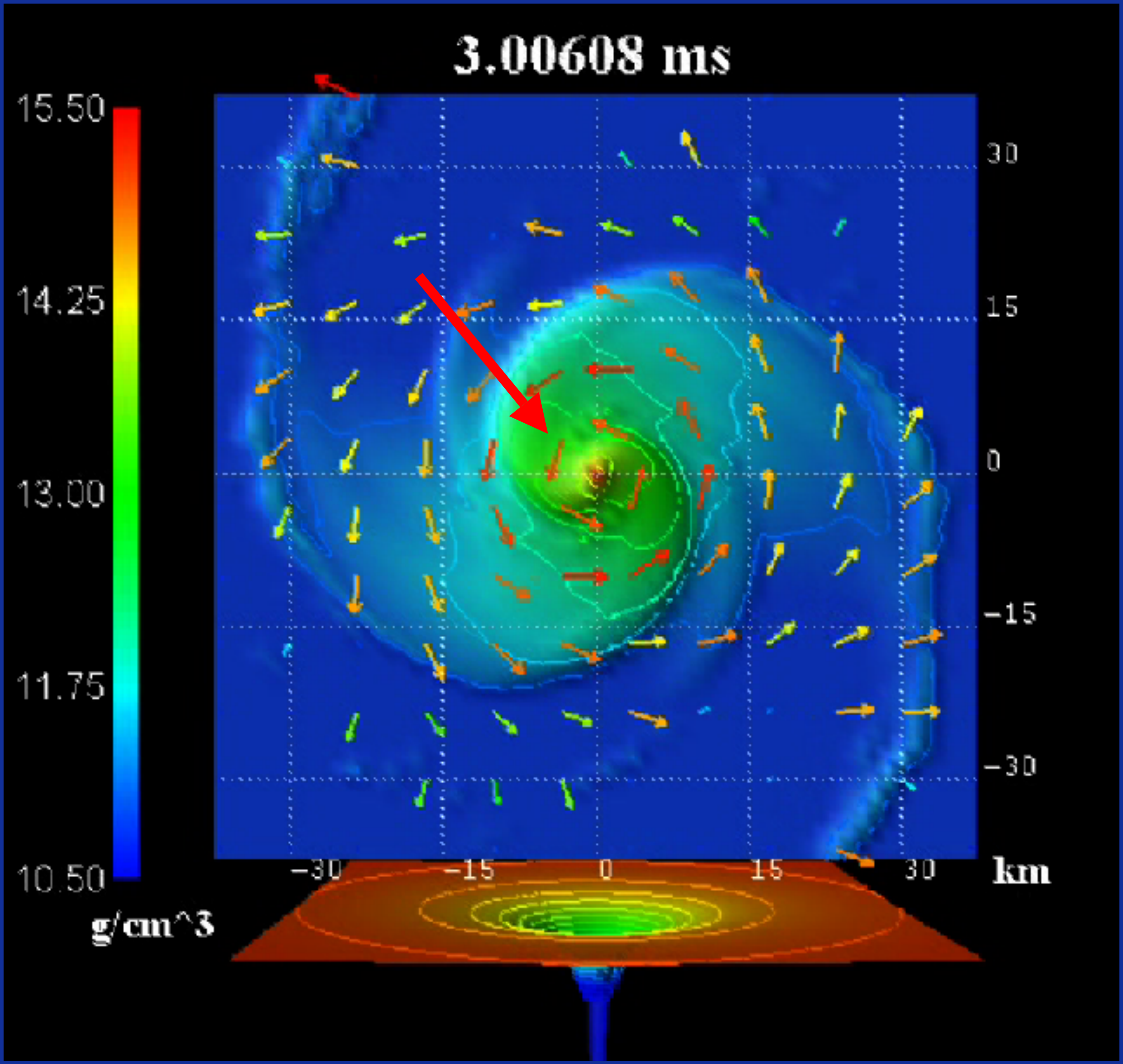
(e.g. Beloborodov 08; BDM+08, 09; Lee+09; Fernandez & BDM 13)

$$Y_e \sim ???$$

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

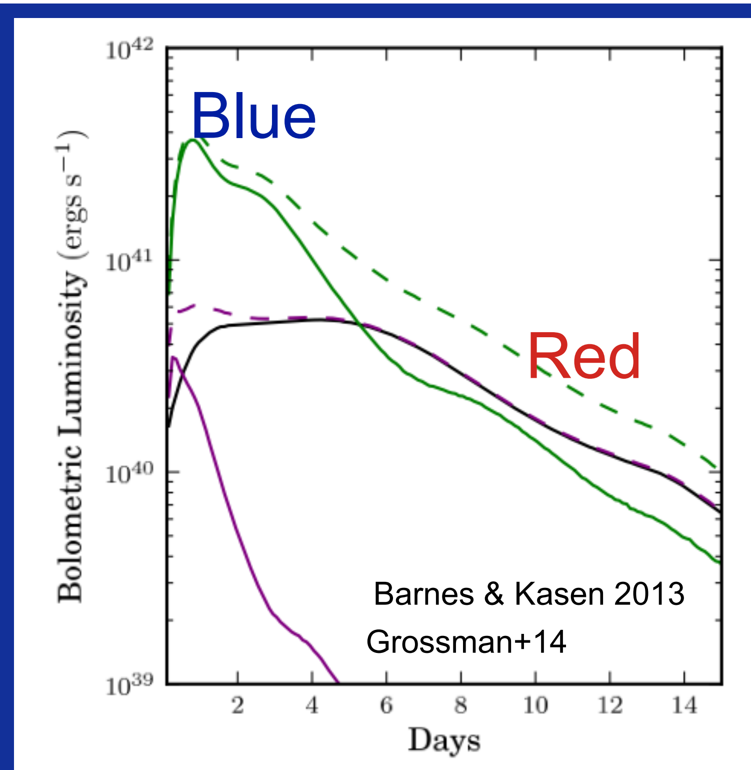


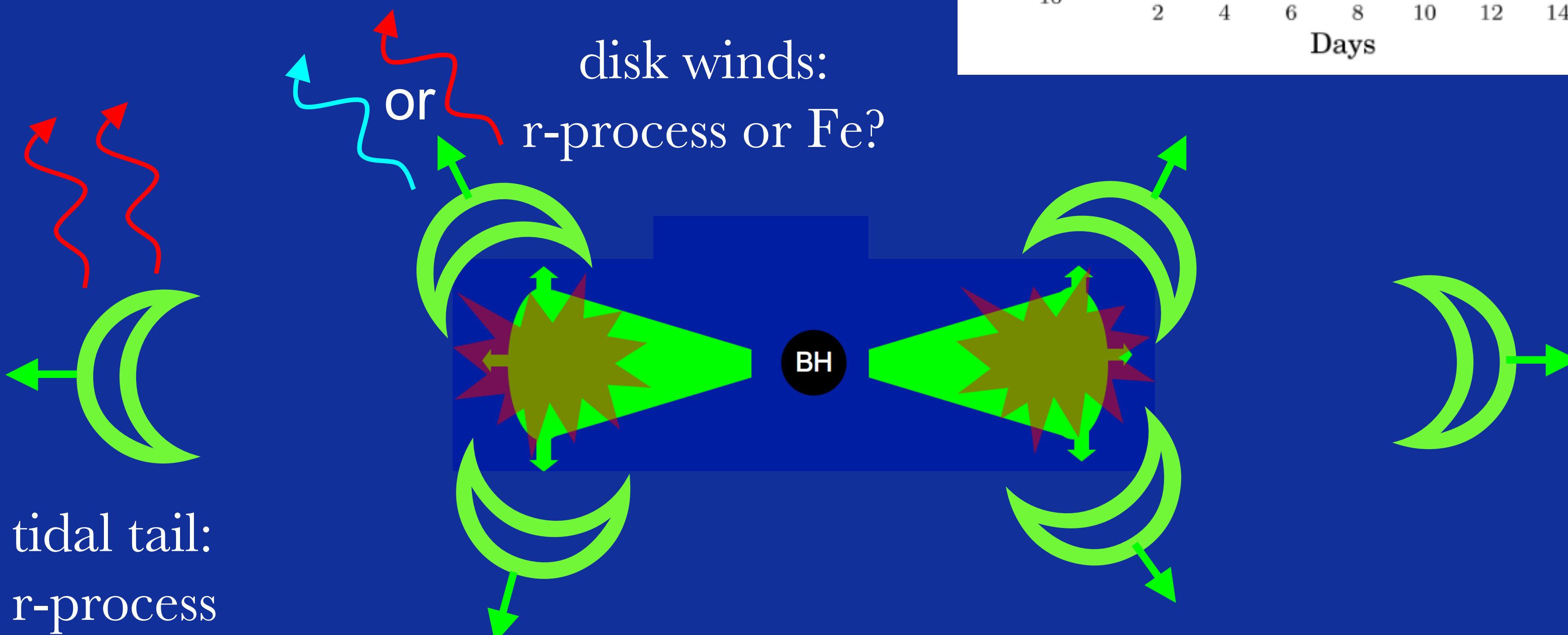
Numerical Simulation - Two 1.4 $M_\odot$ NSs



Courtesy M. Shibata (Tokyo U)

Two Component Light Curve

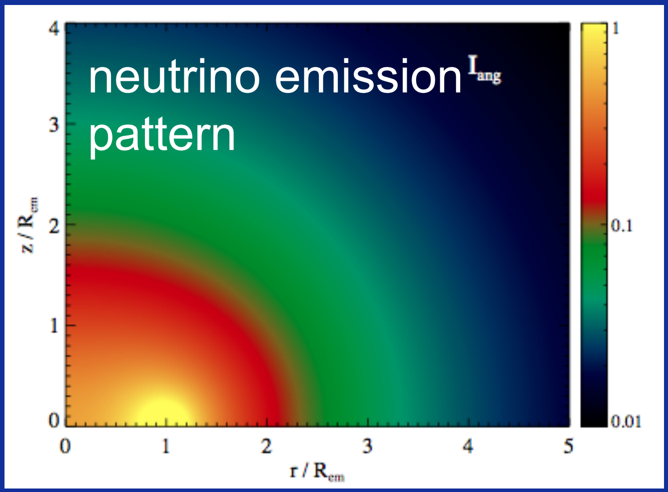


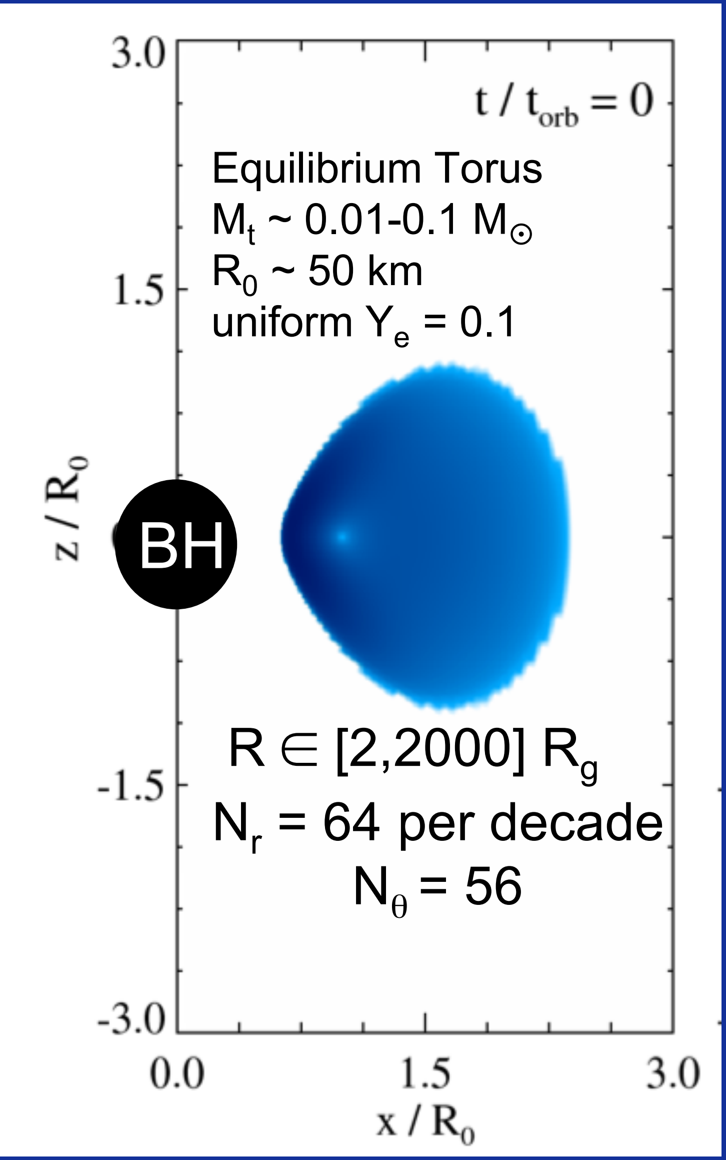


Remnant Torus Evolution

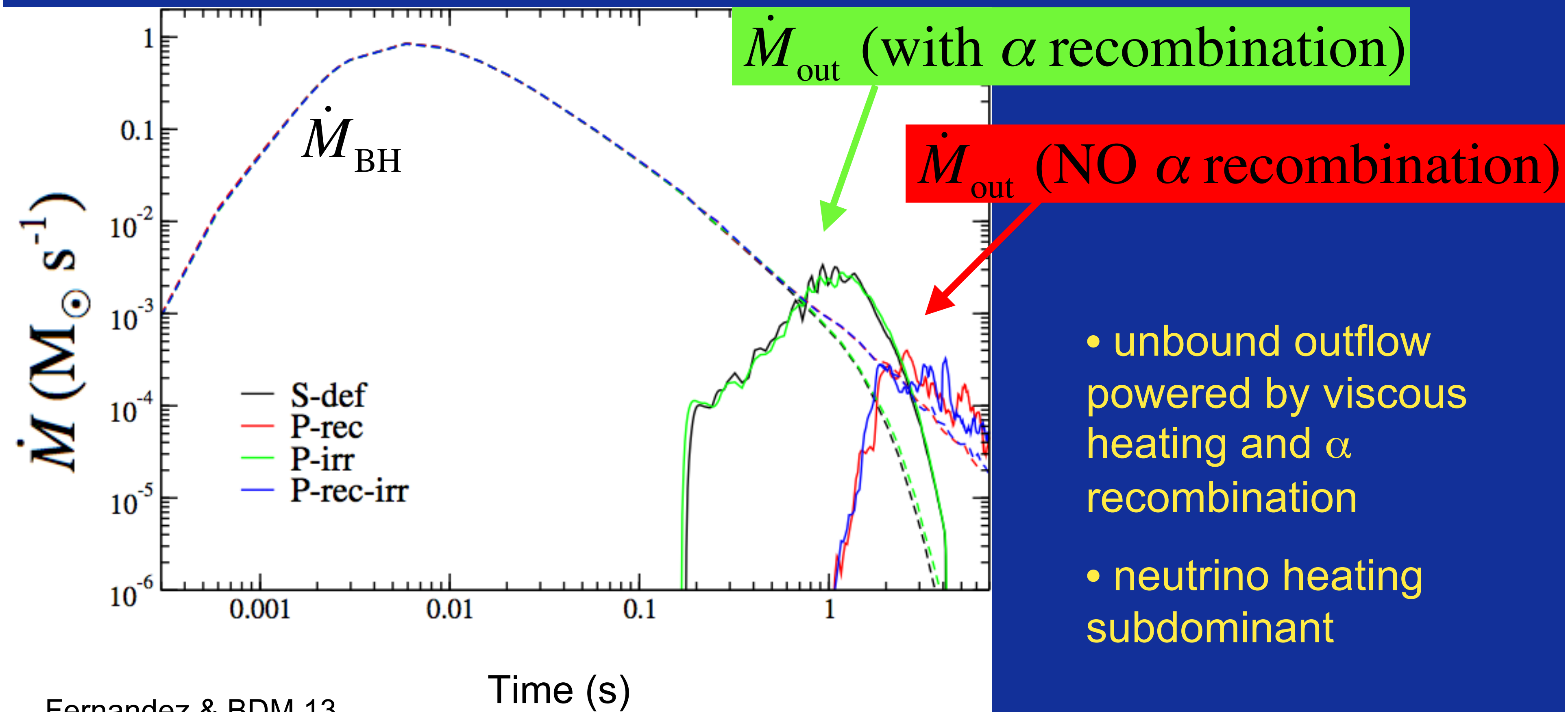
(Fernandez & Metzger 2012, 2013)

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





Delayed Disk Outflows



Fernandez & BDM 13

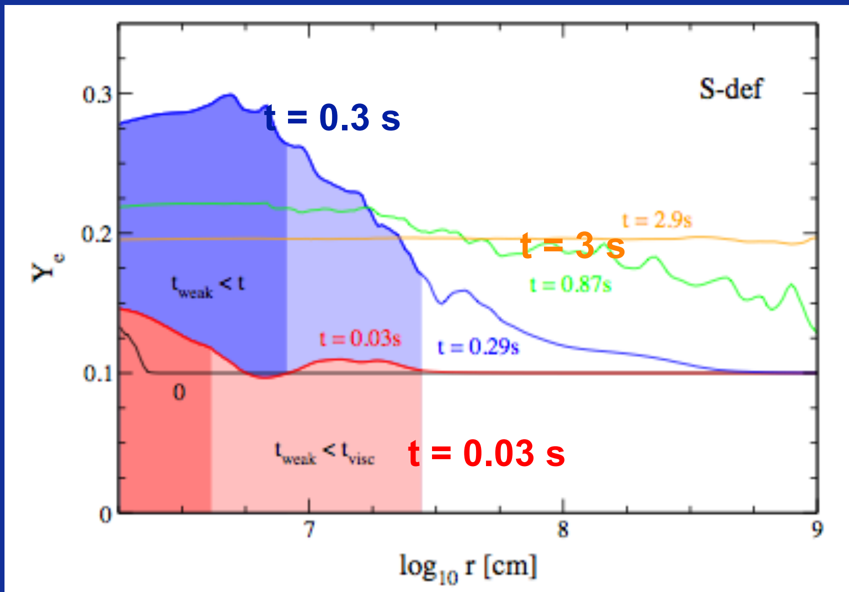
- unbound outflow powered by viscous heating and α recombination
- neutrino heating subdominant

outflow robust

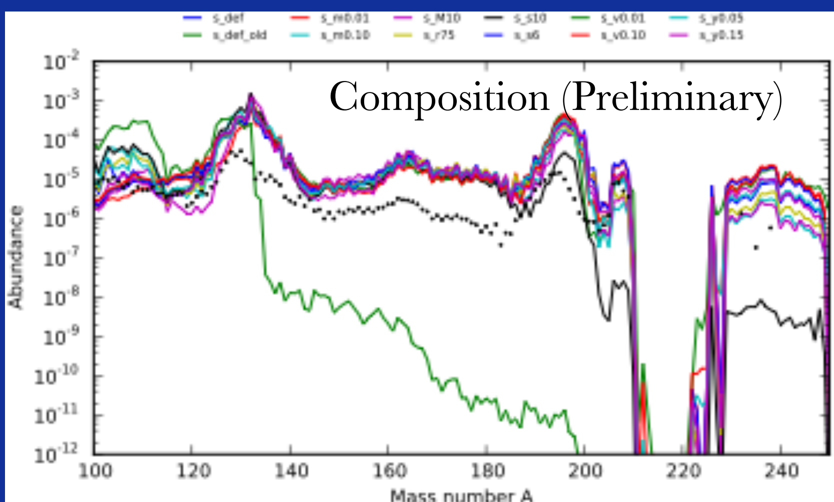
$M_{ej} \sim 0.05\ M_t \quad V_{ej} \sim 0.1\ c$

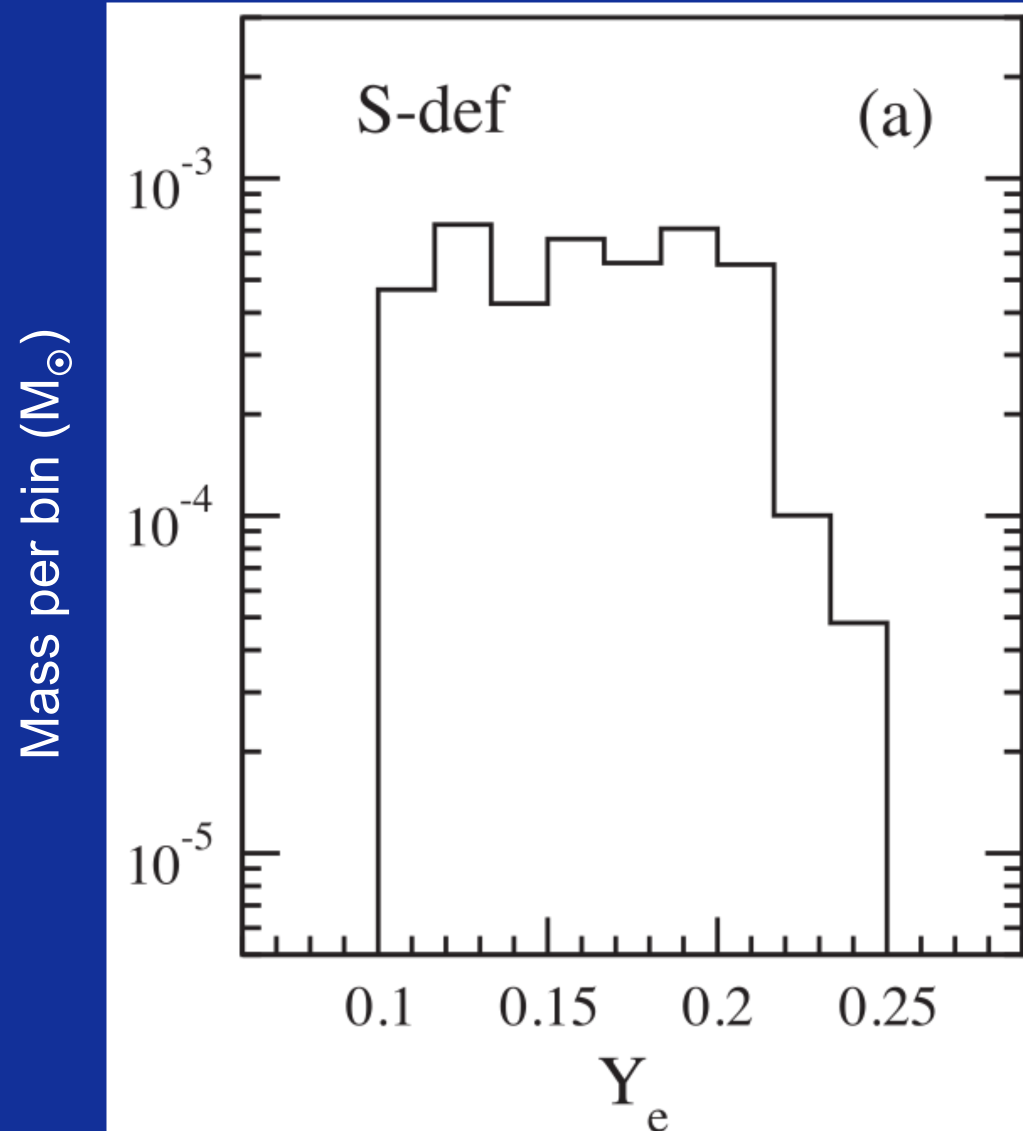
Outflow Composition

Y_e Freeze Out



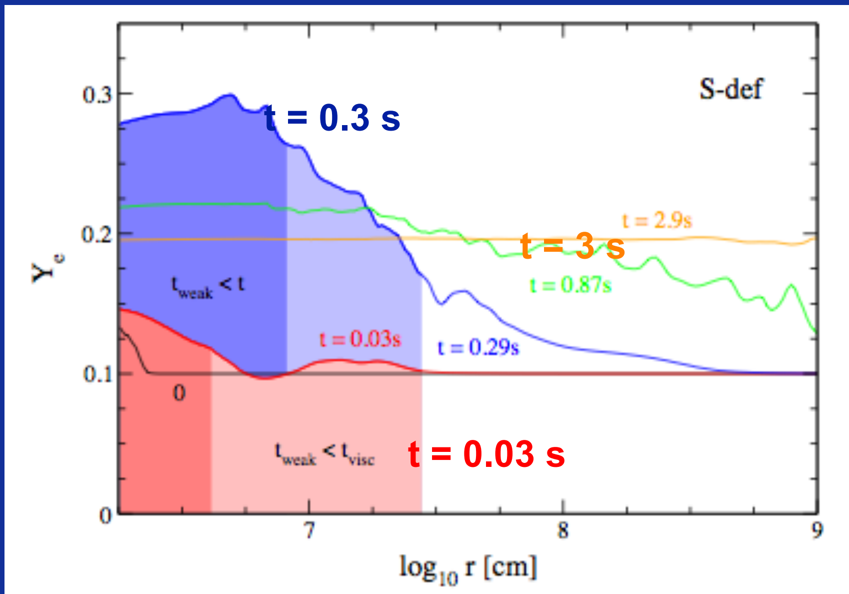
⇒ still produces lanthanides



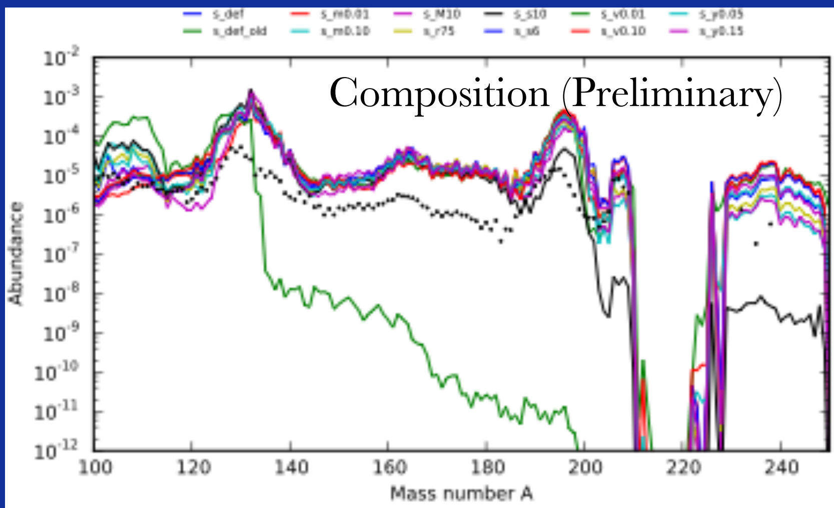


Outflow Composition

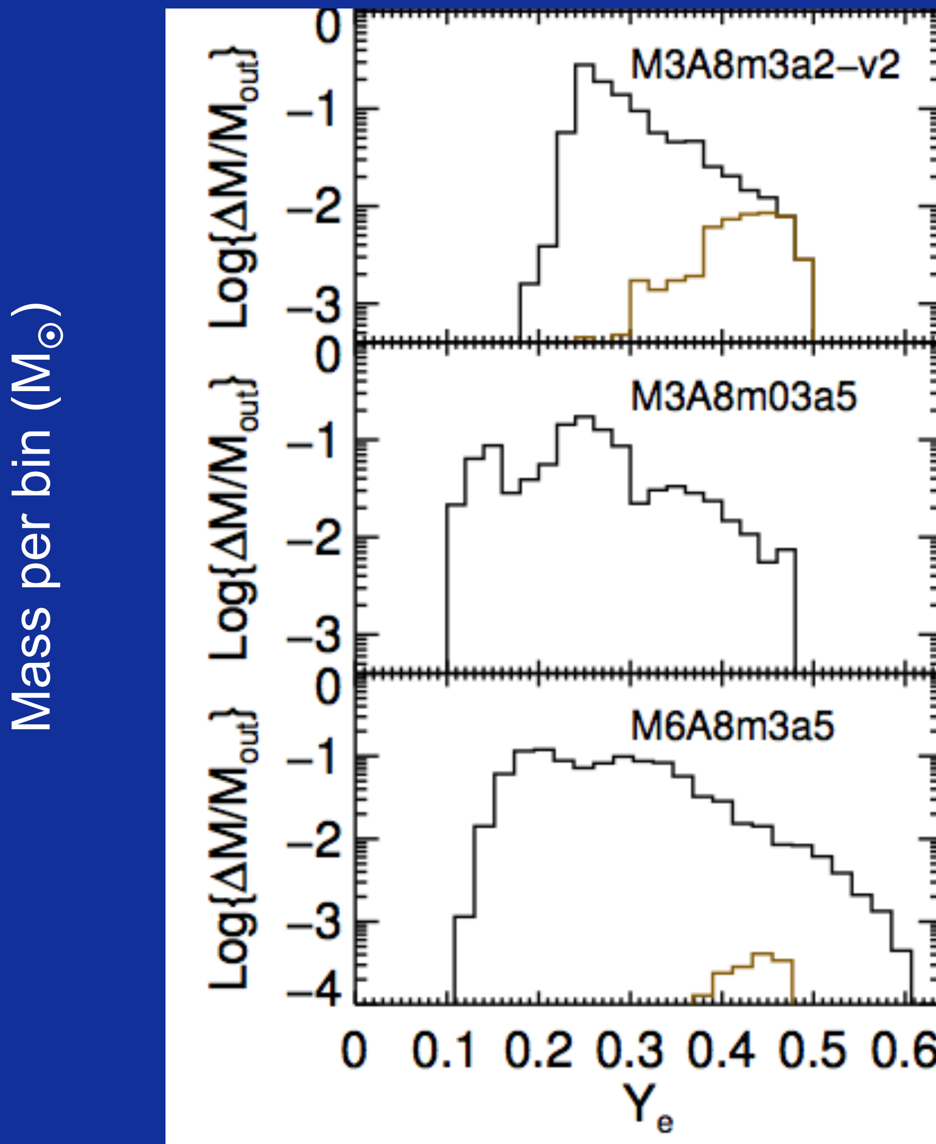
Y_e Freeze Out



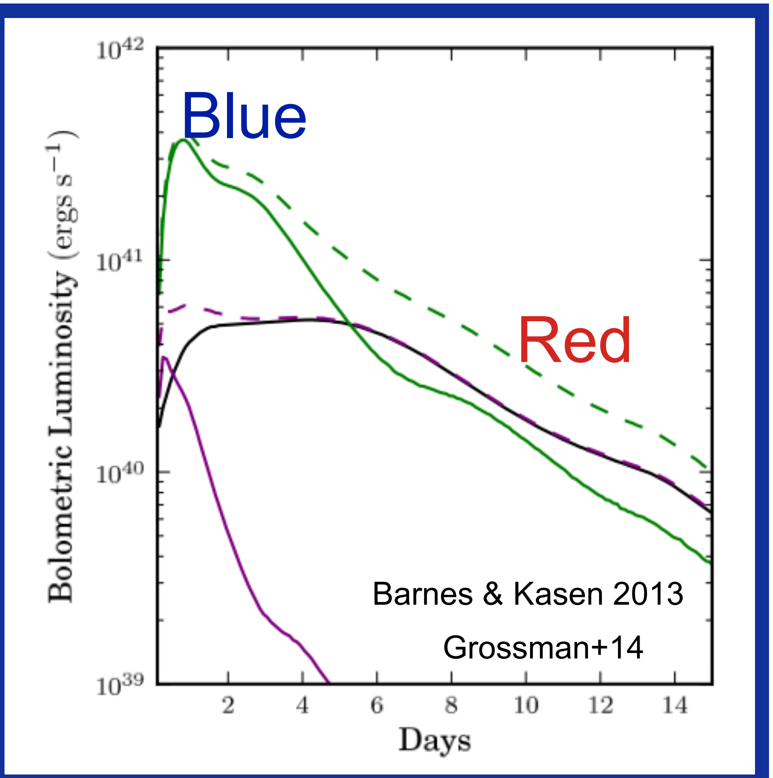
⇒ still produces lanthanides

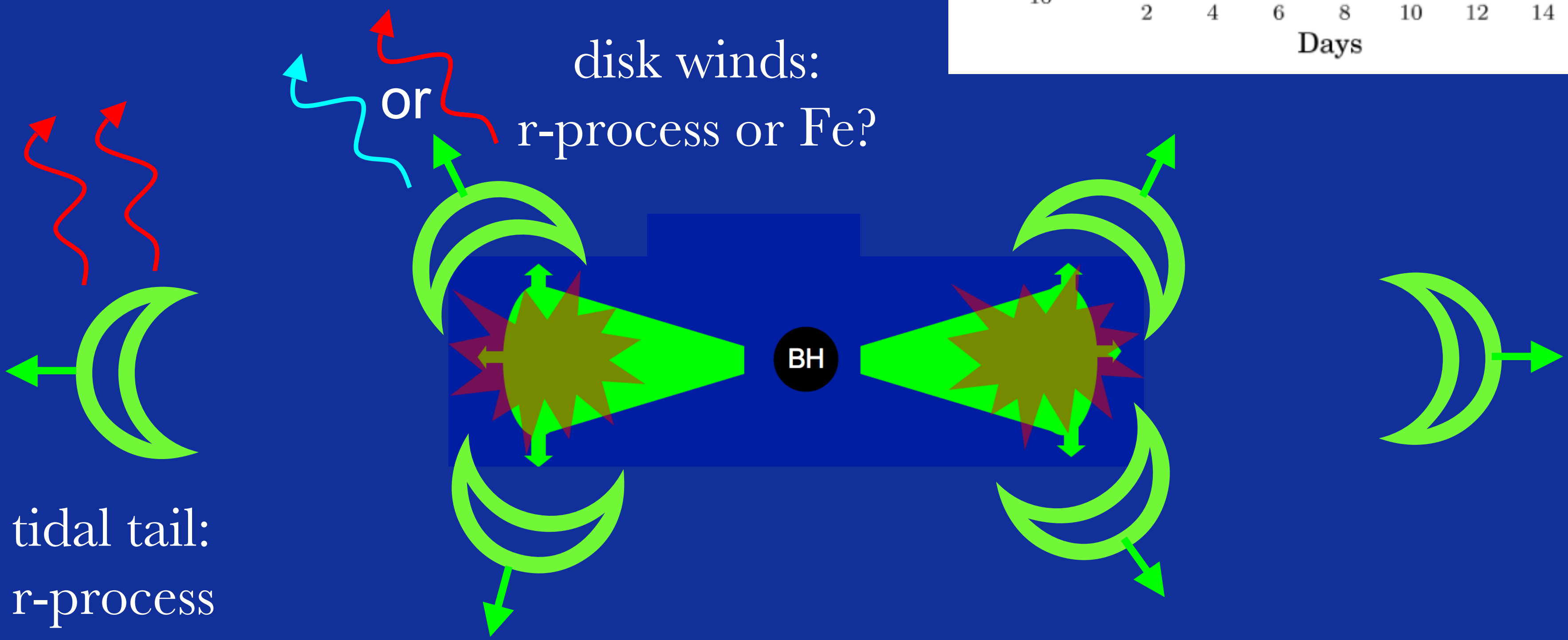


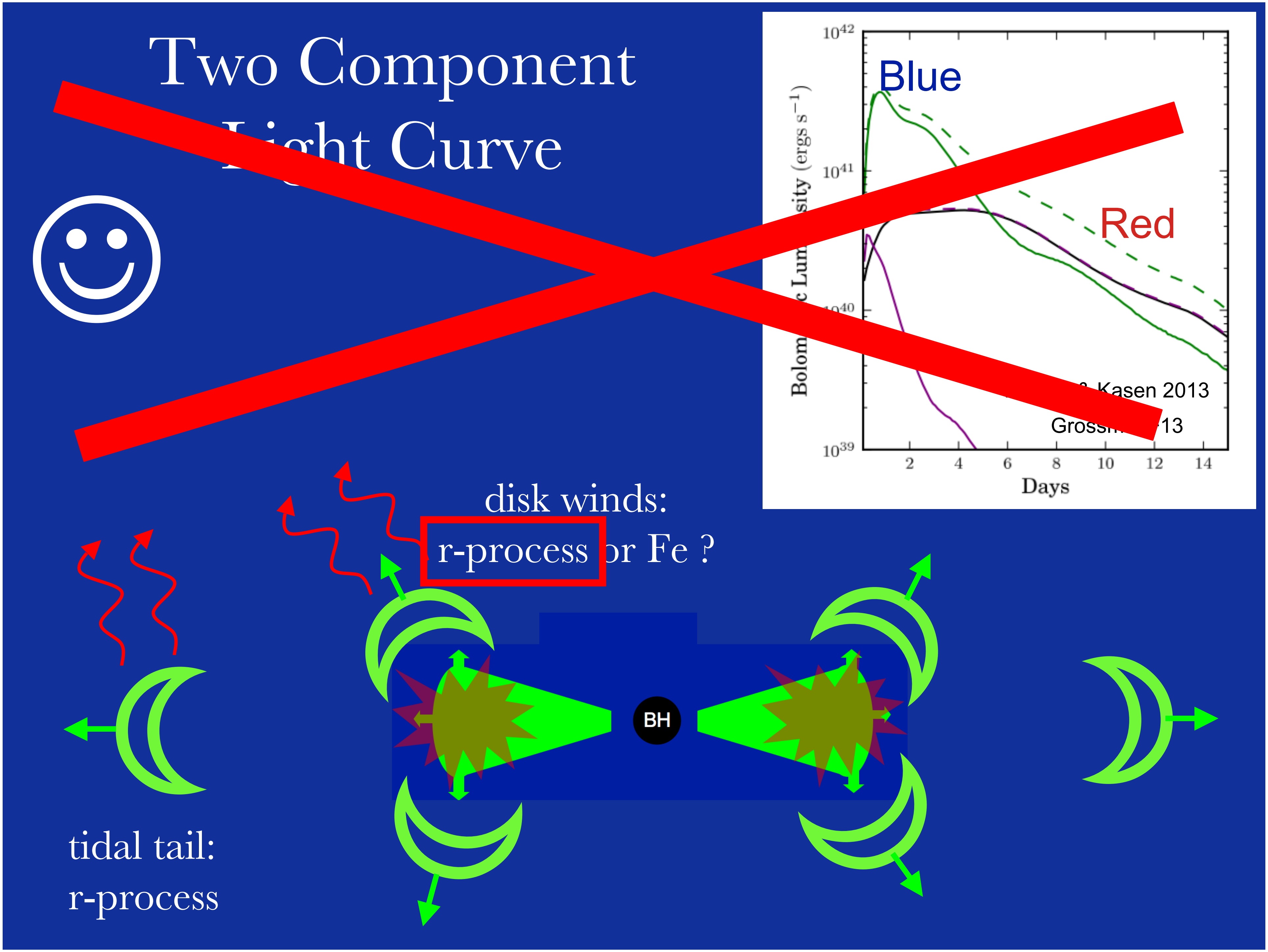
Compare with: Just et al. 2014



Two Component Light Curve







Two Component
Light Curve
Blue
Red
Kasen 2013
Days
2
4
6
8
10
12
14
disk winds:
r-process or Fe ?
BH
tidal tail:
r-process

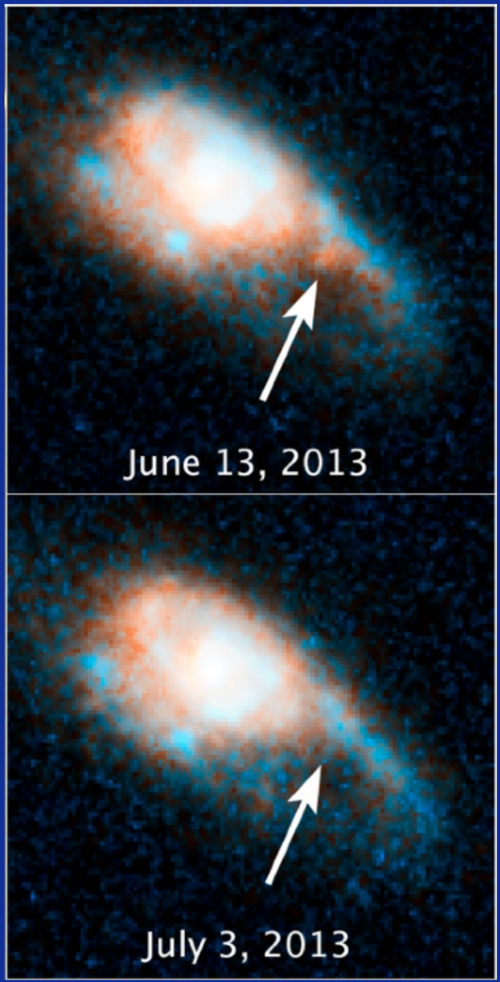
AN R-PROCESS KILONOVA ASSOCIATED WITH THE SHORT-HARD GRB 130603B

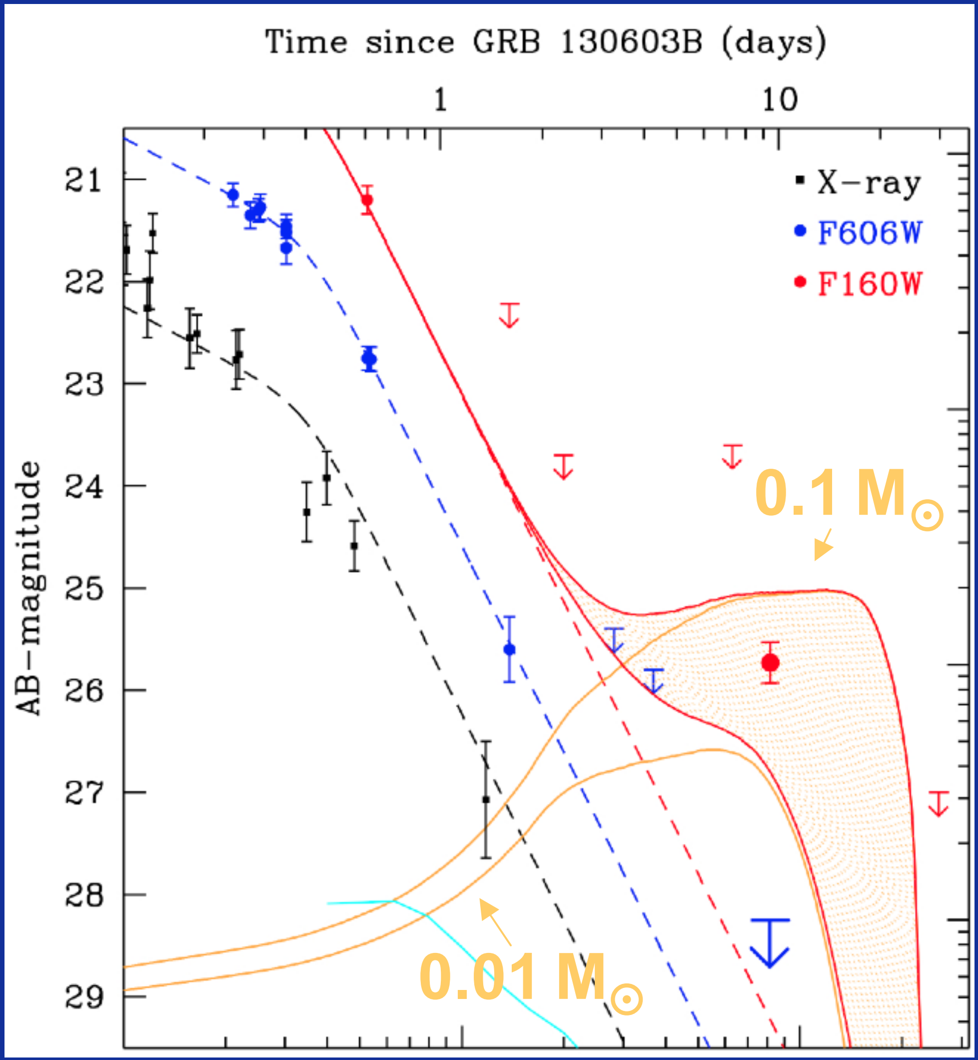
E. BERGER[1], W. FONG[1], AND R. CHORNOCK[1]

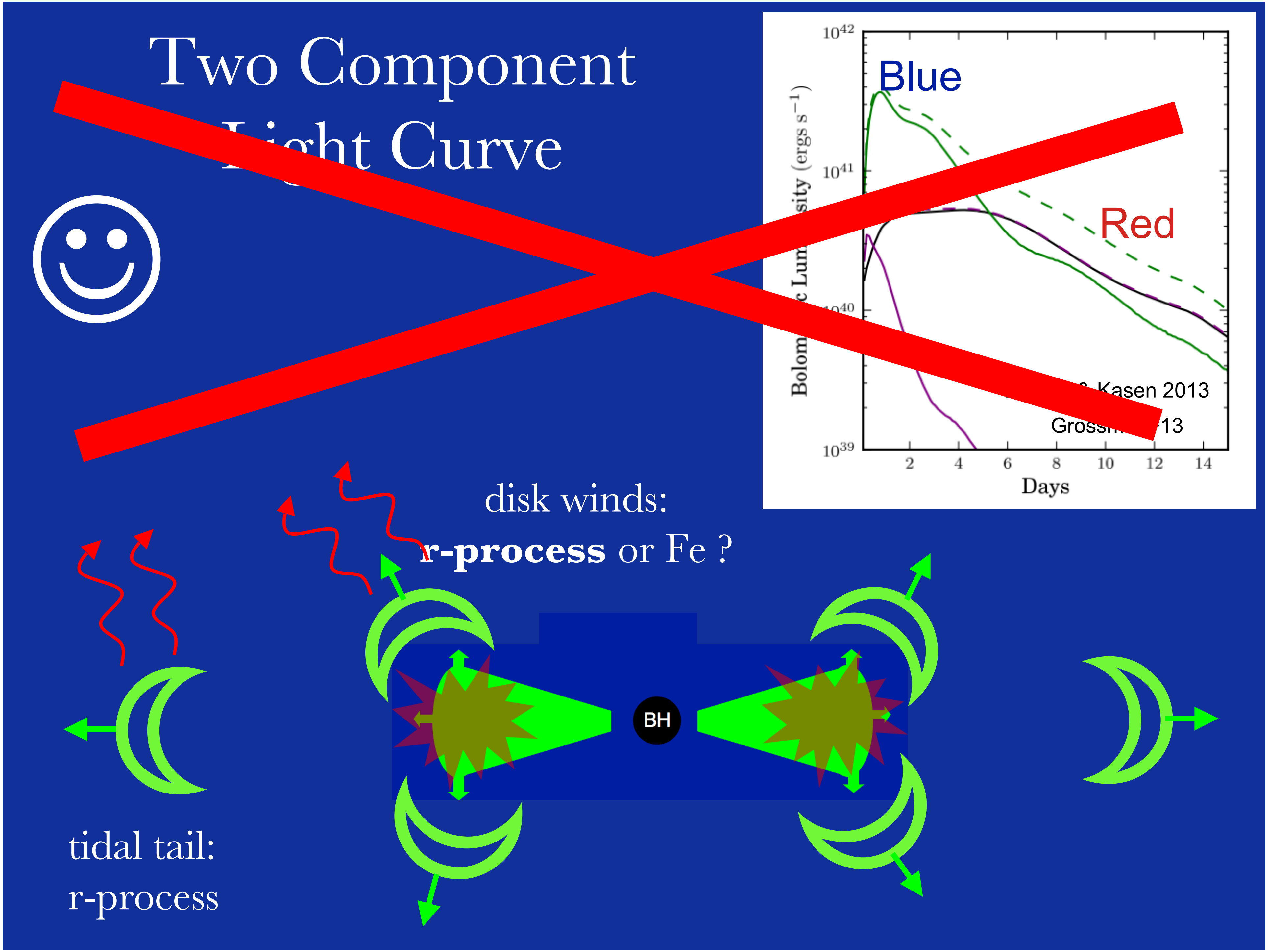
A 'kilonova' associated with the short-duration γ- ray burst GRB 130603B

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

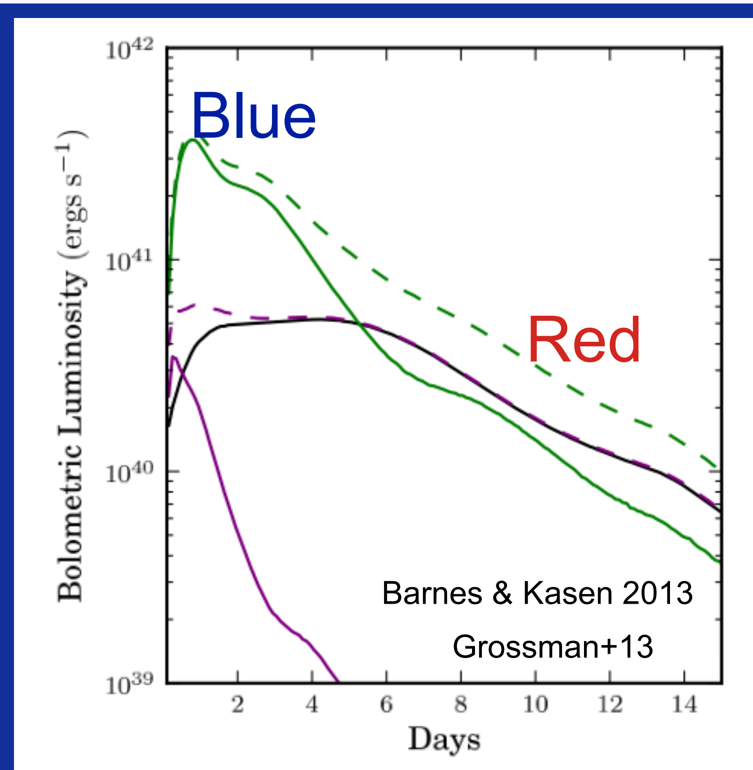
Tanvir et al. 2013

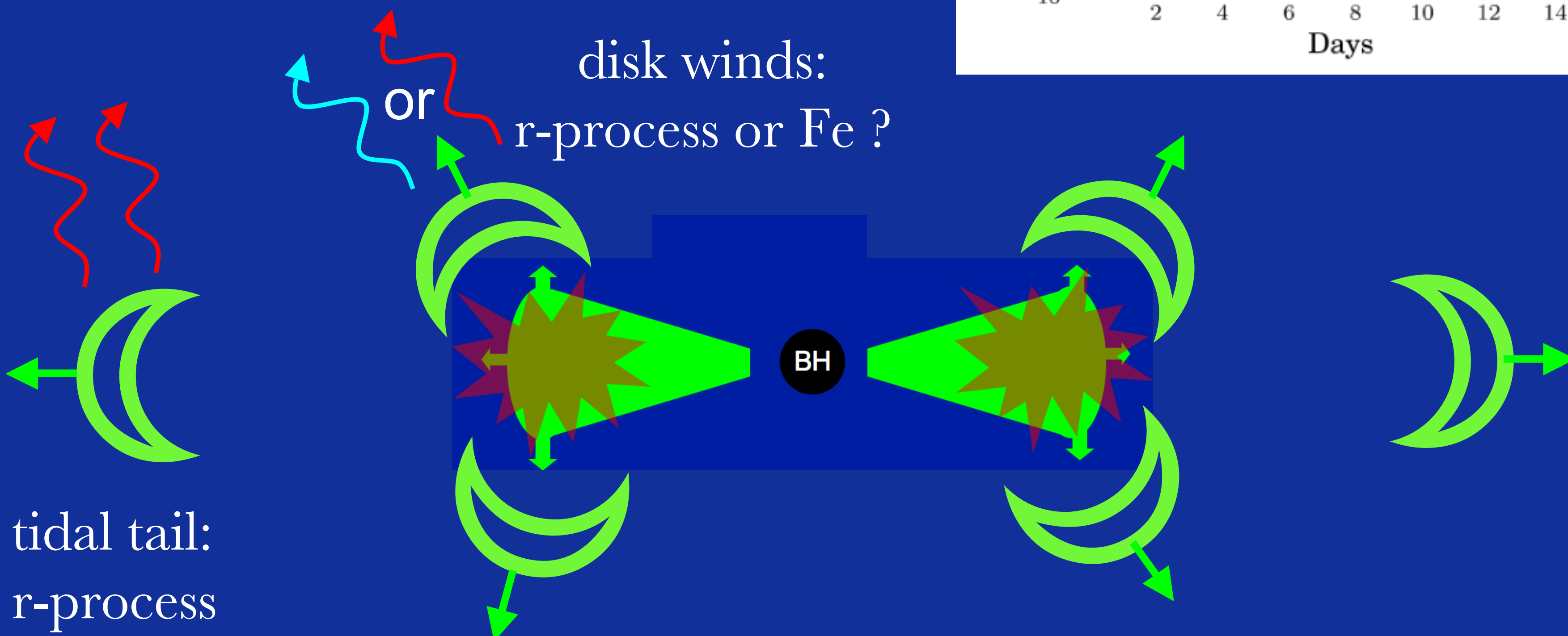




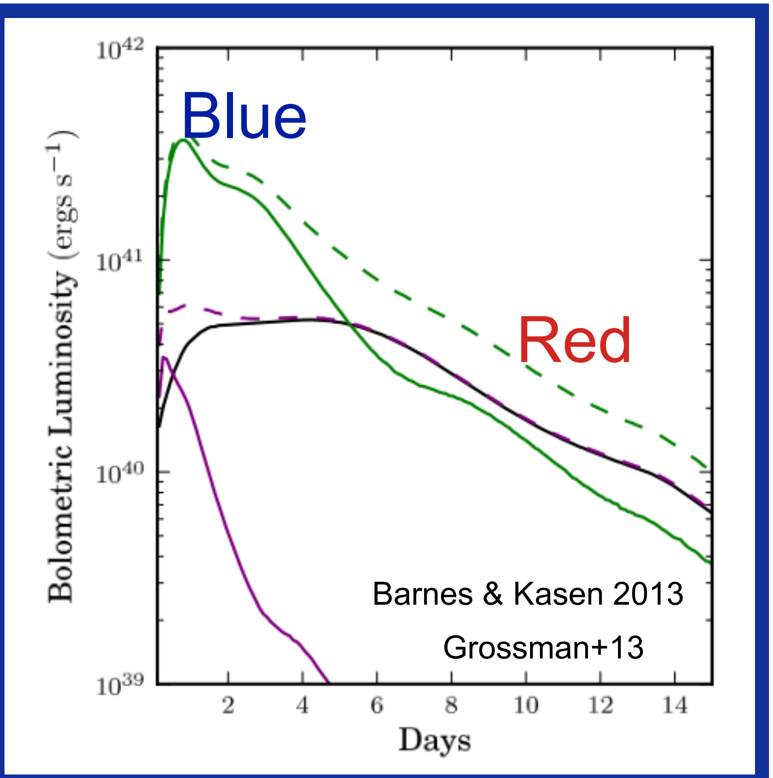

Two Component
Light Curve
Blue
Red
10^42
10^41
10^40
10^39
2
4
6
8
10
12
14
Days
disk winds:
r-process or Fe ?
BH
tidal tail:
r-process

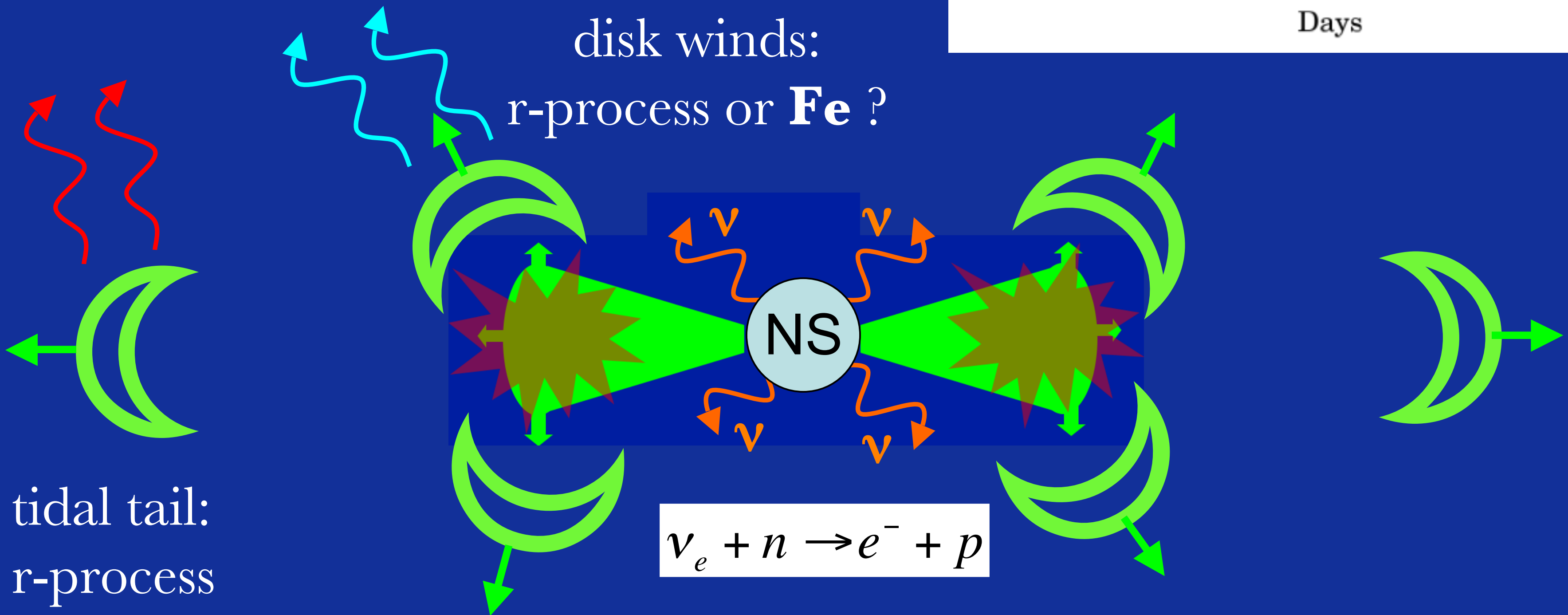
Two Component Light Curve





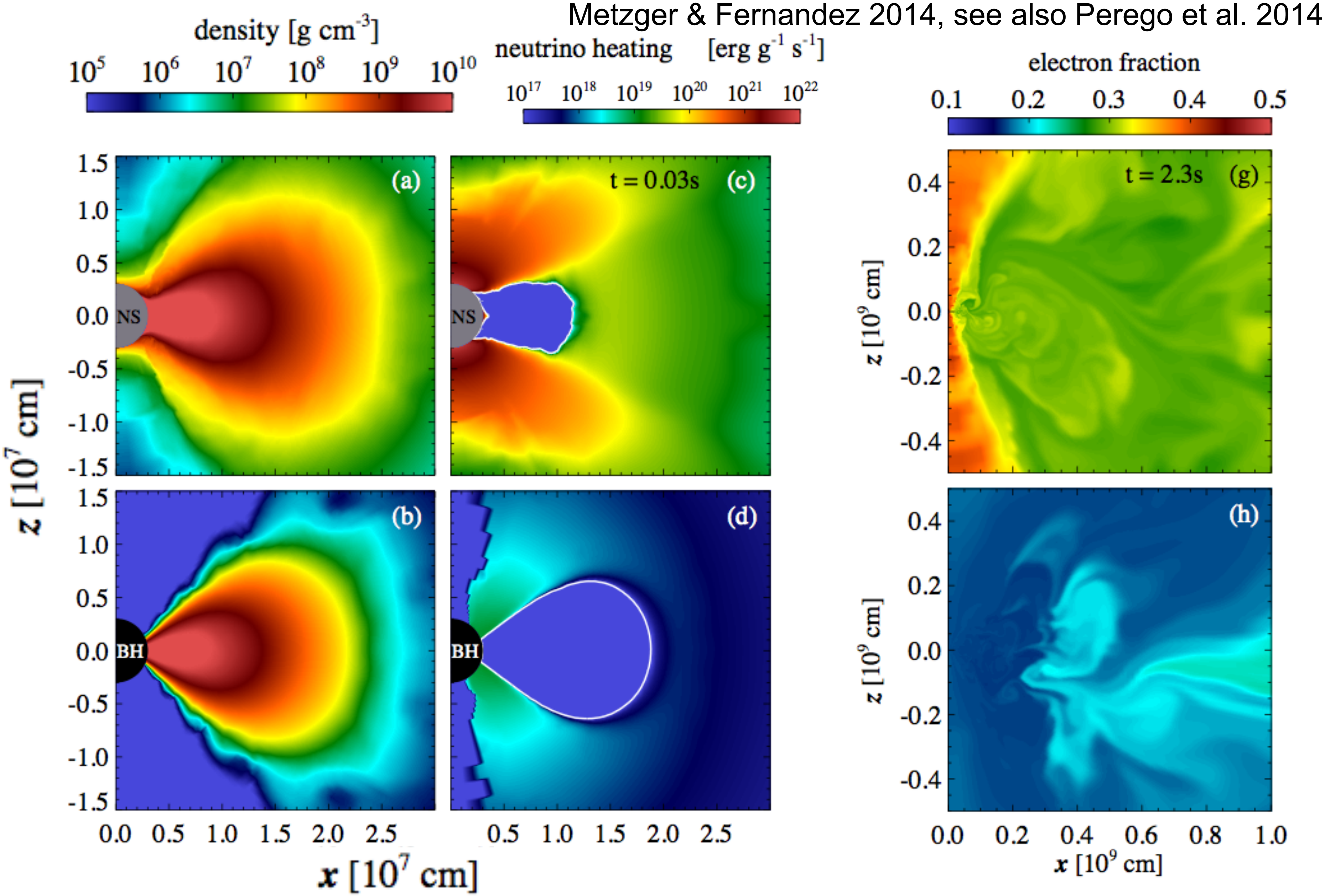
Two Component Light Curve



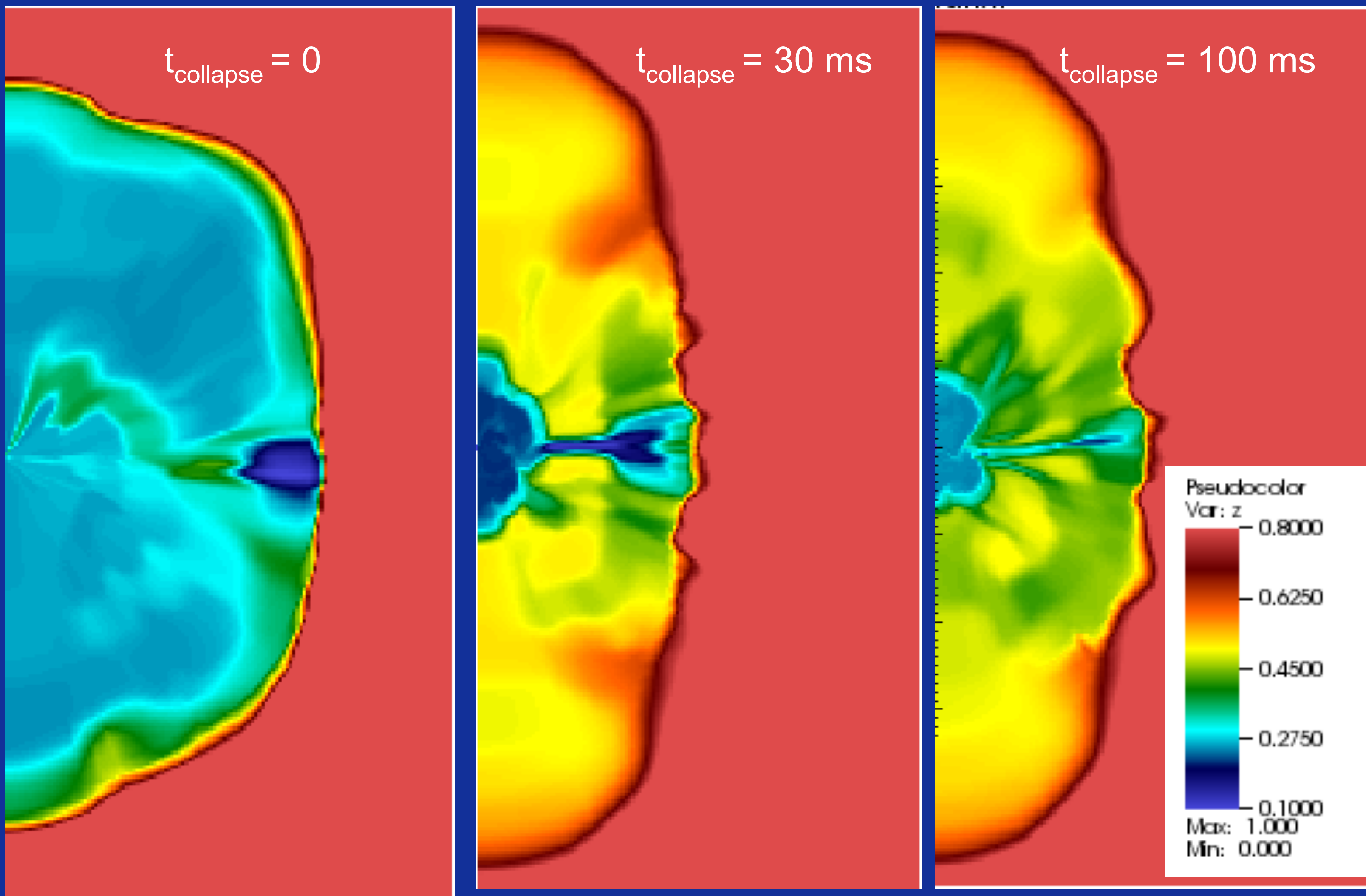


Effect of Hypermassive Neutron Star

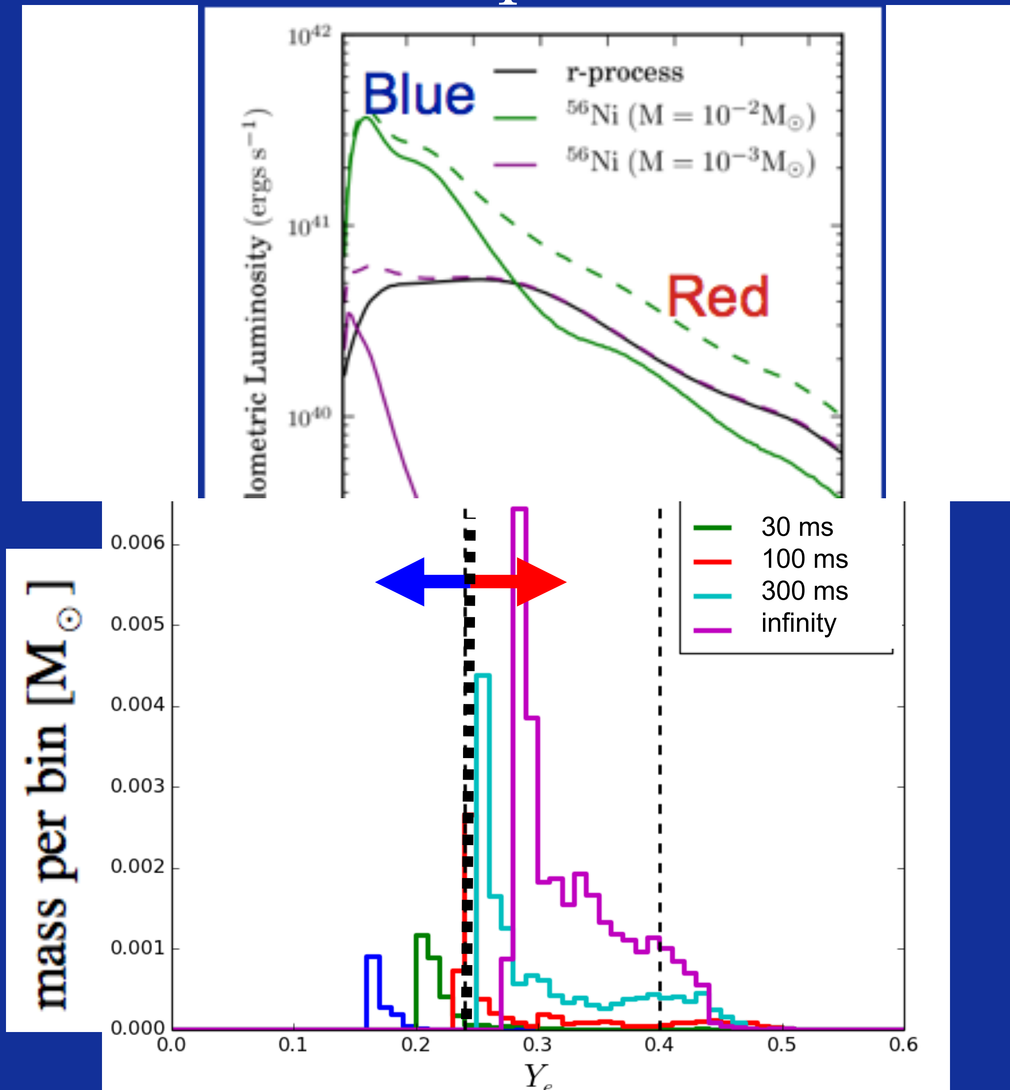
Metzger & Fernandez 2014, see also Perego et al. 2014

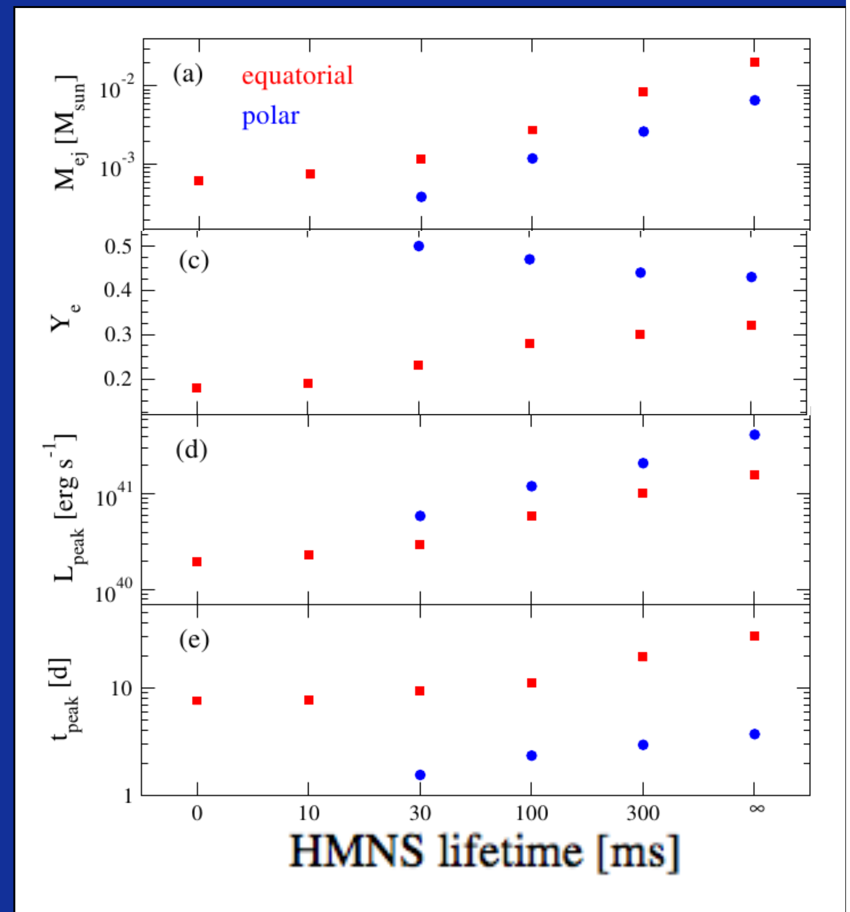


Distribution of Ejecta Y_e for Different Collapse Times



Imprint of the HMNS Lifetime





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

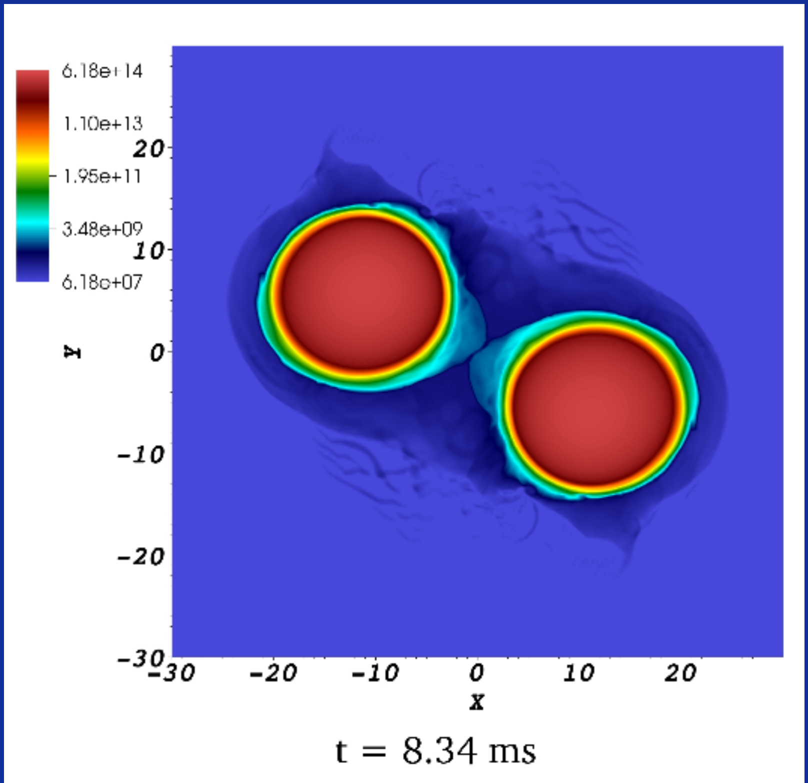
Stable Merger Remnant?

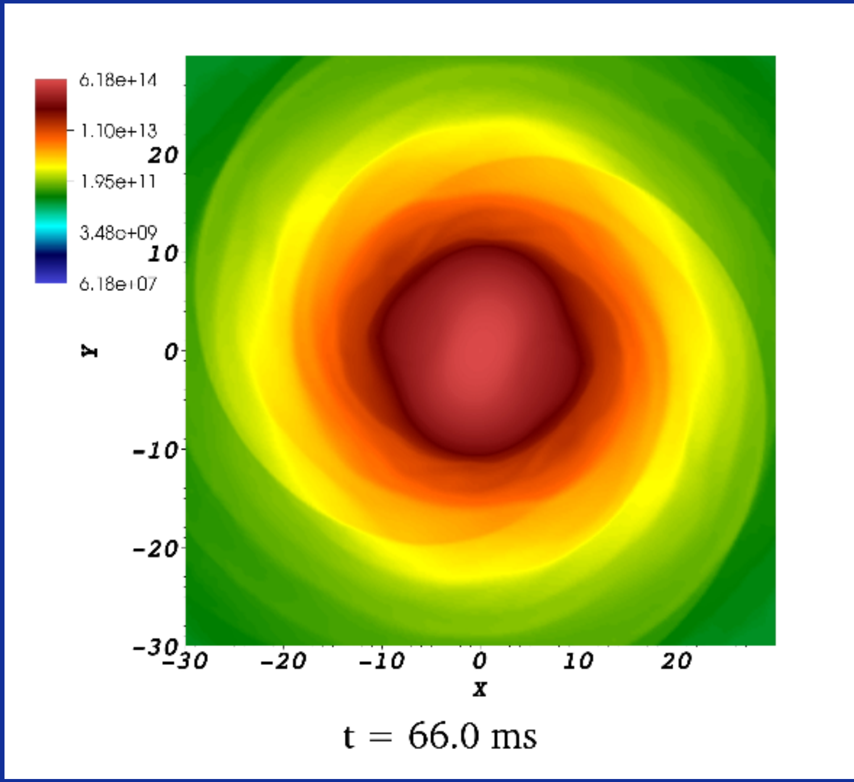
(e.g. BDM+08; Ozel et al. 2010; Bucciantini et al. 2012; Zhang 13; Yu et al. 2013; Giacomazzo & Perna 13; Siegel 2014)

- 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” ?**

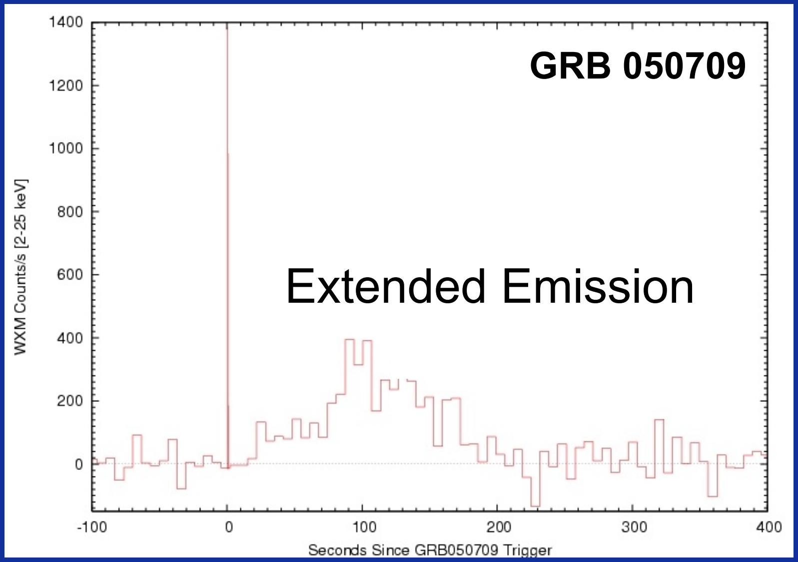


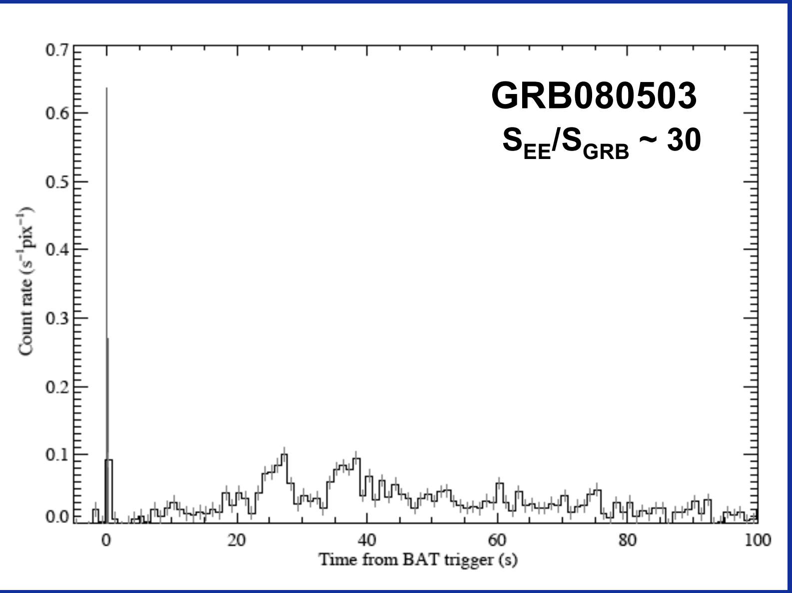


Giacomazzo & Perna 2013

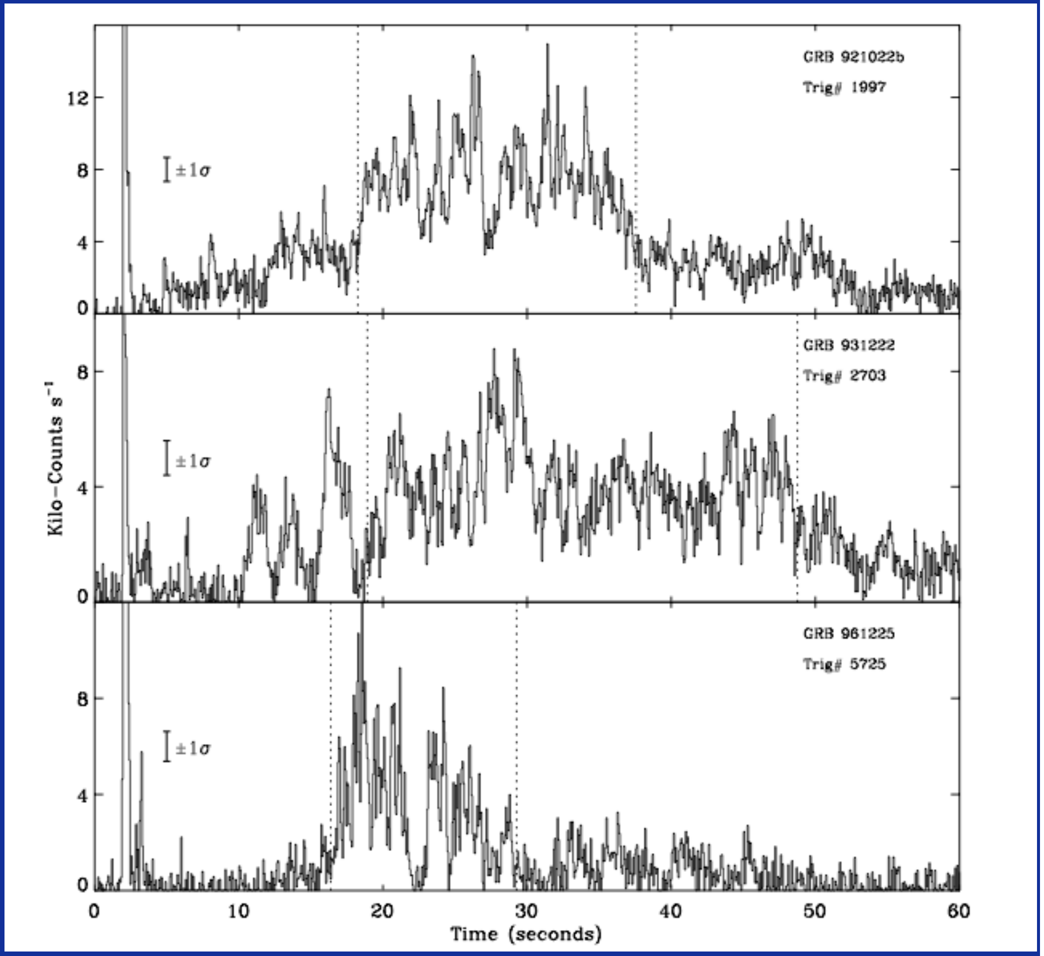
Short GRBs with Extended Emission

- 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)

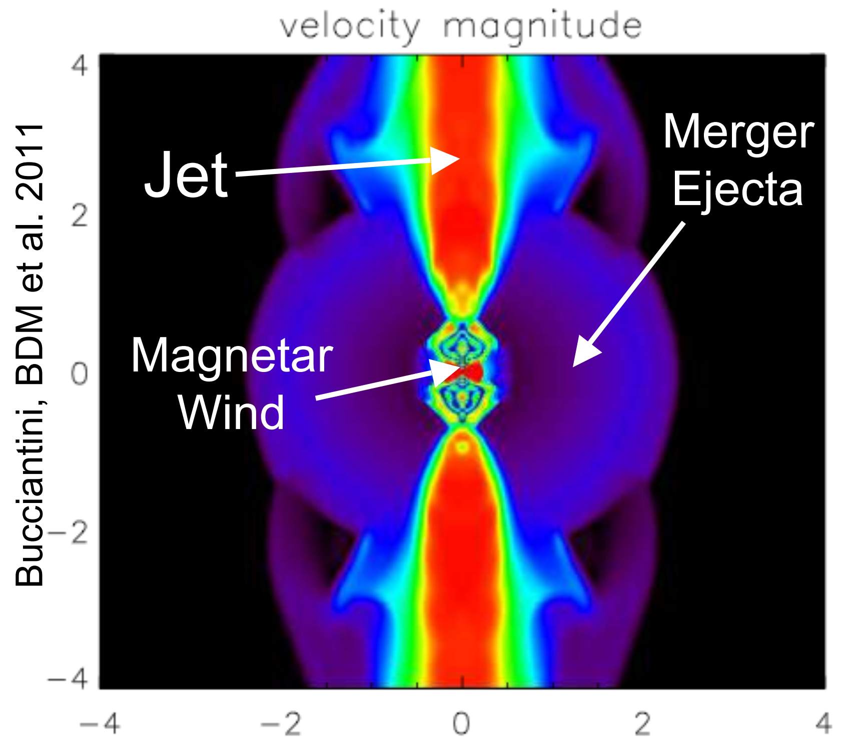
spin-down luminosity :

$$L_{sd} = \frac{\mu^2\Omega^4}{c^3} \approx 6\times10^{49}\left(\frac{P}{1\text{ ms}}\right)^{-4}\left(\frac{\mathrm{B_{dip}}}{10^{15}\text{ G}}\right)^{2}\text{erg s}^{-1}$$

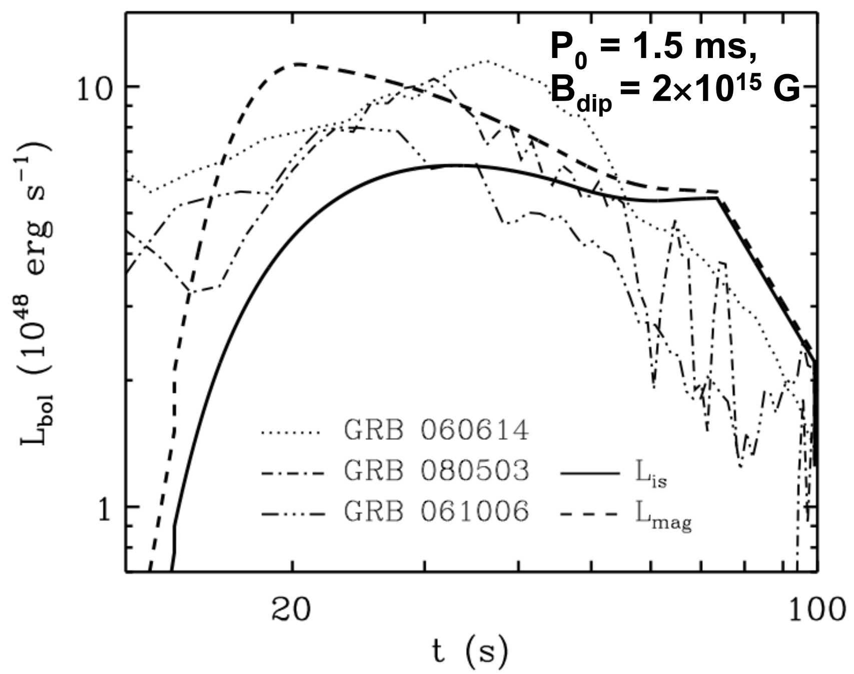
spin-down time :

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

Magnetar wind confined by merger ejecta



Theoretical Light Curves vs. Observed X-ray Tails
(magnetar wind model from Metzger et al. 2011)



Stable Merger Remnant?

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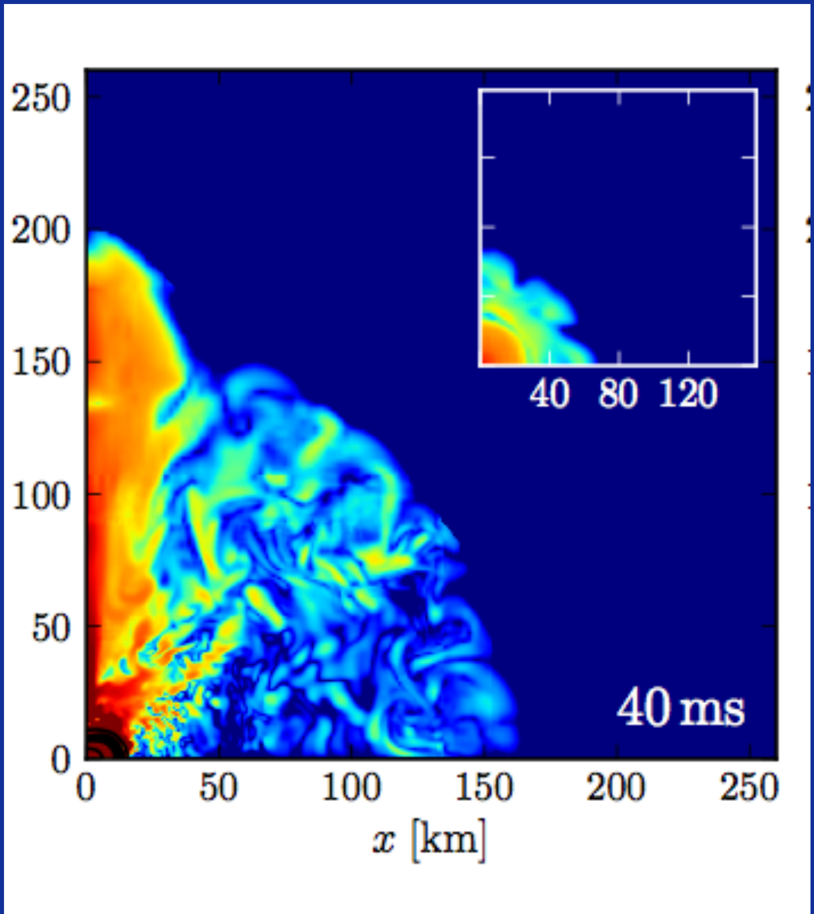
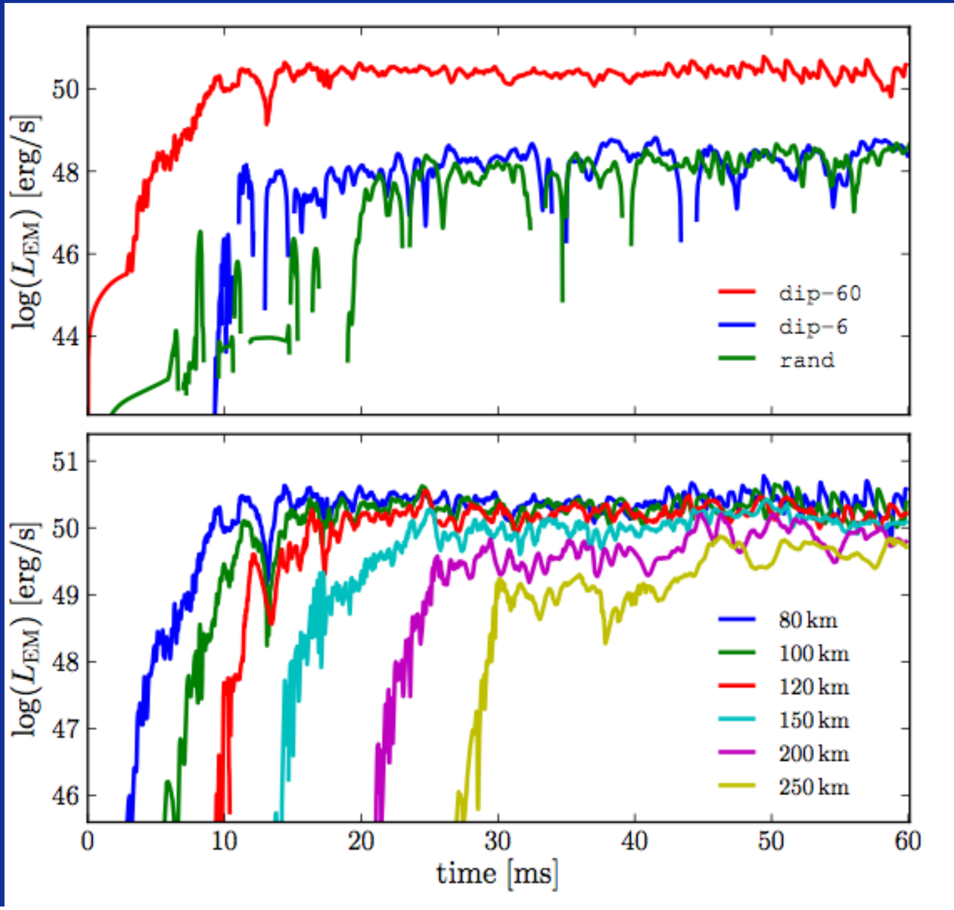
Siegel, Ciolfi, Rezzolla 2014





Radio constraints on stable merger remnants

(BDM & Bower 2013)

• Rotational energy

$$E_{\rm rot} = \frac{1}{2}I\Omega^2 \simeq 3\times10^{52}{\rm ergs}\left(\frac{P}{1\ {\rm ms}}\right)^{-2}$$

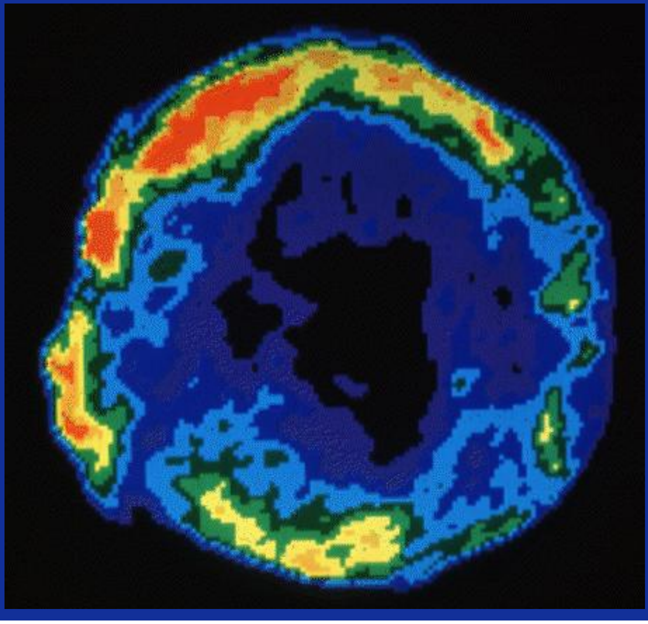
eventually transferred to ISM via relativistic shock ⇒ bright radio emission

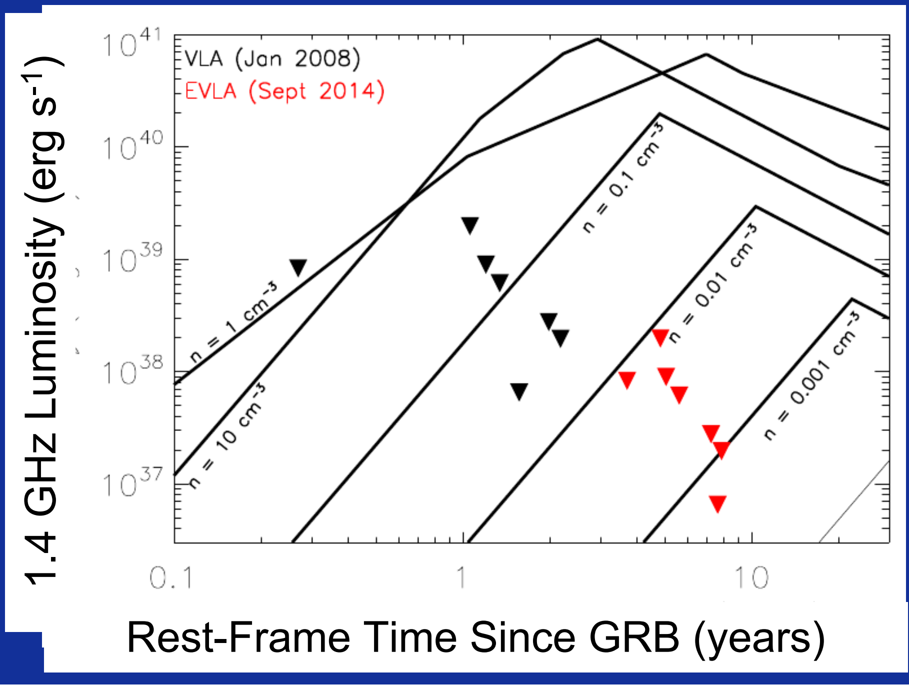
• We observed 7 short GRBs with VLA on timescales ~1-3 years after burst

• 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}) ⇒ delayed BH formation $Y_e > 0.25$ (Optical, $L \sim 10^{42}$ erg s^{-1}) ⇒ stable magnetar (Optical, $L \sim 10^{44}$ erg s^{-1})	 ~ week ~ day ~ day
9. Tidal Tail Kilonova (**IR**)	~ week
10. Ejecta ISM Interaction (**Radio**) ⇒ Much brighter if stable magnetar	~ years

Conclusions

• 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 first kilonova was detected following the gamma-ray burst 130603B last June, confirming the association of mergers with short GRBs.

• Kilonova provide a direct probe of the formation of r-process nuclei, a long standing mysteries in nuclear astrophysics.

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