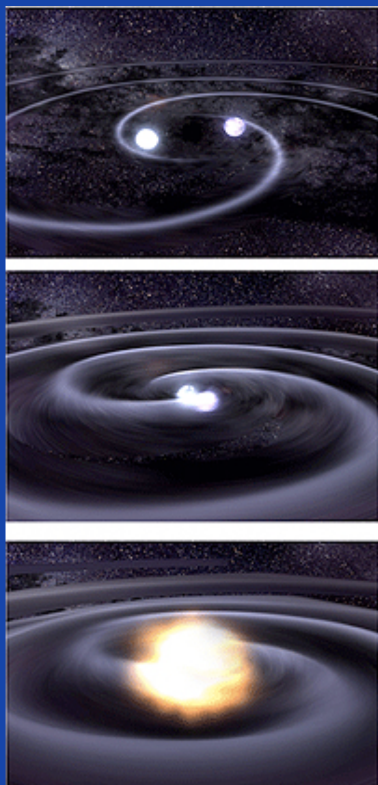
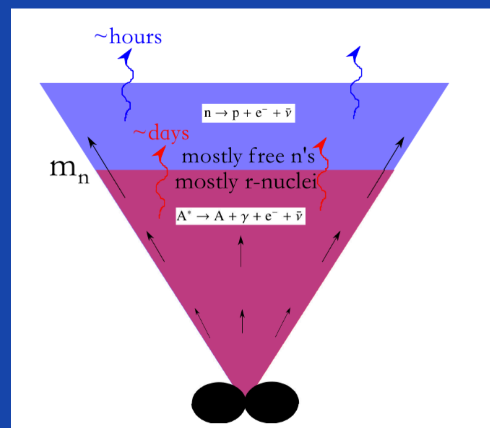
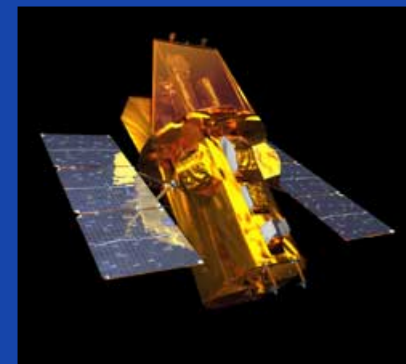
Electromagnetic Signatures of Neutron Star Mergers

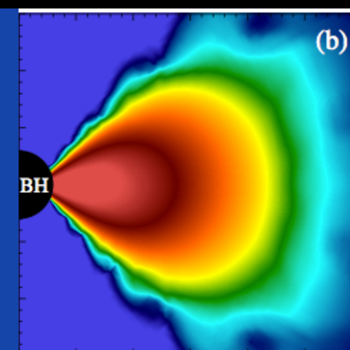


Brian Metzger

Columbia University





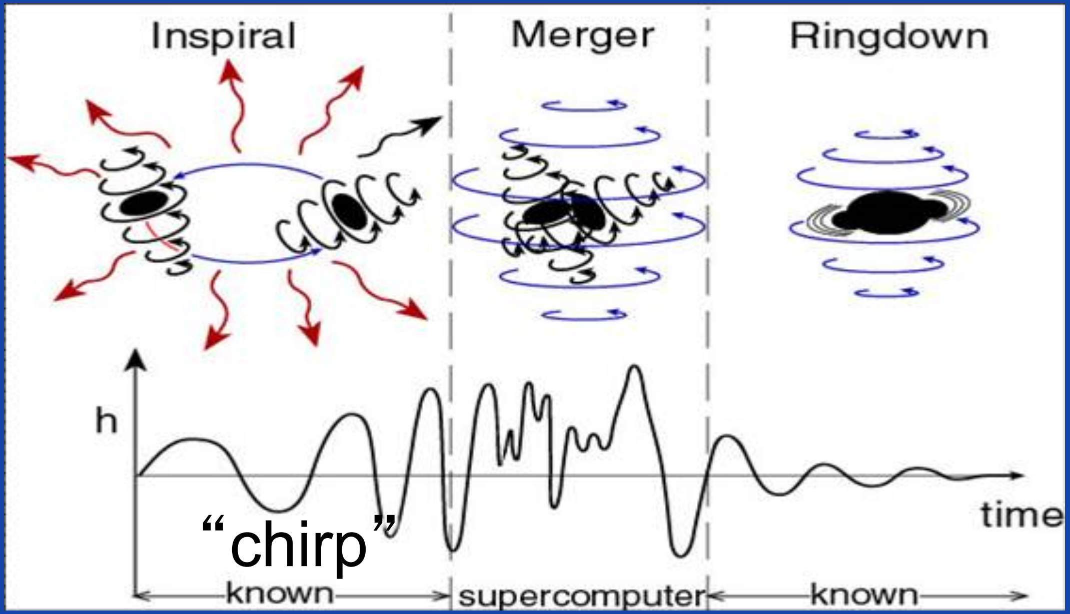


In Collaboration with

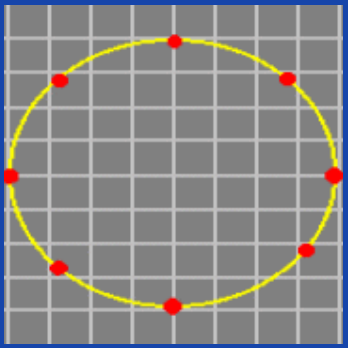
Rodrigo Fernandez, Dan Kasen, Eliot Quataert (UC Berkeley), Tony Piro (Carnegie)
Ben Margalit, Andrei Beloborodov (Columbia), Edo Berger (Harvard)
Almudena Arcones, Gabriel Martinez-Pinedo (GSI/TU Darmstadt) , Dan Perley (Caltech)
Geoff Bower (Hilo), Andreas Bauswein (U Thessaloniki), Stephane Goriely (U Brussels)

Workshop on Binary Neutron Stars, Aristotle University, Thessaloniki

Gravitational Wave Sources



Credit: Kip Thorne



Ground-Based Interferometers

LIGO (North America)

Virgo (Europe)

LIGO 6th Science Run (2010) Range ~ 20-50 Mpc

"Advanced" LIGO+Virgo (~2017) Range ~ 200-500 Mpc

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

Importance of EM Detection:

- Improve "confidence" in GW detection; dig deeper into GW data
- Independently constrain binary parameters
- Astrophysical context (e.g. host Galaxy & environment)
- Cosmology (e.g. H_0, w); test strong-field GR; constrain neutron star EOS

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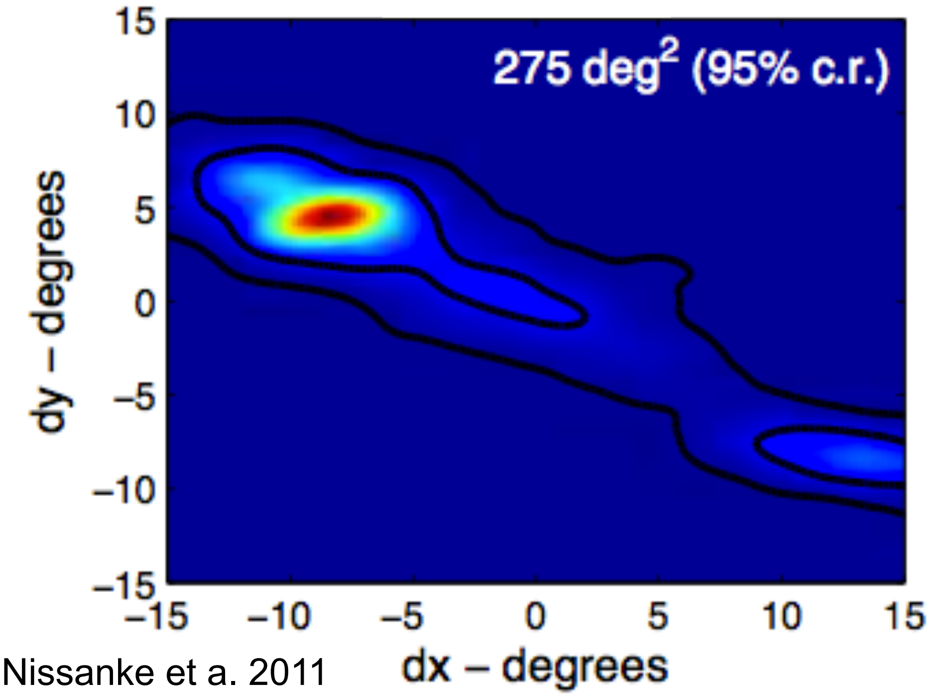
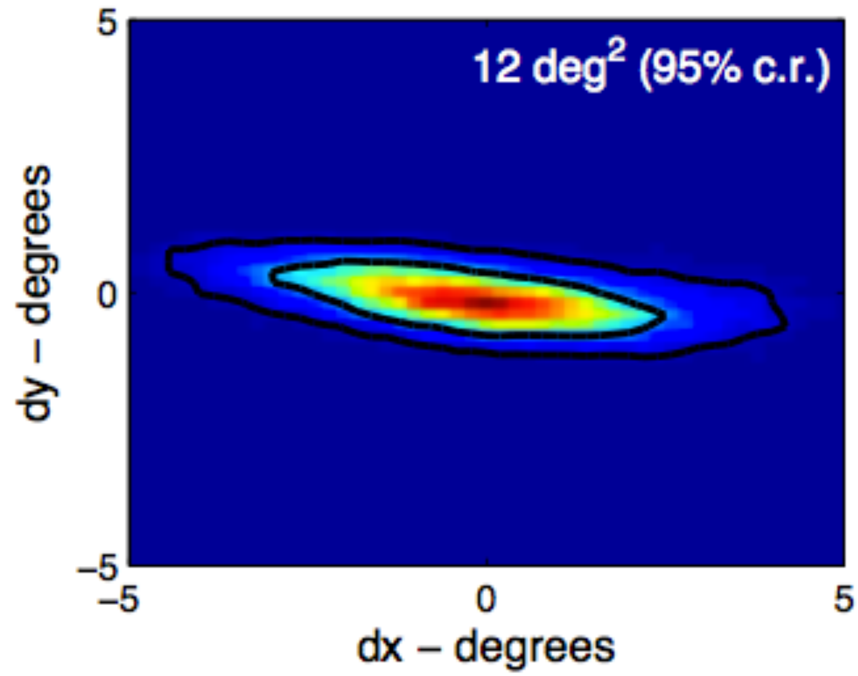
Sky Error Regions ~ 10-100 deg^2 (~2019)

Low SNR



High SNR



Nissanke et a. 2011

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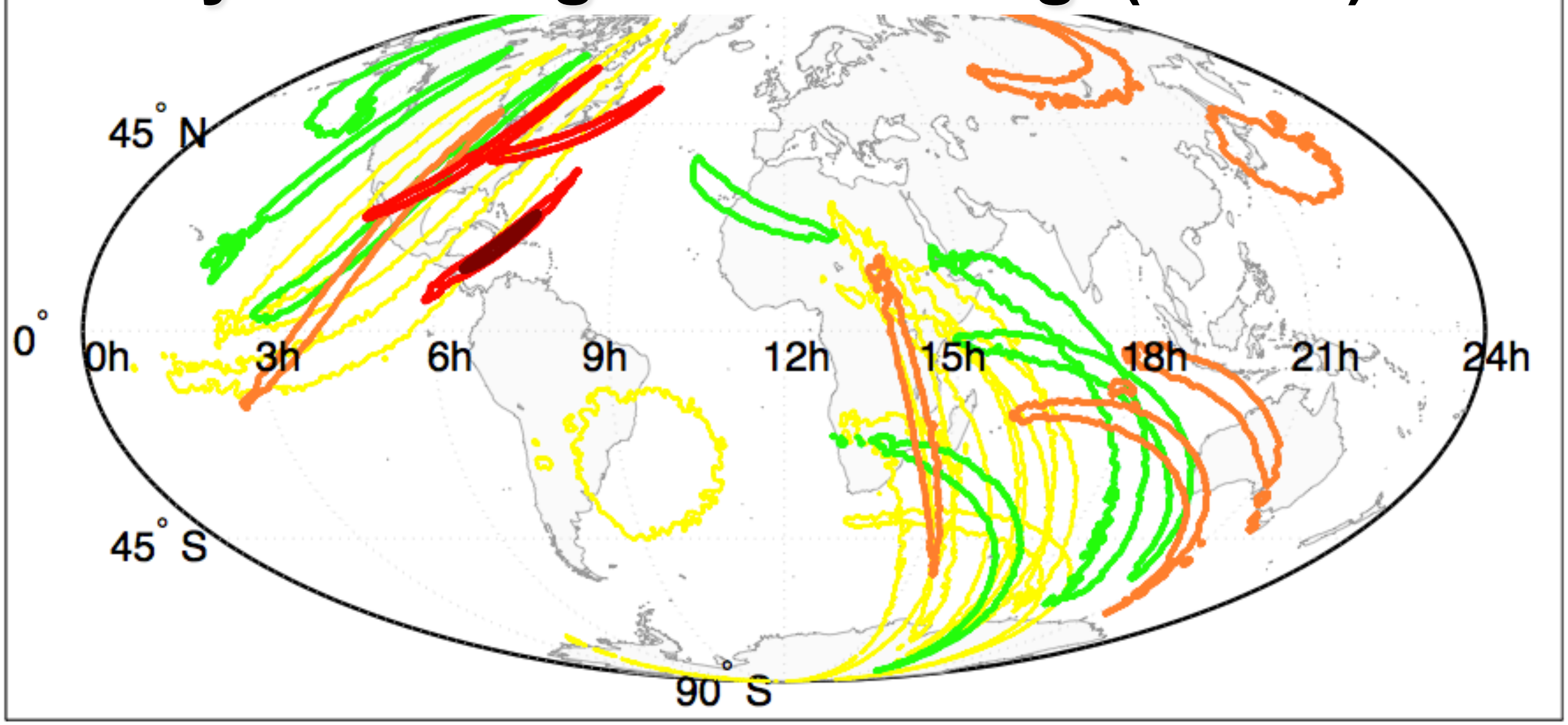
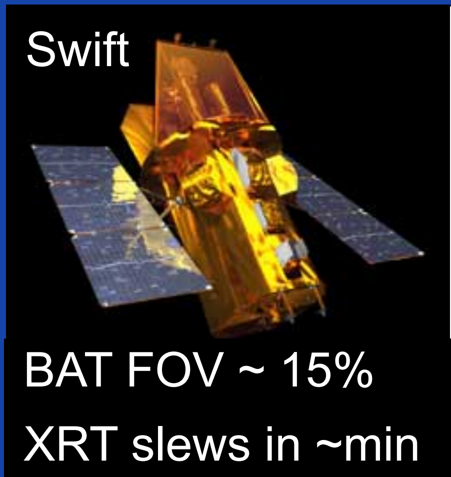
- Independently constrain binary parameters
- Astrophysical context (e.g. host Galaxy & environment)
- Cosmology (e.g. H_0, w); test strong-field GR; constrain neutron star EOS

Sky Error Regions ~300 deg^2 (~2017)



Kasliwal & Nissanke 2014

Gamma-Rays



Fermi Gamma-ray Space Telescope

GBM FOV ~ 60%

Radio

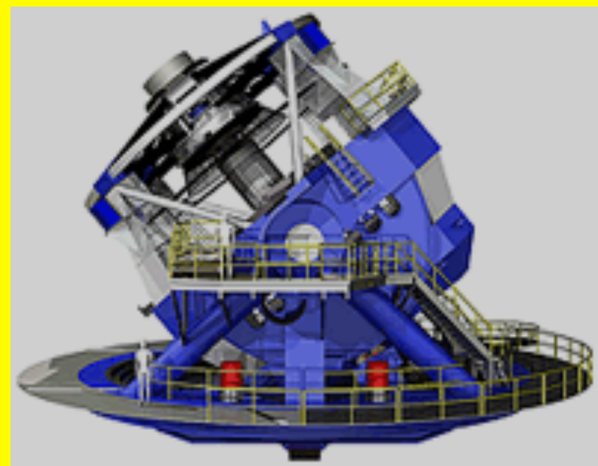
Expanded Very Large Array

Optical ("Now")

THE DARK ENERGY SURVEY

Optical (Future)

Large Synoptic Survey Telescope (LSST)



~All sky m_{AB}<24.5 every ~3 d

- Online >~2020

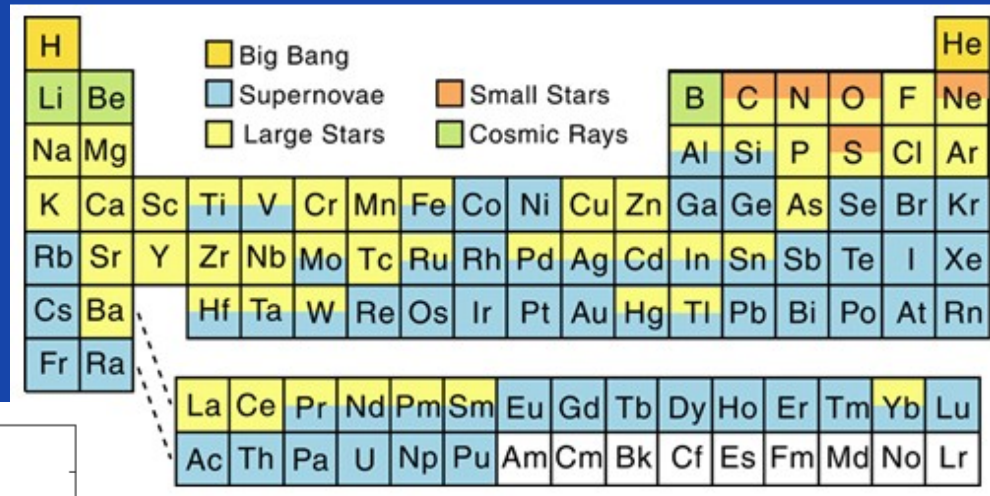
Origin of R-Process Nuclei

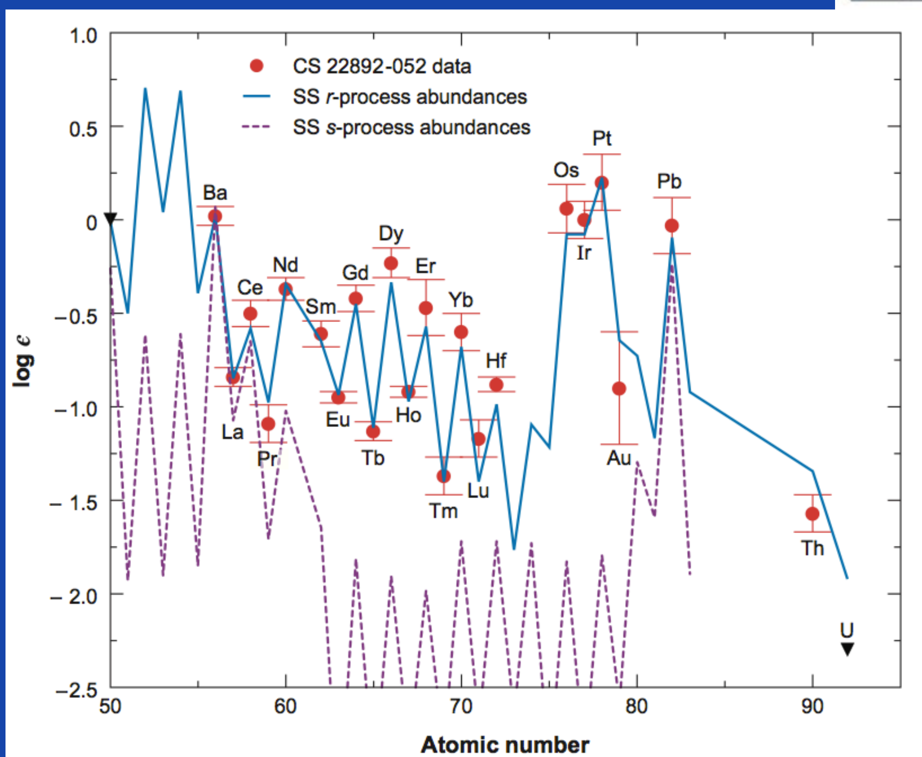
Core Collapse Supernovae or NS Binary Mergers?

Galactic r-process rate:

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

(Qian 2000)



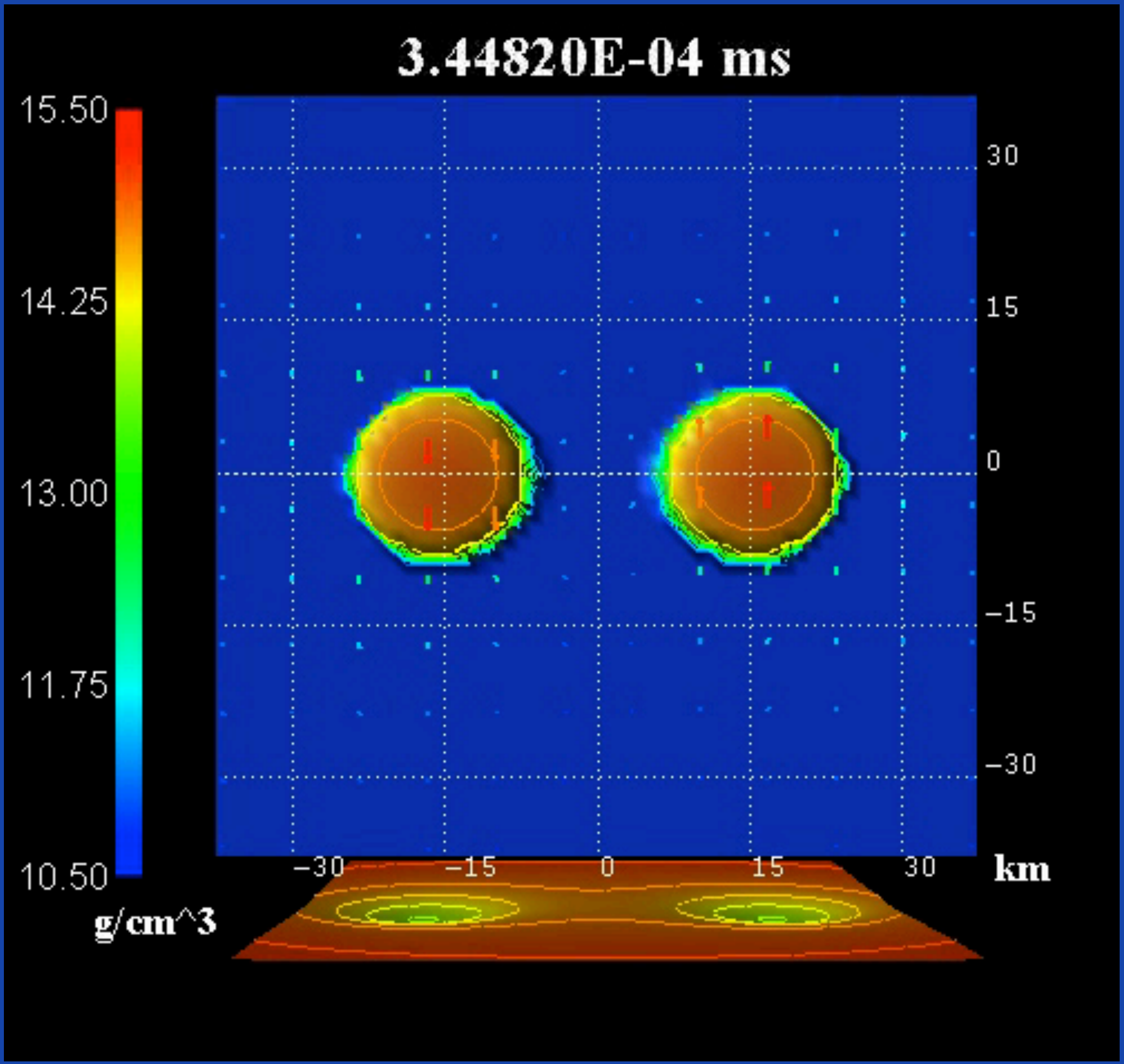


Snedan, Cowan & Gallino 2008

fraction of r-process from NS mergers:

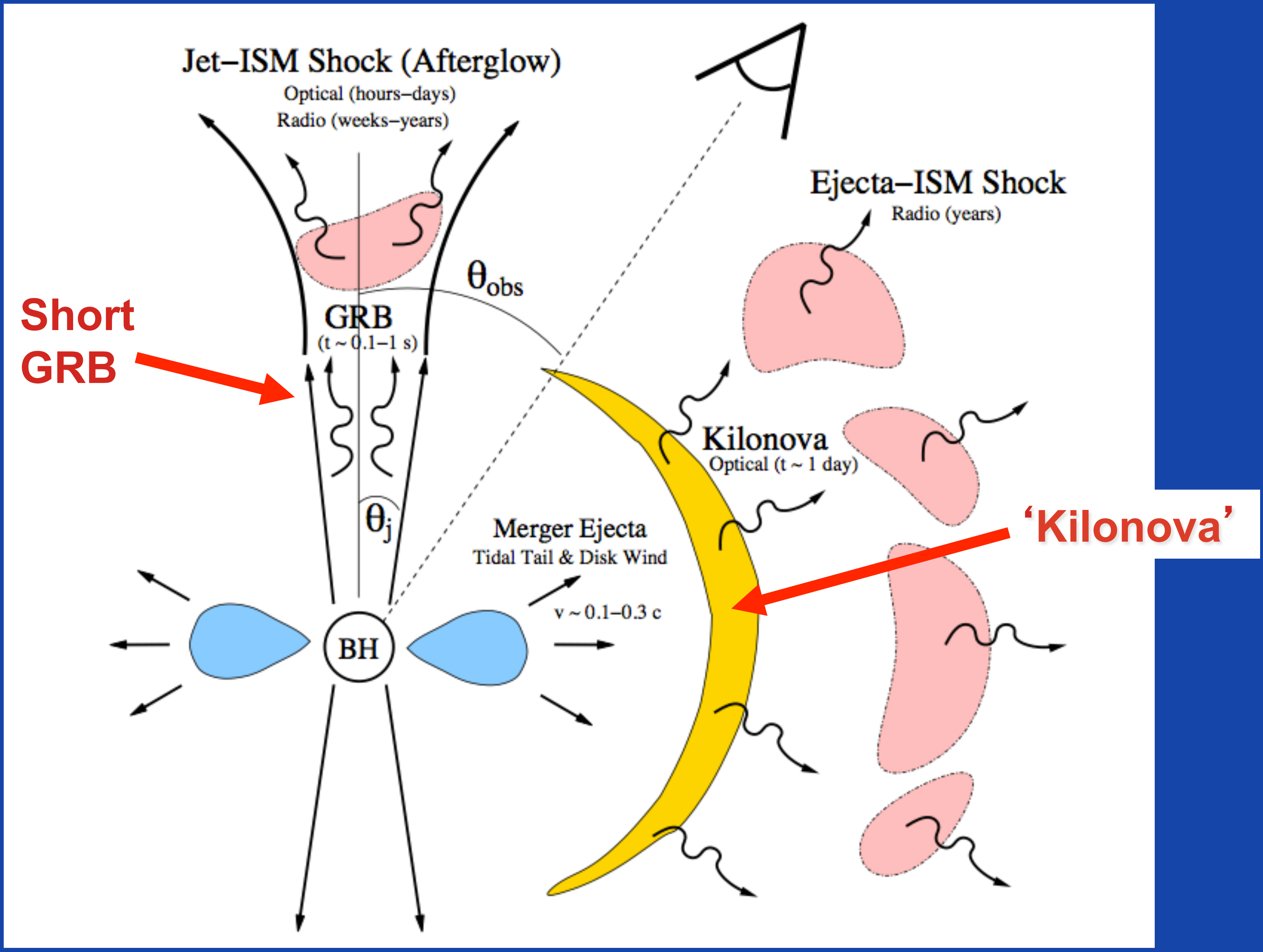
$$f_R \sim \left(\frac{\dot{N}_{\mathrm{merge}}}{10^{-5}\,\mathrm{yr}^{-1}} \right) \left(\frac{\bar{M}_{\mathrm{ej}}}{10^{-2}\,M_\odot} \right)$$

Numerical Simulation - Two 1.4 $M_{\odot}$ NSs



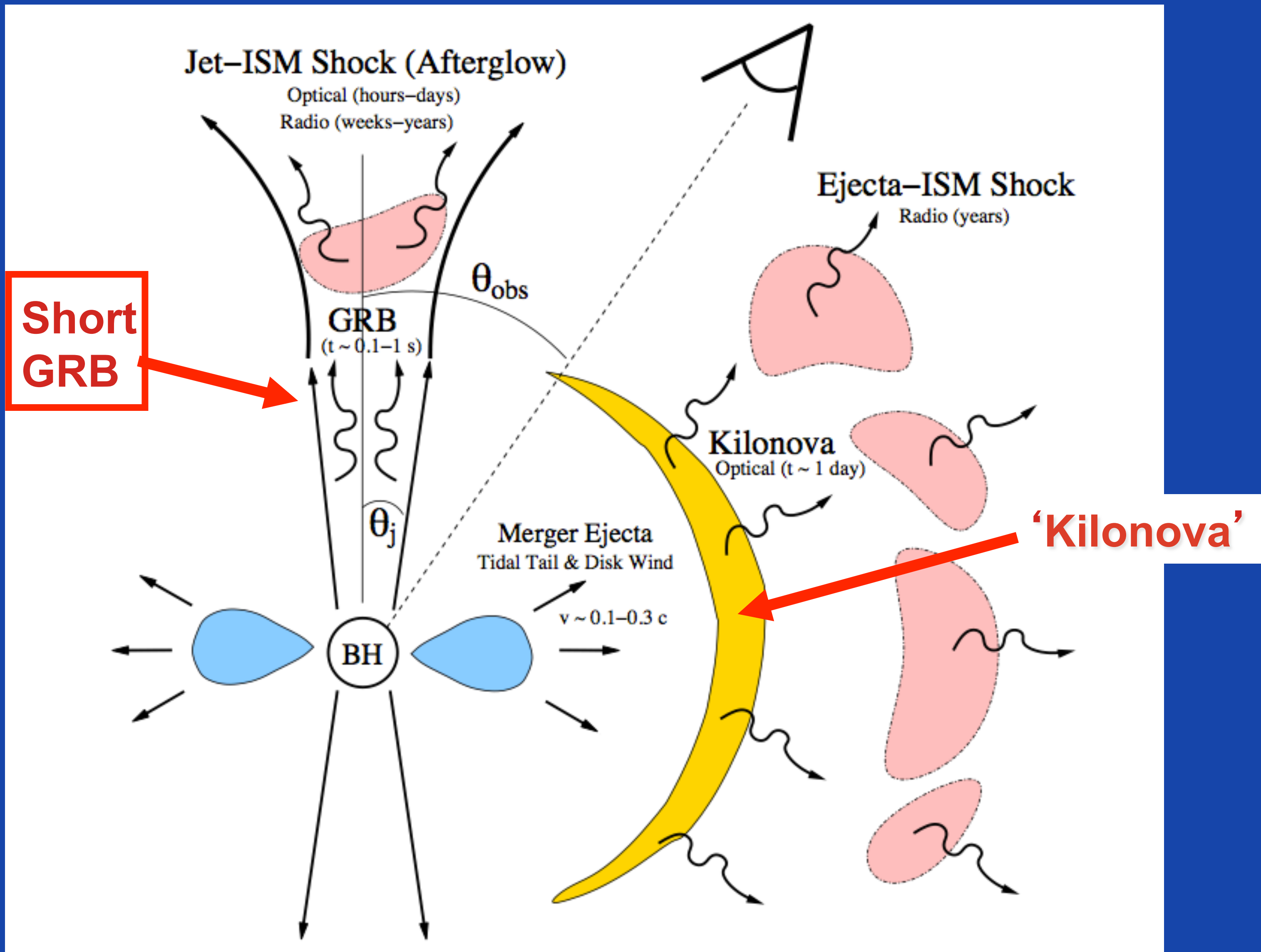
Courtesy M. Shibata (Kyoto)

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



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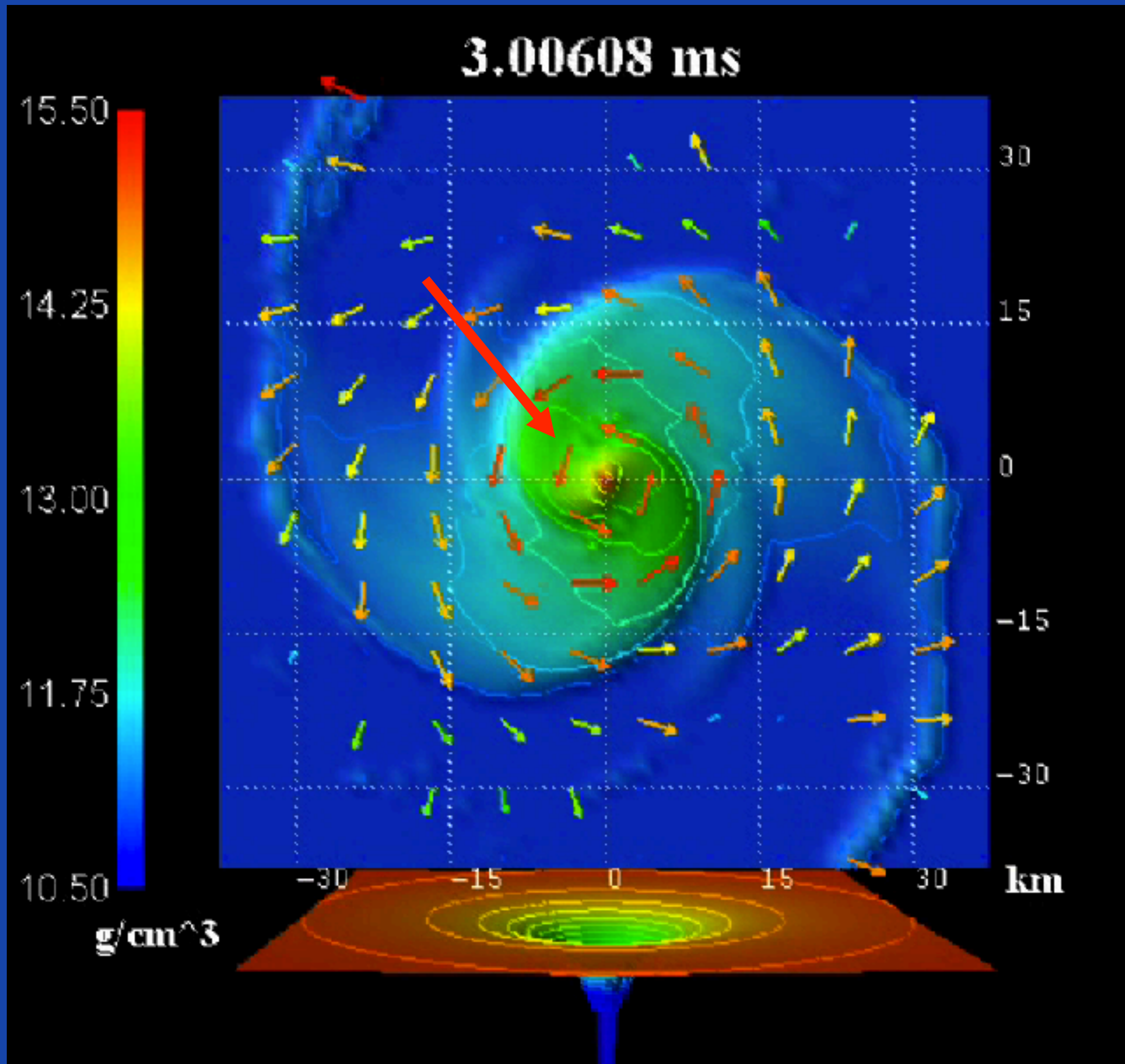
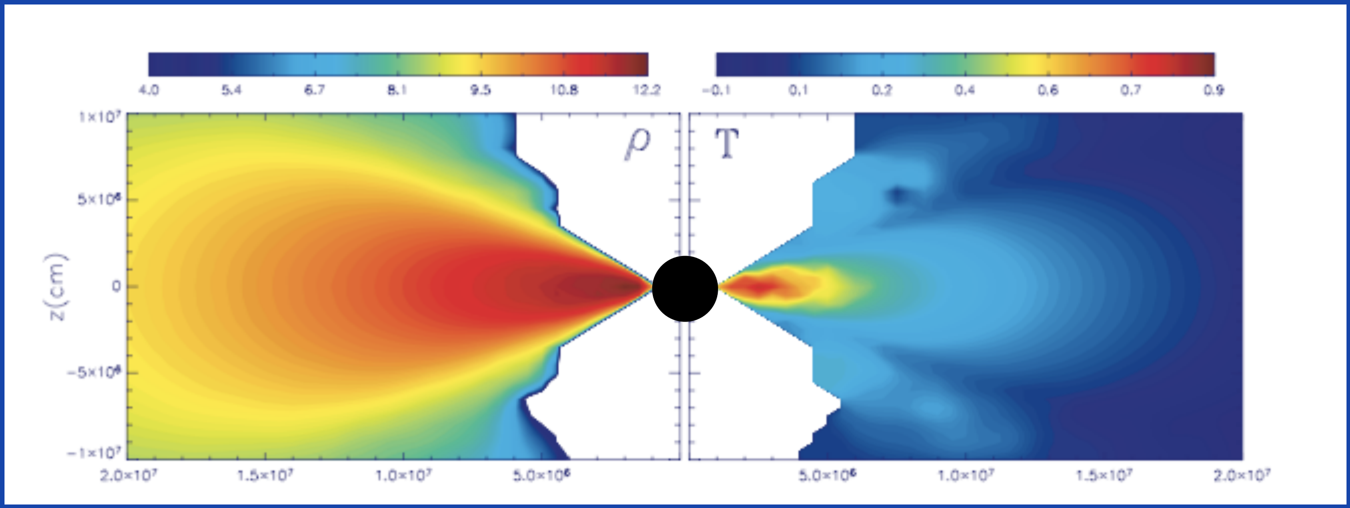


Courtesy M. Shibata (Kyoto)

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

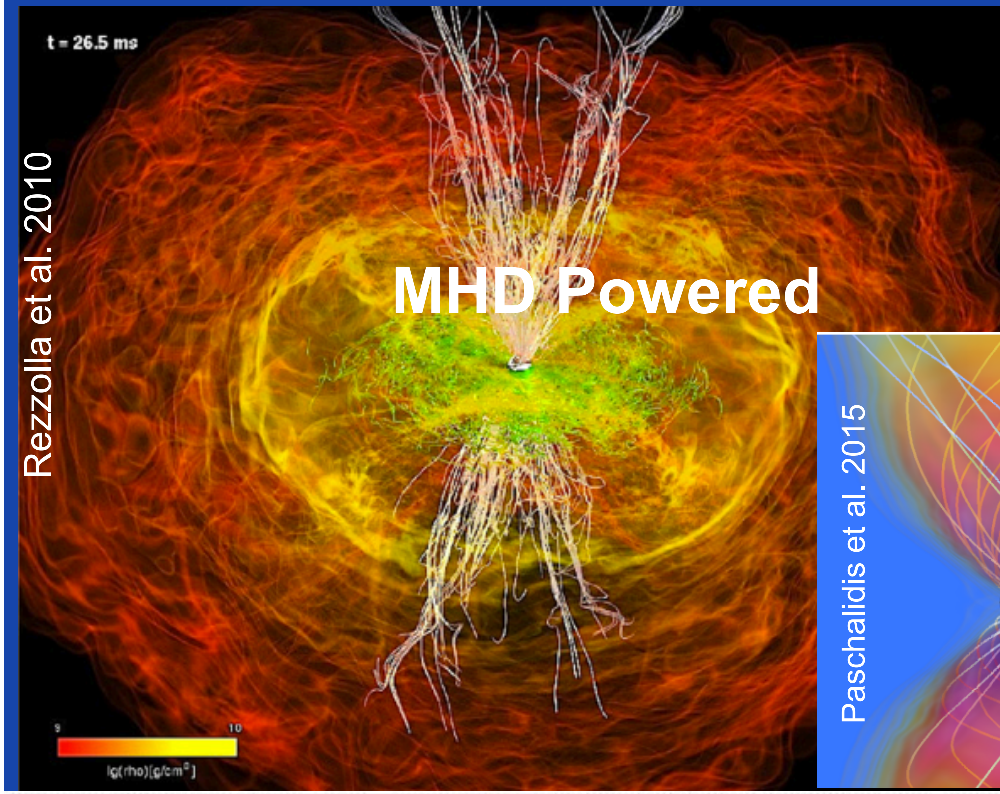
- Disk **Mass ~0.01 - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Hot (T > MeV) & Dense ($\rho \sim 10^8$-10^{12} g cm^{-3})
- Neutrino Cooled: ($\tau_\nu \sim$ 0.01-100)
- Equilibrium $e^+ + n \rightarrow \bar{\nu}_e + p$ vs. $e^- + p \rightarrow \nu_e + n$ $\Rightarrow Y_e \sim 0.1$

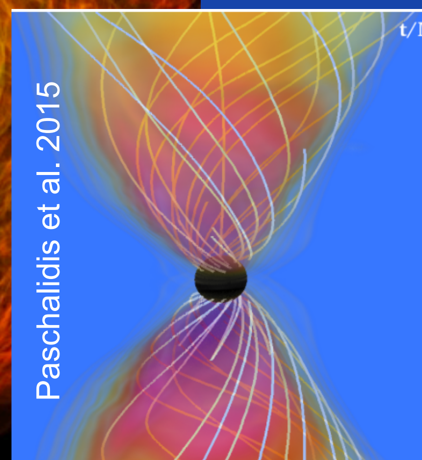
Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\ \mathrm{s}^{-1}$

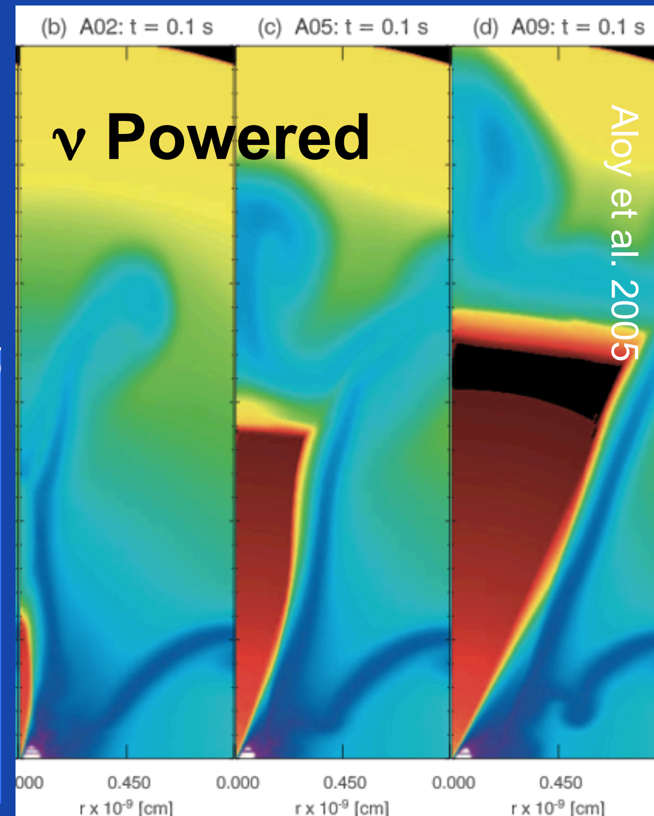
$$t_{\rm visc} \sim 0.1 \left(\frac{M_\bullet}{3M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_d}{100\ \mathrm{km}}\right)^{3/2} \left(\frac{H/R}{0.5}\right)^{-2} \mathrm{s}$$

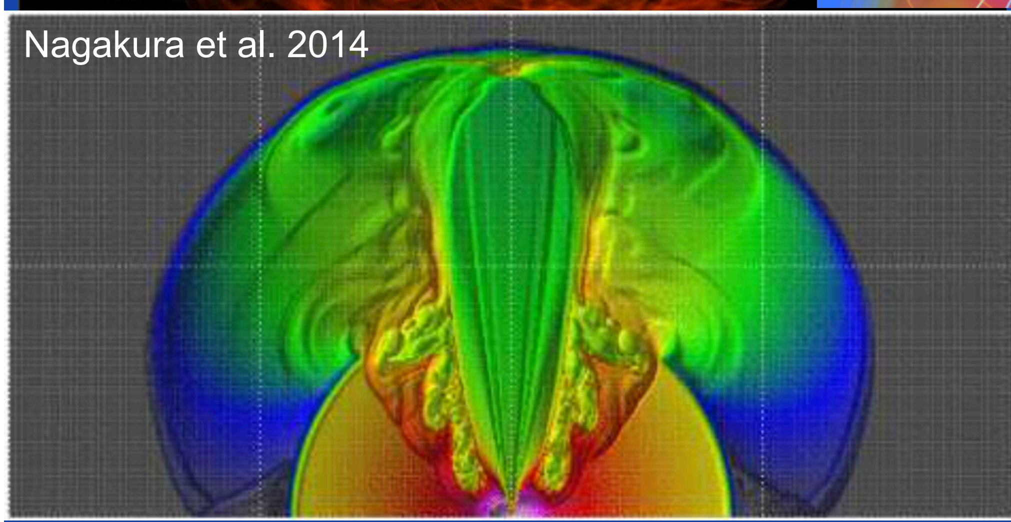
Short GRB Engine?

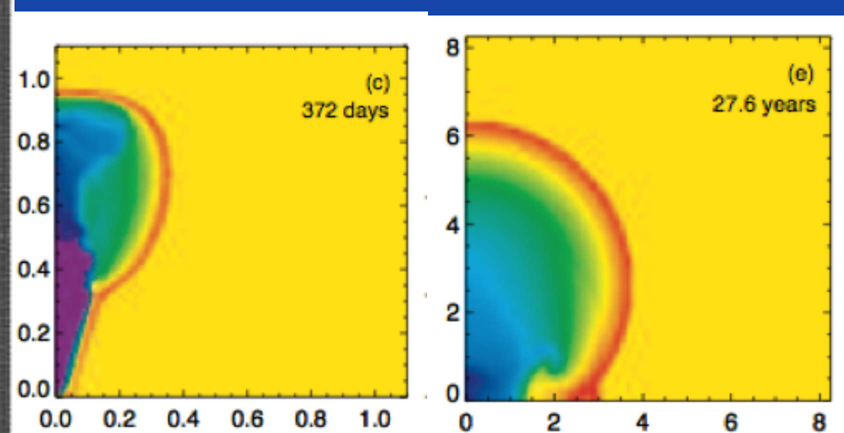
Relativistic Jets and Short GRBs





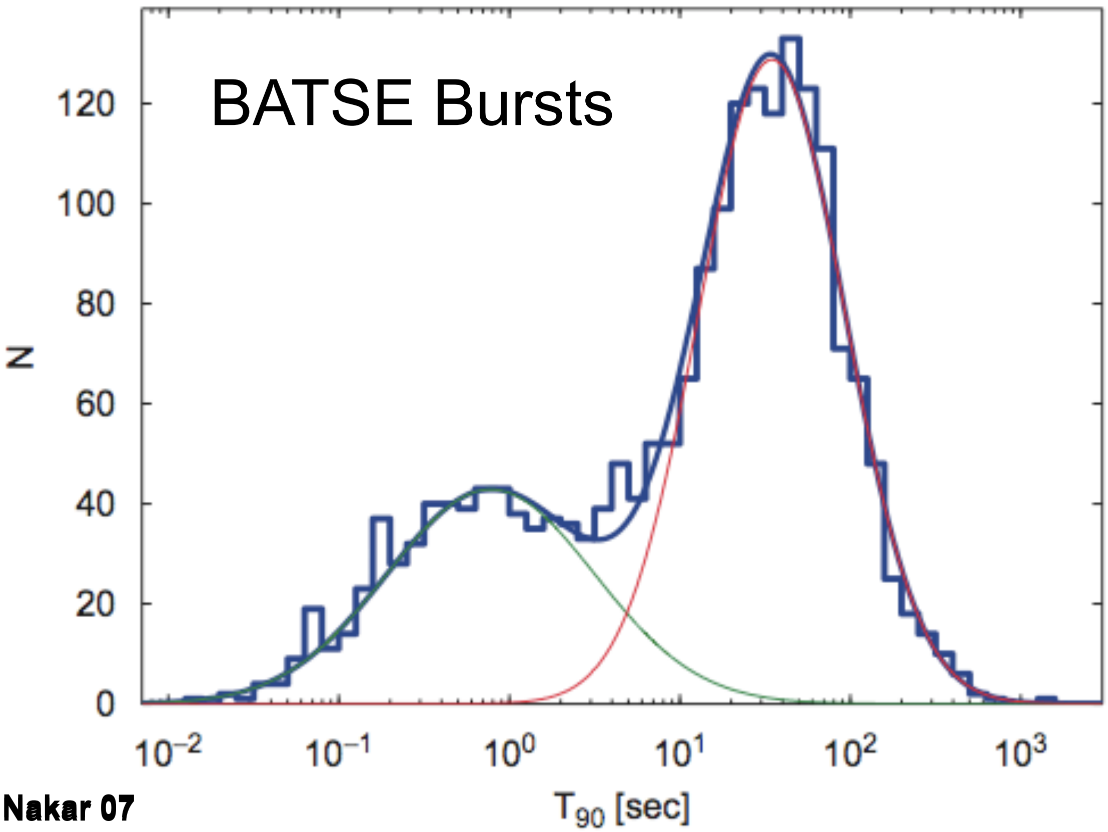






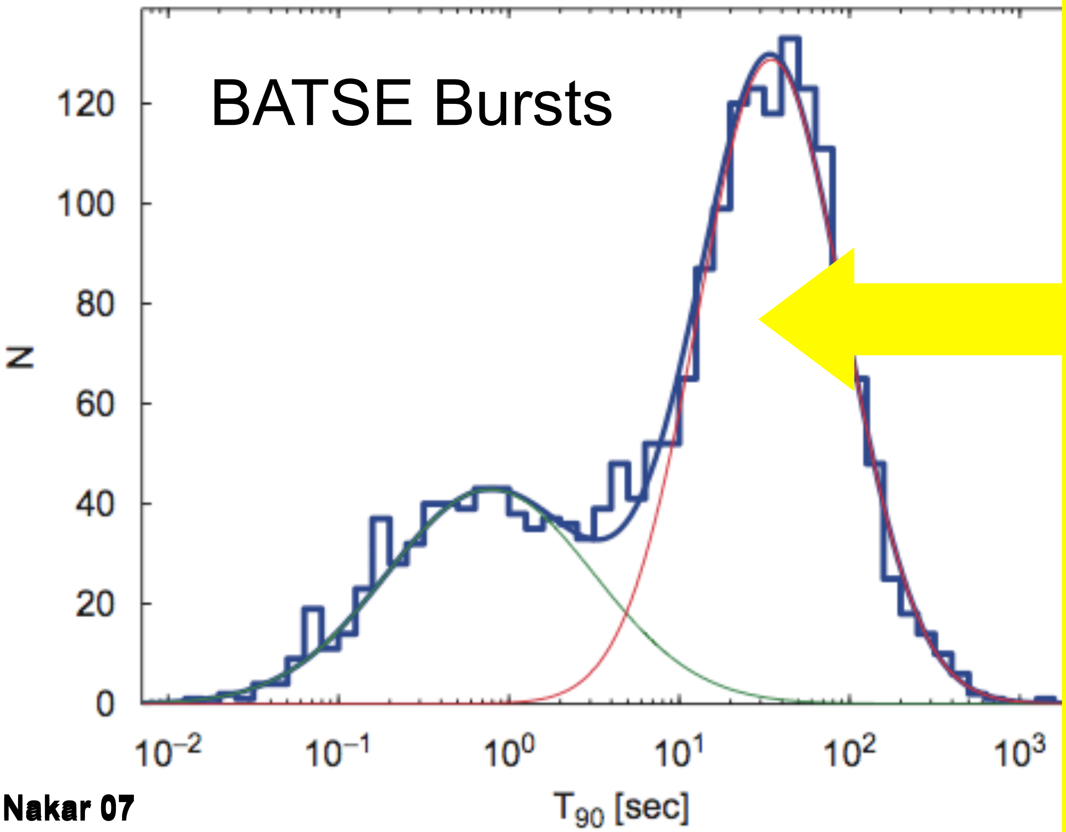
Zhang & MacFadyen 2009

Short & Long Gamma-Ray Bursts



Nakar 07

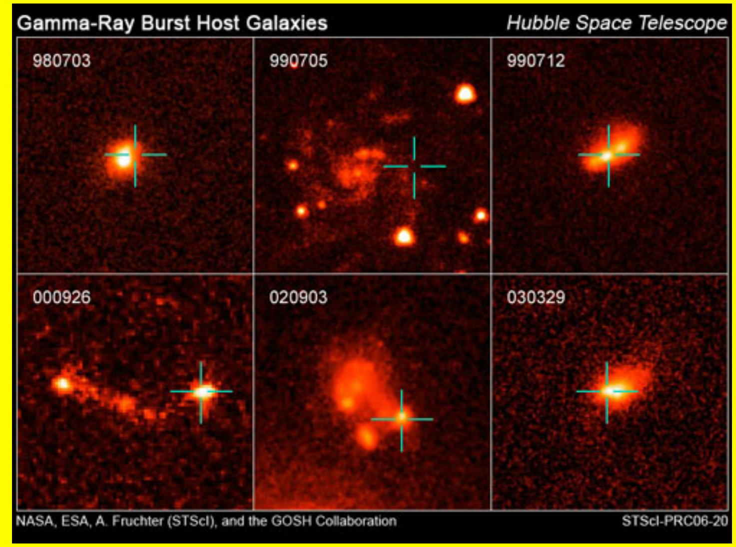
Short & Long Gamma-Ray Bursts



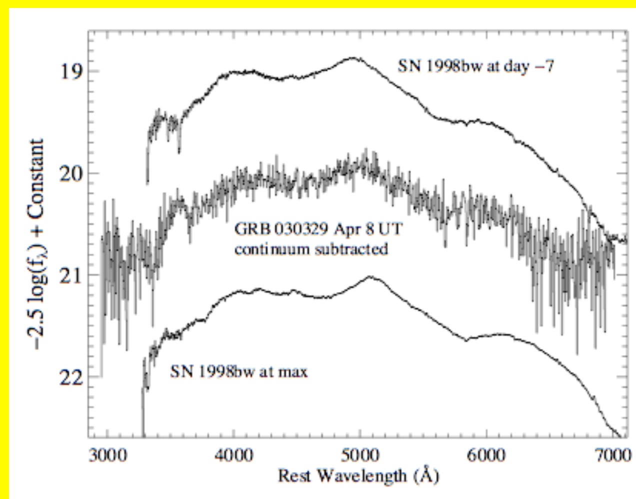
Nakar 07

Long GRBs =
Death of Massive Stars

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

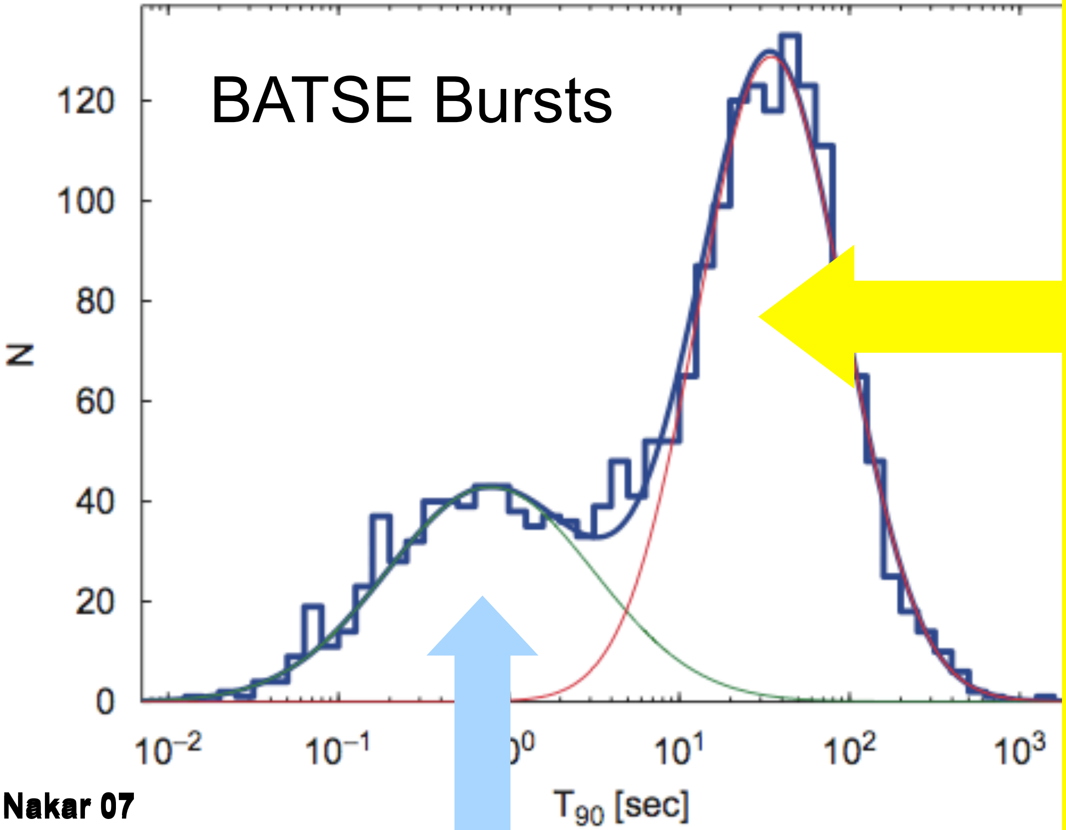


Supernova Connection
GRB 030329 ⇔ SN 2003dh



Stanek et al. 2003

Short & Long Gamma-Ray Bursts



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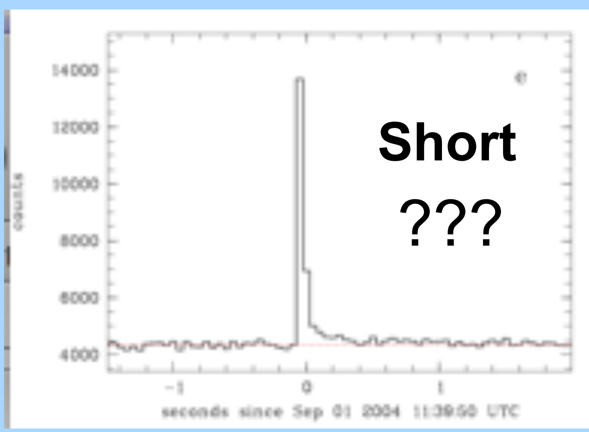

Short

???

Long GRBs =

Death of Massive Stars

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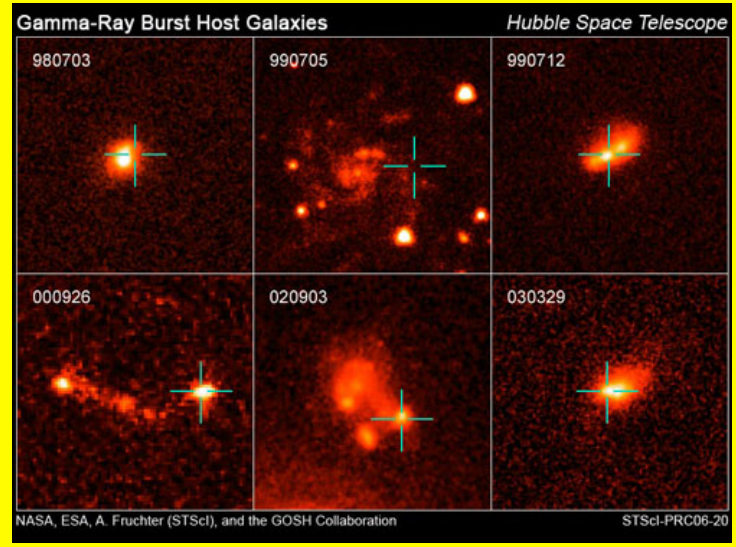

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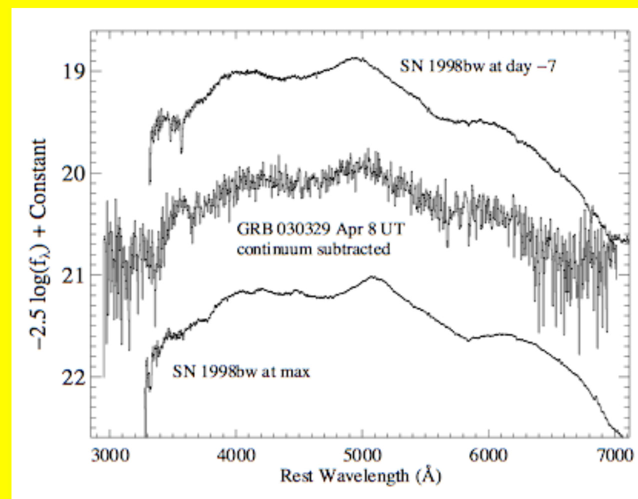
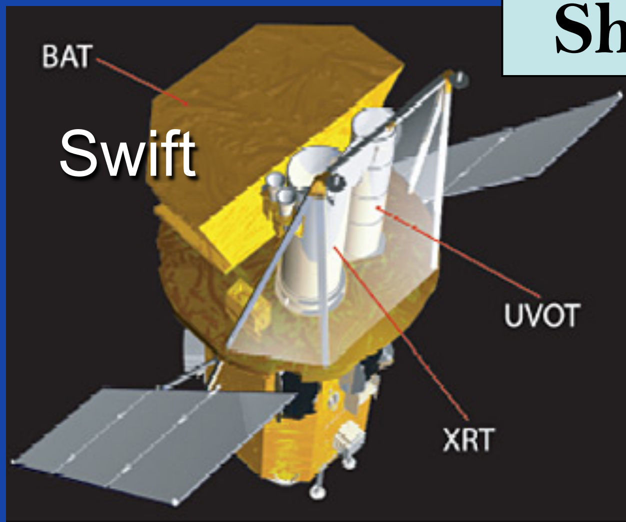
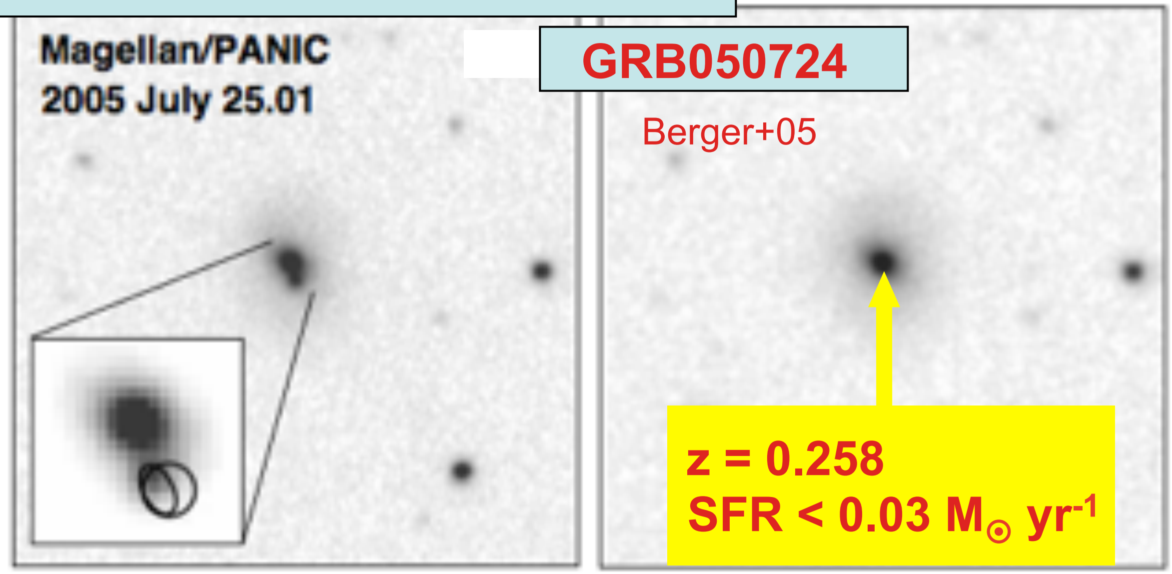
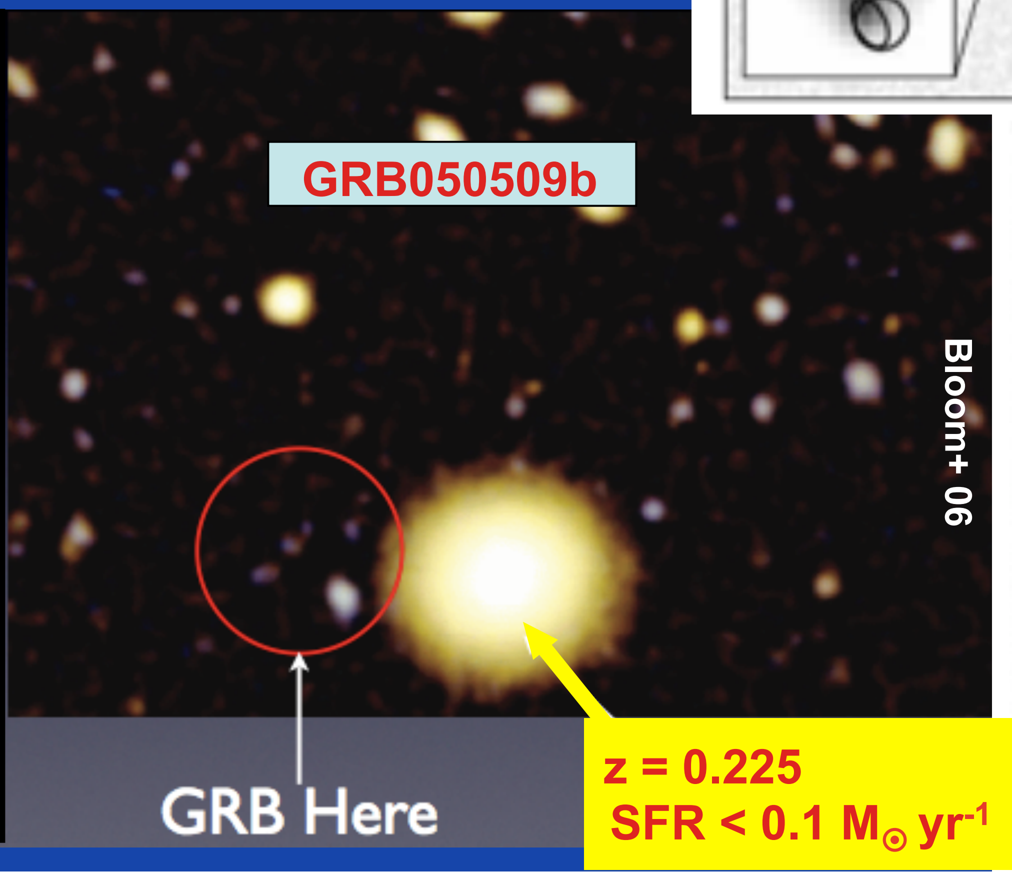


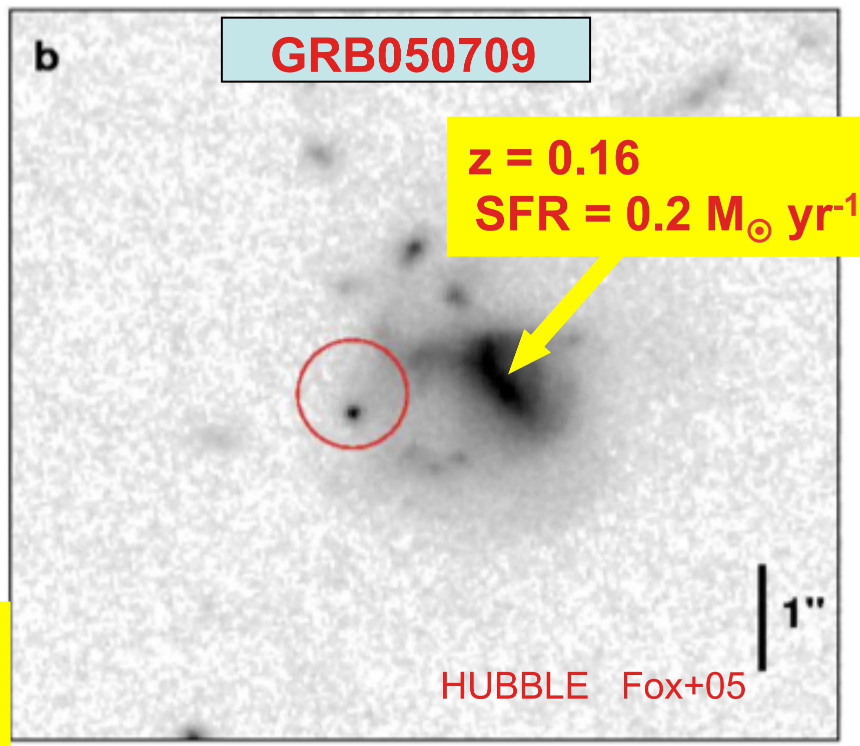
Stanek et al. 2003

Short GRB Host Galaxies

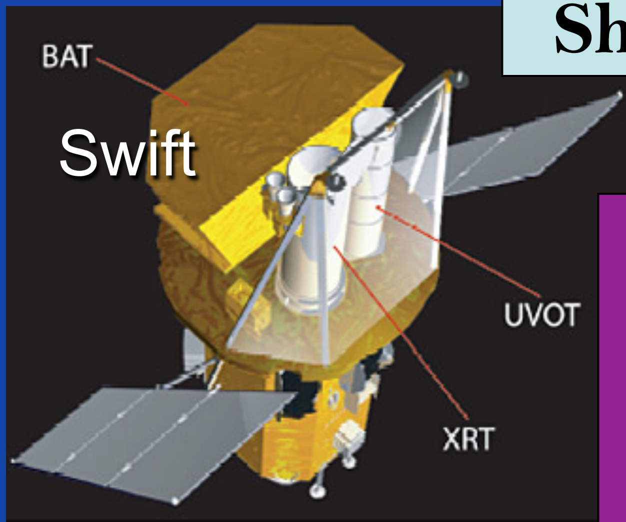




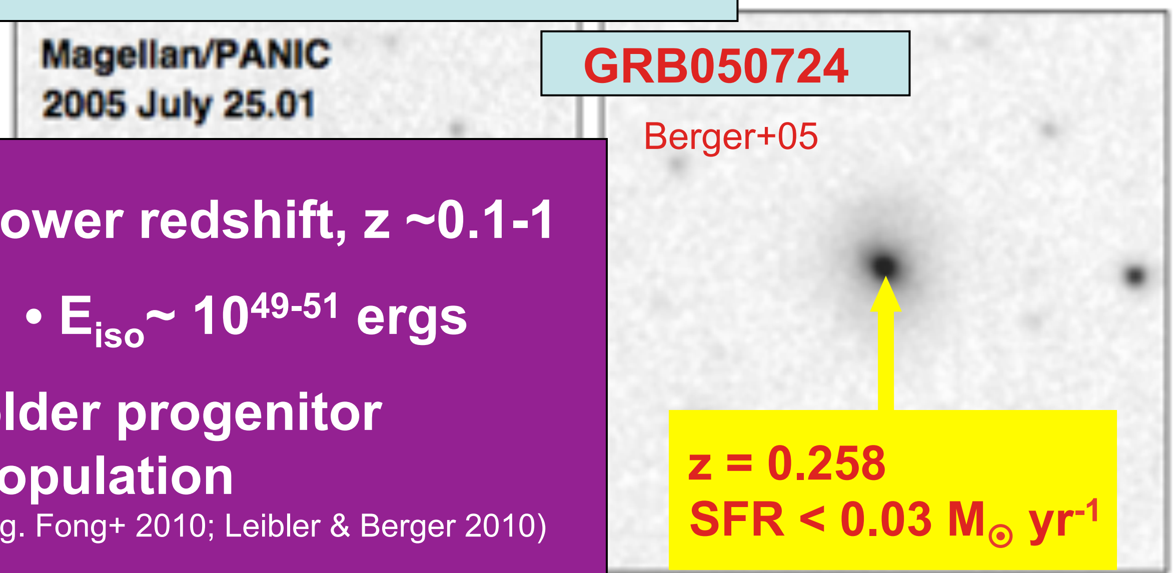


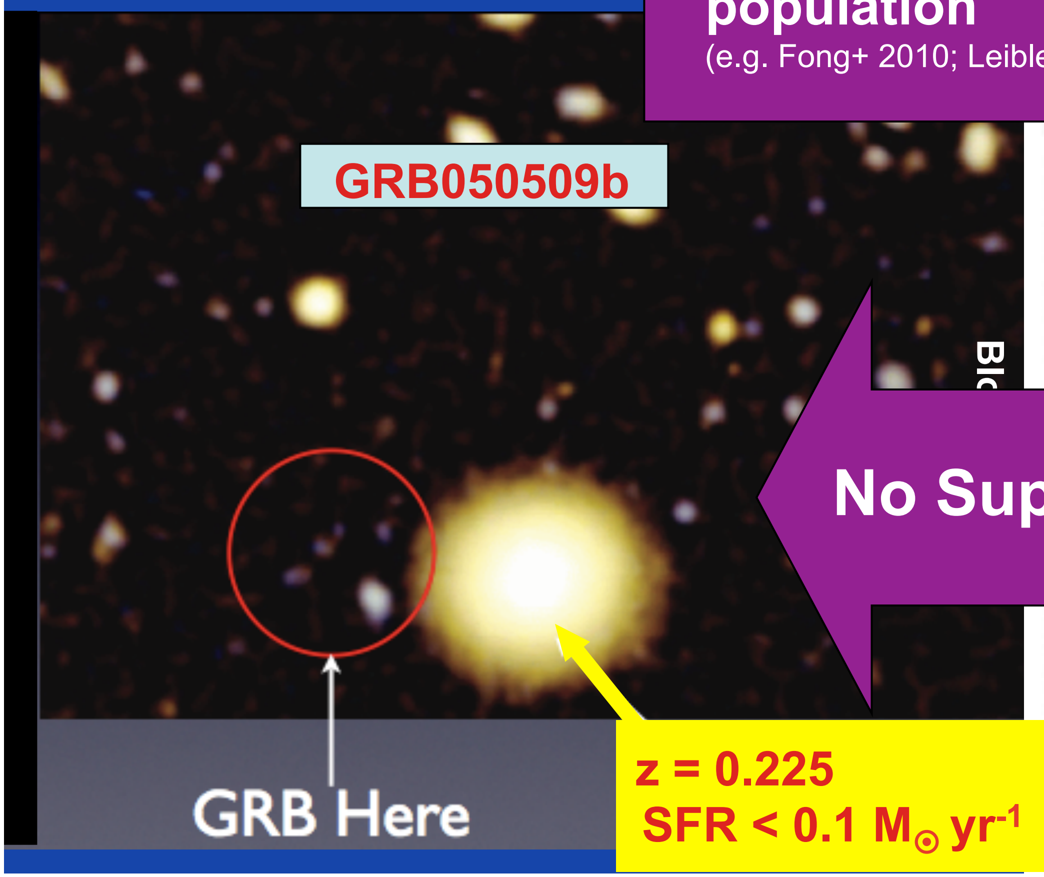


Short GRB Host Galaxies

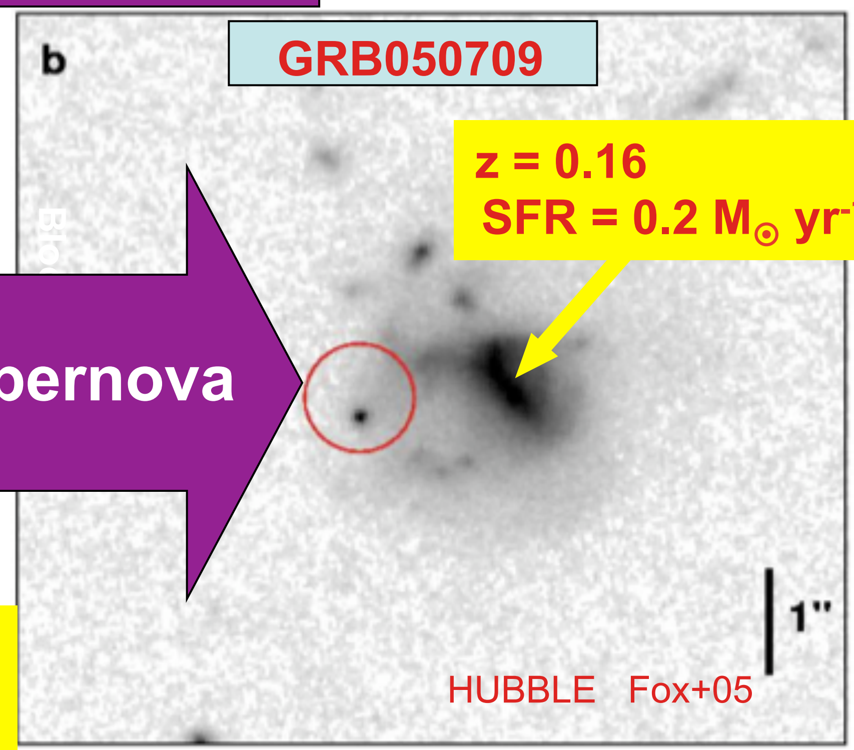


- lower redshift, z ~0.1-1
- E_{iso}~ 10^{49-51} ergs
- older progenitor population
(e.g. Fong+ 2010; Leibler & Berger 2010)





No Supernova

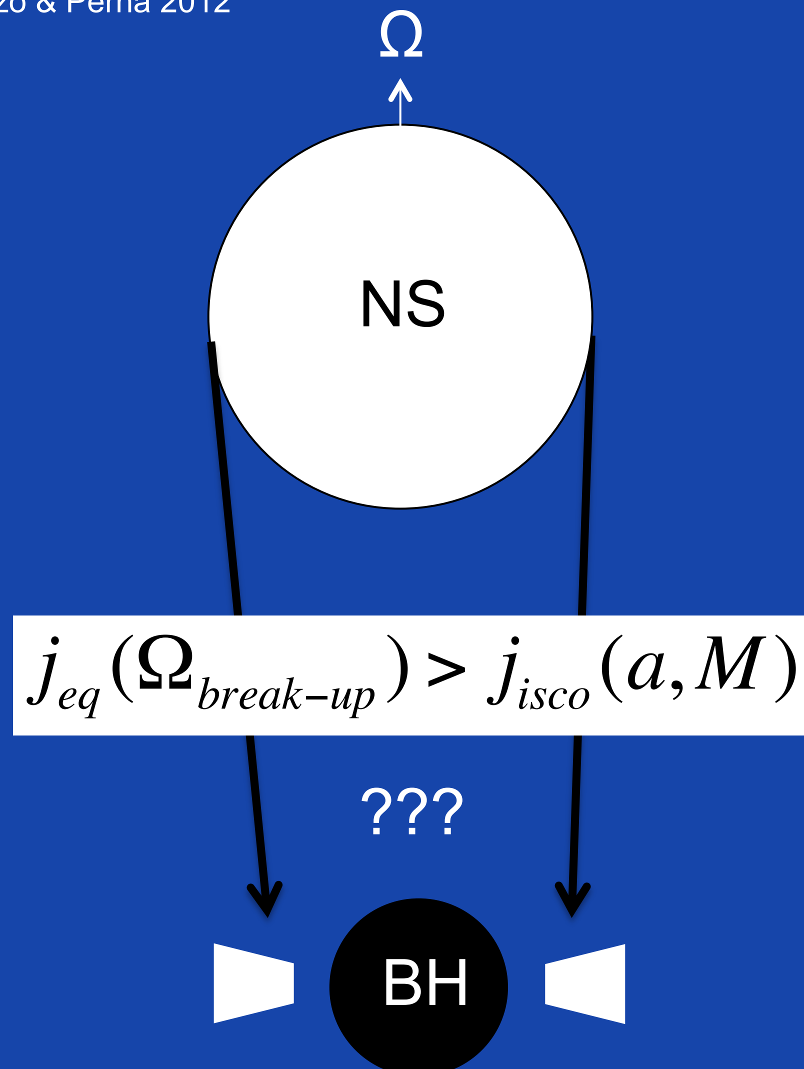


Alternative Short GRB Models?

Neutron Star Accretion-Induced Collapse

MacFadyen et al. 2005, Dermer & Atoyan 2006, Giocomazzo & Perna 2012

Q: Can the collapse of a rotating neutron star leave a debris disk around the new black hole (of the same mass and angular momentum)?



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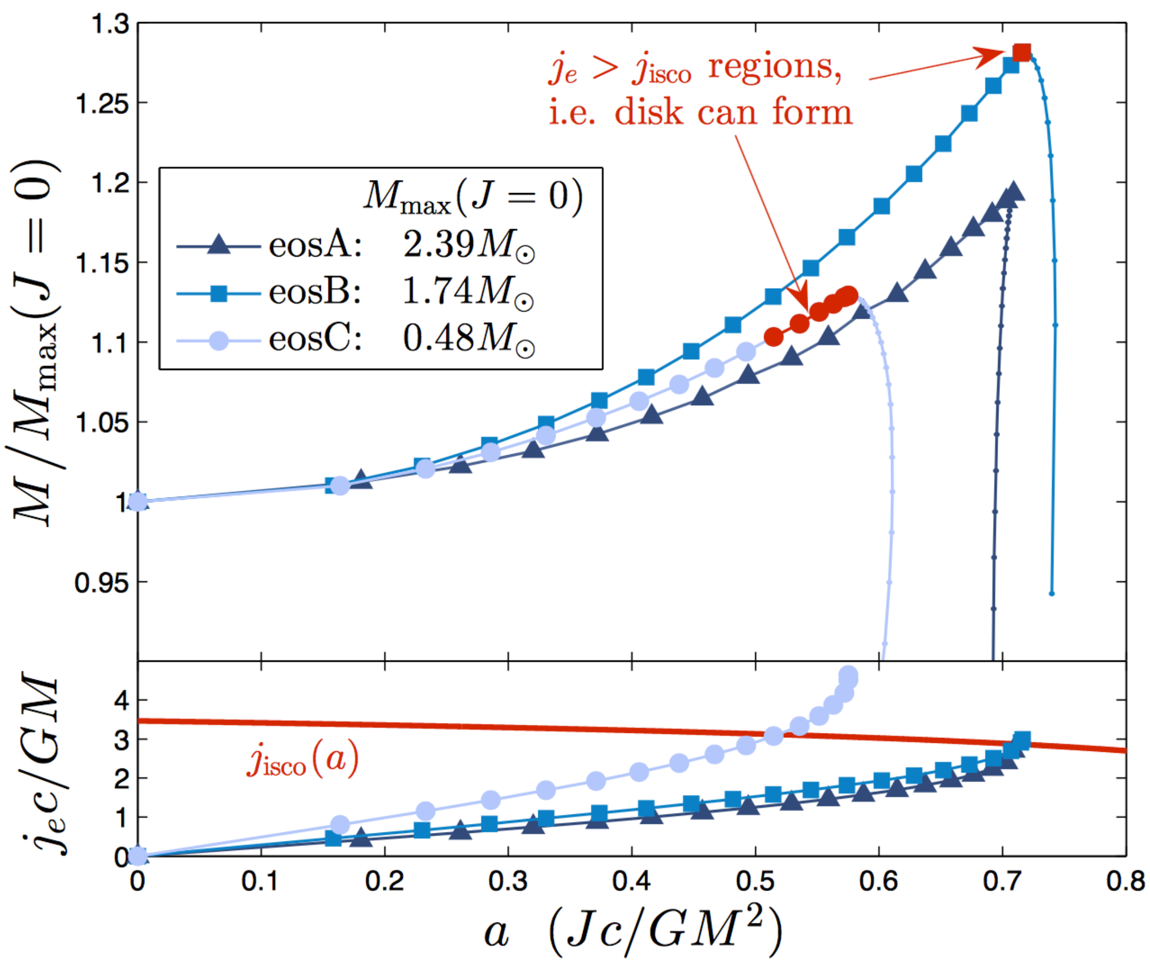

Margalit et al., submitted

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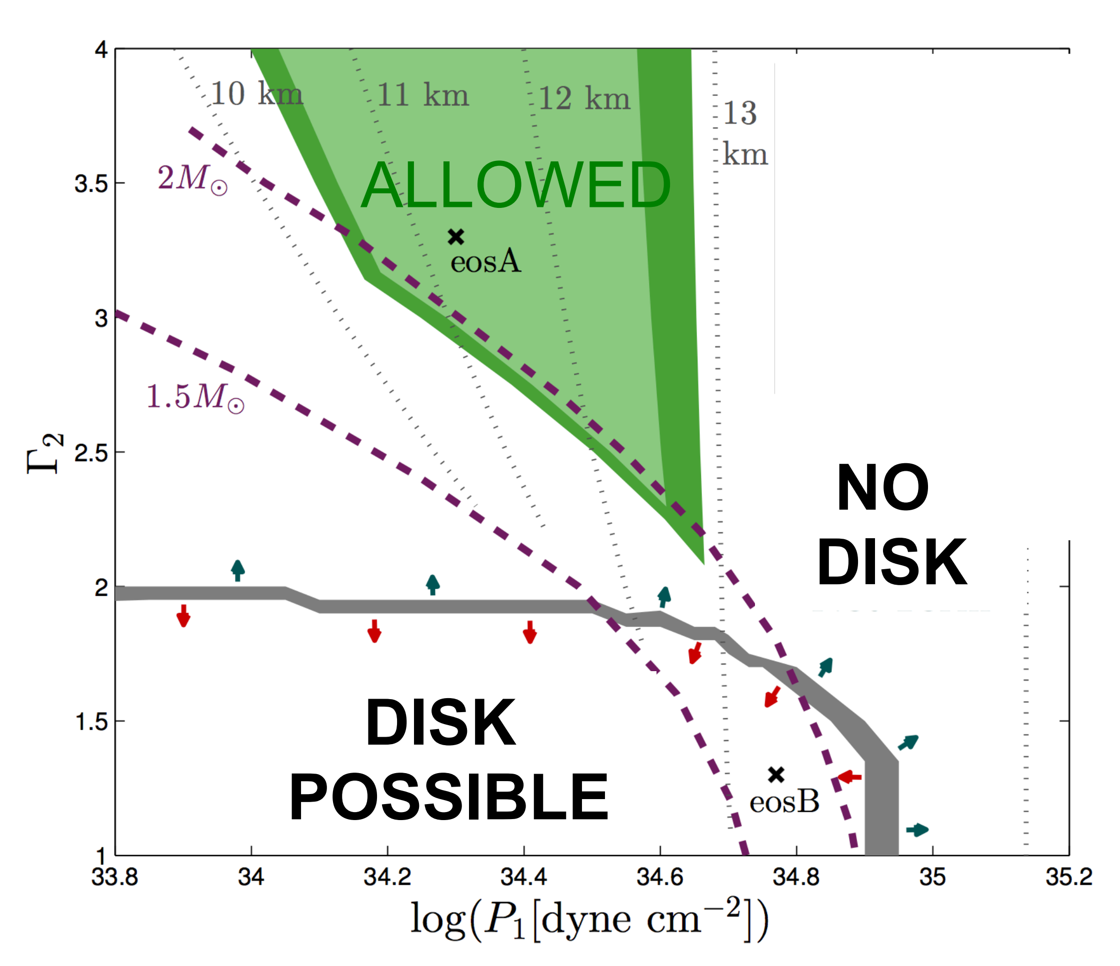
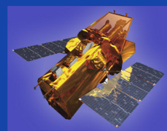


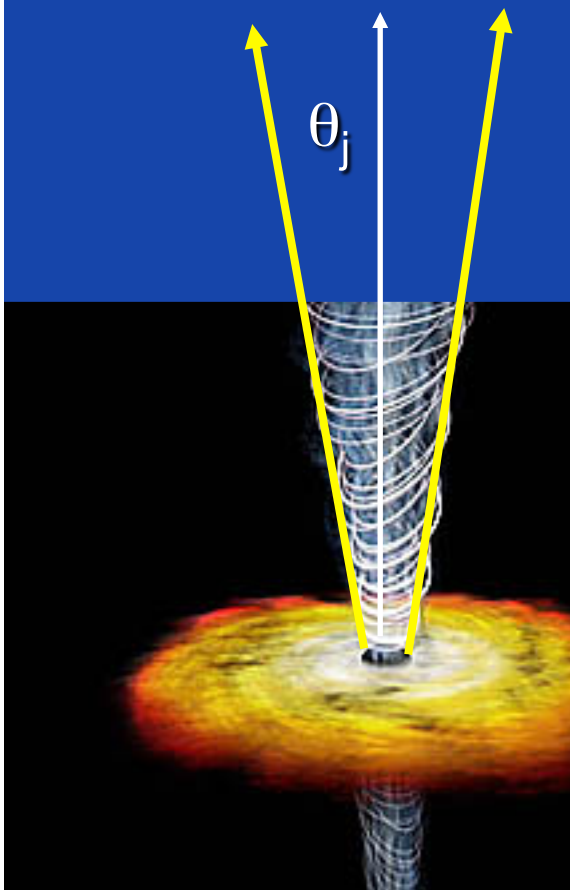
Q: Can the collapse of a rotating neutron star leave a debris disk around the new black hole (of the same mass and angular momentum)?

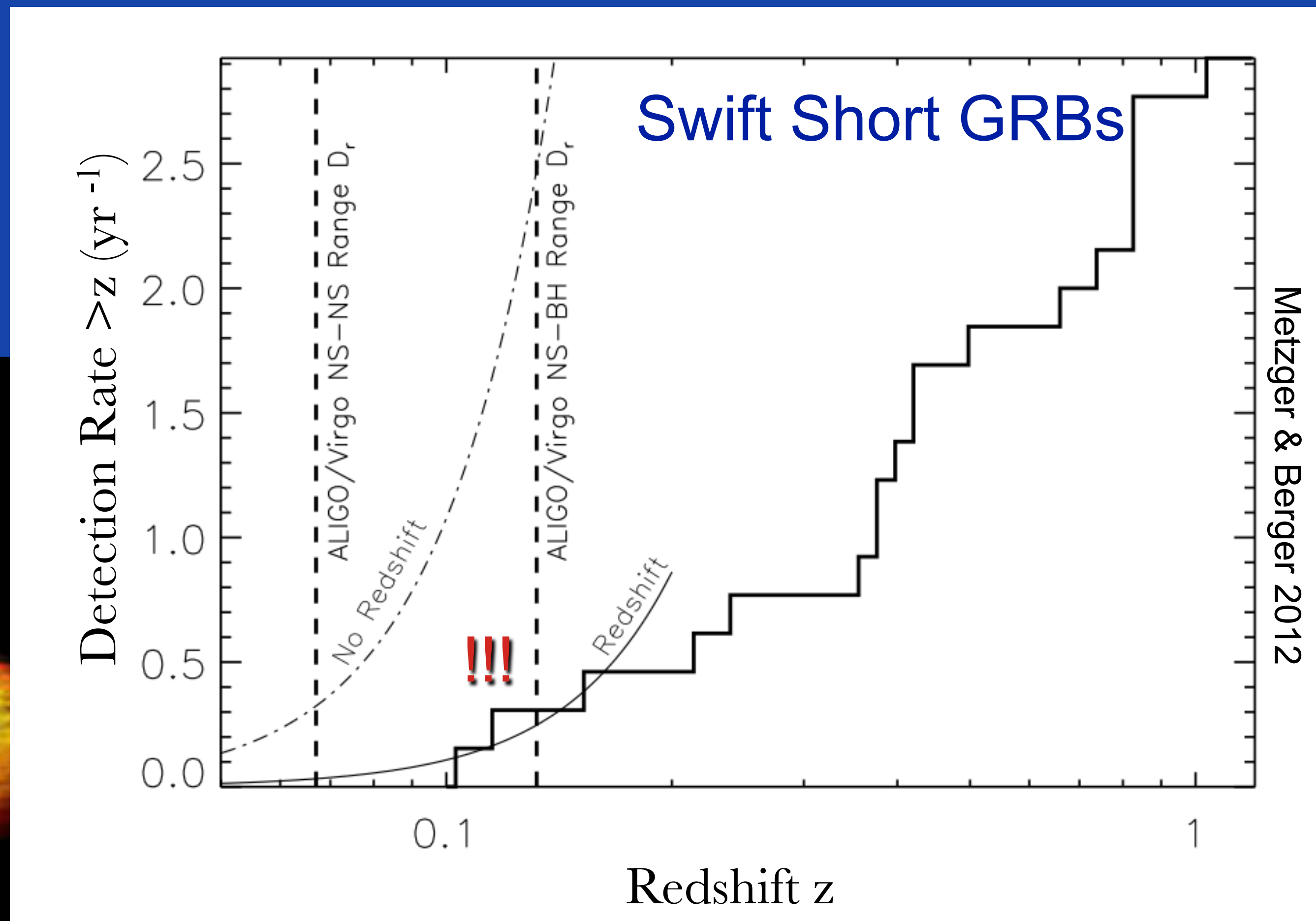
No! (cf. Shibata 2003, Baoitti et al.)

Margalit et al., submitted

Short GRBs are Rare in the LIGO Volume



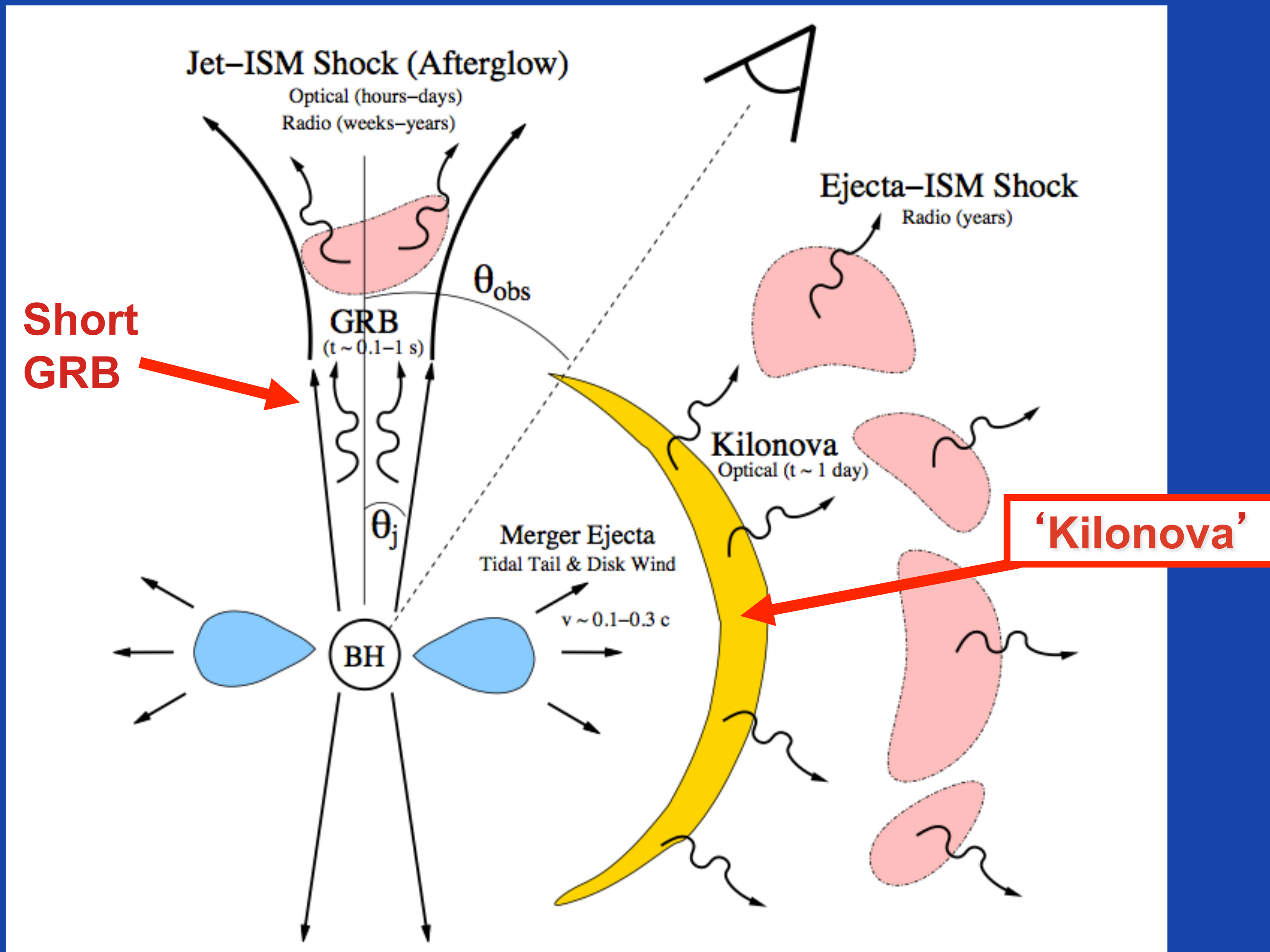




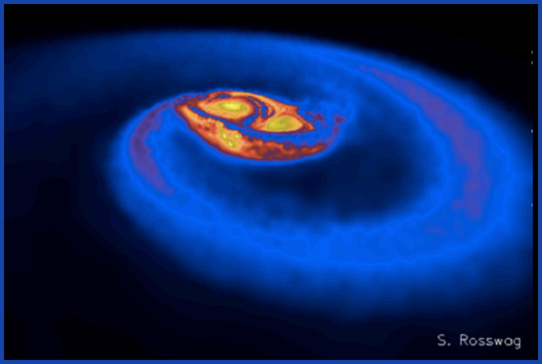
Detectable fraction by all sky γ-ray telescope

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

Electromagnetic Counterparts of NS-NS/NS-BH Mergers



Metzger & Berger 2012



Neutron-Rich Ejecta

Dynamical Tidal Tails

(e.g. Janka et al. 1999; Rosswog 2005; Shibata & Taniguchi 2006; East et al. 2012; Hotokezaka et al. 2013)

$M_{ej} \sim 10^{-3} - 10^{-2}\ M_{\odot}$

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

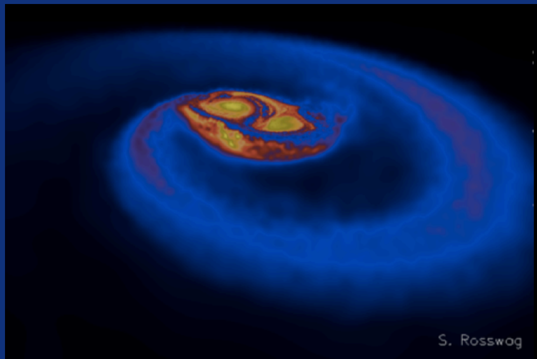
~ ms

but see Wanajo 2014, Goriely et al. 2015!

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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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

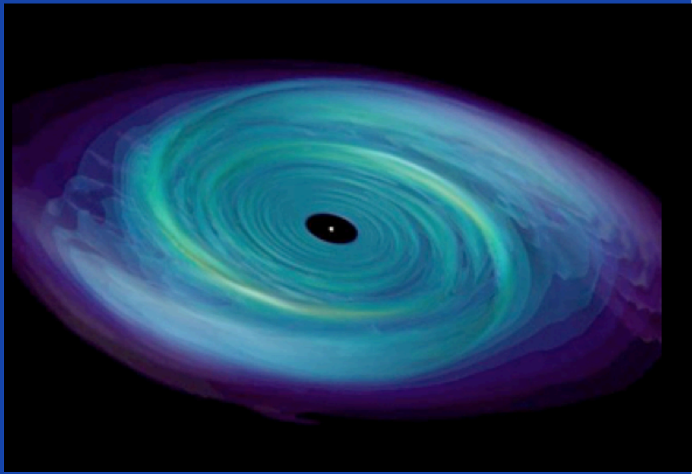
Disk Outflows

Neutrino-Powered (Early)

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

$$Y_e \sim ???$$

"Viscous"-Powered (Late) (e.g. Beloborodov 08; BDM+08, 09; Lee+09; Fernandez & BDM 13; Just+14) ~ seconds



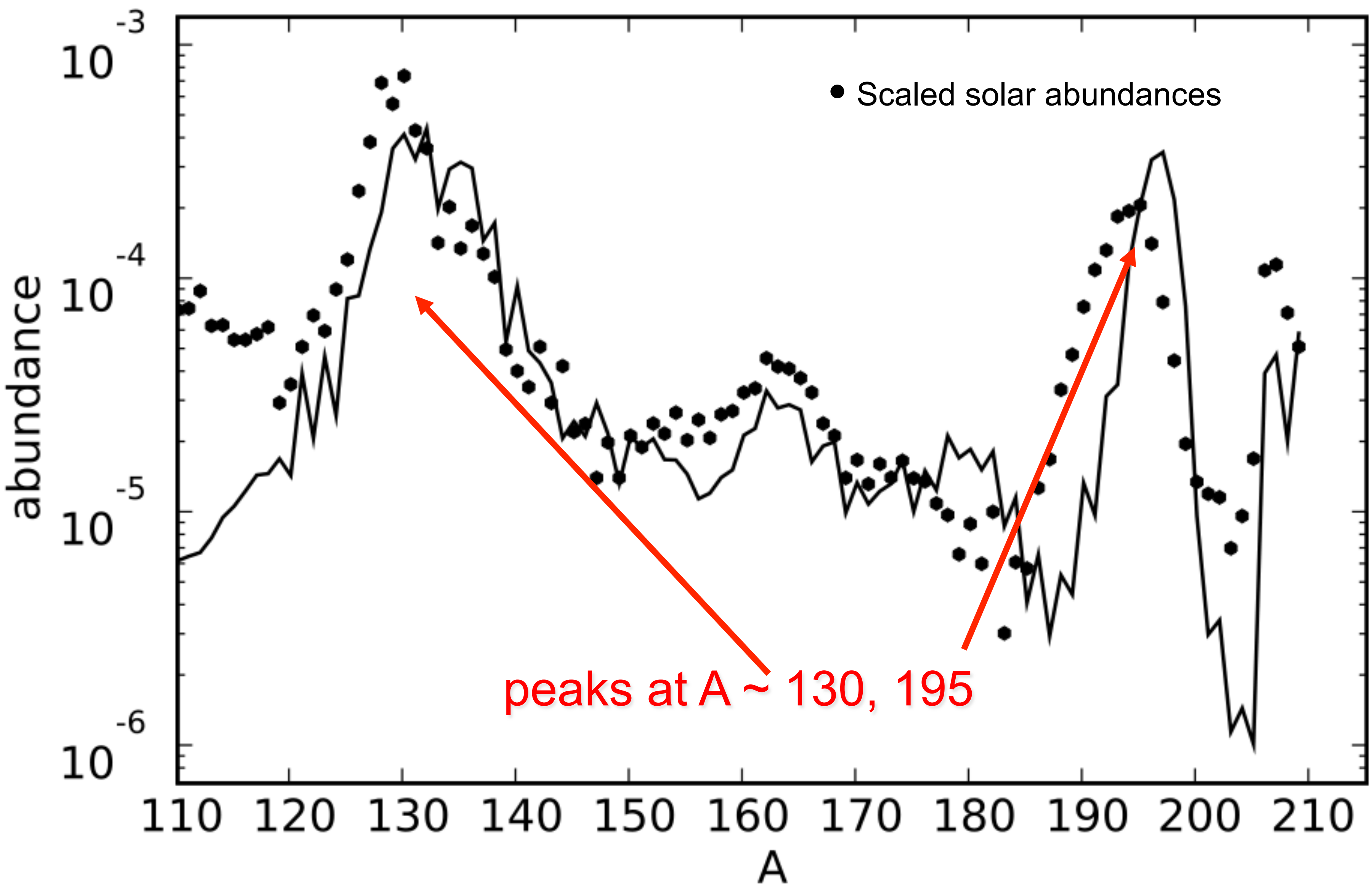
$M_{ej} = f_w M_d \sim 10^{-3}$-$10^{-2}\ (f_w/0.1)\ M_{\odot}$

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

The image part with relationship ID rId5 was not found in the file.

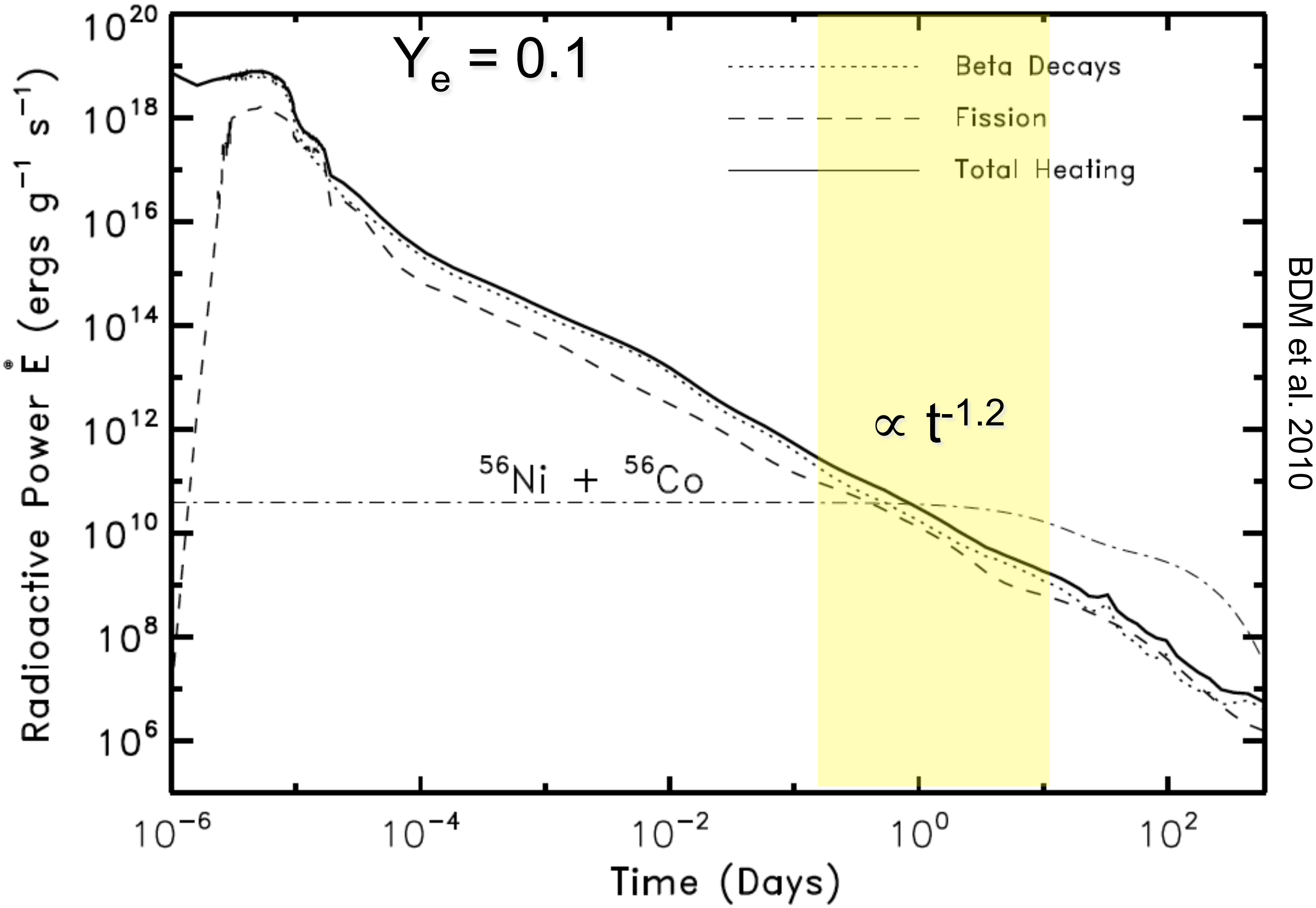
Courtesy G. Martinez-Pinedo

Final Abundance Distribution



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)

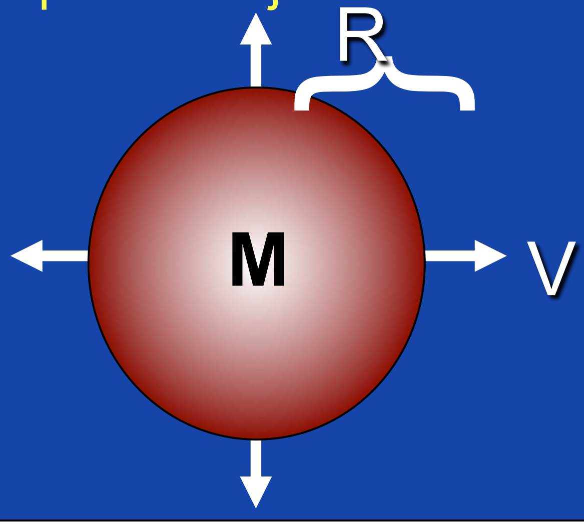


Dominant β-Decays at t ~ 1 day: ^{132,134,135}I, ^{128,129}Sb, ^{129}Te, ^{135}Xe

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



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

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

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

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

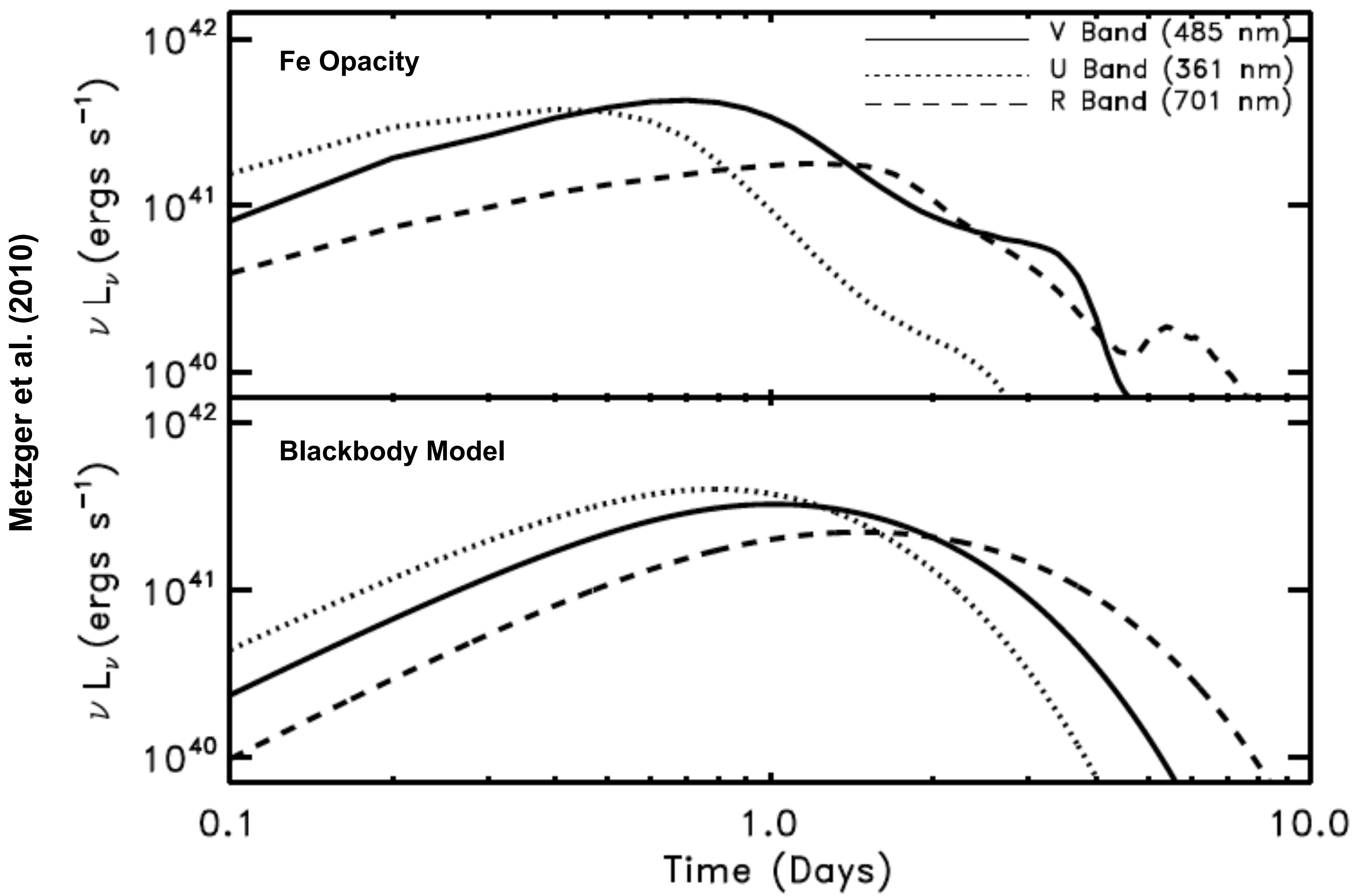
Type Ia Supernova:

$v \sim 10^4$ 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, $M_{ej} \sim 10^{-2} M_\odot$, $f \sim 10^{-6} \Rightarrow t_{peak} \sim 1$ day, $L \sim 3\ 10^{41}$ erg s^{-1}

"Kilo"-nova Light Curves

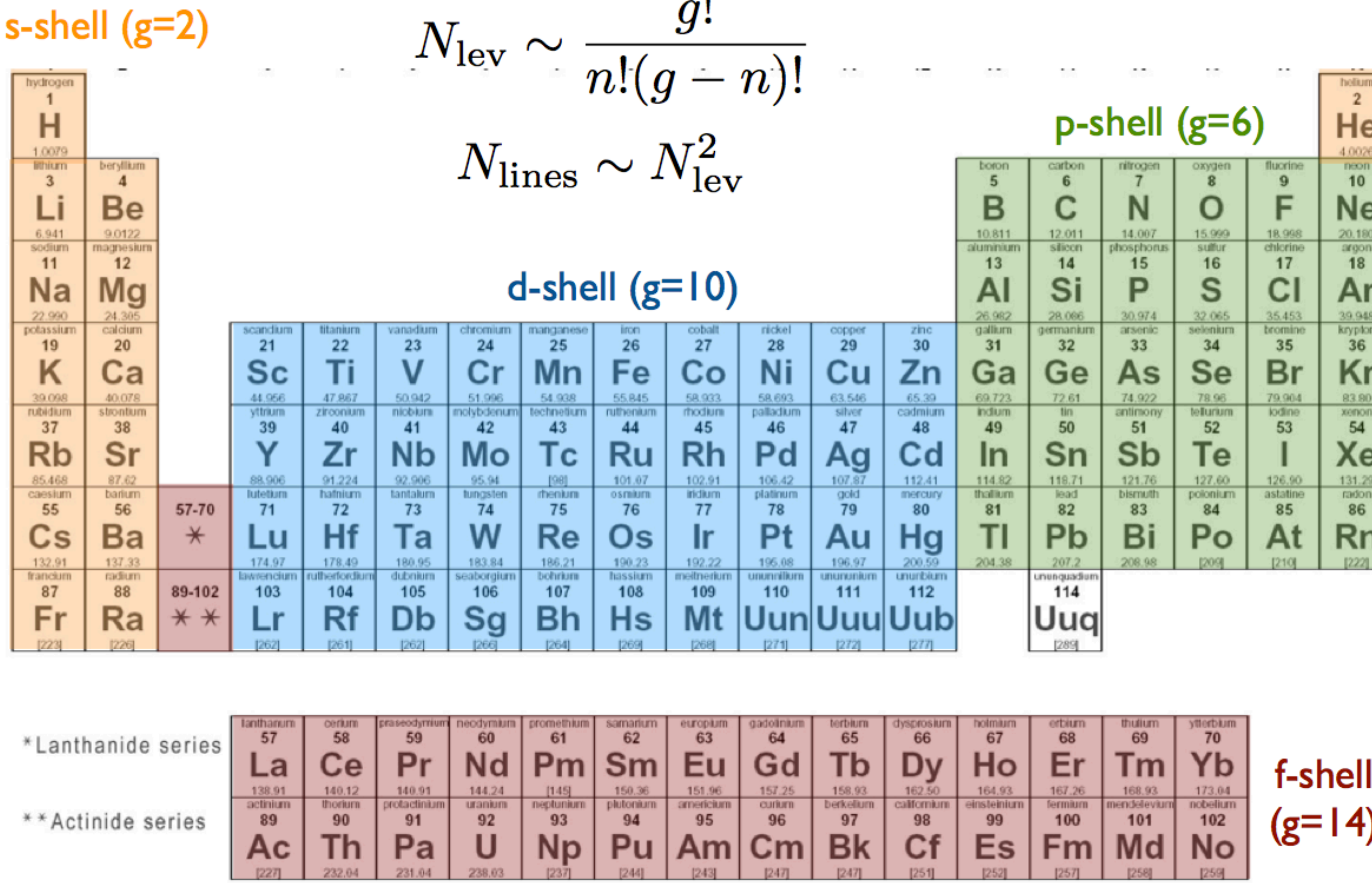


High Opacity of the Lanthanides

(Kasen et al. 2013; Barnes & Kasen 2013)

$$N_{\mathrm{lev}} \sim \frac{g!}{n!(g-n)!}$$

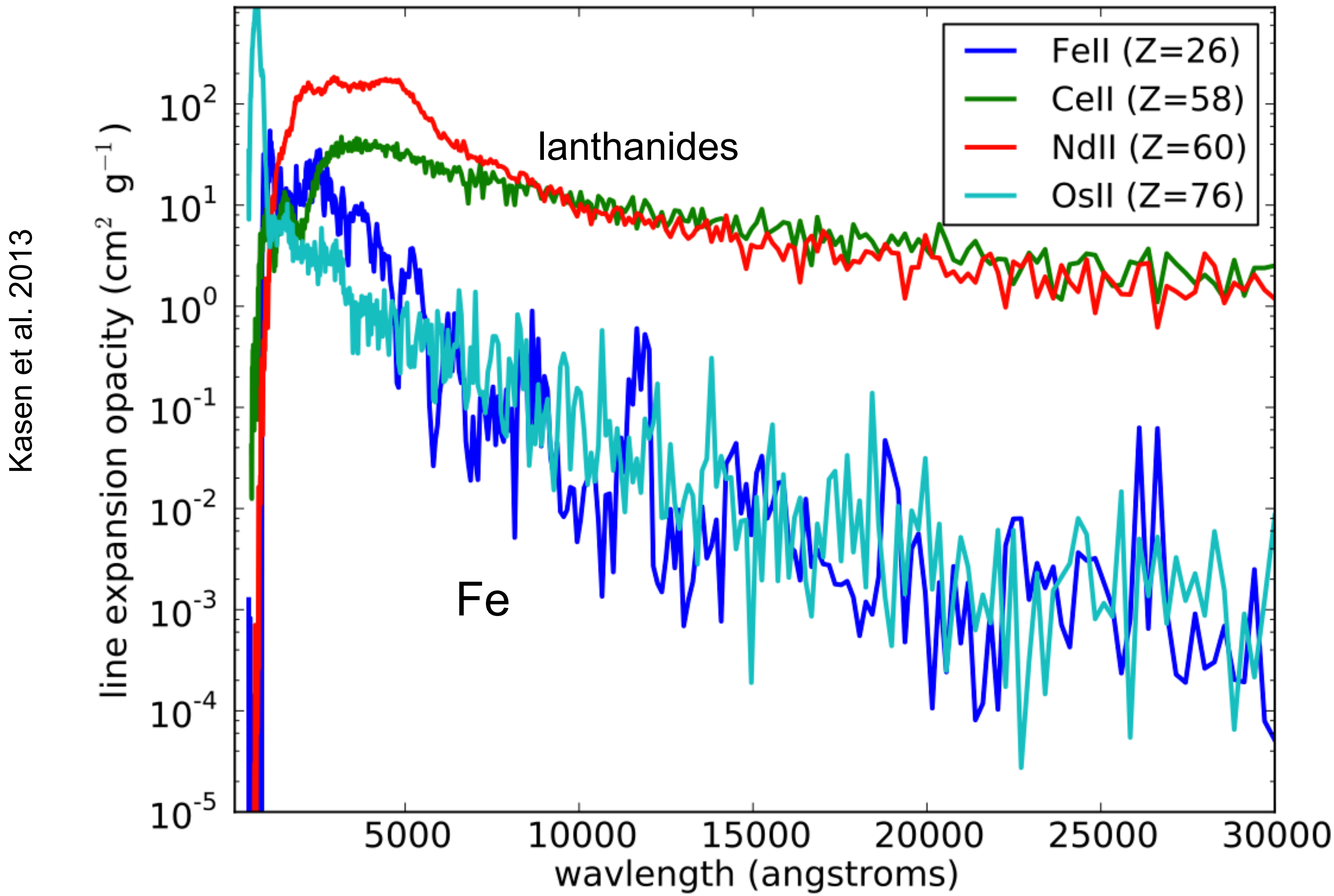
$$N_{\mathrm{lines}} \sim N_{\mathrm{lev}}^2$$



Slide courtesy D. Kasen

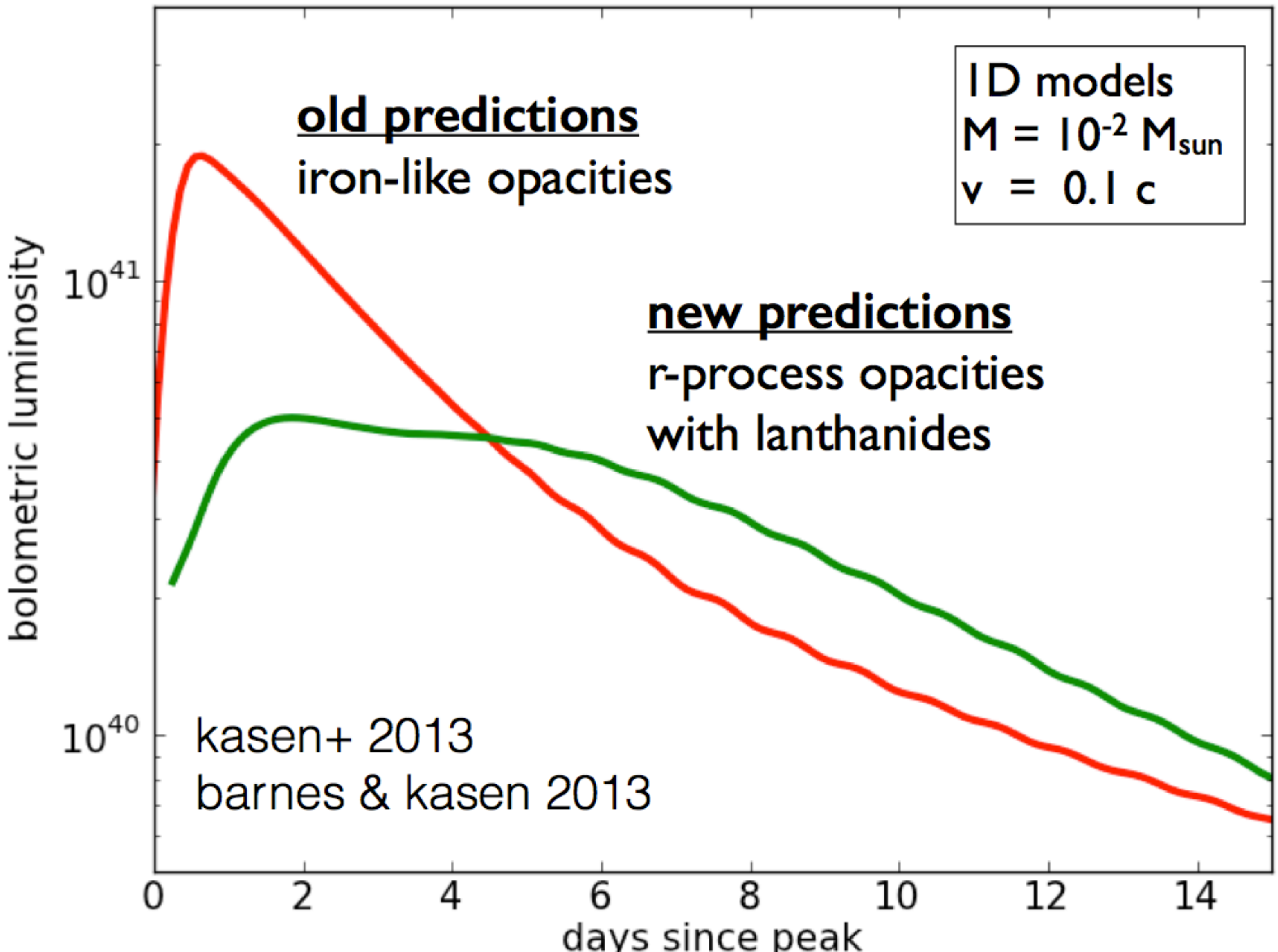
High Opacity of the Lanthanides

(Kasen et al. 2013; Barnes & Kasen 2013)



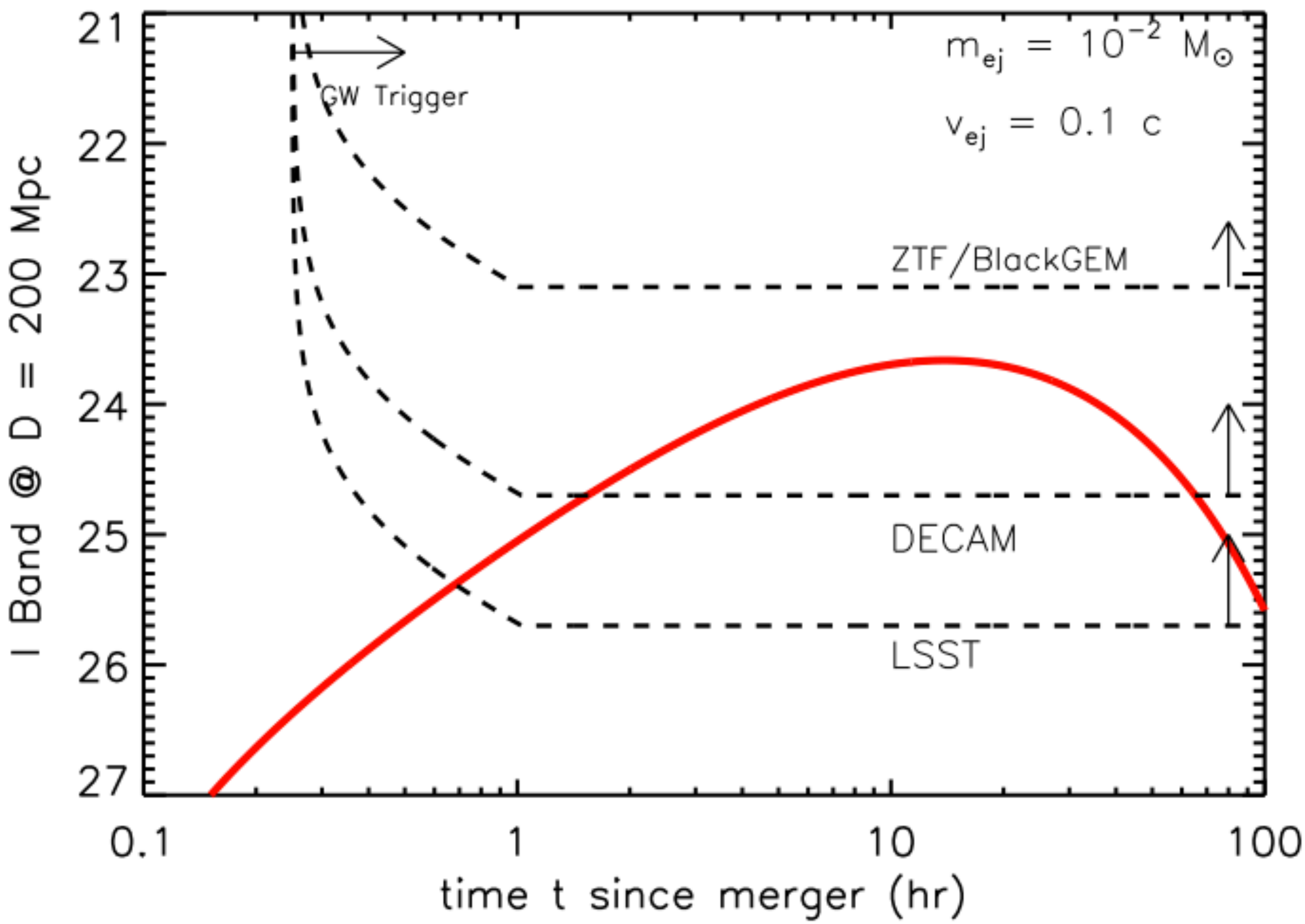
light curves of radioactive transients

effect of high lanthanide opacity

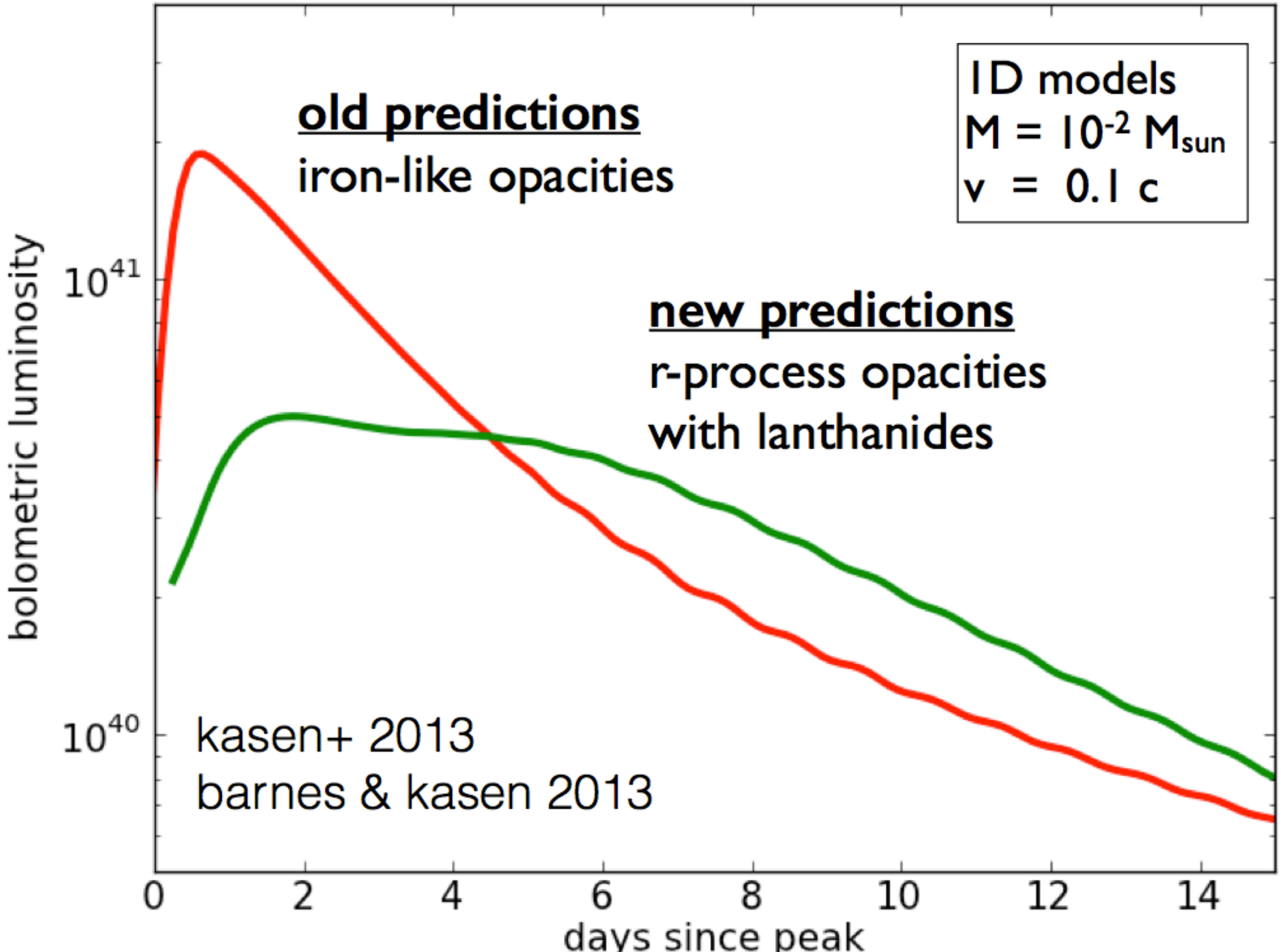


Slide from D. Kasen

Gravitational Wave Follow-Up



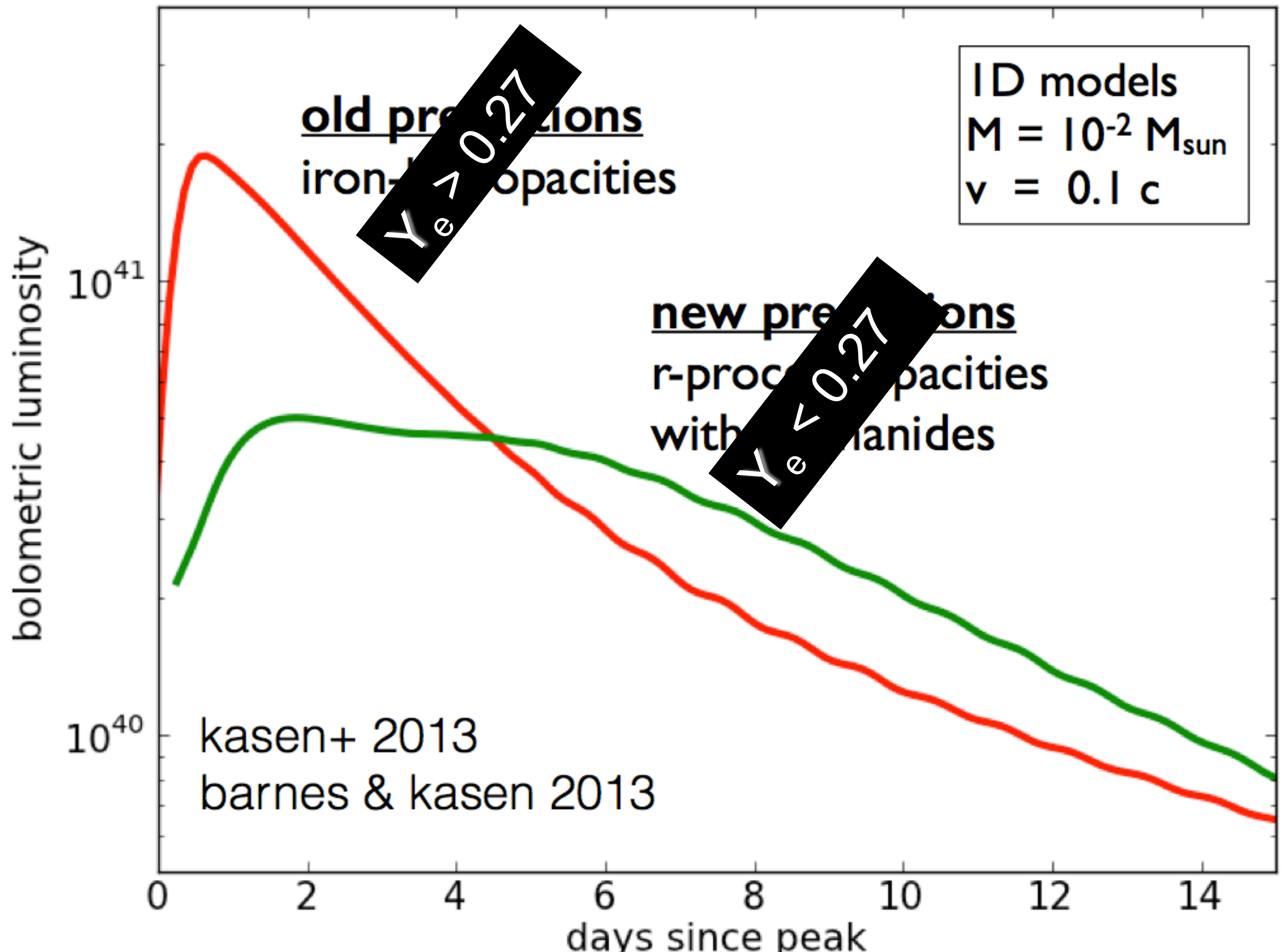
light curves of radioactive transients
effect of high lanthanide opacity



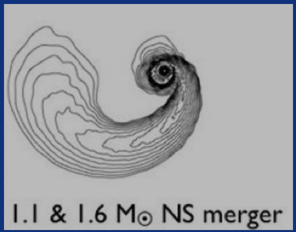
Slide from D. Kasen

light curves of radioactive transients

effect of high lanthanide opacity



Slide from D. Kasen



Neutron-Rich Ejecta

Dynamical Tidal Tails

(e.g. Janka et al. 1999; Rosswog 2005; Shibata & Taniguchi 2006; East et al. 2012; Hotokezaka et al. 2013)

$M_{ej} \sim 10^{-3} - 10^{-2}\, M_{\odot}$

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

~ ms

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)

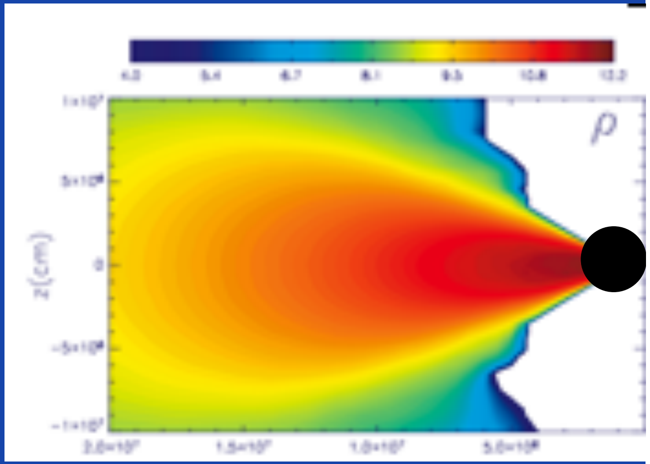
(e.g. McLaughlin & Surman 05; Surman+08; BDM+08; Dessart+09)

"Viscous"-Powered (Late)

Beloborodov 08; BDM+08, 09; Lee+09; Fernandez & BDM 13; Just+14)

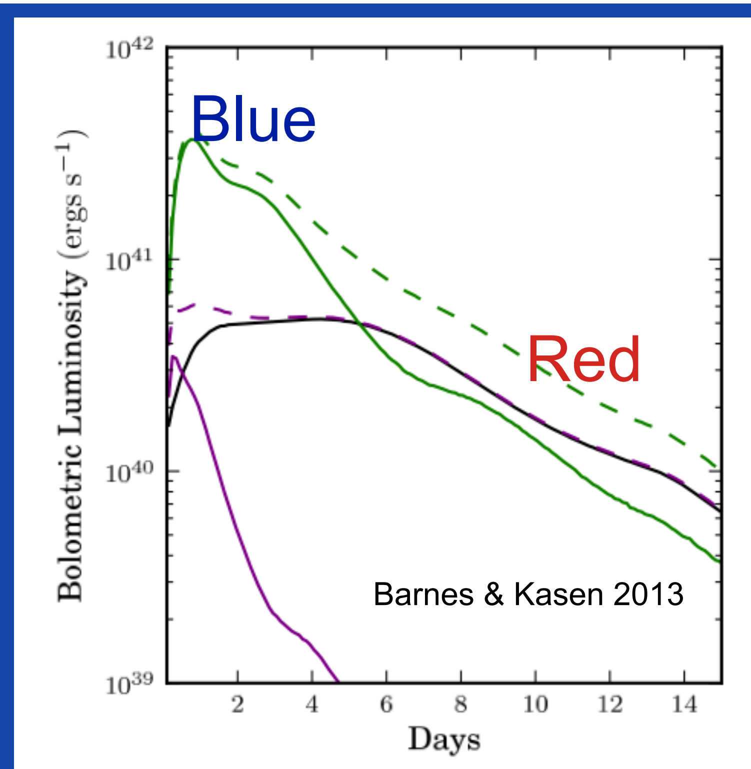
$Y_e \sim ???$

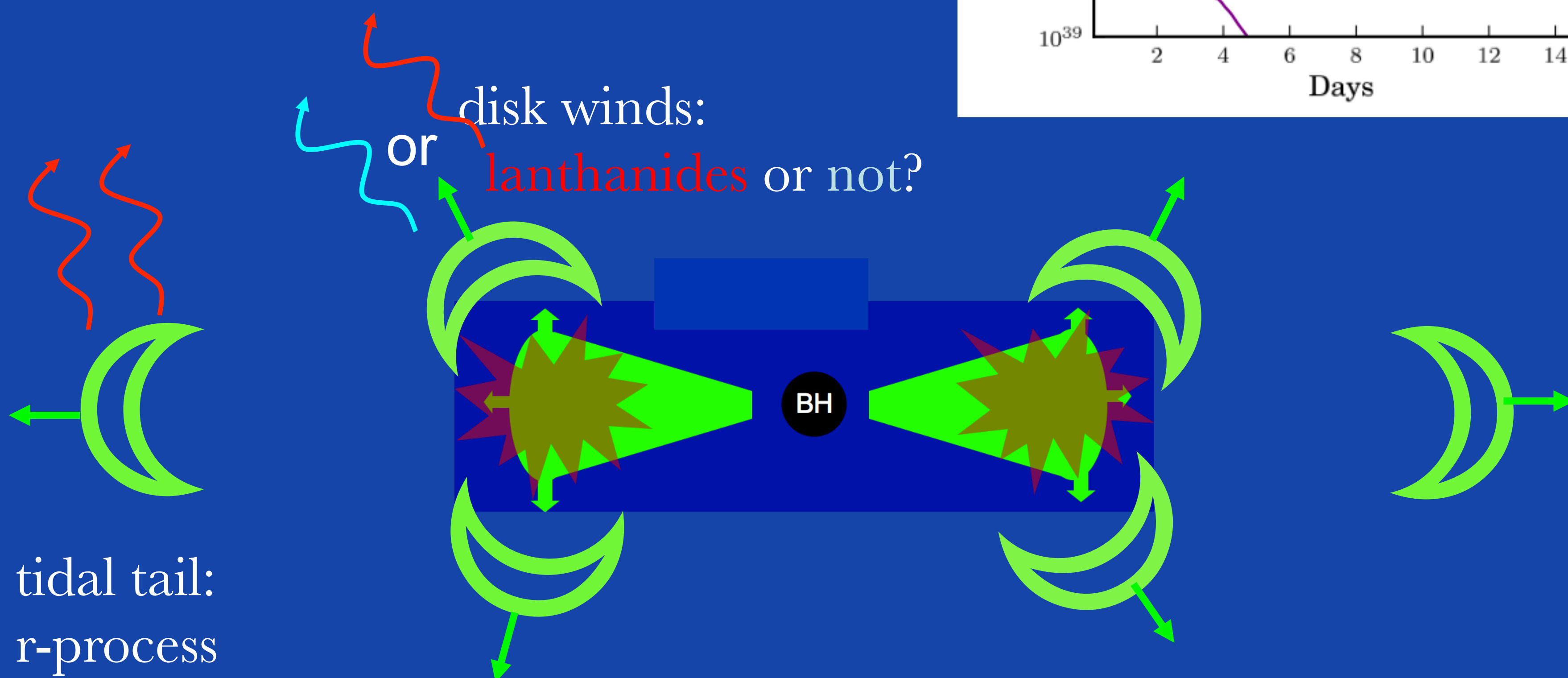
(e.g.



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

Two Component Light Curve

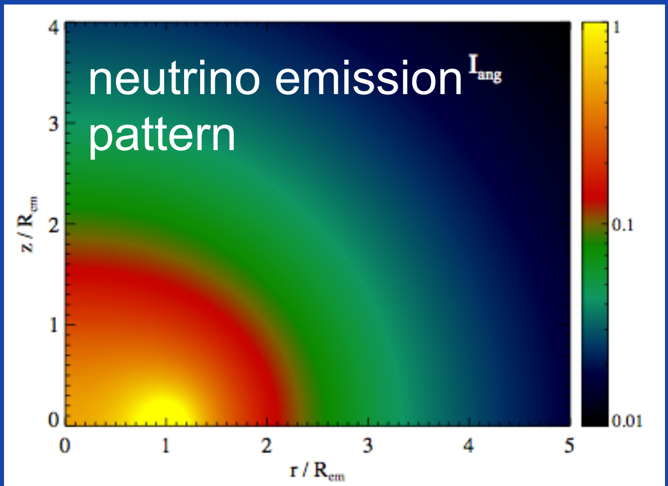


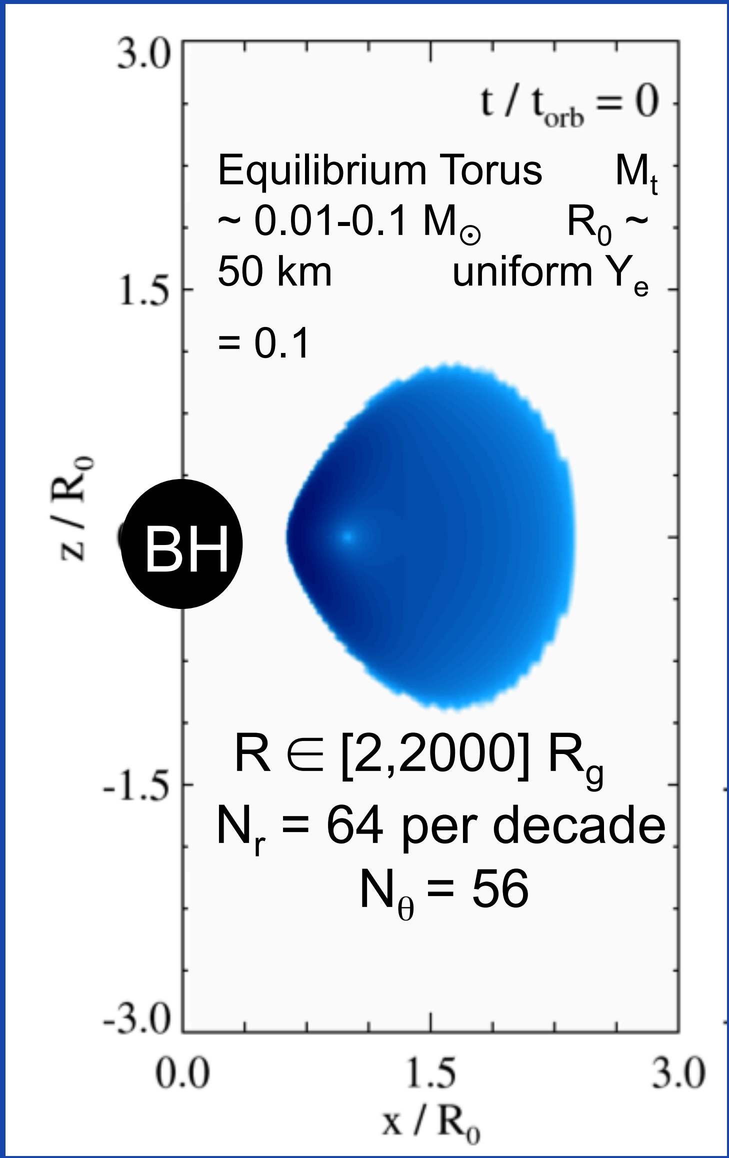


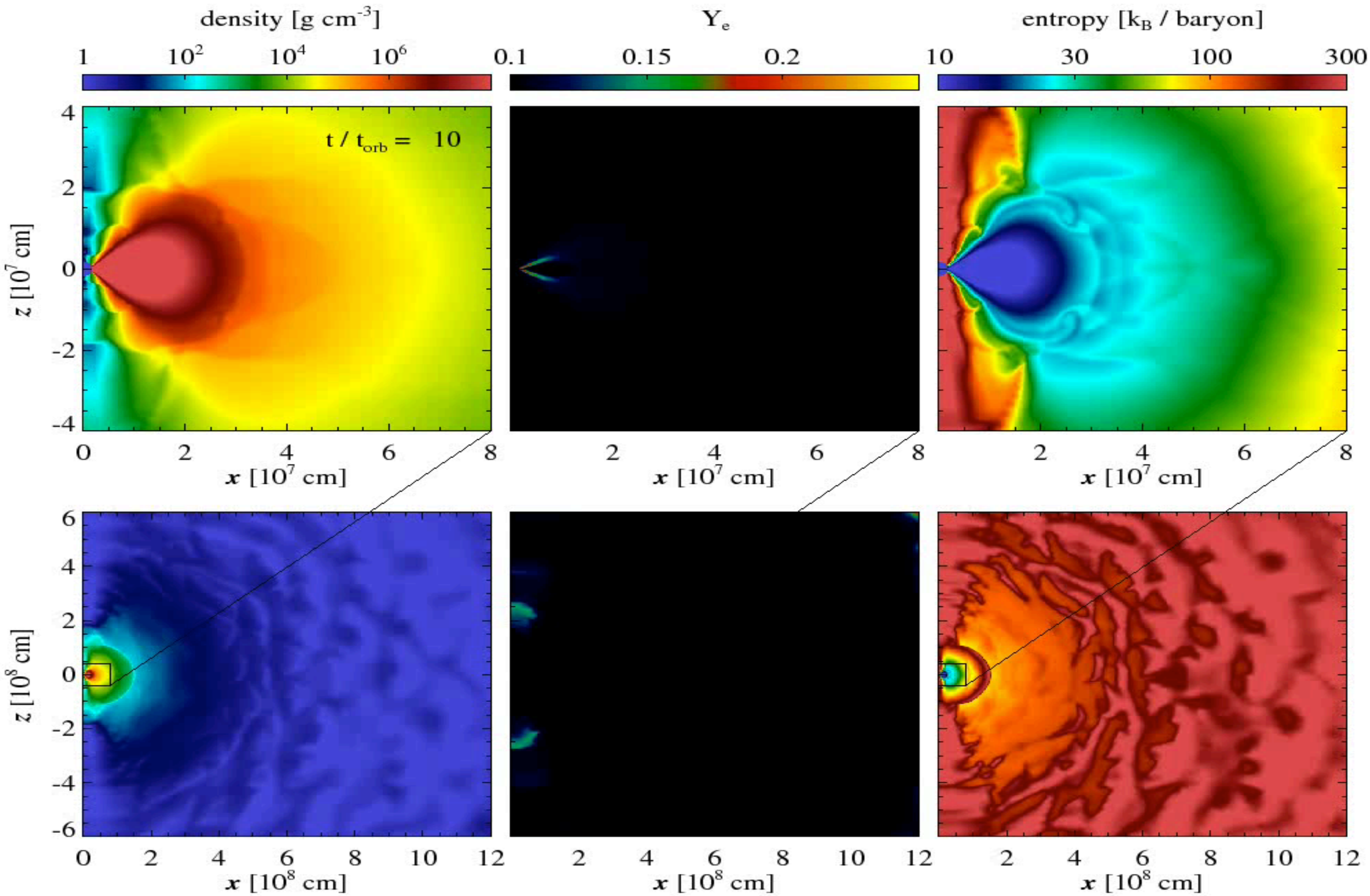
Remnant Torus Evolution

(Fernandez & Metzger 2012, 2013; Fernandez et al., in prep)

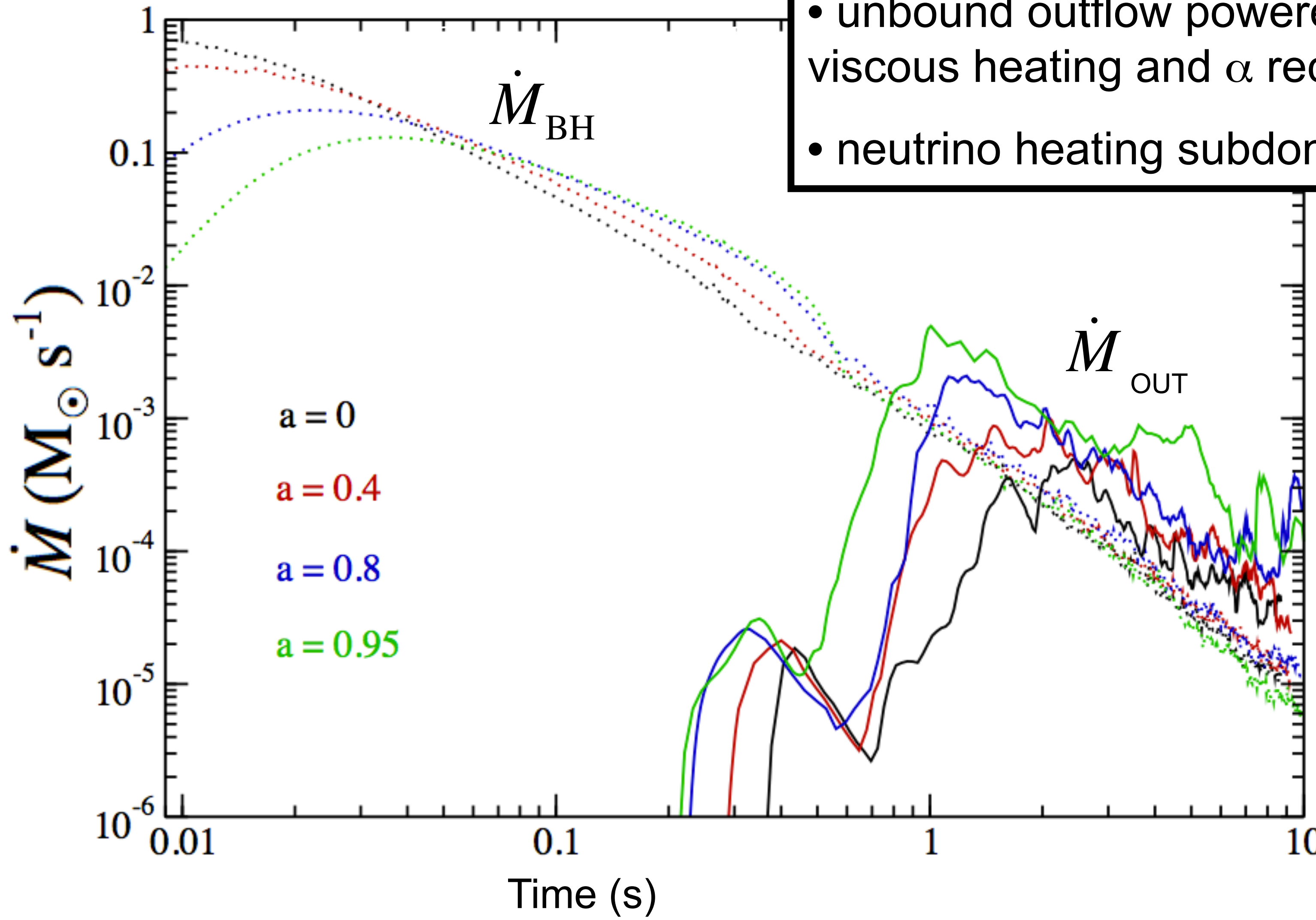
- P-W potential with $M_{BH} = 3,10\ M_{\odot}$
- hydrodynamic α viscosity
- NSE recombination 2n+2p ⇒ ^{4}He
- run-time $\Delta t \sim 1000\text{-}3000\ t_{orb}$
- neutrino self-irradiation: "light bulb" + optical depth corrections:







density [g cm^{-3}]
1
10^2
10^4
10^6
Y_e
0.1
0.15
0.2
entropy [k_B / baryon]
10
30
100
300
t / t_{orb} = 10
z [10^7 cm]
x [10^7 cm]
z [10^8 cm]
x [10^8 cm]



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

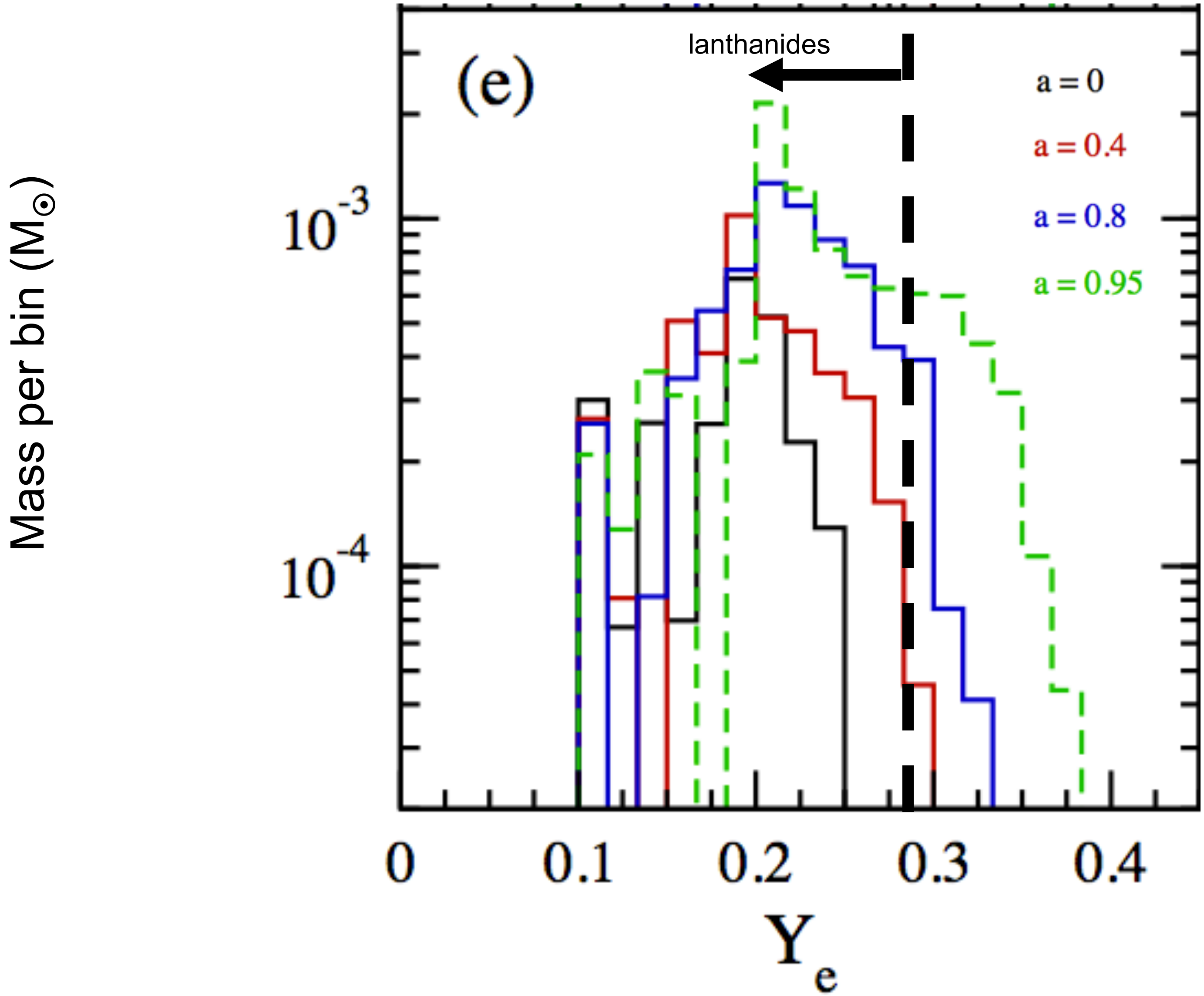
Fernandez & Metzger 2013
Fernandez et al. 2015

outflow robust

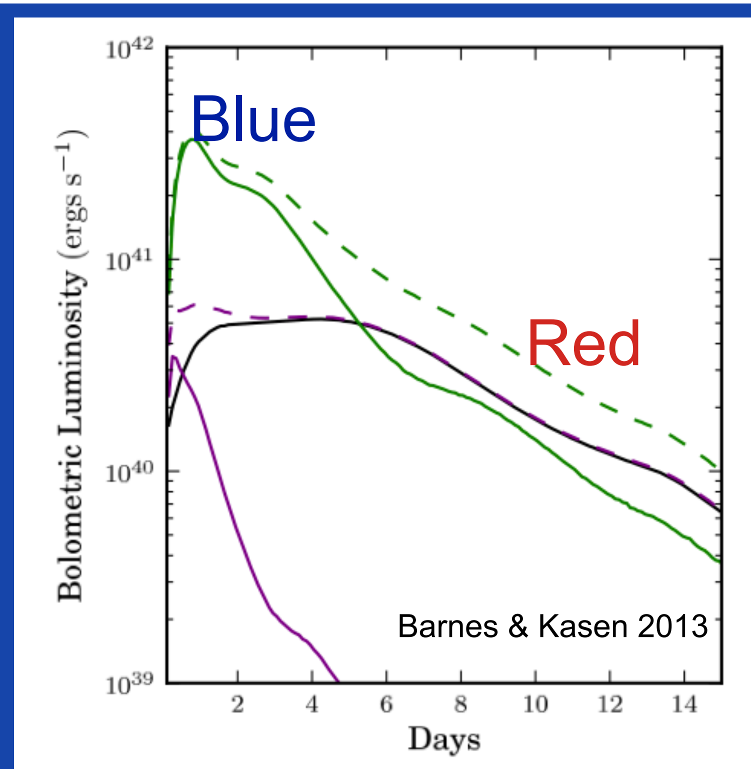
$M_{ej} \sim 0.05\text{-}0.2\ M_t\ \ V_{ej} \sim 0.1\ c$

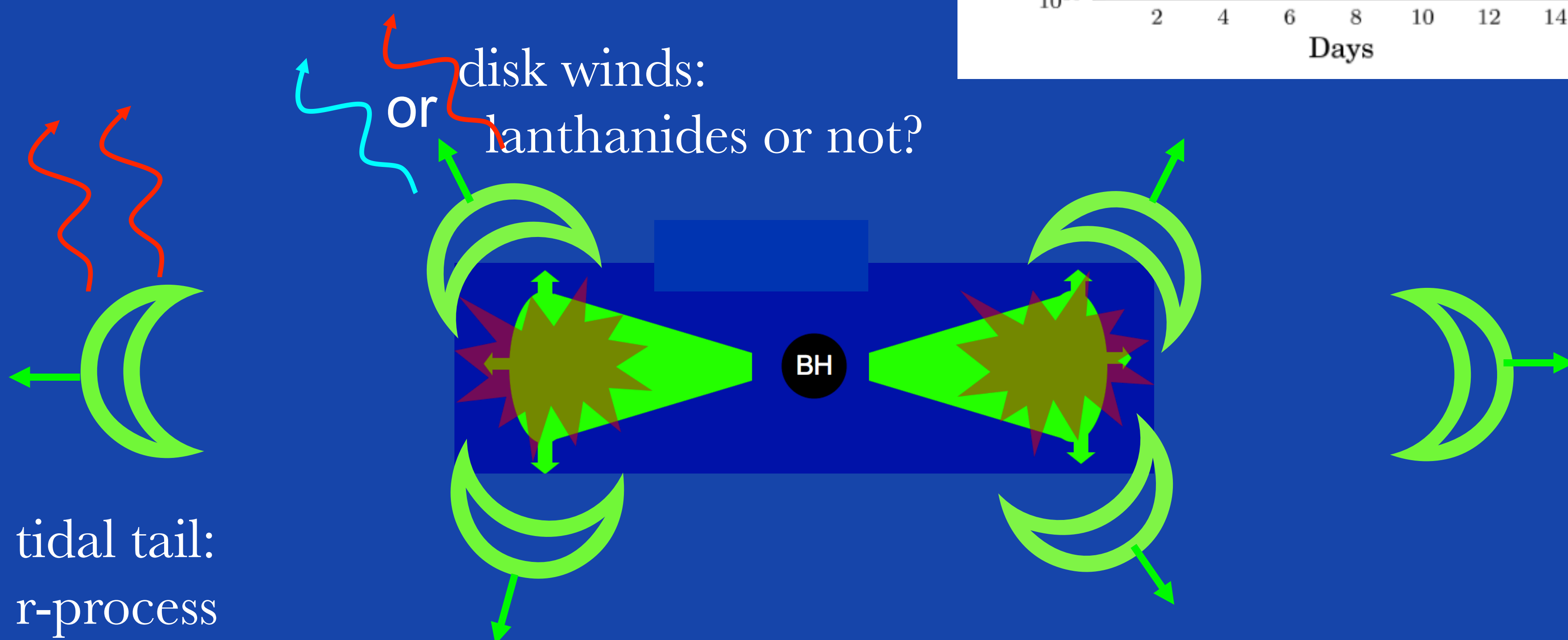
See also Just et al. 2014

Outflow Composition

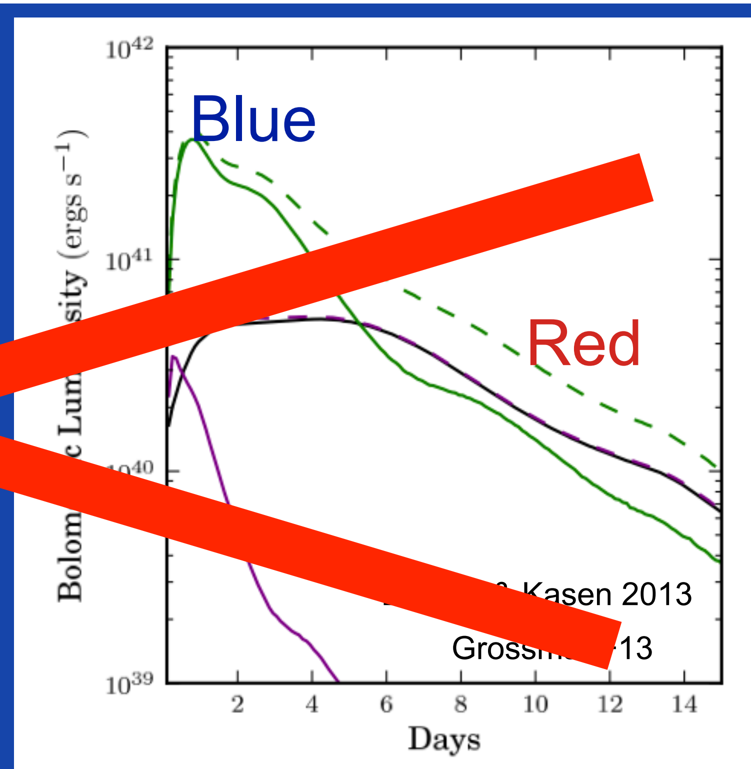


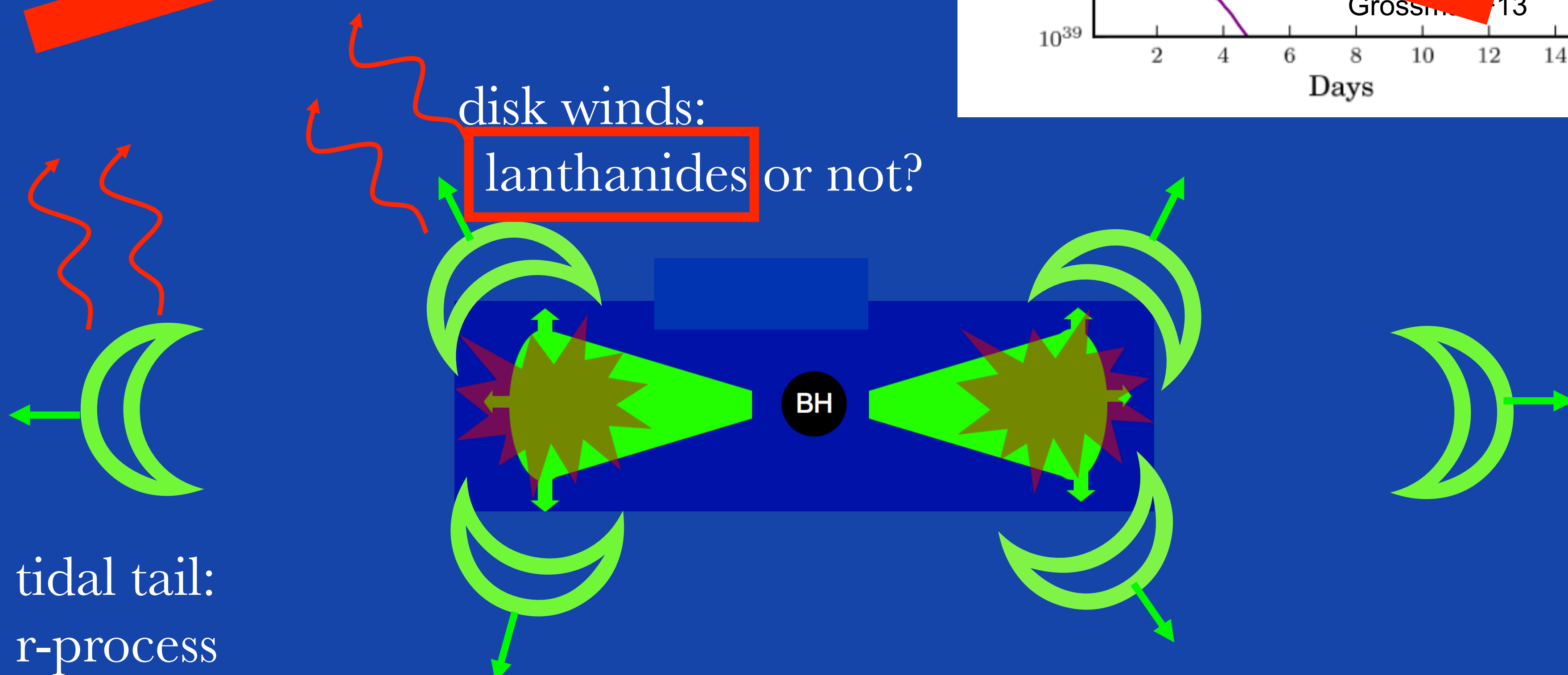
Two Component Light Curve





Two Component Light Curve





tidal tail:
r-process

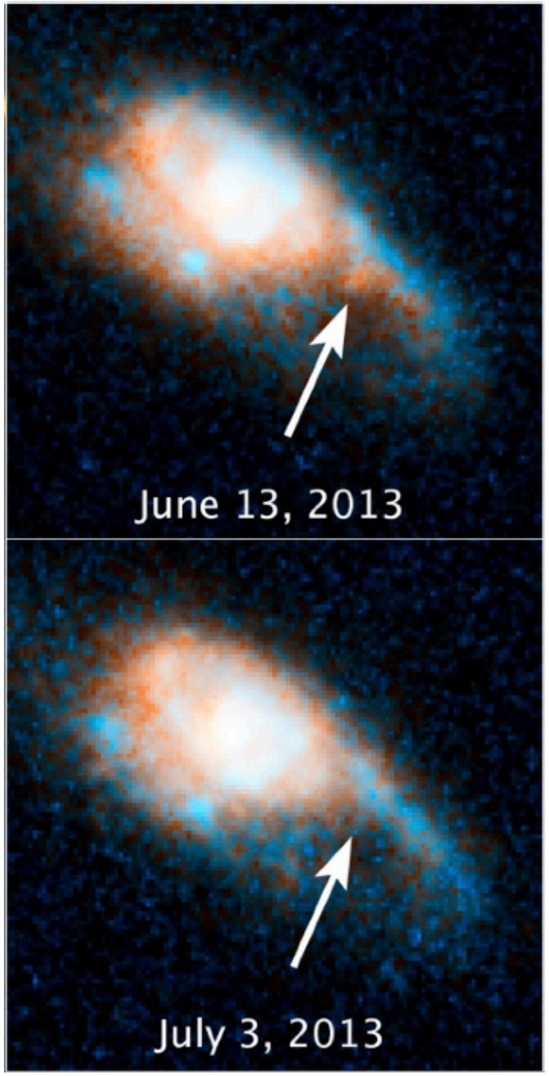
An r-Process Kilonova Associated with the Short-Hard GRB 130603B

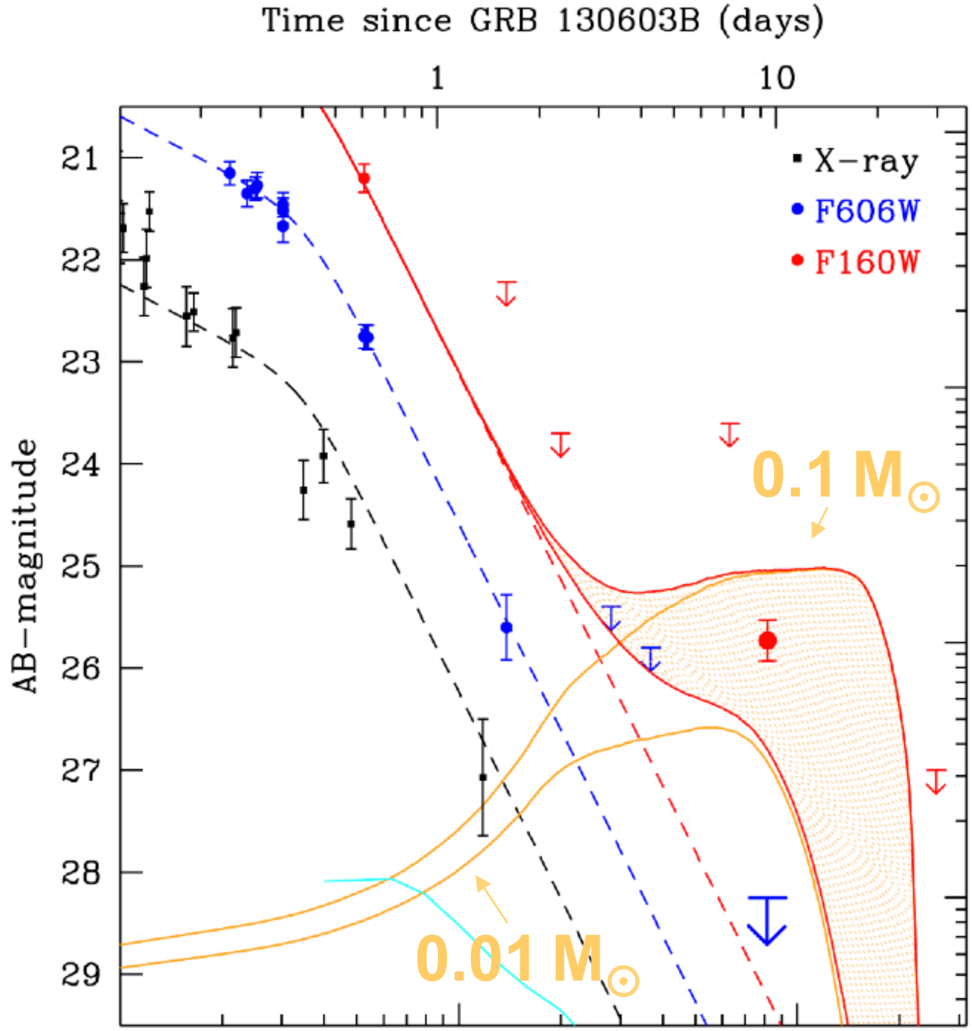
E. Berger[1], W. Fong[1], and R. Chornock[1]

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

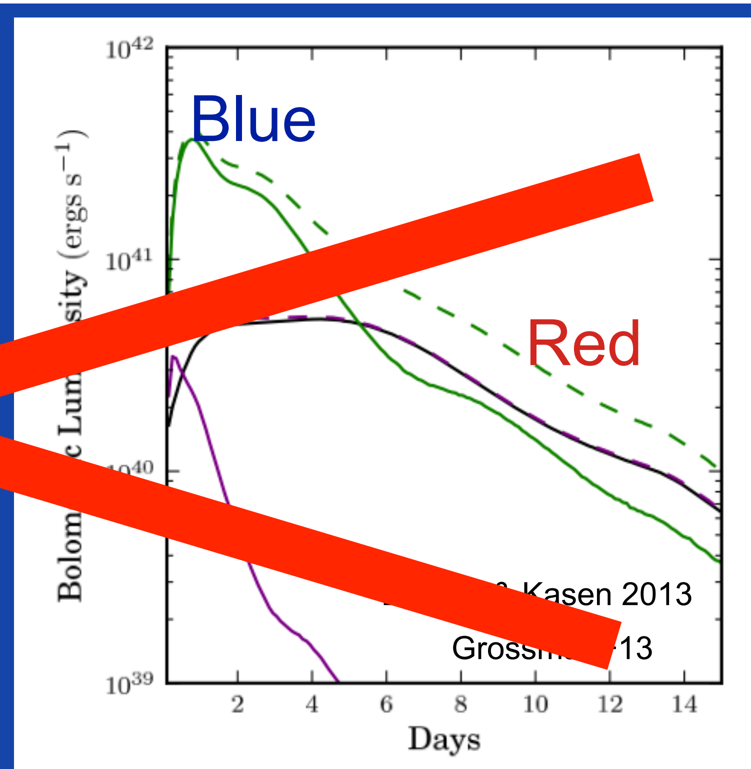
N. R. Tanvir, A. J. Levan, A. S. Fruchter, J. Hjorth, R. A. Hounsell, K. Wiersema & R. L. Tunnicliffe

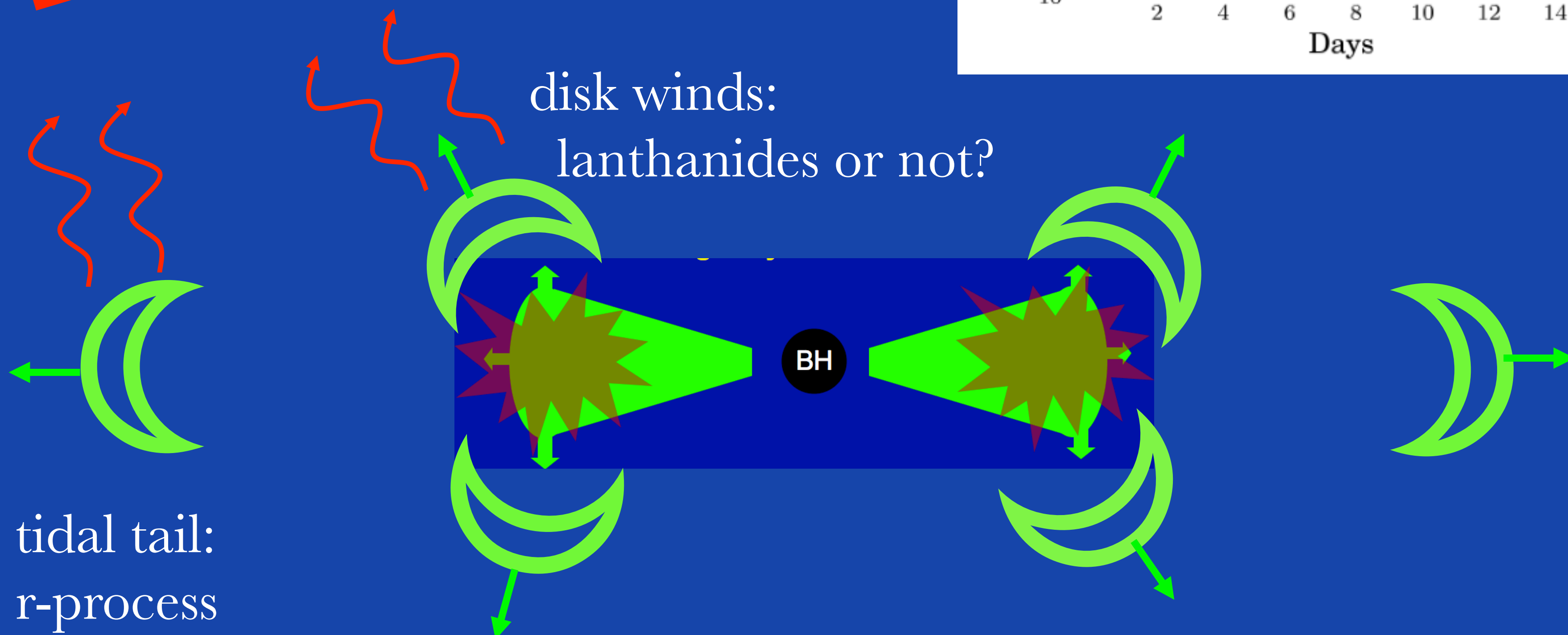
Tanvir et al. 2013



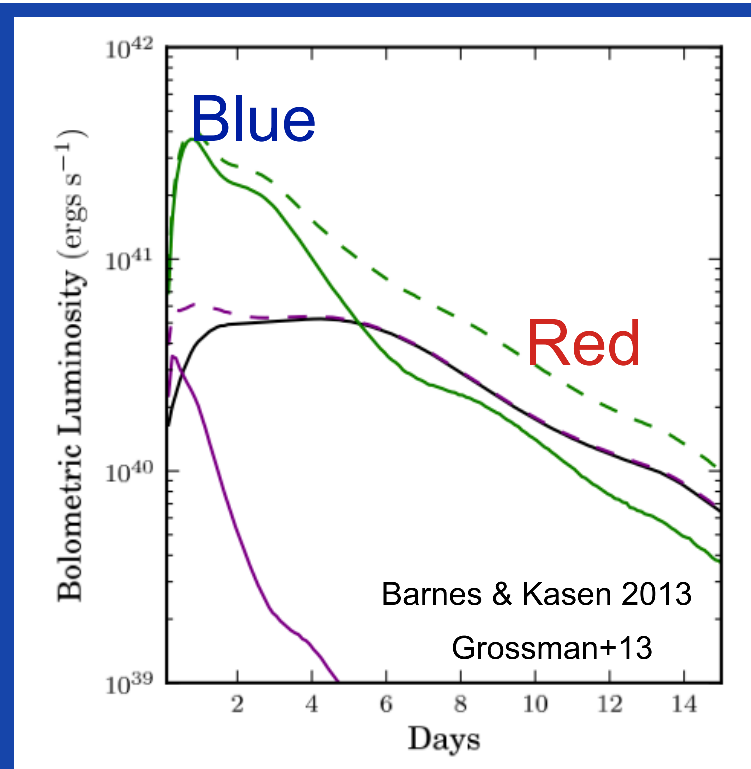


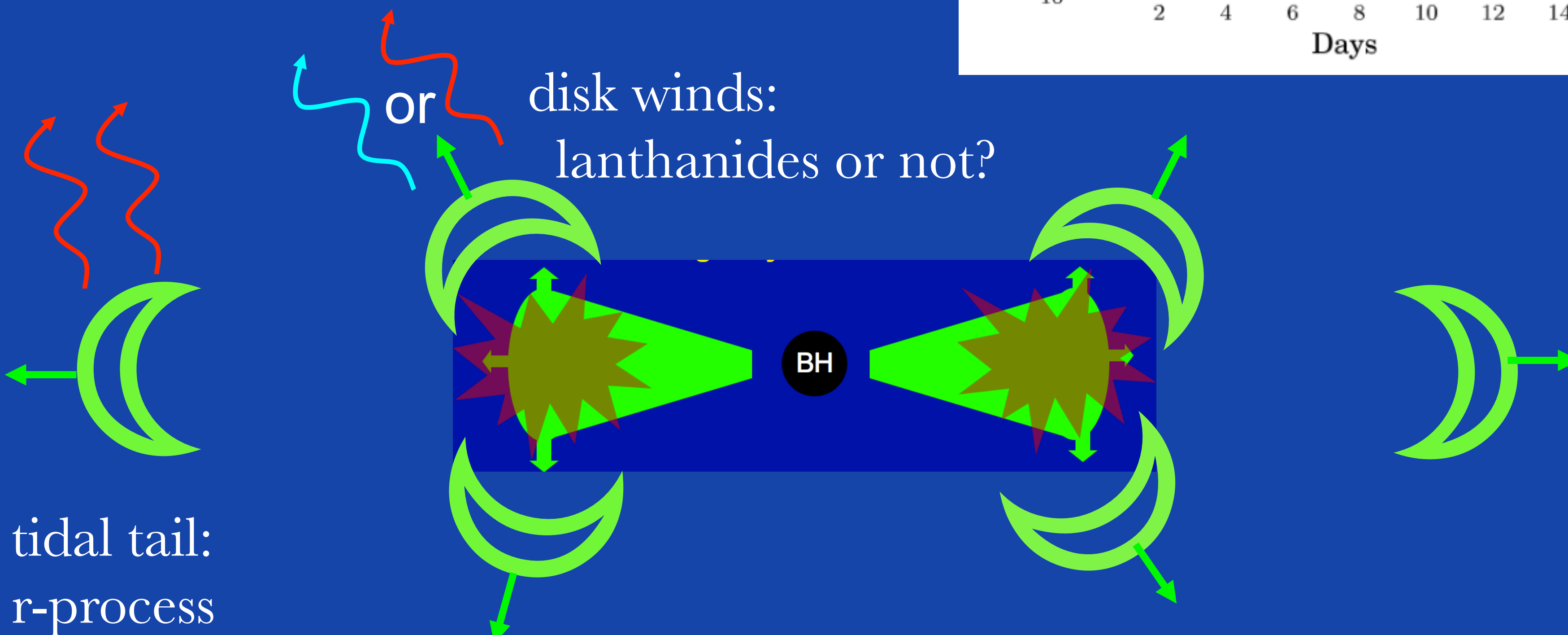
Two Component Light Curve





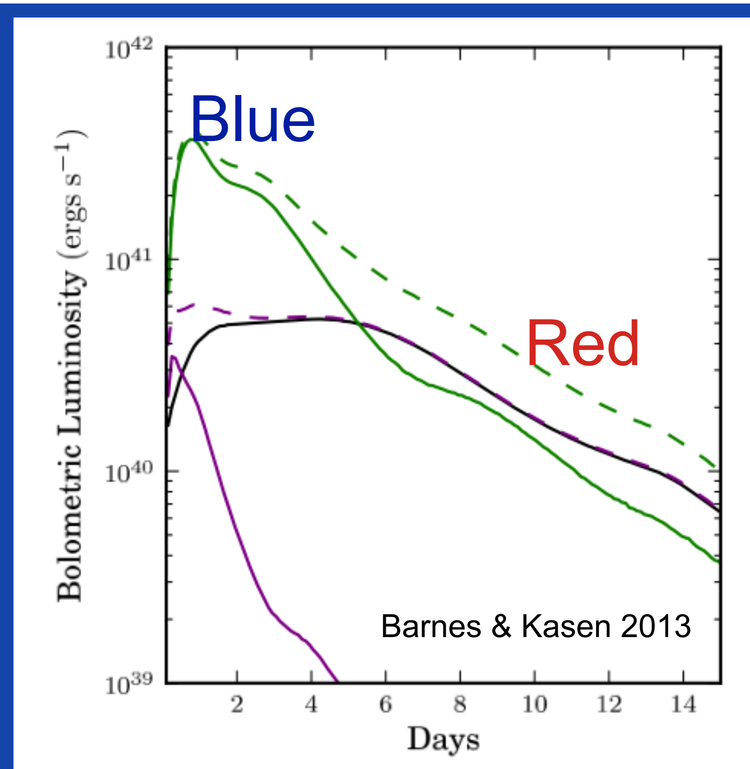
Two Component Light Curve

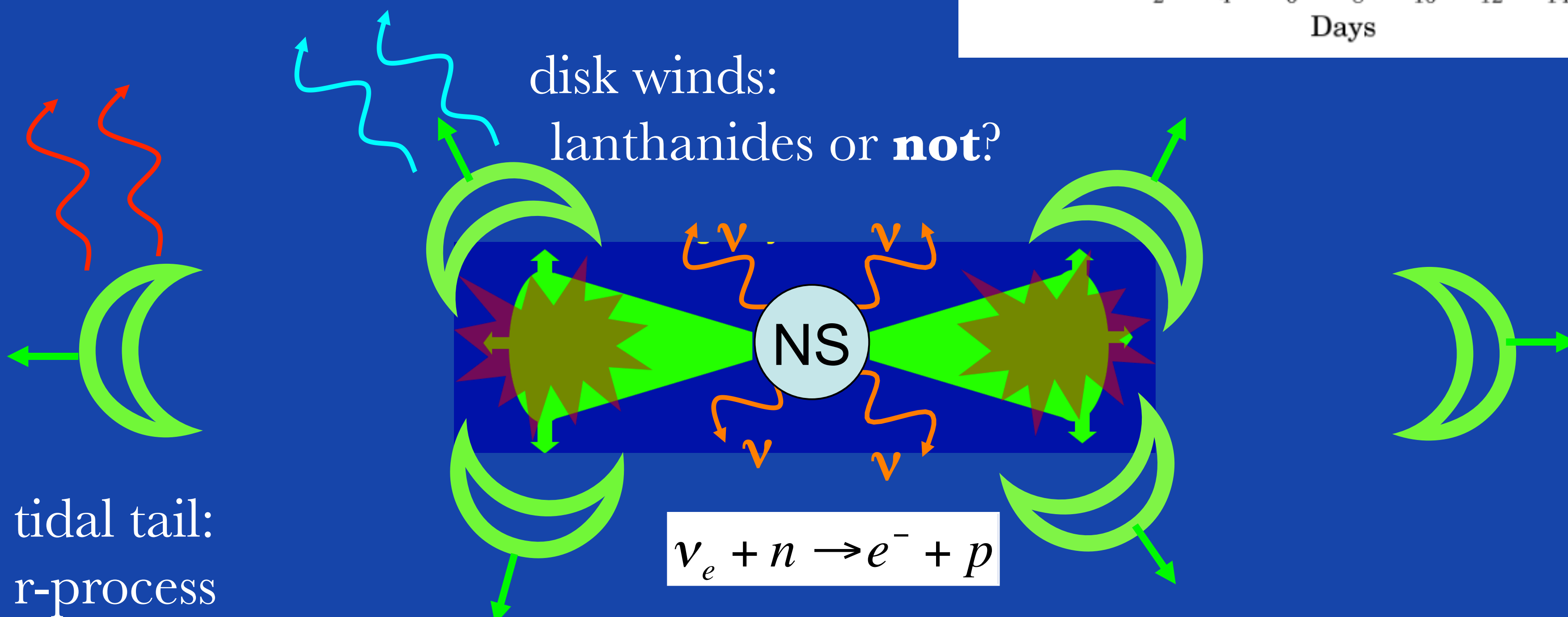




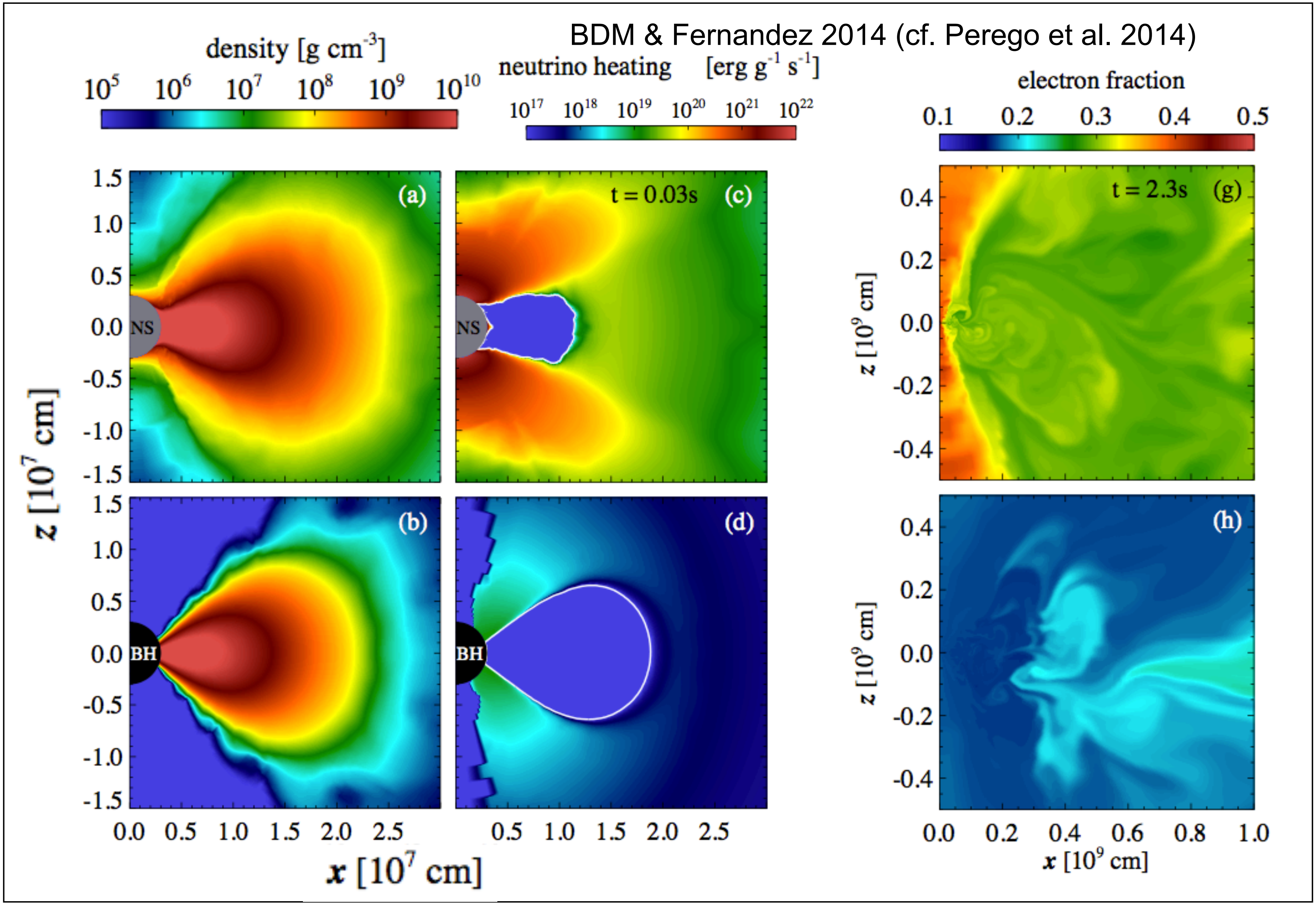
Two Component Light Curve

☺

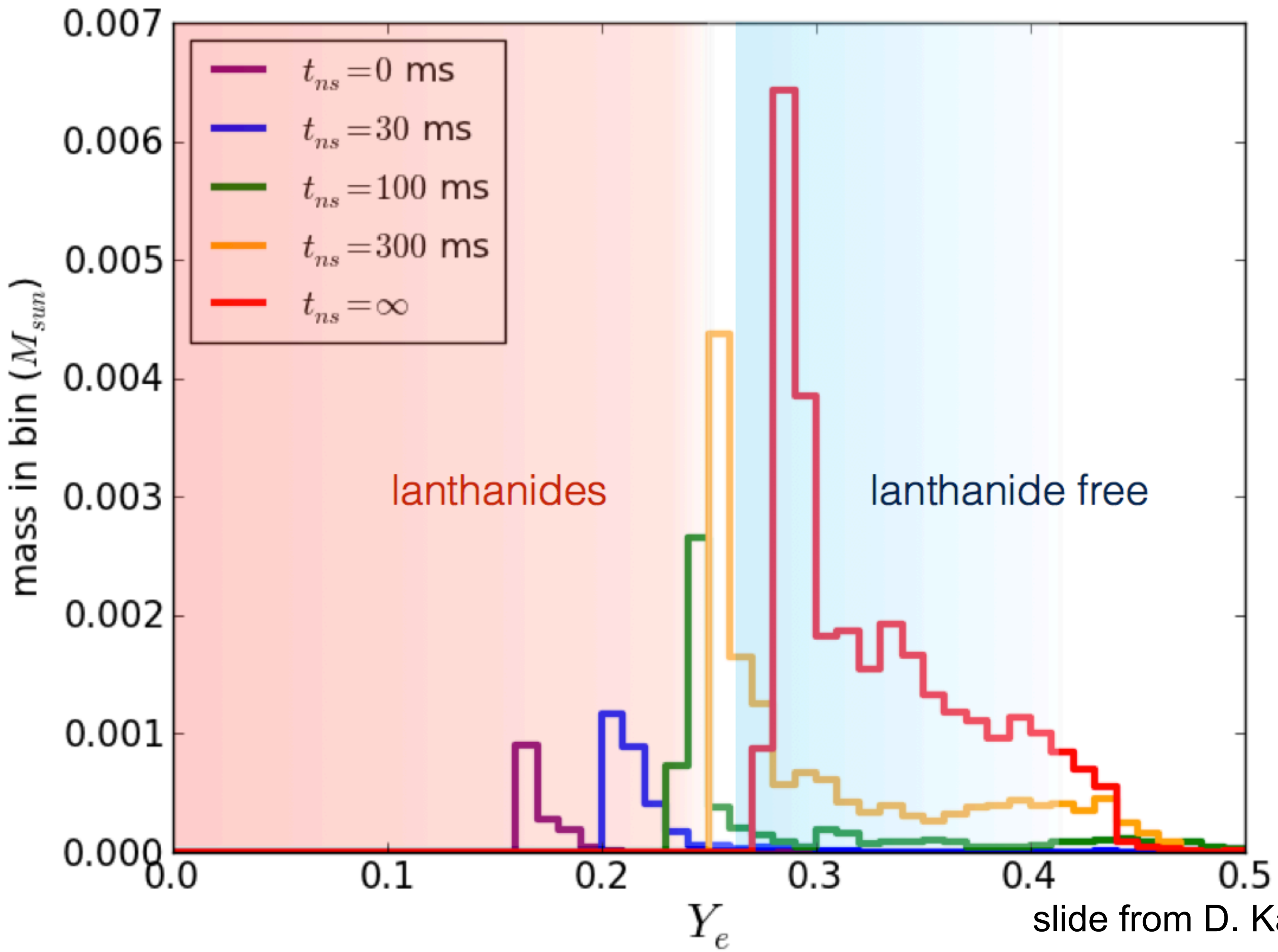




Long-Lived Hyper-massive Neutron Star



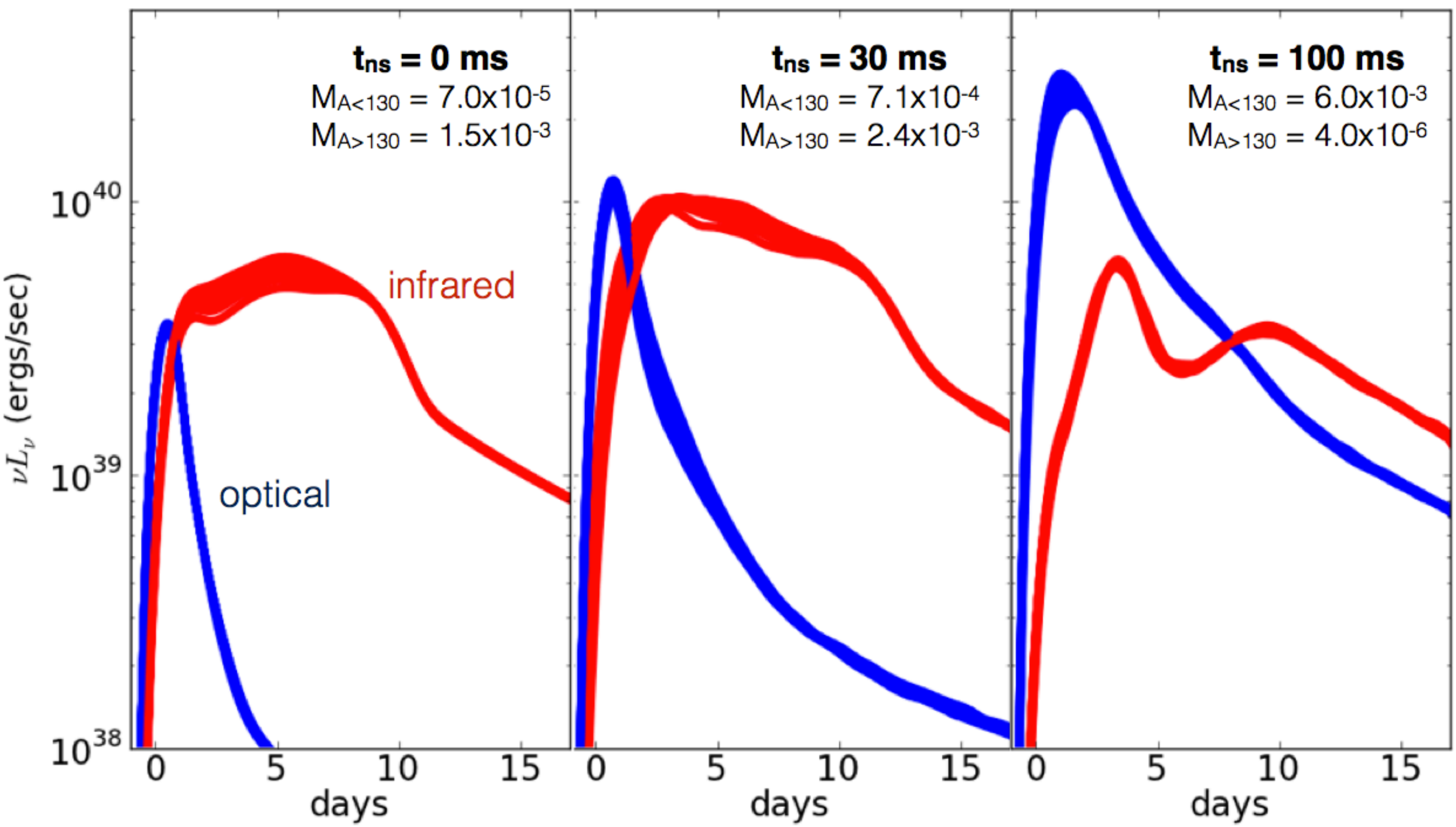
Y_e distribution of wind ejecta



slide from D. Kasen

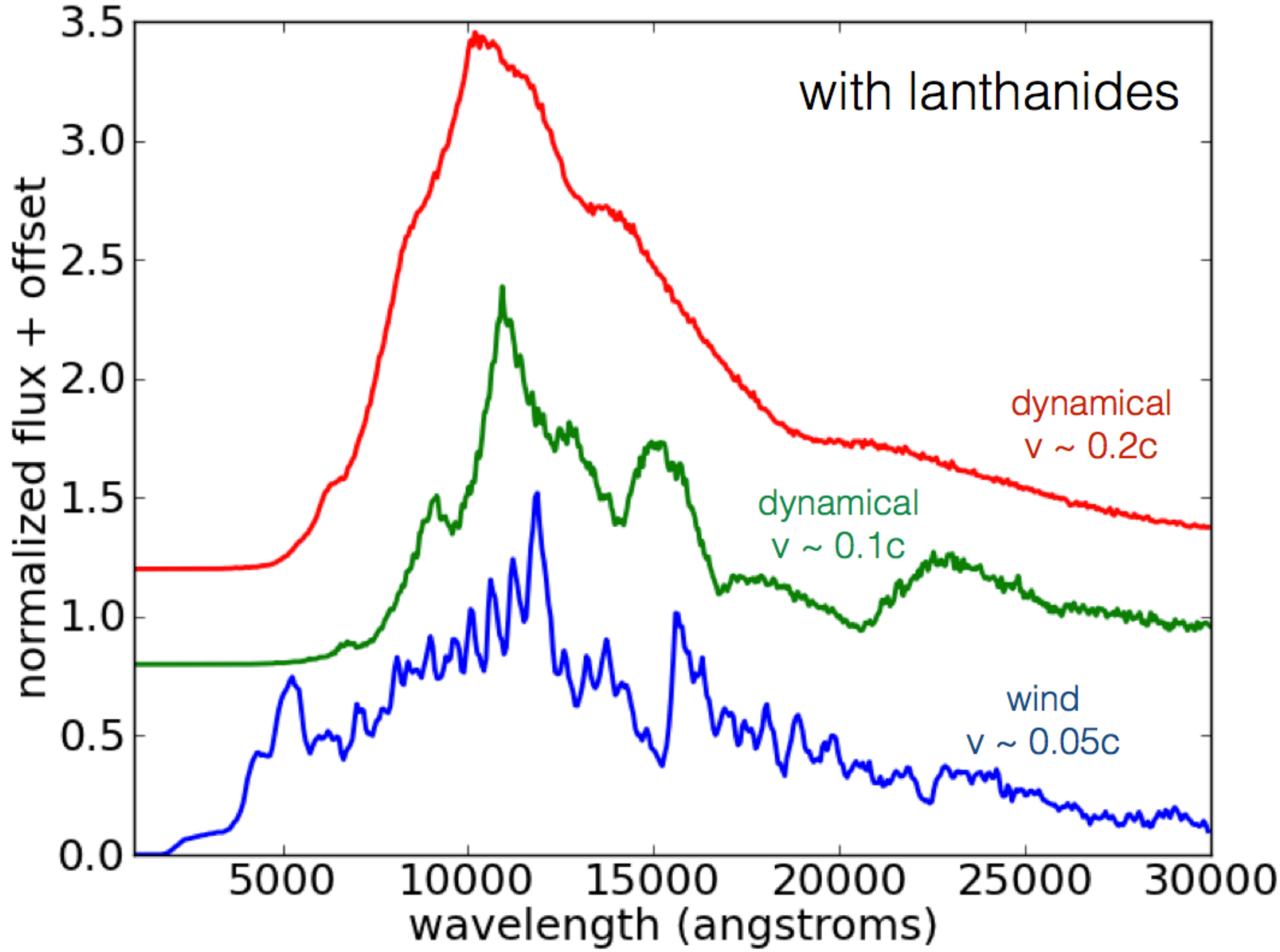
optical and infrared light curves of winds

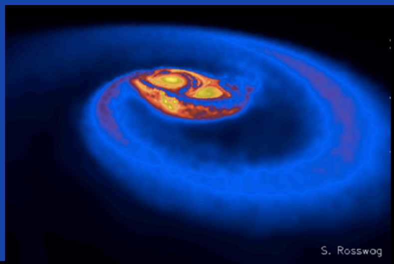
multi-dimensional radiative transport calculations



Kasen, Fernandez, BDM, submitted

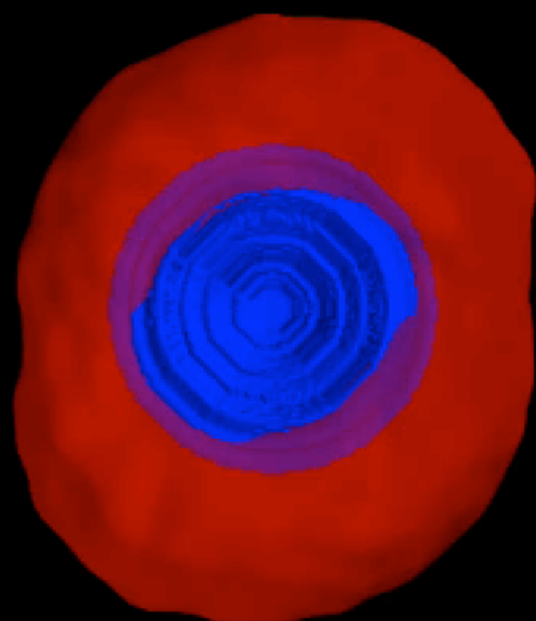
synthetic spectra of NS merger ejecta

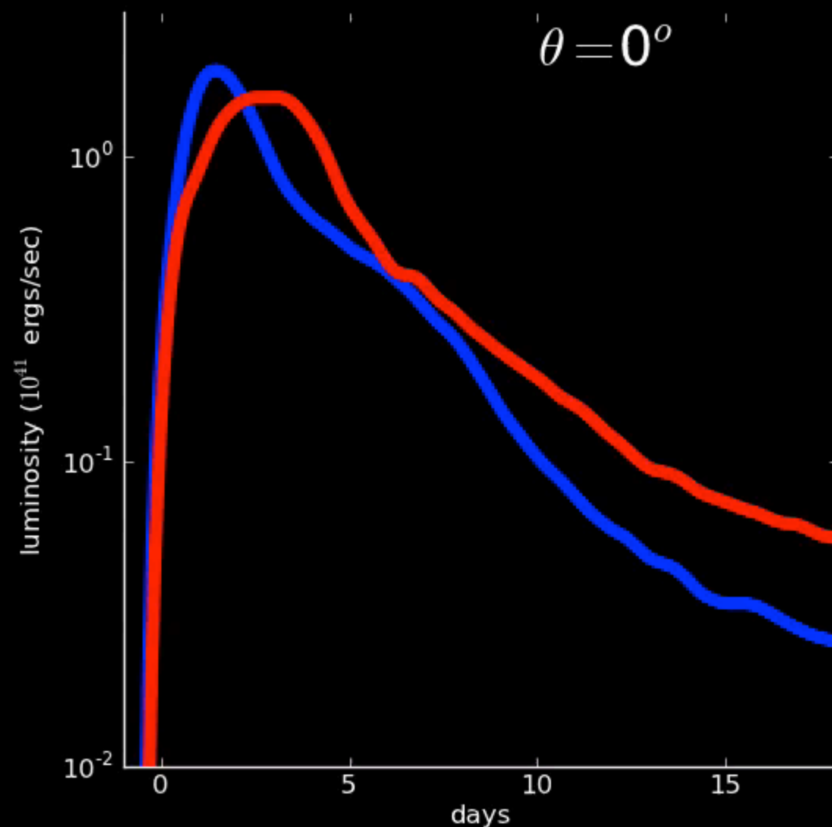




Viewing Angle Dependence

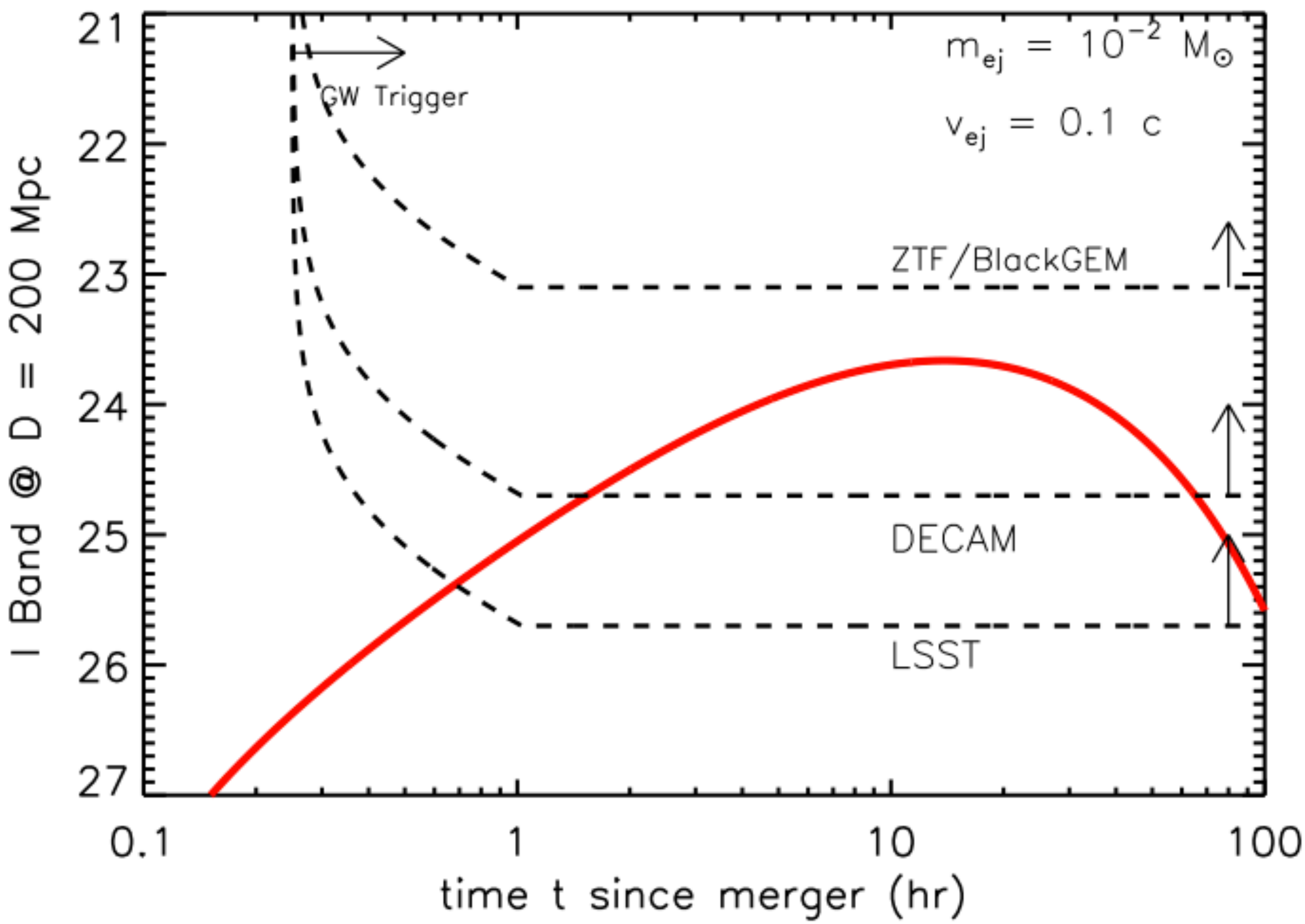
Kasen, Fernandez, Metzger. submitted

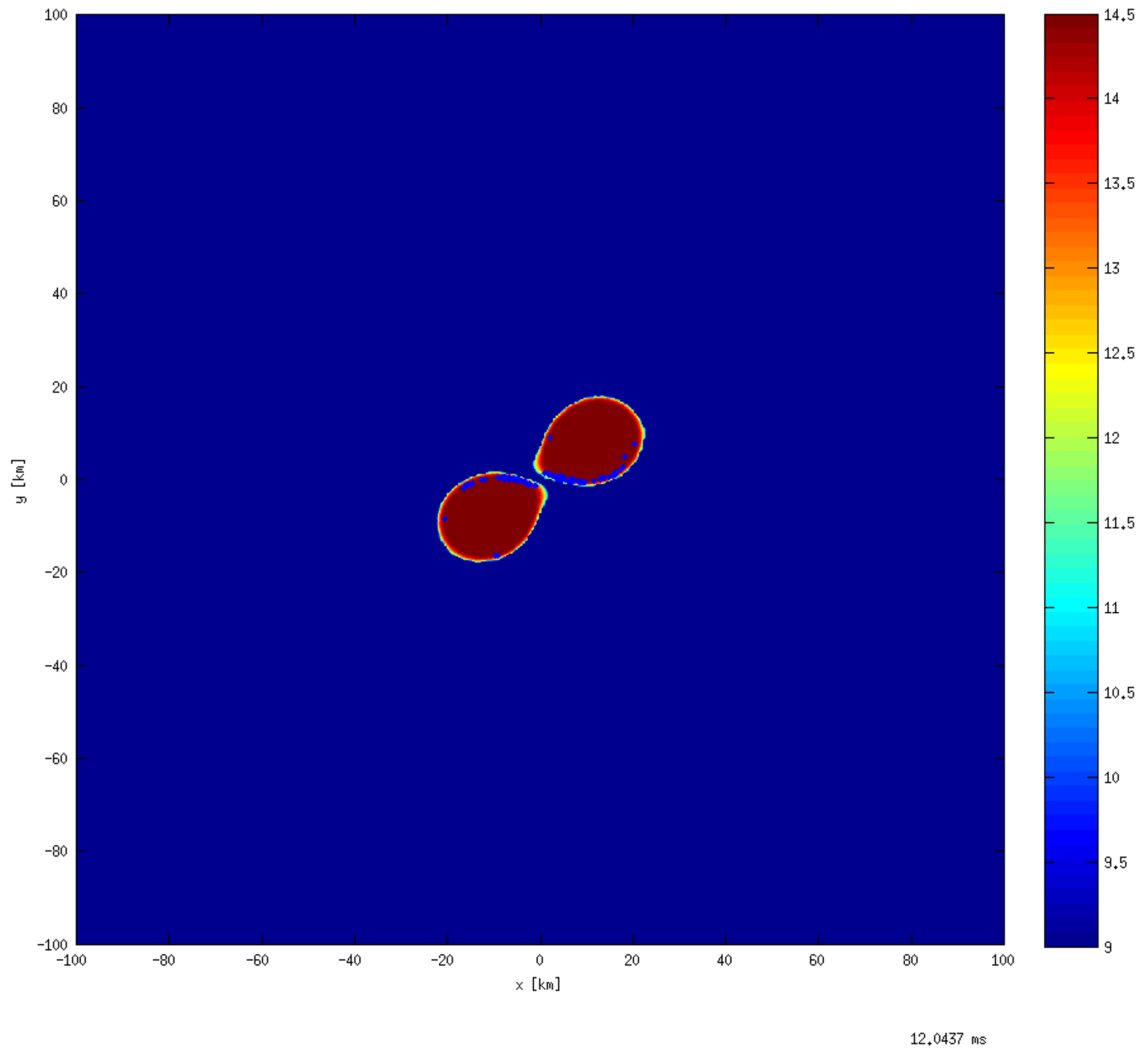




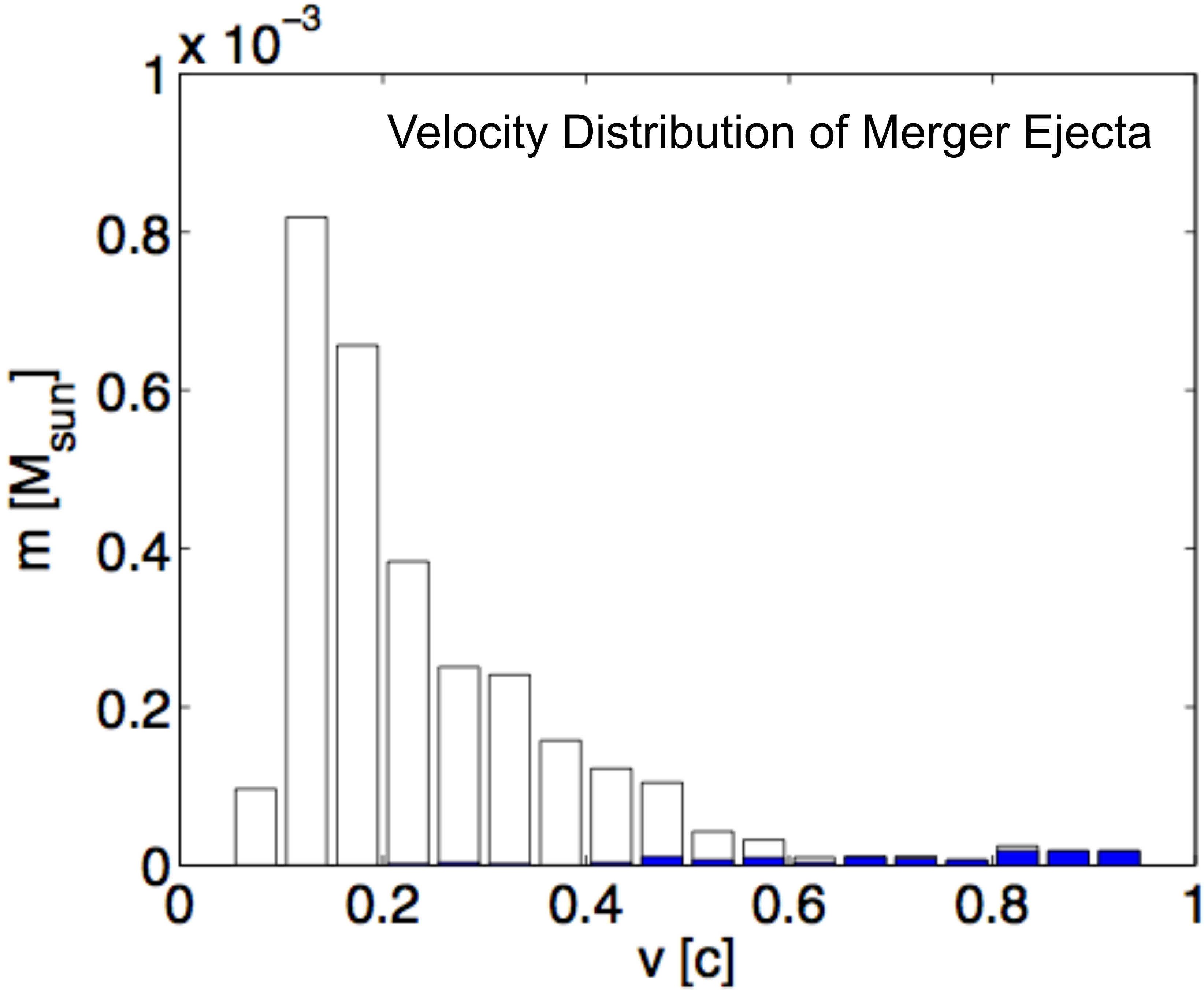
Kilonova light curves probe composition & geometry of merger ejecta ⇒ info on viewing angle and neutron star equation of state

Challenge of Gravitational Wave Follow-Up



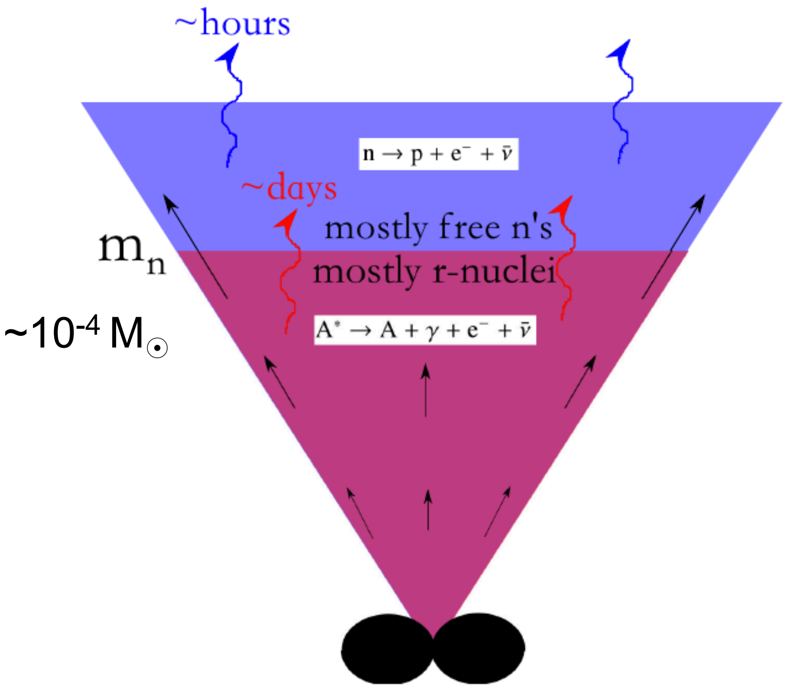


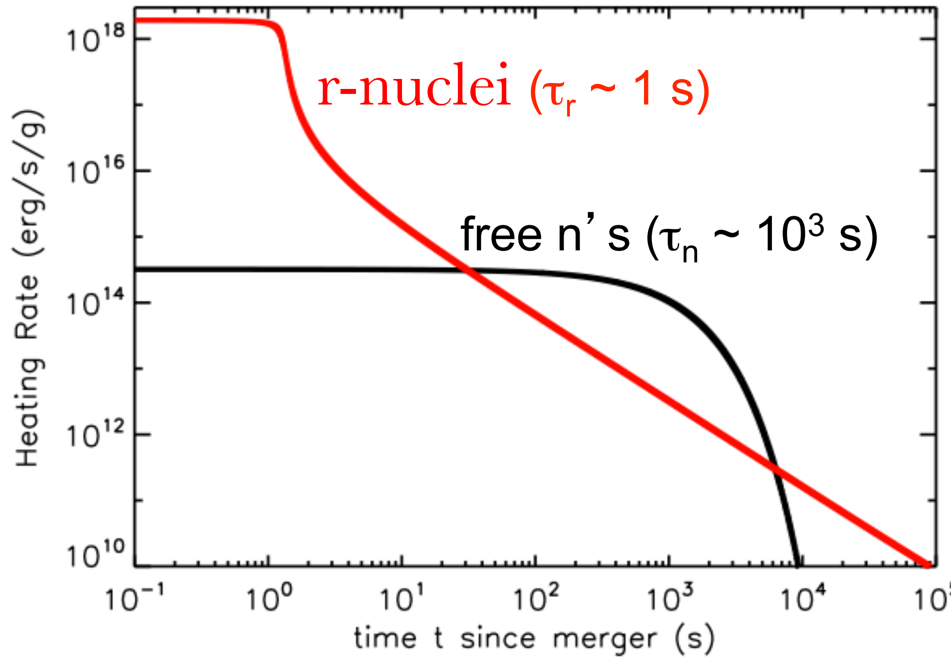
Bauswein et al. 2013



Velocity Distribution of Merger Ejecta
x 10^-3
1
0.8
0.6
0.4
0.2
0
m [M_sun]
0
0.2
0.4
0.6
0.8
1
v [c]

Free Neutrons in the Outermost Ejecta

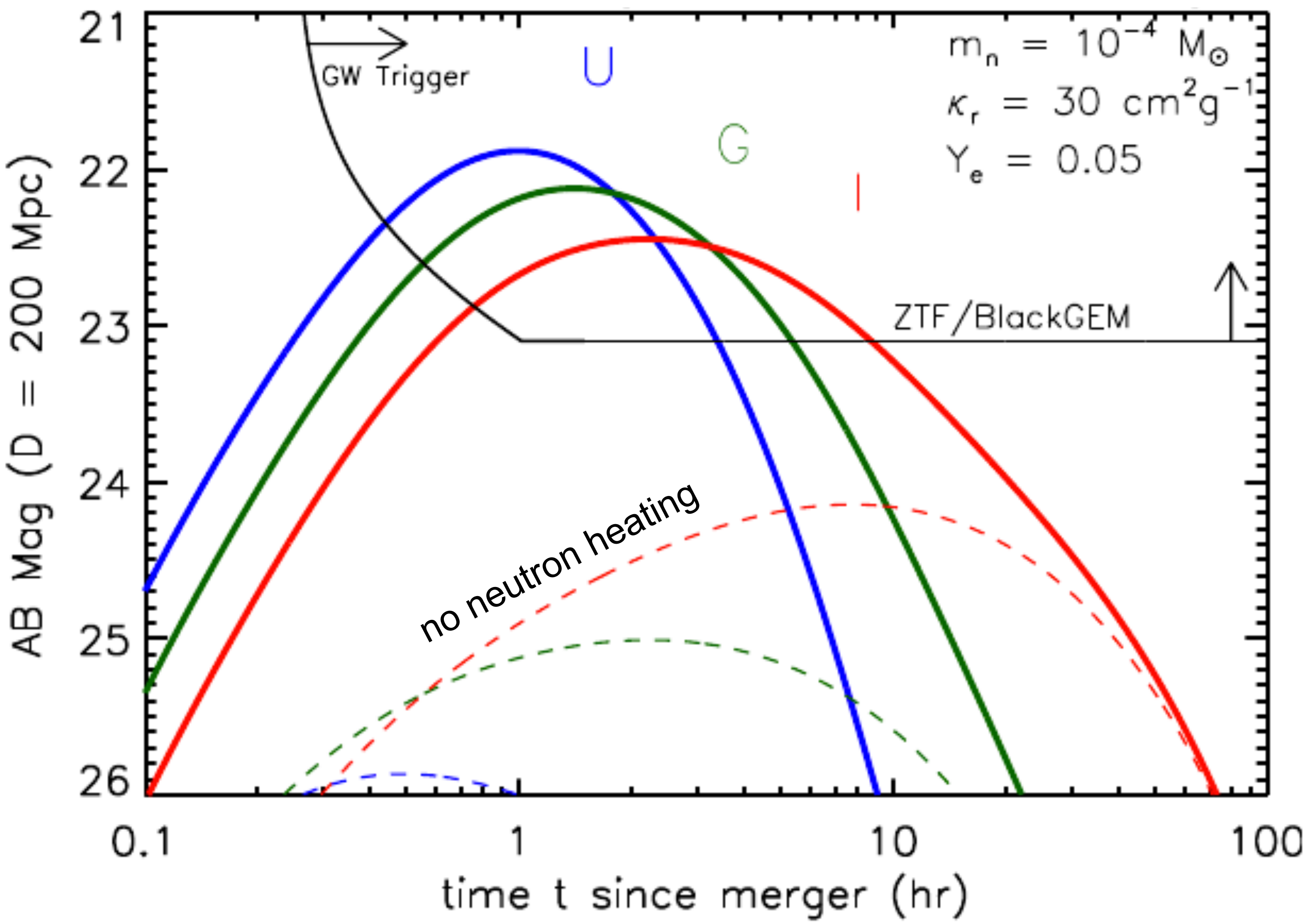




$$t_{\rm d,m} = \left(\frac{3m\kappa}{4\pi\beta v c}\right)^{1/2} \approx 3\,{\rm hr}\left(\frac{m}{10^{-4}M_\odot}\right)^{1/2}\left(\frac{\kappa}{10\,{\rm cm^2\,g^{-1}}}\right)^{1/2}\left(\frac{v}{0.5\,{\rm c}}\right)^{-1/2}$$

Neutron-Powered Precursor

BDM, Bauswein, Goriely, Kasen 2015



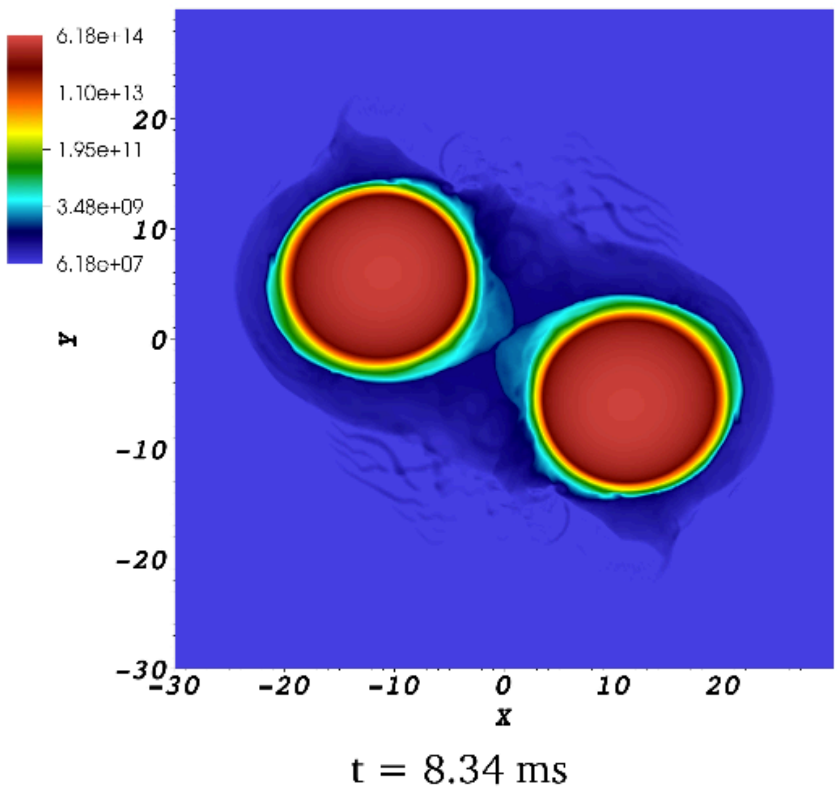
Stable Merger Remnant?

(e.g. BDM+08; Ozel et al. 2010; Bucciantini et al. 2012; Zhang 13; Yu et al. 2013; Giacomazzo & Perna 13; ; Rezzolla & Kumar 15; Ciolffi & Siegel 15)

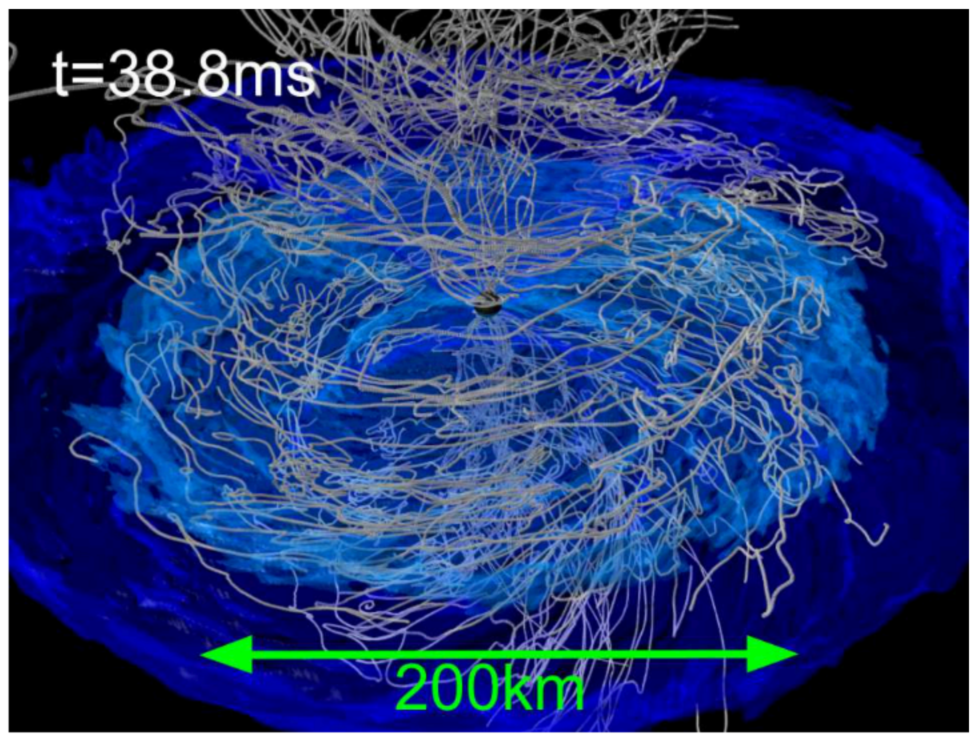
- Requires: low total mass binary, stiff EOS*, and/or mass loss during merger

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

- Remnant rotating at centrifugal break-up limit, spin period P ~ 1 ms
- Magnetic field amplified by rotational energy + convection ⇒ **"Magnetar" ?**

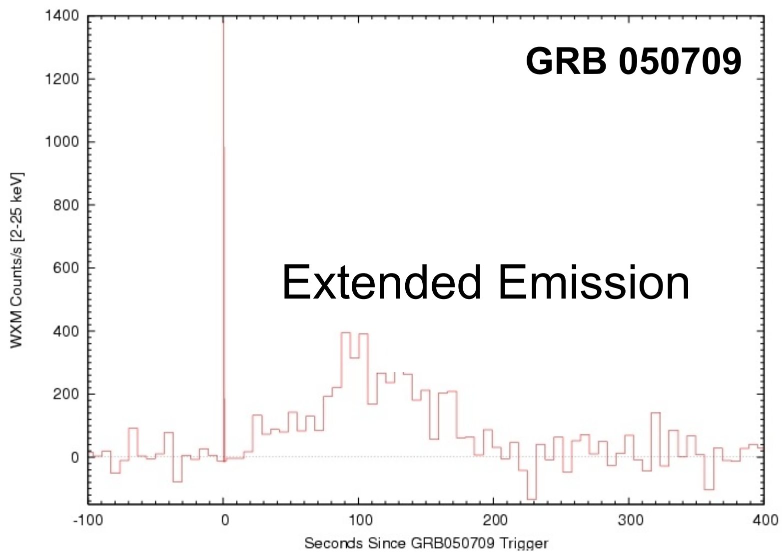


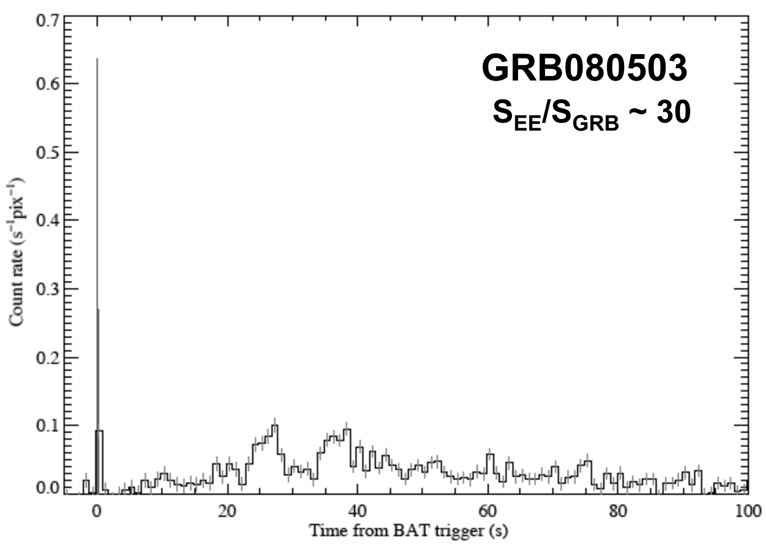
Giacomazzo & Perna 2013



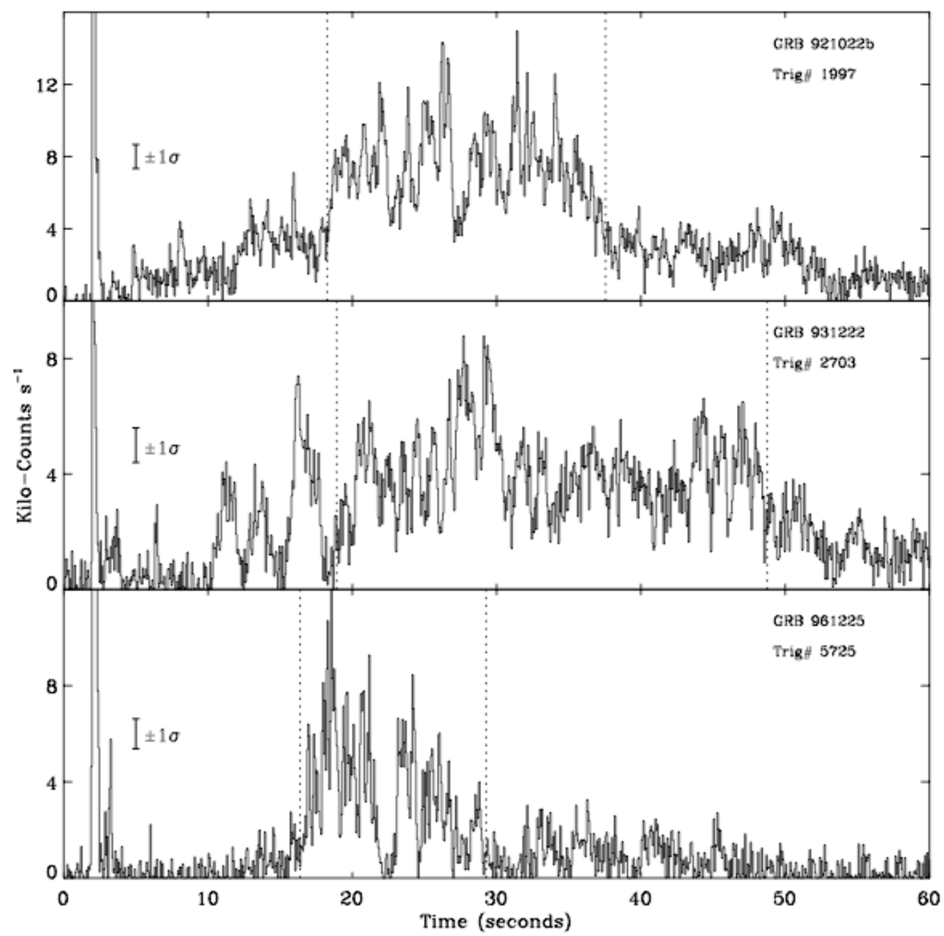
Kiuchi et al. 2014

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!



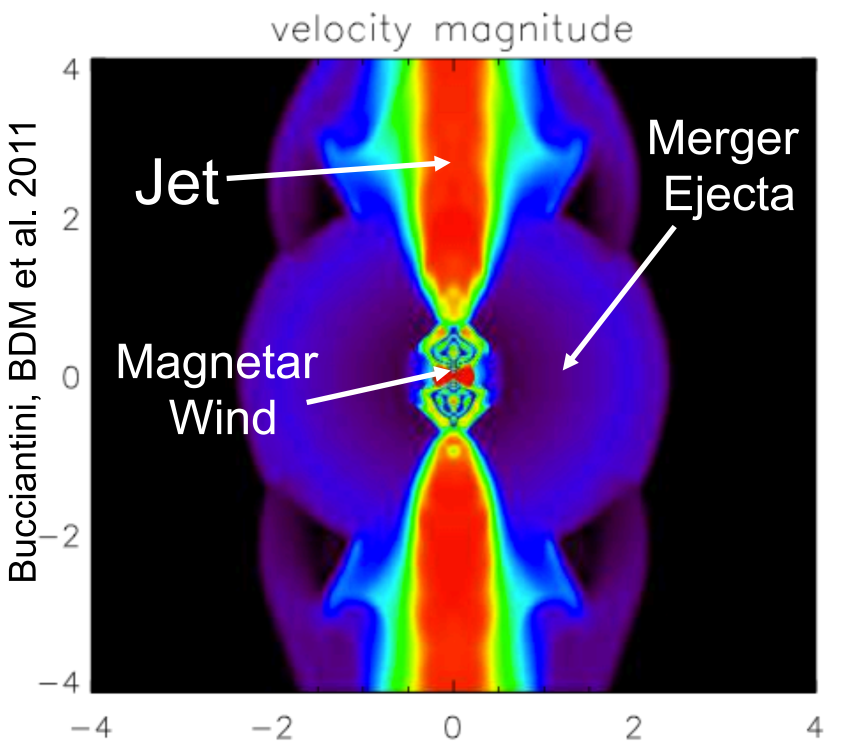
Stable Merger Remnant?

(e.g. BDM+08; Ozel et al. 2010; Bucciantinii+12; Yu+13; Giacomazzo & Perna 13; BDM & Piro 13; Rezzolla & Kumar 15; Ciolffi & Siegel 15)

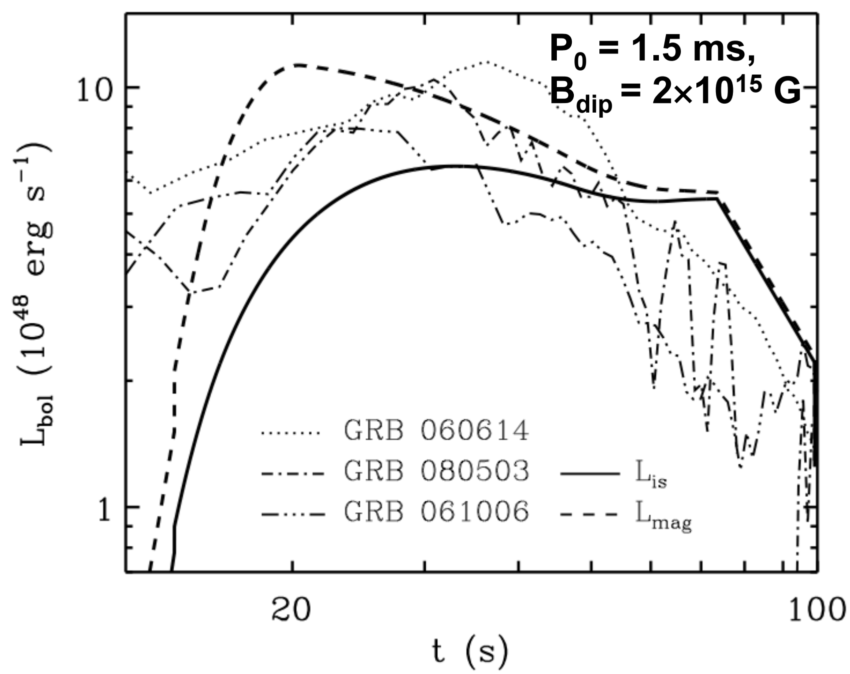
spin-down luminosity $$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{49} \left(\frac{P}{1\ \mathrm{ms}}\right)^{-4} \left(\frac{\mathrm{B_{dip}}}{10^{15}\ \mathrm{G}}\right)^{2} \mathrm{erg\ s^{-1}}$$

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

Magnetar wind confined by merger ejecta

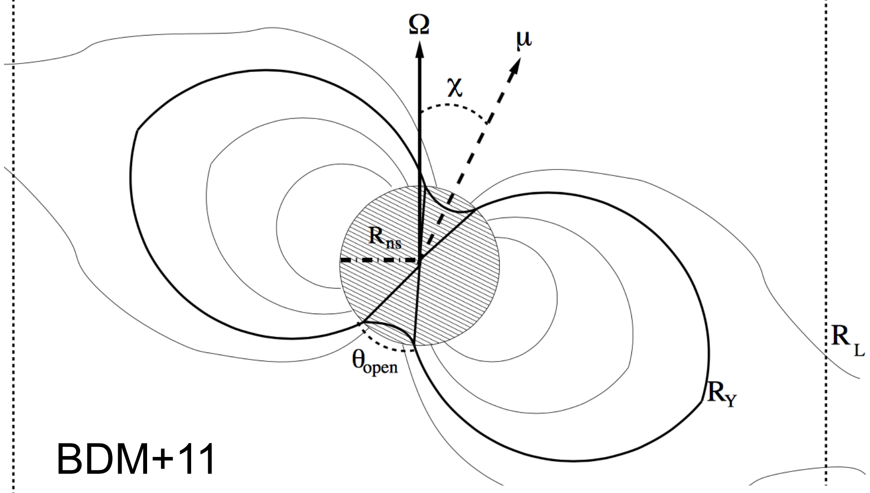


theoretical light curves
vs. observed X-ray emission



Baryon Loading a Game Stopper?

e.g. Murguia-Berthier+14, Fryer+15



BDM+11

$$\Gamma_{max} = L_P / \dot{M}c^2$$

$$\bar{f}_\Phi = R_{ns}/R_L \approx 0.4(R_{ns}/20\,\mathrm{km})(P/\mathrm{ms})^{-1}$$

$$\dot{M} = 2\times 10^{-5} M_\odot\,\mathrm{s}^{-1}\,\frac{f_\Phi}{\bar{f}_\Phi}\left(\frac{L_\nu}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)^{5/3}\left(\frac{\epsilon_\nu}{10\,\mathrm{MeV}}\right)^{10/3}$$

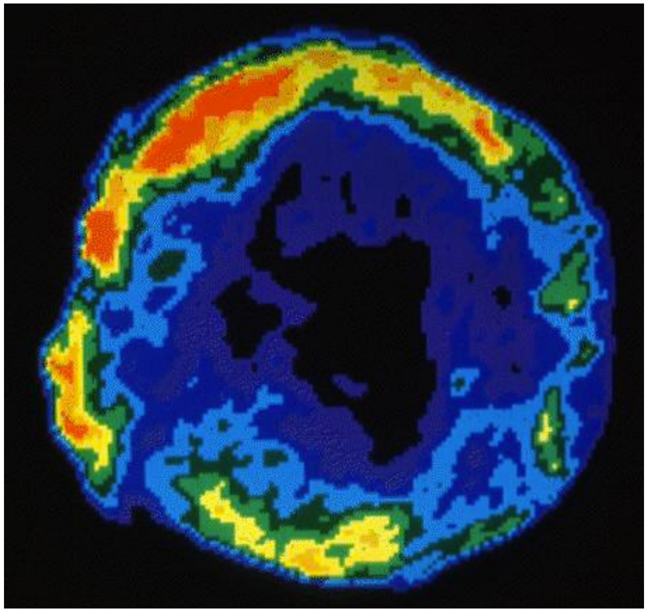
Qian & Woosley 96

$$L_P = \left(\frac{f_\Phi}{\tilde{f}_\Phi}\right)^2 \frac{\mu^2\Omega^4}{c^3} \approx 3\times 10^{51}\left(\frac{f_\Phi}{\tilde{f}_\Phi}\right)^2\left(\frac{B_d}{10^{15}\,\mathrm{G}}\right)^2\left(\frac{P}{\mathrm{ms}}\right)^{-4}\,\mathrm{erg\,s^{-1}}$$

$$\Gamma_{max} = \frac{L_P}{\dot{M}c^2} \approx 100\,\frac{f_\Phi}{\bar{f}_\Phi}\left(\frac{B_d}{10^{15}\,\mathrm{G}}\right)^2\left(\frac{P}{\mathrm{ms}}\right)^{-3}\left(\frac{L_\nu}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)^{-5/3}\left(\frac{\epsilon_\nu}{10\,\mathrm{MeV}}\right)^{-10/3}$$

Radio constraints on stable merger remnants

(BDM & Bower 2013)



- Rotational energy

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

transferred to ISM via relativistic shock
⇒ bright radio emission

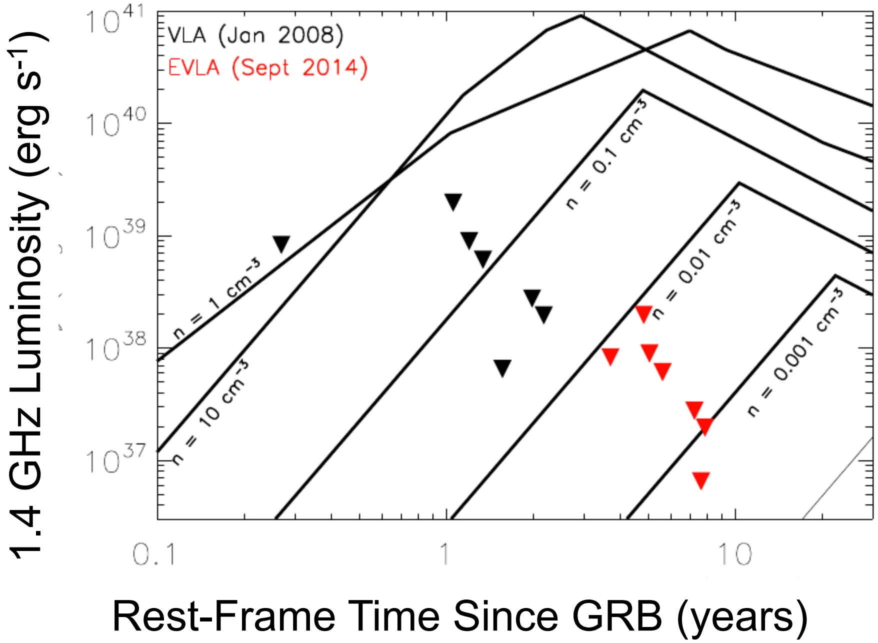
- Observed 7 short GRBs with VLA on timescales ~1-3 years after burst

- NO DETECTIONS
⇒ stable remnant disfavored in 2 GRBs

- Additional JVLA observations **now** much more constraining

- New radio surveys (ASKAP, VLASS, SKA) will tightly constrain birth rate of stable NS merger remnants

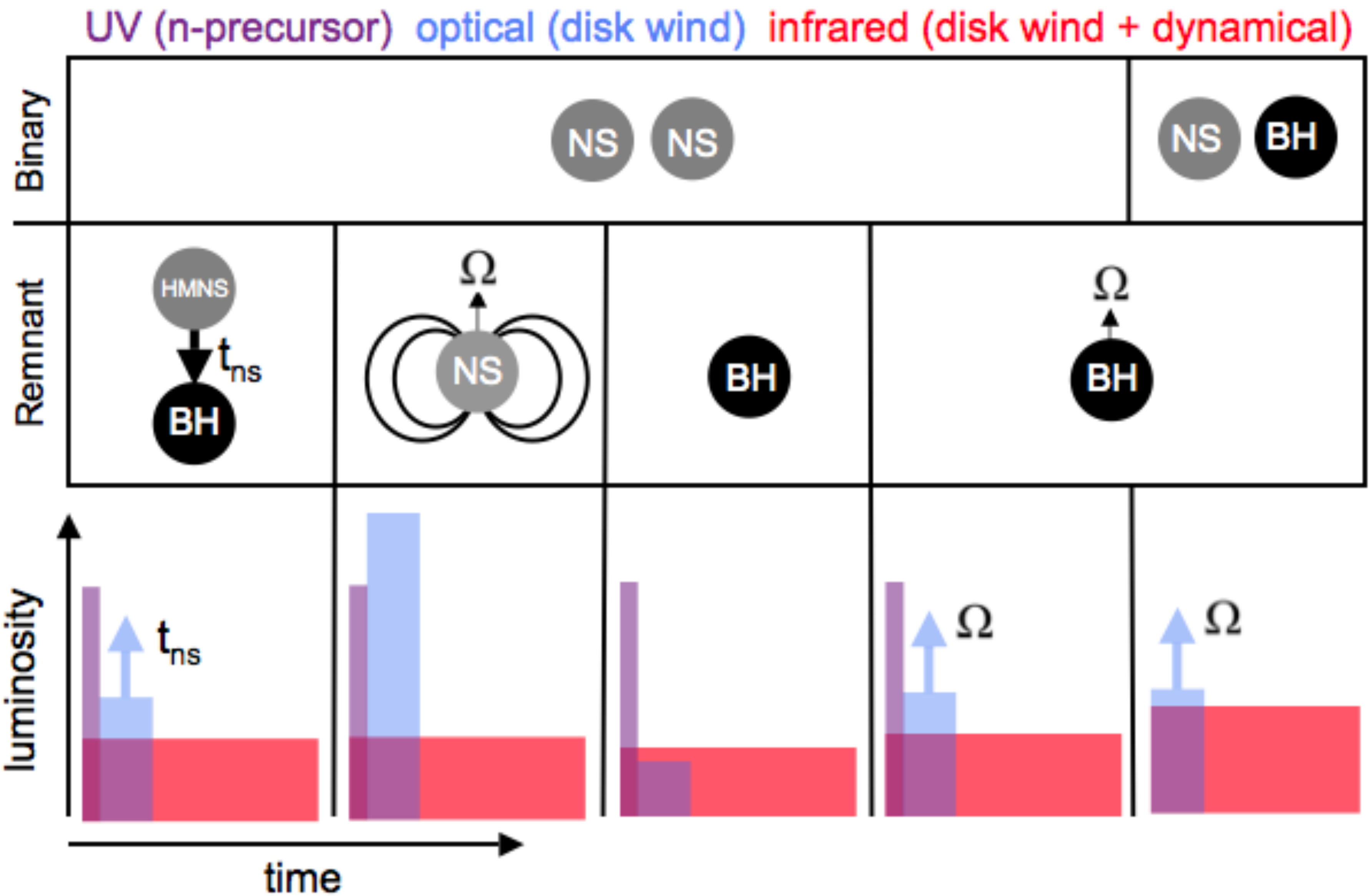
(BDM, Williams, Berger 15).



Timeline of Binary NS Mergers

1.	Chirp enters LIGO Bandpass	t (minus) ~ mins
2.	Precursors (X-ray, coherent radio burst)	t (minus) ~ few s
3.	Last Orbit, Plunge & Dynamical Ejecta	t ~ ms
4.	BH Formation	~ ms - ∞
5.	Accretion of Remnant Disk, Jet Formation (γ-rays)	~ 0.1-1 s
6.	He-Recombination + Disk Evaporation ⇒ outflow Y_e depends on NS collapse time	~ 0.3-3 s
7.	R-Process in Merger Ejecta	~ few s
8.	Jet from Magnetar (X-rays)	~ min (or longer)
9.	Neutron Precursor (Optical/UV, $L \sim 10^{41}$ erg s^{-1})	~ hours
10.	Kilonova ⟹ prompt BH formation $Y_e < 0.25$ (NIR, $L \sim 10^{41}$ erg s^{-1}) ⟹ delayed BH formation $Y_e > 0.25$ (Optical, $L \sim 10^{40-41}$ erg s^{-1}) ⟹ stable magnetar (Optical, $L \sim 10^{44}$ erg s^{-1})	 ~ week ~ day ~ day
11.	Ejecta ISM Interaction (**Radio,** much brighter if stable NS)	~ years

Kasen, Fernandez, Metzger, submitted



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.