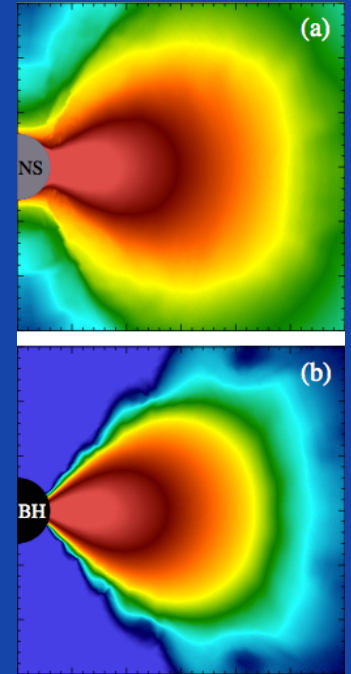
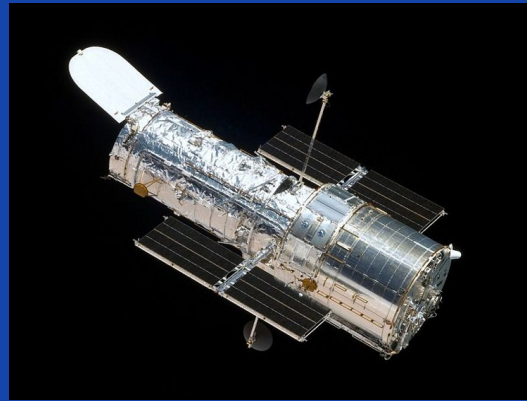
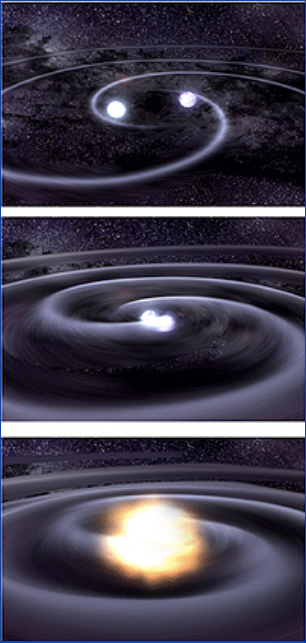


Discovering the Electromagnetic Counterparts of Binary Neutron Star Mergers with WFIRST



Brian Metzger
Columbia University

Rodrigo Fernandez, Dan Kasen, Eliot Quataert (UC Berkeley)

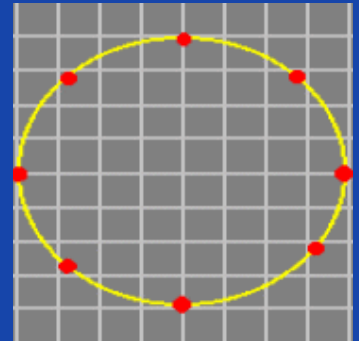
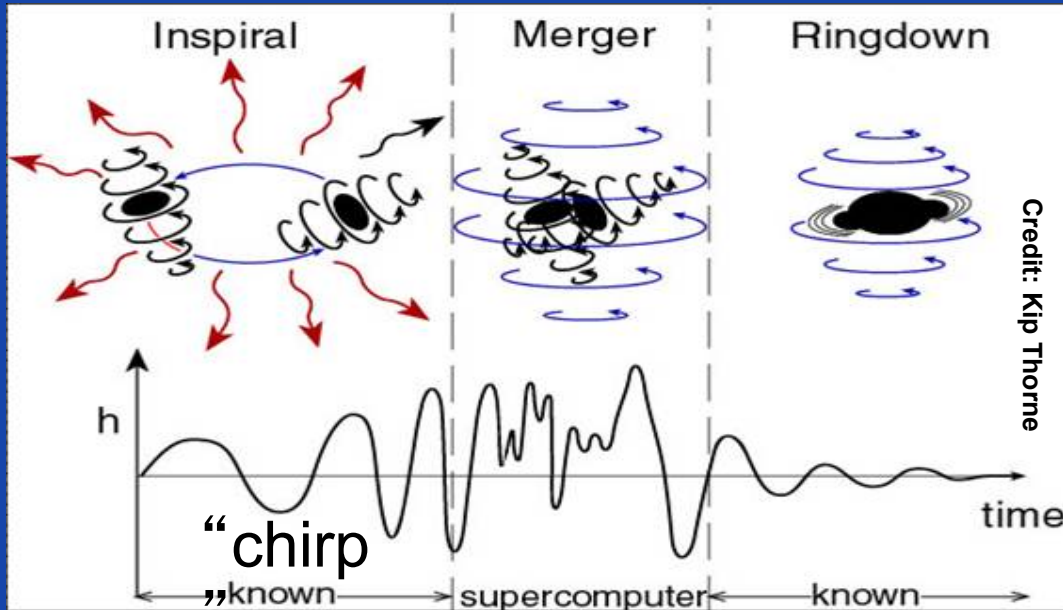
Edo Berger, Wen-Fai Fong (Harvard), Tony Piro (Caltech)

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

Andreas Bauswein (U Thessaloniki), Stephane Goriely (U Brussels)

WFIRST: Science and Techniques, Pasadena, November 17, 2014

Gravitational Waves from Binary NS Mergers



Ground 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

Example: Origin of R-Process Nuclei

Origin Legend																			
Big Bang	Supernovae	Small Stars																	
Large Stars	Cosmic Rays																		
H															He				
Li	Be													B	C	N	O	F	Ne
Na	Mg													Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
Cs	Ba	Hf		Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
Fr	Ra																		
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr			

Core Collapse Supernovae or NS Binary Mergers?

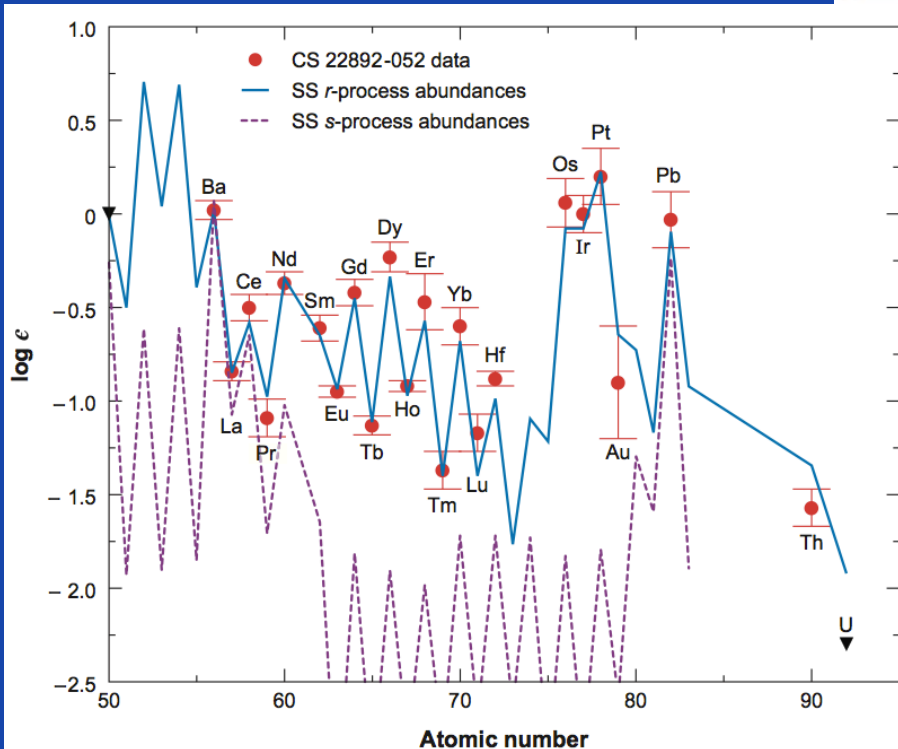
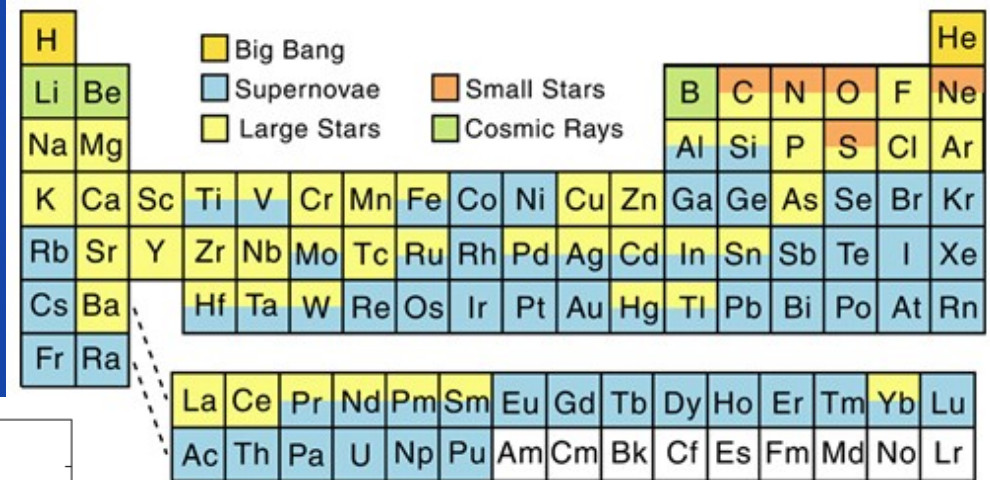
Origin of R-Process Nuclei

Core Collapse Supernovae or NS Binary Mergers?

Galactic r-process rate:

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

(Qian 2000)



fraction of r-process from NS mergers:

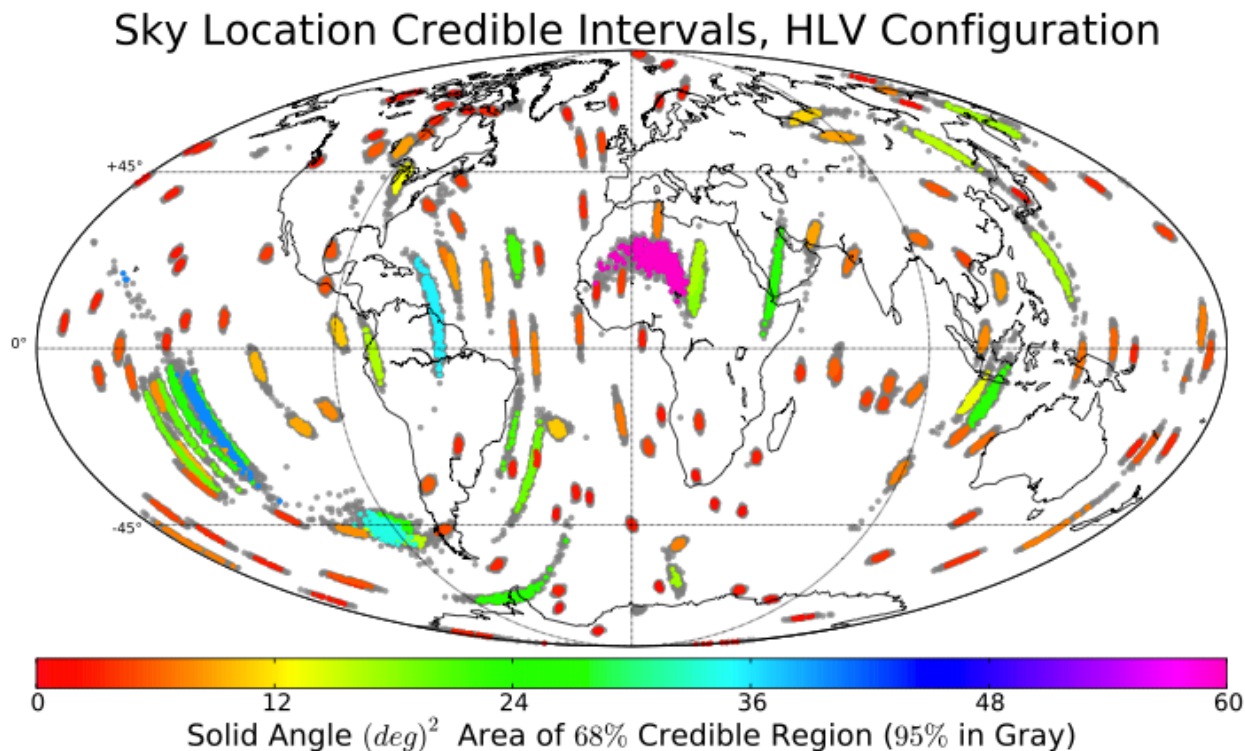
$$f_R \sim \left(\frac{\dot{N}_{\text{merge}}}{10^{-4} \text{ yr}^{-1}} \right) \left(\frac{\overline{M}_{\text{ej}}}{10^{-2} M_{\odot}} \right)$$

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

Sky Error Regions $\sim 10\text{-}100 \text{ deg}^2$ (~ 2019)

Rodriguez et al. 2014

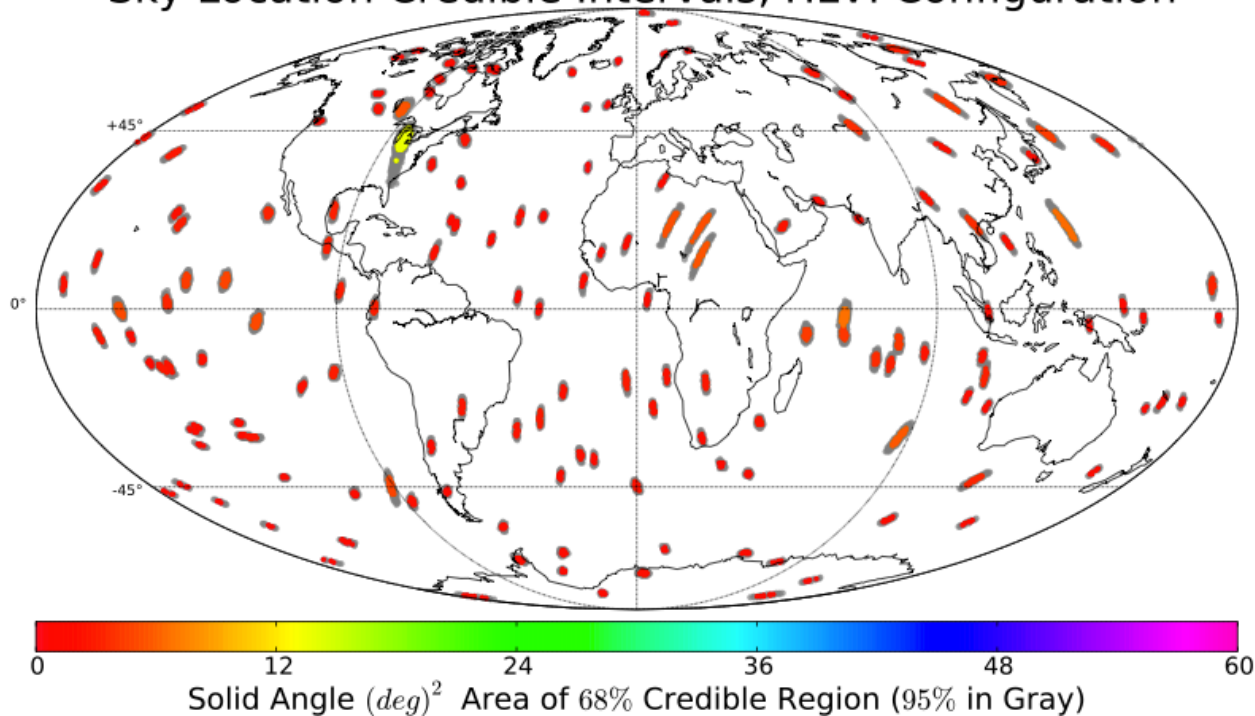


Importance of EM Detection:

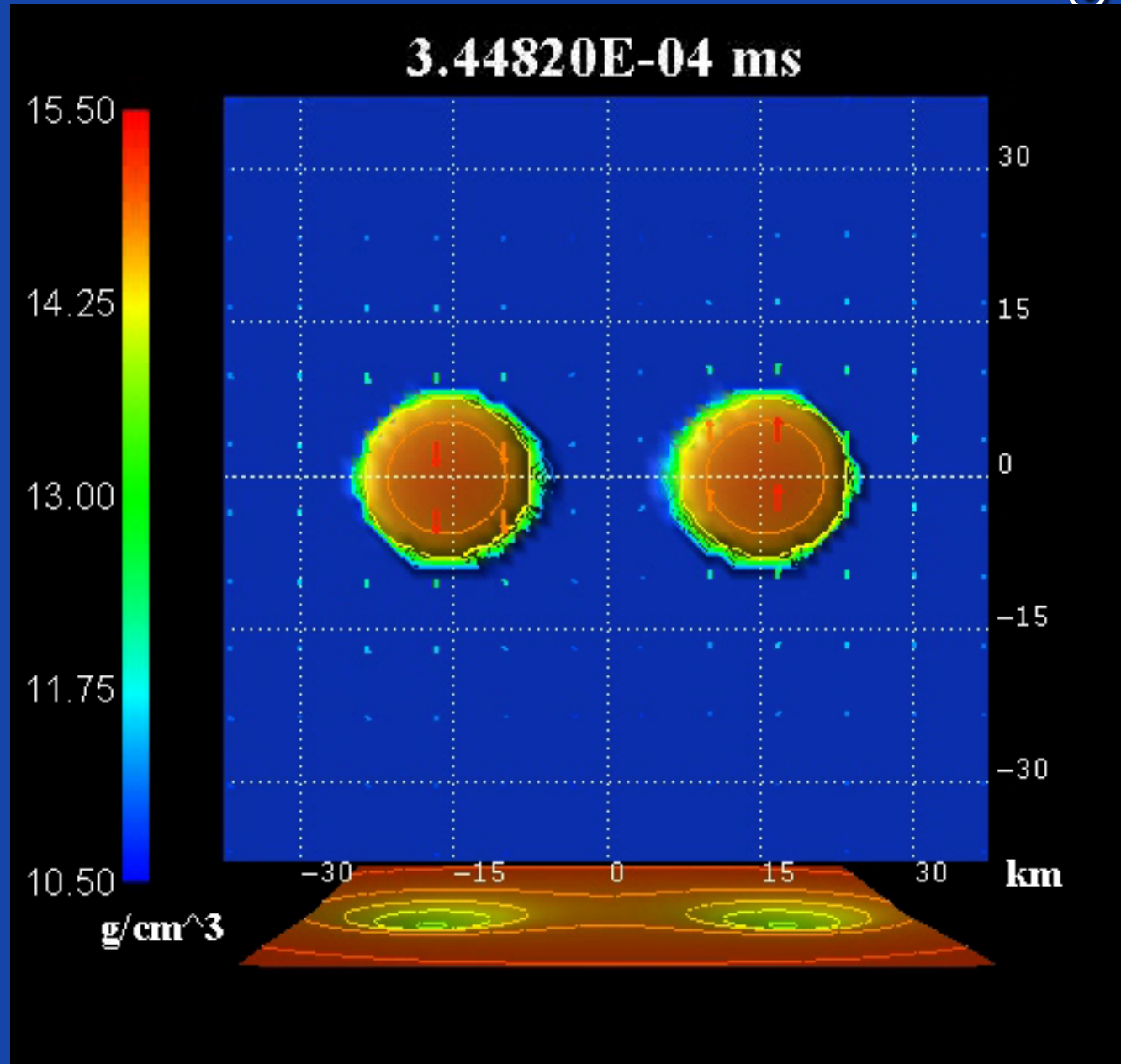
- ◆ Improve “confidence” in GW detection; dig deeper into GW data
- ◆ Independently constrain binary parameters
- ◆ Astrophysical context (e.g. host Galaxy & environment)
- ◆ Cosmology (e.g. H_0 , w); test strong-field GR; constrain neutron star EOS

Sky Error Regions ~ 10 deg² (~2022)

Sky Location Credible Intervals, HLVI Configuration

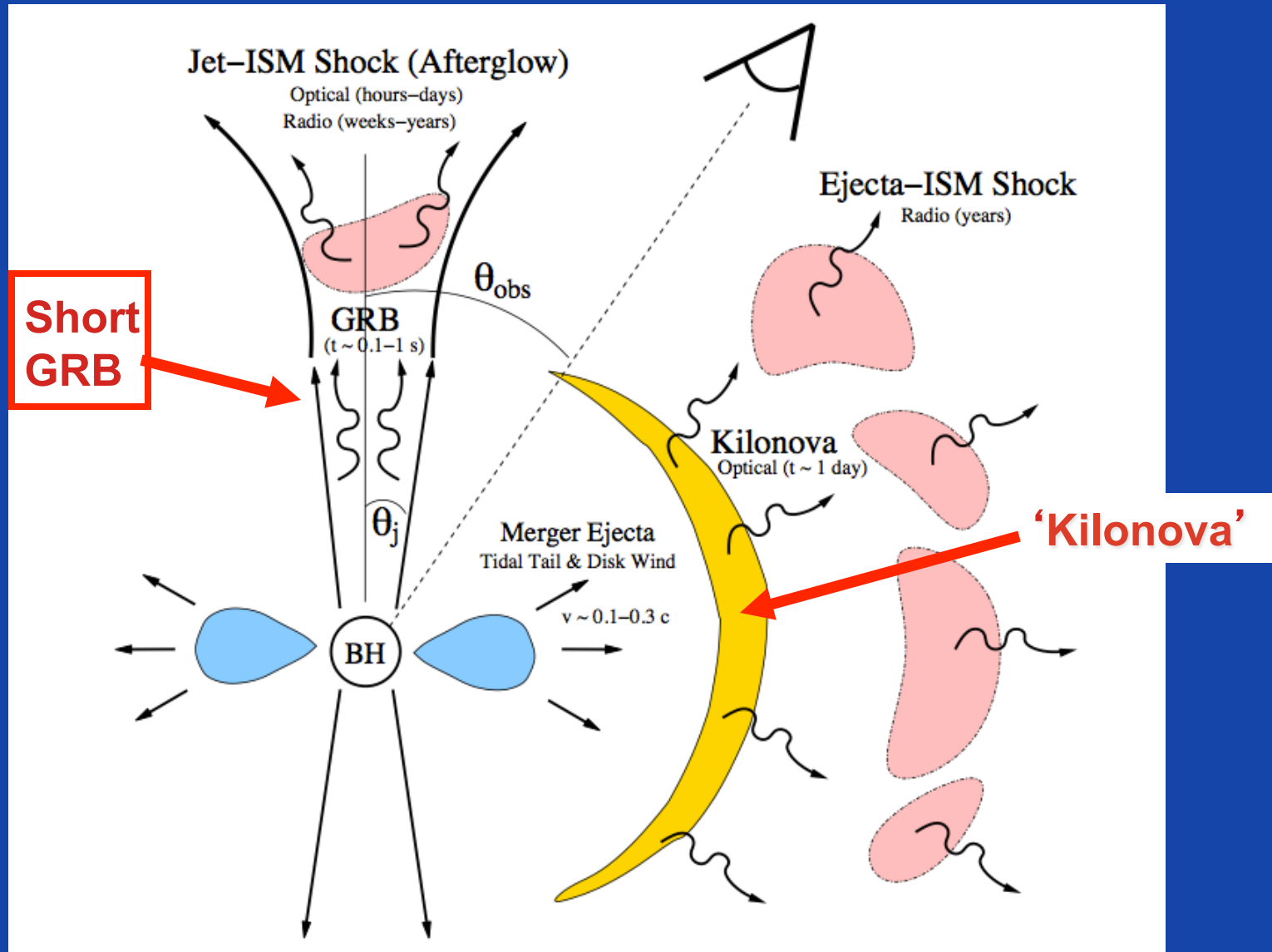


Numerical Simulation - Two $1.4 M_{\odot}$ NSs

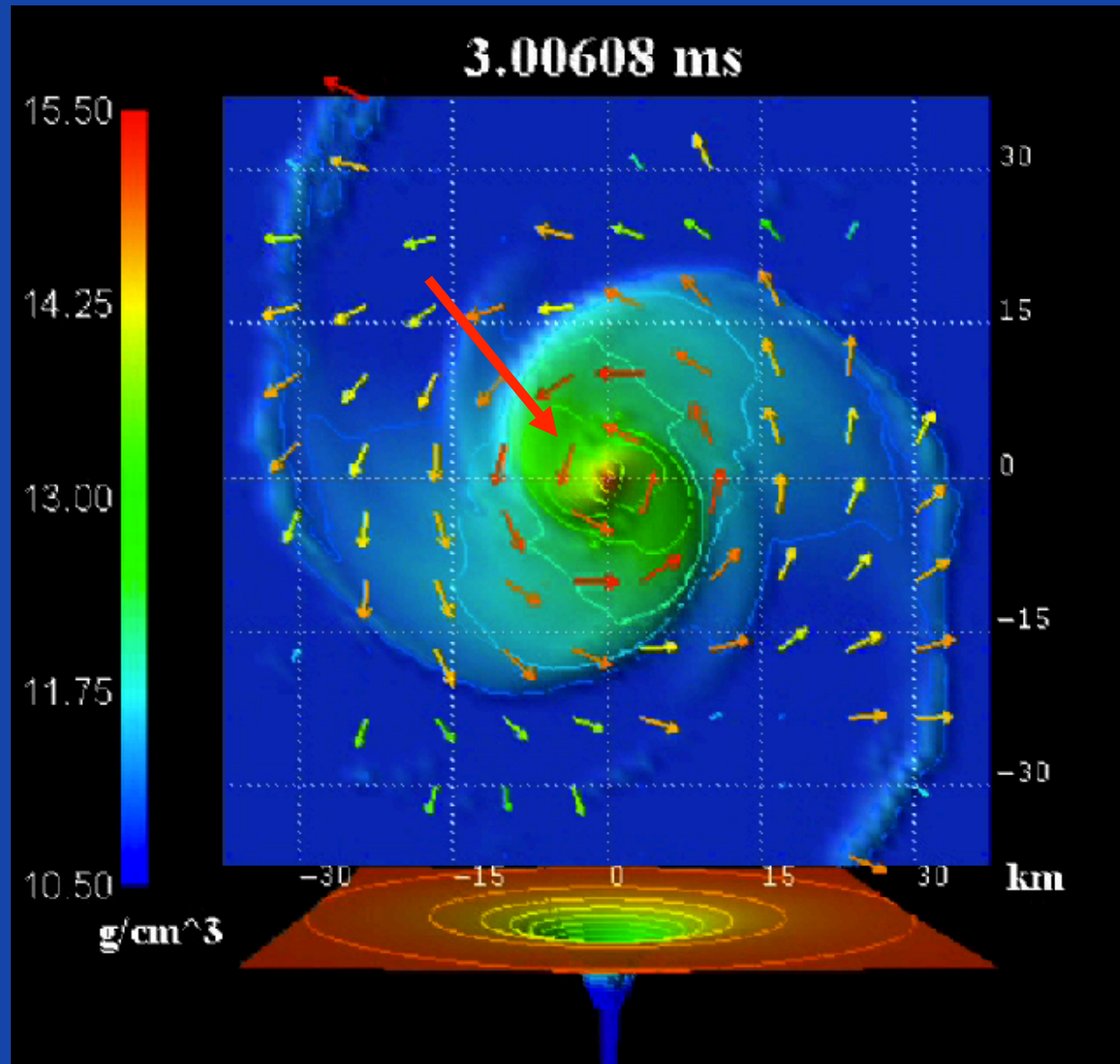


Courtesy M. Shibata (Kyoto)

Electromagnetic Counterparts of NS-NS/NS-BH Mergers

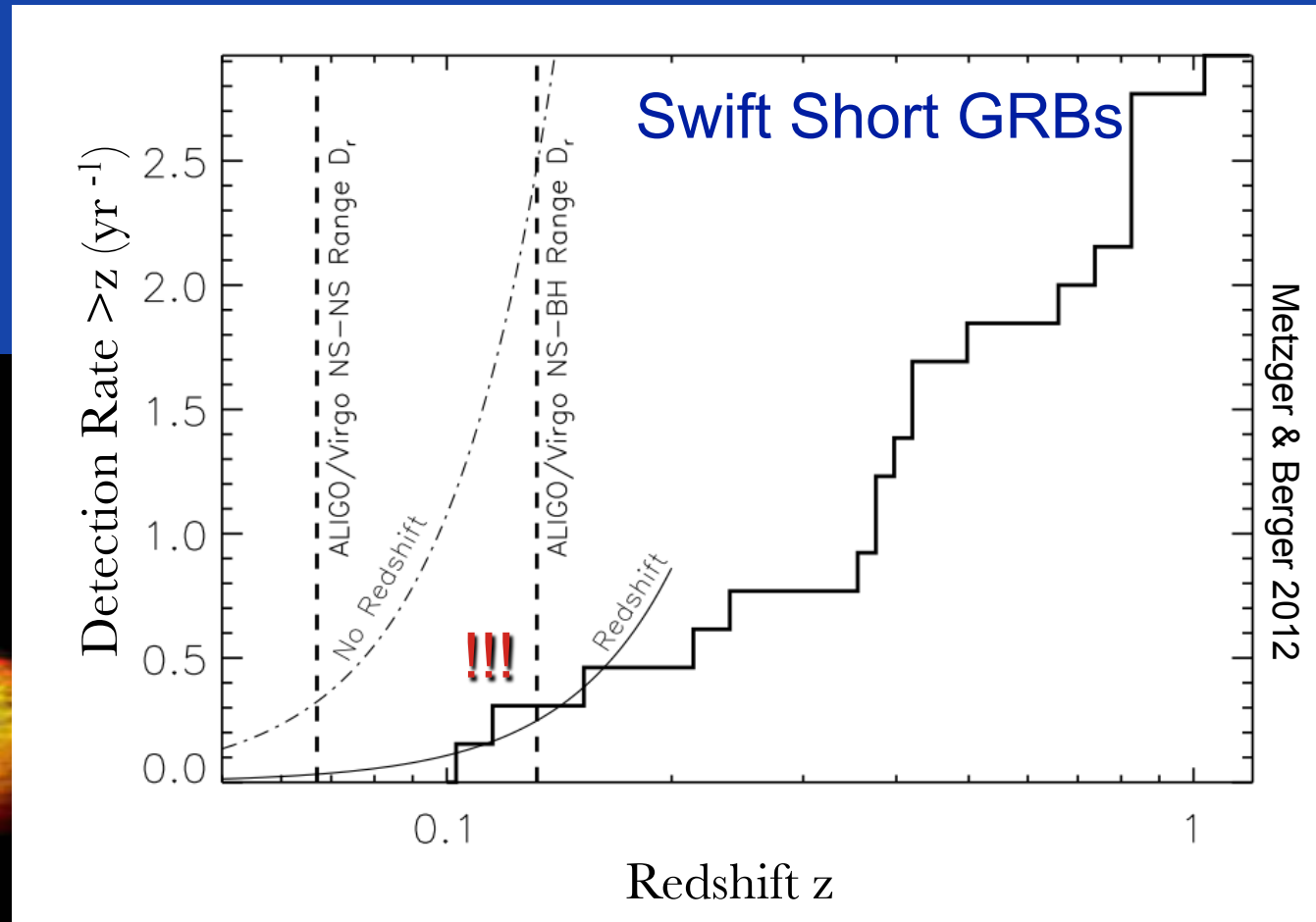
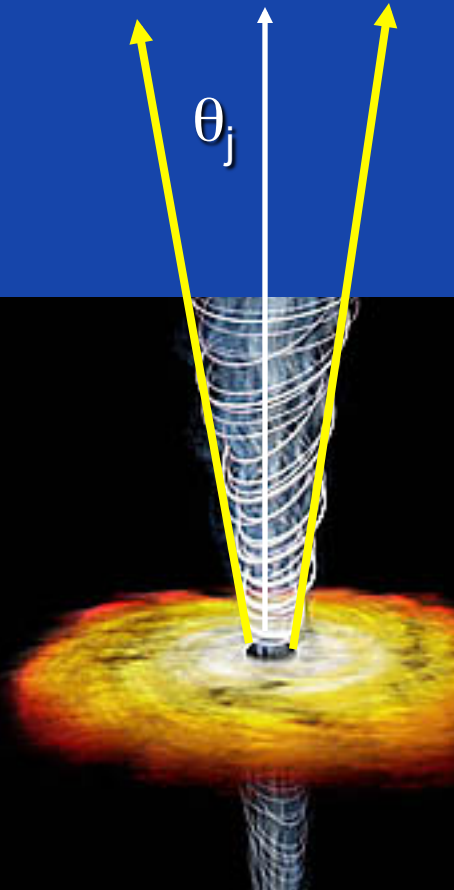


Numerical Simulation - Two $1.4 M_{\odot}$ NSs



Courtesy M. Shibata (Kyoto)

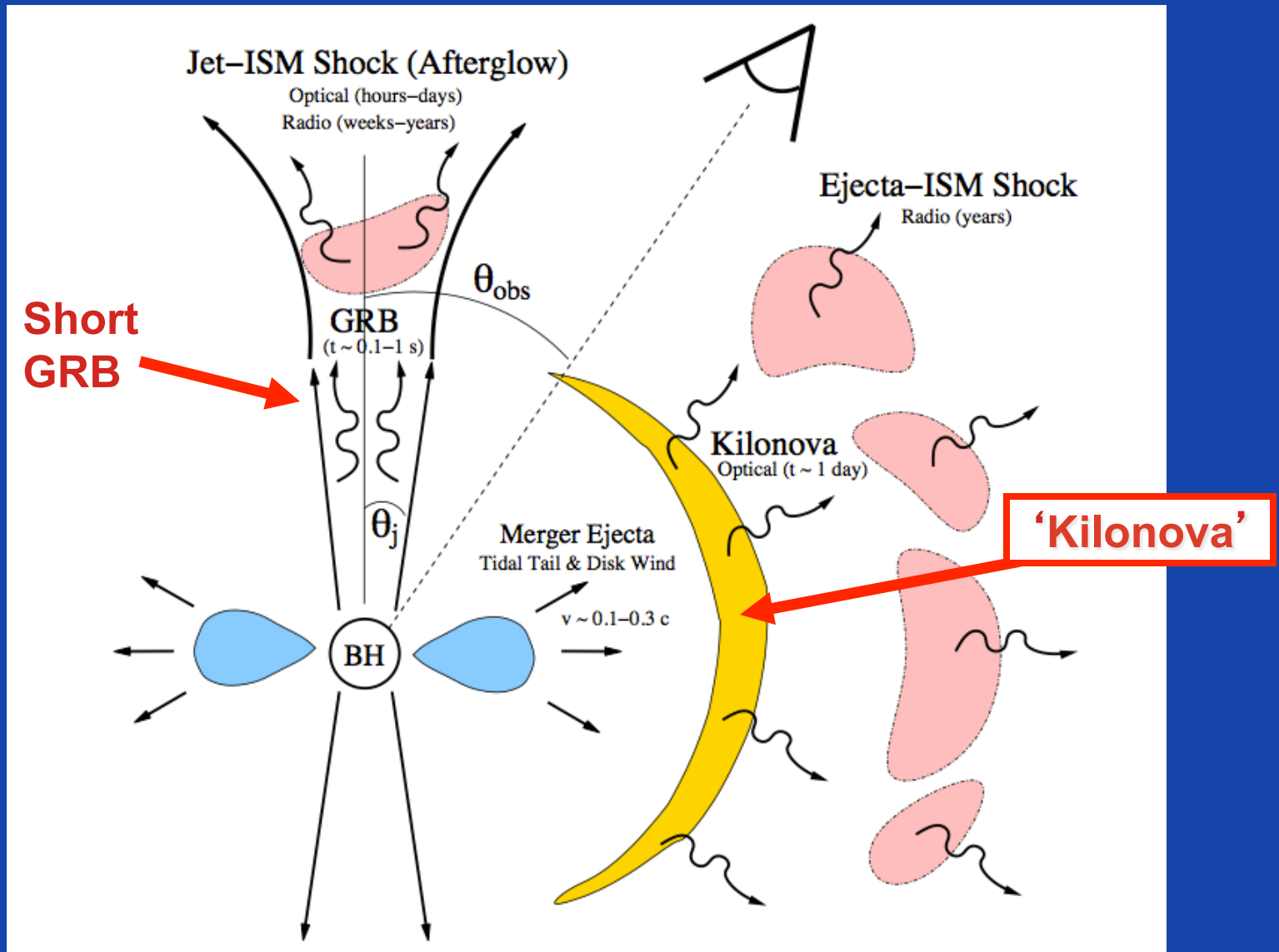
Short GRBs are Rare in the LIGO Volume

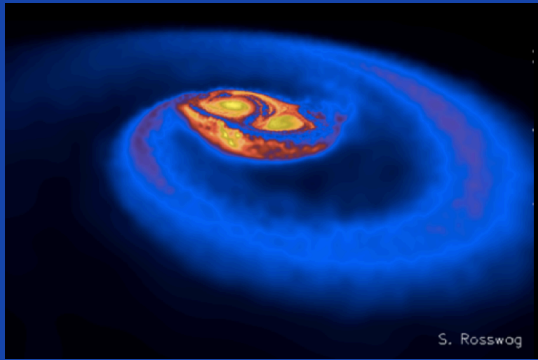


Detectable fraction by all sky γ -ray telescope

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

Electromagnetic Counterparts of NS-NS/NS-BH Mergers





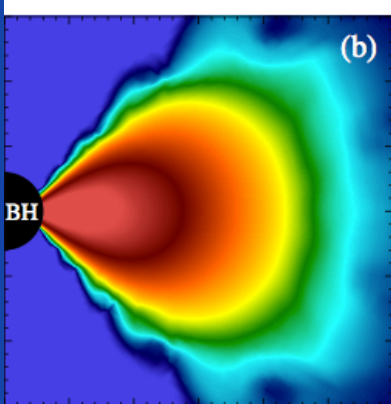
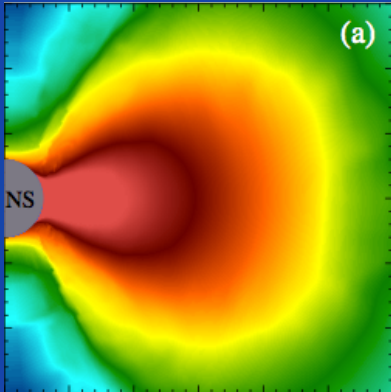
Dynamical Tidal Tails

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

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

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, 14)

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

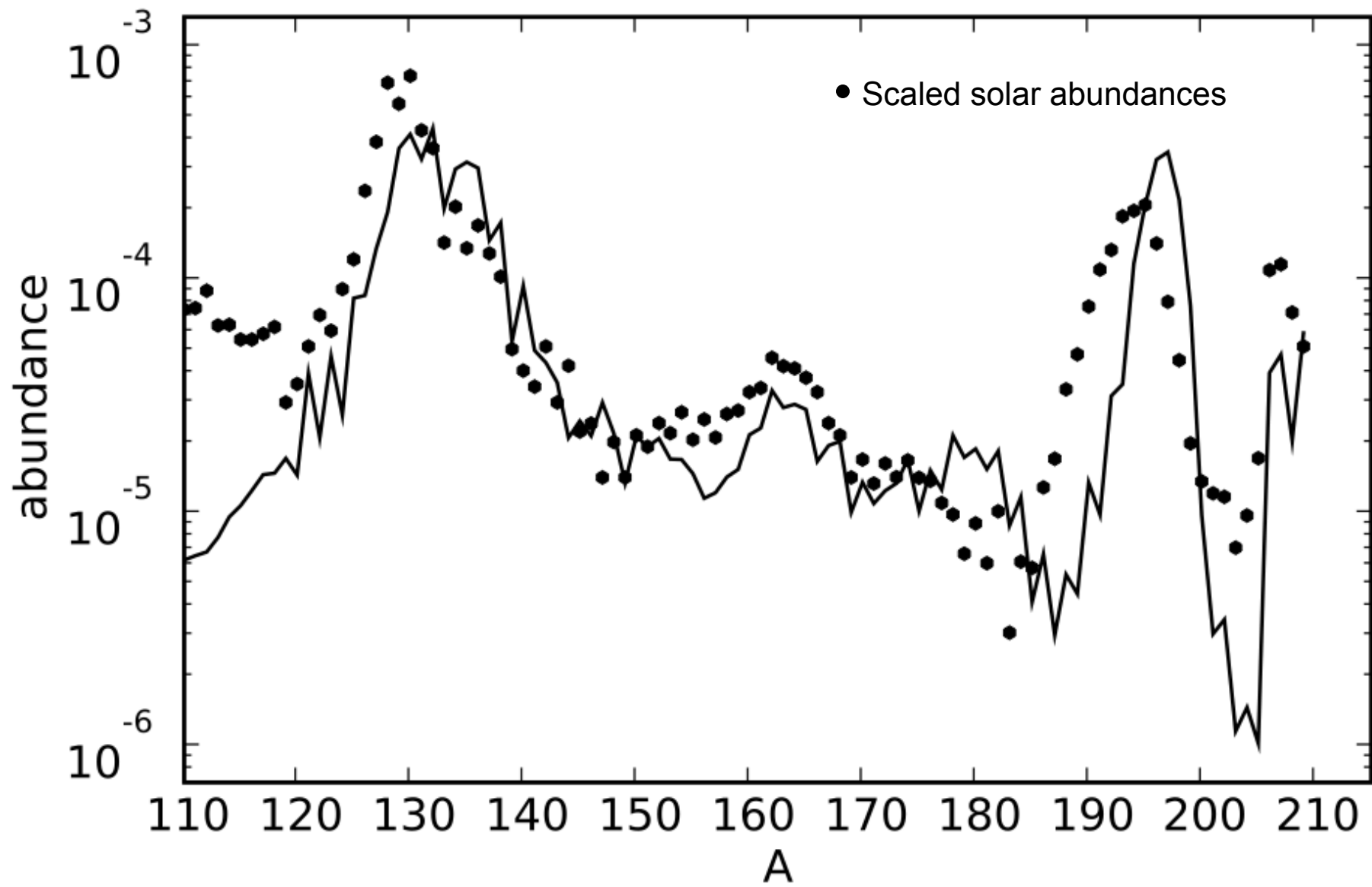
Metzger & Fernandez 2014

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



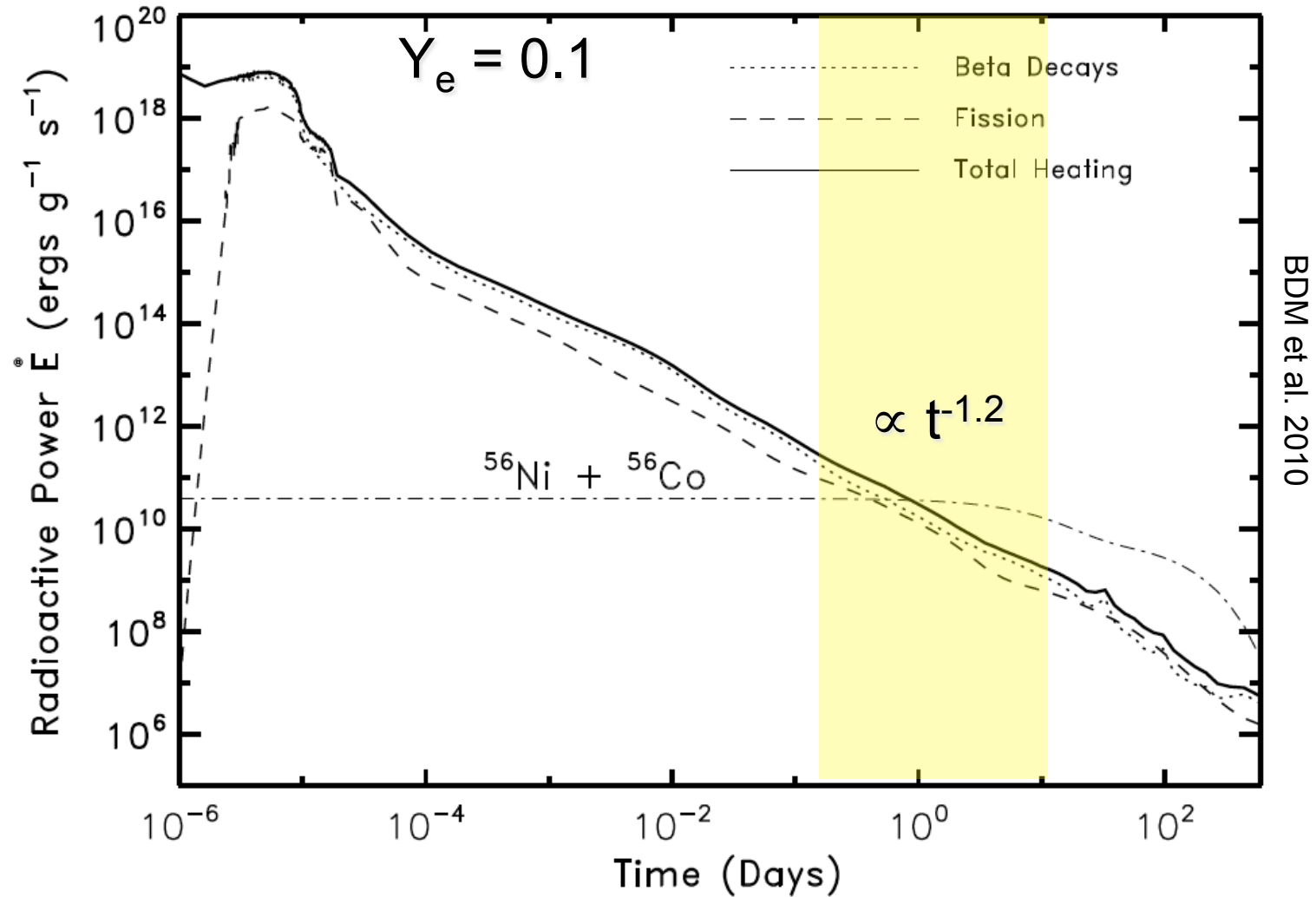
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

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)

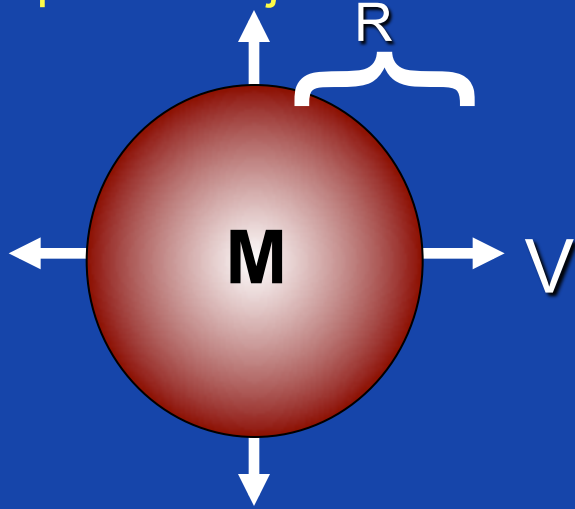


Dominant β -decays at 1 day: $^{132,134,135}\text{I}$, $^{128,129}\text{Sb}$, ^{129}Te , ^{135}Xe

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 $E = f M c^2$, & opacity κ



$$R = v t \quad \rho = \frac{M}{4\pi/3 R^3}$$

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

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

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

Type Ia Supernova:

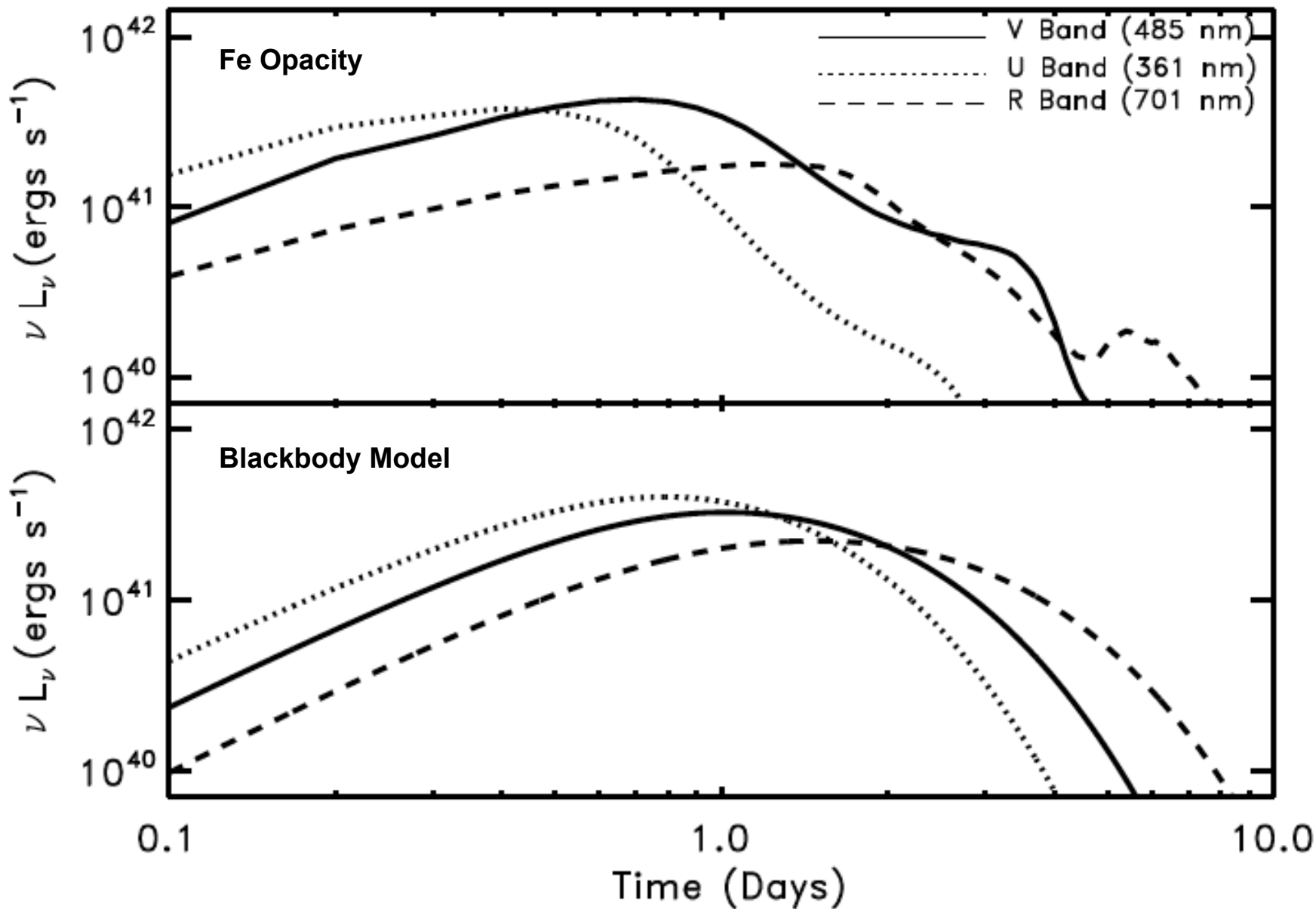
$$v \sim 10^4 \text{ km s}^{-1}, M_{\text{ej}} \sim M_{\odot}, f_{\text{Ni} \rightarrow \text{Co}} \sim 10^{-5} \Rightarrow t_{\text{peak}} \sim \text{week}, L \sim 10^{43} \text{ erg s}^{-1}$$

NS Merger:

$$v \sim 0.1 c, M_{\text{ej}} \sim 10^{-2} M_{\odot}, f \sim 10^{-6} \Rightarrow t_{\text{peak}} \sim 1 \text{ day}, L \sim 3 \cdot 10^{41} \text{ erg s}^{-1}$$

“Kilo”-nova Light Curves

Metzger et al. (2010)



High Opacity of the Lanthanides

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

s-shell (g=2)

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

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

p-shell (g=6)

d-shell (g=10)

hydrogen 1 H 1.0079																			helium 2 He 4.0026						
lithium 3 Li 6.941	beryllium 4 Be 9.0122																			boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305																			aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80								
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29								
caesium 55 Cs 132.91	barium 56 Ba 137.33	lanthanum 57 La 138.91	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]								
francium 87 Fr [223]	radium 88 Ra [226]	actinium 89 Ac [227]	lutetium 71 Lu 174.97	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]									

* Lanthanide series

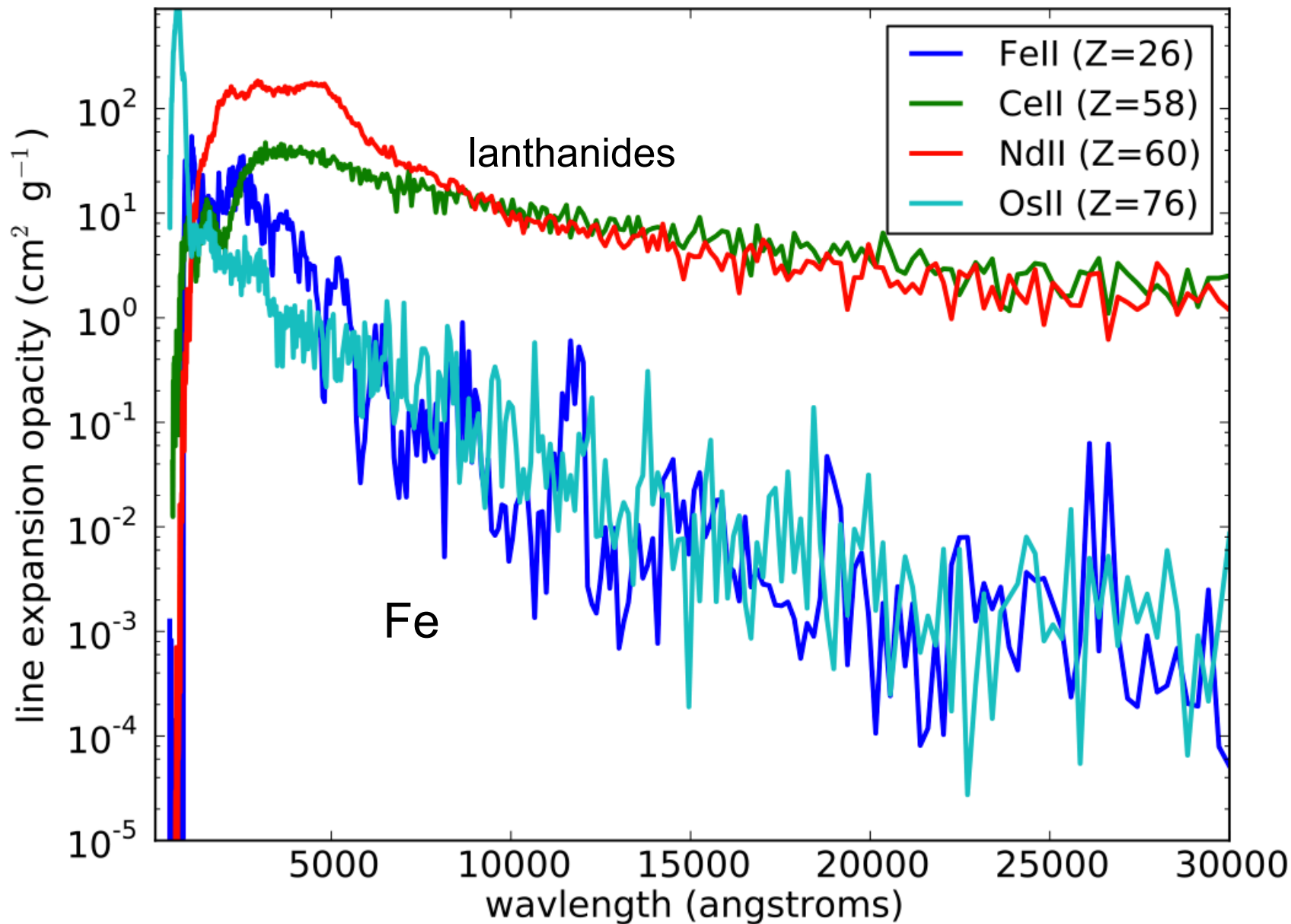
** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

f-shell
(g=14)

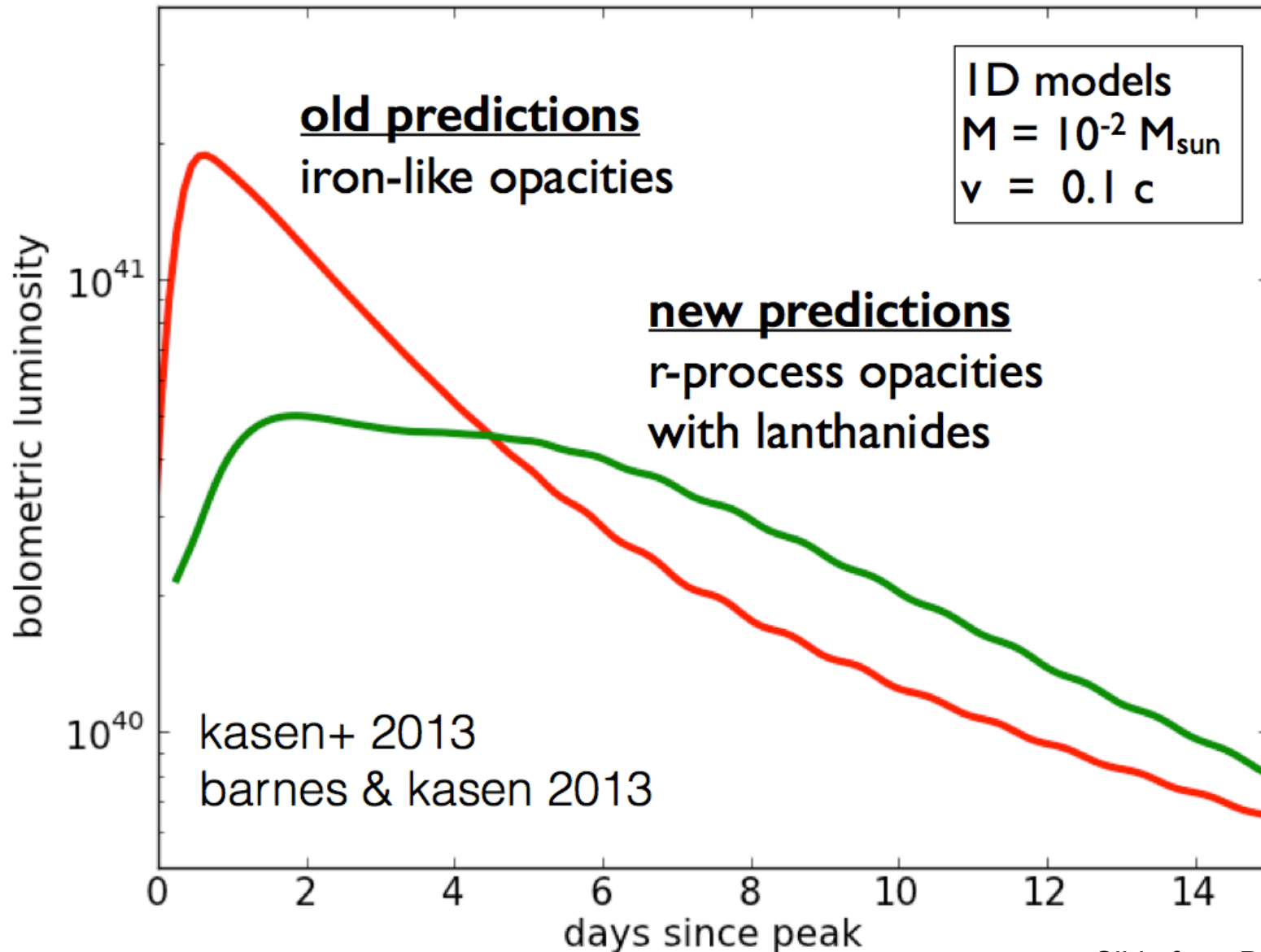
High Opacity of the Lanthanides

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



light curves of radioactive transients

effect of high lanthanide opacity



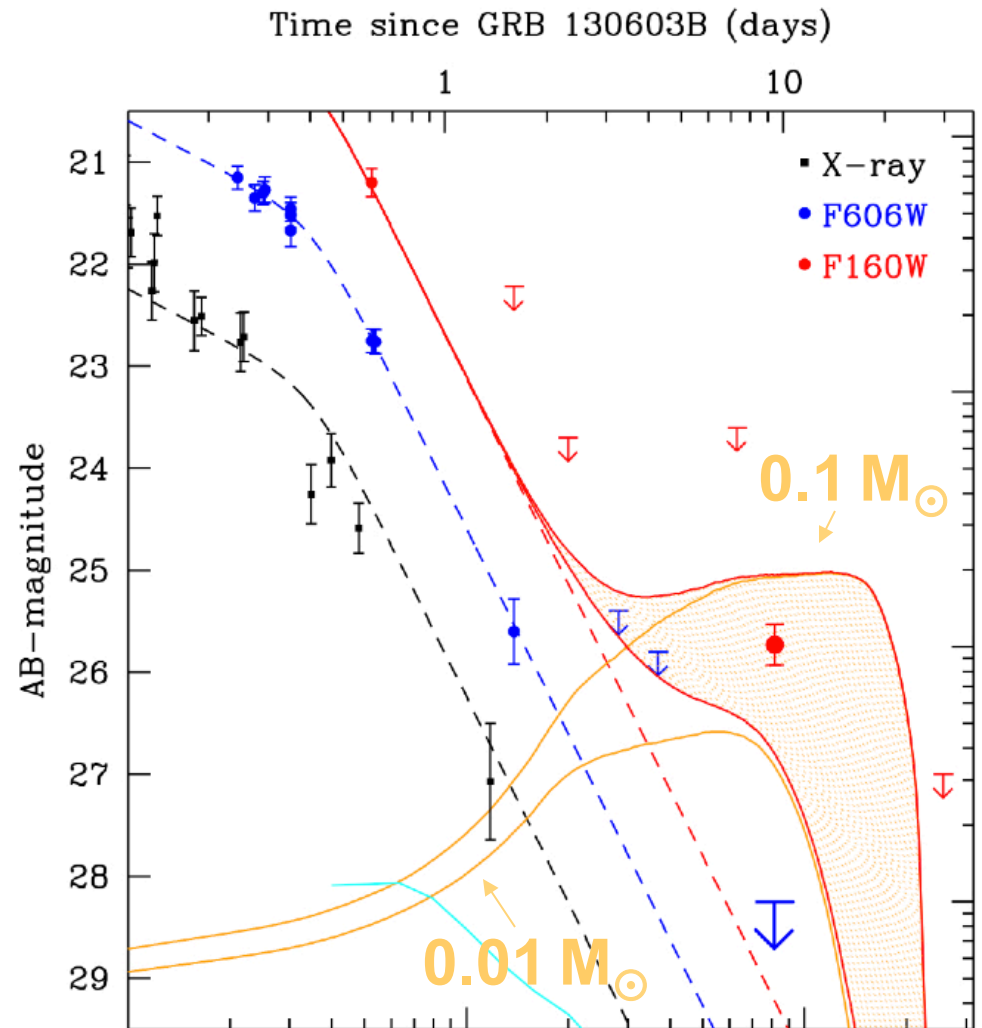
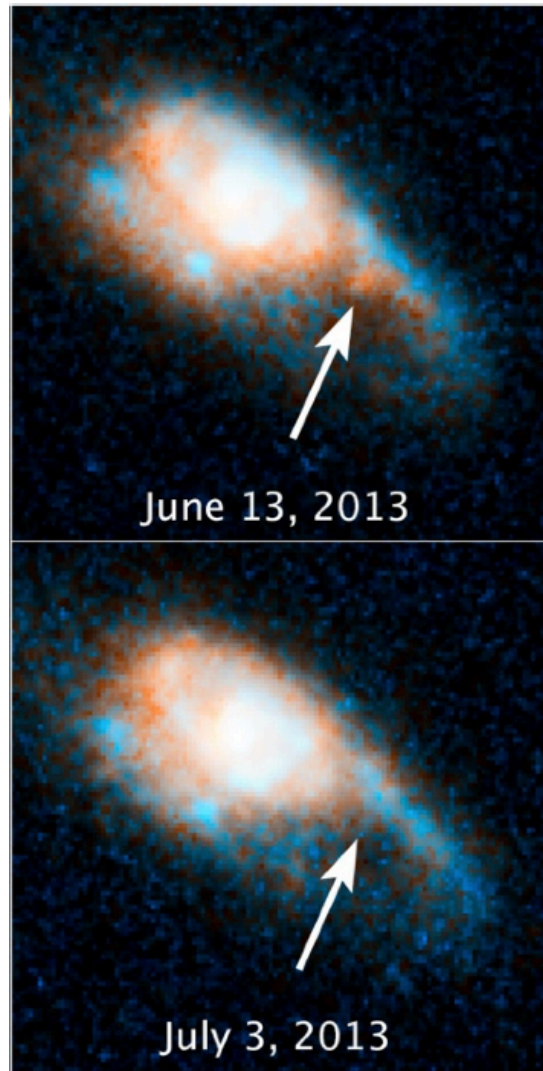
AN R-PROCESS KILONOVA ASSOCIATED WITH THE SHORT-HARD GRB 130603B

E. BERGER¹, W. FONG¹, AND R. CHORNOCK¹

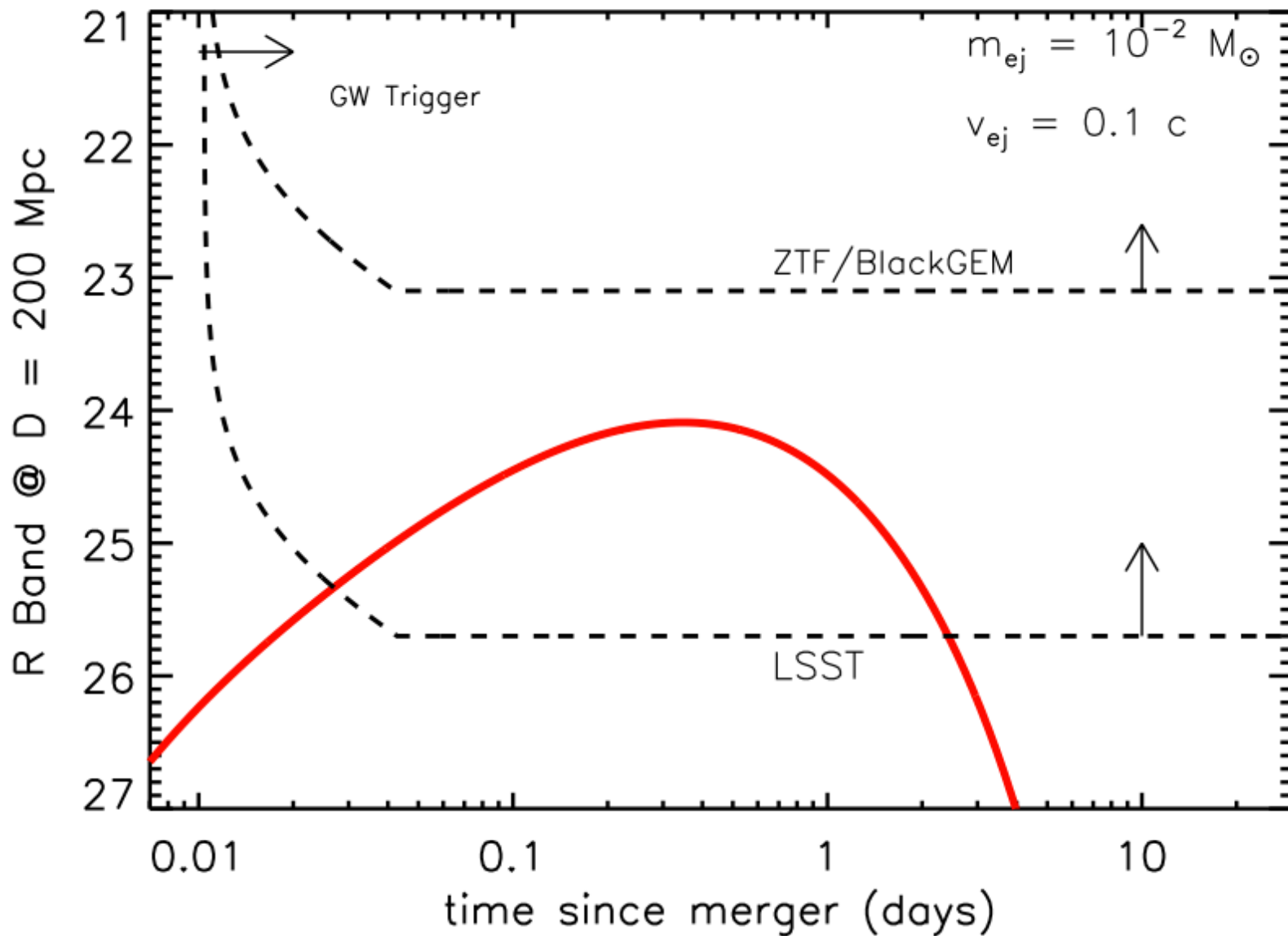
A 'kilonova' associated with the short-duration γ -ray burst GRB 130603B

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

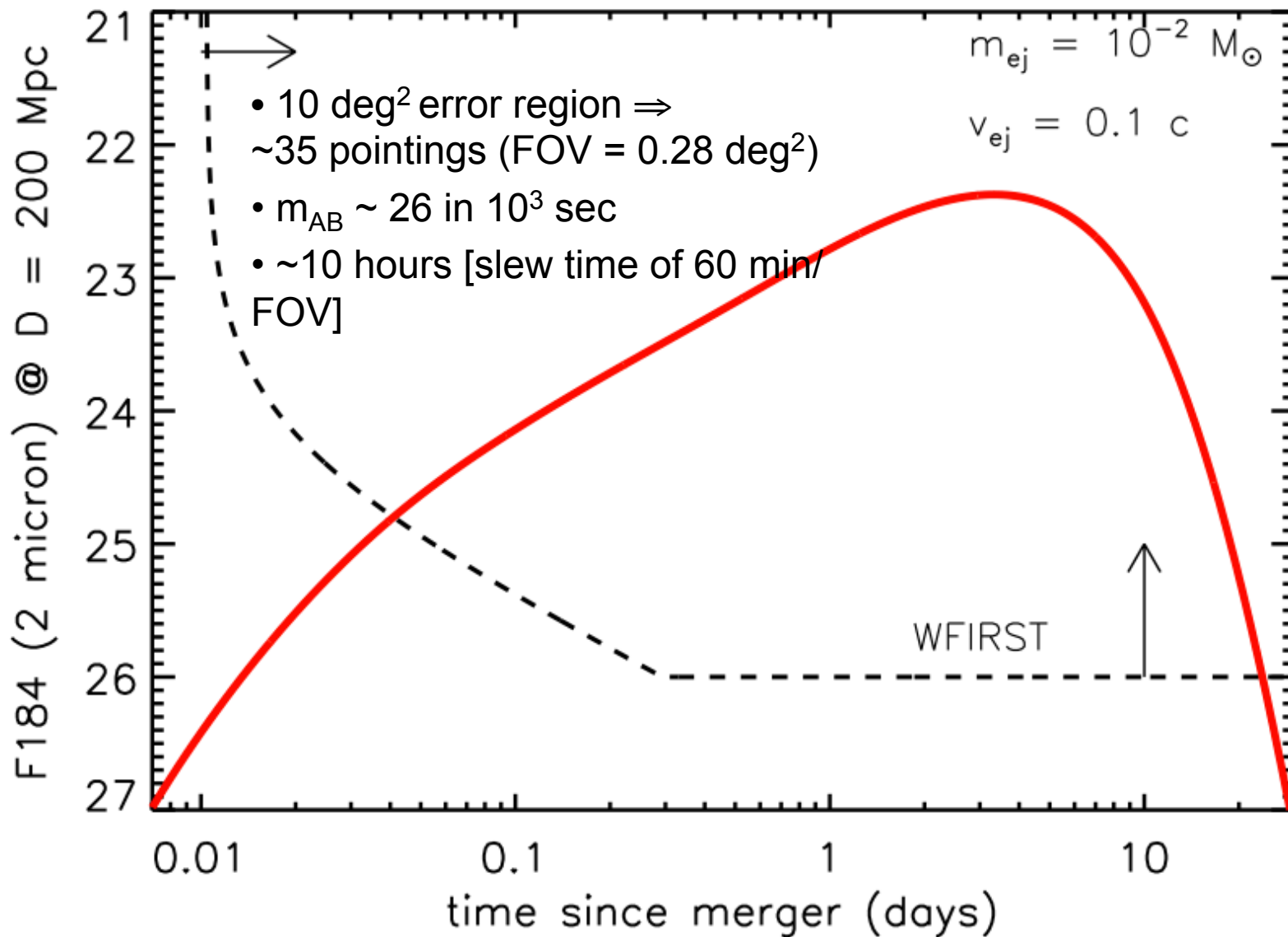
Tanvir et al. 2013



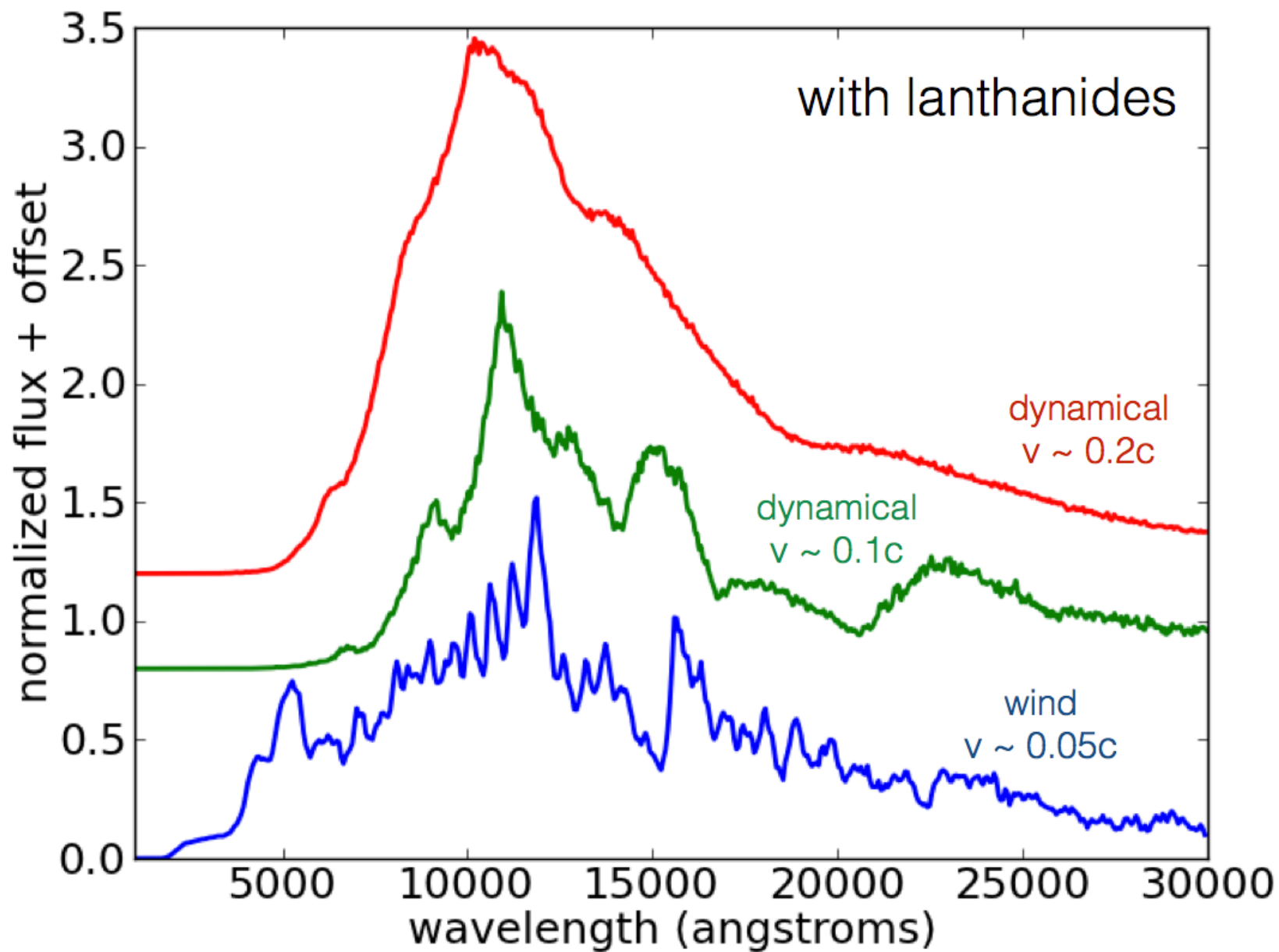
Gravitational Wave Follow-Up



Gravitational Wave Follow-Up



synthetic spectra of NS merger ejecta



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 / NIR transient (“kilonova”) powered by the radioactive decay of r-process nuclei.
- The high opacity of neutron-rich matter causes the kilonova SED to peak in the near infrared.
- First kilonova possibly detected following GRB 130603B last June, confirming the association of mergers with short GRBs.
- Kilonovae directly probe the formation of r-process nuclei, a long standing mystery in nuclear astrophysics, and physical processes at work during the merger, such as the delay until black hole formation
- The wide FoV and NIR sensitivity of WFIRST make it an ideal tool for gravitational wave follow-up in the coming Advanced LIGO/Virgo era.