Delayed Outflows from Accretion Disks formed in NS Binary Mergers

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Overview

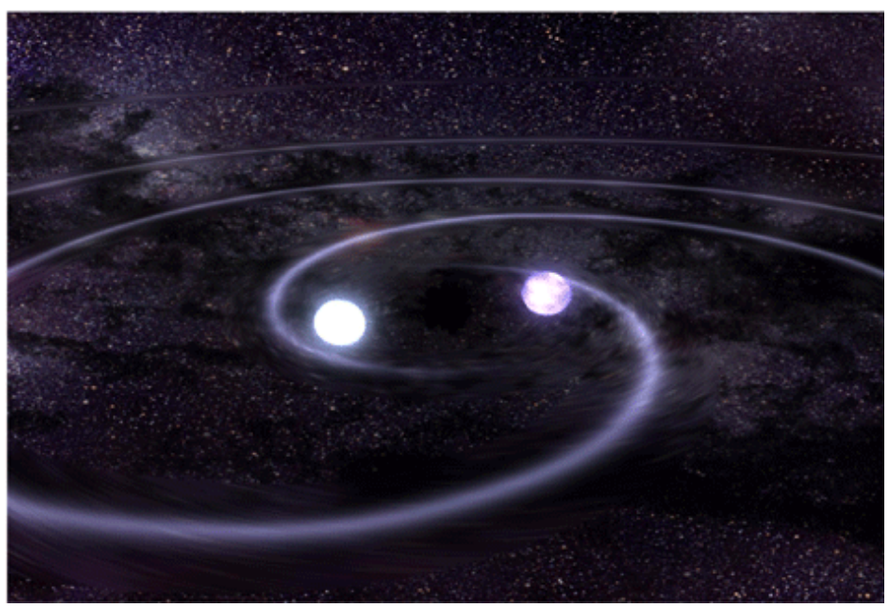
1. Motivation: GW localization & r-process origin

2. EM counterparts to NS-NS/NS-BH binary mergers

3. Viscous evolution of remnant accretion disks

Motivation I: maximize science return of GW detection

NS-NS and NS-BH mergers will likely be detected by next generation of ground based interferometers

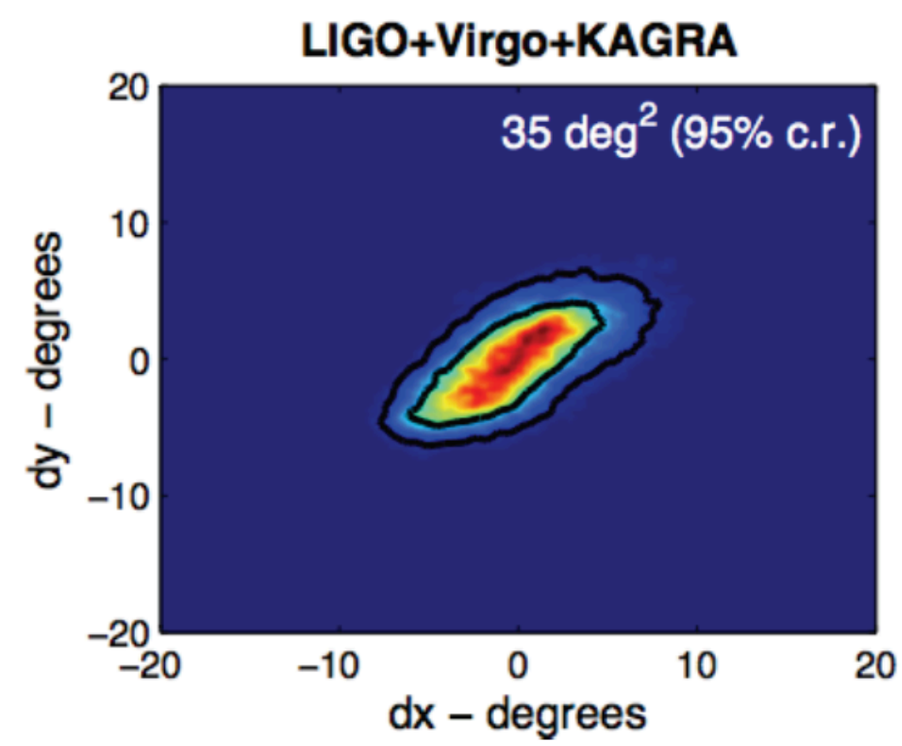


NASA

LIGO Livingstone

But most events are expected to have large sky localization errors:

EM counterpart

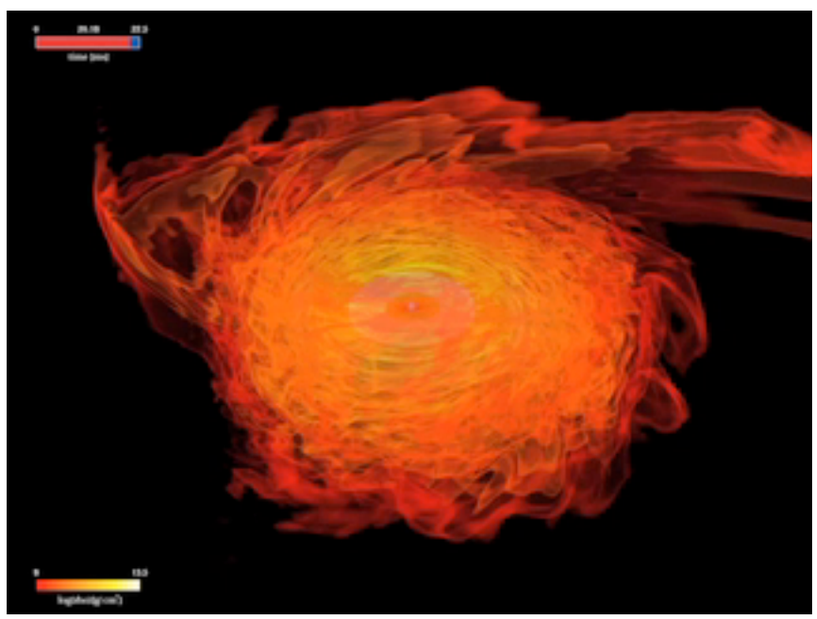


Nissanke et al. (2012)

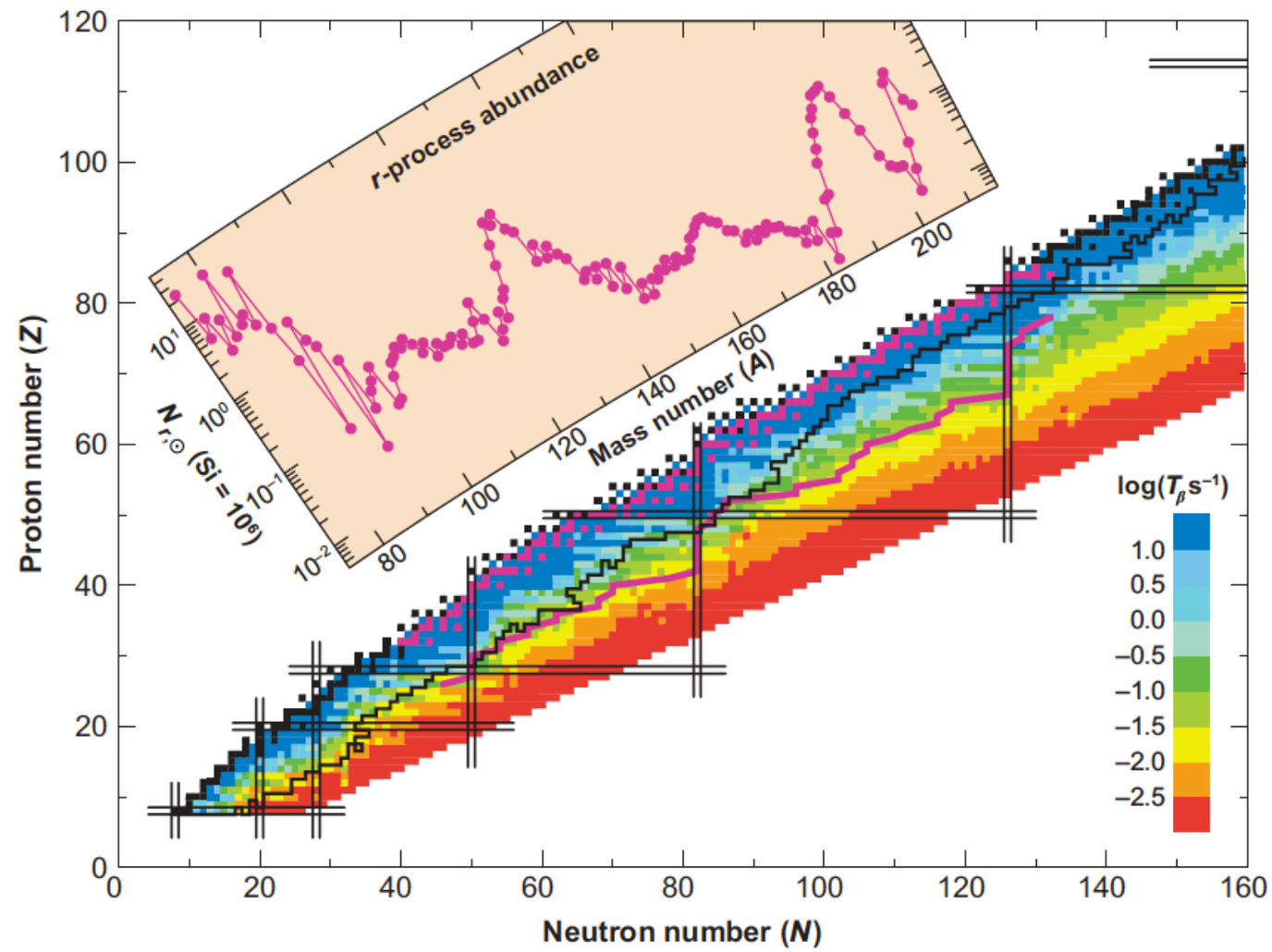
Motivation II: origin of r-process elements

Ejecta from NS-NS and NS-BH mergers is a site the for r-process

Lattimer & Schramm (1974), Freiburghaus+ (1999), Roberts+ (2011), Korobkin+ (2012)



Rezzolla+ (2010)



Möller, Nix, & Kratz (1997)

Material is ejected by tidal forces during the merger (prompt) and later by a wind from the remnant disk (delayed)

Ruffert+ (1997), Rosswog+1999, Oechslin+2007, Hotokezaka+(2013), Bauswein+(2013)

EM Counterparts of NS-NS / NS-BH Mergers

1) SGRB if on-axis $(\theta_j \lesssim 10^\circ)$

Paczynski (1986), Eichler+ (1989)

2) Orphan afterglow $(10^\circ \lesssim \theta_j \lesssim 20^\circ)$

e.g. van Eerten+ (2010), Nakar & Piran (2011)

3) Magnetospheric precursor

Vietri (1996), Lipunov & Panchenko (1996), Hansen & Lyutikov (2001), Palenzuela+ (2013)

4) Late-time radio transient

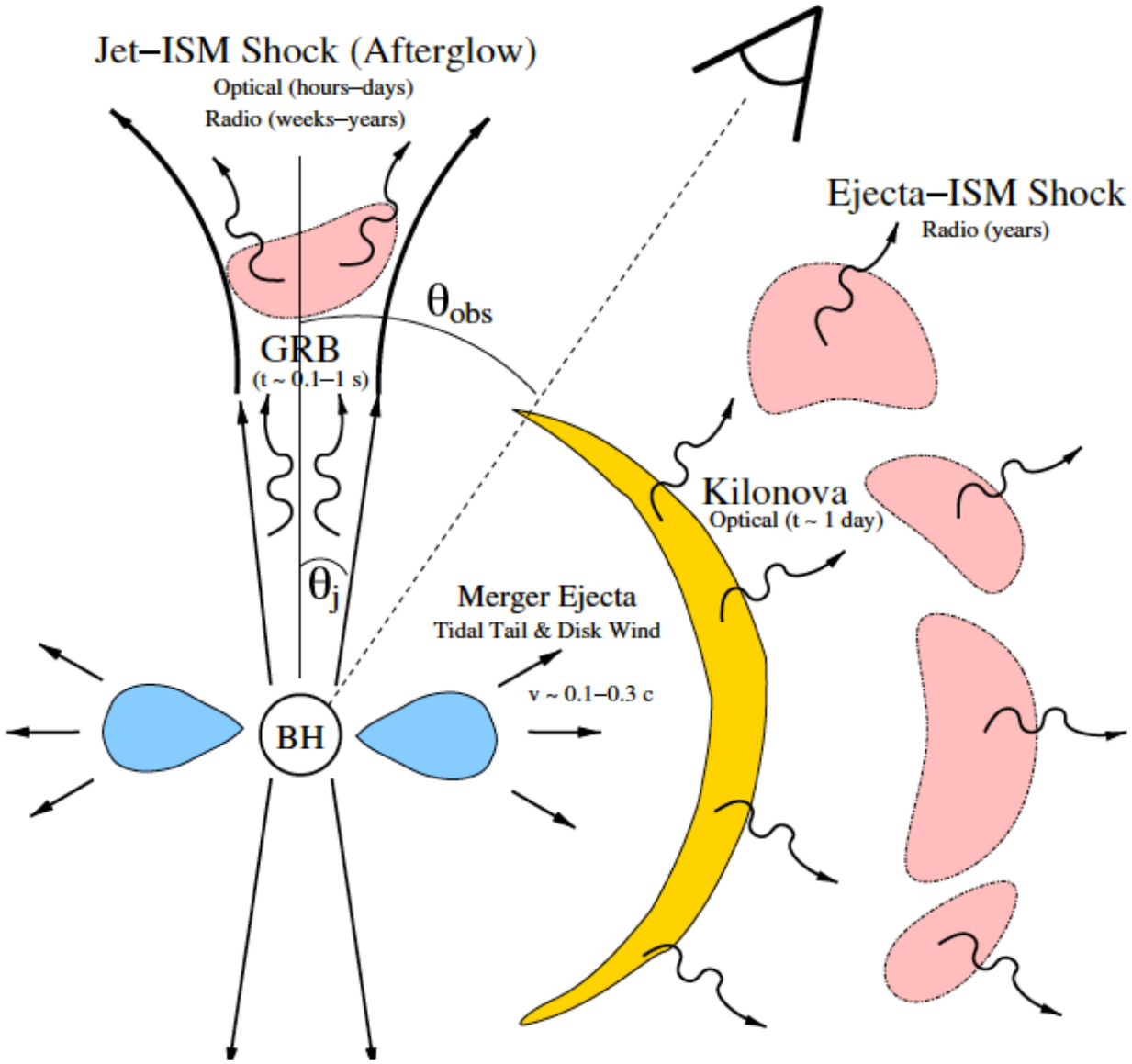
Nakar & Piran (2011)

5) Kilonova (tidal tail)

Li & Paczynski (1998), Metzger+(2010), Roberts+(2011), Bauswein+(2013), Grossman+(2013)

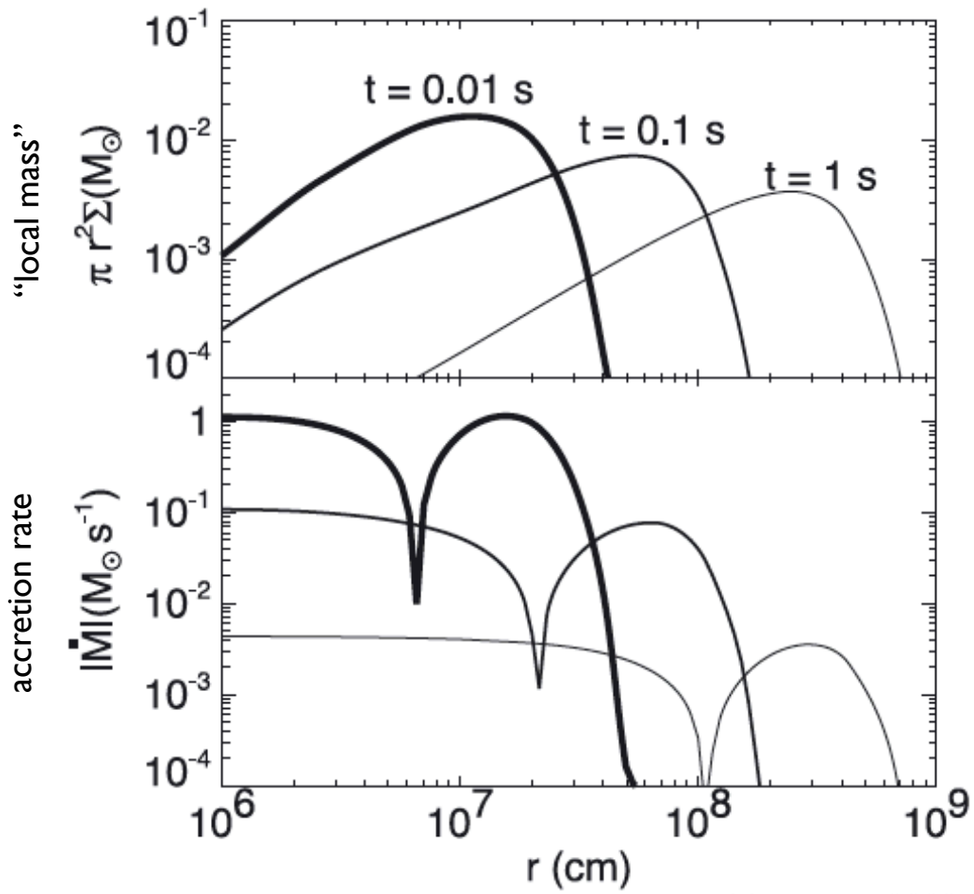
6) **Kilonova** (disk wind)

Metzger+ 2008, RF & Metzger (2013)



Metzger & Berger (2012)

Viscous Evolution of Remnant Accretion Disks



Metzger+ (2008)

Weak interactions freeze-out as the disk spreads viscously: final Ye

Metzger+ (2008)

Unbound outflows driven by:

- Neutrino heating (on thermal time)

  Ruffert & Janka (1999), Dessart+ (2009), Wanajo & Janka (2012)

- Viscous heating and nuclear recombination (on viscous time)

Metzger+ (2008)

$$\frac{E_\alpha}{GM_{\rm BH}/R} \simeq 1 R_{600} M_3^{-1}$$

$$t_{\rm orb} \simeq 3 R_{50}^{3/2} M_3^{-1/2} \ {\rm ms}$$

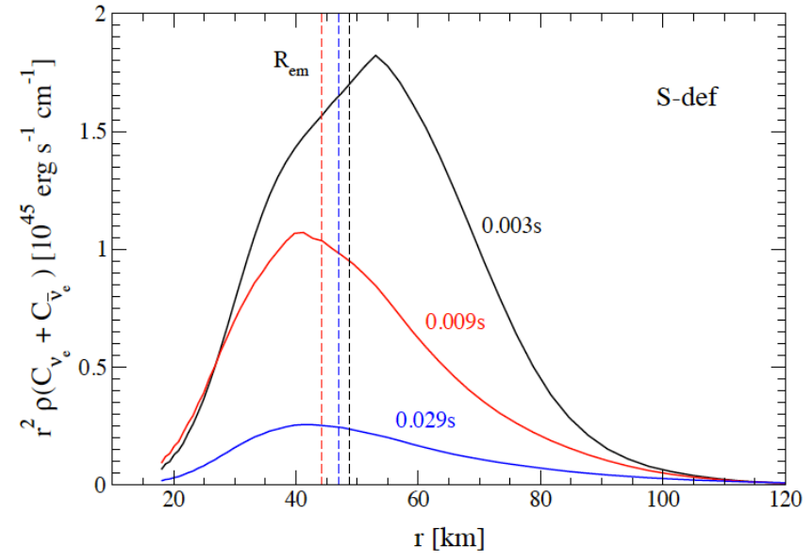
$$t_{\rm visc} \simeq 1 \alpha_{0.03}^{-1} R_{50}^{3/2} M_3^{-1/2} \, (H/3R) \ \ {\rm s}$$

$$t_{\rm therm} \simeq \frac{c_s^2}{v_K^2} t_{\rm visc} \lesssim t_{\rm visc}$$

Desired quantities:

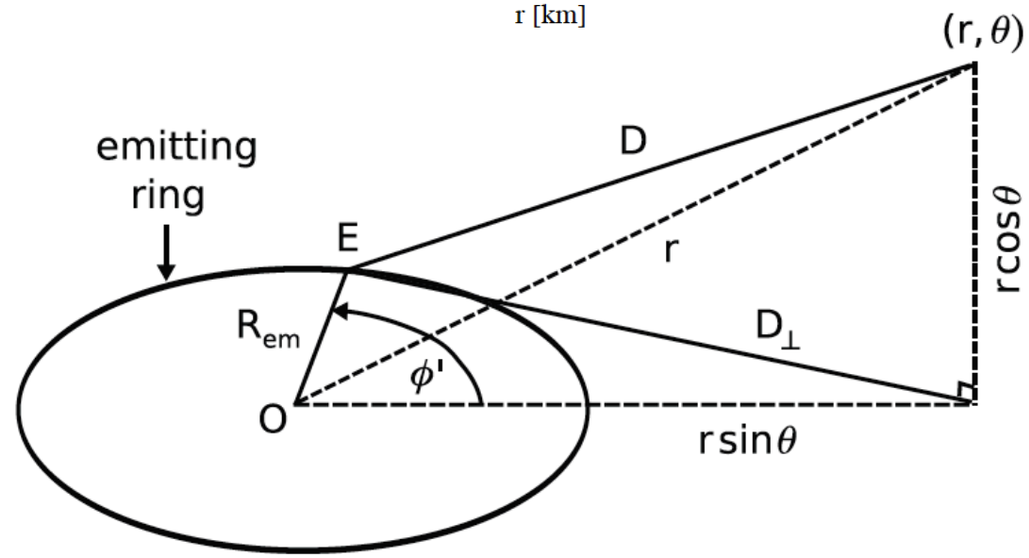
1. Ejecta mass, velocity
2. Ye (r-process yield, opacity)

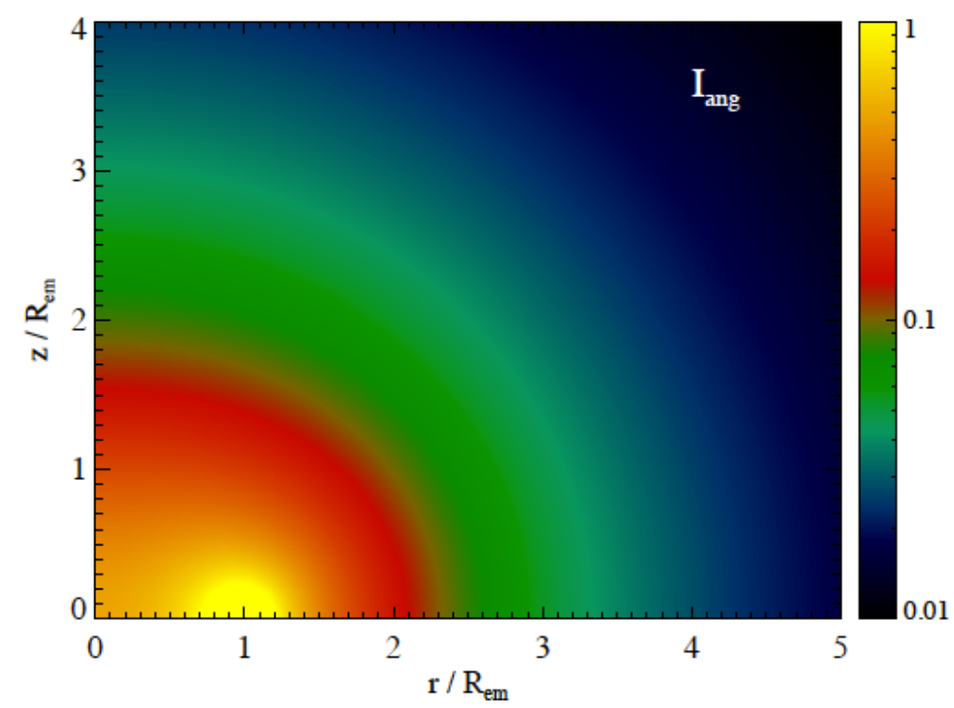
Time-Dependent 2D Evolution of remnant disk around BH



Hydrodynamic simulations with modified version of FLASH3.2

- Helmholtz EOS with NSE abundances
- Pseudo-Newtonian Potential (PW)
- Shear viscosity (α-parameterization)
- Evolution of Ye and cooling due to charged-current weak interactions
- Approximate self-irradiation
- Initial condition: 'relaxed' torus



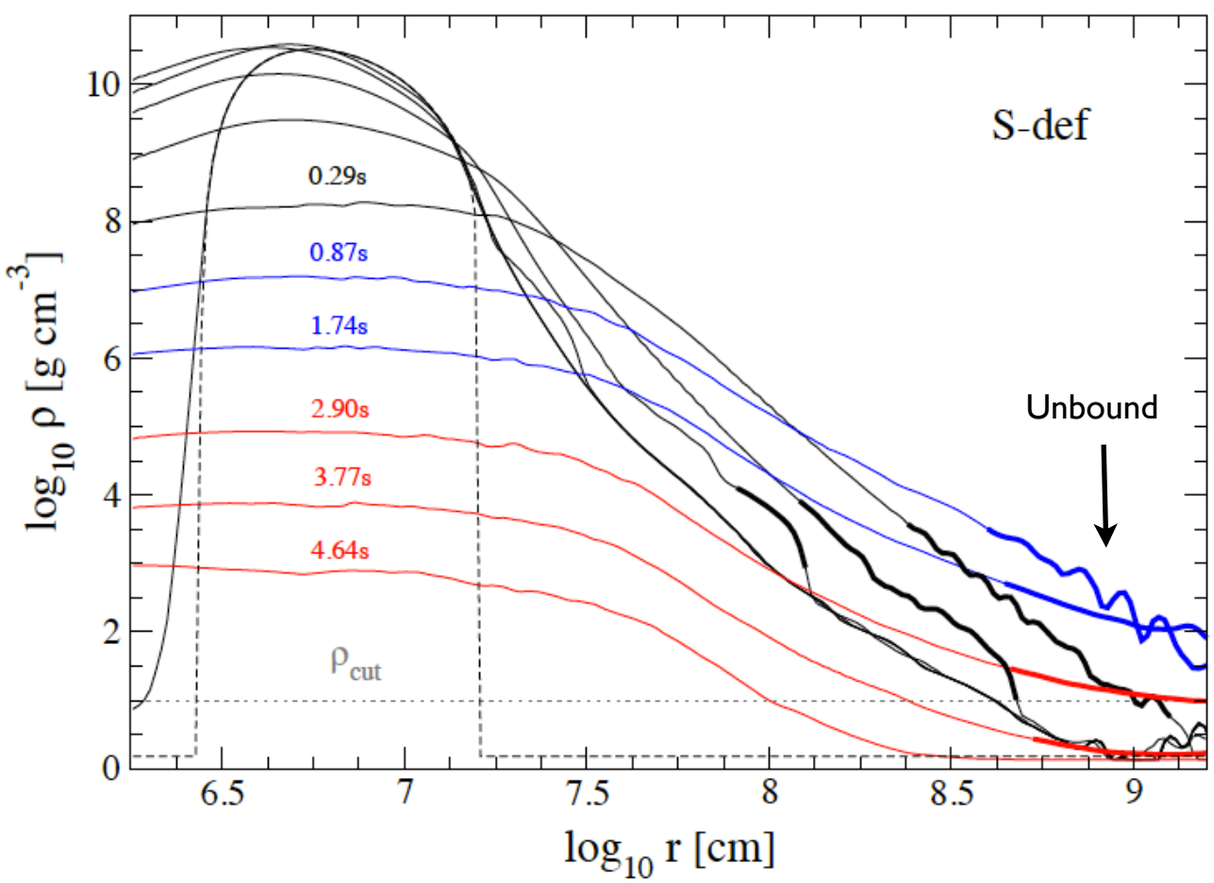


Improves on previous work (Lee+) by evolving Ye to late times (~few seconds)

More realistic models cannot follow evolution to late times and/or low densities

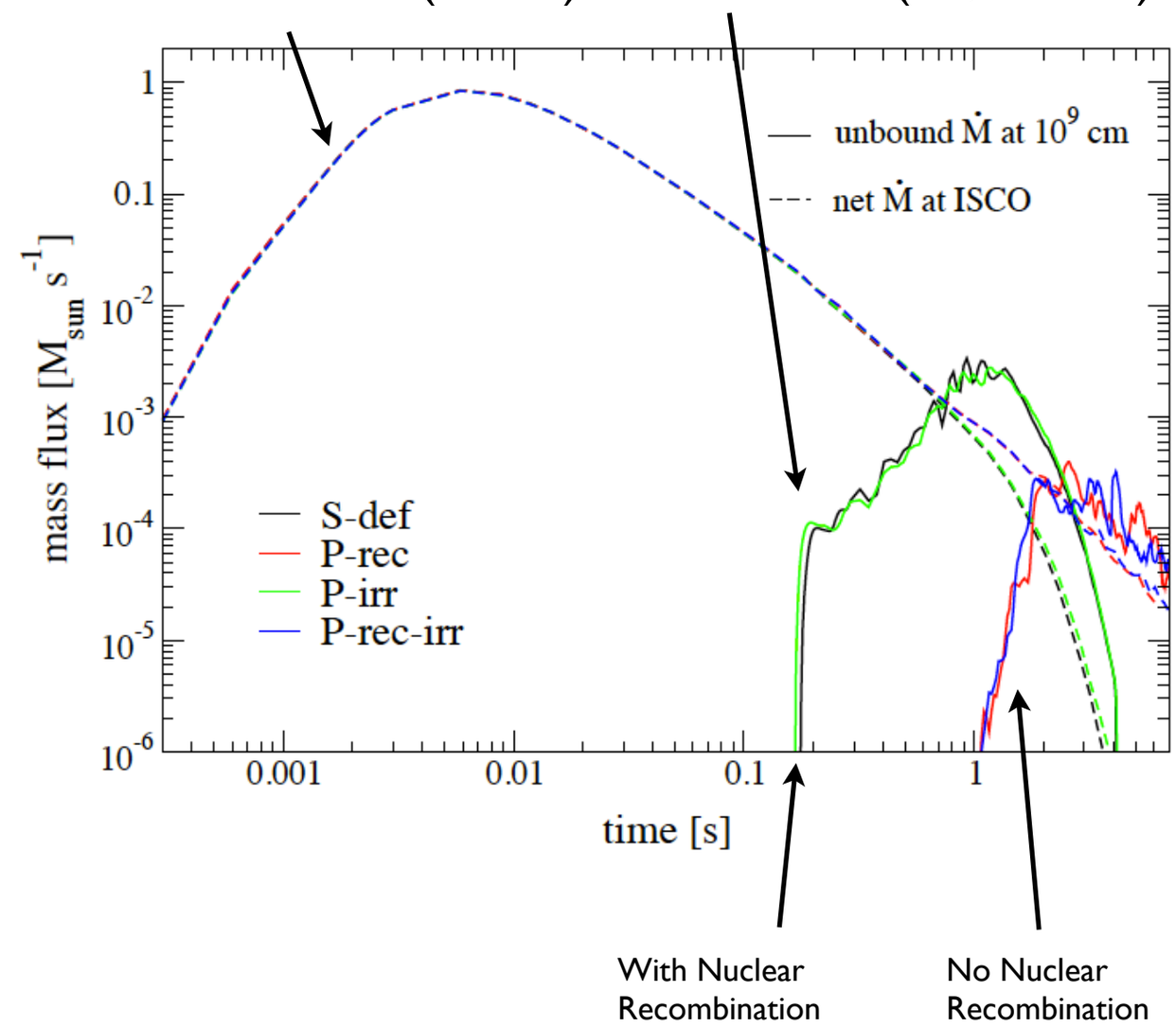
Time-Dependent 2D Evolution of remnant disk around BH

Angle-averaged density:



RF & Metzger, 1304.6720

Accretion (ISCO) and outflow (10,000km):

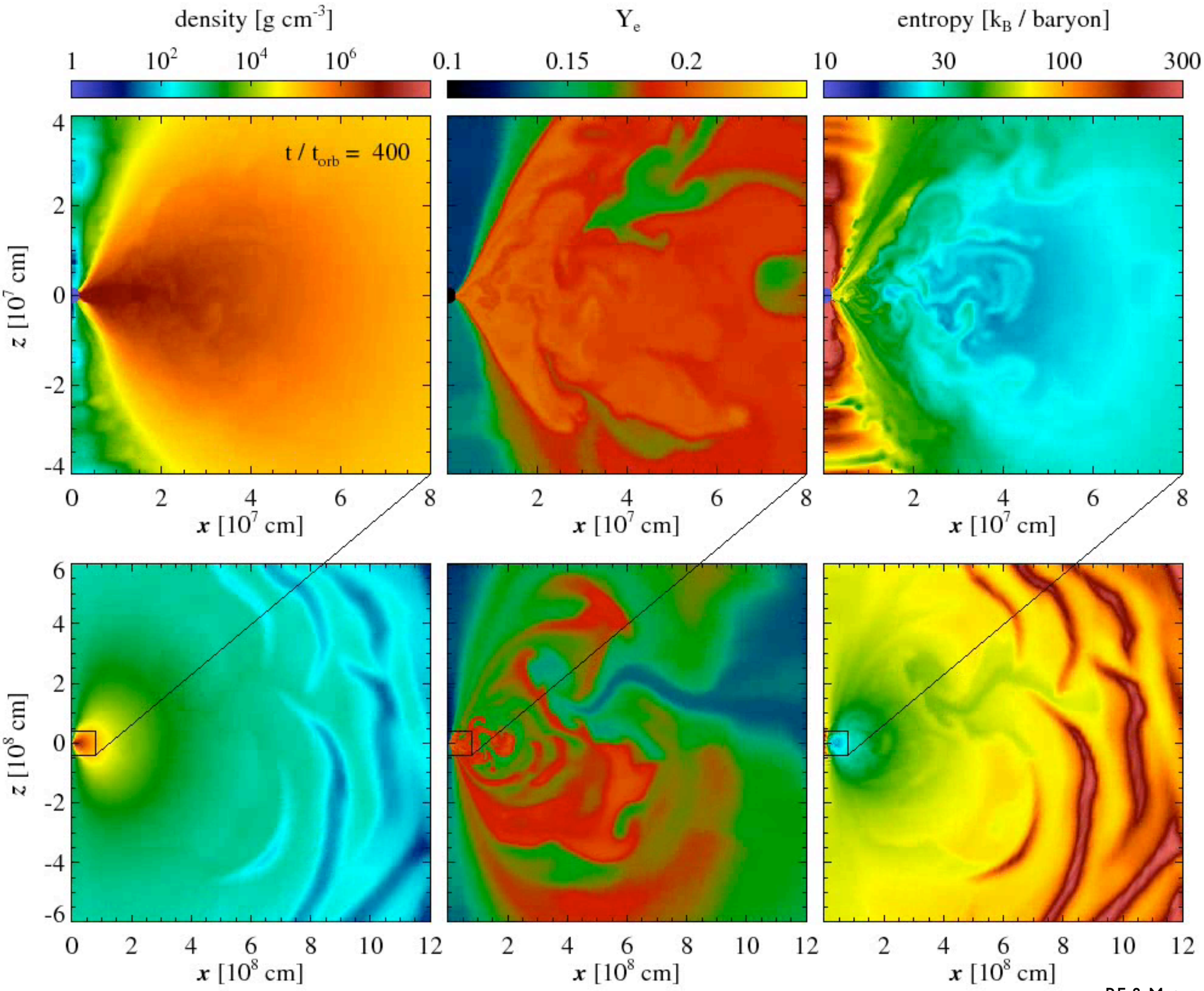


$$t_{\rm orb} \simeq 3 R_{50}^{3/2} M_3^{-1/2} \ \ {\rm ms}$$

$$t_{\rm visc} \simeq 1 \alpha_{0.03}^{-1} R_{50}^{3/2} M_3^{-1/2} \, (H/3R) \ \ {\rm s}$$

Fiducial model:

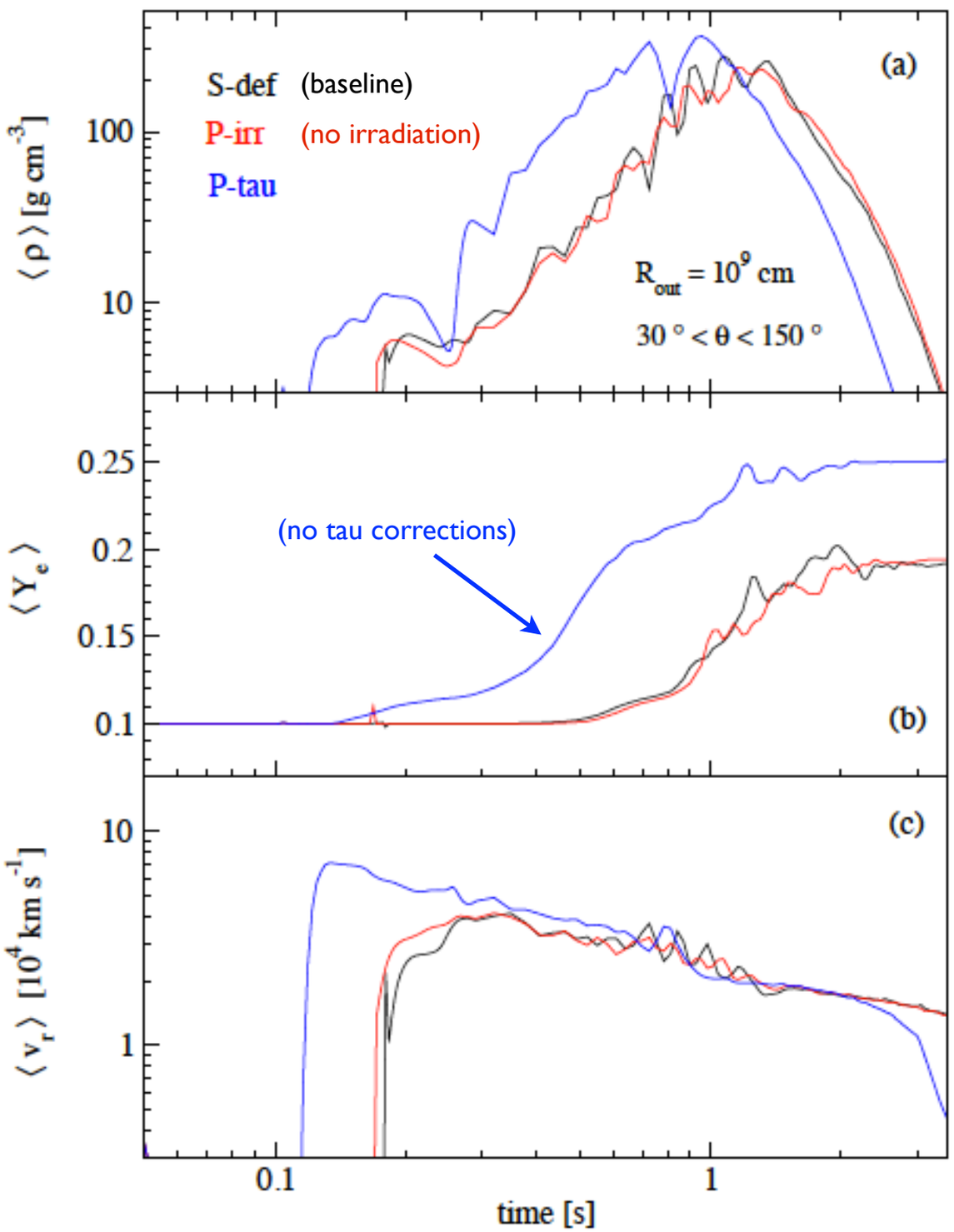
$$M_{\rm BH} = 3 M_\odot \ \ M_{\rm disk} = 0.03 M_\odot \ \ \ s_0 = 8 \ {\rm k}_B/{\rm b}$$
$$\alpha = 0.03 \ \ \ R_{\rm disk} = 50 \ {\rm km} \ \ \ Y_{e0} = 0.1$$



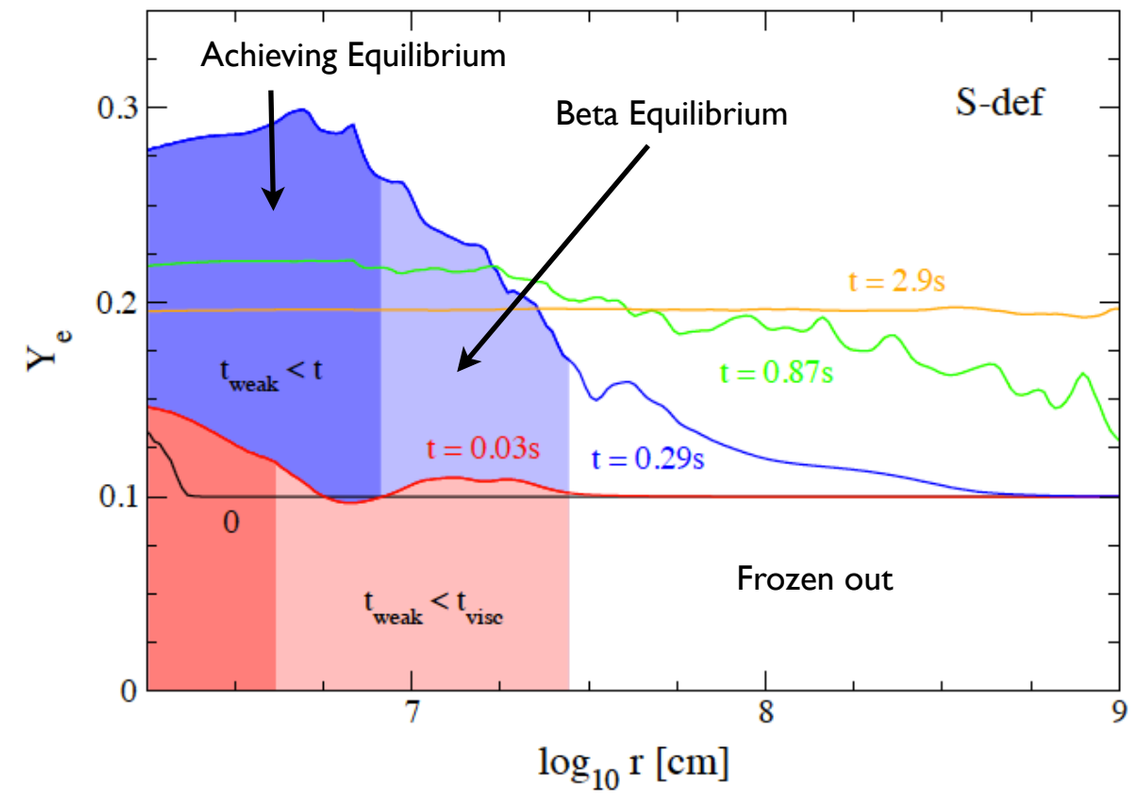
RF & Metzger, 1304.6720

Ejecta Properties

Mass-flux weighted quantities at 10,000 km:



Mass-weighted, angle-averaged Ye:

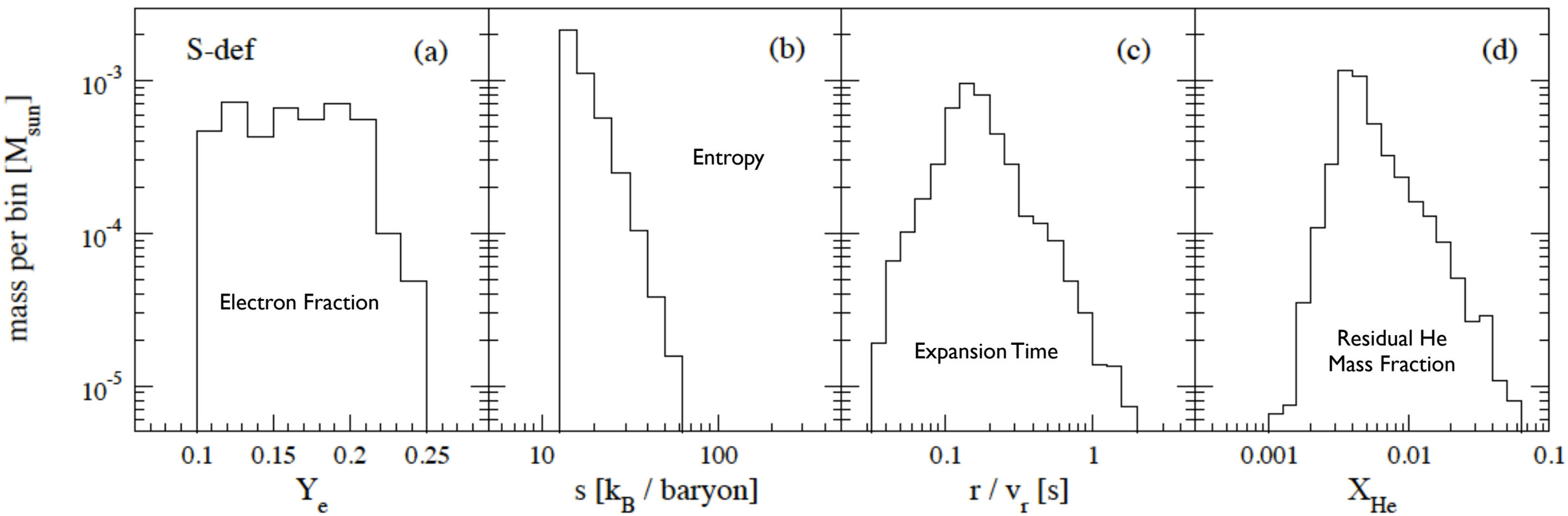


Inner region of the disk in beta equilibrium, but accreted

Outermost ~10% of the mass is ejected

Ejecta Properties

Distribution of quantities at 400km, where mass weighted temperature is 5×10^9 K



Production rate

Expect to make $A \gtrsim 130$

$$\dot{M}_{\rm r} = 10^{-7} M_\odot {\rm yr}^{-1} \left(\frac{\mathcal{R}_{\rm NS^2}}{10^{-4}{\rm yr}^{-1}}\right)\left(\frac{f_{\rm ej}}{0.1}\right)\left(\frac{\bar{M}_{\rm t}}{10^{-2} M_\odot}\right)$$

$$\dot{M}_{\rm obs} \sim 5 \times 10^{-7} M_\odot \ {\rm yr}^{-1}$$ Qian (2000)

Parameter Dependencies

Mass-weighted quantities at radius where T ~ 5×10^9 K

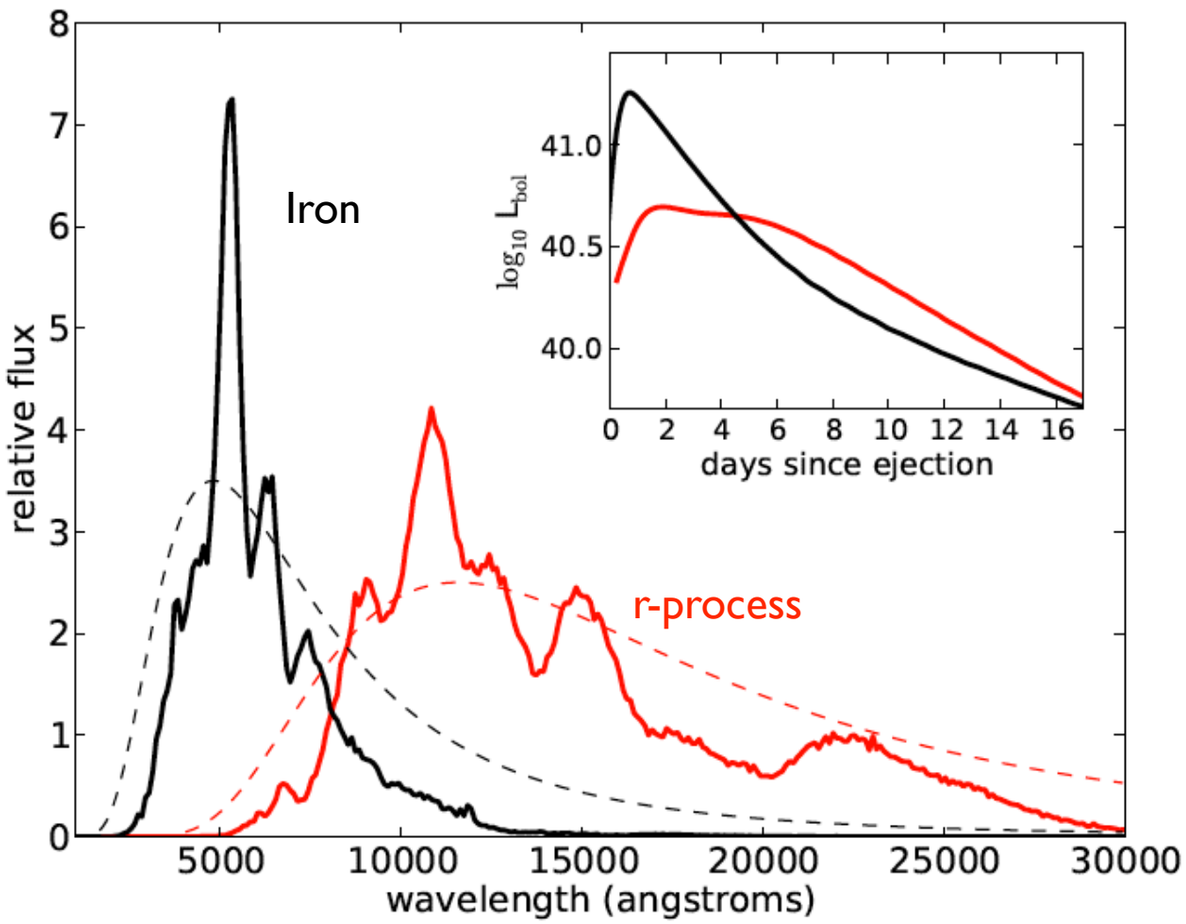
Model	M_{t0} ($M_\odot$)	M_{BH} ($M_\odot$)	R_0 (km)	Y_{e0}	s_0 (k_B/b)	α	Res.	Rec.	Irr.	$\bar{Y}_e$	$\bar{s}$ (k_B/b)	t_{exp} (ms)	M_{ej}/M_{acc} (M_{t0}/M_{t0})	$\bar{\rho}_2$	$\bar{v}_{r,9}$
S-def	0.03	3	50	0.10	8	0.03	std	yes	yes	0.16	16	95	0.10/0.90	1.6	2.2
S-m0.01	0.01	3	50	0.10	8	0.03	std	yes	yes	0.15	18	68	0.10/0.90	0.5	2.2
S-m0.10	0.10									0.17	17	119	0.11/0.89	6.3	2.3
S-R75	0.03	3	75							0.16	16	126	0.22/0.78	3.6	2.2
S-M10		10	150							0.18	17	77	0.04/0.92	0.8	1.8
S-y0.05		3	50	0.05						0.15	16	93	0.10/0.90	1.5	2.2
S-y0.15				0.15						0.17	16	92	0.10/0.90	1.6	2.3
S-s6				0.10	6					0.14	17	86	0.08/0.91	1.2	1.9
S-s10					10					0.19	16	87	0.12/0.88	1.9	2.6
S-v0.01					8	0.01				0.20	18	193	0.11/0.89	1.5	2.5
S-v0.10						0.10				0.14	19	38	0.13/0.87	2.2	2.4
S-hr						0.03	hi			0.15	16	94	0.10/0.90	1.5	2.2
P-rec	0.03	3	50	0.10	8	0.03	std	no	yes	0.18	17	43	0.03/0.93	0.8	0.9
P-irr								yes	no	0.15	16	90	0.10/0.90	1.4	2.2
P-rec-irr								no	no	0.17	17	47	0.03/0.93	0.9	0.6
P-tau								yes	yes	0.21	17	76	0.13/0.87	2.1	2.7

RF & Metzger, 1304.6720

Ejected and accreted mass, in units of initial disk mass

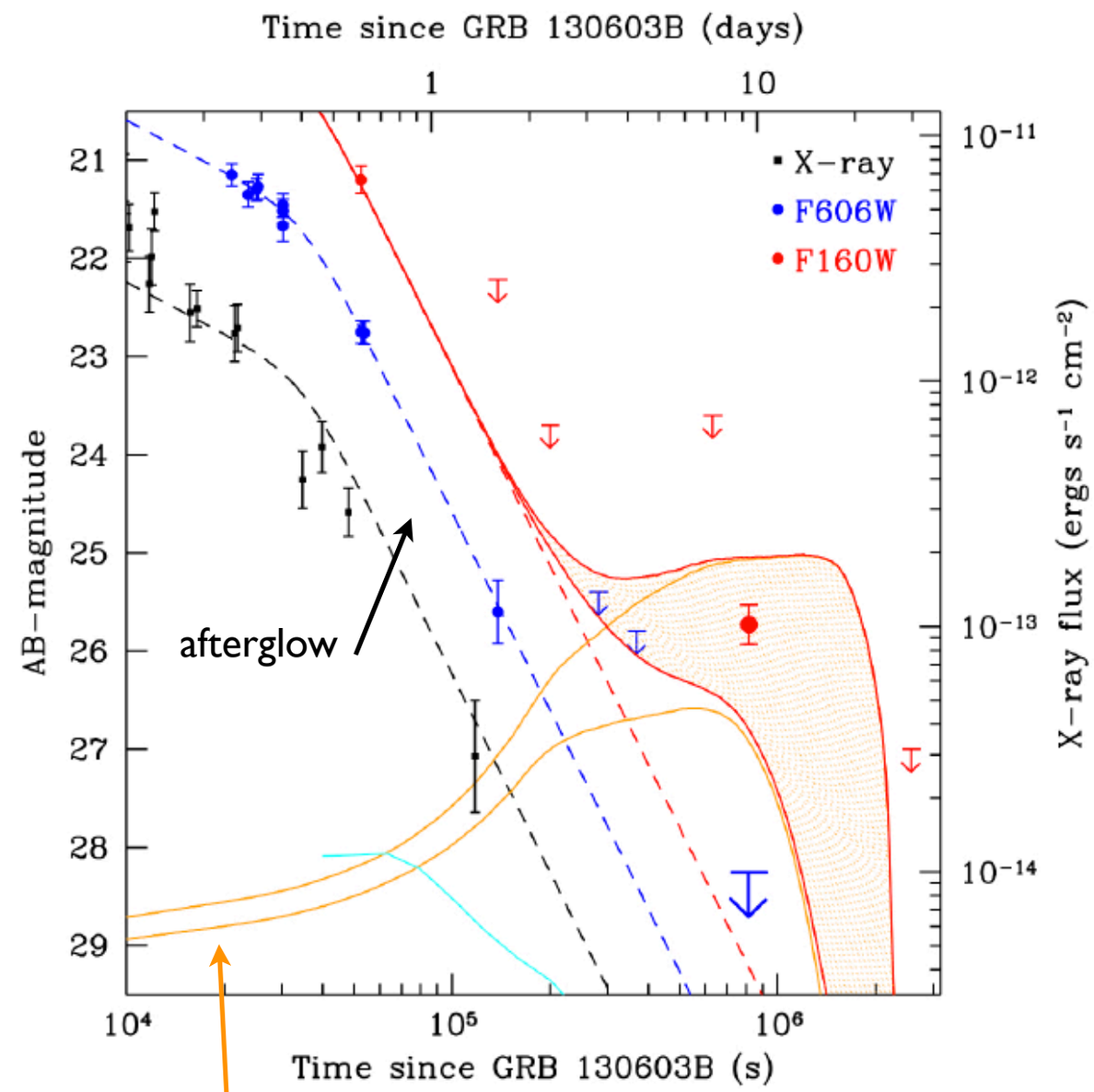
Implications for Kilonovae

Comparison of generic Kilonova spectra



Kasen+ (2013)

First observed Kilonova?



Tanvir+ (2013)

Kilonova models
from Hotokezaka+2013

Lanthanides have dense spectrum of lines in the optical: bulk of energy escapes in IR

Summary

RF & Metzger, 1304.6720

1. Viscous evolution of remnant accretion disks from NS-NS / NS-BH mergers leads to the ejection of ~10% of disk mass if BH is formed promptly

2. Material has Ye ~ 0.2 for a wide range of system parameters

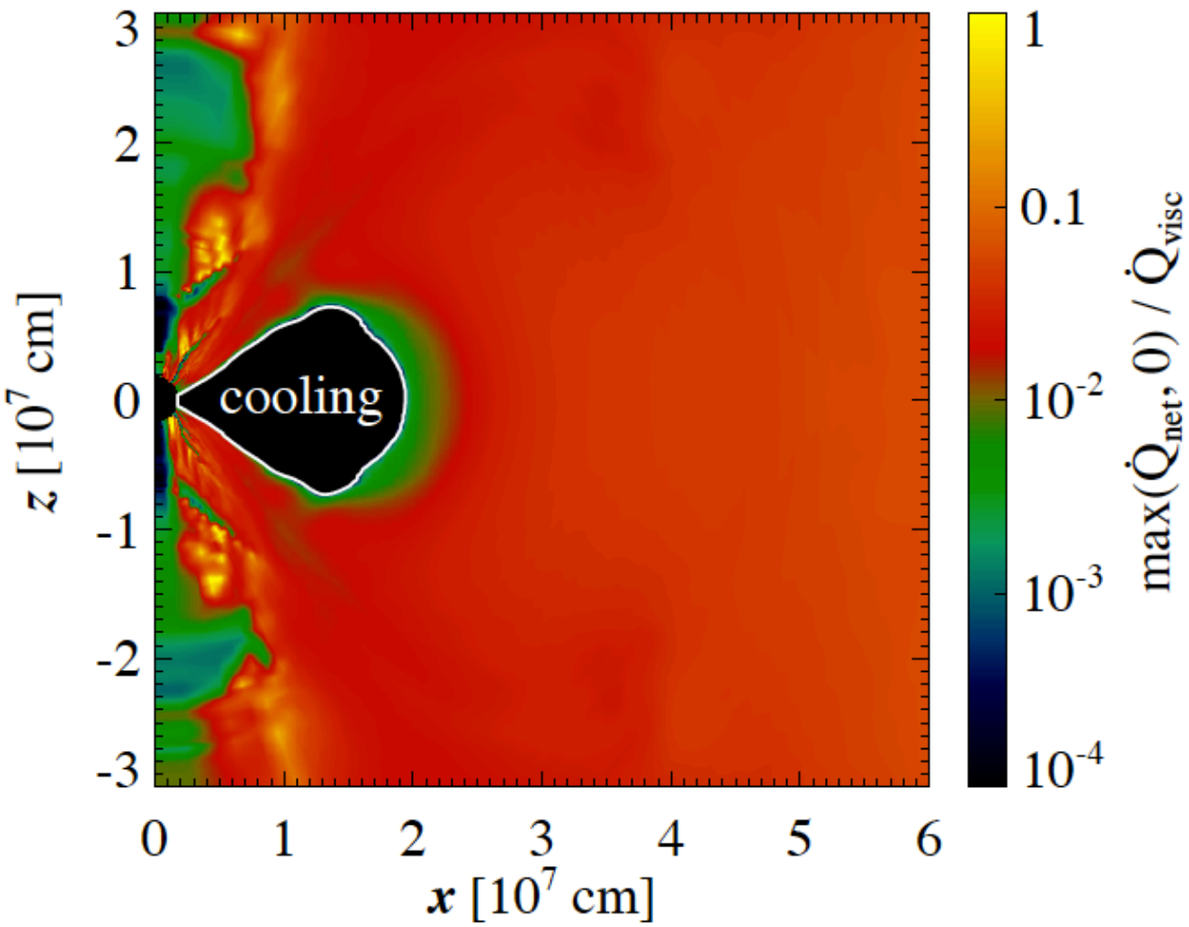
   - Can produce a significant fraction of elements with $A \gtrsim 130$
   - Presence of Lanthanides implies a high opacity: IR transient

3. Neutrino self-irradiation is sub-dominant for disks with $M_{\rm disk} \lesssim 0.03 M_\odot$ and prompt BH formation

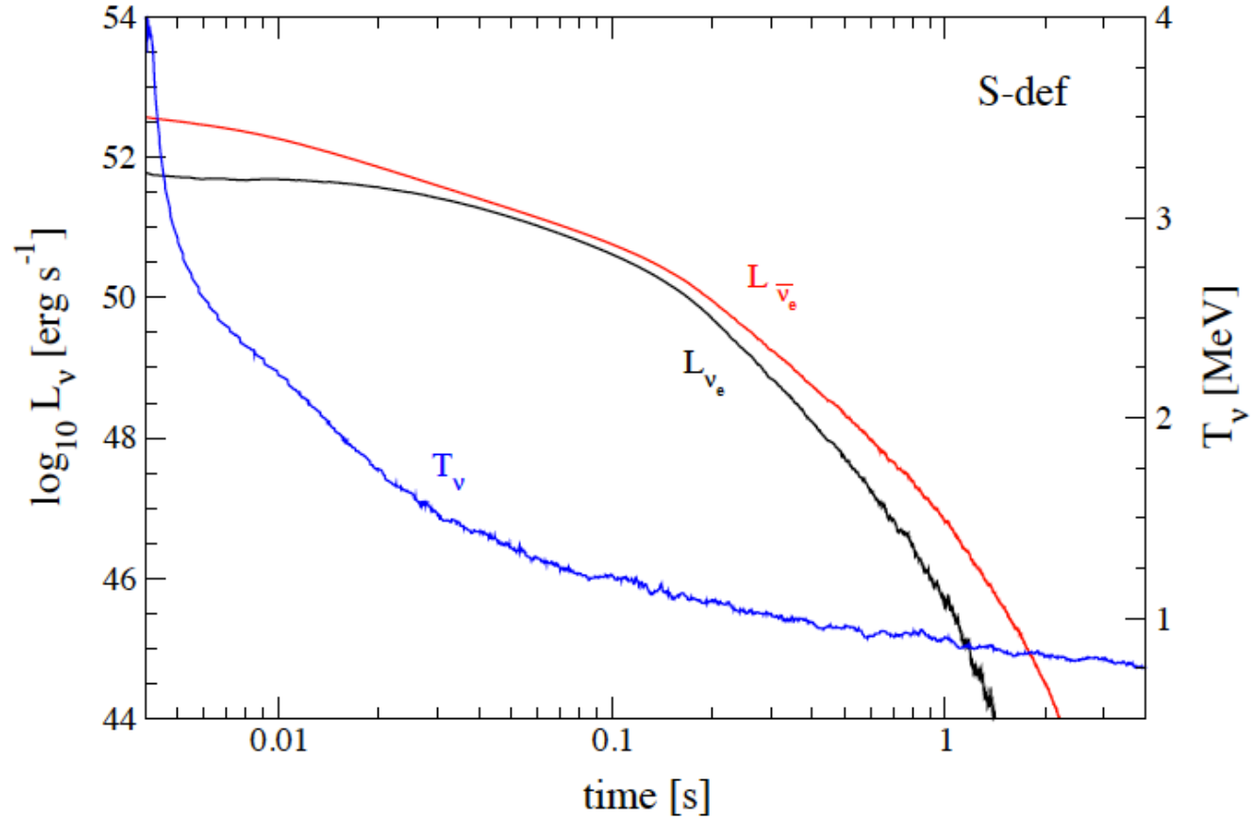
   - Effect of long-lived HMNS?

Viscous heating vs. Neutrino Heating

Ratio of neutrino to viscous heating (60ms)



Evolution of neutrino luminosities and temperature



Neutrino heating is important for
t < 0.3s and near polar region only

Spatial distribution may change in MHD