Title: Electromagnetic transients and r-process nucleosynthesis from the disk wind outflows of neutron star merger remnants

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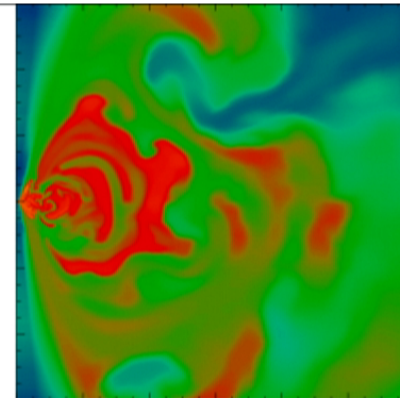
Abstract: <p>The remnant accretion disk formed in binaries involving neutron stars and/or black holes is a source of non-relativistic ejecta. This 'disk wind' is launched on a thermal and/or viscous timescale, and can provide an amount of material comparable to that in the dynamical ejecta. I will present recent work aimed at characterizing</p>

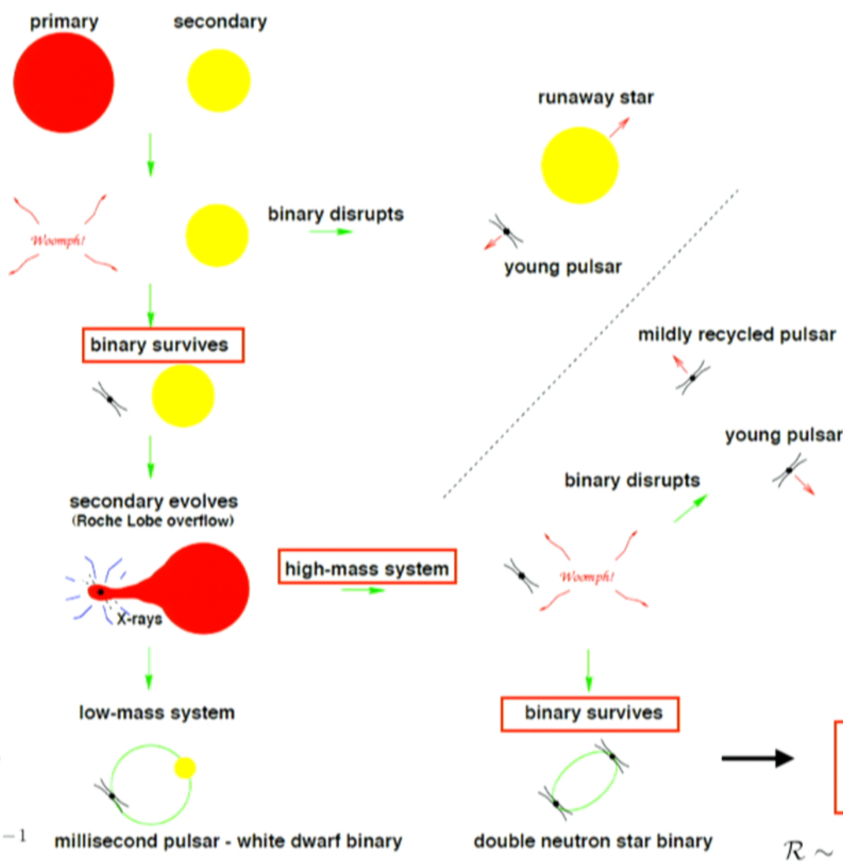
<p>the properties of these winds through time-dependent radiation-hydrodynamic simulations that include the relevant physics needed to follow the ejecta composition. I will focus on the effect of black hole spin and/or hypermassive neutron star lifetime on the disk wind, and on the interaction of the wind with the dynamical ejecta. I will also discuss the implications of these results for the optical/IR signal from these events, and for the origin of r-process elements in the Galaxy.</p>

EM transients and r-process nucleosynthesis from disk wind outflows of NS mergers

Rodrigo Fernández
UC Berkeley



Binary Evolution Paths: Origin



WD-NS/BH merger

$\mathcal{R} \sim [0.2 - 10]\mathrm{Myr}^{-1}\,\mathrm{MWEG}^{-1}$

Kim+(2010)

Lorimer (2008)

NS-NS merger

$\mathcal{R} \sim [1 - 1000]\mathrm{Myr}^{-1}\,\mathrm{MWEG}^{-1}$

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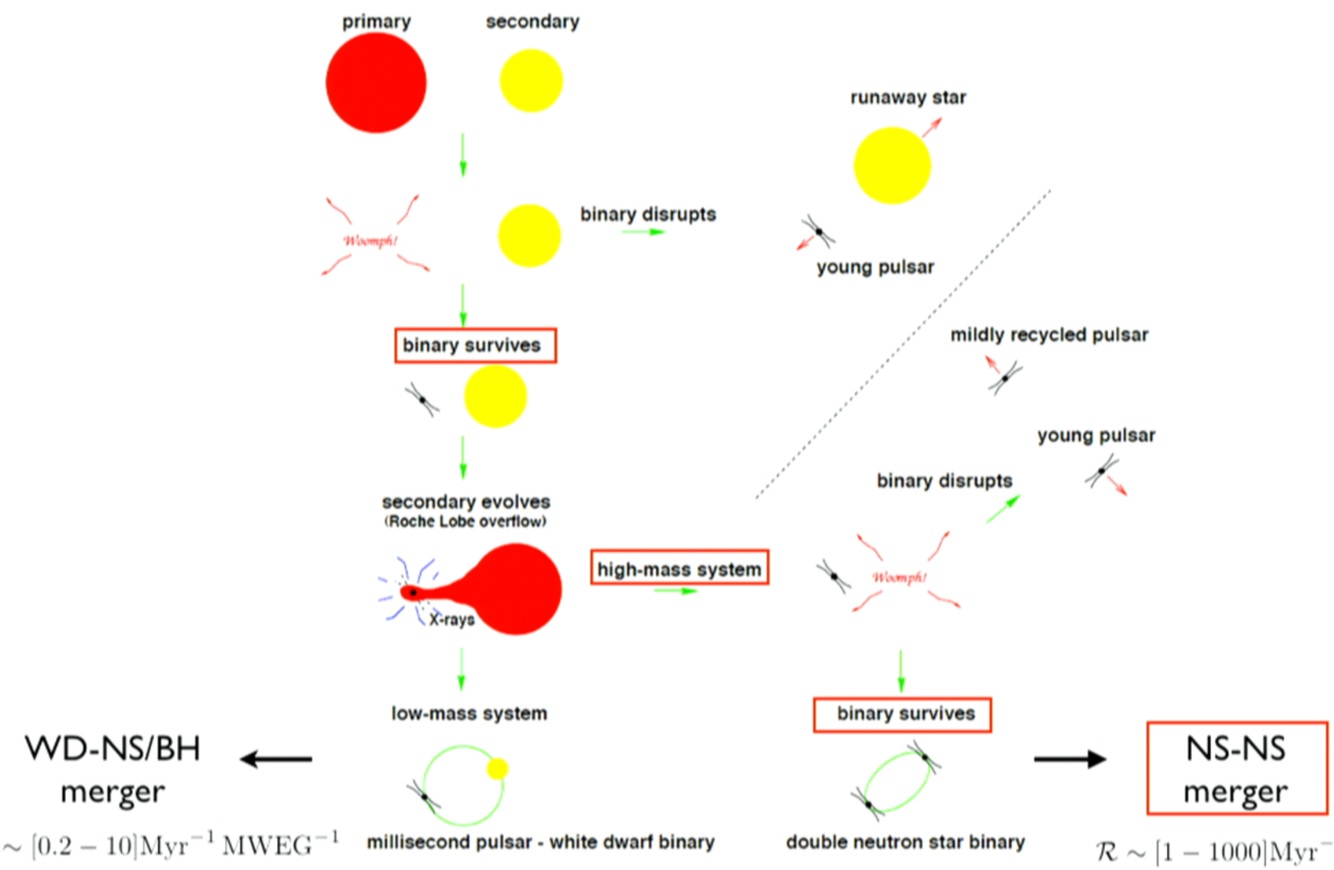

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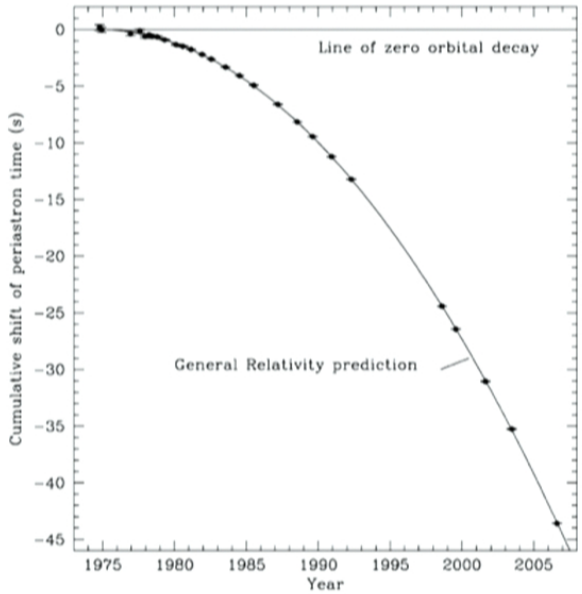
NS binary mergers

~Ten NS-NS binaries known in the Galaxy. No NS-BH binaries known.

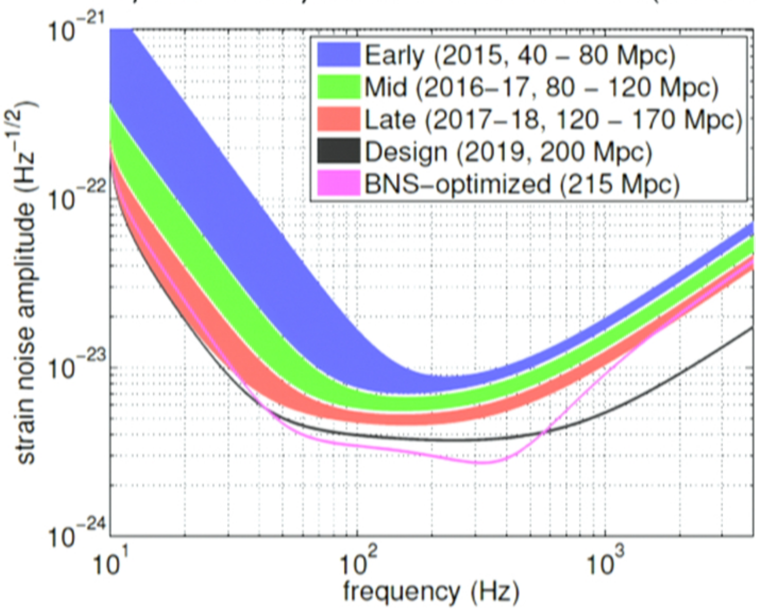
Hulse-Taylor pulsar: gravitational radiation (indirect)



Weisberg, Nice, & Taylor (2010)

Detectable by Advanced LIGO, first science run in summer 2015

Projected sensitivity & maximum distance for BNS (Adv. LIGO)



Aasi+2013 (LIGO collaboration), arXiv:1304.0670

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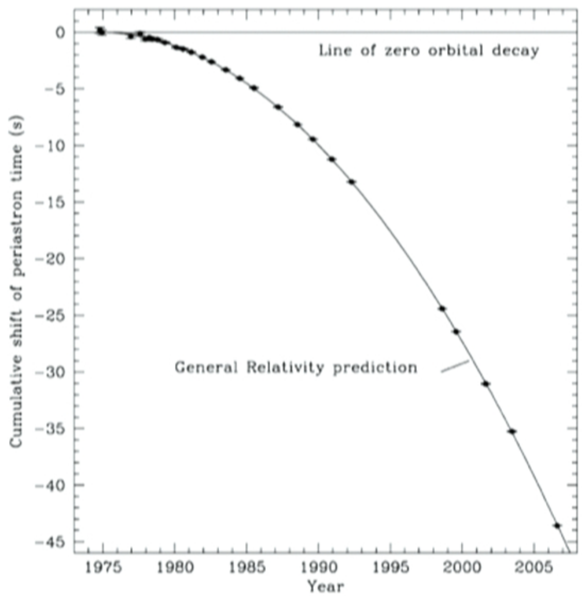

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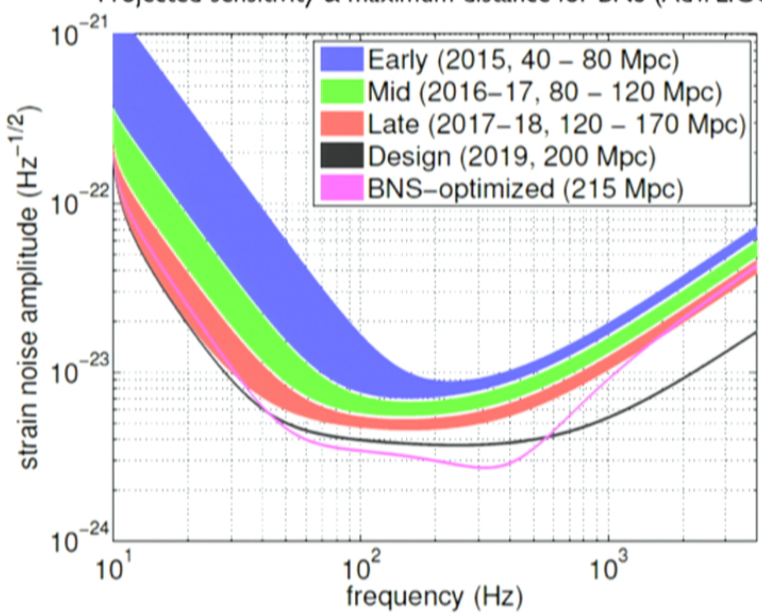

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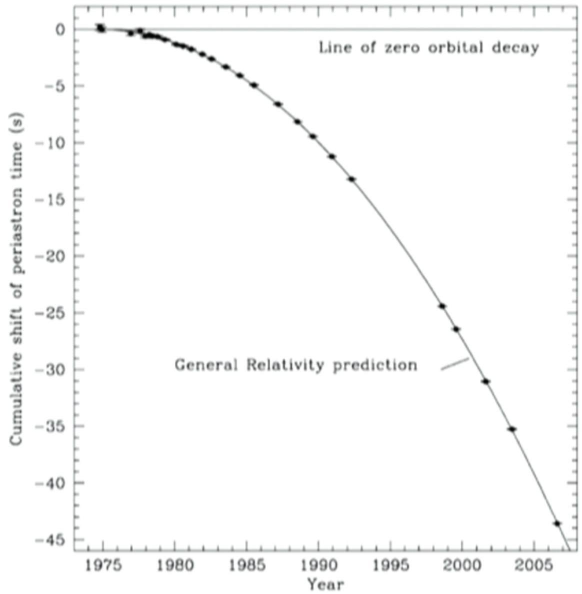

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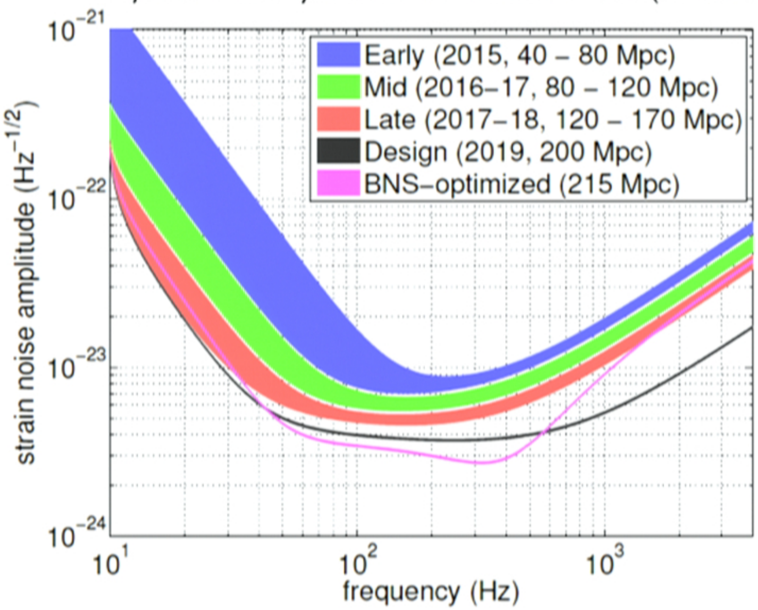

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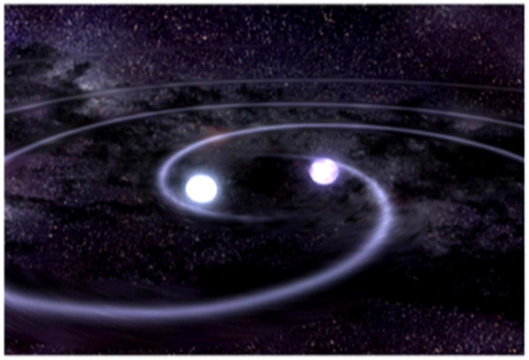
Motivation I: Improving the localization of GW detections

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

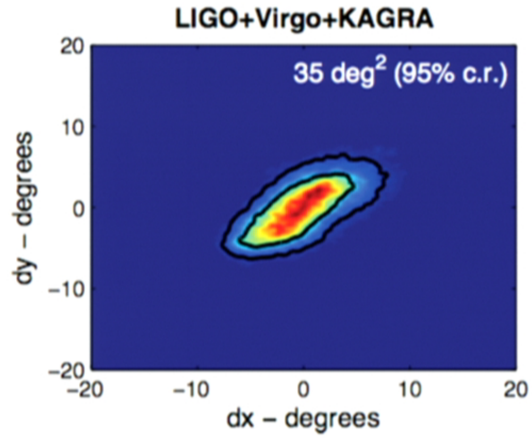


NASA

LIGO Livingstone

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

EM counterpart



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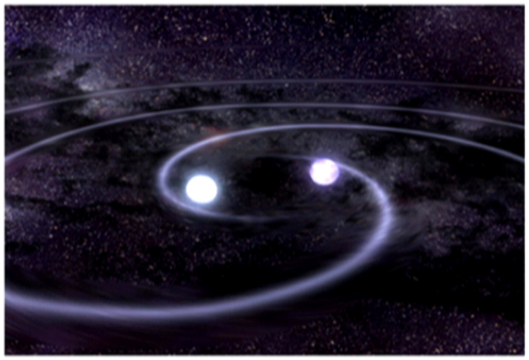

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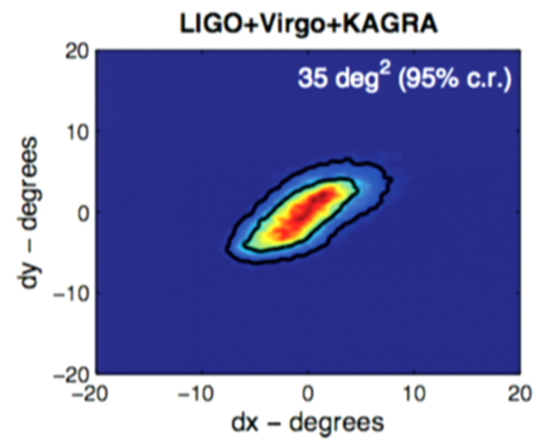

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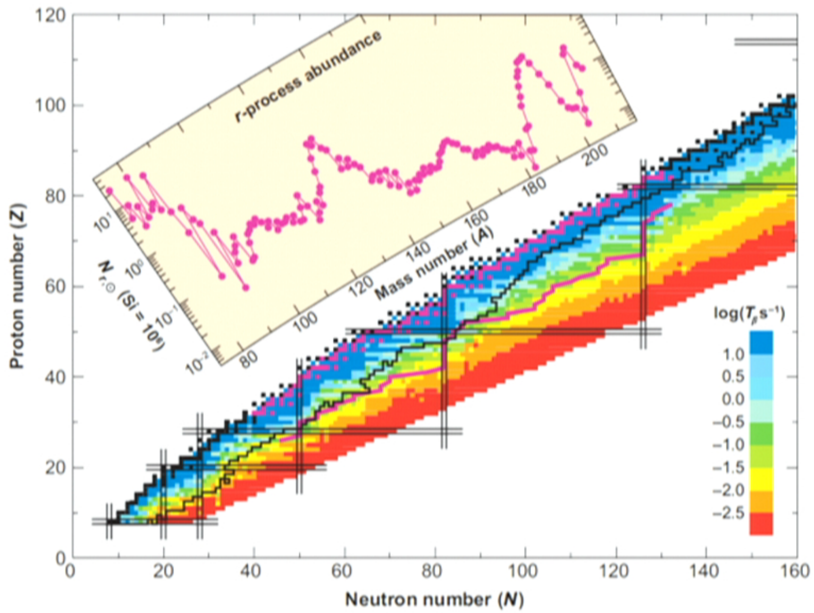
Motivation II: Origin of r-process elements



Möller, Nix, & Kratz (1997)

Need neutron-rich environment

Candidate sites:

1. Ejecta from NS-NS/BH mergers

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

2. Neutrino-Driven Wind in CCSNe

   e.g. Woosley+ (1994), Qian & Woosley (1996)

3. Magnetorotational SNe

   Cameron (2003), Winteler+ (2012), Ono+ (2012).

4. Neutrino absorption in SN He shells

   Epstein+ (1988), Banerjee+ (2011)

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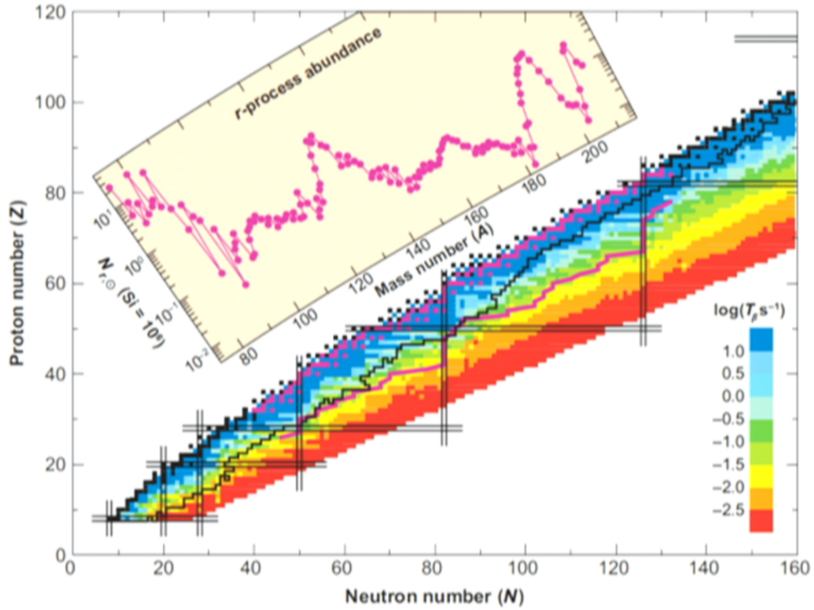

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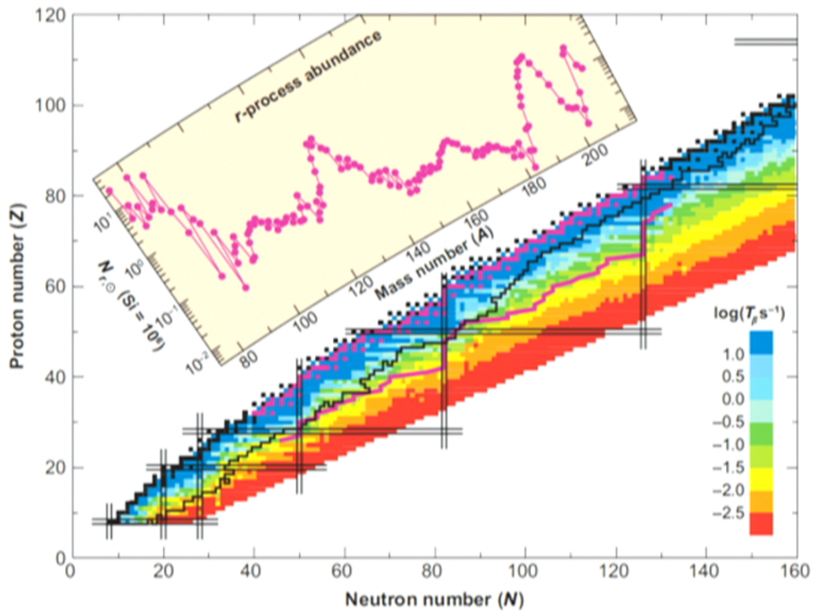

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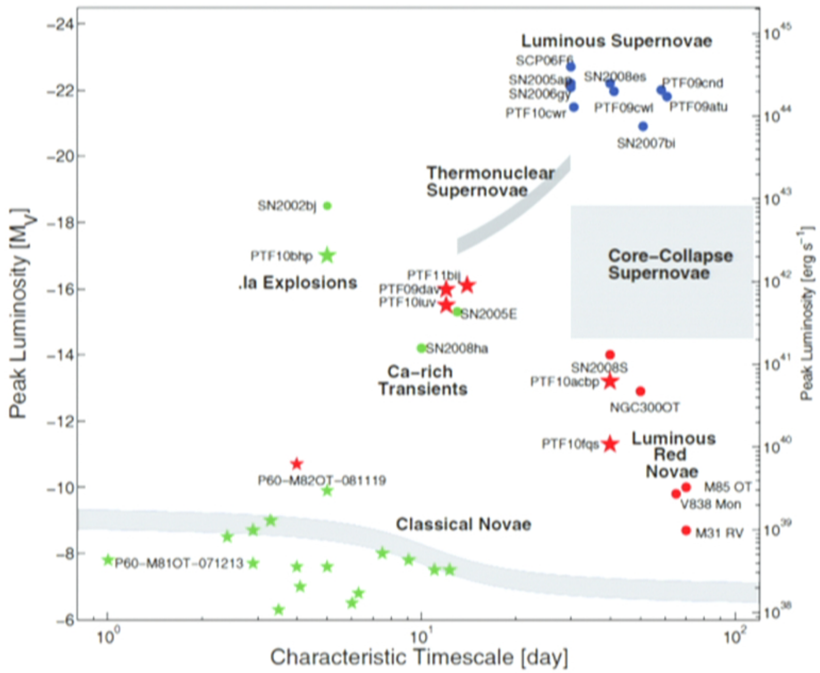
Motivation III: Astrophysical Transients



Kasliwal (2011)

PALOMAR TRANSIENT FACTORY

BlackGEM

Pan-STARRS

ASAS-SN

CRTS

LSST

Large Synoptic Survey Telescope

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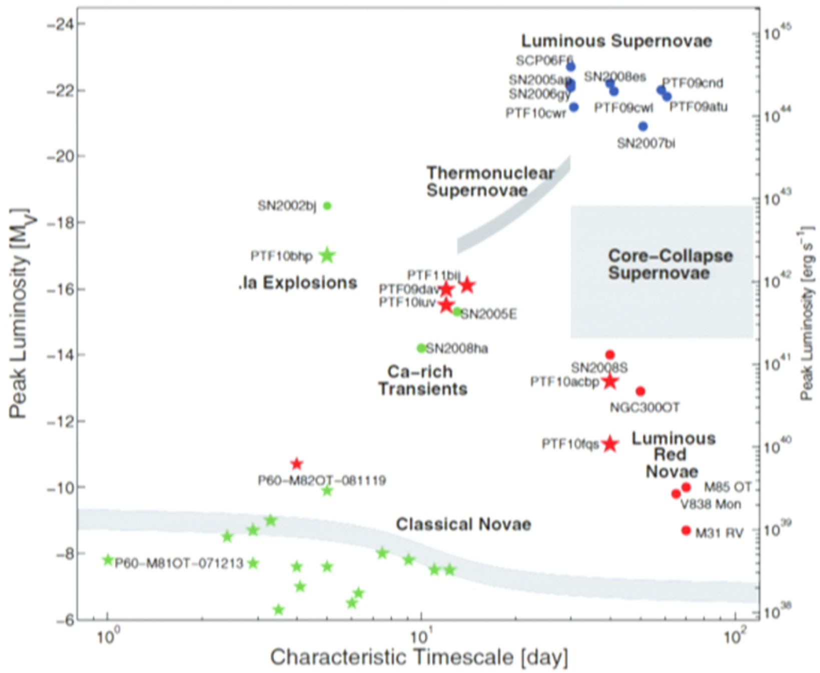

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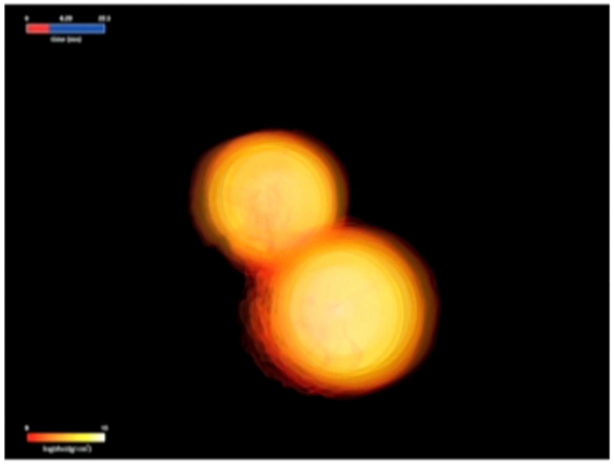


Rezzolla+ (2010)

Merger outcome:

1. Central HMNS or BH

2. Material ejected dynamically

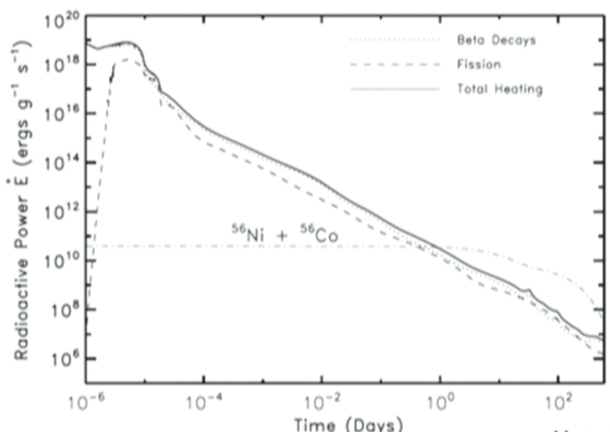
   Ruffert+ (1997), Rosswog+1999, Oechslin+2007, Hotokezaka+(2013), Bauswein+(2013)

3. Remnant disk

   Ruffert & Janka (1999), Oechslin & Janka (2006)

Neutron-rich ejecta undergoes radioactive decay over a long timescale:

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



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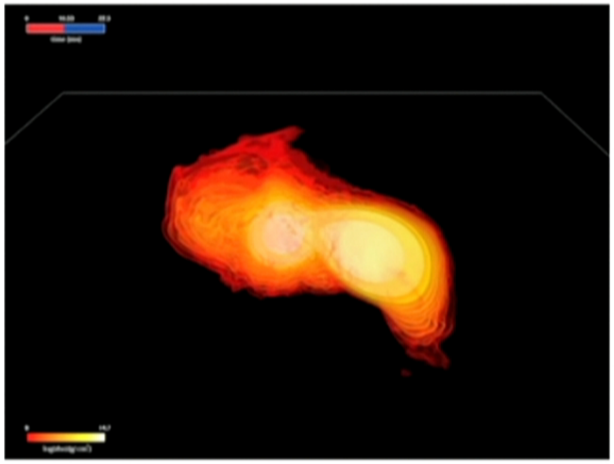

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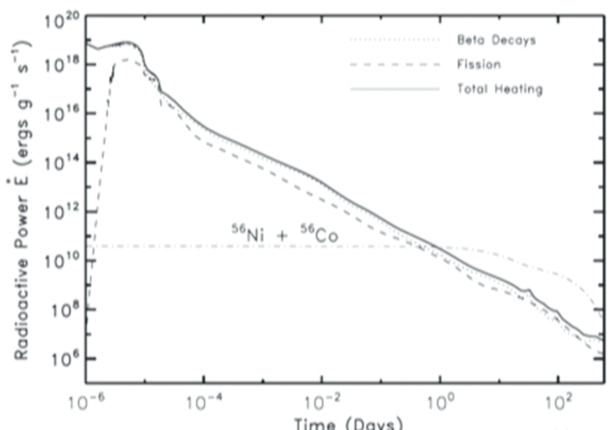

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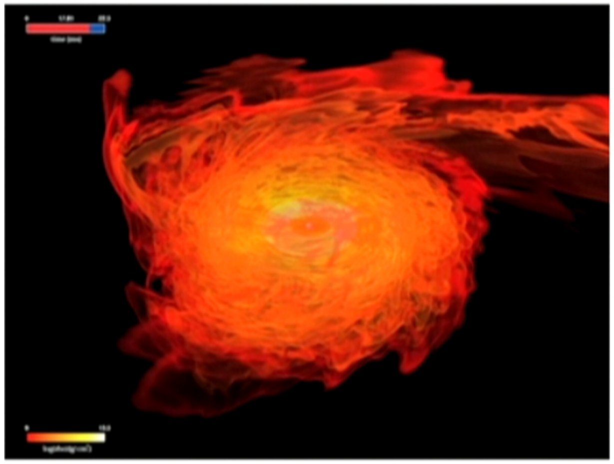

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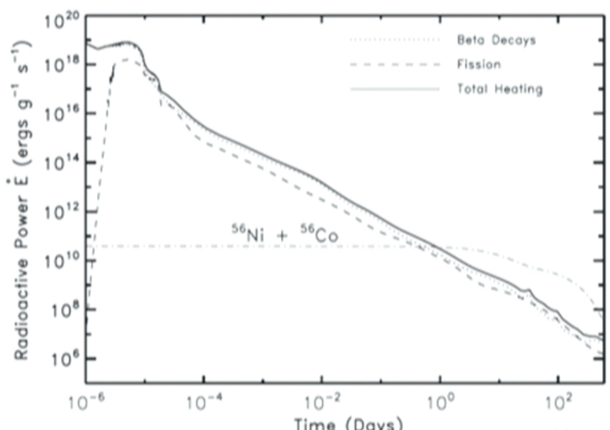

Metzger+(2010)

Kilonova: supernova-like transient

THE ASTROPHYSICAL JOURNAL, 507:L59–L62, 1998 November 1
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TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

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Princeton University Observatory, Princeton, NJ 08544-1001; lxl@astro.princeton.edu, bp@astro.princeton.edu
Received 1998 July 27; accepted 1998 August 26; published 1998 September 21

ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be

Transient peaks when diffusion time is comparable to the expansion time (like a supernova, but shorter & dimmer):

$$\epsilon = \frac{fc^2}{t} \quad \text{for } t_{\min} \le t \le t_{\max},\ t_{\min} \ll t_{\max}. \tag{5}$$

- smaller ejecta mass
- higher velocity

Kilonova: supernova-like transient

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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

e.g., Palenzuela+ (2013)

4) Late-time radio transient

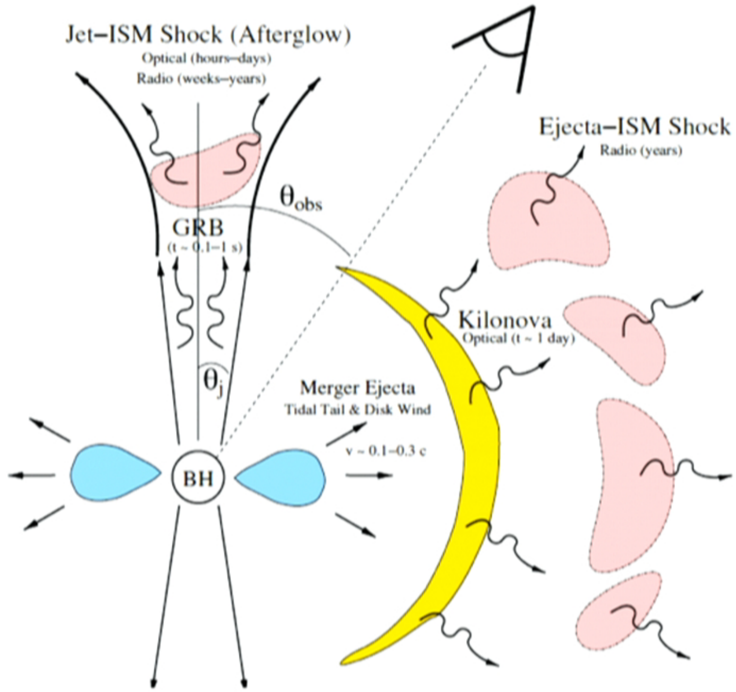
Nakar & Piran (2011)

5) Kilonova (dynamical ejecta)

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

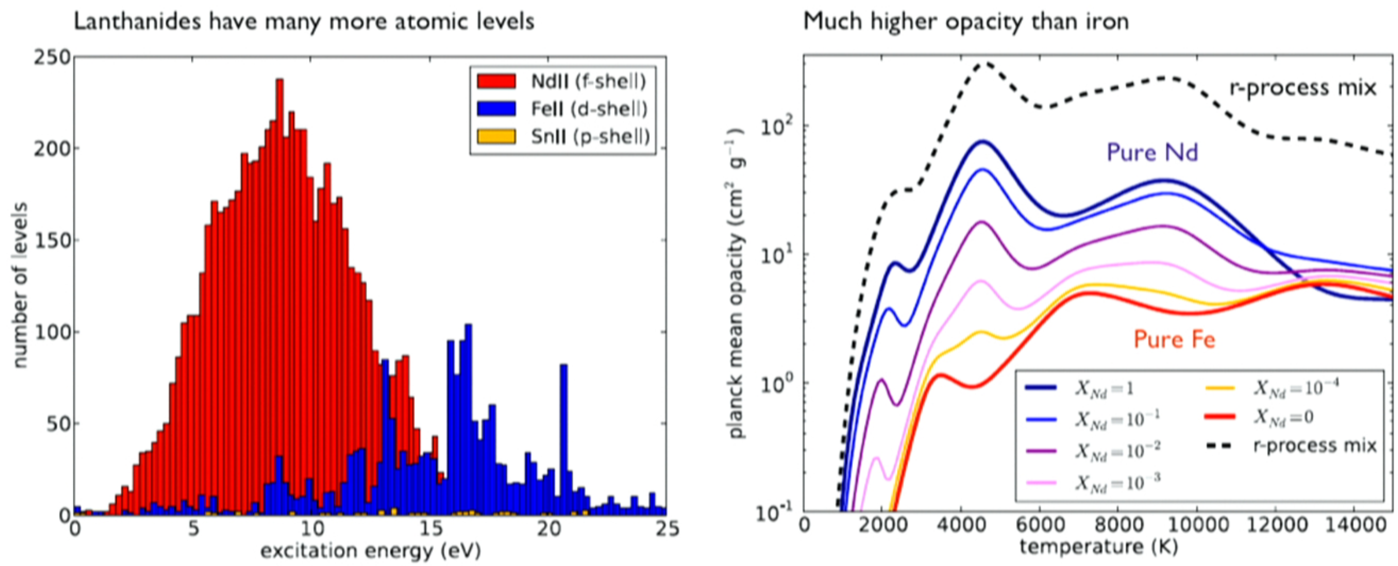
6) Kilonova (disk wind)

Metzger+ 2008, RF & Metzger (2013)



Metzger & Berger (2012)

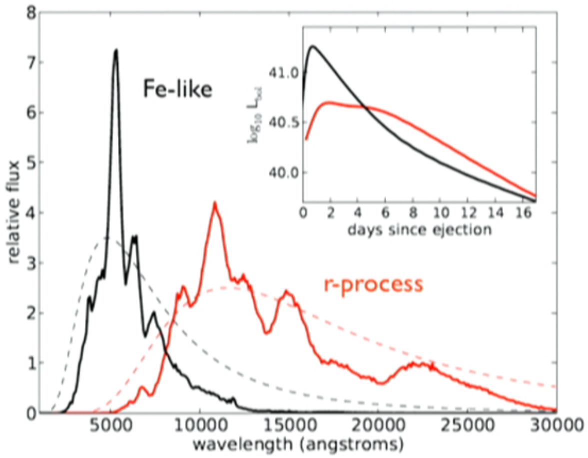
Opacity of Lanthanides



Kasen+ (2013)

Importance of composition: optical opacity

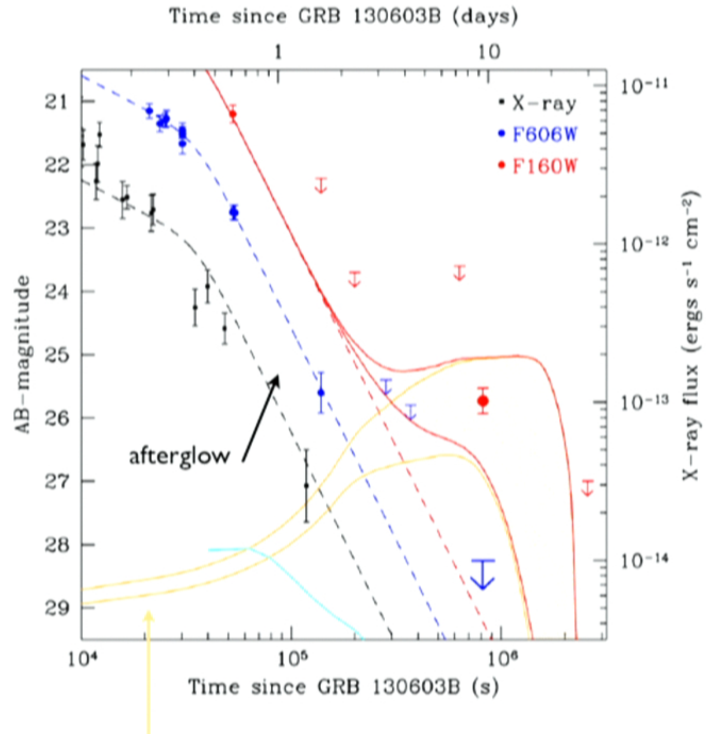
Theoretical kilonova spectra & light curves:



Kasen+ (2013)

r-process-dominated material generates IR transient

(large number of lines in optical)

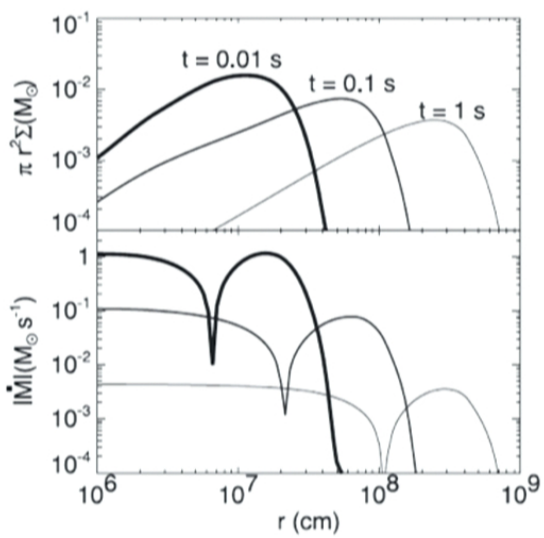


Kilonova models from Barnes & Kasen (2013)

Tanvir+ (2013)
also Berger+ (2013)

Disk contribution?

Evolution of surface density and accretion rate



Metzger+ (2008)

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

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

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

- Disk evolves on timescales long compared to the dynamical (orbital) time, due to viscous processes
- Weak interactions freeze-out as the disk spreads viscously: final Ye
- Gravitationally-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)

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

Multi-dimensional evolution of remnant accretion disk

ρ : density
p : pressure
$\mathbf{v}$: velocity
e_{int} : int. energy
Y_e : electron frac.

mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

momentum conservation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p = -\nabla \Phi + \frac{1}{\rho}\nabla \cdot \mathbb{T}$$

gas pressure — gravity — angular mom. transport

energy conservation:

$$\frac{De_{\mathrm{int}}}{Dt} - \frac{p}{\rho^2}\frac{D\rho}{Dt} = \frac{1}{\rho^2 \nu}\mathbb{T} : \mathbb{T} + Q_{\nu,\mathrm{abs}} - Q_{\nu,\mathrm{em}}$$

viscous heating — neutrino heating — neutrino cooling

lepton # conservation:

$$\frac{DY_e}{Dt} = \Gamma_{\nu,\mathrm{abs}} + \Gamma_{\nu,\mathrm{em}}$$

neutrino absorption — neutrino emission

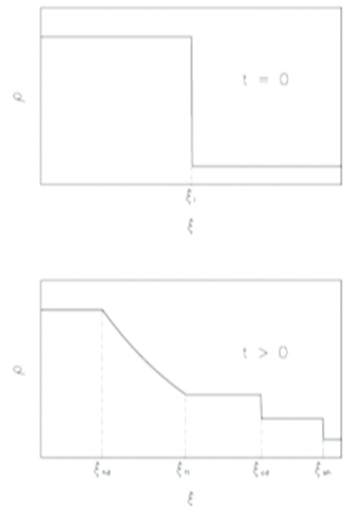
EOS:

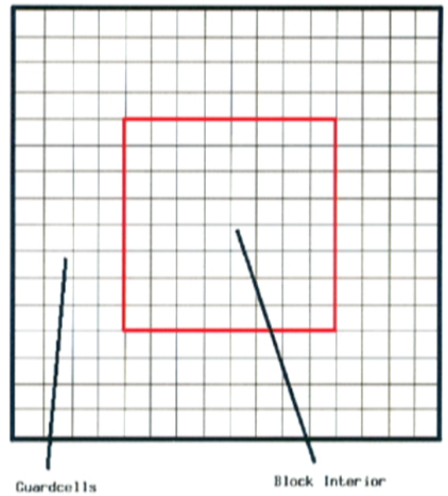
$$p = p(\rho, e_{\mathrm{int}}, Y_e) \qquad Y_e = \frac{n_e}{n} = \frac{n_e}{\rho/m_n}$$

Multi-dimensional evolution of remnant accretion disk

Hydrodynamics: FLASH

- Finite-volume
- Godunov-type method





Fryxell+ (2000)

Gravity: pseudo-Newtonian potential (local)

$$\nabla\Phi = \frac{GM}{r^{2-\beta}(r - r_h)^{\beta}}\hat{r}$$

Artemova+ (1996)

$$\beta = \frac{r_{\rm isco}}{r_h} - 1$$

$$r_h = \left[1 + \sqrt{1 - a^2}\right]\frac{GM}{c^2}$$

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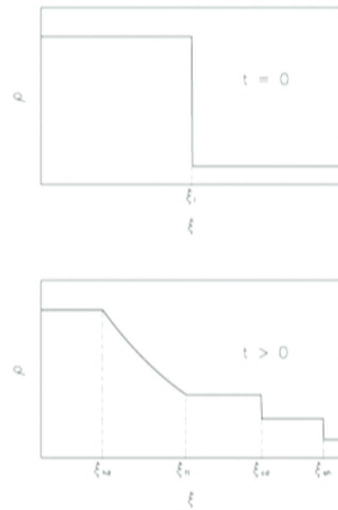

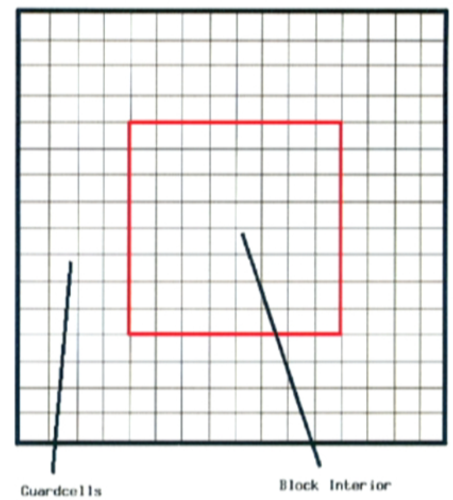

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Multi-dimensional evolution of remnant accretion disk

Angular momentum transport: alpha-viscosity

Shear stress tensor:

$$T_{r\phi} = \rho\nu r \frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right)$$

$$T_{\theta\phi} = \rho\nu \frac{\sin\theta}{r}\frac{\partial}{\partial\theta}\left(\frac{v_\phi}{\sin\theta}\right)$$

Kinematic viscosity:

$$\nu = \alpha\frac{p/\rho}{\Omega_K(r)}$$

Shakura & Sunyaev (1973)

Local diffusion operator: limits simulation time step if explicit

Multi-dimensional evolution of remnant accretion disk

Angular momentum transport: alpha-viscosity

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Kinematic viscosity: $$\nu = \alpha \frac{p/\rho}{\Omega_K(r)}$$ Shakura & Sunyaev (1973)

Local diffusion operator: limits simulation time step if explicit

Multi-dimensional evolution of remnant accretion disk

Neutrino physics:

- charged-current weak interactions (thermal spectrum, 2 species)

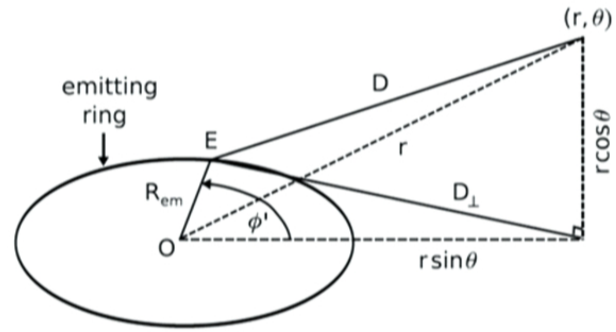
- leakage scheme (emission):

$$\Gamma_{\nu,\mathrm{em}} = \frac{Q^0_{\nu,\mathrm{em}}}{1 + t_{\mathrm{diff}}/t_{\mathrm{n-loss}}}$$

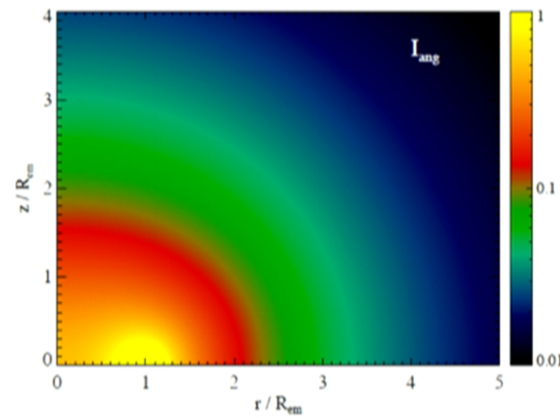
$$Q_{\nu,\mathrm{em}} = \frac{Q^0_{\nu,\mathrm{em}}}{1 + t_{\mathrm{diff}}/t_{\mathrm{e-loss}}}$$

- lightbulb-type self-irradiation (absorption, non-local) →

$$Q_{\nu,\mathrm{abs}} \sim \frac{L_\nu}{m_n}\frac{\sigma_\nu}{r^2} \qquad \Gamma_{\nu,\mathrm{abs}} \sim \frac{L_\nu}{\langle\varepsilon_\nu\rangle}\frac{\sigma_\nu}{r^2}$$



Angular distribution of neutrino irradiation



RF & Metzger (2013), MNRAS

Multi-dimensional evolution of remnant accretion disk

Neutrino physics:

- charged-current weak interactions (thermal spectrum, 2 species)

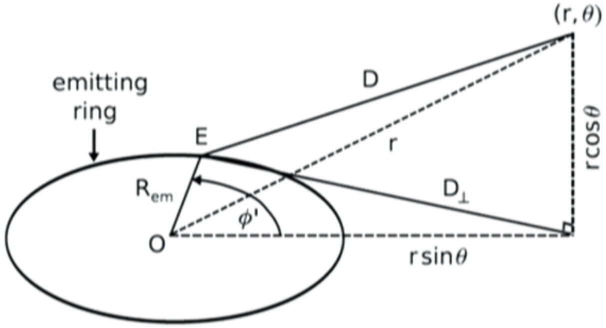
- leakage scheme (emission):

$$\Gamma_{\nu,\mathrm{em}} = \frac{Q^0_{\nu,\mathrm{em}}}{1 + t_{\mathrm{diff}}/t_{\mathrm{n-loss}}}$$

$$Q_{\nu,\mathrm{em}} = \frac{Q^0_{\nu,\mathrm{em}}}{1 + t_{\mathrm{diff}}/t_{\mathrm{e-loss}}}$$

- lightbulb-type self-irradiation (absorption, non-local)

$$Q_{\nu,\mathrm{abs}} \sim \frac{L_\nu}{m_n}\frac{\sigma_\nu}{r^2} \qquad \Gamma_{\nu,\mathrm{abs}} \sim \frac{L_\nu}{\langle\varepsilon_\nu\rangle}\frac{\sigma_\nu}{r^2}$$



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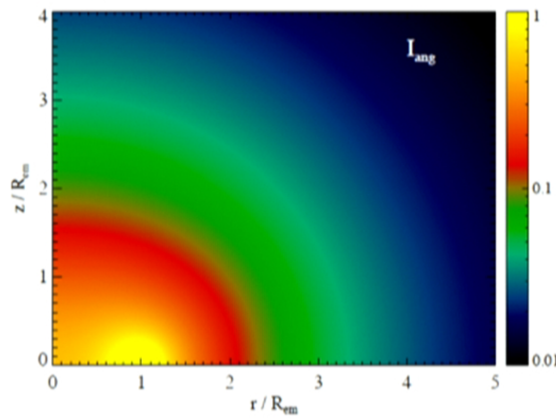

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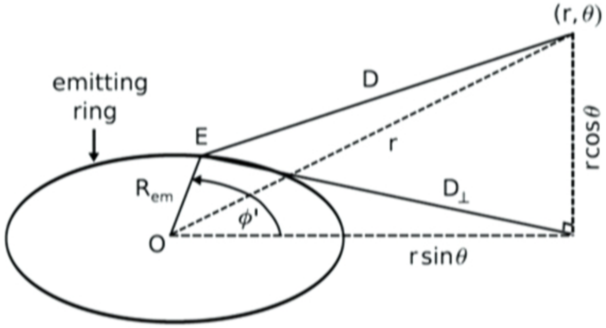

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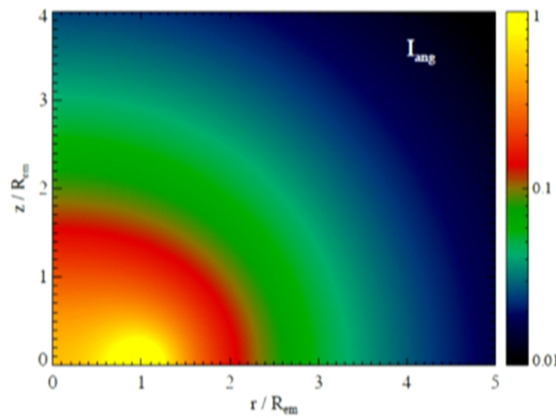
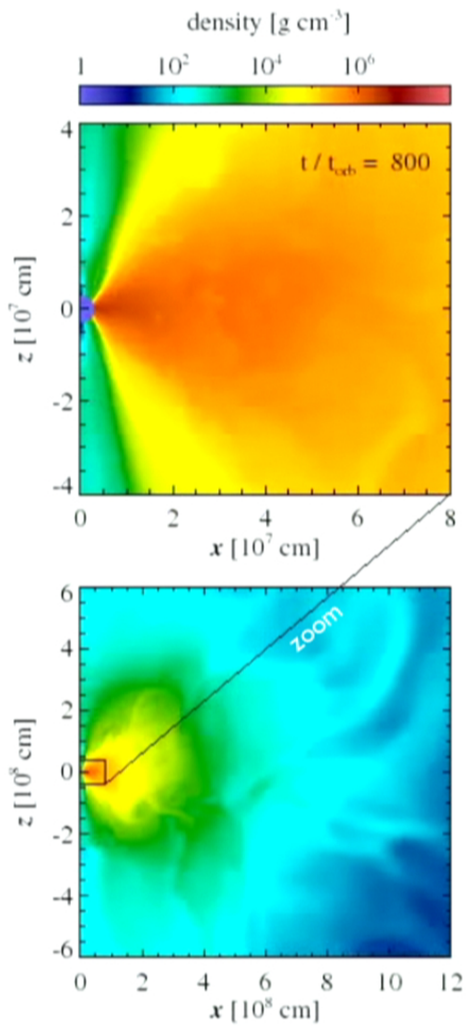


RF & Metzger (2013), MNRAS

Multi-dimensional evolution of remnant accretion disk

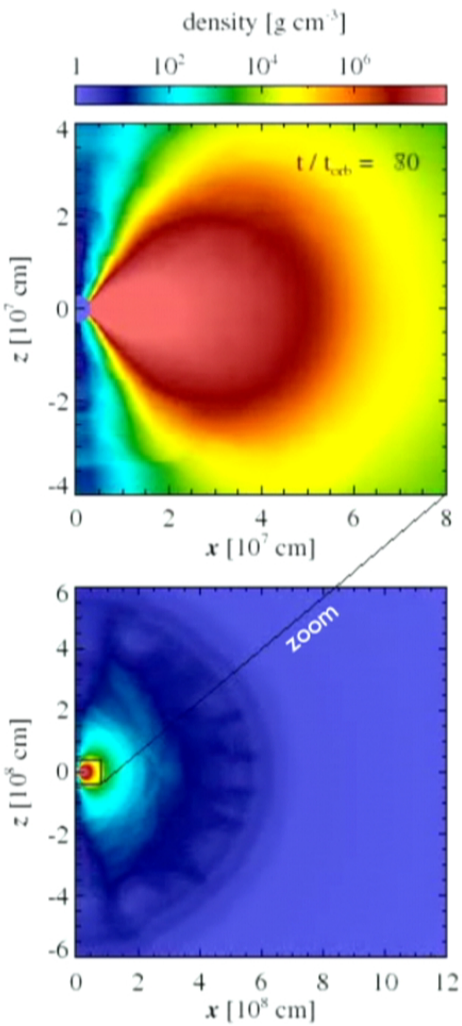
- Helmholtz EOS with NSE abundances (n,p,alpha) $p = p(\rho, e_{\rm int}, Y_e)$
- Solve in spherical polar coordinates, axisymmetry (r, theta)
- Initial condition: equilibrium torus
- Boundary conditions: reflecting in radius, outflow in theta
- Grid size: (192-384 logarithmic in radius) x (56-112 uniform in cos(theta))
- Run on NERSC Carver, ~12 hours on 48 cpus



Wind from remnant Accretion Disk

- Neutrino cooling shuts down as disks spreads (temperature decreases)
- Viscous heating & nuclear recombination are unbalanced
- Fraction ~10% of initial disk mass ejected, ~1E-3 to 1E-2 solar masses
- Material is neutron-rich (Ye ~ 0.2)

RF & Metzger (2013), MNRAS



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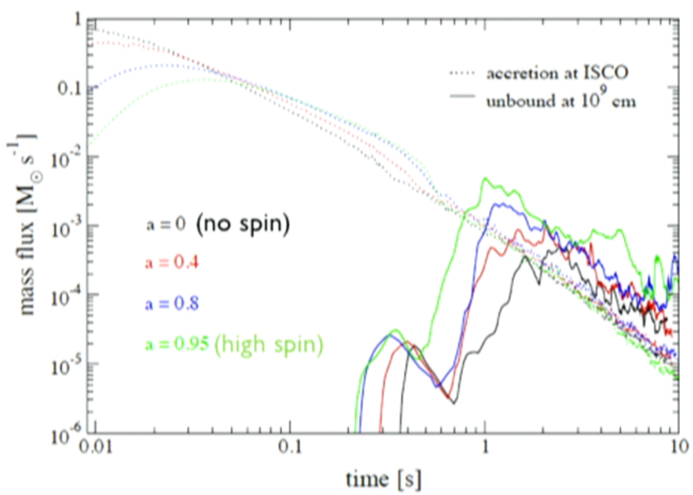
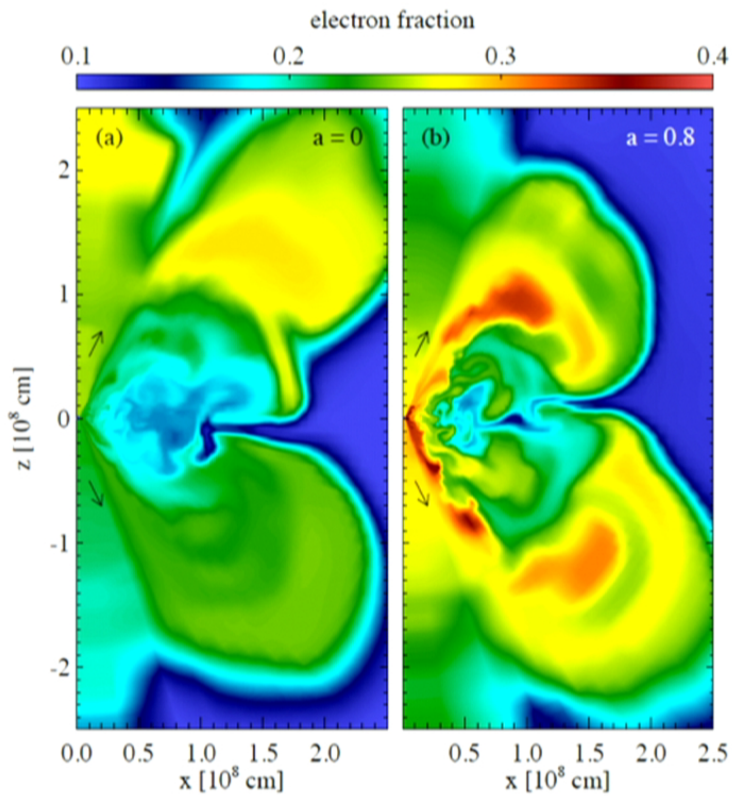
Effect of BH spin on Disk Wind

Mass ejection as a function of time (solid lines):





RF, Kasen, Metzger, Quataert (2015), MNRAS

(see also Just et al. 2015)

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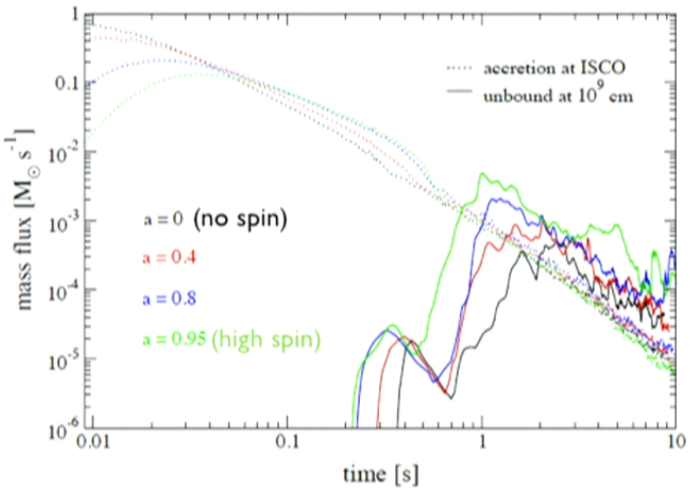

RF, Kasen, Metzger, Quataert (2015), MNRAS

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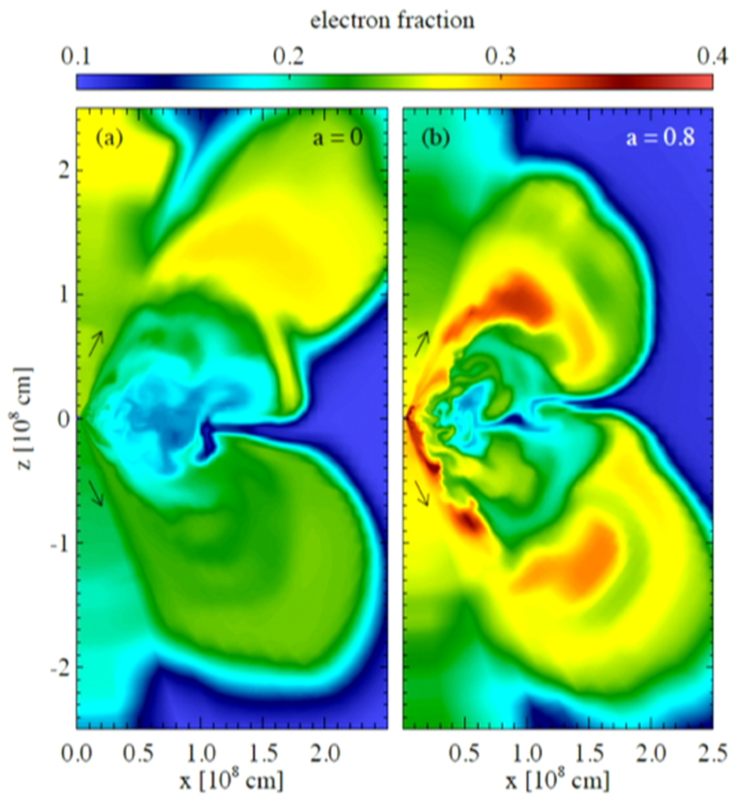
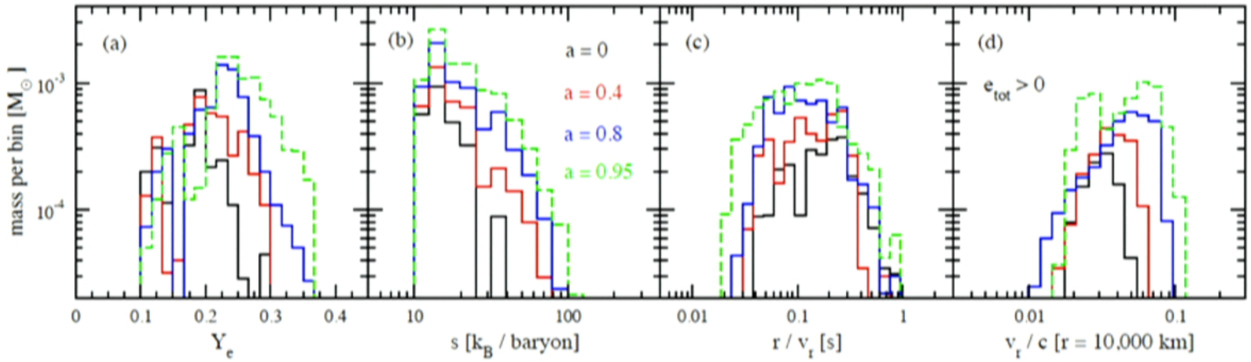
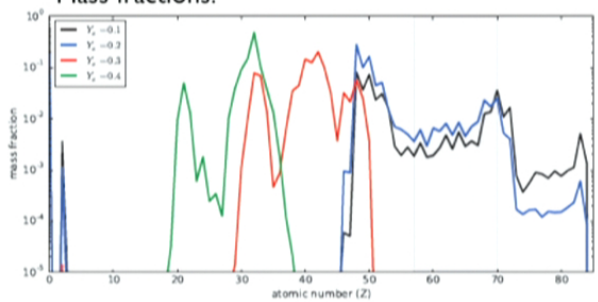


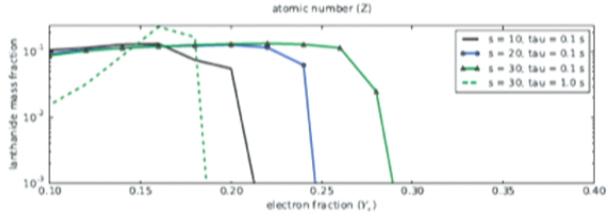
Effect of BH spin on Disk Wind

Nucleosynthesis-relevant quantities in the wind:



Mass fractions:





RF, Kasen, Metzger, Quataert (2015), MNRAS

Thermodynamic trajectories with

$$s \sim 20 \mathrm{k}_B / \text{ baryon}$$

$$t_{\rm exp} \sim 0.1 \text{ s}$$

Yield critical Ye for Lanthanide formation:

$$Y_{e,crit} \sim 0.25$$

Kasen, RF, & Metzger (2014), arXiv:1411.3726

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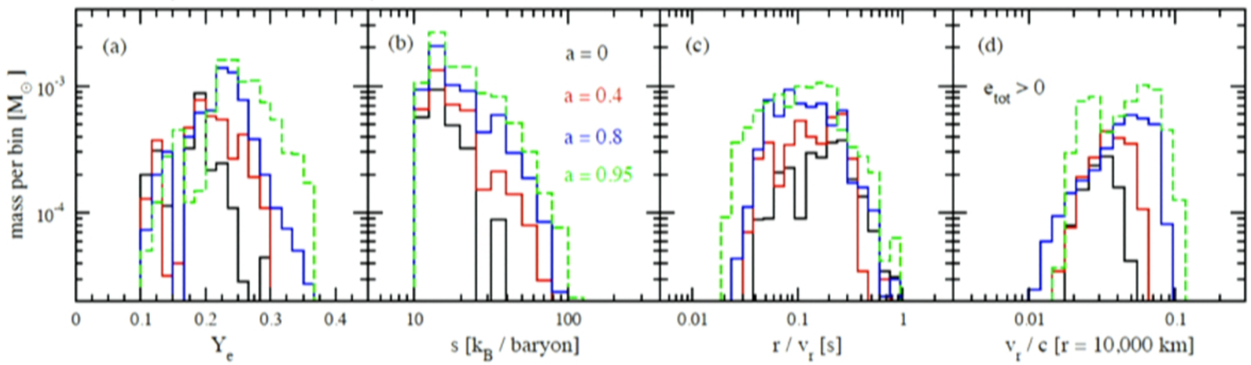

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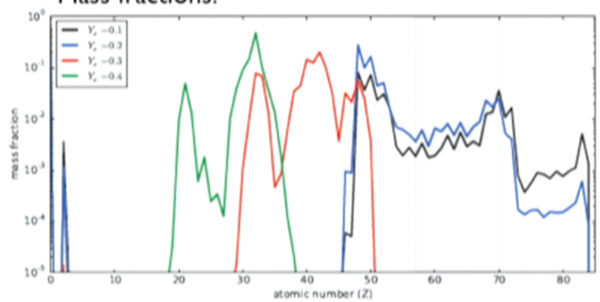

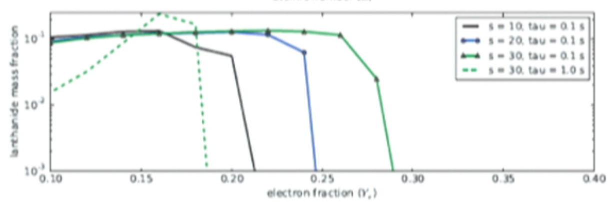

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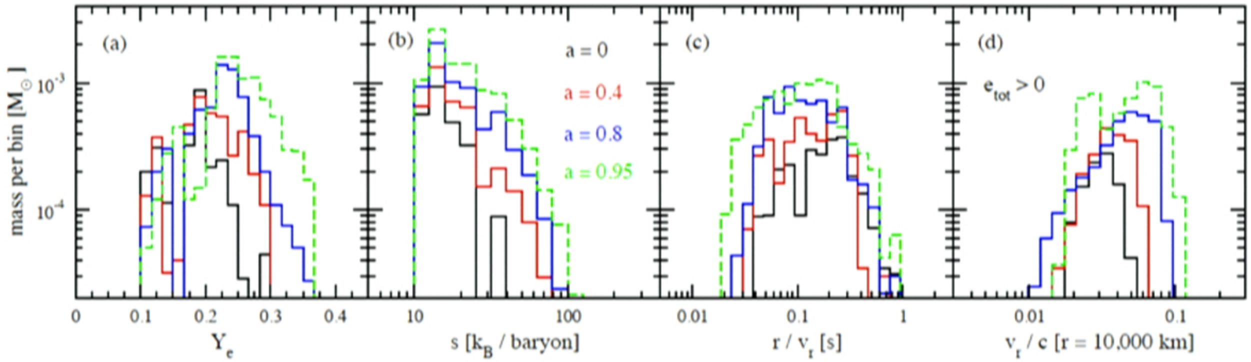

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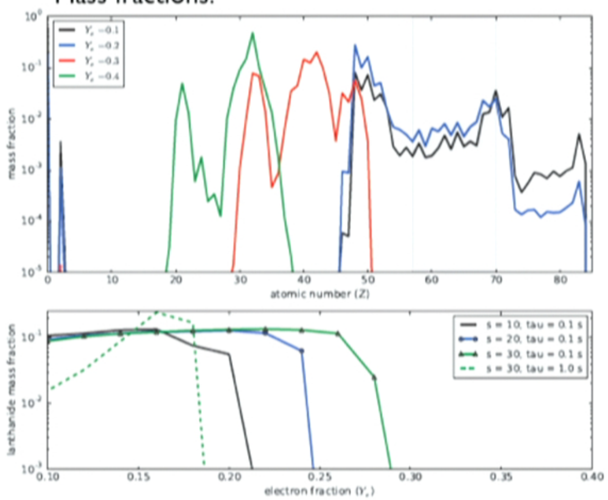

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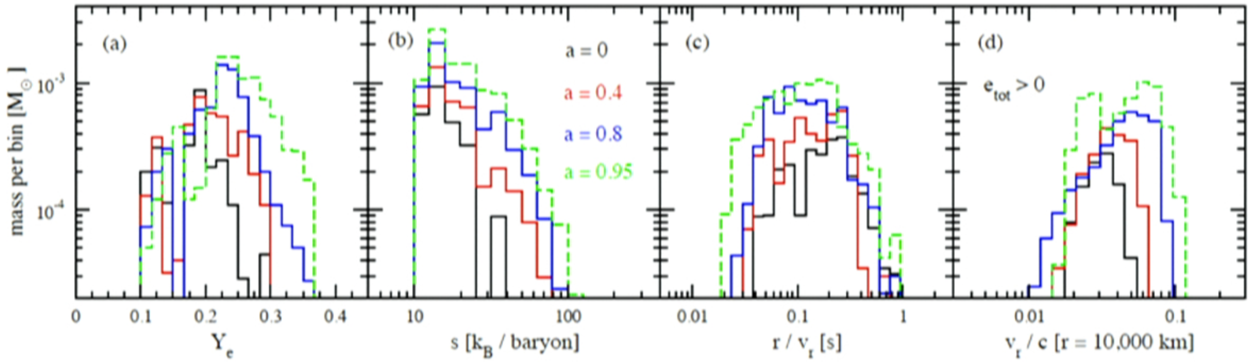

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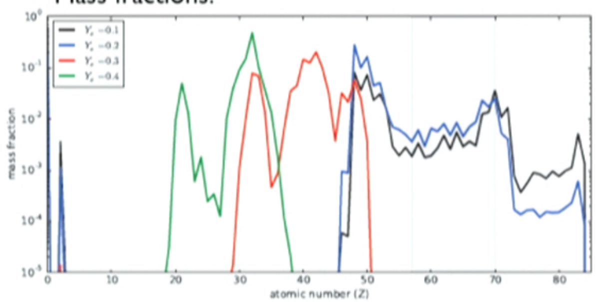

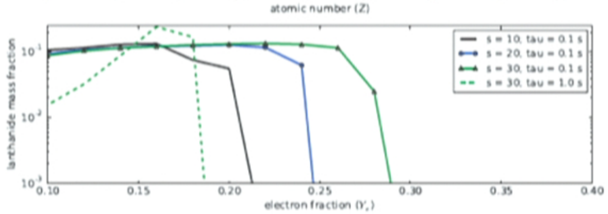

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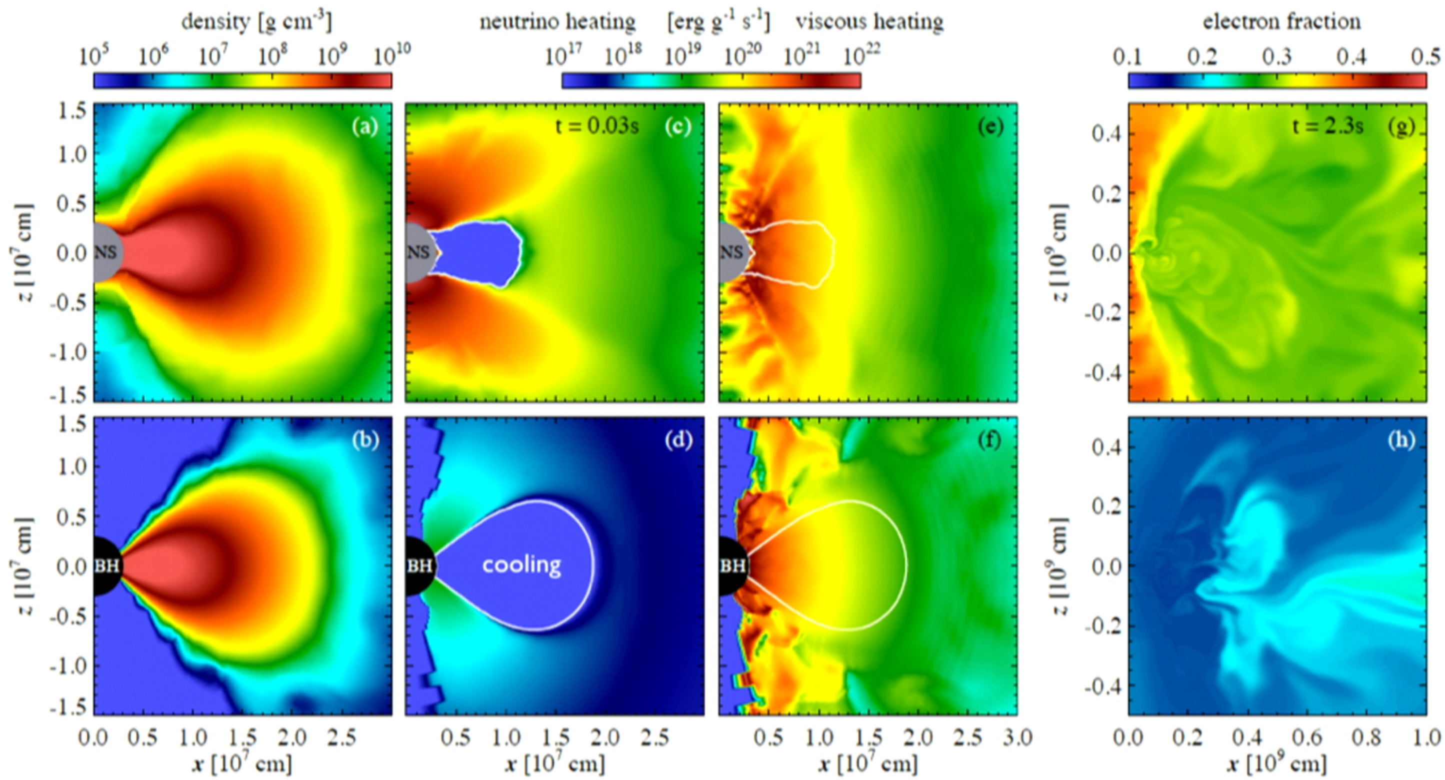
Hypermassive NS vs. BH



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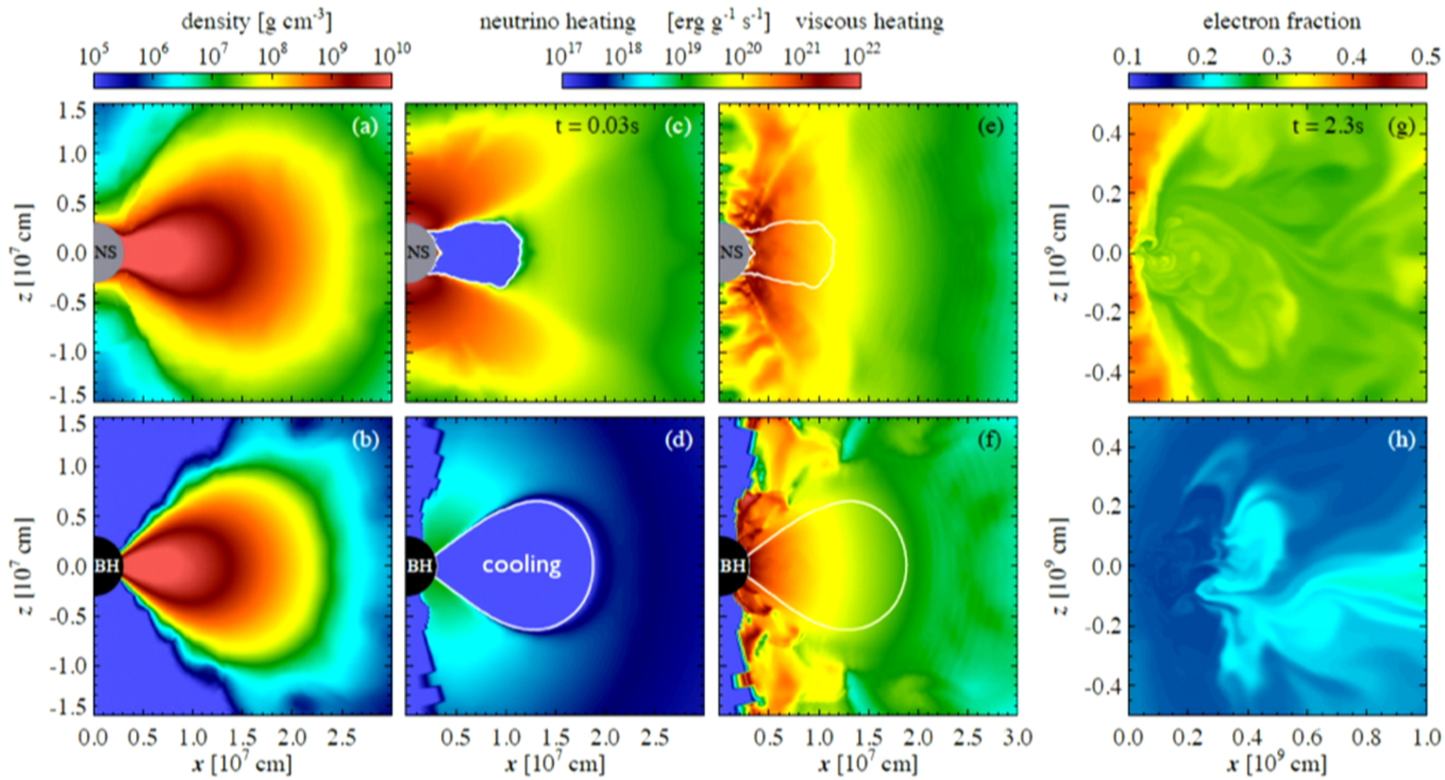

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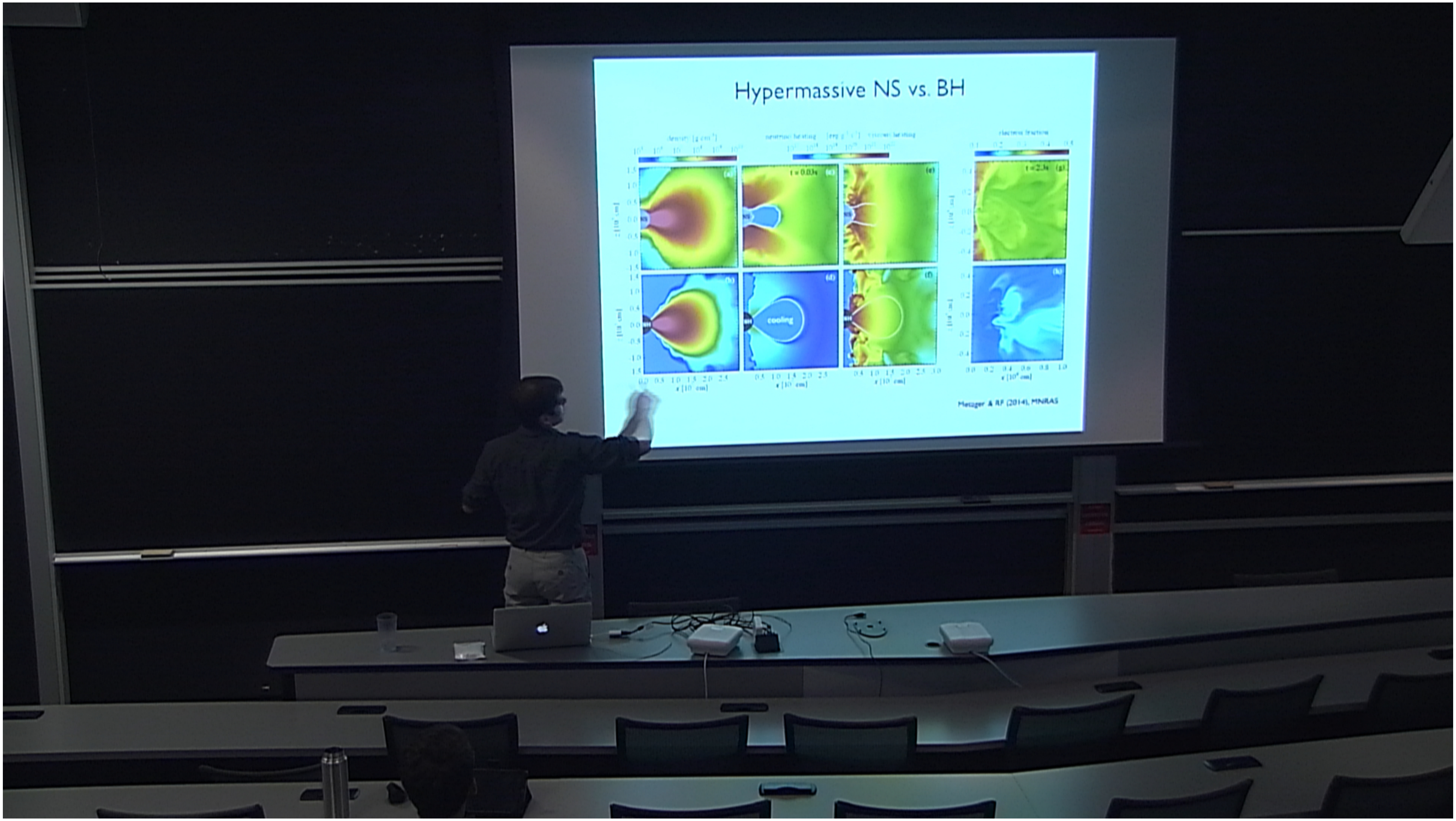
Hypermassive NS vs. BH
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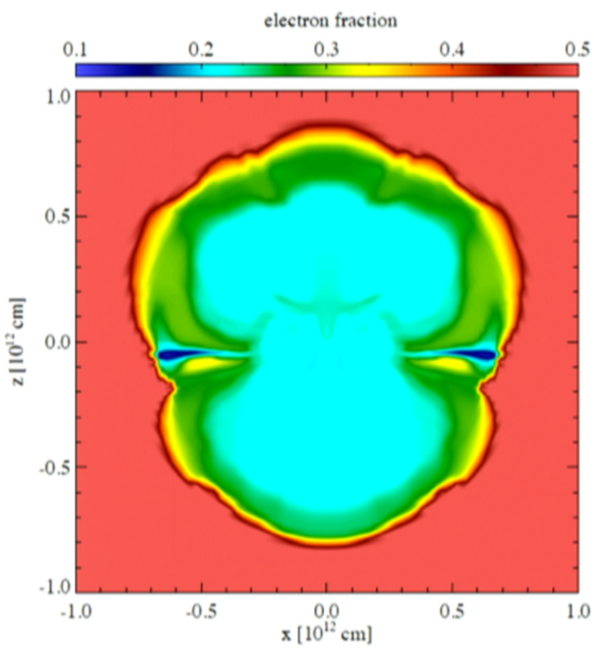
Metzger & RF (2014), MNRAS

Observational implications: radiative transfer

Evolve disk wind until homologous expansion:



RF, Kasen, Metzger, Quataert (2015), MNRAS

Optica/IR radiative transfer with SEDONA:

Kasen+ (2006)

- Monte Carlo method for expanding media
- Wavelength dependent transfer

Need opacity prescription:

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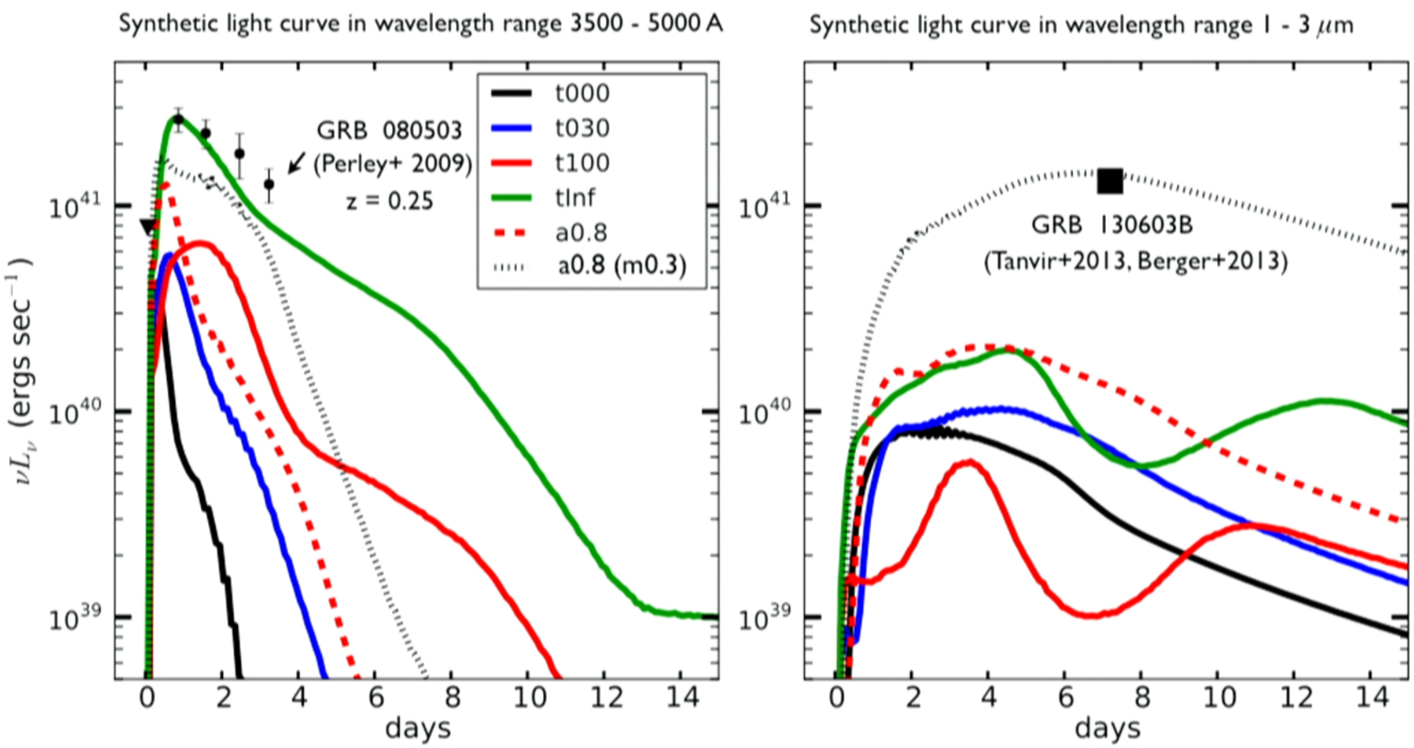
Disk wind contribution to Kilonova



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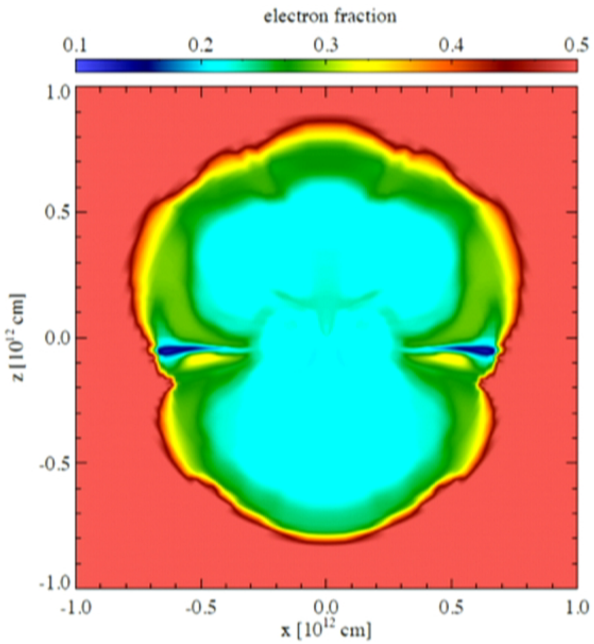

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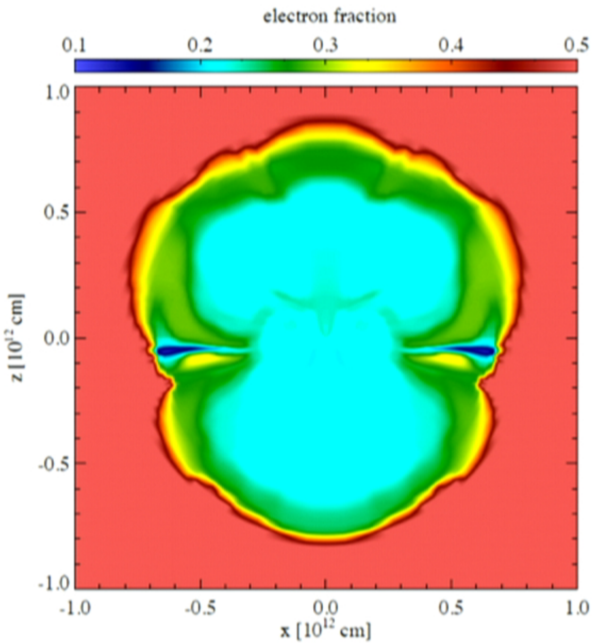

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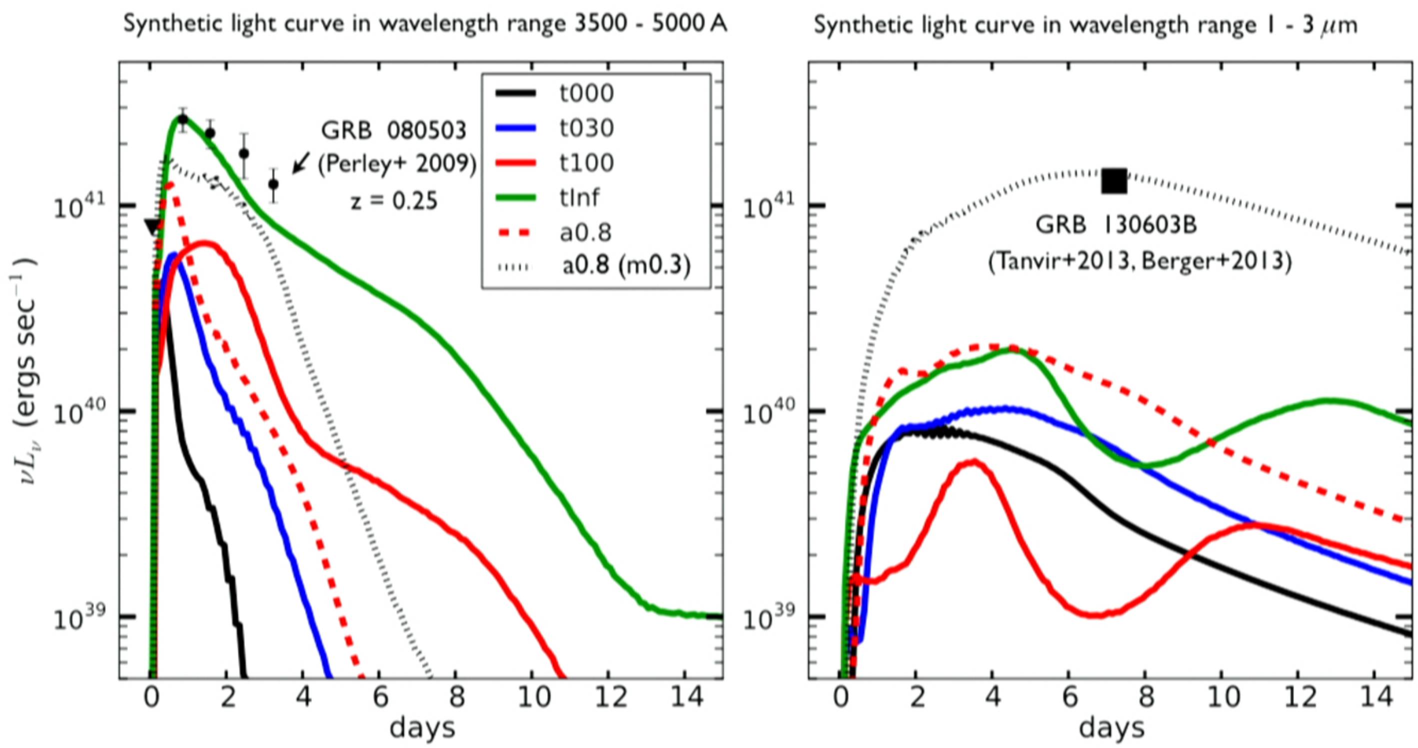

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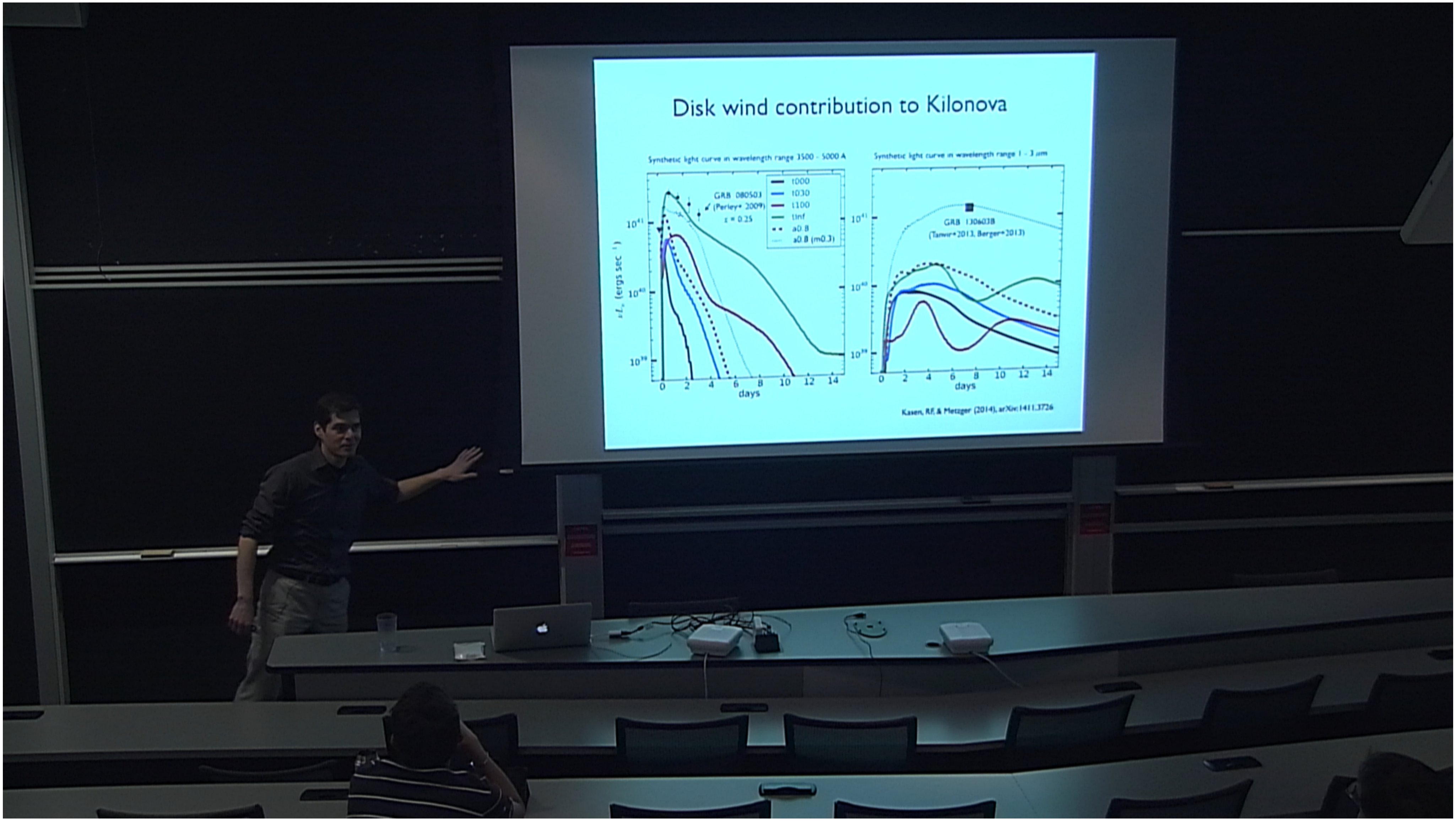
Disk wind contribution to Kilonova
Synthetic light curve in wavelength range 3500 - 5000 A
Synthetic light curve in wavelength range 1 - 3 μm
GRB 080503
(Perley+ 2009)
ε = 0.25
GRB 130603B
(Tanvir+2013, Berger+2013)
t000
t030
t100
tinf
a0.8
a0.8 (m0.3)
days
days
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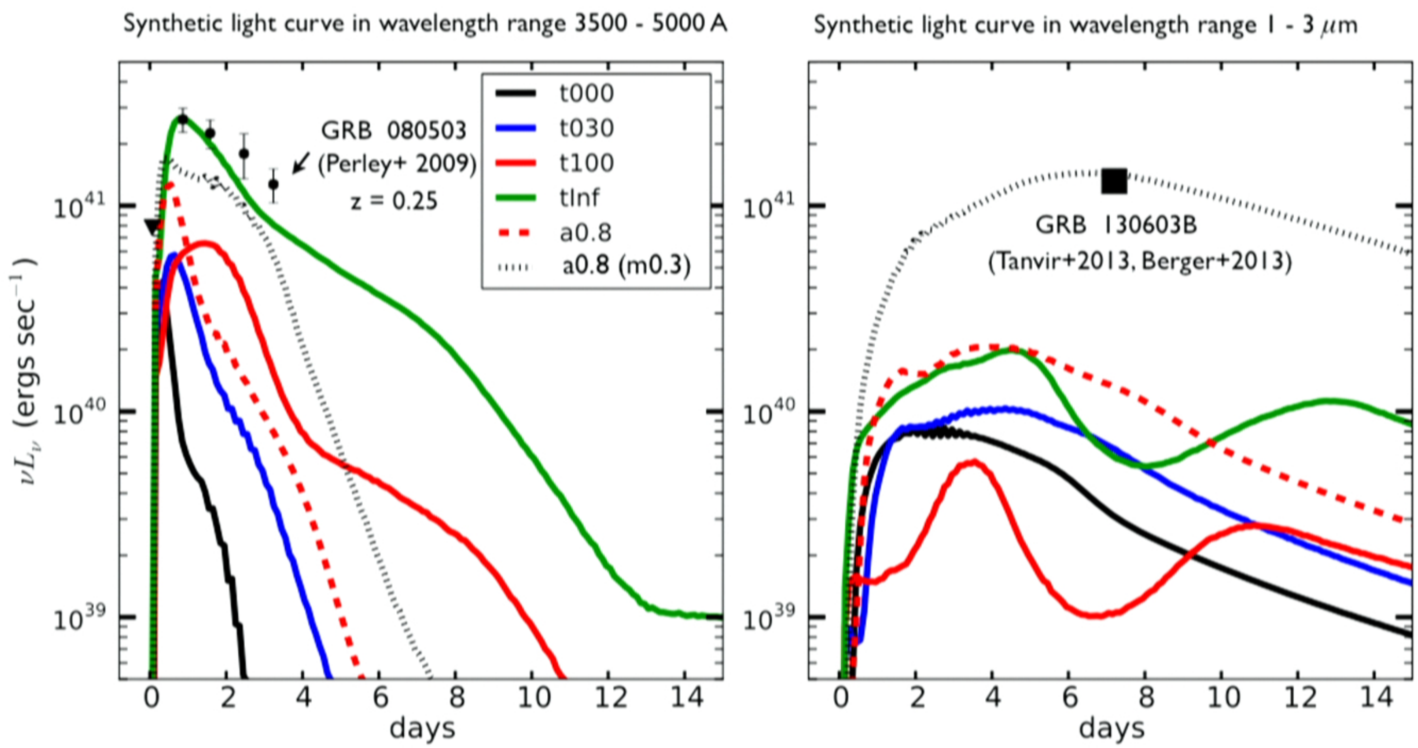

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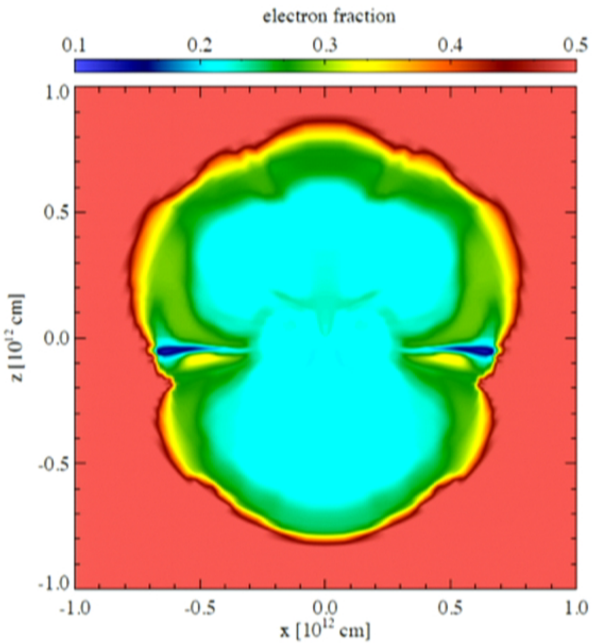

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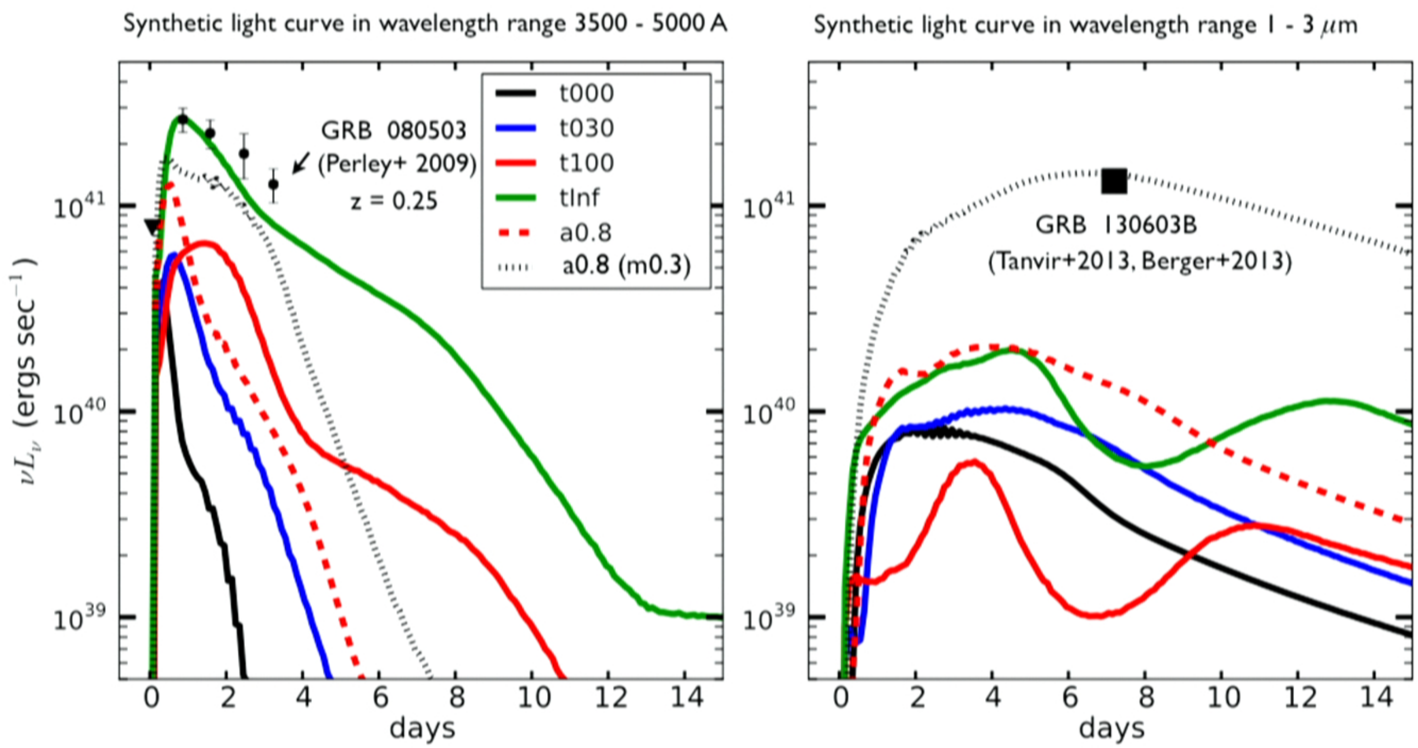

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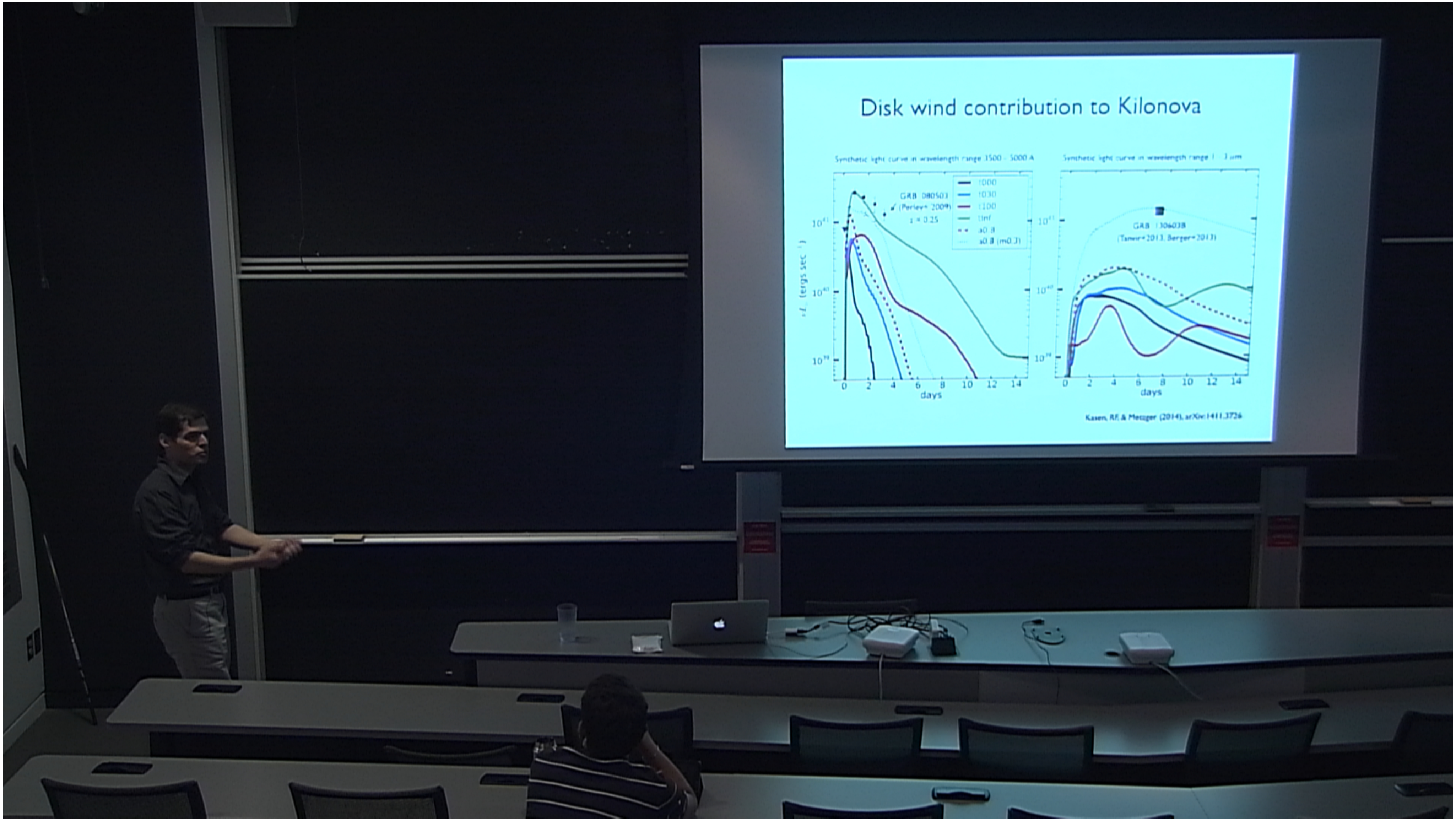

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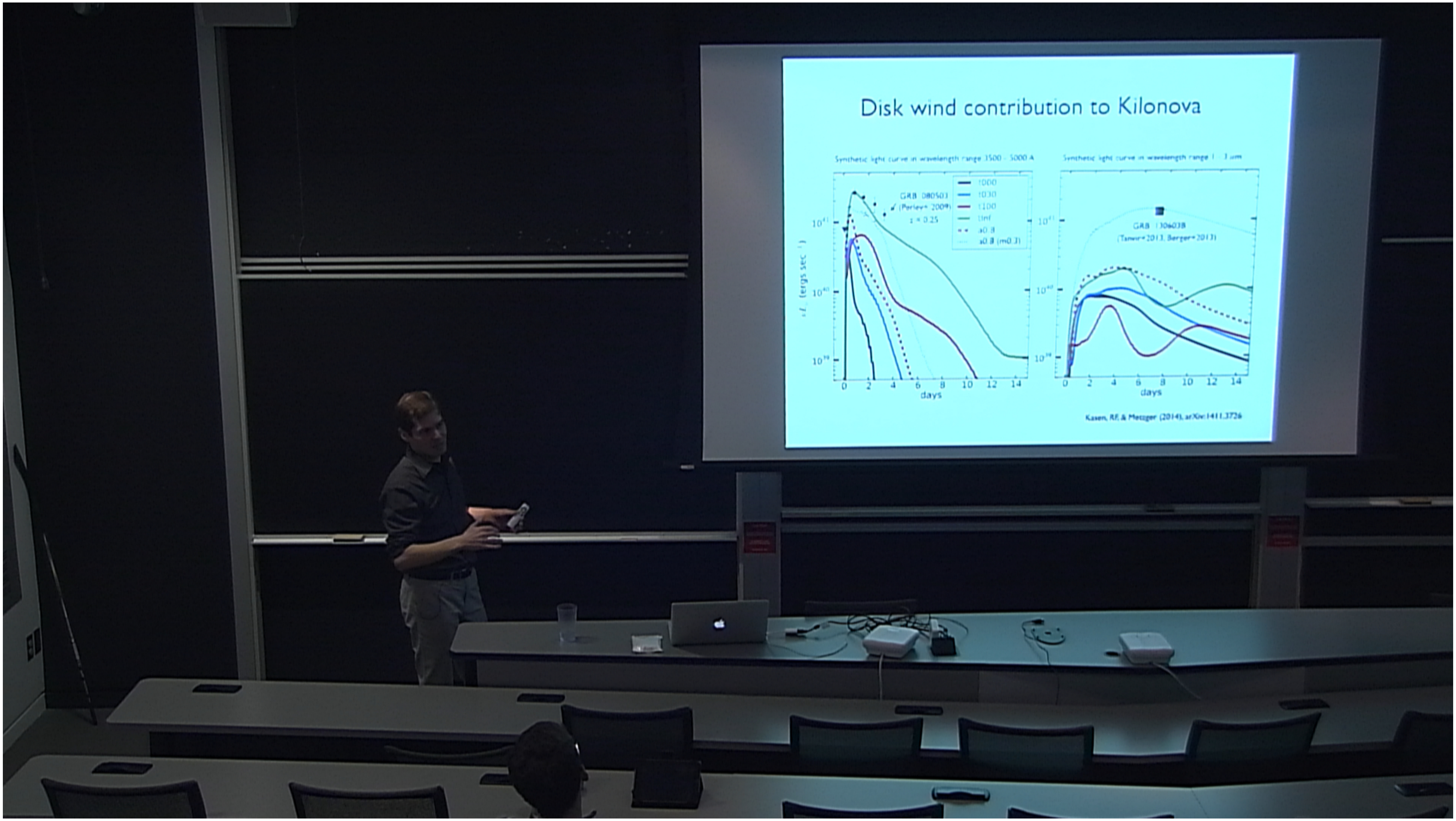

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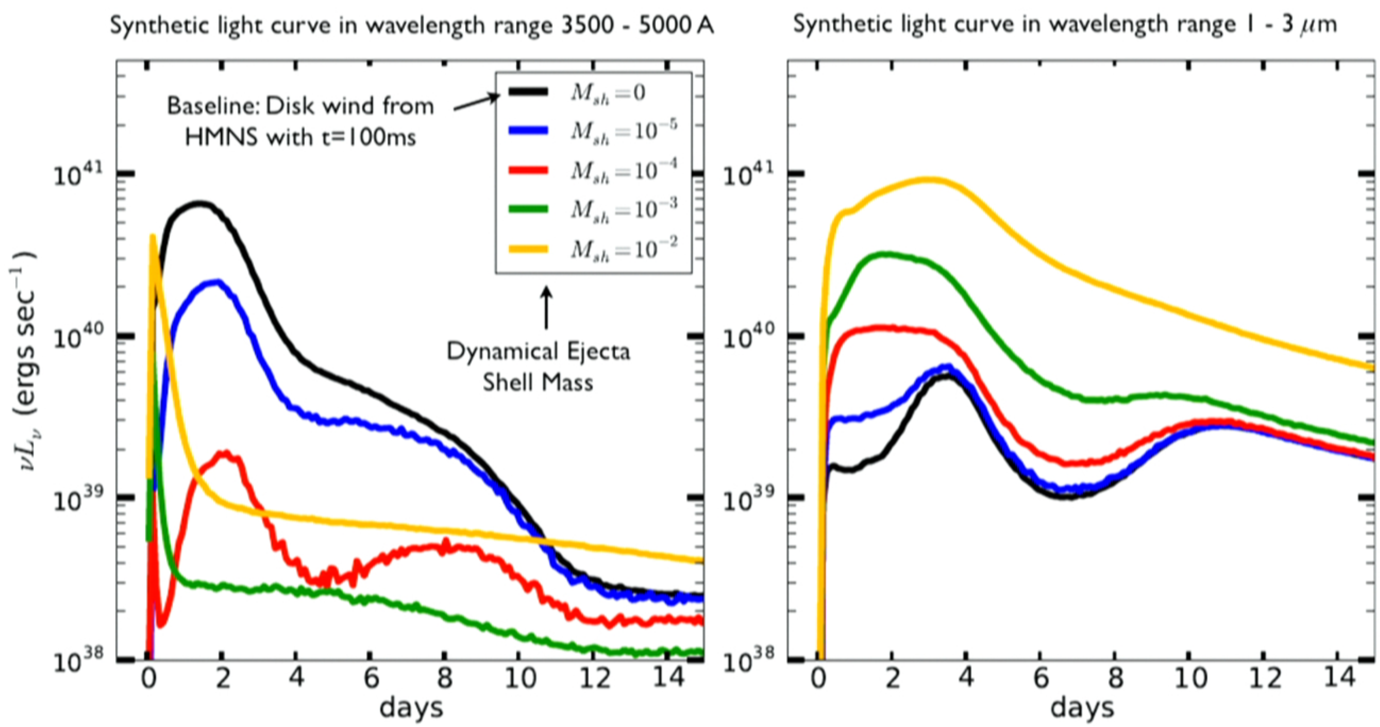
Adding (spherical) dynamical ejecta



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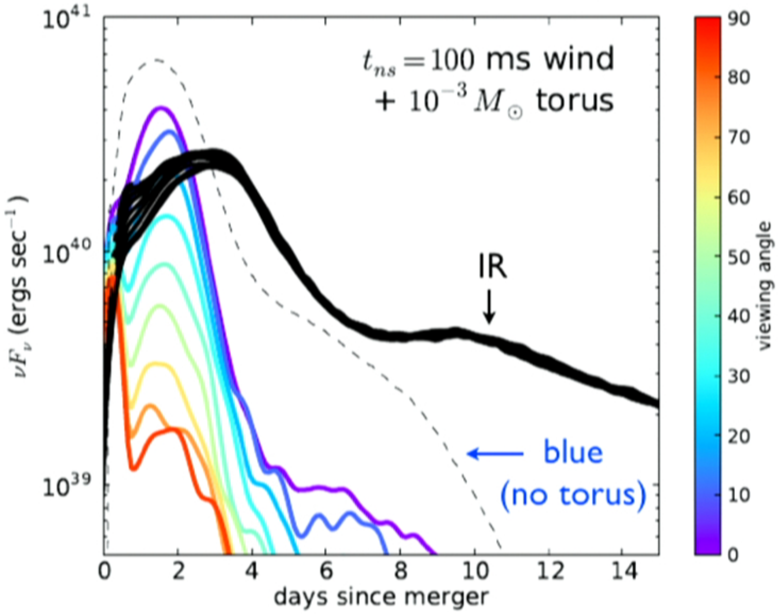
BH-NS mergers: viewing angle dependence



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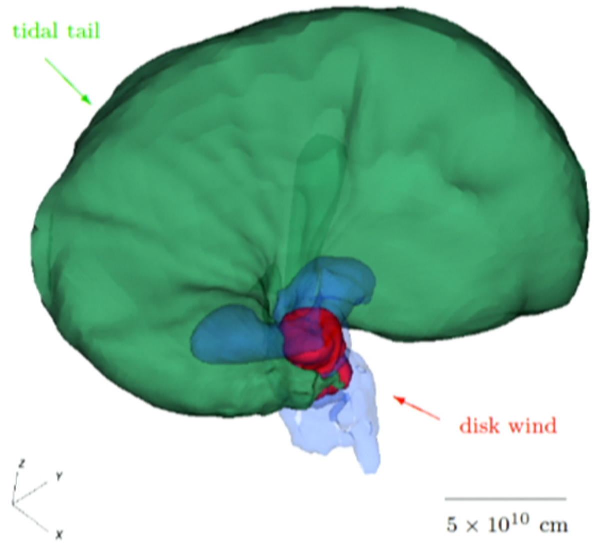

RF, Quataert, Schwab, Kasen & Rosswog (2014)
arXiv:1412.5882

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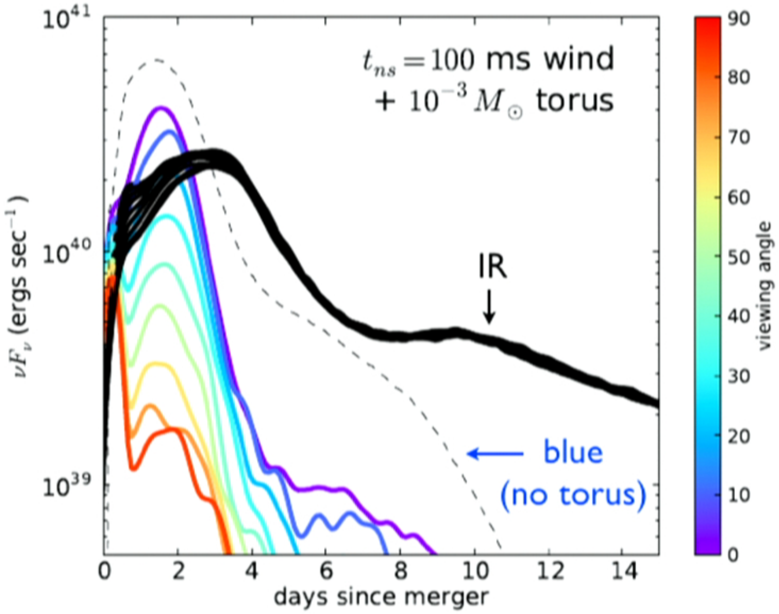
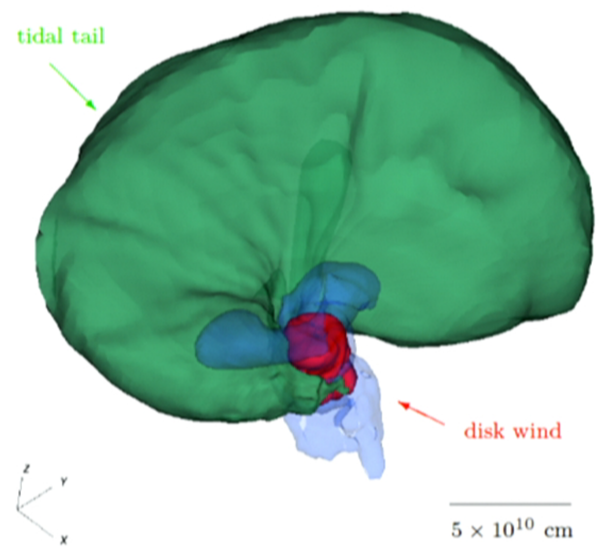
3500 - 5000 A light curve as fn. of viewing angle



Kasen, RF, & Metzger (2014), arXiv:1411.3726

BH-NS merger remnant:



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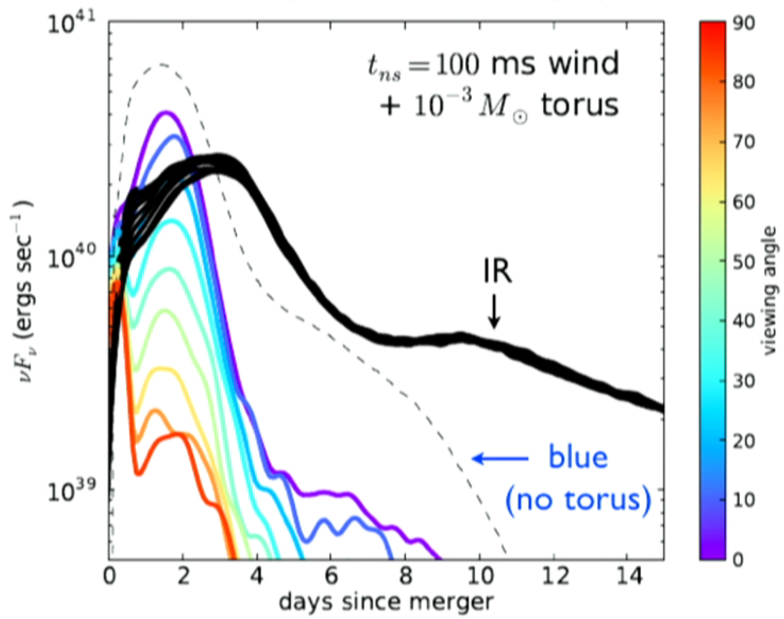

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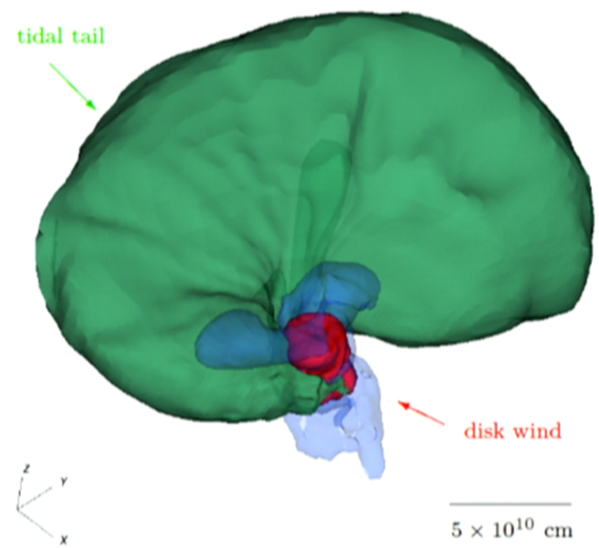

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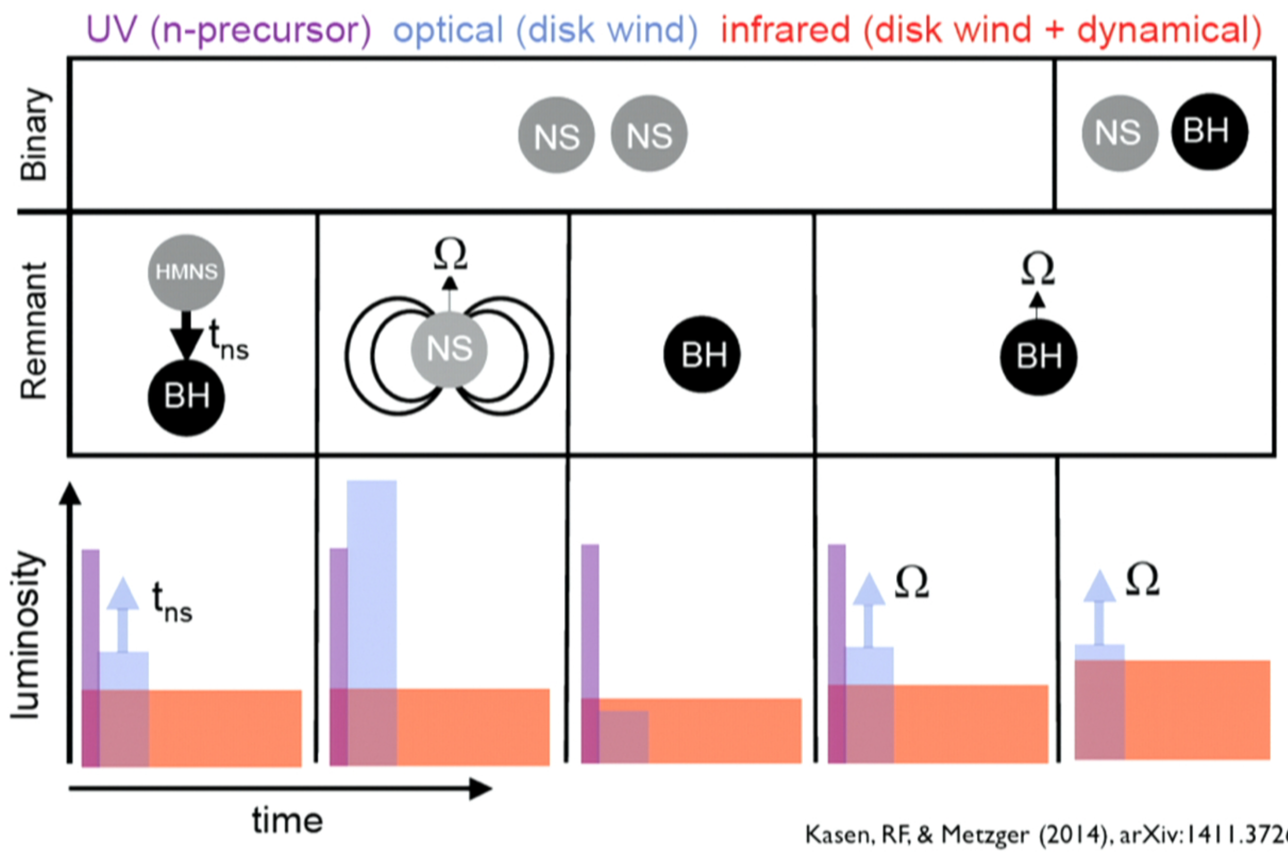
Diversity of Outcomes & Transients



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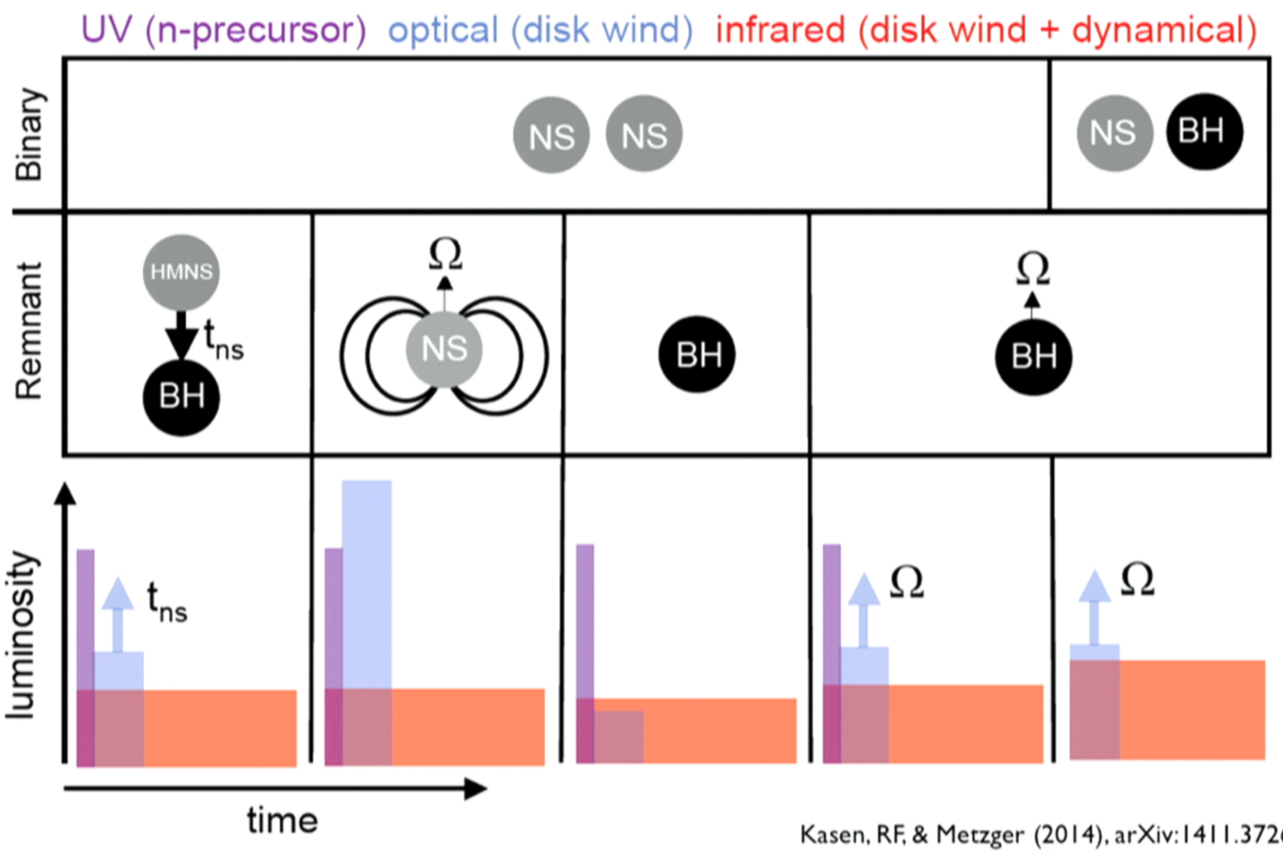

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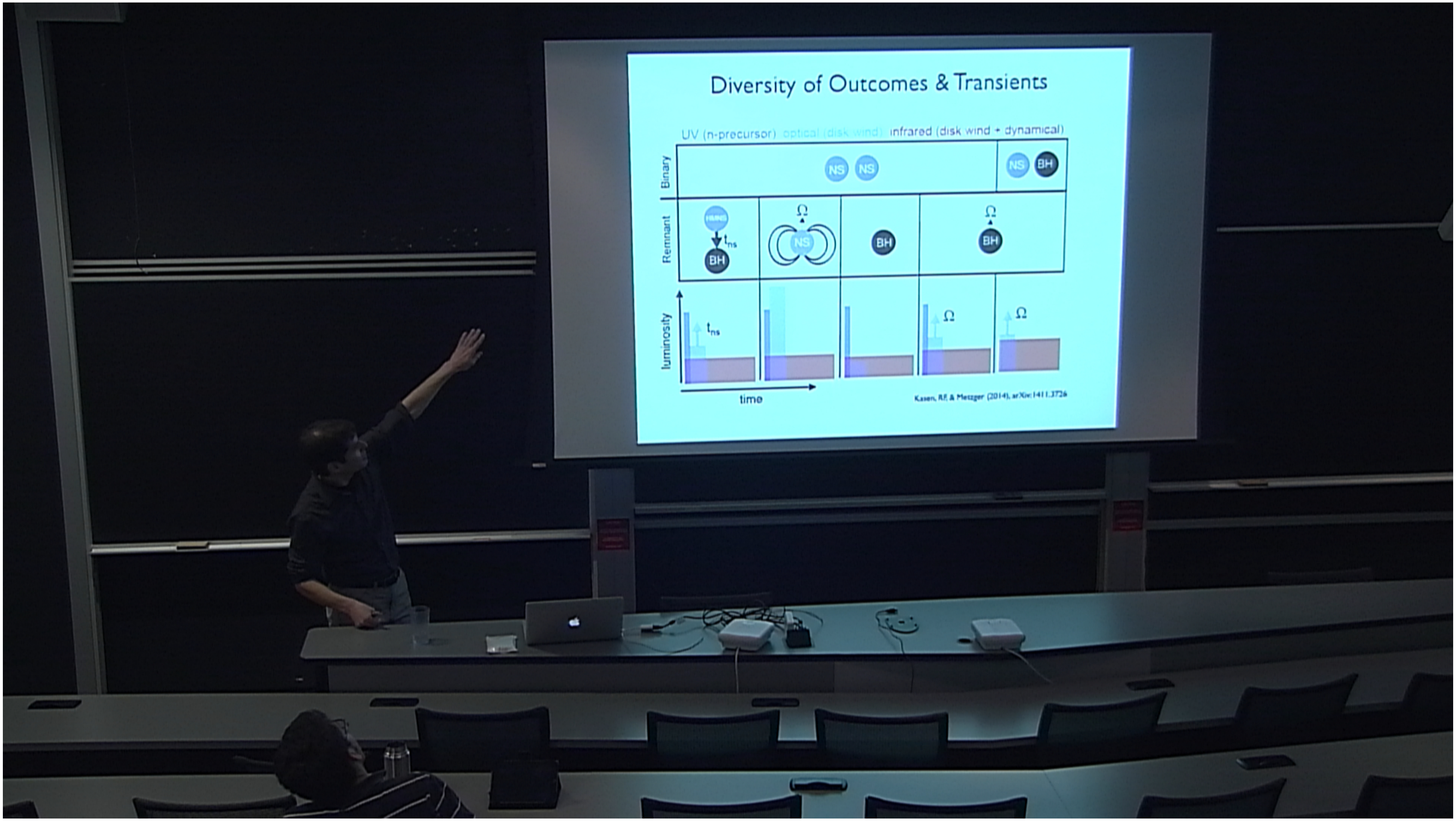
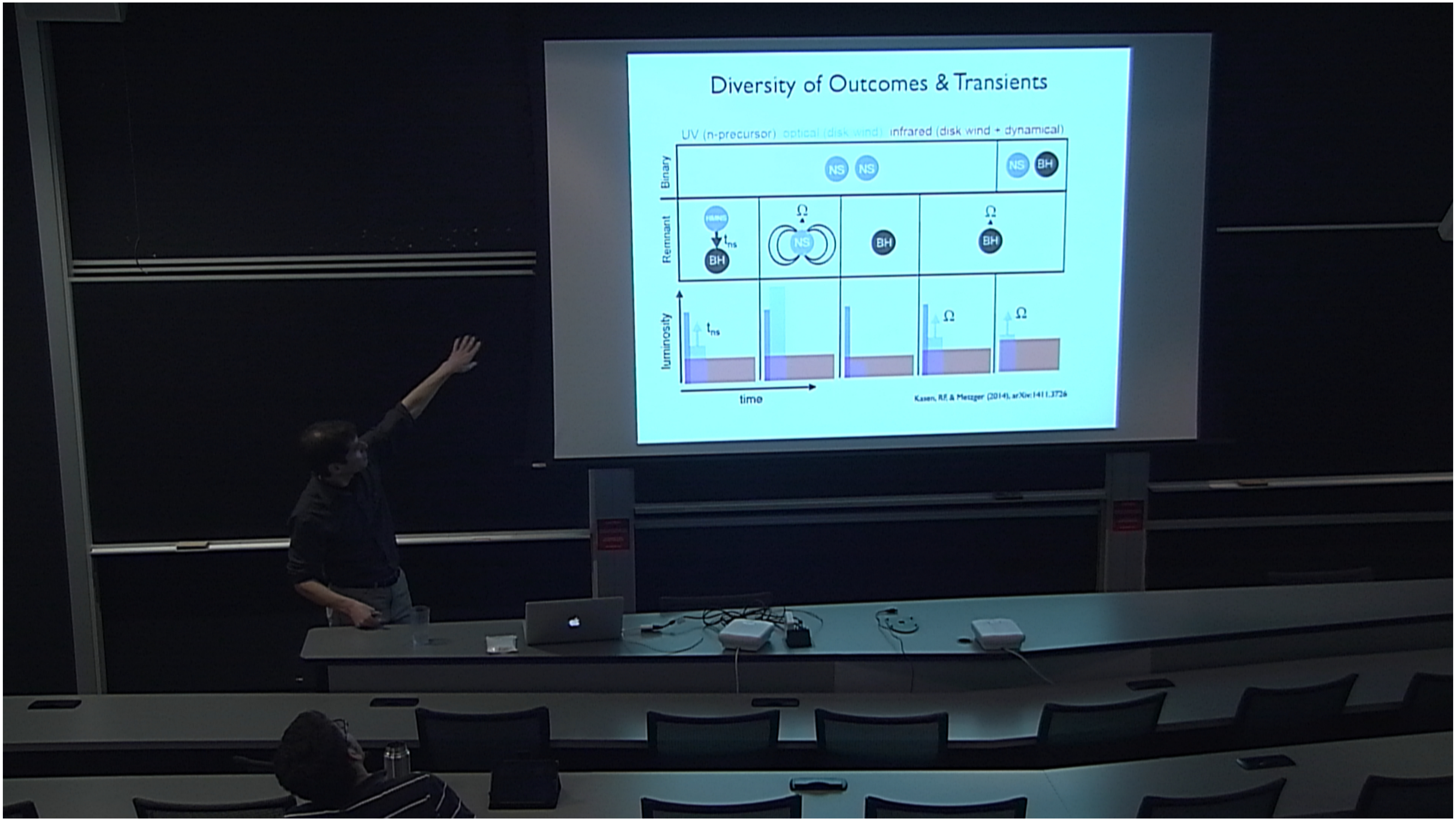


Diversity of Outcomes & Transients
UV (n-precursor) optical (disk wind) infrared (disk wind + dynamical)
Binary
Remnant
luminosity
time
NS
BH
Kasen, RF, & Metzger (2014), arXiv:1411.3726



Diversity of Outcomes & Transients
UV (n-precursor)
optical (disk wind)
infrared (disk wind + dynamical)
Binary
NS
NS
NS
BH
Remnant
HMNS
BH
NS
BH
BH
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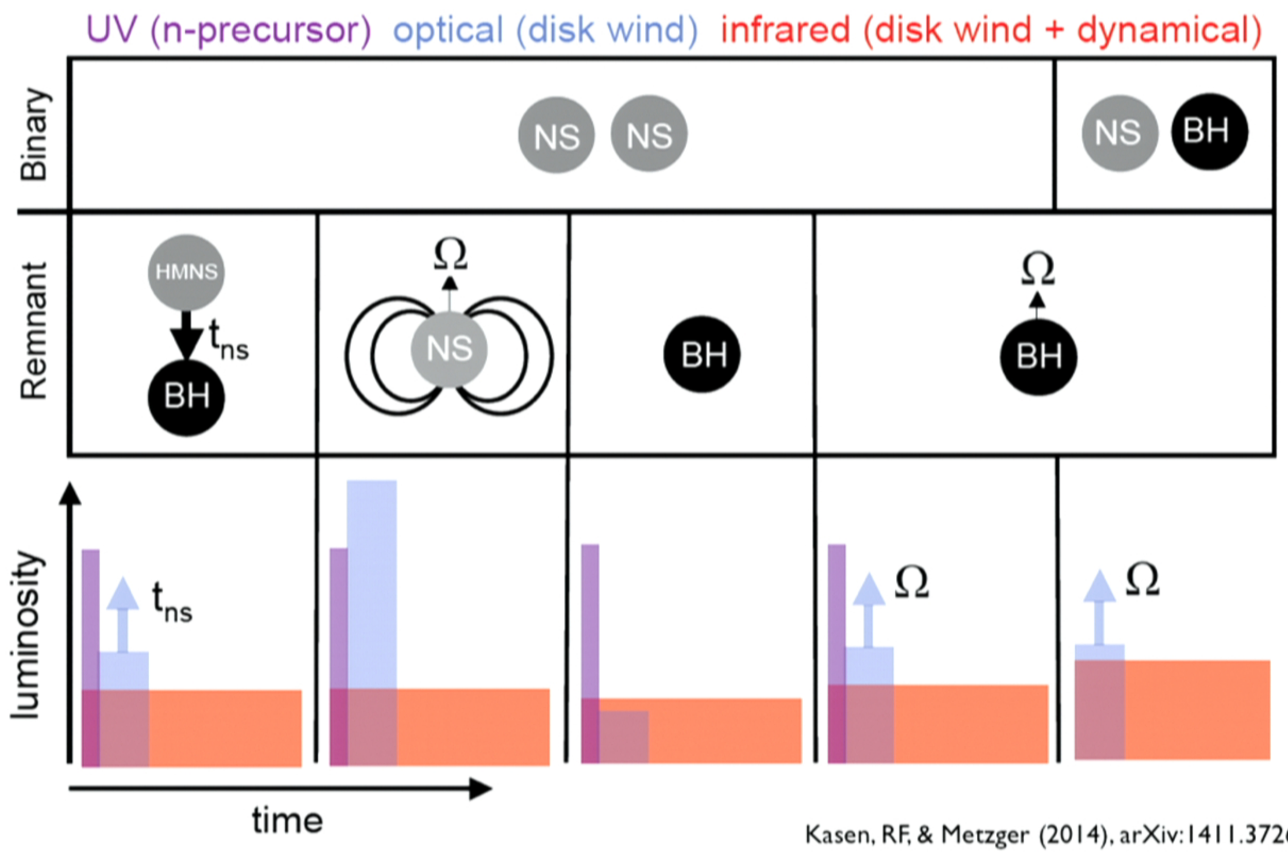

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Future Work

Improve the physics to obtain more reliable observational predictions:

- More realistic initial conditions
- Combined dynamical ejecta & wind evolution
- 3D MHD: amount of mass ejected
- Better neutrino physics: initial ejecta composition
- Couple to nuclear reaction network: final ejecta composition
- Improve atomic data: r-process opacities

Summary

1) NS merger science:

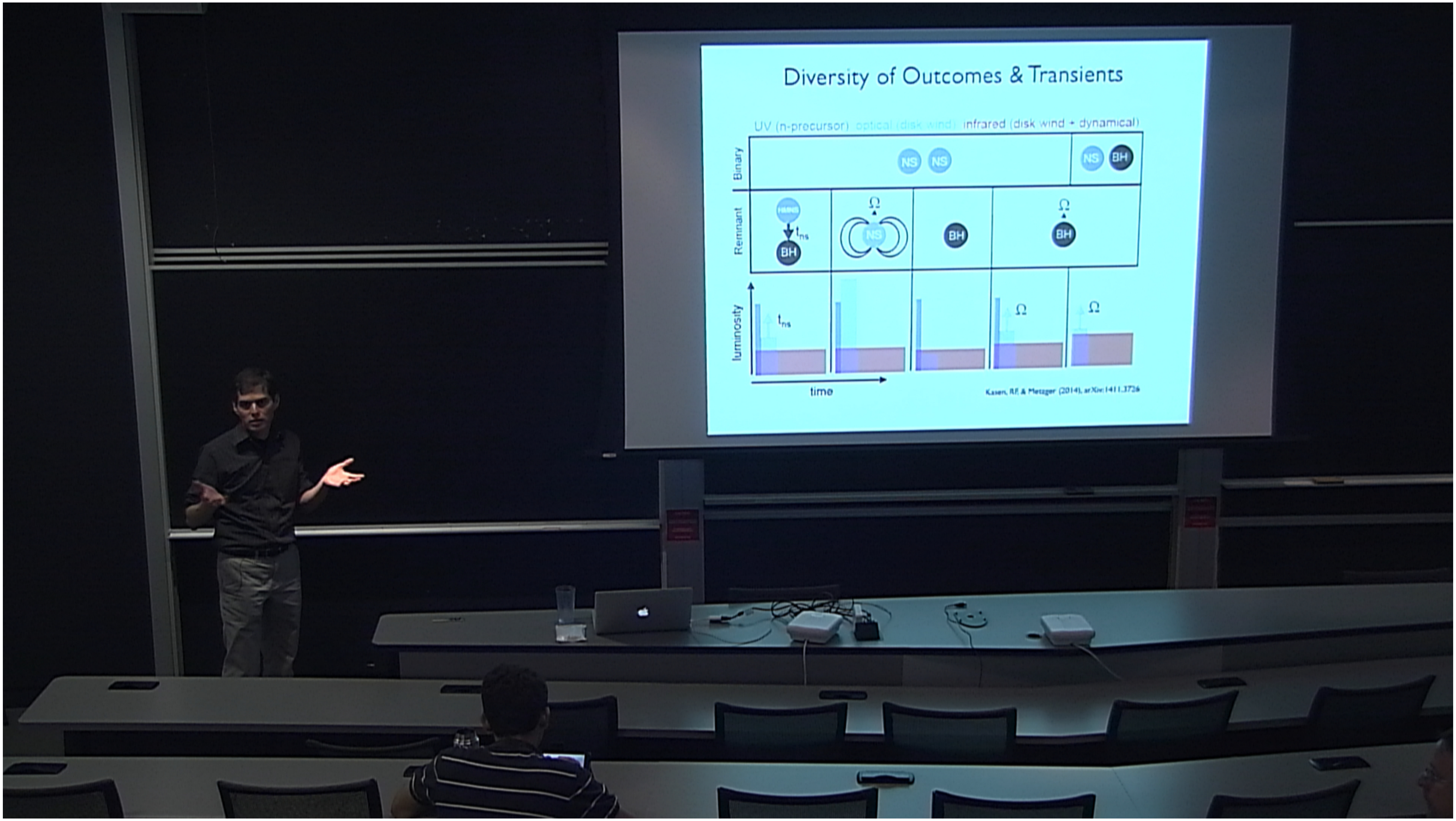
- Gravitational Waves
- r-process nucleosynthesis
- Transients

2) Kilonova: a promising EM counterpart

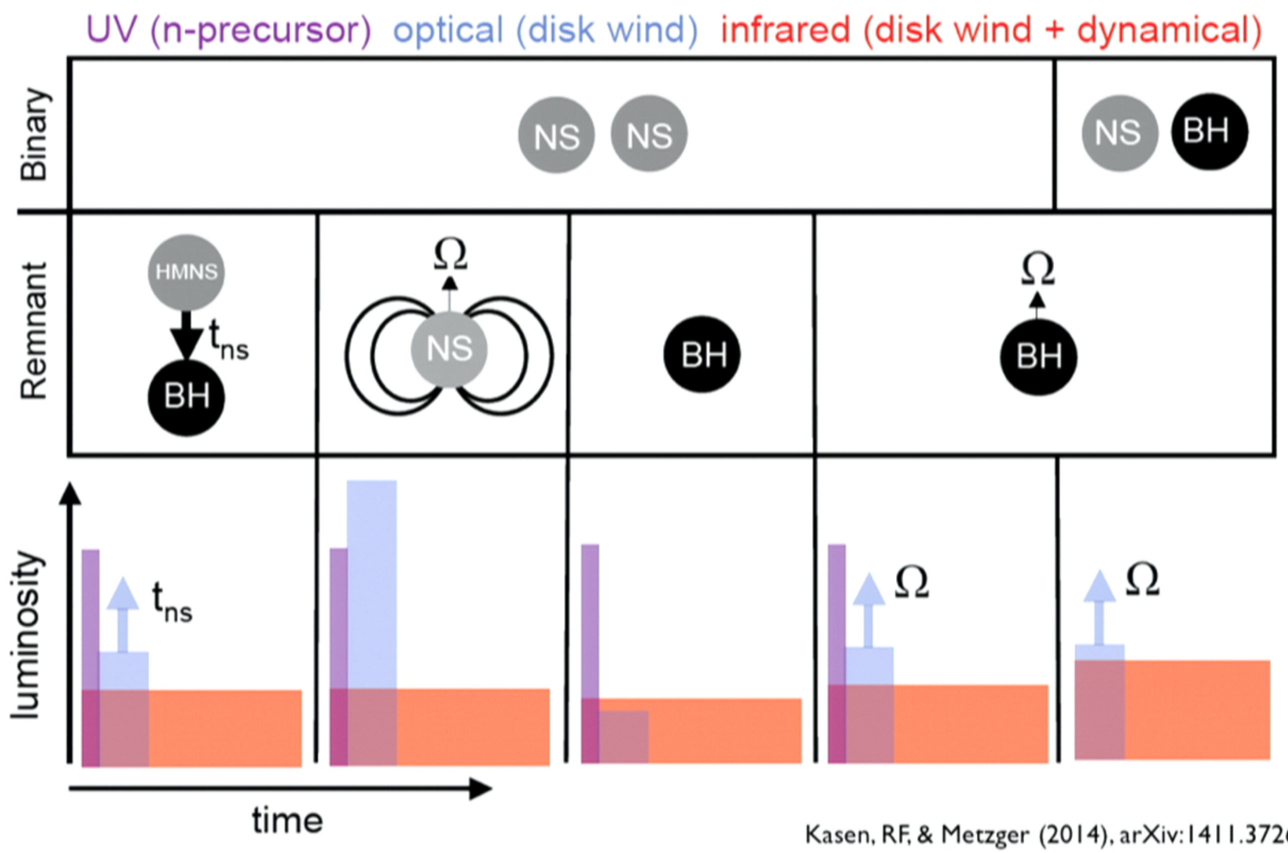
- Improve localization of GW detections
- Diagnose physics of the merger and remnant

3) Disk winds: a critical contribution to the kilonova

- Blue optical component, ease detectability
- Provides variation in the lighter r-process abundances

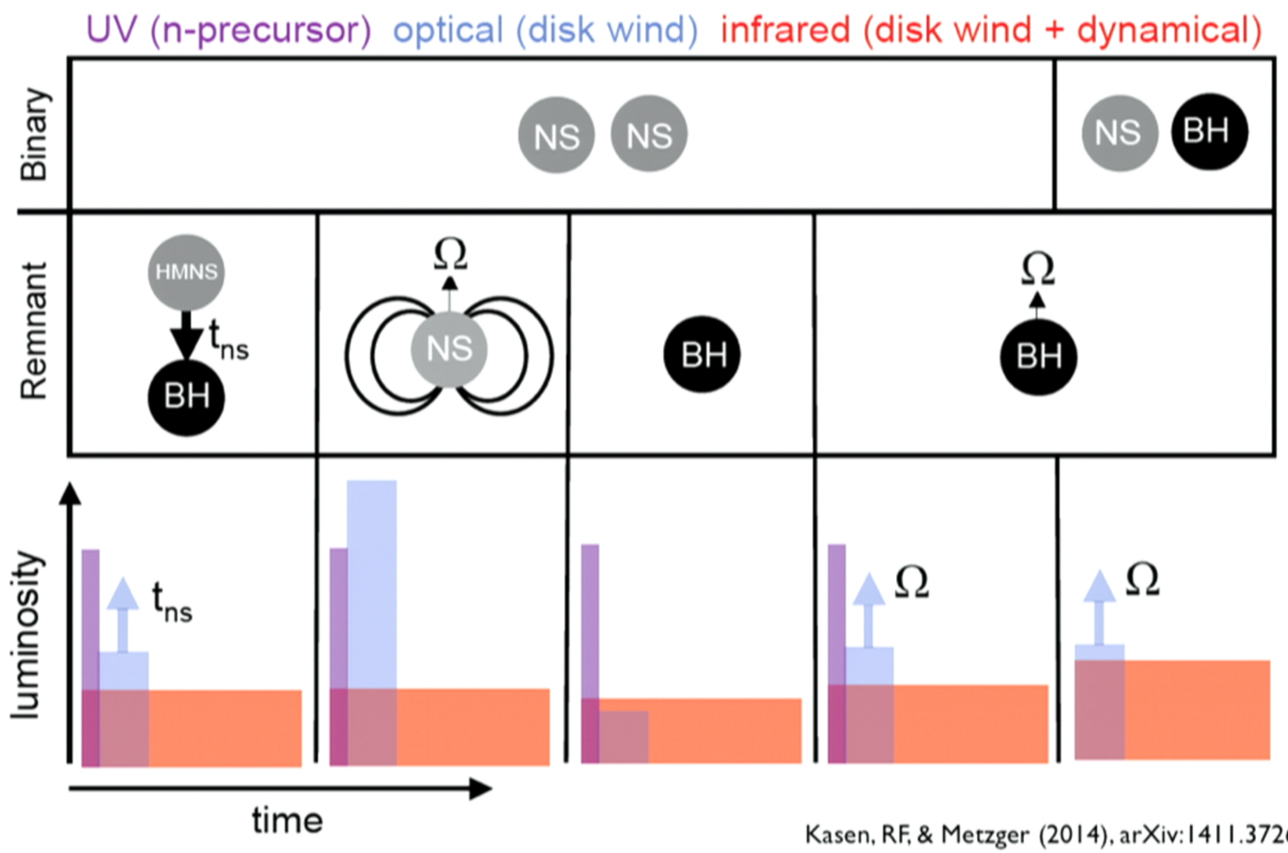

Diversity of Outcomes & Transients
UV (n-precursor)
infrared (disk wind + dynamical)
Binary
Remnant
luminosity
time
NS
BH
Ω
Kasen, RF & Metzger (2014), arXiv:1411.3726

Diversity of Outcomes & Transients

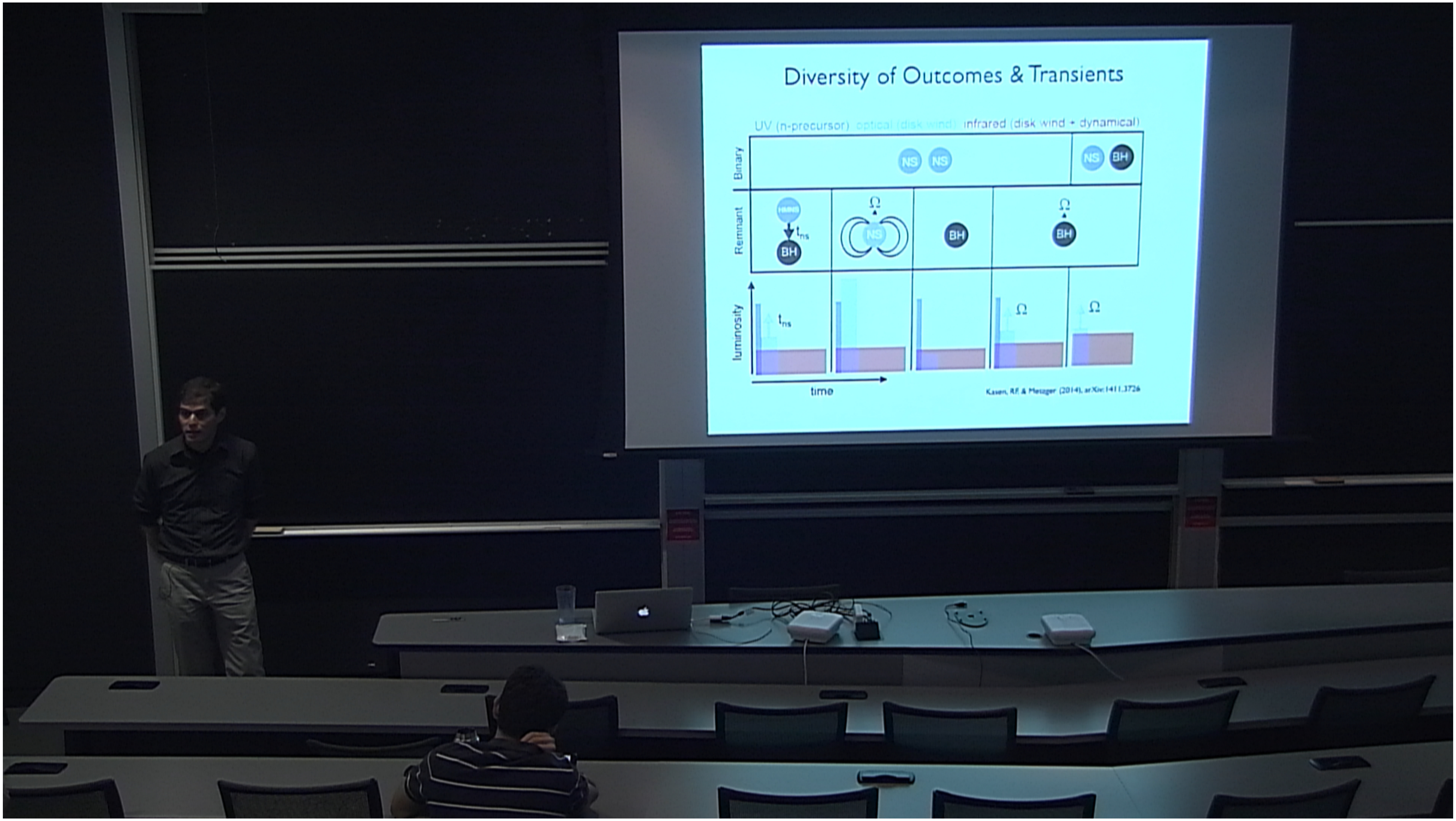


Kasen, RF, & Metzger (2014), arXiv:1411.3726

Diversity of Outcomes & Transients



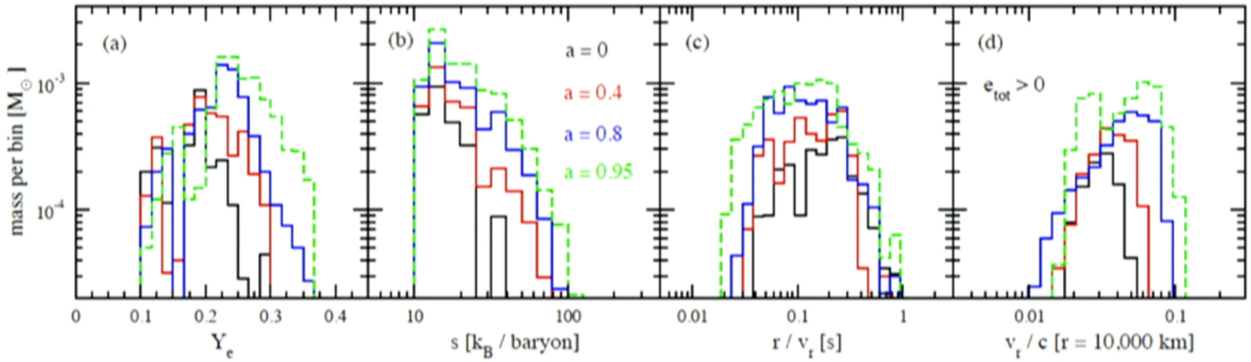
Kasen, RF, & Metzger (2014), arXiv:1411.3726



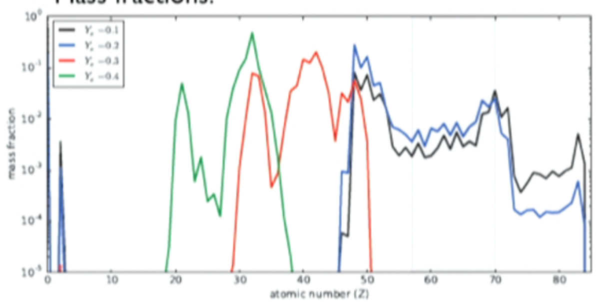
Diversity of Outcomes & Transients
UV (n-precursor) optical (disk wind) infrared (disk wind + dynamical)
Binary
NS
NS
NS
BH
Remnant
BH
NS
BH
BH
luminosity
time
Kasen, RF & Metzger (2014), arXiv:1411.3726

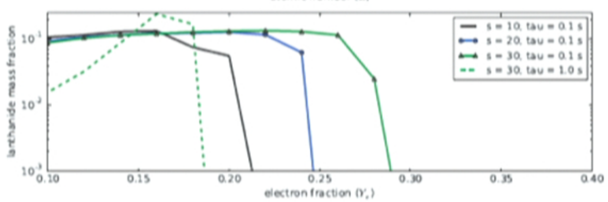
Effect of BH spin on Disk Wind

Nucleosynthesis-relevant quantities in the wind:



Mass fractions:





RF, Kasen, Metzger, Quataert (2015), MNRAS

Thermodynamic trajectories with

$$s \sim 20 k_B / \text{ baryon}$$

$$t_{exp} \sim 0.1 \text{ s}$$

Yield critical Ye for Lanthanide formation:

$$Y_{e,crit} \sim 0.25$$

Kasen, RF, & Metzger (2014), arXiv:1411.3726