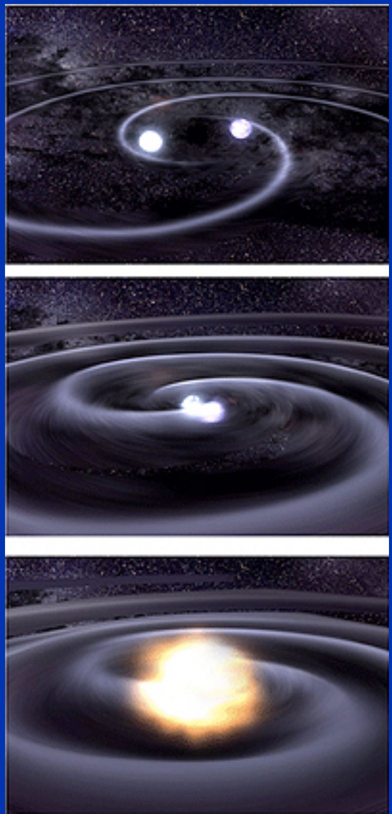
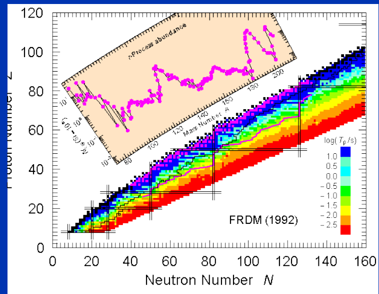
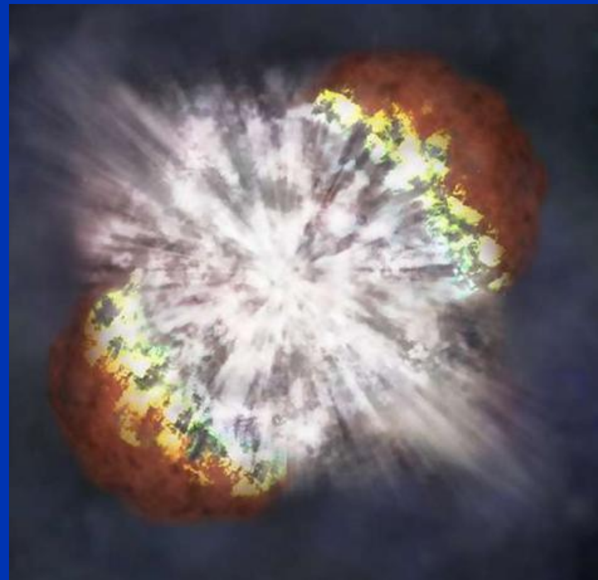
Radioactively-Powered Optical Counterparts of Neutron Star Mergers







Brian Metzger

Princeton University

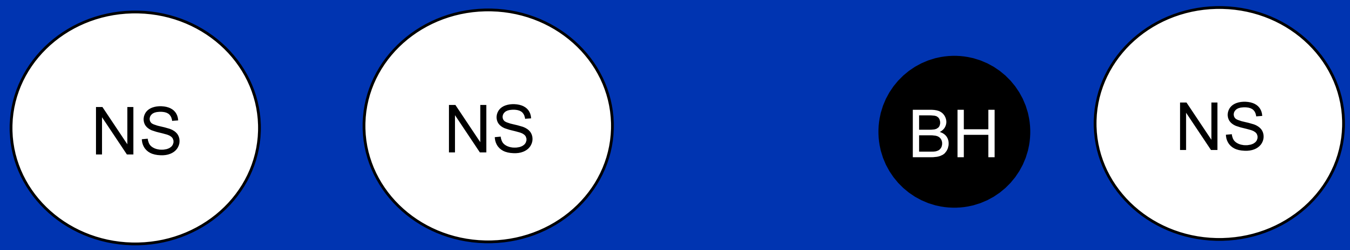
NASA Einstein Fellow

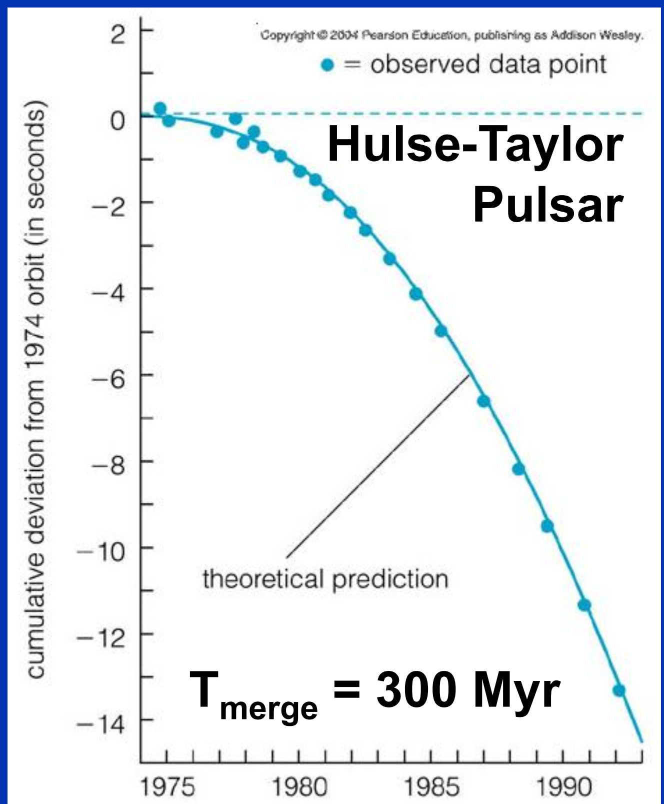
In Collaboration with

Gabriel Martinez-Pinedo, Siva Darbha, Eliot Quatert, Almudena Arcones,
Dan Kasen, Roland Thomas, Peter Nugent, Daniel Perley, Igor Panov, Nikolaj Zinner

Nuclei in the Cosmos, July 20, 2010 (Heidelberg, Germany)

Binary Compact Object Mergers





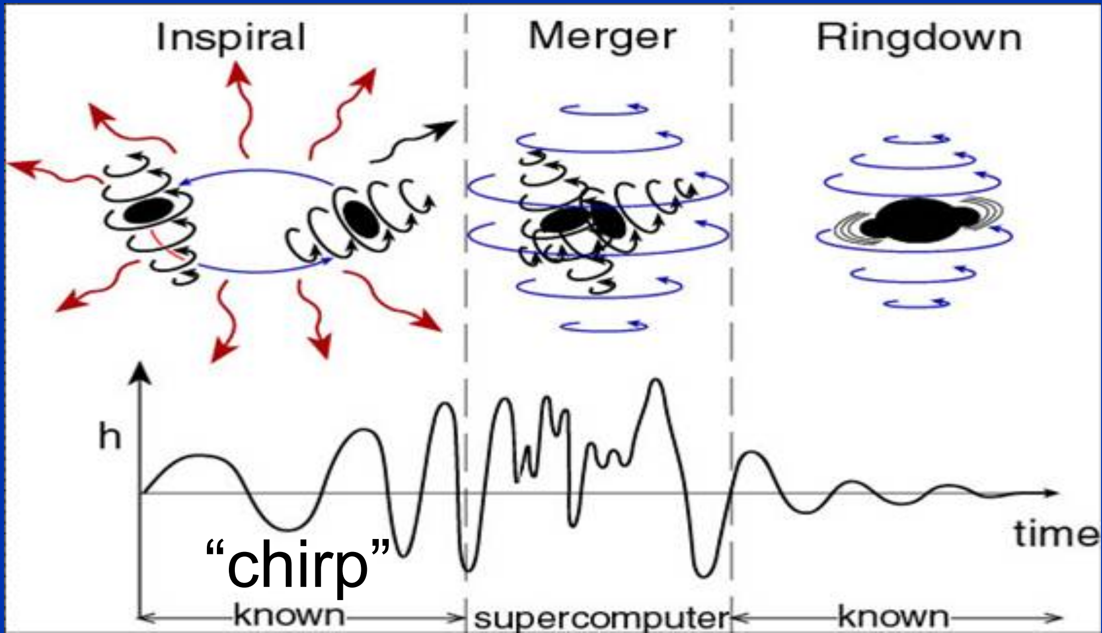
Known Galactic NS-NS Binaries

1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$

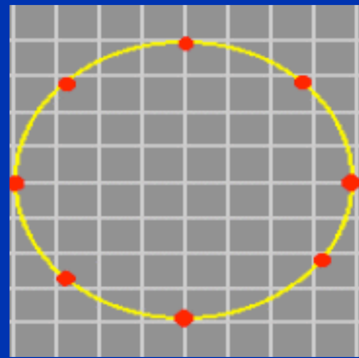
$$\dot{N}_{merge} \sim 10^{-5} - 10^{-4}\ yr^{-1}$$

(e.g. Kalogera et al. 2004)

Gravitational Waves from Inspiral and Merger



Credit: Kip Thorne



Ground-Based Interferometers

LIGO 5th Science Run (2007) Range ~ 10 Mpc

"Advanced" LIGO + Virgo (~2015) Range ~ 300-600 Mpc

LIGO (North America)

Virgo + GEO 600 (Europe)

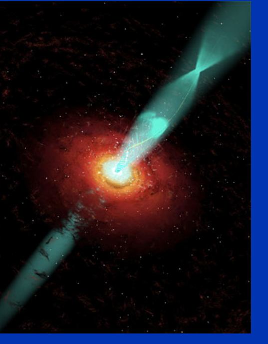
Electromagnetic Counterparts of NS-NS/NS-BH Mergers

Importance of EM Detection:

- Place Merger into Astrophysical Context
  - ⇒ Host Galaxy, Local Environment, & Binary Properties
- Improve Effective Sensitivity of G-Wave Detectors (Kochanek & Piran 93)
  - ⇒ Advanced LIGO Detection Rates Uncertain ($\sim 1 - 10^3$ yr^{-1})
- Cosmology: Redshift ⇒ Measurement of H_0 (e.g. Krolak & Shutz 87)

Electromagnetic Counterparts of NS-NS/NS-BH Mergers

Short-Duration Gamma-Ray Burst
Blinnikov+84, Paczynski 86; Goodman 86; Eichler+89



Supernova-Like Transient Powered by Radioactive Ejecta
Li & Paczynski 98; Kulkarni 05; Rosswog 05; Metzger+08, 10

Bright, but Beamed

Dimmer, but Isotropic

Importance of EM Detection:

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Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

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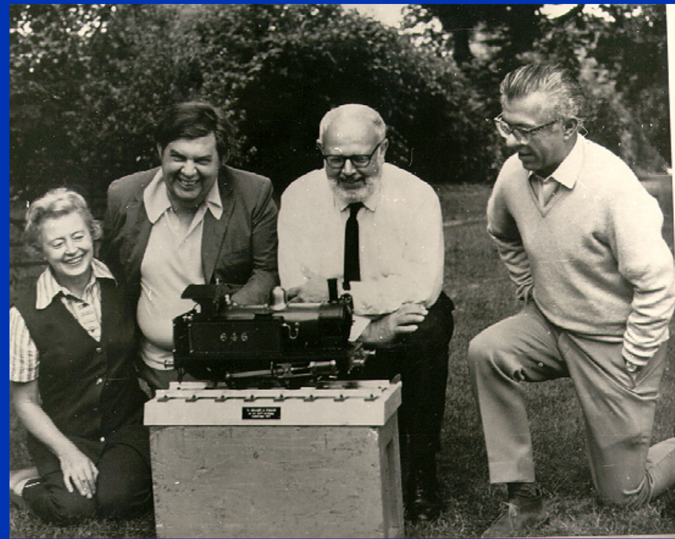

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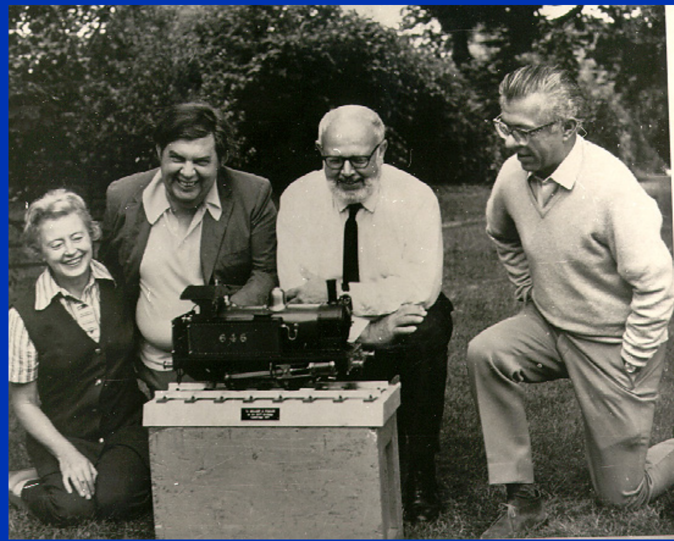

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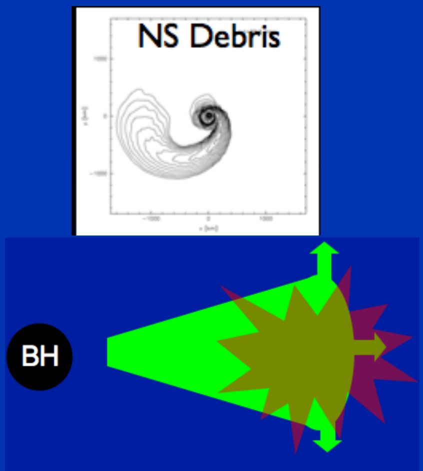
NS Merger Ejecta



TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

Li-Xin Li and Bohdan Paczyński
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

Similar to a Supernova, but …

Faster Evolving

$$t_{peak} \approx 0.5\,\mathrm{days} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{1/2}$$

Dimmer

$$L_{peak} \approx 5 \times 10^{41} \mathrm{ergs\ s^{-1}} \left(\frac{f}{10^{-6}}\right) \left(\frac{v}{0.1c}\right)^{1/2} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{1/2}$$

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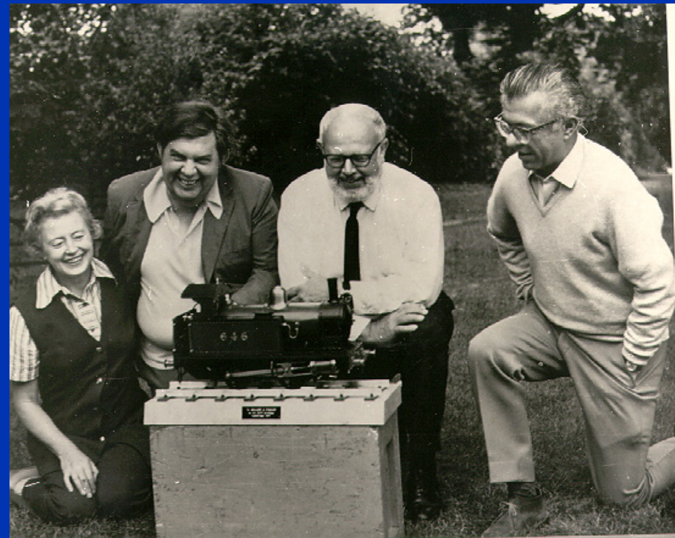

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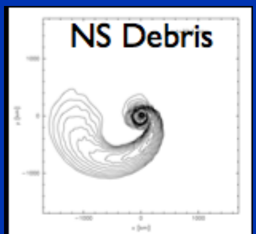

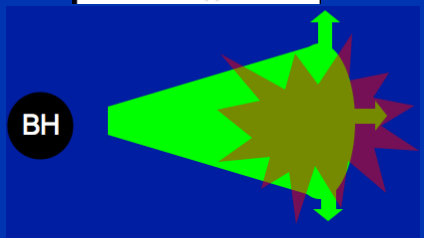

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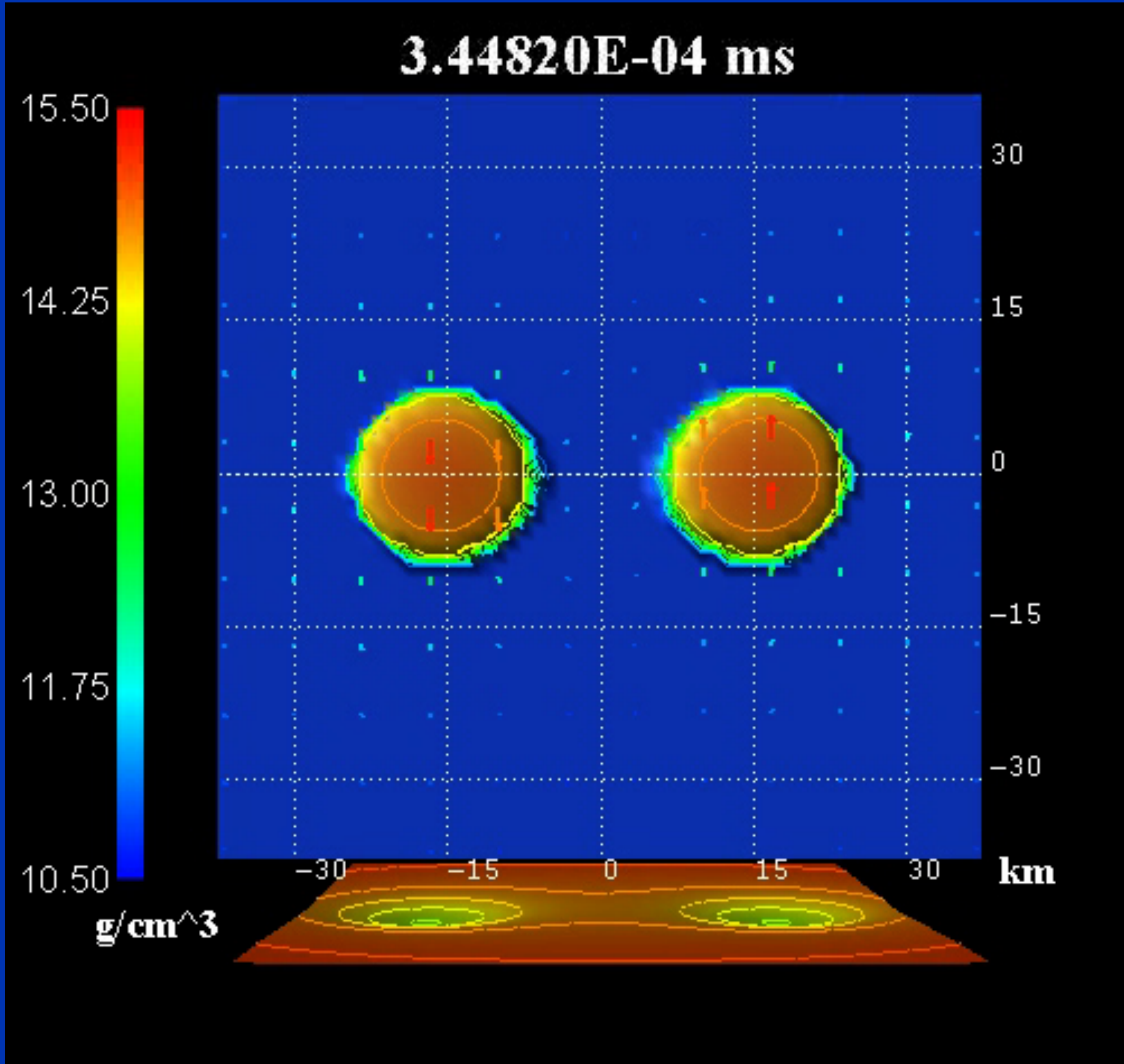


Credit: M. Shibata (U Tokyo)

Sources of Neutron-Rich Ejecta

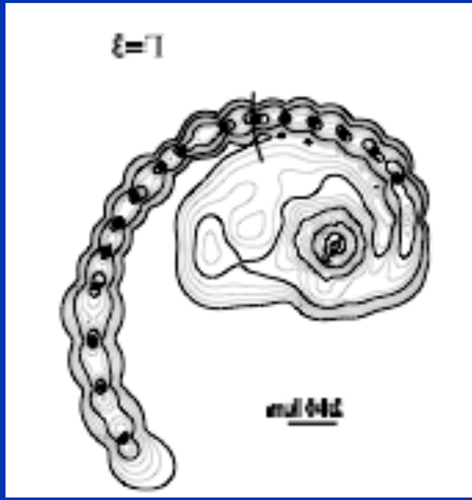
Tidal Tails (Dynamical Ejecta)

(e.g. Janka et al. 1999; Lee & Kluzniak 1999; Ruffert & Janka 2001; Rosswog et al. 2004; Rosswog 2005; Shibata & Taniguchi 2008)

Full GR / Simple EOS

Current Sims: $M_{ej} \sim 0 - 10^{-1}\ M_{\odot}$

Newtonian / Realistic EOS



Lee & Ramirez-Ruiz 07

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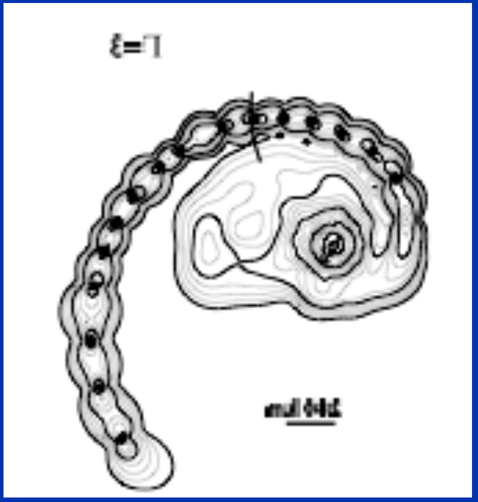


Lee & Ramirez-Ruiz 07

Accretion Disk Outflows

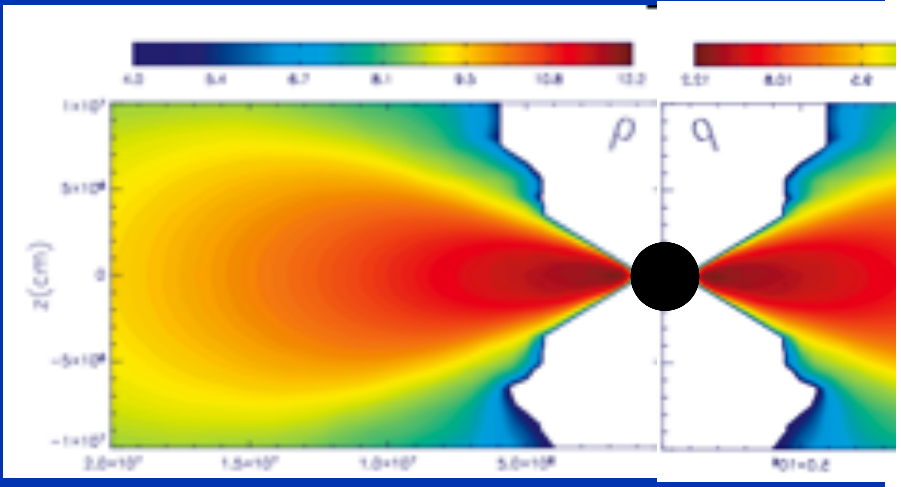
- **Neutrino-Driven Winds (Early)**

  (McLaughlin & Surman 05; Surman+ 06, 08; BDM+08)

- **Thermonuclear-Driven Winds (Late)**

  (Metzger, Piro & Quataert 2008; Lee et al. 2009)

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



Lee et al. 2004

Neutron-Rich Freeze-Out $Y_e \sim 0.1\text{-}0.4$ (BDM + 2009)

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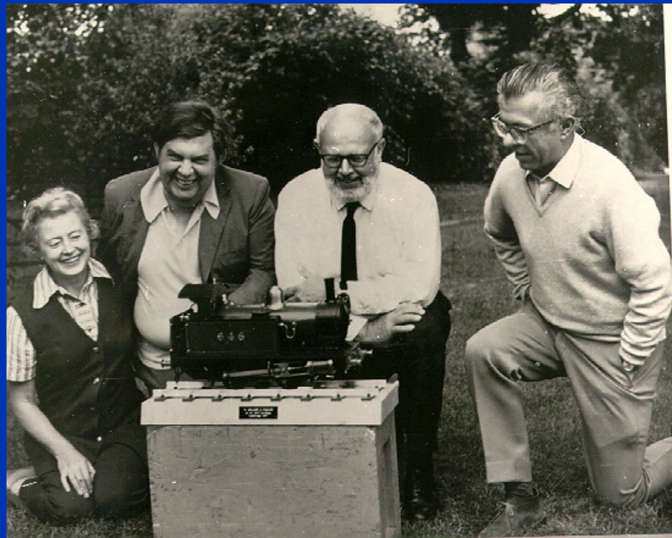

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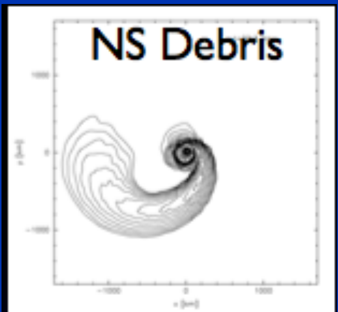

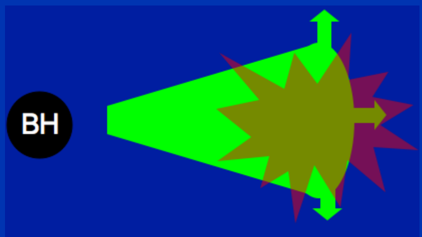

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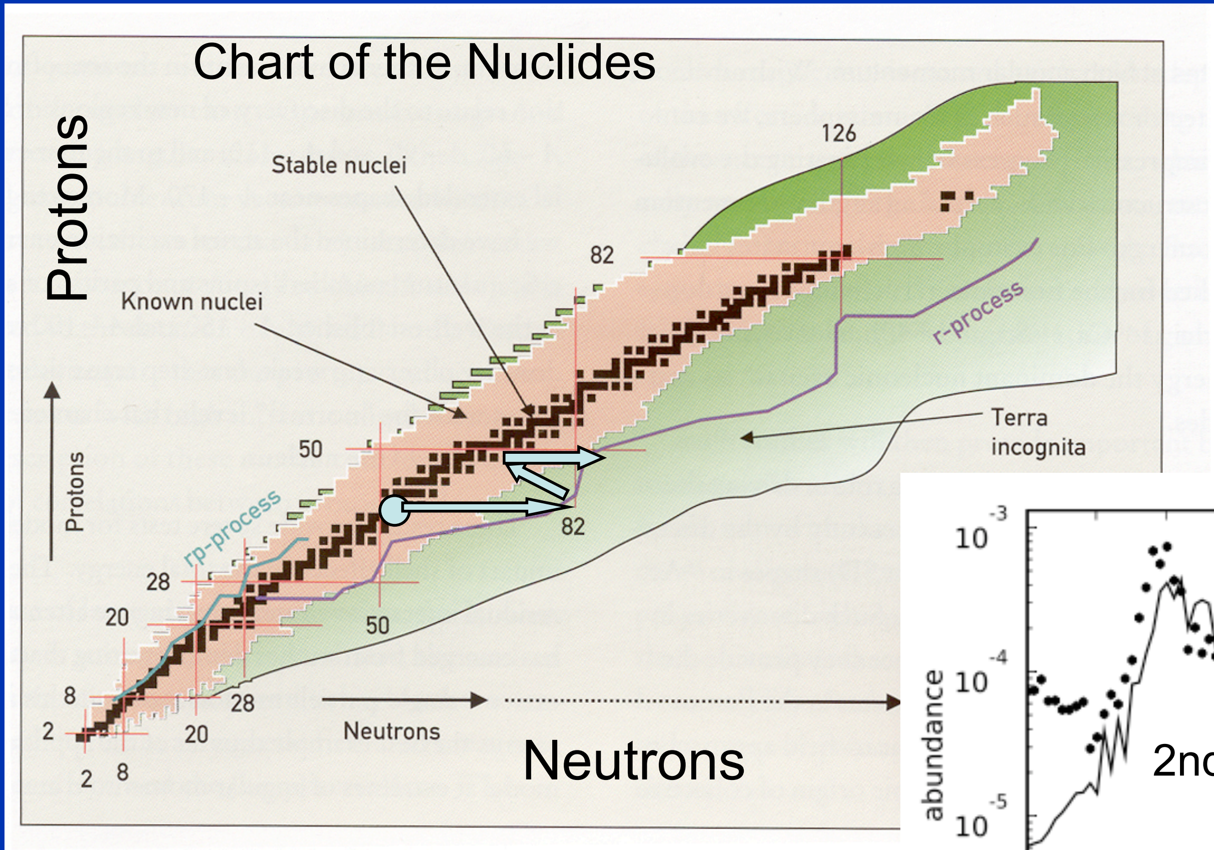
} "mini -supernova"

R-Process Nucleosynthesis

Decompressing NS Matter ⇒ A ~ 100 Nuclei + Free Neutrons

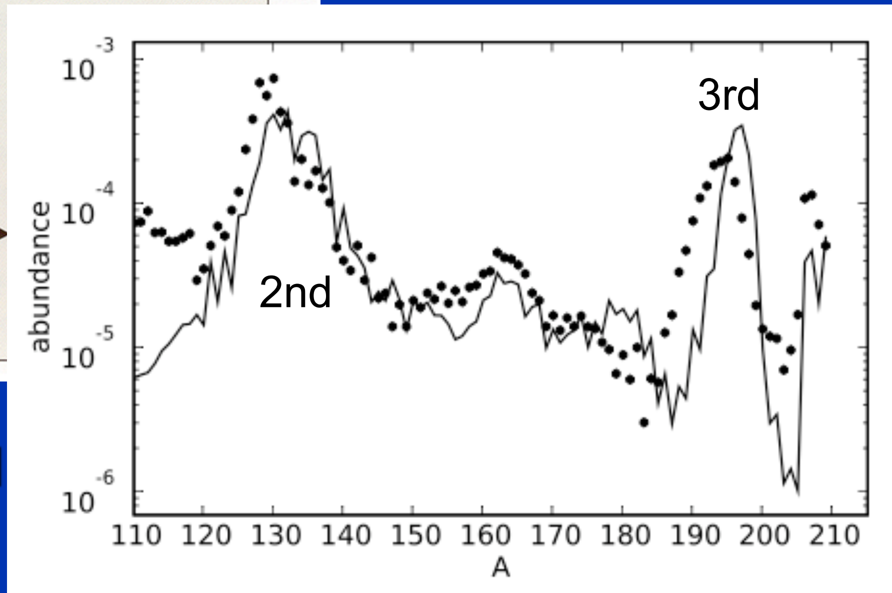
(Lattimer et al. 1977; Meyer 1989; Freiburghaus et al. 1999; Goriely et al. 2005)



R-Process Network

(Martinez-Pinedo 2008; Petermann et al. 2008)

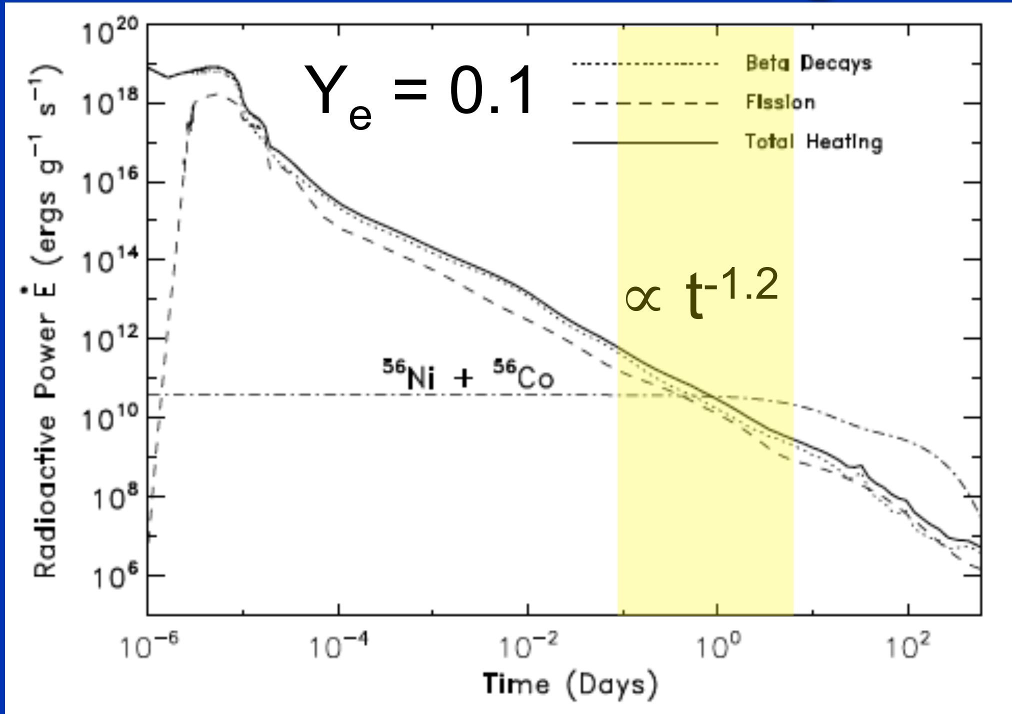
- neutron captures (Rauscher & Thielemann 2000)
- photodissociations, α- and β -decays
- fission reactions (Panov et al. 2009).



BDM et al. 2010

Abundance Peaks at A ~ 130 and A ~ 195

Radioactive Heating of NS Merger Ejecta



@ t ~ 1 day :

- R-process & Ni heating similar
- ~1/2 Fission, ~1/2 β-Decays
- Dominant β-Decays: ^{132,134,135}I, ^{128,129}Sb, ^{129}Te, ^{135}Xe

Nucleosynthesis Calculations by G. Martinez-Pinedo & A. Arcones

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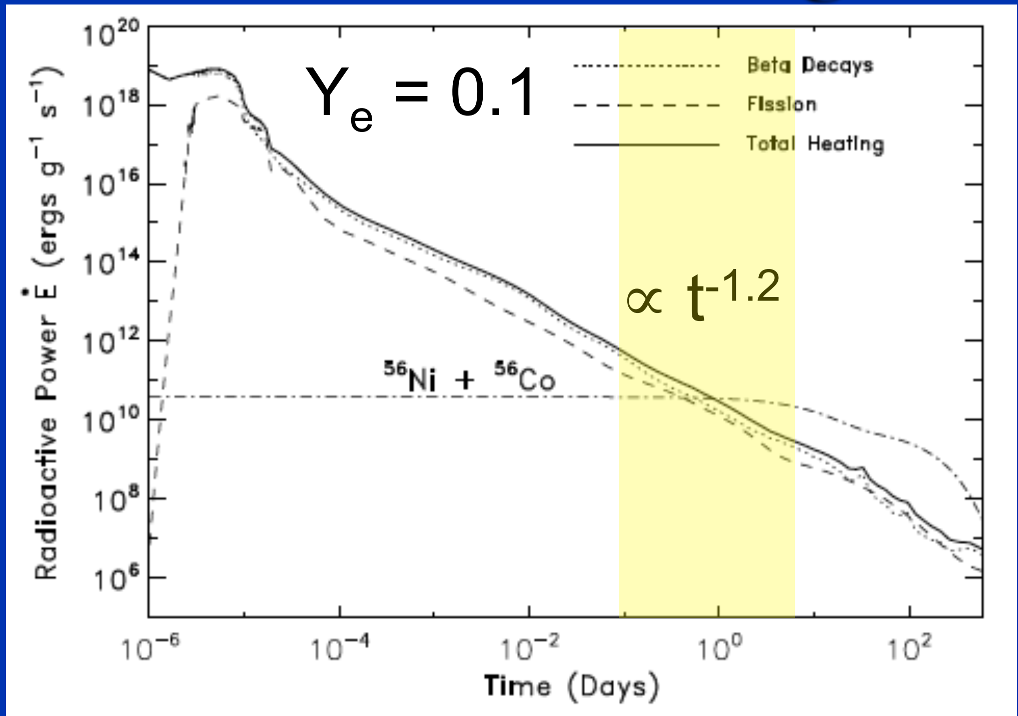

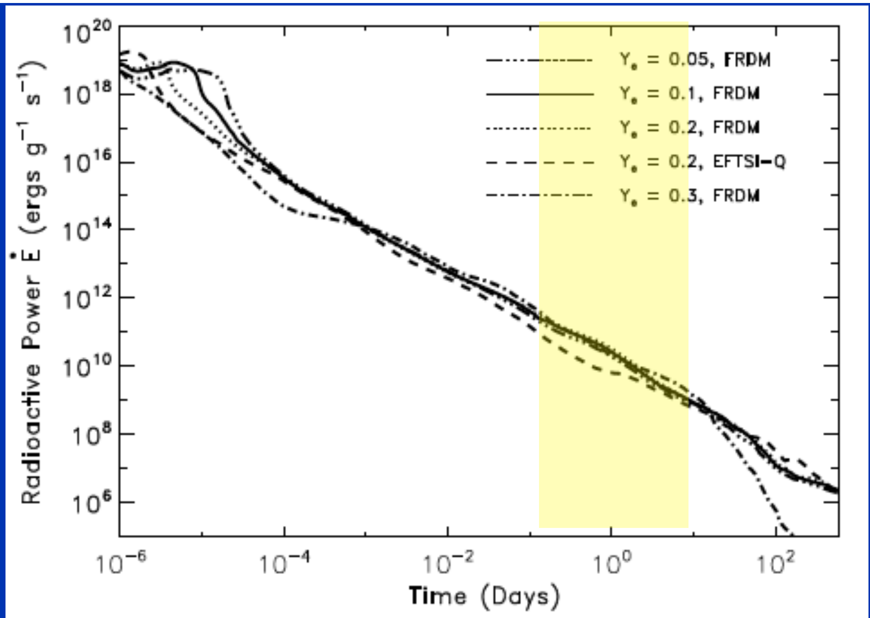

@ t ~ 1 day :

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- **~1/2 Fission, ~1/2 β-Decays**
- **Dominant β-Decays:** ^{132,134,135}**I,** ^{128,129}**Sb,** ^{129}**Te,** ^{135}**Xe**

f_{LP} = 3 x 10^{-6}

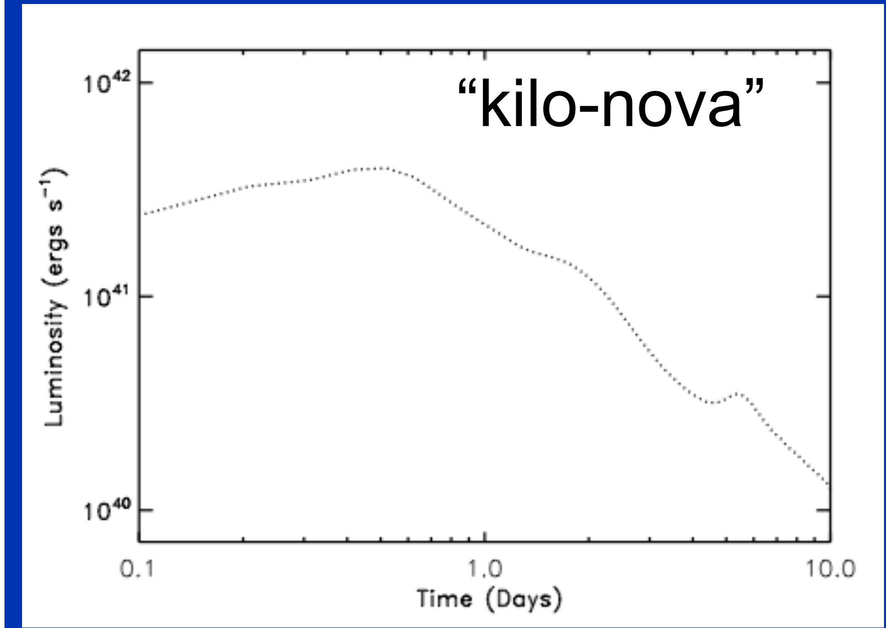
Results Robust to:

- ejecta composition (Y_e = 0.05 - 0.3)
- nuclear mass model
- outflow trajectory (dynamically-ejected or wind-driven)

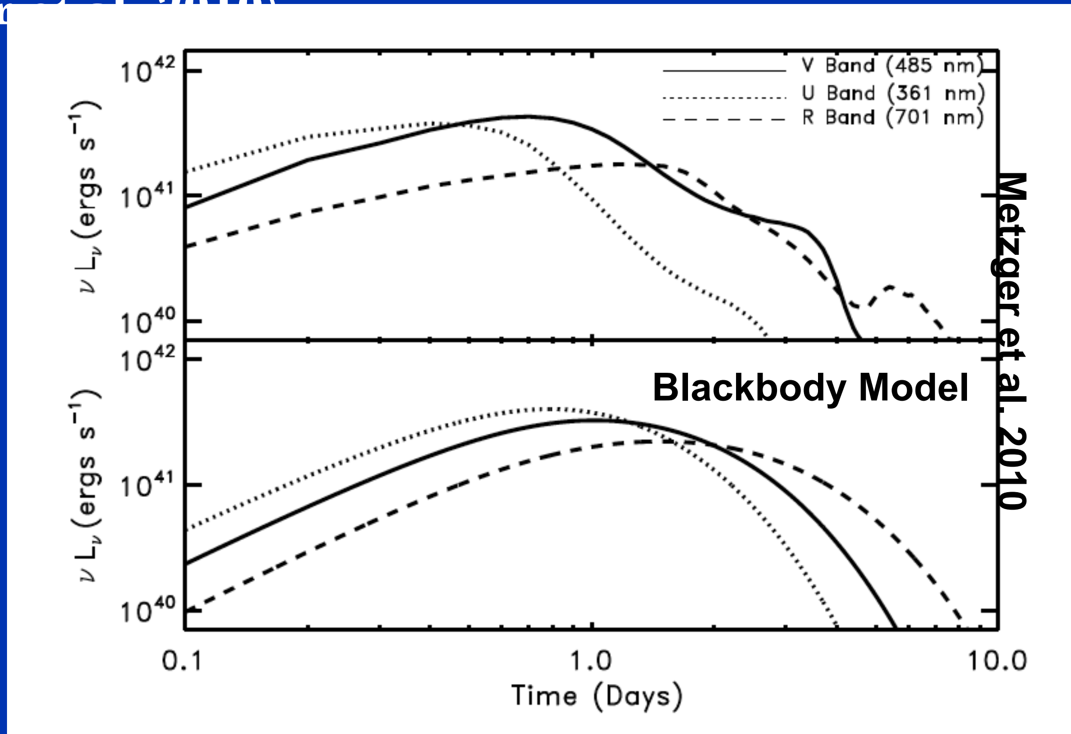
Light Curves

(Metzger et al. 2010)

Bolometric Luminosity



Color Evolution



Monte Carlo Radiative Transfer (SEDONA; Kasen et al. 2006)

Peak Brightness M_V= -15 @ t ~ 1 day for M_{ej} = 10^{-2} $M_\odot$

Red Transient (Line Blanketing), Reddens in Time

CAVEAT: Fe composition assumed for opacity

What *does* a pure r-process photosphere look like?

Three Detection Methods

1) Gravitational-Wave Triggered Follow-Up

V < 22-24 to probe entire Advanced LIGO merger volume (for M_V = -15)

Positional Uncertainty ~ several arcminutes - degrees

} ⟹ Wide-Field, Sensitive Telescope (e.g. LSST)

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3) Short Gamma-Ray Burst Follow-Up

Upper Limits

GRB 070724A $M_{ej} < 0.1 M_{\odot}$

(Kocevski et al. 2009)

GRB 050509b $M_{ej} < 10^{-3} M_{\odot}$

(Hjorth et al. 2005)

GRB 080503

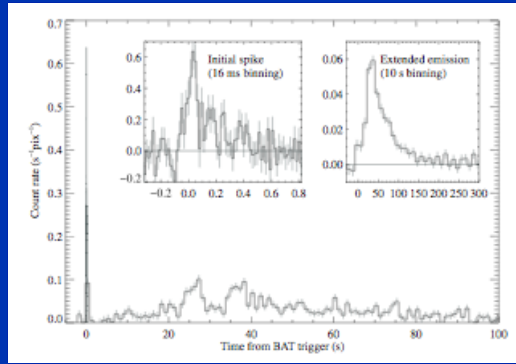
(Perley, BDM, et al. 2009)

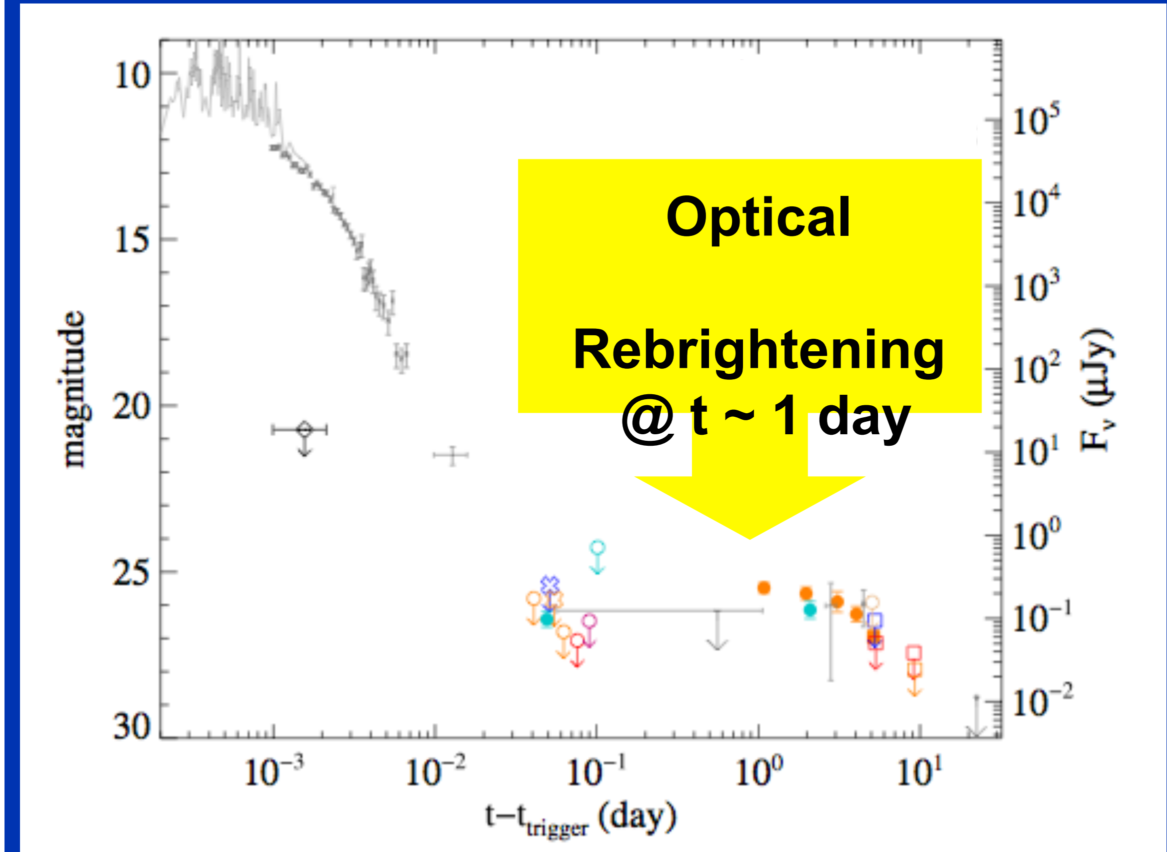
Possible Detection

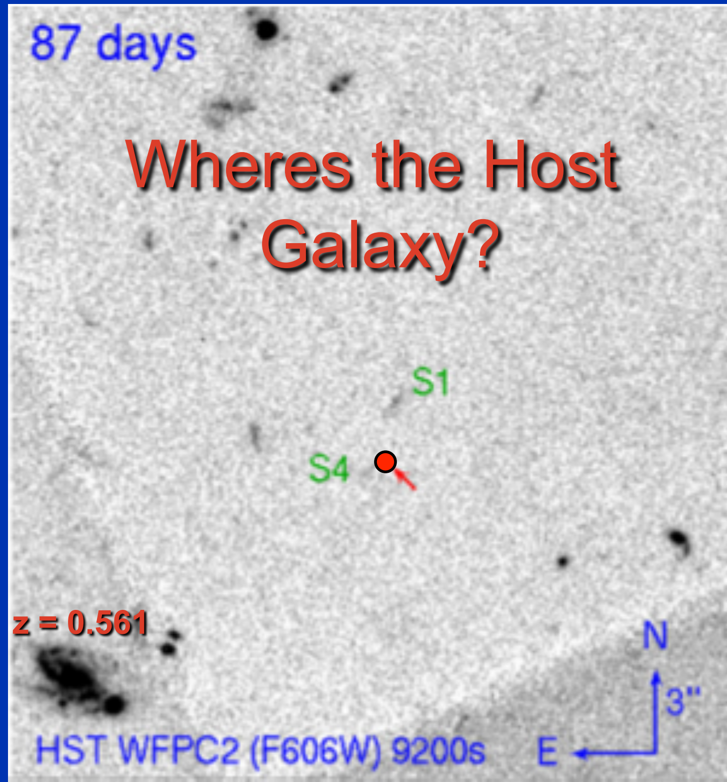
Fundamental Obstacle? Bright Optical Afterglow

GRB 080503: Candidate Kilonova

(Perley, BDM et al. 2009)







Kilonova Parameters: v ~ 0.1 c, M_{ej} ~ few 10^{-2} $M_{\odot}$, **z ~ 0.1**

Three Detection Methods

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GRB 080503

(Perley, BDM, et al. 2009)

Possible Detection (but no redshift)

Fundamental Obstacle? Bright Optical Afterglow

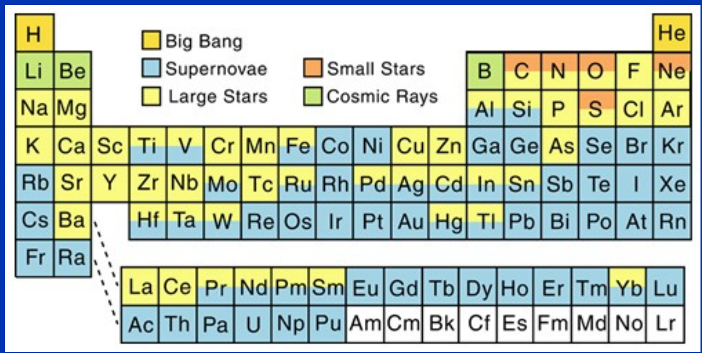
5) "Blind" Optical Transient Surveys

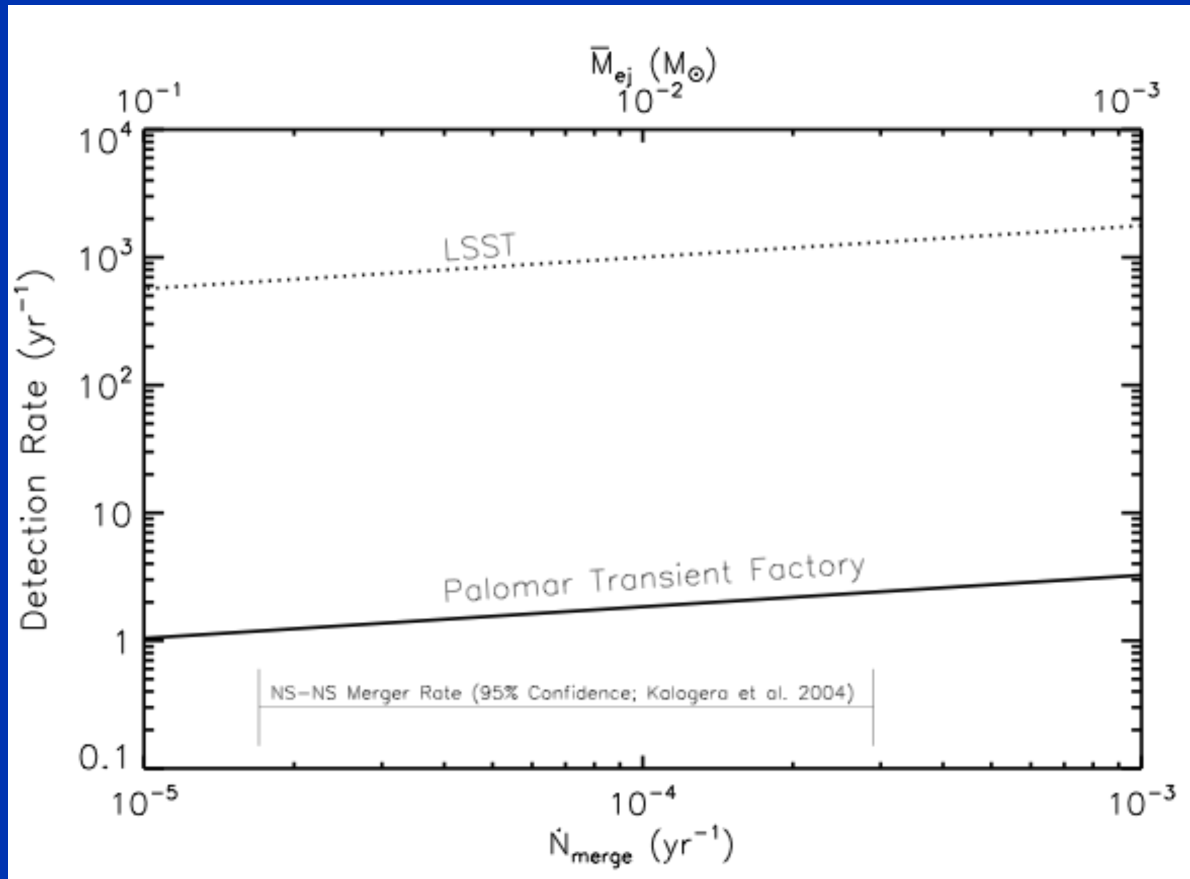
(e.g. Palomar Transient Factory, Pan-STARRs, LSST)

$\dot{N}_{merge} \sim 10^{-4}\ \mathrm{yr}^{-1},\ M_{\mathrm{ej}} = 10^{-2} M_\odot$ ⇒ PTF ~ 1 yr^{-1} & LSST ~ $10^3\ \mathrm{yr}^{-1}$

"Direct" Probe of the R-Process Origin

- ***Unknown*** origin of 1/2 of elements more massive than Fe
- Rival Models: Core Collapse SNe and NS Mergers





Galactic R-Process Production Rate:

$$\dot{M}_R \sim 10^{-6} M_\odot \, \mathrm{yr}^{-1}$$

Fixes Merger Rate to Avg. Ejecta Mass:

$$\dot{N}_{\rm merge} = 10^{-4}\,{\rm yr}^{-1}(\bar{M}_{\rm ej}/10^{-2}M_\odot)^{-1}$$

Conclusions

- Direct gravitational wave detection may be possible within a decade, but maximizing the resulting science will require identifying an EM counterpart.
- The most promising *isotropic* emission source may be a supernova-like optical transient ("kilo-nova") powered by the radioactive decay of the r-process ejecta. We have performed a self-consistent calculation, which includes a full r-process network and radiative transport. Future improvements: multi-D ejecta + transport, merger + disk sims to determine $M_{ej}(Y_e)$.
- Detecting, identifying, and characterizing merger transients will require cooperation between the gravitational wave, astrophysics, and nuclear physics communities.
- Rates of merger transients (or upper limits) may someday independently constrain the elusive origin of the r-process.

GRB 080503: Candidate Kilonova

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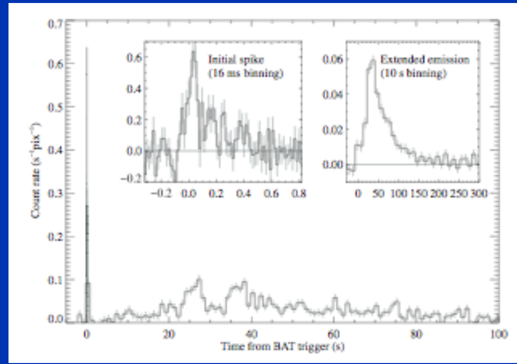

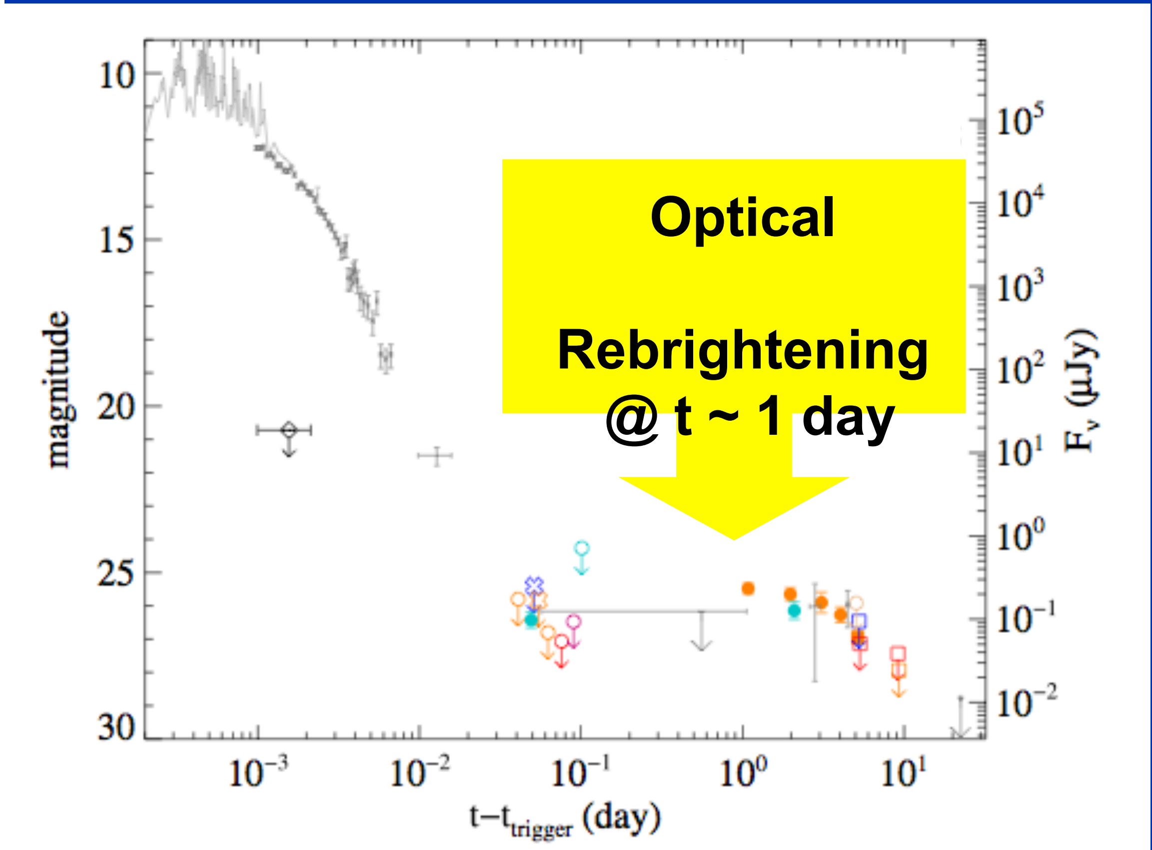

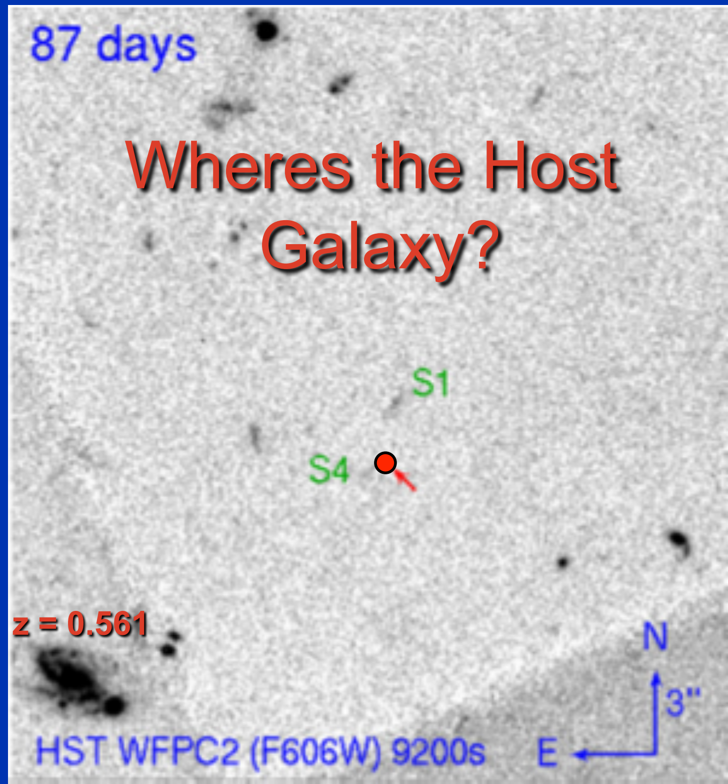

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