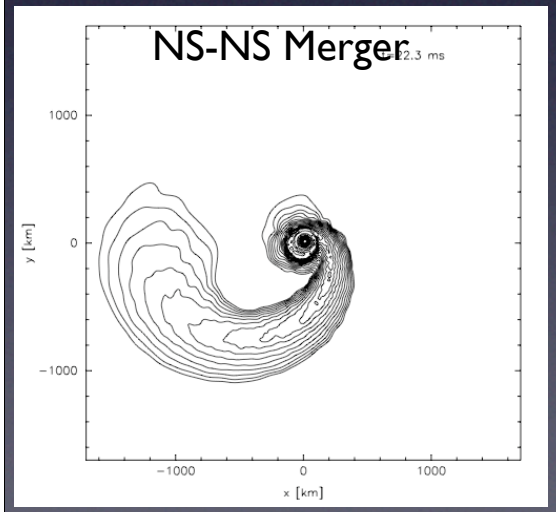
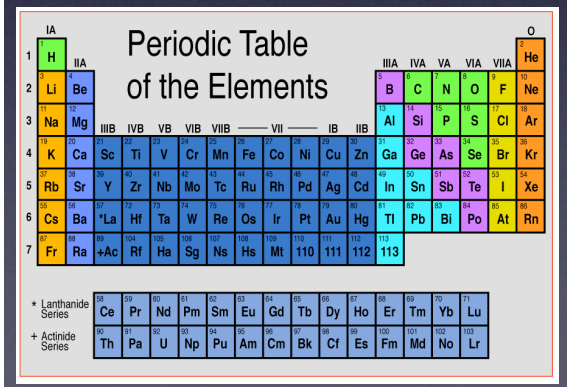
# Compact Object Mergers

Eliot Quataert (UC Berkeley)

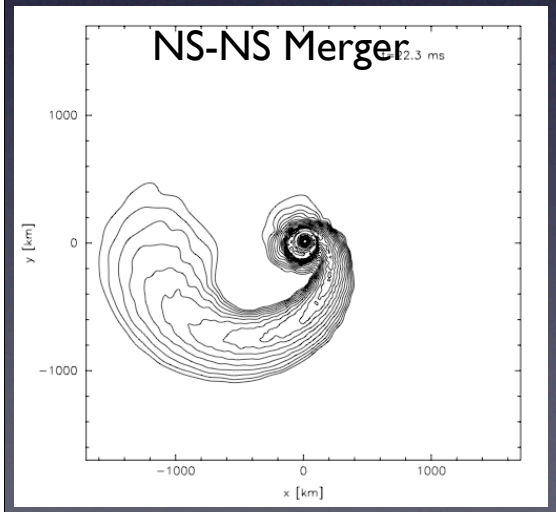



Rosswog 2007




# Overview

- Diversity of Mergers & Outcomes
- WD-WD:
  - R Cor Bor *s? Type Ia SNe? AIC of WD→NS?
- NS-NS, NS-BH
  - Gamma-ray Bursts & Gravitational Wave Astrophysics

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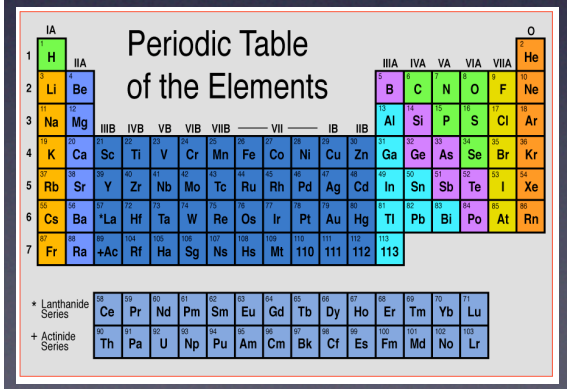


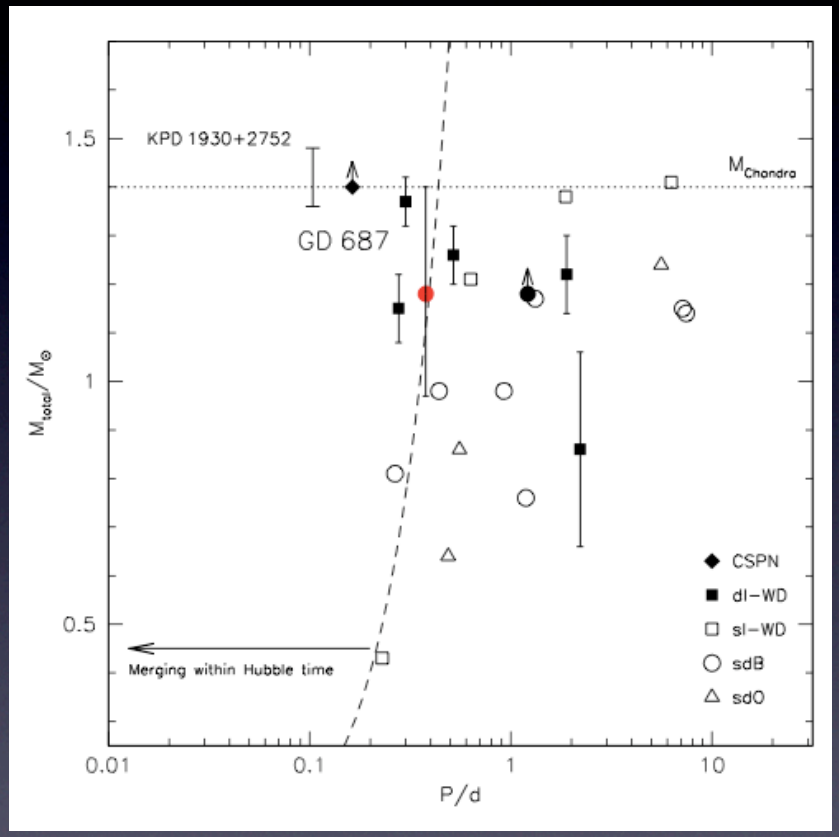

# Stability of Mass Transfer

- Mass transfer begins when stellar R ~ $R_L \equiv$ Roche Lobe
- Subsequent evolution depends on how $R_*$ & a of orbit change
  - stable mass transfer? ... or ... merger on ~ a dynamical time?
- If $M_{tot}$ & $J_{tot}$ conserved: (2 = star losing mass) (1 = star gaining mass)
  - unstable transfer (merger!): $M_2 \gtrsim M_1$
- GR: Close Binaries w/ Compact Objects: $\frac{dJ_{tot}}{dt} = \dot{J}_{GW} < 0$
  - $\gamma = 5/3$ polytropes: unstable if $M_2 \gtrsim (2/3)\, M_1$ but ... mass loss, direct impact, tides, ...
  - NS-NS, BH-NS? unstable for plausible mass ratios

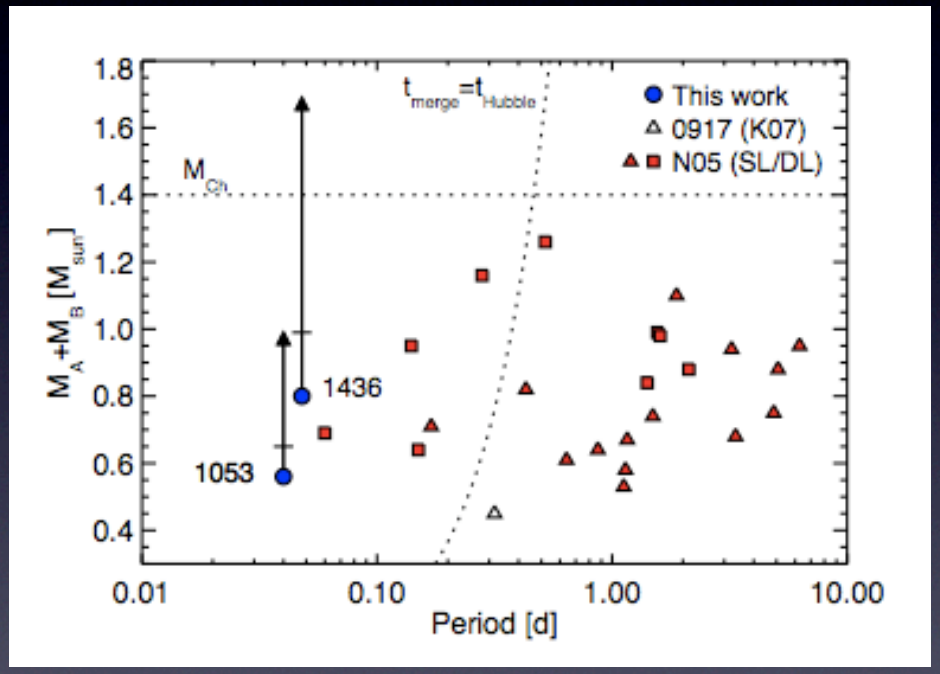
# Diversity of Mergers & Why We Care

- WD-WD
  - $M \gtrsim M_{CH}$: Type Ia supernovae? AIC of WD→NS?
  - $M \lesssim M_{CH}$: weird stars (e.g., R Cor Bor, extreme He *)
- NS-NS & NS-BH
  - most likely kHz gravitational wave source (LIGO, VIRGO)
  - short duration gamma-ray bursts
  - source of some n-rich heavy nuclei in nature (r-process)
- WD-NS
  - unusual GRB? unusual SNe? less well explored/constrained

# WD-WD Mergers: What do we Know Empirically?




SPY



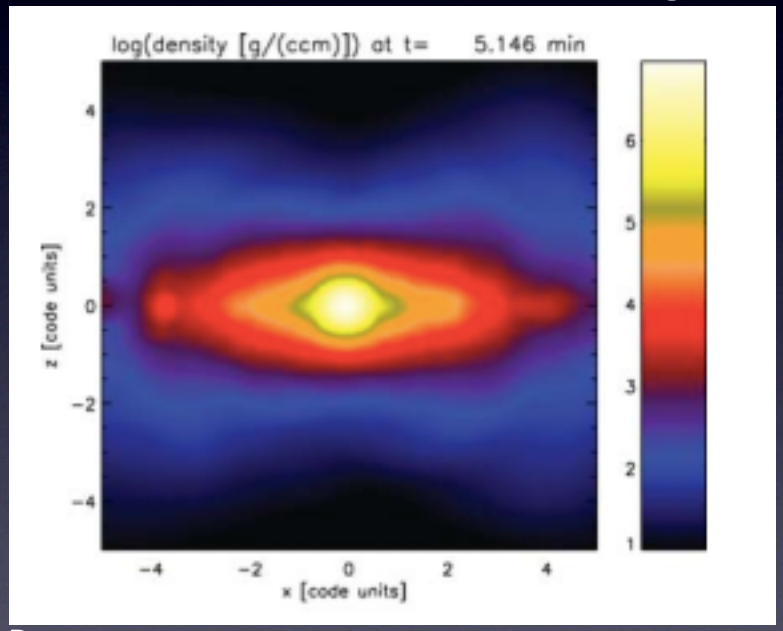

SWARMS

Rates uncertain (~ Ia from pop synthesis);
no several σ detection of system w $M_{tot} > M_{CH}$

# WD-WD Mergers: $M \gtrsim M_{CH}$

(the story due to Ken Shen ....)

Remnant of WD-WD Merger




Rosswog

## Key Evolutionary Phases (C/O WDs)

1. Dynamical Disruption (~ min)
   (C ignition possible in some cases?)

If *s survive merger ...

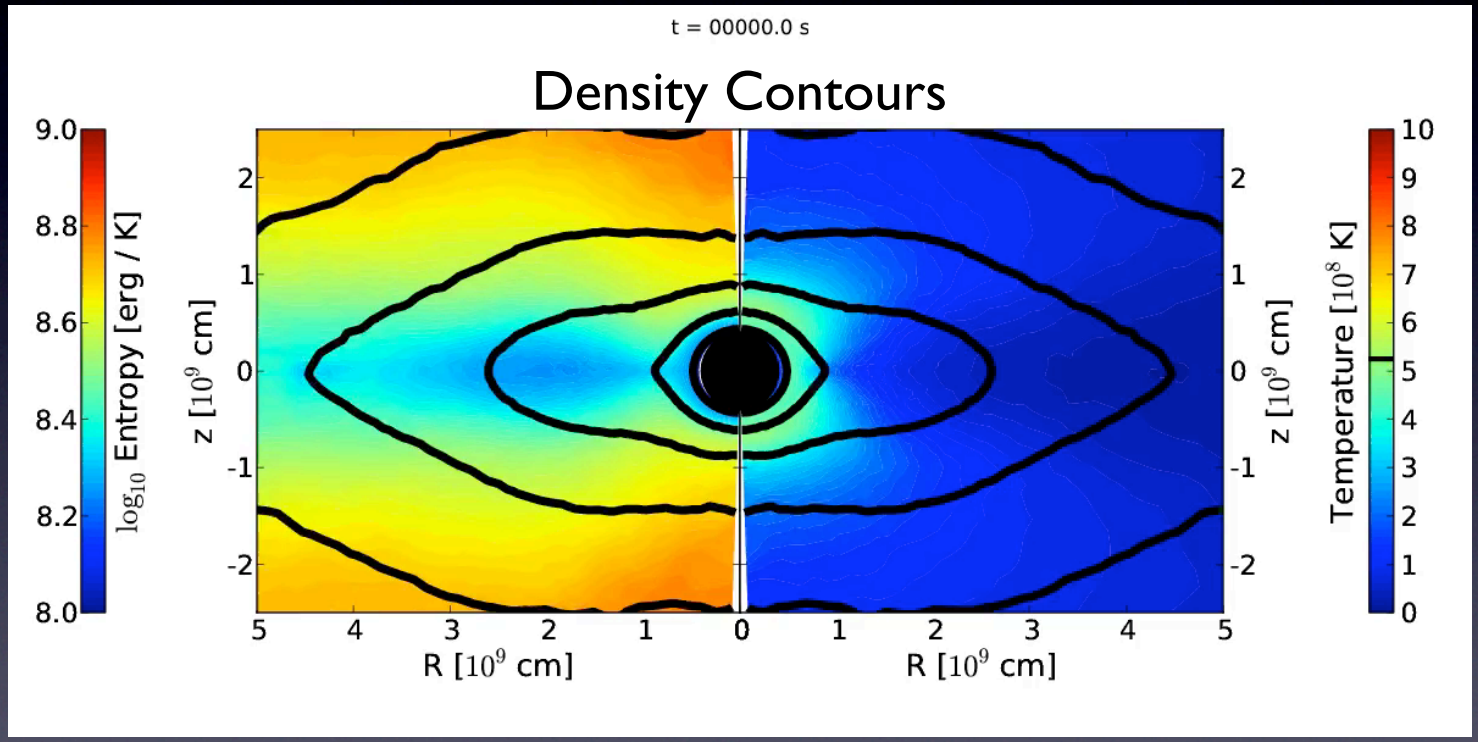
2. Viscous evolution of remnant (~hrs-year)

3. Cooling of the remnant (~$10^{4\text{-}5}$ yr)

Key Physics (pre-explosion): MHD, EOS, Opacity, ...
Computational Challenge: Merger, then ~ Multi-D Stellar Structure

# WD-WD Mergers: $M \gtrsim M_{CH}$

(the story due to Ken Shen ....)

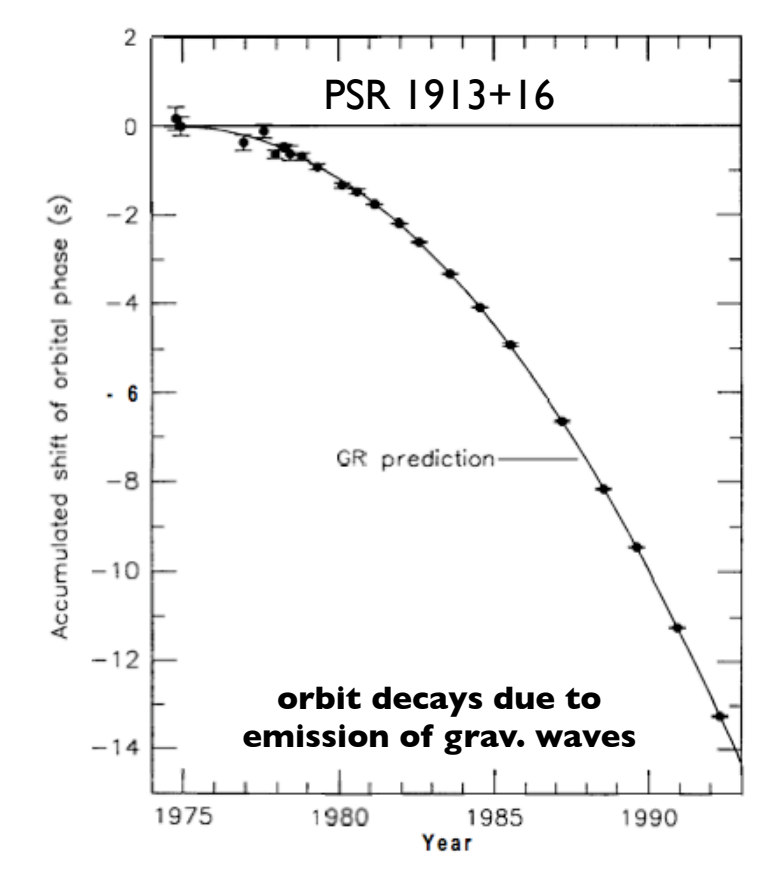



Josiah Schwab

2. Viscous evolution (~hours-year) → spherical remnant w/ significant thermal support at large radii

3. Cooling of the remnant (~$10^{4\text{-}5}$ yr): **AIC or Ia?**

# NS-NS Mergers: What do we Know Empirically?




3 known NS-NS binaries in our galaxy will merge in a Hubble time (no BH-NS systems known)

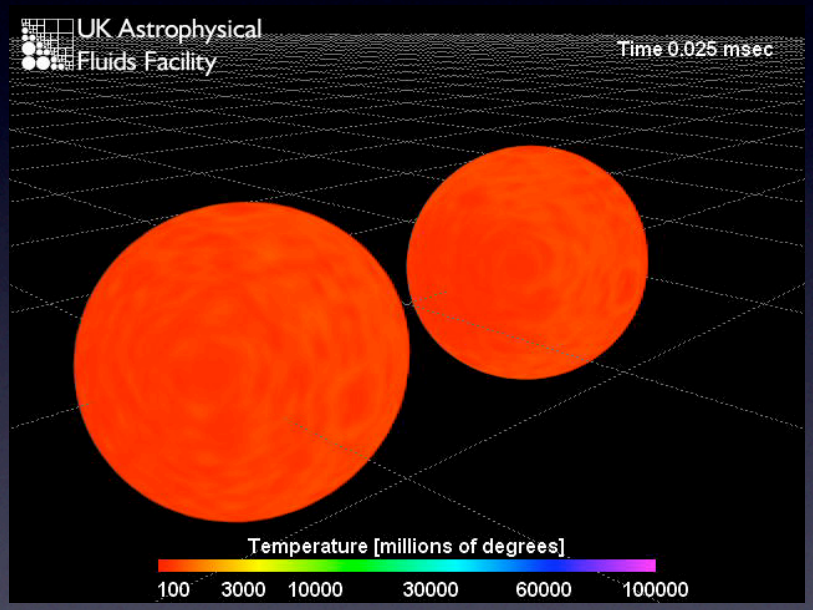
$$\dot{N}_{\rm merge} \simeq 10^{-5} - 3 \times 10^{-4}\,{\rm yr}^{-1}\,{\rm per\,MW\,galaxy}$$

(Kalogera et al. 2004)

Taylor Nobel Prize Lecture

# NS-NS & NS-BH Mergers

## NS-NS Merger




Rosswog

### Key Evolutionary Phases

1. Dynamical Disruption + Tidal Tails (~ ms)
2. Possible hypermassive NS; $\alpha$-mom transport (B-fields) → collapse to BH ( ~ 10s ms)
3. Viscous evolution of disk (~ 0.1-1 sec)
4. Disk 'Explosion' + Fallback ($\gtrsim$ sec)

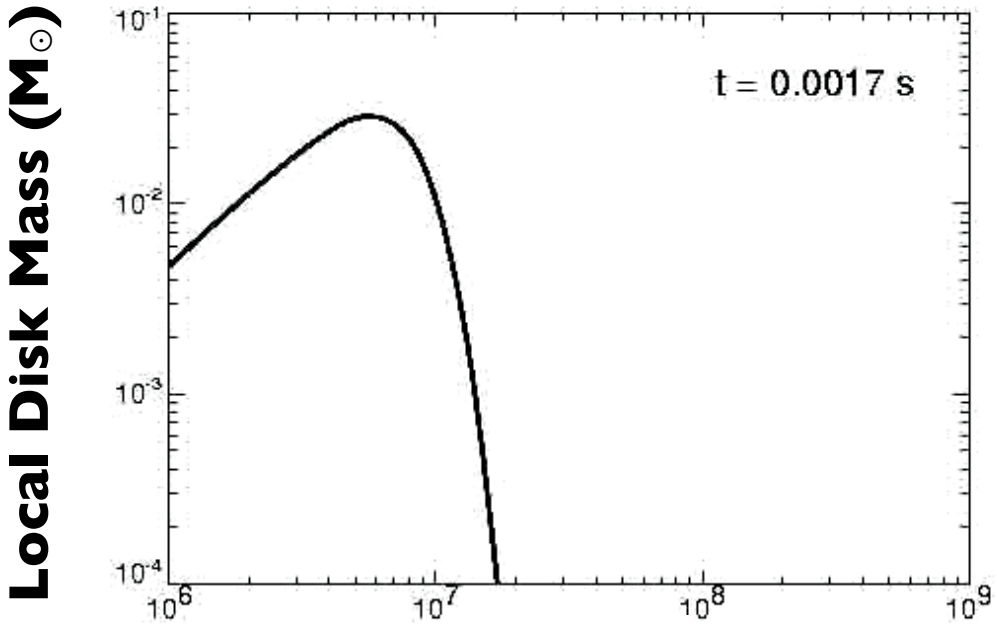
GW Signal

EM Signal

Key Physics: GR, MHD, weak interactions, $\nu$ transport, nuclear htg, ....

# The Evolution of the Remnant Disk

ang momentum conservation → disk spreads (& cools)




1D time-dependent Models

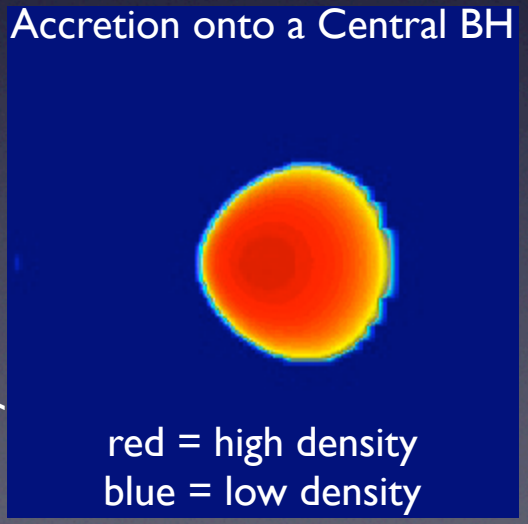
(α-viscosity; realistic EOS, ν-microphysics)

$$\dot{M} \sim M_\odot\, s^{-1}$$

$$\tau_{\rm photons} \gg 1;\ \tau_\nu \sim 1$$

→ only neutrino cooling impt

Accretion onto a Central BH



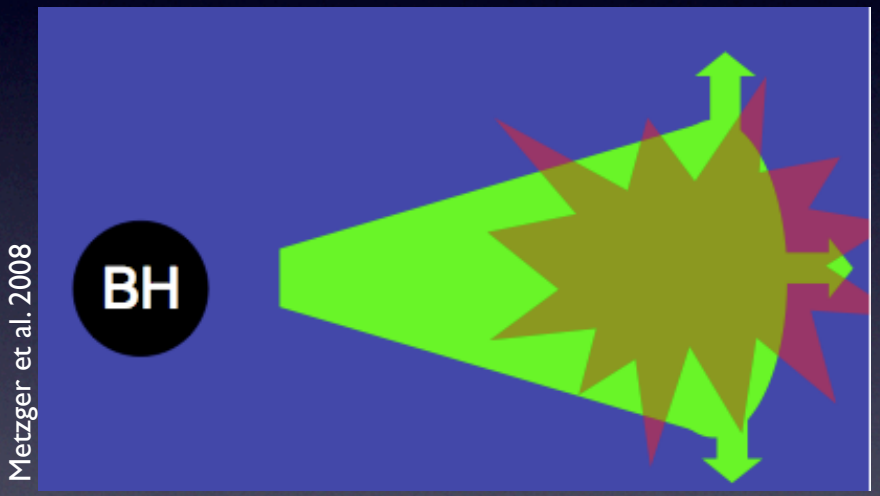
red = high density
blue = low density

Hawley

multi-D MHD but no realistic physics for NS debris

# The Little Bang: Late-time Disk 'Explosion'

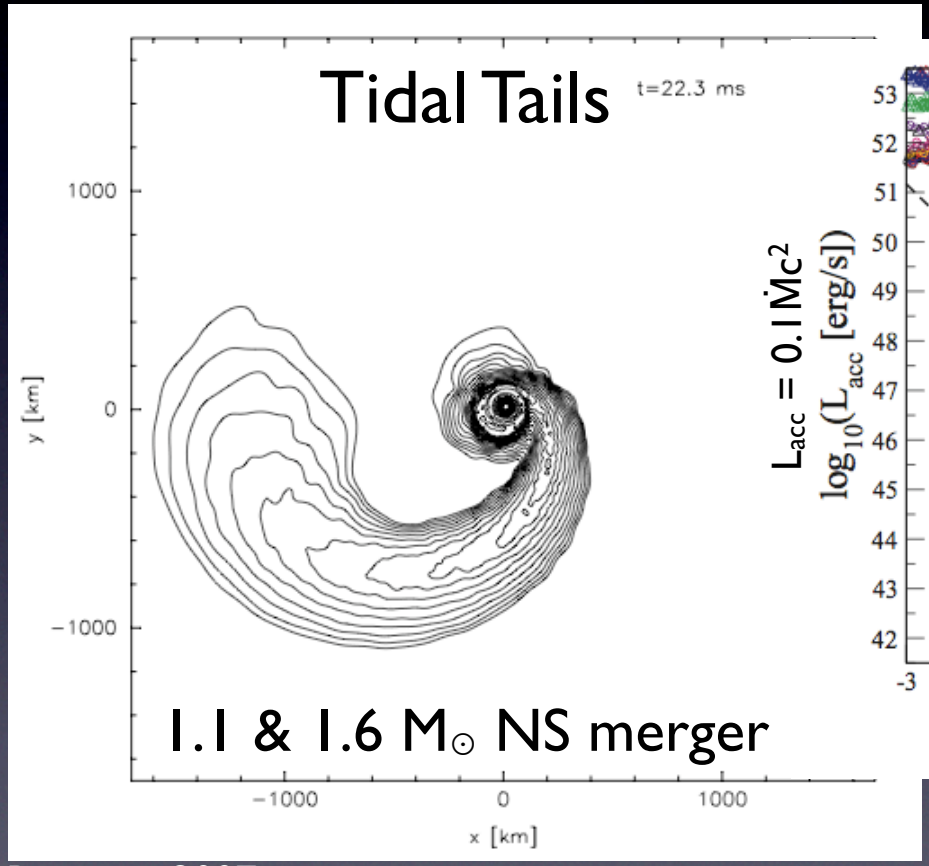
Initially T ~ few MeV; disk mostly free neutrons
After ~ sec, R ~ 500 km & T ≲ 0.5 MeV
free n & p recombine to He
fusion (~ 7 Mev/nucl) unbinds disk




Metzger et al. 2008

Ejected Mass ~ 1/2 Initial Disk ~ $10^{-2}\ M_{\odot}$, at v ~ 0.1 c
Neutron-rich matter ($Y_e$ ~ 0.3)

# Late-Time Activity from Fall-back Accretion?

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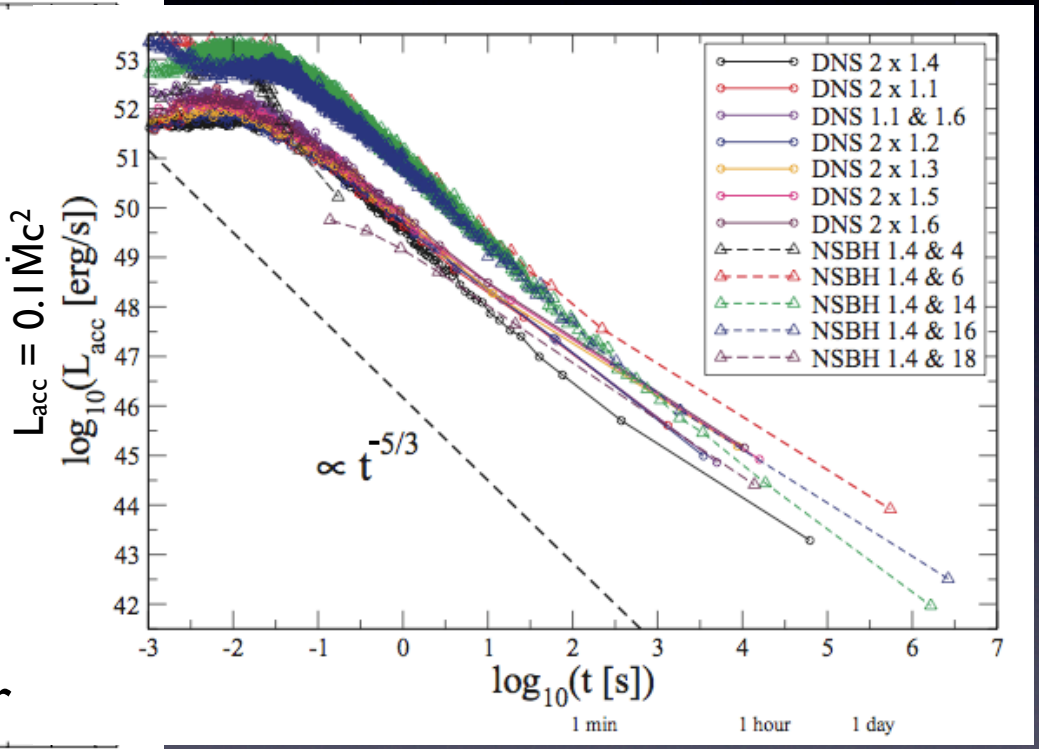
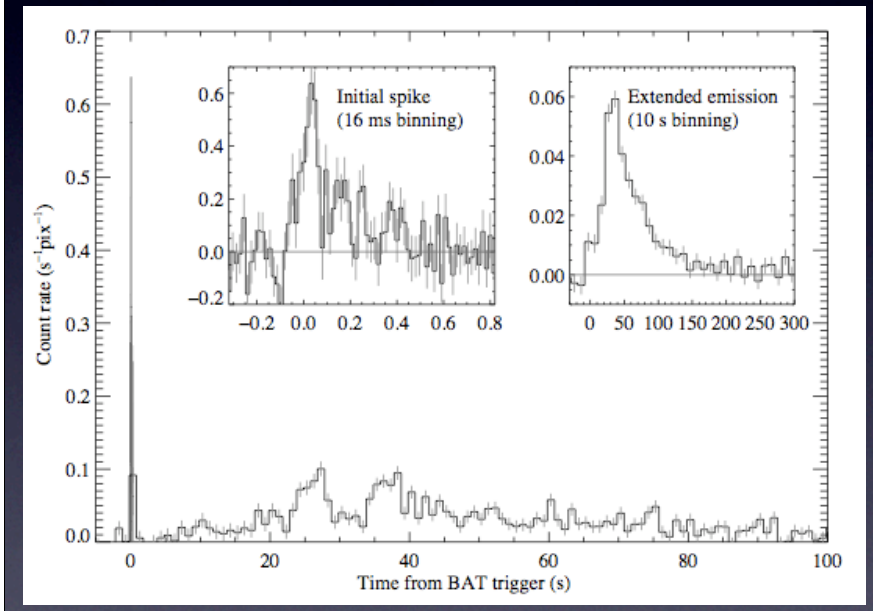



But at least partially suppressed by r-process heating in ejecta

# NS-NS & NS-BH Mergers

Short(ish)-Duration GRB




Key Evolutionary Phases

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3. Viscous evolution of disk (~ 0.1-1 sec)
   (consistent w/ short GRB durations)
4. Disk 'Explosion' + Fallback (≳ sec)

**next frontier**

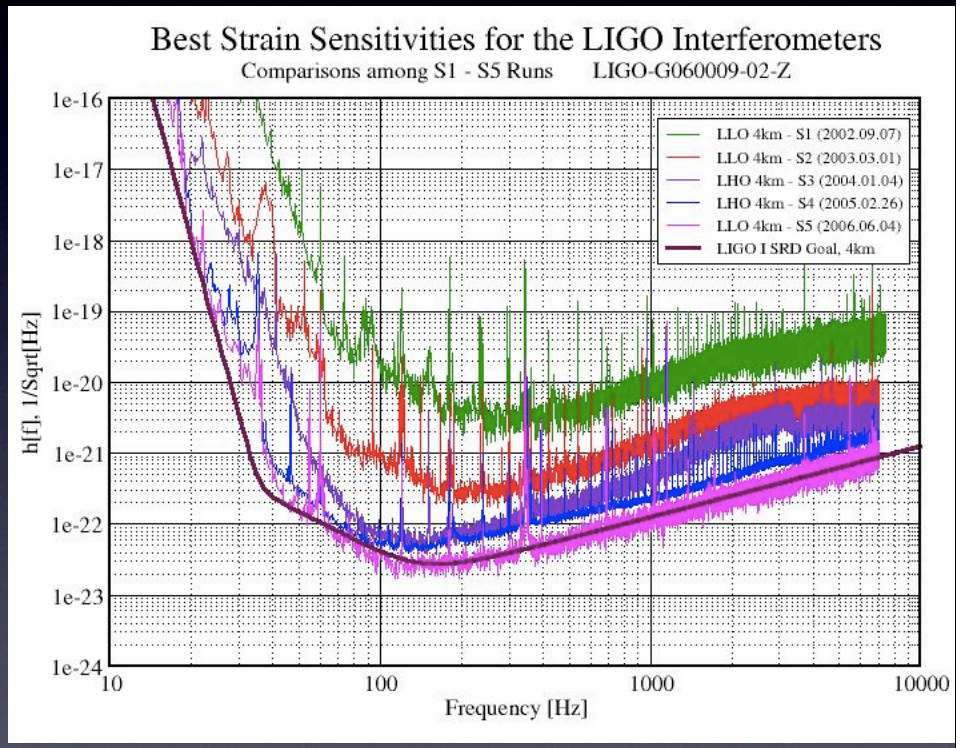
GW Signal

EM Signal

***likely detected***

# ~ kHz GWs: a New Frontier in Compact Object Astrophysics

- Direct detection of GWs: unique insights into compact objects
  - masses, spins, orientation to line of sight, ...
  - no bias re. photons escaping to observer!
  - probes of nuclear physics, relativity, ....
- Critical to connect these GW detections to wealth of EM data on similar (same?) sources




LIGO reached design sensitivity in ~ 2006: $h \sim \Delta L/L \sim 10^{-21}$
(no detections; as expected)

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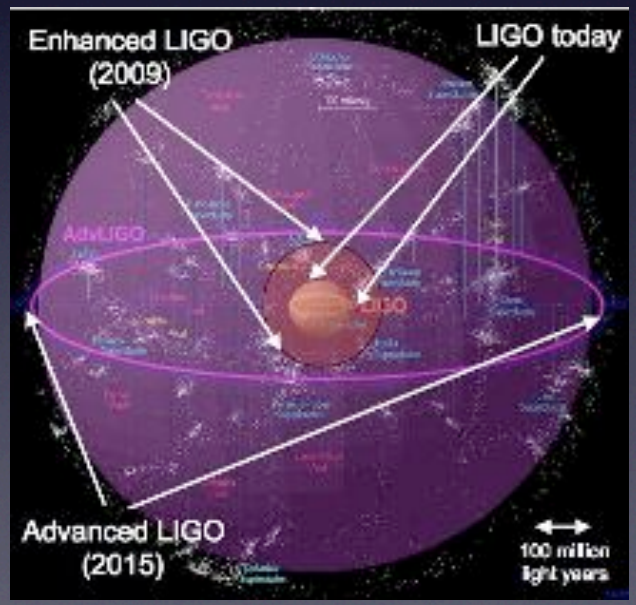
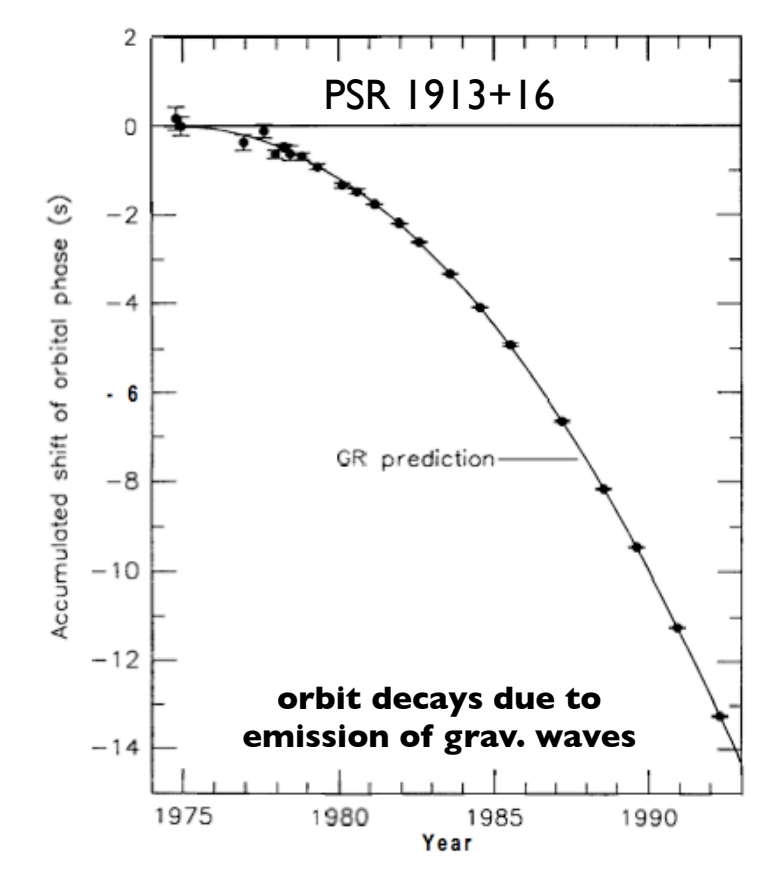
Advanced LIGO & Virgo in ~ 2015

~10x sensitivity → $10^3$ x volume/rate

worldwide effort: Geo600 (Germany), LCGT (Japan), LIGO Australia (??), ...



# NS-NS Mergers: What do we Know Empirically?




Taylor Nobel Prize Lecture

3 known NS-NS binaries in our galaxy will merge in a Hubble time (no BH-NS systems known)

$$\dot{N}_{\rm merge} \simeq 10^{-5} - 3 \times 10^{-4}\,{\rm yr}^{-1}\,{\rm per\,MW\,galaxy}$$

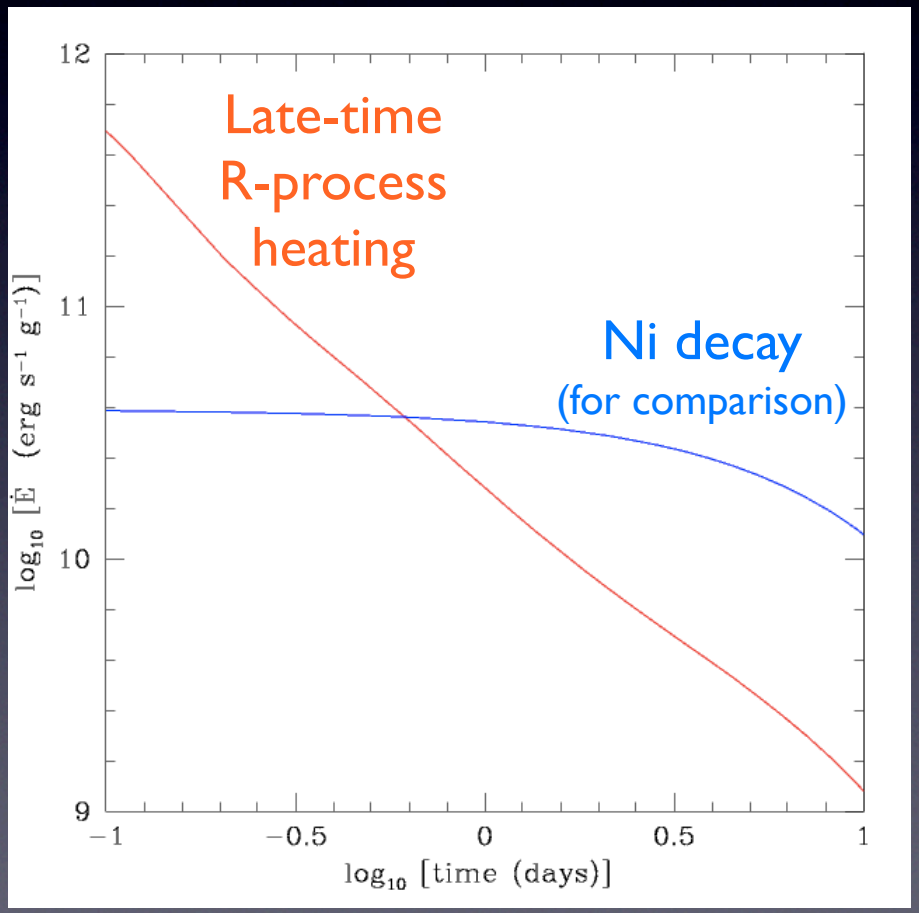
$$\text{Advanced LIGO}: \sim 20 - 10^{3}\ {\rm yr}^{-1} \quad \sim 100\ {\rm yr}^{-1}\ \text{'reasonable'}$$

(Kalogera et al. 2004)

**Advanced LIGO/VIRGO:**
**NS-NS Mergers at ~ 200 Mpc**
**BH-BH Mergers at ~ Gpc**

# Most Promising Isotropic EM Counterpart

## Heating of NS Debris in Compact Object Mergers




Heating Rate (log)

**~2 hrs** **1 day** **10 days**

~ $10^{-3}$-$10^{-2}$ $M_\odot$ unbound during dynamical phases of merger & disk explosion (v~0.1c)

Initial thermal energy lost to adiabatic expansion

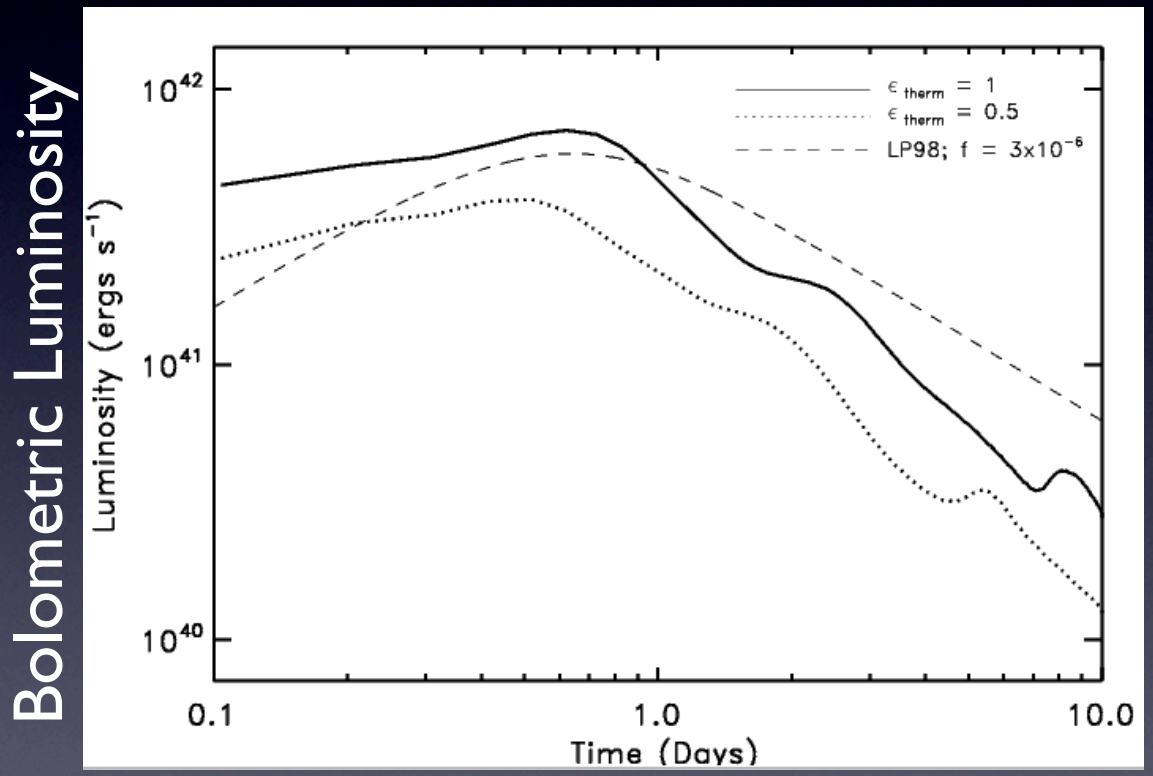
Luminosity of Unbound Ejecta Depends on Heating

Heating due to decay of n-rich nuclei created via r-process

emission peaks when $t_{diff} \lesssim t_{exp}$
**t ~ 1 day** for NS ejecta

# Most Promising Isotropic EM Counterpart

**R-process Powered Transient**




spherical RT w/ SEDONA: $10^{-2}\ M_\odot$

Observational Diagnostics

**few day "kilonova":**
**$L \sim 3\ 10^{41}$ ergs s$^{-1}$**
**($M_V \sim -15$)**

$T \sim 10^4$ K at peak: **optical**

spectroscopic: all n-rich elements
(no Ni, Fe, C, O, He, Si, H, Ca, ...)

colors, etc. hard to predict bec.
insufficient atomic line info
for relevant nuclei!

# NS-NS & NS-BH Mergers: Computational Challenges

## Astrophysical Observable

GWs: GR (M?)HD Sims of Merger & Collapse to BH; Realistic EOS; r-process htg to correctly model ejecta

GRB: GR MHD Sims of disk & jet; weak interactions; nuclear heating; $\nu$ transport;

EM Counterpart to GW: 3D RT problem given ejecta mass, kinematics from merger & disk sims

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