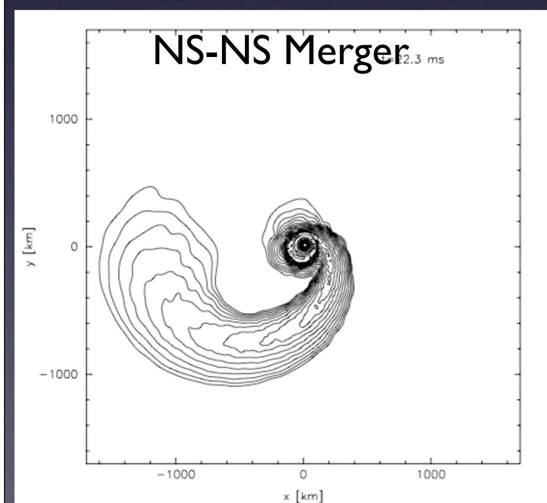
The Biermann Lectures:
Adventures in Theoretical Astrophysics

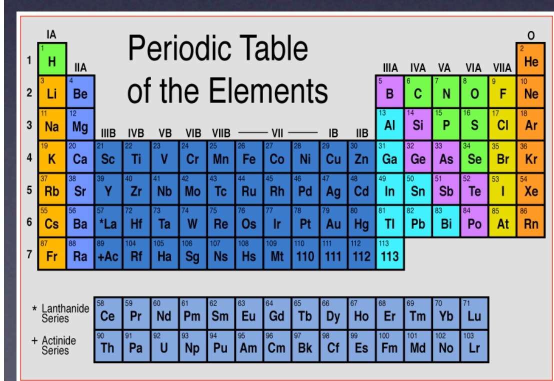
III Searching for the Electromagnetic Counterparts of Gravitational Wave Sources

Eliot Quataert (UC Berkeley)

w/ Brian Metzger, Tony Piro, Siva Darbha, Almudena Arcones,
Gabriel Martinez Pinedo, Dan Kasen, Todd Thompson, ...

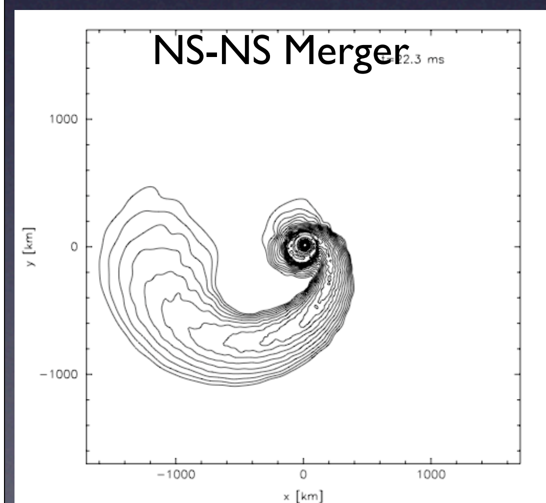


Rosswog 2007

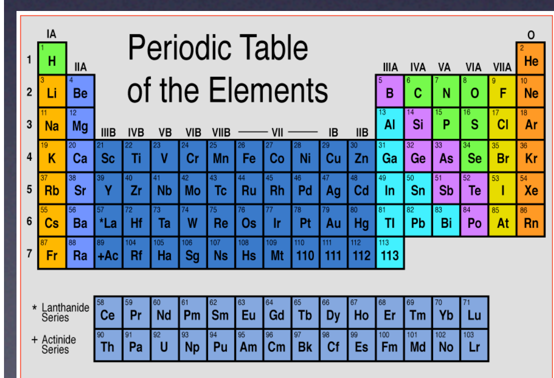


Overview

- Context: kHz Gravitational Wave Astrophysics
  Likely Astrophysical Sources
- Why worry about EM Counterparts?
- Compact Object Mergers: GWs & Gamma-Ray Bursts
- EM Counterparts & Transient Surveys

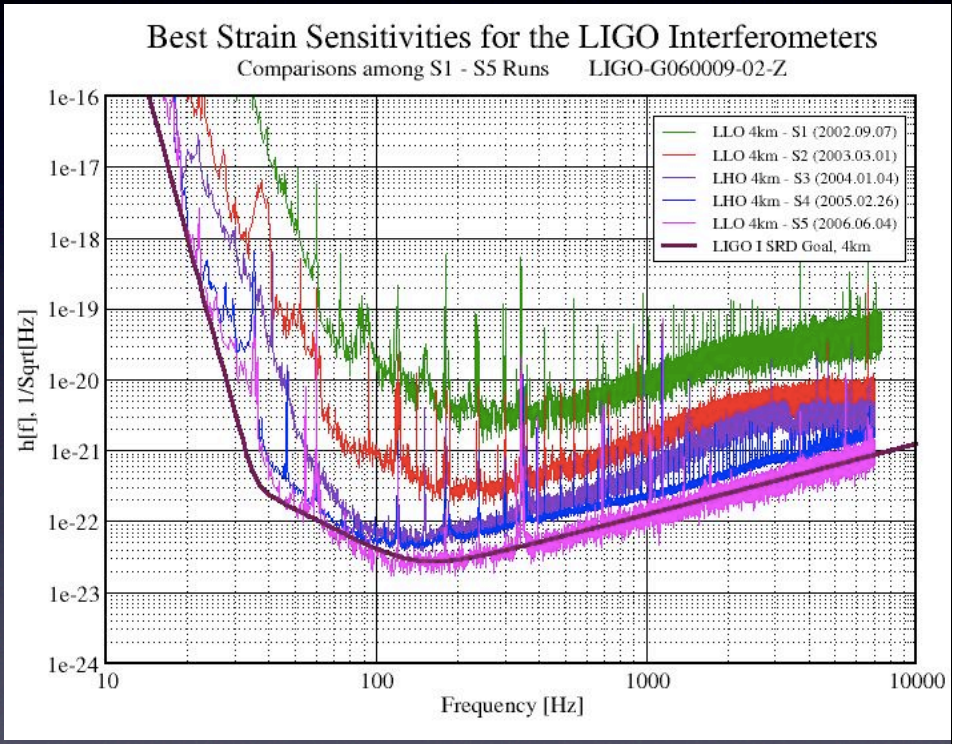


Rosswog 2007



~ 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 ~ $\Delta L/L$ ~ 10^{-21}

(no detections; as expected)

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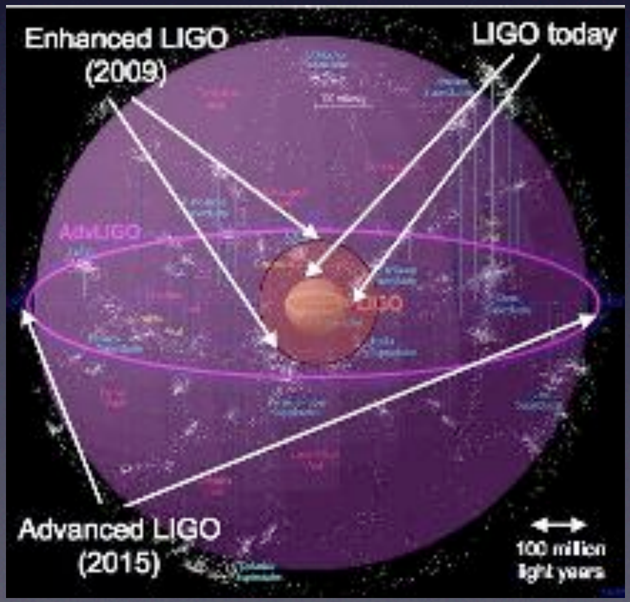
Advanced LIGO & Virgo in ~ 2015
~10x sensitivity → 10^3 x volume/rate

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



Astrophysical Sources of ~ kHz GWs

$$\dot{E}_{GW} \sim \frac{G}{c^5} \left(\frac{d^3 Q}{dt^3} \right)^2 \qquad Q \sim M_{na} L^2$$

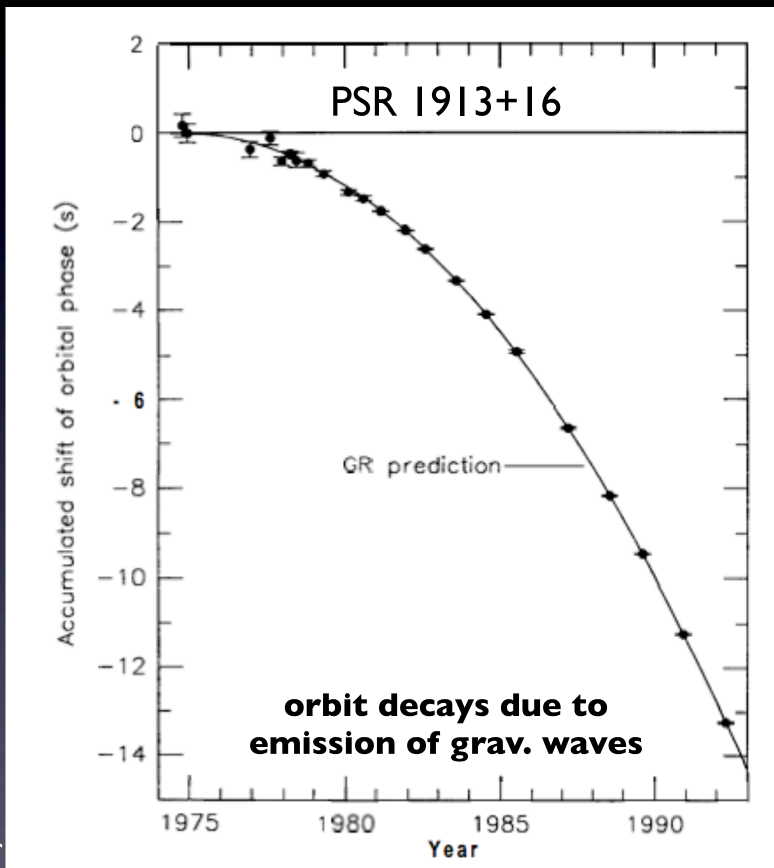
na = non-axisymmetric part of mass distribution

$$\dot{E}_{GW} \sim \frac{c^5}{G} \left(\frac{v}{c} \right)^6 \left(\frac{r_s}{L} \right)^2$$

r_s associated w/ non-axisymmetric mass distribution

- NS-NS, NS-BH, BH-BH Mergers (~ $M_\odot$)
- Asymmetric stellar collapse
  - core-collapse supernovae, AIC of WD→NS
- Rapidly rotating NSs; max obs ~ 700 Hz

Astrophysical Sources of ~ kHz GWs



Taylor Nobel Prize Lecture

'Guaranteed' Source:

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

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

$$\text{Advanced LIGO} : 20 - 10^{3}\ \text{yr}^{-1}\ \ \sim 100\ \text{yr}^{-1}\ \text{best guess}$$

(Kalogera et al. 2004)

Advanced LIGO/VIRGO:
NS-NS Mergers at ~ 300 Mpc
BH-BH Mergers at ~ Gpc

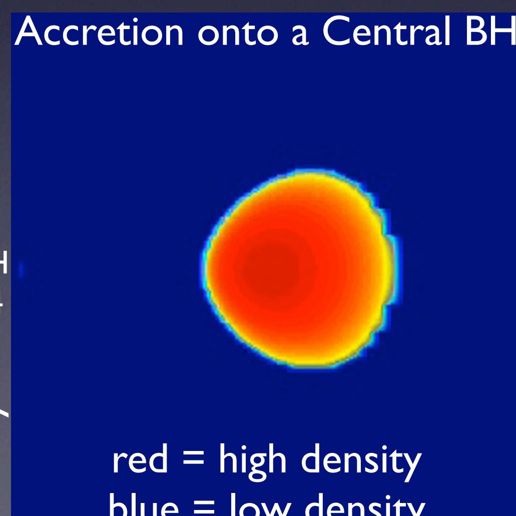
Why Worry about EM Counterparts?

(i.e., can't we do all this great science w/ GWs alone?)

- post Nobel Prize, LIGO/VIRGO are astronomical observatories
- With EM counterparts, astrophysicists can
  - identify host galaxy (H_0; constrain progenitors)
  - connect to wealth of transient phenomenology (SNe, GRBs, new sources, ...)
  - uniquely constrain models: know masses, spins, orientation, ...

e.g.,
3 $M_\odot$ BH
a = 0.84

Hawley



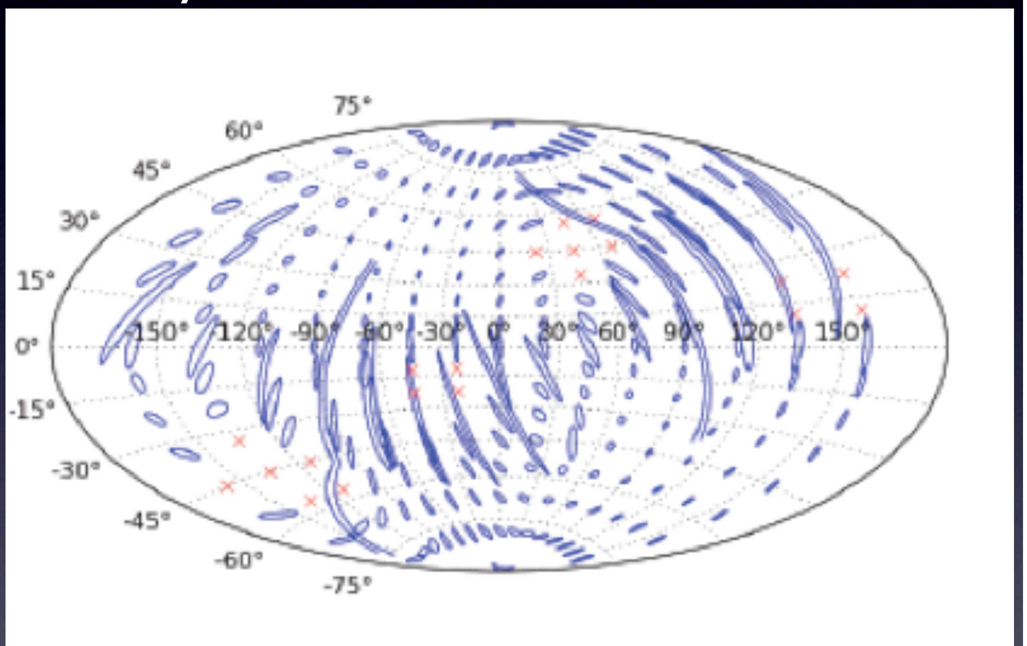
Why Worry about EM Counterparts?

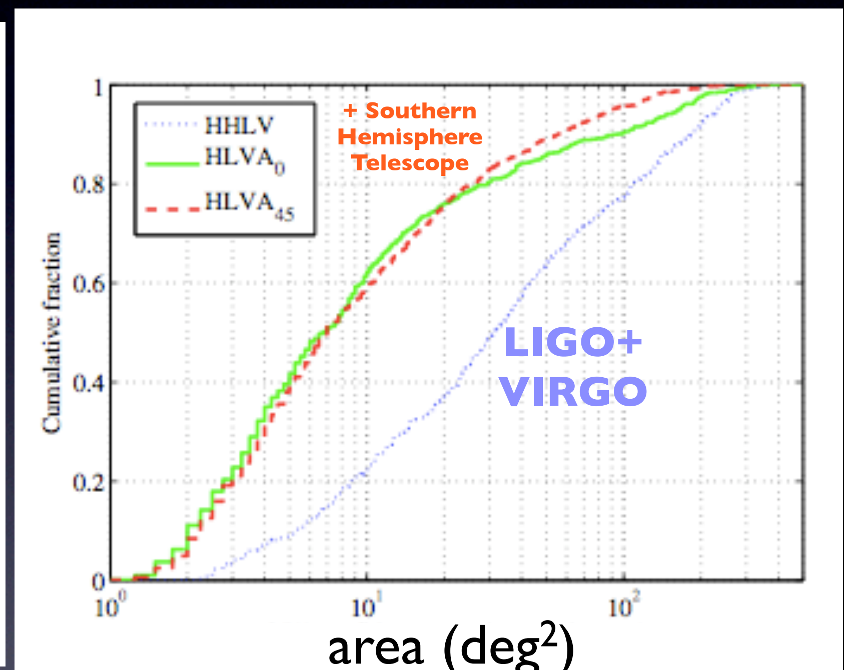
(i.e., can't we do all this great science w/ GWs alone?)

- post Nobel Prize, LIGO/VIRGO are astronomical observatories
- With EM counterparts, GW astrophysicists can
  - improve parameter estimation on detections
  - cross-correlate GW w/ EM searches
    - gain factor of ~ 2 in sensitivity and ~ 10 in rate!
    - if merger rate low: EM signal critical to significant # of GW detections

Why Finding EM Counterparts is Hard

Sky Localization: LIGO + VIRGO





Aylott+ 2011

Problem: Poor positions ~ 3-100 deg^2 from few-arm interferometer
Challenge: significant observational & theoretical work needed now

Astrophysical Sources of ~ kHz GWs

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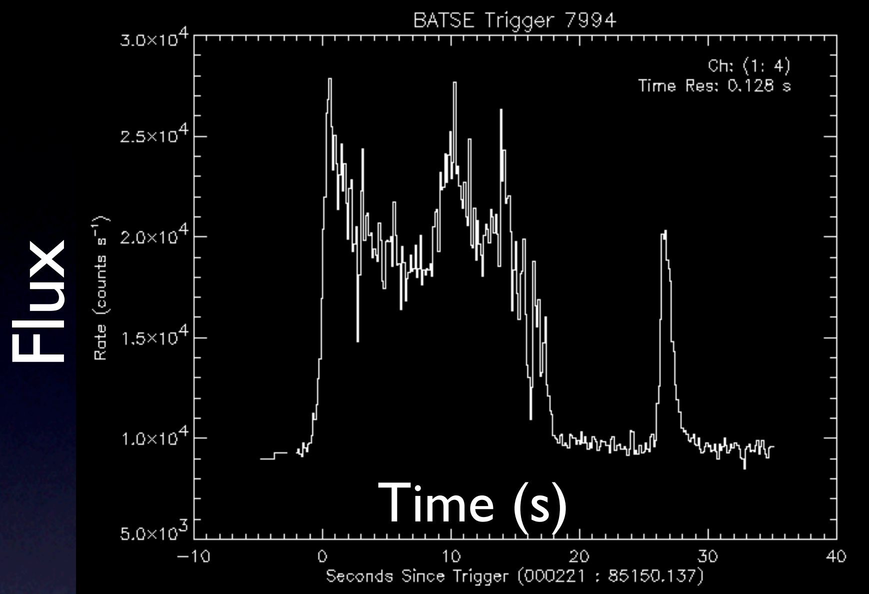
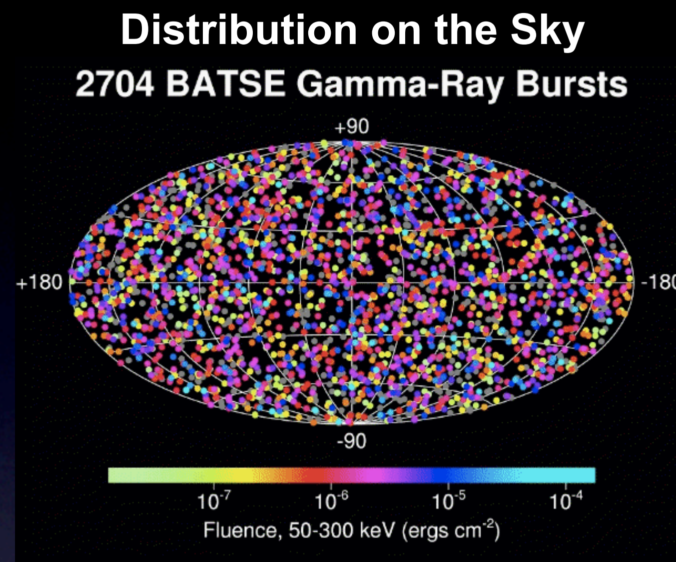
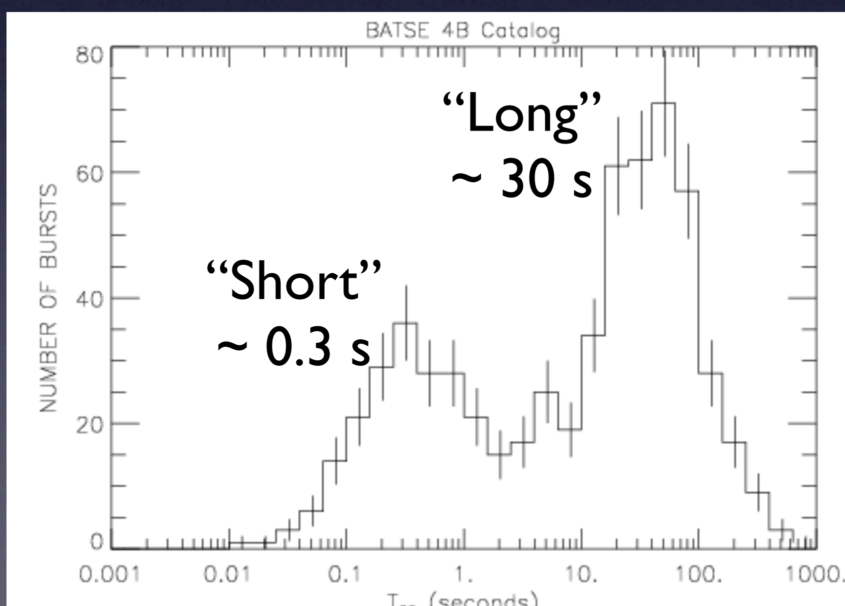
GWs & GRBs

Best Guess Progenitors of Gamma-ray Bursts

Gamma-Ray Bursts



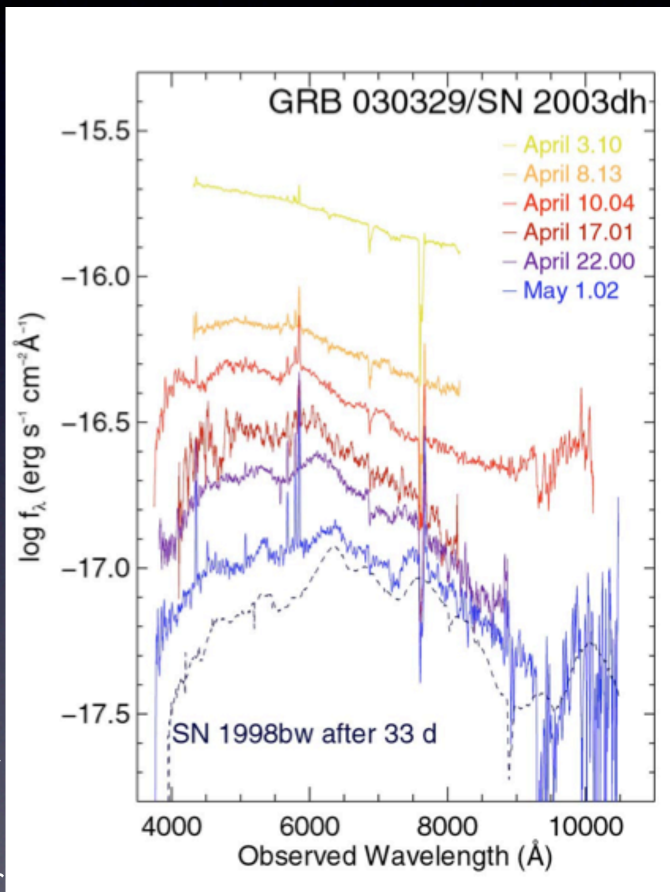




- Bursts of ~ 0.1-10 MeV γ-rays (non-thermal)
- "Long" (~ 30 s) & "Short" (~ 0.3 s)
- Isotropic & Cosmological: $z \sim 0.1\text{-}8.3$
- Very Energetic: ~ $10^{48\text{-}55}$ ergs (isotropic)
- Highly Relativistic: $\Gamma \sim 10^{2\text{-}3}$
- Rare: GRB Rate ~ 10^{-6}/yr/galaxy ~ 10^{-4} SN rate

Long-Duration GRBs

As GRB fades, a supernova appears



Hjorth et al; Stanek et al.

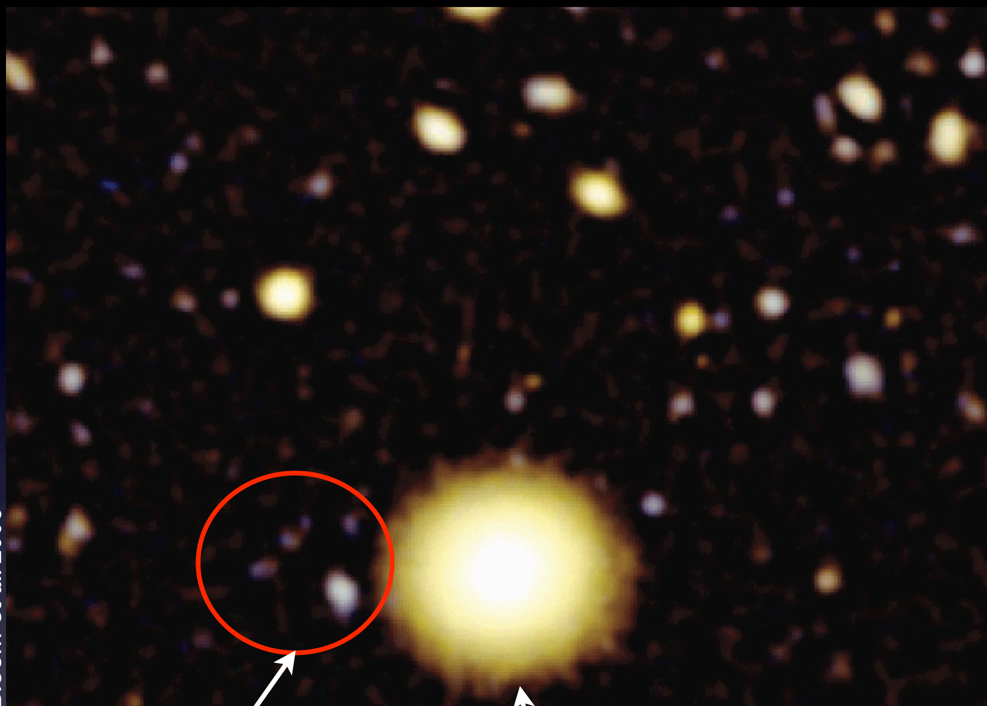
Associated with massive star formation and Type 1bc supernovae

→ Birth of a BH or NS during core-collapse

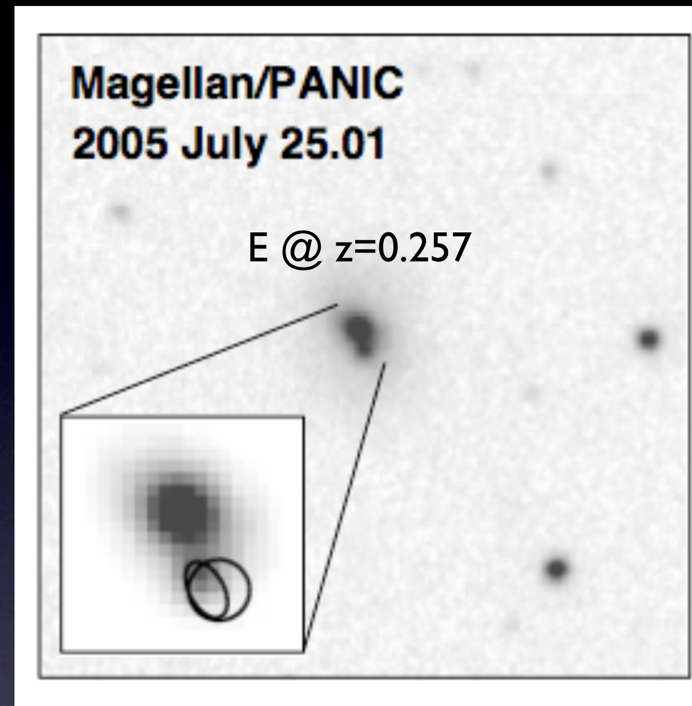
Distinguished from typical SNe by rapid rotation but ...

Level of Rotation Required in Long GRBs $\not\Rightarrow$ GW Emission (can be ~ axisymmetric)

Short GRBs Hosts



Bloom et al. 2006



Berger et al. 2005

GRB Here

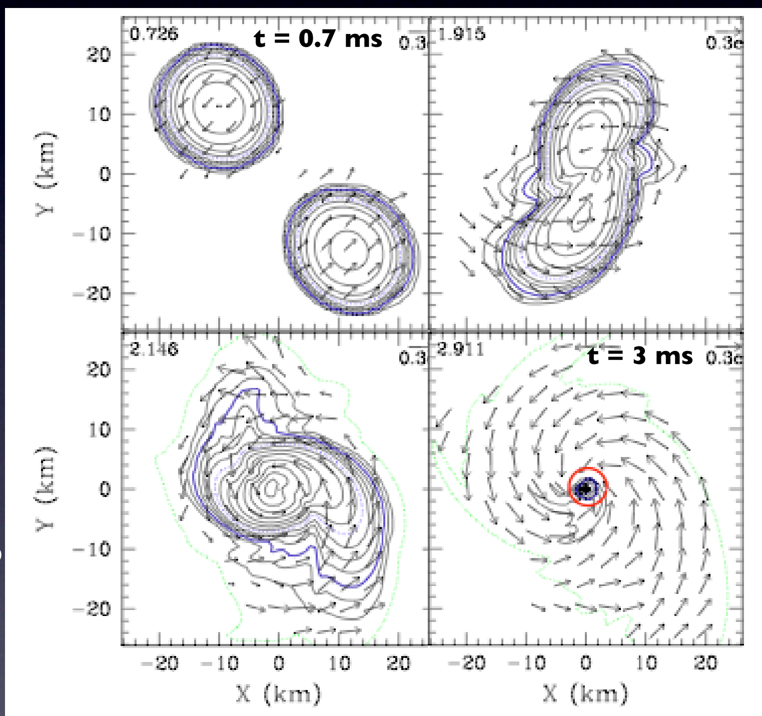
Elliptical @ z = 0.22
SFR < 0.1 $M_\odot$ yr^{-1}

No Coincident SNe
Older Stellar Population
Distinct Progenitor

NS-NS & NS-BH Mergers

(Paczynski 1986; Goodman 1986; Eichler et al. 1989; Narayan et al. 1992 ....)

NS-NS Merger



Shabata & Taniguchi 2006

density contours & velocity vectors

Merger Leaves Behind
Disk ~ 10^{-3}-0.1 $M_\odot$
(mostly free neutrons initially)

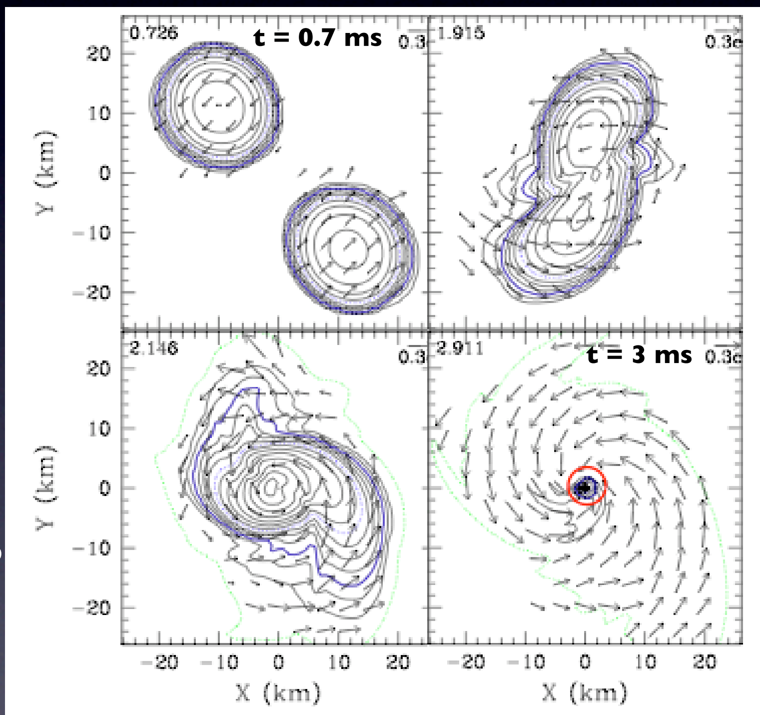
$$t_{\rm visc} \sim 0.1 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{100\,{\rm km}}\right)^{3/2} \, sec$$

consistent w/ short GRB durations

NS-NS & NS-BH Mergers

(Paczynski 1986; Goodman 1986; Eichler et al. 1989; Narayan et al. 1992 ....)

NS-NS Merger



Shabata & Taniguchi 2006

density contours & velocity vectors

3 known NS-NS binaries in MW
will merge in a Hubble time

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

(Kalogera et al. 2004)

short grb rate ~ 10^{-6} yr^{-1}per MW

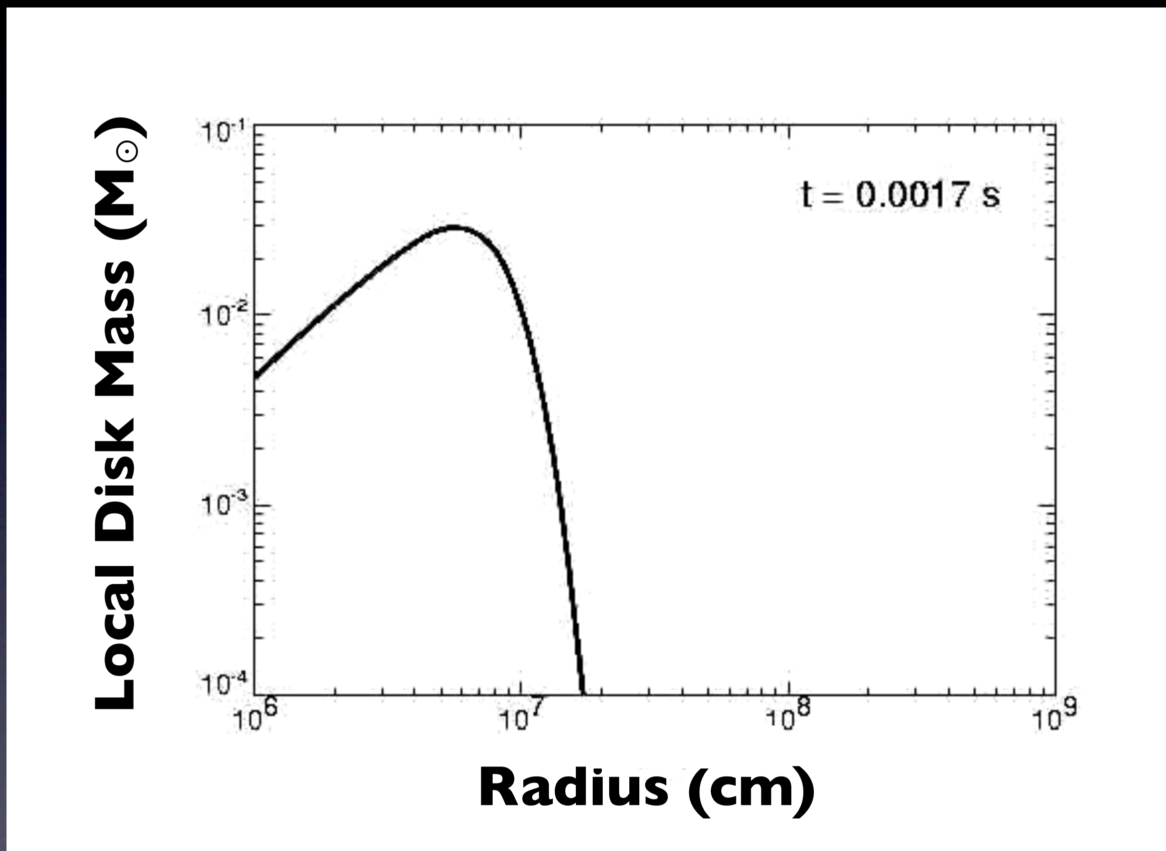
⇒ emission beamed

(or not all mergers ⇒ GRB)

EM counterpart to GW detection
unlikely GRB; need ~ isotropic emission

The Evolution of the Remnant Disk

ang momentum conservation → disk spreads (& cools)



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

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

→ only neutrino cooling impt

$L_{\rm photon} \lesssim L_{\rm Edd}$

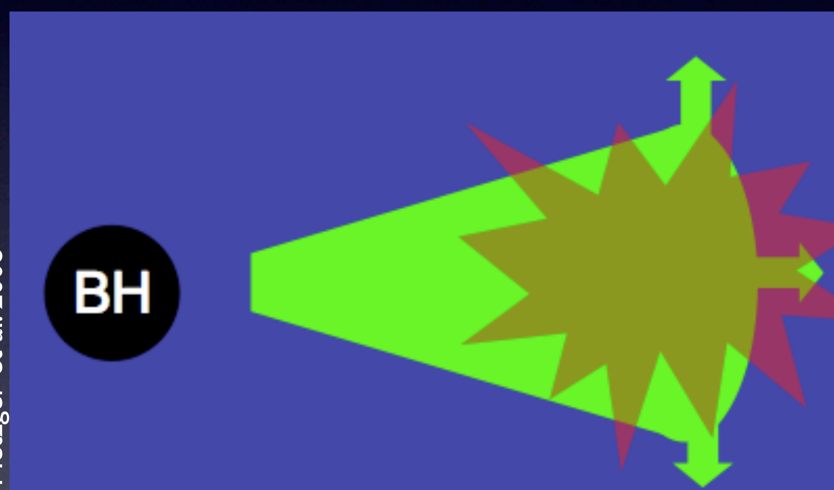
(undetectable at ~ 100 Mpc!)

1D time-dependent Models

(α-viscosity; realistic ν-microphysics)

The Little Bang: Late-time Disk Winds

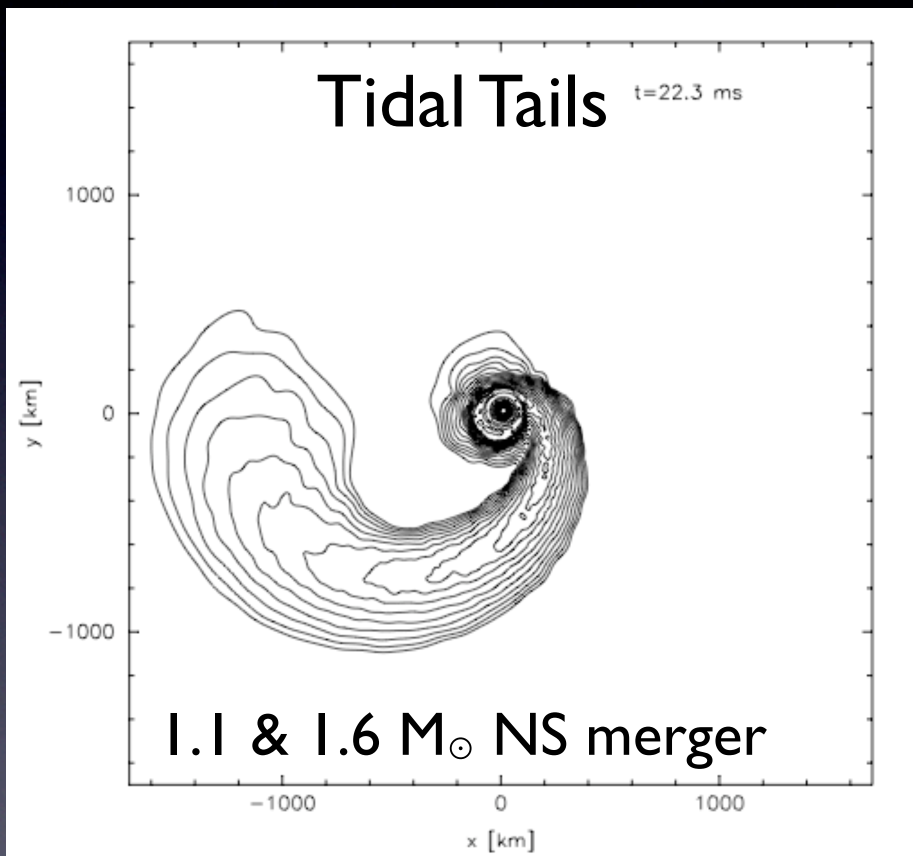
Initially T ~ few MeV; disk mostly free neutrons
After ~ sec, R ~ 500 km & T ≲ 0.5 MeV
free n & p recombine to He
fusion (~ 7 Mev/nucl) unbinds disk



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)

Dynamical Ejecta in NS Tidal Tails



Rosswog 2007

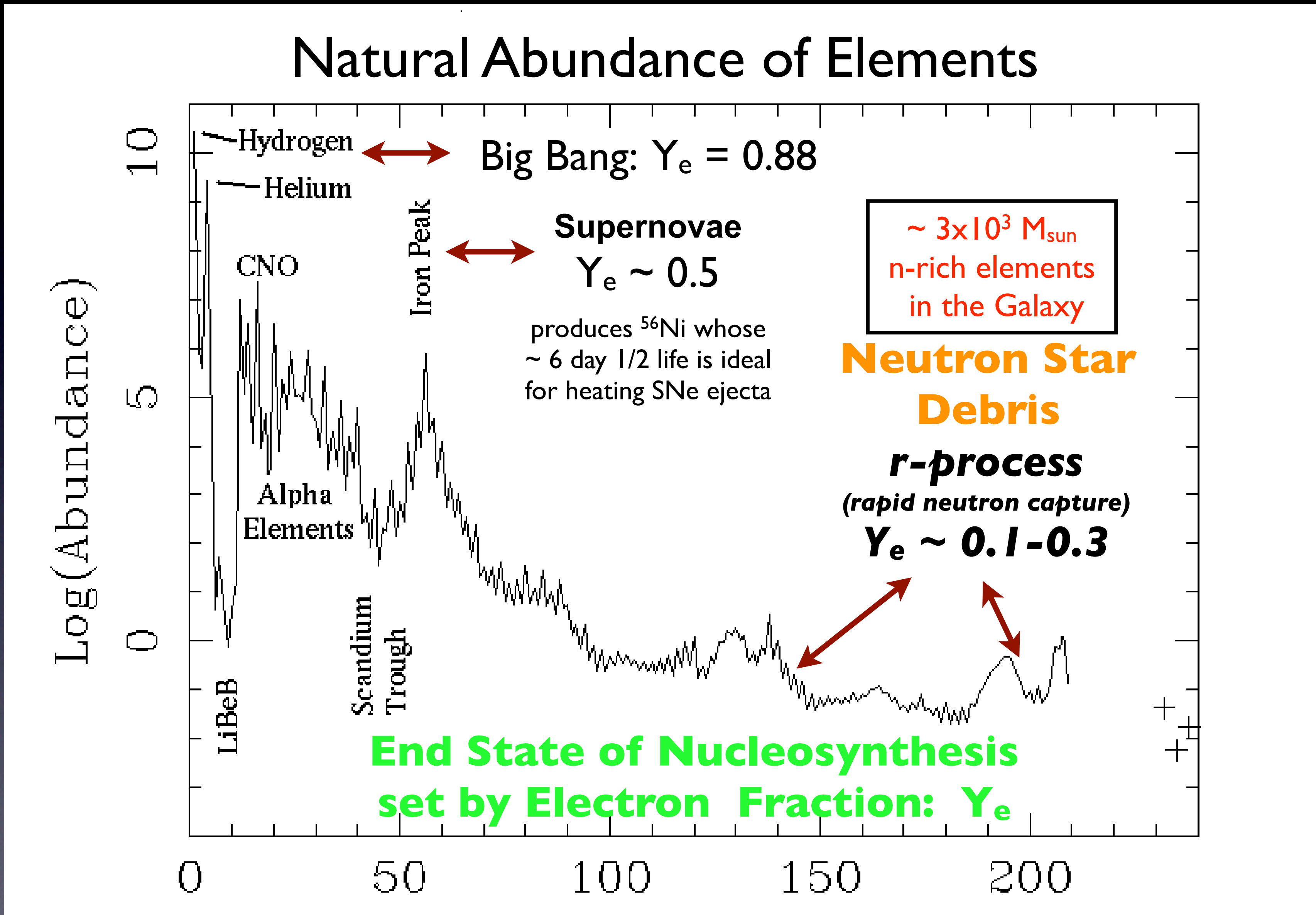
10^{-3}-10^{-2} $M_\odot$ unbound during early dynamical phases of merger
eg., Rosswog 2007; Goriely+ 2011 ...

Luminosity of Ejecta (Dynamical & Disk)
Depends on Heating

Initial thermal energy
lost to adiabatic expansion

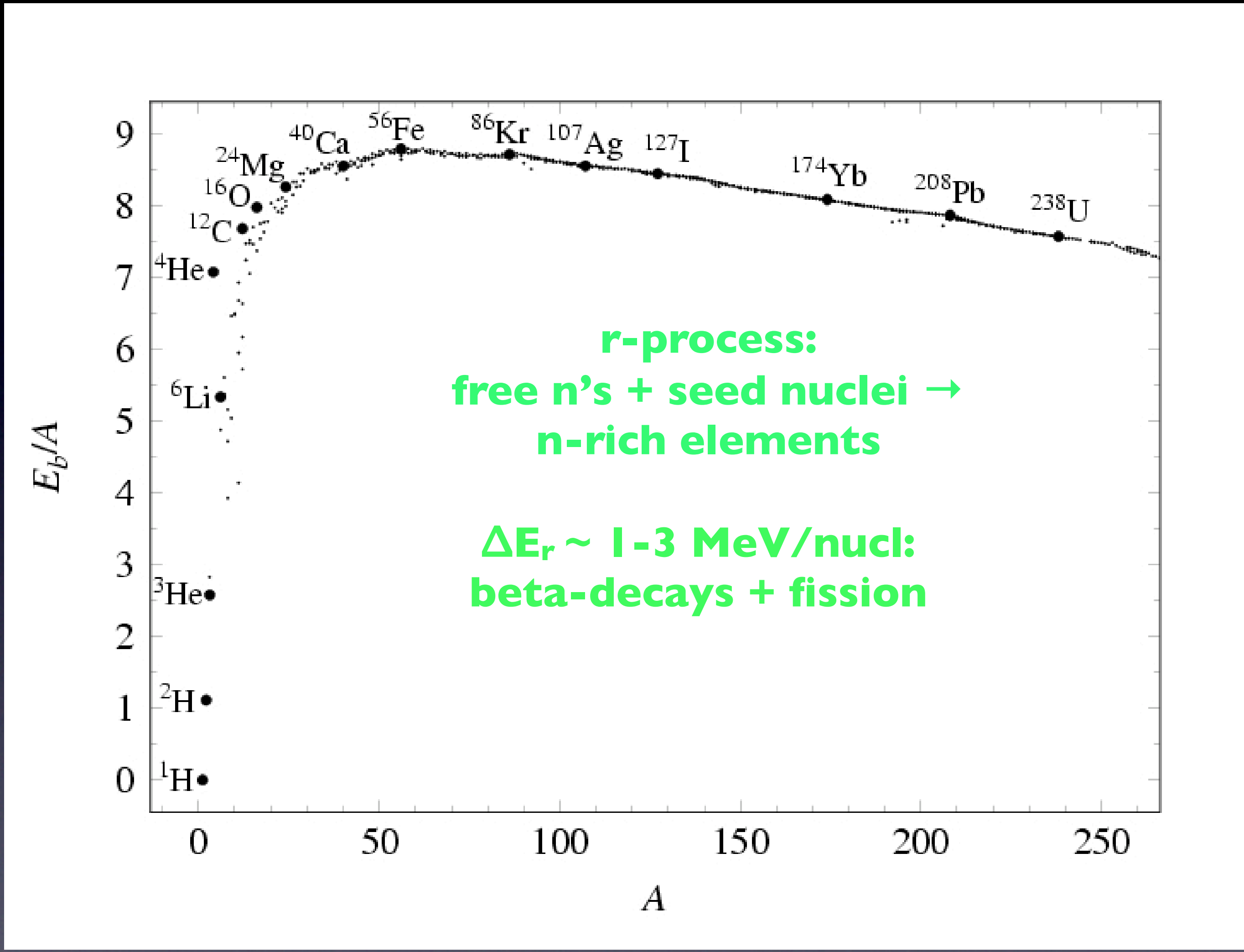
emission peaks when $t_{diff} \lesssim t_{exp}$
t ~ 1 day for NS ejecta

Nucleosynthesis in NS Debris



Atomic Mass

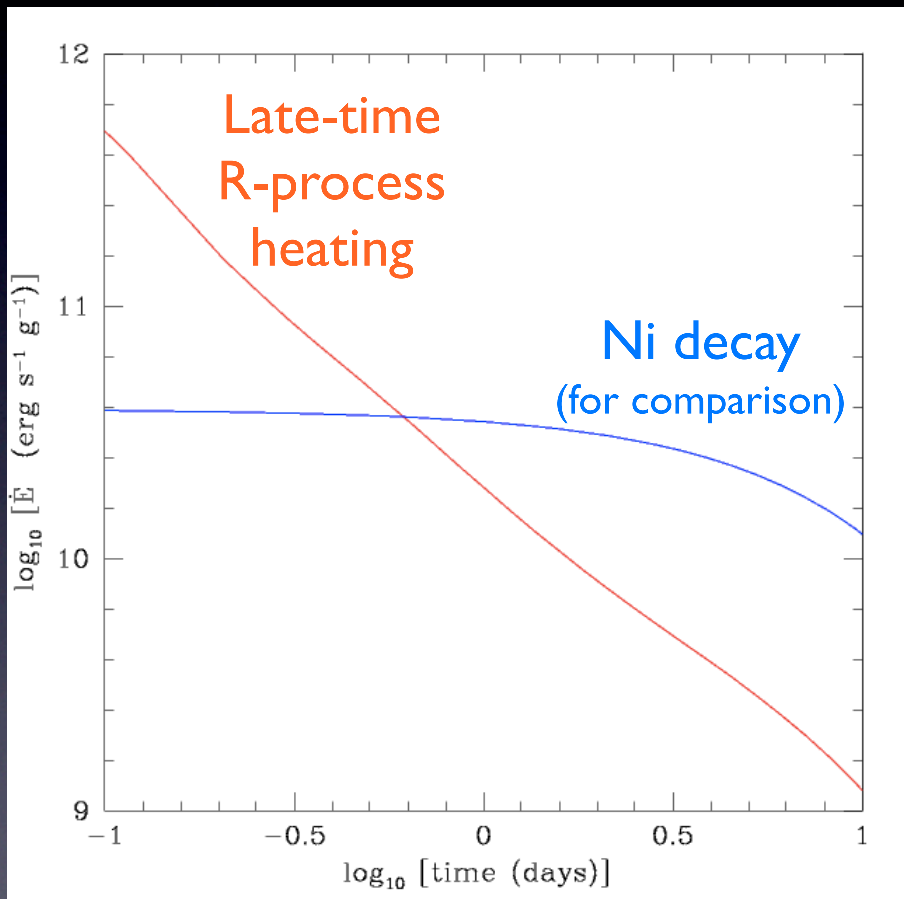
Binding Energy
(per nucleon)



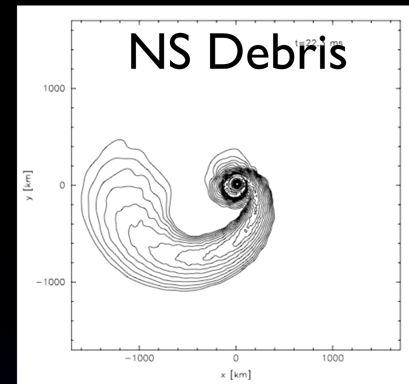
Atomic Mass

Heating of NS Debris in Compact Object Mergers

Heating Rate (log)



~2 hrs | 1 day | 10 days



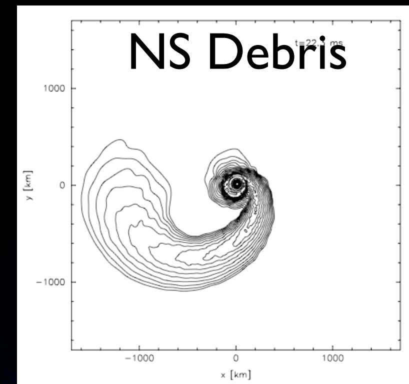
R-process produces significant heating (~ Ni) at ≲ day

largely β-decays & fission (some γ-rays)

thermalization ~ 50%
(Coulomb scattering)

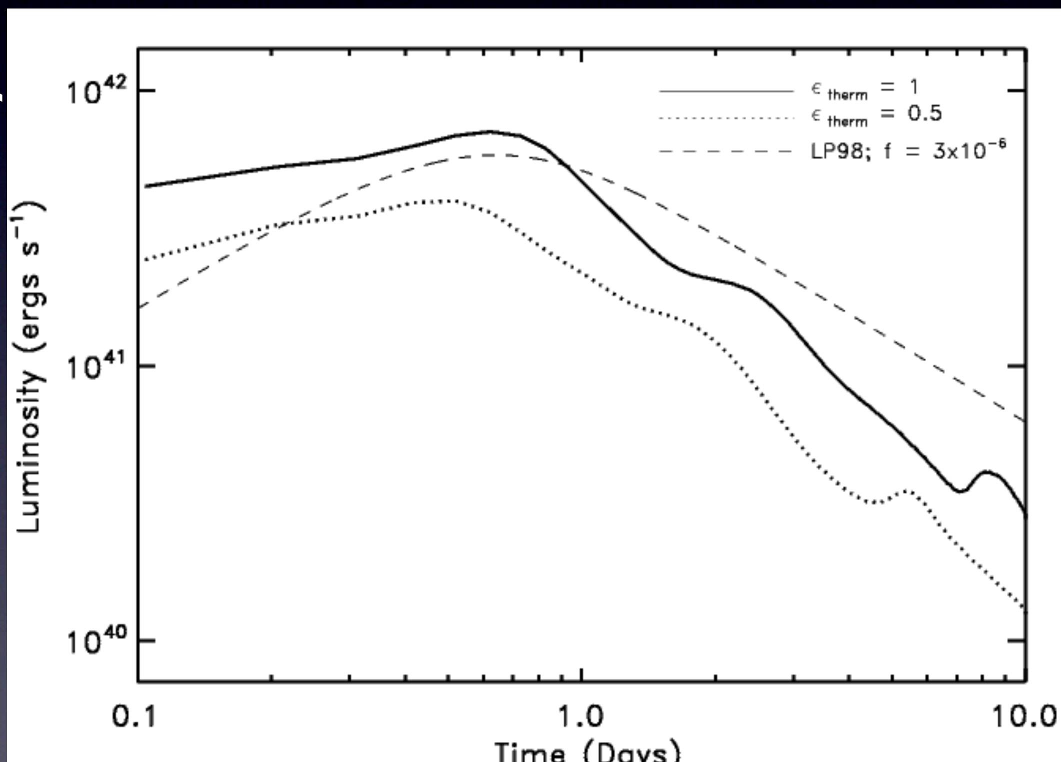
Power-law htg $\propto t^{-1.2}$ ~ identical to that of radioactive waste from fission reactors
(Cottingham & Greenwood 2001)

R-process calcs by Almudena Arcones & Gabriel Martinez-Pinedo



R-process Powered Transient

Bolometric Luminosity



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

Observational Diagnostics

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

T ~ 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!

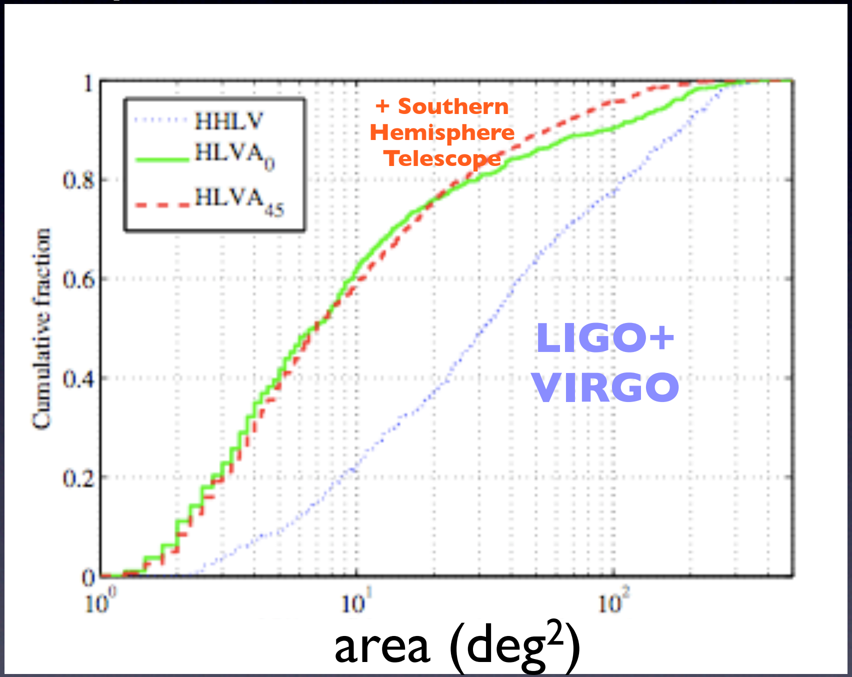
The EM Counterpart Challenge

NS-NS/BH Mergers:

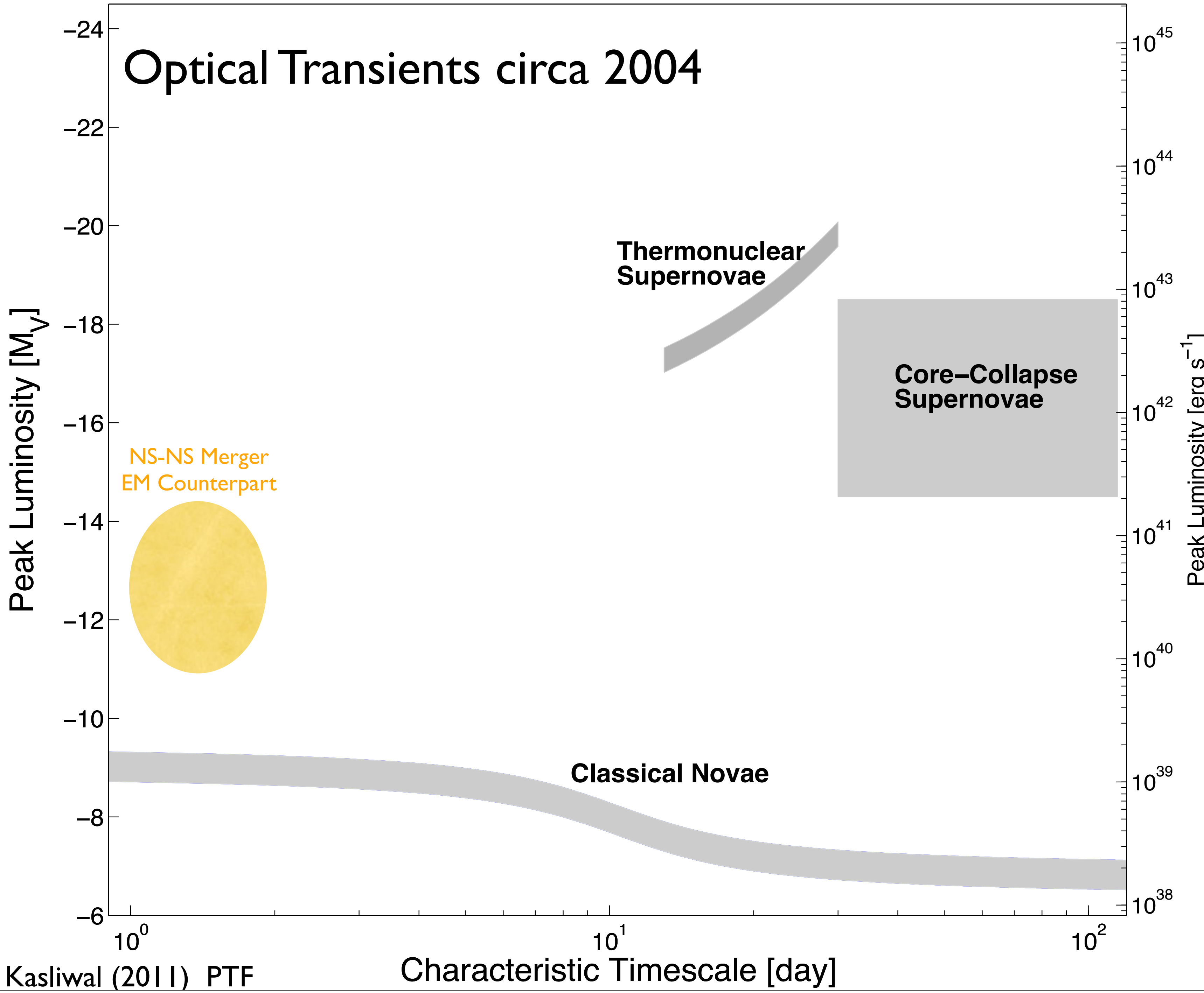
- Large FOV ~ many deg^2
- rapid cadence ≲ day
- sensitivity to sources ~ 30 x fainter than SNe

reasonably matched to optical imaging surveys: PTF, LSST, ...

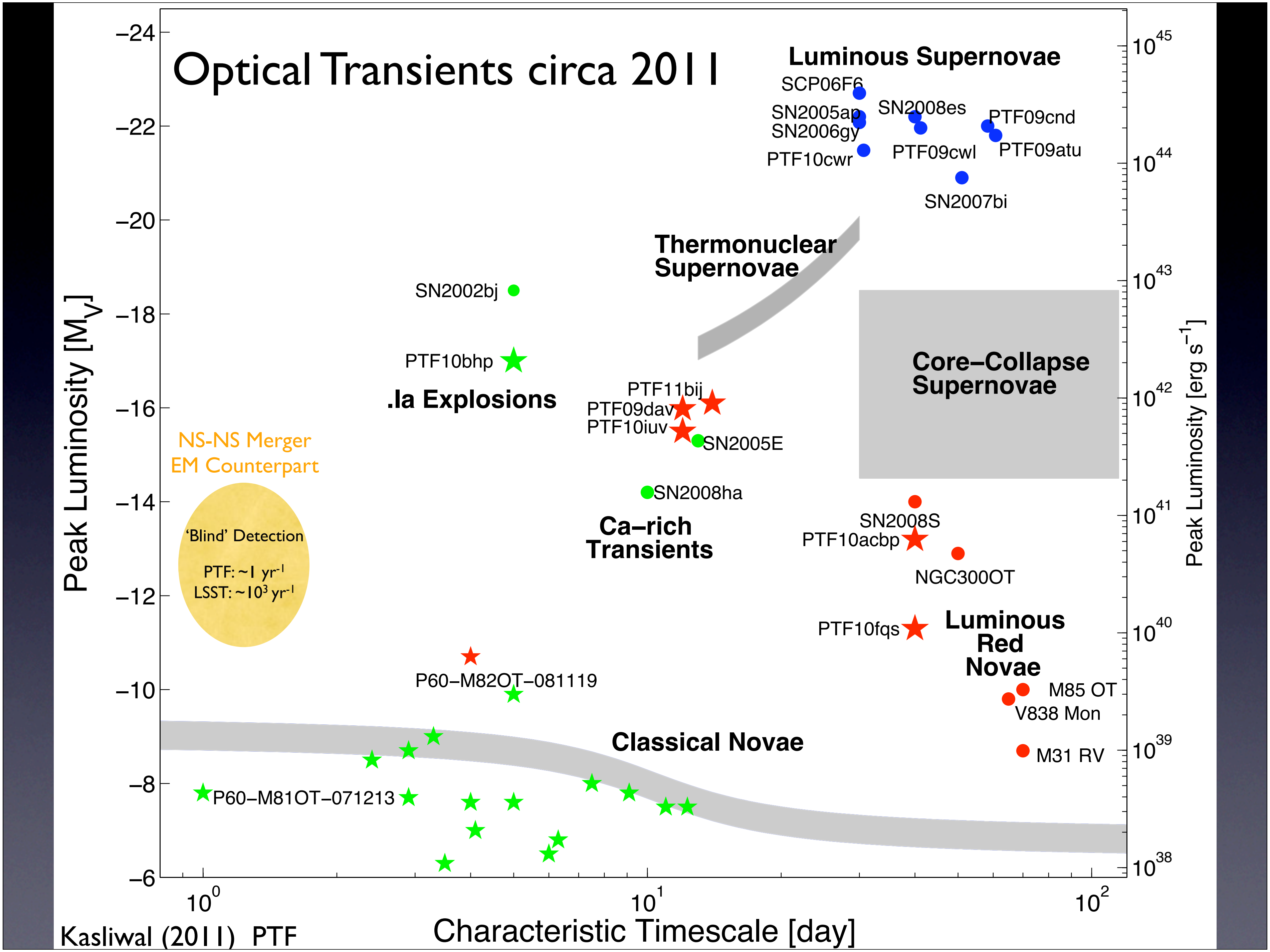
Sky Localization: LIGO + VIRGO



Aylott+ 2011



Kasliwal (2011) PTF


Optical Transients circa 2011
Luminous Supernovae
SCP06F6
SN2005ap
SN2006gy
SN2008es
PTF09cnd
PTF09cwl
PTF09atu
PTF10cwr
SN2007bi
Thermonuclear Supernovae
Core–Collapse Supernovae
SN2002bj
PTF10bhp
.Ia Explosions
PTF11bij
PTF09dav
PTF10iuv
SN2005E
SN2008ha
Ca–rich Transients
NS-NS Merger EM Counterpart
'Blind' Detection
PTF: ~1 yr⁻¹
LSST: ~10³ yr⁻¹
SN2008S
PTF10acbp
NGC300OT
PTF10fqs
Luminous Red Novae
M85 OT
V838 Mon
M31 RV
P60–M82OT–081119
Classical Novae
P60–M81OT–071213
Peak Luminosity [M_V]
Peak Luminosity [erg s⁻¹]
Characteristic Timescale [day]
Kasliwal (2011) PTF

EM Counterparts to kHz GW Sources

Prediction: NS-NS/BH Mergers

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

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

Observational Requirements:

- Large FOV ~ many deg^2
- rapid cadence $\lesssim$ day
- sensitivity to sources ~ 30 x fainter than SNe

feasible w/ optical imaging surveys: PTF, LSST, ...

"There are more things in Heaven and Earth, Horatio, than are dreamt of in your philosophy" (Hamlet)

The Biermann Lectures: Adventures in Theoretical Astrophysics

- work on a range of problems: 'model building' & studying key processes
  - Compact Object Astrophysics
    - gamma-ray bursts, transients, accretion theory, the Galactic Center
  - Galaxy Formation
    - massive black hole growth, galactic winds, 'feedback', star formation in galaxies
  - Plasma Astrophysics
    - plasma instabilities (disks, galaxy clusters, ...), plasma turbulence (incl solar wind)
  - Stellar Astrophysics
    - stellar seismology, tides

Thanks for your hospitality!