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# Neutron star mergers, their nucleosynthesis and electromagnetic transients

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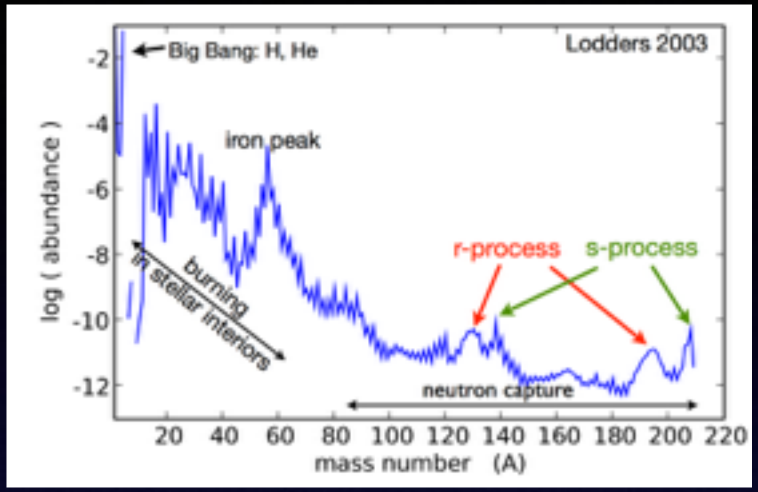
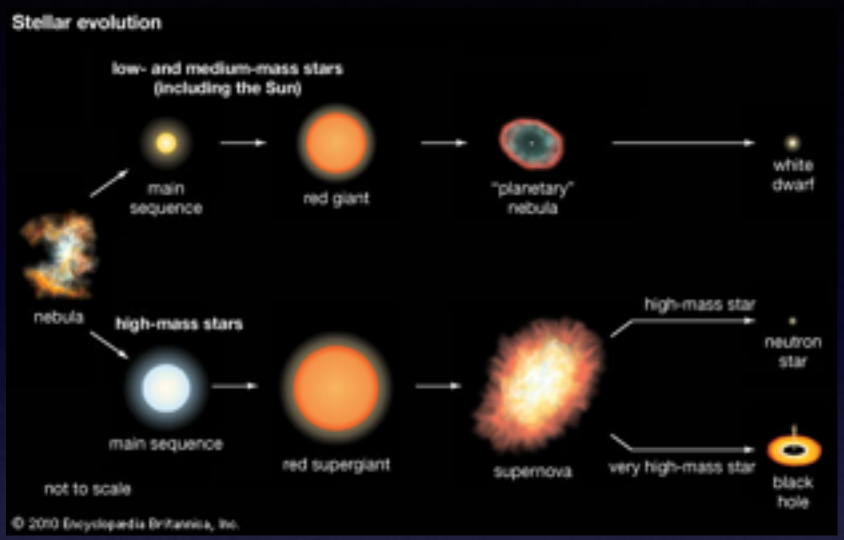
In **collaboration** with many “Brainstorming and Fun” colleagues…

# Neutron star mergers: “glueing together separate field”

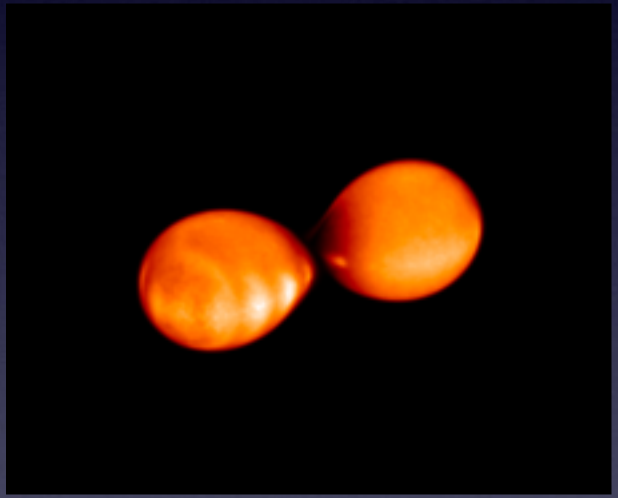
nucleosynthesis



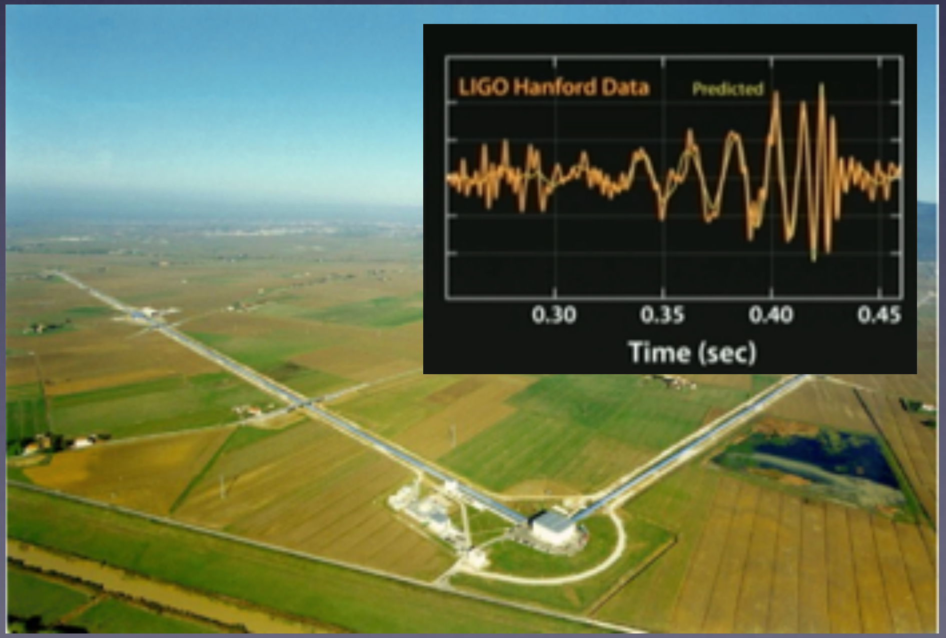

Stellar (binary) evolution




Chemical enrichment of the Cosmos



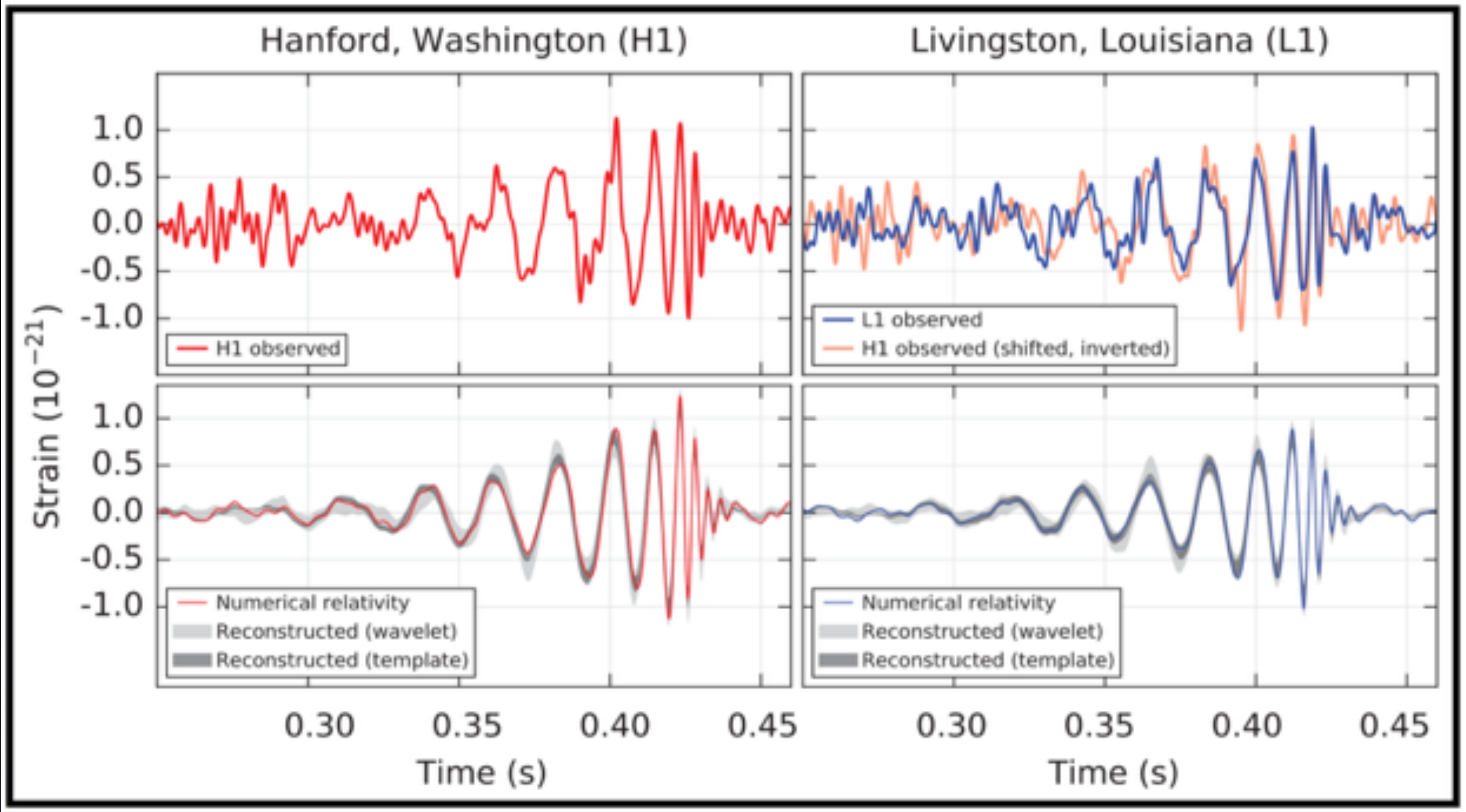
Gravitational wave detection

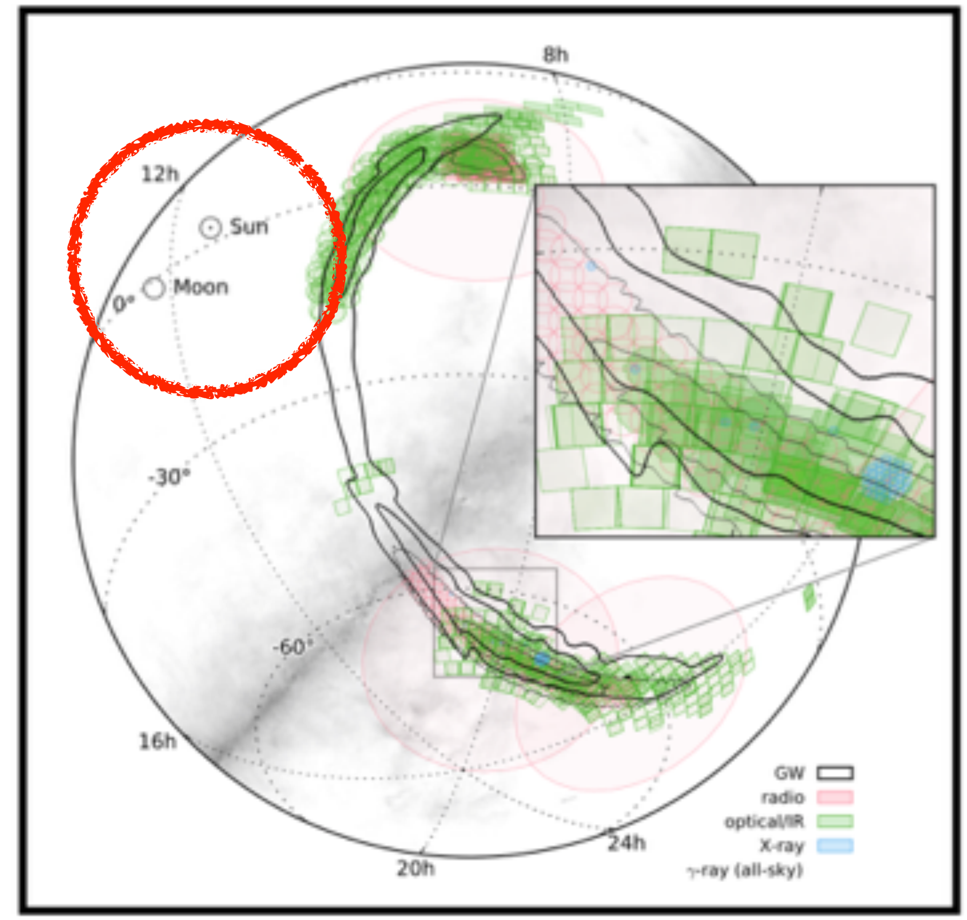



Radioactively powered transients (“macronovae”)

(short) Gamma-Ray Bursts

# The first gravitational wave detection GW150914




⇒ "physics from gravitational wave signal"

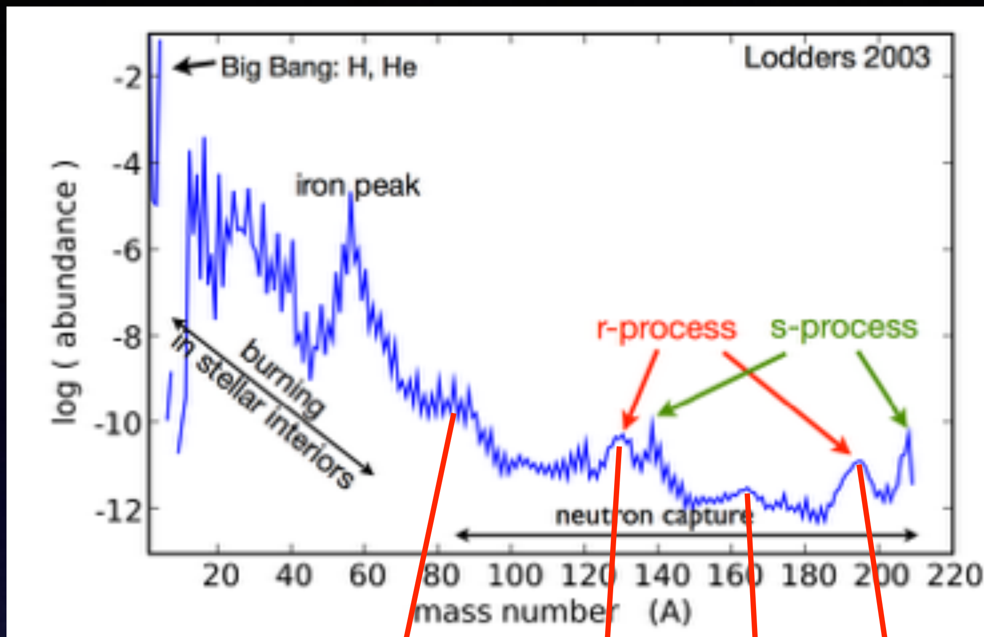
⇒ "astronomy/astrophysics from the electromagnetic (EM) transient"

location in the sky essentially unknown,

~ 600 deg$^2$ error region

==> EM-transient needed for sky location!

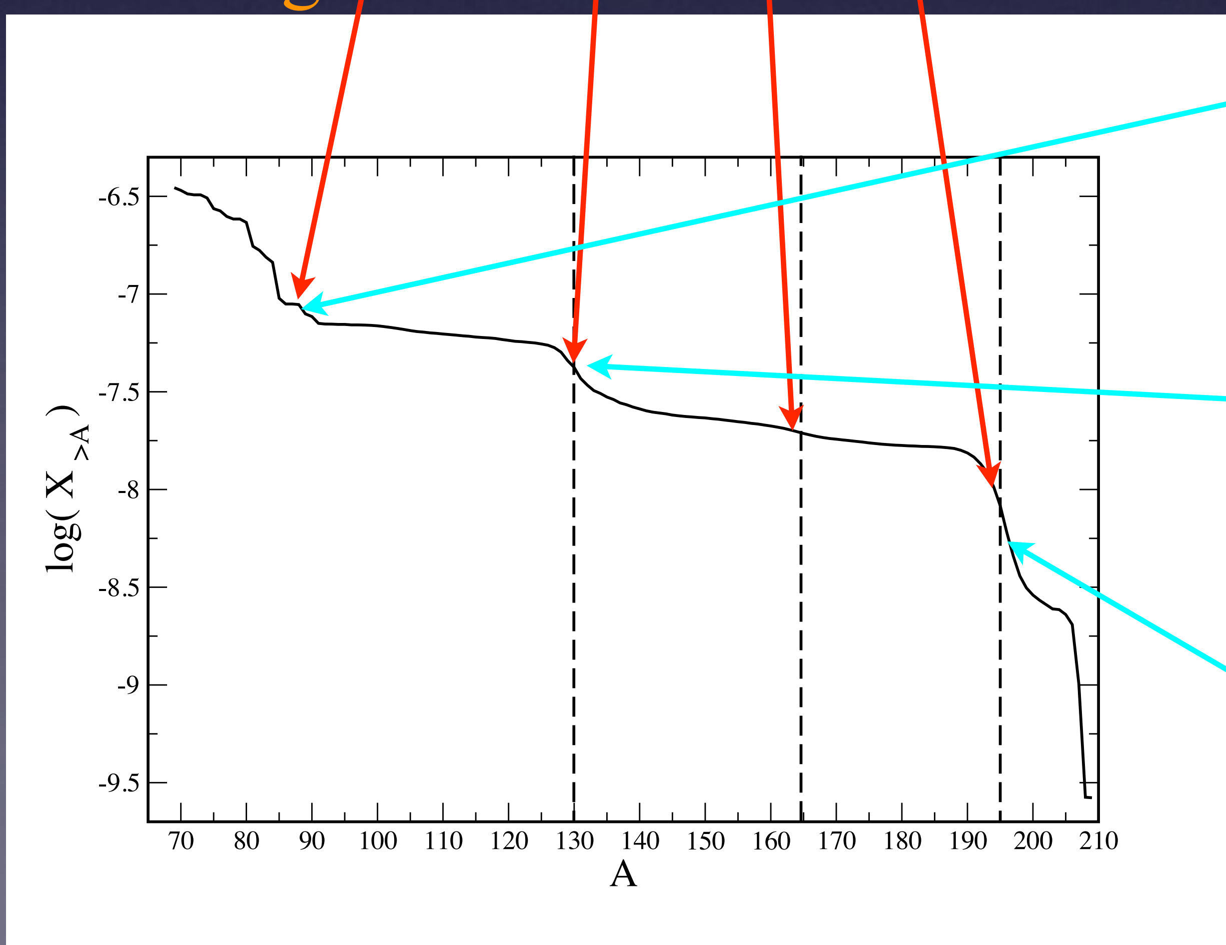
# How much r-process material in our Galaxy?




Total amount Galaxy?
($6 \times 10^{10}\ M_\odot$ baryonic; McMillan+ 2011)

total: $19\ 000 M_\odot$

What is the fraction of r-process material above a given nucleon number A?




2.4 x $10^{-7}$ of nuclei beyond the A= 80 peak — $14\ 000\ M_\odot$

4.2 x $10^{-8}$ of nuclei beyond the A= 130 peak — $2530\ M_\odot$

8.3 x $10^{-9}$ of nuclei beyond the "platinum peak" (A= 195) — $500\ M_\odot$

# What does this imply for the production rate?

$$M_r = m_{\rm ej} \times \mathcal{R} \times \tau_{\rm Gal}$$

total r-mass — typical ejecta mass — average rate — age of Galaxy

- degeneracy $m_{\rm ej} \times \mathcal{R} = \dfrac{\rm M_r}{\tau_{\rm Gal}}$

all r-process: $1.9 \times 10^{-6} \dfrac{\rm M_\odot}{\rm yr}$

r-process A > 80: $1.4 \times 10^{-6} \dfrac{\rm M_\odot}{\rm yr}$

r-process A > 130: $2.5 \times 10^{-7} \dfrac{\rm M_\odot}{\rm yr}$

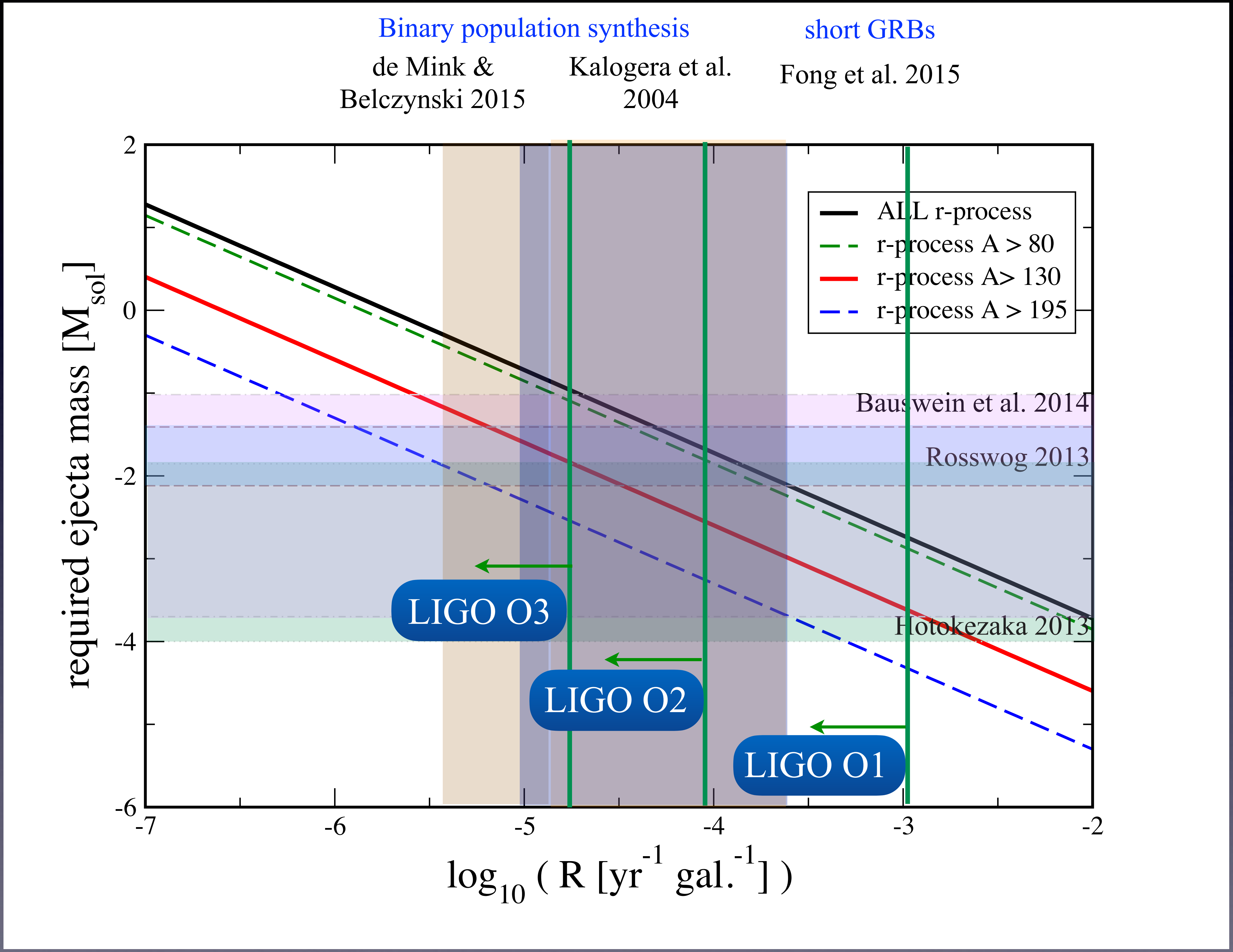
r-process A > 195: $5.0 \times 10^{-8} \dfrac{\rm M_\odot}{\rm yr}$

$\Rightarrow$ "rare high-mass or frequent low mass event(s)?"

$\Rightarrow$ geological evidence argues for "rare high-mass" for $^{244}$Pu

(e.g. Hotokezaka et al. 2015)

# NSNS estimates only




ejecta mass range from hydro-simulations

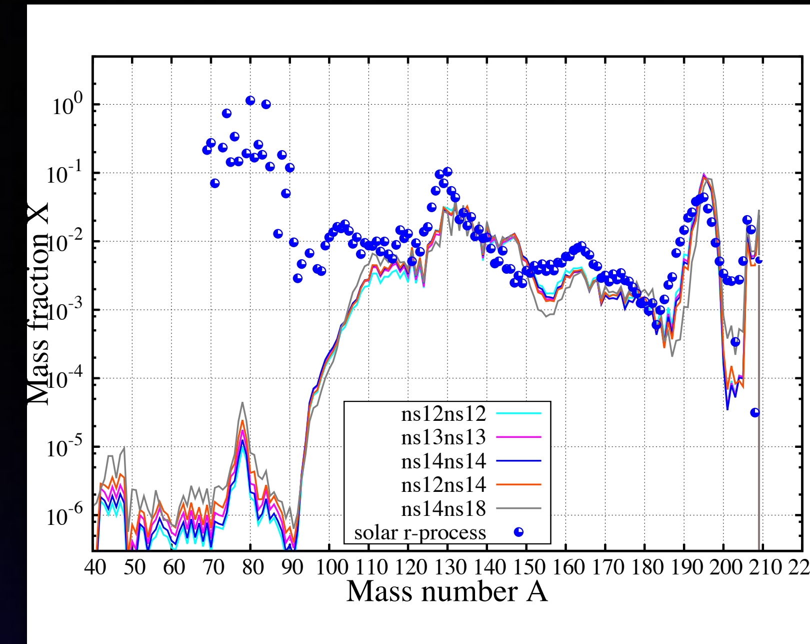
# Punchlines nsns-mergers as sources r-process

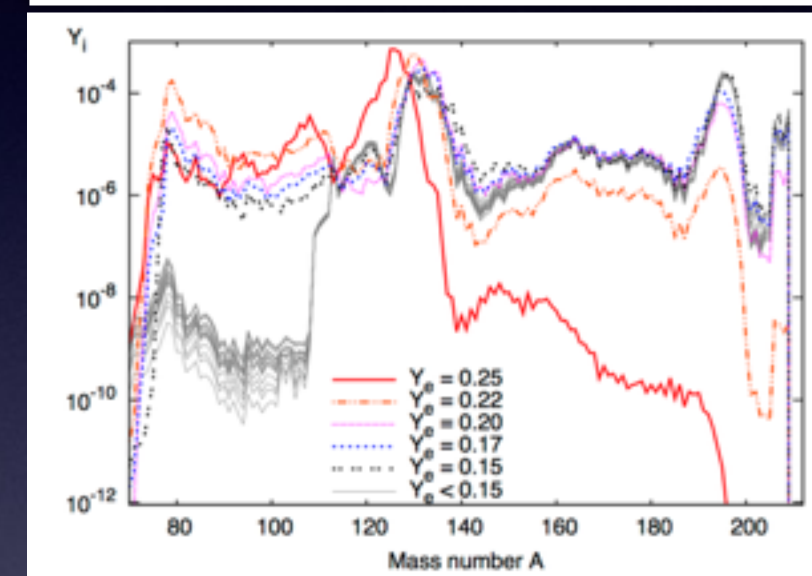
- "required heavy r-process rate" ≈ estimated rate for double neutron star mergers

- r-process A ≳ 130:
  - occurs without any fine tuning
  - ≈ solar pattern
  - critical value for third peak Ye≈ 0.25
  - extremely robust with respect to astrophysics
  - sensitivity to nuclear input physics (e.g. Eichler++ 2015, Goriely++15)

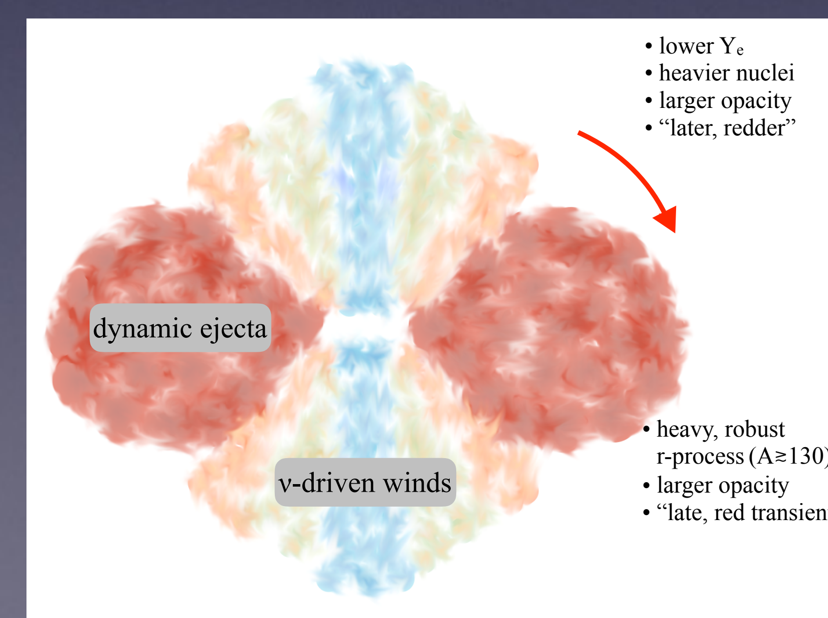
- r-process A≲ 130:
  - several recent studies (e.g. Wanajo++14, Perego++14,Just++15,Wu++16) find also interesting weak r-process contributions
  - ejection mechanism(s) likely different
  - several possibilities

- (rough) geometry

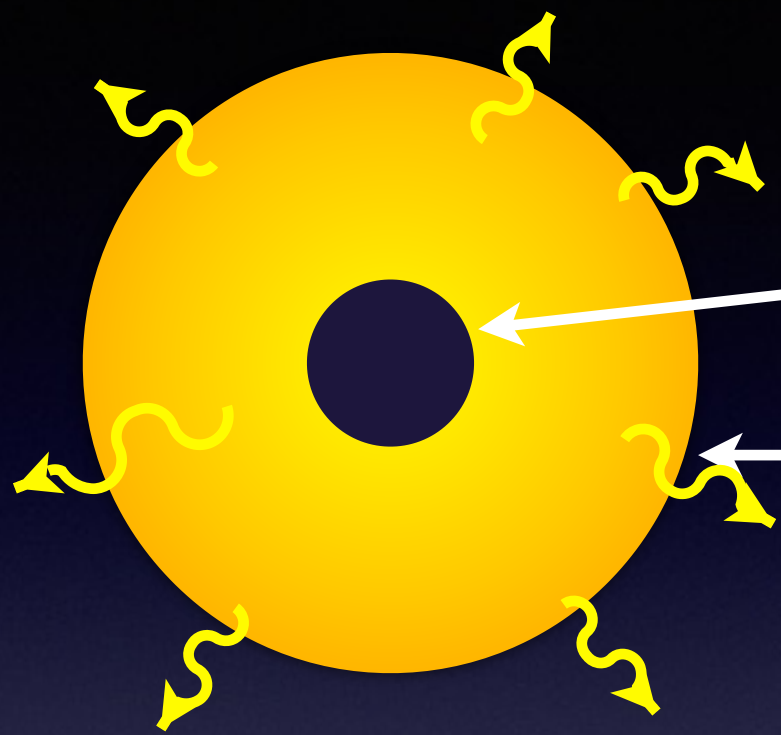



(Korobkin++ 2012)



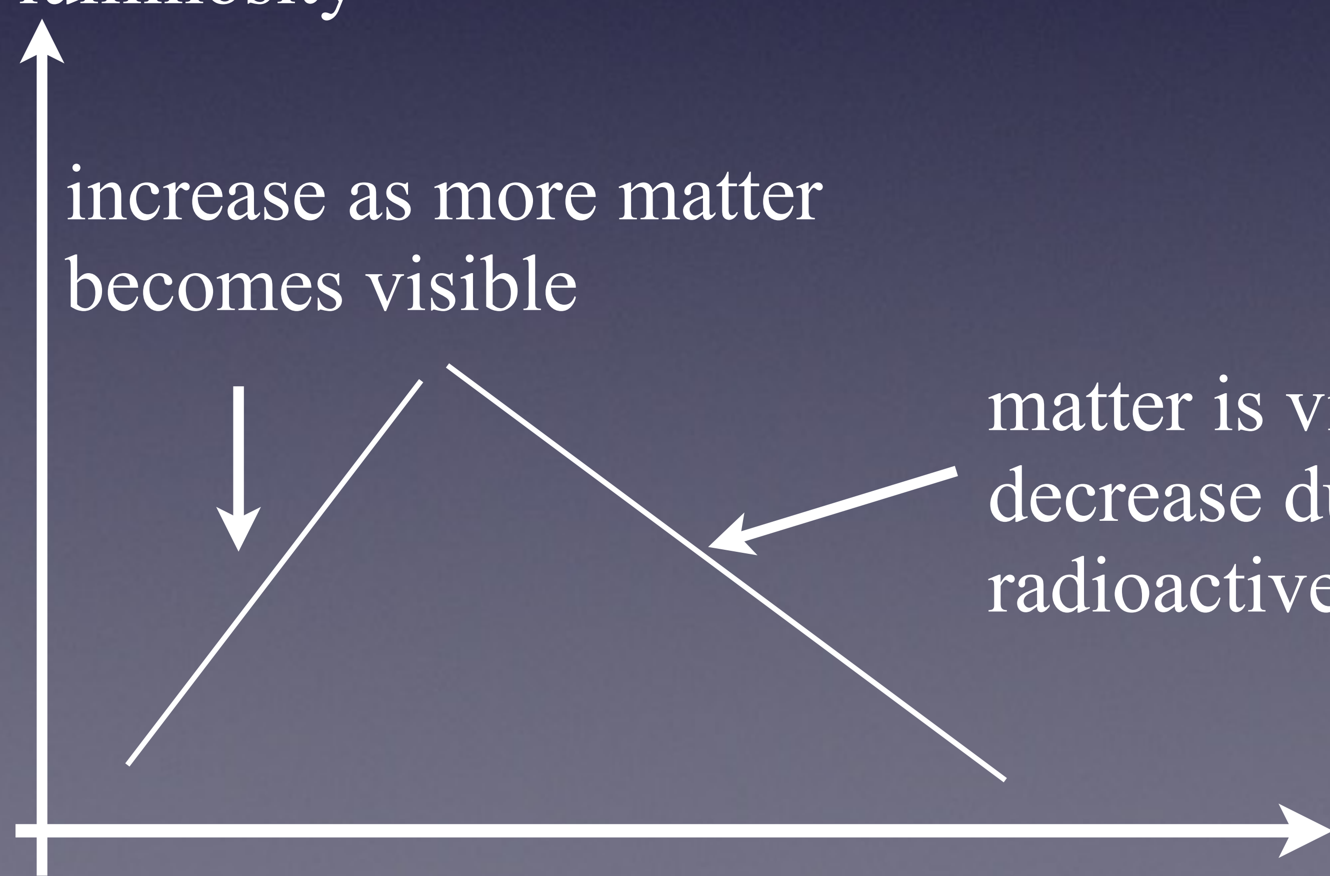
# EM-transients/“macronova”

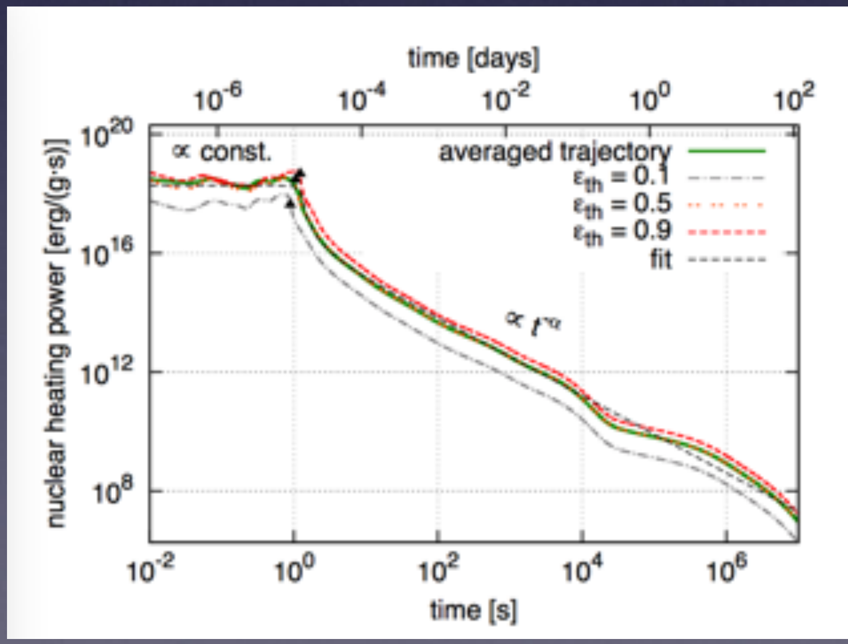


diffusion time $t_{\rm diff} \approx \frac{m_{\rm ej}\kappa}{4\pi c v_{\rm ej} t}$

photons escape from photosphere $\tau_{\rm esc} = \frac{c}{v}$

fastest moving material




(Korobkin et al. 2012)

$$\left(\frac{dE}{dt}\right)_{\rm nuc} \propto t^{-1.3}$$

# Interesting open issue:

"Has the decay of freshly synthesized r-process material really been observed as macronovae?"

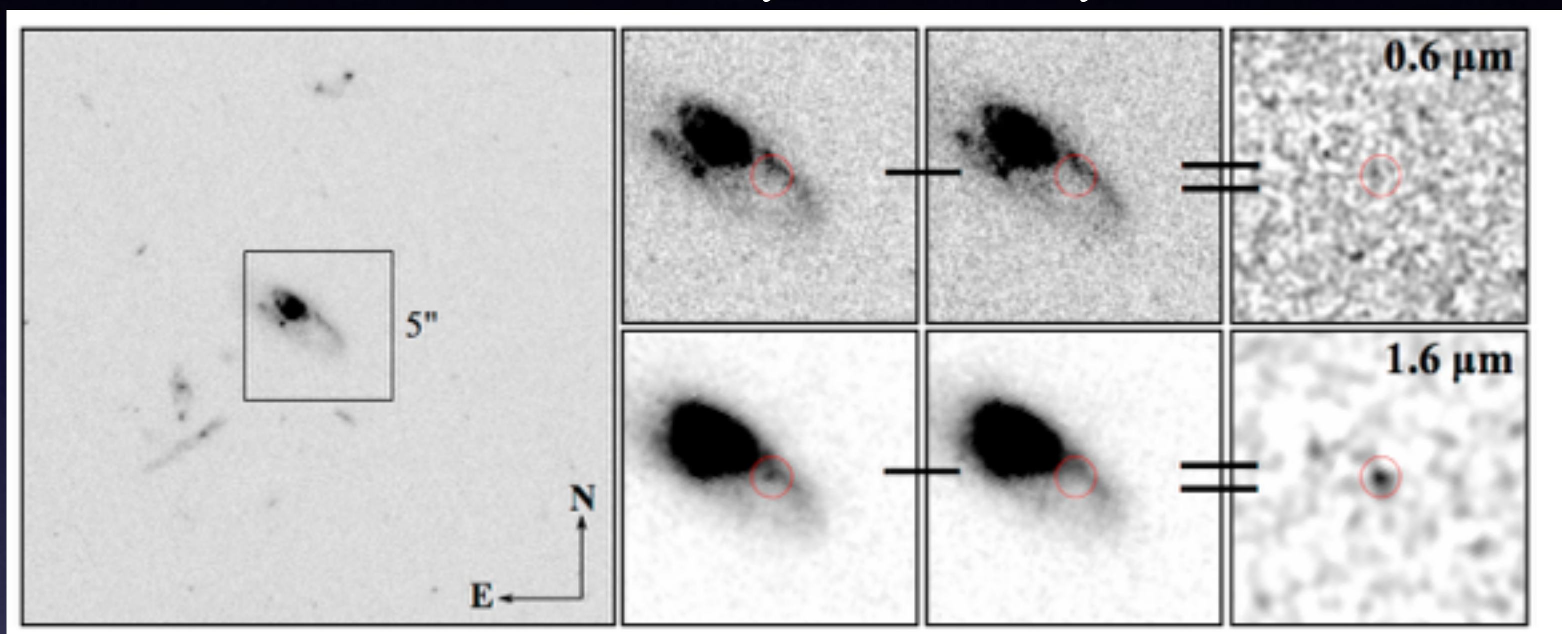



**Figure 1 HST imaging of the location of SGRB 130603B.** The host is well resolved

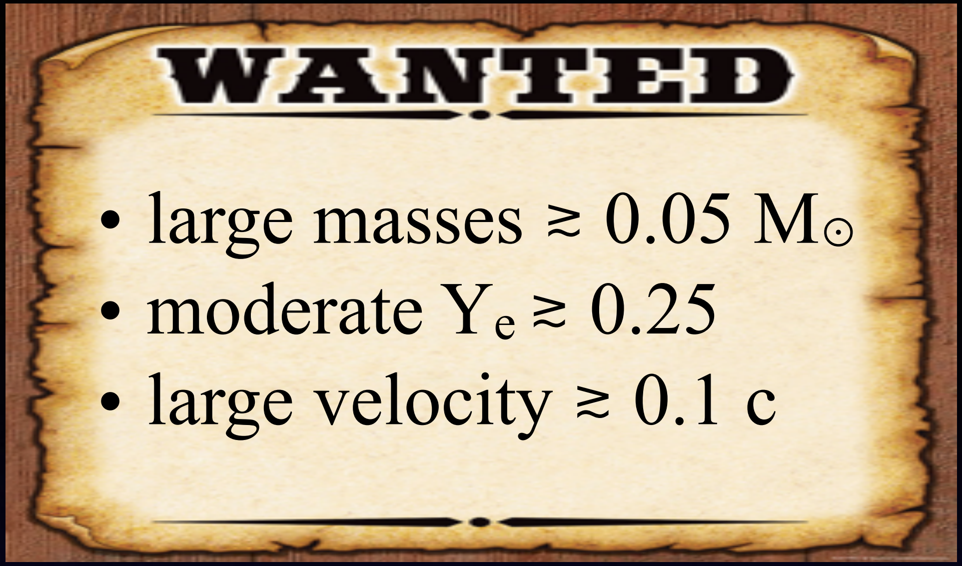
sGRB130603B (Tanvir et al. 2013):

- $T_{90} \approx 0.18$ s, $z = 0.356$
- nIR-transient, present at $\approx$9 days, but faded away after 30 days

estimated masses:

- 0.03 - 0.08 $M_\odot$ for "Tanvir-event" GRB130603B
- ~0.1 $M_\odot$ at 0.2c for GRB 060614 (Yang et al. 2015)
- ~0.05 $M_\odot$ for GRB 05079 (Jin et al. 2016)

$\Longrightarrow$ these (already very large) masses are based on very optimistic assumptions




## Astrophysics

- Do we understand (all) the ejection mechanisms well enough?
- Can "wind-like" outflows provide the right conditions?
  - viscous/nuclear recombination-driven torus unbinding
  - magnetically launched winds?
  - combinations of all
- EC/PC vs. neutrino absorption
- Are our estimates of the opacities ok?
- What is the efficiency? How much is lost in neutrinos and gamma-rays?
- (How much) Should we be thinking of alternative scenarios for macronova candidates?

## Nuclear physics

- Is it possible/likely that the heating rates are substantially larger?