Constraining the Long-living Supramassive Neutron Stars by Magnetar-boosted Kilonovae

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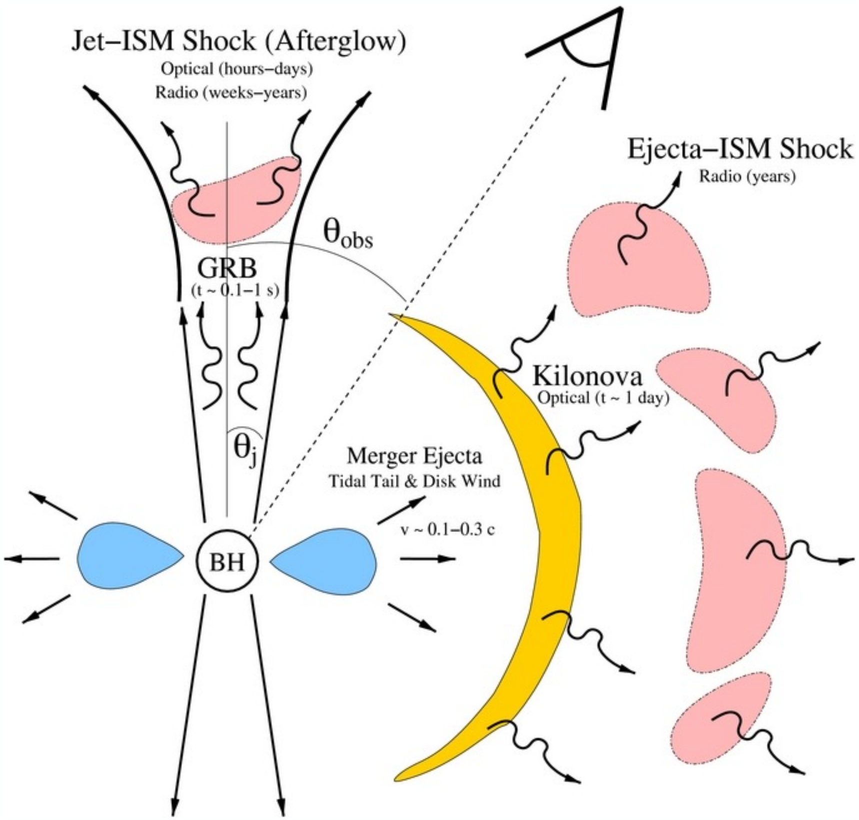
Kilonovae

Background



Metzger & Berger 2012

Neutron star merger

↓

Merger ejecta: heavy elements

↓

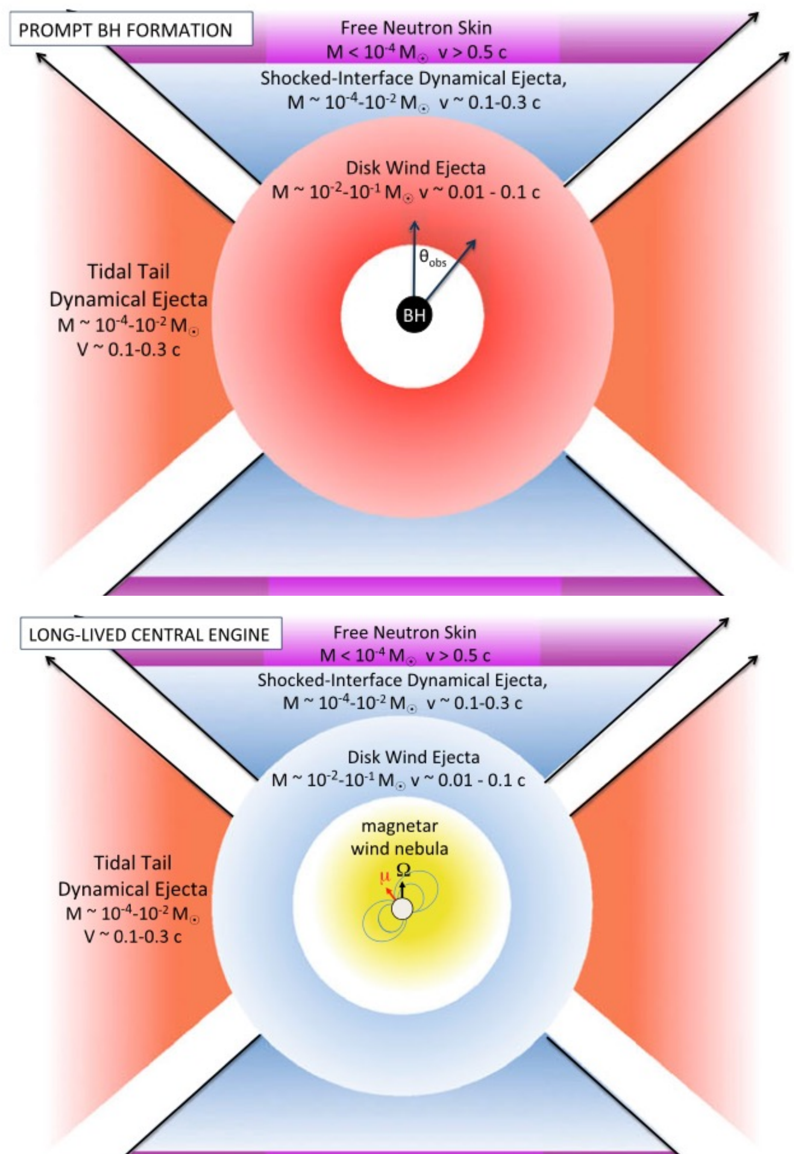
Radioactive heating

↓

Thermal radiation: kilonova

- Peak luminosity: ~ 10^{41} erg/s
- Peak time: ~ 1 day
- Waveband: ~ optical
- (Regular)

Magnetar-boosted Kilonovae



Metzger 2020

Active merger remnant

↓

Continuous outflow

↓

Energy injected to ejecta

↓

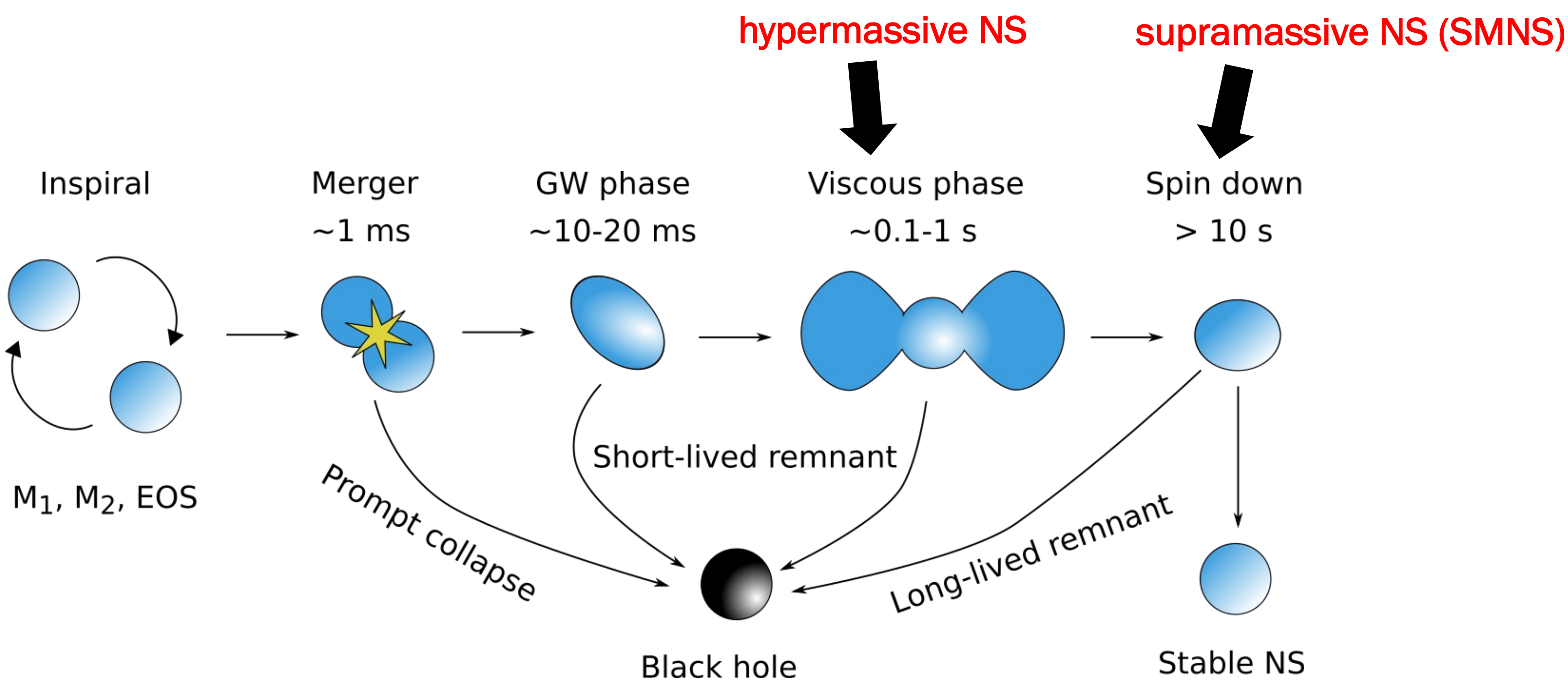
Boosted luminosity

Types central engines:
BH accretion / magnetar spin-down

Magnetars:
highly magnetized neutron stars

Supramassive Neutron Stars

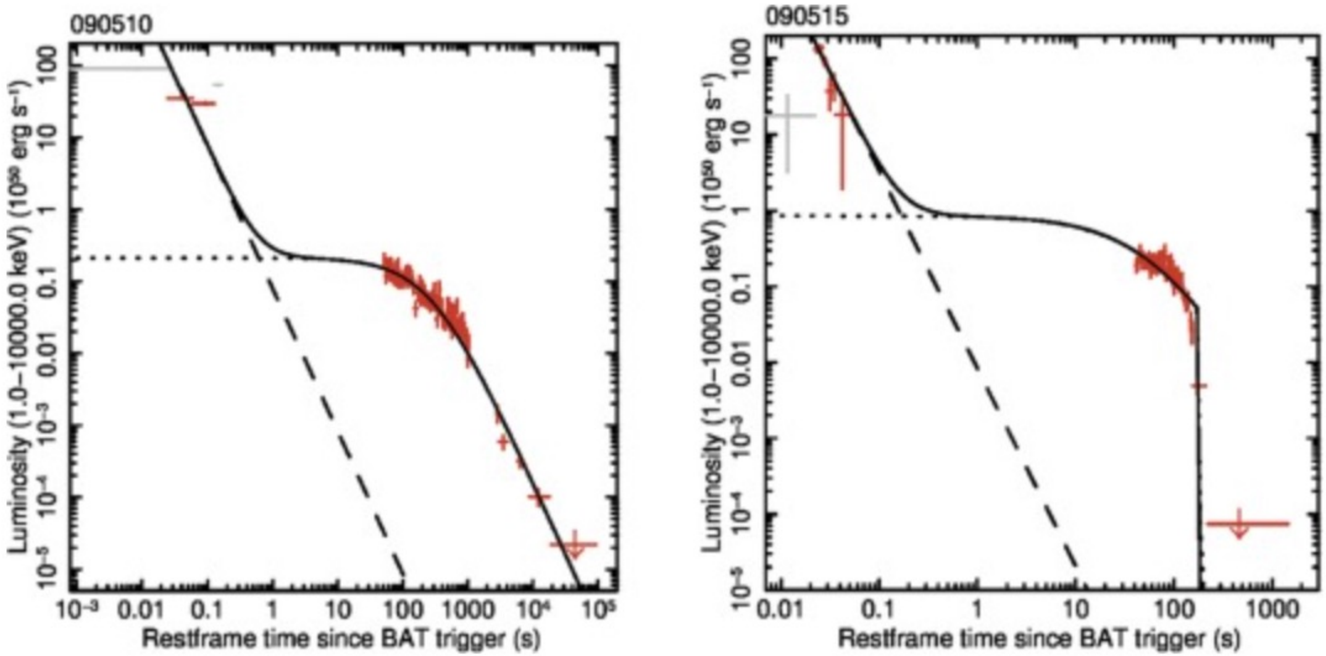
formation



- SMNS are magnetars
- Rotational energy: 10^{52} – 10^{53} erg!
- Boosted luminosity: 10^{2} - 10^{5} brighter!

Supramassive Neutron Stars: sGRB

Why magnetars



Magnetars are also used to model X-ray plateau in sGRB afterglow

Bright Nature vs. Absence of Detection

Simple estimation

Theory

Maximum luminosity: >> 10^2 times

Detectable distance: >> 10^1 times

Detectable volume: >> 10^3 times

Expected detection number:
Magnetar-boosted KNe > regular KNe!

Observation: sky survey

Zwicky Transient Facility (ZTF),
Panoramic Survey Telescope and Rapid Response System (Pan-STARRS),
...

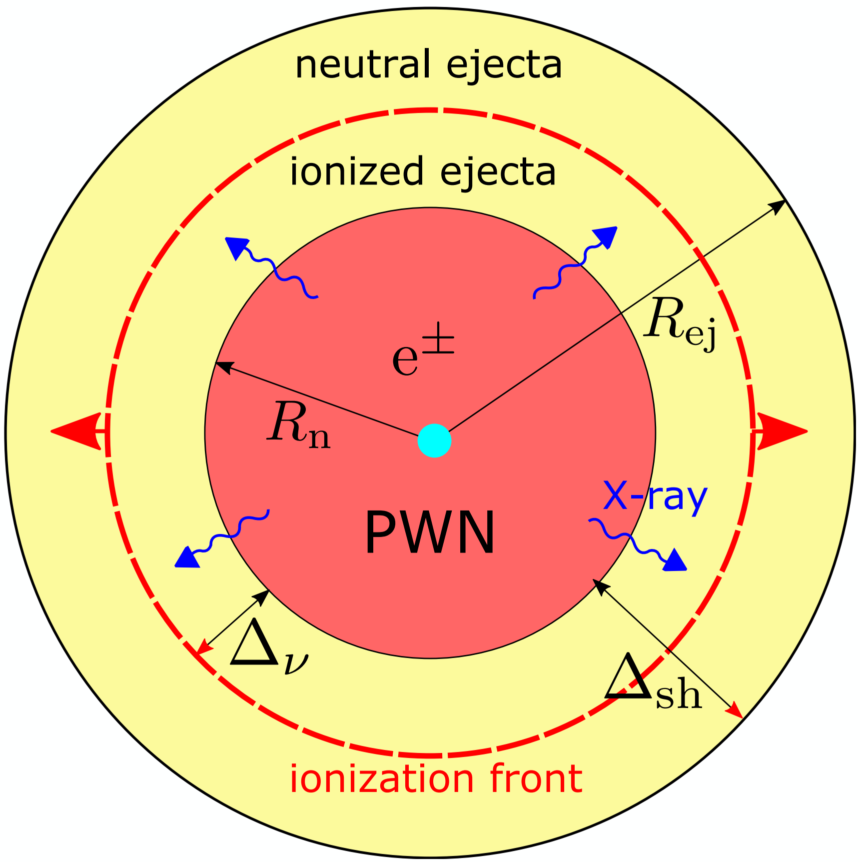
Time: > 4 years

No detection!

Constraint on boosted kilonova model or SMNS

Model

Basic ingredients



Magnetar

↓ Spindown power

Pulsar wind nebula

↓ X-ray ionization

Ejecta

↓ Thermal radiation

Boosted Kilonova

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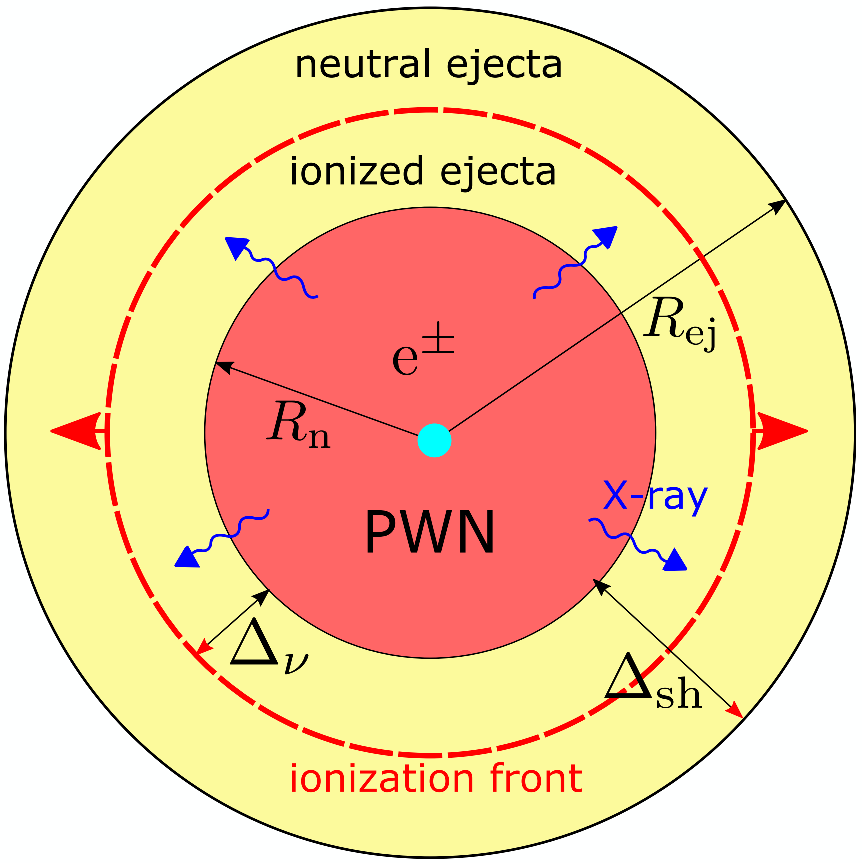
Model: Magnetar

spindown power



Dipole power:

$$L_{sd} = L_{sd,0}(1 + t/t_{sd})^{-2}$$

$$L_{sd,0} \approx 10^{50} \left(\frac{E_{ini}}{10^{53} erg}\right)^2 \left(\frac{B}{10^{15} G}\right)^2 \text{erg/s}$$

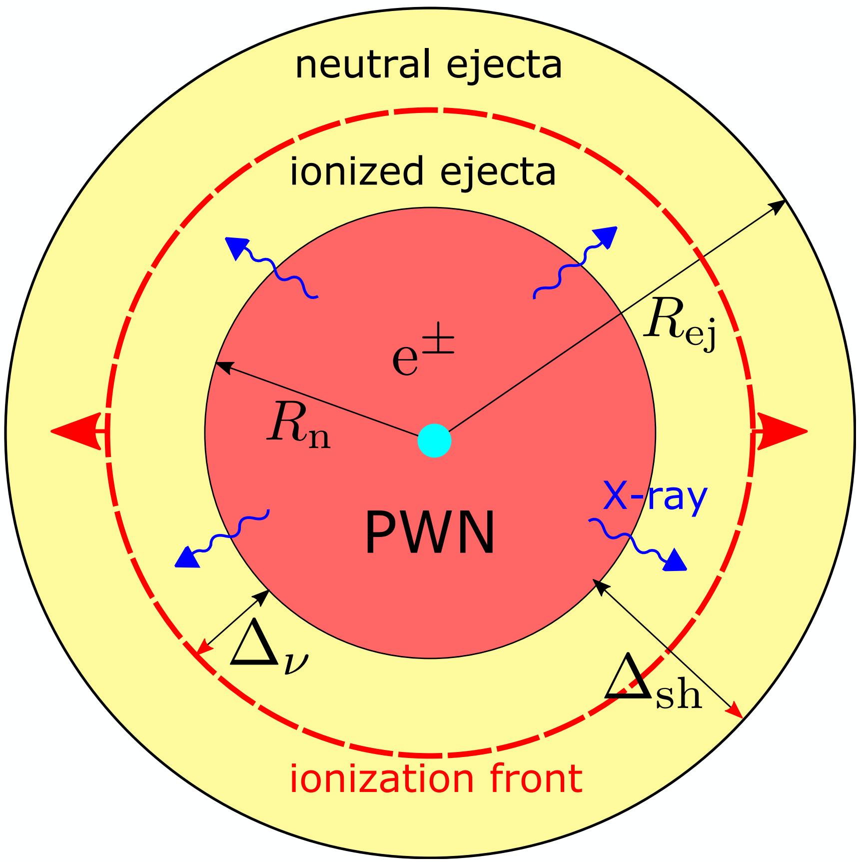
$$t_{sd} = 0.01 \left(\frac{E_{ini}}{10^{53} erg}\right)^{-1} \left(\frac{B}{10^{15} G}\right)^{-2} \text{d.}$$

Magnetar has limited survival timescale:

$$\eta = \frac{\int_0^{t_c} L_{sd} dt}{E_{ini}} = \frac{t_c}{t_c + t_{sd}}$$

Model: Pulsar Wind Nebula

pair cascade



Saturated pair cascade: balance

$$n_\pm = \sqrt{\frac{16 Y L_{sd}}{3\sigma_T m_e c^3 V_n}}.$$

Optical depth: Thomson scattering

X-ray luminosity:

$$L_n \sim \frac{E_n}{t_n^d} = \frac{c E_n}{R_n(1+\tau_n)}$$

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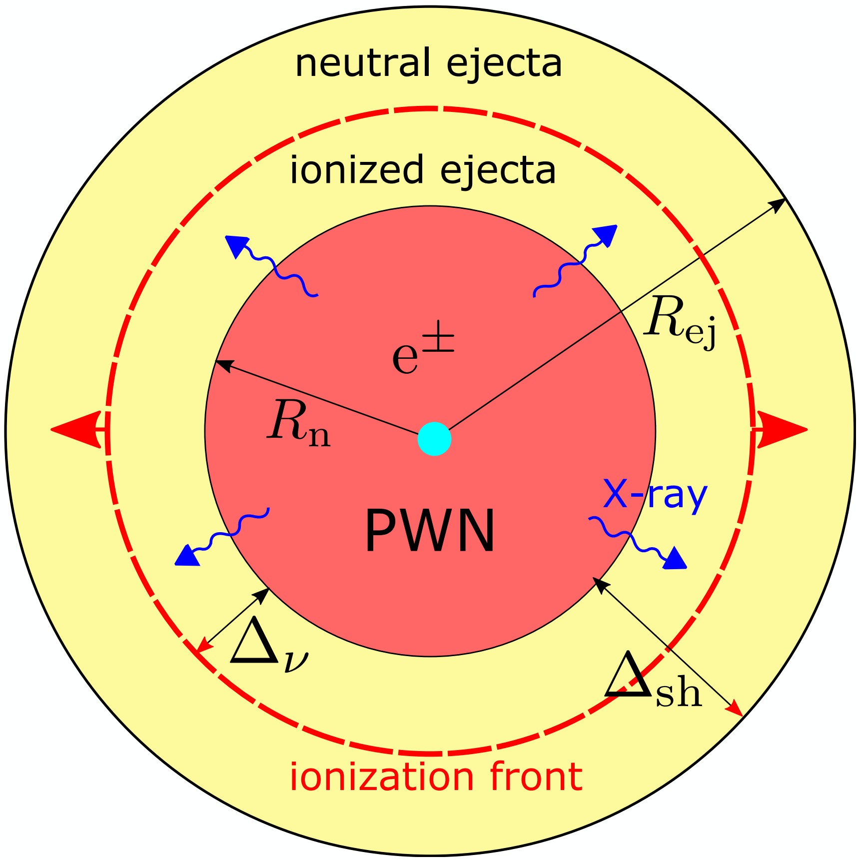
Model: Ejecta

Photoionization



Ionization balance:

$$f^i \int \frac{4\pi J_\nu}{h\nu} \sigma_\nu^i d\nu = n_{\rm Fe} \alpha_{\rm rec}^i f^{i+1} \sum_{i=1}^{i=27} (i-1) f^i$$

$$\sum_{i=1}^{i=27} f^i = 1$$

Bound-free opacity:

$$\kappa_{{\rm bf},\nu} = \frac{1}{56 m_{\rm p}} \sum_{i=1}^{26} f^i \sigma_\nu^i$$

Photoionization Heating

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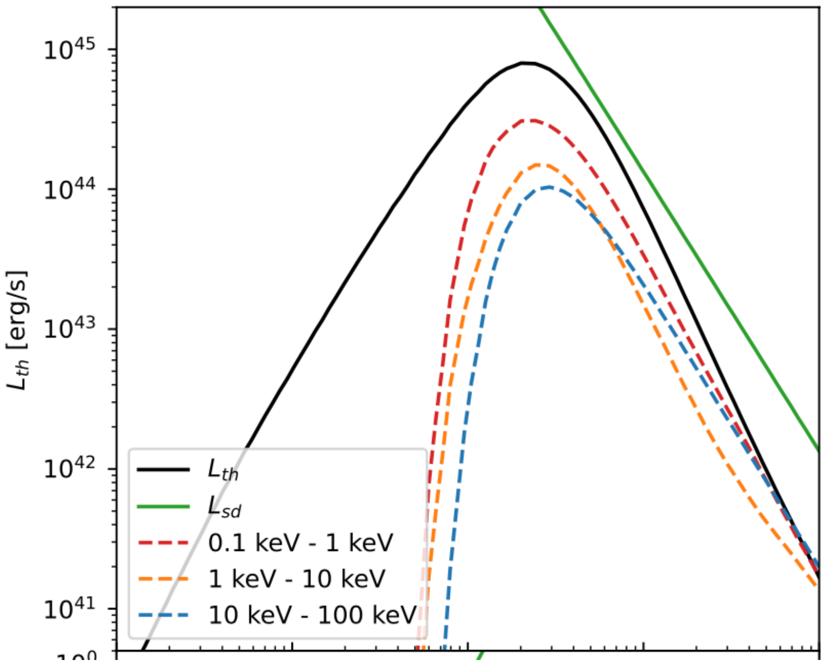
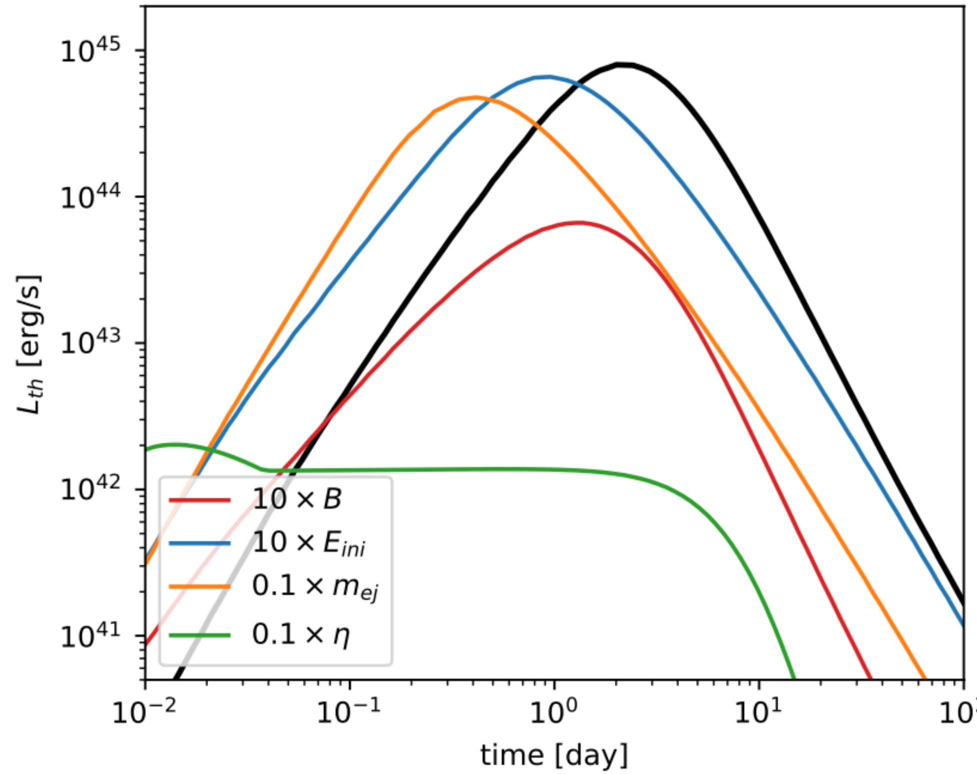
Observational Features

features





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Observational Expectation

We expect way more KNe
than we really have!

But it's not easy to estimate
the number of detection…

Model-independent study:

Explore the parameter space

Model-dependent study:

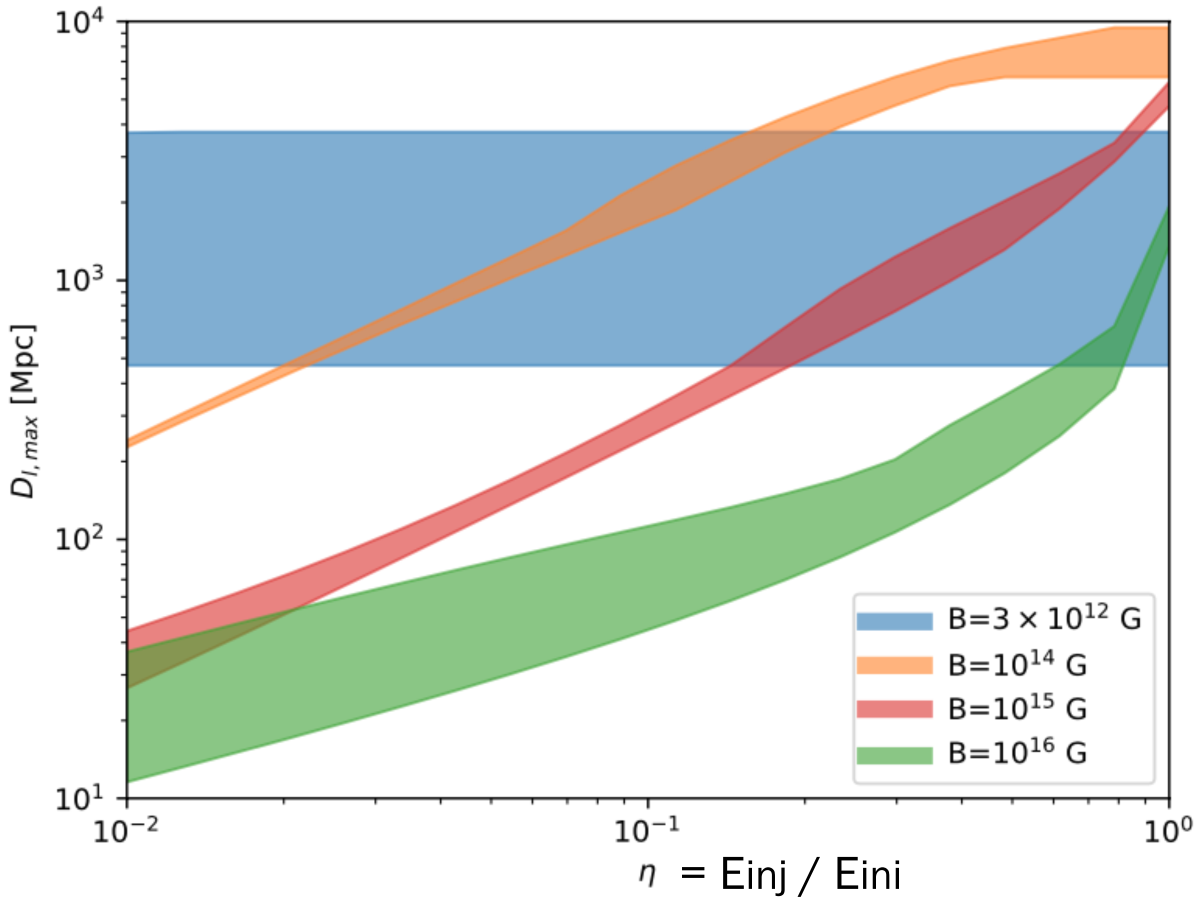
EoS and sky survey strategy

One more possibility:
Rayleigh-Taylor Instability?

Model-independent Study: detectable distance

Detectable distance

Explore the Parameter space



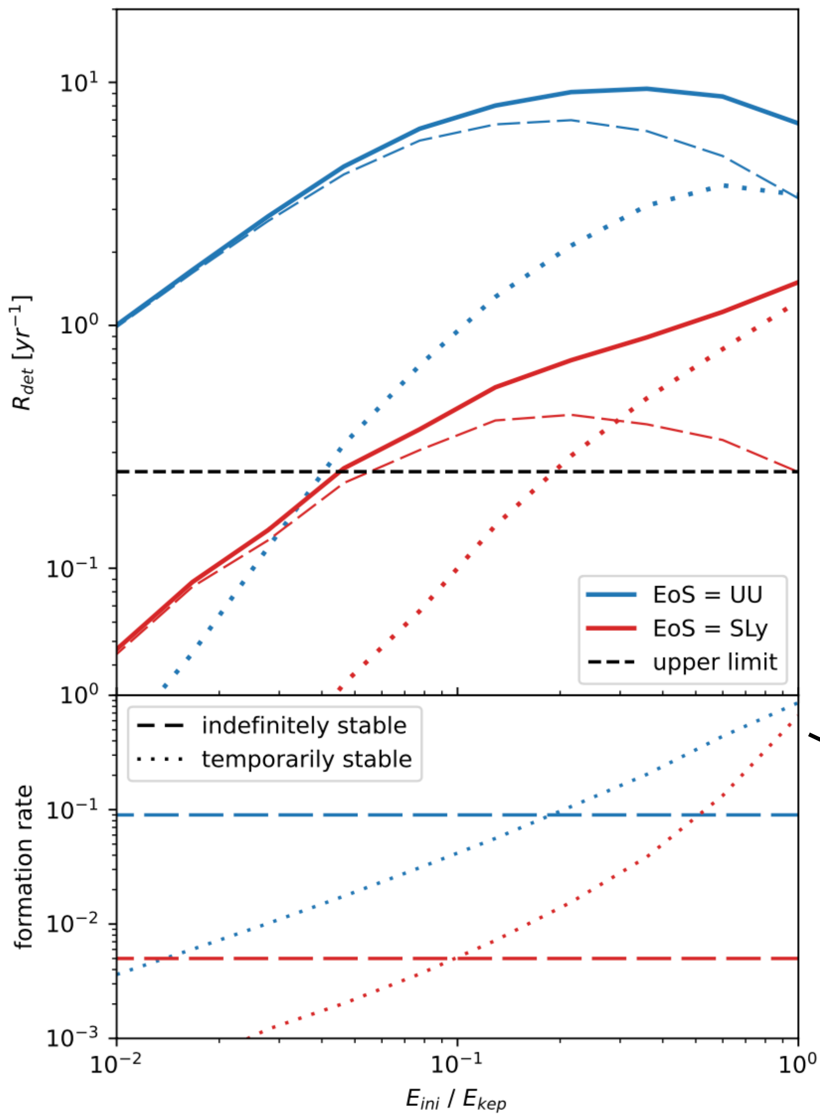
Model-dependent Study

Monte Carlo simulation

- Equation of States: UU (M_{TOV} = 2.0 M_{sun}), SLy (M_{TOV} = 2.2 M_{sun})
- From BNS population (galactic) to remnant population
- Evolve the remnant by "*RNS* code"
- Mimic ZTF sky survey strategy
- A free parameter: E_{ini} / E_{kep}

Model-dependent Study: detection number

result



UU (M_{TOV} = 2.0 M_{sun}),

SLy (M_{TOV} = 2.2 M_{sun})

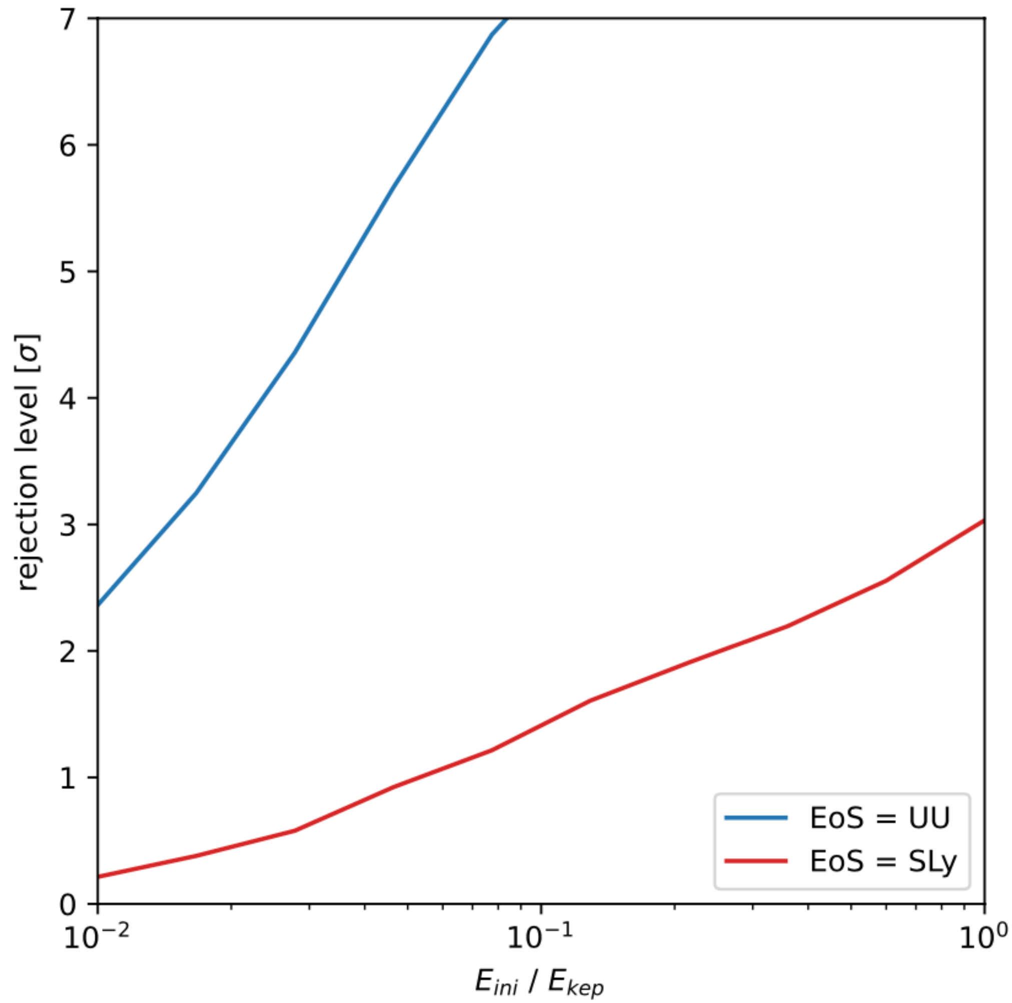
Upper limit

SMNS formation rate

Model-dependent Study

Constraint

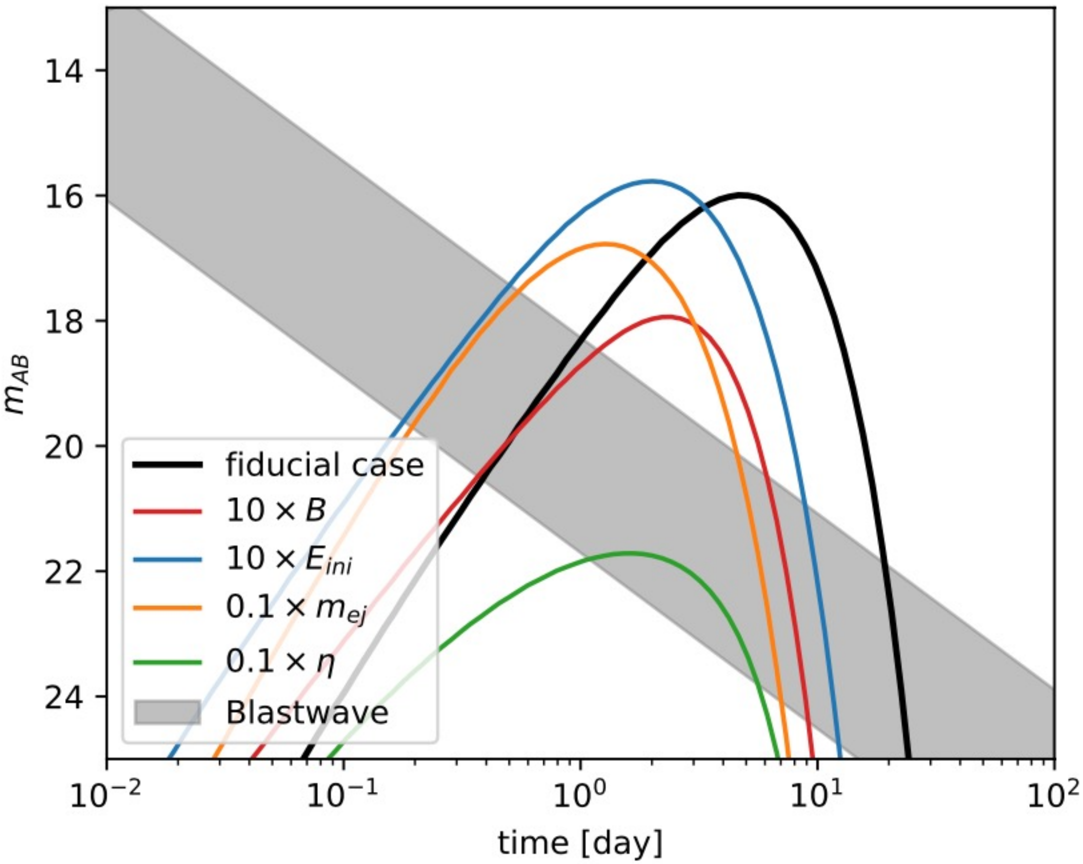
Significance of rejection (σ)



Rayleigh-Taylor Instability

Isotropic blastwave

- Acceleration of ejecta leads to RT instability.
- The PWN matter can leak away from the ejecta and forms blastwave!
- We assume the blastwave is like GRB afterglow
- We don't see so many orphan afterglow!



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Implications

- SMNS are likely to be rare
- Boosted-kilonovae candidates (e.g., GRB 200522A): too faint
- Orphan GRB afterglow: a new class of orphan afterglow
- sGRB plateau: unlikely from magnetars
- FRB: dispersion measure is too high
- Multimessenger observation: will place further constraint to our model

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Summary & Conclusion

- Magnetar-boosted kilonovae are extremely bright optical transients yet not discovered so far.

- The absence of detection places strict constraint on the “magnetar” model

- SMNS must be rare and can’t be “long-living”

Thank You

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