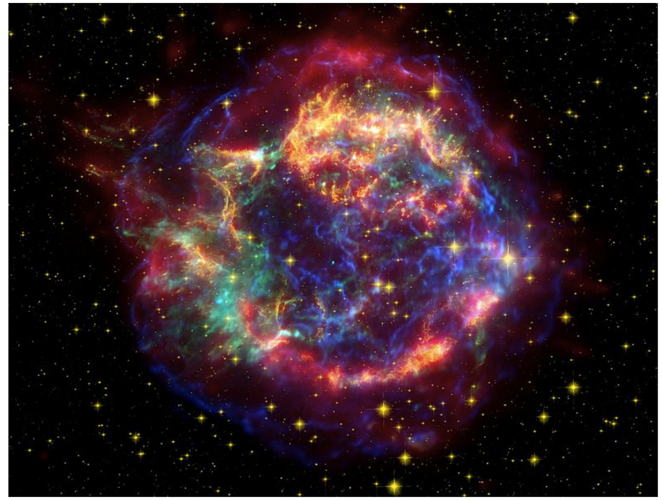

Towards Predictions of Neutron Star Birth Properties using 3D Supernova Models

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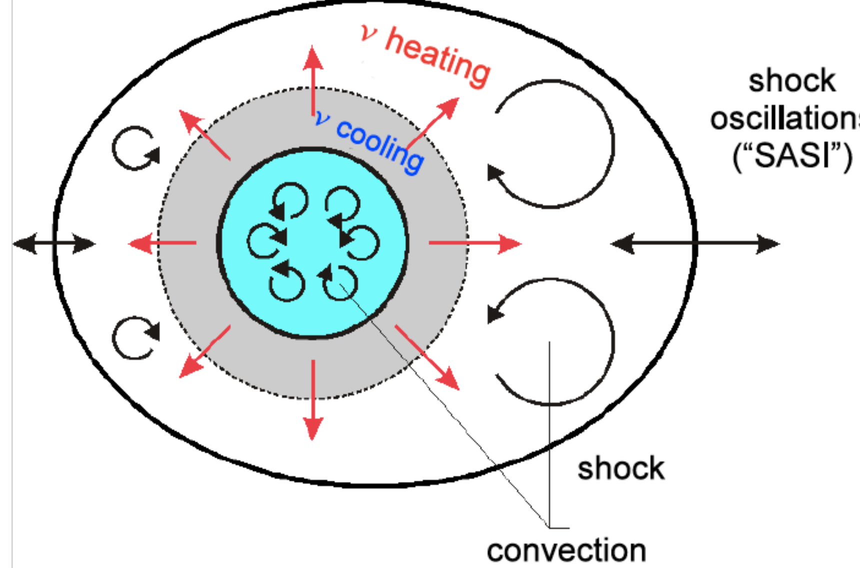
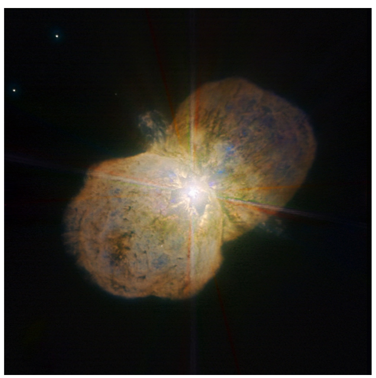
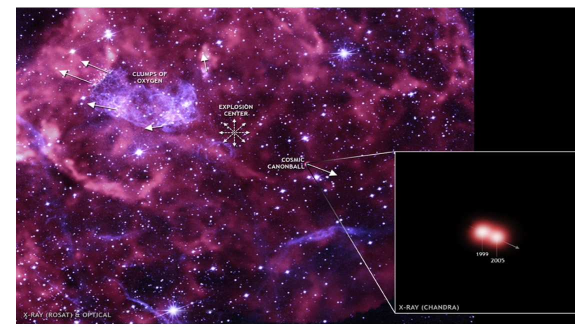
heavy elements



massive stars

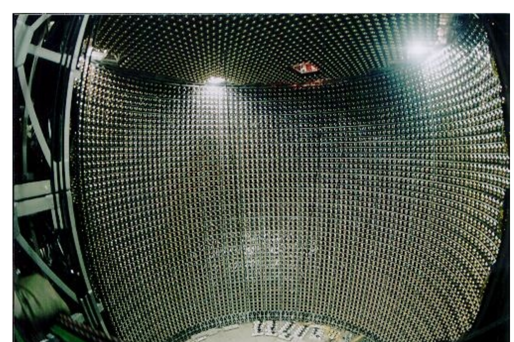




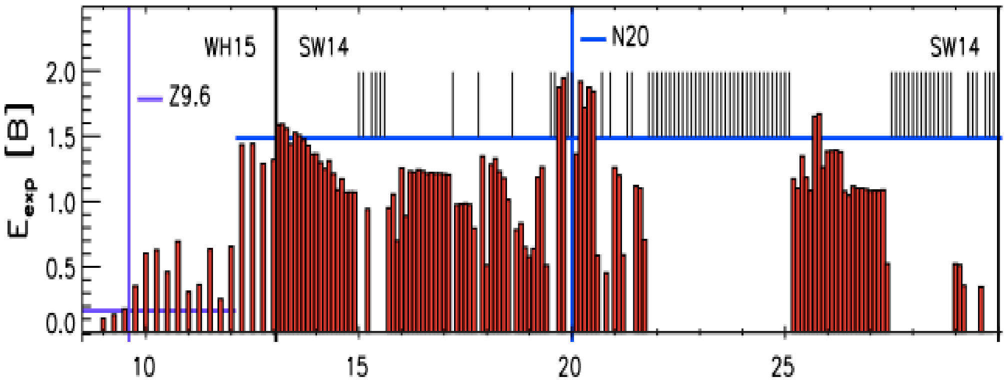
neutron stars & supernova remnants

gravitational waves

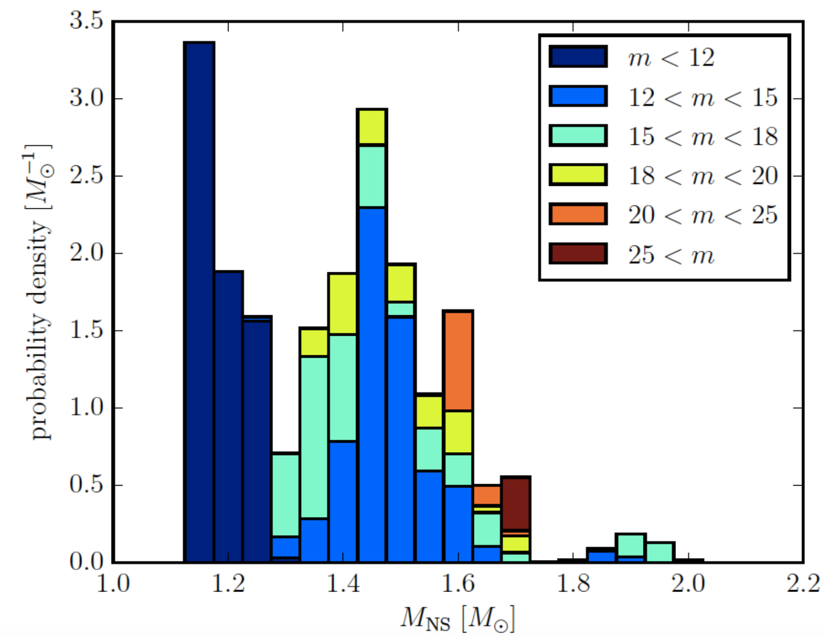
neutrinos



Understanding the Systematics of Explosion & Compact Remnant Properties



Sukhbold, Ertl, Woosley, Brown & Janka (2016)



Distribution of NS birth masses (Müller, Heger, Liptai & Cameron 2016)

Parameterised model (T. Ertl's talk):

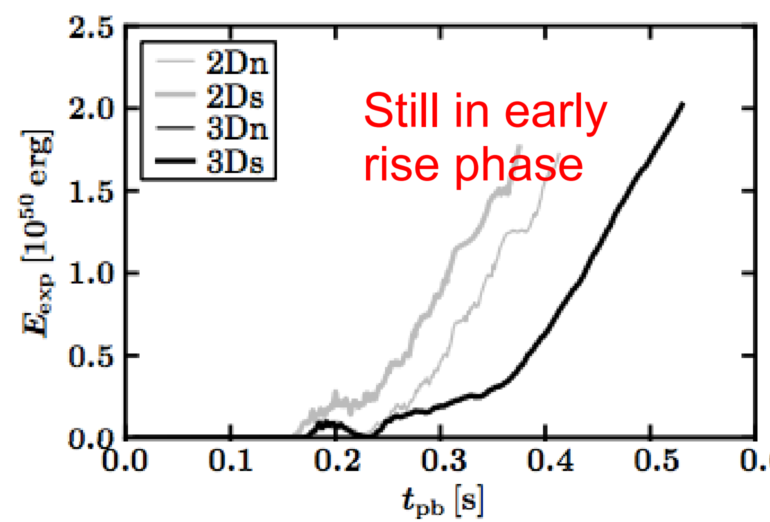
- Considerable progress in predicting distribution of explosion energies, neutron star masses, etc.
- But need to be calibrated
- Non-trivial to get some neutron star properties (kick & spin)

So we need a few reference marks from self-consistent simulations

Status of 3D Explosion Models

- Growing number of successful models in 3D (Melson et al. 2015a/b, Lentz et al. 2015, Müller 2015, Summa et al. 2017, Takiwaki 2013,...)
- No single decisive factor - **combination of ingredients** responsible for successes
- Longer models (>0.3s in 3D)
- Tweaks in neutrino rates (Melson et al. 2015b, Burrows et al. 2016) and equation of state (e.g. inclusion of muons: Bollig et al. 2017)
- Seed perturbations in progenitor (Couch et al. 2013, 2015, Müller et al. 2015, 2016, 2017)

20 $M_\odot$ Melson et al. (2015b)



Explosion energy

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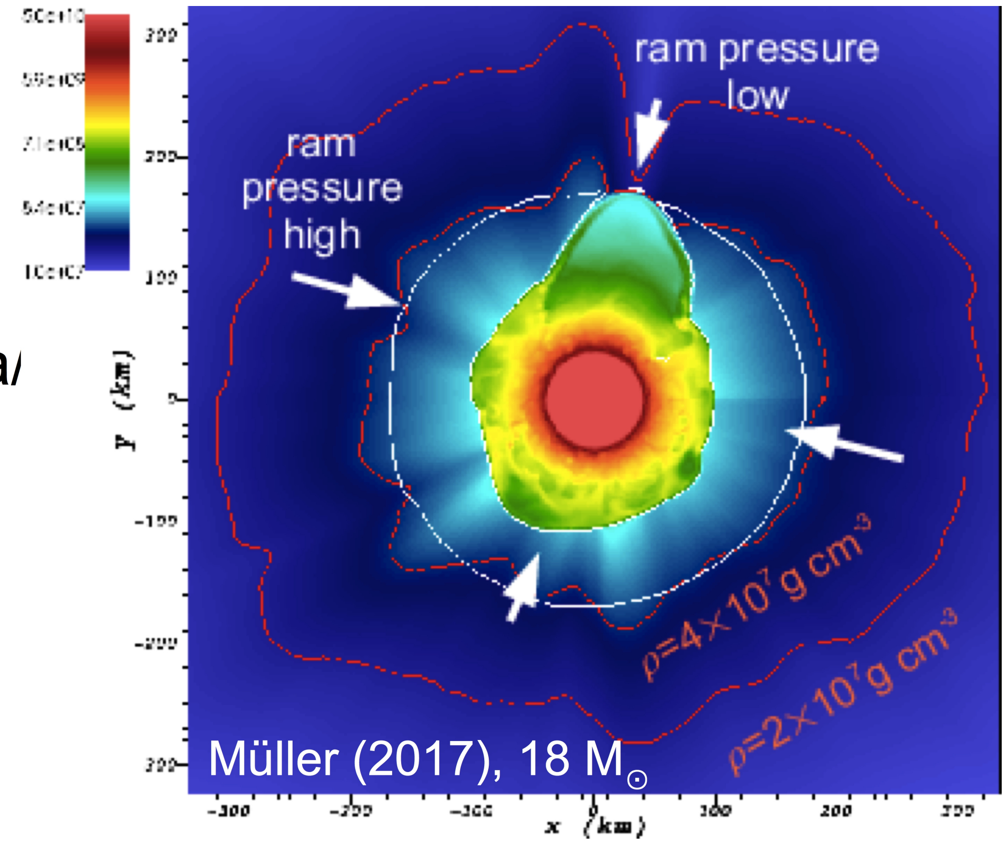
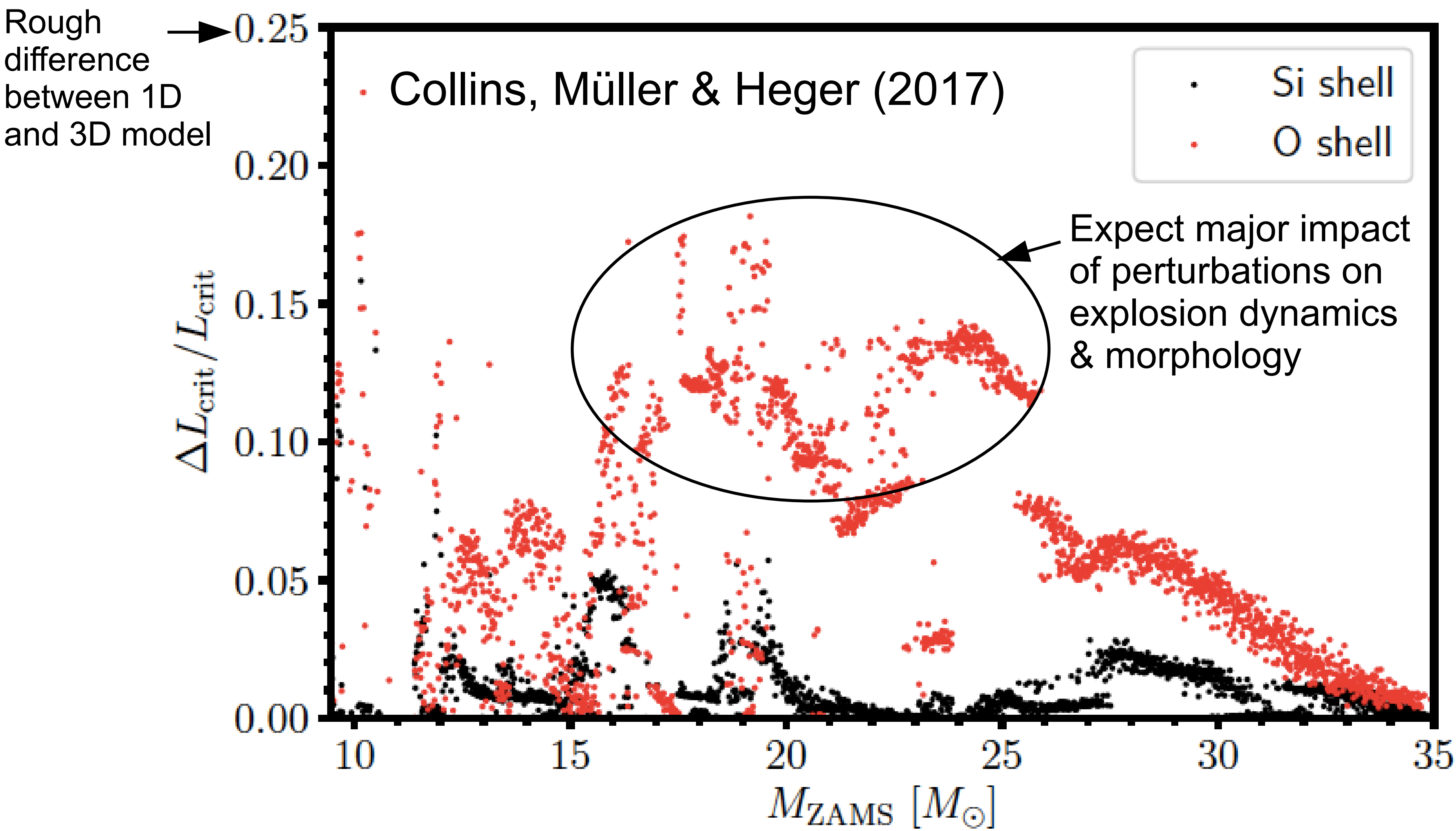
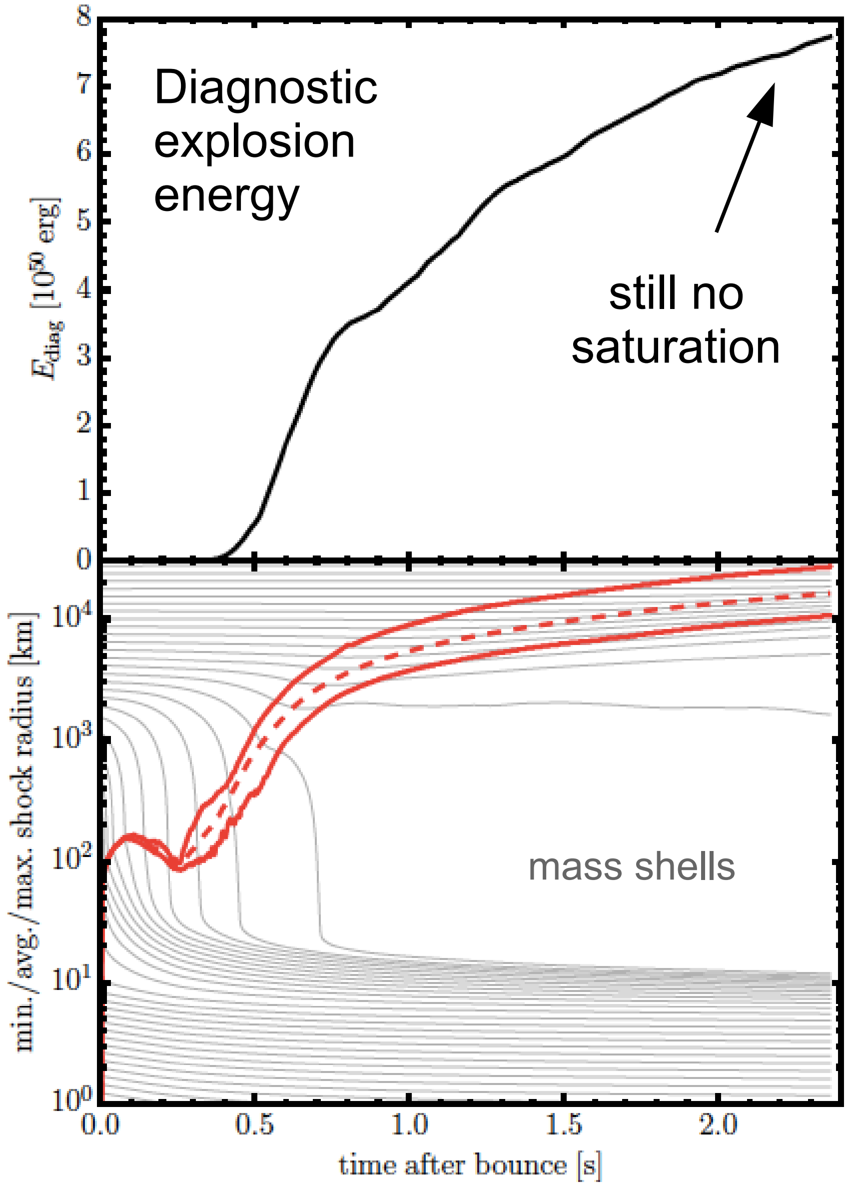


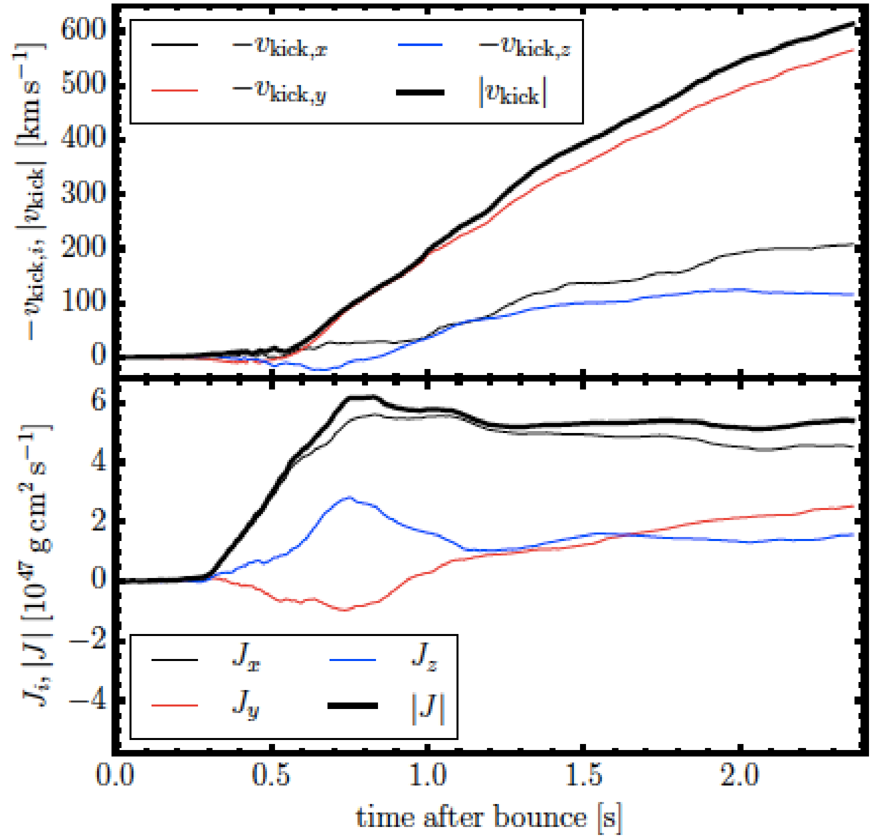
Effect Size of Convective Seed Perturbations



- Can now tentatively extrapolate effect size based on 1D progenitor models
- Region between $16M_\odot$ and $25M_\odot$ as "sweet spot" for perturbation-aided explosions
- Effect of perturbations from O shell burning often sizeable, but just one among many ingredients for robust explosions below $16M_\odot$

Towards Realistic Explosion & Remnant Properties



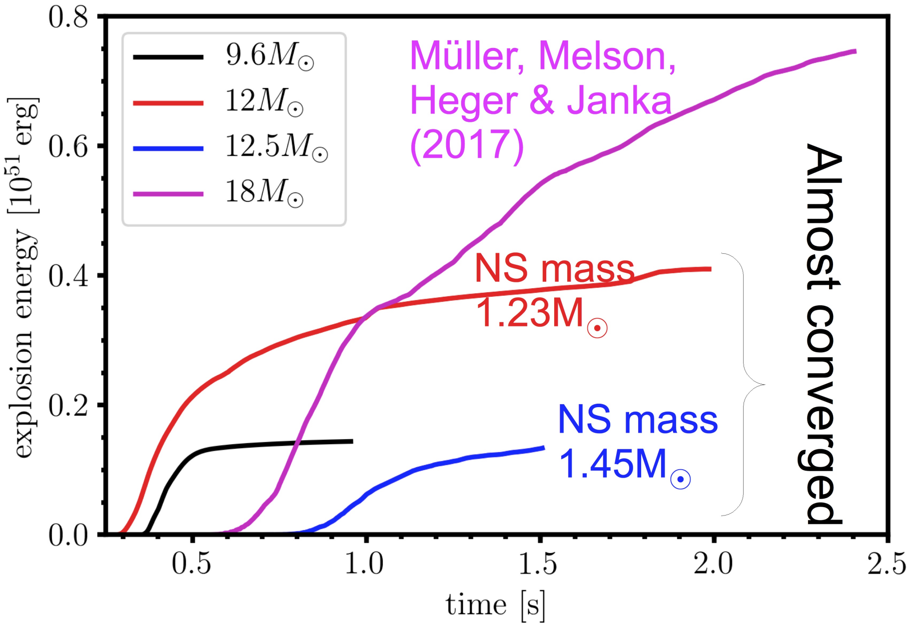


Neutron star mass ($1.7M_\odot$), kick, and spin period (~20ms) a bit atypical, but within observed range

First long-term 3D simulation of self-consistent explosion (Müller, Melson, Heger & Janka 2017):
Still facing problem of continuing accretion

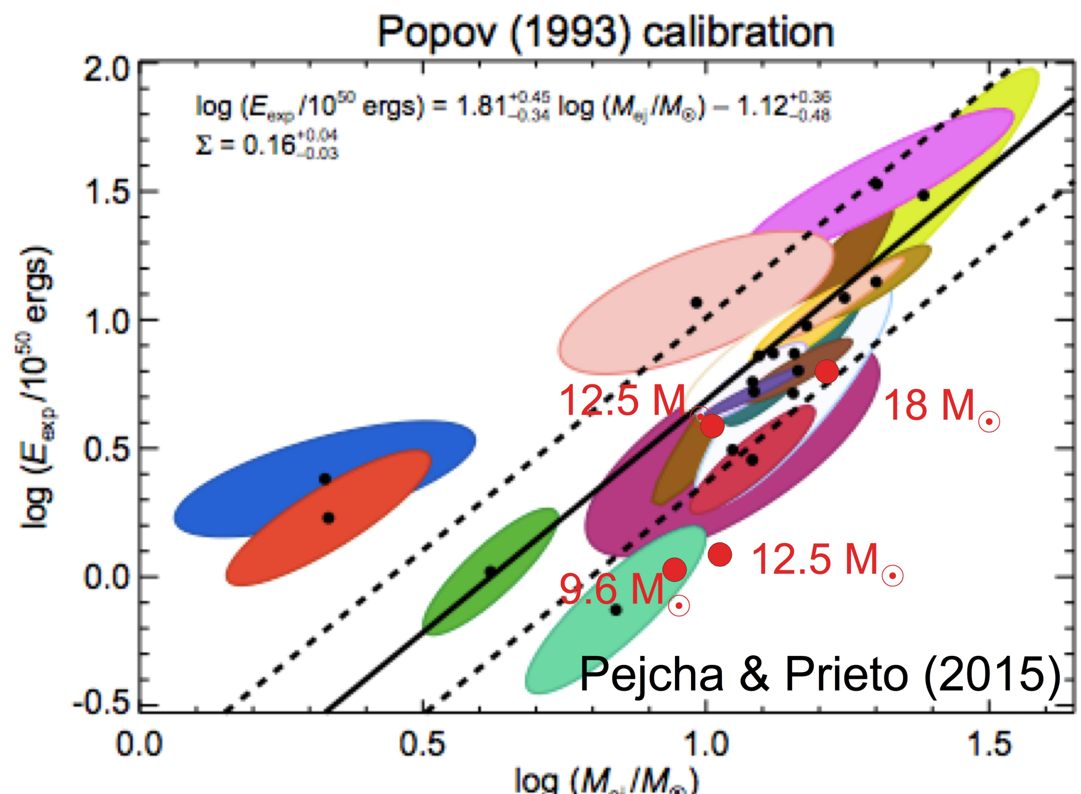
Even correction for "overburden" of envelope gives lower limit of E_{exp}>0.5foe
→ not far from "typical" energies (~0.9foe; Kasen & Woosley 2009)

Dependence on Progenitor Mass



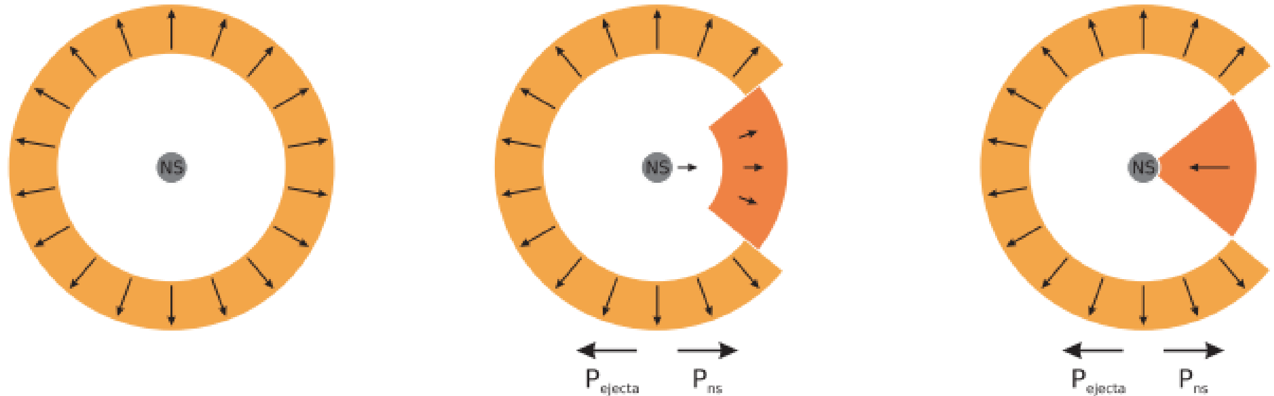
- Better luck with final explosion properties for low- to intermediate-mass models
- 12M☉ progenitor particularly noteworthy:
  - NS starts to lose mass by neutrino-driven wind
  - Final gravitational mass of 1.23M☉

Theory vs. observations



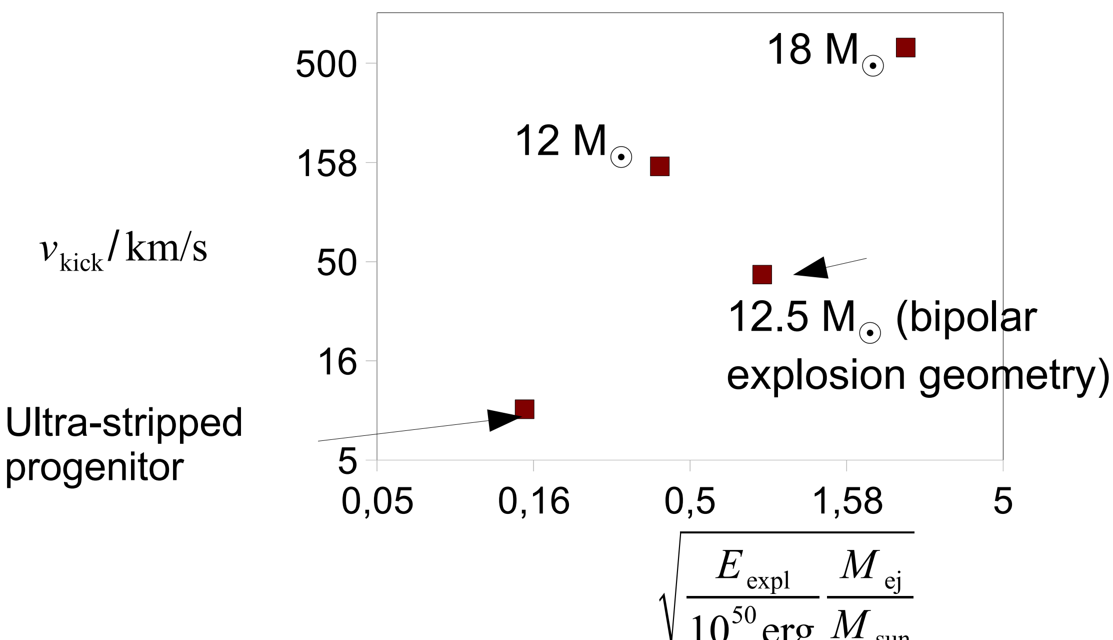
- Models starting to cover the observed range of explosion energies of IIp supernovae from red supergiants
- But can we get >10^{51}erg?
- Models support weak correlation of progenitor mass with explosion energy

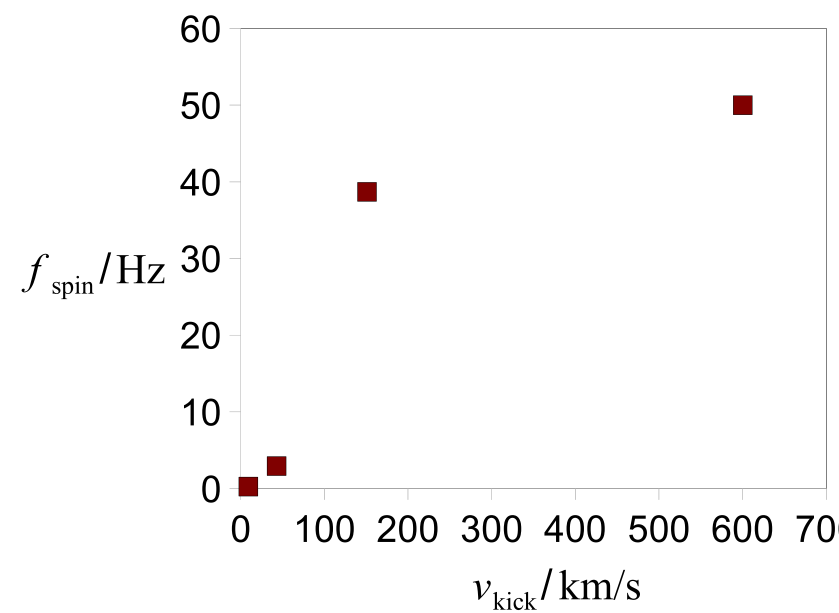
Neutron Star Kicks & Spins



Gravitational tug-boat mechanism (Scheck et al. 2006, Wongwathanarat et al. 2013):

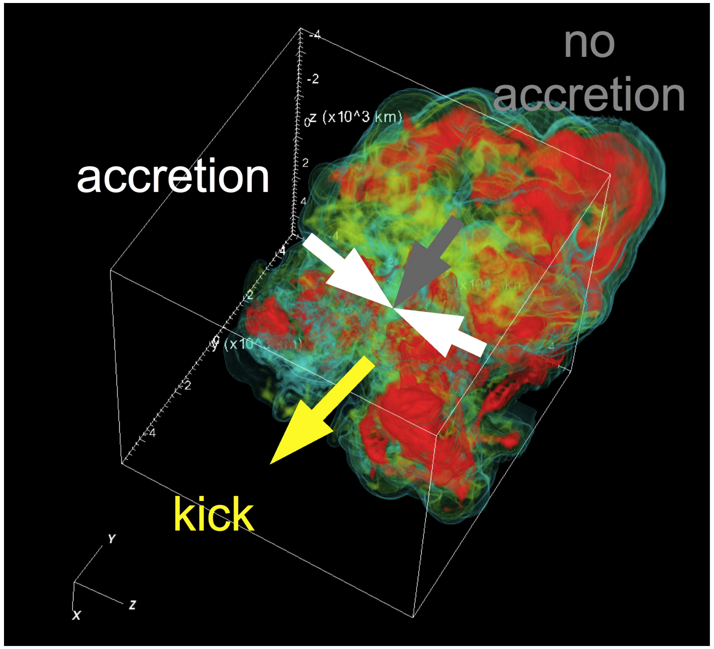
- Ejecta asymmetries result in net gravitational acceleration of the neutron star
- Explosion energy (→ kinetic energy) and mass of *asymmetric* ejecta set kick scale

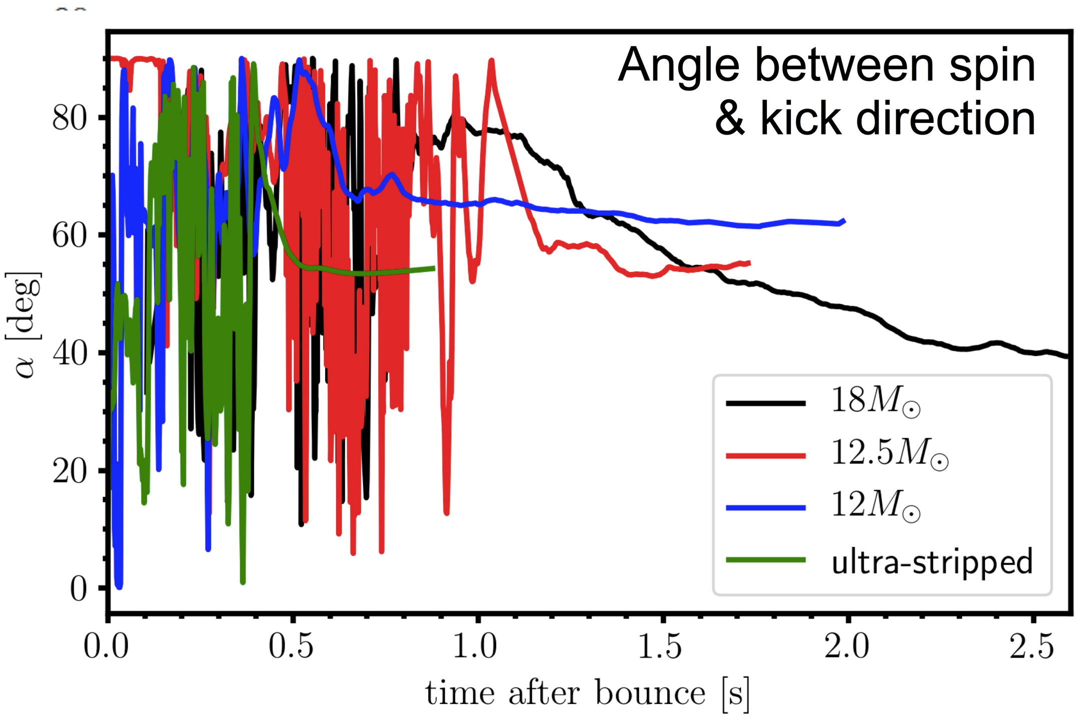




- Simulations now cover plausible range of kicks & spins
- Very tentative evidence that more energetic explosion with higher ejecta mass have higher kicks (confirming hypotheses of Bray & Eldridge 2016, Janka 2017), but big scatter
- Spin-up during explosion can be considerable, also weakly correlated with kick

Orientation of Spin and Kick





- Observations: tendency towards spin-kick alignment (e.g. Johnston & Romani 2004, Wang et al. 2007, Noutsos et al. 2013)
- 18M$_\odot$ of Müller et al. (2017) showed trend towards alignment at late times due to geometry of post-explosion accretion flow
- Not seen in newer 3D models
- None of the suggested explanation for spin-kick alignment (Spruit & Phinney 1998, Janka 2017) borne out yet

Conclusions

- 3D supernova models converging towards more robust explosions due to combination of improvements (3D initial conditions, microphysics)
- Simulations sufficiently long for tentative prediction of explosion & compact remnant properties
- Predicted neutron star kicks, spins & masses now fairly typical in growing sample
- Confirms loose correlations of explosion energy, progenitor mass & neutron star mass seen in parameterised models (and adds correlation of kicks & spins)
- But challenges remain:
  - Red supergiant explosions above 10^{51}erg
  - Mechanism for spin-kick alignment?