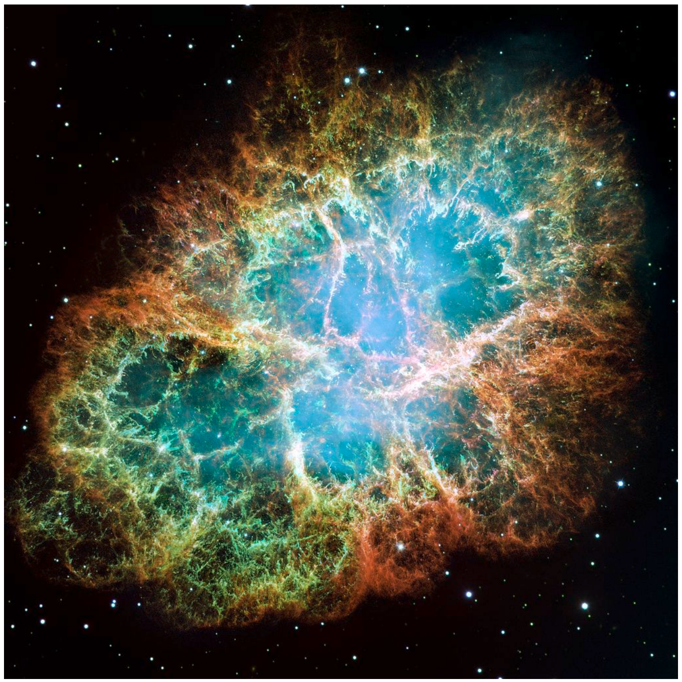
Linking Supernova and Neutron Star Properties

Thomas Ertl

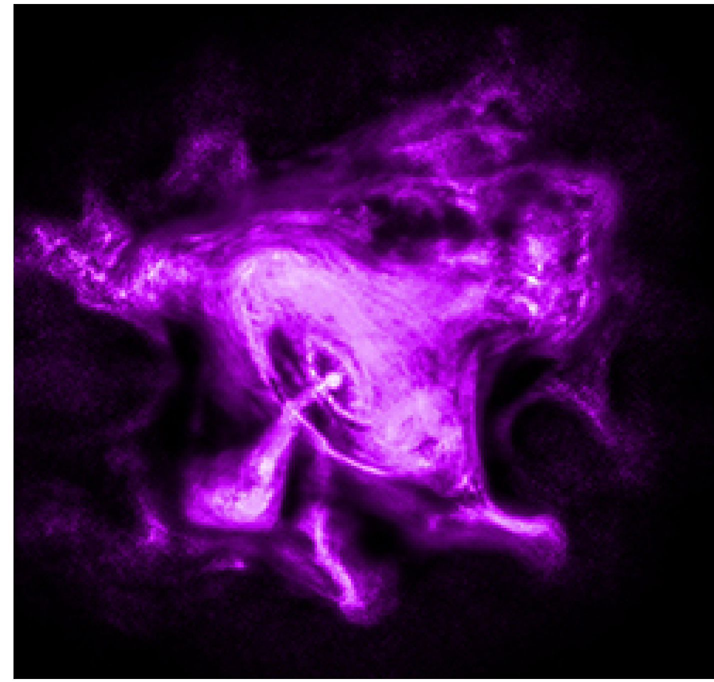
11th BONN workshop – 12.12.2017

Max Planck Institute for Astrophysics

Direct connection: SN 1054 best case?



HST



CHANDRA

SN 1054*

- E_{exp} = ~0.1 B
- Nucleosynthesis
- “Lightcurve”
- Mass of the Progenitor Star

Pulsar

- Spin
- Kick (>100 km s^{-1})**

Bernhard’s talk

- No radius or mass of the NS

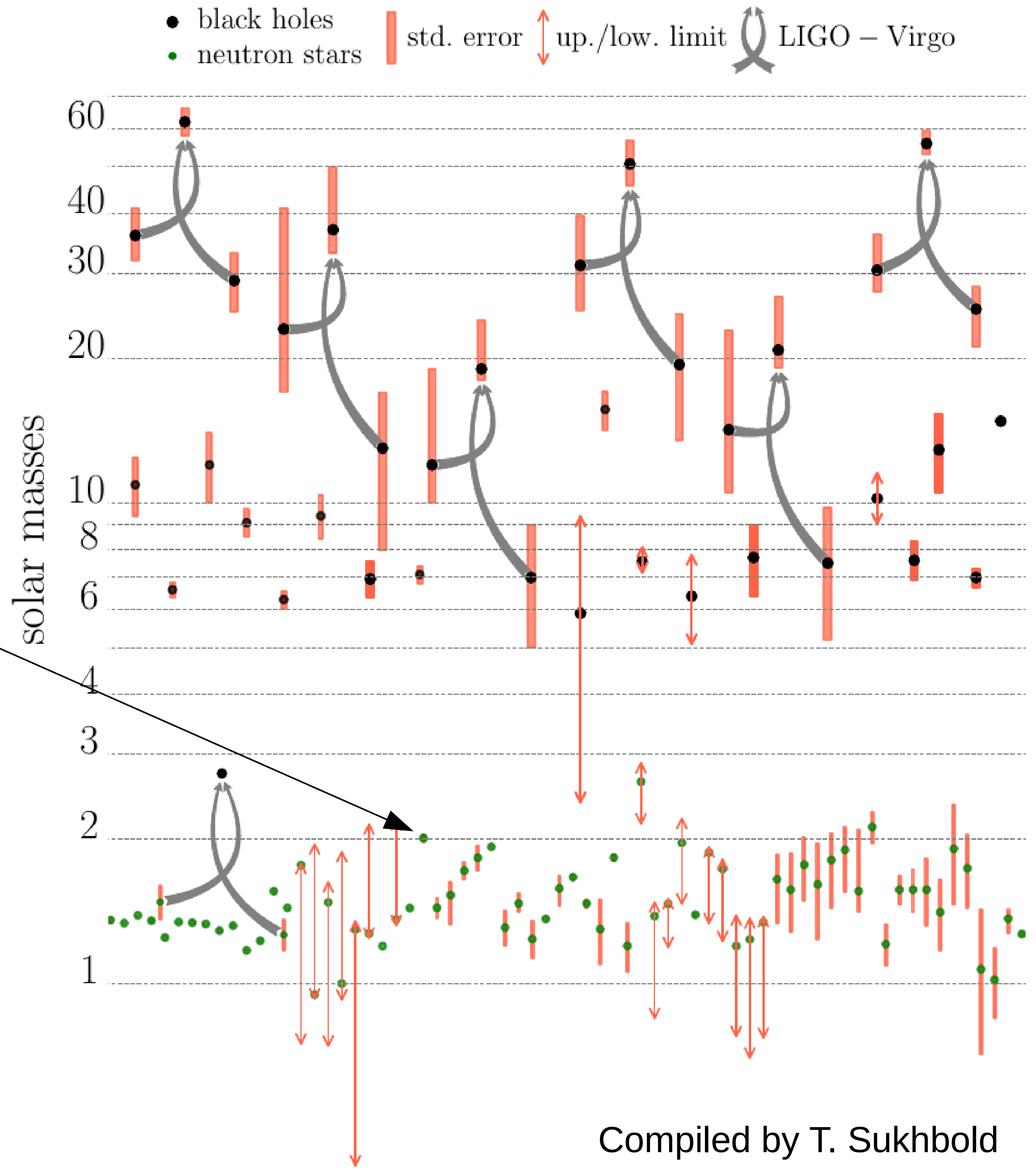
BUT: No direct connection of key observables

*e.g. Tominaga+2013, Smith 2013, Yang & Chevalier 2015

**e.g. Kaplan+2008

NS Masses from Binary Systems

- **Masses** from
  - Binaries w/ Pulsars
  - Gravitational Waves from NS merger
- Constraints high-density EOS
  → **Next talk**
- **Problem:** No Information about the preceding Supernova(e)
- **The link between SNe and NS masses can be established only statistically**



Compiled by T. Sukhbold

How to Connect Theoretical Models to Observations?

A **multi-step process** is needed to connect theoretical models of core-collapse SNe to the observed NS mass distribution!

1. **Stellar Evolution Models**

↓

2. **First-principle simulations** to understand the expl. mechanism

↓

3. Phenomenological/**systematic parameterised models**

How to Connect Theoretical Models to Observations?

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3. Phenomenological/**systematic parameterised models**

↓

(4. Population synthesis)

First Step:

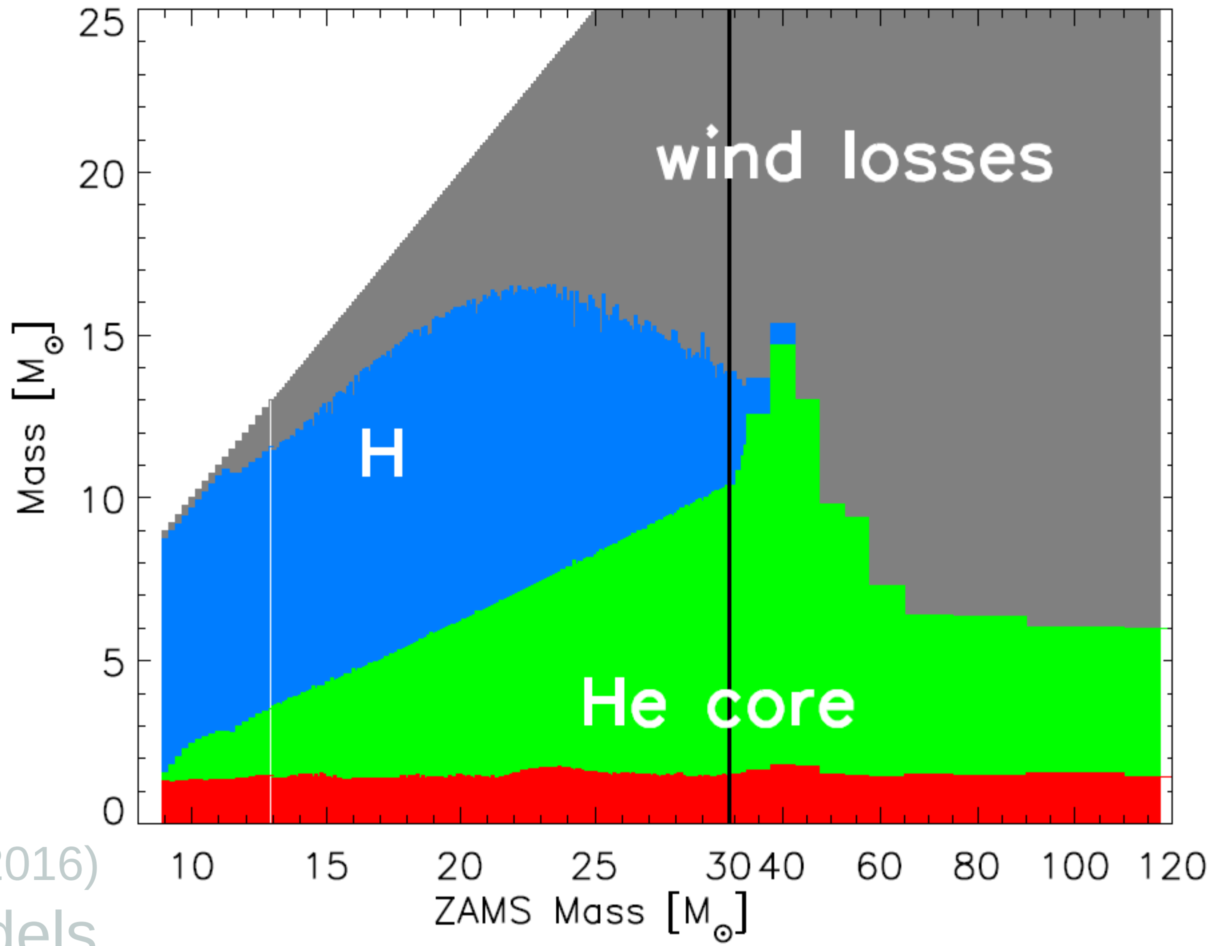
Stellar Evolution Modelling

Stellar Evolution Models

Directions of stellar evolution

- A **dense** ZAMS* mass grid is needed to explore the parameter space:
  - **Metallicity**
  - **Rotation + magnetic fields**
  - **binary evolution**

- **Multi-D effects**:
  - Validity of the employed parameters (e.g. Jones et al. 2016)
  - More realistic pre-SN models => large scale perturbations (Couch+2015, Müller 2016, Müller+2017)



Models from Sukhbold+2014/2016

*Zero-Age Main-Sequence

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→ **Talk by R. Farmer**

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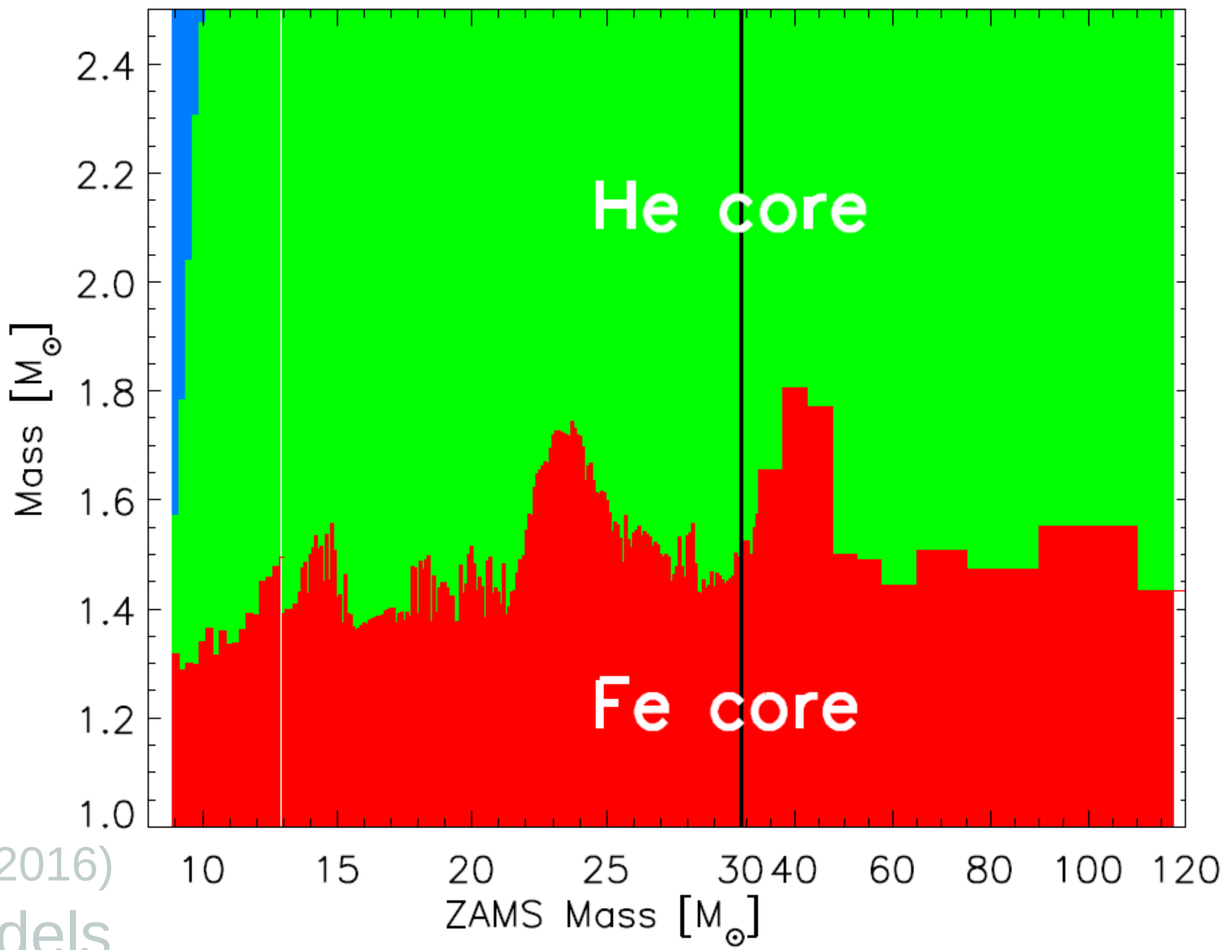

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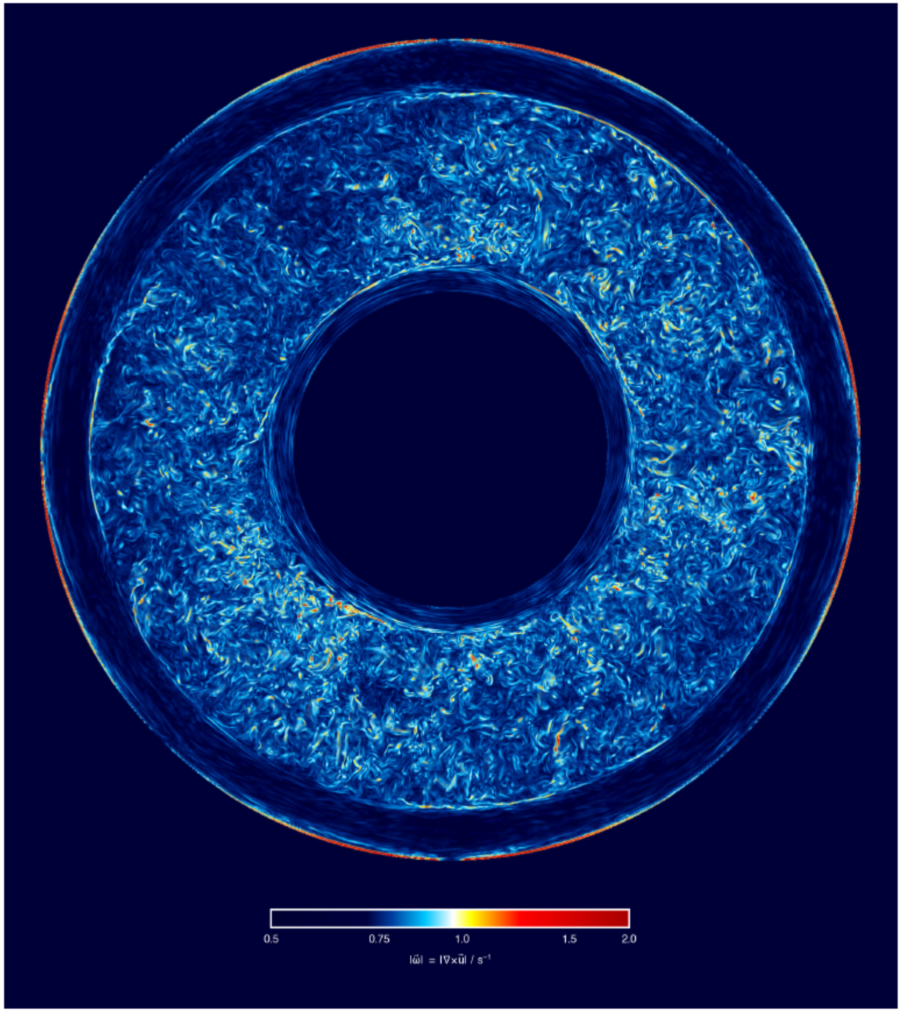


O-burning shell Jones+2016

Second Step:

Understanding the Explosion Mechanism with First-Principle Models

(Focusing only on the delayed neutrino-driven explosion mechanism.)

Core Collapse and Shock Stagnation

Core collapse

⬇

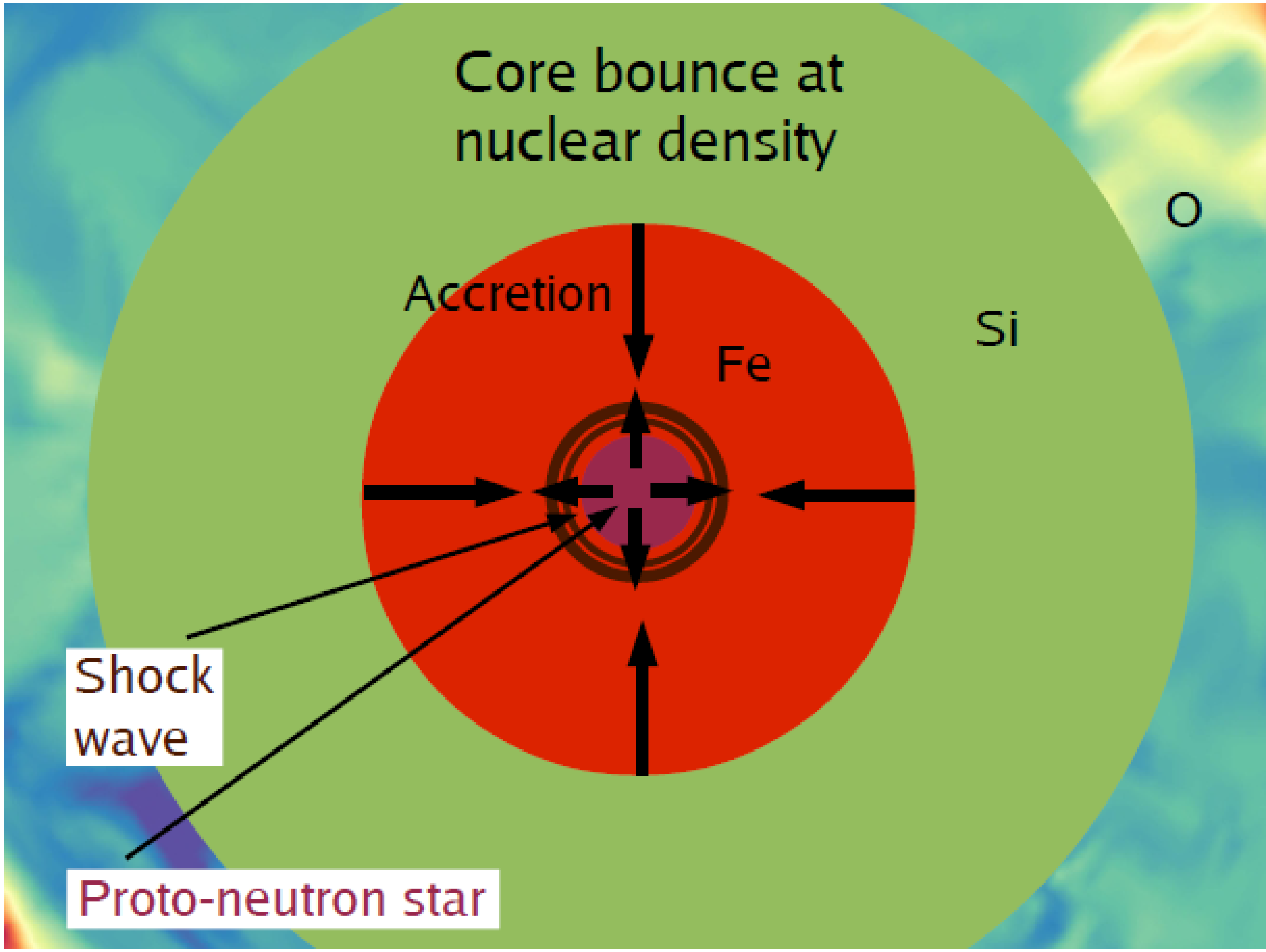
Central density reaches nuclear density

⬇

Core bounce

⬇

A Shock wave is launched

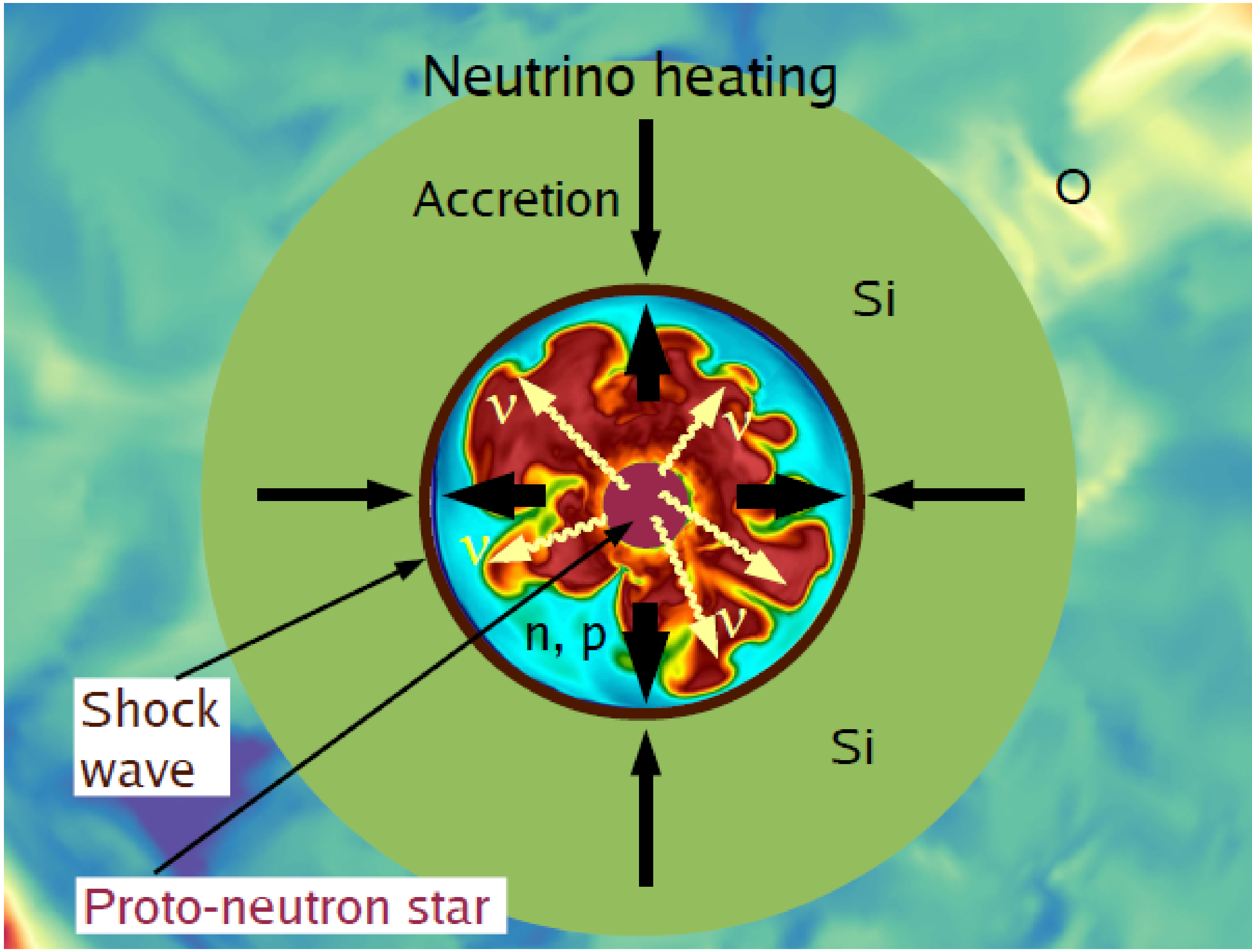


Janka+2017

$$E_b \sim E_g \approx \frac{3}{5}\frac{GM_{ns}^2}{R_{ns}} \approx 3.6 \times 10^{53} \left(\frac{M_{ns}}{1.5\,M_\odot}\right)^2 \left(\frac{R_{ns}}{10\,\mathrm{km}}\right)^{-1} \mathrm{erg}$$

The Neutrino-Driven Mechanism

- **Shock stagnates**
- **Critical phase (~ 1s)** for the explosion to set in and success of the mechanism
- **Competing processes:**
  - **Ram pressure** of the infalling material
  - **Neutrino heating**



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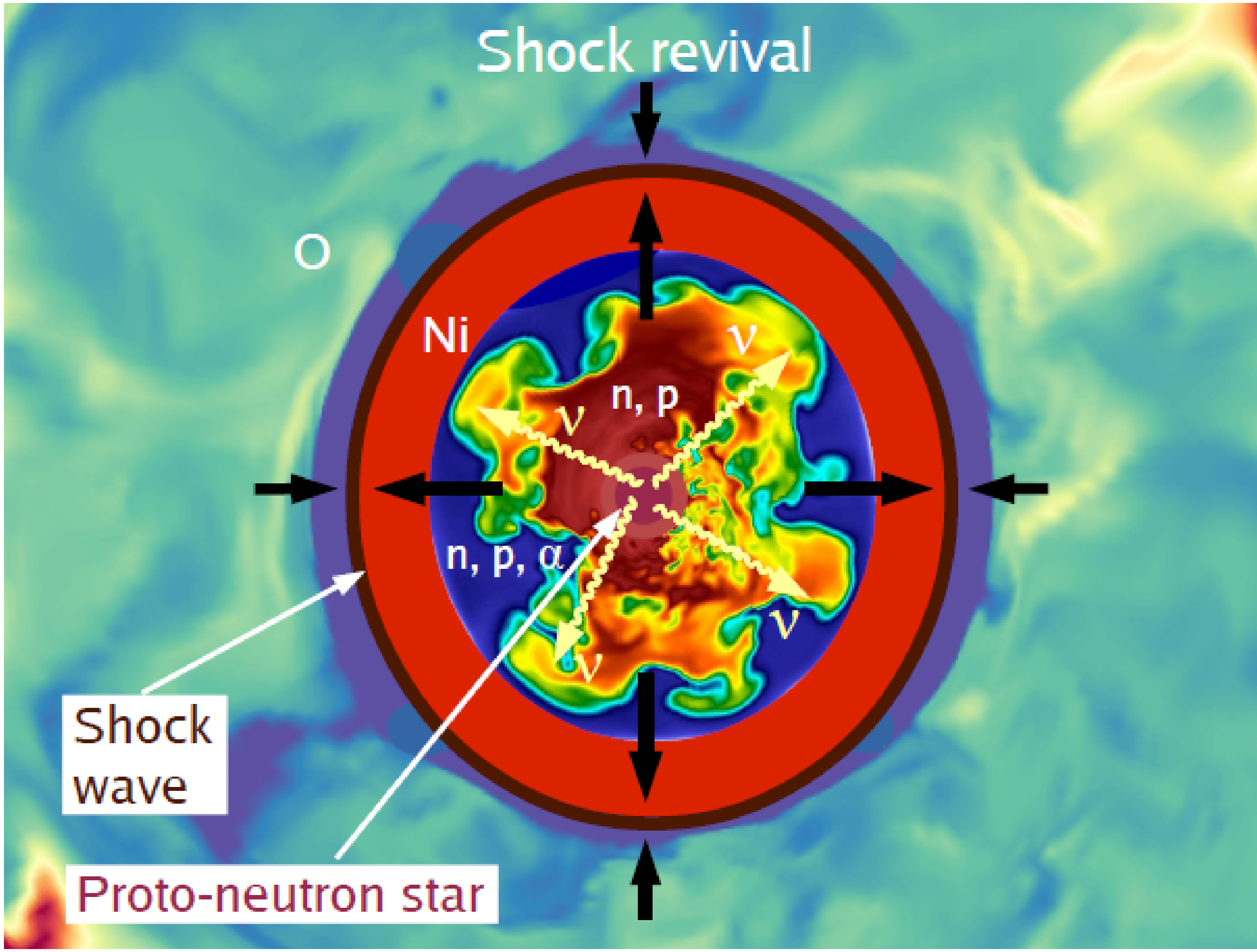

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Status and Developments of First-Principle Modelling

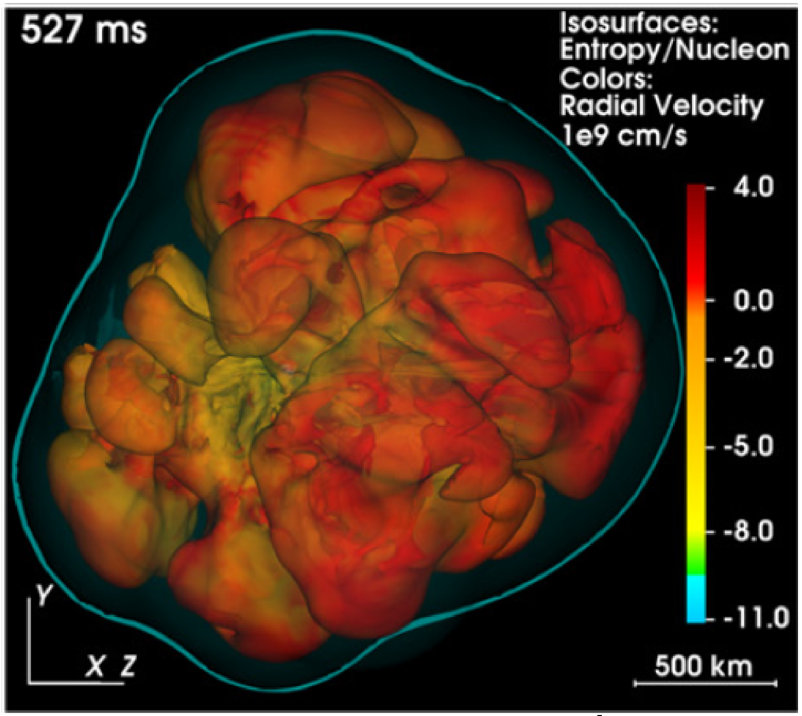
- 1D models fail (except for the low-mass end)
- 2D models explode routinely and are useful for comparisons (e.g. Müller 2015), but seem to be low energetic and with artificial geometry

- 3D models seemed to be harder to explode (Hanke+2013)

- **Better Microphysics, e.g.**
  - Nucleon strangeness effecting neutrino opacity (Melson+2015)
  - Muon creation (Bollig+2017)

- **Progenitor perturbations**
  (Müller 2016 for a review)

=> Computationally very expensive and mechanism not completely understood!



Melson+2015

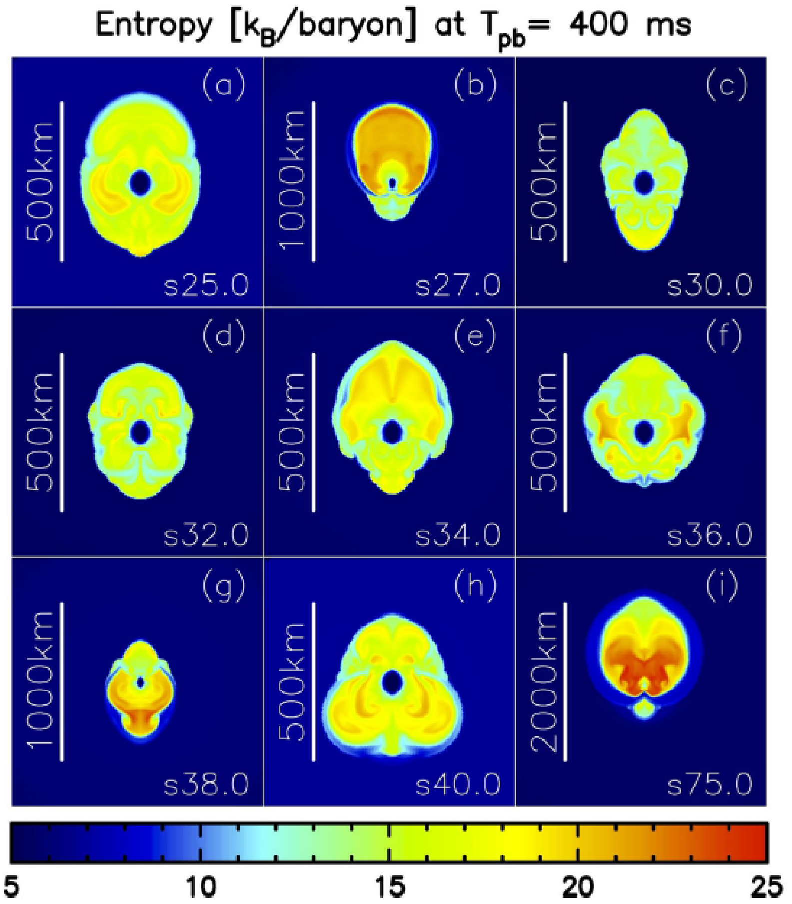
Third Step:

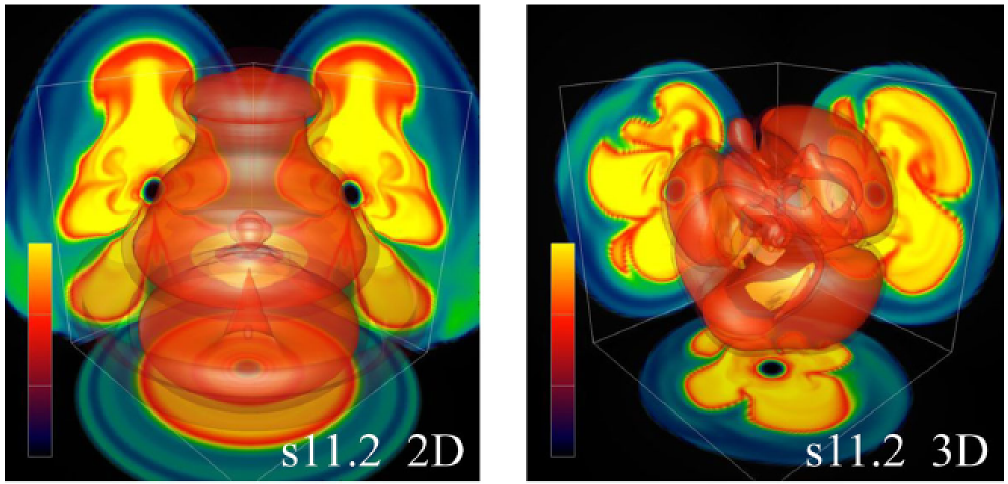
Exploring the Supernova Landscape with Phenomenological (Parameterised) Models

2D Simulations with Simplified Neutrino-Transport

e.g. Nakamura et al. 2015

- **Includes multi-D effects**
- No long-term evolution
- **Computationally expensive**
- Explode to readily compared to 3D simulations with sophisticated neutrino transport and are often dominated by the axis





Horiuchi+2014, for cautioning against 2D results

Analytic models

- **Analytic Models + Hydrodynamic Simulations**
  - **Pejcha&Thompson 2015:** scaling laws for the critical luminosity combined with 1D neutrino-hydro simulations
  - **Fryer+2012, Belcynski+2012:** explosion energy from internal energy in the gain layer + thermal bombs

- **Müller+2016: Set of differential equations and scaling laws without hydrodynamic simulations based on latest**

- Computationally inexpensive

  => Useful to explore the stellar parameter space

- Includes some of the multi-D effects (especially after shock revival)

- Easy assessment of individual components of the models

  (e.g. NS contraction, efficiency of downflows after shock-revival, ...)

- Type and final mass of the remnant not determined

1D Models with Enhanced Heating/Neutrino Luminosity

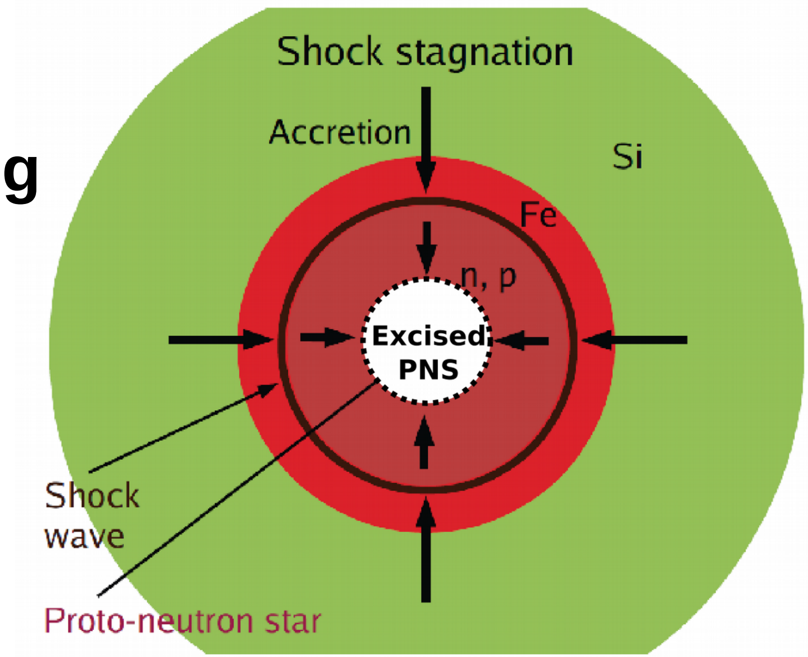
- **O'Connor&Ott 2011:** leakage+ extra heating
- **PUSH by Perego+2015:** coupling the heavy lepton neutrinos for additional heating over a predefined period of time
- **PROMETHEUS-HOTB (next slides)**

- Following the explosion with hydrodynamics
- Typically computational inexpensive
- Follow the evolution of the explosion up to and beyond breakout

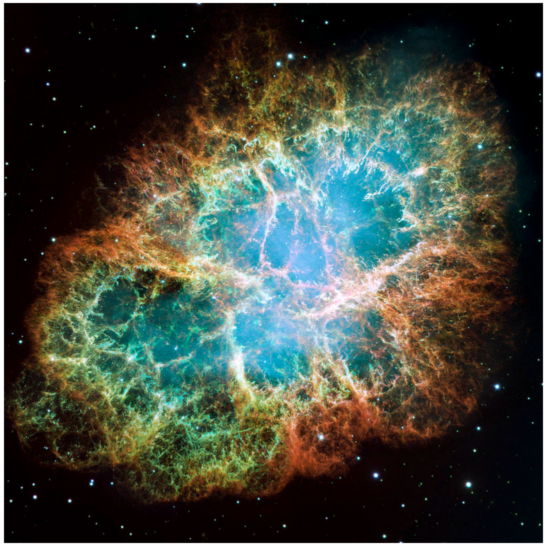
  =>Determination of mass and type of remnant possible
- Artificial onset of the explosion (freedom in extra heating)
- Multi-D effects are hard to include (only imitated)

Calibrated 1D Neutrino-Hydro Models with PROMETHEUS-HOTB

- **Proto-neutron star** is **excised and replaced by an Analytic core-cooling model** with tunable parameters



- Calibration on two well-observed Supernovae:
  - **SN 1987A** (E_{exp} = (1.3 - 1.5) x10^{51} erg, M_{Ni} ejecta mass of ~0.07 $M_{\odot}$, Neutrino signal, Progenitor star M(He) = 6±1 $M_{\odot}$, M(H) ~ 10 $M_{\odot}$)
  - **SN 1054** for a low-mass star (8-10 $M_{\odot}$) based on observations and self-consistent simulations (e.g. Melson+2015)

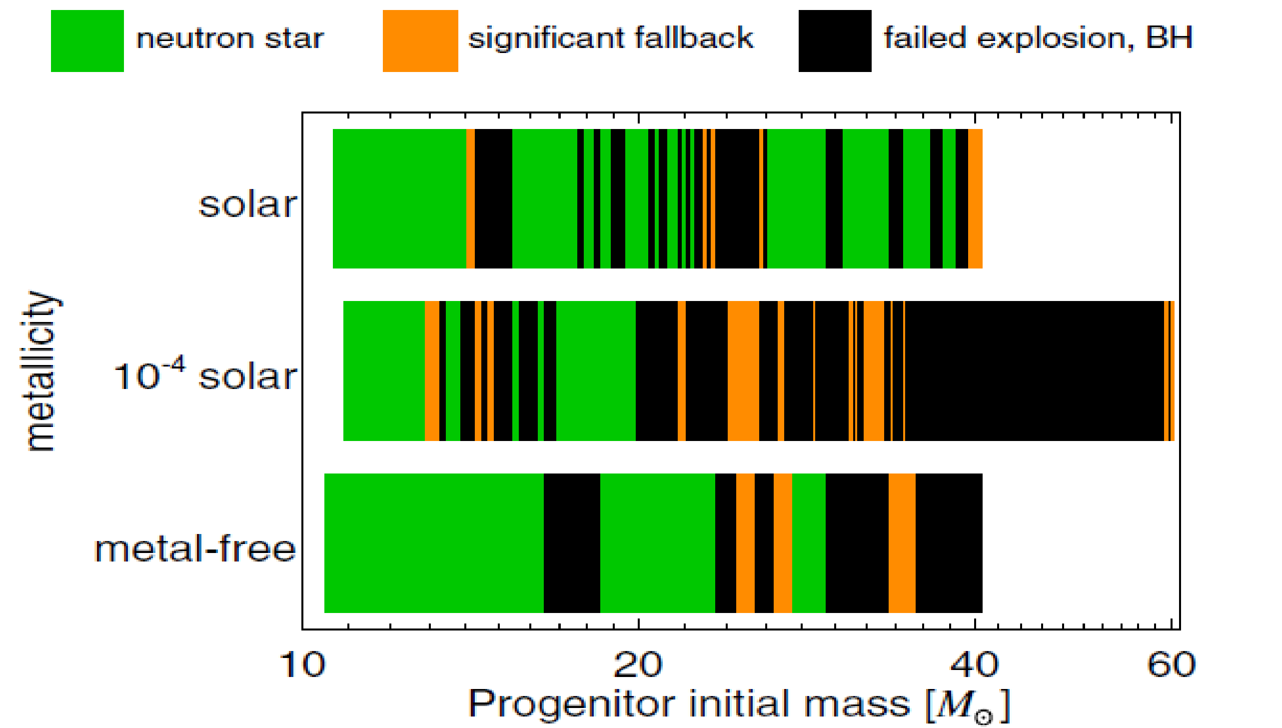


HST

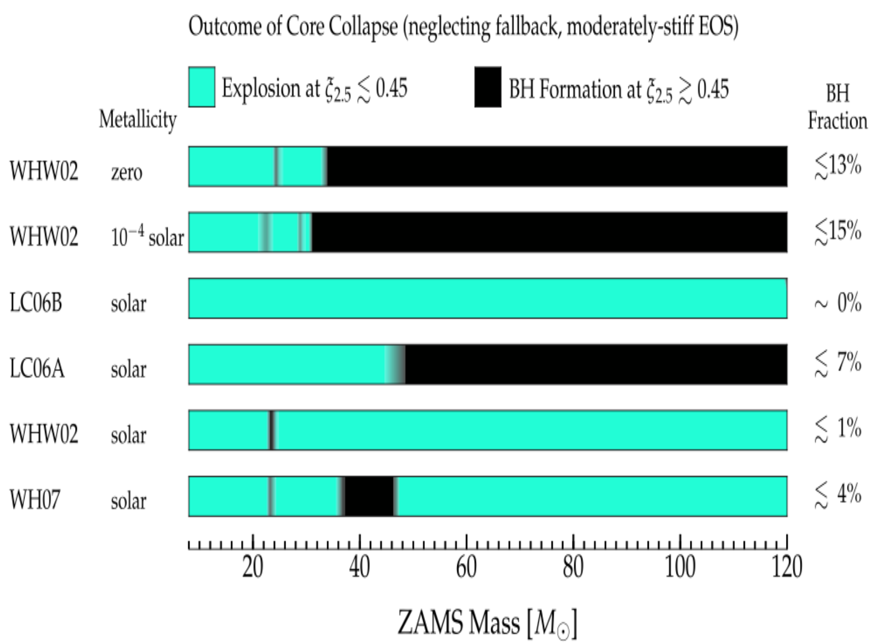
HST

Landscape of Explosions and Implosions

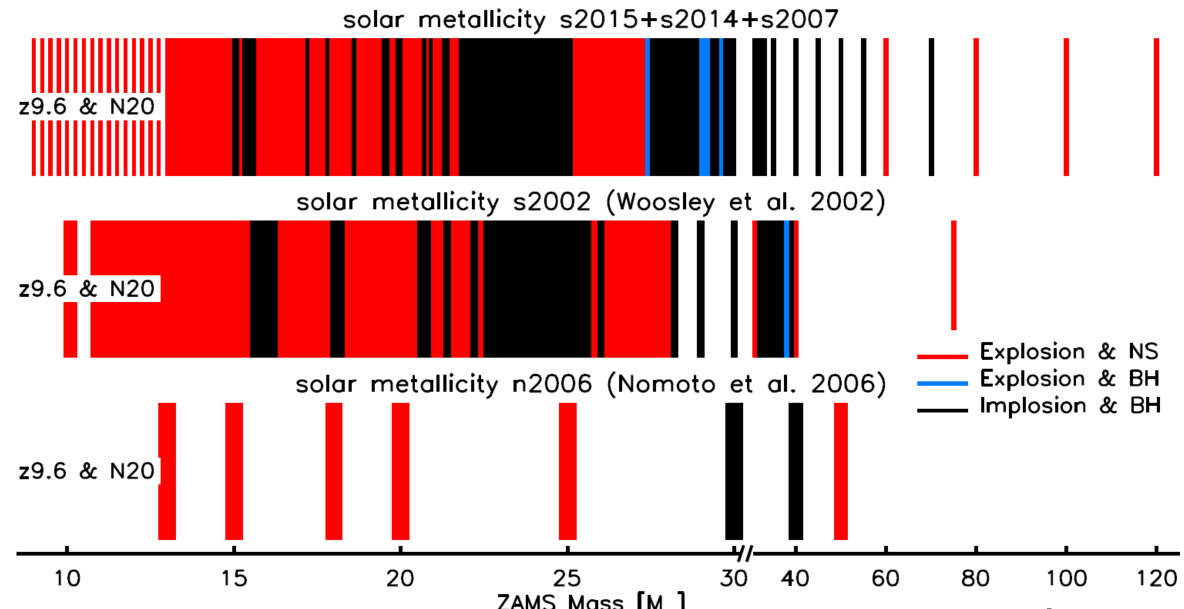
- Non-monotonic outcome pattern
- Imprint of the core structure resulting from stellar evolution



Pejcha&Thompson 2015

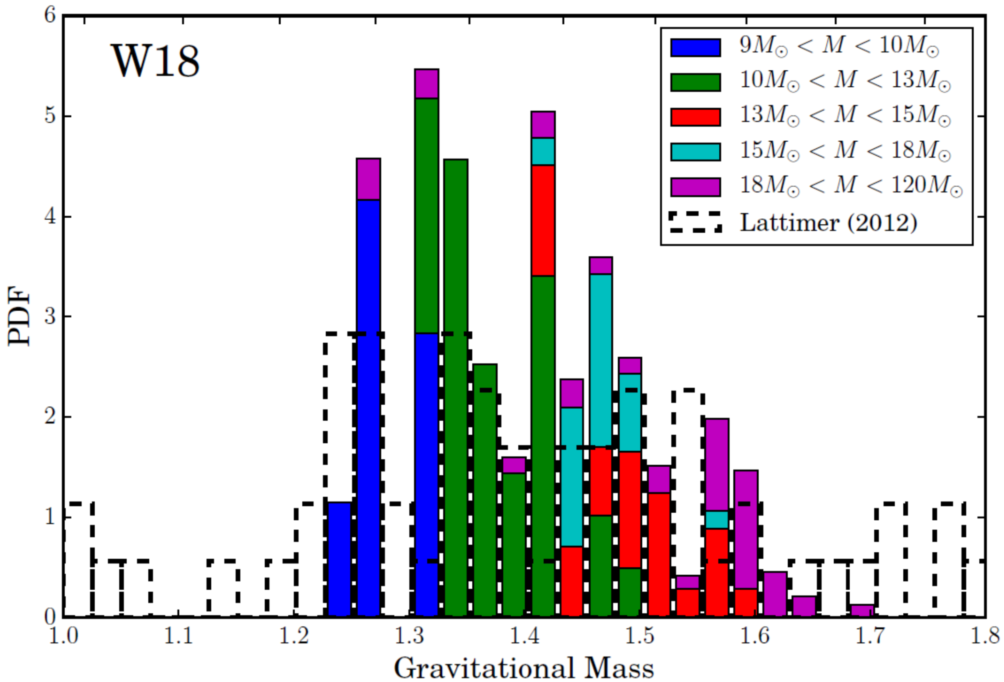


O'Connor&Ott 2011

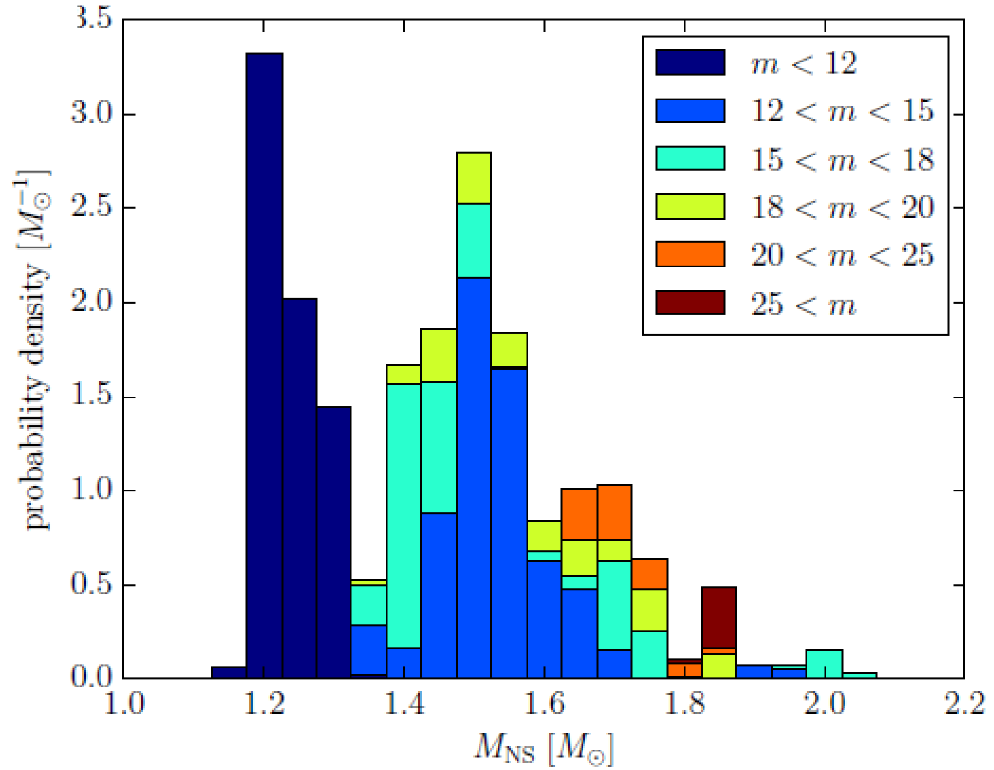


Ertl 2016

Neutron Star Masses



Ertl+2016

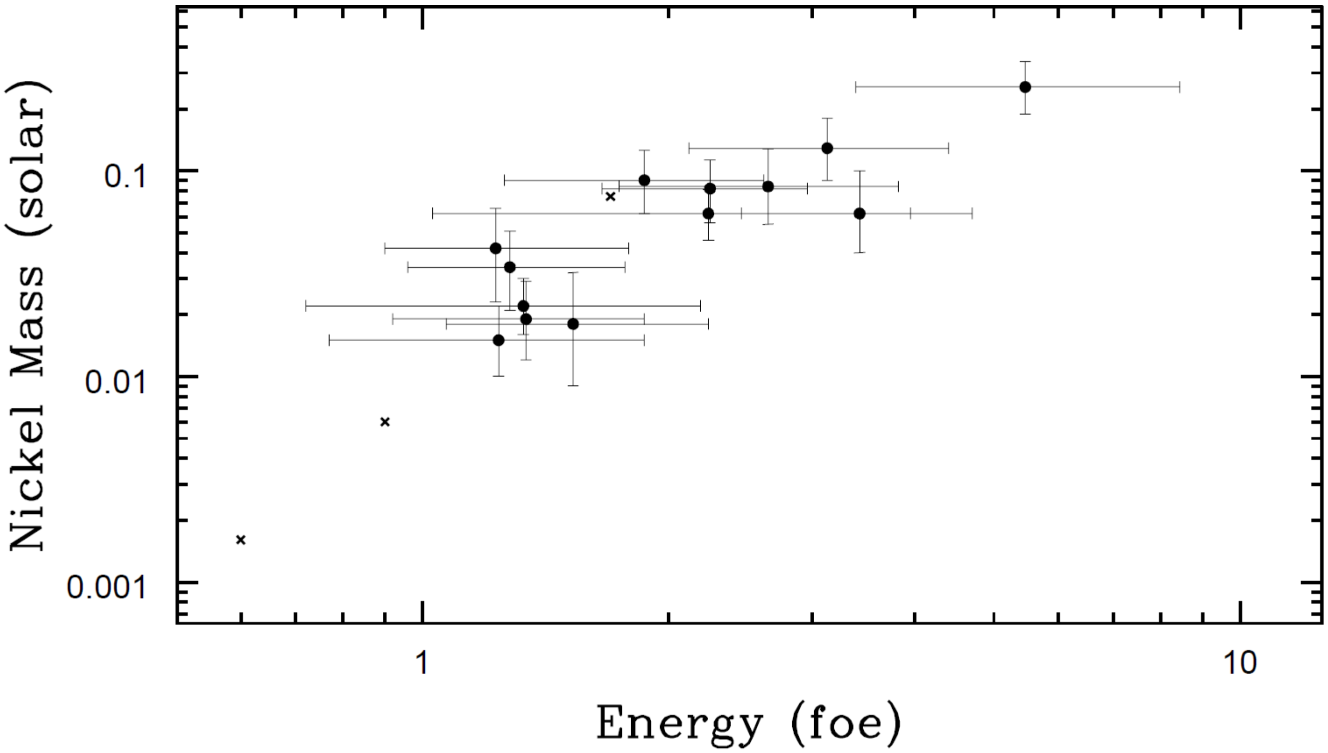


Müller+2016

- **IMF-weighted** (Salpeter initial mass function) NS masses
- Results in NS with typical masses, but strong conclusions are hard to make: No binary evolution, Uncertainties in explosion mechanism and uncertain stellar evolution modelling

Further Observational Constraints for These Models

Nickel Masses and Explosion Energies

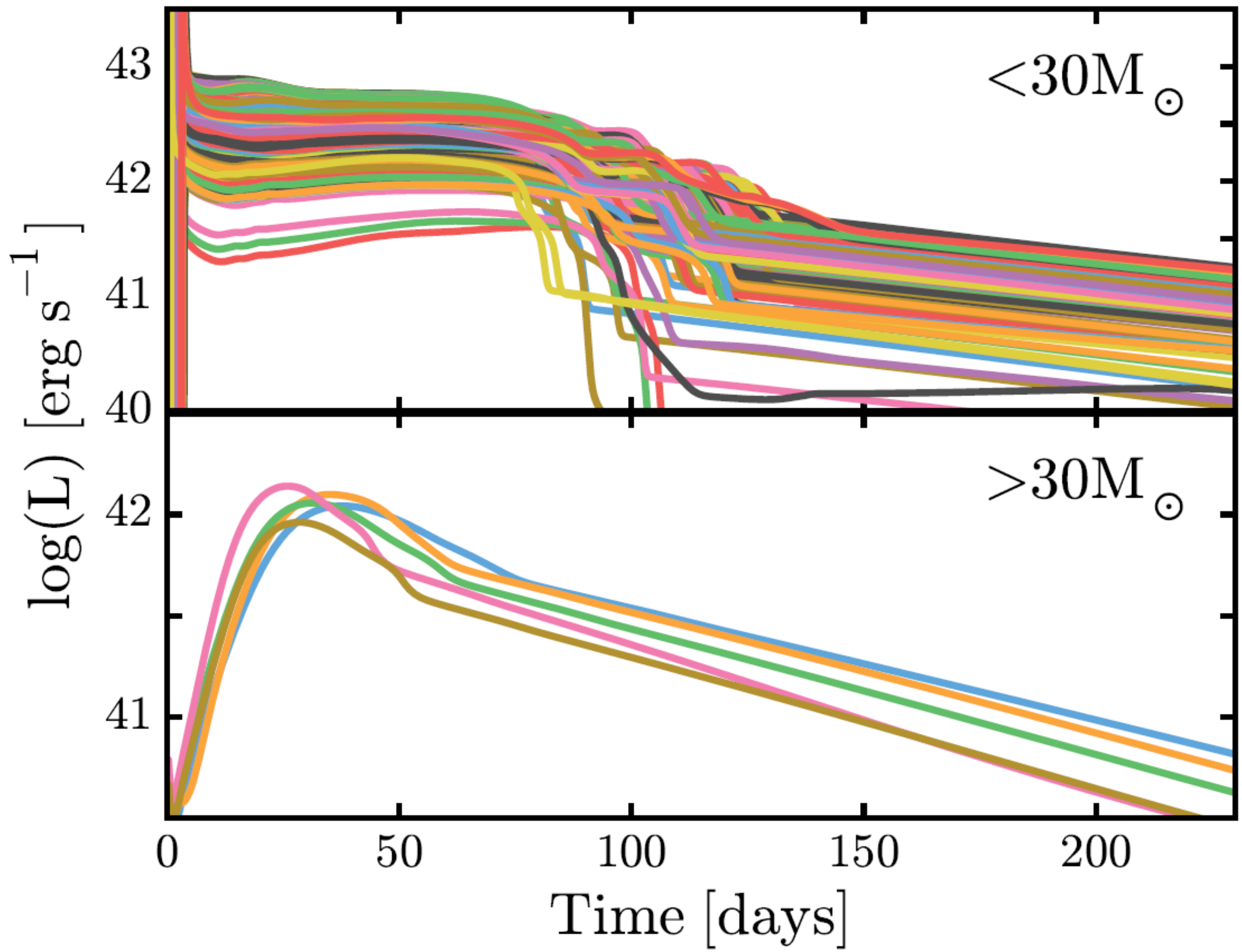


Hamuy 2003

- Explosion energies range from ~**10^{50} to 2.0×10^{51} erg**
- 0.001 to ~0.2 $M_{\odot}$ of **ejected nickel**

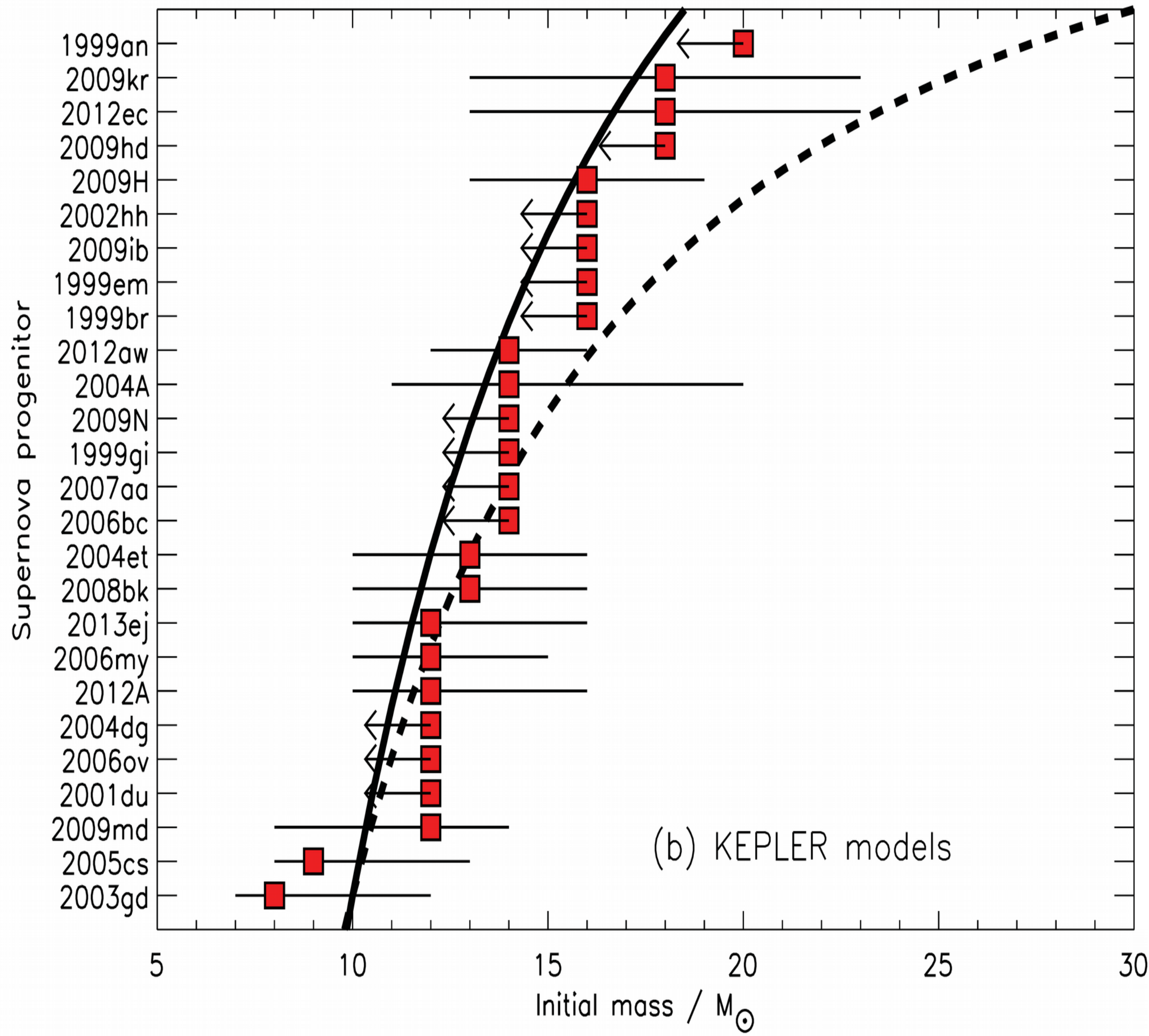
Lightcurves

- **95%** of stars result in **Type IIP** supernovae
- No type IIL
- **No common Ibc** (too broad and faint)
  - → Stripping in **binary systems**?



Observed Progenitors of Type IIP SNe

- No Type IIP SN >20 $M_\odot$
- **Line:** Assuming successful explosions only up to 18.0 $M_\odot$ (IMF-weighted)
- **Dashed line:** Assuming successful explosions up to 30 $M_\odot$ (IMF-weighted)



Smartt 2015

(IMF = Salpeter Initial Mass Function)

Conclusions

A link NS masses and SNe can only be established statistically:

- **Stellar evolution:**
  - Exploring the parameter space (mass loss, rotation+B-fields, ...)
  - Verifying the models with multi-D simulations
- **First-principle models** to understand the explosion mechanism
  => Kick, Spin, and magnetic fields of NSs
- **Phenomenological modelling** necessary, because of computational cost and uncertainties in the explosion physics

- These models have to explain the observed **NS masses** as well as ...
  - **Chemical abundances**
  - The red supergiant problem (A lack of exploding high-mass stars)
  - Observed SN **lightcurves** and **Nickel ejecta**

Thank you!