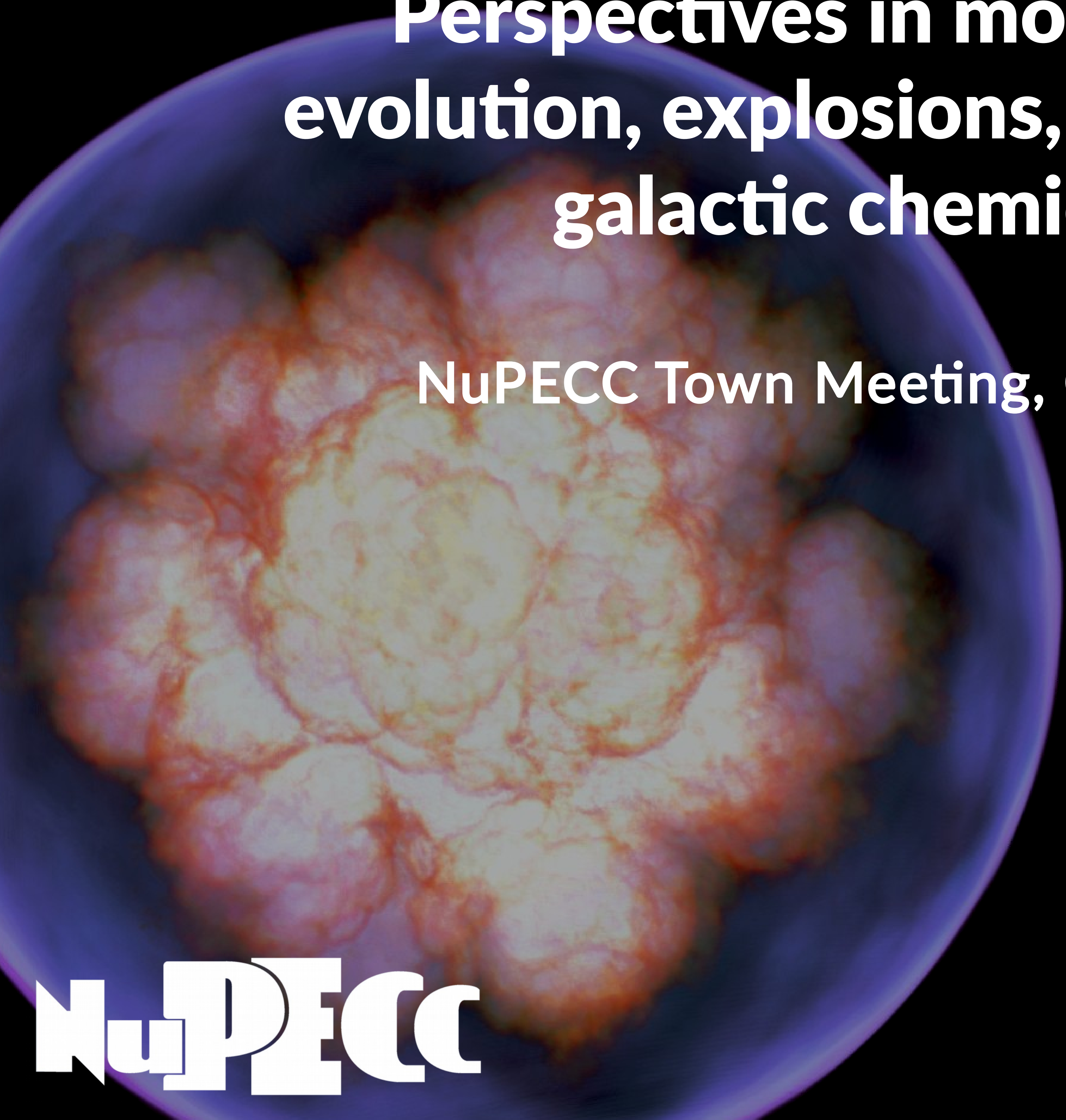
Perspectives in modeling stellar evolution, explosions, mergers and galactic chemical evolution



NuPECC Town Meeting, GSI, 02/17/2016

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Raphael Hirschi

et al.

NuPECC

Contributors

Input was provided by

- Diego Bossini
- Jordi Jose
- Andrea Miglio
- Bernhard Müller
- Marco Pignatari
- Luciano Rezzolla
- Thomas Tauris
- Friedel Thielemann
- Claudia Travaglio
- Chris Belczynski

Stellar physics modeling

- Usually computational approaches
- **Conventional 1D models** assuming symmetries
  - Constantant improvement of “microphysics” input → nuclear physics data is critical (but also EoS, opacities, transport processes, etc.)
- **New direction:** extended **multi-D dynamical simulations** to replace or improve 1D models
  - Consistent description of fluid dynamics effects
  - Avoid artificial symmetries
  - More complex, demanding in computational resources
  - Possible due to advanced simulation techniques and constant growth of computational power

Multi-D modeling

- Starting in stellar structure/evolution
- Common practice in stellar explosions
- Unavoidable in mergers

- Multi-D chemodynamical galaxy models emerging

Challenges:

- Qualified personnel
- Sustained expertise in research groups

  → is there enough training in computational astrophysics for students?

Supercomputers

- Prerequisite for successful multi-D dynamical modeling of stellar physics processes
- Good access to resources in Europe?
- Training for young researchers?

Nuclear physics input

- How critical is precise nuclear physics data for models given the many other uncertainties?

Main goals of modeling:

- Determine sites of astrophysical nucleosynthesis and understand cosmic cycle of matter
- Reproduce astronomical observations
  - Precise input necessary in many cases as observables result from nuclear processes
  - Nuclear processes leave chemical fingerprints of physical processes in stellar objects

Stellar fluid dynamics

- Mass conservation

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

- Momentum balance

$$\frac{\partial (\rho \vec{v})}{\partial t} = -\nabla \cdot \rho \vec{v} \otimes \vec{v} - \nabla p + \rho \vec{f}$$

- Species balance

$$\frac{\partial (\rho X_i)}{\partial t} = -\nabla \cdot (\rho X_i \vec{v}) - \rho \omega_{X_i}, \qquad i = 1, \ldots, N$$

- Energy balance

$$\frac{\partial (\rho E)}{\partial t} = -\nabla \cdot (\rho E \vec{v}) - \nabla (p \vec{v}) + \rho \vec{v} \cdot \vec{f} + \rho S$$

Challenges

Extremely **wide range in scales** in

- Space
- Time
- Velocities
- Correct modeling of source terms

I. Stellar evolution modeling

(Sam Jones)

II. Stellar explosion modeling

(Fritz Röpke)

Supernova modeling

- Transonic regime → conventional codes for fluid dynamics apply
- Problem with spatial scales → resolve thermonuclear flames, shocks, NS ...
- Modeling of source terms and transport processes challenging

- Goals: complete description of explosion phase and connection to stellar evolution, remnants
- Determine role of supernovae in cosmic nucleosynthesis

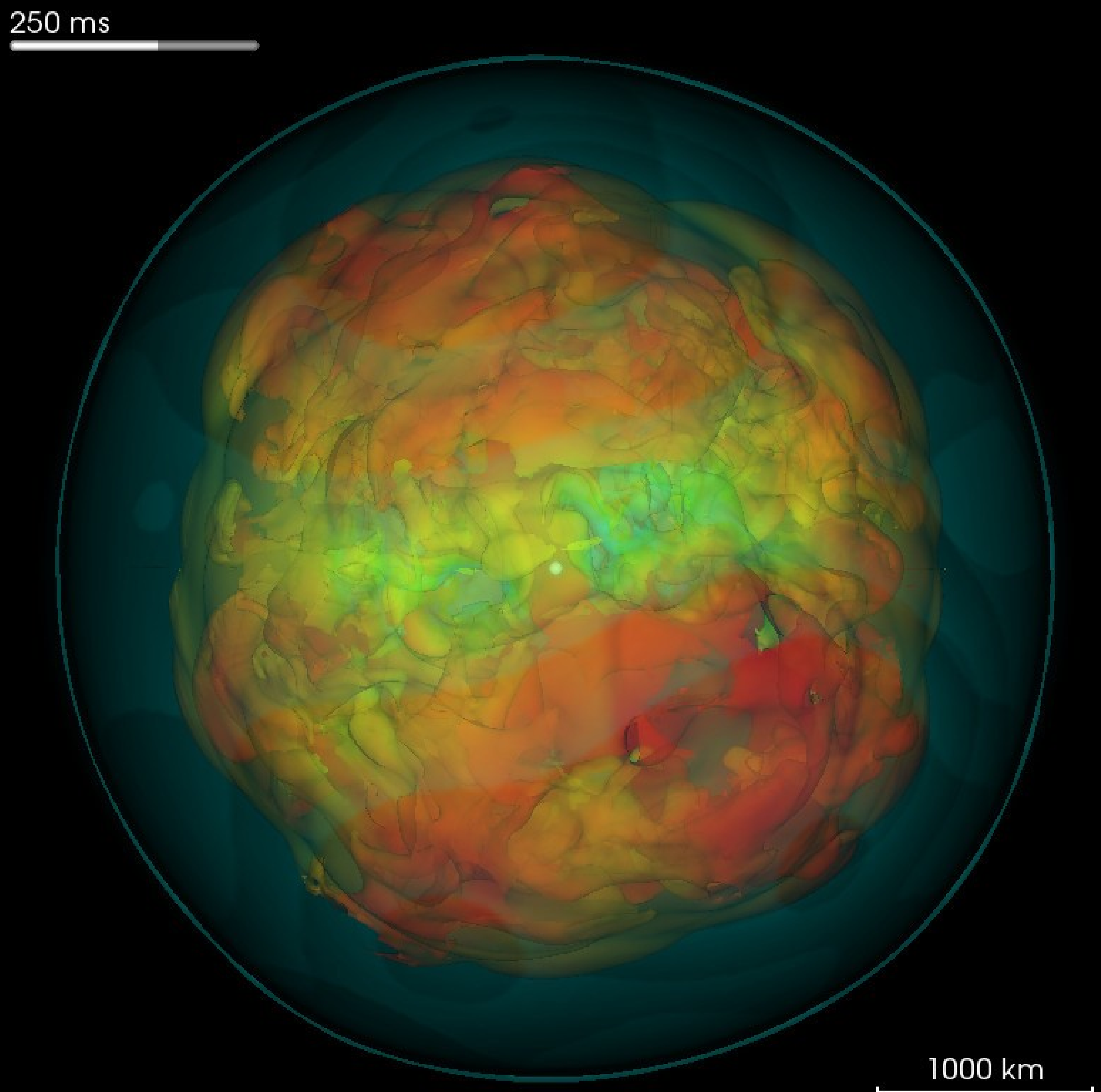
Challenges:

- details of explosion mechanism
- Initial conditions, i.e. progenitors

Core collapse supernovae

Main task for future research:

Establish explosion mechanism



MPA, Melson, Janka

Status:

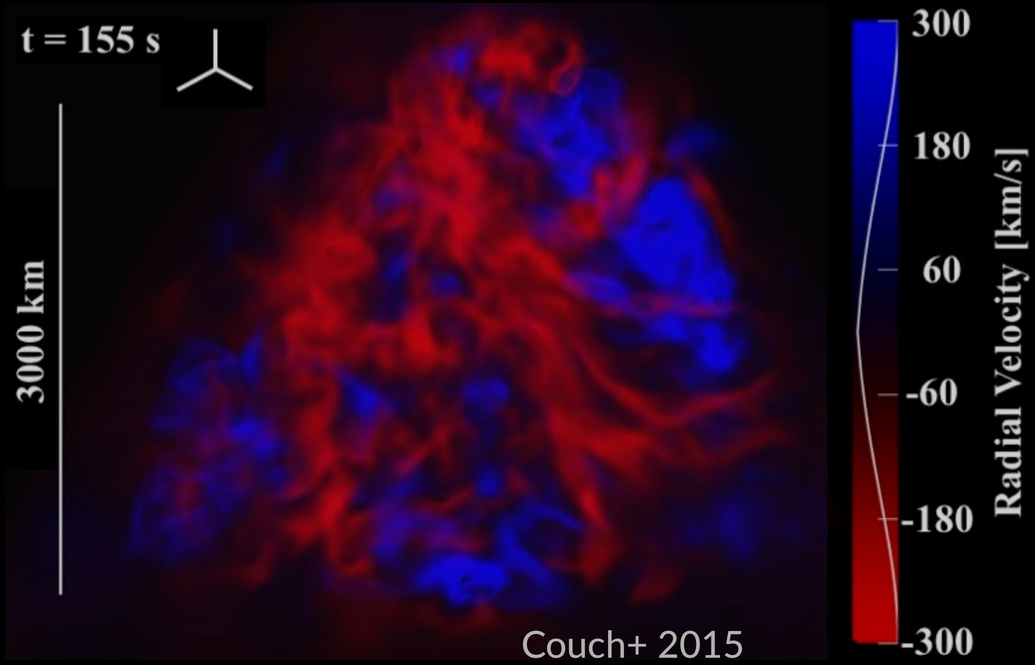
- Progenitors observationally established
- Explosion mechanism unclear
- Recent successes in extended 2D simulations, but problems in 3D (?)

Core collapse supernovae

Open questions:

Initial conditions:

- Realistic progenitor models
- Success of explosion depends sensitively on progenitor structure
- What is the impact of multi-D effects?
- How does the outcome (NS or BH) depend on progenitor structure?
- Compactness parameter?
- Stochastic?
- Does a 25 $M_\odot$ star explode as SN?

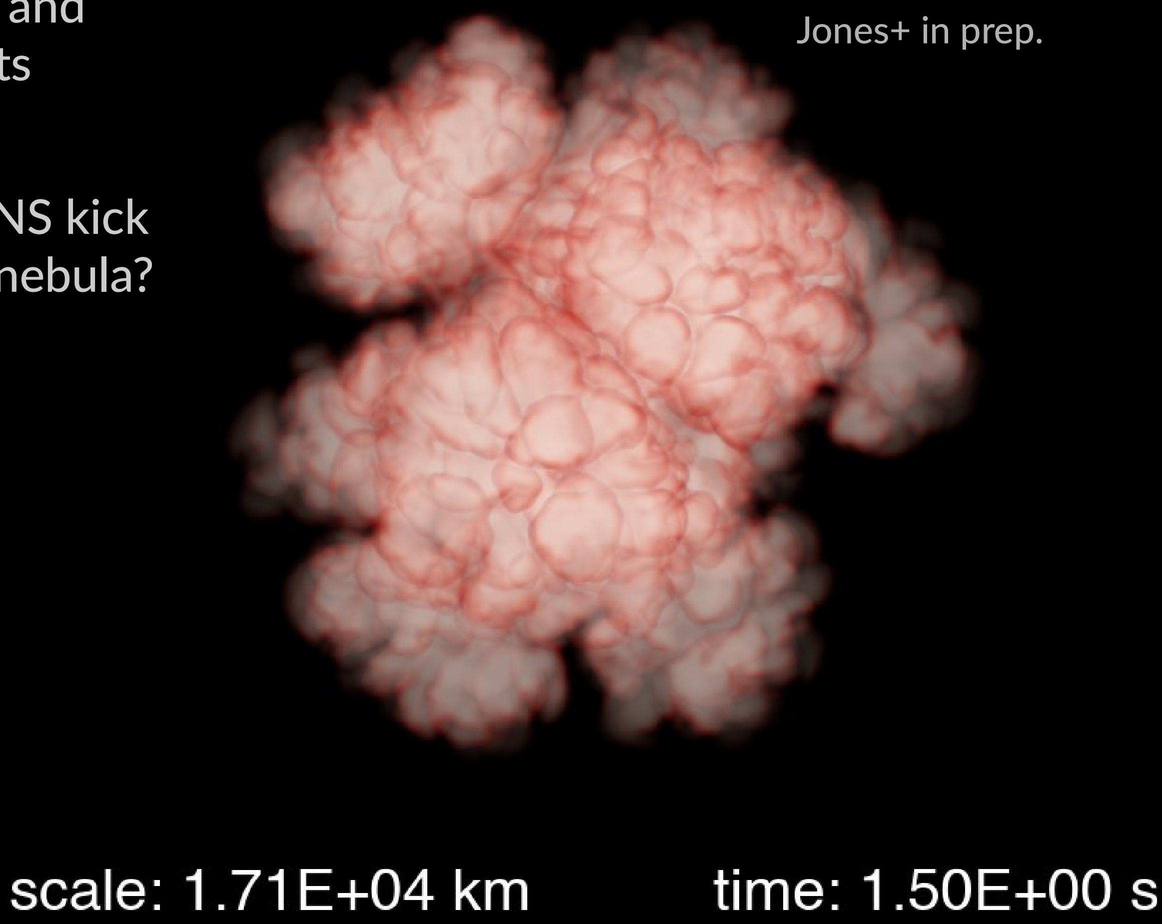


Core collapse supernovae

Open questions

Initial conditions:

- Do electron capture supernovae and accretion-induced collapse events exist?
- Do they explain double pulsars, NS kick velocities, weak r-process, Crab nebula?



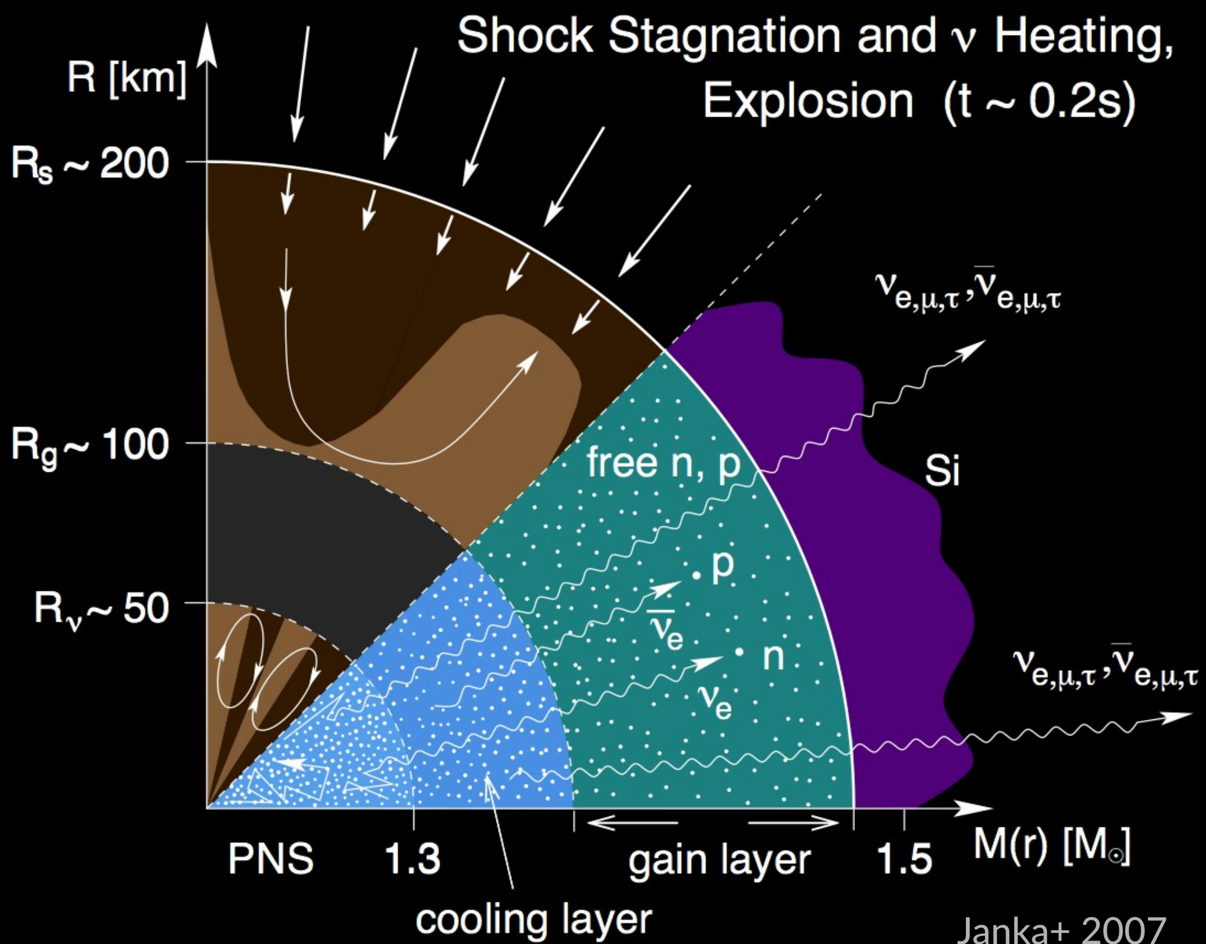
Jones+ in prep.

Core collapse supernovae

Open questions:

Explosion mechanism:

- Is neutrino-driven mechanism exhaustively studied?
- Is the neutrino-matter interaction modeled with sufficient accuracy?
- What role play multi-D effects and instabilities?



Janka+ 2007

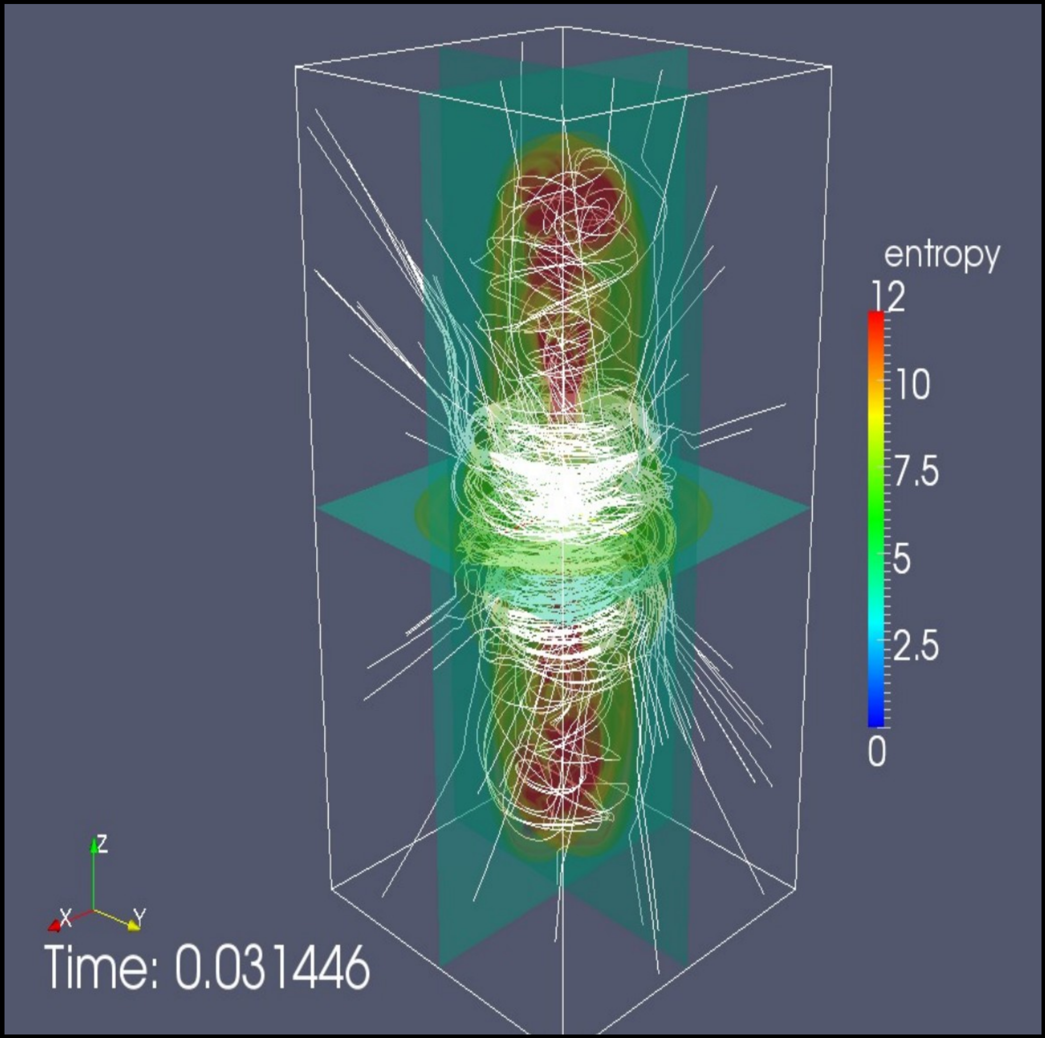
Core collapse supernovae

Open questions:

Additional input physics:

- Magnetic fields → how to form magnetars?
- EoS of neutron stars → see discussion of WG1
- Transport properties of NS matter → WG1

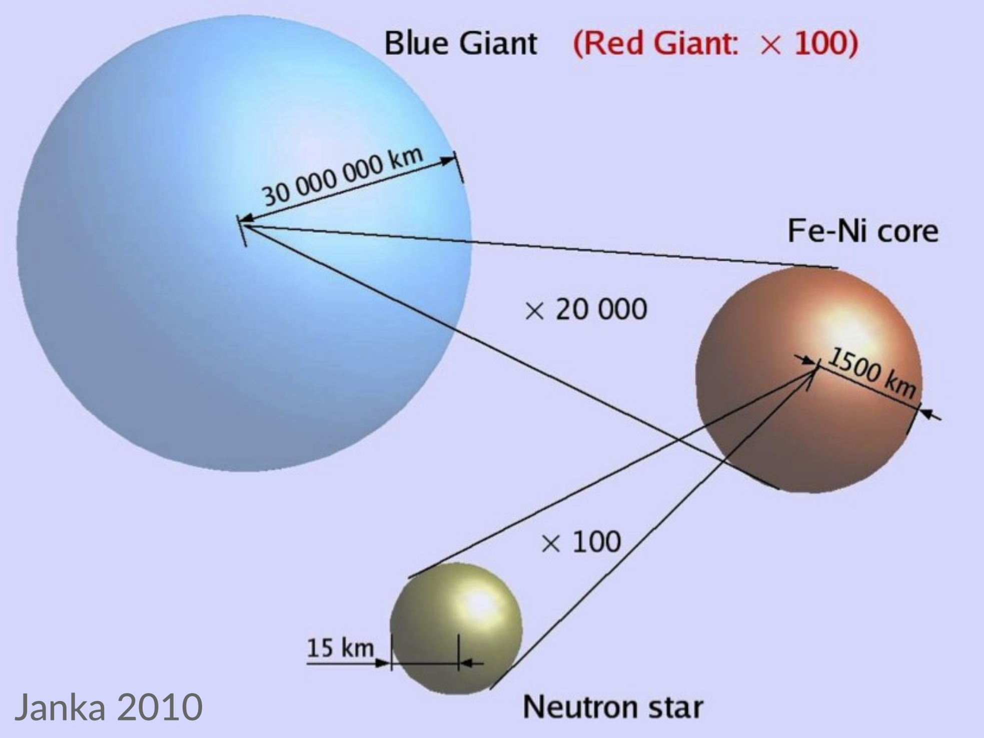
Winteler+ 2012



Core collapse supernovae

Challenges in numerical modeling:

- Computationally expensive in multi-D
- Scale problem:
  - Time scales in progenitor evolution
  - Spatial scales in explosion simulstions
- Problem of resolving the relevant processes

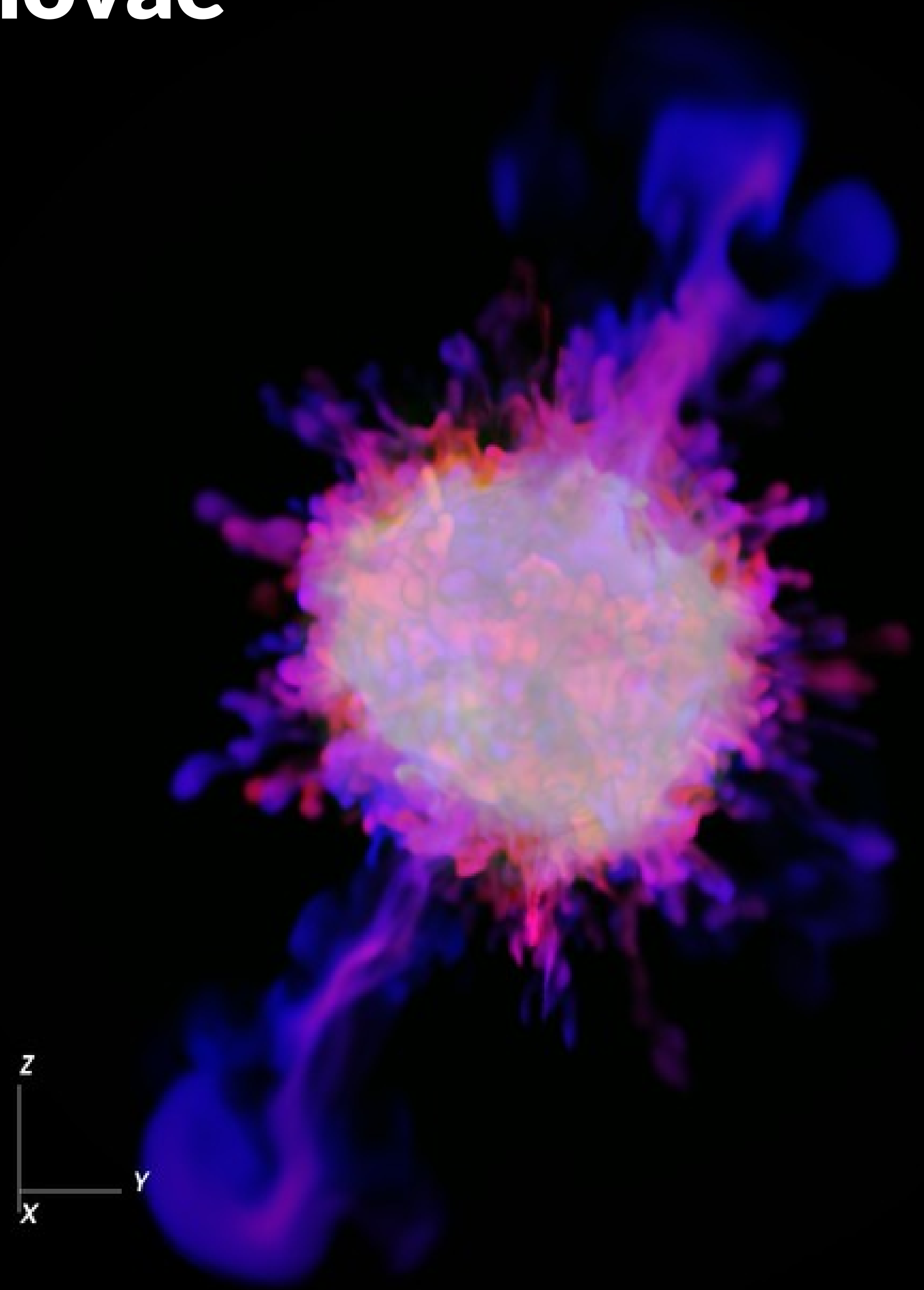


Janka 2010

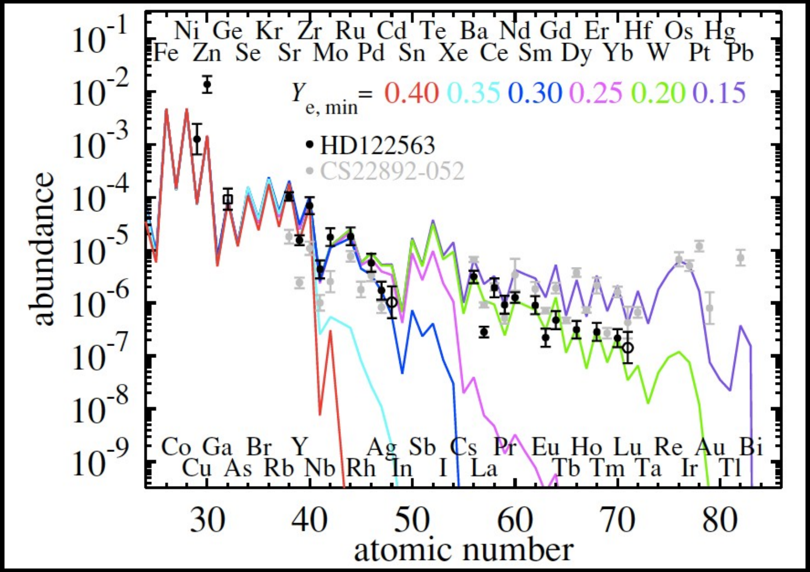
Core collapse supernovae

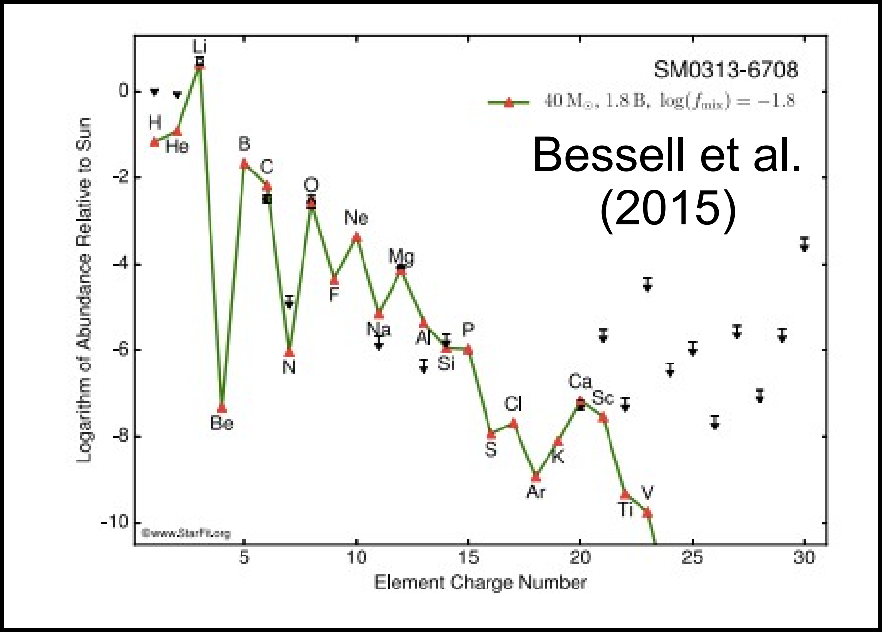
Goals:

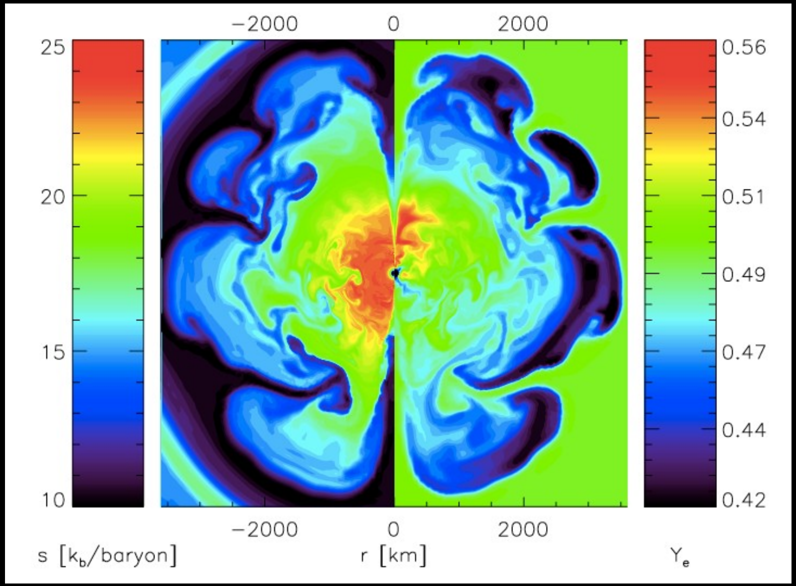
- Clarify their role in cosmic nucleosynthesis
- Predict and measure neutrino signals
- Predict and measure gravitational wave signals
- Derive predictions for optical observables from explosion models
- Establish link to remnant structure → What can we learn from spatial distribution of abundances in SNRs?
- Explain exotic objects: long GRBs, pair instability supernovae...



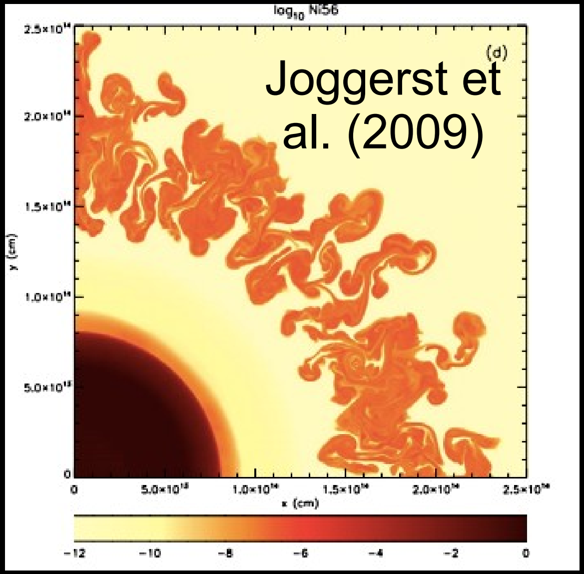
Different SN Nucleosynthesis Channels at Low Metallicity







Wanajo et al. (2011)

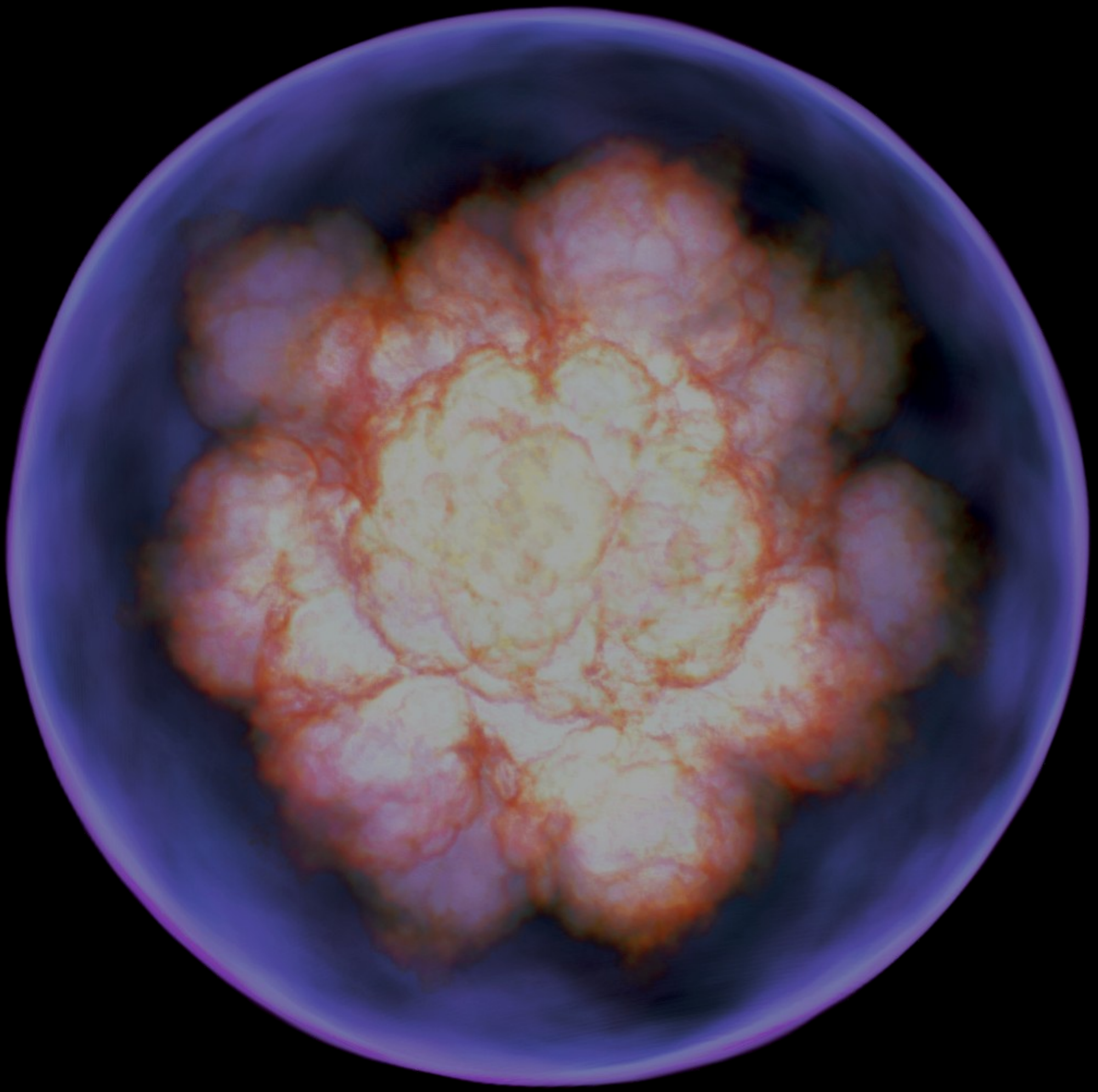


B. Müller

Thermonuclear supernovae

Status:

- Main problem: unknown nature of progenitor system(s)
- Different scenarios at work? → supported by diversity and newly observed astrophysical transients
- A number of explosion scenarios is relatively well explored
- Successful connection to observables
- Some detail of explosion mechanism remain unclear (e.g. triggering of combustion waves, deflagration-to-detonation transition)

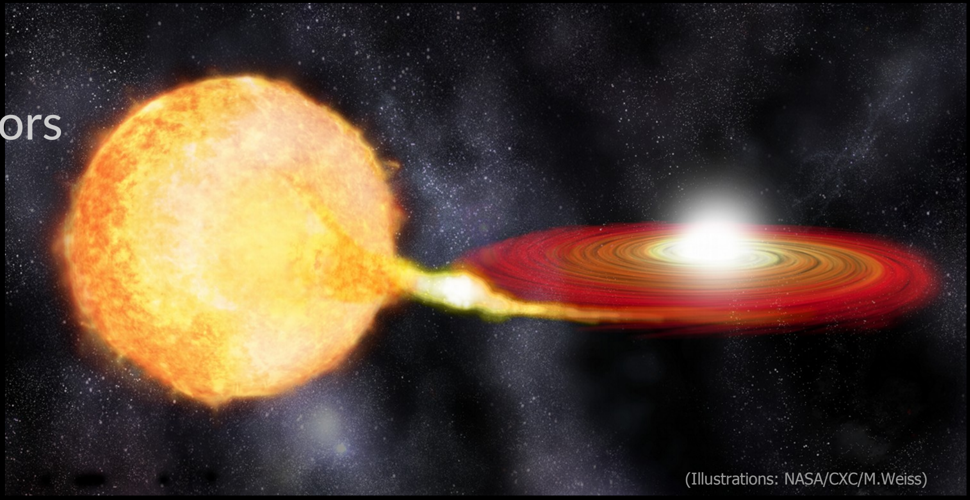


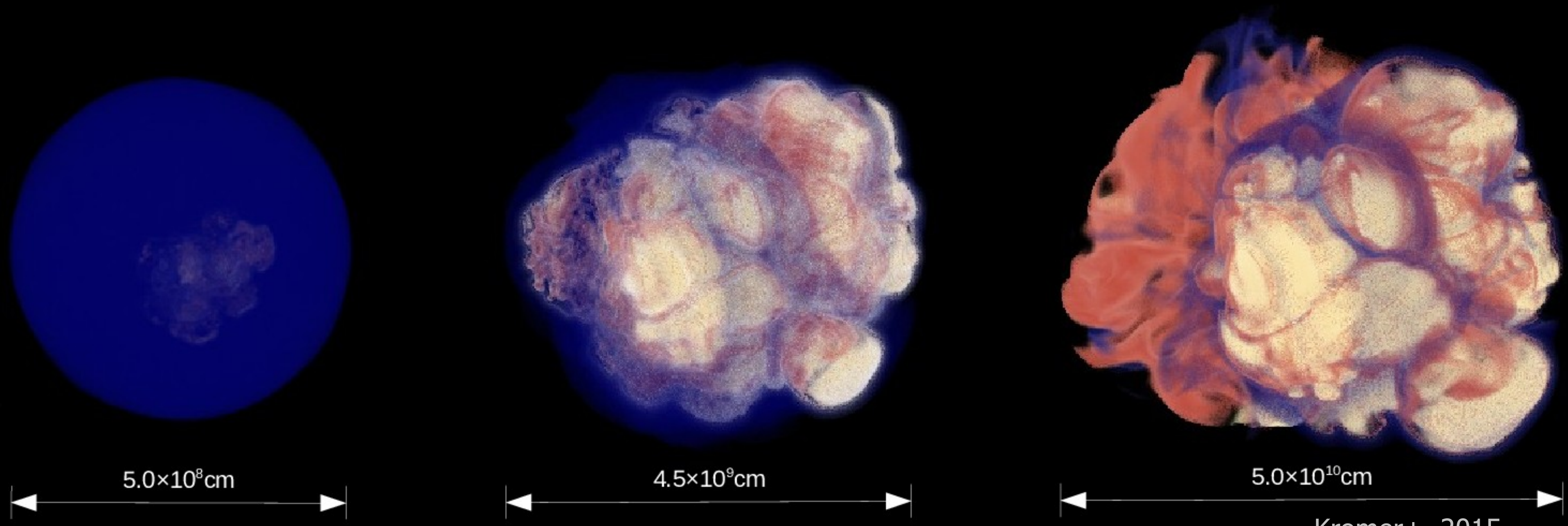
Thermonuclear supernovae

Open questions:

Chandrasekhar mass explosions and SD progenitors

- Do they exist
- Are they the dominant channel of Type Ia supernovae?
- Do they give rise to peculiar sub-classes?





Kromer+, 2015

Thermonuclear supernovae

Fink+, 2010

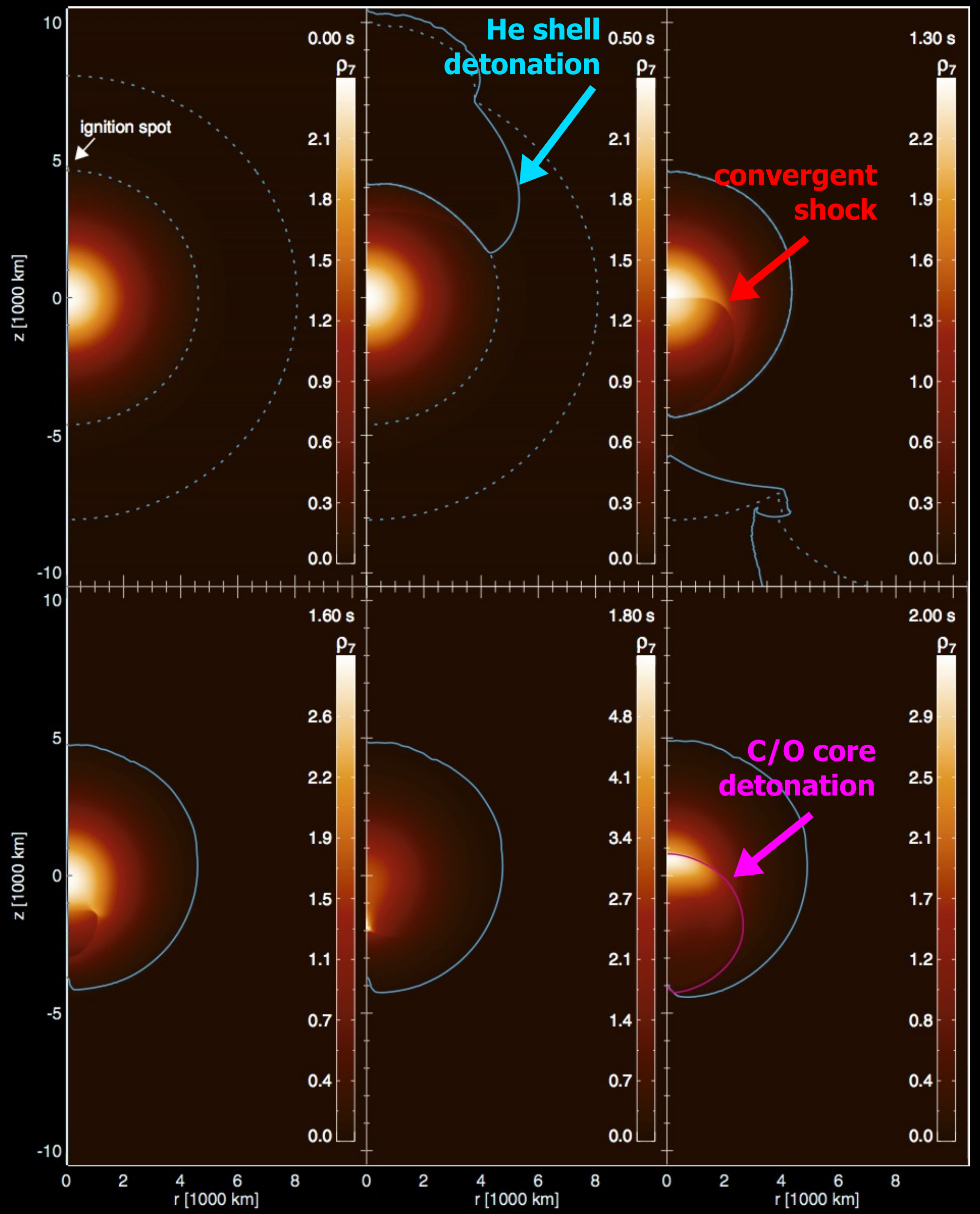
Open questions:

Sub-Chandrasekhar mass explosions:

- In priciple capable of reproducing normal SNe Ia (Sim+, 2010)

double detonations?

- Problem with He shell detonation products when triggered in hydrostatic equilibrium configuration

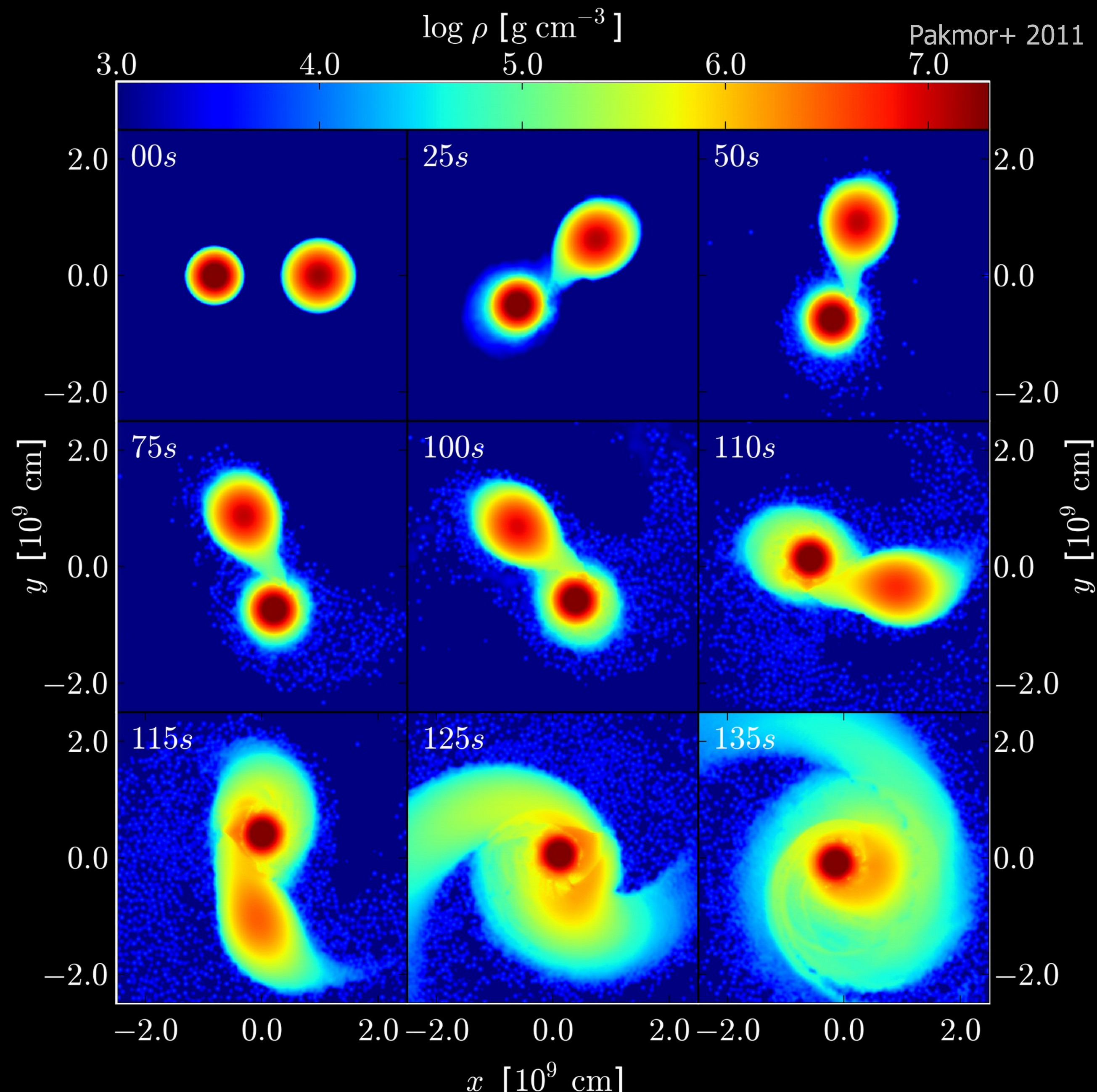


Thermonuclear supernovae

Open questions:

White dwarf mergers:

- Scenario looks very promising, but parameter space not fully explored
- Explosion triggering needs more study



Pakmor+ 2011

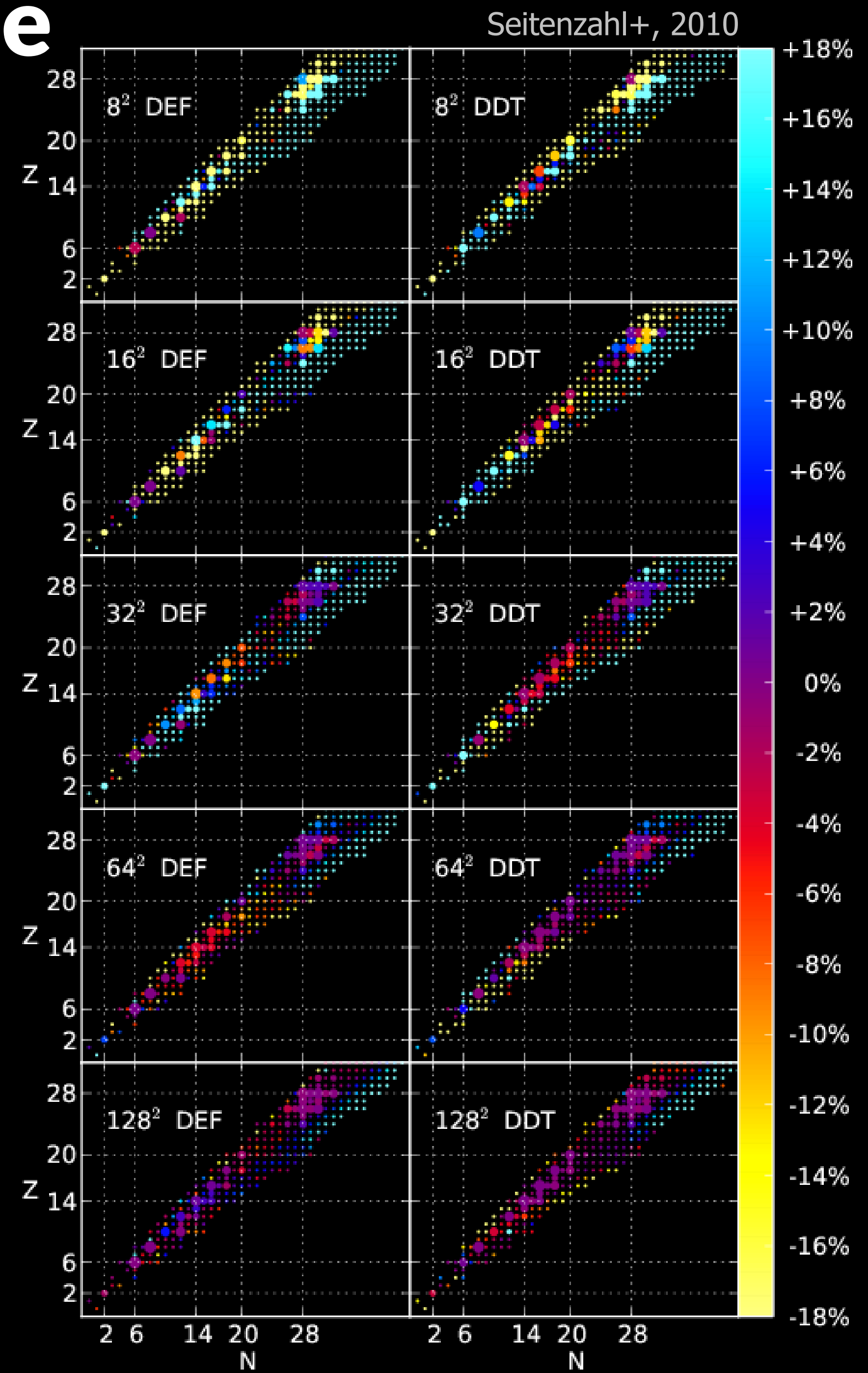
Thermonuclear supernovae

Modeling challenges:

- Explosion triggering
- Modeling unresolved combustion fronts
  → tracers sufficient?
- Nuclear processes and resulting observables

Observational challeges:

- Progenitors
- Gamma rays
- Late time light curves



KEY ROLE OF SNIA & SNII FOR GALACTIC CHEMICAL EVOLUTION OF *P*-NUCLEI

Travaglio C. **INAF Astrophysical Observatory Turin (Italy)**

Collaborators: Seitenzahl I. Roepke F. Heger A. Pignatari M. Bisterzo S.

WORK in progress

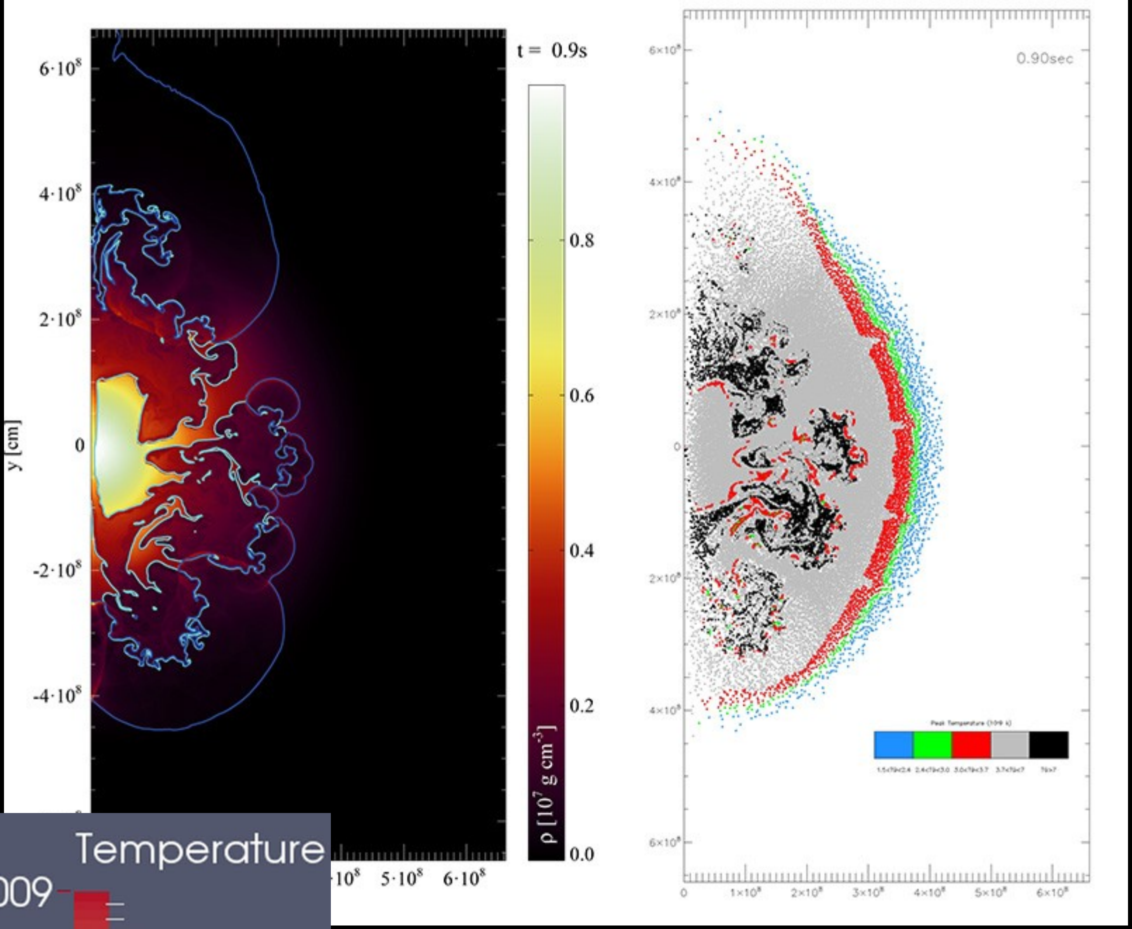
- SNIa: the role of γ-process in multi-D (comparison between 2D and 3D)

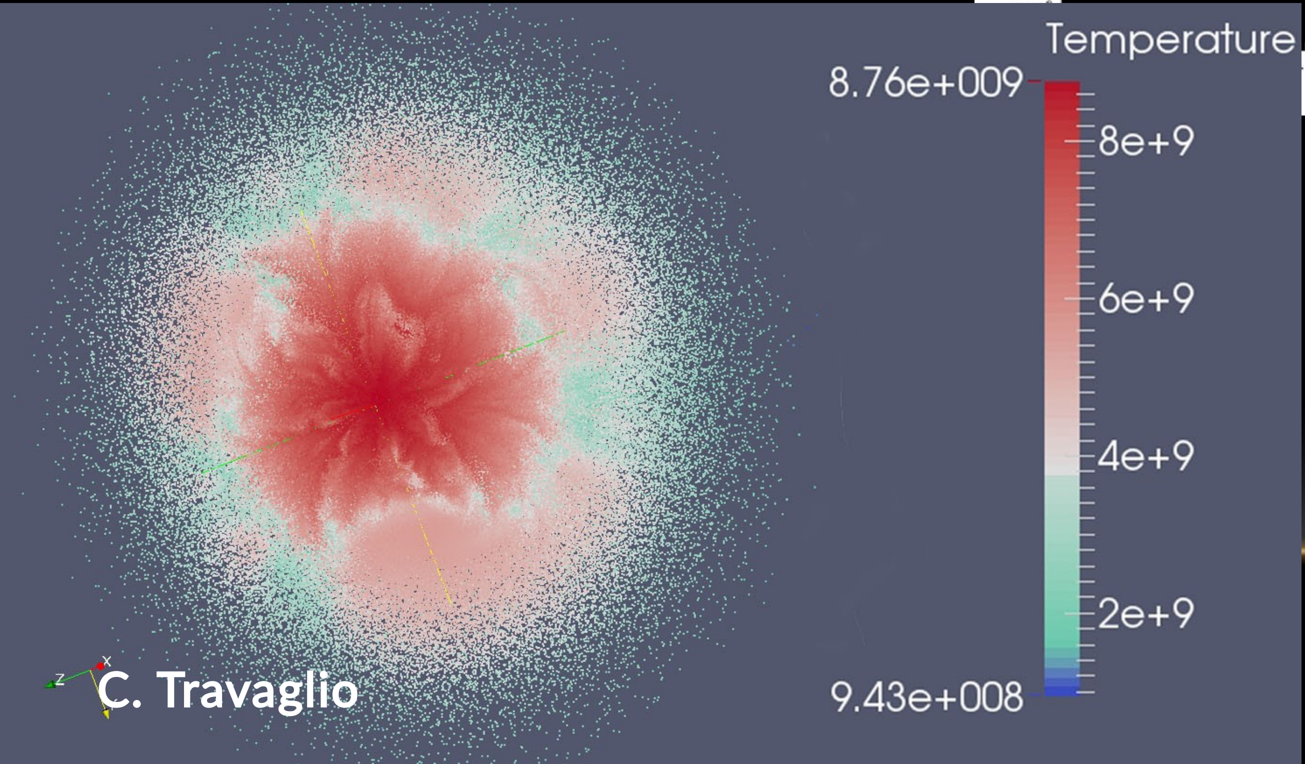
- SNII+ECSN: the role of γ-process and what is predicted by νp-process

- Interplay of different sources in galactic chemical evolution

2D model DDT-a, 51200 tracers

(Travaglio et al. 2011)





3D N100, 1 million tracers

(Seitenzahl et al. 2013)

Open problems, work in progress

- *A more detailed analysis of the role of* ***SNII*** *in GCE of p-nuclei:*
  - *grid of models at different Z with rotation*
  - *multi-D role in p-production*
    - *role of νp process in electron capture SNe*

- *To better understand the role of* ***SNIa*** *in GCE of p-nuclei:*
  - *more detailed analysis of 3D models*
  - *s-seeds composition*
  - *sub-Chadrasekhar and mergers as alternative contributors to explain the solar p-nuclei composition*
  - *Constraints from spectroscopic observations and meteorites measurements*

C. Travaglio

Observational constraints

❖ Spectroscopic observations:
no way to get isotopic composition.
Search for correlations
(Hansen et al. 2014)

❖Interstellar grains: CHILI
(THE CHICAGO INSTRUMENT FOR LASER IONIZATION)
is planning to measure p-isotopes
(ref. A. Davis)

III. Stellar merger modeling

(Andreas Bauswein)

IV. Galactic chemical evolution modeling

(Cristina Chiappini)