Numerical simulations of core-collapse supernovae

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Agence Nationale de la Recherche ANR

SN2NS
Supernovae explosions, from stellar core-collapse to neutron stars and black holes

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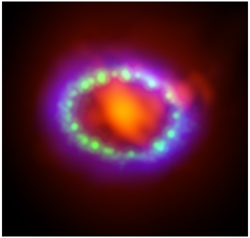
Plan

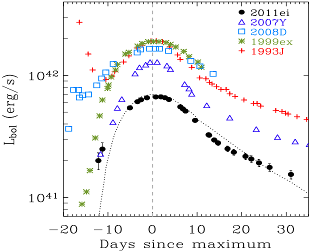
Core-collapse supernovae

Observations of "supernovae" reported since Antiquity (SN185) $\Rightarrow$explosions common
Categories, depending on the spectrum:

- Type I: no hydrogen. Ia: ionized silicon, Ib/Ic : strong/weak presence of helium.
- Type II: presence of hydrogen. IIP/IIL depending on the light curve shape, IIb: spectrum changing from II to Ib.



ALMA/Hubble/Chandra



Milisavljevic et al. 2013

Two kinds of theoretical models:

- Thermonuclear supernovae: explosion of a white dwarf (runaway nuclear reactions).
- Core-collapse supernovae: collapse-bounce-explosion of a massive main-sequence star.

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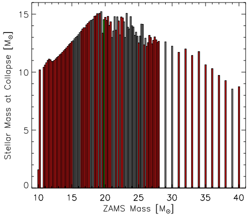
Open questions. . .

- Why / How do massive stars explode?
- What are the properties of the final compact object at the center?
- How / Where do heavy elements form?
- What are observable signals?
- What can we learn for fundamental physics?



Ugliano et al. 2012

Growing number of groups:

MPA Garching (H.-T. Janka), Princeton (A. Burrows), Oak Ridge (T. Mezzacappa), Univ. Basel (M. Liebendörfer), Tokyo (S. Yamada), NAOJ/Fukuoka (K. Kotake), Caltech (C. Ott), Los Alamos (C. Fryer), France (T. Foglizzo), Univ. Valencia (M.-A. Aloy), . . .

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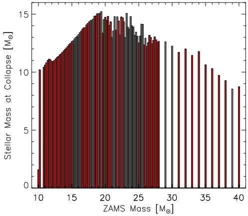

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Model description

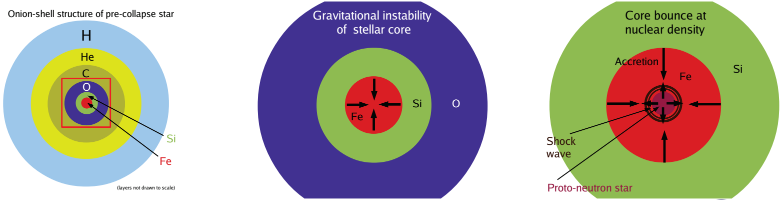
Collapse and bounce

Massive ($\gtrsim 10 M_\odot$) main-sequence star with onion-like structure:

- Iron core becomes unstable (electron degeneracy pressure)
- Collapse with electron captures on nuclei/free protons

$$p + e^- \rightarrow n + \nu_e$$

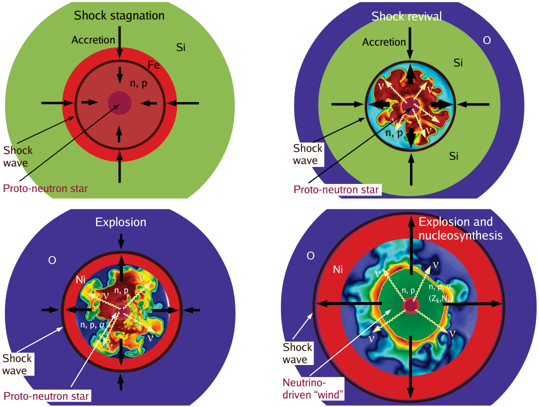
- Central density $\sim$ nuclear density $\Rightarrow$nuclear repulsion
- Shock wave expanding outwards. . .



Janka et al. 2012

Shock evolution

Shock stalls, due to energy loss by iron nuclei photodissociation

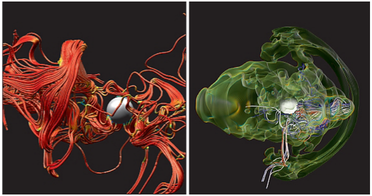


Janka et al. 2012

⇒there must be some mechanism to revive the shock: transfer energy from the gravitational well to the shock.

Physical ingredients

- Progenitor model
  ⇒evolution for massive stars
- Gravitation – hydrodynamics
  ⇒relativistic?
- Microphysics: equation of state for hot, dense matter, out of β-equilibrium : $p(\rho, T, Y_e)$
  ⇒very large range of densities, temperatures and asymmetry
- Microphysics: electron capture and neutrino reaction rates (opacities)
- Neutrino transport
  ⇒6+1 dimensions ?
- Magnetic field evolution
  ⇒resistivity?



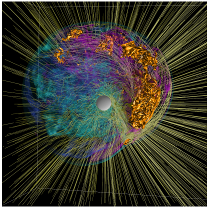
Endeve et al. 2009

Numerical challenges

Most of supernova core-collapse simulations run on HPC centers, with millions of CPU-hours used (sometimes) for a single run:
⇒need for exaflop?

PRACE/Curie

- Neutrino transport: ~ 100 points in each dimension $\rightarrow 10^{12}$ points ...
- Hydrodynamics: high-resolution shock-capturing methods need CPU and have poor convergence properties near the shock (unavoidable?)
- Some physical processes may need many hydro time scales to appear (e.g. SASI) ⇒millions of time-steps (implicit for νs)



Blondin & Mezzacappa 2007

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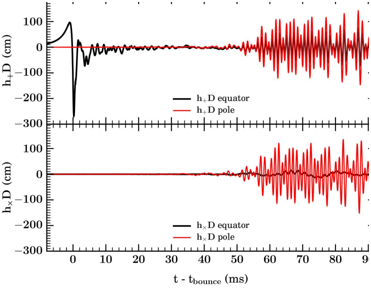
Gravitational waves

see also talk by M. Was

Core-collapse supernovae are good sources of GW, although not the best ones (talk by U. Sperhake) : too close to spherical symmetry!

3 phases of GW emission associated with current simulations:

- bounce,
- post-bounce convective instabilities,
- long-term instabilities (SASI-like)



Ott 2009

What can we learn from core-coolapse GW?

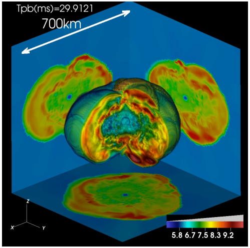
⇒multiple bounces?

⇒importance of convection?

⇒development/saturation of long-term instabilities. . .

What is missing?

Recent 2D/3D runs show at best weak explosions : the released energy is too small!



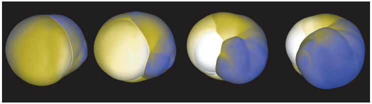
Kuroda et al. 2014

- Dimensionality: spherically symmetric simulation known not to succeed...
  2D: weak explosions ... 3D?
- Resolution: are all features resolved? (turbulence, instabilities) or simulated long enough?
- Neutrino transport: too much simplified?
- More physics: Relativistic gravity (and hydro)? Magnetic field (MRI) ? Progenitor models (rotation)?
- Microphysics: are reaction rates and EoS controlled?
- ...

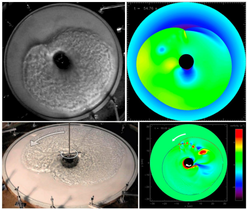
“Recent” developments

Analogue SASI

Standing Accretion Shock Instability: advective-acoustic cycle between the proto-neutron star surface and the stalled shock



Blondin & Mezzacappa 2007



Foglizzo et al. 2012

- Provides energy to the shock and helps neutrino heating
- Exhibited in the simplified adiabatic case (pure hydro)
- Analogy with shallow water 2D model, studied in laboratory with a simple experiment.

⇒very strong indication for the existence of SASI in supernovae: not numerical artifact

⇒study of growth, saturation and properties of the instability, much faster than with a code

⇒public outreach...

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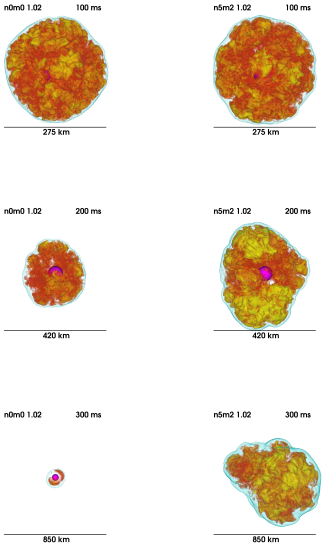
Progenitor dependence



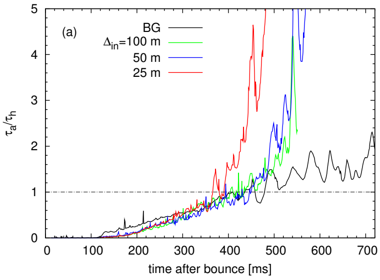
Couch & Ott 2013

Models for progenitors very sophisticated but not enough : rotation, magnetic field, stellar atmosphere, advanced nuclear burning stages...

- Possibility of asymmetries from nuclear burning : deviation from spherical symmetry
- Study of generic asymmetries
- Evidence of more energy transmitted to the shock
- Help in explosion?

Magnetic field

- Magnetic field is present in massive main-sequence stars
- By conservation of magnetic flux, can reach (usual) pulsar observed values . . . what about magnetars?



Sawai & Yamada 2014

Magneto-rotational instability (MRI) is very likely to appear during core-collapse : differential rotation, magnetic field are present

⇒Very poor knowledge on initial magnetic field and rotation profile

⇒Need for very high numerical resolution in global simulations

⇒What is the resistivity of matter at such densities and temperatures?

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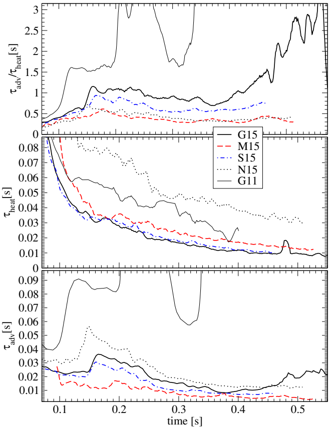
General relativity



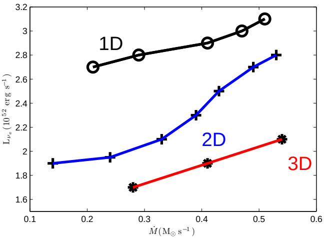
Mueller et al. 2012

- Relativity is needed both for gravity $\left(\frac{2GM}{Rc^2} \sim 0.1\right)$ and hydrodynamics $\left(\frac{v}{c} \sim 0.3\right)$
- But difficult to build a code: coupling of dimensions in hydro, many non-linear equations for gravity, nightmare for neutrinos…

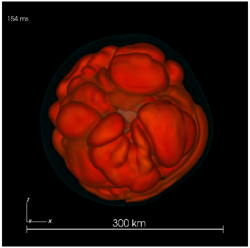
$\Rightarrow$Deepening of gravitational well: more energy available Vs. more difficulties for the shock to escape …

Unexpected : GR helps the shock !

3D simulations



Nordhaus et al. 2010



Hanke et al. 2013

Dimensionality can have great influence on the explosion mechanism:

- 1D (spherical symmetry) : no convective / turbulent motion
- 2D (axial symmetry) : inverse energy cascade for turbulence
- For neutrinos: exchange of energy in the radial directions

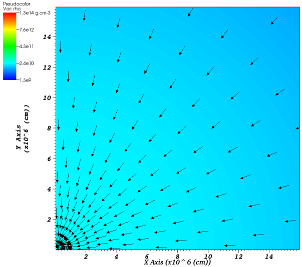
Debate on the necessity of full 3D simulations : does it help the shock to escape?

⇒Recent simulations in 3D / GR, with sophisticated neutrino transport do not show any such trend...

Microphysics

Input from the nuclear and particle physics communities:

- New equations of state, considering full nuclear statistical equilibrium distribution (e.g. Hempel & Schaffner-Bielich 2010)
- or additional particles, as hyperons (e.g. Oertel et al. 2012)
- New electron capture rates change the shock energy (Fantina et al. 2012)



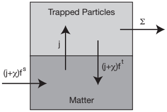
Peres et al. 2013

- Full nuclear distribution Vs. mean nucleus : not much effect $\Rightarrow$what about neutrino rates ?
- Phase transition to quarks or hyperons $\Rightarrow$second shock reviving the first? (Sagert et al. 2009) $\Rightarrow$Not expected in core-collapse to a neutron star; relevant for the collapse to a black hole?

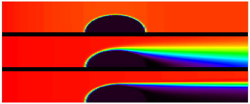
Neutrino transport

Neutrino transport uses a distribution function $f(t, x^i, p^i)$: almost impossible to solve without symmetry / approximation

- Leakage scheme (in GR: Sekiguchi 2010)
- Flux-limited diffusion (not relativistic, Bruenn et al. 1978)
- Momenta schemes + M1 closure relation (Gonzalez et al. 2007, possibly relativistic)
- Isotropic Diffusion Scheme Approximation (not relativistic, Liebendörfer et al. 2009)
- Spectral transport / ray-by-ray-plus (in GR: Müller et al. 2010)
- Full Boltzmann (in GR : Peres et al. 2014)



Liebendörfer et al. 2009



Gonzalez et al. 2007

Conclusions

- Rapidly evolving field: first 3D-GR runs, 3D-MHD approach, …
- Multi-disciplinary field: collaborations with nuclear/particle physics ⇒better microphysics
- Heavy numerical simulations, but also laboratory physics and/or analytic approaches on simplified problems
- Recent 3D simulations do not provide any definitive answer on the explosion mechanism (un)fortunately…

Possible answers:

- neutrino heating + SASI ?
- magnetic field (generic mechanism?)
- microphysics : ν-reaction rates, electron captures, …
- ??? (not neutrino oscillations)

But we see them explode! Do we need more computer power, or a better physical model?

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