# HP2C Project 'Stellar explosions'

UNI BASEL

## Productive 3D Models of Stellar Explosions

M. Liebendörfer, M. J. Gander
University of Basel, University of Geneva

- Accelerate supernova models by 3 orders of magnitude
- 3D models with spectral neutrino transport approximations

--> Unique and reliable parameter studies

(Starting with 25 3D models of Scheidegger et al., A&A 2010)

- Supernova explo-sion mechanism?
- SN visible in most astronomical windows
- Matter under extreme conditions
- Preparation for models of stellar atmospheres, accretion discs, mergers

# Supernova Observables

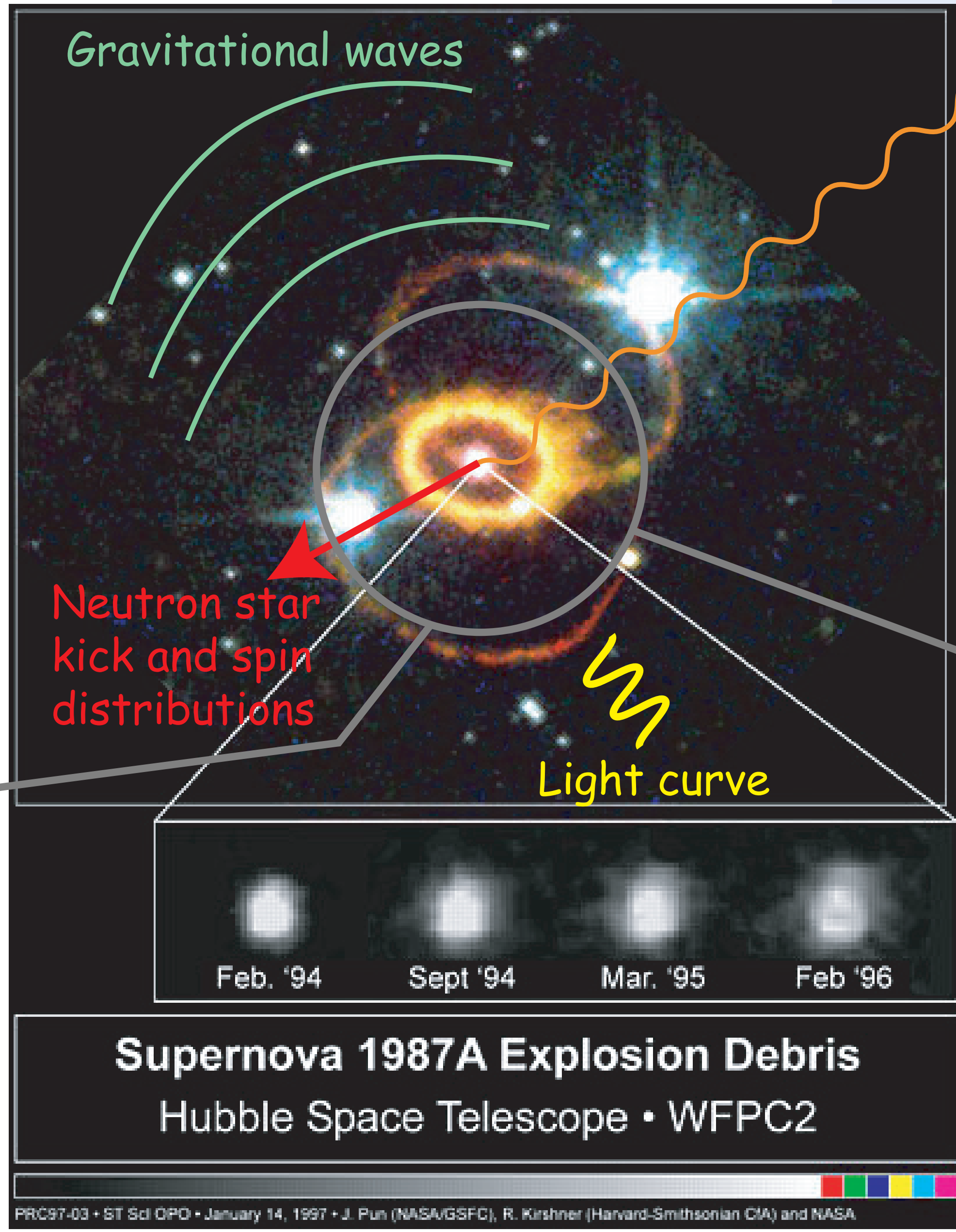
Huge energy scale:
1e+53 erg neutrinos
1e+48 erg elmag
1e+41 erg visible.

Energy from mass-defect by gravitational binding

(Baade, Zwicky, 1934)

Indirect observation of ejecta:

- contamination of metal-poor stars by SN ejecta.
- galactic evolution.
- solar abundance.




Immediate neutrino signal from innermost region.

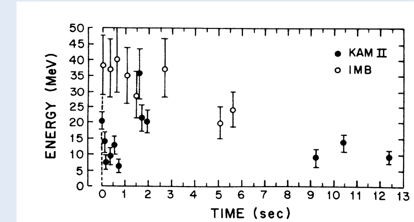



FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t = 0$.

Hirata et al. 1988

Direct observation of ejecta:

- elemental composition and velocity distribution from spectra.
- asymmetry from polarization.

# The Supernova Problem

1) ~~Prompt explosion mechanism, E(bounce)~~
(e.g. Baron et al. 1985)

2) Neutrino-driven explosion mechanism, E(therm.)
(Colgate 1966, … Marek & Janka 2007)

3) Magneto-rotational explosion mechanism, E(rot.)
(Bisnovatyi-Kogan 1976, Leblanc & Wilson 1979, ...)

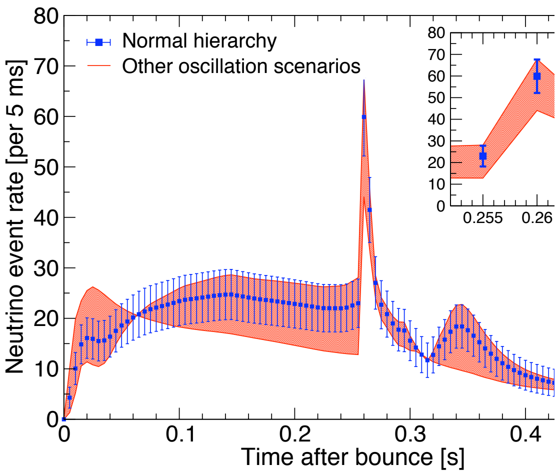
4) Acoustic explosion mechanism, E(osc.)
(Burrows et al. 2006)

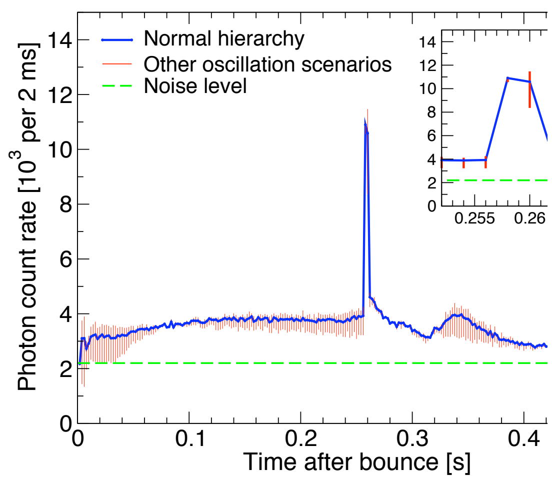
5) Magneto-sonic/viscous expl. mech., E(buoyancy)
(Akiyama et al. 2003, Thompson et al. 2003, Socrates et al. 2005)

6) Phase transition induced expl. mech., E(compact)
(Migdal et al. 1971, … Sagert et al. 2009)

- How does the collapse of single stars lead to explosions that outshine a galaxy?
- Which new physics is observable in the extreme conditions of matter during the explosion?
- Does the nucleosynthesis of heavy elements explain the abundances on Earth, the Sun and distant stars?

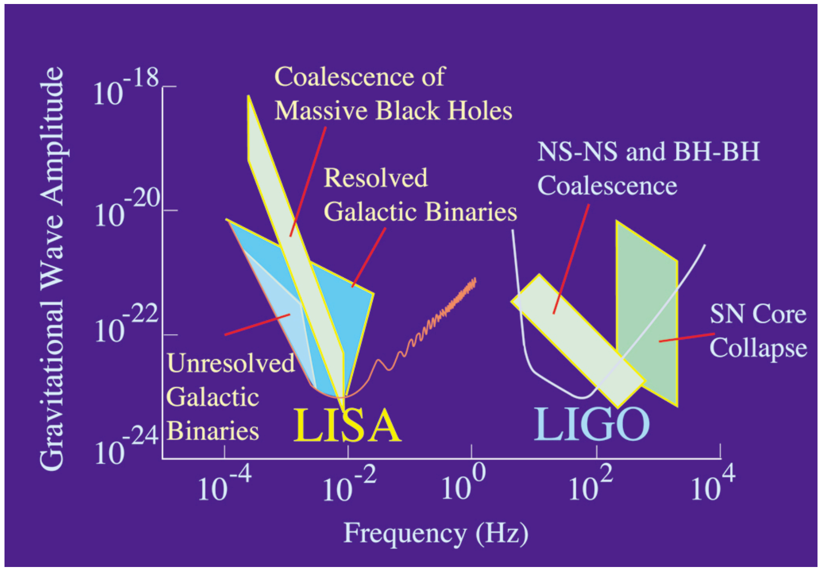
# SN as QCD/Nuclear physics laboratory

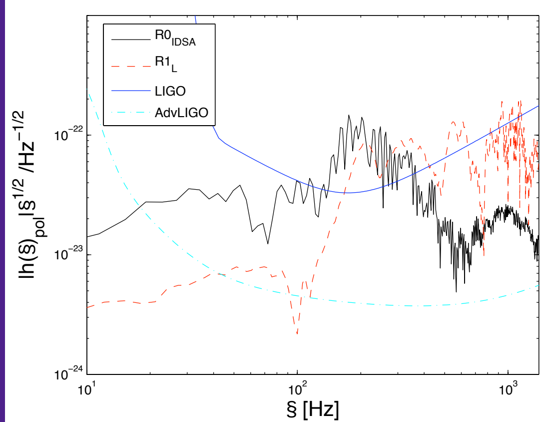



Neutrino signature from QCD phase transition in proto-neutron star

Sagert, Fischer et al. 2009,
Dasgupta et al. arXiv:0912.2568




Gravitational wave signal from 3D simulations with spectral ν-transport that simulate the T/|W|-Instability

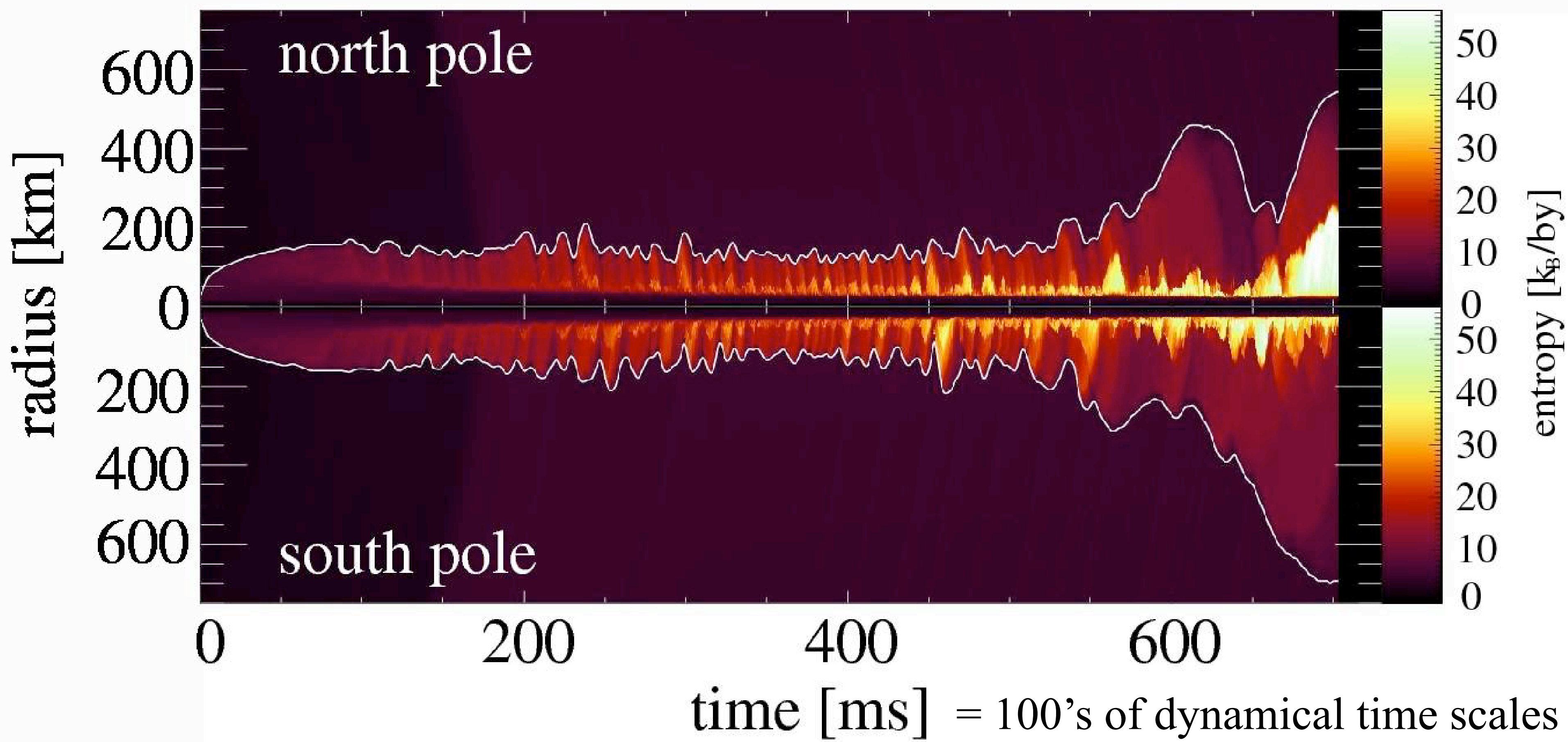
Scheidegger et al., CQG 2010 accepted, arXiv:0912.1455v2

# Numerical models in axisymmetry

- Standing Accretion Shock Instability (SASI) perturbs shock radius  Blondin, Mezzacappa 2003, Foglizzo et al. 2007
- Weak explosion after extended postbounce phase

Full problem only affordable for few selected runs
~6 months wallclock

Marek & Janka 2009

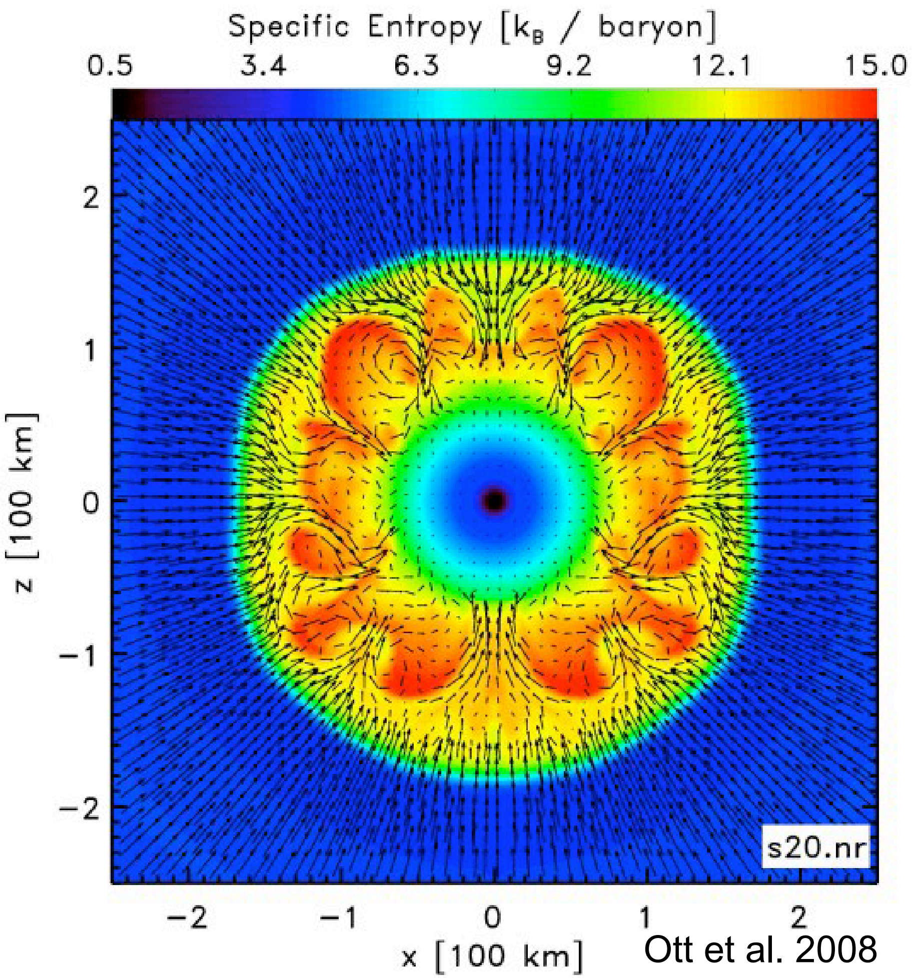



= 100's of dynamical time scales

# Convergence in 2D not yet demonstrated

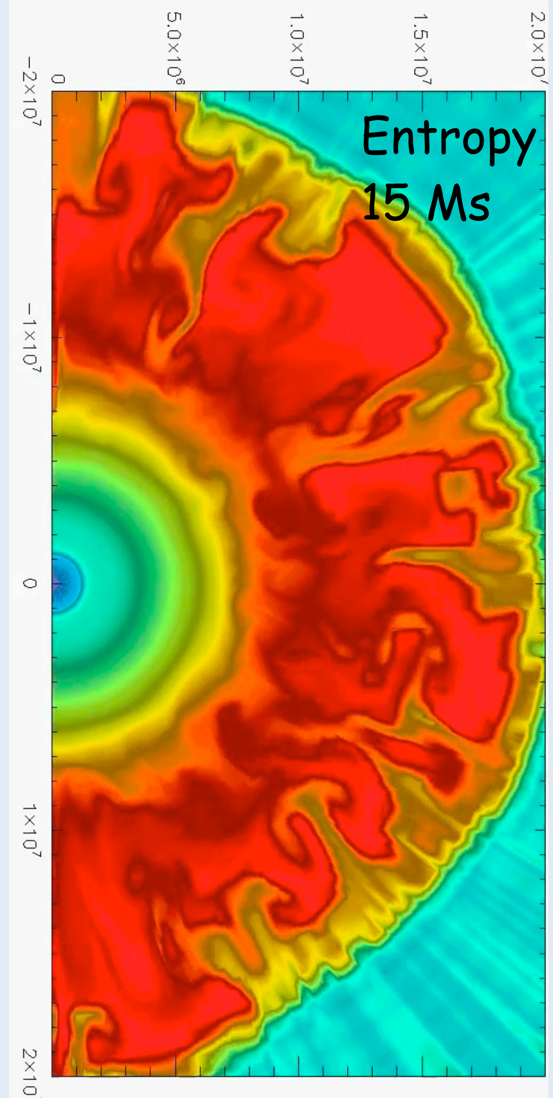
Explosion at 1200 ms by acoustic mechanism:

- unconfirmed by other groups — Burrows et al. 2006
- coupling to higher modes? — Weinberg & Quataert 2008




Ott et al. 2008

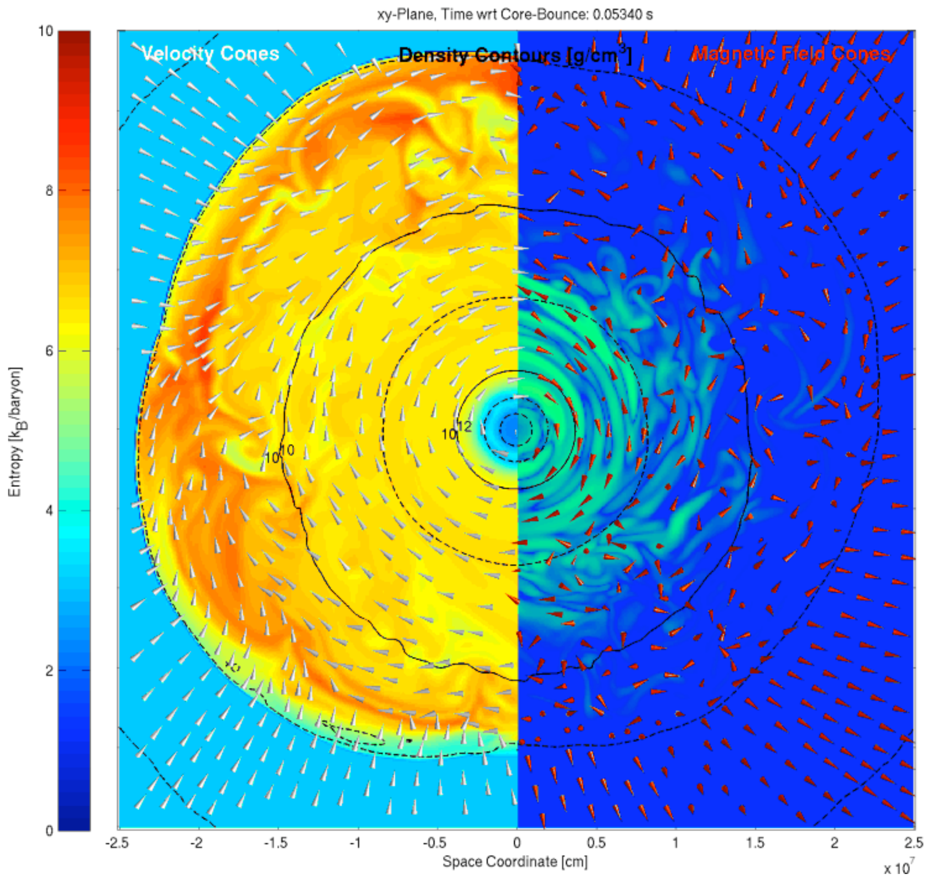
Entropy
at 160 ms
20 Ms



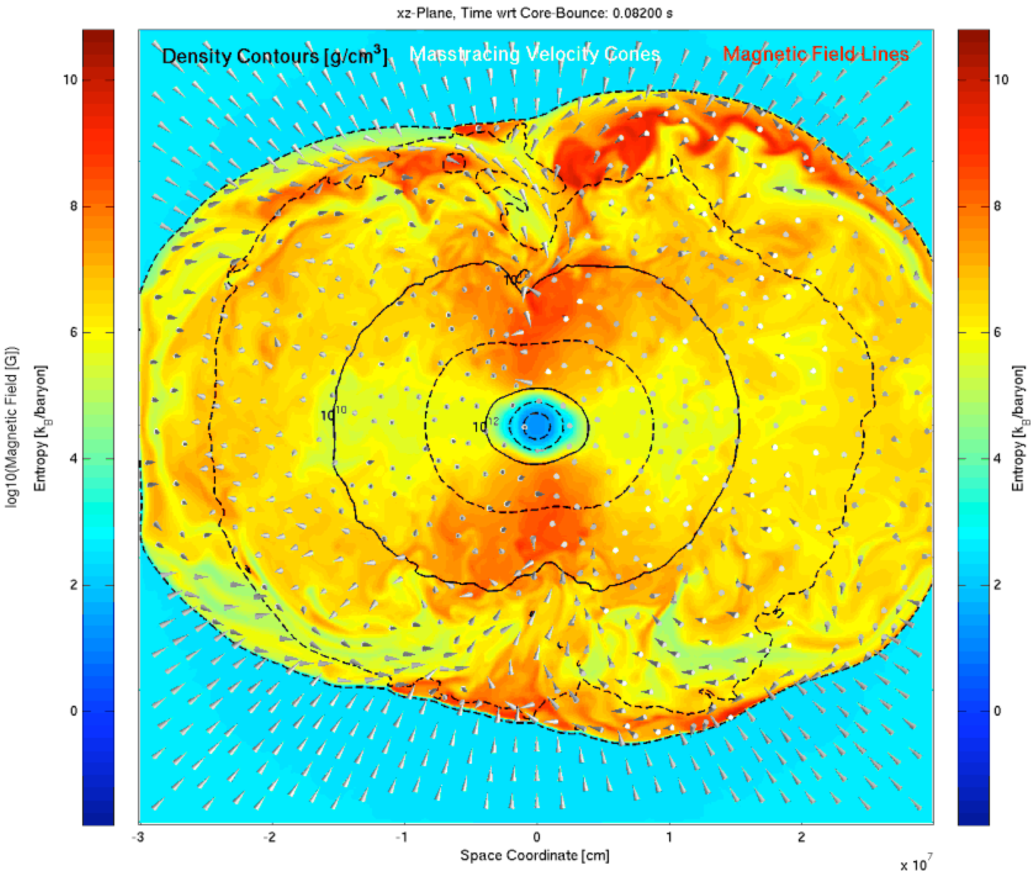

Explosion ~400ms?

Messer et al. 2008

# Basel: From Axisymmetry to 3D



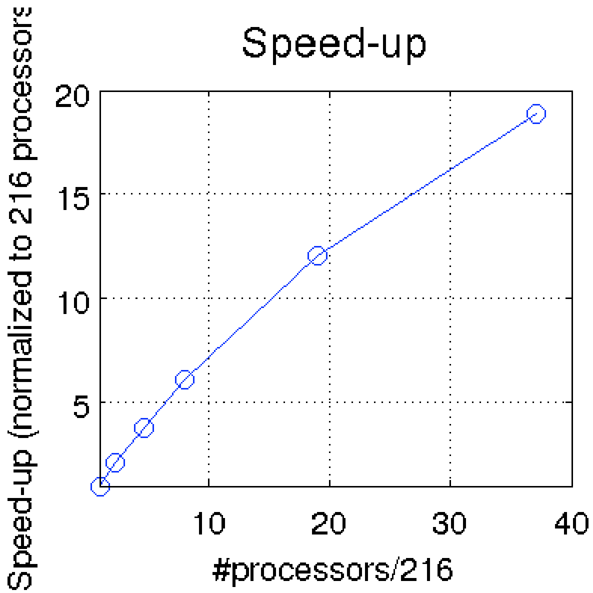

Liebendörfer et al. 2006




Scheidegger et al. 2009

- Convective turnover in 2D is restricted to toroidal shapes!
- Narrow downstreams and broad upflows cannot be modelled in 2D.
- Fluid instabilities and coupling to magnetic fields may behave differently in 3D.

# Parallelisation of 3D MHD code





- Production at Swiss National Supercomputing Centre CSCS

FISH code, Käppeli et al., arXiv:0910.2854

- 3D cubic domain decomposition (MPI)
- Directional operator-splitting
- Physical x-, y-, z-sweeps by data rotation
- Data consecutively loaded and stored into and from cache
- OpenMP applicable to parallelise sweeps on one node

# Neutrino transport approximations

| | Diffusive regime | Semi-transparent | Transparent regime |
|---|---|---|---|
| Boltzmann solver | Truncation errors in flux | | Inefficient ang. resol. |
| Flux-limited diffusion | | Flux-factor estimated | Flux-factor unknown |
| Ray-tracing | Short mean free path | Limited by reaction rates | |

"The more initial conditions, input parameters and model variations can be evaluated in a given time frame the larger is the rate of scientific insight and the easier it is to identify and amend possible problems with the model."

Parameterised $\nu$ physics in collapse phase

(Liebendörfer, ApJ, 2005)

Isotropic Diffusion Source Approximation

in postbounce phase

(Liebendörfer et al., ApJ, 2009)

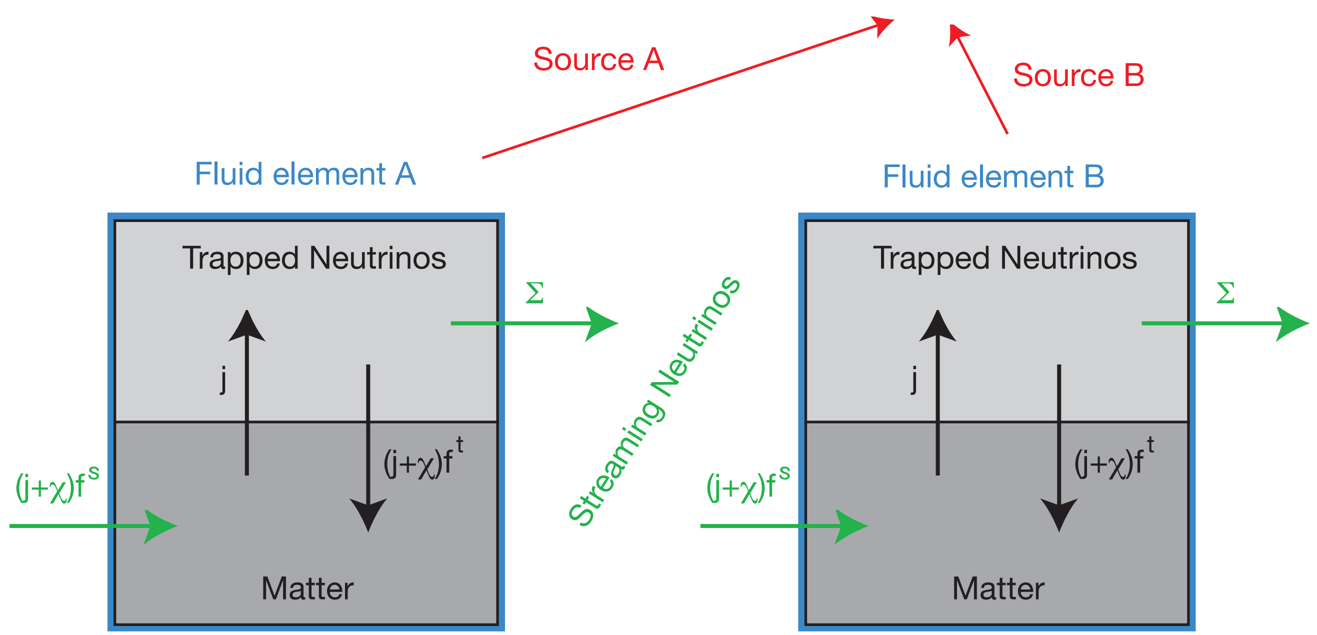
# Spectral neutrino transport after bounce

$D(f) = j - \chi^* f$
$f = f(\text{trapped}) + f(\text{streaming}) = ft + fs$

$D(ft) = j - \chi^* ft - \Sigma \quad (1)$
$D(fs) = - \chi^* fs + \Sigma \quad (2)$

Different approx. for trapped & streaming neutrino components!

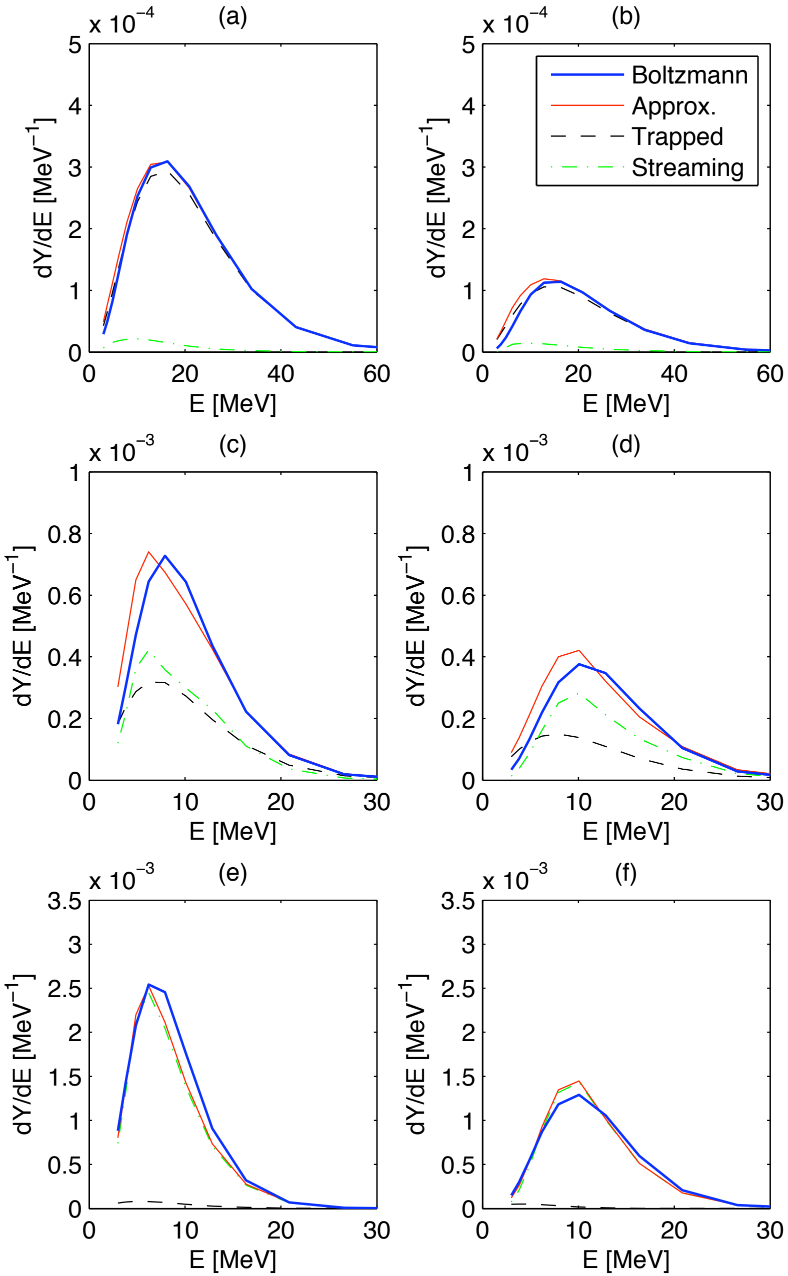
$\Sigma$ determined by diffusion limit of (1)
Stationary state approx. for (2) --> Poisson Eq.




Crucial CPU time-intensive solvers:

- local reaction network
- advection-diffusion problem
- 20+1 Poisson solves per step
- Geometrical analysis of neutrino-spheres

# Comparison of IDSA Spectra




at 40 km radius
(trapped regime)

at 80 km radius
(semi-transparent)

at 160 km radius
(free streaming)

Tokyo: complete implementation
(Suwa et al., arXiv:0912.1157)

Caltech: partial implementation
(Ott, CQG, 2009)

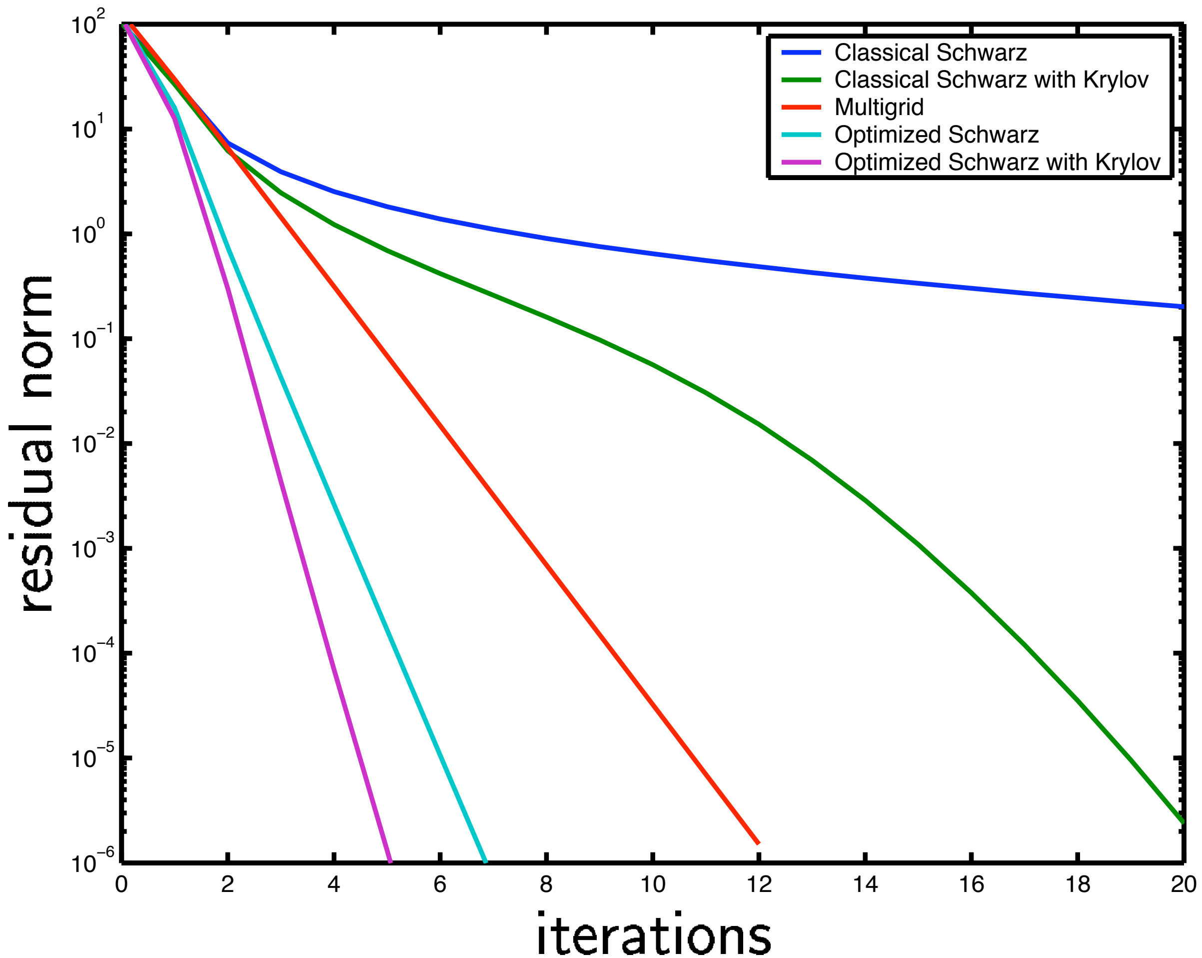
Oak Ridge: partial implementation
(Endeve et al., JPhCS, 2008)

ITEP Moscow: evaluation

Meudon/Paris: evaluation

# Comparison of Optimized Schwarz with Multigrid

Comparison of MS as an iterative solver, as a preconditioner, multigrid, and an optimized Schwarz methods used iteratively and as a preconditioner:



# Project Tasks

A) FISH (Fast and Simple Ideal magneto-Hydrodynamics) Refactor FISH, implement mesh refinement, release public domain version.

B) ELEPHANT (ELEgant Parallel Hydrodynamics with Approximate Neutrino Transport): Develop and implement parallel algorithms for diffusion-advection problems, evaluate ROCK and other semi-implicit methods. Refactor ELEPHANT in the end.

C) Parallel Poisson solver, compare Multi-Grid and optimised Schwarz methods. Implement for modern computer architecture.

D) In-situ data processing and visualisation, I/O optimisation, implement multi-dimensional ray-tracing for free streaming regime.

Modular approach:

- part of code always in production mode
- refactoring solver by solver using standard interfaces
- individ. distribution --> open source

# Project Team (very preliminary)

Basel (Support Physics):
Prof. M. Liebendärfer (SNF)
Dr. T. Fischer & successor (SNF)
Dr. NN (HP2C)
NN (HP2C)
R. Käppeli (SNF)
A. Perego (University)
S. Scheidegger (SNF)

Geneva (Support Algorithms):
Prof. M. J. Gander (University)
Dr. NN (HP2C)
Jerome Michaud (HP2C)

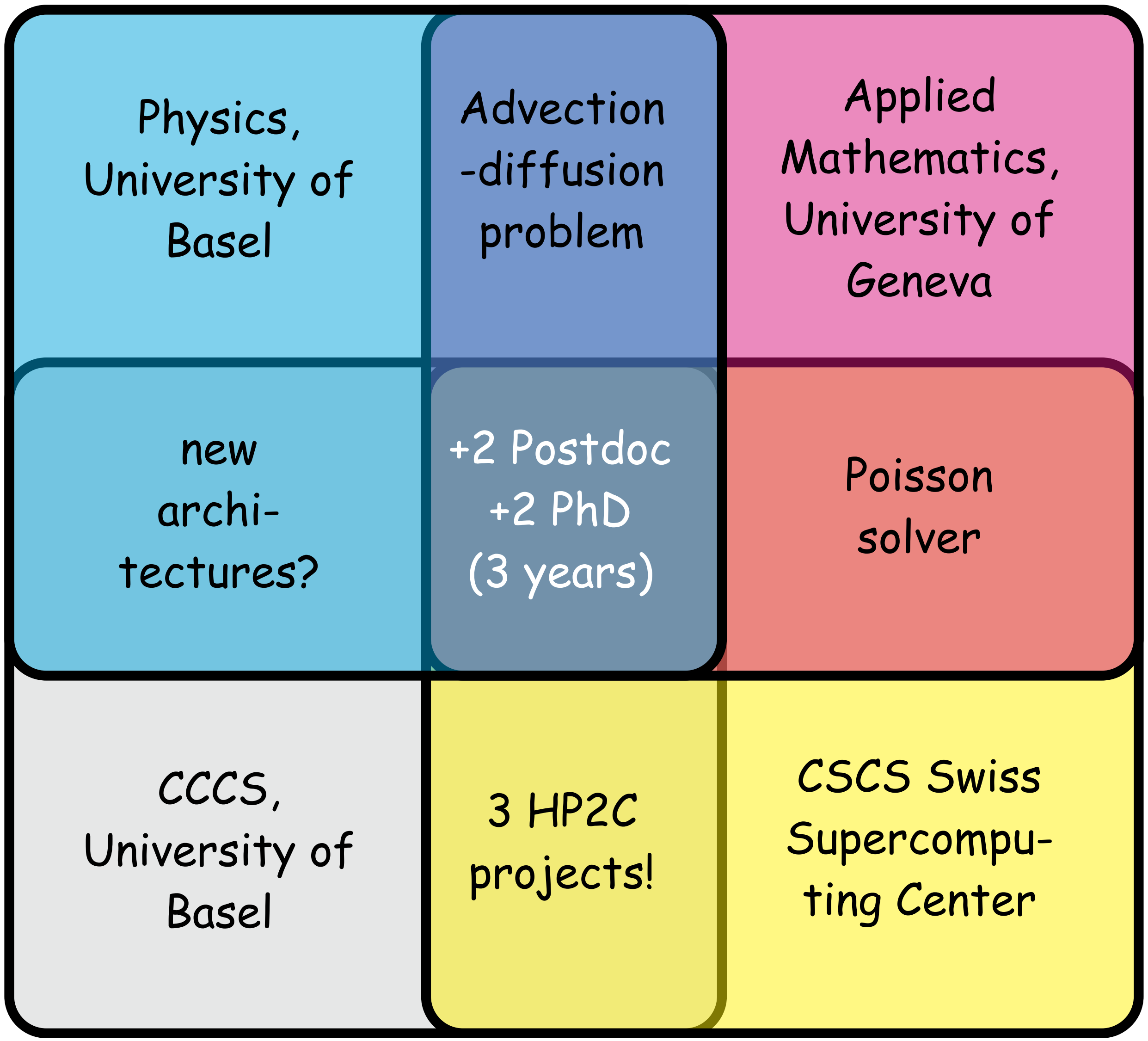
CSCS/USI (Support Hardware & Viz.)
...

Postdoc positions advertised at www.aas.org:

- Interviews of four candidates (computational physicists) underway

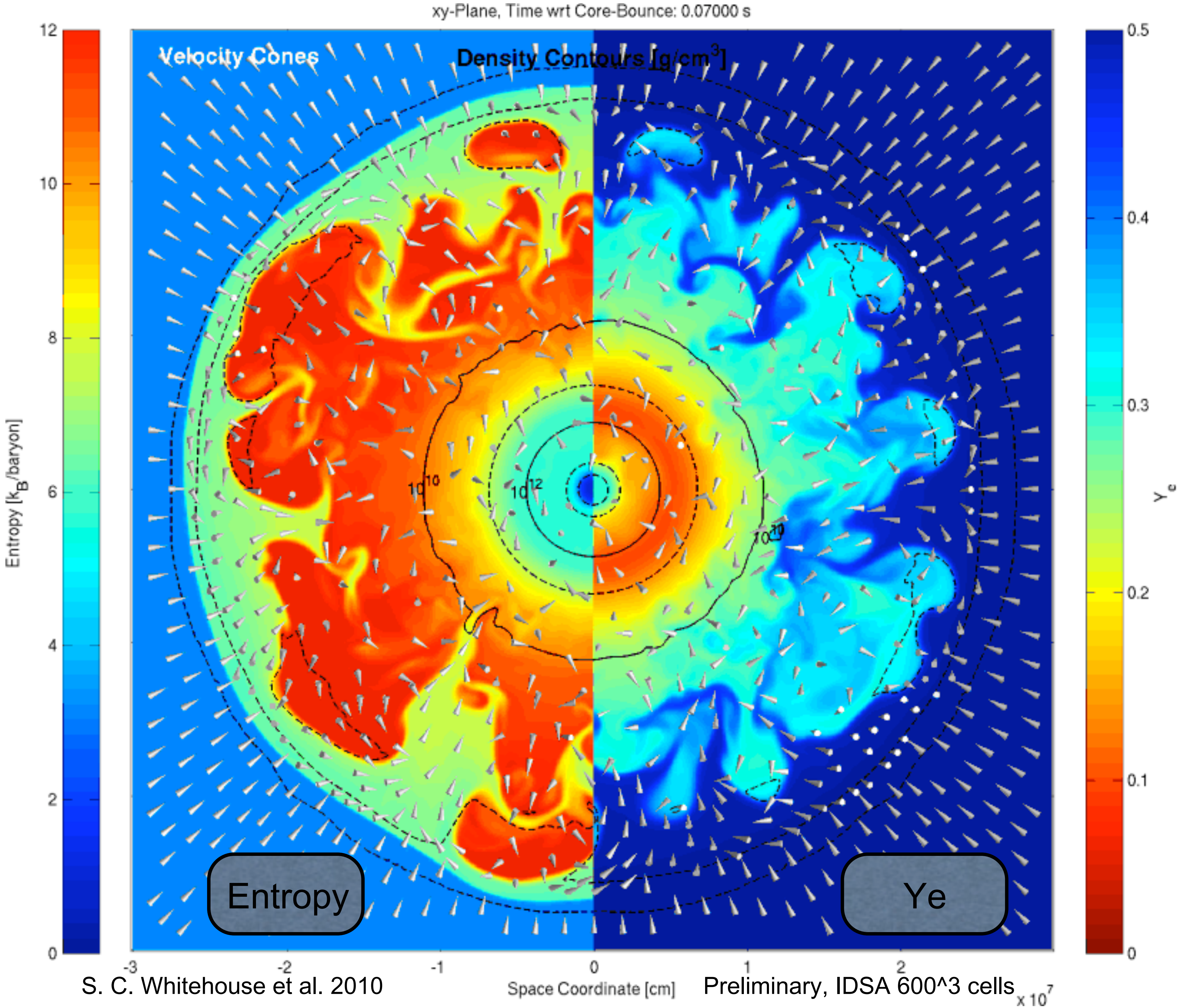
- PhD position in Basel not advertised, still open, applications are welcome (numerical focus)

# Stellar explosions: Project resources




Two phases:

- 1.1.2010-31.8.2011 Refactoring of FISH, developing physics and ν algorithms for ELEPHANT
- 1.9.2011-31.12.2012 Refactoring ELEPHANT for extensive 3D parameter studies




S. C. Whitehouse et al. 2010

Preliminary, IDSA 600^3 cells