Max-Planck-Institut für Astrophysik

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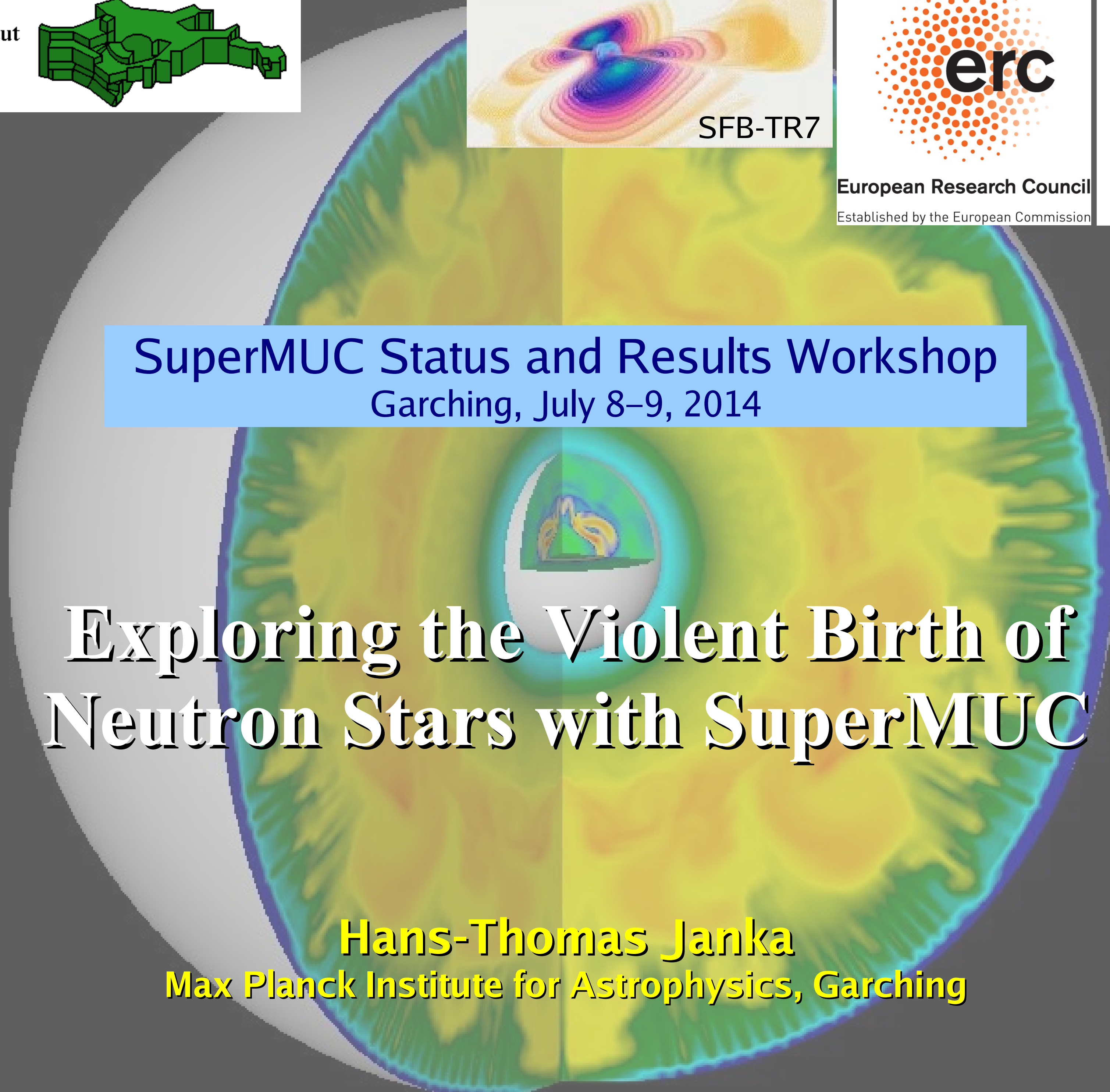
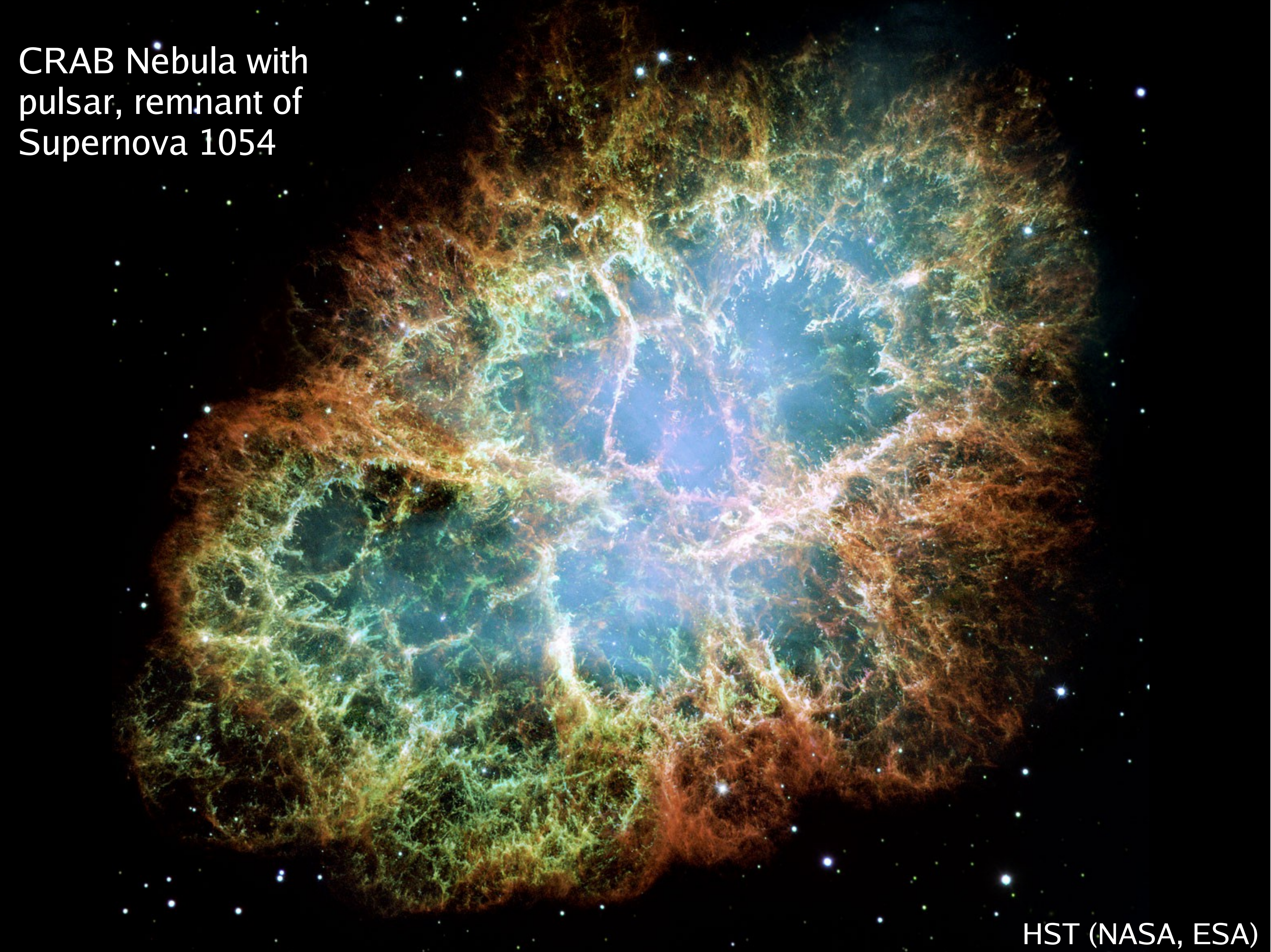
Excellence Cluster Universe

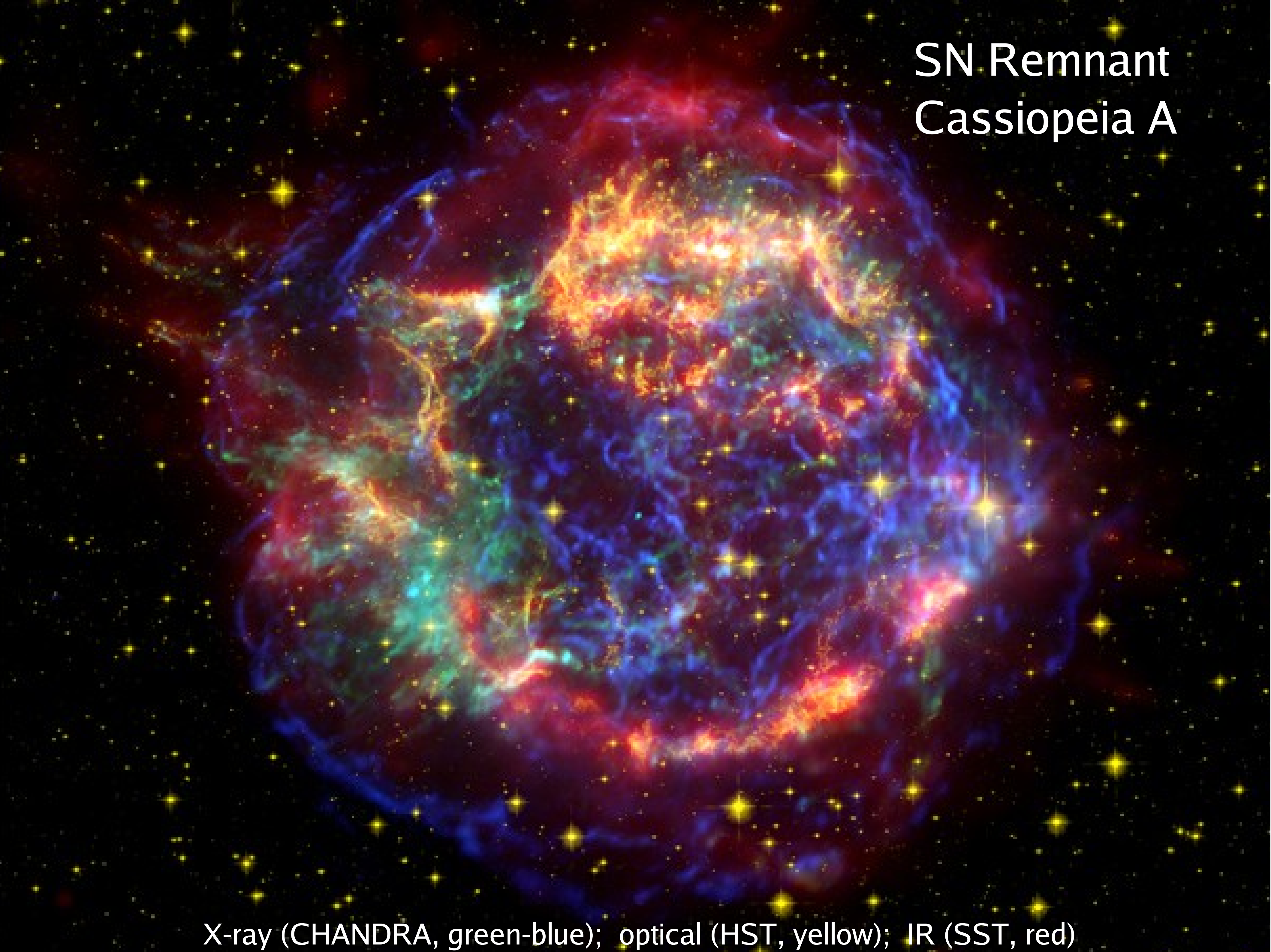


SuperMUC Status and Results Workshop
Garching, July 8–9, 2014

# Exploring the Violent Birth of Neutron Stars with SuperMUC


**Hans-Thomas Janka**
Max Planck Institute for Astrophysics, Garching


CRAB Nebula with pulsar, remnant of Supernova 1054
HST (NASA, ESA)


SN Remnant
Cassiopeia A
X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)

# How do massive stars explode?

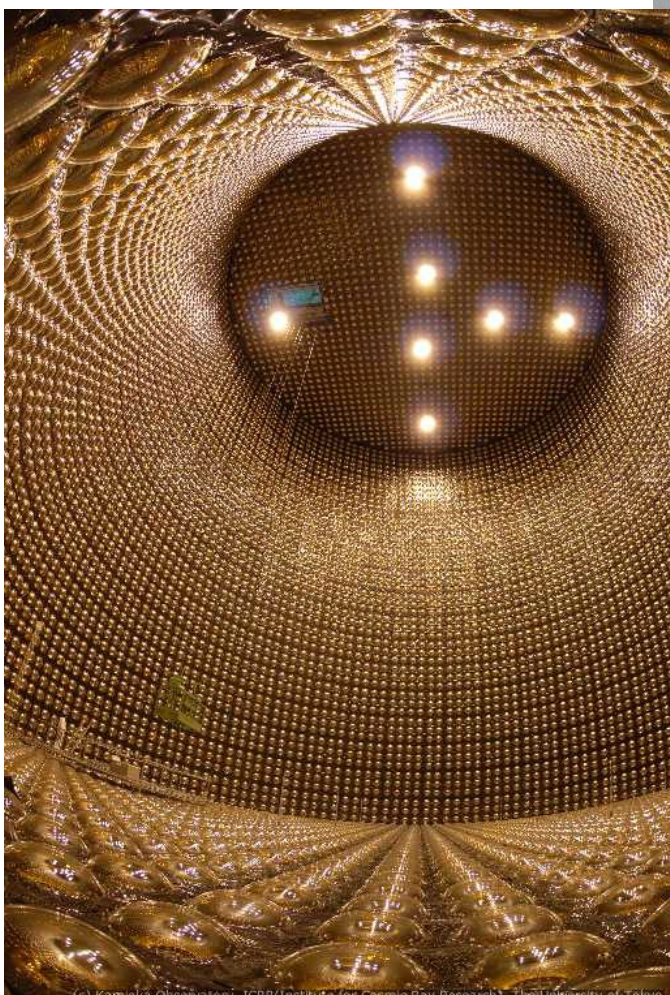
- **Supernovae:**

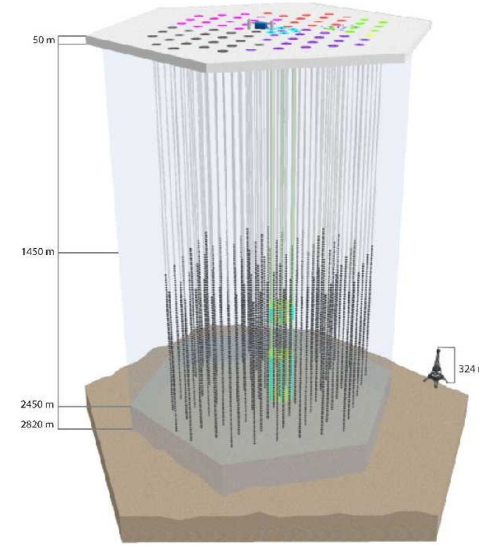
  **Spectacularly bright end stages of stellar evolution**

- **Birth of neutron stars and black holes**
- **Origin of heavy elements**
- **Observational signals: neutrinos, gravitational waves**

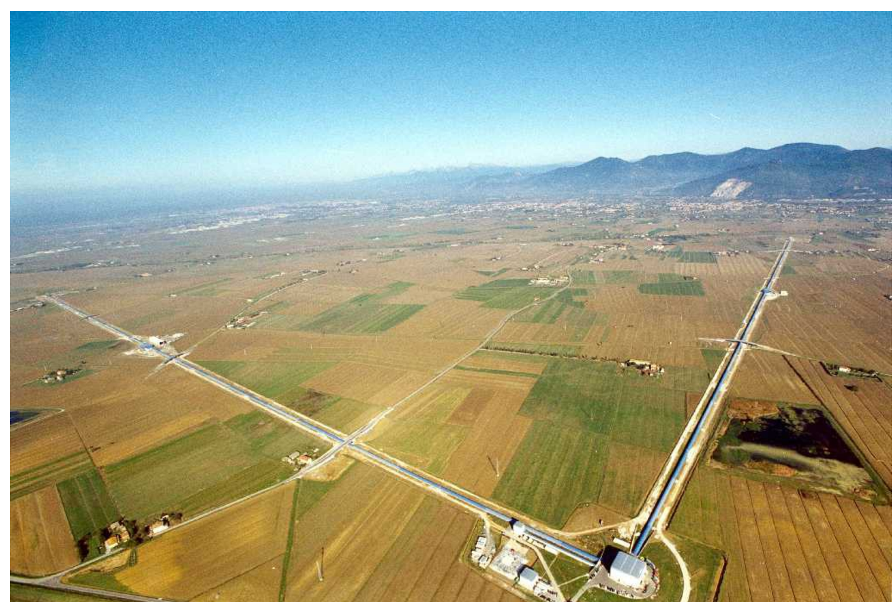
# Detecting Core-Collapse SN Signals

Superkamiokande




IceCube



VIRGO

# The Team

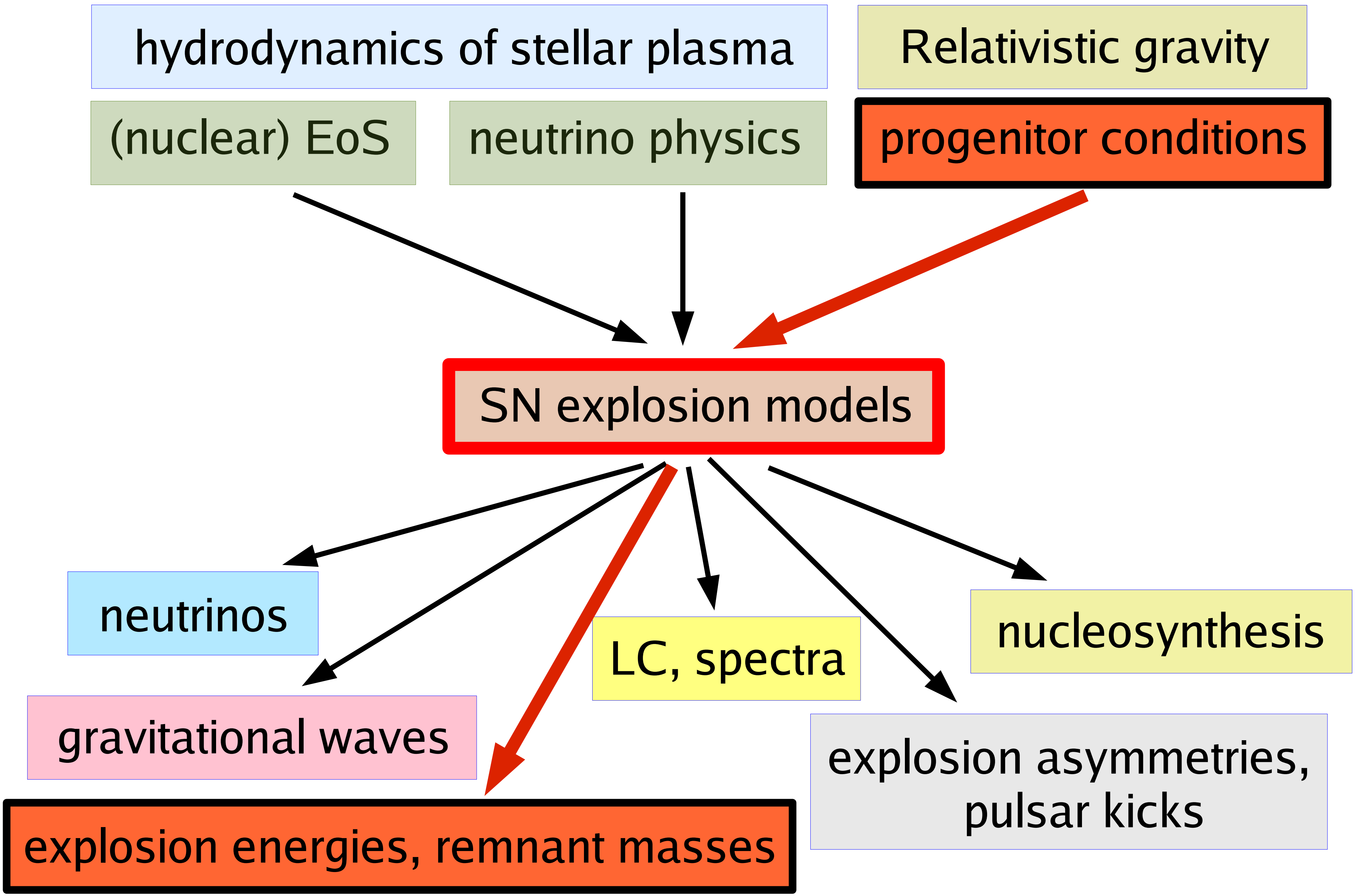
## Students, Postdocs, Collaborators

- Tobias Melson, Florian Hanke
- Alexander Summa
- Michael Gabler, Maxime Viallet

- Andreas Marek  (High Level Application Support, RZG)

- Ewald Müller, Bernhard Müller (Monash Univ., Melbourne), Annop Wongwathanarat
- Irene Tamborra (Univ. Amsterdam), Georg Raffelt (MPP)

# Supernova Modeling: Multi-Physics Problem



# The Simulation Code

## Prometheus/CoCoNuT – VERTEX: 1D, 2D, 3D

- **Hydro modules:**
  **Newtonian: *Prometheus* + effective relativistic grav. potential.**
  **General relativistic: *CoCoNuT***
  **Higher-order Godunov solvers, explicit.**
- **Neutrino Transport: *VERTEX***
  **Two-moment closure scheme with variable Eddington factor based on model Boltzmann equation; fully energy-dependent, O(v/c), implicit, ray-by-ray-plus in 2D and 3D.**
- **Most complete set of neutrino interactions applied to date.**
- **Different nuclear equations of state.**
- **Spherical polar grid or axis-free Yin-Yang grid.**

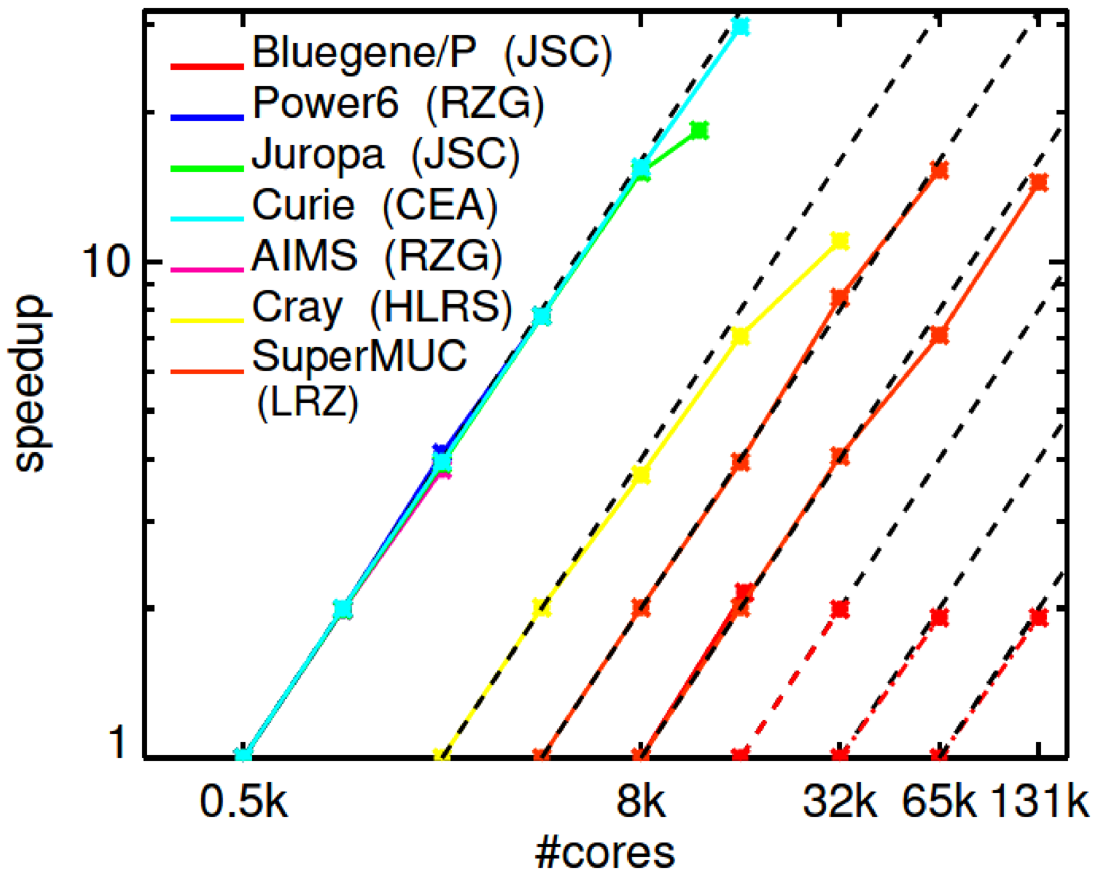
# Parallel-Programming Model

- ✔ Mixed (hybrid) MPI-OpenMP parallelization:
  - Hydro module fully MPI parallelized
  - Transport module MPI+OpenMP parallelized over radial "rays"
- ✔ Several OpenMP threads (↔ cores) per MPI task (↔ nodes)
- ✔ GPUs can be used for special-physics "sub-problems" (speed-up by factor 2–3; A. Marek, RZG)
- ✗ Memory RAM: 1–2 Gbyte/core needed (tables, transport variables)
- ✗ Need powerful cores:
  - Microphysics is compute-intense
  - Tabular input would require even more memory/core

# Performance and Portability of our Supernova Code *Prometheus-Vertex*

- Code employs hybrid MPI/OpenMP programming model (collaborative development with **Katharina Benkert, HLRS**).
- Code has been ported to different computer platforms, optimized, and further parellelized by **Andreas Marek, High Level Application Support, Rechenzentrum Garching (RZG)**.
- Code shows excellent parallel efficiency, which can be fully exploited in 3D.

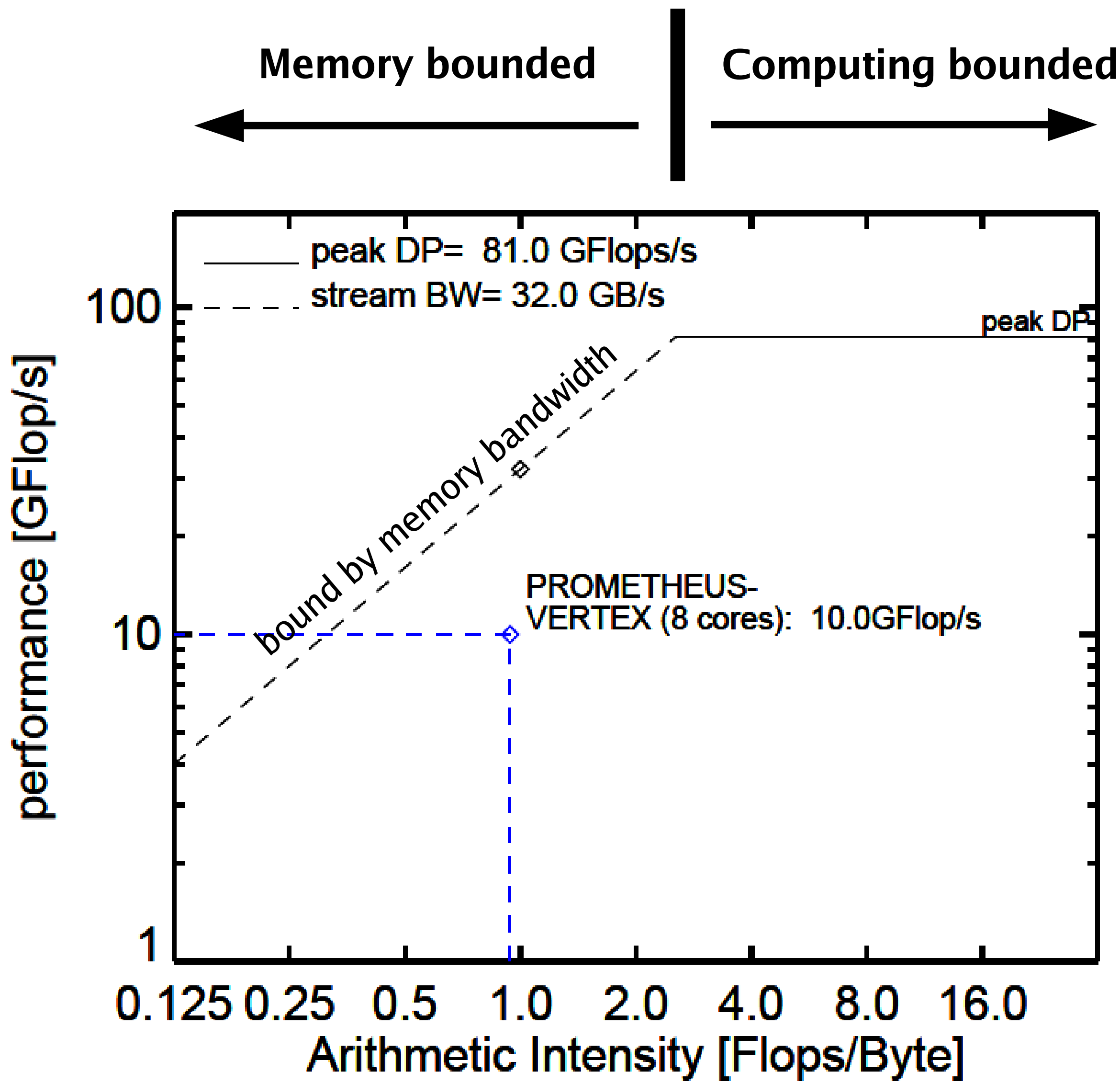
## Strong Scaling




A. Marek et al. (CUG 2013)

# Performance and Portability of our Supernova Code *Prometheus-Vertex*

- **Floating-point performance within roof-line model.**
- P-V achieves ~12% of peak performance for double precision calculations on 8-core node with two Intel Xeon E5540 “Nehalem” CPUs (2.53 GHz).
- Around 10% of peak performance obtained also on other platforms.
- Good performance for complex scientific application with non-trivial instruction mix.
- Further optimization by reducing number of memory references.




A. Marek et al. (CUG 2013)

# Computing Requirements for 2D & 3D Supernova Modeling

**Time-dependent simulations: t ~ 1 second, ~ $10^6$ time steps!**

CPU-time requirements for one model run:

- **In 2D with 600 radial zones, 1 degree lateral resolution:**

  **~ $3*10^{18}$ Flops, need ~$10^6$ processor-core hours.**

- **In 3D with 600 radial zones, 1.5 degrees angular resolution:**

  **~ $3*10^{20}$ Flops, need ~$10^8$ processor-core hours.**

PRACE Partnership for Advanced Computing in Europe

NIC

John von Neumann Institut für Computing

HLRIS

rzg IPP Rechen-Zentrum Garching

Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

# 3D Supernova Simulations

**EU PRACE and GAUSS Centre grants of ~360 million core hours allow us to do the first 3D simulations on 16.000 cores.**

PRACE
PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

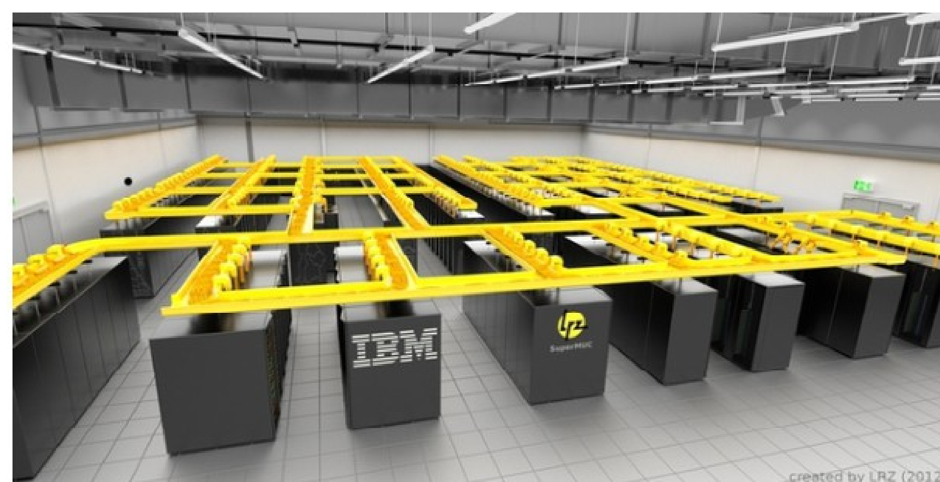
GCS
Gauss Centre for Supercomputing

DE LA RECHERCHE À L'INDUSTRIE
cea
HPC CALCUL HAUTES PERFORMANCES
TGCC

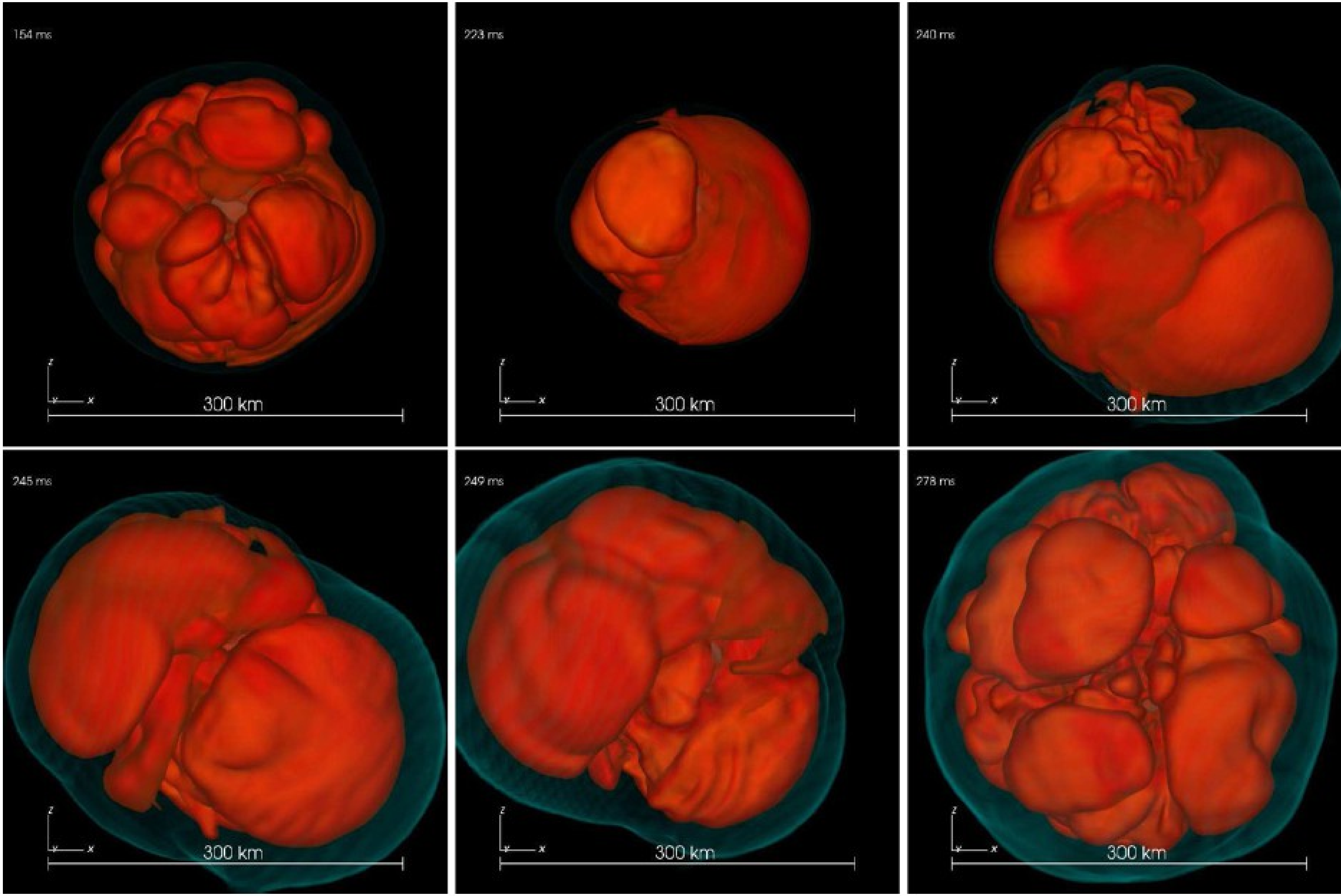
Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

TGCC Curie

SuperMUC Petascale System



# 3D SN Models: SASI in the Postshock Accretion Layer



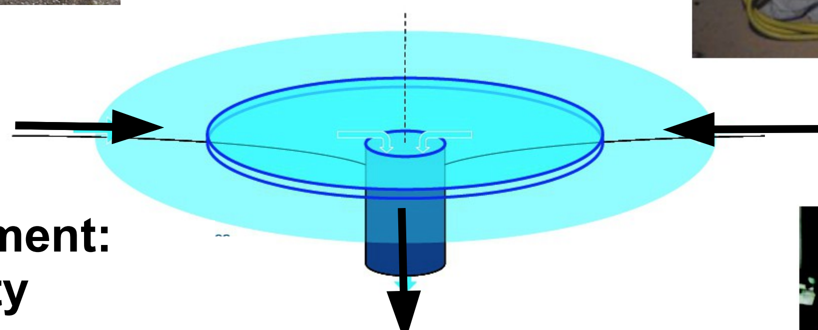

27 $M_{sun}$ progenitor (WHW 2002)

F. Hanke et al., ApJ 770 (2013) 66

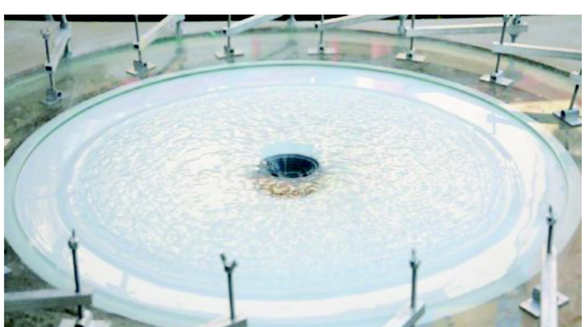
# Laboratory Astrophysics

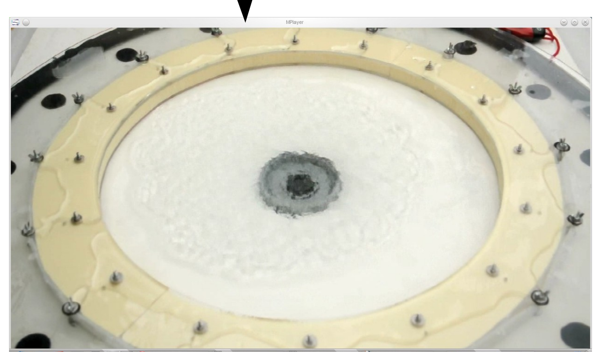
## "SWASI" Instability as an analogue of SASI in the supernova core

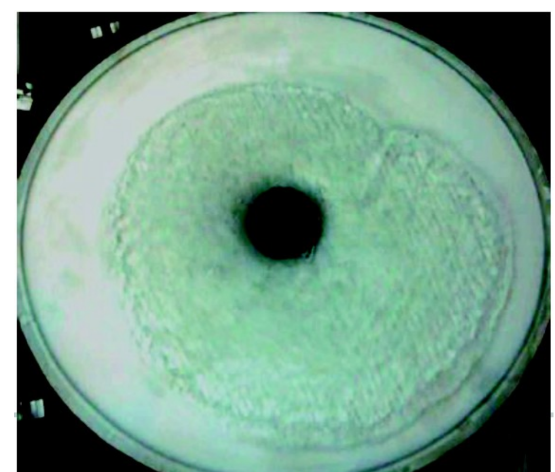
Foglizzo et al., PRL 108 (2012) 051103



**Constraint of experiment:**
**No convective activity**



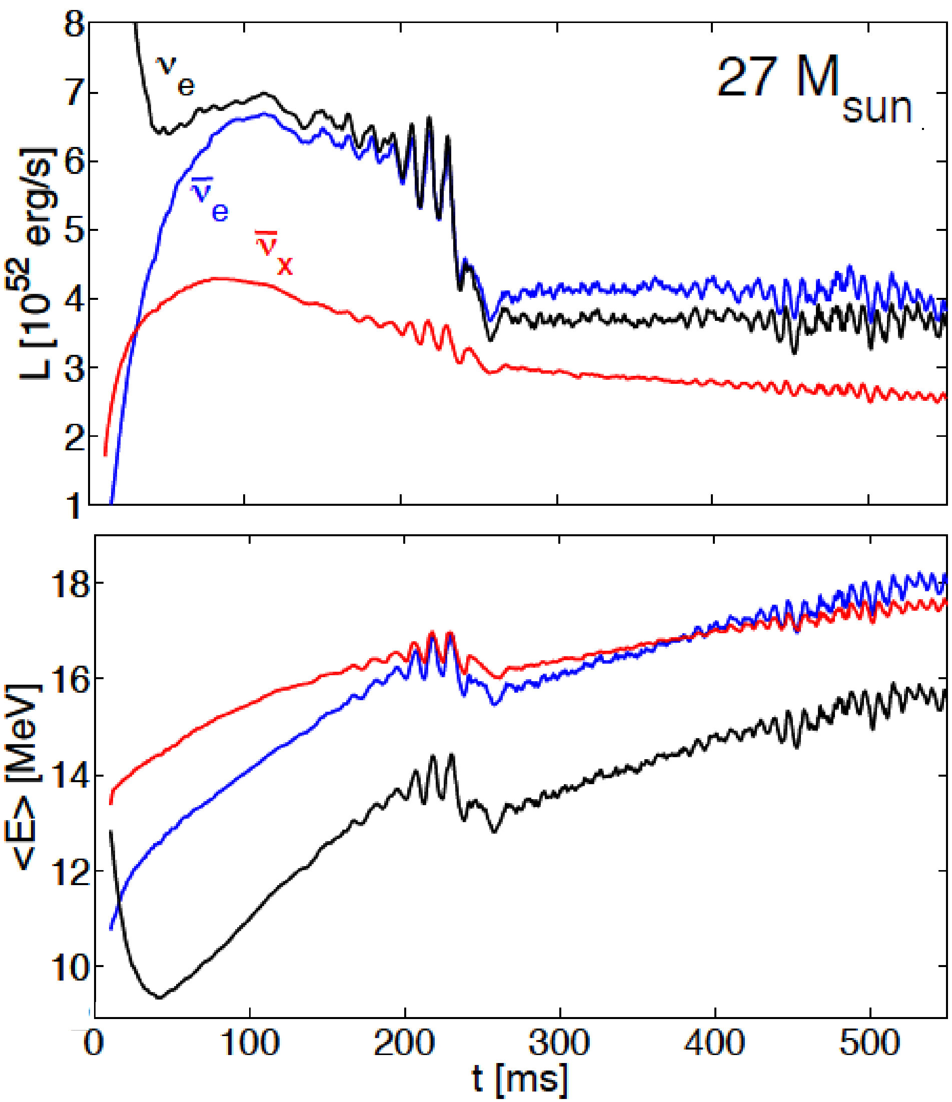


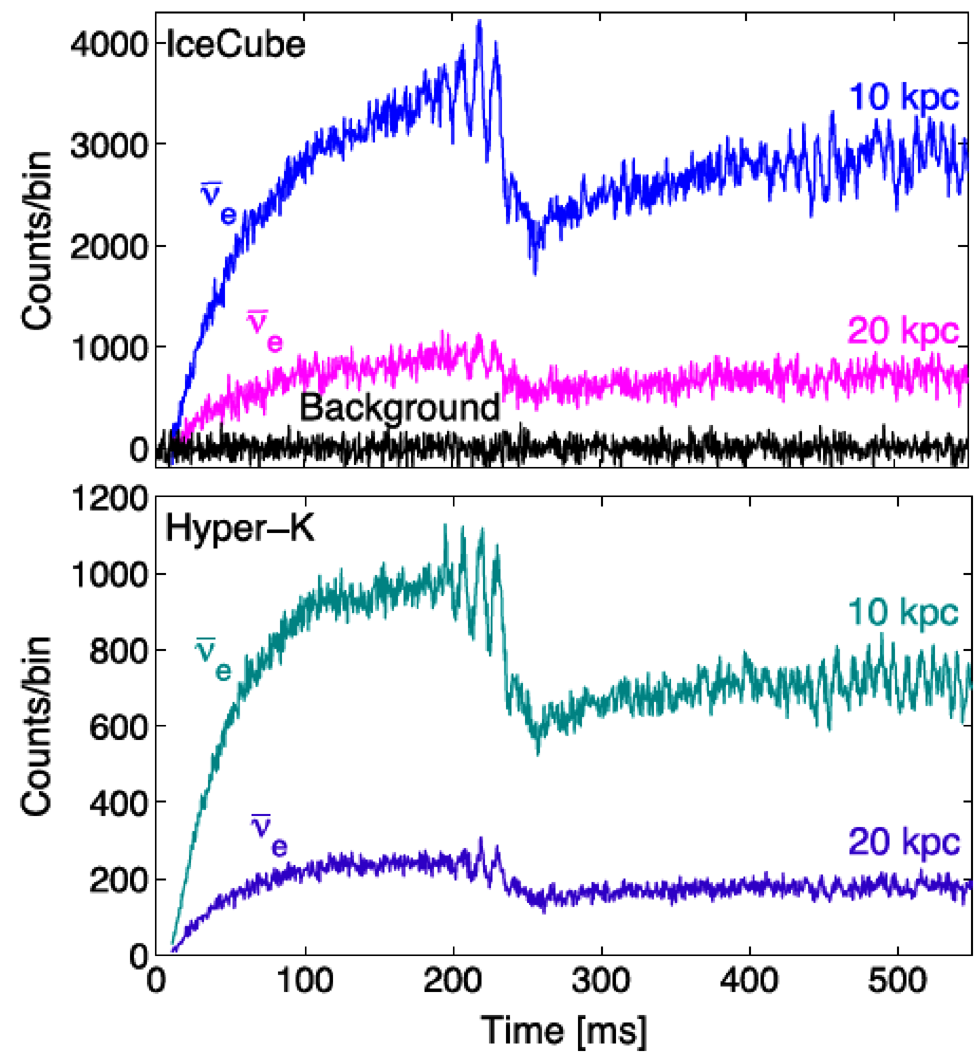


# 3D Core-Collapse Models: Neutrino Signals

## 11.2, 20, 27 $M_{sun}$ progenitors (WHW 2002)

SASI produces modulations of neutrino emission and gravitational-wave signal.




(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

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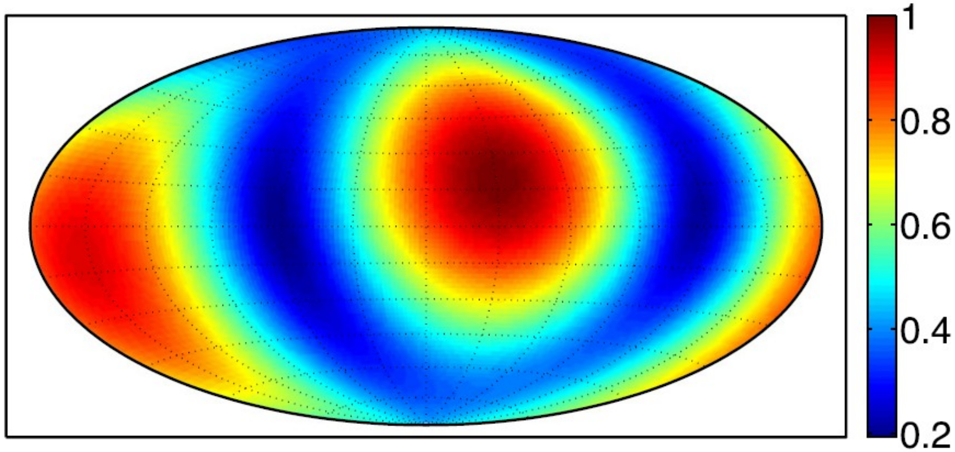
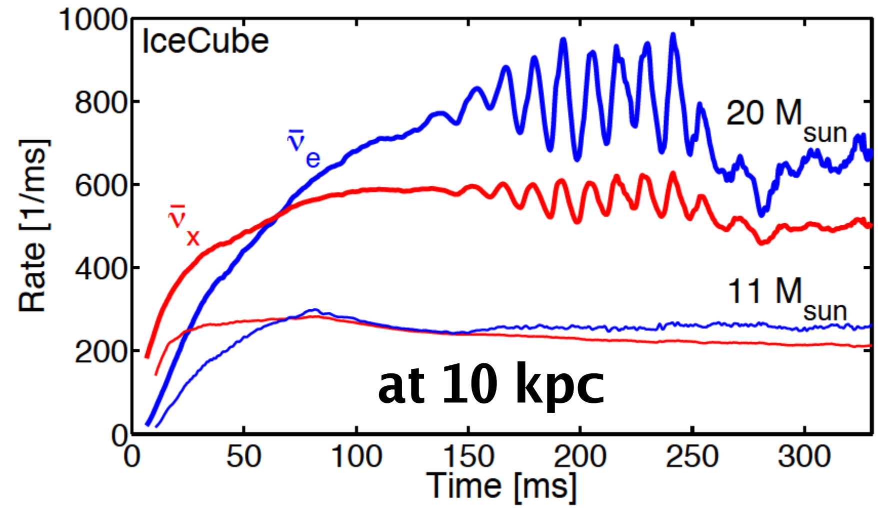
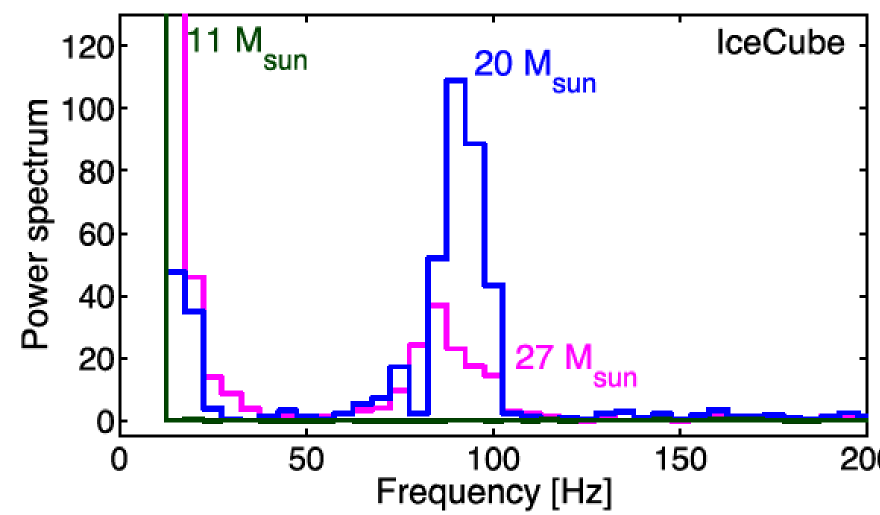


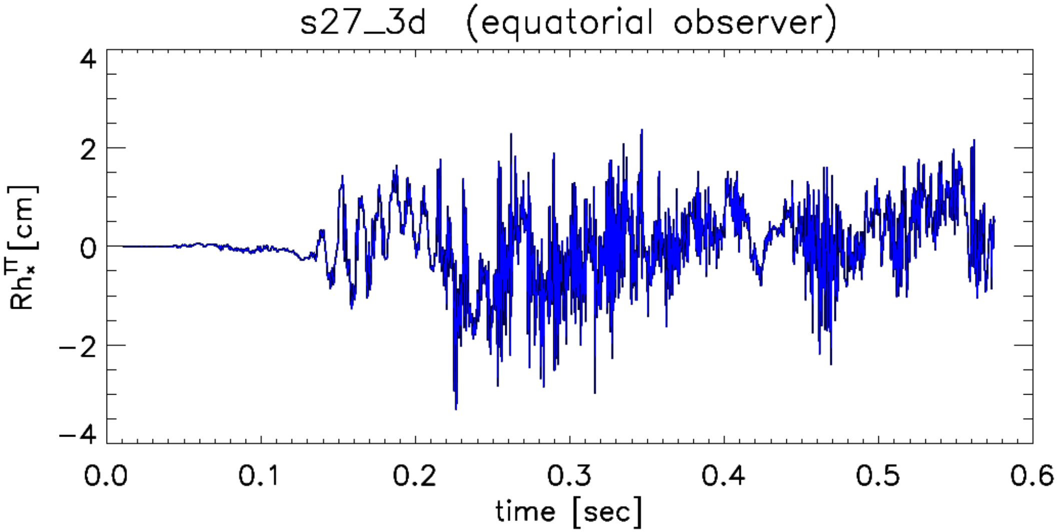

$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$

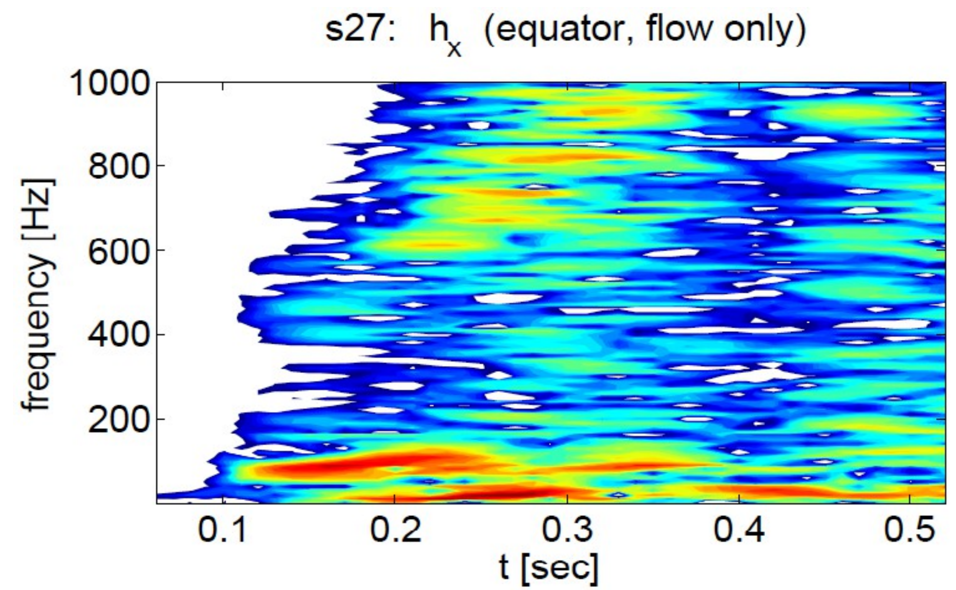


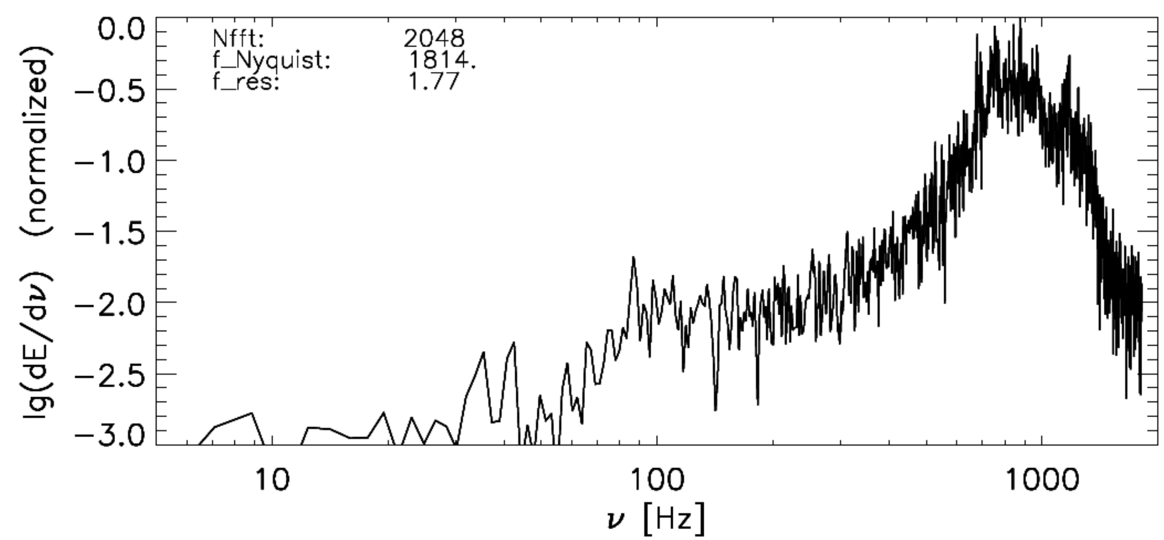

(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)

# 3D Core-Collapse Models: Gravitational Waves

## 27 $M_{sun}$ progenitor (WHW 2002)

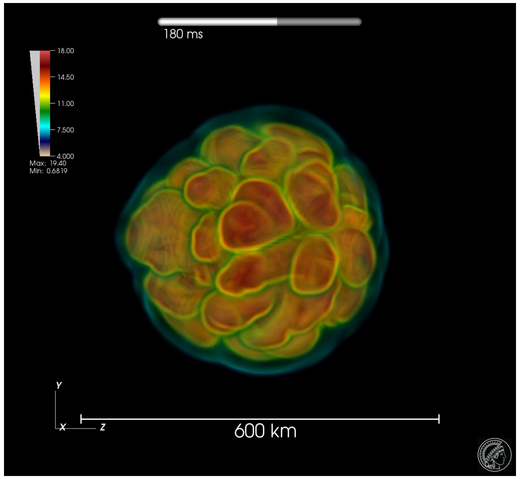



Preliminary analysis
by E. Müller of
model from
F. Hanke et al.,
ApJ 770 (2013) 66

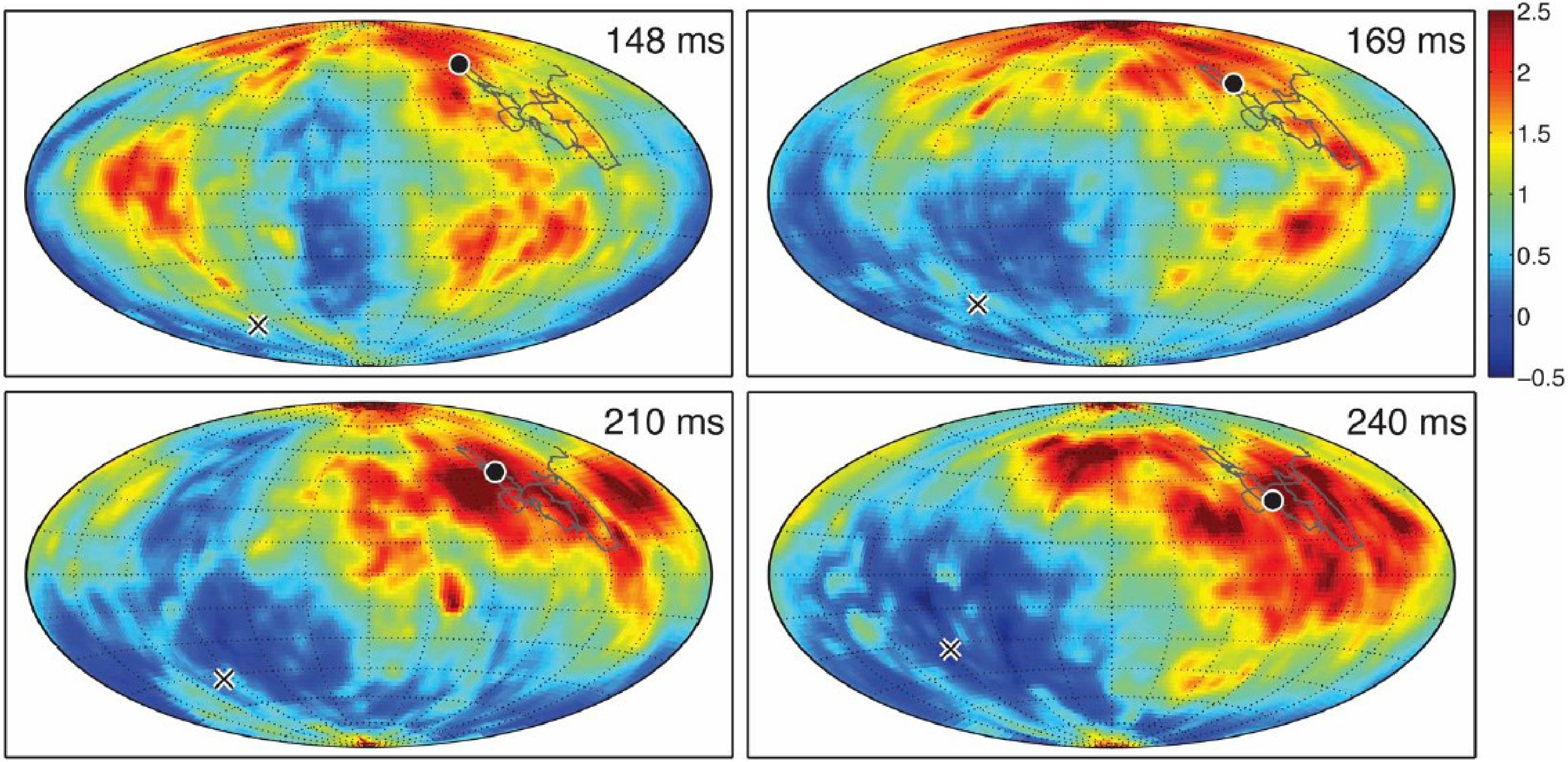
# A New Nonradial 3D Instability




## Dipole asymmetry of lepton number emission

**Lepton number flux: $\nu_e$ minus anti-$\nu_e$**

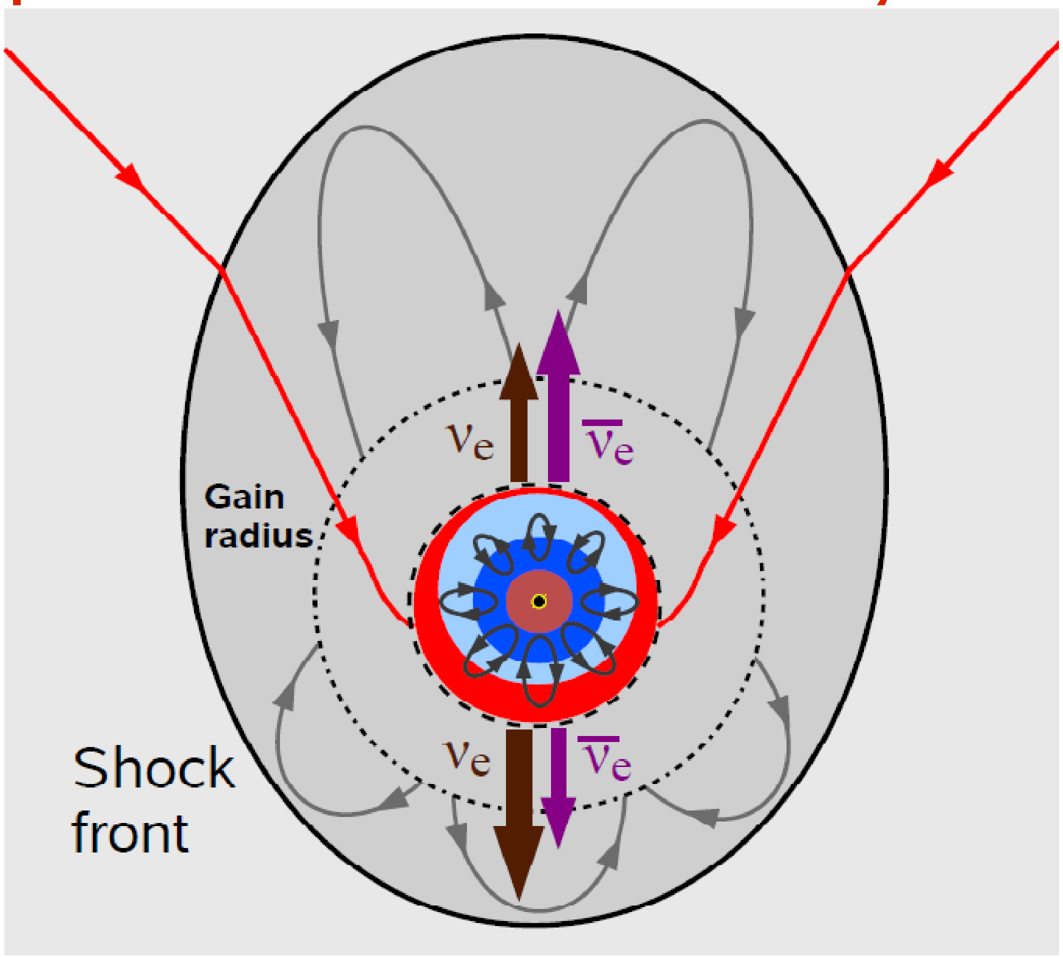
$$(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e} \rangle$$



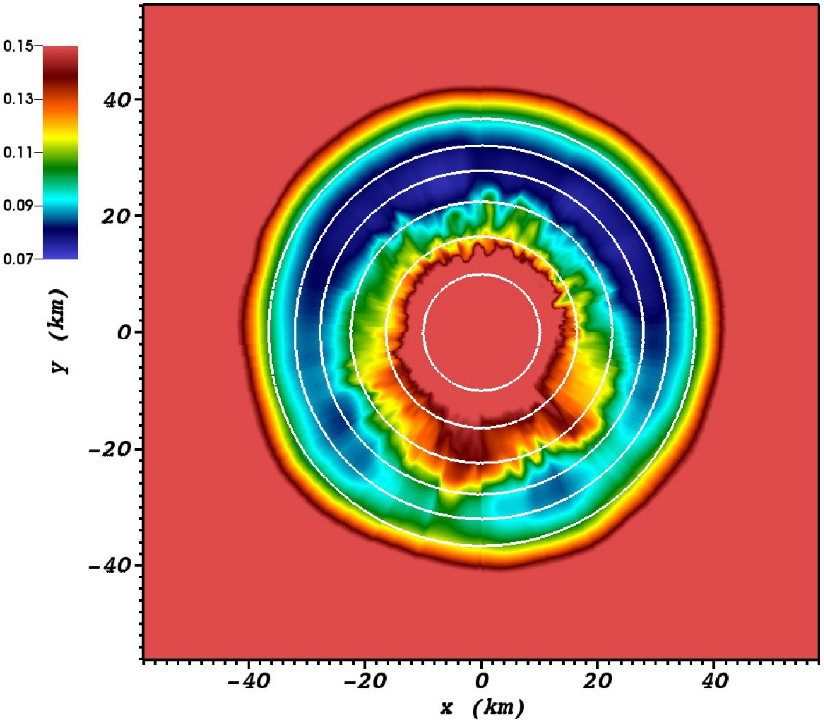

Tamborra, Hanke, THJ, Müller, Raffelt & Marek, arXiv:1402.5418

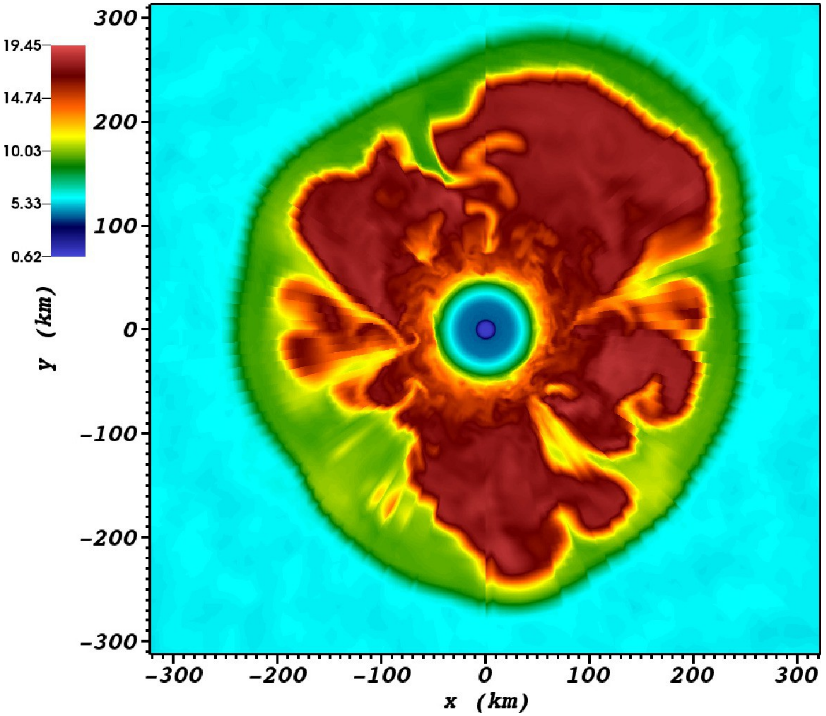
# A New Nonradial 3D Instability: "LESA"

**Lepton Emission Self-sustained Asymmetry**
**caused by**
**dipolar convection and accretion asymmetry**




$$\dot{q} \propto \frac{\sigma_0}{r^2}\left(L_{\nu_e}\left\langle\epsilon^2_{\nu_e}\right\rangle Y_n + L_{\bar{\nu}_e}\left\langle\epsilon^2_{\bar{\nu}_e}\right\rangle Y_p\right)$$




Tamborra, Hanke, THJ, Müller, Raffelt & Marek, arXiv:1402.5418

# Summary

3D supernova models reveal new, interesting phenomena

3D supernova simulations are making progress towards successfully exploding models!

**Stay tuned!**