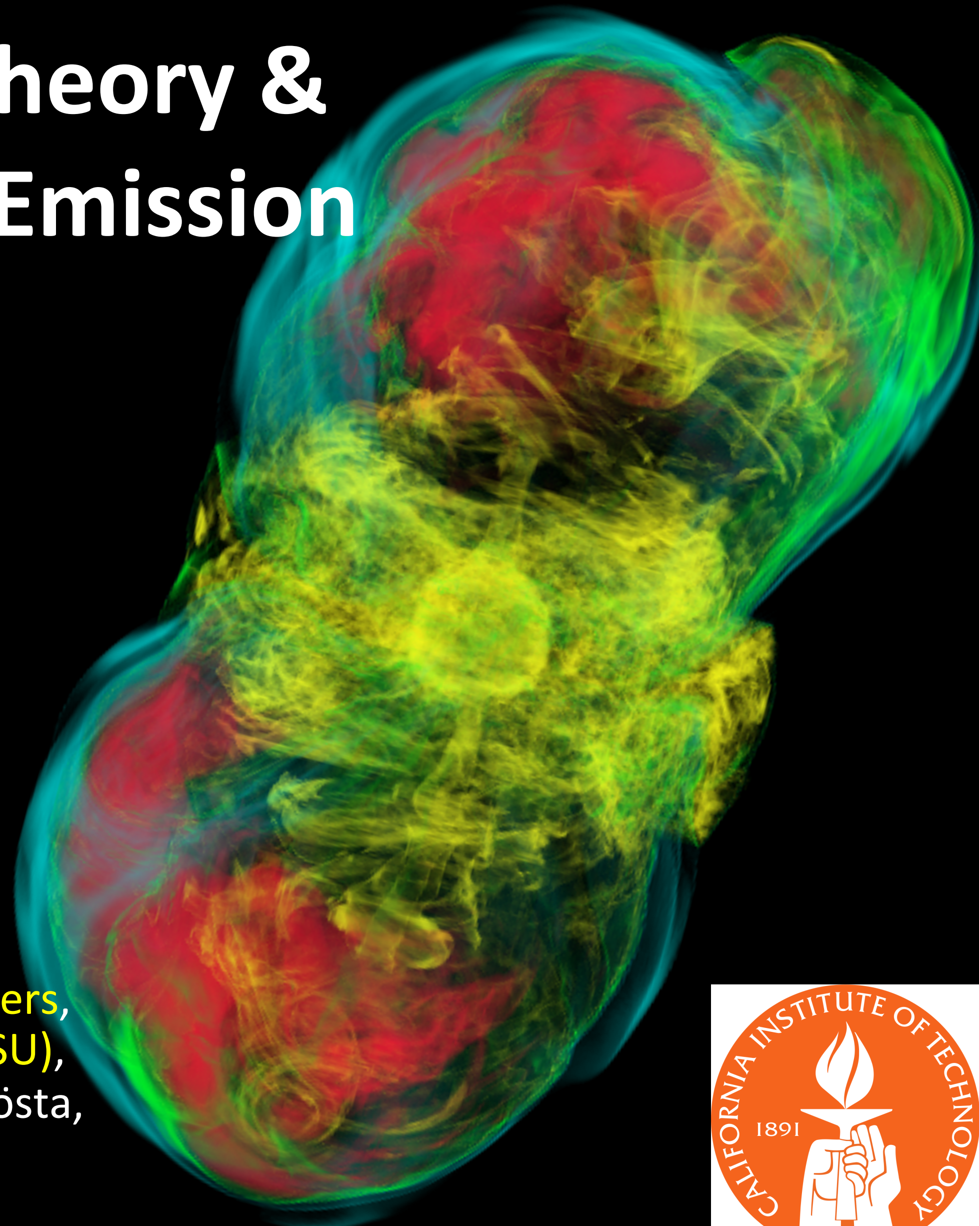
Core-Collapse Supernovae Recent Progress in Theory & Gravitational-Wave Emission



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TAPIR

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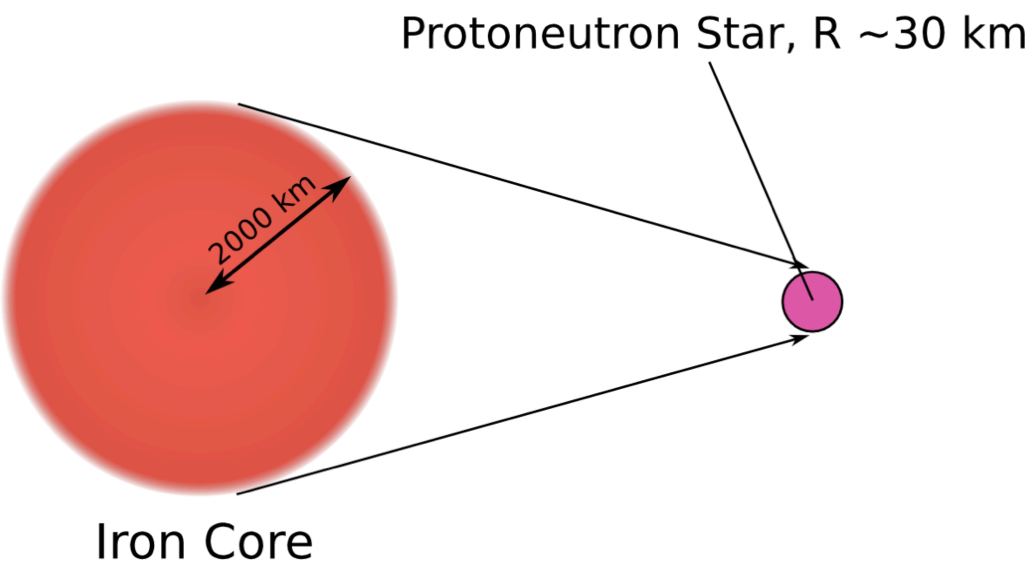
and Erik Schnetter

Overview

- Update on Core-Collapse Supernova Theory
- What’s going on with Advanced LIGO/Virgo?
  (for the LIGO Scientific Collaboration & Virgo)
- Gravitational Waves from Core-Collapse Supernovae

Reminder: Core Collapse Basics



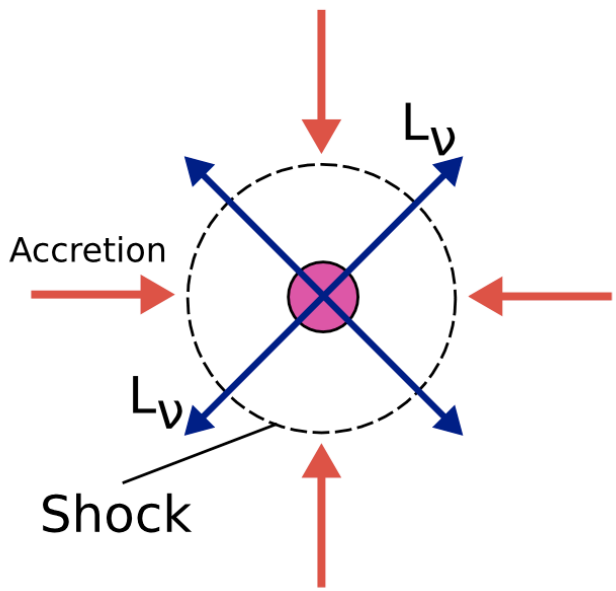
Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (~0.5 M_{Sun}) -> protoneutron star core. Shock wave formed.

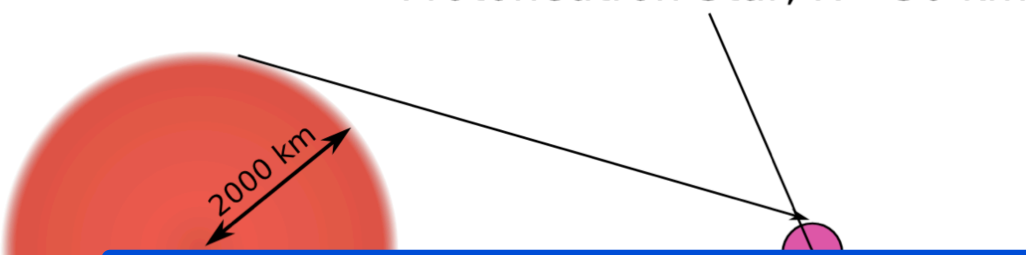
Outer core accretes onto shock & protoneutron star with O(1) $M_{\odot}$/s.

-> **Shock stalls at ~100 km, must be "revived" to drive explosion.**

Reviews:
Bethe'90
Janka+'12



Reminder: Core Collapse Basics



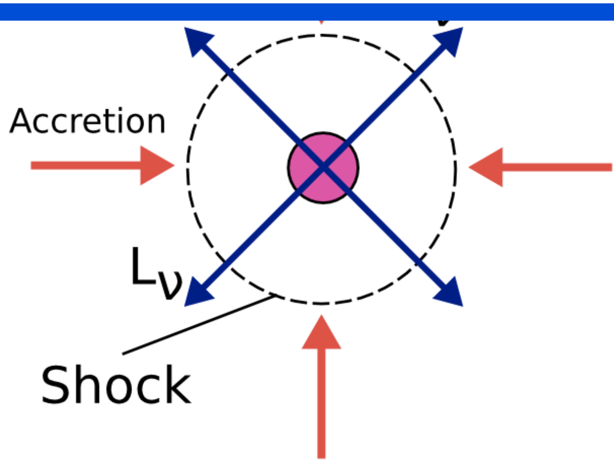
Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (~0.5 M_{Sun})

Key Question:

What is the mechanism that revives the stalled shock?

Revie
Bethe ’90
Janka+‘12



-> **Shock stalls at ~100 km, must be “revived” to drive explosion.**

Neutrino Mechanism

Bethe & Wilson 85; also see: **Janka 01**, +07, 12

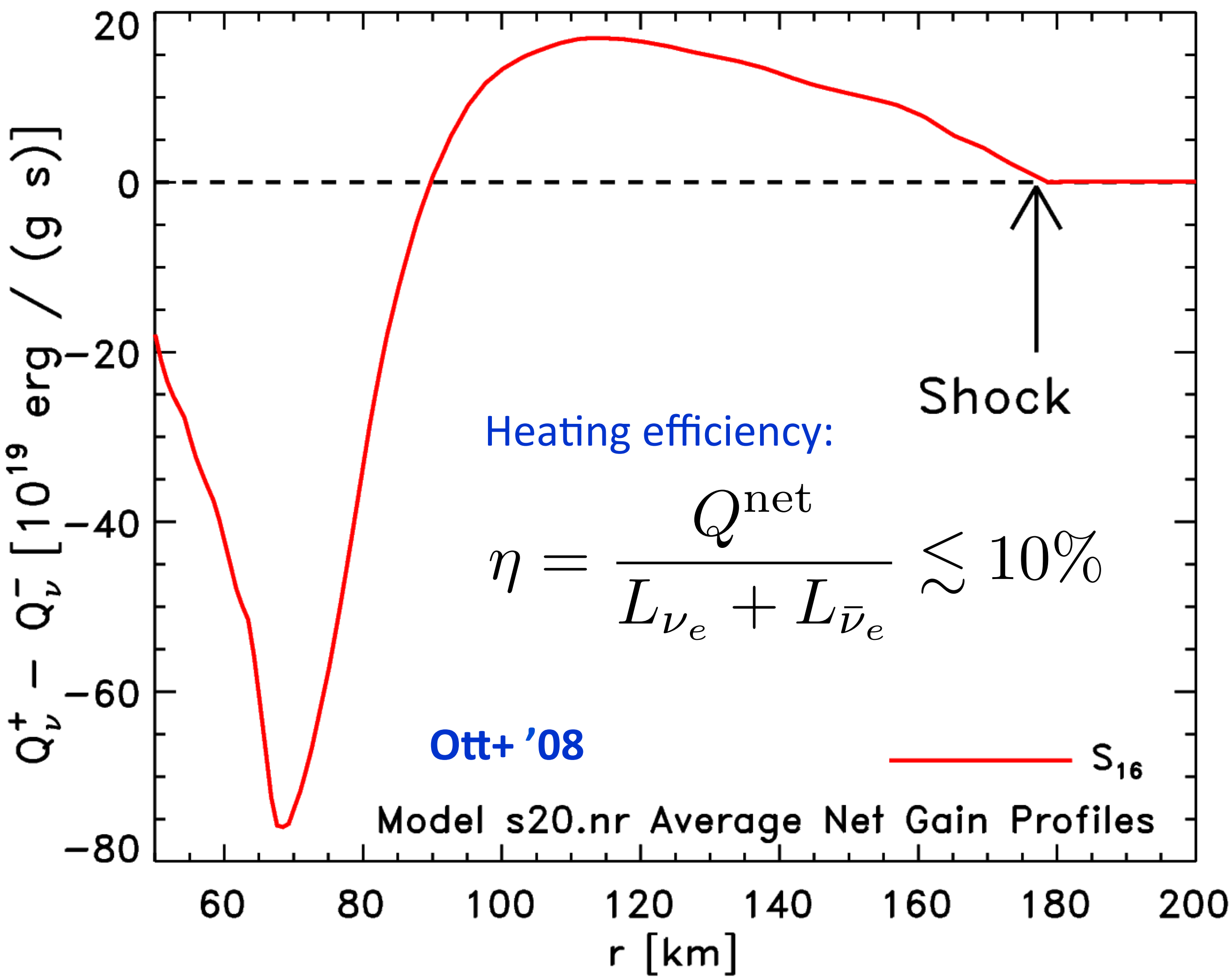
Cooling:

$$Q_\nu^- \propto T^6$$

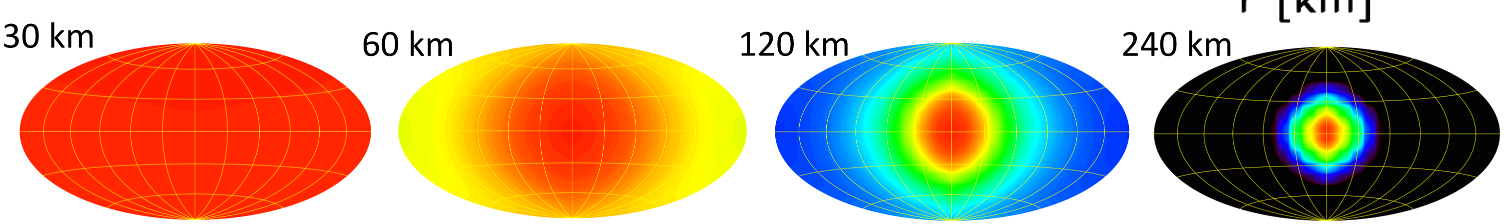
Heating via charged-current absorption:

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$Q_\nu^+ \propto \left\langle \frac{1}{\mathrm{F}_\nu} \right\rangle L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$$



Neutrino radiation field:

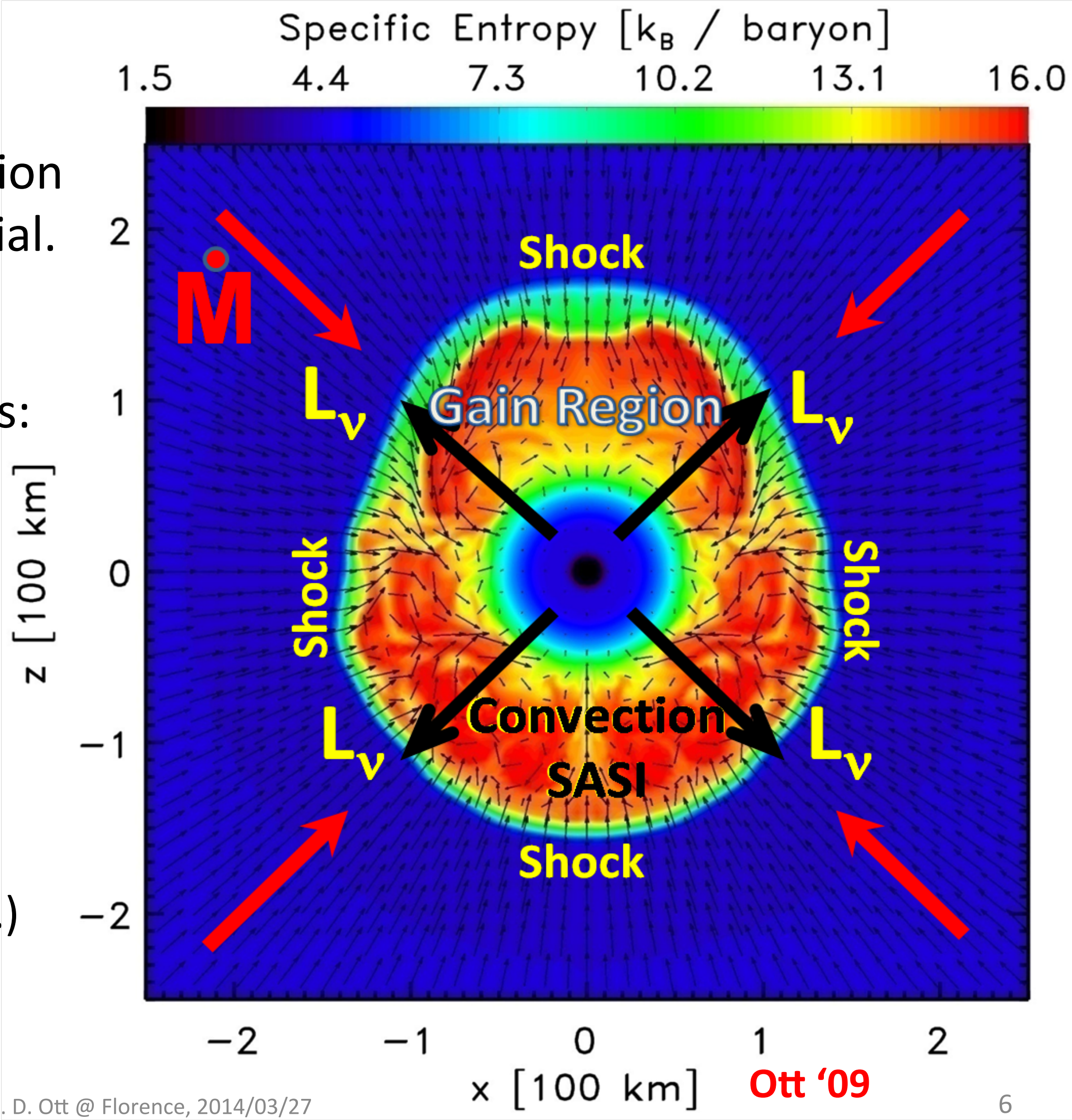


Neutrino Mechanism: Status

- **Multi-D dynamics**: convection, standing accretion shock instability (**SASI**) crucial.
- Detailed 2D (axisymmetric) simulations show explosions:

  B. Müller+ 12ab, 13, 14
  Bruenn+ 13
  Takiwaki+14

  But: *no 2D explosions in Dolence+14*
  (but different EOS, Newt. grav.)
- **What about 3D?**

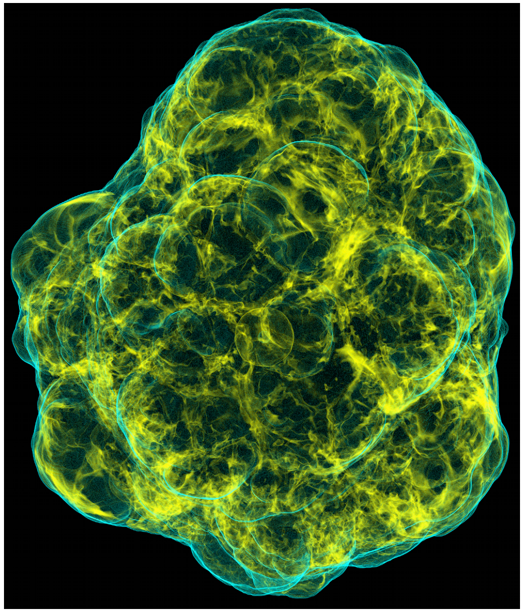


Ott '09

The Frontier: 3D Core-Collapse Supernovae

- **Is the neutrino mechanism robust in 3D?**

- 1D -> 2D: neutrino heating more efficient, some models explode.
- 2D -> 3D: (1) Character of turbulence changes; energy cascades to small scales (large scales in 2D).
  (2) Additional degree of freedom: nonaxisymmetric flow.



- Some "early" work: Fryer & Warren 02, 04 (SPH)
- **Lots of new work**: Fernandez 10, Nordhaus+10, Takiwaki+11, Burrows+12, Murphy+13, Dolence+13, Hanke+12,13, Kuroda+12, Ott+13, Couch 13, Takiwaki+13, Couch & Ott 13, Couch & O'Connor 13
- Approximations currently made:
  (1) **Gravity** (2) Neutrinos (3) Resolution

Ott+2013
Caltech,
full GR,
parameterized
Neutrino heating

-6.18 ms

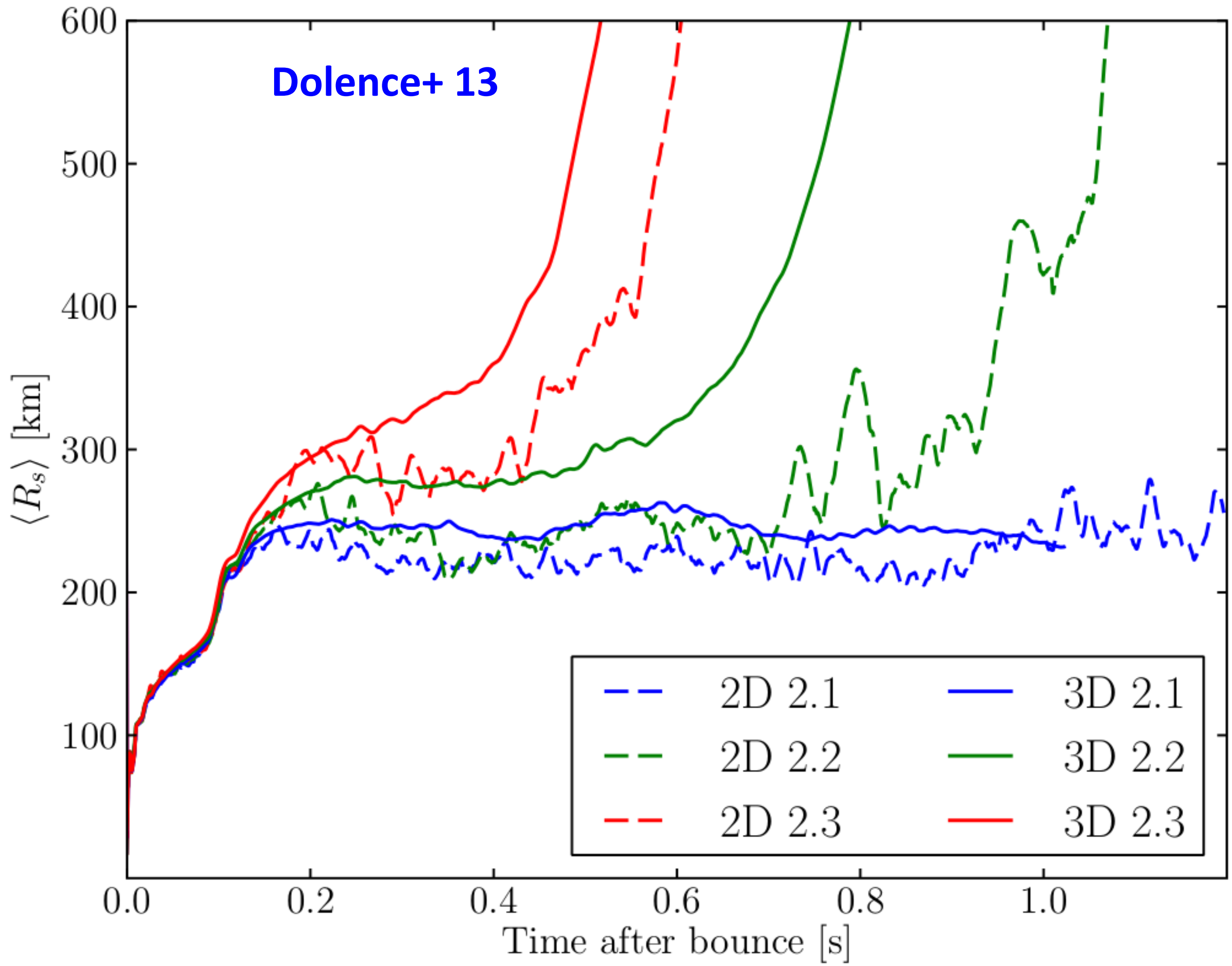
Results of current 3D Simulations

Does 3D help the explosion?

Yes:

Explosions start earlier in 3D.

Nordhaus+10,
Burrows+12,
Dolence+13,
Handy+13,
Takiwaki+12



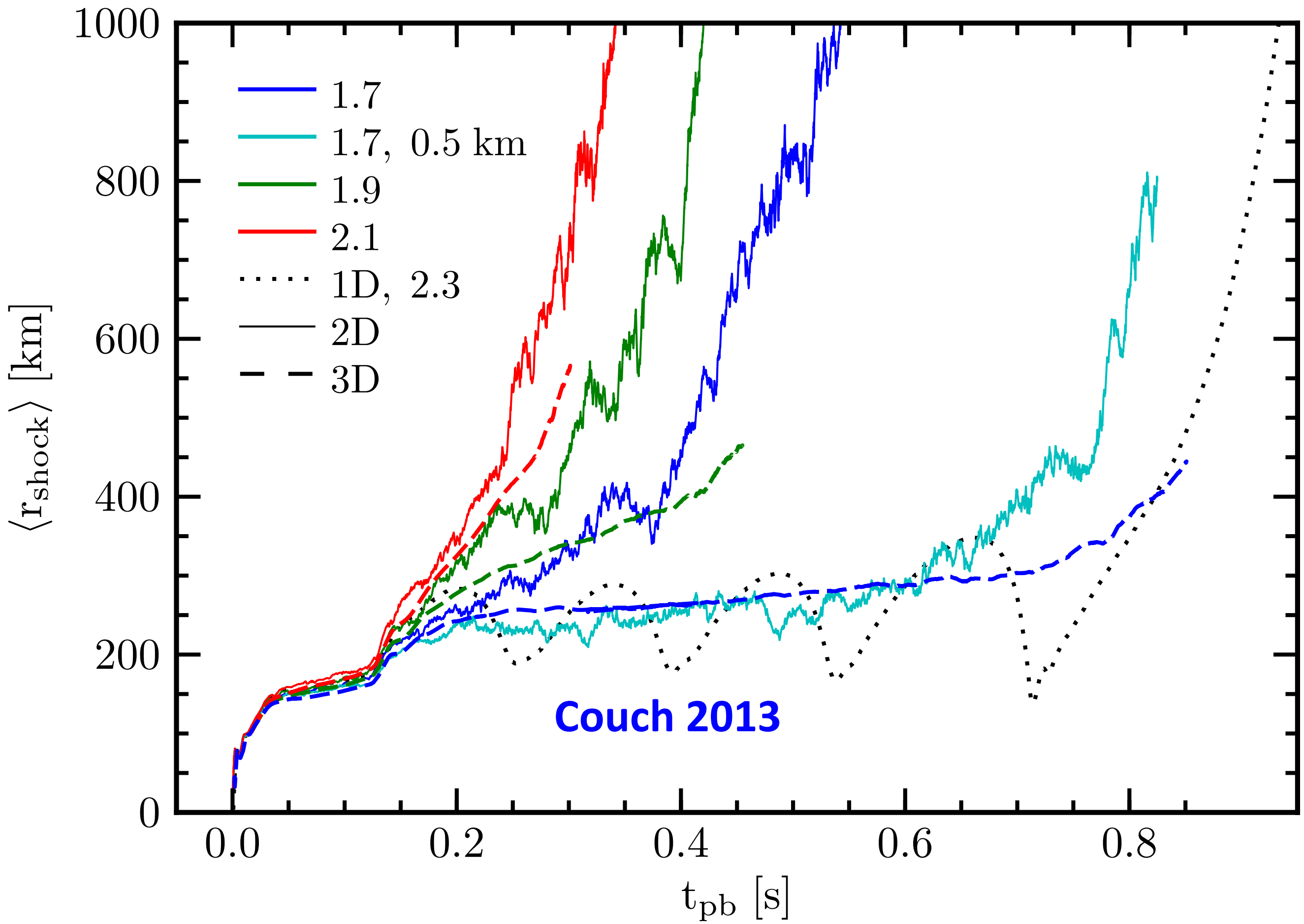
Results of current 3D Simulations

Does 3D help the explosion?

No:

Hanke+12,13
Couch 13
Couch & O'Connor 13
Takiwaki+13

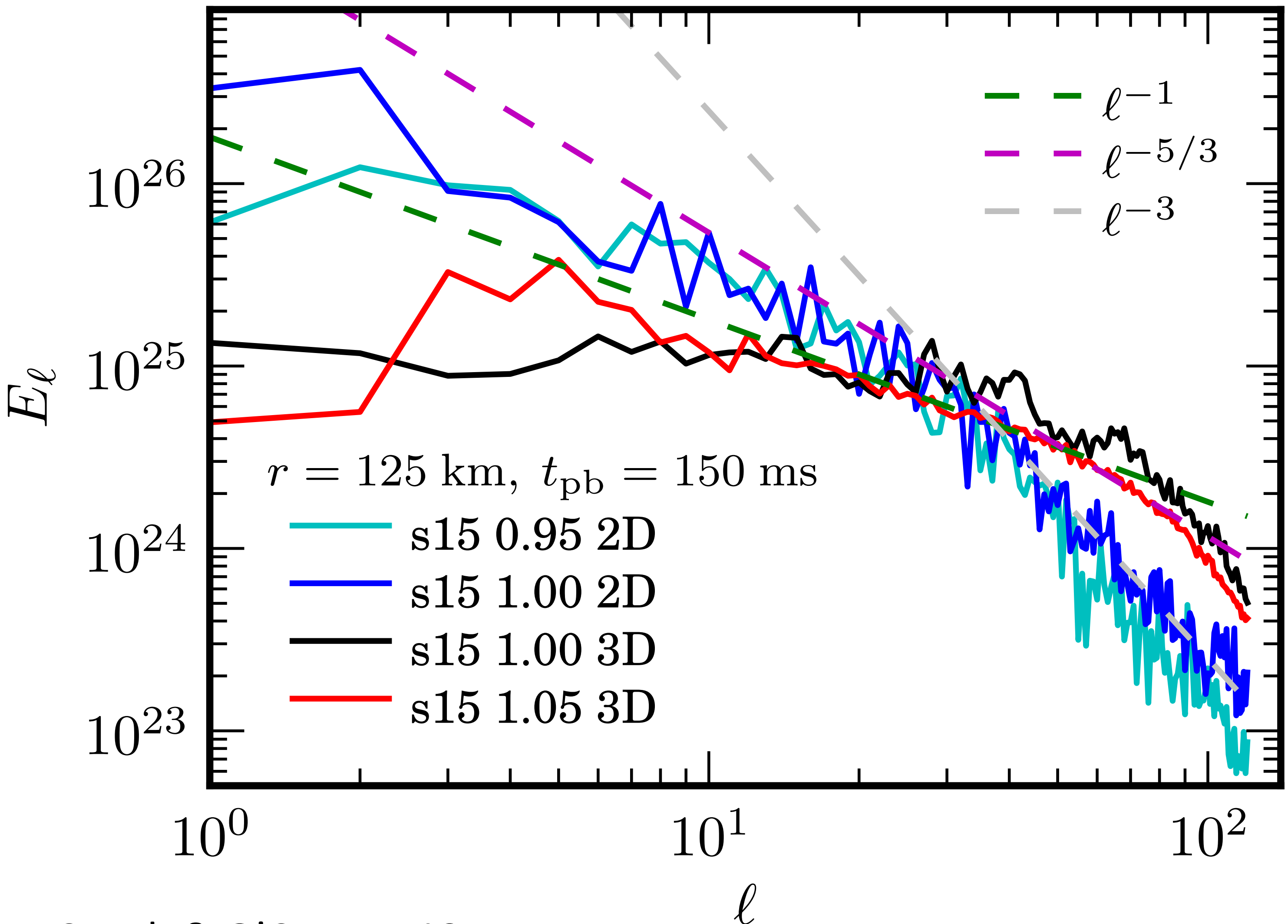
3D simulations explode later than 2D ones.



Explanation(s)?

-> Hanke+12,13, Couch & O'Connor 13: Turbulent cascade

Turbulent Cascade: 2D vs. 3D



Couch & O'Connor 13
see also: Dolence+13, Hanke+12,13, Abdikamalov+'14 (in prep.)

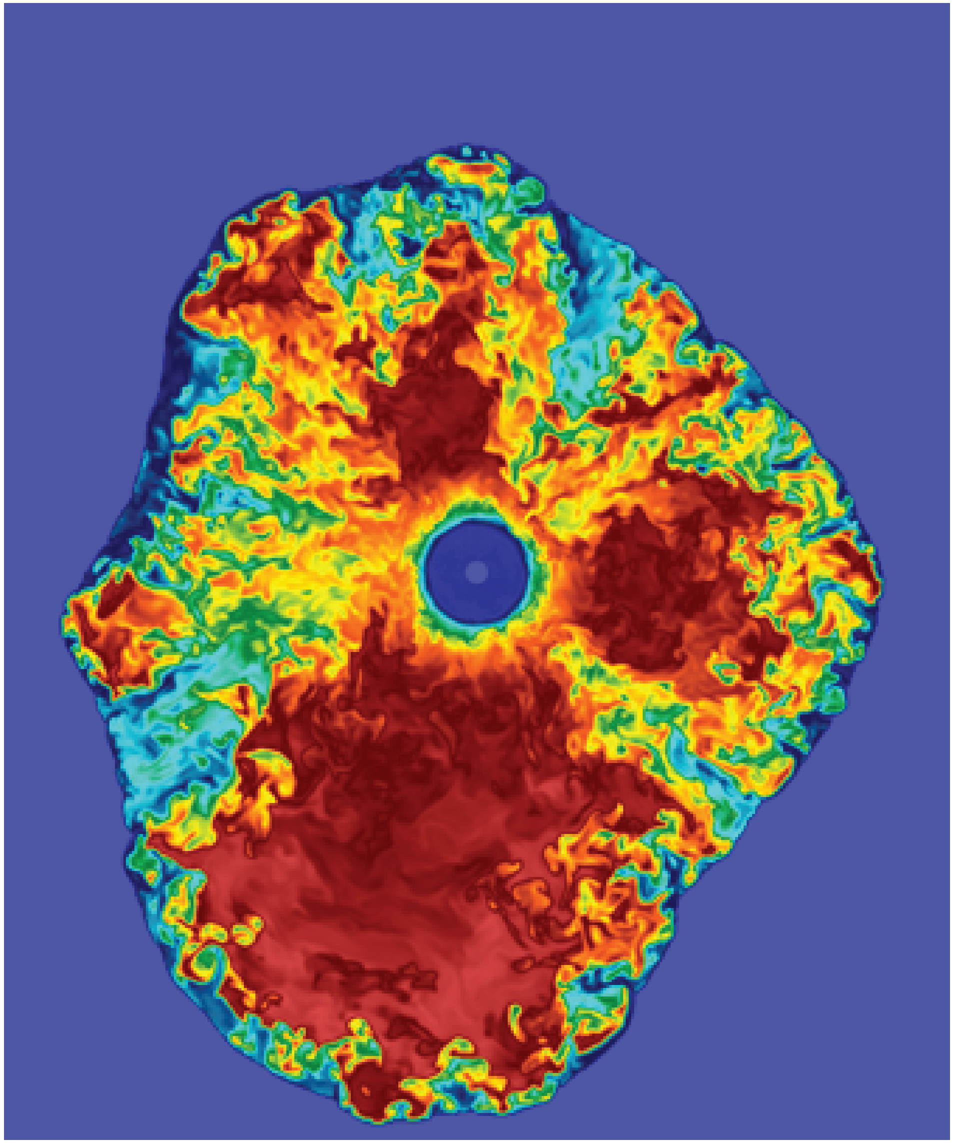
Summary of 3D Simulations:

- Explosions:
  low-mode asymmetry
  -> pulsar kicks, SN remnants

- Downsides of current 3D models:
  Either underresolved or
  parameterized (or both).

- **3D may make it harder to explode!**

What else could be missing?

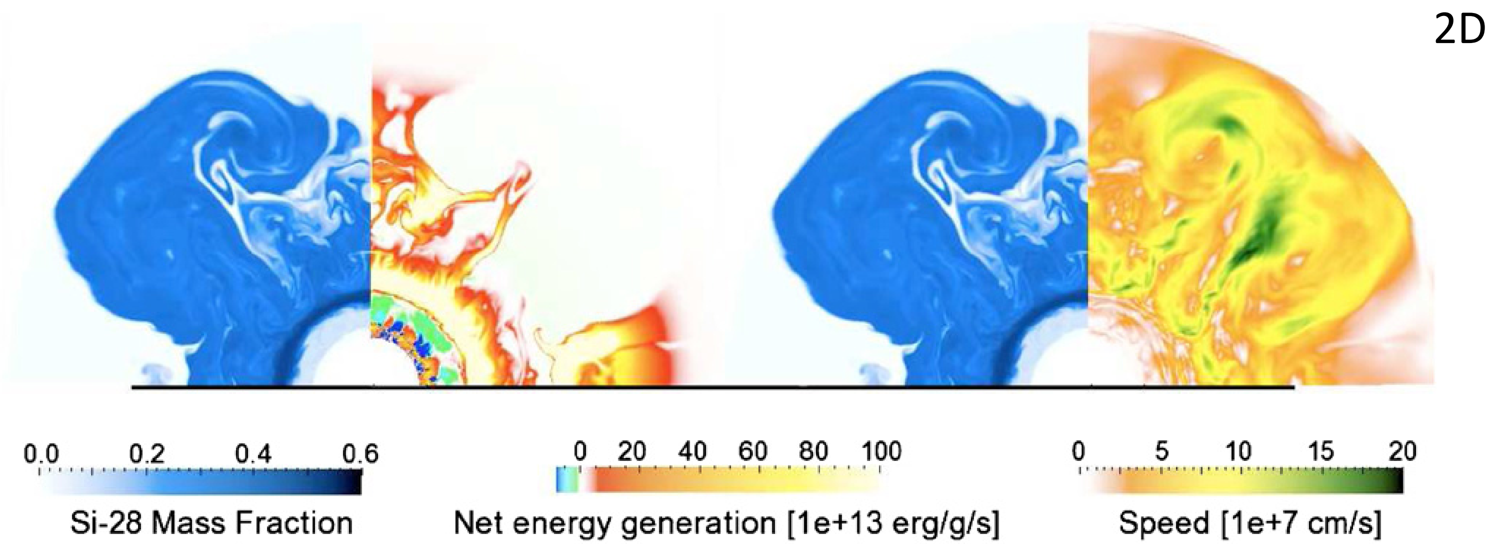


Ott+13

Perhaps: Multi-D Stellar Evolution

All available stellar models are spherically symmetric!

(But stars are not perfectly spherical!)



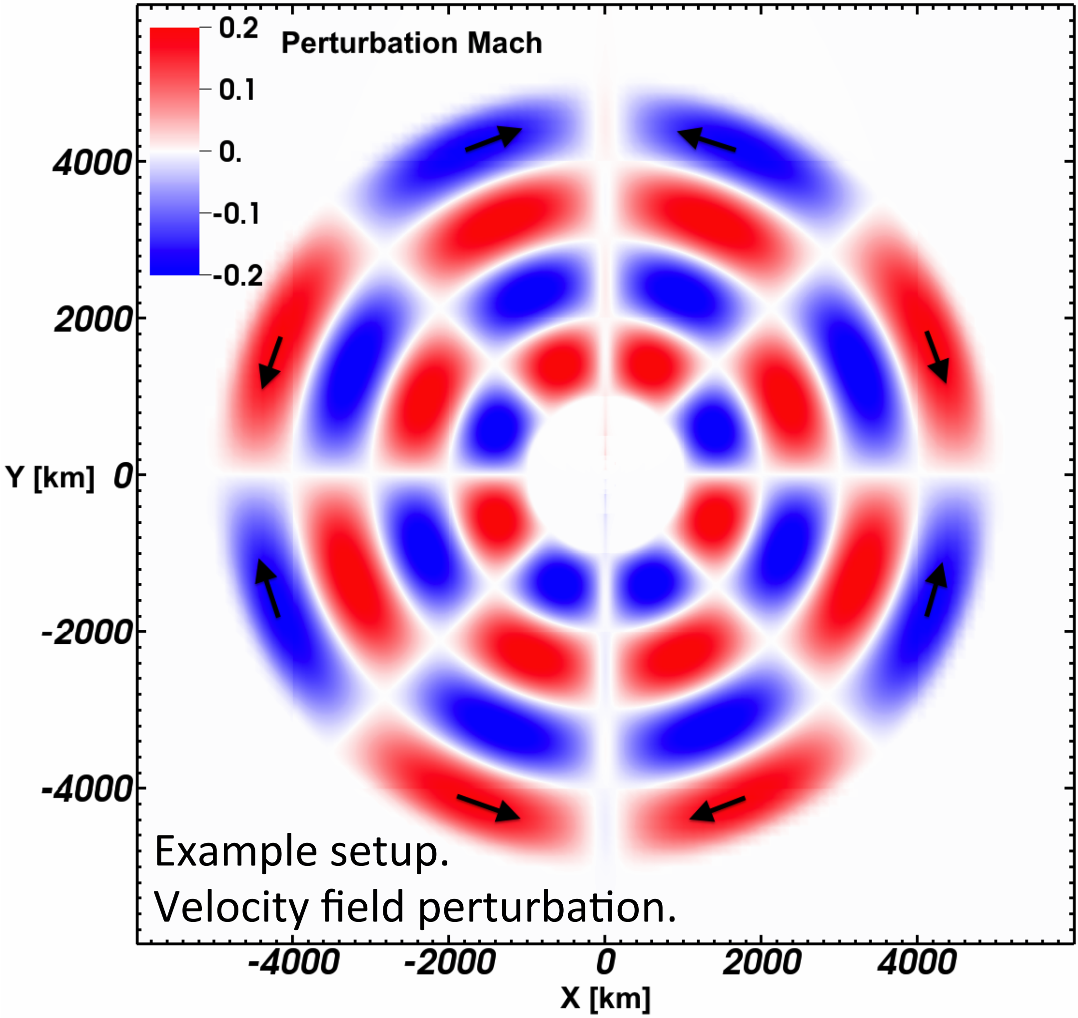
Arnett & Meakin 2011

- Late-stage oxygen burning very violent
  -> may lead to large-scale deviations from sphericity in O/Si layer.
- Could this have an effect on the explosion mechanism?

Precollapse Asphericity

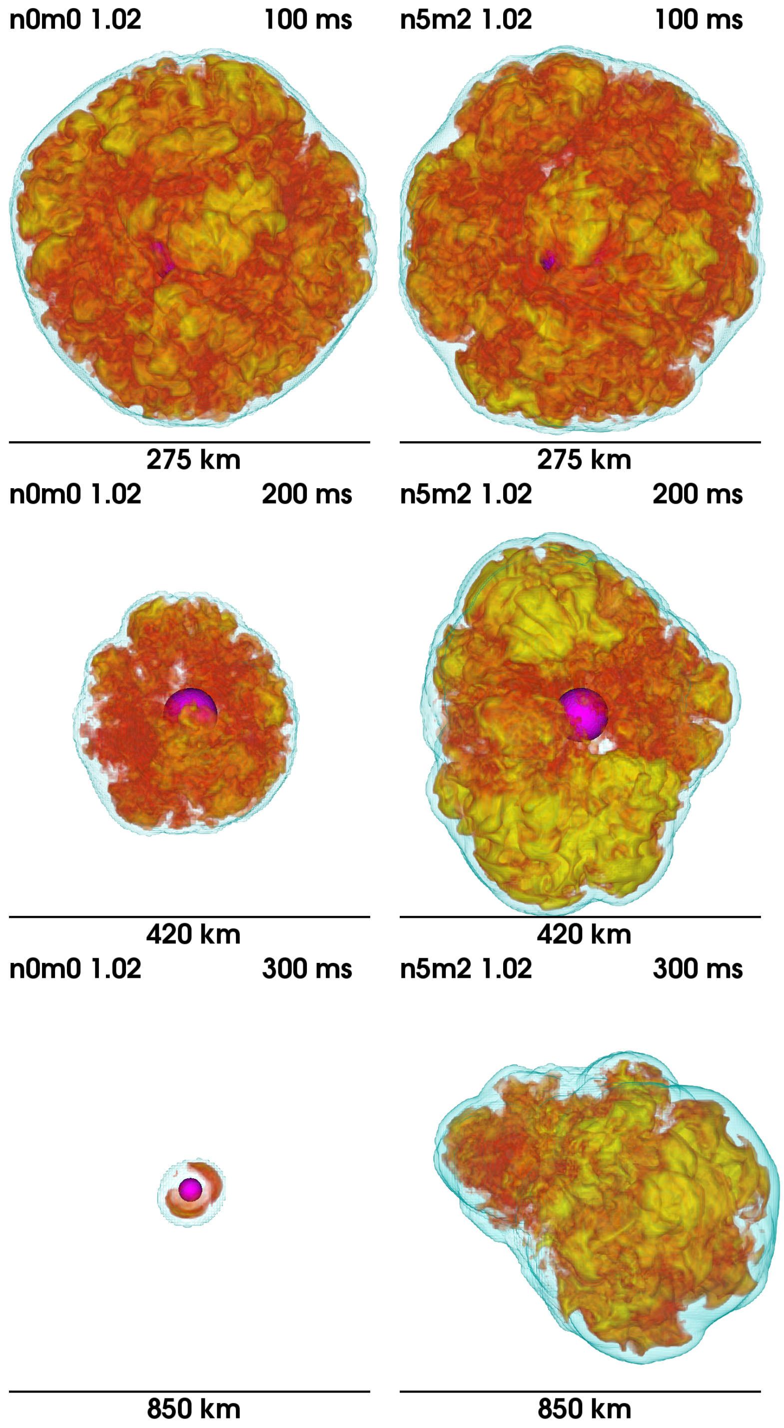
Couch & Ott 13, ApJL

- 3D simulations using FLASH with parameterized neutrino heating (Ott+13).
- Periodic velocity perturbations up to Mach 0.2, motivated by multi-D stellar models.



Example setup.
Velocity field perturbation.

Couch & Ott 13, ApJL

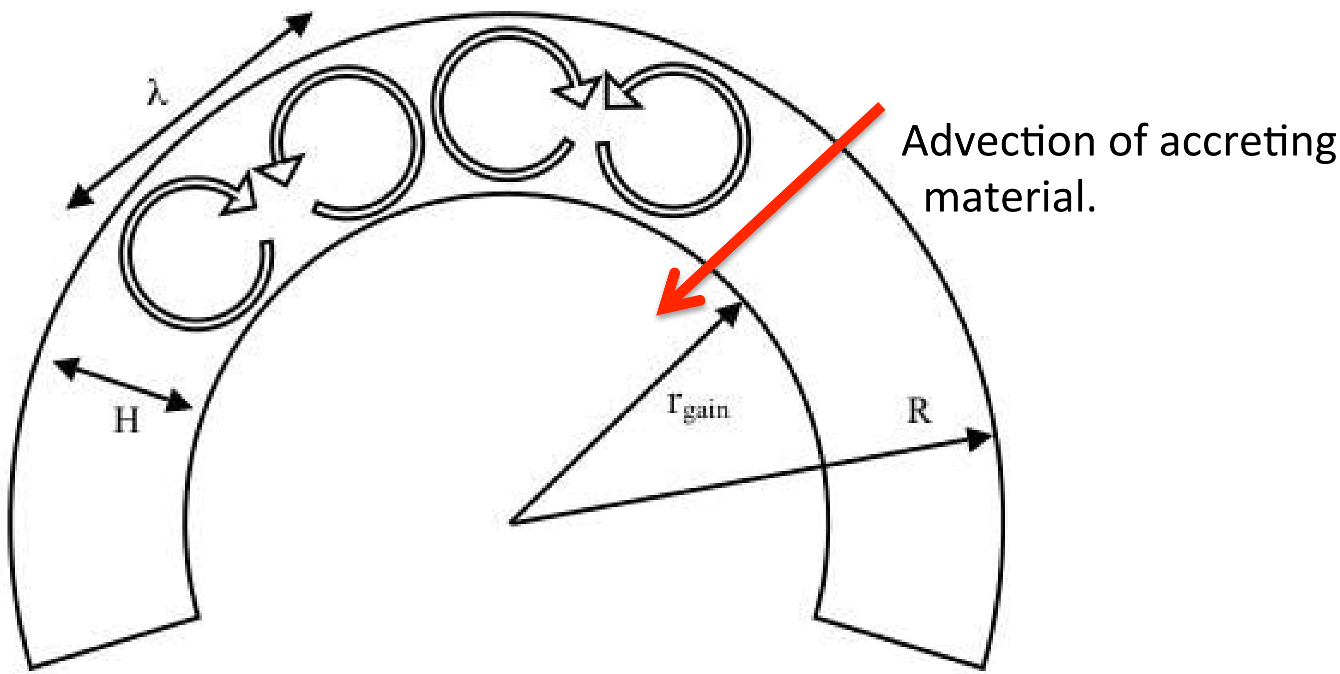


unperturbed

perturbed

The Role of Perturbations

Couch & Ott'13, ApJL

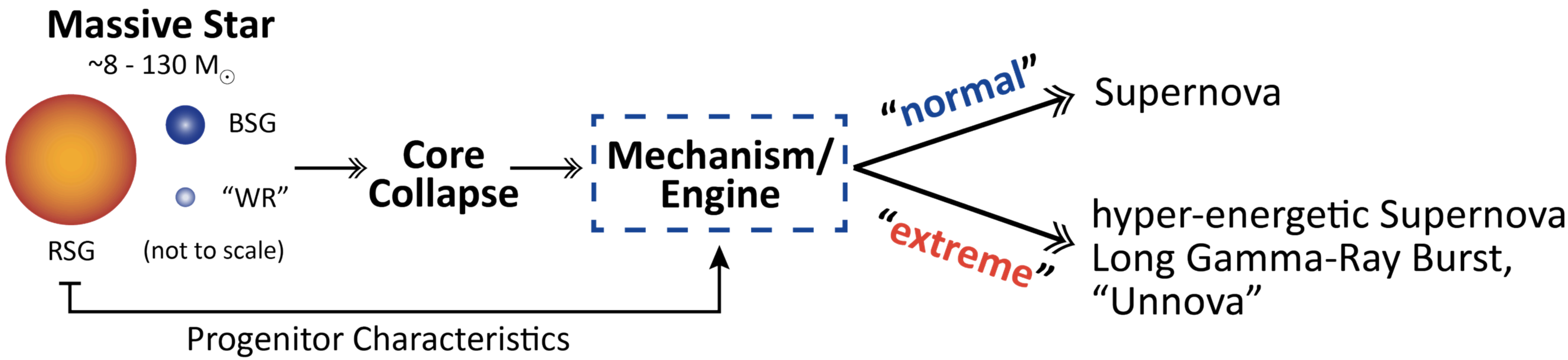


(Foglizzo+06, Scheck+08)

$$\chi \equiv \frac{\tau_{\rm adv}}{\tau_{\rm buoy}} \sim \frac{H}{v}\omega_{\rm BV}$$

- **Perturbations can be important**
  - **-> Larger perturbations -> stronger convection.**
  - -> 3D stellar evolution must tell us what they are!
  - -> Must study sensitivity to magnitude/type of perturbation.

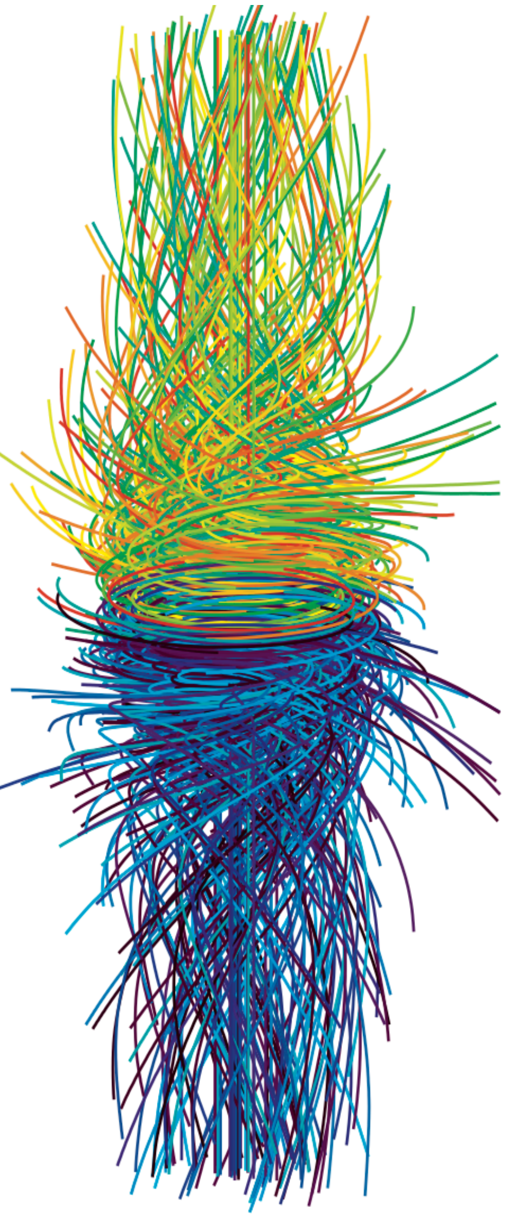
More Problems: Hypernovae & GRBs



- 11 long GRB – core-collapse supernova associations.
- **All GRB-SNe are of type "Ic-bl"**: no H, He in spectra, relativistic velocities (bl: "broad lines"), hypernova energies ($\sim 10^{52}$ erg).
- Neutrino mechanism is inefficient ($\eta \sim 10\%$);
  can't deliver a hypernova.
- What mechanism drives these extreme explosions?

Magnetorotational Mechanism

[LeBlanc & Wilson ‘70, Bisnovatyi-Kogan ’70, Burrows+ ‘07, Takiwaki & Kotake ‘11, Winteler+ 12]



Burrows+’07

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI]; difficult to resolve, but see, e.g, Siegel+13)

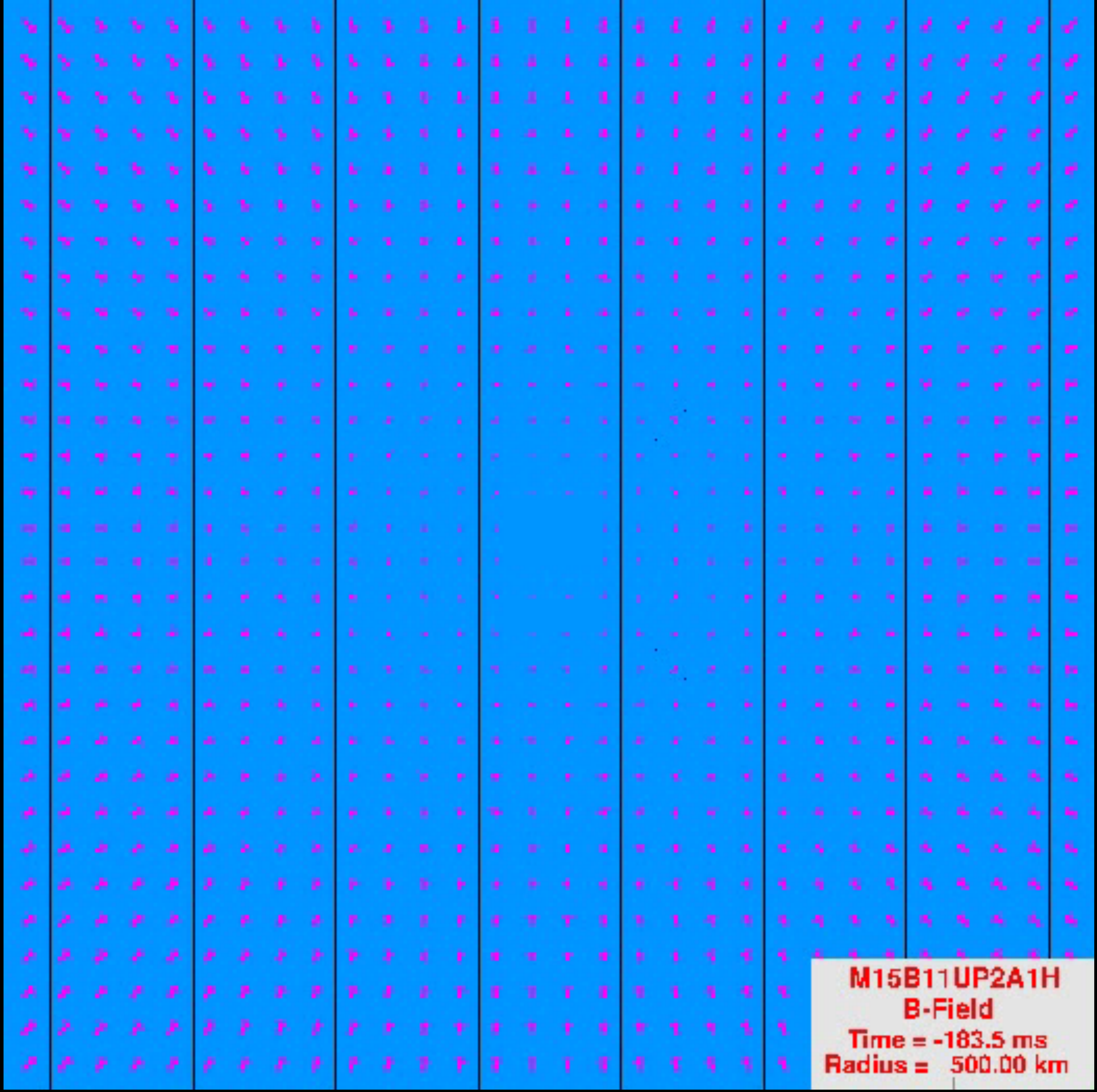
2D: Energetic bipolar explosions.

Results in ms-period proto-magnetar.
GRB connection?

Caveat: Need high core spin; only in very few progenitor stars?

Burrows+'07

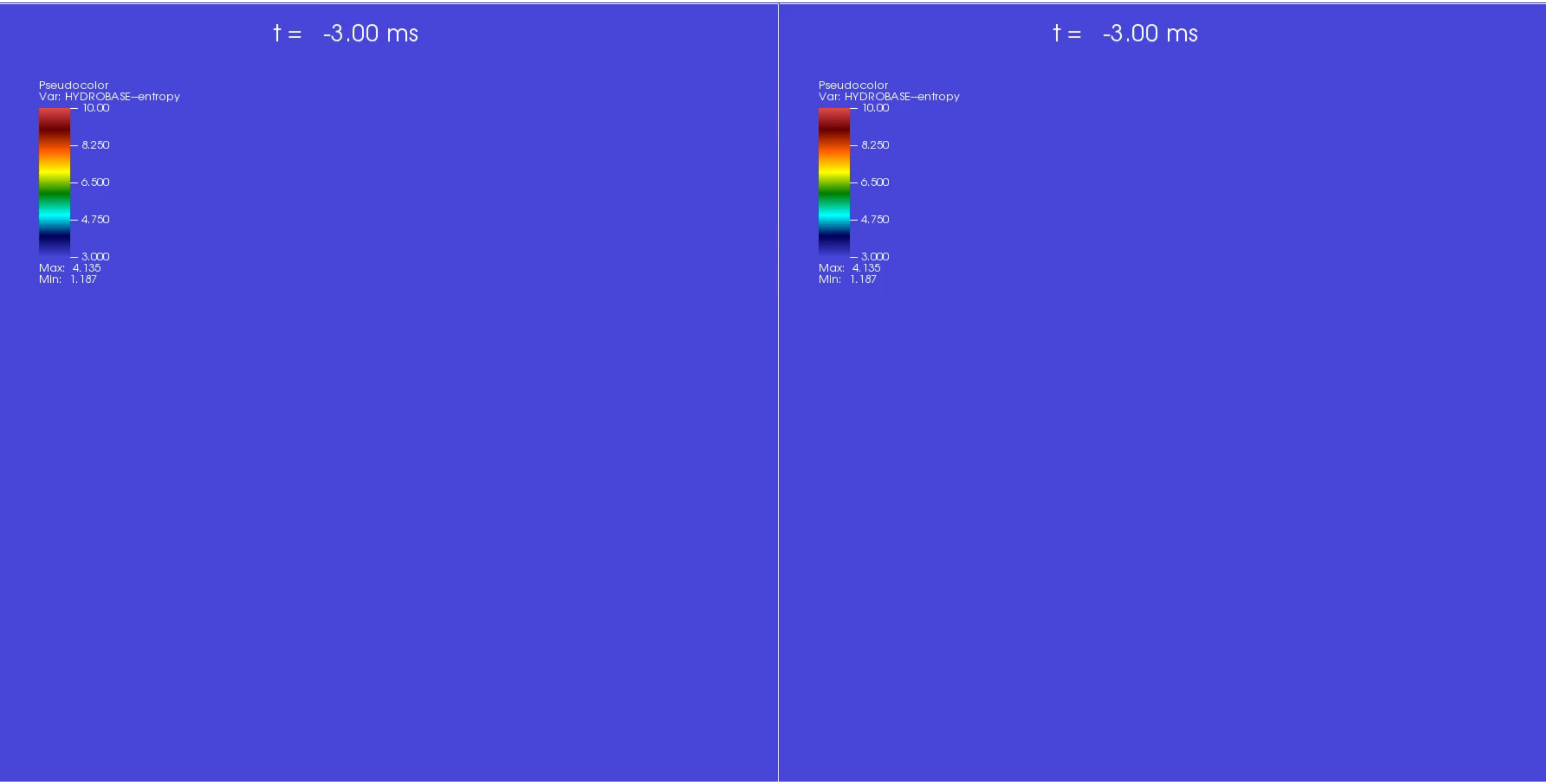
(10^{11} G
seed field)



3D Dynamics of Magnetorotational Explosions

New, full 3D GR simulations. **Mösta et al. 2014**, ApJL accepted.
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km → ← 2000 km →



Octant Symmetry (no odd modes) Full 3D

$$\beta = \frac{P_{\mathrm{gas}}}{P_{\mathrm{mag}}}$$

t = -4.95 ms

Mösta et al. 2014

Some Other Candidate Mechanisms

Magneto-viscous/sonic Mechanism

[Akiyama+'03, Thompson+ '05, Suzuki+'08, Obergaulinger+'11]

-> viscous heating by the magnetorotational instability [MRI];
-> and/or dissipation of Alfven waves.

Phase-Transition Induced Mechanism

[e.g., Sagert +'09]

-> hadron-quark phase transition: second "collapse" and bounce of protoneutron star + shock -> explosion;
-> requires soft equation of state, now disfavored.

Acoustic Mechanism

[e.g., Burrows+'06,'07, Ott+'06, Weinberg&Quataert'08]

-> excitation of protoneutron star pulsations, damping via sound waves that become shocks & dissipate -> explosion;
-> disfavored: non-linear mode couplings limit amplitudes, amplification seen only by one group.

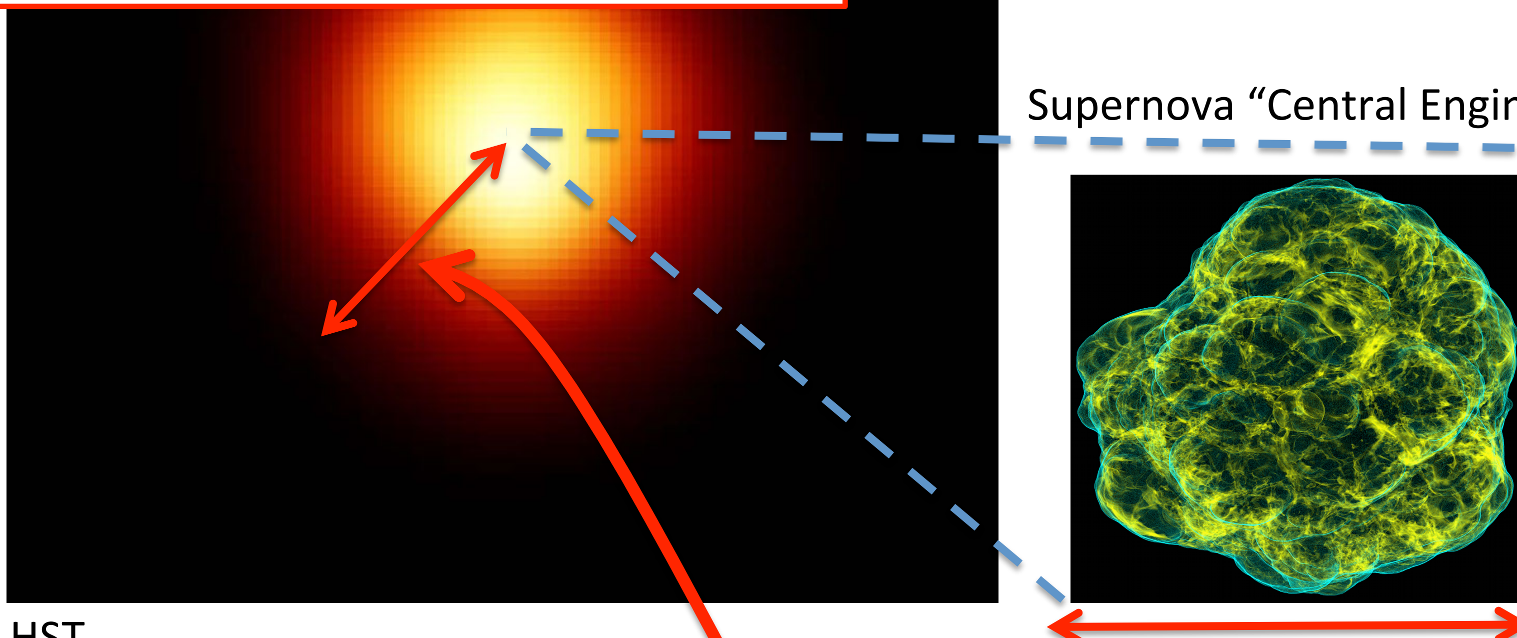
Observing the CCSN Mechanism

Probing the "Supernova Engine"

- **Gravitational Waves**
- Neutrinos (<- topic of another talk…),

EM waves (optical/UV/X/Gamma):
secondary information,
late-time probes of engine.

Red Supergiant
Betelgeuse
D ~200 pc



Gravitational Wave (GW) Refresher

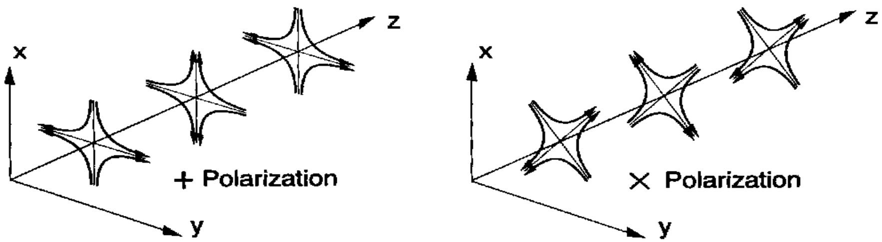
- Emission: **Accelerated quadrupole bulk mass-energy motion.**

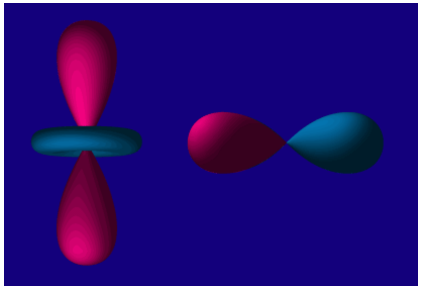
Quadrupole approximation

$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t-\frac{|\vec{x}|}{c})\right]^{TT}$$

$$\frac{G}{c^4} \approx 10^{-49}\,\mathrm{s}^2\,\mathrm{g}^{-1}\,\mathrm{cm}^{-1}$$

$$10\,\mathrm{kpc} \approx 3\times 10^{22}\,\mathrm{cm}$$





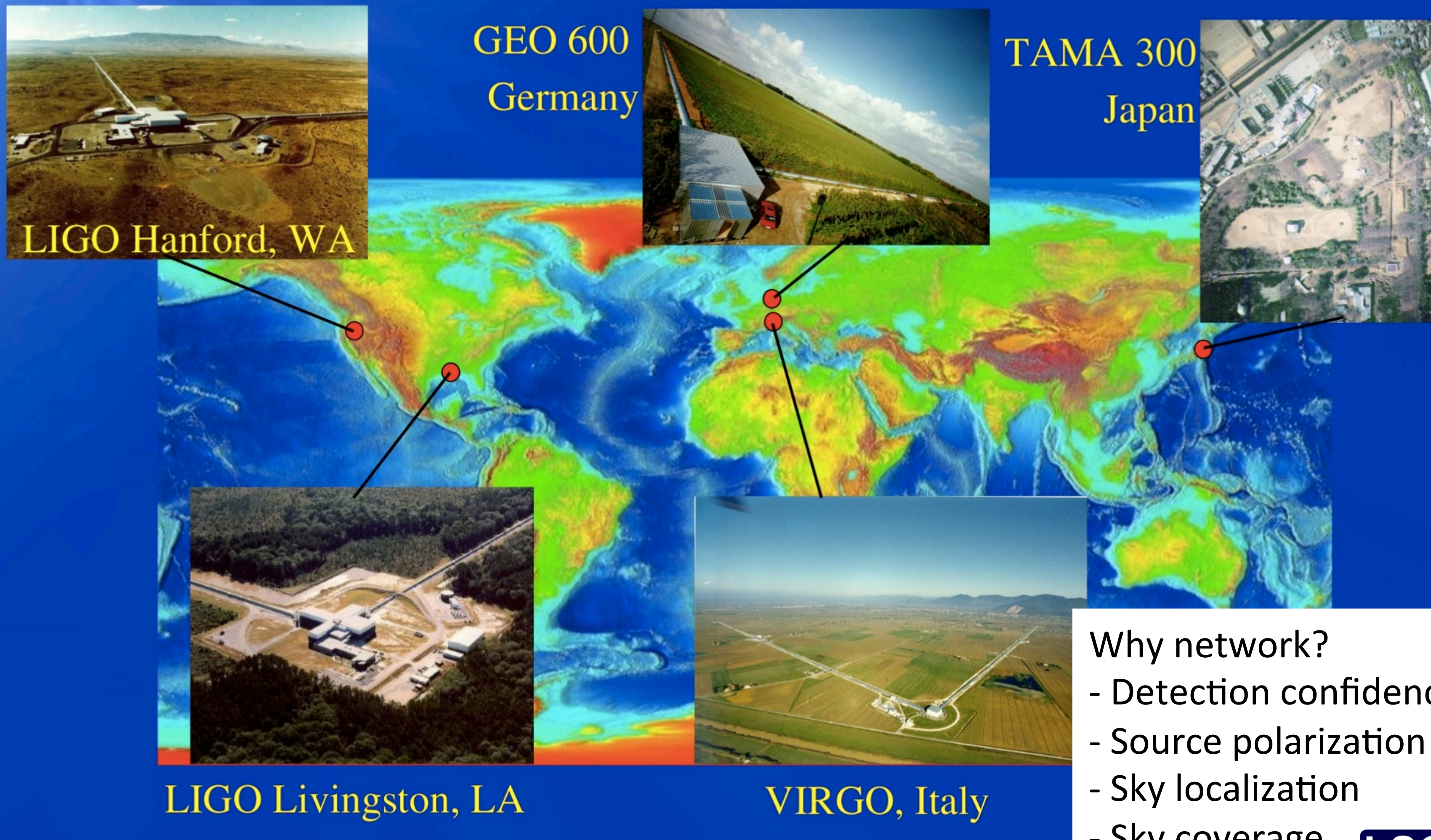
-> must measure relative displacements of 10^{-22}

- Detection:
  Measure changes in separations of test masses with laser interferometry.

Gravitational Wave Astronomy

International Network of LIGOs

First Generation: 2000 – 2010 – Haven't seen anything (yet)



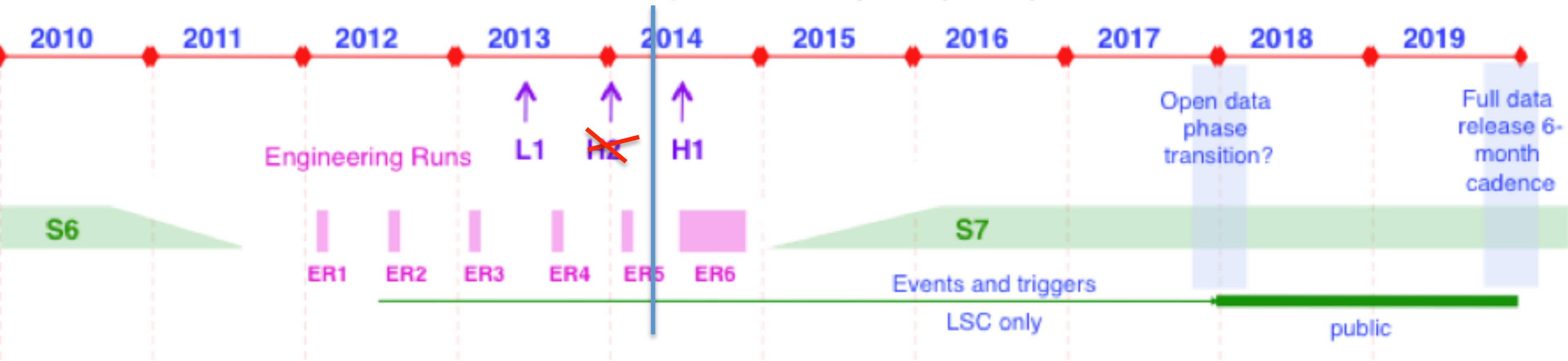
Why network?
- Detection confidence
- Source polarization
- Sky localization
- Sky coverage
- Duty cycle

Joint LIGO/GEO + Virgo data in most recent science runs.

What's going on with LIGO/Virgo?

- Upgrades to existing intoferometers
  -> **LIGO & Virgo are currently offline**. "Astrowatch" by GEO600.
- 10 x sensitivity -> 1000 x probed volume.
  Expect $\mathcal{O}(10)$ events / year.
- New interferometers: LIGO India (2020+), KAGRA (Japan, 2016+)

Advanced LIGO Schedule: https://dcc.ligo.org/LIGO-M1000066/public
http://www.ligo.org/magazine



- ~April 2014: Installation complete.
- ~Fall 2015: S7 science run (1 month)
- ~Summer 2014: Meet NSF detector-lock criterion.

Expected Detection Rates: Coalescence (at full sensitivity)

- Summarized in Abadie et al., CQG 27, 173001 (2010) :

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

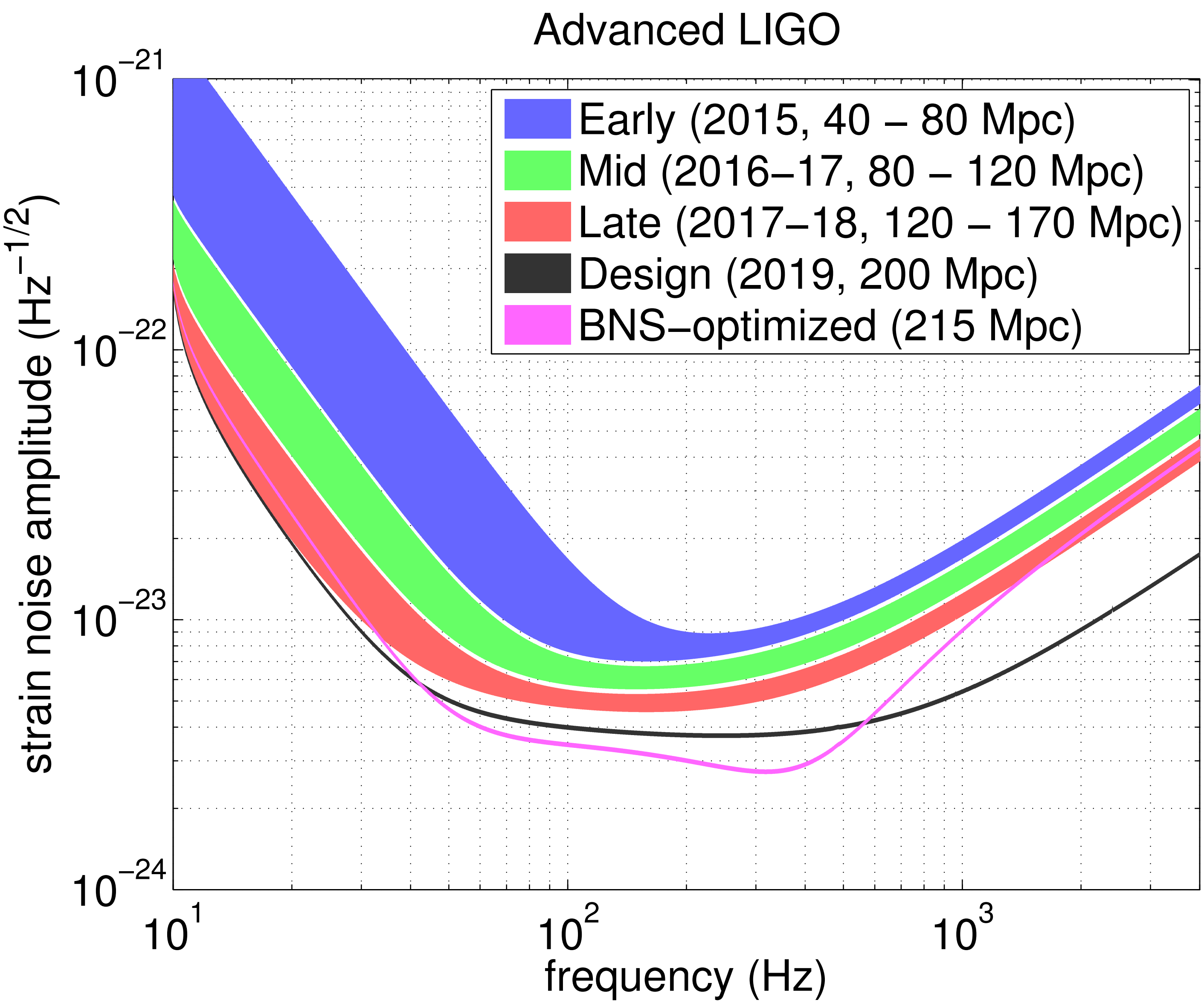
Warning:
Population synthesis!

"Realistic" (=best-guess) event rates per year with advanced detectors later this decade

LSC VIRGO

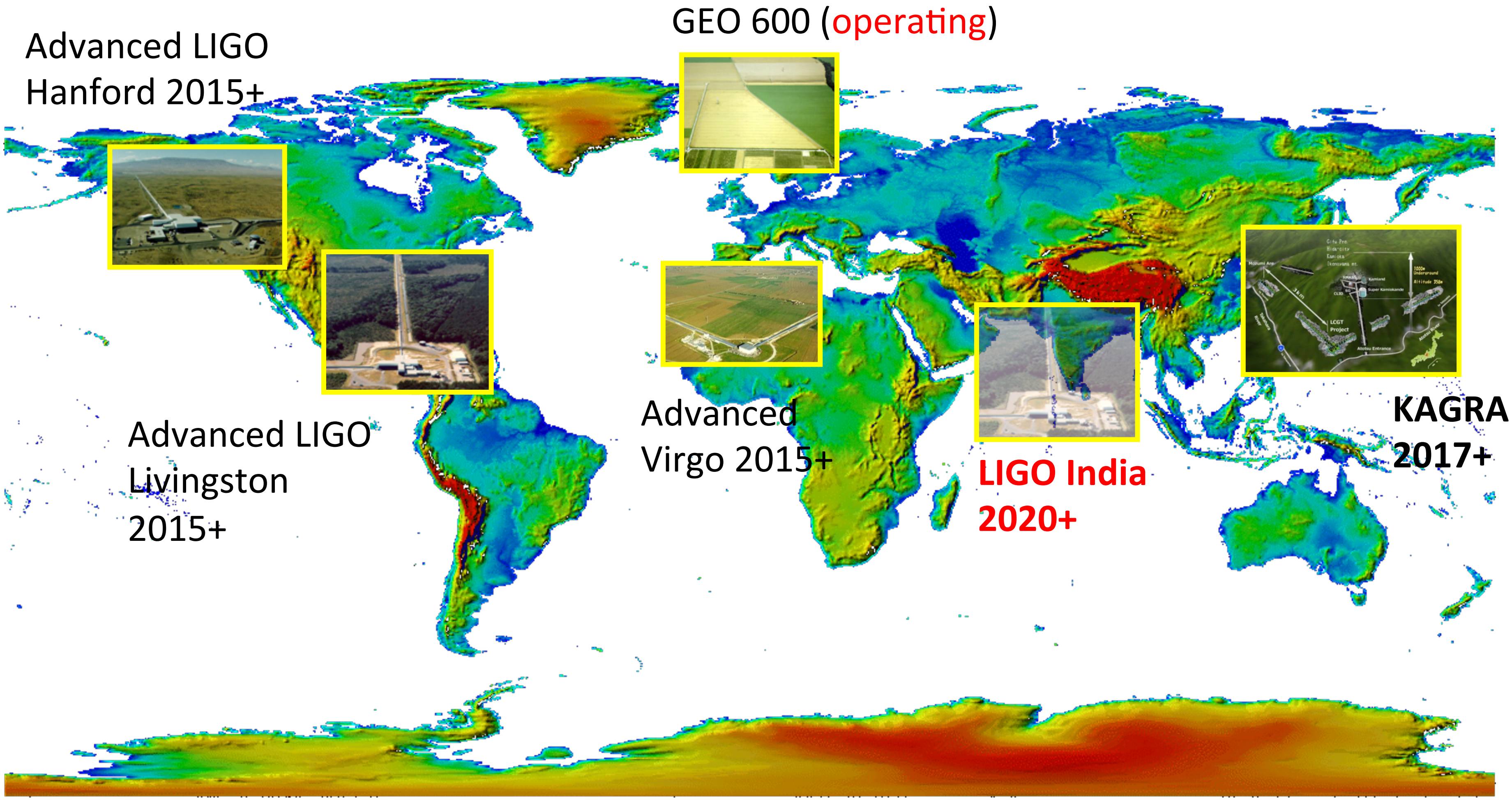
Expected Sensitivity

arXiv:1304.0670



Adv. Virgo on similar schedule, shifted by 1-2 years.

The Advanced GW Detector Network: 2020+



Gravitational-Waves from Core-Collapse Supernovae

Recent reviews: Ott 09, Kotake 11, Fryer & New 11

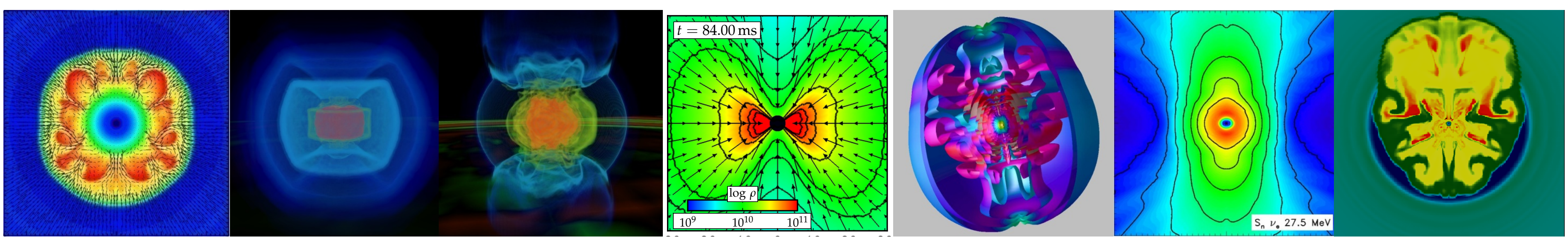
Need:

$$h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}(t-\frac{|\vec{x}|}{c})\right]^{TT}$$

→ accelerated aspherical (quadrupolar) mass-energy motions

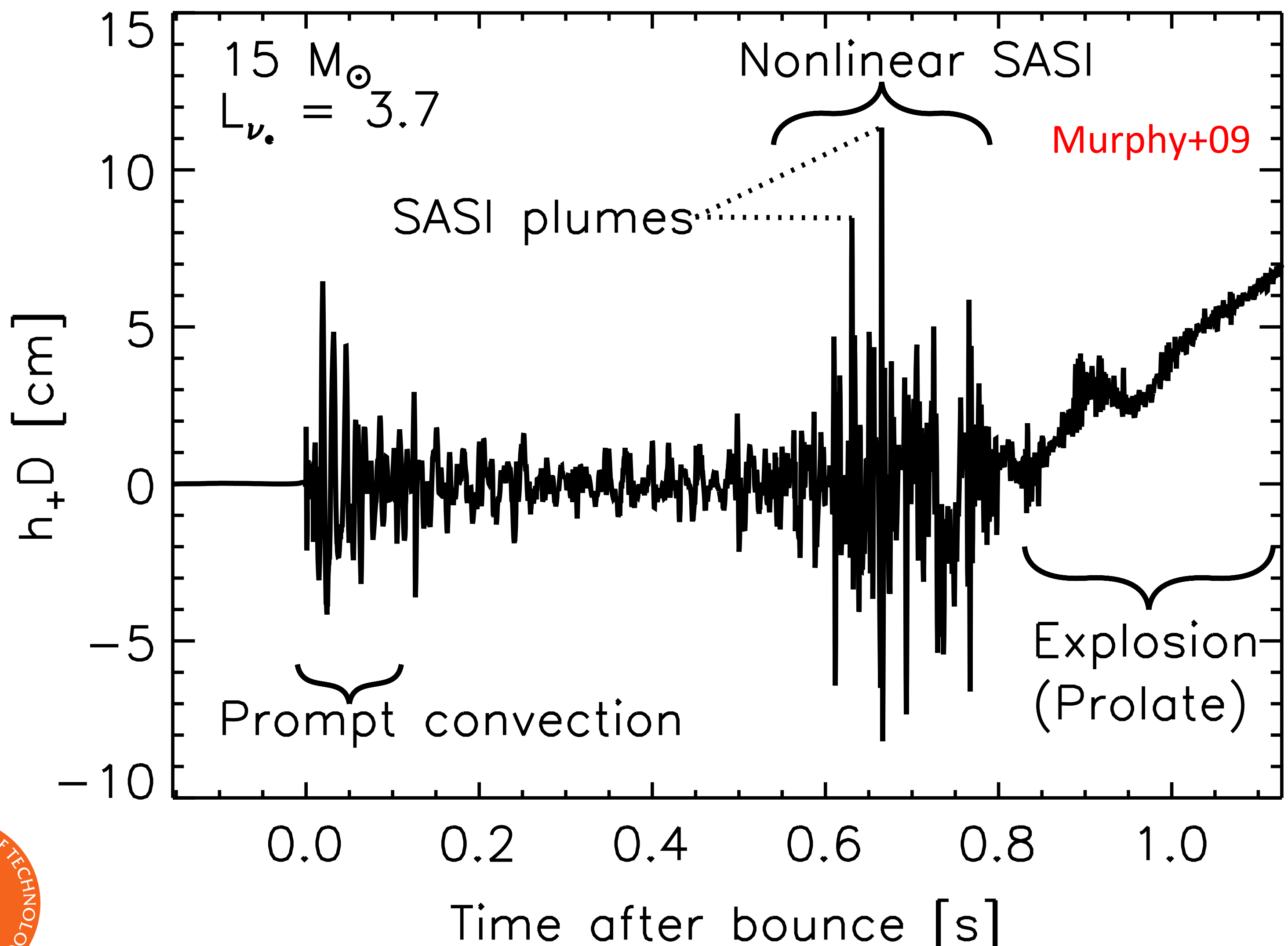
Candidate Emission Processes:

- **Turbulent convection/SASI**
- **Rotating collapse & bounce**
- 3D MHD/HD instabilities
- Aspherical mass-energy outflows



GWs from Convection & Standing Accretion Shock Instability

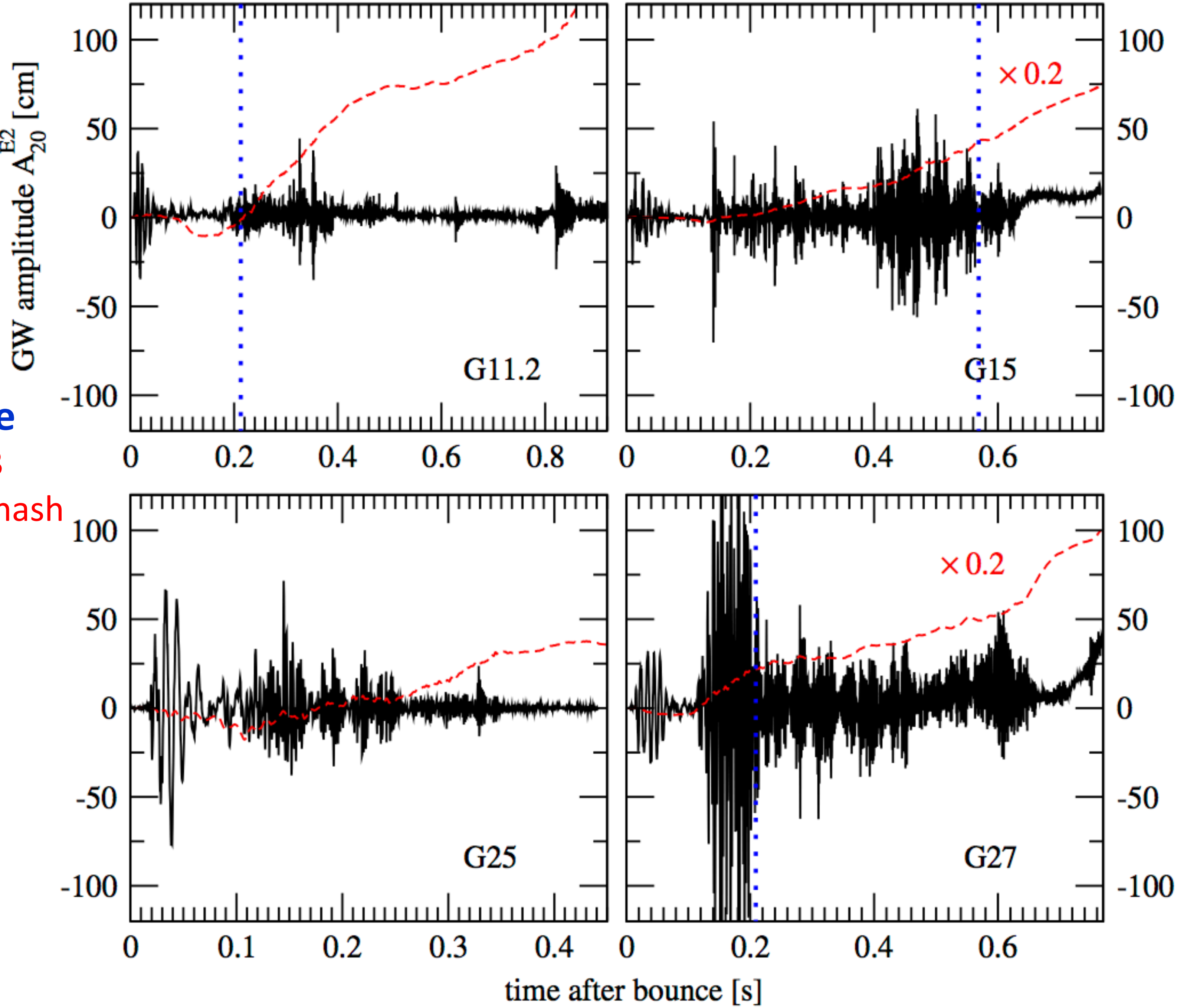
Recent work: Murphy+09, Kotake+09, 11, Yakunin+10, E. Müller+12, **B.Müller+13**



Progenitor Dependence

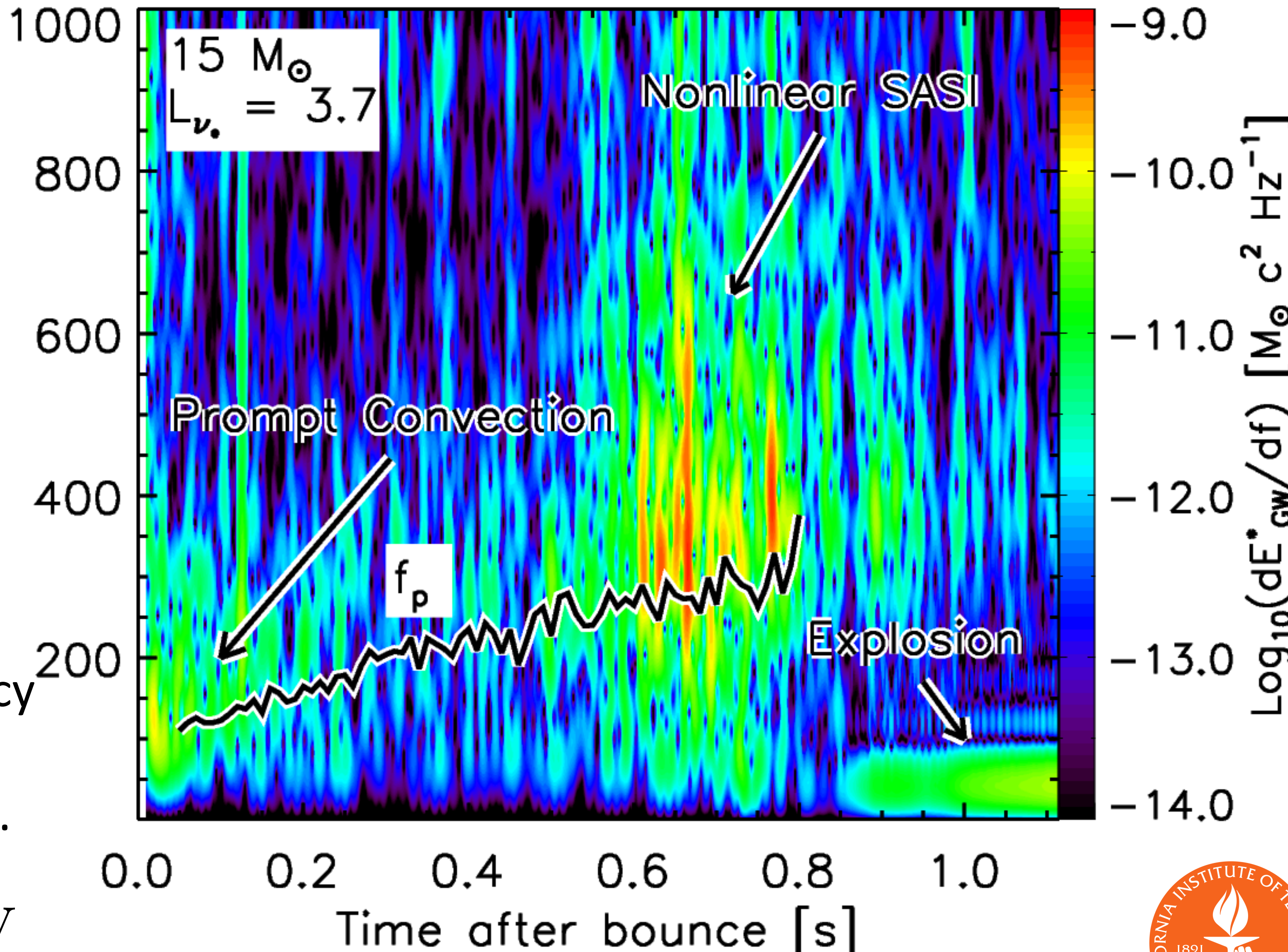
B. Mueller+13

Garching/Monash



Time-Frequency Analysis of GWs

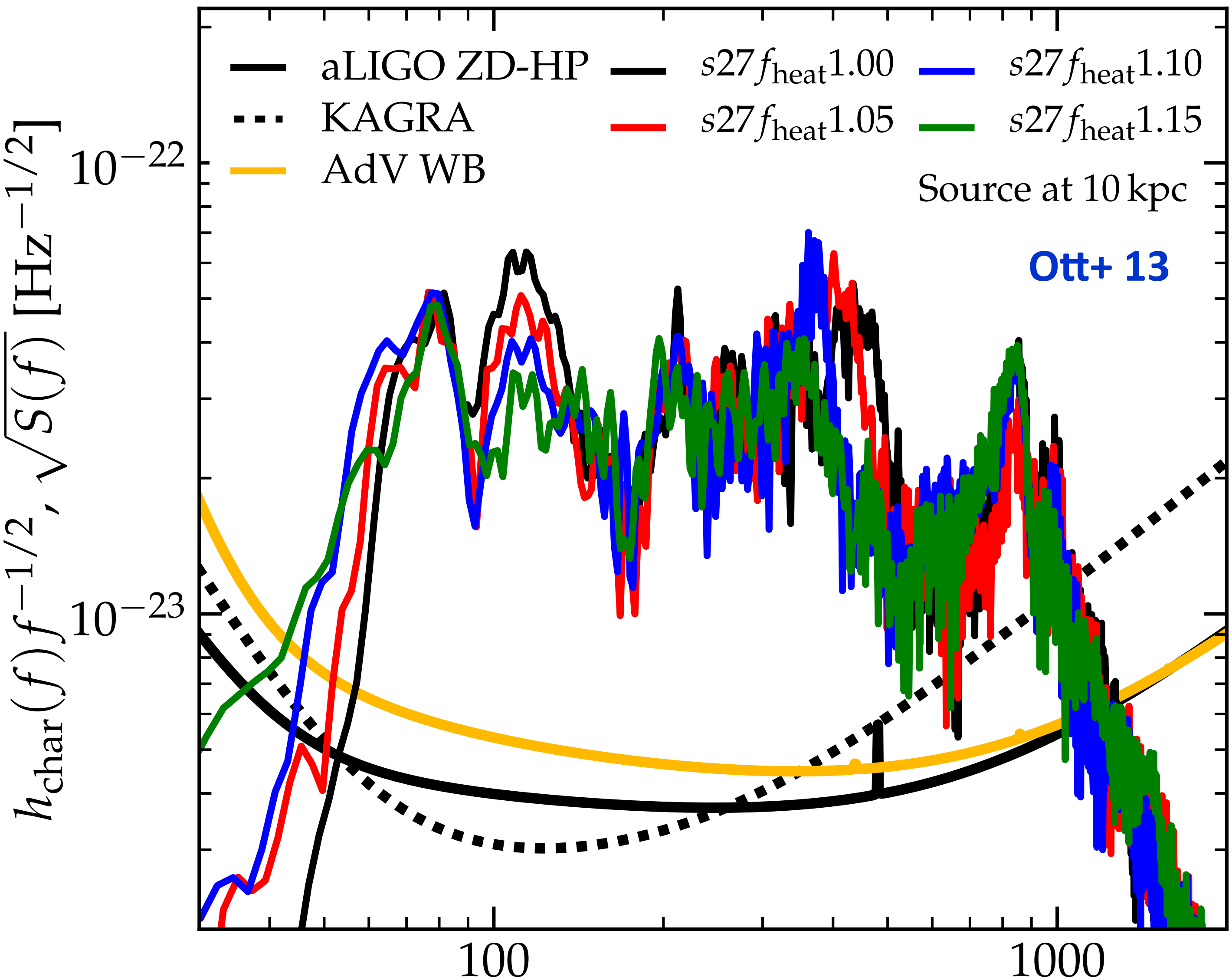
Murphy, Ott, Burrows 09, **see also B. Müller+13**



Peak emission traces buoyancy frequency at proto-NS edge.

$$f_p \sim \frac{\omega_{\mathrm{BV}}}{2\pi}$$ (buoyancy frequency)

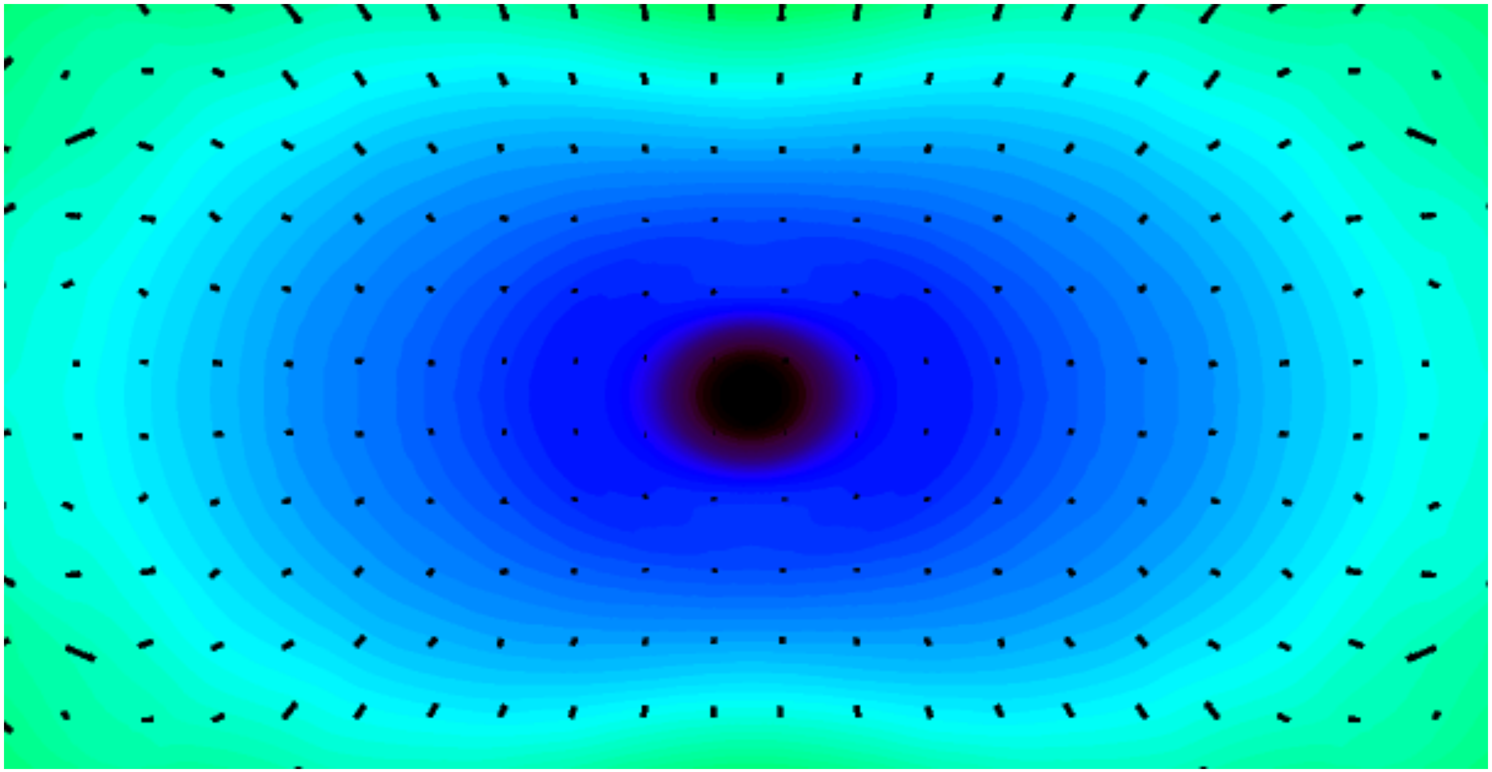
Detectability?



$$h_{\rm char}(f) = \sqrt{\frac{2}{\pi^2} \frac{G}{c^3} \frac{1}{D^2} \frac{dE_{\rm GW}(f)}{df}},$$

GWs from Rotating Collapse & Bounce

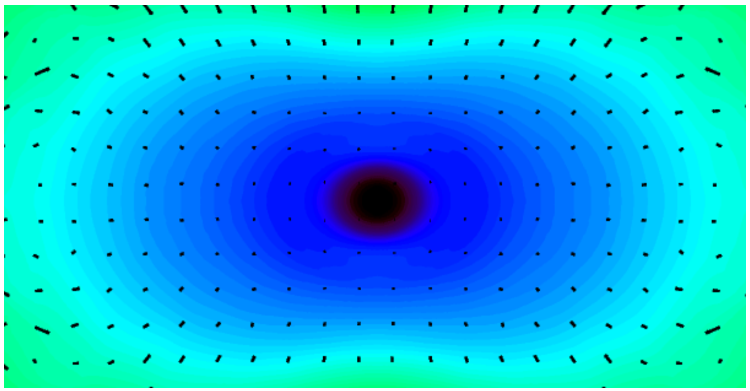
Recent work: Dimmelmeier+08, Scheidegger+10, Ott+12, Abdikamalov+13



GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+08, Scheidegger+10, Ott+12, Abdikamalov+13

Rapid rotation:
Oblate deformation of the inner core

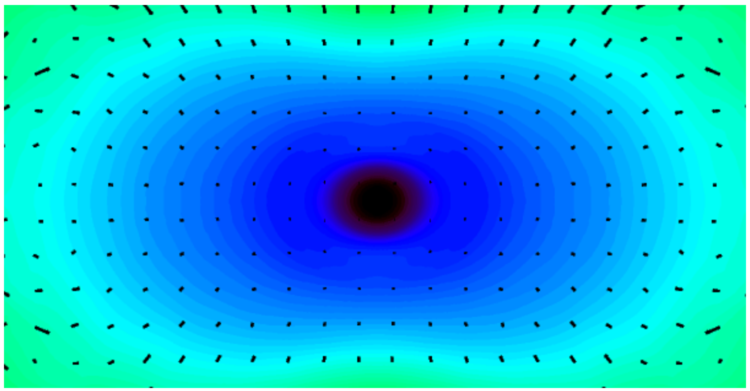


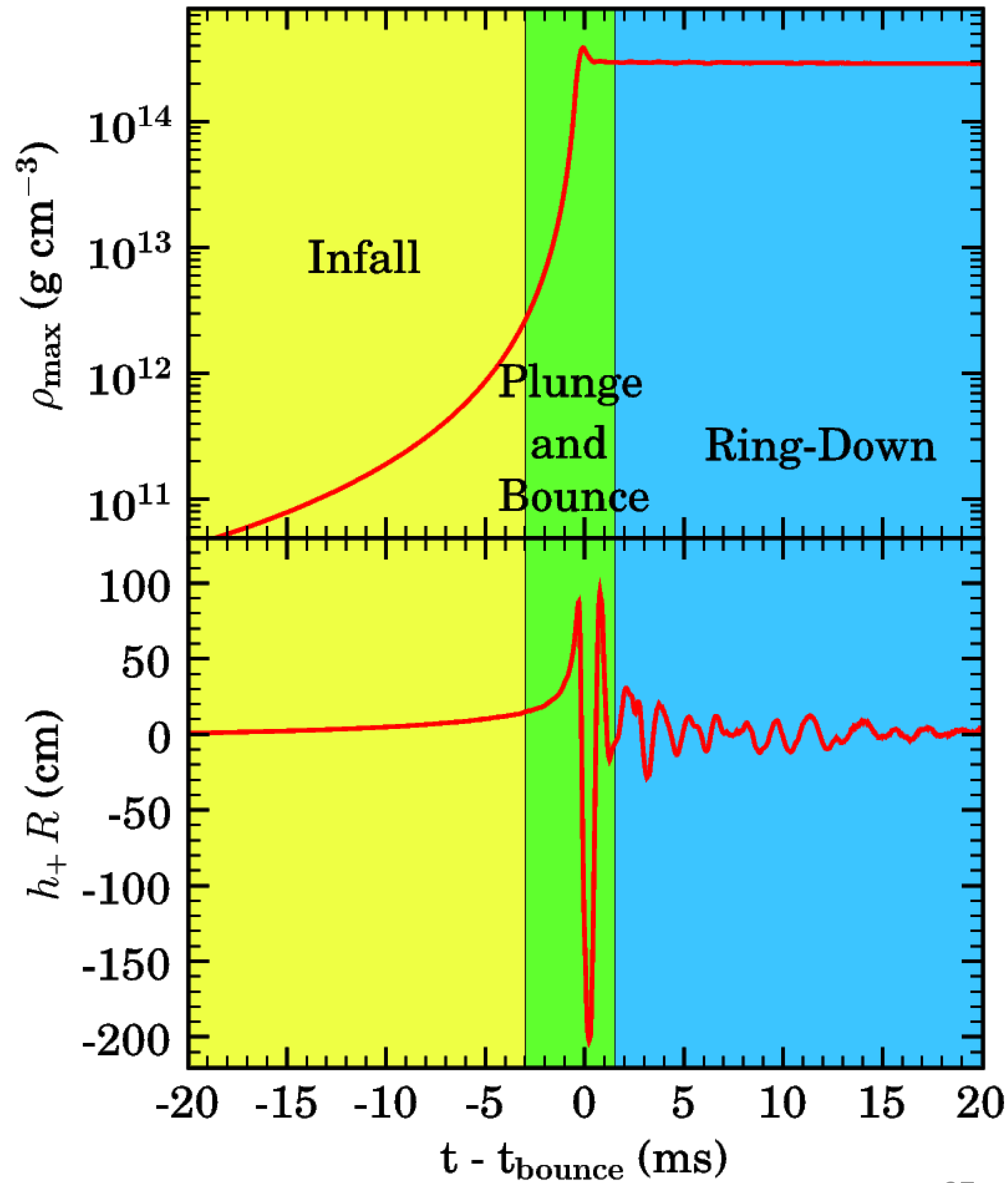
- **Axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + mass of the inner core + **gravity** + **stiffening of nuclear EOS**
- Strong signals for rapid rotation (-> millisecond proto-NS).

GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+08, Scheidegger+10, Ott+12, Abdikamalov+13

Rapid rotation:
Oblate deformation of the inner core



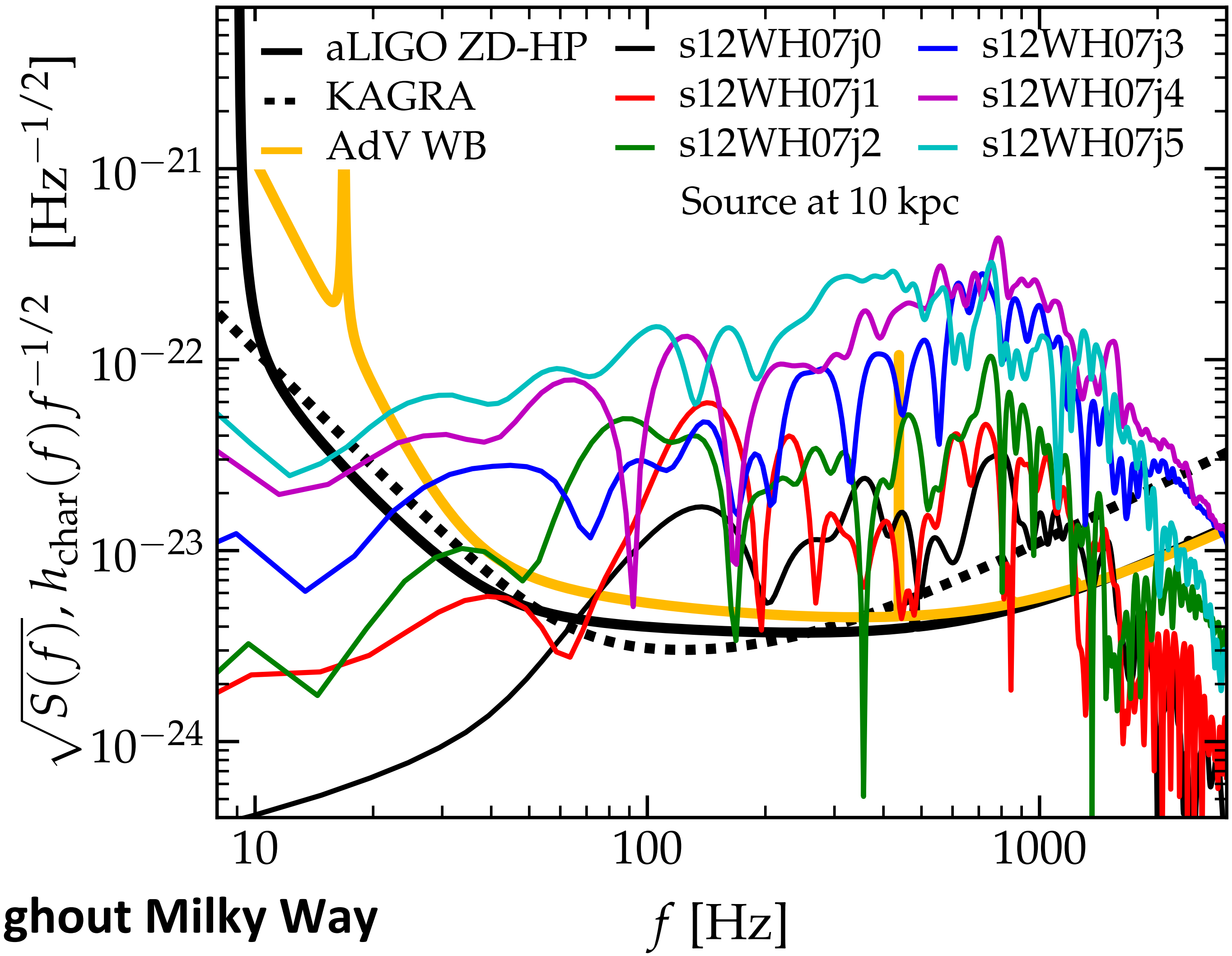


- **Axisymmetric:** **ONLY h_+**
- Simplest GW emission process: **Rotation** + mass of the inner core + **gravity** + **stiffening of nuclear EOS**
- Strong signals for rapid rotation (-> millisecond proto-NS).

Can we observe these waves?

Ott+ 12, PRD

Gravitational Waves $E_{GW} \lesssim 10^{-8} M_{\odot} c^2$

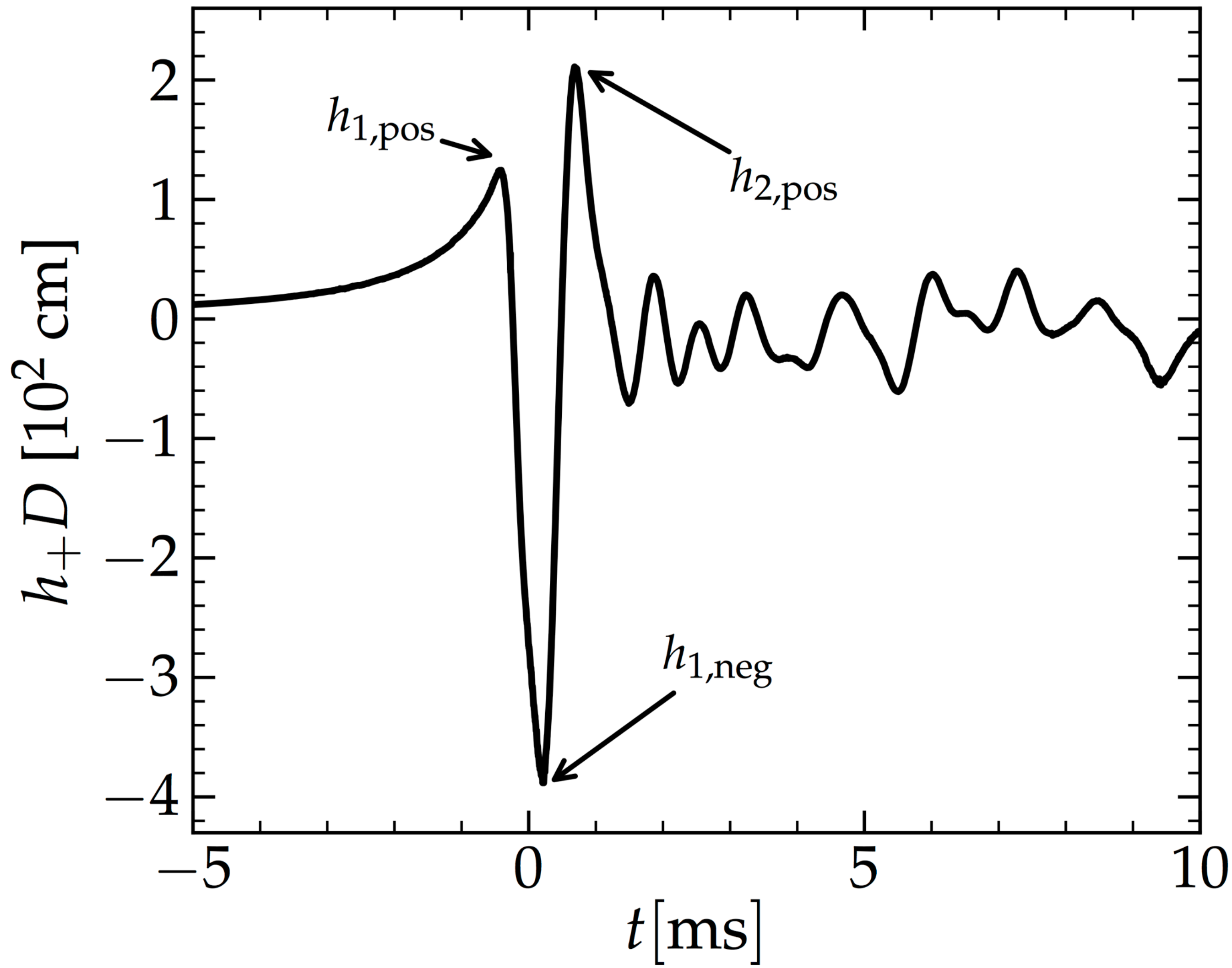


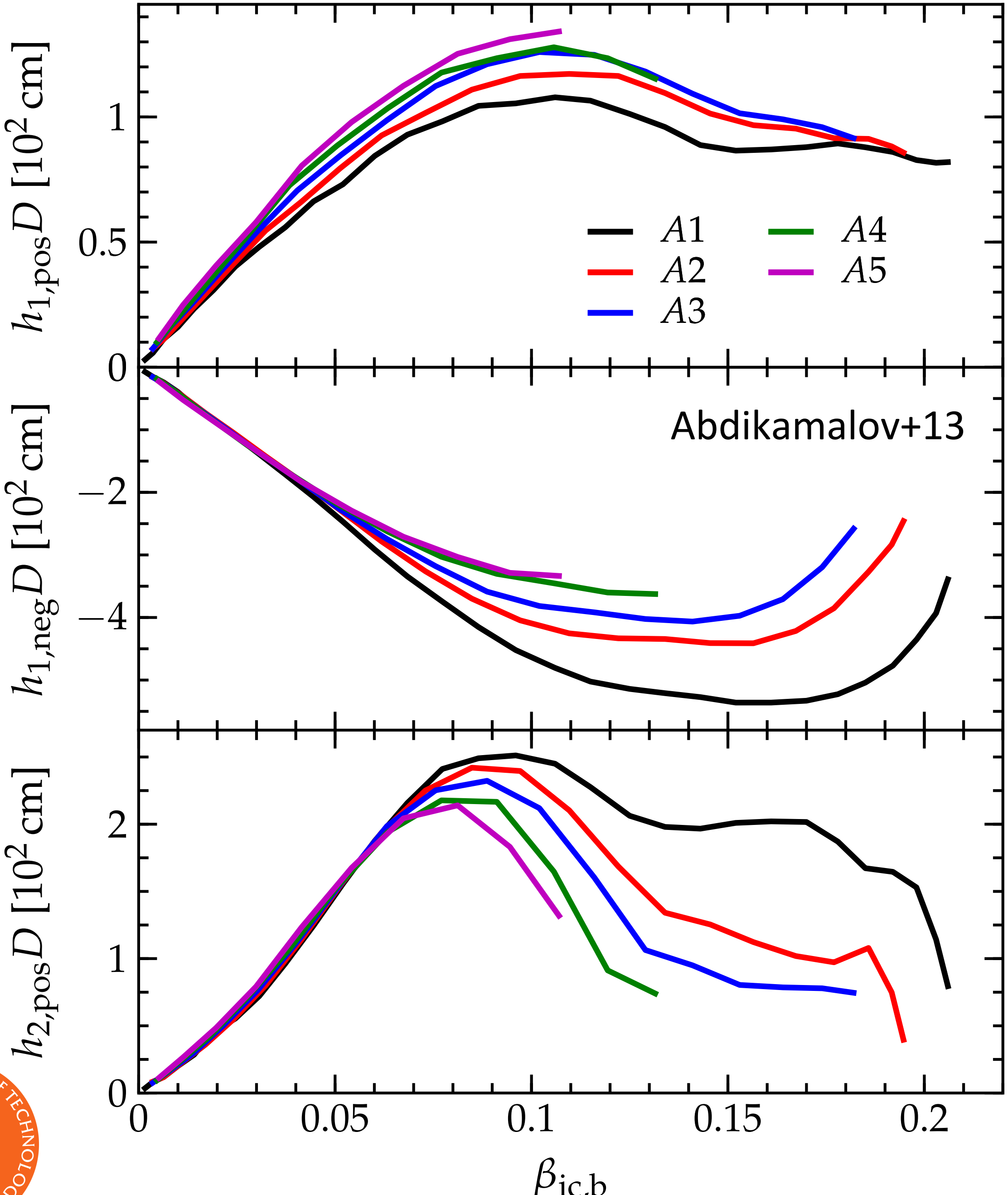
-> Throughout Milky Way with aLIGO

GWs from Rotating Collapse & Bounce

Abdikamalov, Gossan, DeMaio, Ott, arXiv:1311.3678

Simple signal features:





Measure for "total rotation" of the inner core:

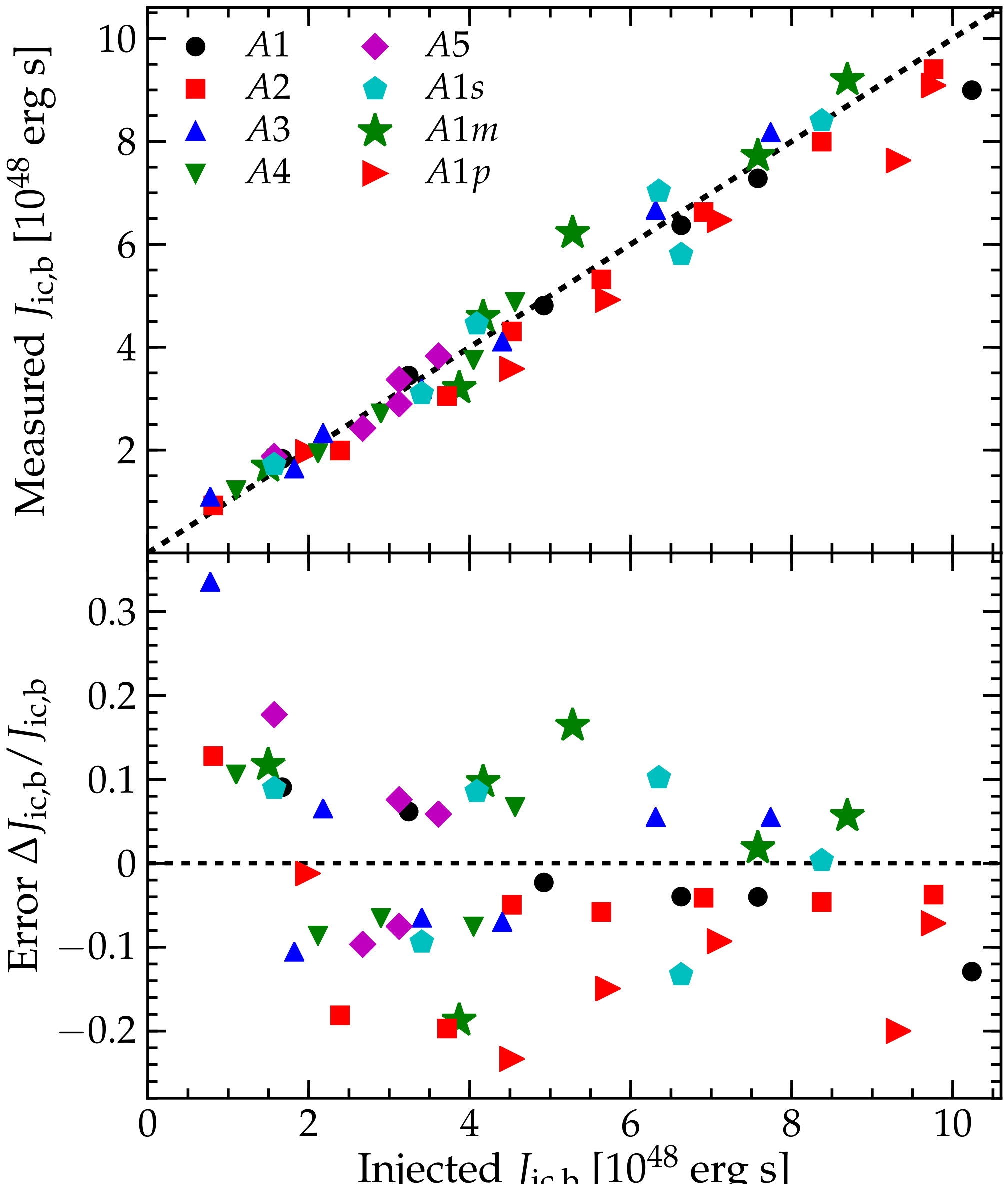
$$\beta = \frac{T}{|W|}$$

Closely related to inner core angular momentum

A1(most) – A5(least) differential rotation.

Measuring Inner Core Angular Momentum

Abdikamalov, Gossan, DeMaio, Ott, arXiv:1311.3678



Matched-filtering analysis.

Unknown signal injected into simulated detector noise.

Can measure inner core angular momentum with < 30% error!

Summary

- We are still not sure how precisely core-collapse supernovae explode.
- Multi-D neutrino mechanism is the best bet. 3D presupernova structure important (?).
- 3D dynamics breaks 2D MHD-driven jets.
- **The next galactic core-collapse supernova has already exploded.**
  (But its GWs/neutrinos/EM waves won't arrive until 2015+ [-> advanced LIGO].)
- Gravitational waves and neutrinos probe the supernova dynamics and progenitor star properties.