(1) Update on Gravitational-Wave Detectors

(2) Studying Core-Collapse Supernovae with Gravitational Waves (and Neutrinos)

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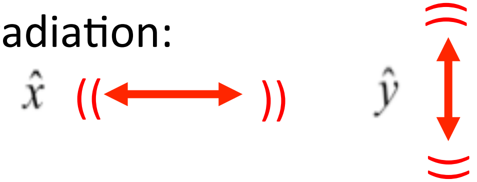
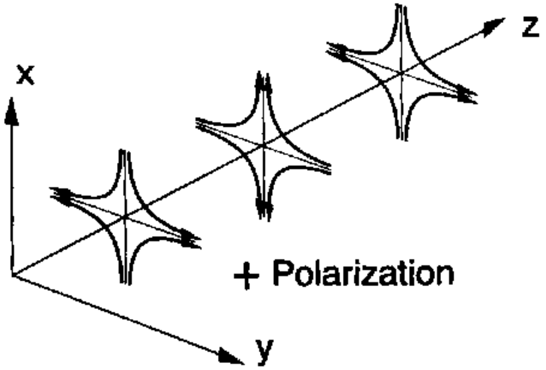
Part (1) is for the LIGO Scientific Collaboration and the Virgo Collaboration

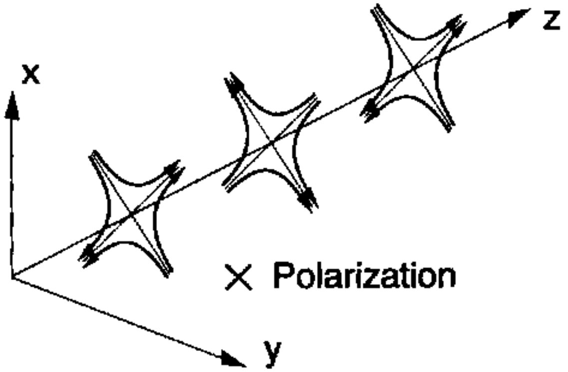
What are Gravitational Waves?

Two Polarizations:

Contrast with EM dipole radiation:







Slow-Motion, Weak-Field Quadrupole Approximation

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

"Transverse-Traceless Gauge"

dimensionless GW "strain" (displacement)

mass quadrupole moment

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

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

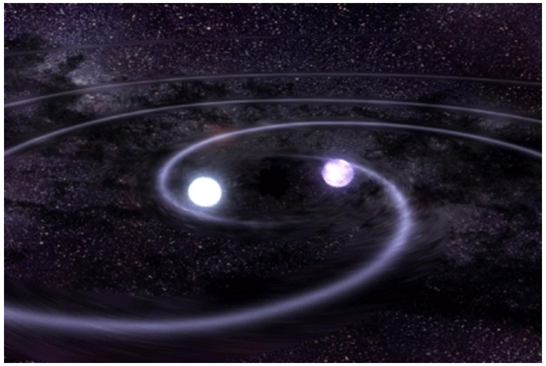
- GWs are very weak and interact weakly with matter.
  - No human-made sources.
  - Bad: *Very hard to detect.*
  - Good: ***Travel from source to detectors unscathed by intervening material.***

$$h \lesssim 10^{-21}$$

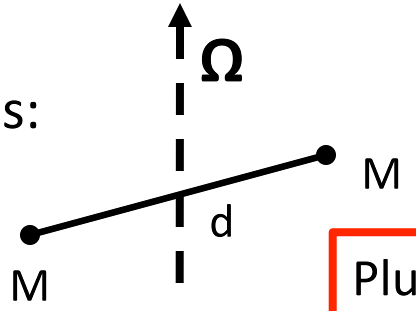
(for most astrophysical sources)

Gravitational Wave Emission

Canonical example:
Binary of two compact stars (mix of WDs,NSs,BHs).
Inspiral and merger driven by GW emission.



What GW amplitudes to expect?
Some back of the envelope physics:



$$I \sim M d^2 \sin 2\Omega t \qquad \Omega = \sqrt{\frac{GM}{d^3}}$$

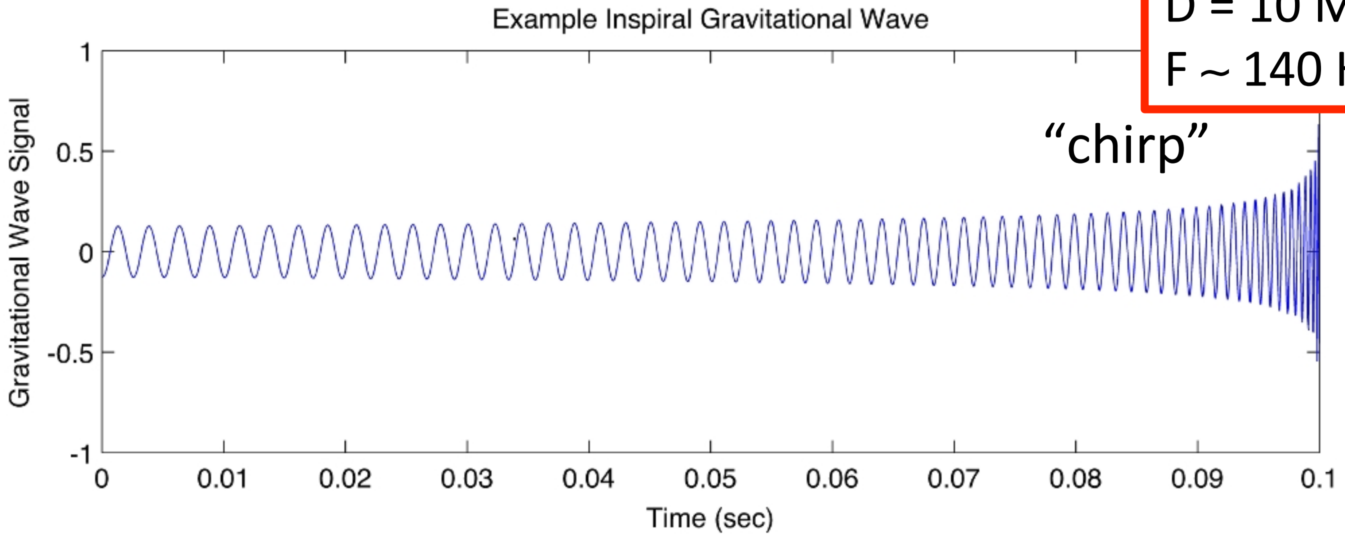
$$h \sim \frac{G}{c^4}\frac{2}{D} I \sim \frac{G}{c^4}\frac{8 M d^2 \Omega^2}{D} \sin 2\Omega t$$

Plugging in some numbers:
$M = 1.4\ M_{Sun}$
d = 100 km
D = 10 Mpc
F ~ 140 Hz.

-> **$h \sim 10^{-21}$**

Detecting GWs is really hard!

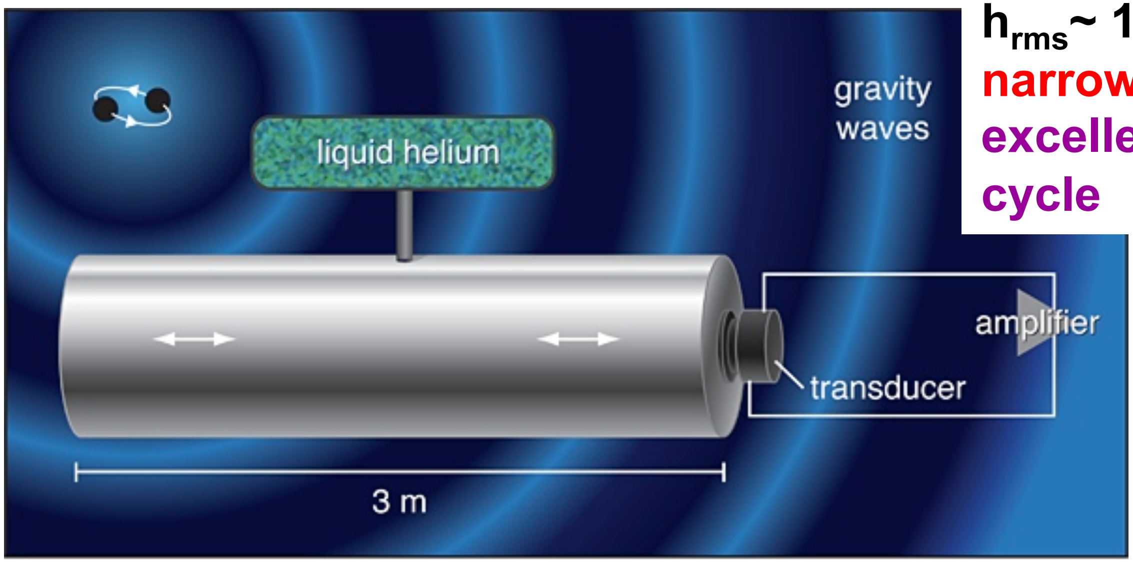
Example Inspiral Gravitational Wave



"chirp"

Detecting Gravitational Waves

Initial idea: **Resonant Bar Detectors**



Auriga

sensitivity:
$h_{rms} \sim 10^{-19}$;
narrow-band,
excellent duty cycle

Joe Weber

Multiple bars on-line:
Explorer (at CERN)
Auriga (Padova)
Nautilus (Frascati)
Allegro (LSU)
Schernberg (Sao Paulo)

Broadband Gravitational-Wave Detectors

Laser Interferometer
Rai Weiss 1973, MIT
(idea floating around since mid-1950s)

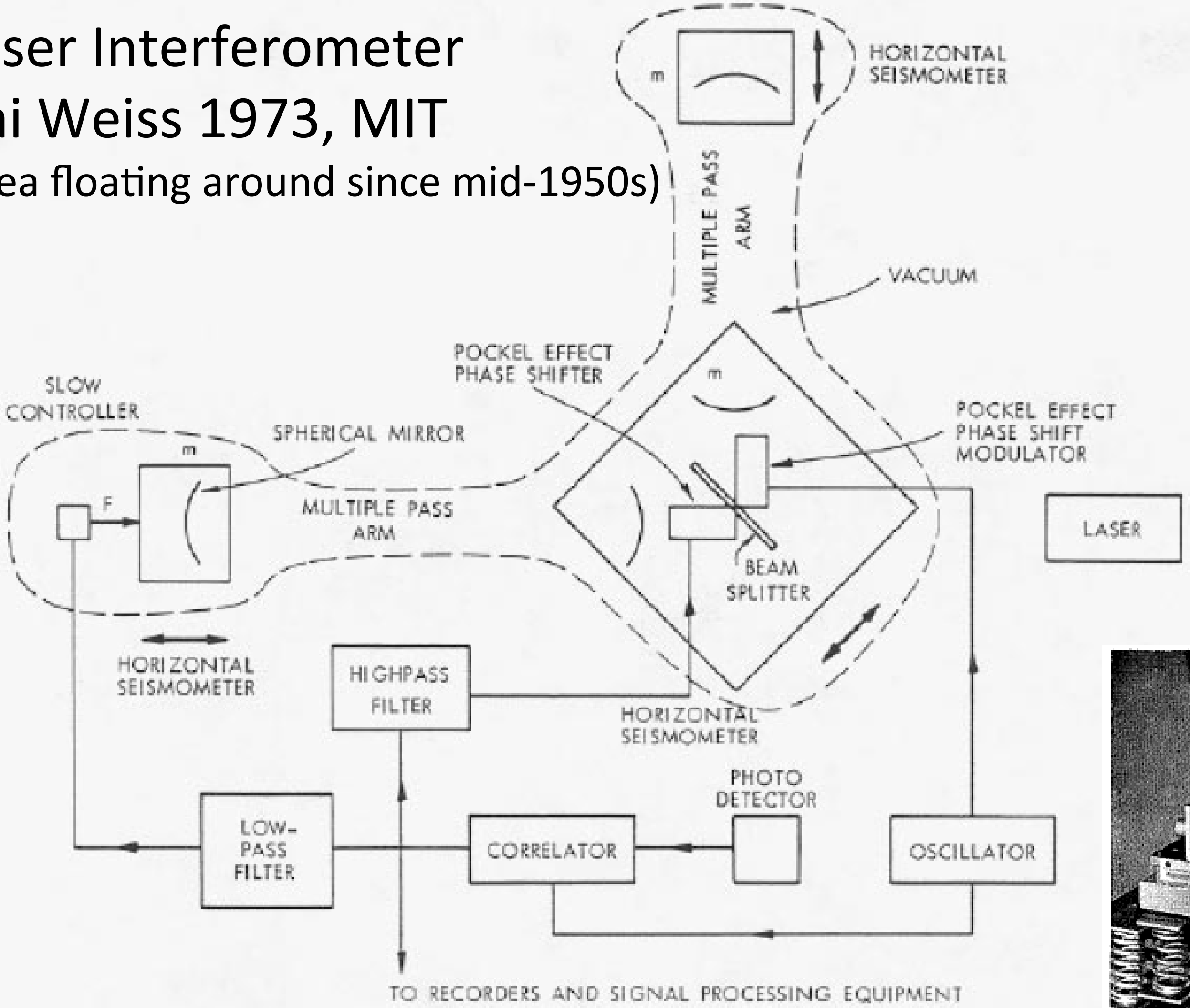


Fig. V-20. Proposed antenna.

Rai Weiss

R. L. Forward,
Hughes Research, 1973

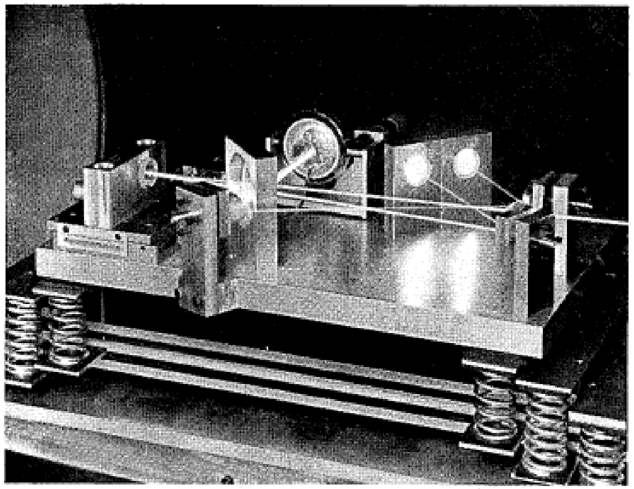


Fig. 4. Photograph of interferometer setup on 3-Hz isolation suspension.

Prototypes in 70's & 80's at Garching, Glasgow, Caltech & other institutions.

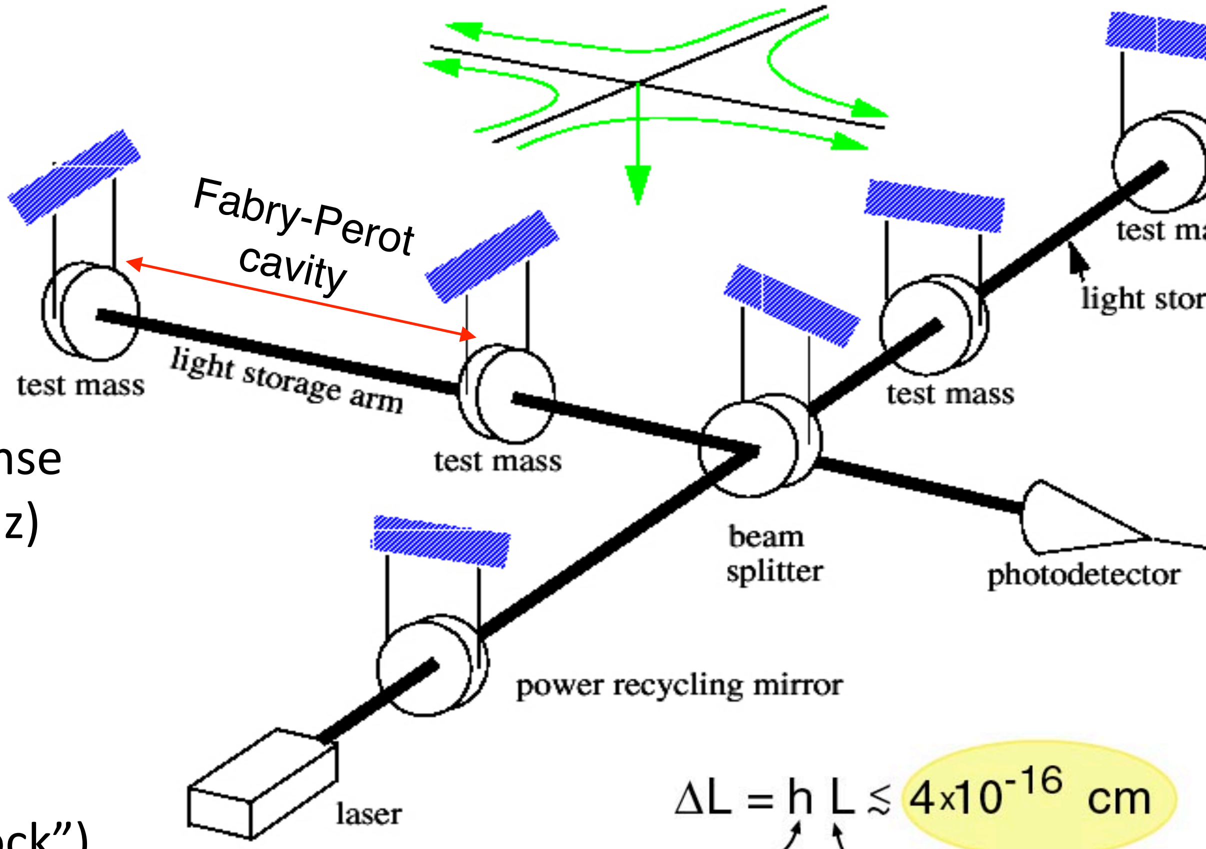
Detecting Gravitational Waves: Laser Interferometers

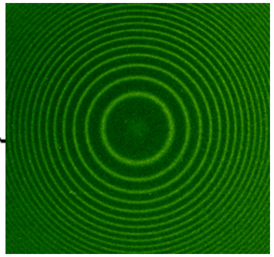
Advantages:

- Broadband response (~50 Hz to few KHz)
- High sensitivity

Disadvantage:

- Very difficult to keep stable ("in lock") -> relatively poor duty cycle. (Virgo ~80%, LIGO ~60%)



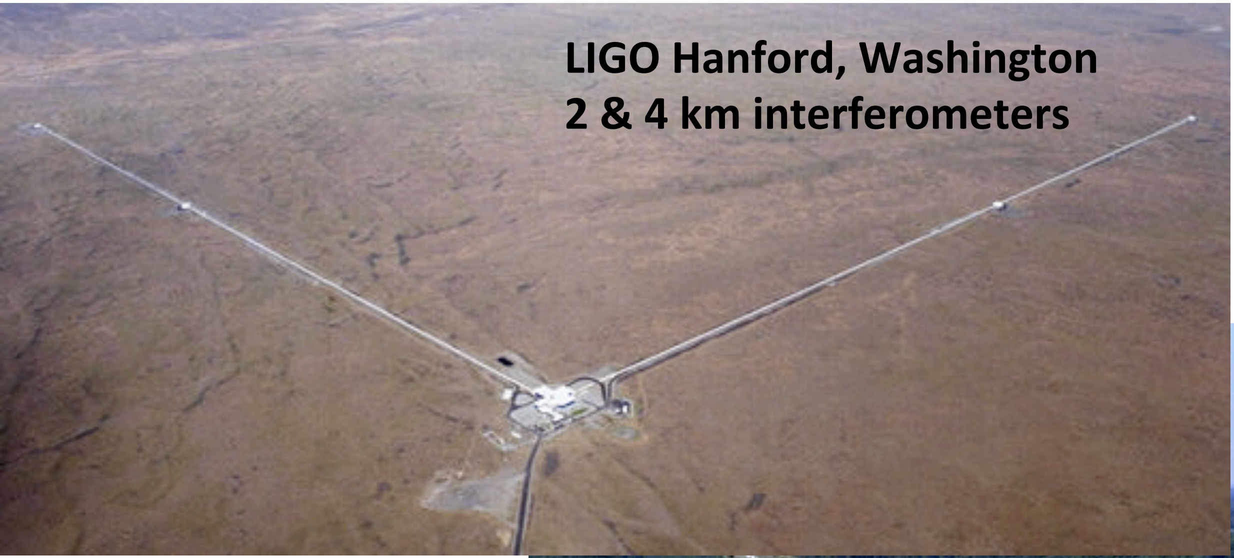


GW output port

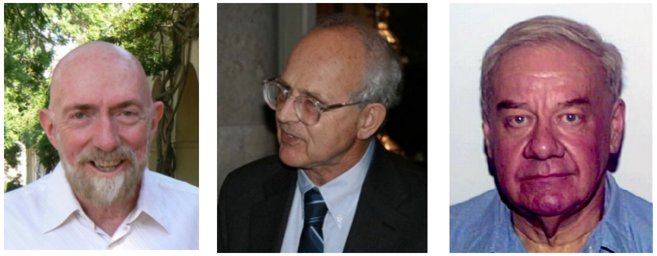
$$\Delta L = \underbrace{h}_{\lesssim 10^{-21}}\,\underbrace{L}_{4\text{ km}} \lesssim 4{\times}10^{-16}\ \text{cm}$$

Basic Michelson Interferometer design + upgrades (power recycling, Fabry Perot cavities)

Laser Interferometer Gravitational-Wave Observatory



LIGO Hanford, Washington
2 & 4 km interferometers



Kip Thorne, Rai Weiss, Ron Drever

LIGO Livingston, Louisiana
4 km interferometer

Envisioned in the 1980s by
Kip Thorne, Rai Weiss, Ron Drever

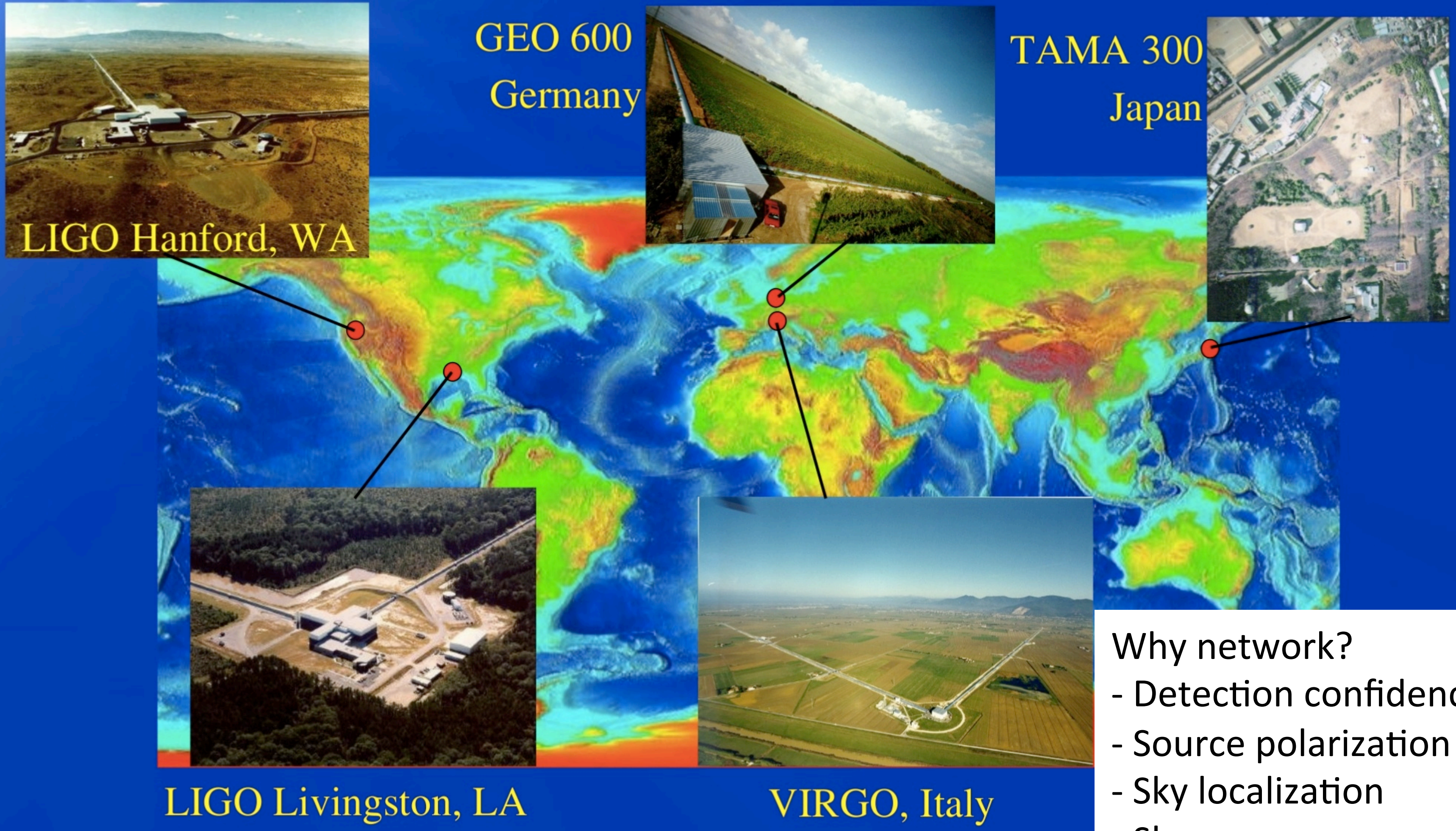
Built in the 1990s.

6 “science runs” 2002-2010.

Gravitational Wave Astronomy

International Network of LIGOs

First Generation – 2000 -- 2010



Why network?

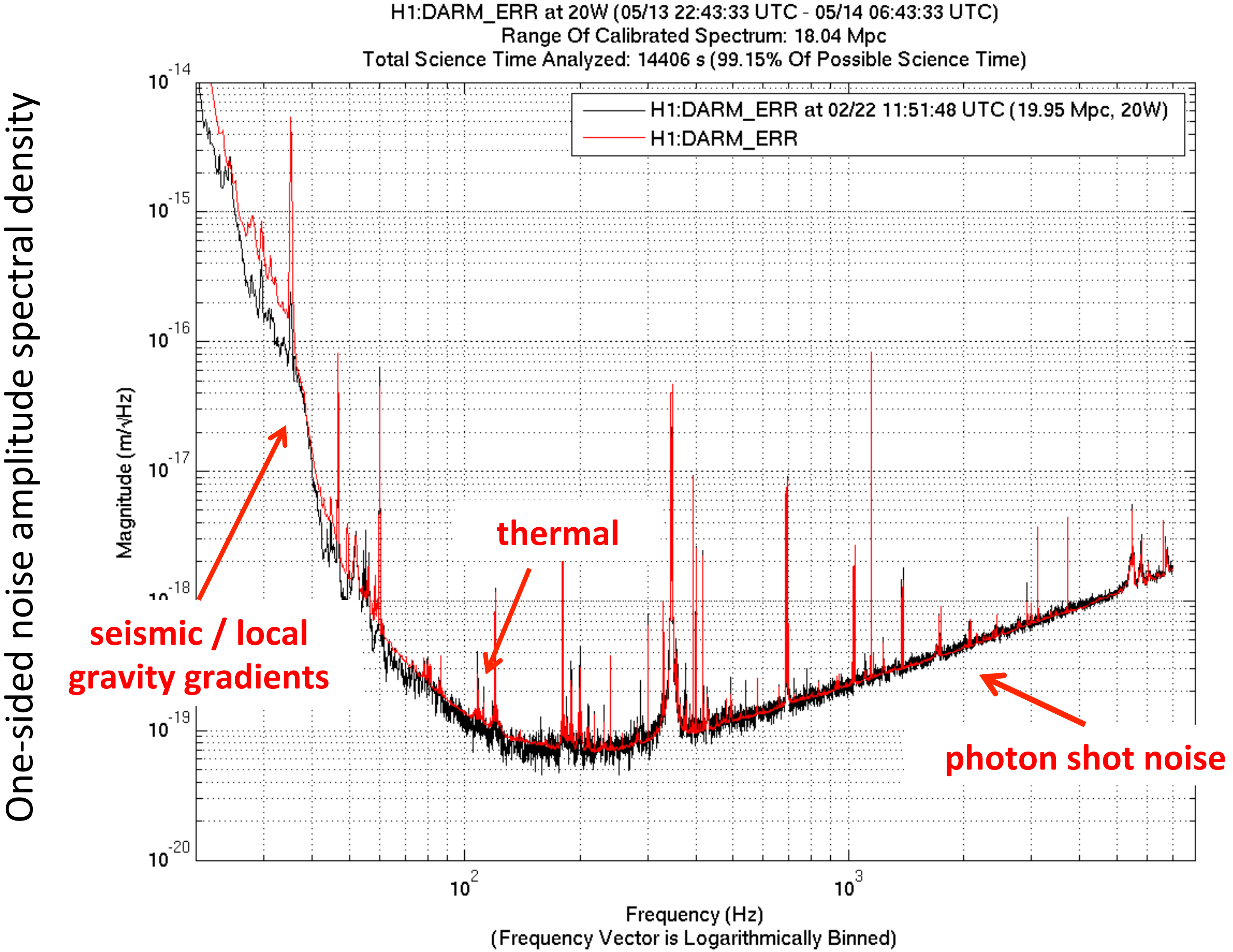
- Detection confidence
- Source polarization
- Sky localization
- Sky coverage
- Duty cycle


mid station
35

Initial LIGO

Abbott et al., LSC, Rep. Prog. Phys. **72** (2009) 076901

Noise Budget



One-sided noise amplitude spectral density

seismic / local gravity gradients

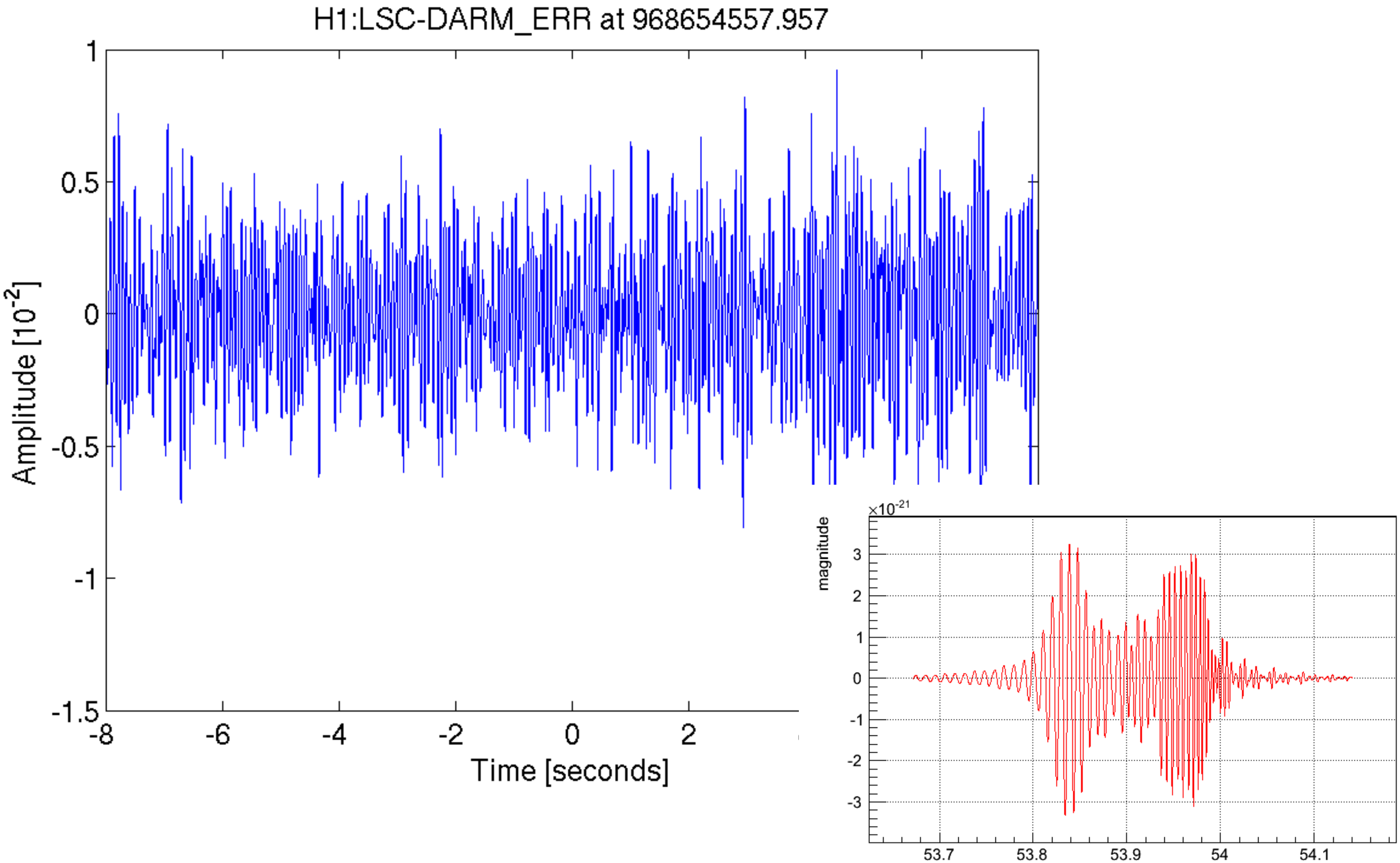
thermal

photon shot noise

Anthropogenic Noise...

+ trucks, trains, tree cutting, rush hour on highways...

The Data Analysis Challenge: Digging out the Signal



Gravitational Wave Data Analysis

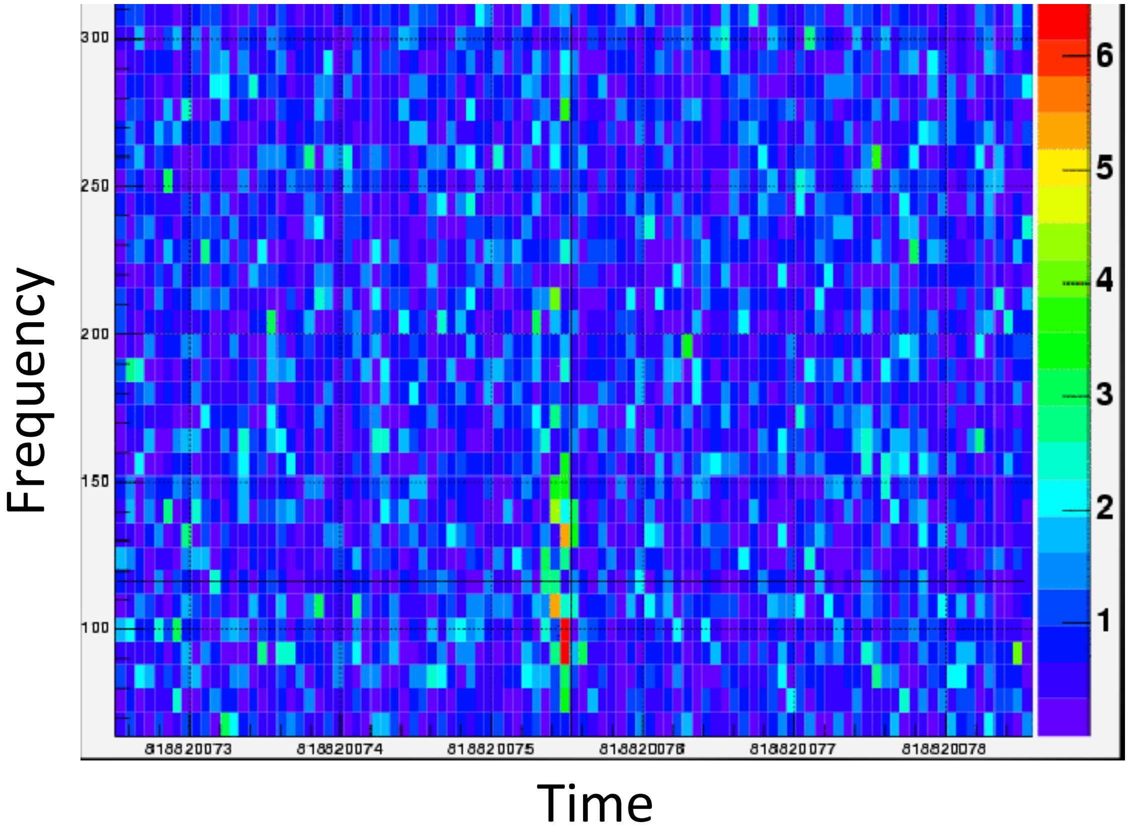
Must deal with a variety of source types:

- **Binary Coalescence**: Inspiral signal predicted nearly exactly. Merger can be predicted exactly for BH-BH. -> “Matched Filtering”

- **Bursts**: Signals that can’t be predicted exactly – Core-collapse supernovae, postmerger NSNS/NSBH, long GRBs, SGRs, and unknown sources. -> Excess-Power Searches.

Excess Power Search Method

GW Spectrogramm



- Decompose data stream into time-frequency pixels.
- Normalize power by noise level.
- Search for “hot” regions with excess power.
- Use intelligent “clustering” algorithms to optimize search/exclude background.

Gravitational Wave Data Analysis

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- **Binary Coalescence**: Inspiral signal predicted nearly exactly. Merger can be predicted exactly for BH-BH. -> "Matched Filtering"
- **Bursts**: Signals that can't be predicted exactly – Core-collapse supernovae, postmerger NSNS/NSBH, long GRBs, SGRs, and unknown sources. -> Excess-Power Searches.
- **Continuous sources:** pulsars with tiny mountains or r-modes. Must integrate for many cycles (computationally limited); http://einstein.phys.uwm.edu/ : Einstein@Home
- **Stochastic:** Cosmic GW background – primordial and summed-up signals from cosmological supernovae, mergers, GRBs etc.

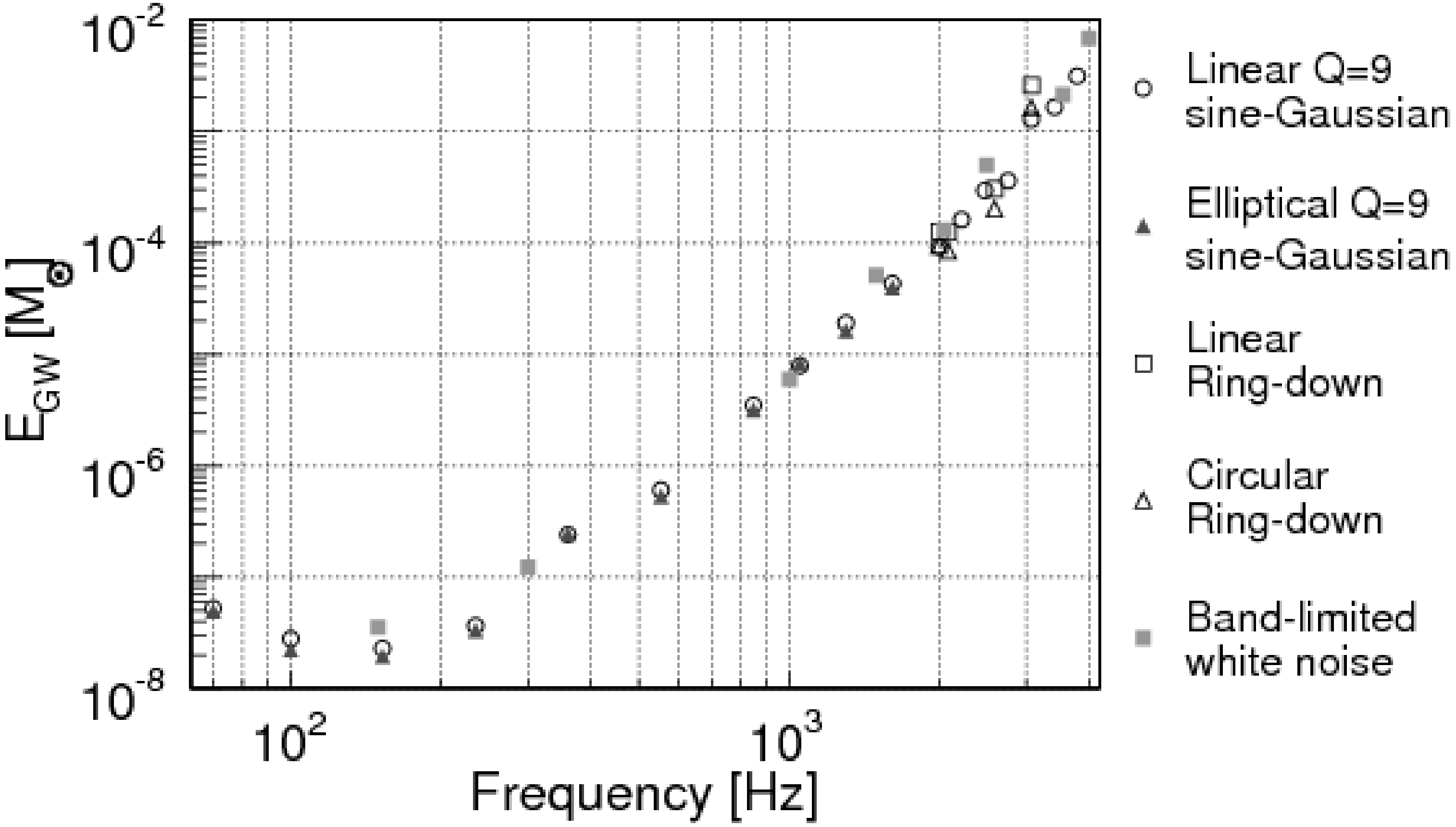
-> There is a working group for each signal type in LSC/Virgo.

Some Results: Most recent Search for Gravitational-Wave Bursts (i.e. not binary inspirals)

Abadie et al. (LSC+Virgo), PRD 2012, arXiv:1202.2788

- All sky search for GW bursts.
- Model agnostic excess-power search across 64-5000 Hz.
- Upper limits based on simplified model waveforms; “Sine-Gaussians”

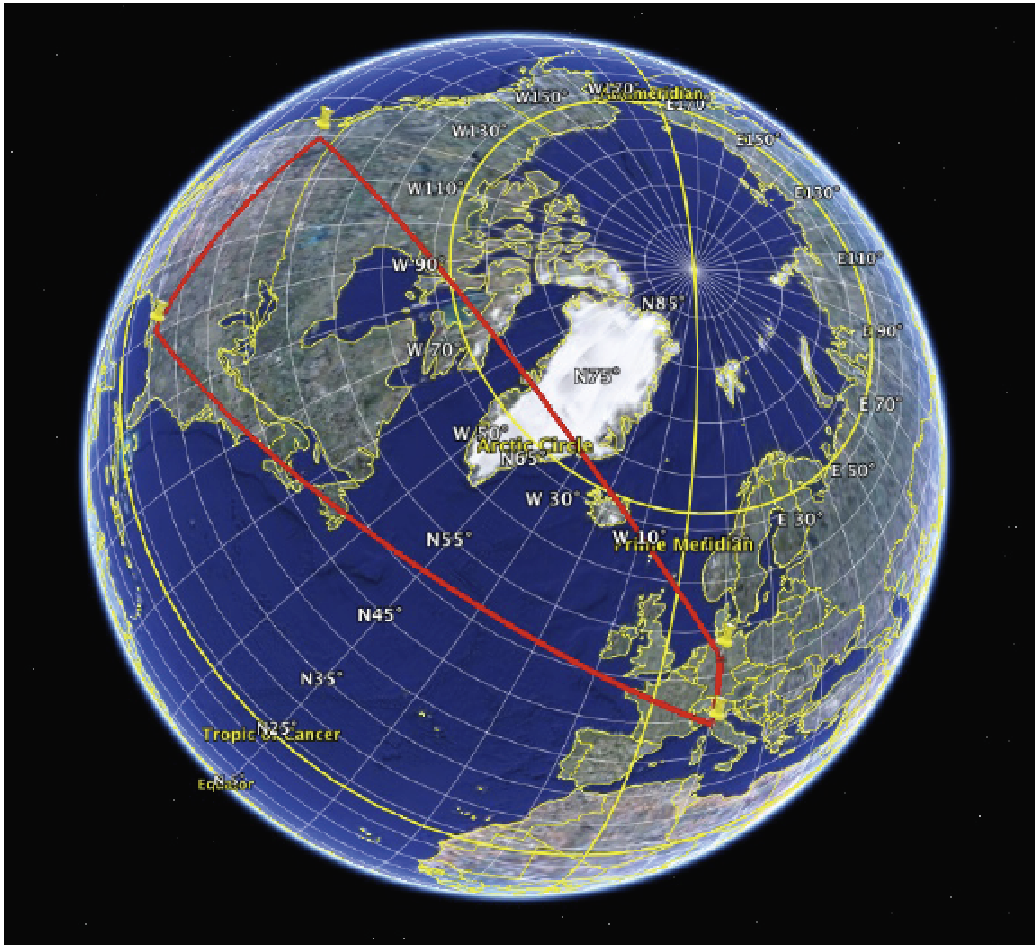
Covering the galaxy: GW energy exclusion within 10 kpc (50% CL)



Electromagnetic Follow-Up Observations

- Sky localization of GW event possible via triangulation between 3 (or more) detectors.
- S6A/B science run:
  V1/L1/H1/G1
  Dec 17, '09 – Jan 8, '10
  Sep 4, '10 – Oct 20, '10
- Low-latency data analysis.
  High-significance triggers passed to telescope partners.

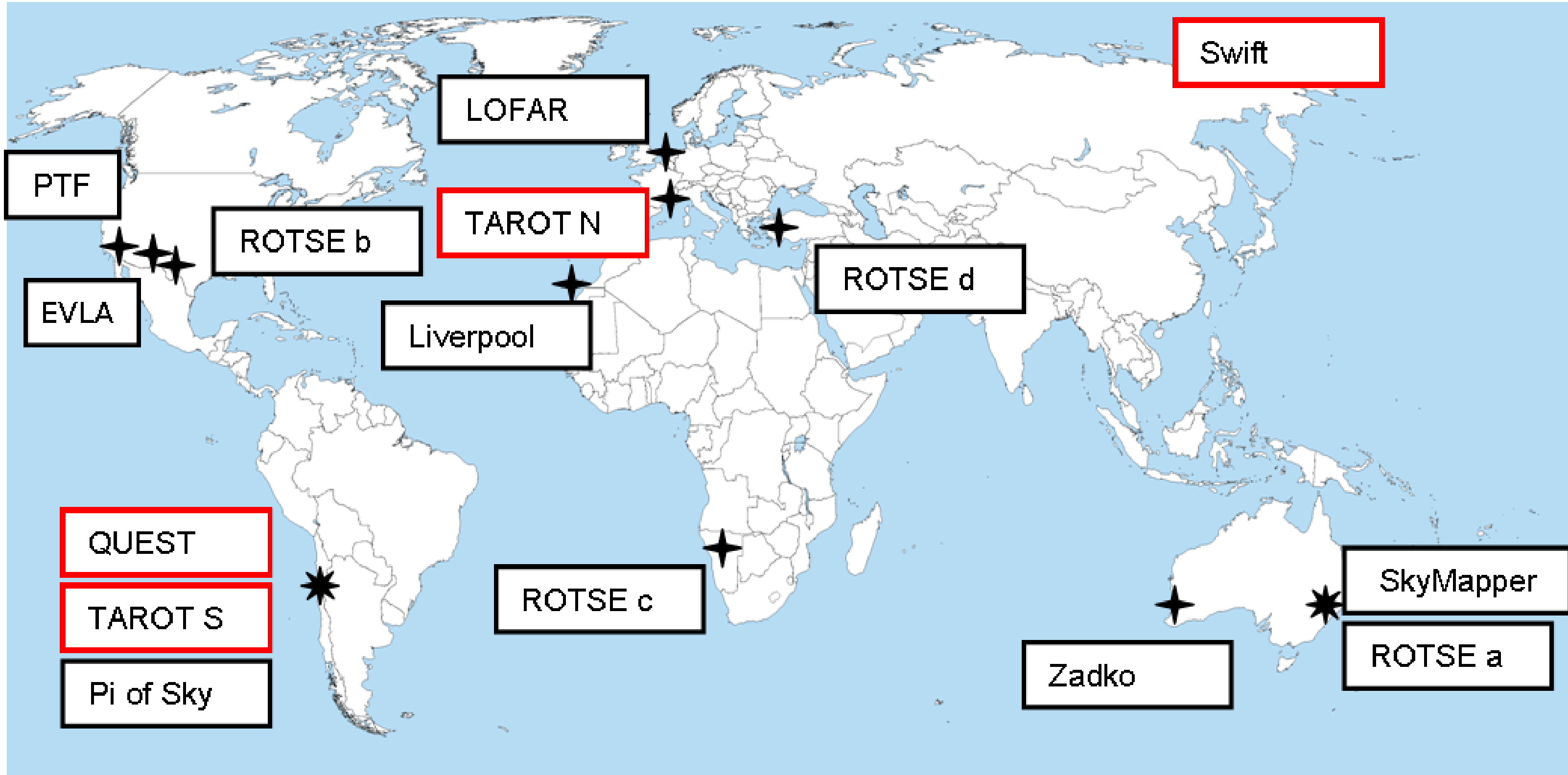
Abadie et al. (LSC+Virgo),
Astron. Astrophys. 539, A124 (2012)



- Large error boxes – few to tens of square degrees (timing/calibration uncertainties, weak signals)

Electromagnetic Follow-Up Observations

Abadie et al. (LSC+Virgo), Astron. Astrophys. 539, A124 (2012)



Taken from Abadie et al. 1109:3498

Optical Telescopes:

- TAROT – 3.4 sq. deg.
- Zadko – 0.17 sq. deg.
- ROTSE – 3.4 sq deg.
- QUEST – 9.4 sq. deg.
- SkyMapper – 5.7 sq. deg.
- Pi of the Sky – 400 sq. deg.
- PTF – 7.8 sq deg.
- Liverpool – 21 sq. arcmin.

Radio Interferometers:

- LOFAR (30 – 240 MHz) – 25 sq. deg.
- EVLA (5 GHz) – 7 sq. arcmin.

X-Ray and UVOT:

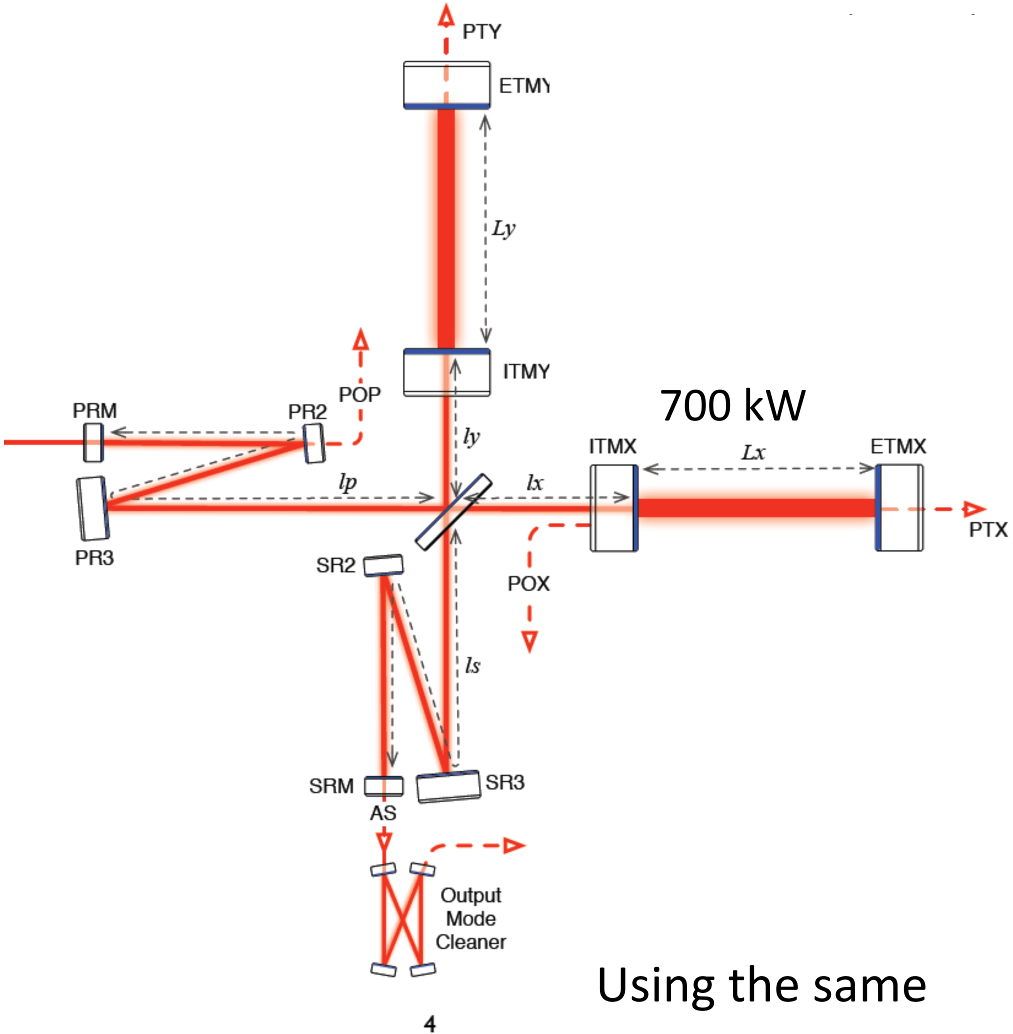
- Swift – 0.15 sq. deg.

Advanced LIGO

Advanced LIGO

What is Advanced?

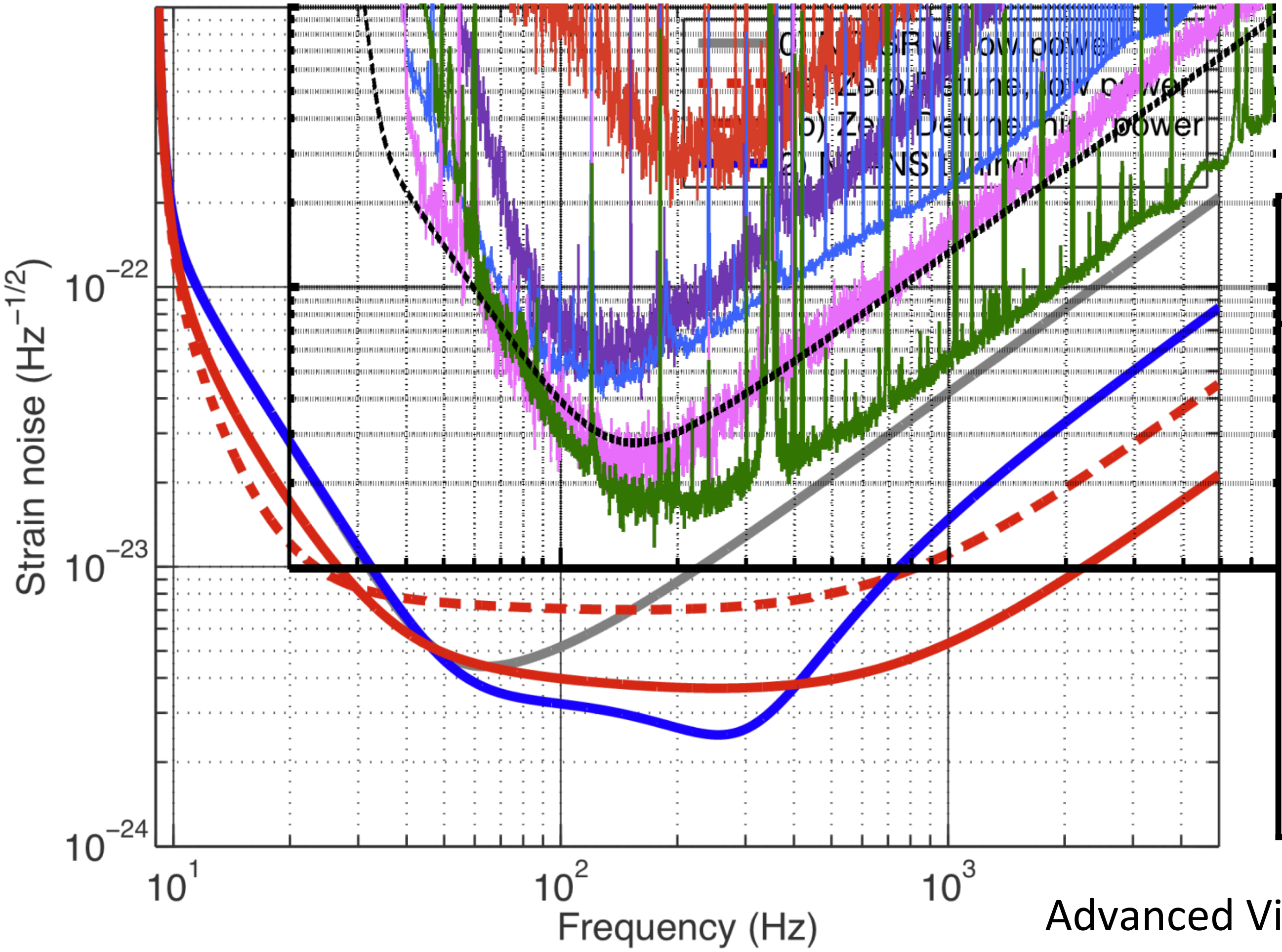
Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	10 W (10 kW arm)	**180 W** (>700 kW arm)
Mirror Mass	10 kg	**40 kg**
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable RC)
Optimal Strain Sensitivity	3 x 10^{-23} / rHz	Tunable, better than 5 x 10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 12 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum



700 kW

Using the same vacuum system as Initial LIGO.

Projected Advanced LIGO Performance



Orientation-averaged detection range for binary inspirals

case	NS-NS	BH-BH (30 $M_{\odot}$)
Early	150 Mpc	1.60 Gpc
0-det low	145 Mpc	1.65 Gpc
0-det high	190 Mpc	1.85 Gpc
NS-NS tuned	200 Mpc	1.65 Gpc

Advanced Virgo: similar characteristics

- Factor of ~10 better amplitude sensitivity than Initial LIGO
  → Factor of ~1000 greater volume of space

What will Advanced Detectors see?

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

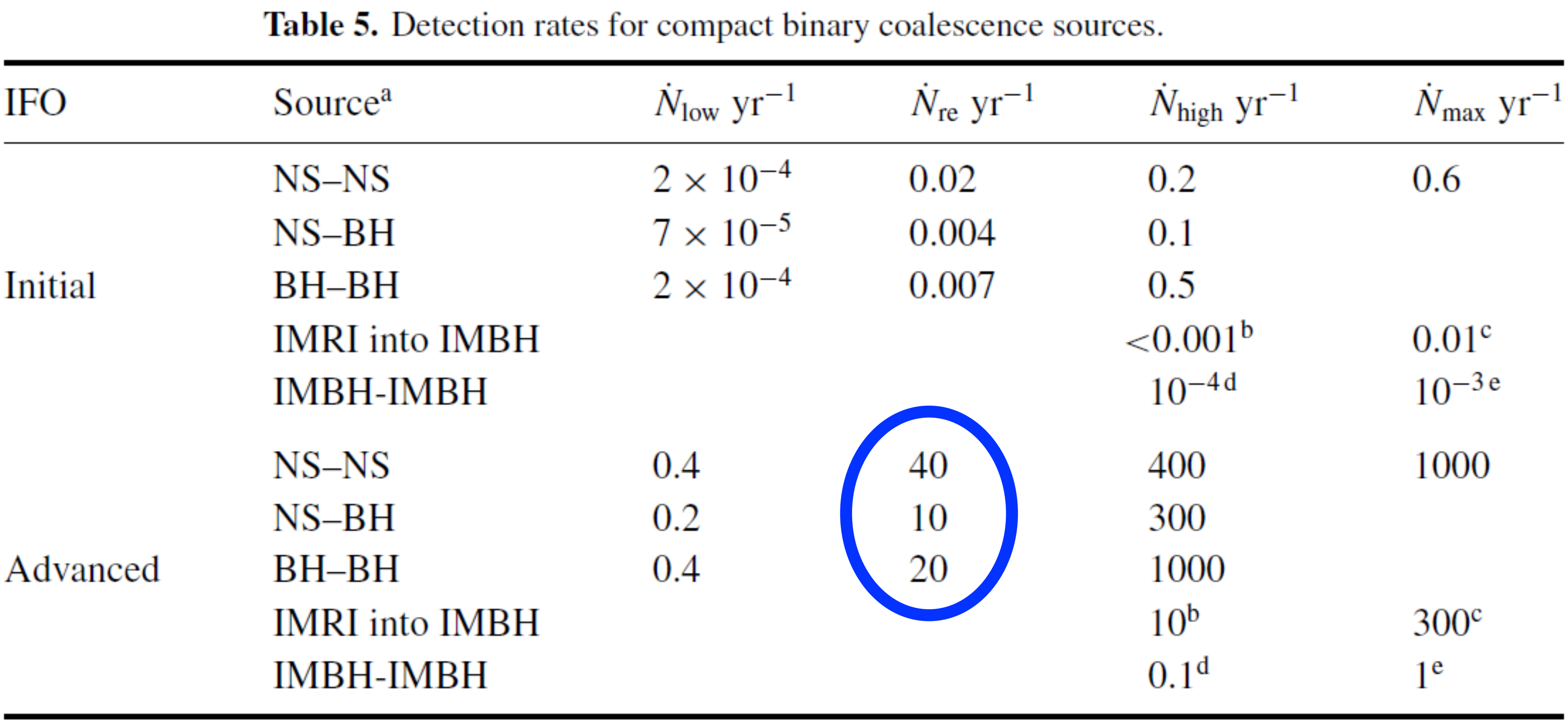
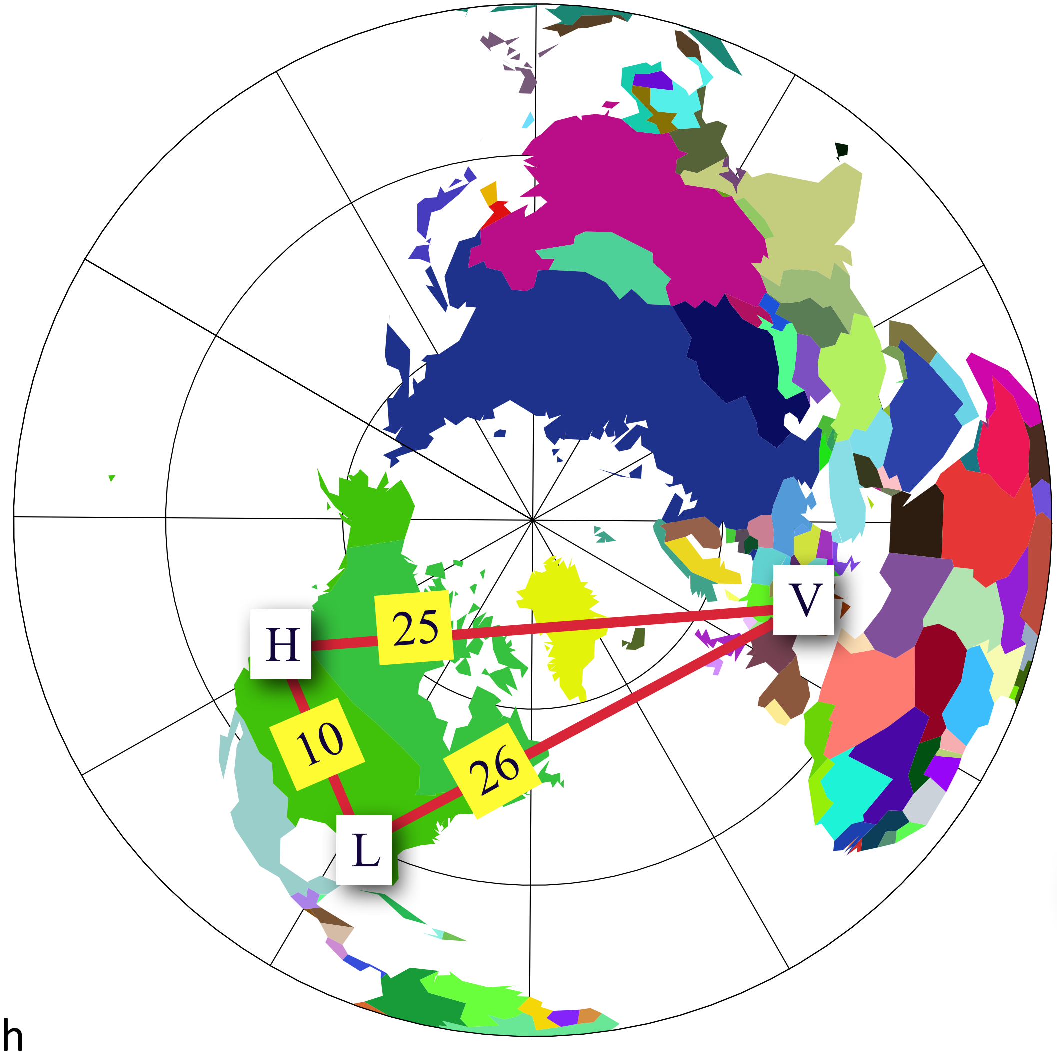


Table 5. Detection rates for compact binary coalescence sources.

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

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

Networks of Advanced Detectors

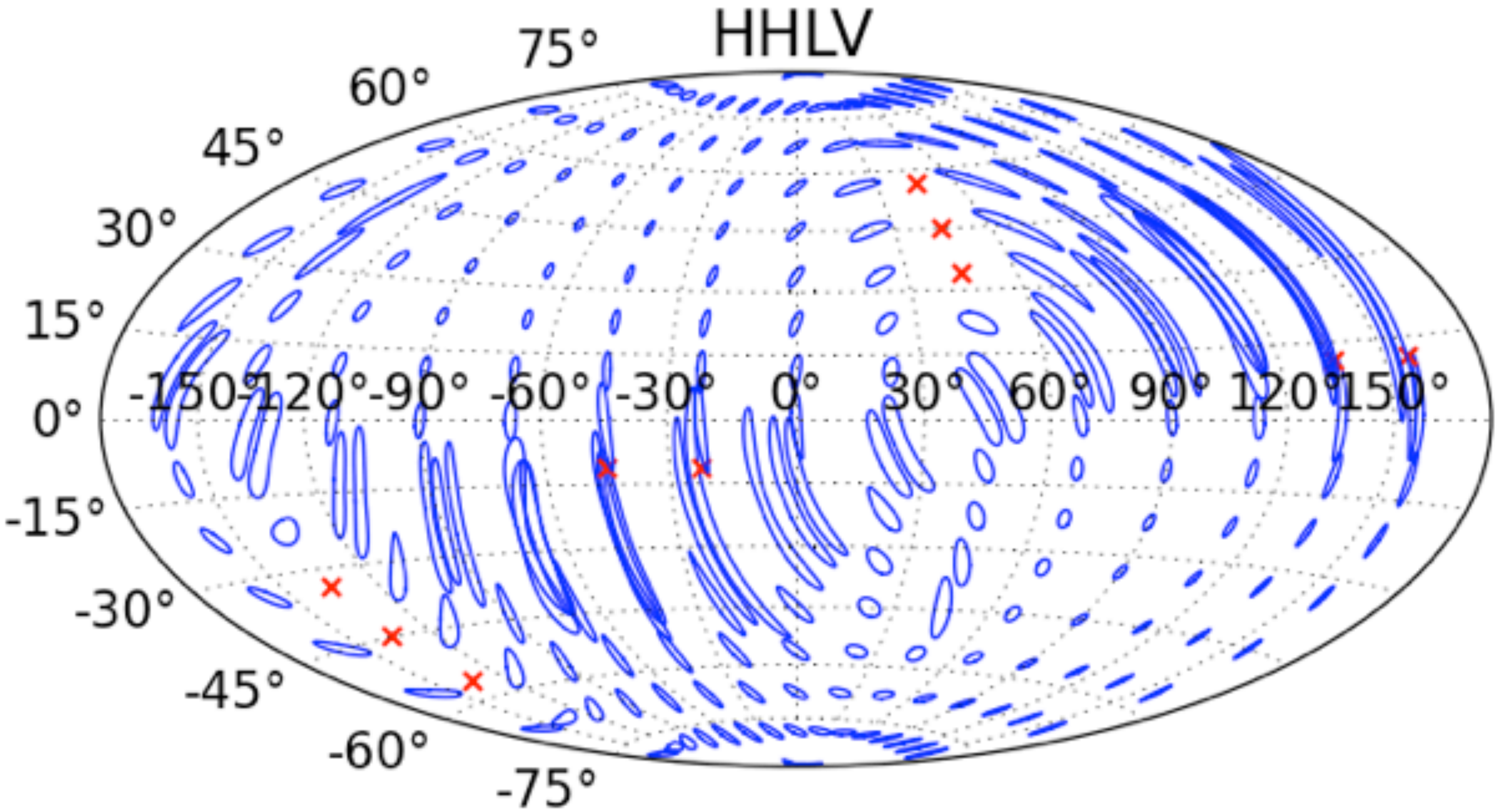


Detector Networks

Baselines
in light travel time (ms)

Sathyaprakash Fairhurst 2011

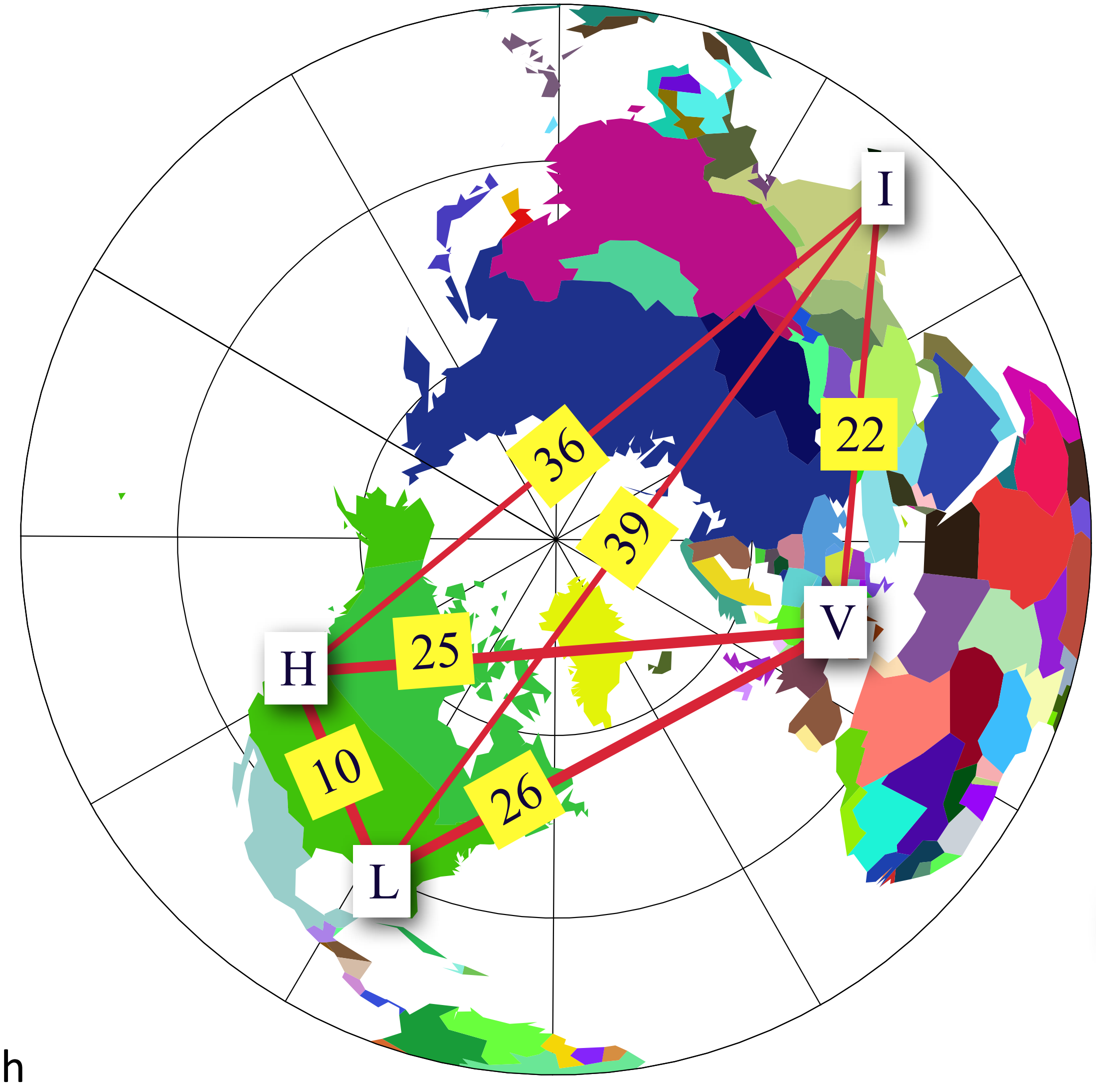
Sky Localization Error Ellipses



Fairhurst 2011

Red crosses denote regions where the network has blind spots

Networks of Advanced Detectors: Case 2



Detector Networks

Baselines

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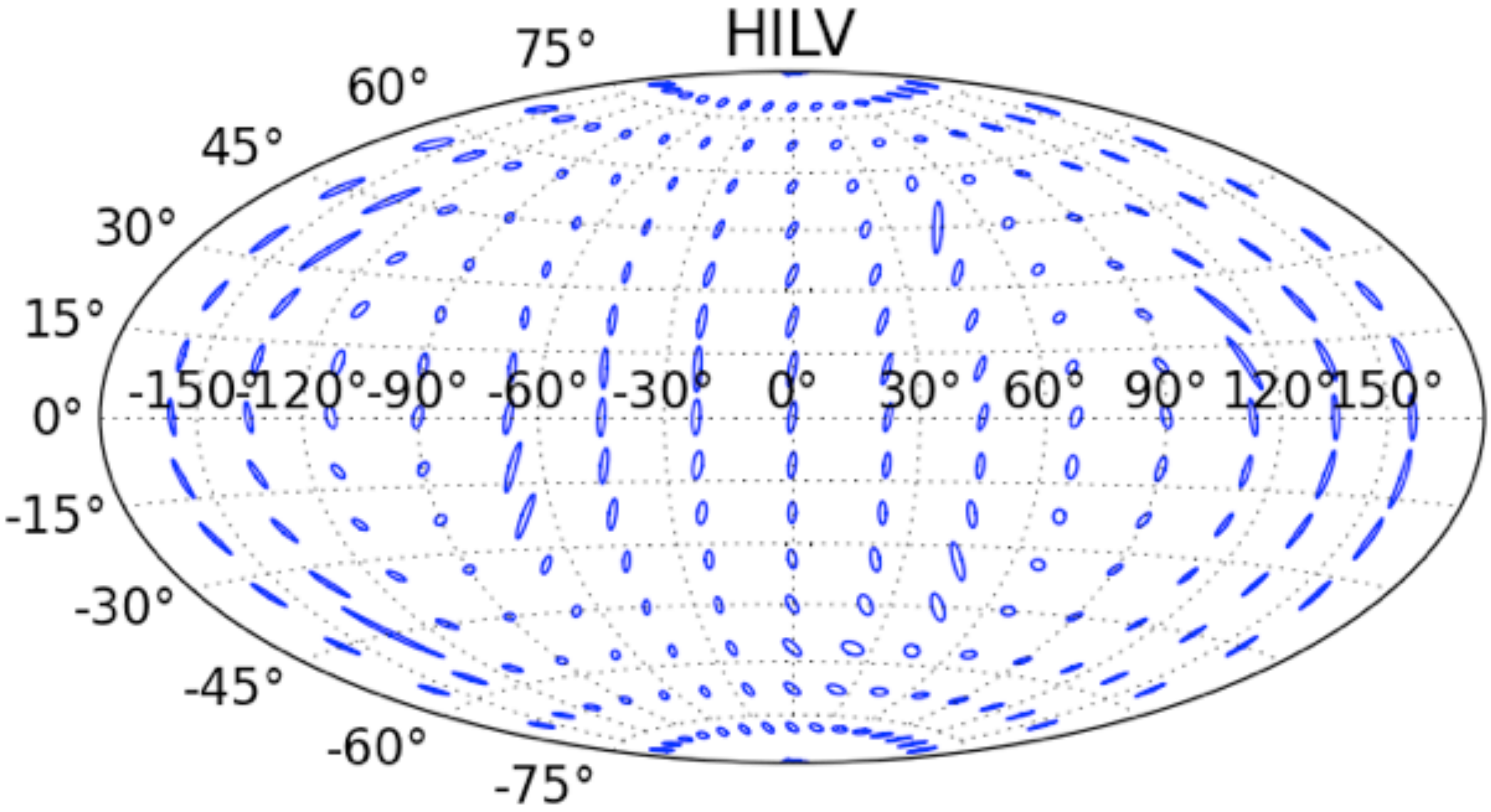
Sathyaprakash
Fairhurst 2011

Sky Localization Error Ellipses



Fairhurst 2011

Adding detector in India would remove blind spots and improve pointing accuracy for follow-up.

LIGO India

- Direct partnership between LIGO Laboratory and the IndIGO consortium + 3 lead institutions to build a GW detector in India.
- LIGO will provide hardware of second Hanford Advanced LIGO interferometer.
- India will provide infrastructure, staff, and operating costs.
- Approved by LIGO, LSC.
  Final NSF Review done and passed on to National Science Board.
- $200M "mega-project" in Indian 5-year plan.
  Biggest proposed bilateral US-India science project.

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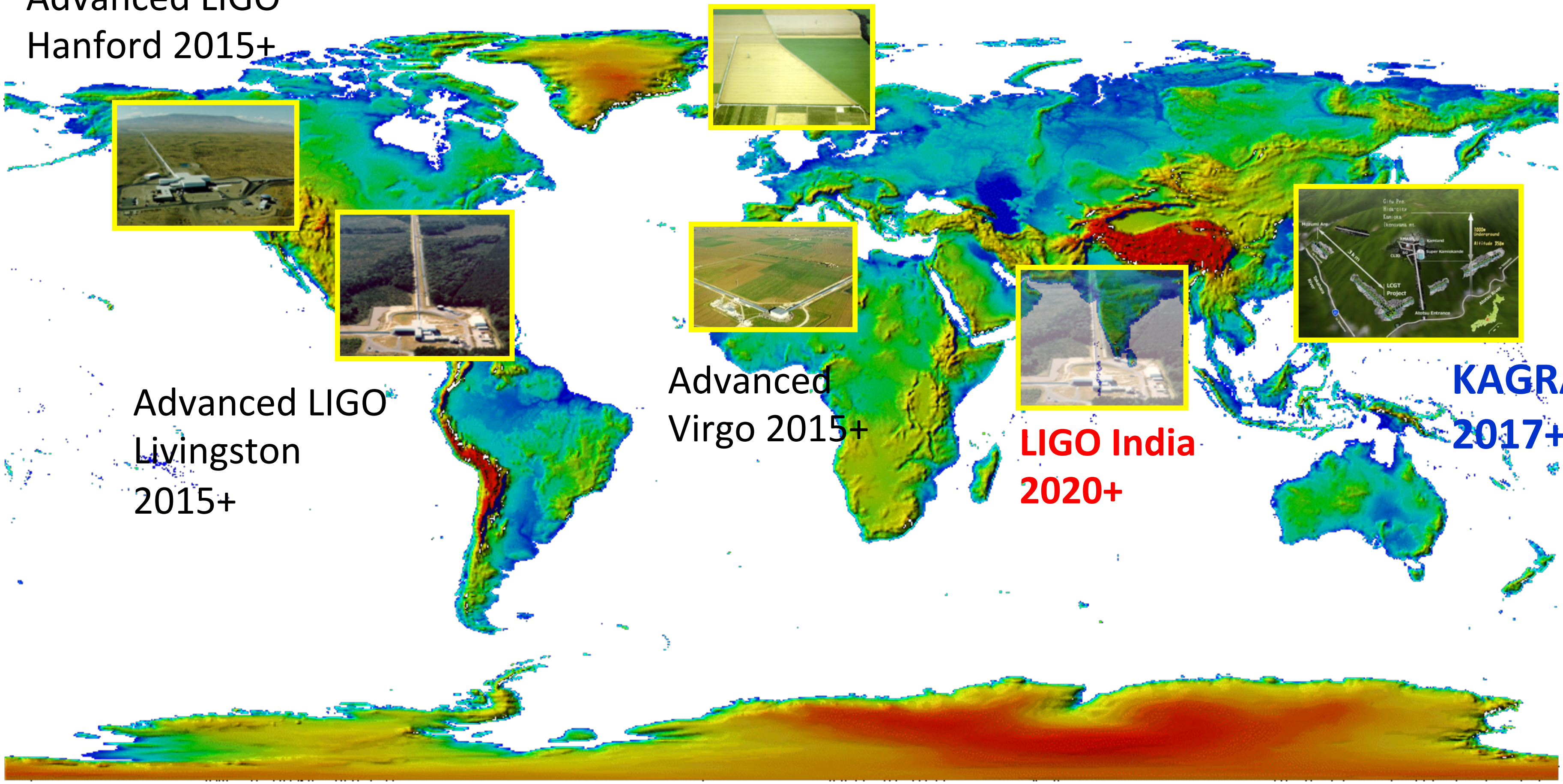
LIGO-India will have three phases:
(1) Site selection and facility design.
(2) Site/facility/vacuum construction.
(3) Detector installation and commissioning
(> 2018-2020)

The Advanced GW Detector Network: 2020+



GEO 600 (HF) 2011

Advanced LIGO
Hanford 2015+

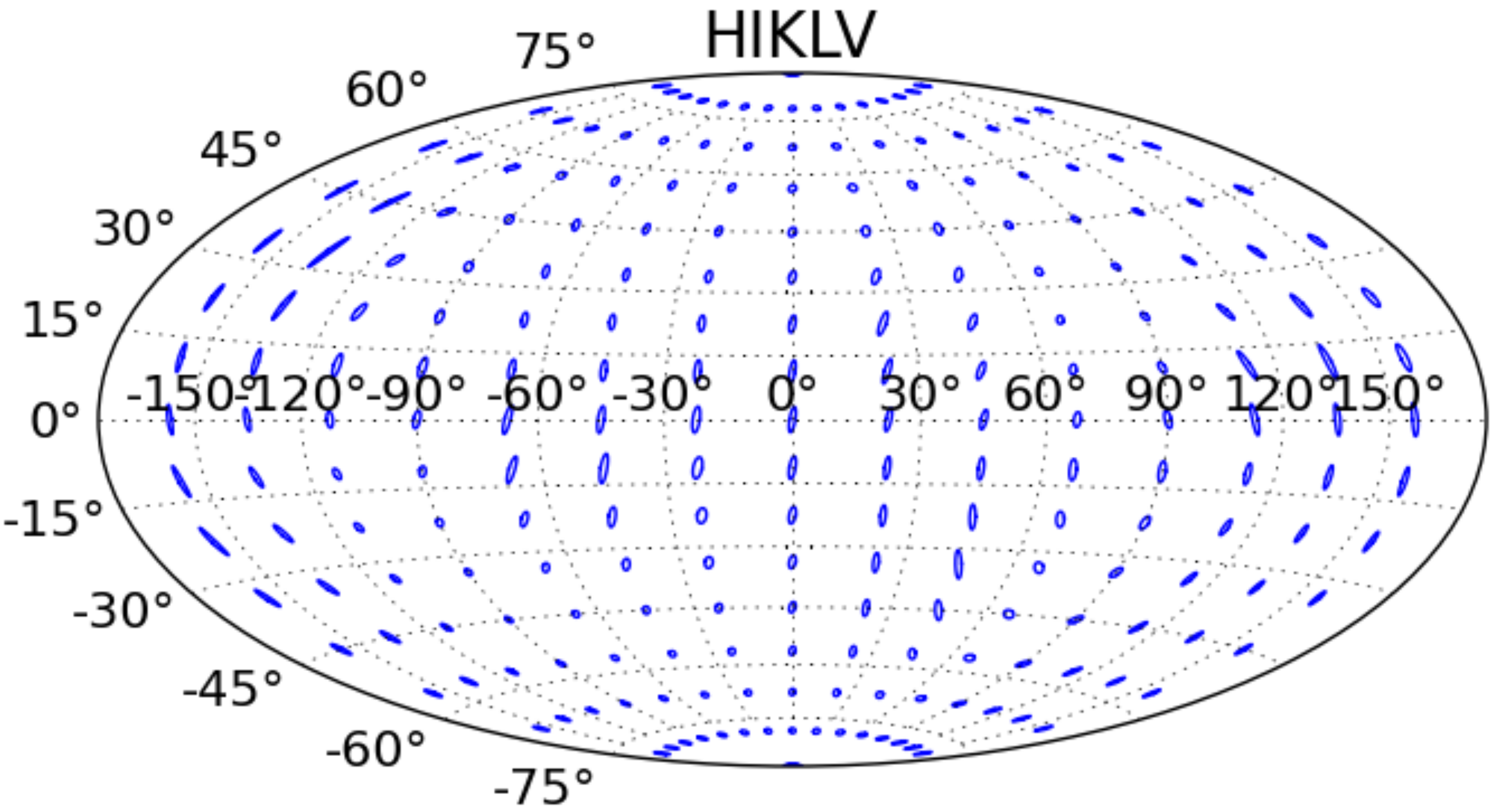
Advanced LIGO
Livingston
2015+

Advanced
Virgo 2015+

**LIGO India
2020+**

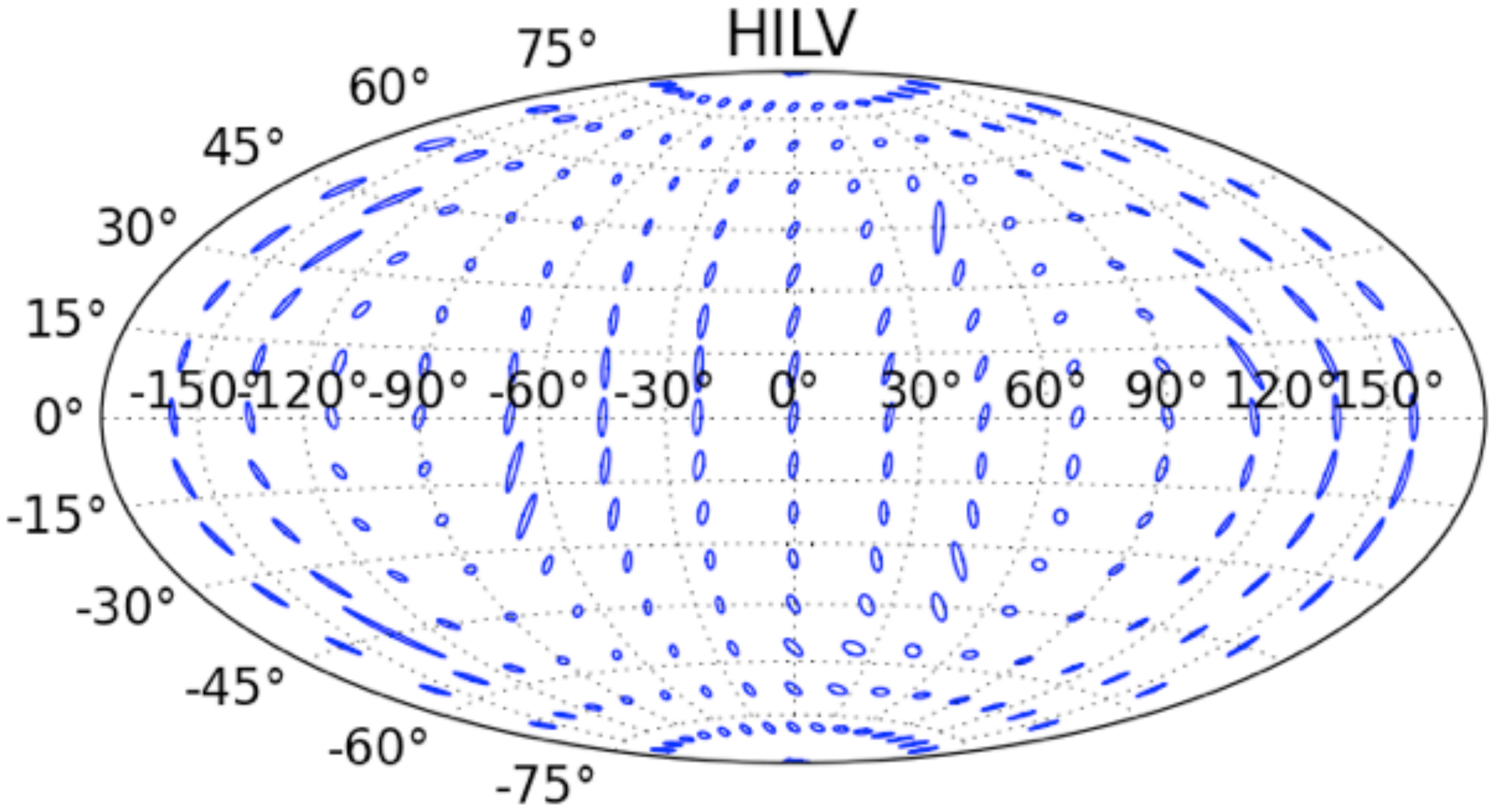
**KAGRA
2017+**

The Ultimate Network:
Hanford—LIGO India—KAGRA—Livingston--Virgo



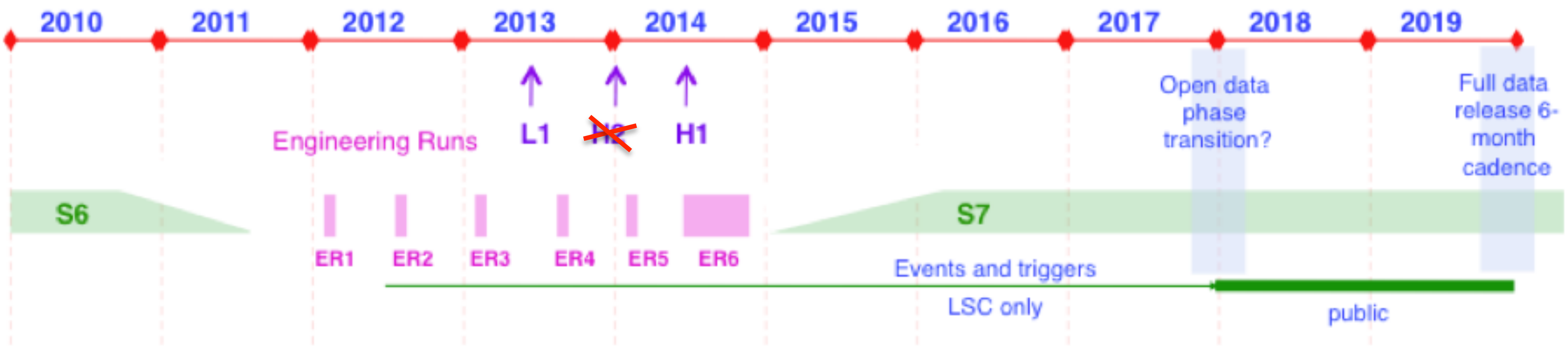
Sky Localization Error Ellipses

For comparison:



Fairhurst 2011

Advanced LIGO Timeline and Trigger Release



Discovery Phase

- 2015/16+, until multiple (N=4) detections have been made.
- Trigger release to partner collaborations (via MoU) and electromagnetic telescopes for follow-up.
- No low-latency public data release.

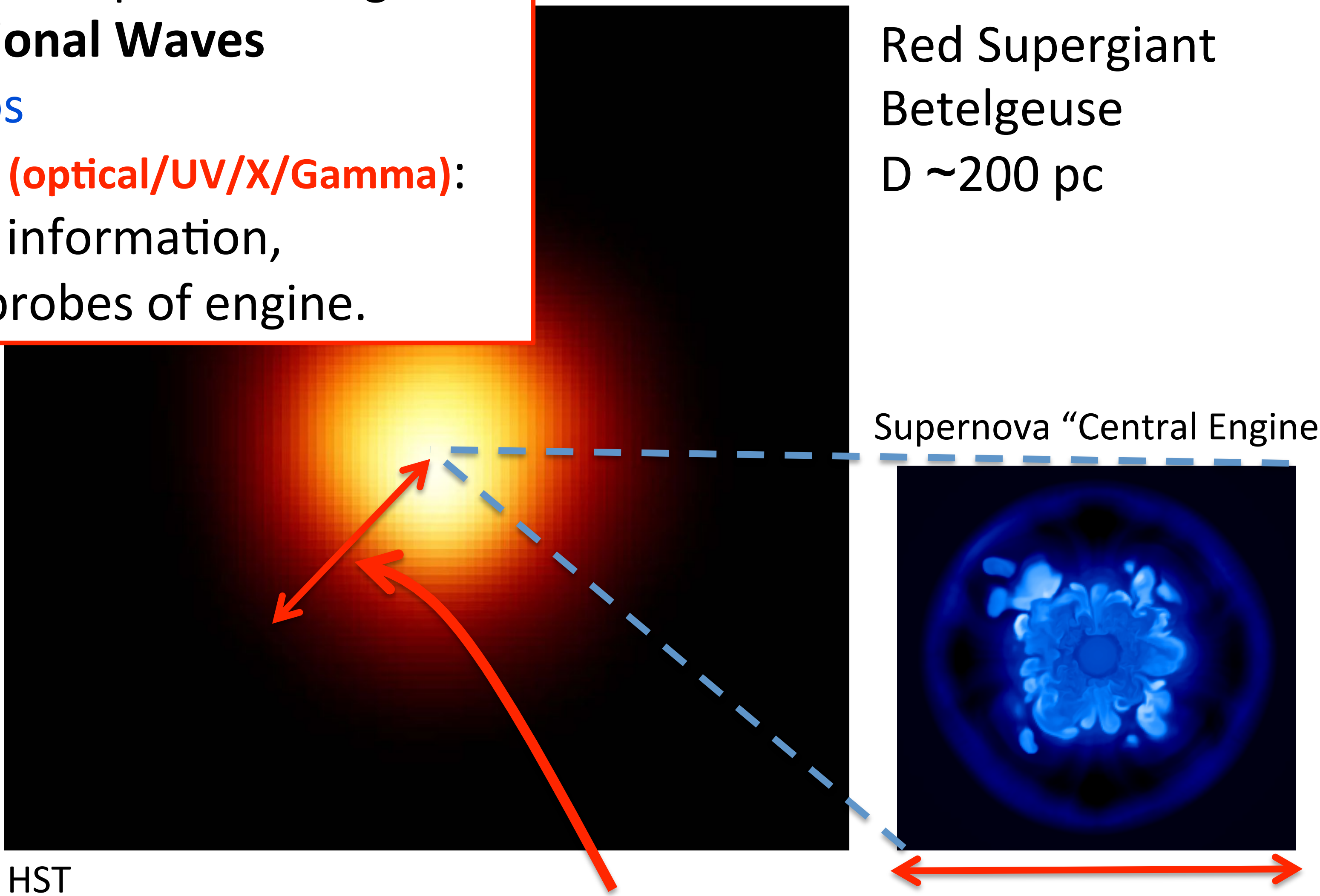
Observational Phase

- 2017+ (?), after at 4 detections/publications.
- High-confidence triggers released to public (-> SNEWS).
- Full data release with 2 year latency, 6 month cadence.

Observing the CCSN Mechanism

Probing the "Supernova Engine"
- **Gravitational Waves**
- Neutrinos

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



Red Supergiant
Betelgeuse
D ~200 pc

Supernova "Central Engine"

HST

800 million km

300 km

Gravitational-Waves from Core-Collapse Supernovae

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

Need:

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

accelerated aspherical (quadrupolar) mass-energy motions

Candidate Emission Processes:

- Neutrino-driven Convection and SASI
- Prompt convection
- Protoneutron star convection
- Rotating collapse & bounce
- Rotational 3D instabilities
- Black hole formation
- Pulsations of the protoneutron star
- Anisotropic neutrino emission
- Aspherical accelerated outflows
- Magnetic stresses

Tasks:

(1) Determine GW signals from these emission processes.
(2) Connect GW emission processes to CCSN Mechanism.
(3) Detection: How far out can we detect GWs from CCSNe and can we infer the explosion mechanism (and other physics)?

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- (Black hole formation)
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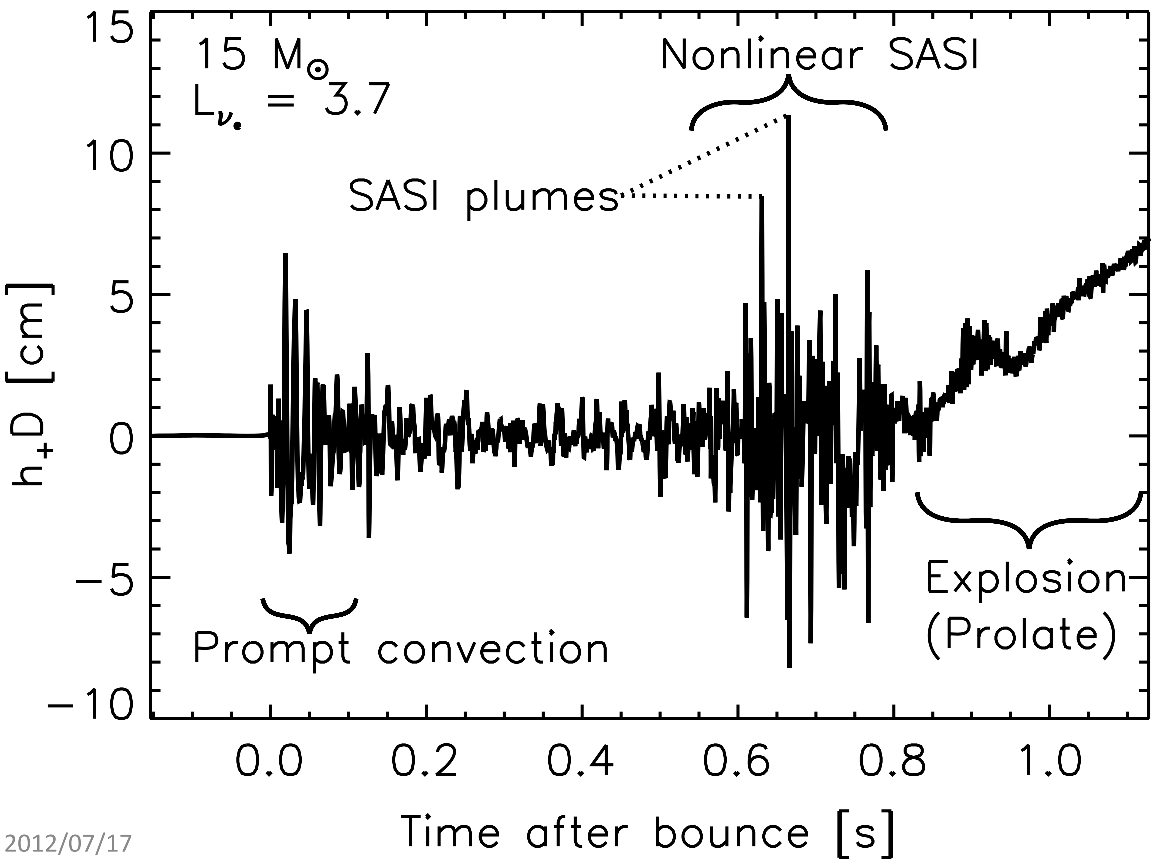
GWs from Convection & SASI

Recent work: Kotake et al. ‘09, ‘11, Murphy et al. ’09, Müller (B&E) et al. ‘11/‘12

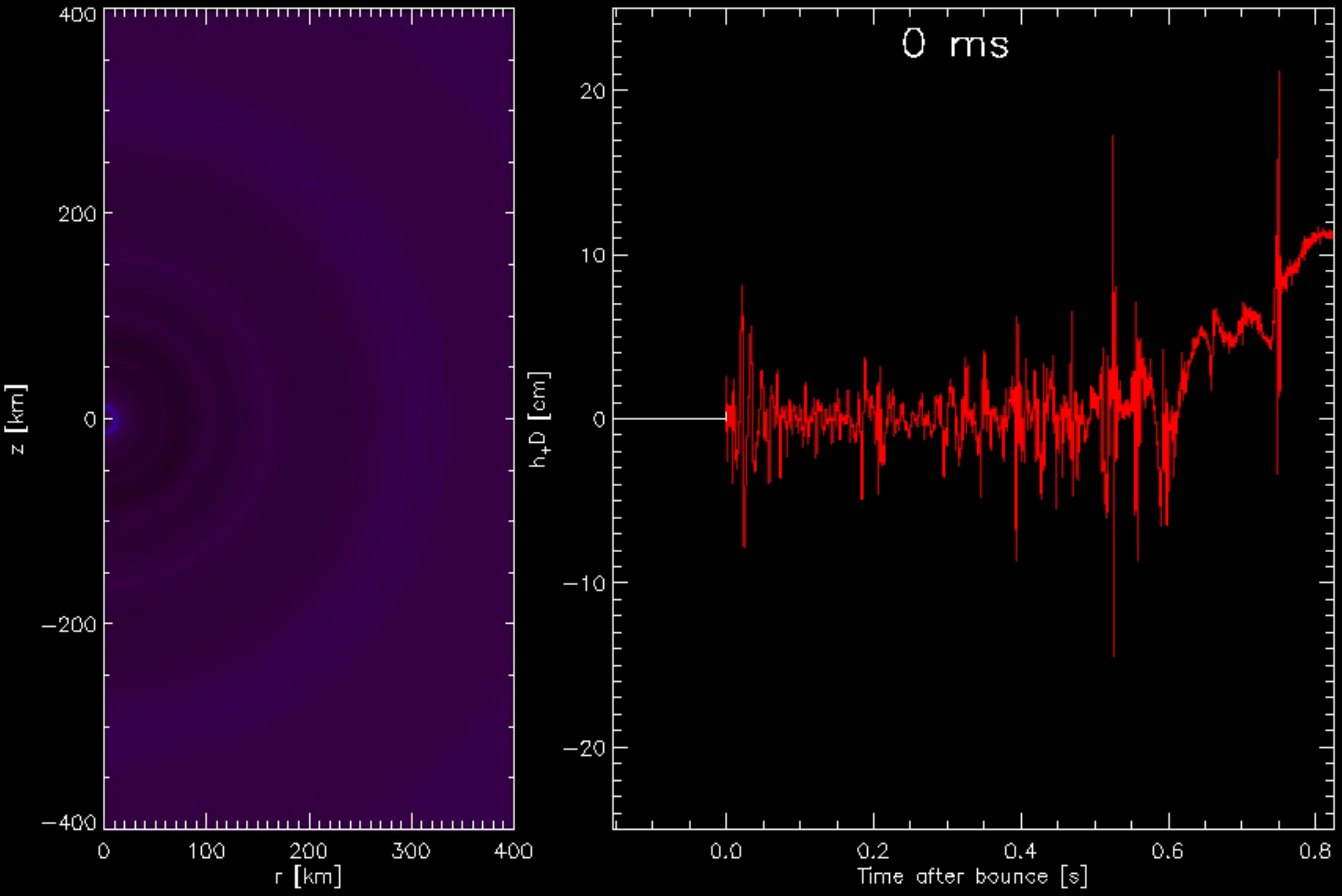
Here: **2D simulations** (see Annop Wongwathanarat’s talk for 3D this afternoon!)

- Prompt convection soon after bounce (Marek et al. ‘09, Ott ‘09).
- Neutrino-driven convection & SASI (many authors).
- Protoneutron star convection (Keil et al. ‘96, Müller & Janka ‘07, Müller et al. ’04)



Murphy et al. ’09, using simplified heating/cooling scheme.

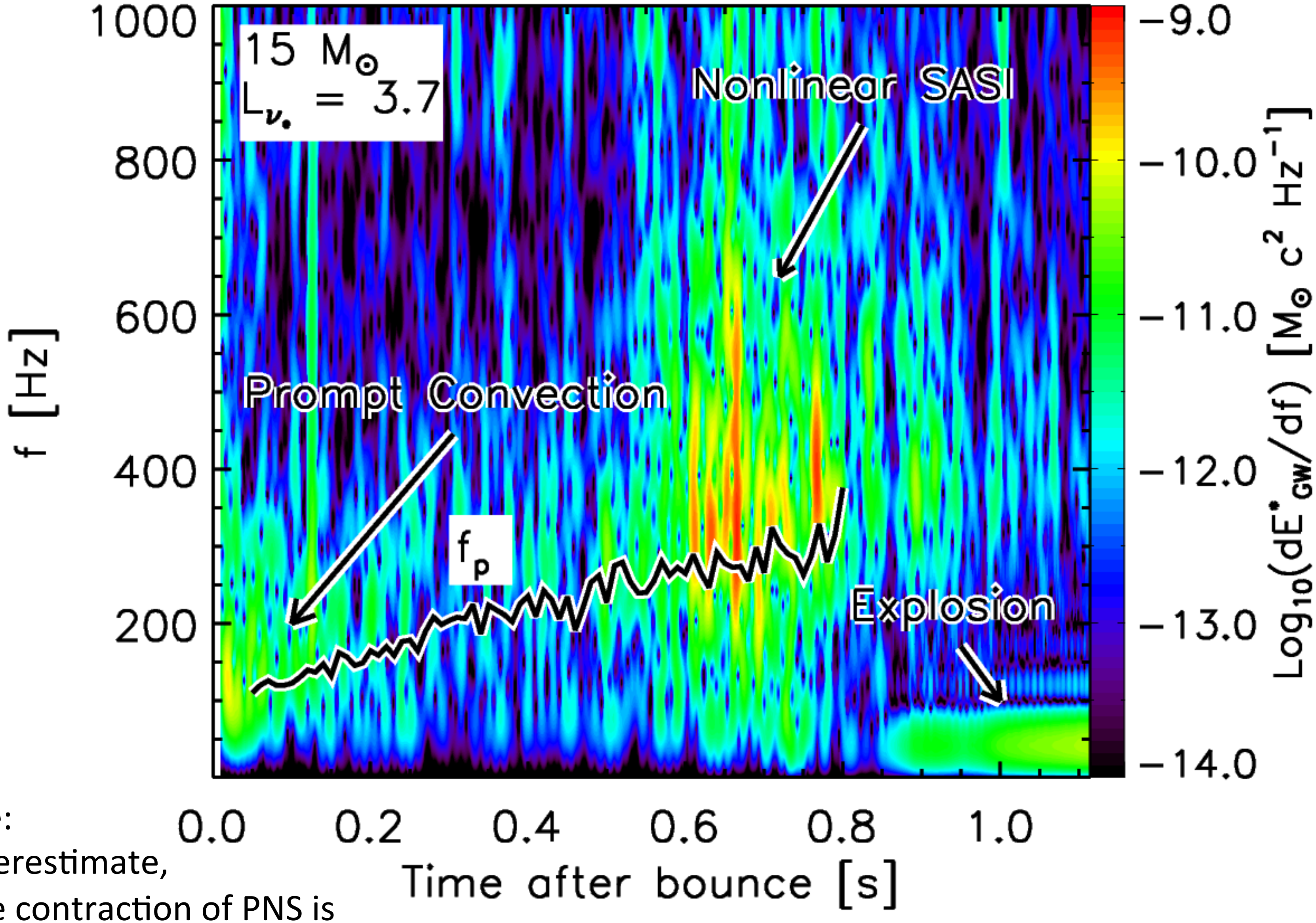
Expect also: Correlations with neutrino signal. Lund+ ‘10, Marek+’09, Müller+ ‘12, Brandt+’11



Murphy, Ott, Burrows ‘09

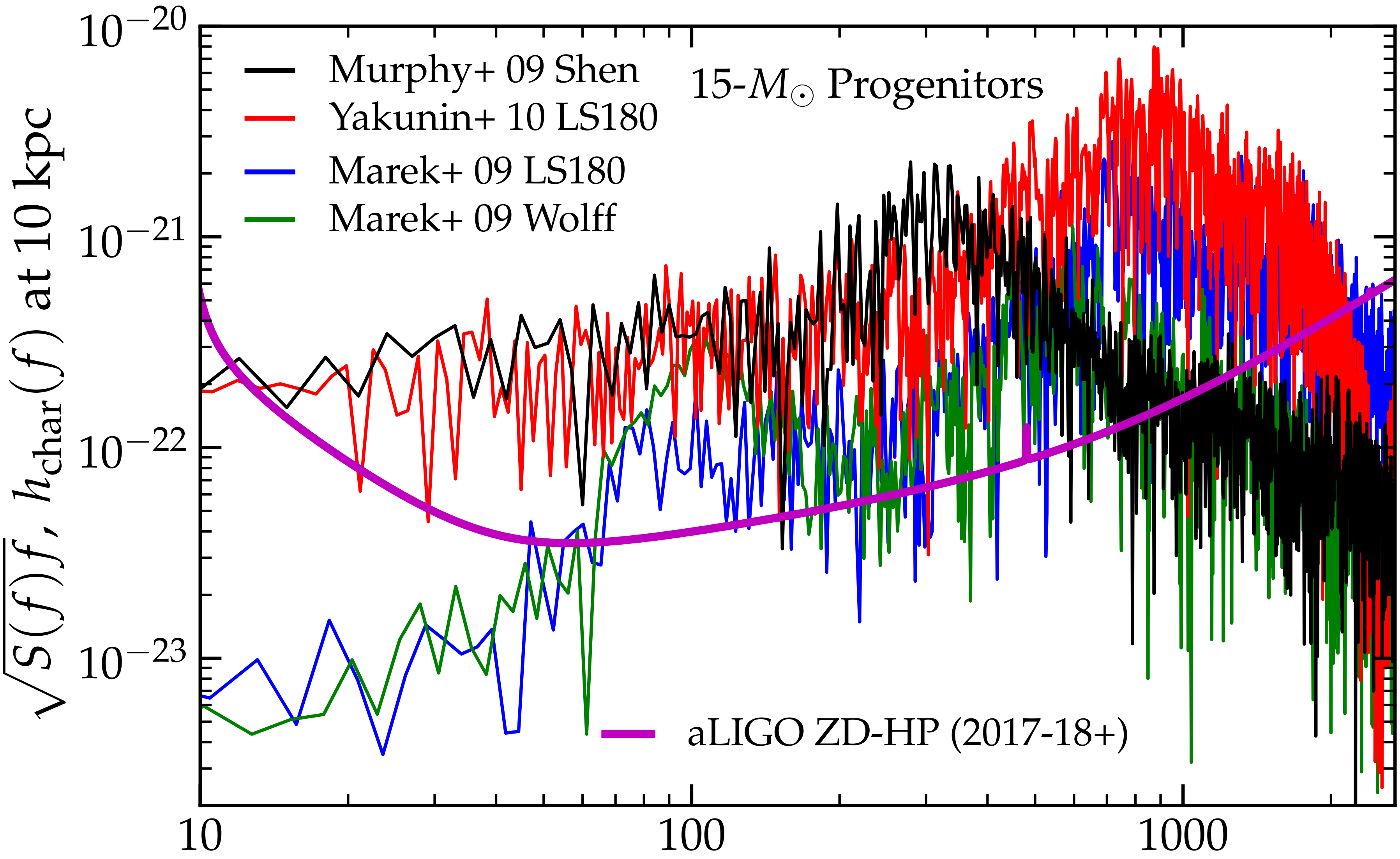
GWs from Convection & SASI

Murphy, Ott, Burrows '09



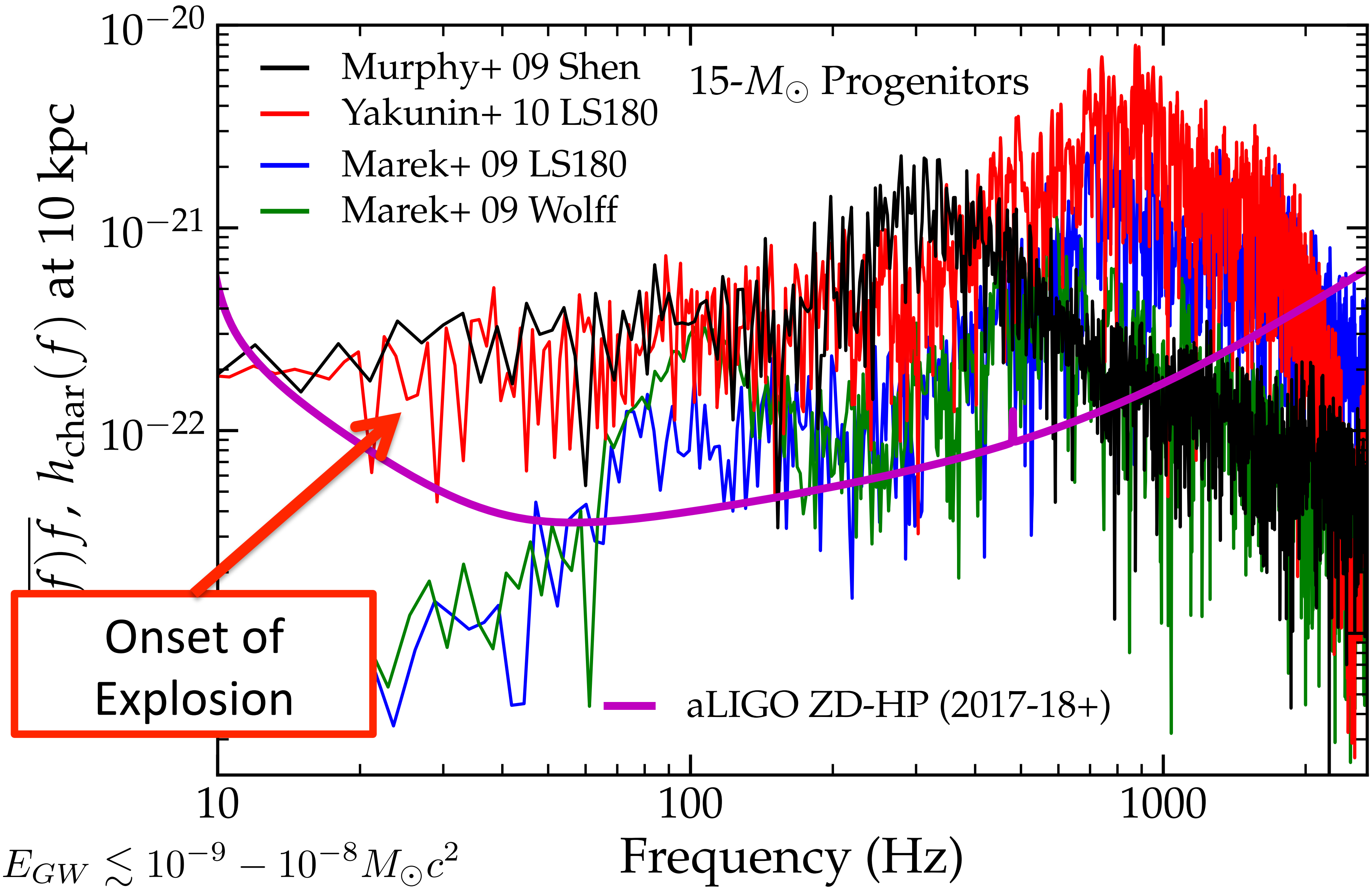
Here:
Underestimate,
since contraction of PNS is underestimated.

GWs from Convection & SASI (2D)



$E_{GW} \lesssim 10^{-9} - 10^{-8} M_\odot c^2$

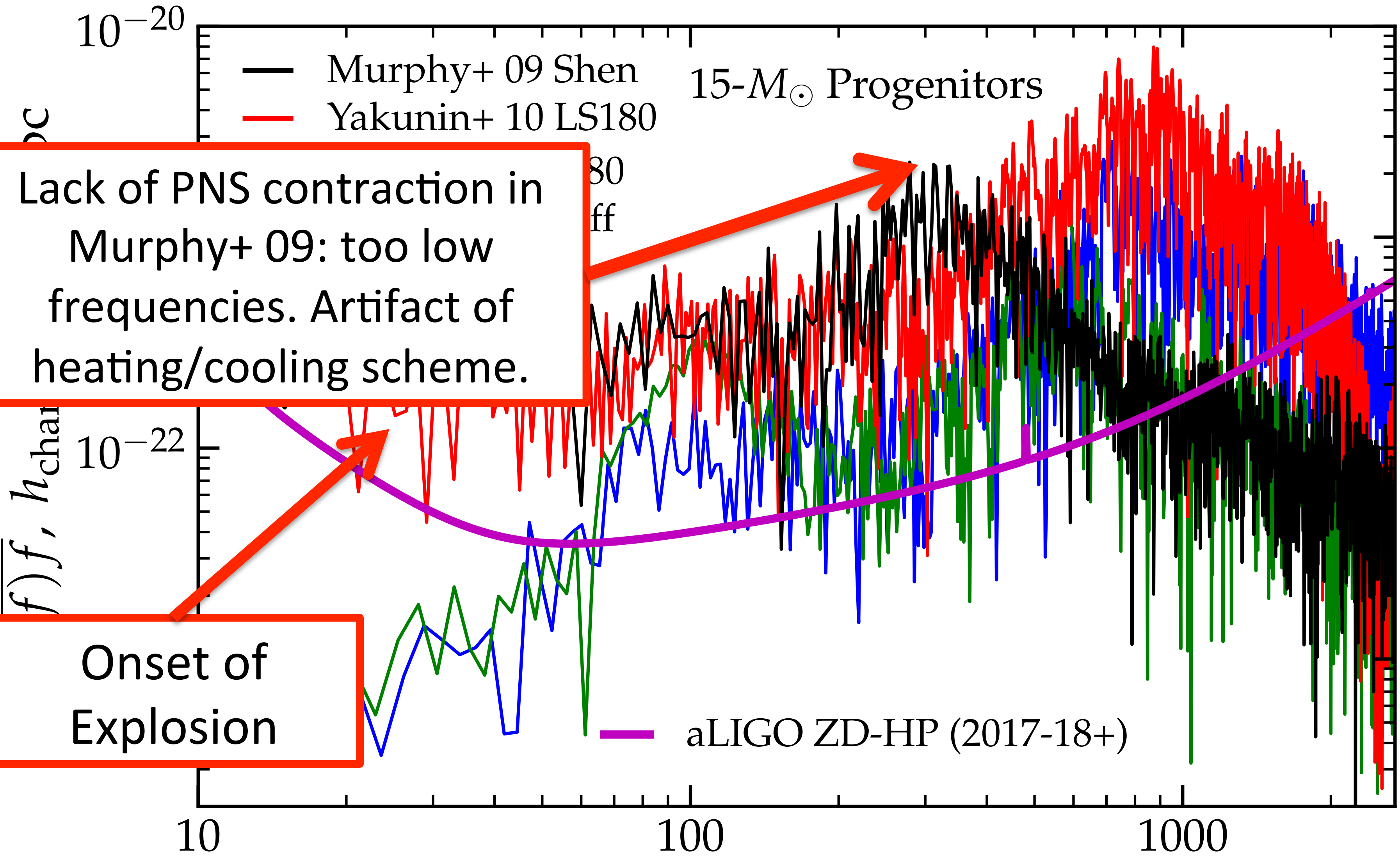
GWs from Convection & SASI (2D)



Onset of Explosion

$E_{GW} \lesssim 10^{-9} - 10^{-8} M_\odot c^2$

GWs from Convection & SASI (2D)



Lack of PNS contraction in Murphy+ 09: too low frequencies. Artifact of heating/cooling scheme.

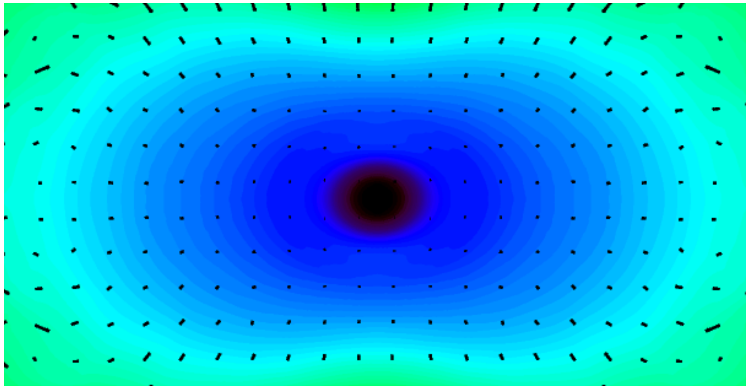
Onset of Explosion

$E_{GW} \lesssim 10^{-9} - 10^{-8} M_\odot c^2$

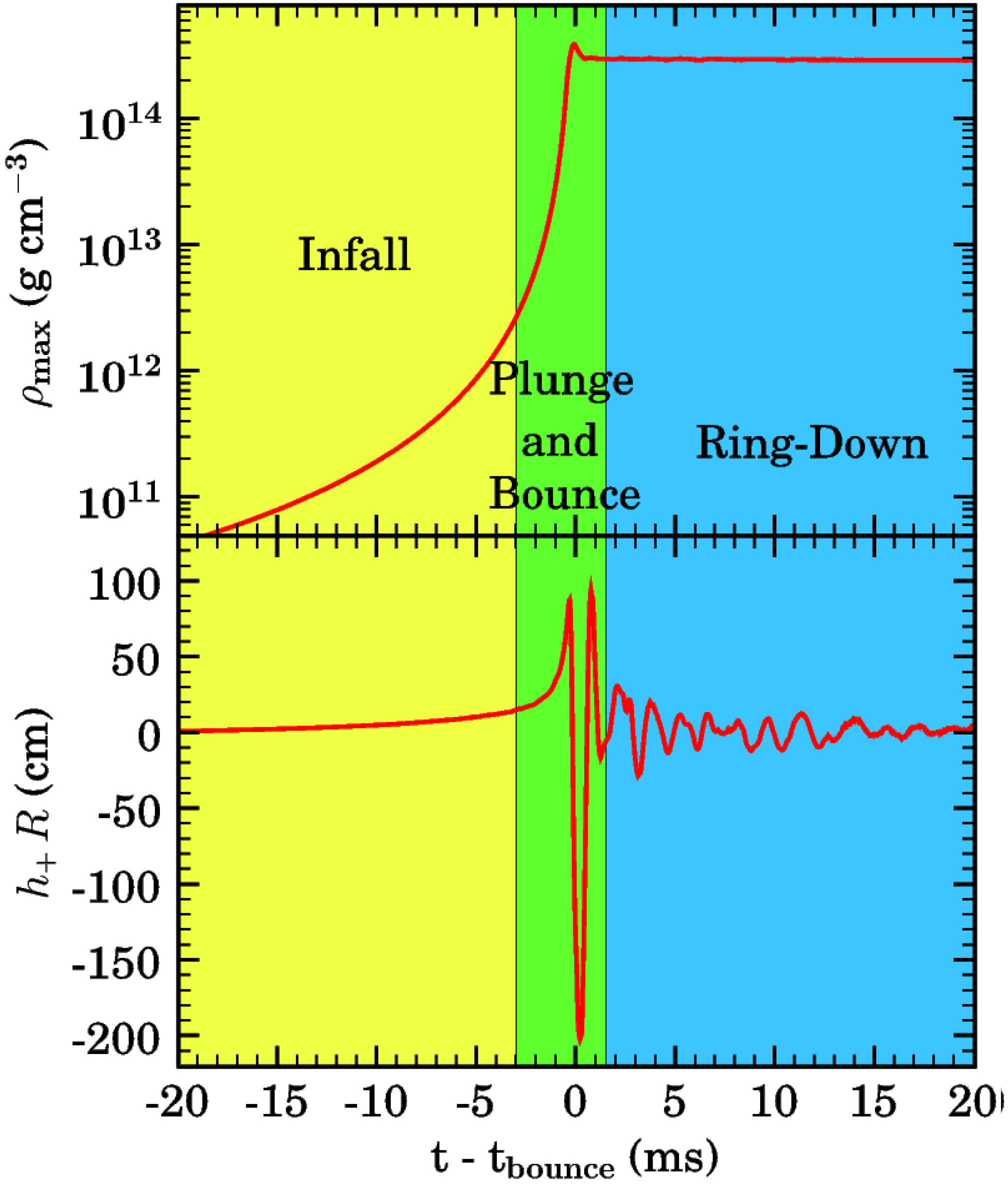
GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+ '08, Takiwaki & Kotake '11, Scheidegger+ '10, Ott+ '12

Rapid rotation:
Oblate deformation of the inner core



- Most extensively studied GW emission in core collapse
- **Axisymmetric: ONLY h_+**
- Simplest GW emission process: Rotation + Gravity + **Stiffening of EOS**.

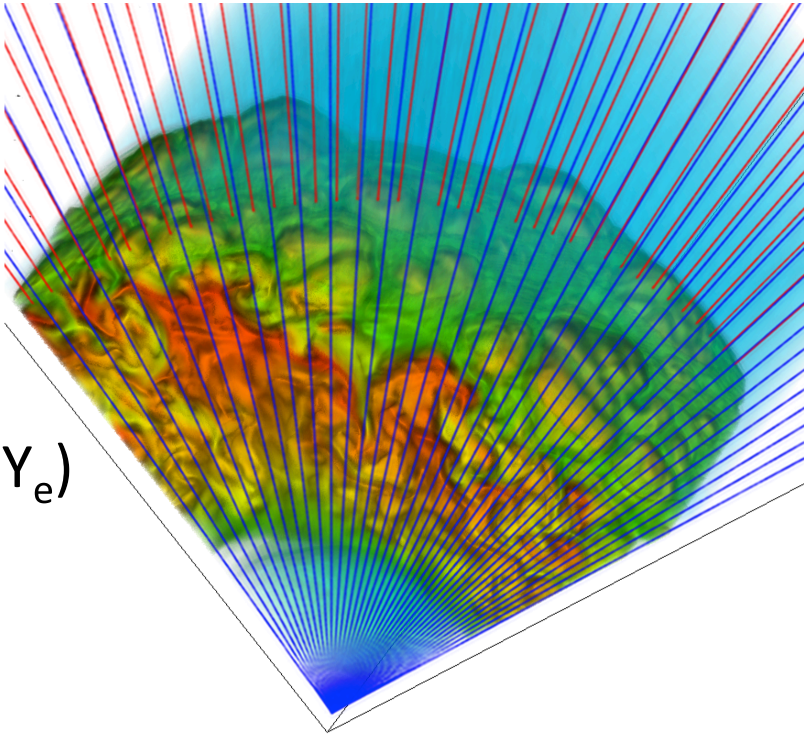


GWs from Rotating Collapse & Bounce: New Study

Team: Ott, **Abdikamalov**, **O'Connor**, Reisswig, Haas, Kalmus, Drasco, Burrows, Schnetter

[Ott et al. '12, arXiv:1204.0512, PRD in press]

- 3D GR hydro
  + full spacetime evolution.
- Simulation in a 3D octant.
- Approximate neutrino treatment:
  - 3 species *leakage* scheme
    $\nu_e, \bar{\nu}_e, \nu_x = \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$
  - Heating/cooling & deleptonization (ΔY_e)
  - Improvement over
    Murphy/Nordhaus/Burrows+ '08,'09,'12.
  - Somewhat worse than Kuroda+ '12.
  - Far inferior to B. Müller+ '09, '12ab.



- Open-source 3D adaptive-mesh refinement code based on the Einstein Toolkit (einsteintoolkit.org).
- Open EOS/neutrino microphysics at stellarcollapse.org.

GWs from Rotating Collapse & Bounce: New Study

Team: Ott, **Abdikamalov**, **O'Connor**, Reisswig, Haas, Kalmus, Drasco, Burrows, Schnetter

[Ott et al. '12, arXiv:1204.0512, PRD in press]

Simulation Goals and Setup

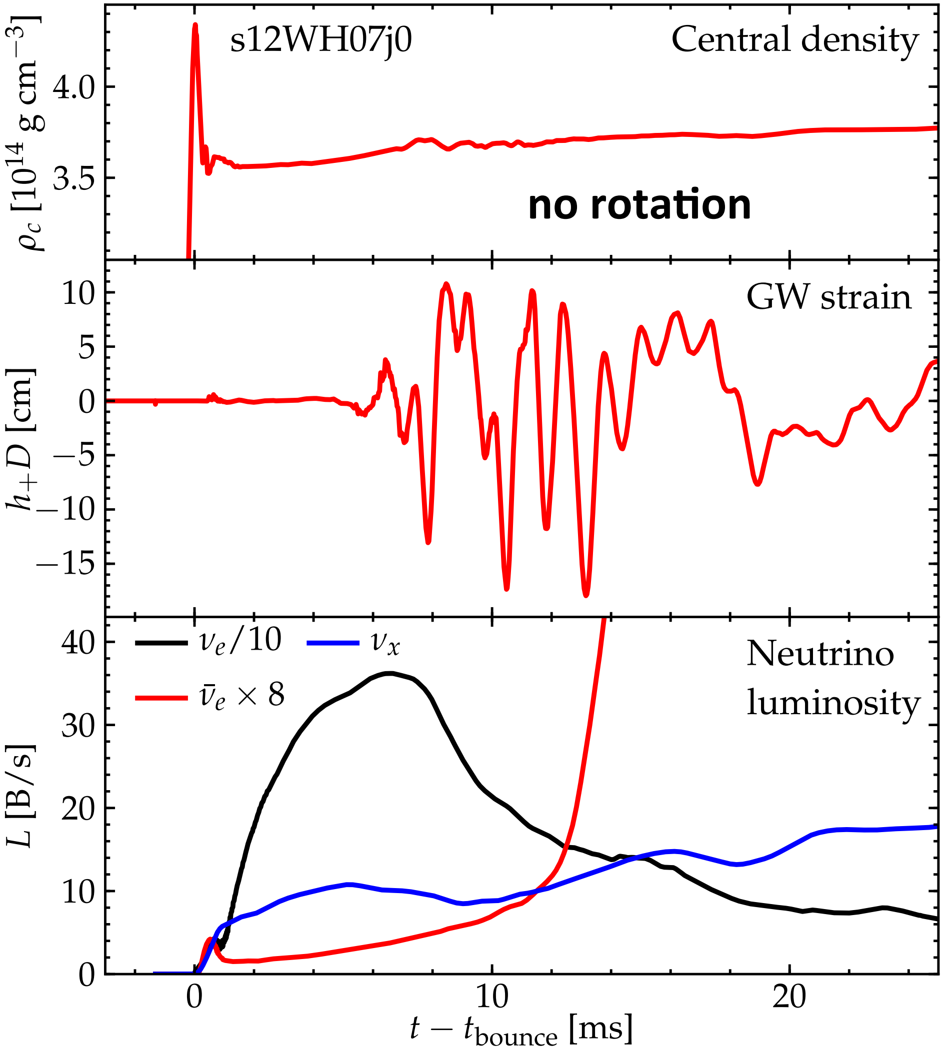
- How sensitive is the GW signal to neutrino emission after bounce? What is the dependence on progenitor star structure?
- 12 M_{Sun} & 40 M_{Sun} model; set up to have nearly the same angular momentum within ~0.5 M_{Sun}.
- Initial rotation rates leading to PNS with 10 ms to 2 ms periods (-> very rapid rotation).
- Neutrinos: Y_e(ρ) [Liebendörfer '05] & leakage after bounce.
- LS220 EOS.

Baseline Results

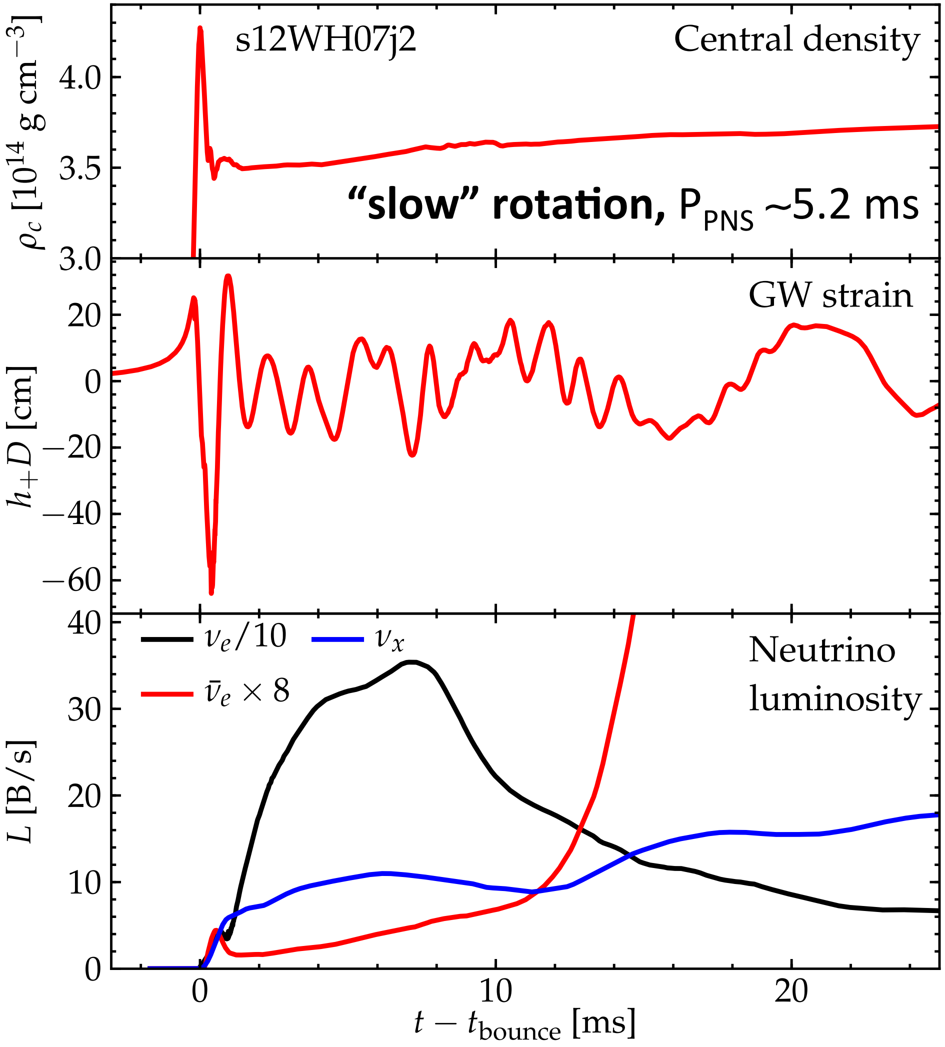
- Very weak sensitivity to neutrino emission after bounce.
- Very weak dependence on progenitor ("universality of core collapse").

Correlated GW and Neutrino Signals: Rotation

[Ott et al. ‘12, arXiv:1204.0512]



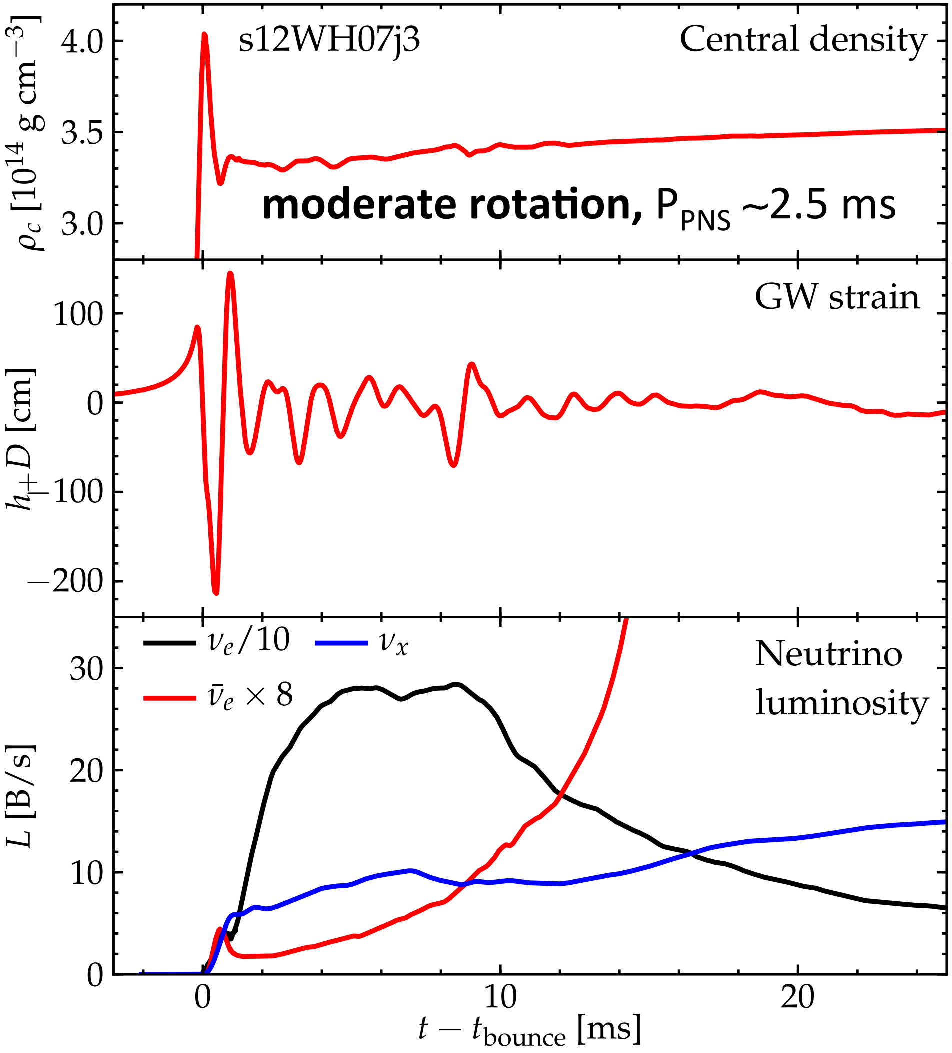
no rotation



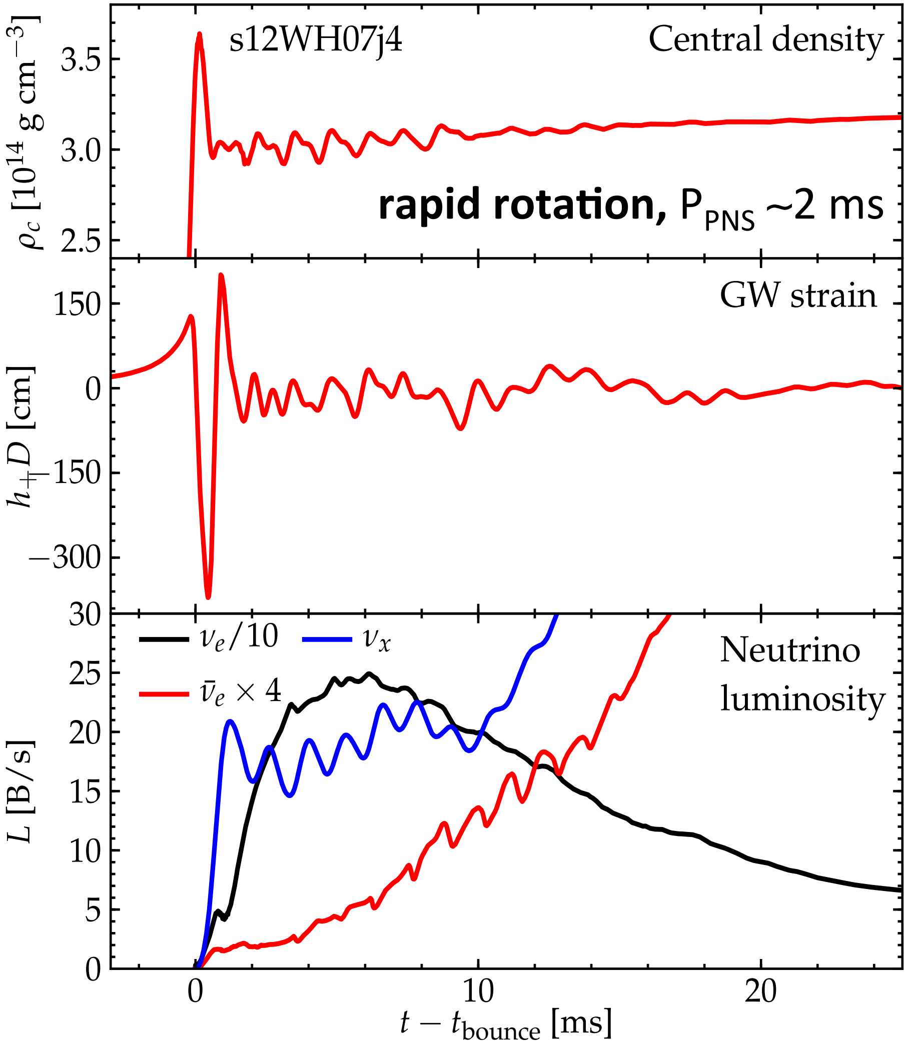
“slow” rotation, P_{PNS} ~5.2 ms

Correlated GW and Neutrino Signals: Rotation

[Ott et al. ‘12, arXiv:1204.0512]



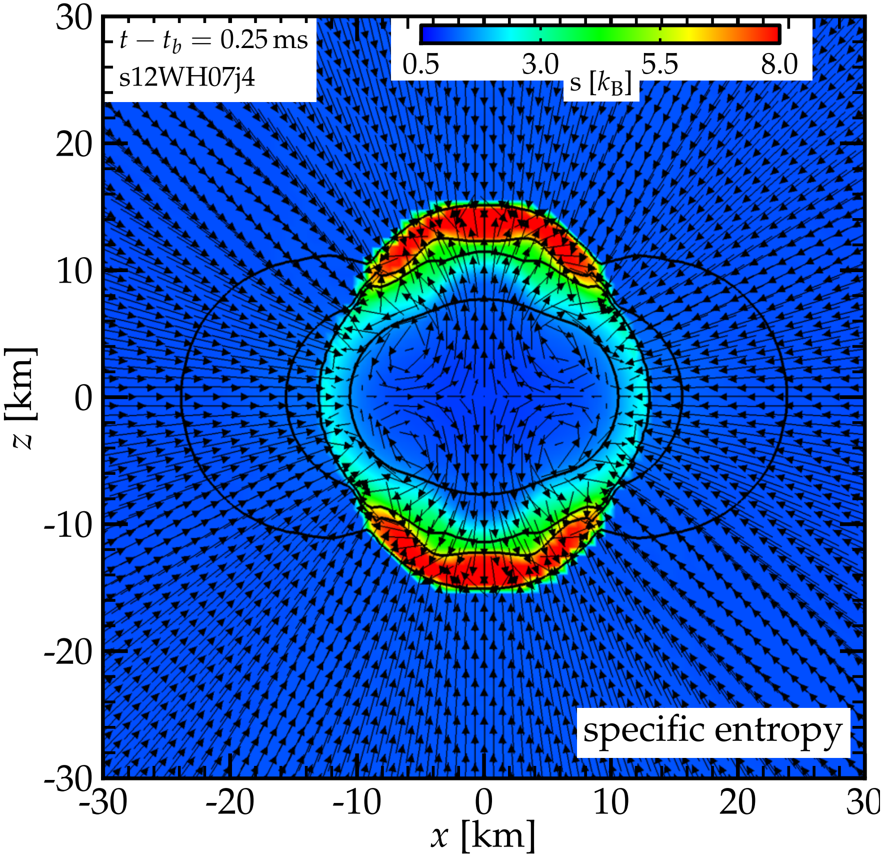
moderate rotation, P$_{\mathrm{PNS}}$ ~2.5 ms

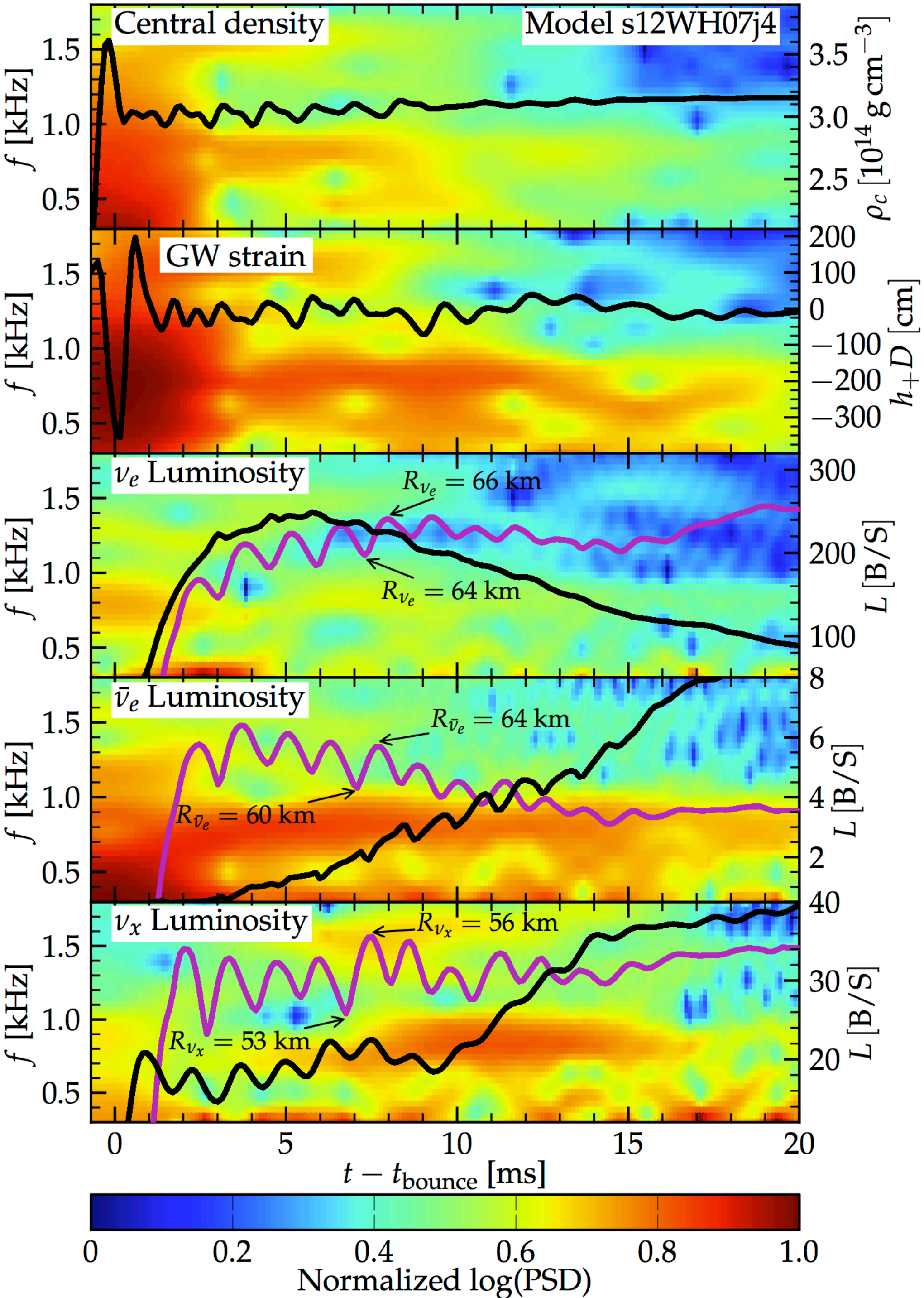


rapid rotation, P$_{\mathrm{PNS}}$ ~2 ms

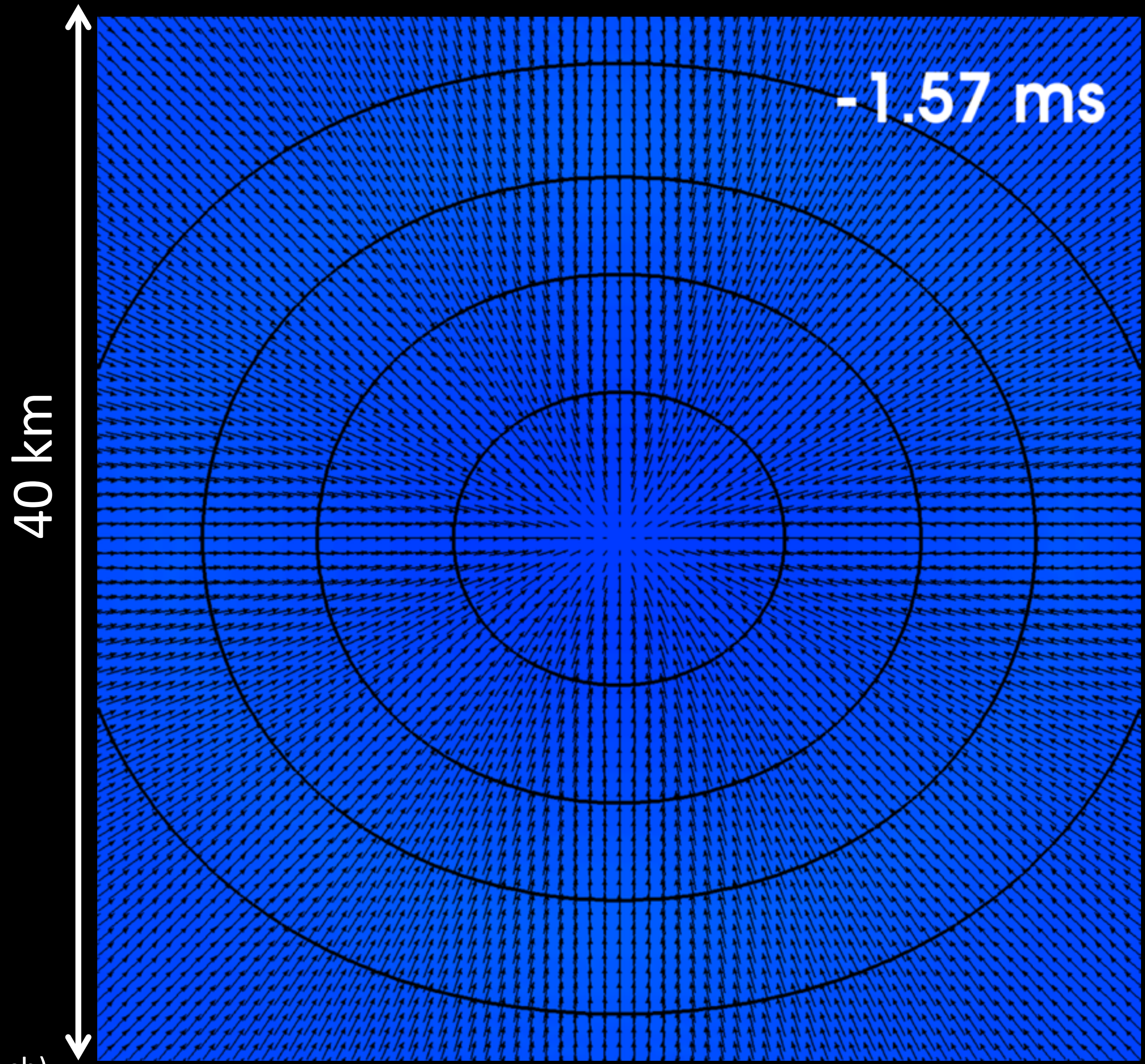
What is going on?

[Ott et al. ‘12, arXiv:1204.0512]





-> prolate bounce of oblate core excites fundamental quadrupole oscillation mode.

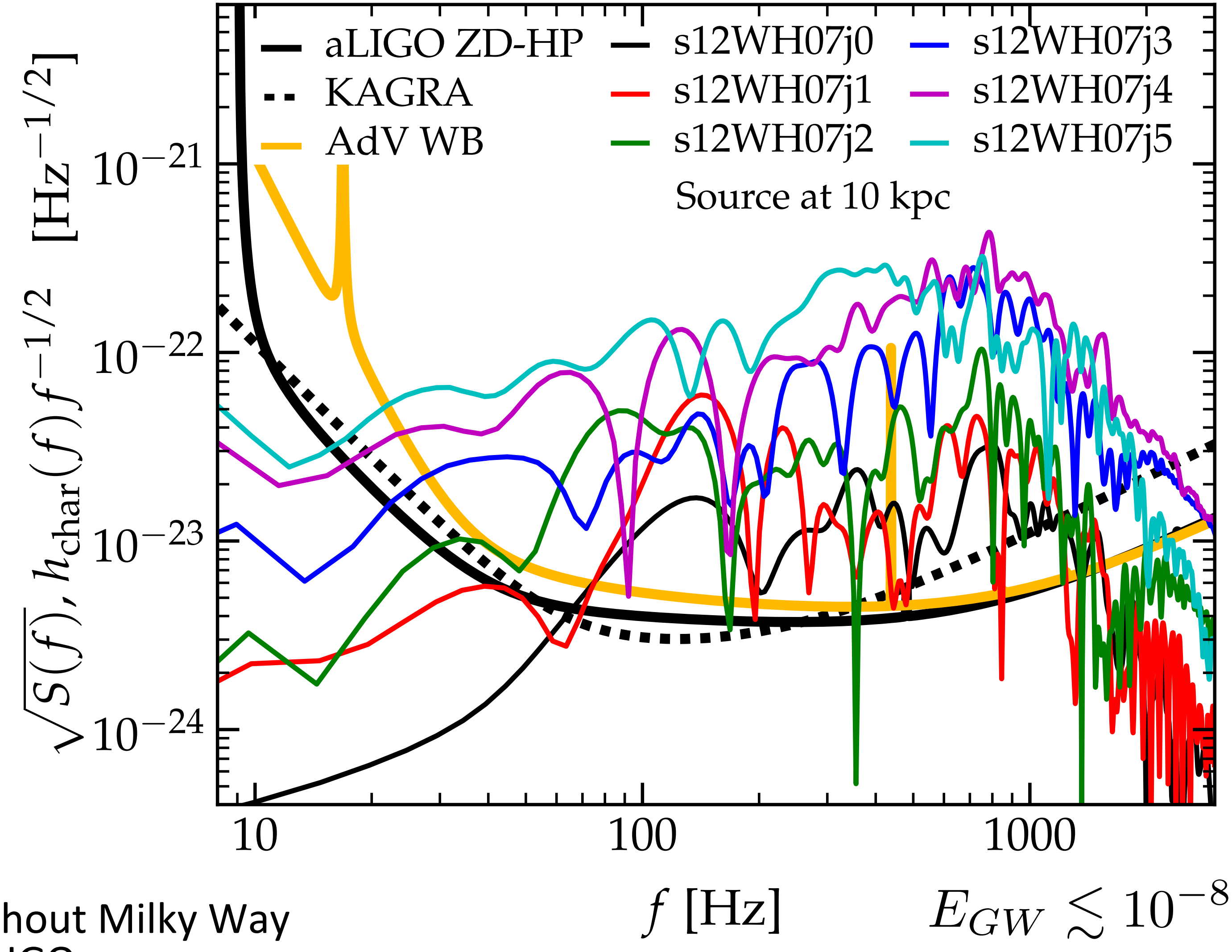


Movie by
Steve Drasco
(CalPoly/Caltech)

Can we observe this?

[Ott et al. ‘12, arXiv:1204.0512]

Gravitational Waves



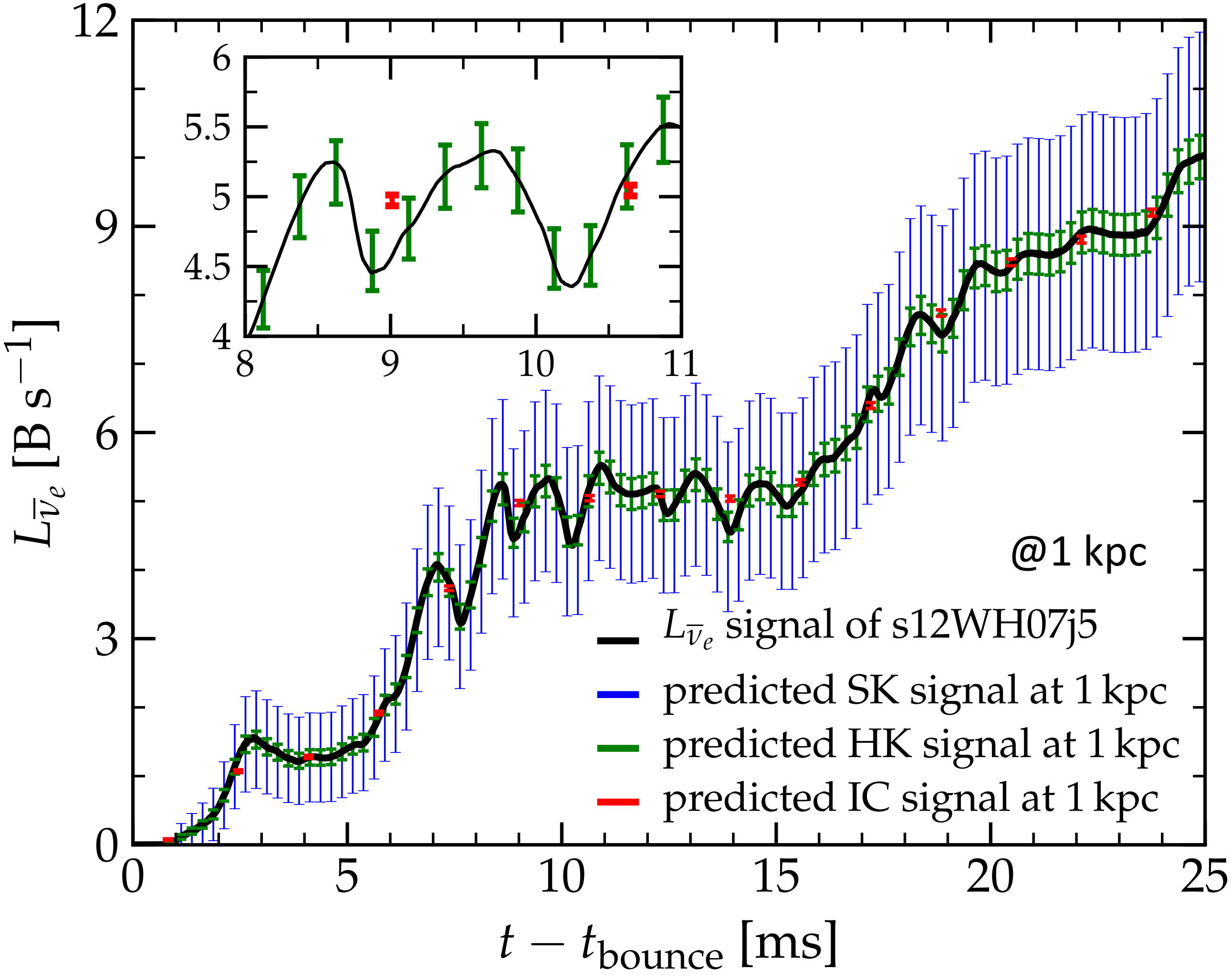
$E_{GW} \lesssim 10^{-8} M_\odot c^2$

-> Throughout Milky Way
with aLIGO

Can we observe this?

[Ott et al. ‘12, arXiv:1204.0512]

Neutrinos



~1 kpc with a megaton water-Cherenkov detector.
IceCube limited by readout rate.

(2) Connecting GW Signals and Explosion Mechanisms

Ott ’09, CQG
see also Kotake ‘11, Kotake et al.’12

Connecting GW Signals and Explosion Mechanisms

Ott ‘09, CQG 26, 063001

Dominant GW Emission Processes

Neutrino Mechanism → Turbulent convection, **S**tanding-**A**ccretion-**S**hock **I**nstability

[e.g. Yakunin et al. ‘10, Müller et al. ‘12ab]

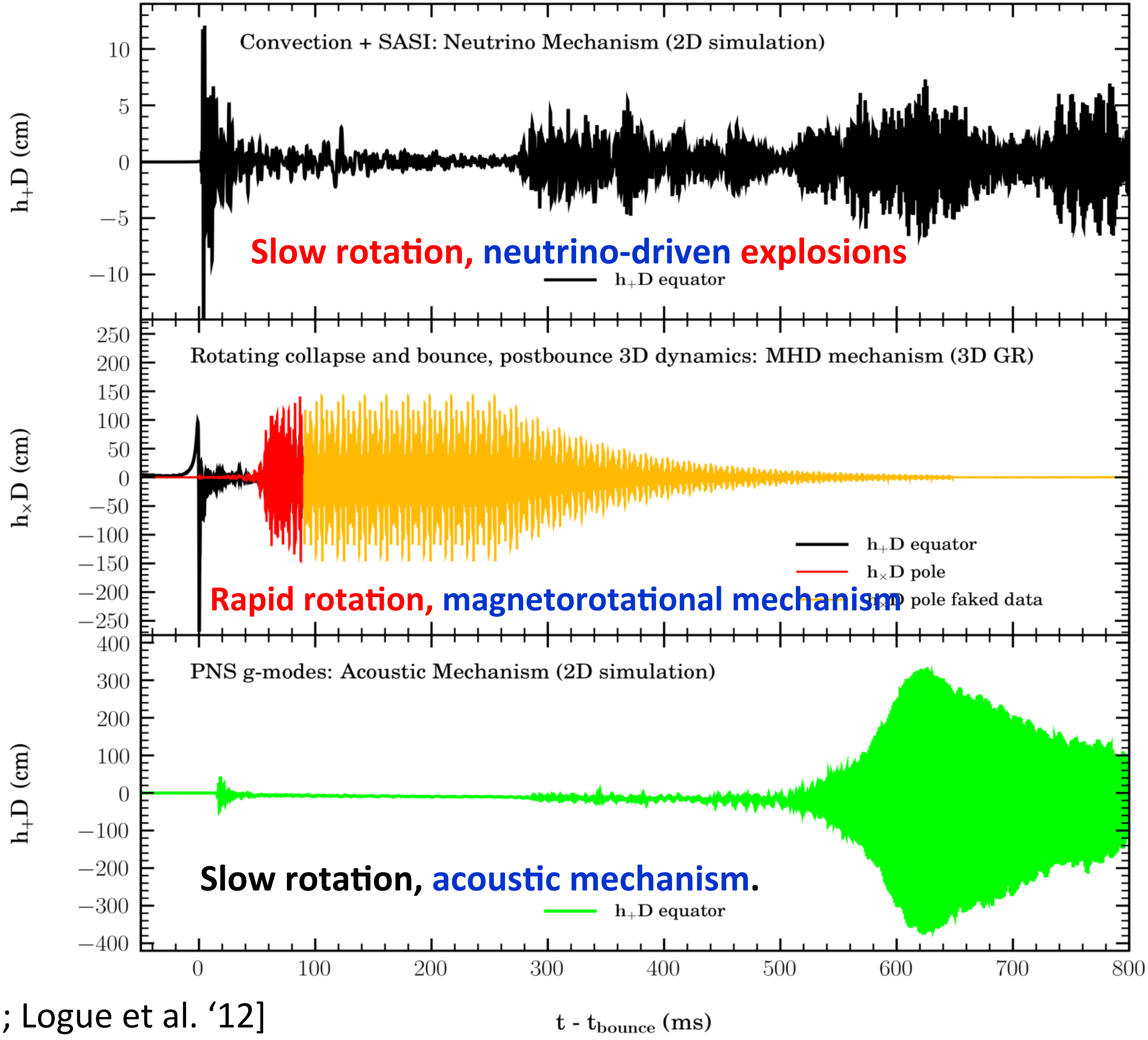
Magnetorotational Mechanism → Rotating core collapse & bounce, rotational 3D instabilities.

[e.g. Burrows et al. ’07, Takiwaki & Kotake ‘11]

Acoustic Mechanism → Protoneutron star pulsations.
(Caveat: Weinberg & Quataert ’08,
Marek & Janka ‘09 -> may not
occur in nature)

[e.g. Burrows et al. 06, Ott et al. ’06]

Connecting GW Signals and Explosion Mechanisms



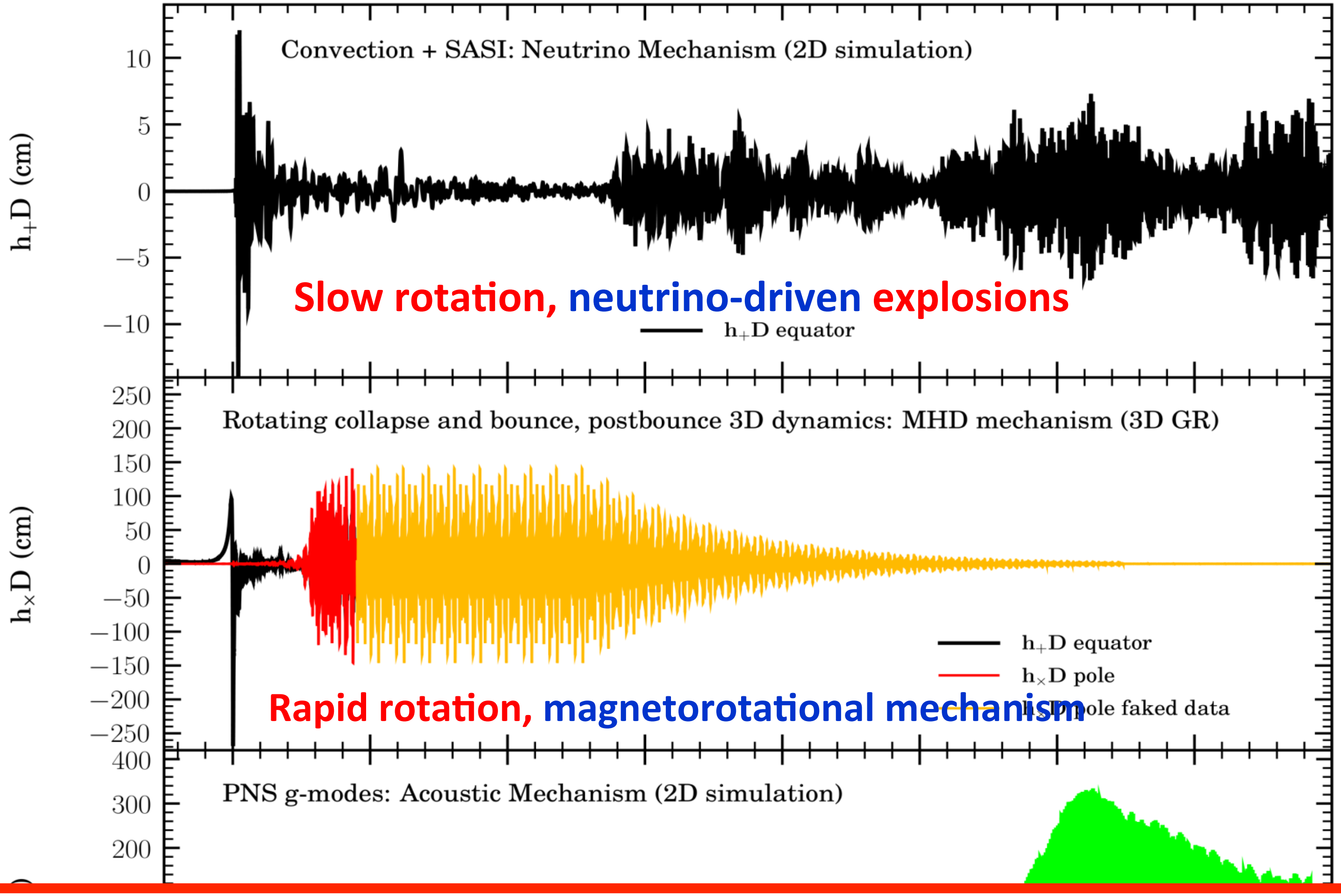
Slow rotation, neutrino-driven explosions

Rapid rotation, magnetorotational mechanism

Slow rotation, acoustic mechanism.

[Ott ’09; Logue et al. ‘12]

Connecting GW Signals and Explosion Mechanisms



Slow rotation, neutrino-driven explosions

Rapid rotation, magnetorotational mechanism

Caveats:

- GW signal predictions still mostly based on 2D simulations.
- Advanced LIGO sensitivity:
  Need core-collapse supernova in the Milky Way.

(3) Inferring Physics from GW Observations of Core-Collapse Supernovae

Logue, Ott, Heng, Kalmus, Scargill 2012, arXiv:1202.3256

Supernova Model Evidence Extractor (SMEE)

Logue et al. '12, arXiv:1202.3256, PRD in press

- Can we really tell these signals apart in a noisy detector?
- Approach: Bayesian Model Selection

M: Model
D: Data
I: Prior information

Bayes Theorem:

$$P(M|D,I) = \frac{P(M|I)P(D|M,I)}{P(D|I)}$$

"Posterior Probability"

"Prior Probability"

Normalization

"Evidence (Likelihood)"

- For model selection: When comparing two models, odds ratio is sufficient:

$$O_{ij} = \frac{P(M_i|I)P(D|M_i,I)}{P(M_j|I)\underbrace{P(D|M_j,I)}_{B_{ij}}}$$

Ratio of Priors

B_{ij} Bayes Factor

"Marginal Likelihood"

$$P(D|M,I) = \int_\theta p(\theta|M,I)p(D|\theta,M)d\theta$$

θ: Model Parameters

$$\log B_{ij} = \log P(D|M_i,I) - \log P(D|M_j,I)$$

Supernova Model Evidence Extractor (SMEE)

Logue et al. '12, arXiv:1202.3256, PRD in press

Must consider two cases:

(1) Is signal different from noise?

$$\log B_{SN} = \log P(D|M_S, I) - \log P(D|M_N, I)$$

M_S signal model M_N noise model (here: Gaussian,stationary)

(note: real detector noise: non-Gaussian, non-stationary)

(2) Comparison of signal models

$$\log B_{ij} = \log P(D|M_i, I) - \log P(D|M_j, I)$$

Problem: How to describe signal mode? GW signals cannot be predicted exactly (turbulence! + unknown physics).

SMEE: Signal Models

Logue et al. ‘12, arXiv:1202.3256, PRD in press

Consider waveforms representative for:

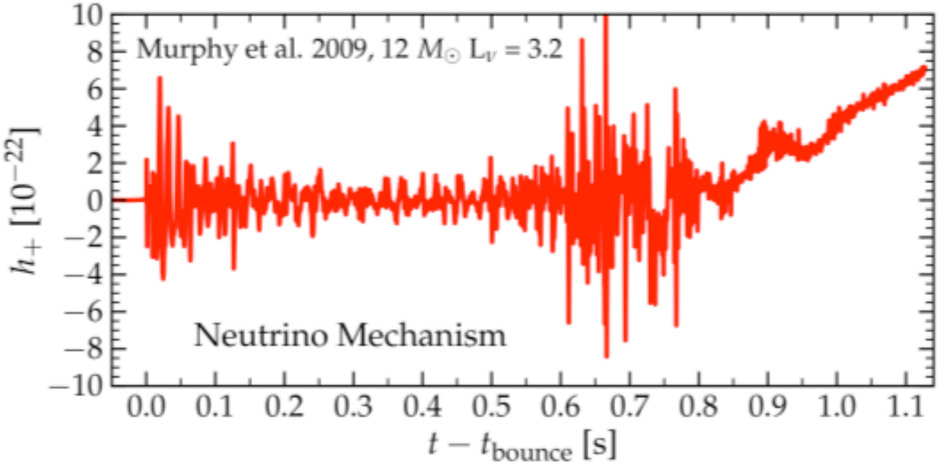
Neutrino Mechanism

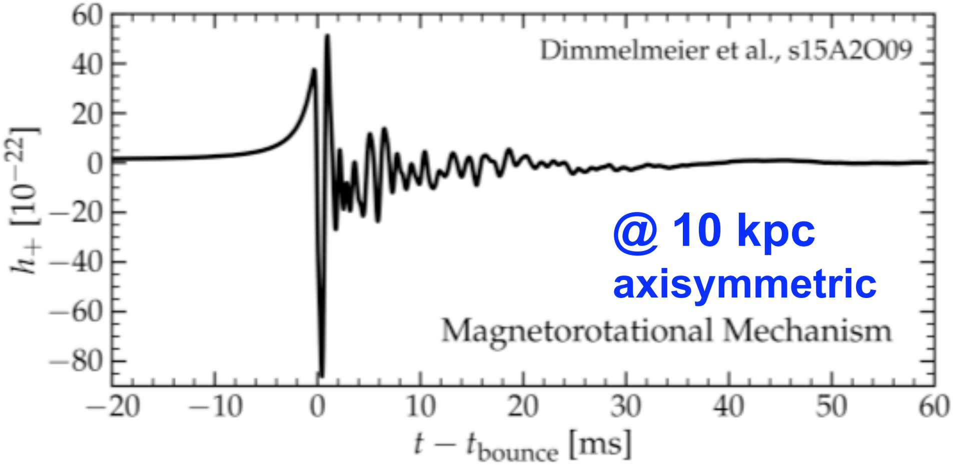
Magnetorotational Mechanism

Acoustic Mechanism

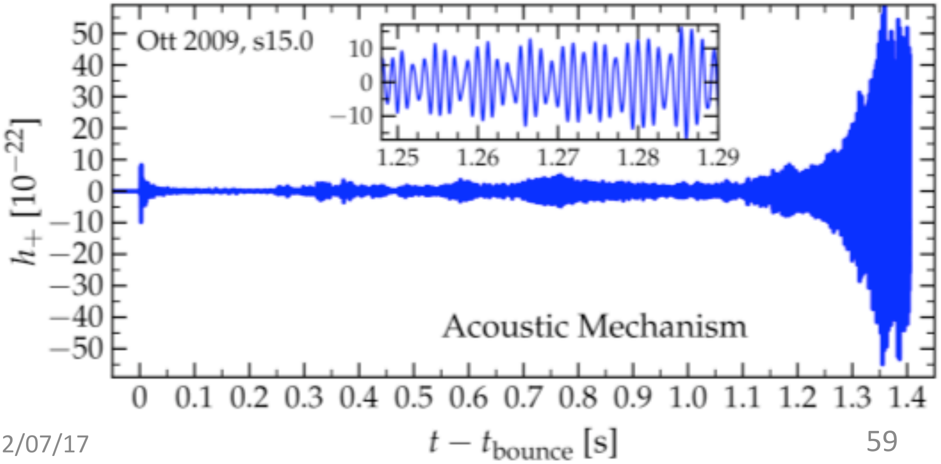
Uncertainties in Signals:
Use **P**rincipal **C**omponent **A**nalysis (**PCA**) to extract **robust signal features** from model catalogs, then **look for linear combinations** of these features.

In this study: Simplified analysis
Single aLIGO detector, Gaussian noise, single polarization, optimal orientation

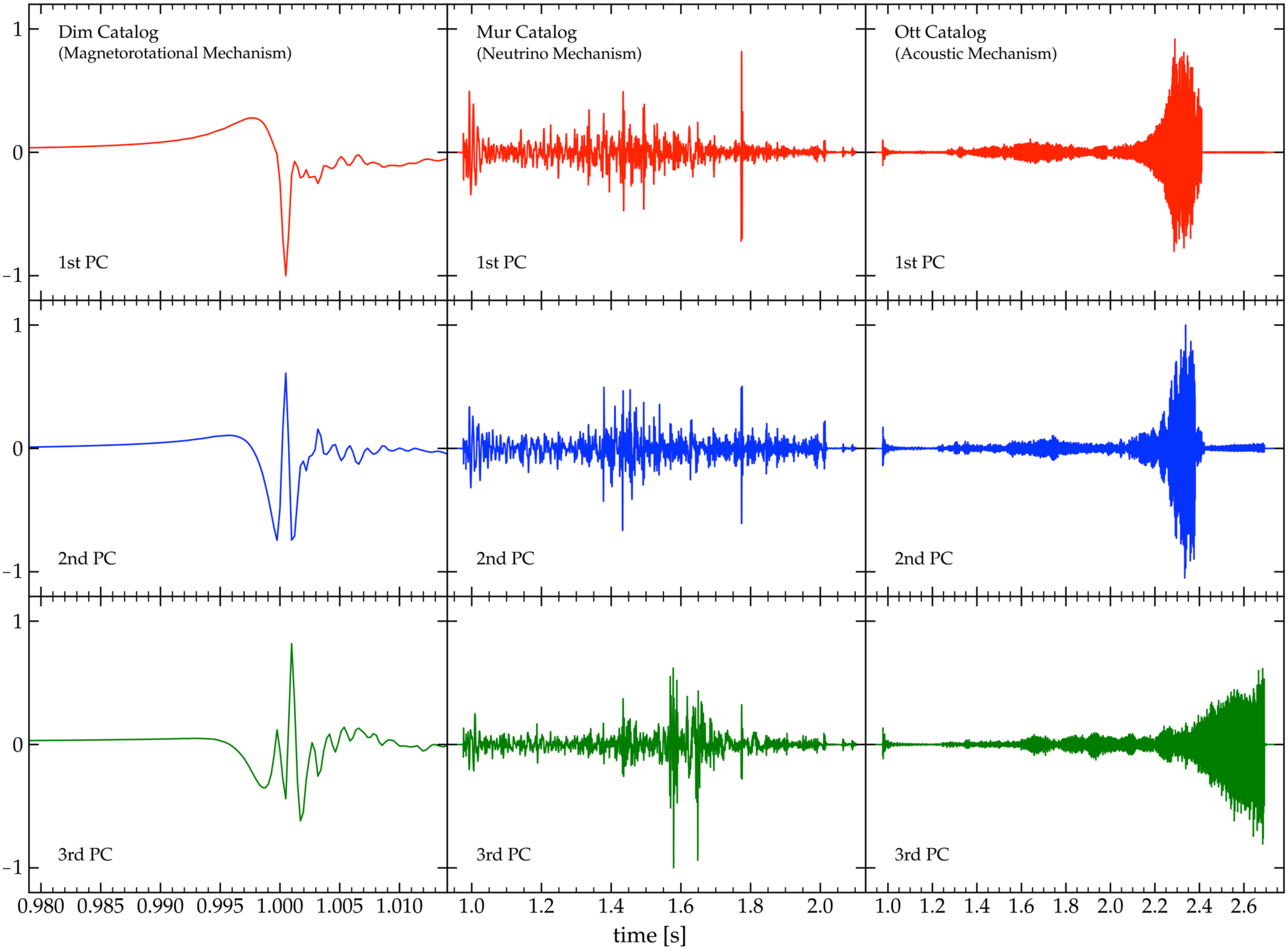




@ 10 kpc
axisymmetric



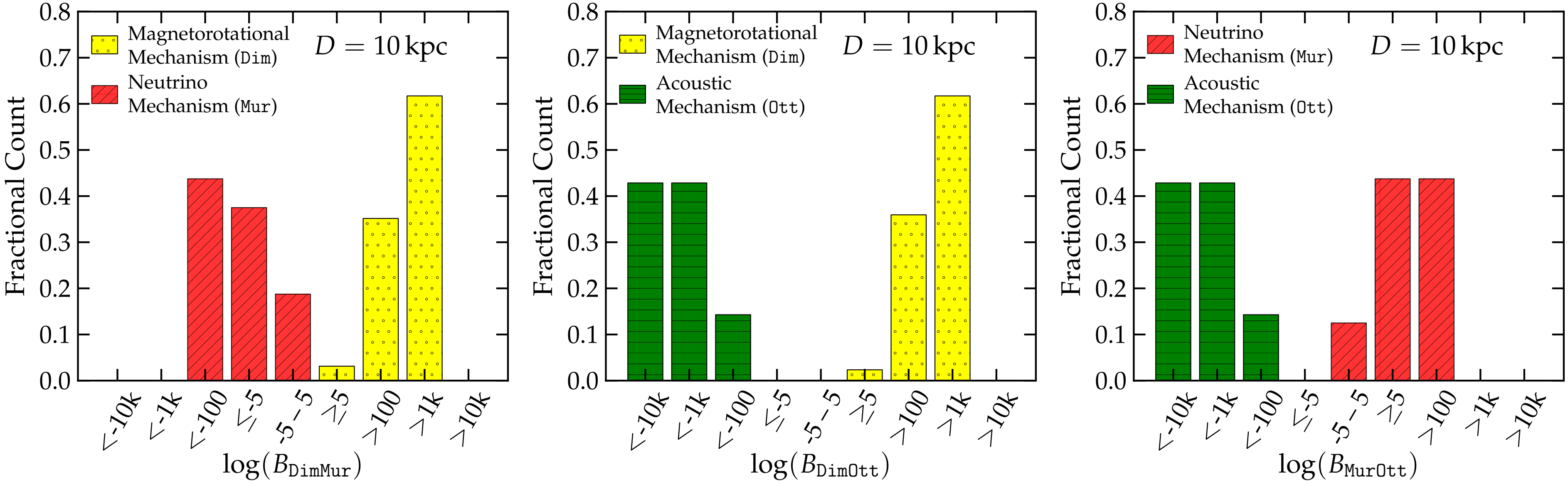
Principal Component Analysis



Results: Ideal Case

Logue et al. ‘12, arXiv:1202.3256, PRD in press

Injected “known” waveforms from catalogs that were used to generate principle components (PCs); use first 7 PCs.



$$\log B_{ij} = \log P(D|M_i, I) - \log P(D|M_j, I)$$

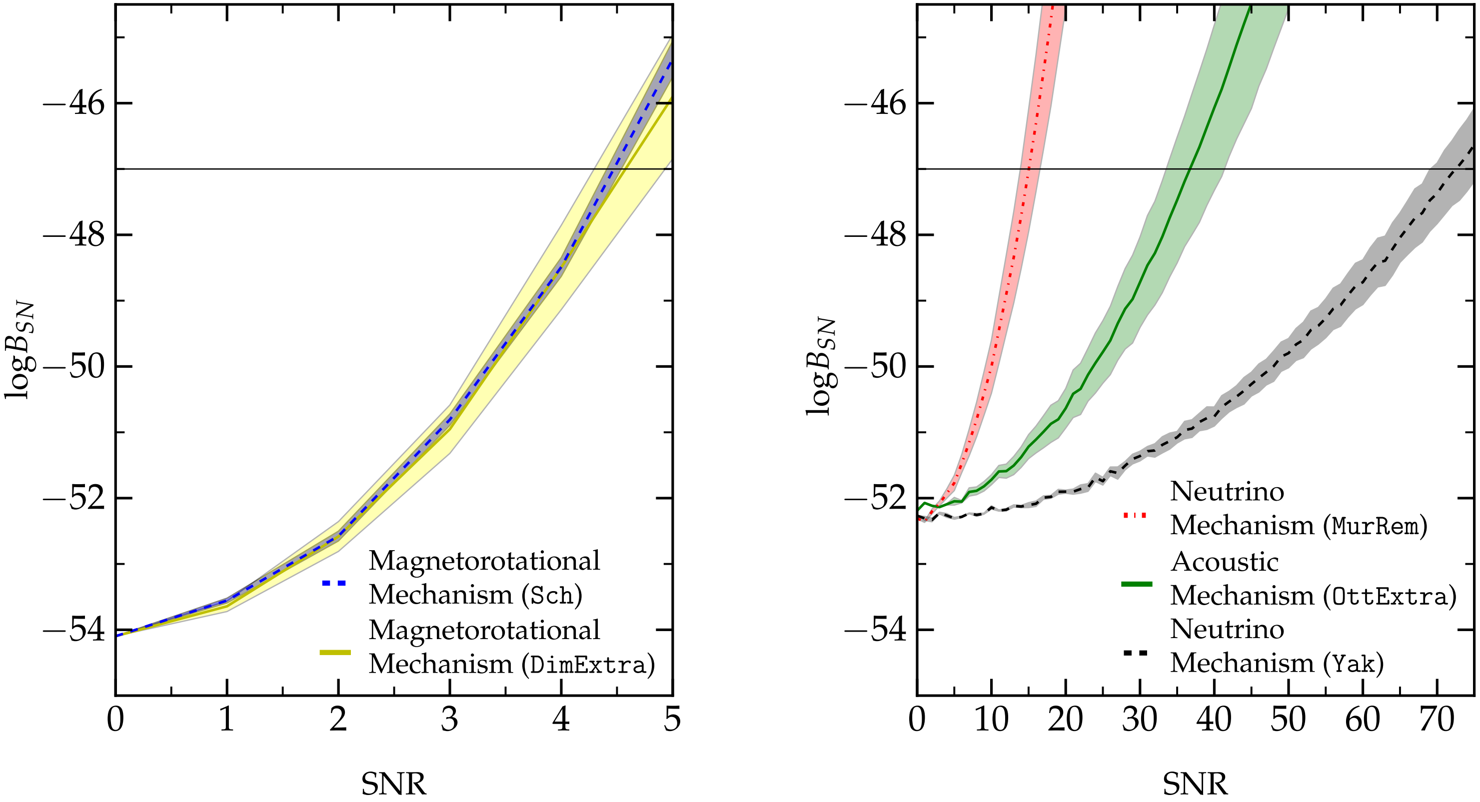
Results: More realistic case

Logue et al. ‘12, arXiv:1202.3256, PRD in press

Use **unknown waveforms** from different studies modeling the same physics.

Scheidegger et al. ‘10: magnetorotational mechanism.

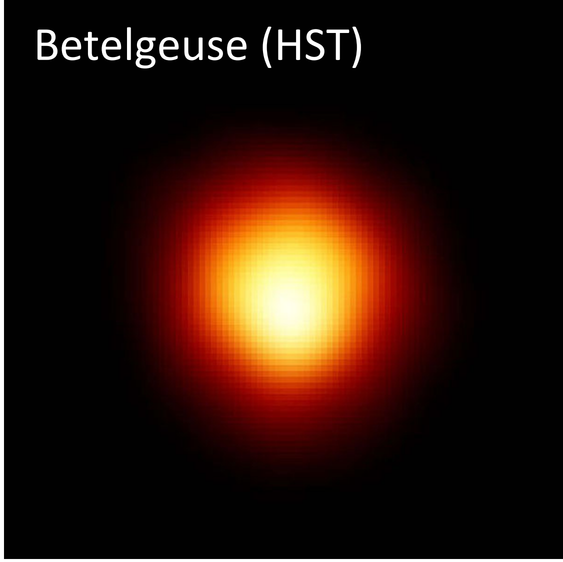
Yakunin et al. ‘10: neutrino mechanism



-> Method robust for magnetorotational mechanism out to 10 kpc.

-> Can identify neutrino mechanism out to ~2 kpc (using Murphy+ 09 PCs).

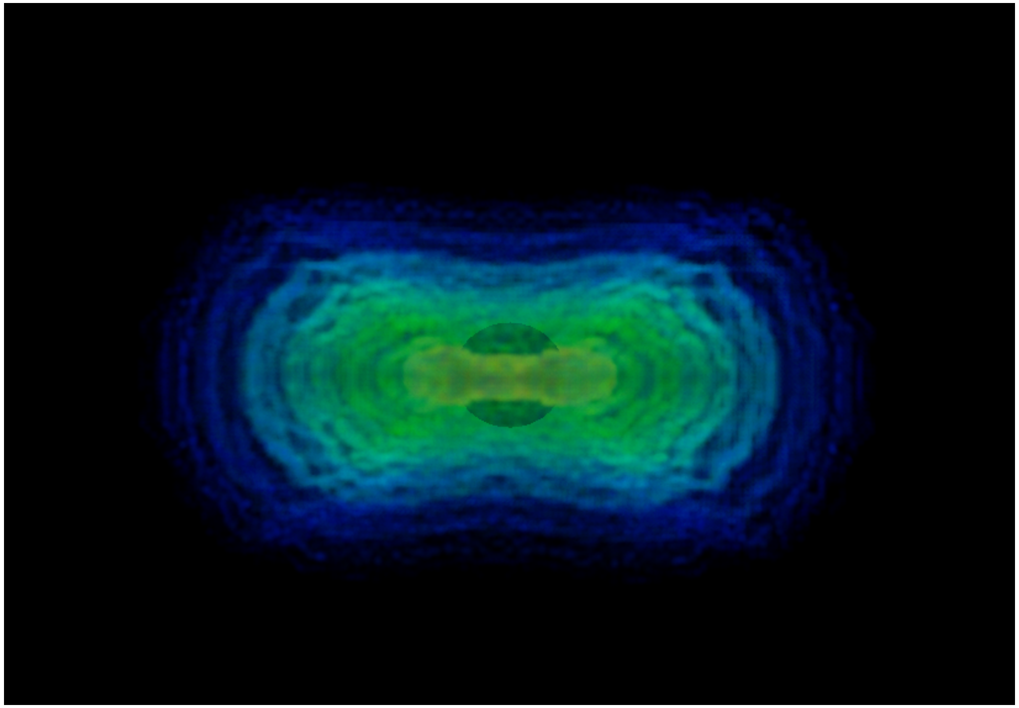
Summary


Betelgeuse (HST)

- Advanced LIGO/Virgo/KAGRA are on track.
  L1/H1 online in ~2015 at initial aLIGO sensitivity.
  LIGO India likely to happen.
  2020: L1/H1/V1/K1/I1 network.
- Core-collapse supernovae do emit GWs, but emission is weak & even advanced detectors can only see galactic (+LMC/SMC) events.
- GW observations (combined with neutrino observations) could provide crucial insight into the heart of the next galactic supernova.
  -> *Need detailed, robust, reproducible GW+ν predictions from self-consistent models*.
- **The next galactic core-collapse supernova has already exploded, but its GWs (& neutrinos & light) better not get here until ~2015...**

Supplemental Slides

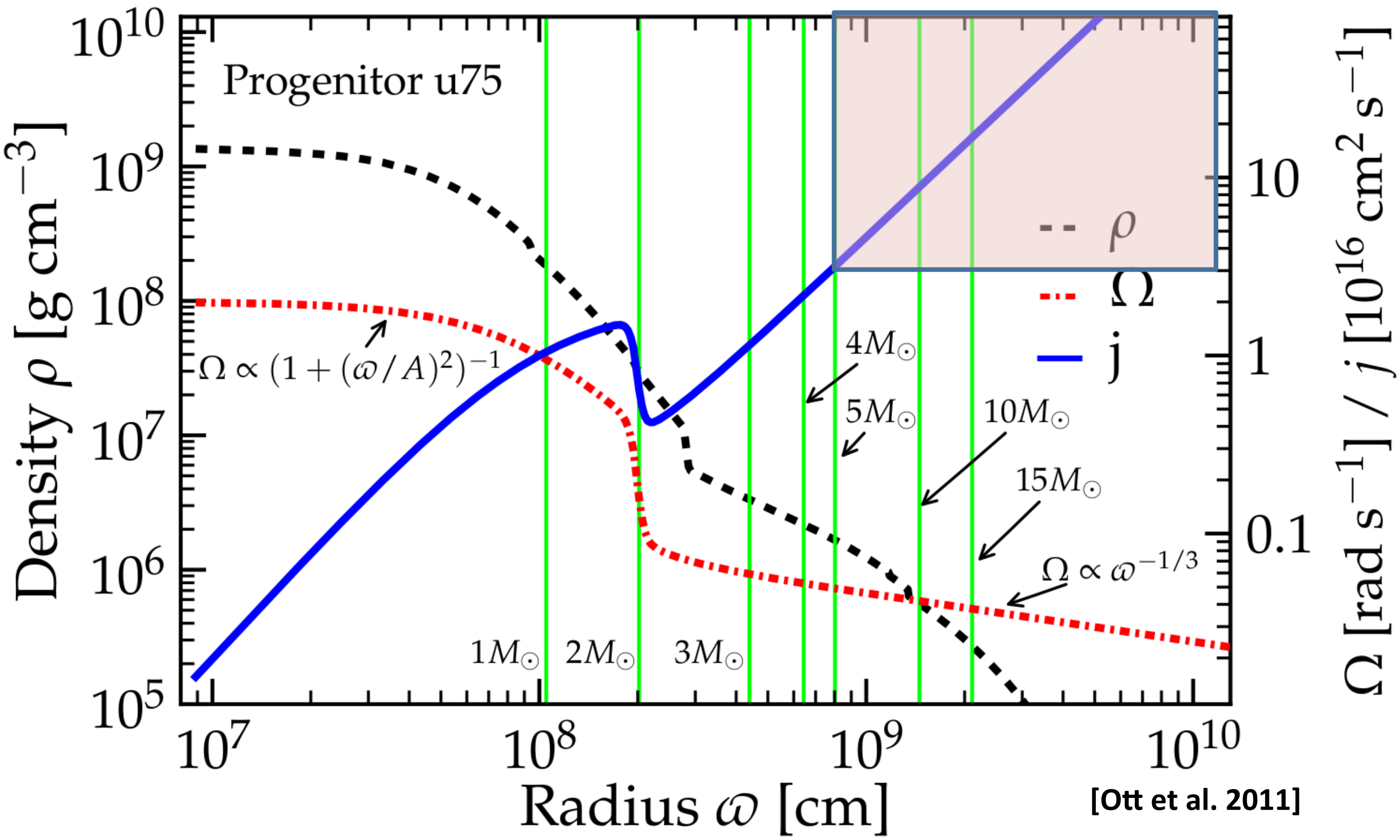
Gravitational Waves from Black Hole Formation



Ott, Reisswig (Einstein Fellow), Schnetter, **O'Connor**, Sperhake, Löffler, Diener, **Abdikamalov**, Hawke, Burrows
PRL 106, 161103 (2011)

Setup

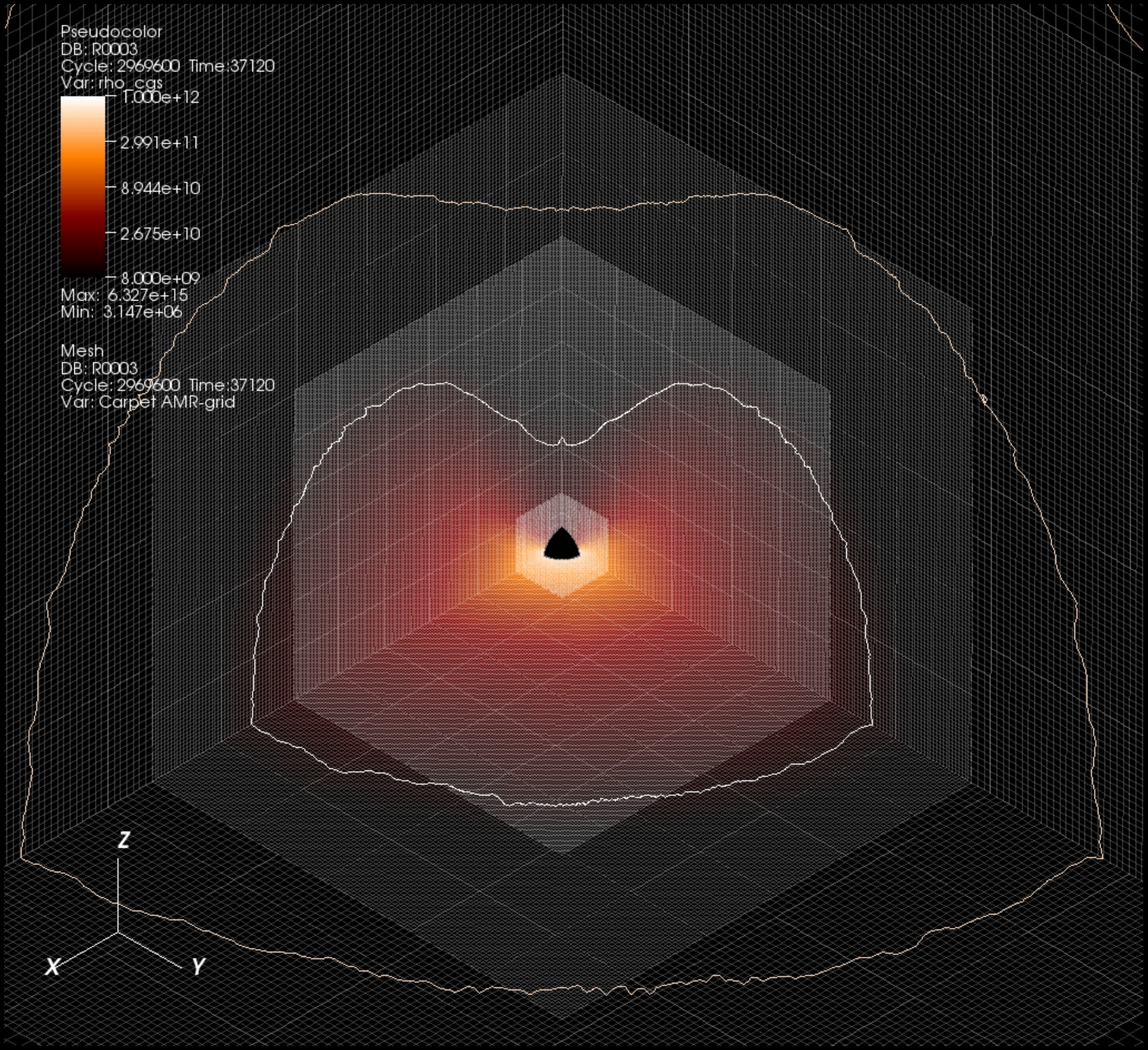
Spec. angular momentum to support disk at r > ISCO.



[Ott et al. 2011]

- 75-M_{Sun} 10^{-4} solar-metallicity progenitor of Woosley et al. 2002., **ξ~1.14**
- Rotation law based on Woosley & Heger 2006.
- Soft EOS with M_{max} ~1.7 M_{Sun}. Neutrino cooling; no heating.

Computational Setup



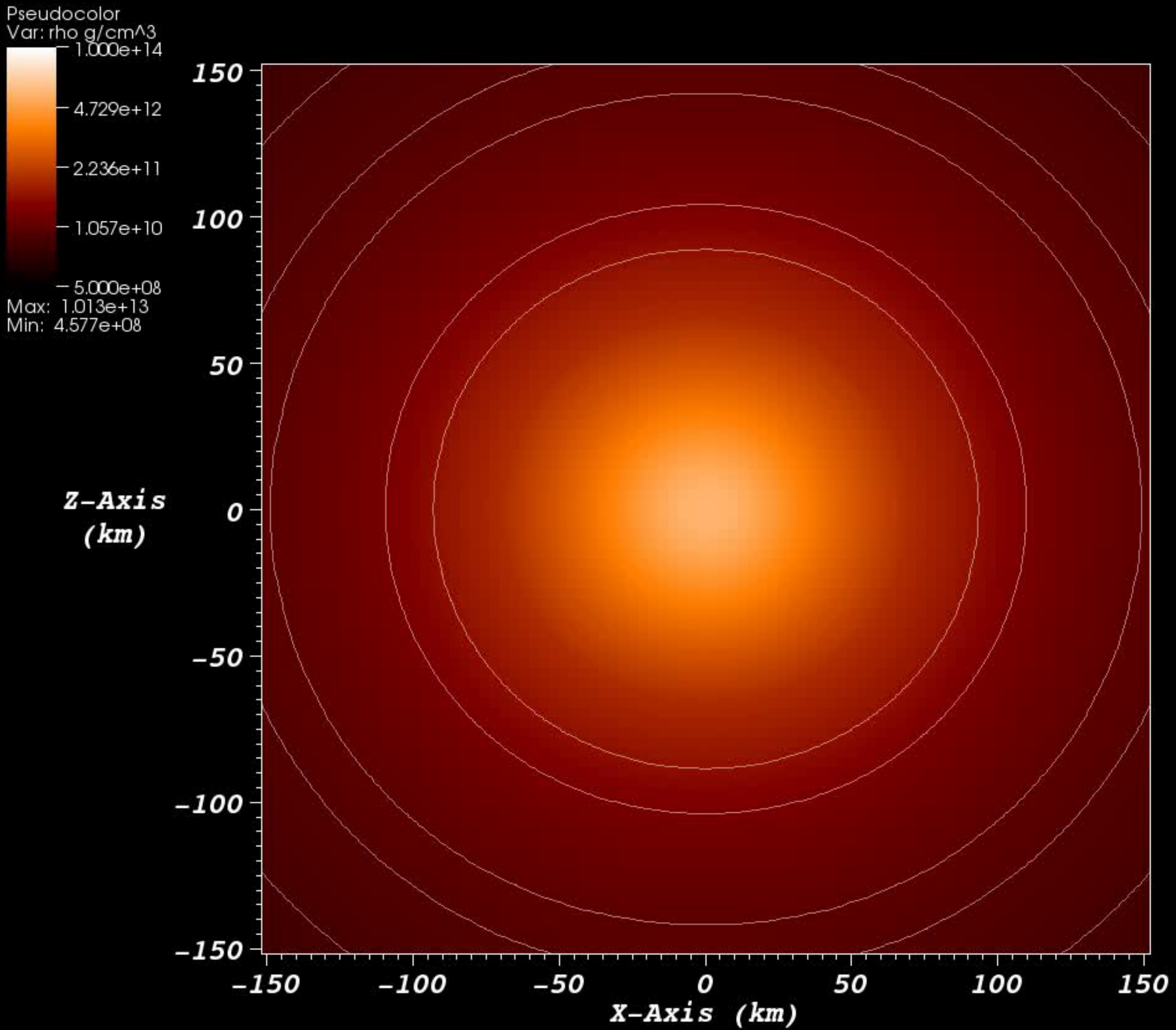
3+1 full GR simulations.

3D, but octant symmetry

11 levels of Berger-Oliger AMR

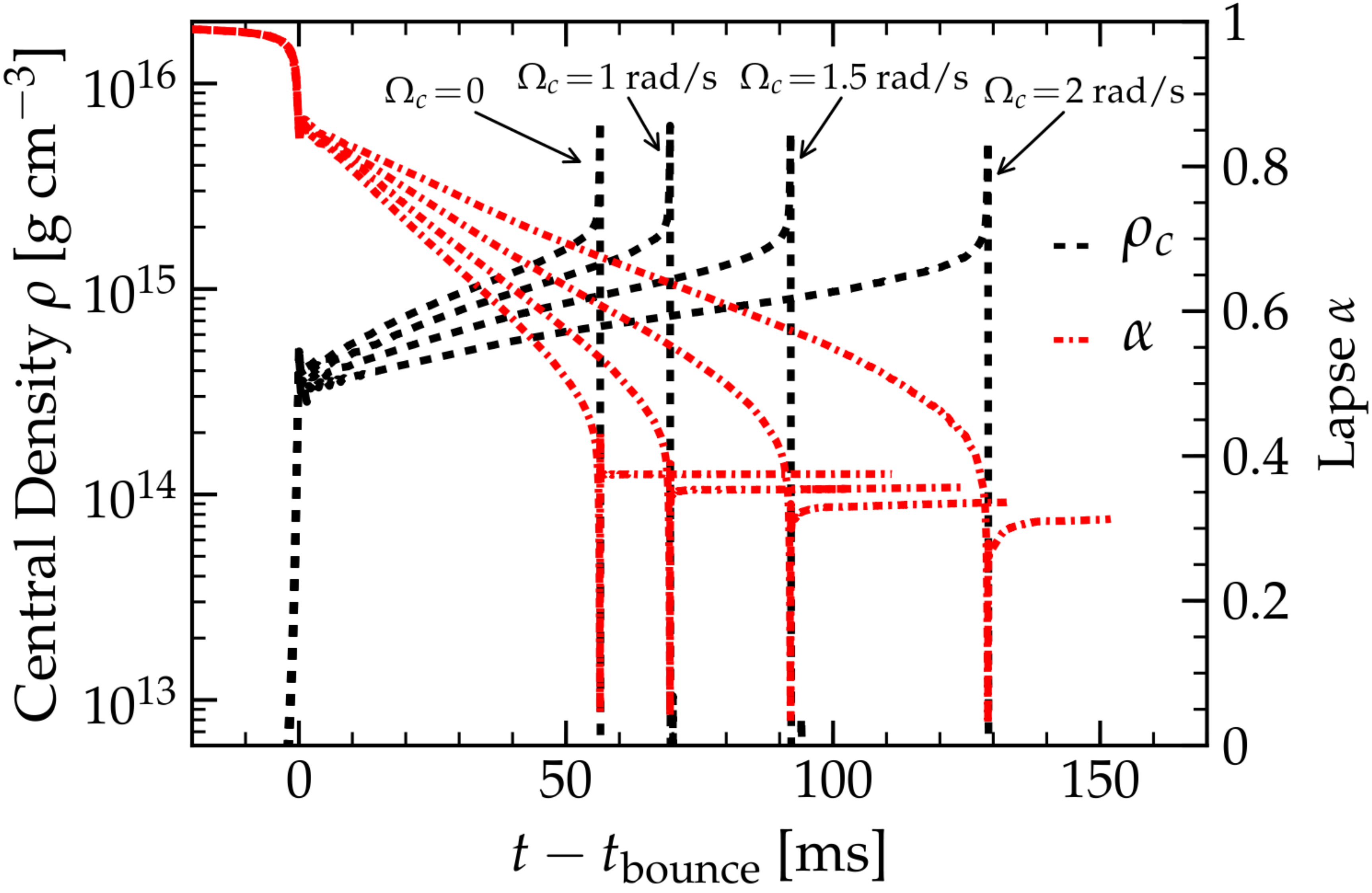
Finest level: dx = 100 m

Time: -1.49 ms


Pseudocolor
Var: rho g/cm^3
1.000e+14
4.729e+12
2.236e+11
1.057e+10
5.000e+08
Max: 1.013e+13
Min: 4.577e+08
Z-Axis (km)
150
100
50
0
-50
-100
-150
X-Axis (km)
-150
-100
-50
0
50
100
150

3D BH Formation: First Results

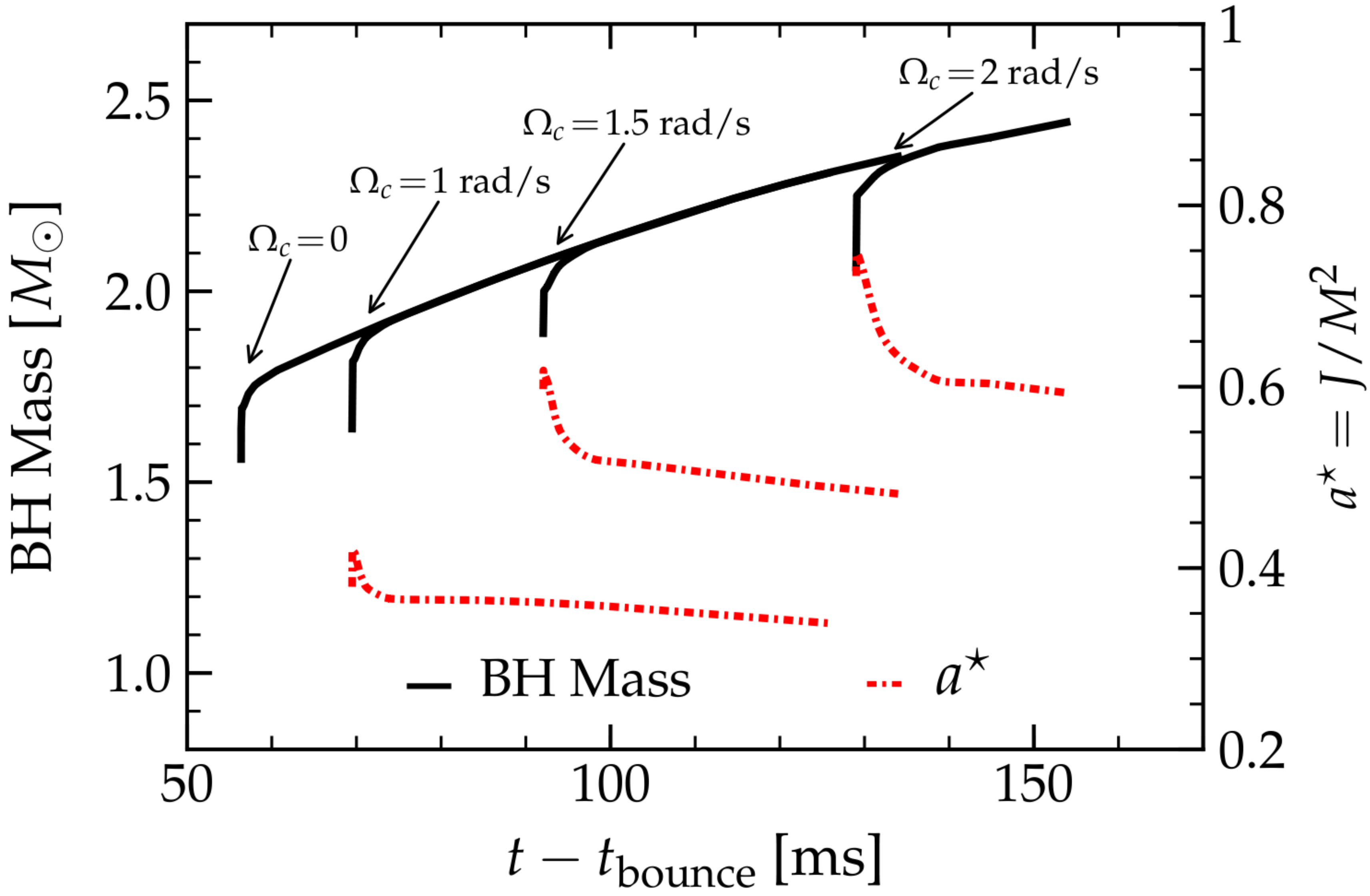
[Ott et al. 2011, PRL]



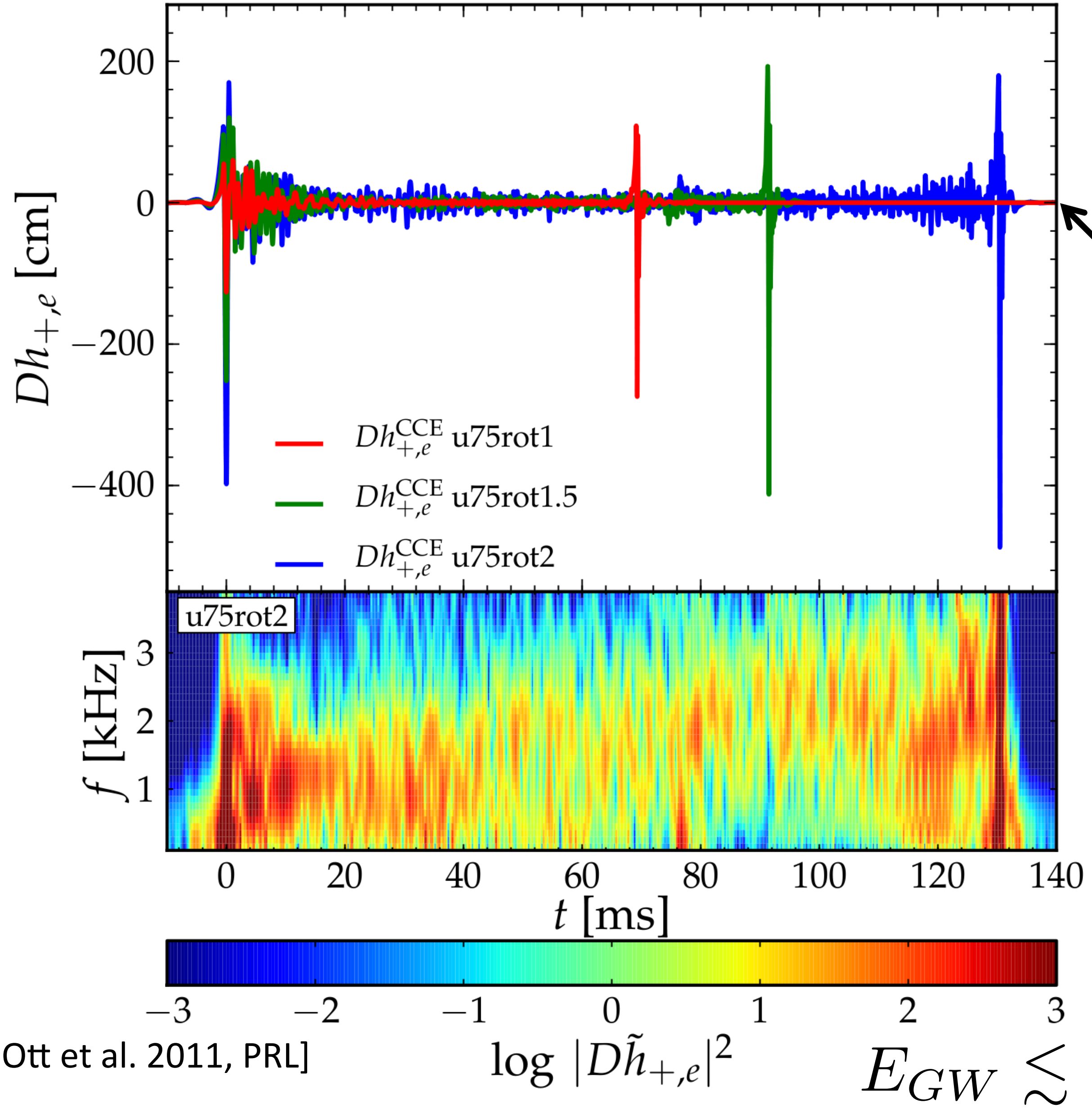
α – lapse function: $d\tau = \alpha dt$

Nascent BH Spin Evolution

[Ott et al. 2011, PRL]



Gravitational Waves from BH Formation



[Ott et al. 2011, PRL]

Hyperaccretion phase begins; **lasts multiple seconds before disk forms.**

$$E_{GW} \lesssim 10^{-7} M_\odot c^2$$