Core Collapse & Neutron Star Mergers

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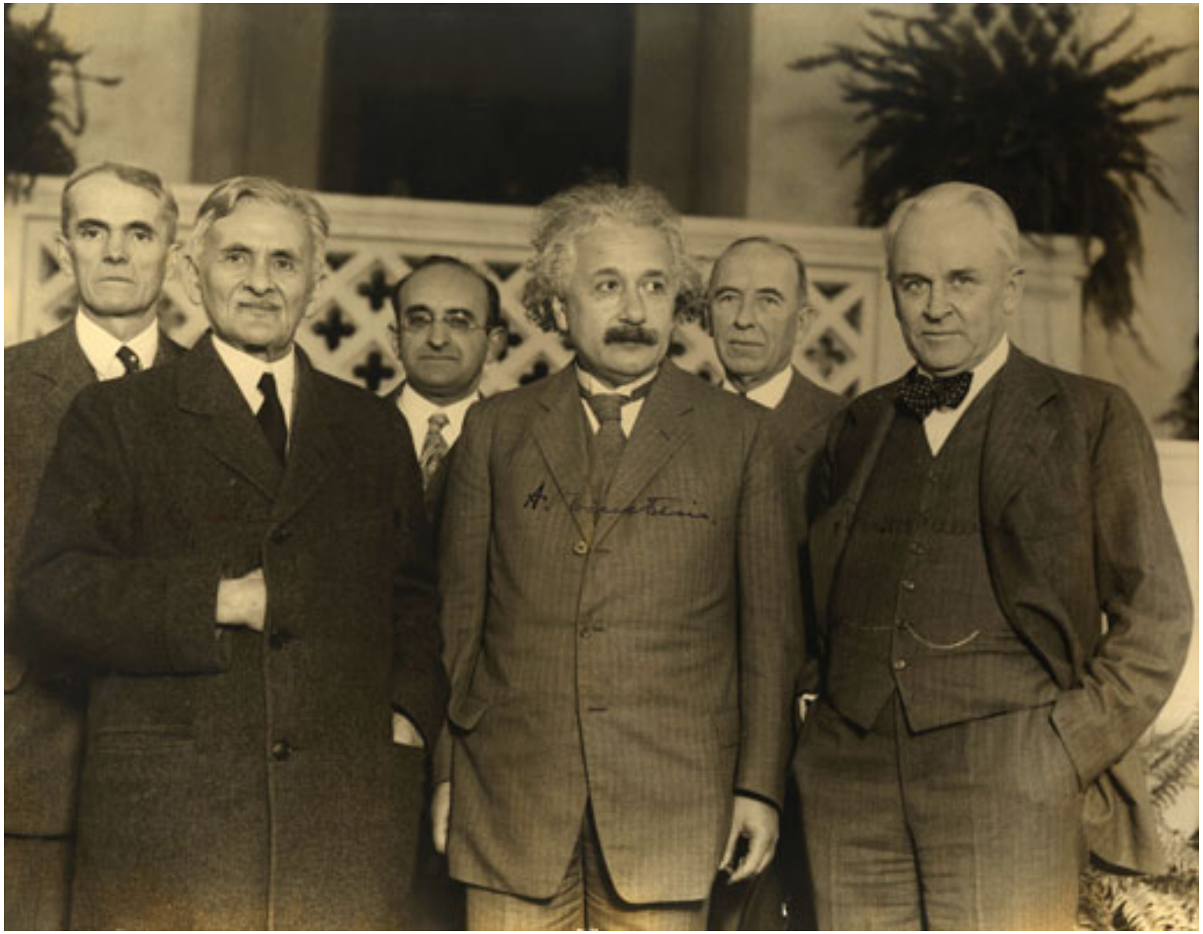
Lecture Plan

- Lecture 1 (yesterday)
  - Core collapse supernovae (CCSNe), the nuclear equation of state, and neutron star structure.
  - Numerical relativity, general-relativistic hydrodynamics, and neutron star merger simulations with the `Einstein Toolkit`.
- "Workshop" (yesterday afternoon)
  - Neutron star structure calculations
  - Black hole formation in stellar collapse
  - Neutron star merger simulations
- Lecture 2 (now!)
  - LIGO and Gravitational-Wave Astronomy
  - Phenomenology of neutron star mergers.
  - Extreme core collapse events and the CCSN-LGRB relationship.
  - Gravitational waves from core-collapse supernovae.

Gravitational Waves



Caltech

$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

Gravitational Waves

$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

linearize

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

flat space metric → $\eta_{\mu\nu}$

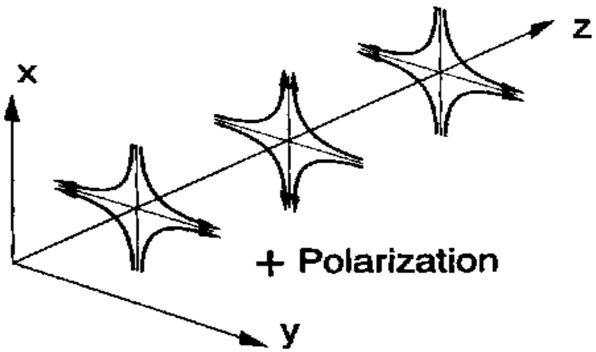
metric perturbation → $h_{\mu\nu}$

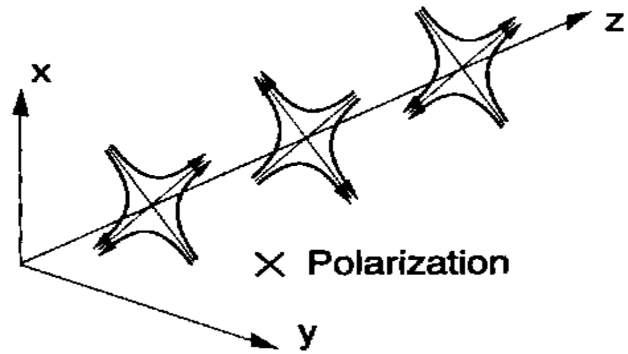
$$\Box h^{\mu\nu} = \left(-\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h^{\mu\nu} = -\frac{16\pi G}{c^4} T^{\mu\nu}$$

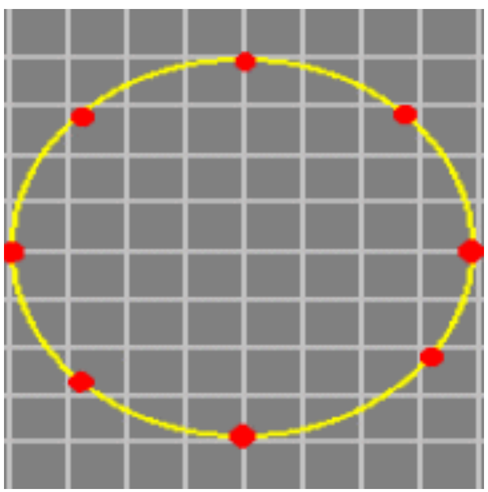
inhomogeneous wave equation -> gravitational waves (GWs)

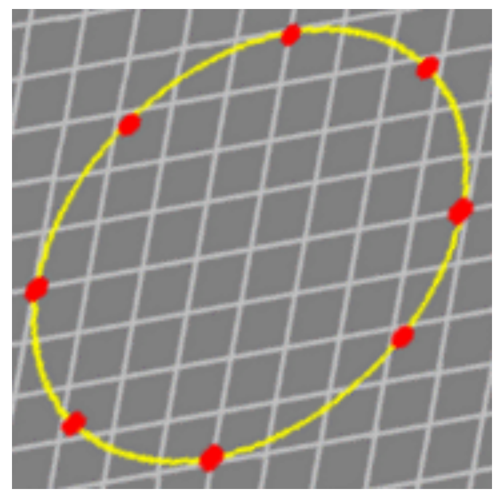
Gravitational Waves

In transverse-traceless gauge (TT) all gauge degrees of freedom fixed:









http://www.johnstonsarchive.net/relativity/pictures.html

"+ Polarization"   "x Polarization"

Gravitational Wave Emission

- GWs are to lowest-order **quadrupole waves**.
- Emitted by accelerated aspherical bulk mass-energy motions.
- 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

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

First Numerical Estimate: $M \equiv \text{"aspherical mass"}$

$$I_{jk} = \int \rho x_j x_k d^3x \quad \frac{d^2}{dt^2} I \sim \mathcal{O}(Mv^2) \quad h \sim \frac{2G}{c^4 D} M v^2$$

$$M = 1 M_\odot \quad v = 0.1c$$
$$D = 10\,\mathrm{kpc}$$
$$\longrightarrow \quad h \sim 10^{-19}$$

Gravitational Wave Emission

- **GWs** are very weak and interact weakly with matter.
    - No human-made sources.

Gravitational Wave Emission

- **GWs** are very weak and interact weakly with matter.

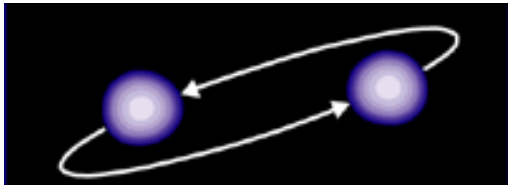
GW generator,
TAPIR group,
Caltech

Gravitational Wave Emission

- **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.***

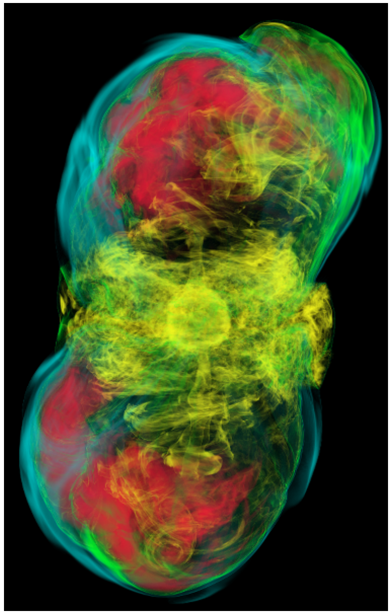
Astrophysical GW Sources

- **Coalescing binaries:**



NS/NS, NS/BH $h \approx 10^{-22}\,@\,100\,\mathrm{Mpc}$

BH/BH (2 x 30 M_{Sun}) $h \approx 10^{-22}\,@\,1\,\mathrm{Gpc}$



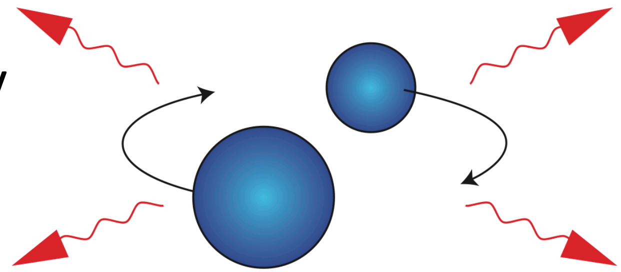
- **Core-collapse supernovae**:

convection, rotation etc. $h \approx 10^{-22}\,@\,10\,\mathrm{kpc}$

- **Other**:
  - Spinning NSs with mountains.
  - Glitching pulsars.
  - Bursting soft-gamma repeaters.
  - Cosmological background, cosmic string cusps.
  - At low frequencies: double WDs, supermassive BH-BH binaries.

Key GW Sources: Coalescing Binaries

Consider a circular binary of point particles.



$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

$$M = m_1 + m_2$$

$$r_1^i(t) = \frac{\mu a}{m_1}\{\cos\theta, \sin\theta, 0\} \qquad a = |r_1| + |r_2| \text{ (semi-major axis)}$$

$$r_2^i(t) = \frac{\mu a}{m_2}\{-\cos\theta, -\sin\theta, 0\}$$

$$\theta = \omega t = 2\pi f_{\rm orb} t = 2\pi \frac{t}{P_{\rm orb}} \qquad \omega = \sqrt{\frac{GM}{a^3}}$$

Now evaluate:

$$I_{jk} = \int \rho x_j x_k d^3x \qquad h_{jk}^{TT}(t,\vec{x}) = \left[\frac{2}{c^4}\frac{G}{|\vec{x}|}\ddot{I}_{jk}\left(t - \frac{|\vec{x}|}{c}\right)\right]^{TT}$$

GWs from Coalescing Binaries

$$I_{xx} = \int d^3x(\rho x^2) = m_1 x_1^2 + m_2 x_2^2$$

$$= \left(\frac{\mu^2 a^2}{m_1^2} m_1 + \frac{\mu^2 a^2}{m_2^2} m_2 \right) \cos^2 \omega t$$

$$= \mu^2 a^2 \left(\frac{1}{m_1} + \frac{1}{m_2} \right) \cos^2 \omega t$$

$$= \mu a^2 \cos^2 \omega t \; = \frac{1}{2} \mu a^2 (1 + 2 \cos 2\omega t)$$

GWs from Coalescing Binaries

Similarly, obtain the other components:

$$I_{ij} = \frac{1}{2}\mu a^2 \begin{pmatrix} \cos 2\omega t & \sin 2\omega t & 0 \\ \sin 2\omega t & -\cos 2\omega t & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Second time derivative:

$$\ddot{I}_{ij} = 2\mu a^2 \omega^2 \begin{pmatrix} -\cos 2\omega t & -\sin 2\omega t & 0 \\ -\sin 2\omega t & \cos 2\omega t & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

For observer at distance D along the z axis already in TT gauge:

$$h_{ij}^{TT} = \frac{4G}{c^4}\frac{\mu a^2 \omega^2}{D} \begin{pmatrix} -\cos 2\omega t & -\sin 2\omega t & 0 \\ -\sin 2\omega t & \cos 2\omega t & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

GWs from Coalescing Binaries

$$h_+ = -\frac{4G}{c^4}\frac{\mu a^2 \omega^2}{D}\cos 2\omega t$$

$$h_\times = -\frac{4G}{c^4}\frac{\mu a^2 \omega^2}{D}\sin 2\omega t$$

$$\frac{dE_{\mathrm{GW}}}{dt} = P = \frac{G}{c^5}\langle \dddot{I}_{ij} \dddot{I}_{ij} \rangle$$

time average over a cycle

Radiated energy must come from orbital energy -> also change of angular momentum. Change of orbital separation:

$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5}\frac{G^3}{c^5}\frac{m_1 m_2 M}{a^3} \qquad a(t) = \left(\frac{256}{5}\frac{G^3}{c^5}\mu M^2\right)^{\frac{1}{4}} (t_c - t)^{\frac{1}{4}}$$

GWs from Coalescing Binaries

Coalescence time:

$$\tau_{\rm merge} = a_0^4 \frac{5}{256} \frac{c^5}{G^3} \frac{1}{\mu M^2}$$

m1=m2=1.4 $M_\odot$

a_0 = 10^6 km -> τ_{merge} ~ 120 x 10^6 yrs.

a_0 = 1000 km -> τ_{merge} ~ 3700 s

a_0 = 100 km -> τ_{merge} ~ 370 ms

(but: Newtonian estimates!)

GW Frequency Evolution

Frequency evolution: $$\dot{a} = -\frac{64}{5}\frac{G^3}{c^5}\frac{\mu M^2}{a^3}$$

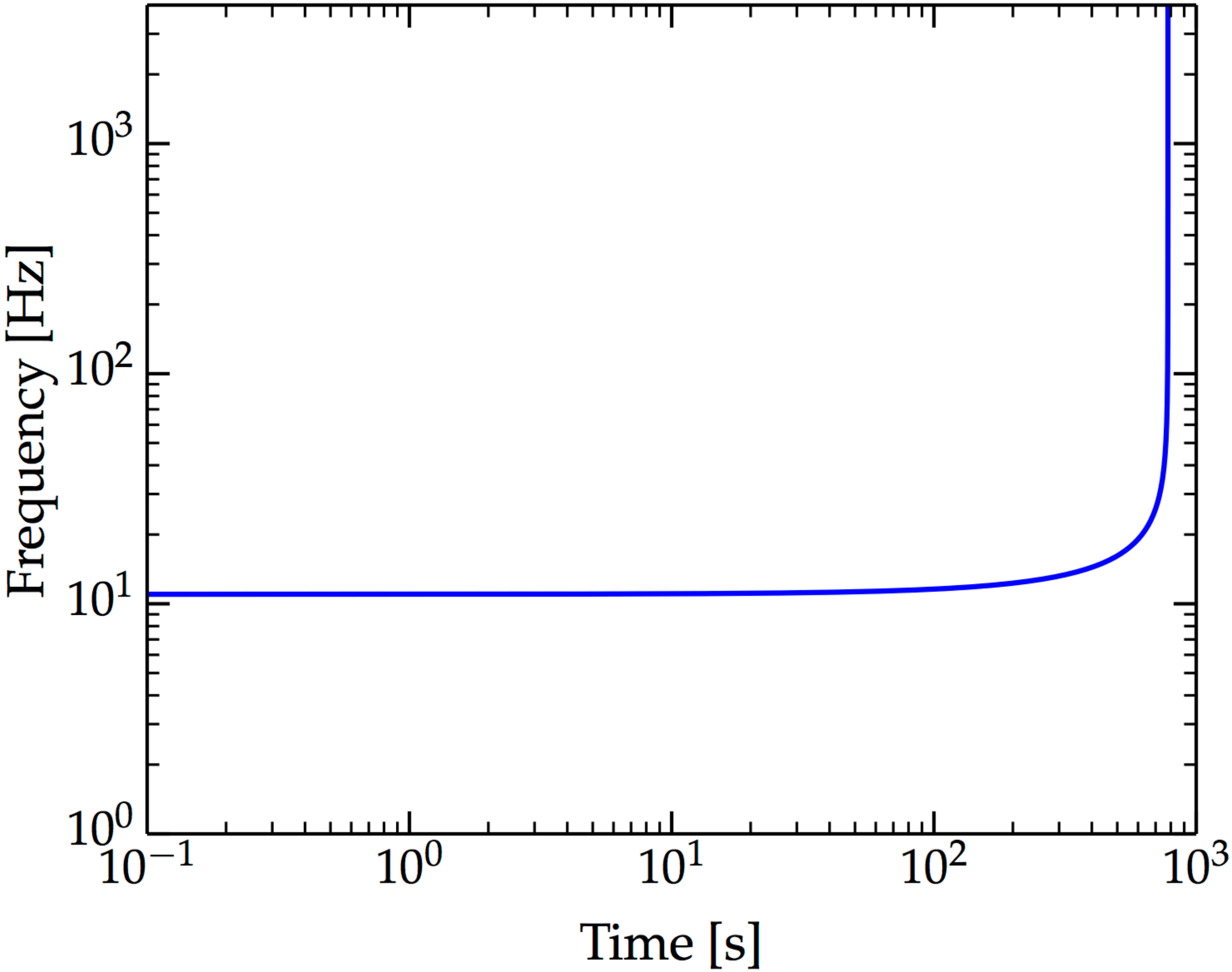
$$f = 2\frac{\omega}{2\pi} = \frac{1}{\pi}(GM)^{\frac{1}{2}}a^{-\frac{3}{2}}$$

$$\dot{f} = \frac{96}{5}\pi^{8/3}\frac{G^{\frac{5}{3}}}{c^5}\mu M^{\frac{2}{3}} f^{\frac{11}{3}}$$

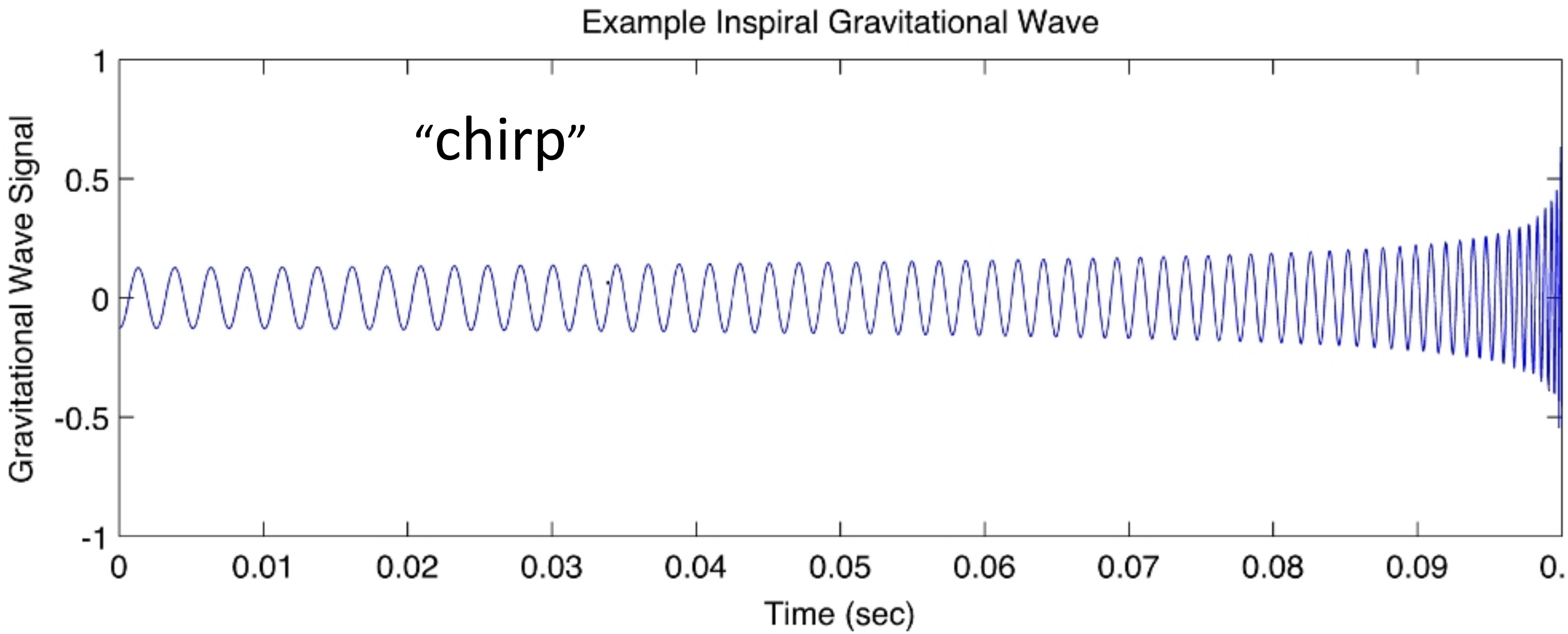
$$\dot{f} = \frac{96}{5}\pi^{\frac{8}{3}}\frac{G^{\frac{5}{3}}}{c^5}\mathcal{M}^{\frac{5}{3}} f^{\frac{11}{3}}$$

$$\mathcal{M} = \mu^{3/5} M^{2/5}$$ "Chirp Mass"

GW Frequency Evolution

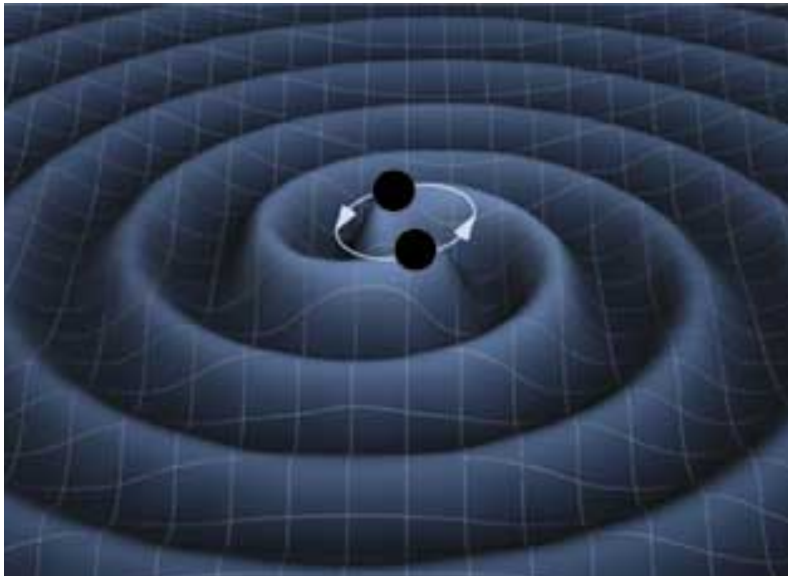


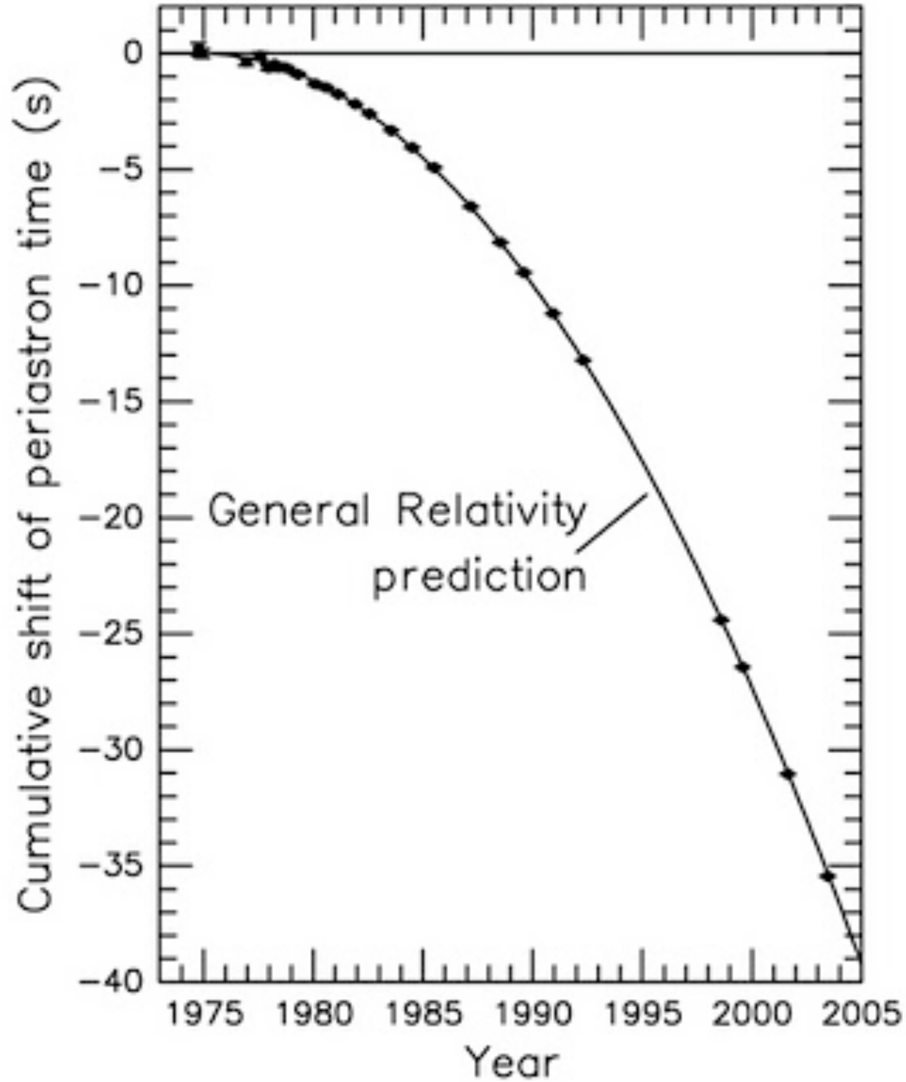
GW Signal



Example Inspiral Gravitational Wave
"chirp"
Gravitational Wave Signal
1
0.5
0
-0.5
-1
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (sec)

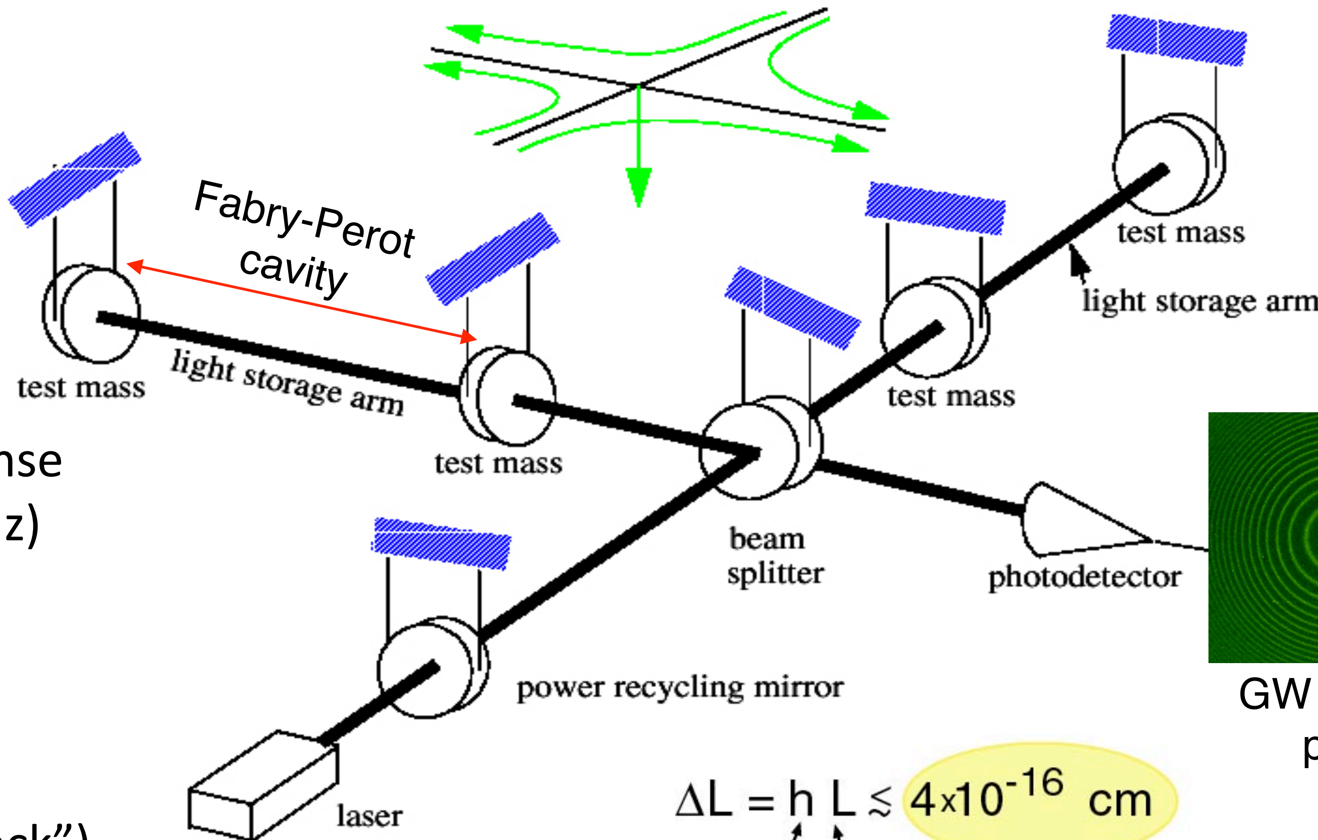
Gravitational Waves: Indirect Evidence

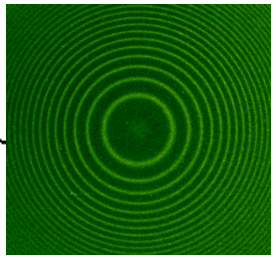




- GWs lead to "orbital decay" -> binary stars get closer to each other.
- Double neutron star systems in the Milky Way.
- PSR 1913+16: "Hulse-Taylor Pulsar" -> Nobel prize in Physics 1993

Gravitational Wave Detection





GW output port

Advantages:

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

Disadvantage:

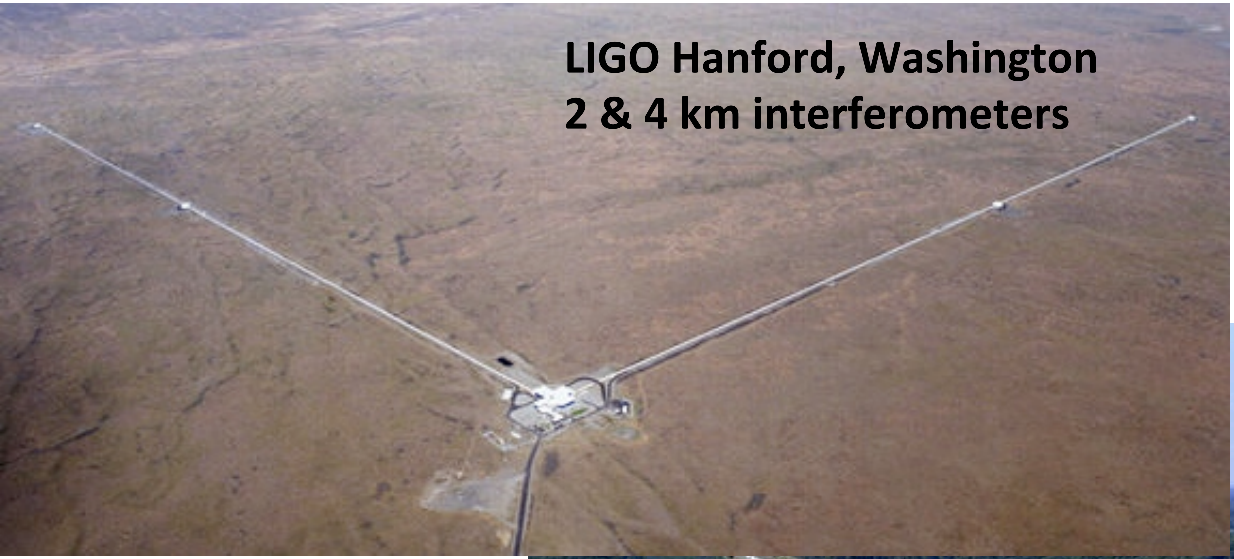
- Very difficult to keep stable ("in lock") -> relatively poor duty cycle. (LIGO ~60%, Virgo ~80%)

$$\Delta L = h\, L \lesssim 4\times10^{-16}\ \mathrm{cm}$$

$h \lesssim 10^{-21}$, L = 4 km

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

Laser Interferometer Gravitational-Wave Observatory



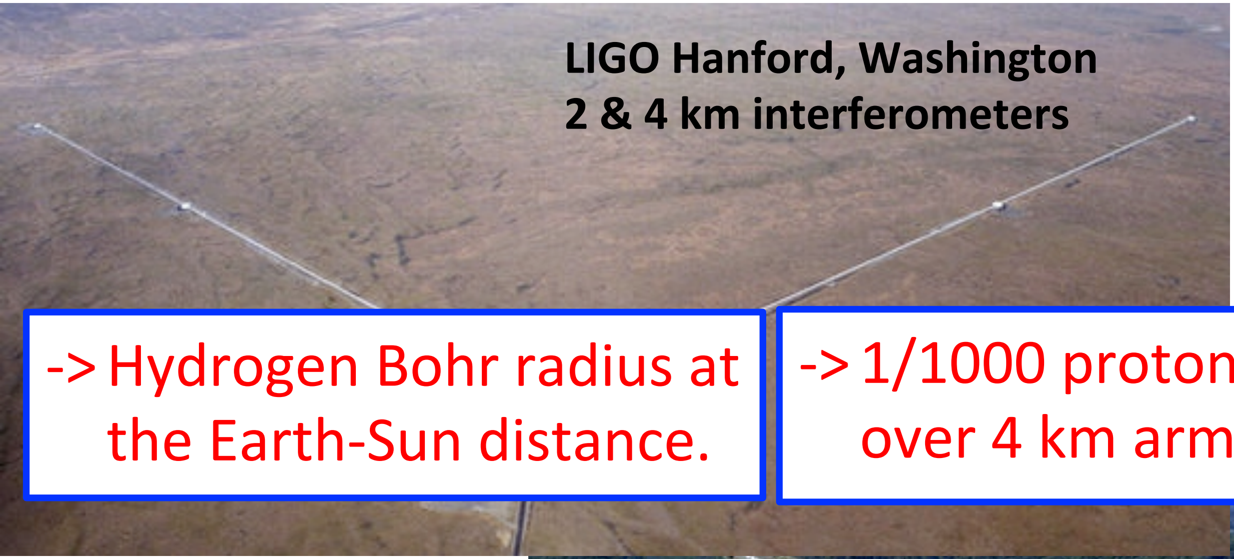
Measure relative displacements of 10^{-22}

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

Built in the 1990s.

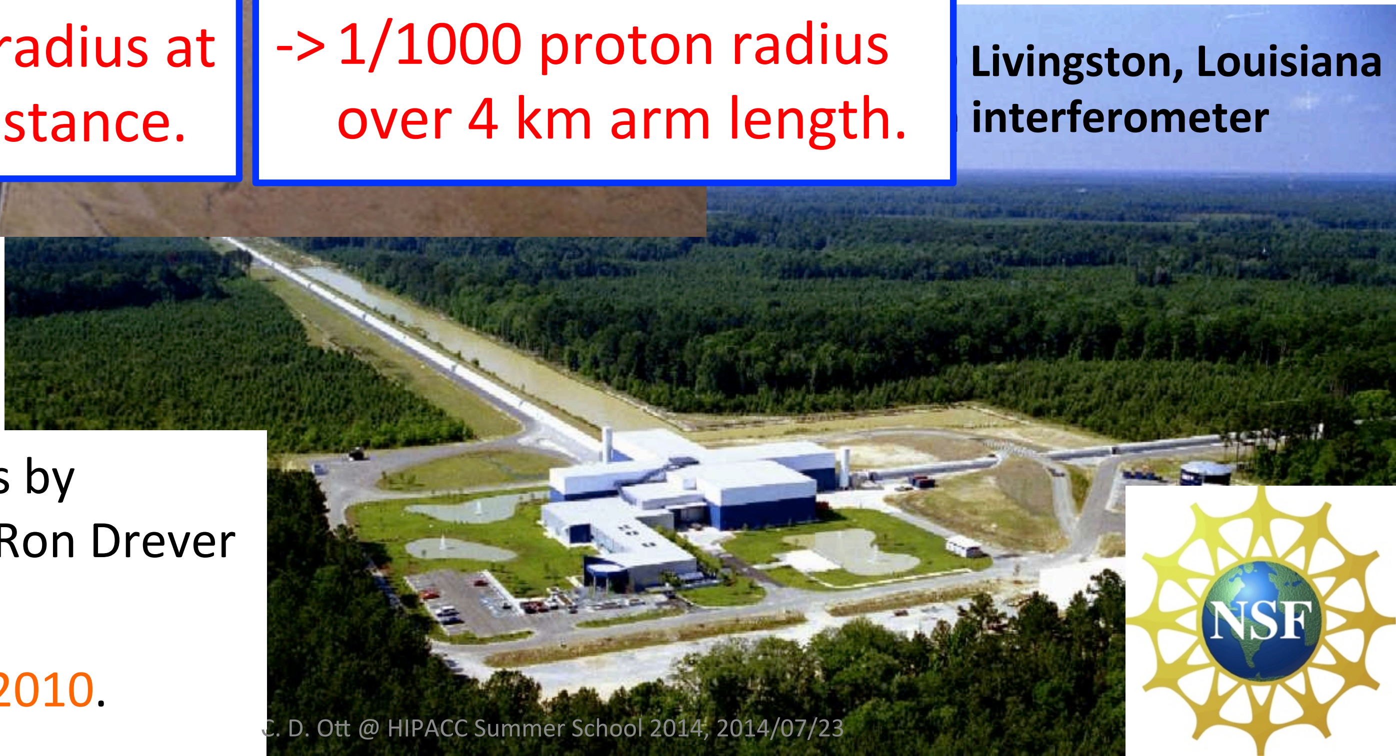
6 “science runs” 2002-2010.

Laser Interferometer Gravitational-Wave Observatory



-> Hydrogen Bohr radius at the Earth-Sun distance.

-> 1/1000 proton radius over 4 km arm length.



Measure relative displacements of 10^{-22}

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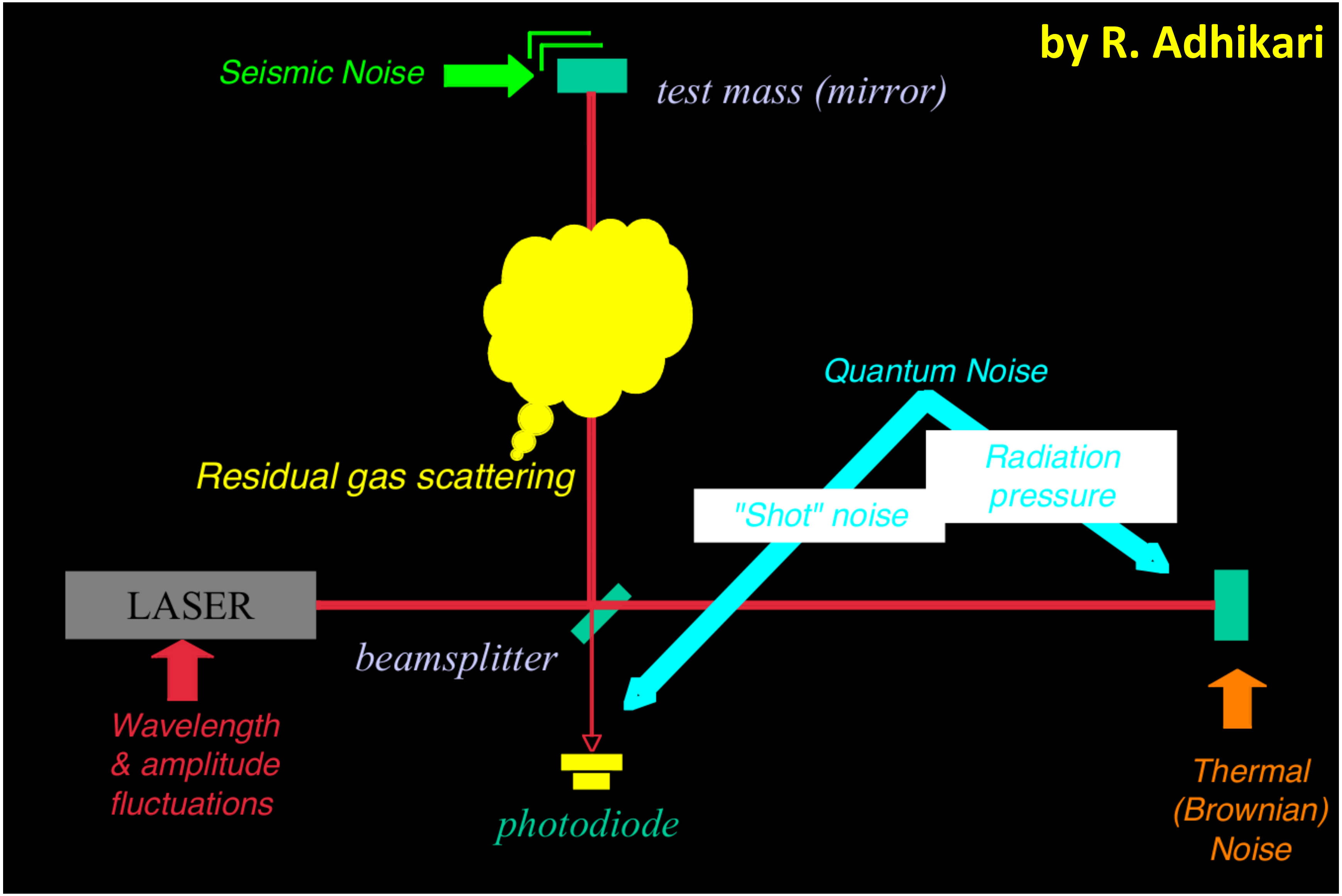
6 “science runs” 2002-2010.


mid station
35

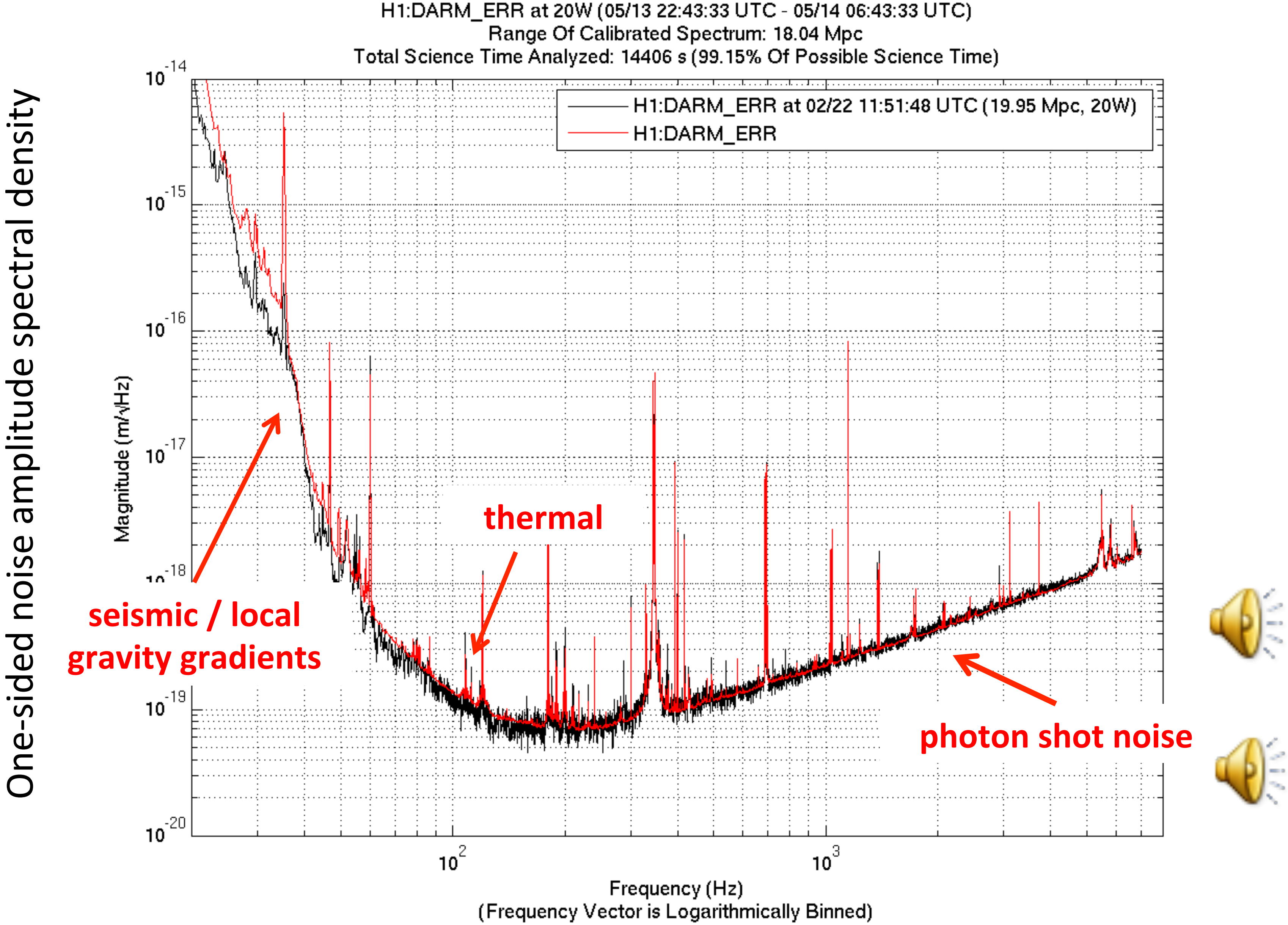
Initial LIGO: 2000-2010 currently being upgraded to Advanced LIGO

Advanced LIGO will be 10 x more sensitive!

Noise Sources



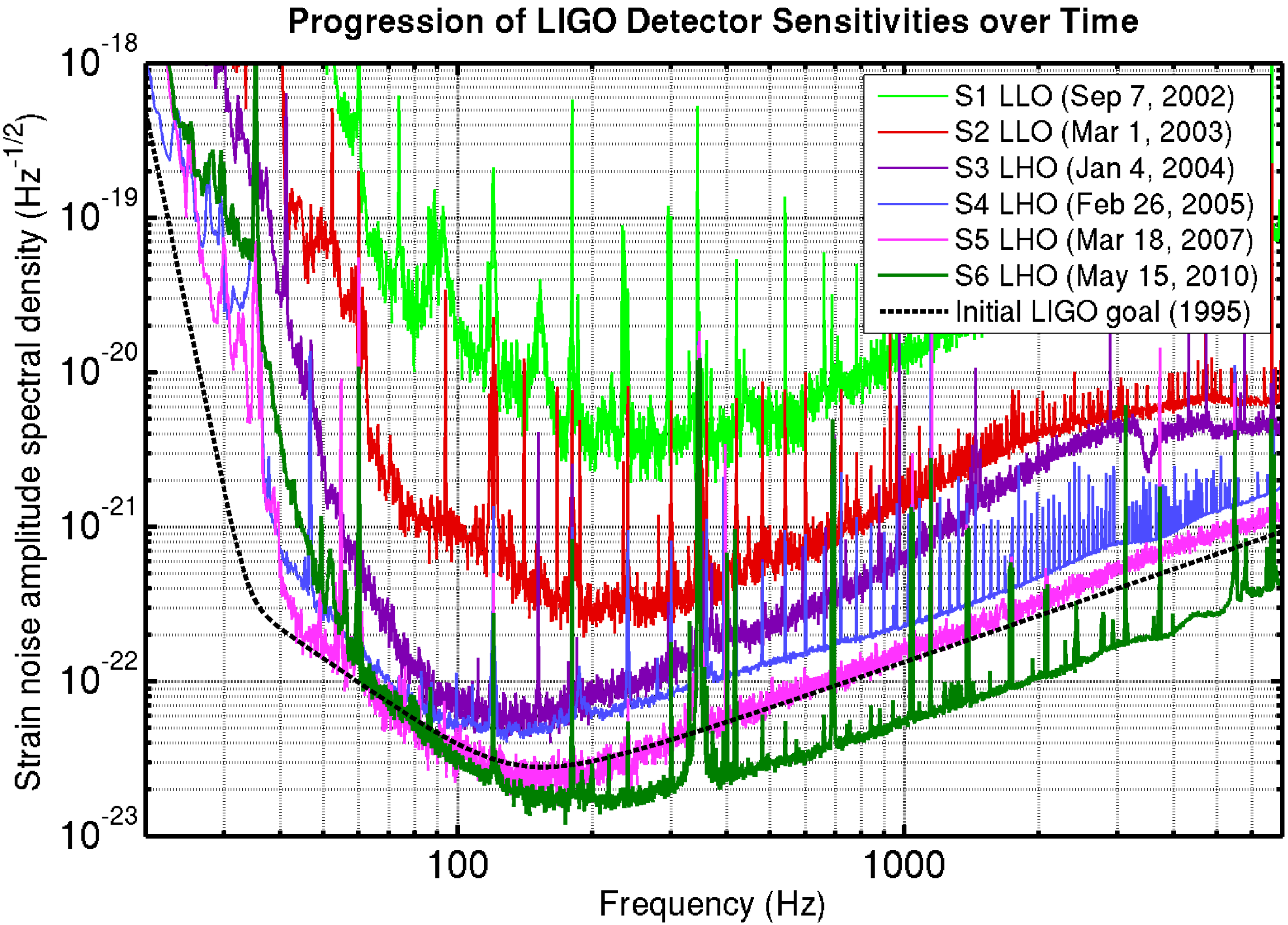
Noise Budget



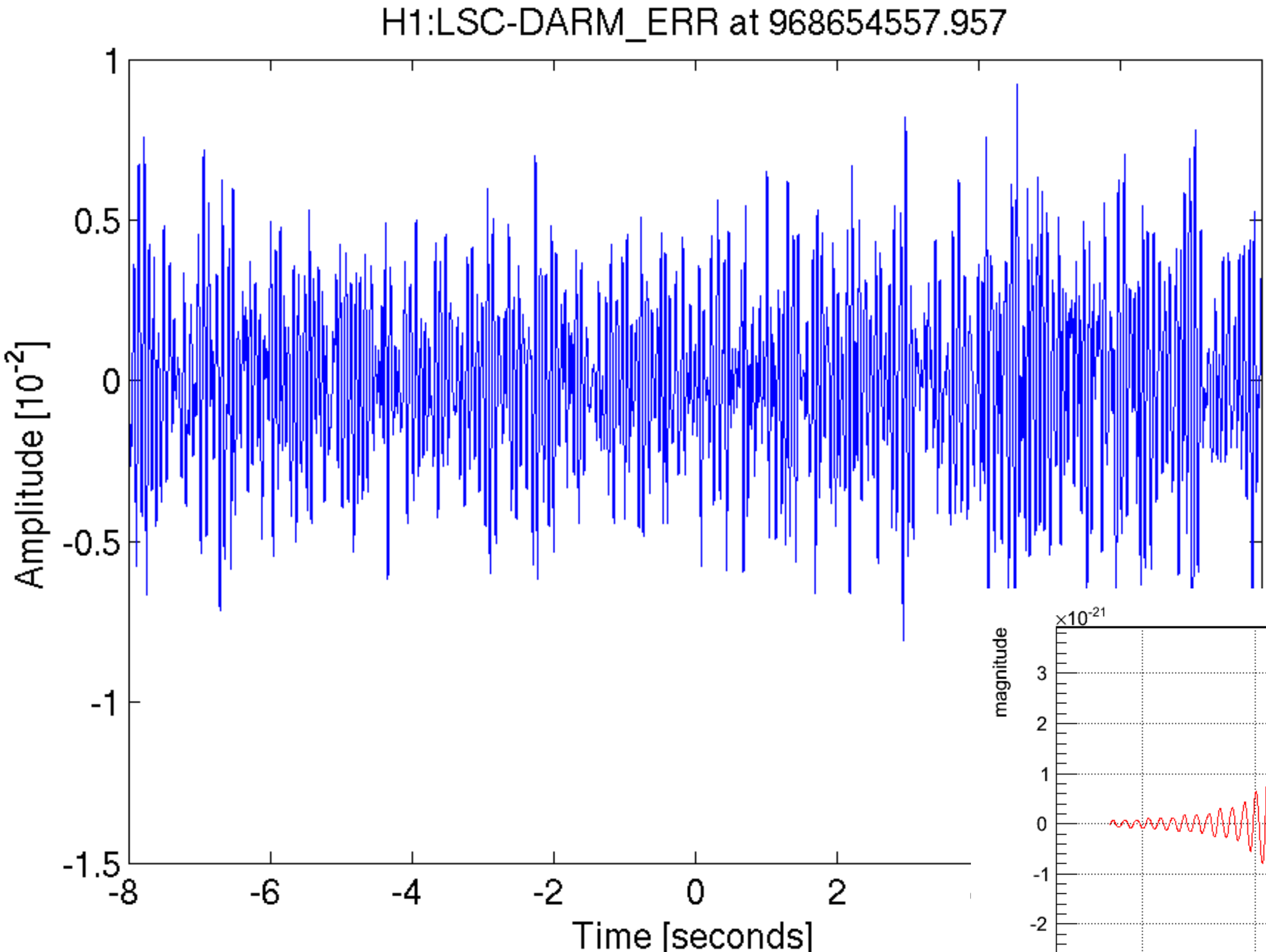
Anthropogenic Noise...

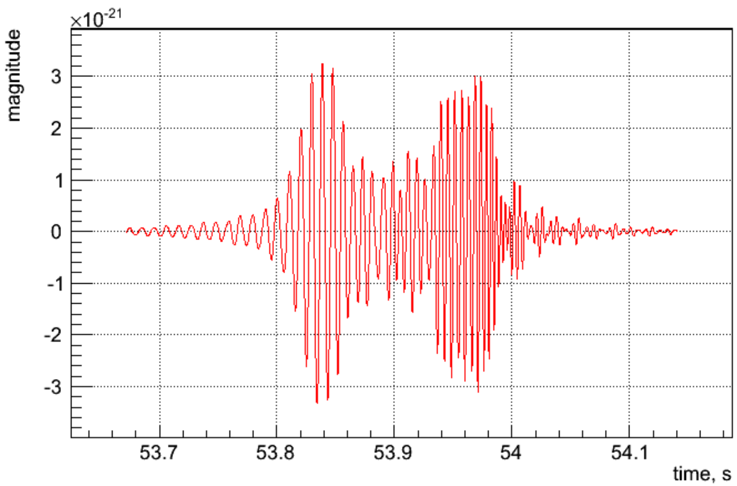
+ trucks, trains, tree cutting, rush hour on highways...

Initial LIGO Interferometers: Sensitivity



The Data Analysis Challenge: Digging out the Signal

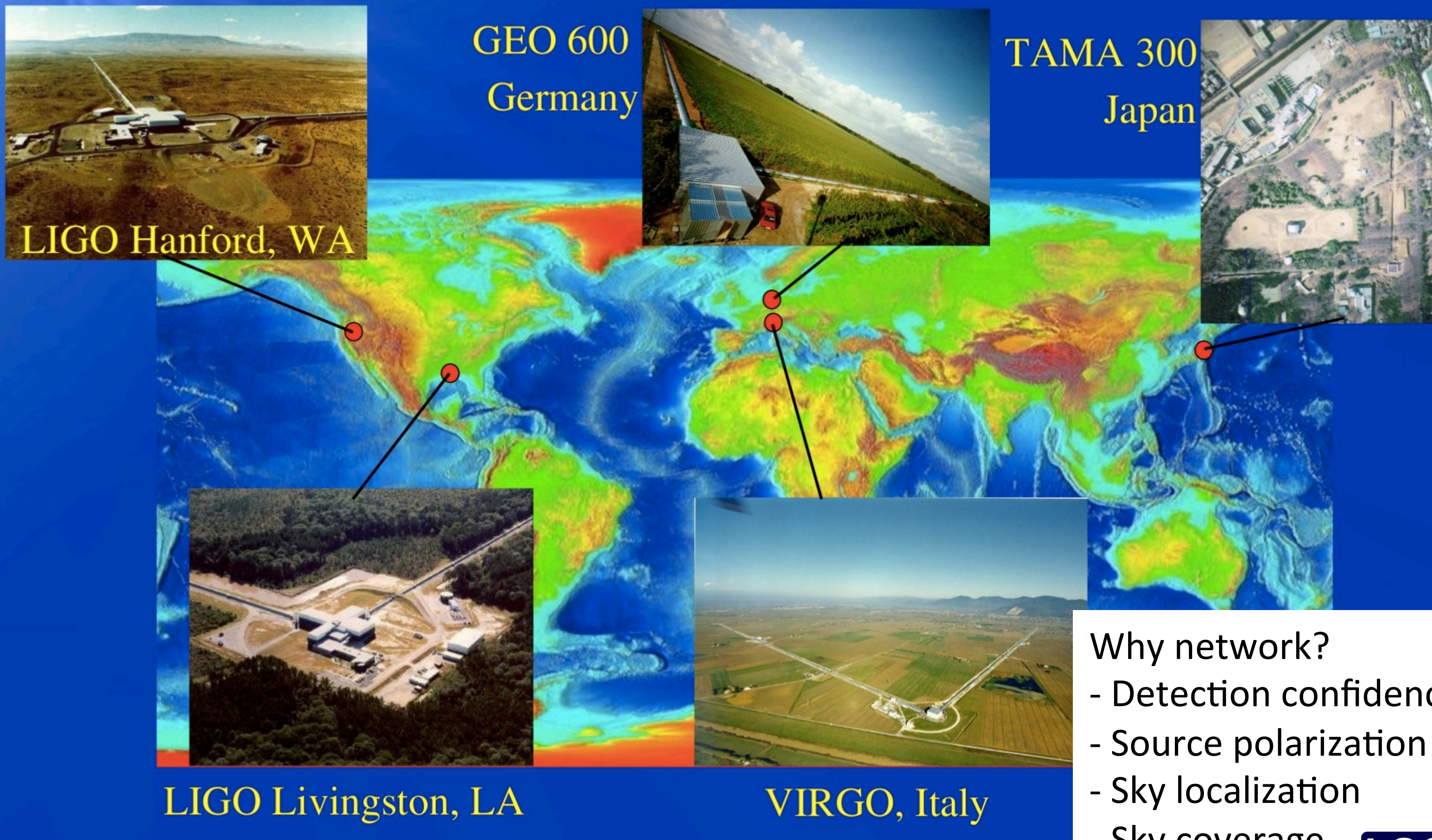




Gravitational Wave Astronomy

International Network of LIGOs

First Generation – 2000 -- 2010



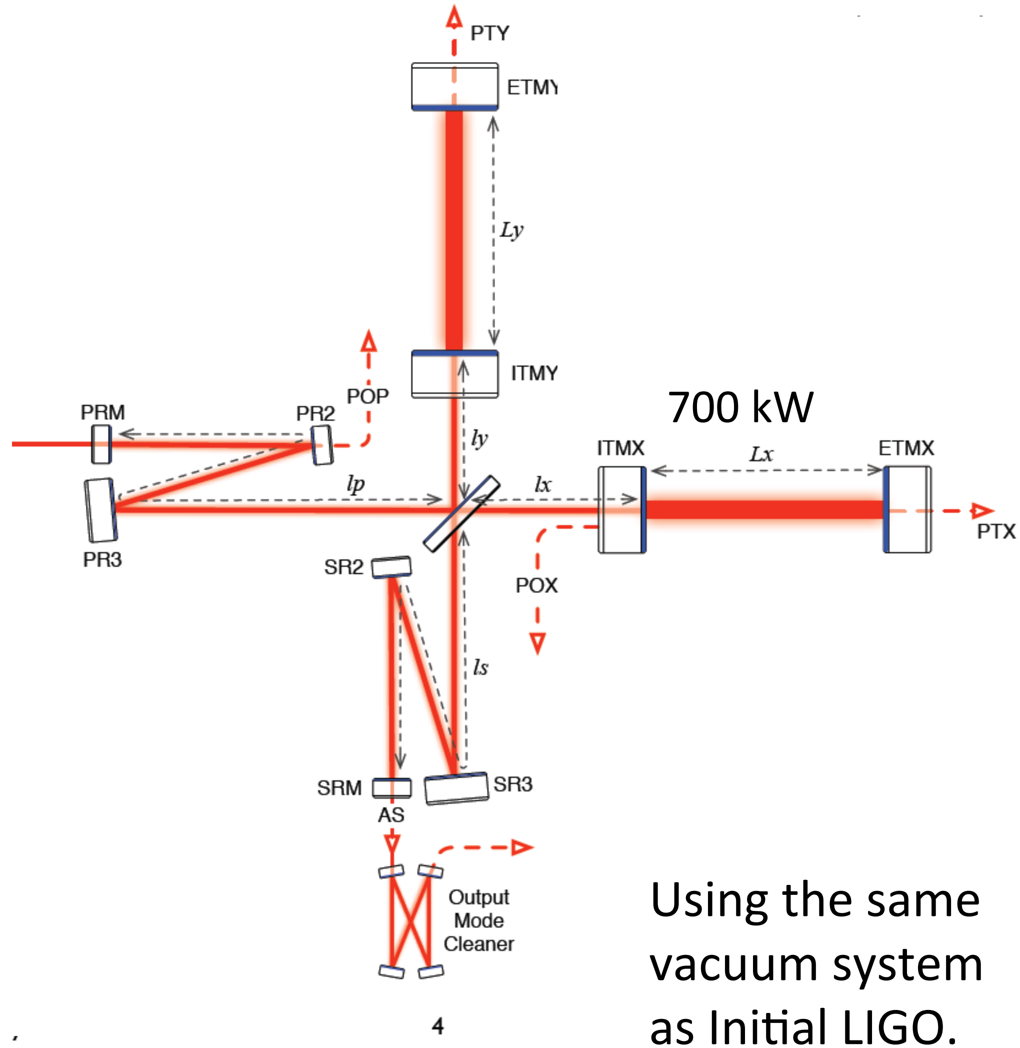
Why network?
- Detection confidence
- Source polarization
- Sky localization
- Sky coverage
- Duty cycle

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

Advanced LIGO

What is Advanced?

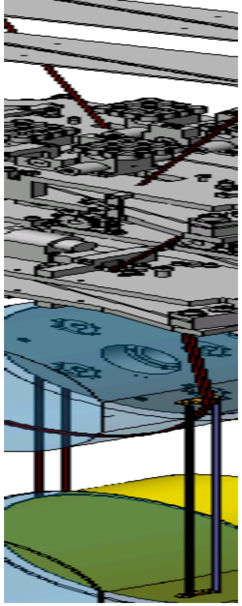
Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	10 W (10 kW arm)	**180 W** (>700 kW arm)
Mirror Mass	10 kg	**40 kg**
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable RC)
Optimal Strain Sensitivity	3 x 10^{-23} / 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



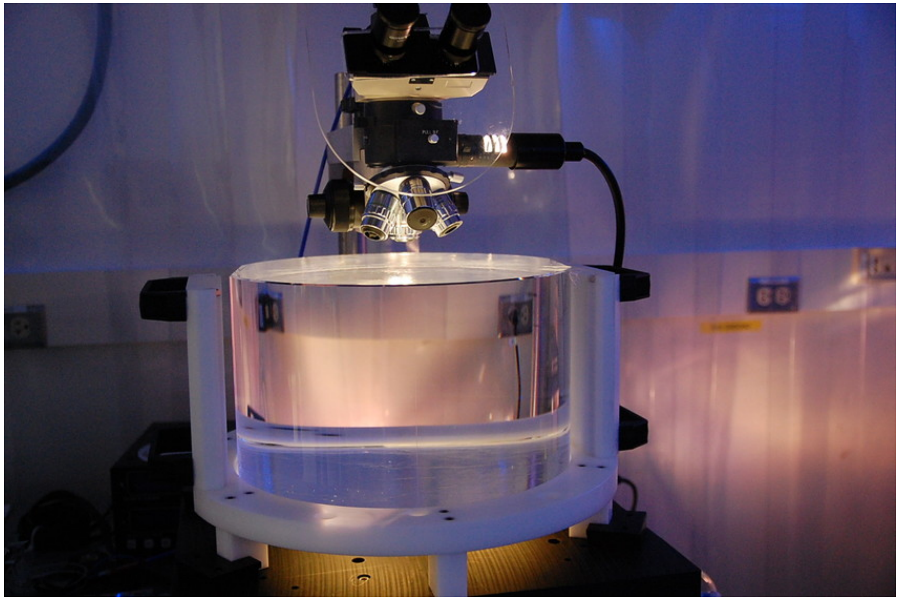
700 kW

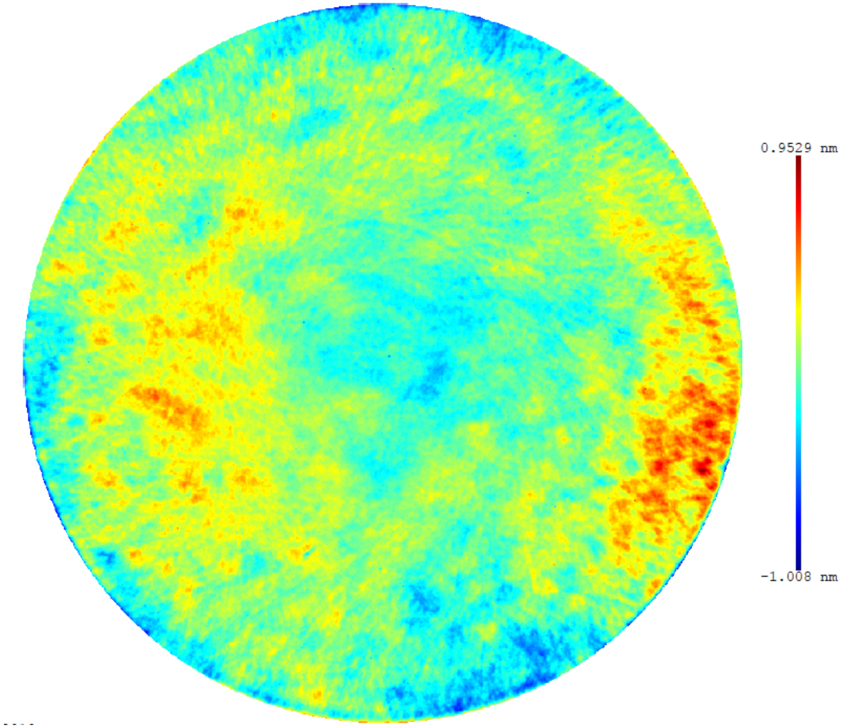
Using the same vacuum system as Initial LIGO.

Advanced LIGO Mirrors



- Made of high-purity fused silica.
- Initial LIGO: 25 cm diameter, 10 cm thick, 10.7 kg.
  Advanced LIGO: 34 cm diameter, 20 cm thick, 40 kg.
- Surfaces polished to ~1 nm, most with slight curvature.
- Coated to reflect with extremely low scattering loss.

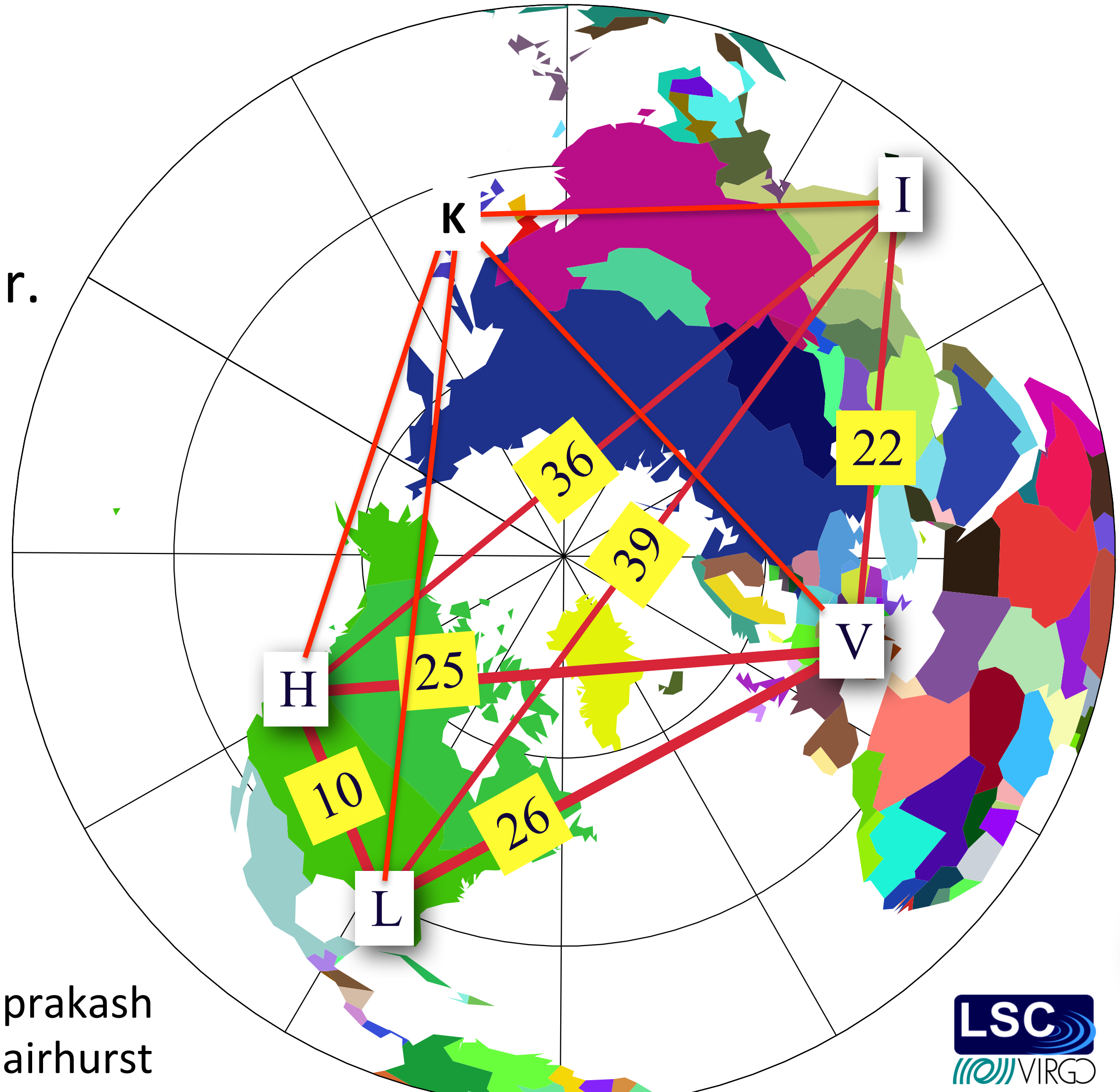




(Source: P. Shawhan, UMD)

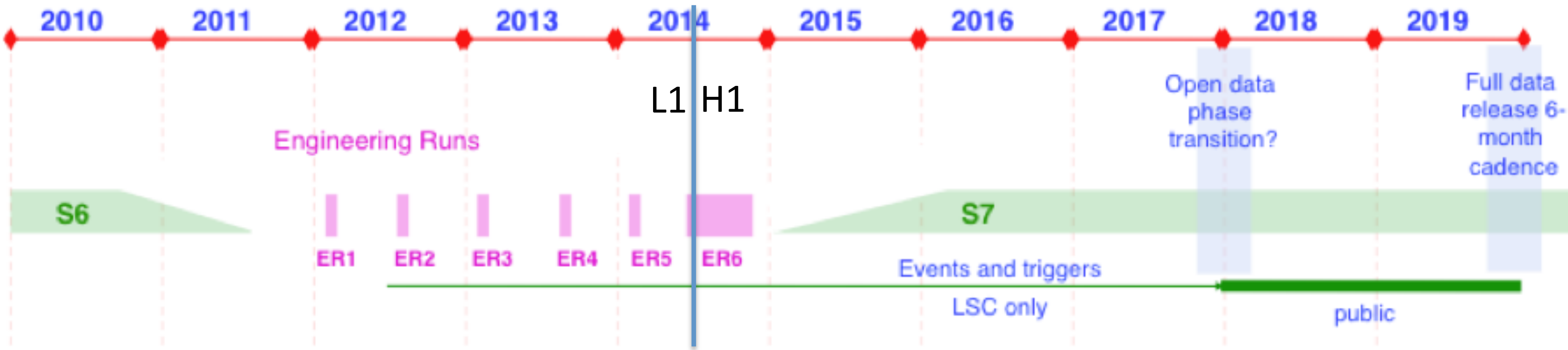
The Future: Advanced Detectors

- Upgrades to existing IFOs -> **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
  KAGRA (Japan)



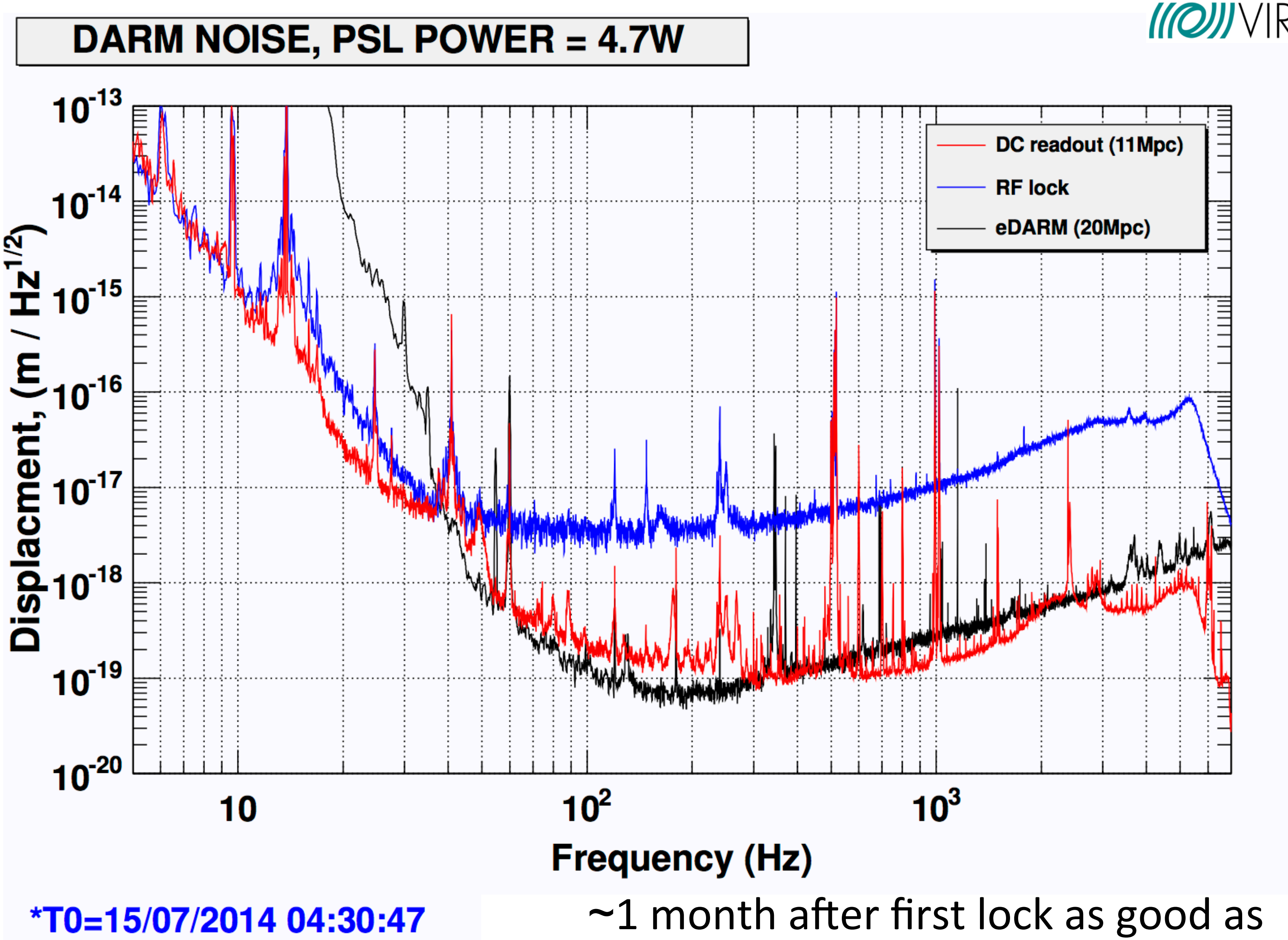
Sathyaprakash
Fairhurst

Advanced LIGO: Status & Timeline



- Advanced LIGO:
  - Livingston (L1) detector completed, locked for > 2h.
  - Hanford (H1) in final stages of installation.
  - On track for first science data in mid/late 2015.
  - Design sensitivity expected 2017-2020.
    NS-NS range ~200-300 Mpc; CCSNe: galaxy, LMC/SMC
  - First science run 2-detector (poor sky localization).
- Advanced Virgo & KAGRA: 2015/16+
- LIGO India: 2021-22+

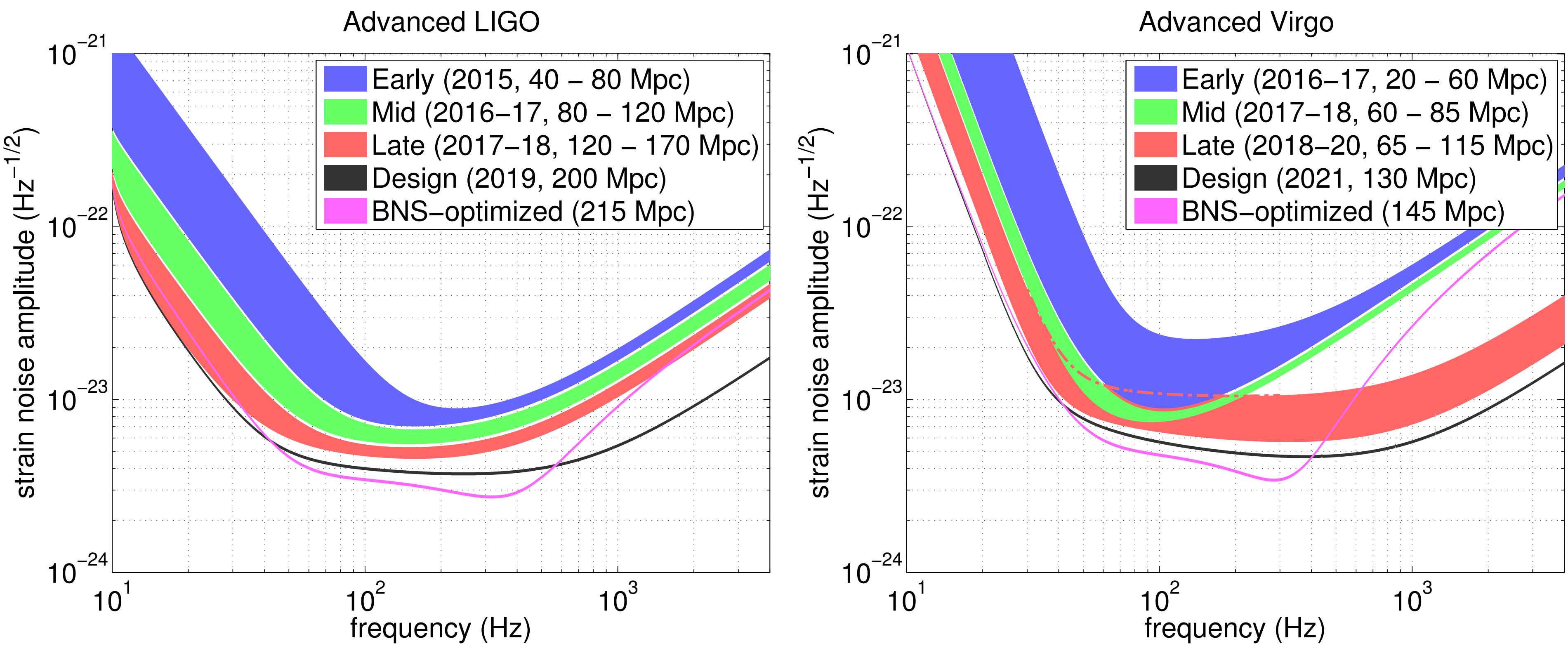
Current L1 Sensitivity



~1 month after first lock as good as initial LIGO after ~2.5 years.

Expected Sensitivity Evolution

arXiv:1304.0670



What will Advanced LIGO see?

(and how often will it see it?)

- Nearby core-collapse supernova rate: (1– 3) / 100 yrs. (No galactic core-collapse supernova until aLIGO ready!)

- Binary merger rate? Rough Estimate:
  - Merger rate in the Milky Way: few per 10^6 yrs.
  - Advanced LIGO NSNS range: 200 Mpc
  - Milky Way-equivalent galaxy density: 1 / 100 Mpc^3
  - Detection rate: $\mathcal{O}(1)$/yr

What will 2019 Advanced LIGO see?

(and how often will it see it?)

- 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]

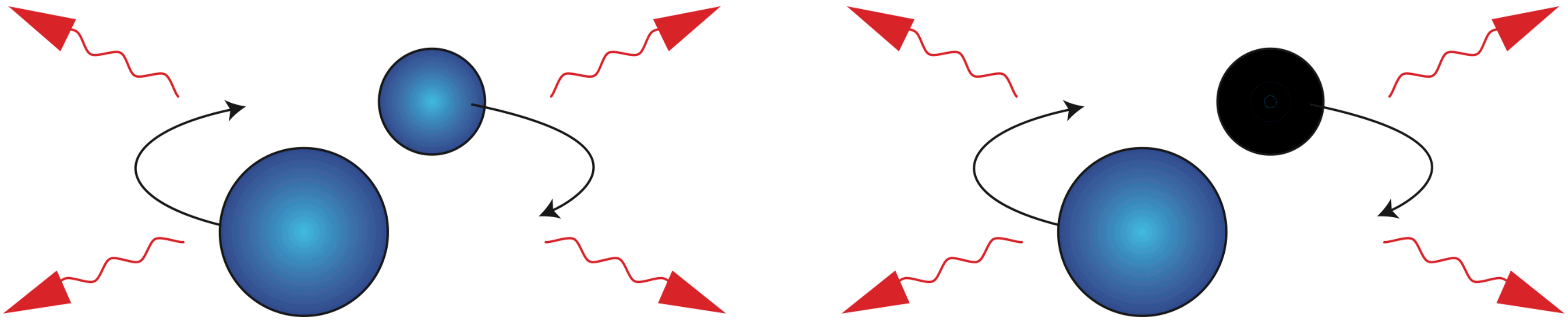
Warning:
Population synthesis!

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

Neutron Star Mergers

- Neutron Star + Neutron Star (NSNS)
- Black Hole + Neutron Star (BHNS)

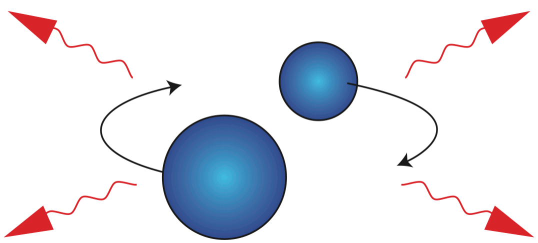
credit: J. Read



$M_1 \sim M_2 \sim 1.4\ M_{Sun}$
-> galactic NSNS binaries!

$M_{BH} \sim$ 7-10 x M_{NS} (Belczynski+'10)
(but no BHNS systems known)

NSNS Merger Scenarios



m_1, m_2

$M = m_1 + m_2$

Prompt BH

HMNS -> BH

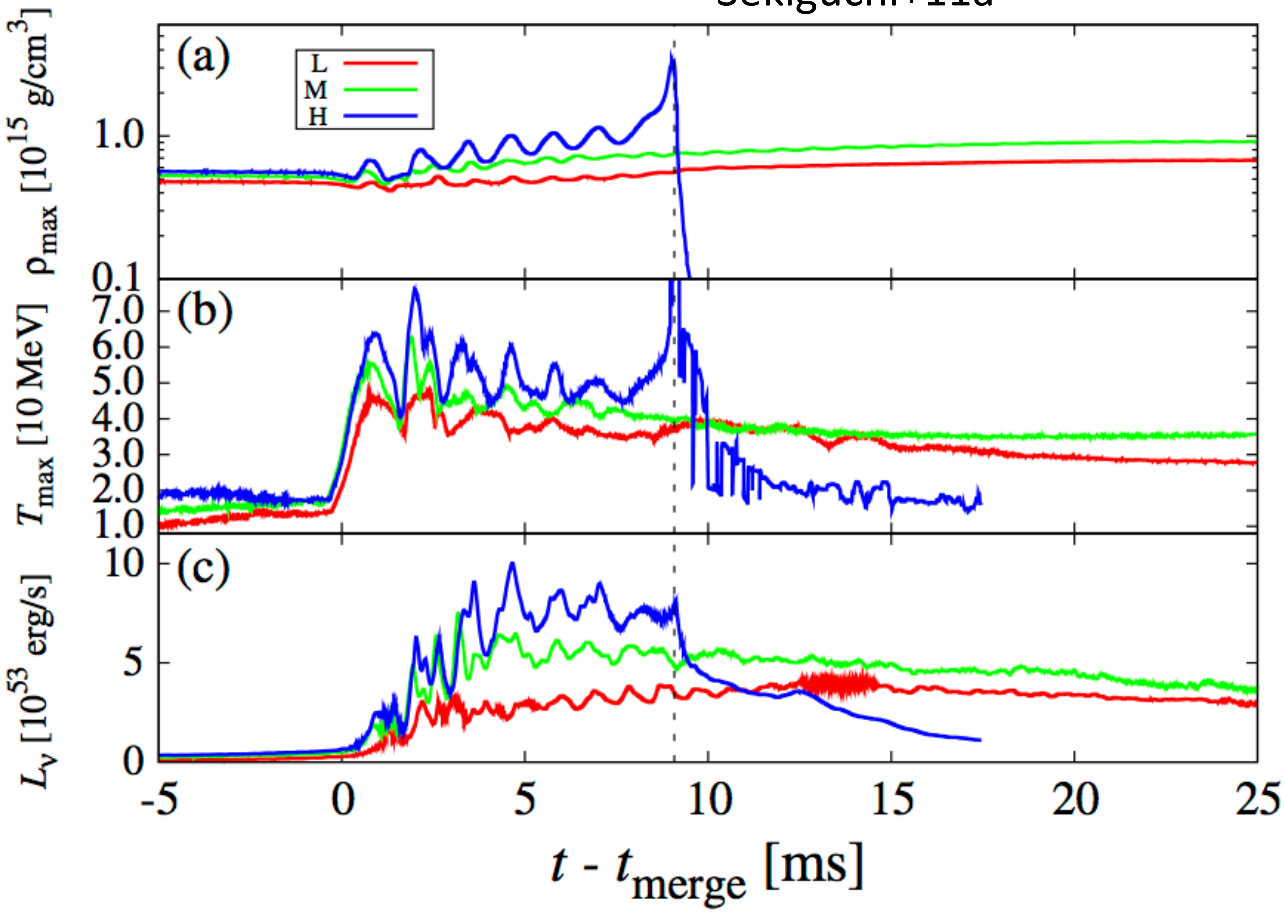
Stable NS Remnant

$M < M_{max}(EOS)$

Outcome most sensitive to total mass of binary and nuclear EOS.

NSNS Postmerger Evolution

Sekiguchi+11a



H. Shen EOS

L: 2x1.35 $M_\odot$;
M: 2x1.5 $M_\odot$;
H: 2x1.6 $M_\odot$

Total baryonic masses:
(2.90, 3.28, 3.54) $M_\odot$

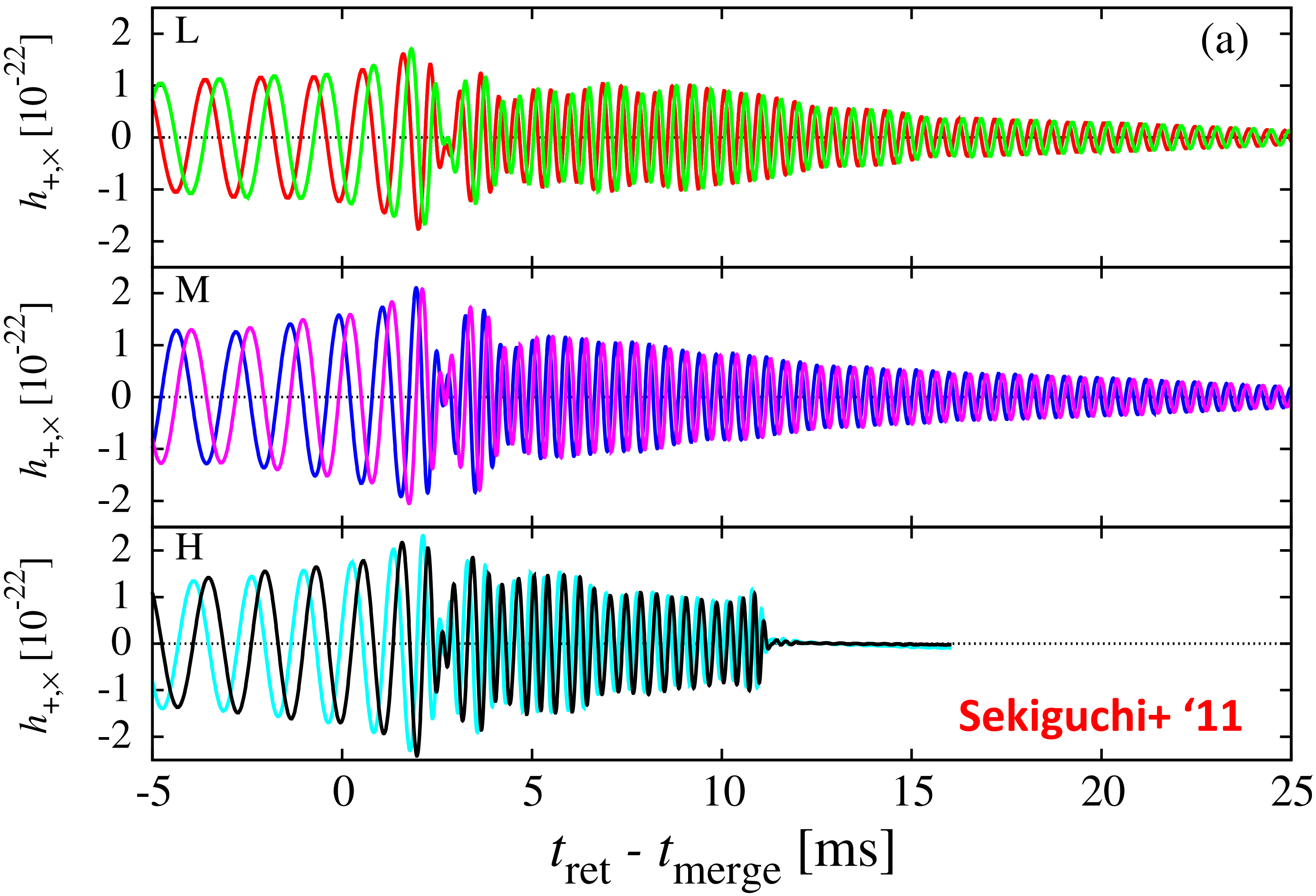
TOV: 2.56 $M_\odot$;
uniform rot.: 3.05 $M_\odot$;
diff. rot: no formal limit

-> see also
Bauswein+10,12,13

HMNS: support by differential rotation, only small thermal contribution.
Secular evolution: governed by energy loss to GWs, neutrinos, and angular momentum redistribution by 3D torques / magnetorotational instability.

NSNS Postmerger Evolution

Sekiguchi+11a



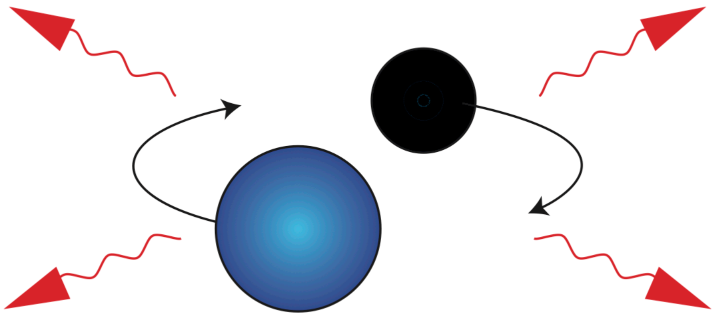
Mass [M_{Sun}]

1.35 + 1.35

1.50 + 1.50

1.60 + 1.60

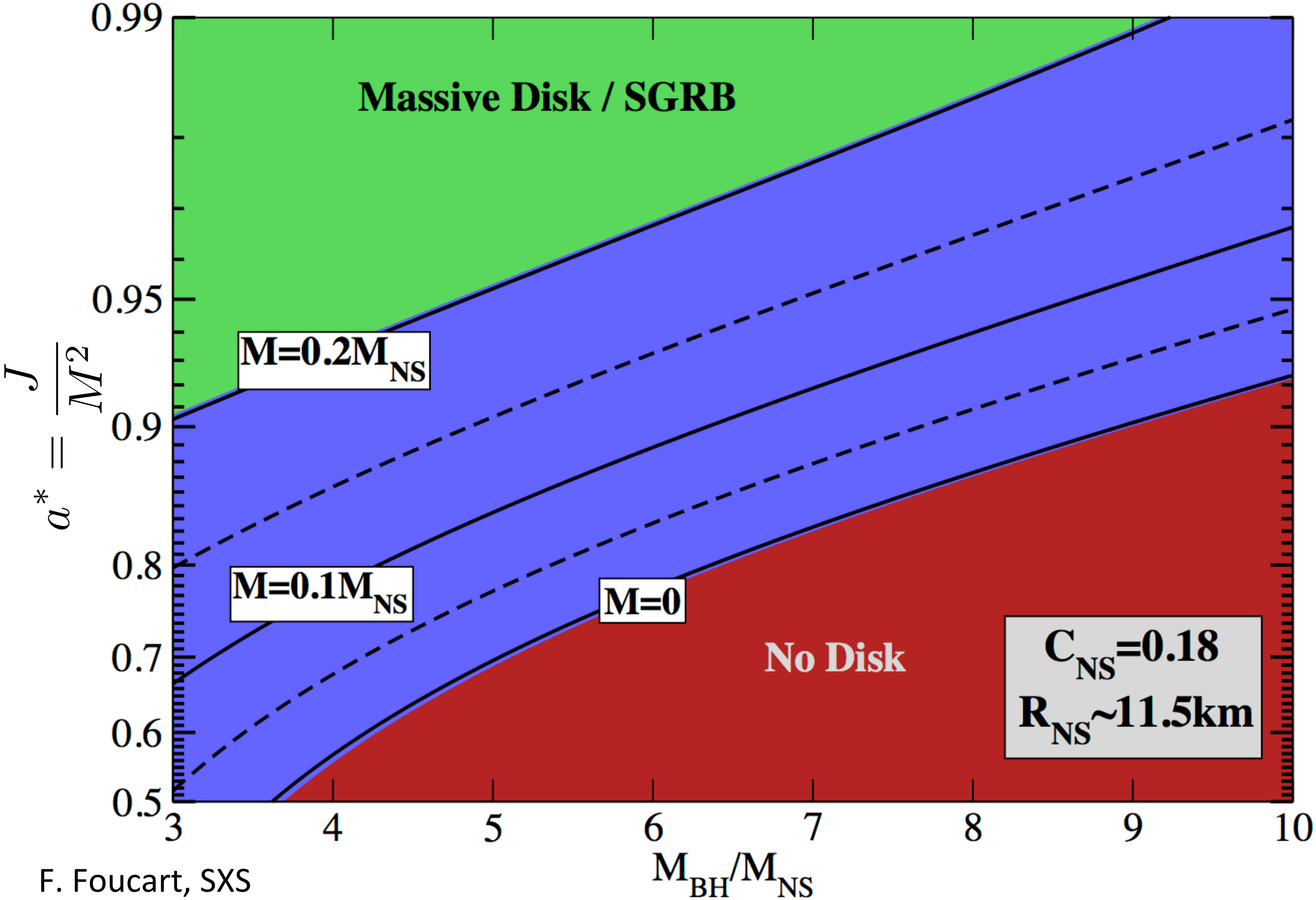
BHNS Merger Scenarios



$$a^* = \frac{J}{M^2}$$

- Tidal disruption or complete "swallow".
- The greater BH spin a*, the stronger disruption.
- The larger M_{BH}, the more spin required for disruption.
- Typical BH/NS mass-ratio uncertain.
  Best guess: 7/1 – 10/10.

BHNS Merger Scenarios: Remnant

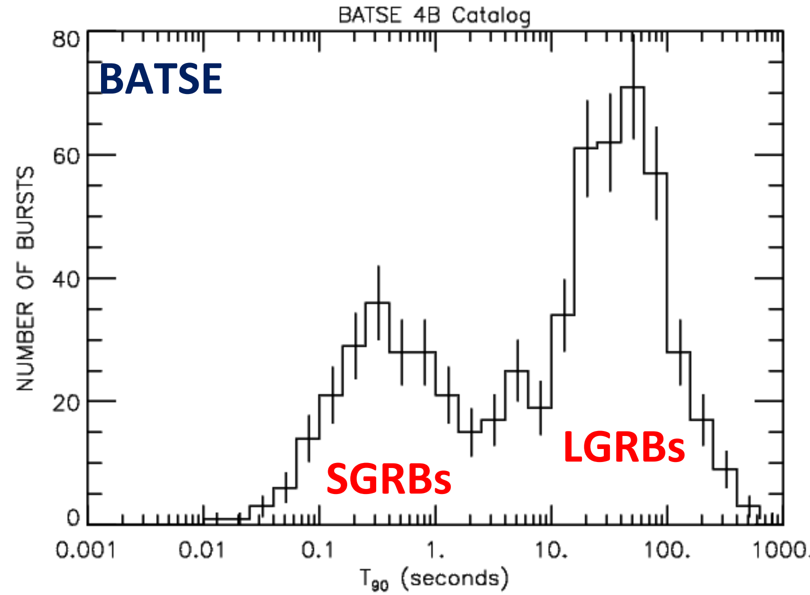


F. Foucart, SXS

Gamma-Ray Bursts

[Reviews: e.g. Woosley & Bloom '06, Piran '05, Meszaros '05]

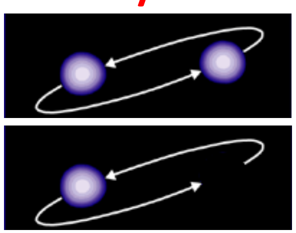
- Two general groups of GRBs: Long and Short
- Favored model: Beamed Ultrarelativistic outflow emitting γ-rays.

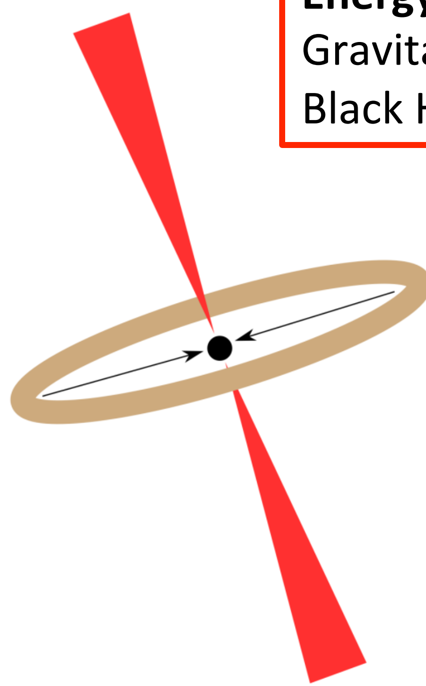


Simplistic Engine Picture:

Energy sources:
Gravitational energy (accretion)
Black Hole/NS spin energy.

NS-NS / NS-BH merger





Massive H/He-poor Star

Disk Mass: ~0.1-0.2 M_{Sun} → **SGRB**

Disk Mass: ~1 M_{Sun} → **LGRB**

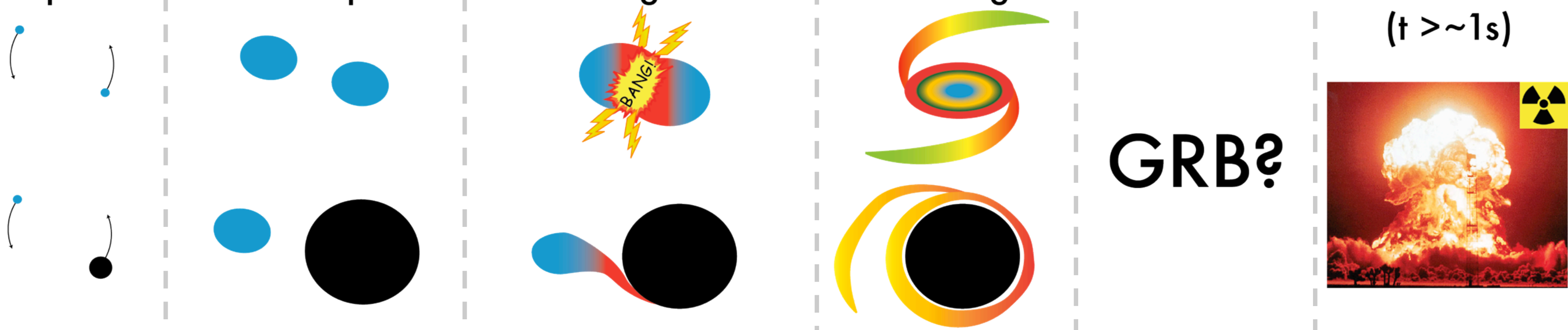
Mediating Processes:
Neutrino Pair Annihilation
Magnetohydrodynamics

Nuclear Astrophysics with Binary Mergers

Nuclear Equation of State (EOS) **Crust Physics & Superfluidity (SF)**

Neutrinos/Neutrino Interactions **Nuclear Reactions & Opacities**

Inspiral	Late Inspiral	Merger	Postmerger		Late Time (t >~1s)

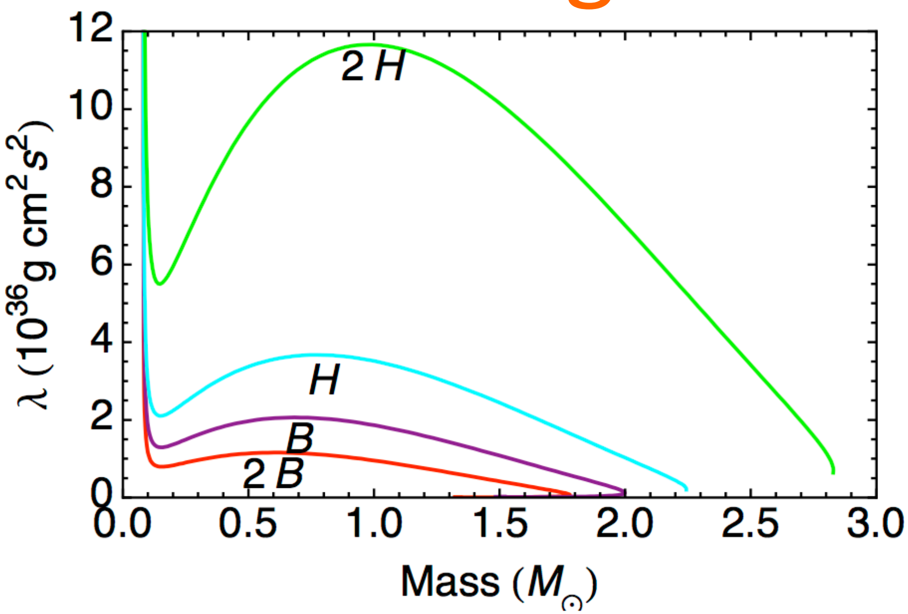


Inspiral	Late Inspiral	Merger/Disruption	Postmerger		
	Crust/SF				
	EOS	EOS	EOS	EOS	
		Neutrinos	Neutrinos	Neutrinos	Neutrinos
			Nuclear	Nuclear	Nuclear

NSNS Mergers and the Nuclear EOS

- LIGO will measure M_{chirp}, mass ratio.
- Late inspiral: Tidal deformation of the NSs
  -> EOS-dependent effect on phase evolution of the waveform
- Merger / postmerger:
  - Survival of the HMNS
  - Oscillation frequencies of the postmerger HMNS.

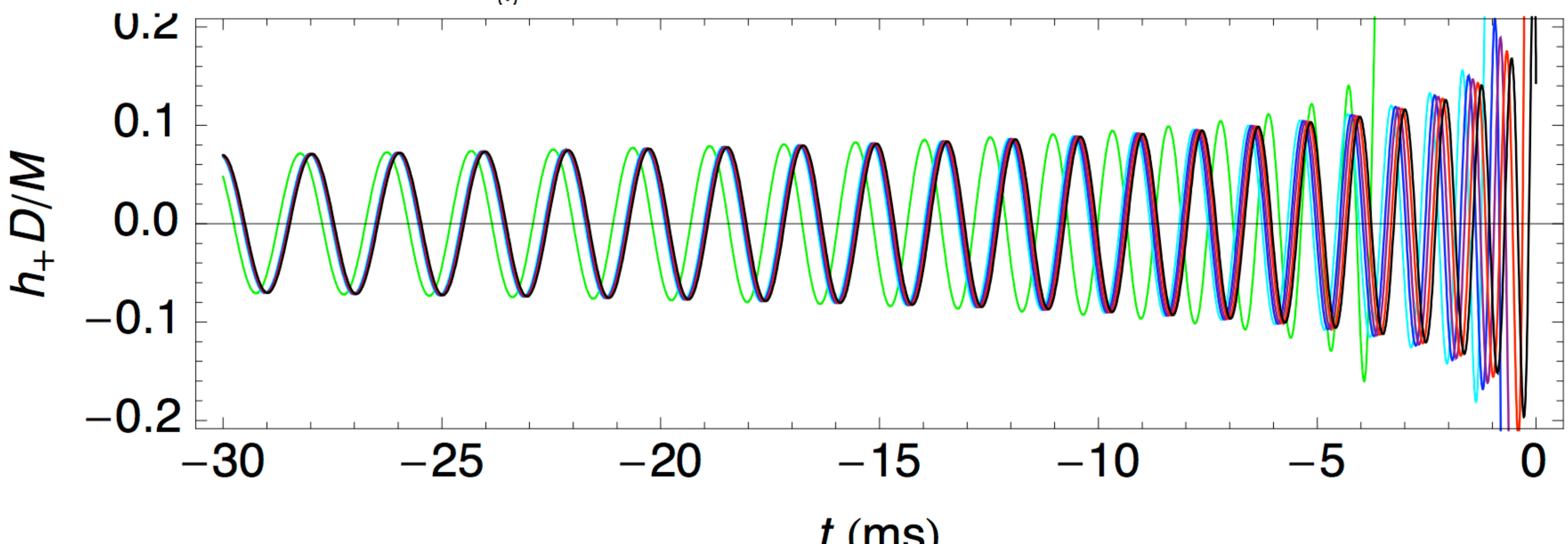
NSNS Mergers and the Nuclear EOS



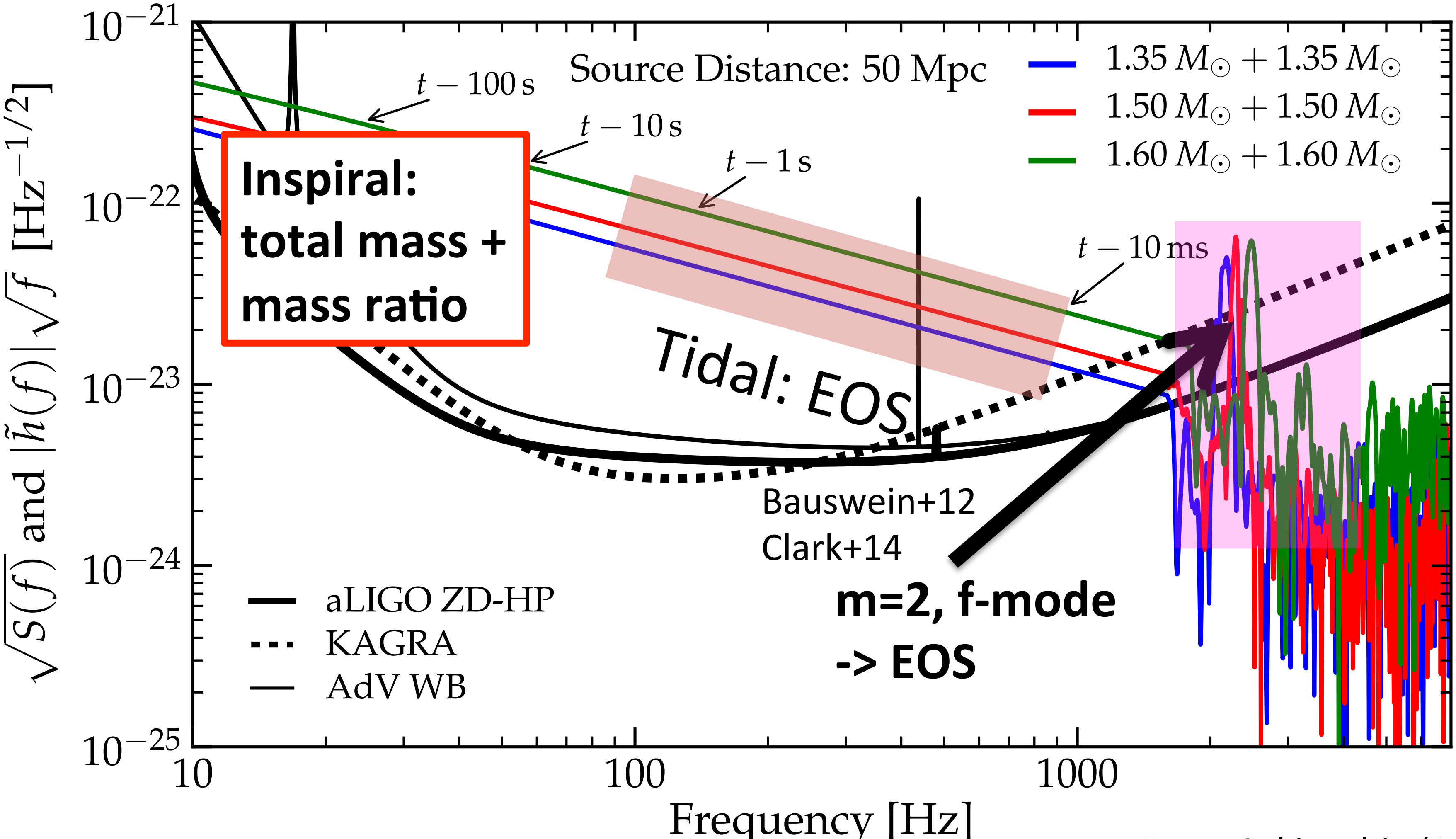
$$\lambda \propto k R^5$$

tidal Love number

Source:
Jocelyn Read
CSU Fullerton



NSNS Mergers and the Nuclear EOS



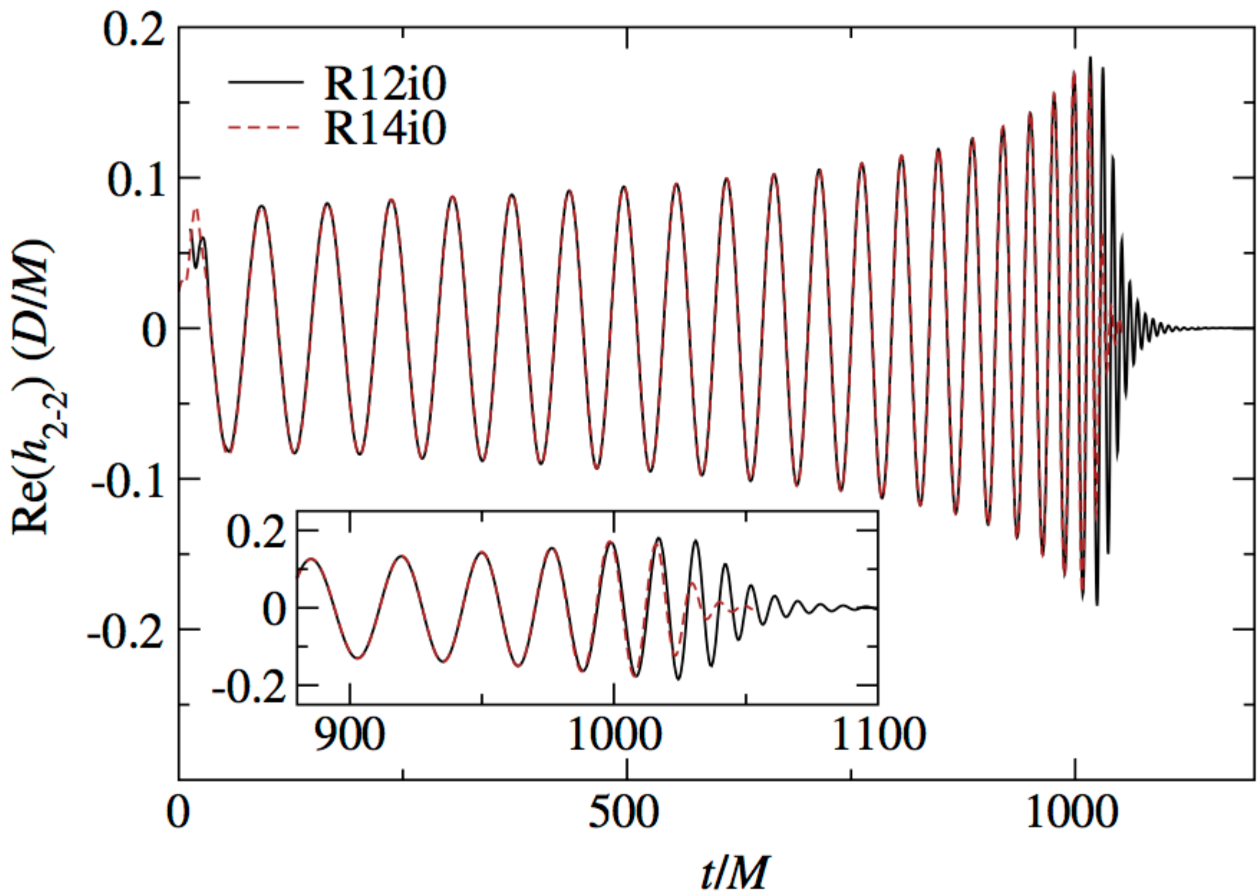
Data: Sekiguchi+ '11
Figure: Sarah Gossan

Late inspiral + merger: $E_{\mathrm{GW}} \sim 0.1 M_\odot c^2$

Best guess: ~0.5 event/year @50 Mpc at design sensitivity

BHNS Mergers and the Nuclear EOS

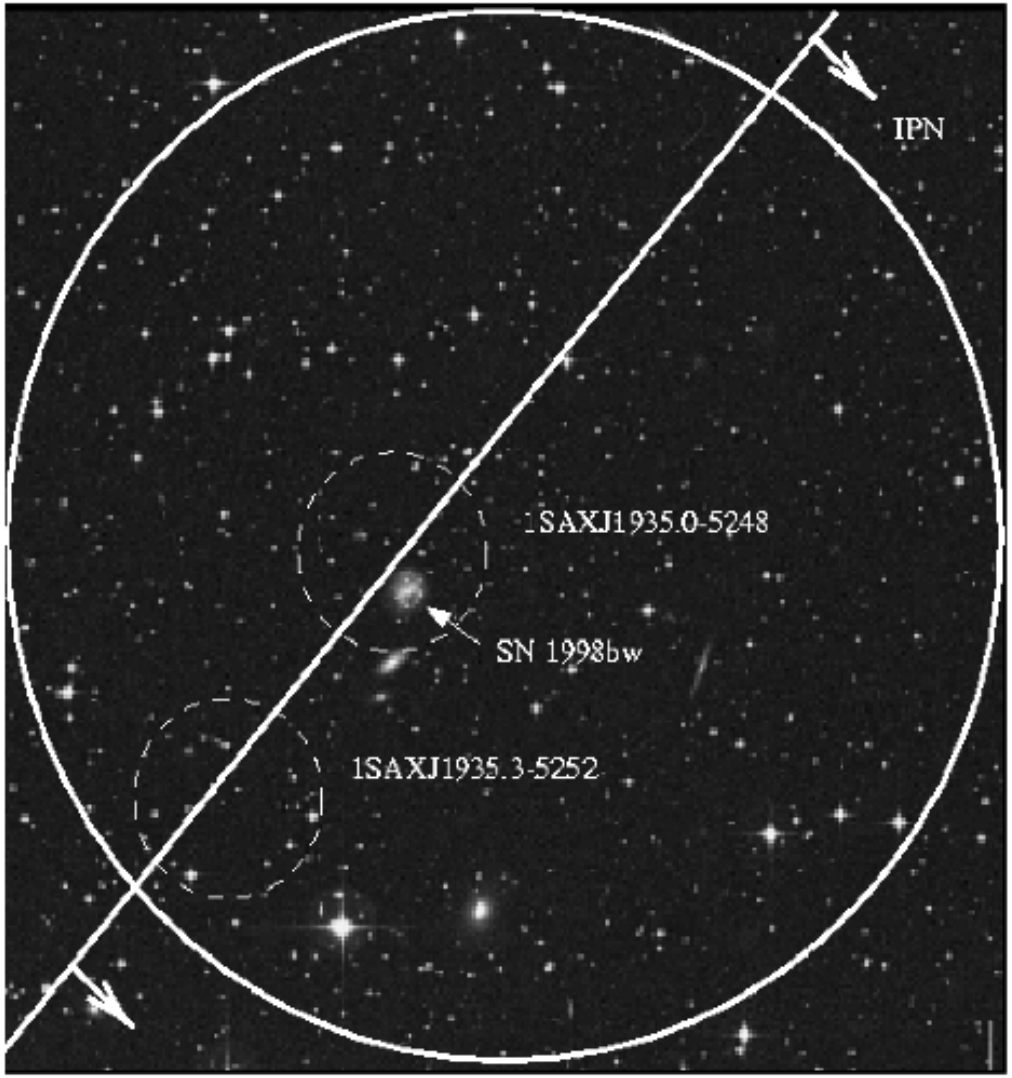
- LIGO will measure M_{chirp}, mass ratio.
- Tidal deformations during late inspiral very small.
- If NS disrupted, cut-off frequency of GW signal sensitive to NS radius.

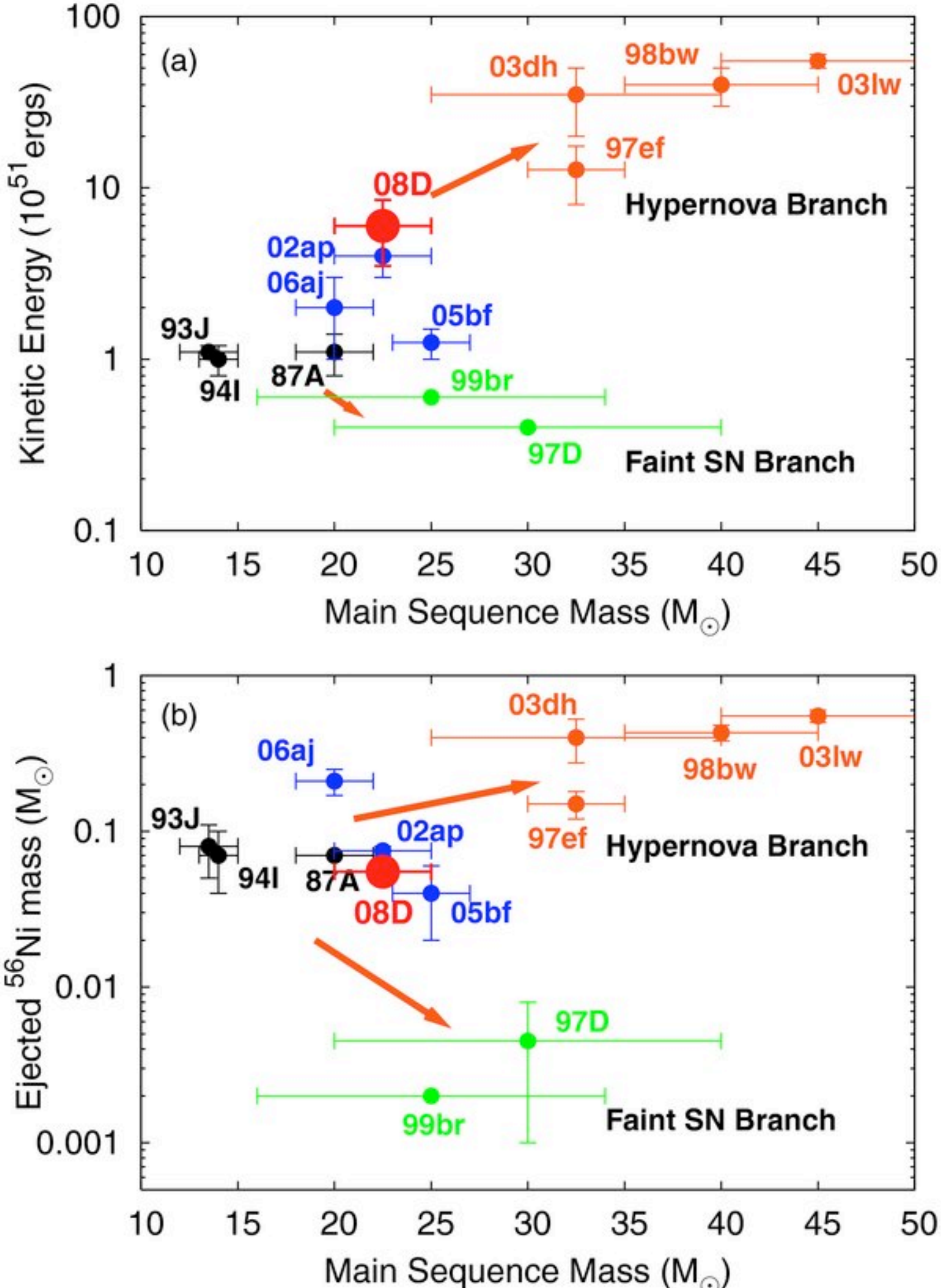


Extreme Core-Collapse Supernovae
and
the Long-GRB – CCSN Relationship

Extreme Core-Collapse Supernovae

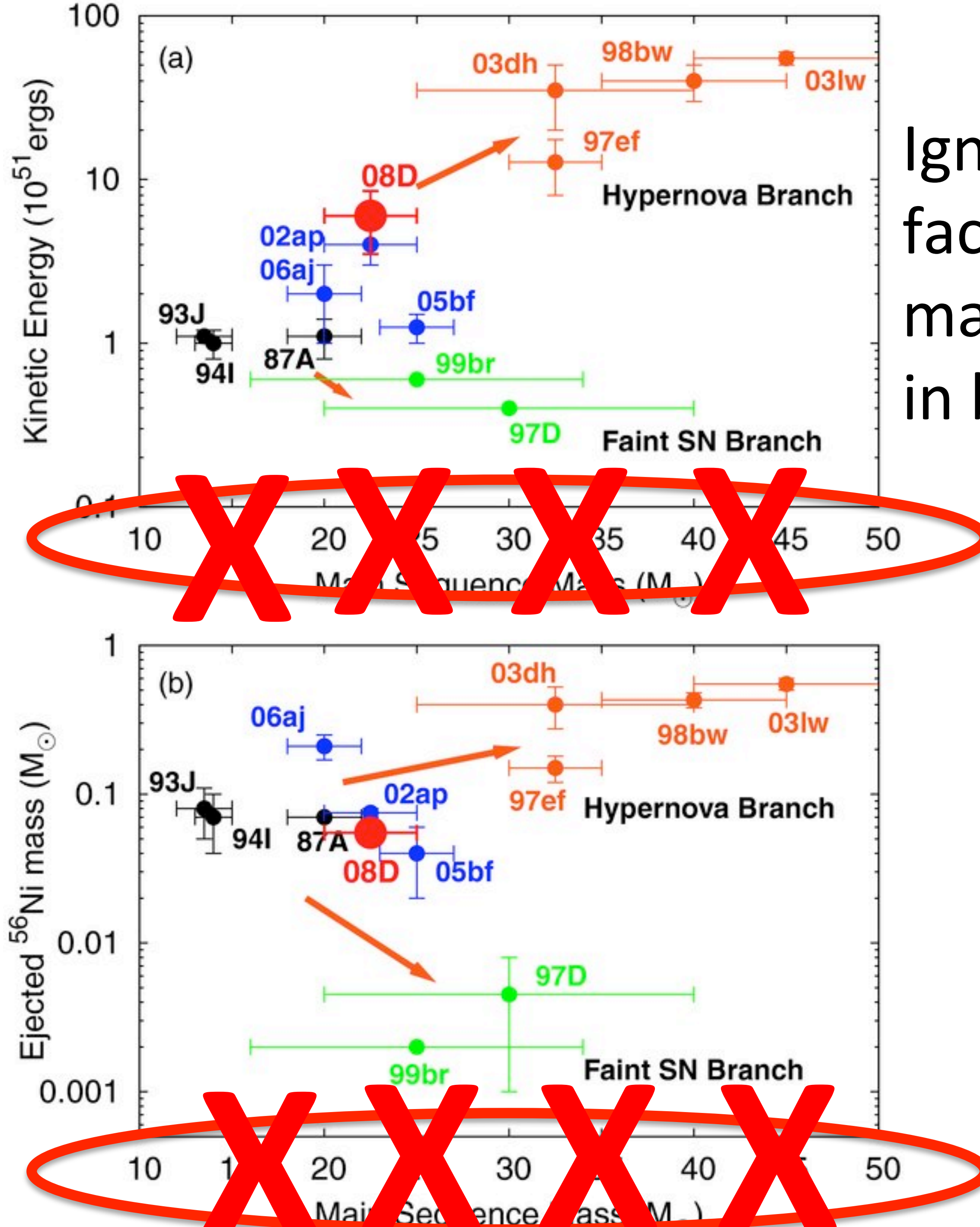
- Type Ic-bl (“broad lined”) core-collapse supernovae
- Relativistic outflows, hyperenergetic: $\sim 10^{52}$ erg = 10 B
- ~1% of all CCSNe
- ~10% of Type Ic-bl CCSNe associated with a long GRB.
- All CCSNe associated with GRBs are Type Ic-bl. 11 GRB-CCSNe known.





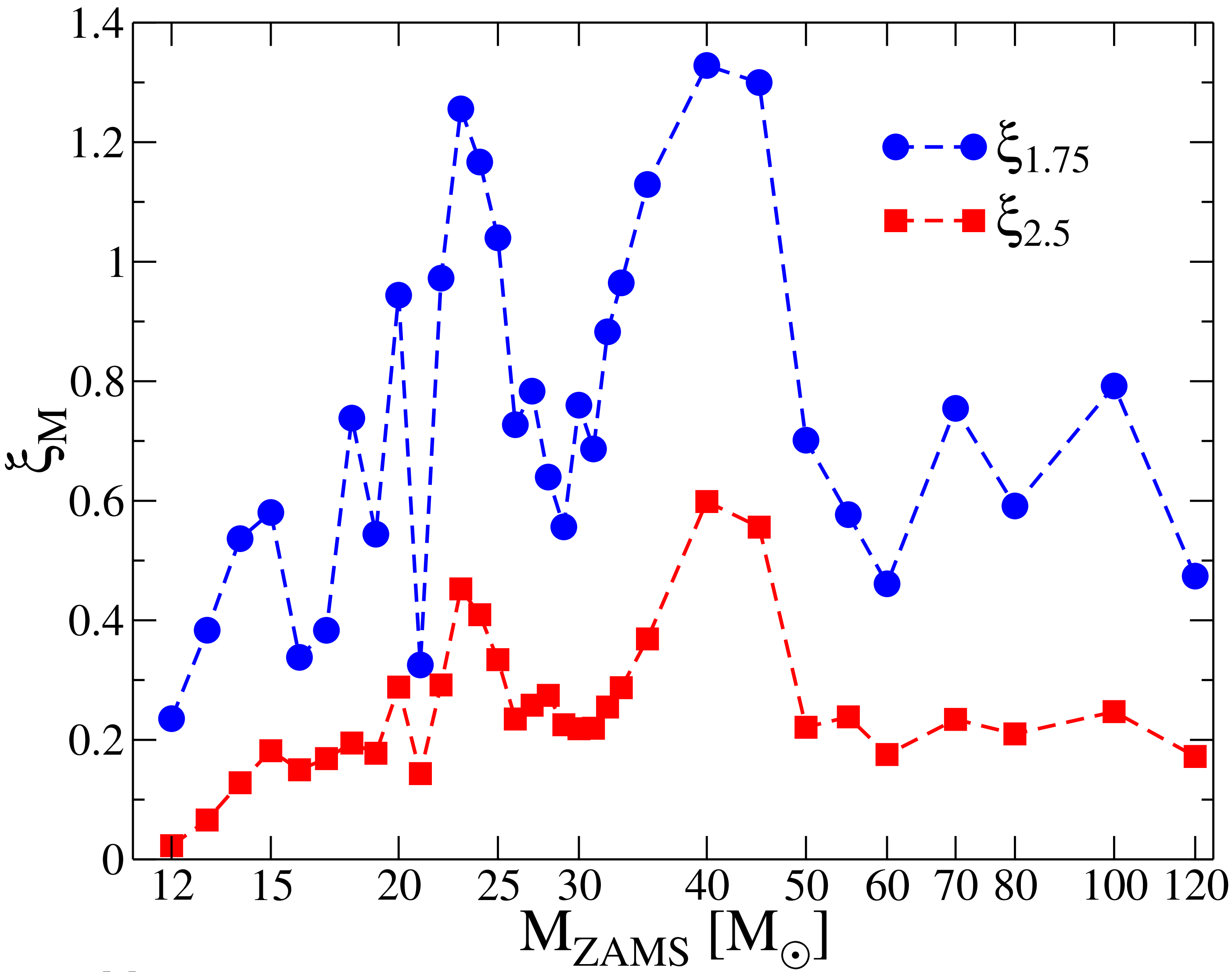
(a)
Kinetic Energy (10^{51}ergs)
100
10
1
0.1
03dh
98bw
03lw
97ef
08D
Hypernova Branch
02ap
06aj
05bf
93J
94I
87A
99br
97D
Faint SN Branch
10 15 20 25 30 35 40 45 50
Main Sequence Mass ($M_\odot$)
(b)
Ejected ^{56}Ni mass ($M_\odot$)
1
0.1
0.01
0.001
03dh
06aj
98bw
03lw
97ef
93J
02ap
Hypernova Branch
94I
87A
08D
05bf
97D
99br
Faint SN Branch
10 15 20 25 30 35 40 45 50
Main Sequence Mass ($M_\odot$)

Ignores fact that ~all massive stars in binaries



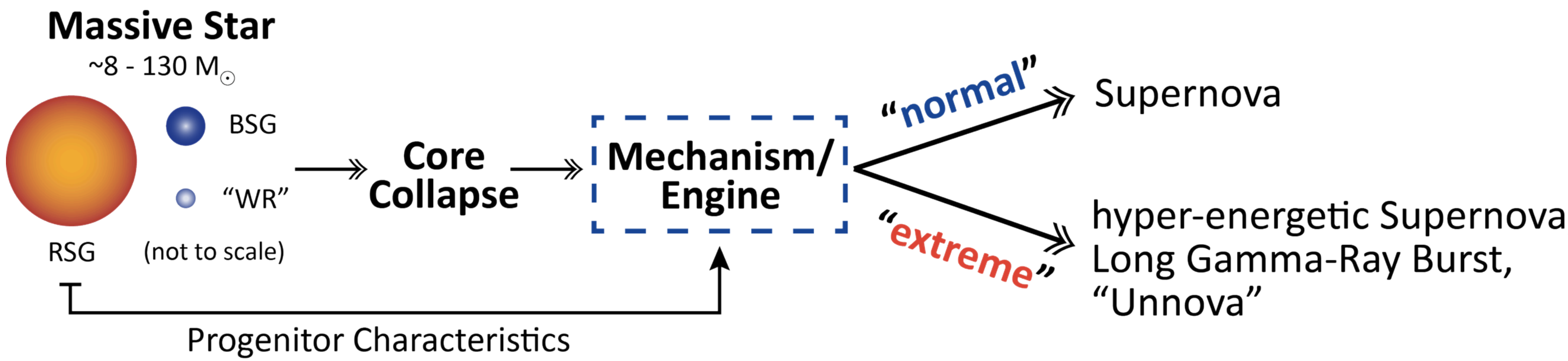
largely made up!

largely made up!



$$\xi_{2.5} = \frac{2.5 M_\odot}{R(M_{\rm bary} = 2.5\ M_\odot)}\Big|_{t=t_{\rm bounce}}$$

Extreme Core-Collapse Supernovae

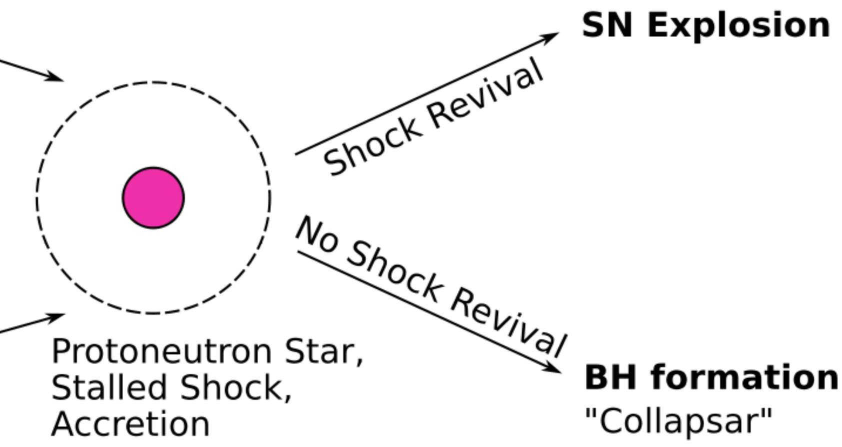


- What powers a hypernova / a long GRB?
  Neutrino-driven CCSN mechanism is inefficient (η~10%); difficult to obtain 1 B!

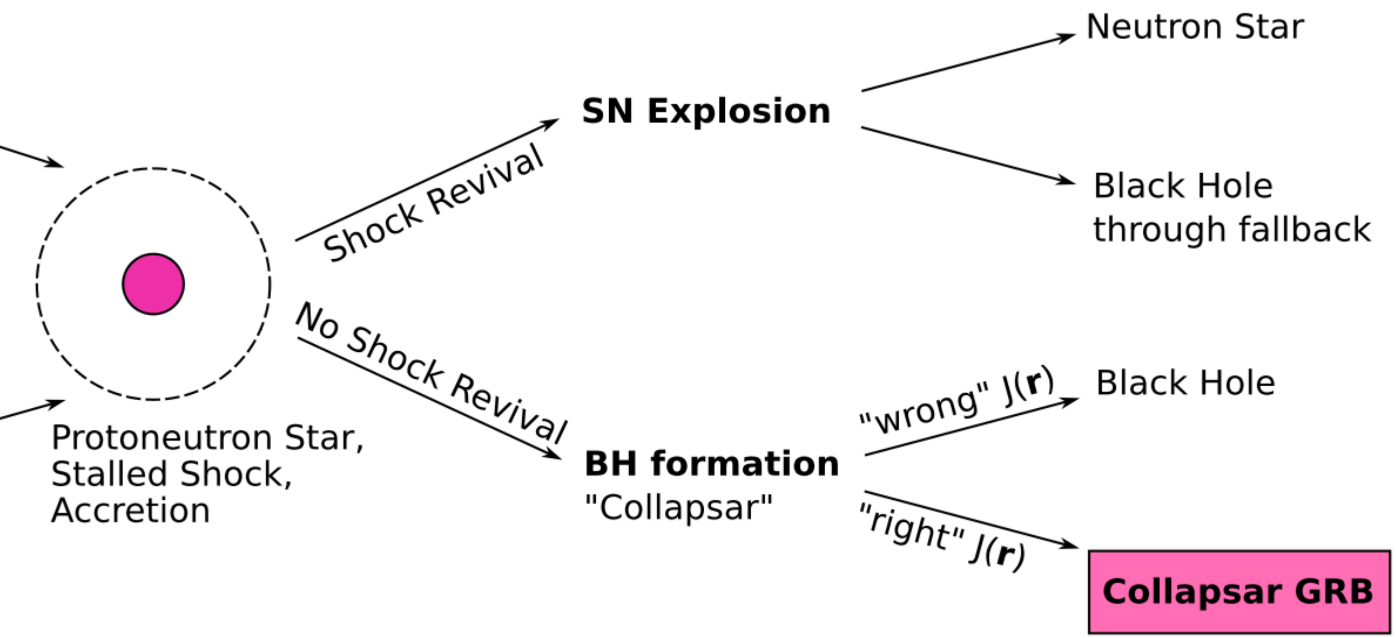
Possiblity:

Rapid rotation + strong magnetic fields
-> energetic collimated outflows

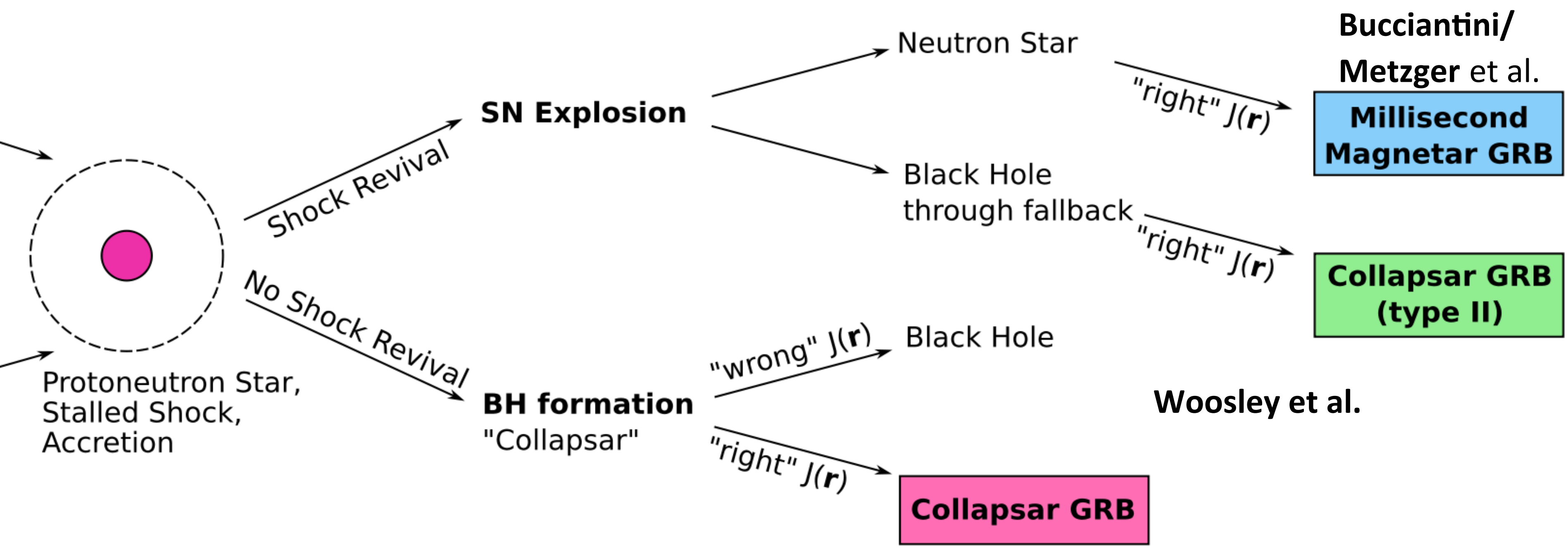
The CCSN – Long Gamma-Ray Burst Connection



The CCSN – Long Gamma-Ray Burst Connection



The CCSN – Long Gamma-Ray Burst Connection



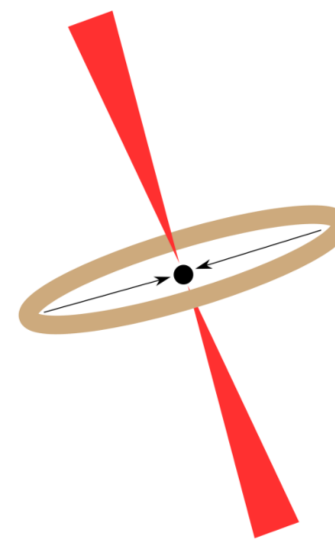
(1) **Millisecond Proto-Magnetar Model**

-> GRB driven by spindown; requires O(ms) initial period. Subsequent to a successful CCSN explosion.

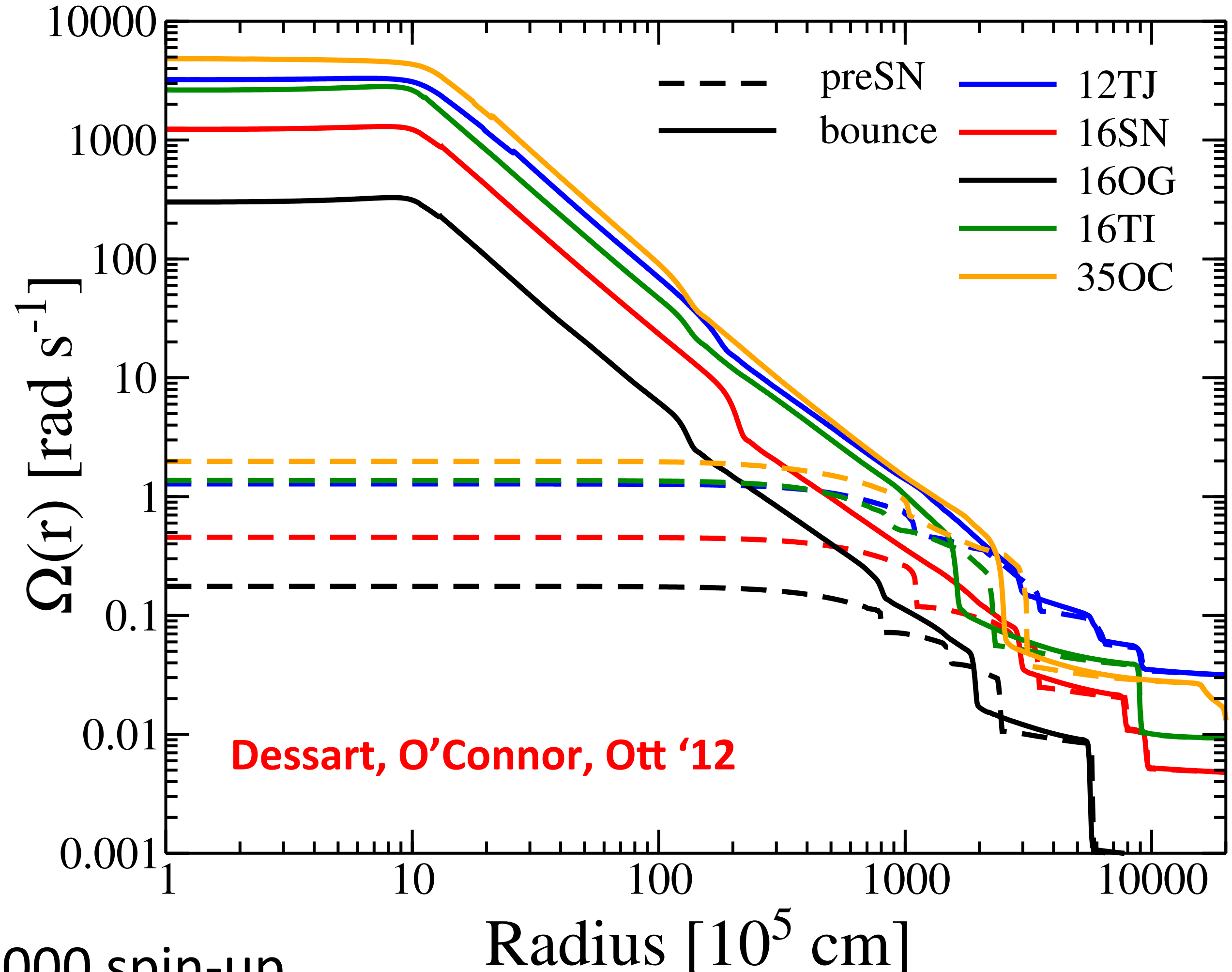
(2) **Collapsar Model**

-> Requires accretion disk near ISCO;

$j = \Omega r^2 = 10^{16}\text{-}10^{17}\ \mathrm{cm^2/s}$.



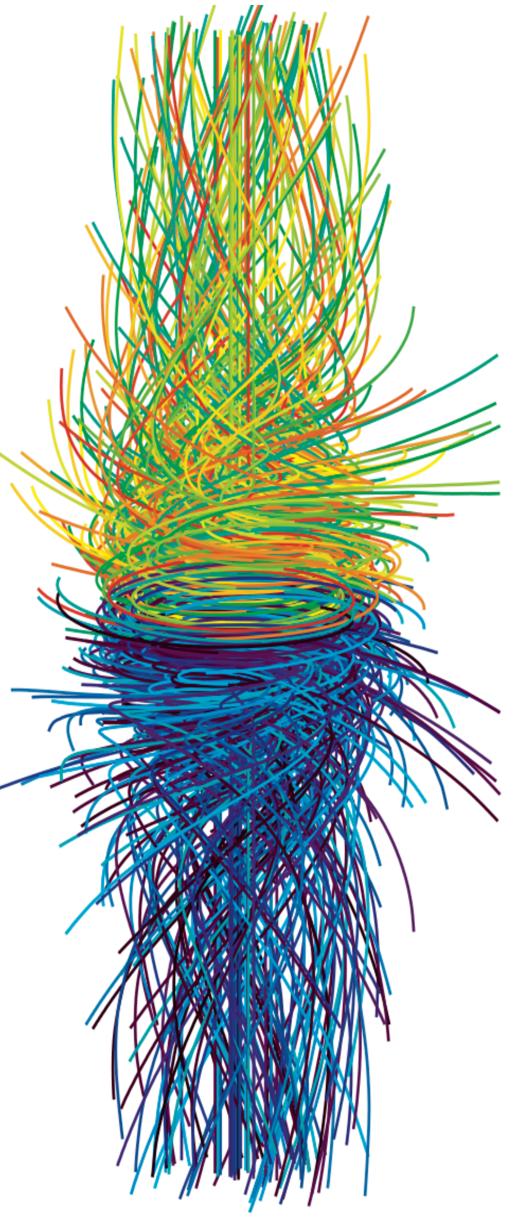
“Magnetorotational Explosions”



- Core: x 1000 spin-up
- Differential rotation -> reservoir of free energy.
- Spin energy tapped by **magnetorotational instability** (MRI)?

Magnetorotational Mechanism

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

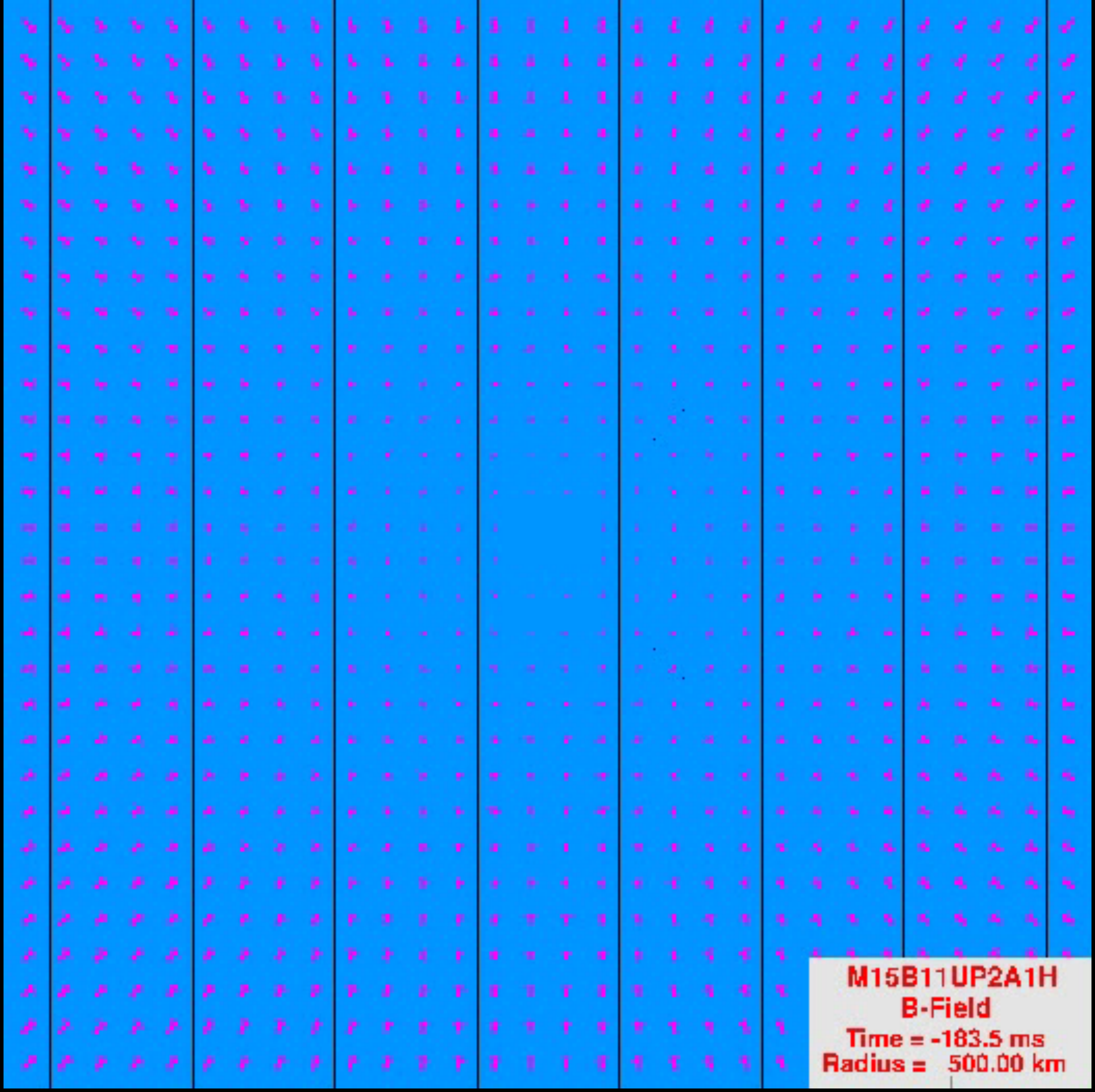

Burrows+'07

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI];
difficult to resolve in stellar cores)

2D: Energetic bipolar explosions.

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

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



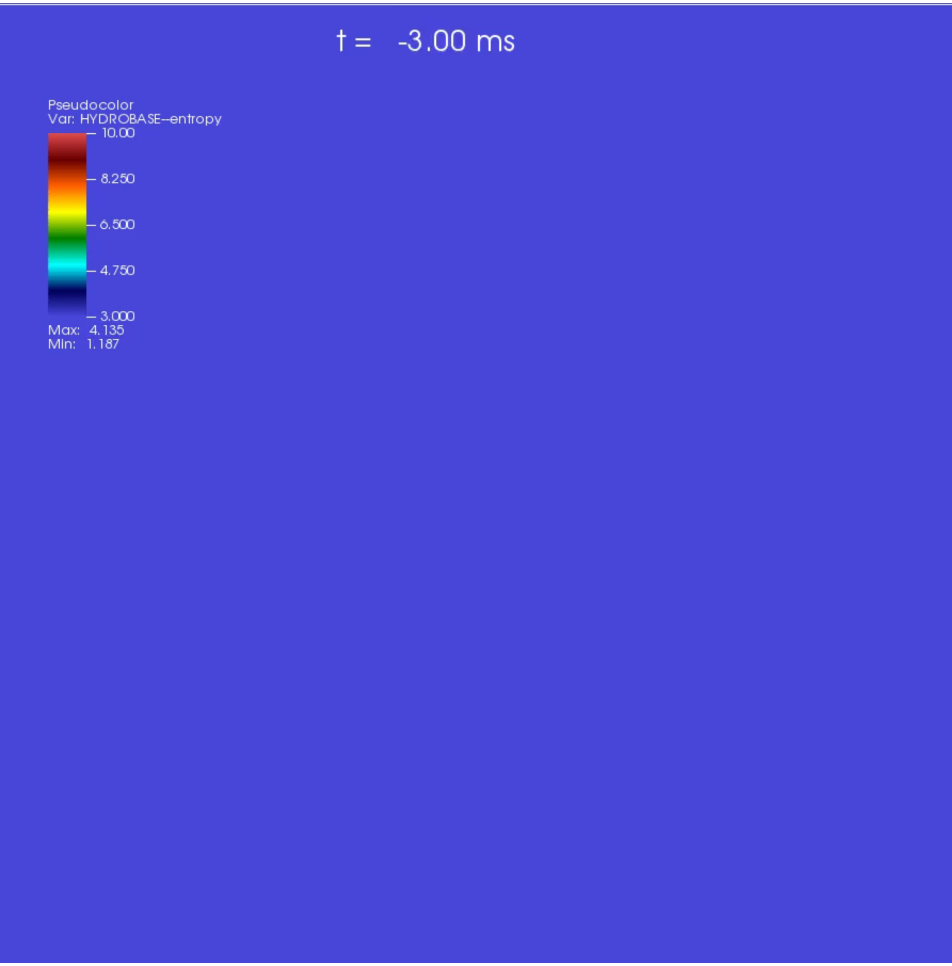
Burrows+’07

(10^{11} G
seed field)

3D Dynamics of Magnetorotational Explosions

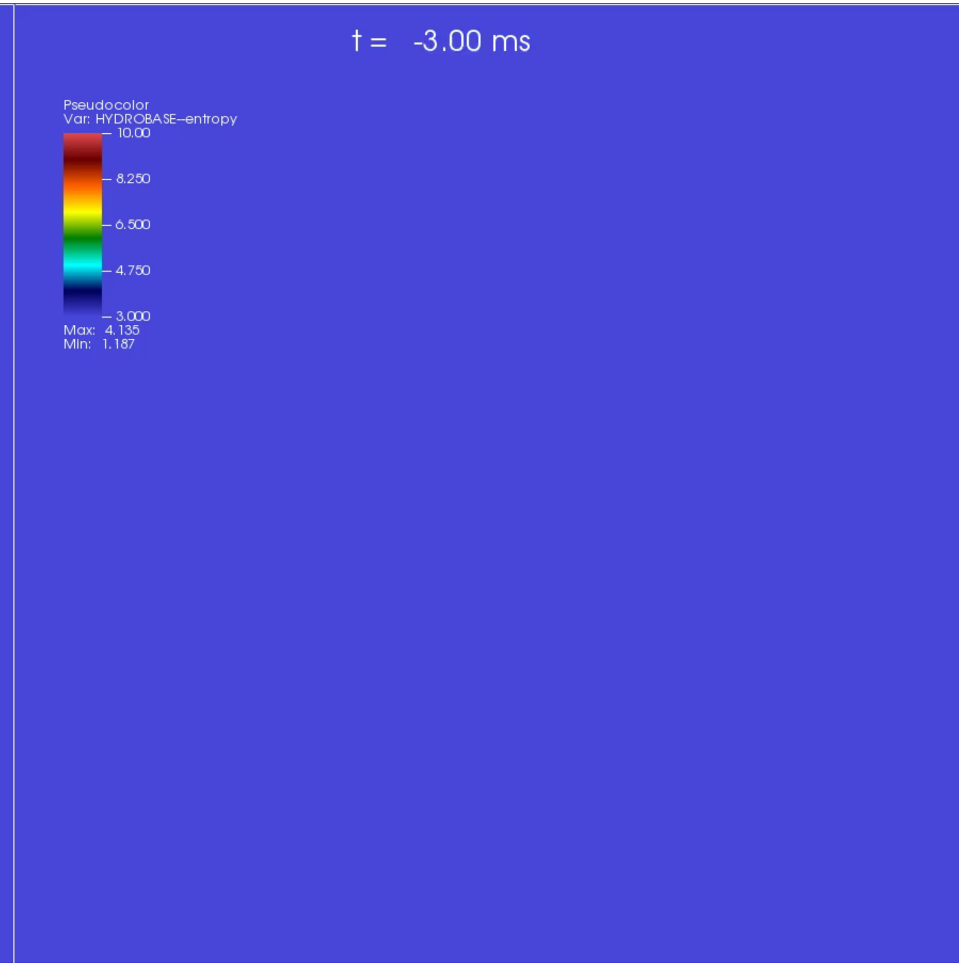
New, full 3D GRMHD simulations. **Mösta+ 2014**, ApJL.
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km →

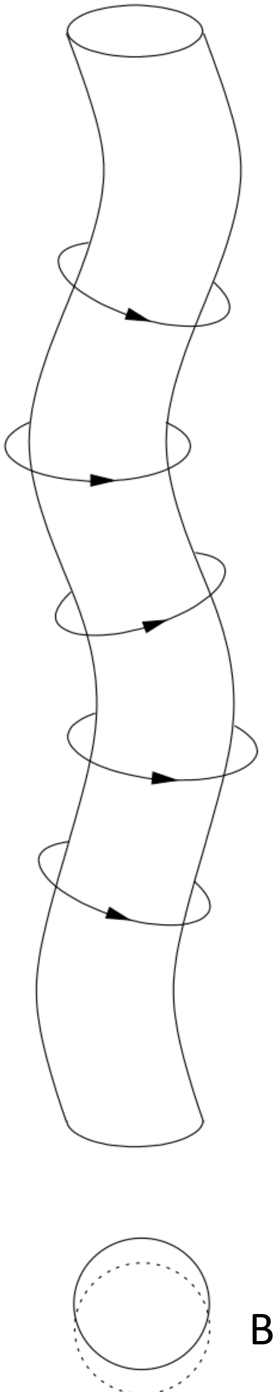


Octant Symmetry (no odd modes)

← 2000 km →



Full 3D

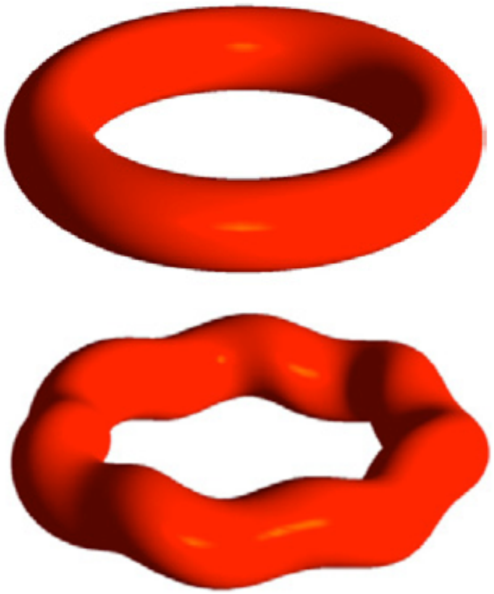


What is happening here?

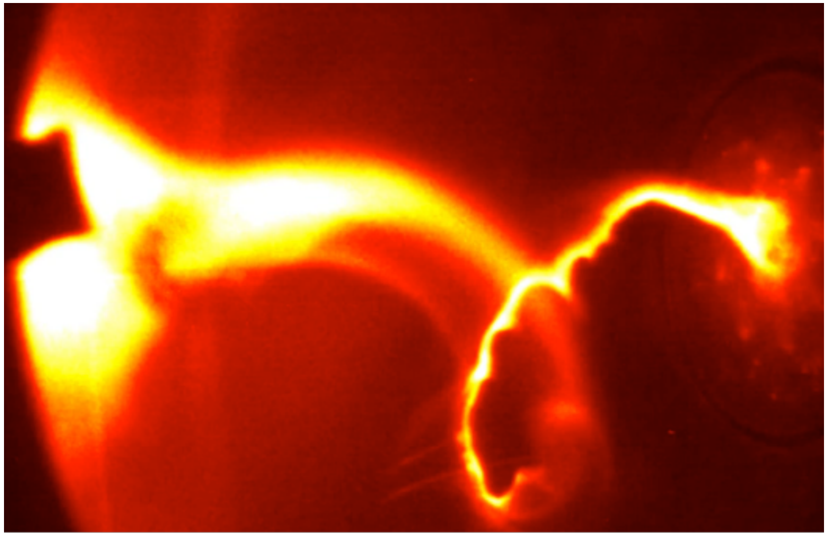
Mösta+14, ApJL

Philipp Mösta Sherwood Richers

- B-field near proto-NS: $B_{tor} >> B_z$
- Unstable to MHD screw-pinch kink instability.
- Similar to situation in Tokamak fusion reactors!



Sarff+13



Credit: Moser & Bellan, Caltech

Braithwaite+ ’06

t = -3.00 ms

Mösta+ 2014
ApJL

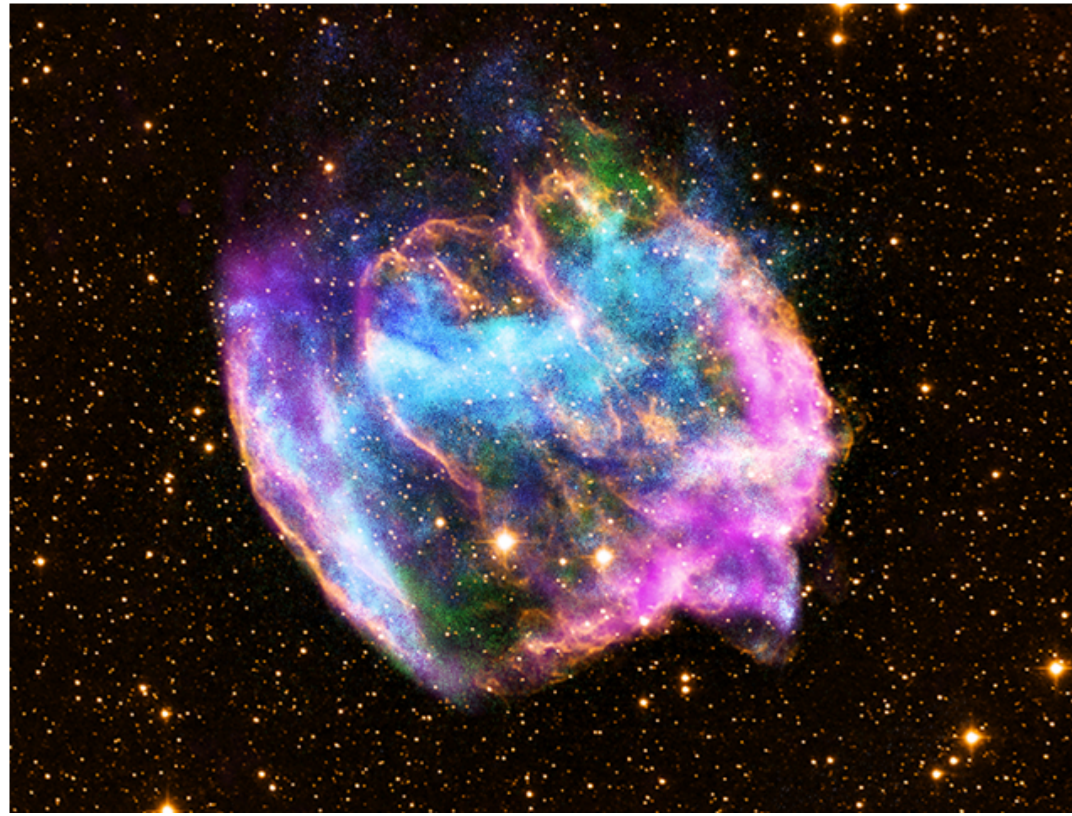
t = -4.95 ms

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

Mösta+ 2014
ApJL

Consequence?

- If explosion fails to develop: BH formation
- ms Proto-magnetar scenario for GRBs might not work.
- Type Ic-bls might be coming from collapsars.

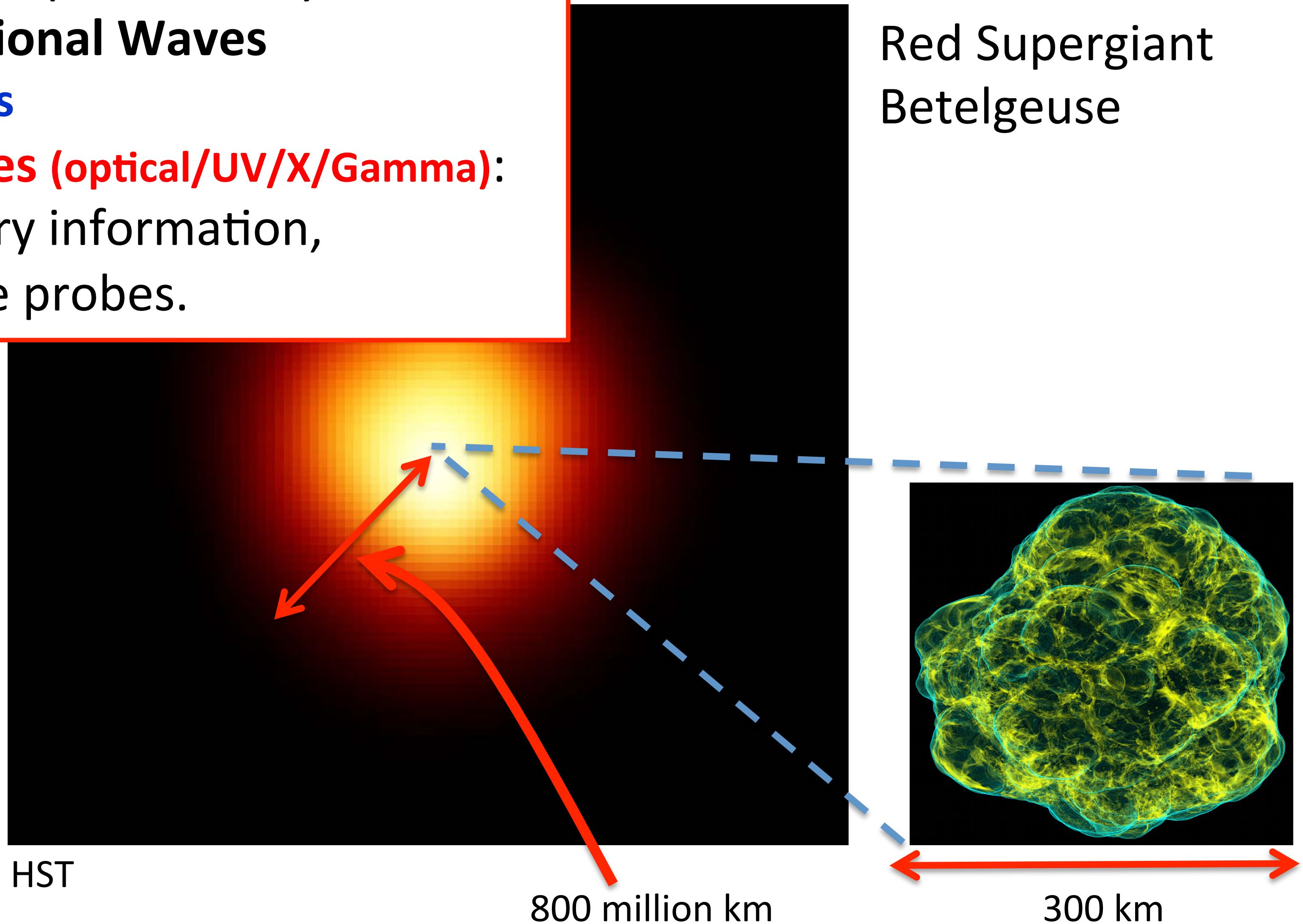


SNR W49B; harboring a black hole? (Lopez+13)
Image credit: Composite X/IR/Radio image NASA/CXC/MIT/Lopez et al./ Palomar/SF/NRAO/VLA

Gravitational Waves from Core-Collapse Supernovae

Observing the Heart of a Supernova

Probes of Supernova Physics:
- **Gravitational Waves**
- **Neutrinos**
- **EM waves** **(optical/UV/X/Gamma)**: secondary information, late-time probes.



Gravitational-Waves from Core-Collapse Supernovae

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

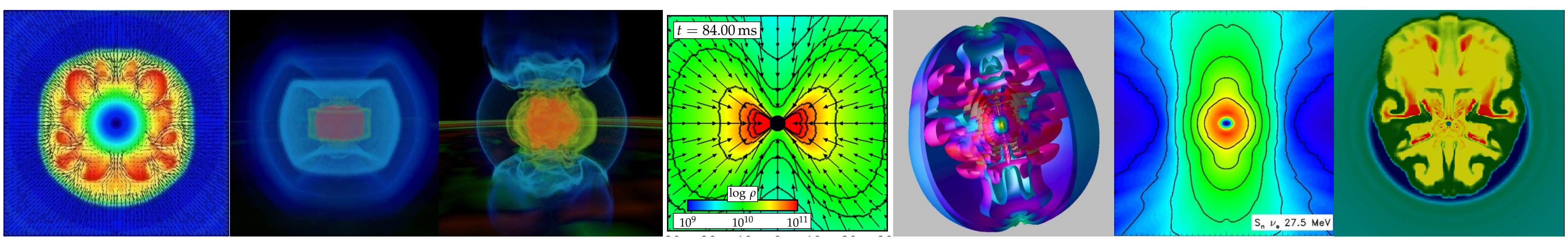
Need:

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

→ accelerated aspherical (quadrupole) mass-energy motions

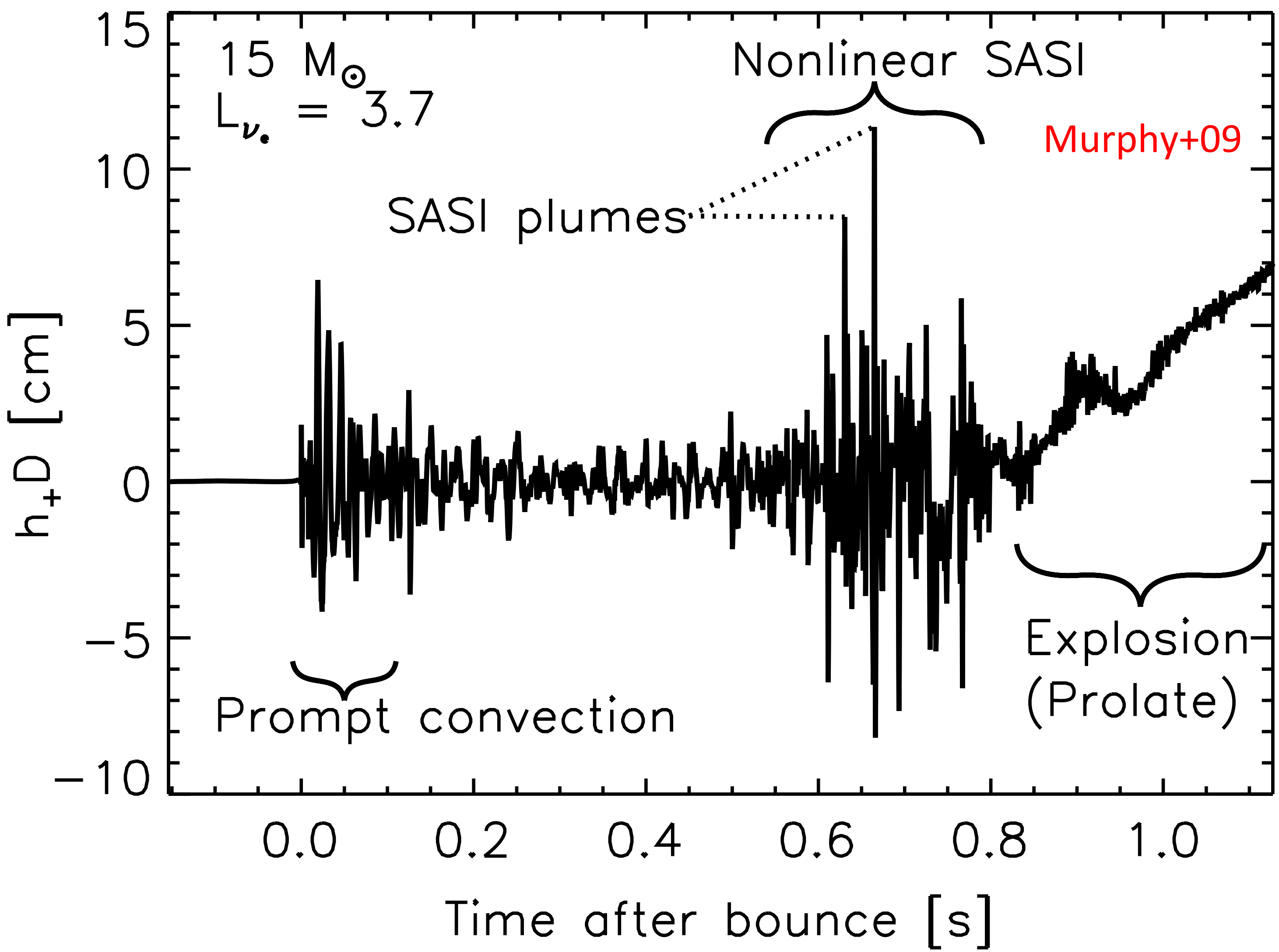
Candidate Emission Processes:

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



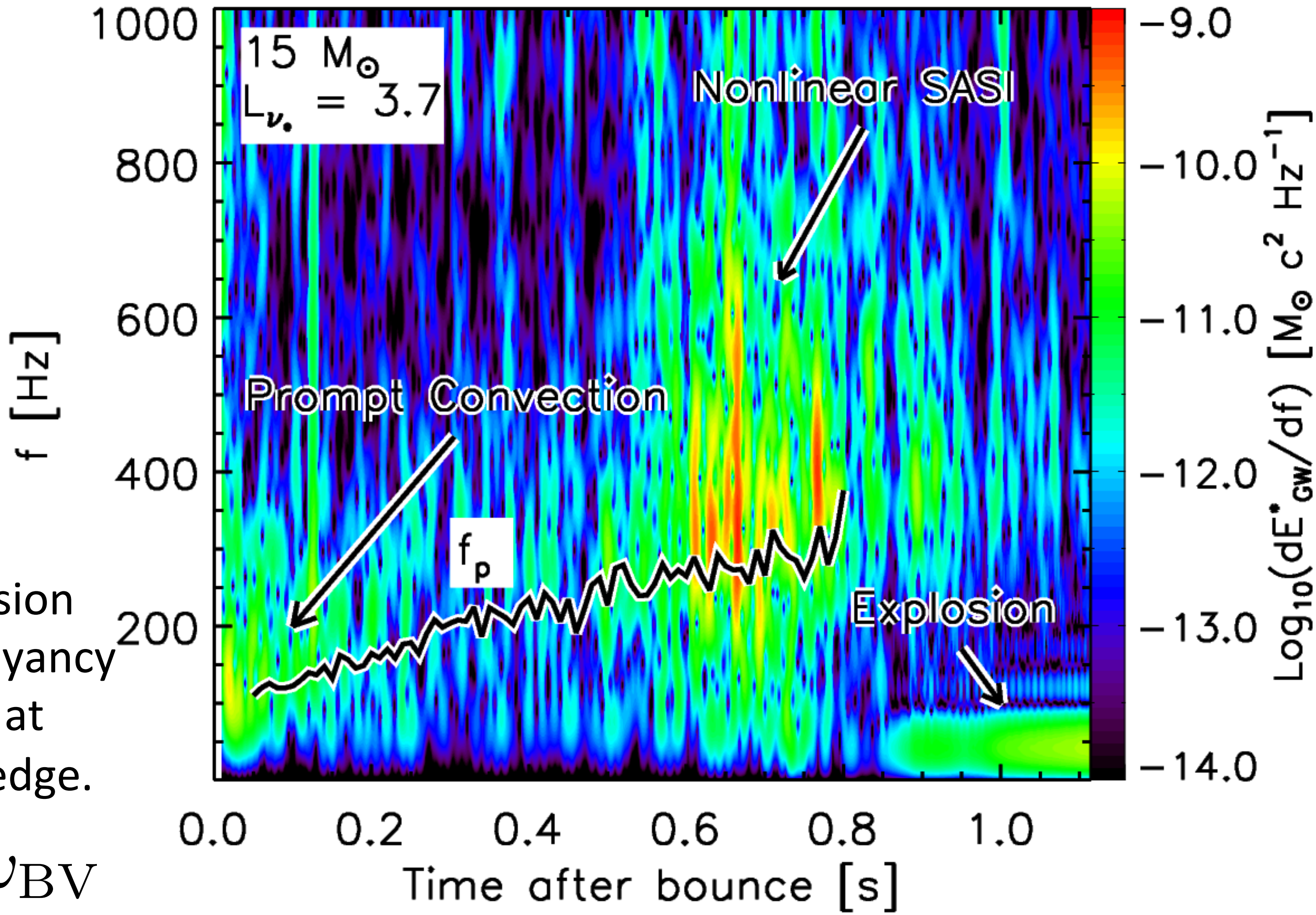
GWs from Convection & Standing Accretion Shock Instability

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



Time-Frequency Analysis of GWs

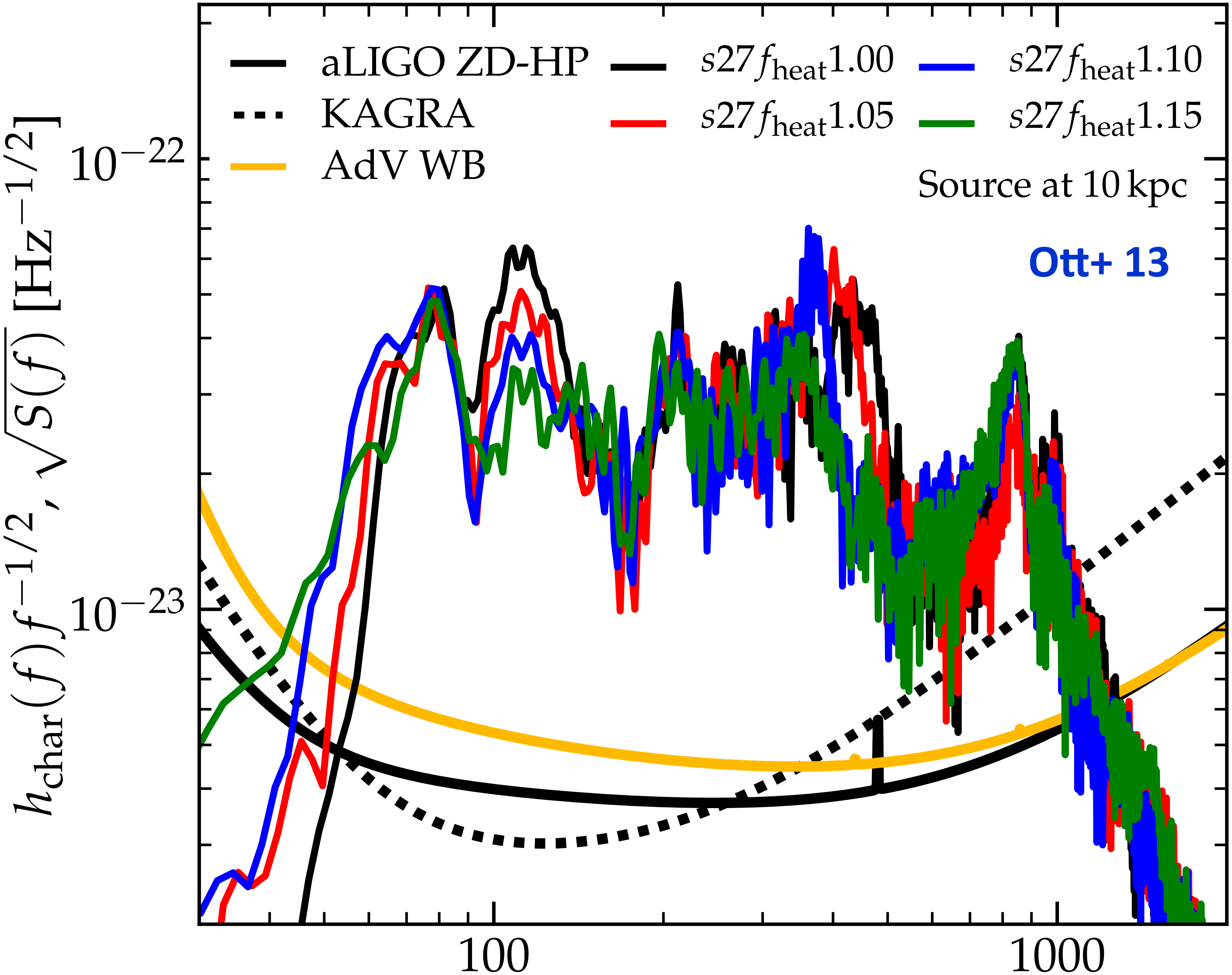
Murphy, Ott, Burrows 09, see also B. Müller+13



Peak emission traces buoyancy frequency at proto-NS edge.

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

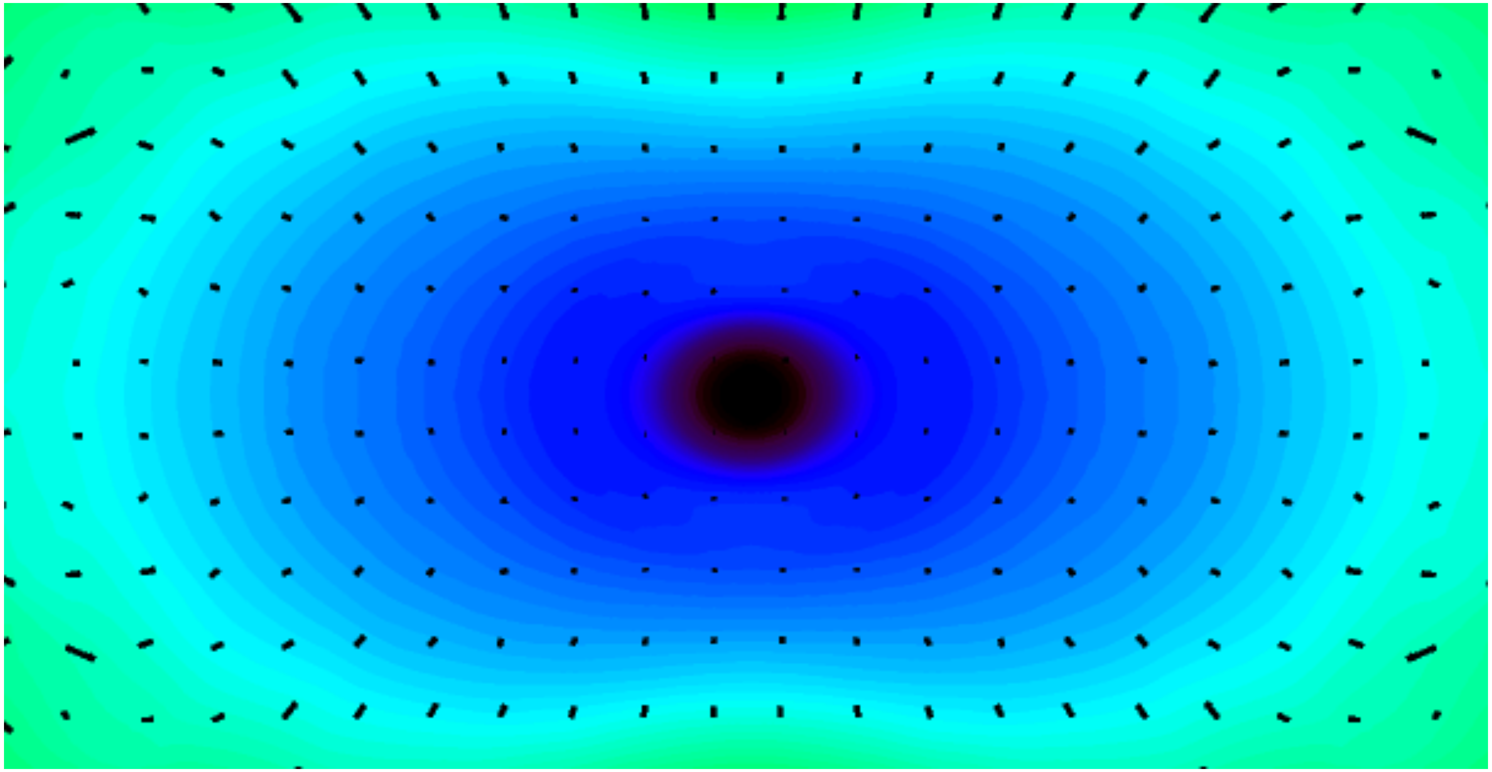
Detectability?



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

GWs from Rotating Collapse & Bounce

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

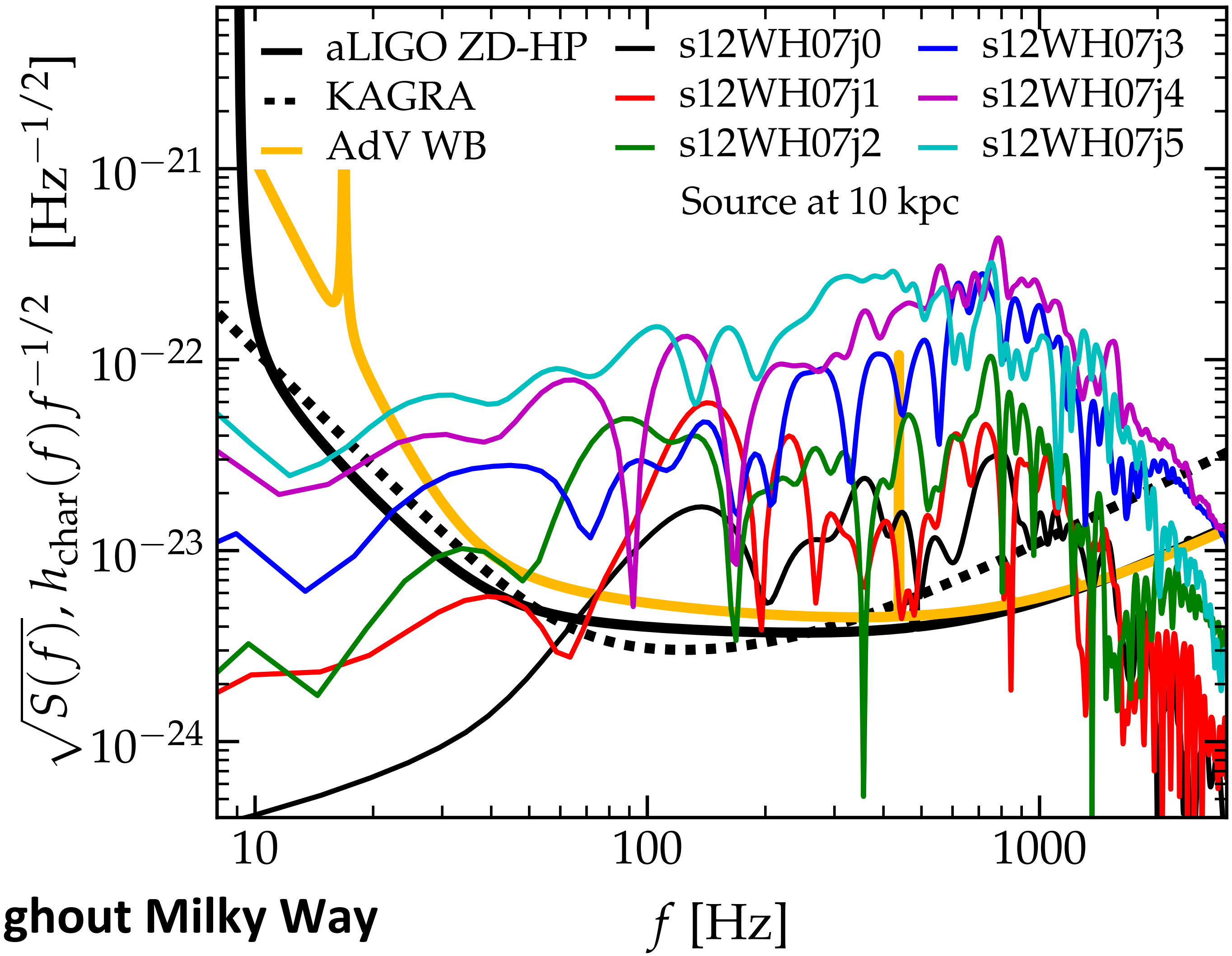


- **Axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + mass of the inner core + **gravity** + **stiffening of nuclear EOS**
- Strong signals for rapid rotation (-> millisecond proto-NS).

Can we observe these waves?

Ott+ 12, PRD

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

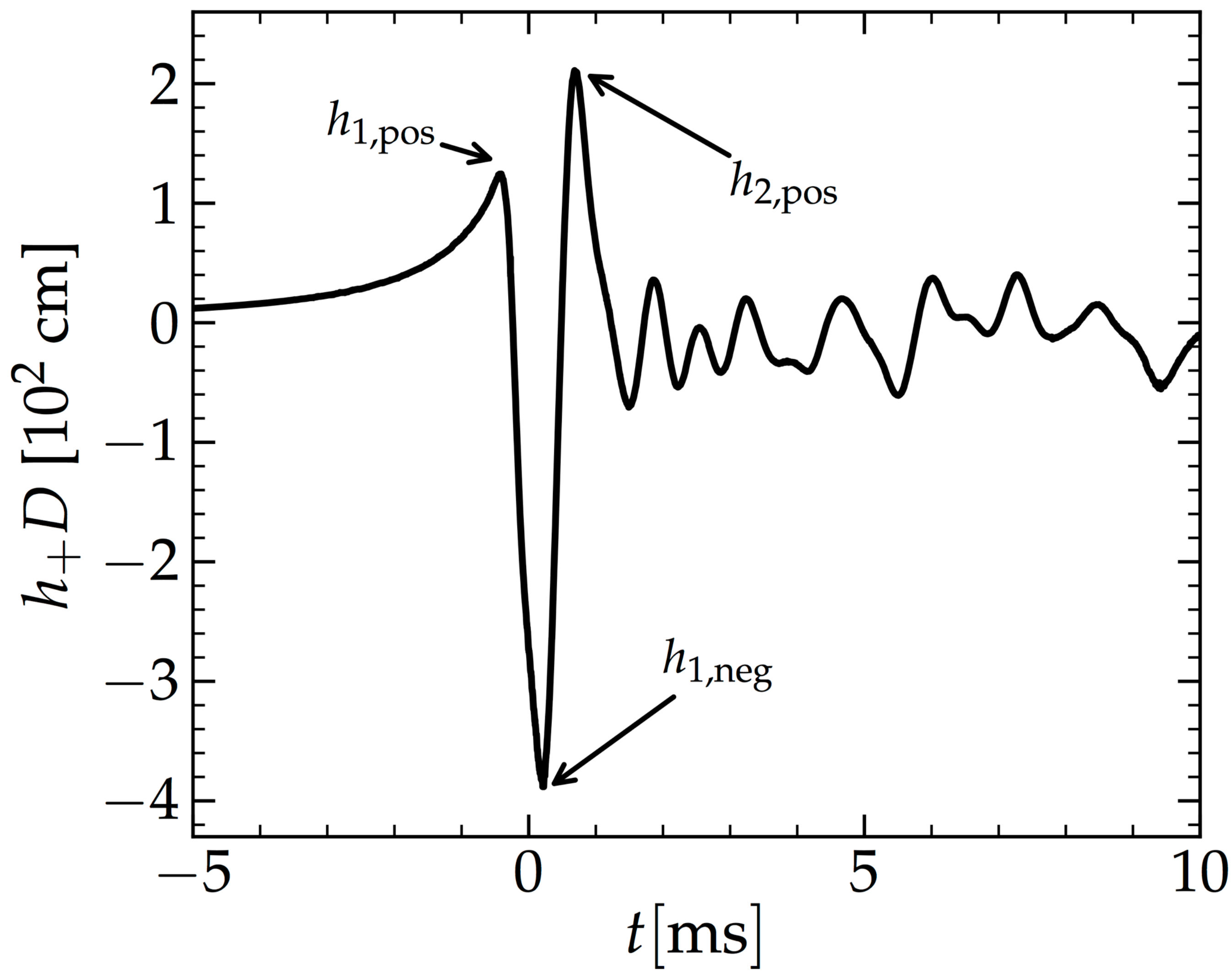


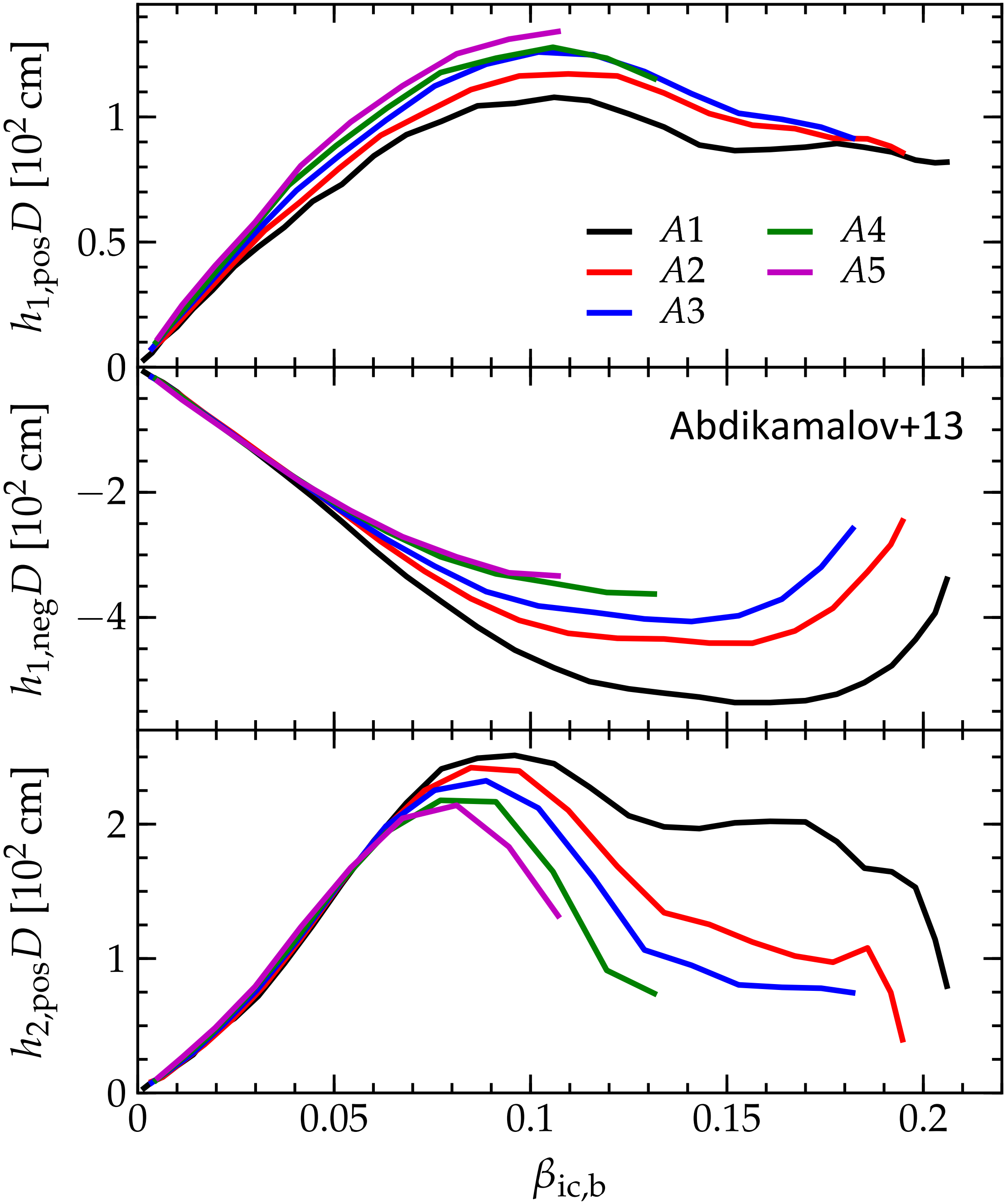
-> Throughout Milky Way with aLIGO

GWs from Rotating Collapse & Bounce

Abdikamalov, Gossan, DeMaio, Ott, arXiv:1311.3678

Simple signal features:





Measure for "total rotation" of the inner core:

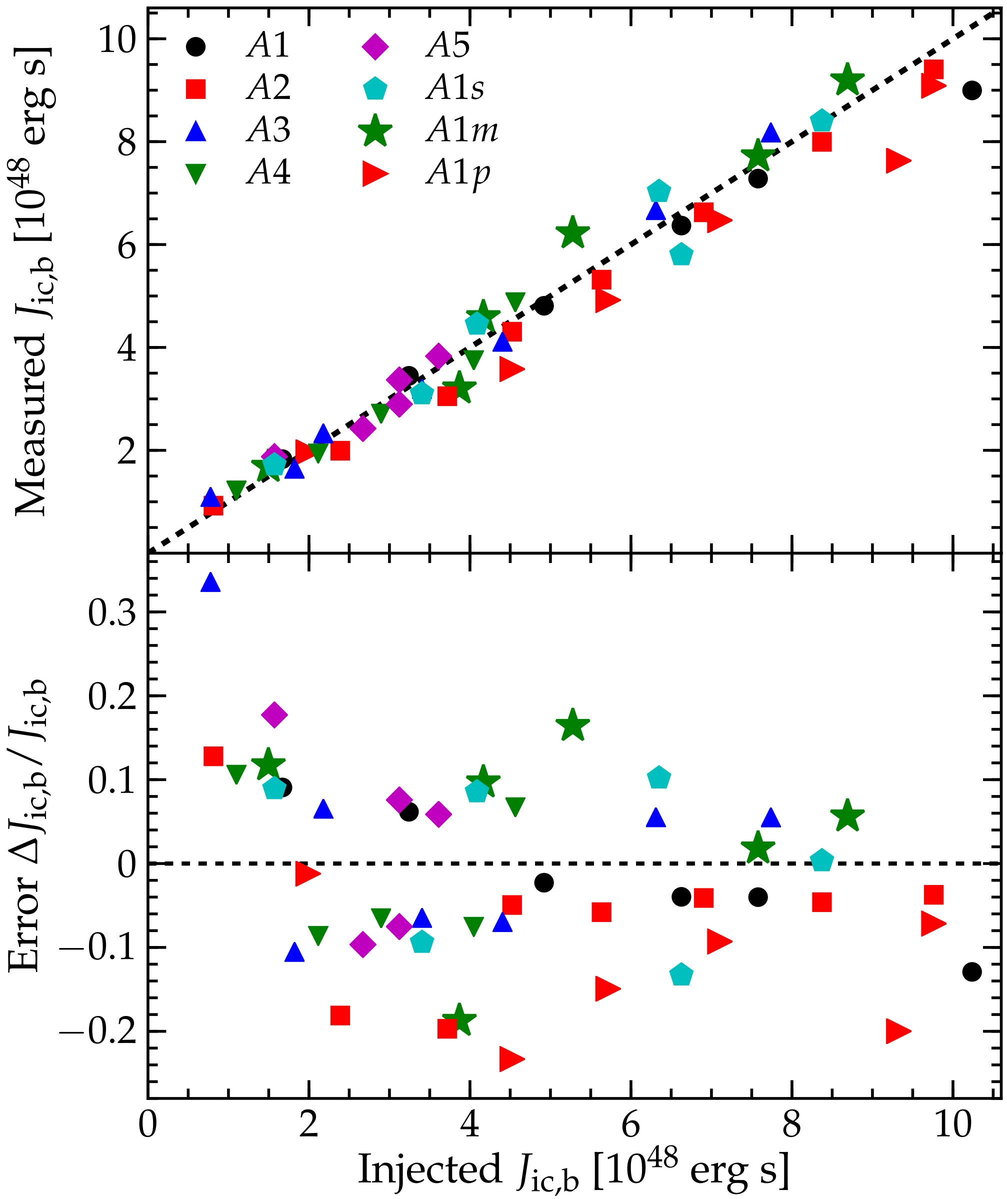
$$\beta = \frac{T}{|W|}$$

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!

APS

Join the American Physical Society Topical Group in Gravitation (GGR)!!!

http://www.aps.org/units/ggr/

Now is a great time to join to help us gain APS division status by 2015, the centennial of General Relativity!