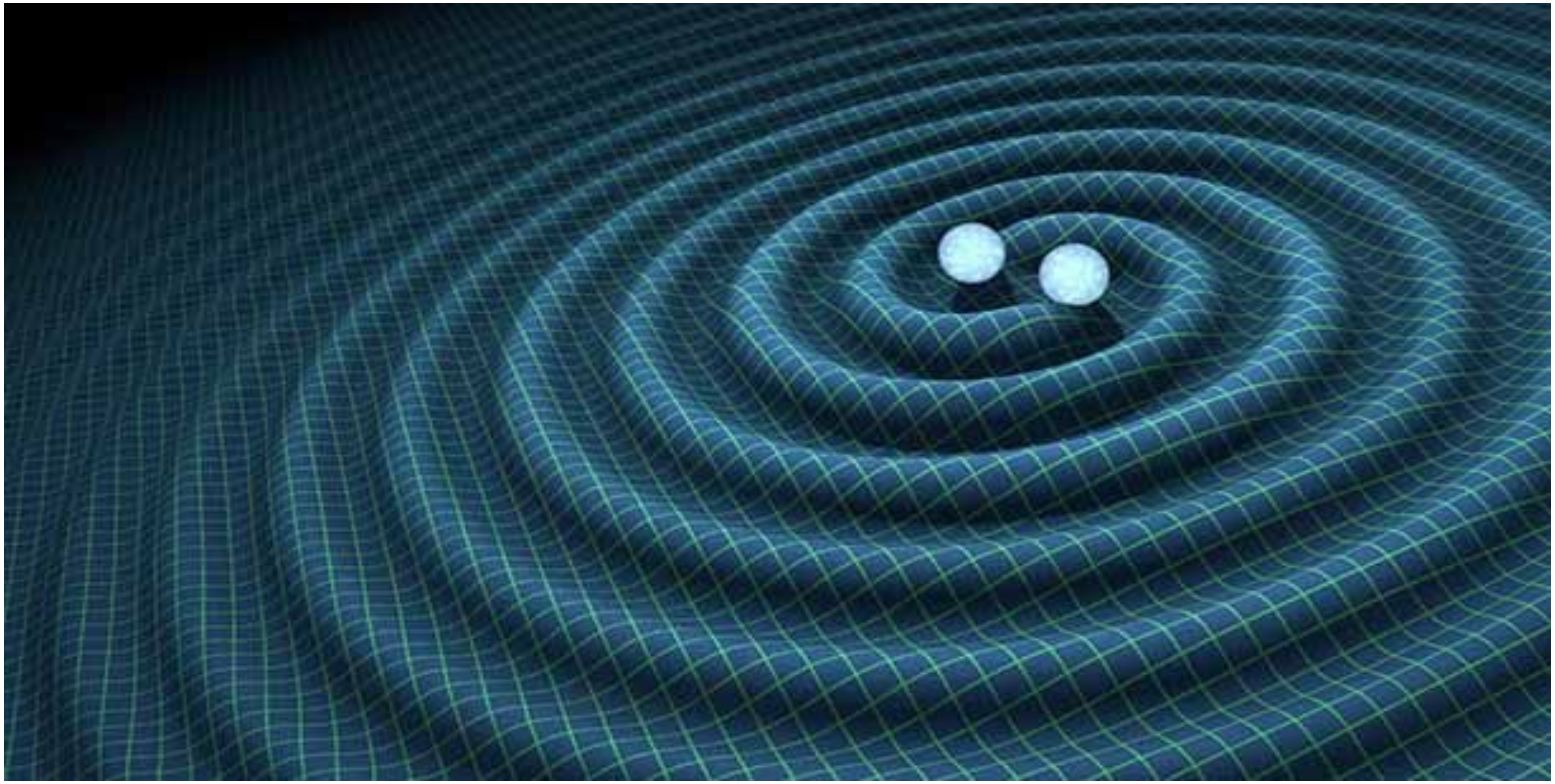
L'Aquila - 14/11/2018

Multi-messenger studies of NS mergers, GRBs and magnetars



Simone Dall'Osso

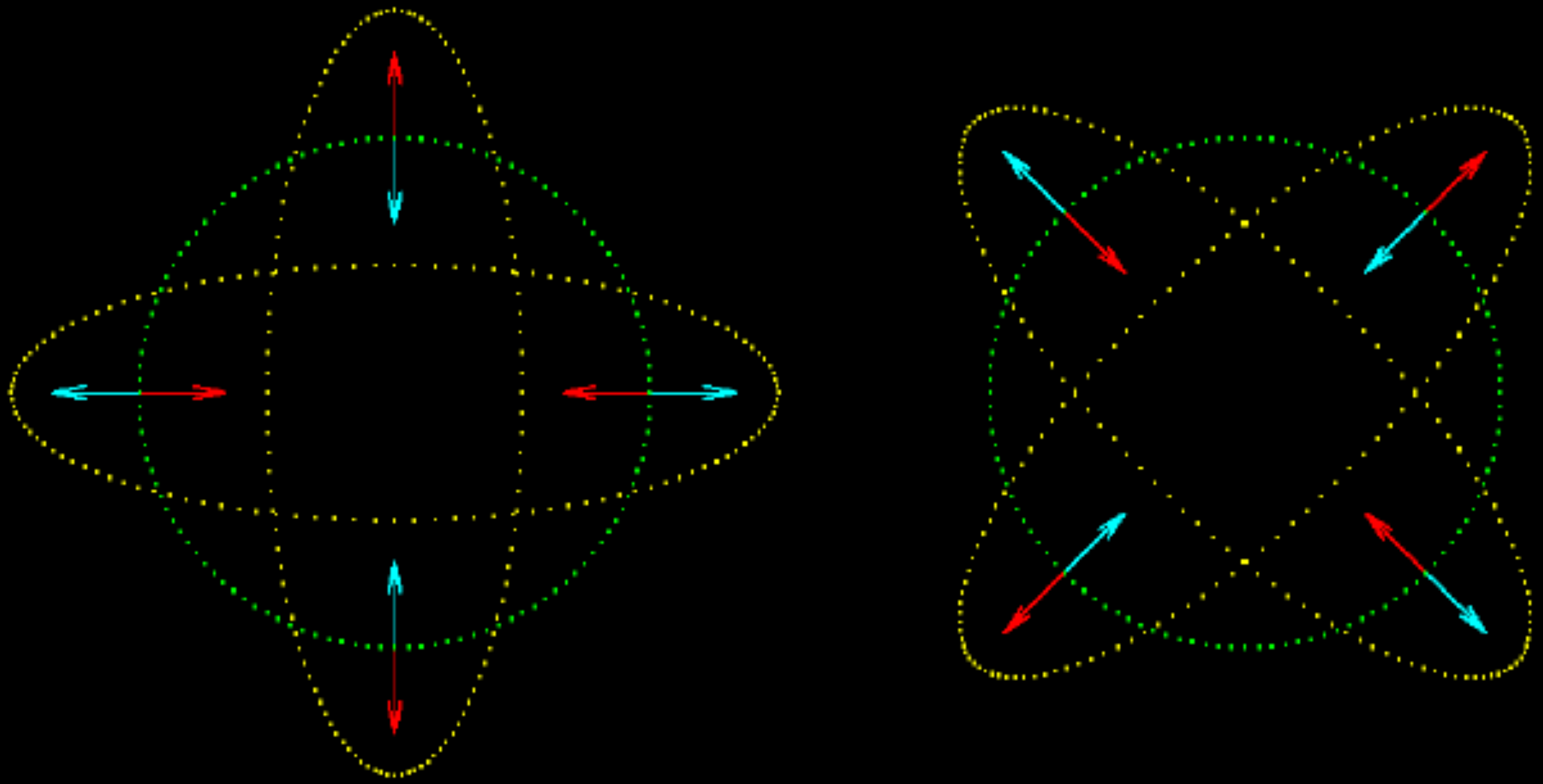
OUTLINE

1. Overview of GW/EM discoveries since 2015
    - binary black hole mergers
    - binary neutron star mergers
    - electromagnetic counterpart(s)

2. Magnetars: what we know and what we think we know
    - observed properties of magnetars in the Milky Way
    - possible formation scenarios and proposed association with gamma-ray bursts

3. Magnetars: GW emission and future work on EM counterparts

GRAVITATIONAL WAVES



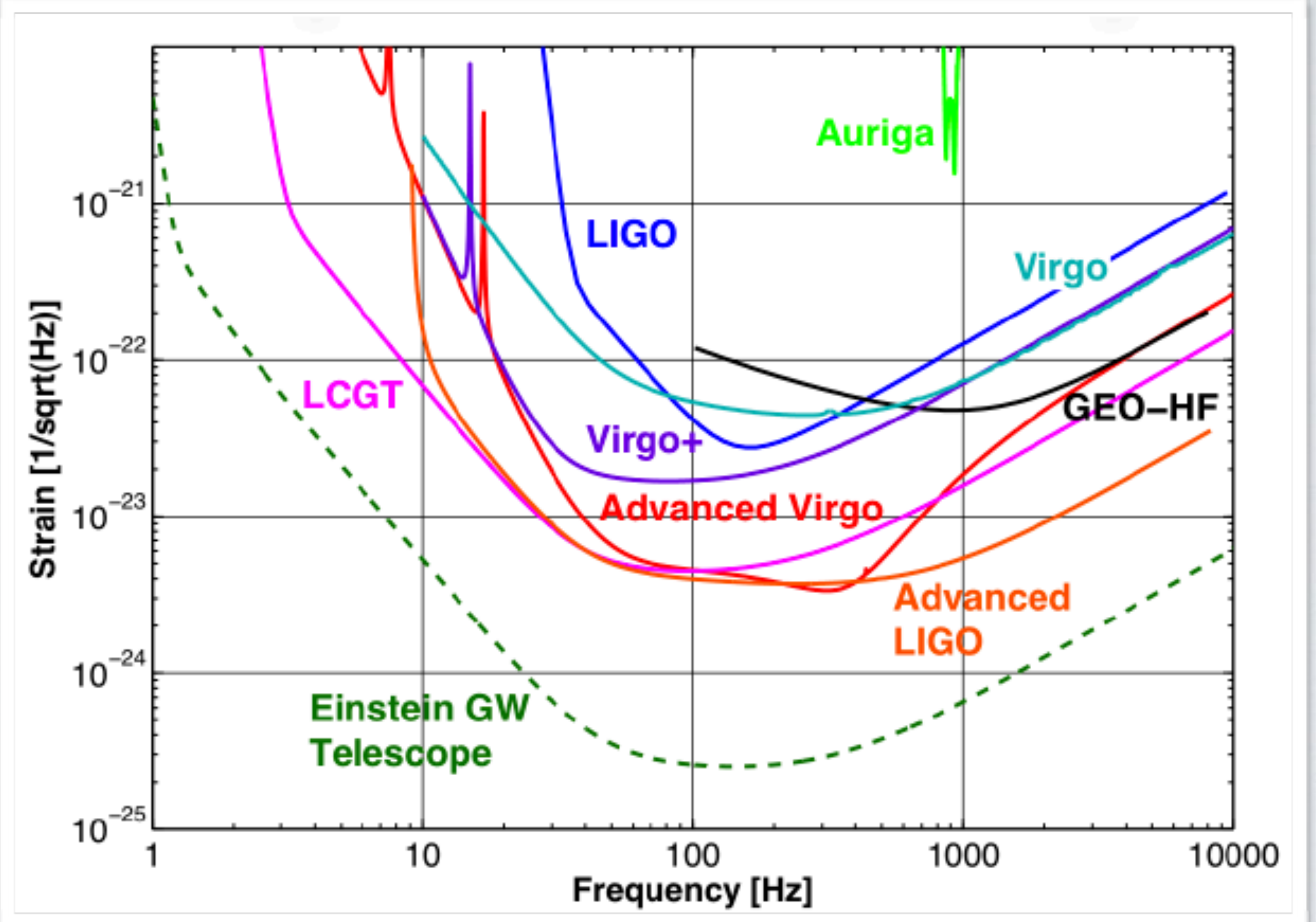
GRAVITATIONAL WAVE DETECTORS

THE ADVANCED INTERFEROMETERS

LIGO @LIVINGSTON

VIRGO @CASCINA

SENSITIVITY CURVES

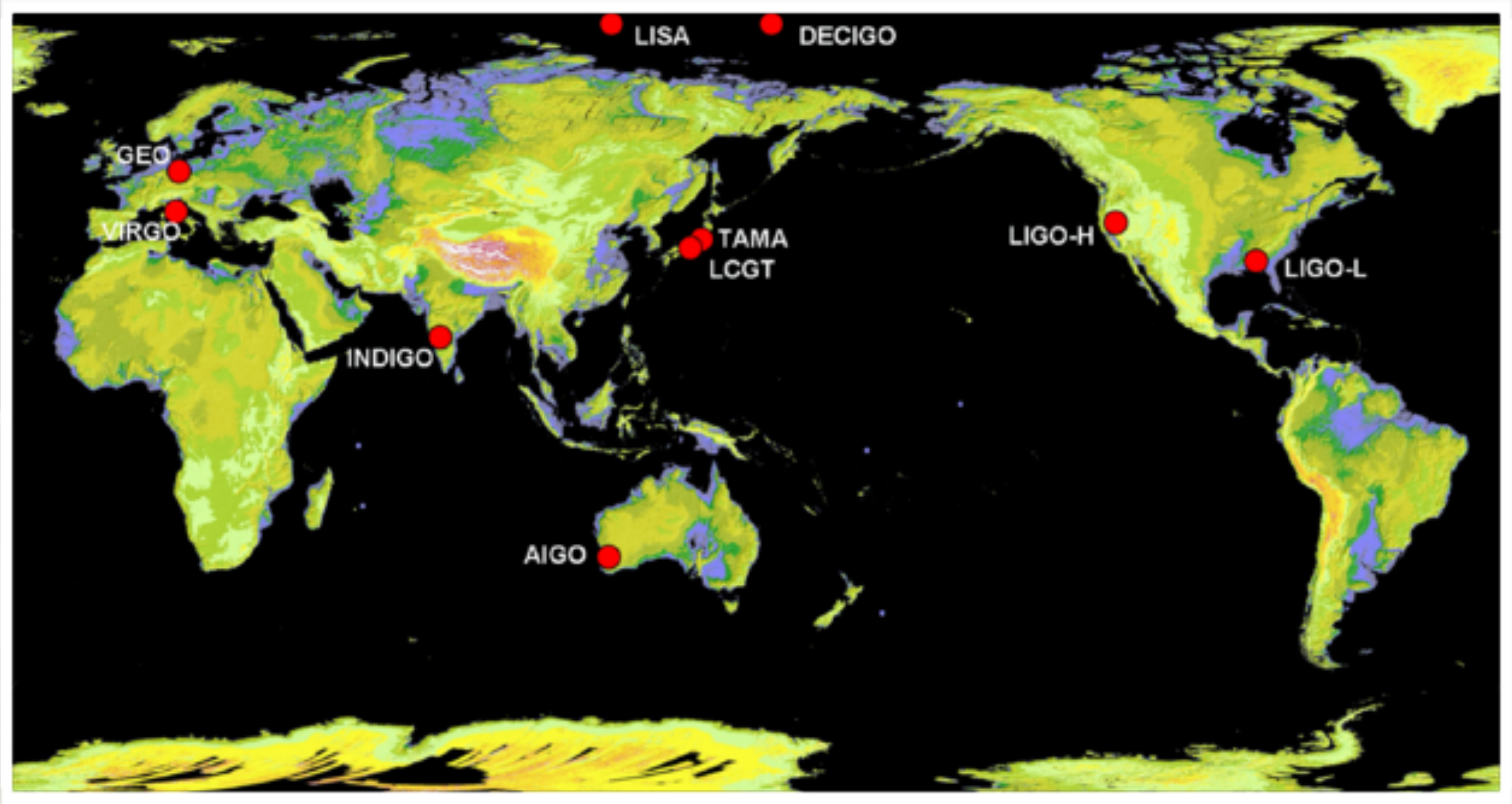


FUTURE GW DETECTORS

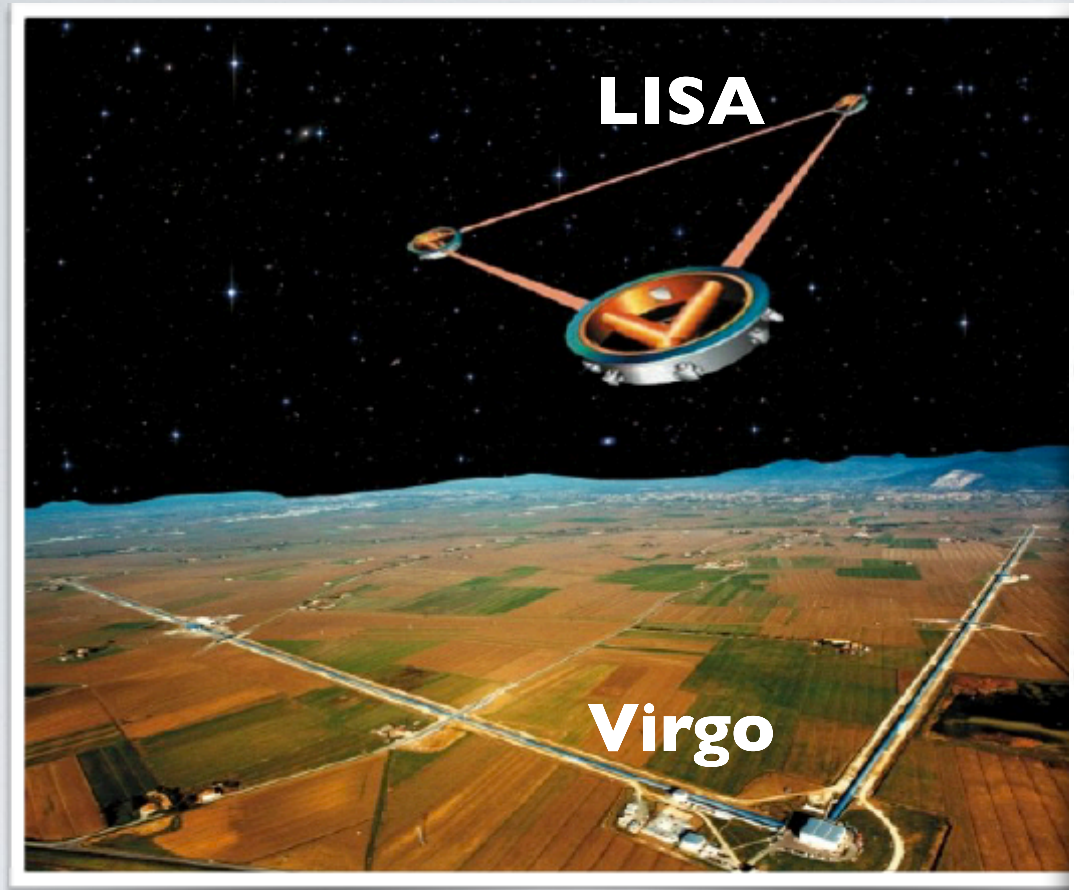
THE ADVANCED INTERFEROMETERS

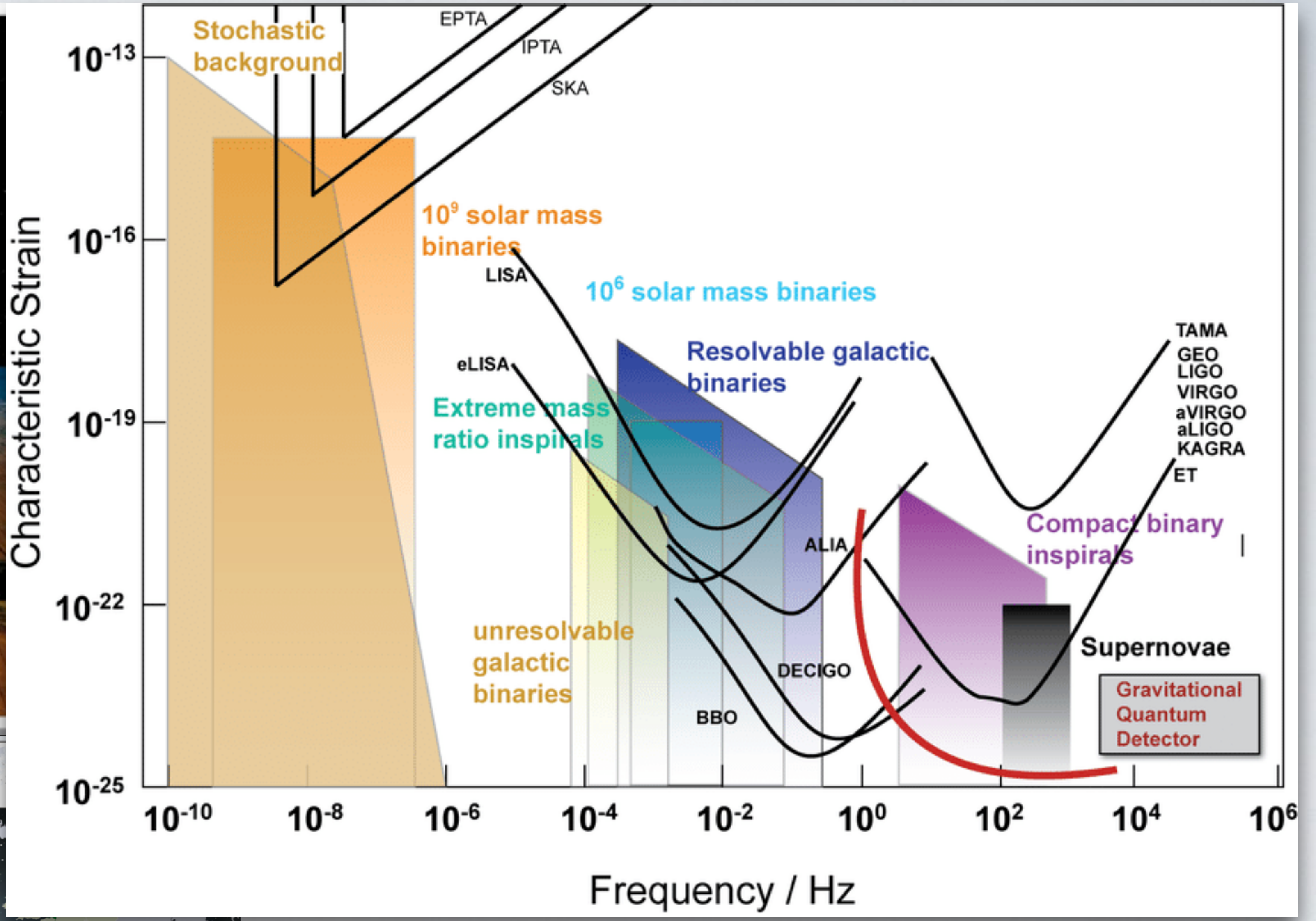
LIGO @LIVINGSTON

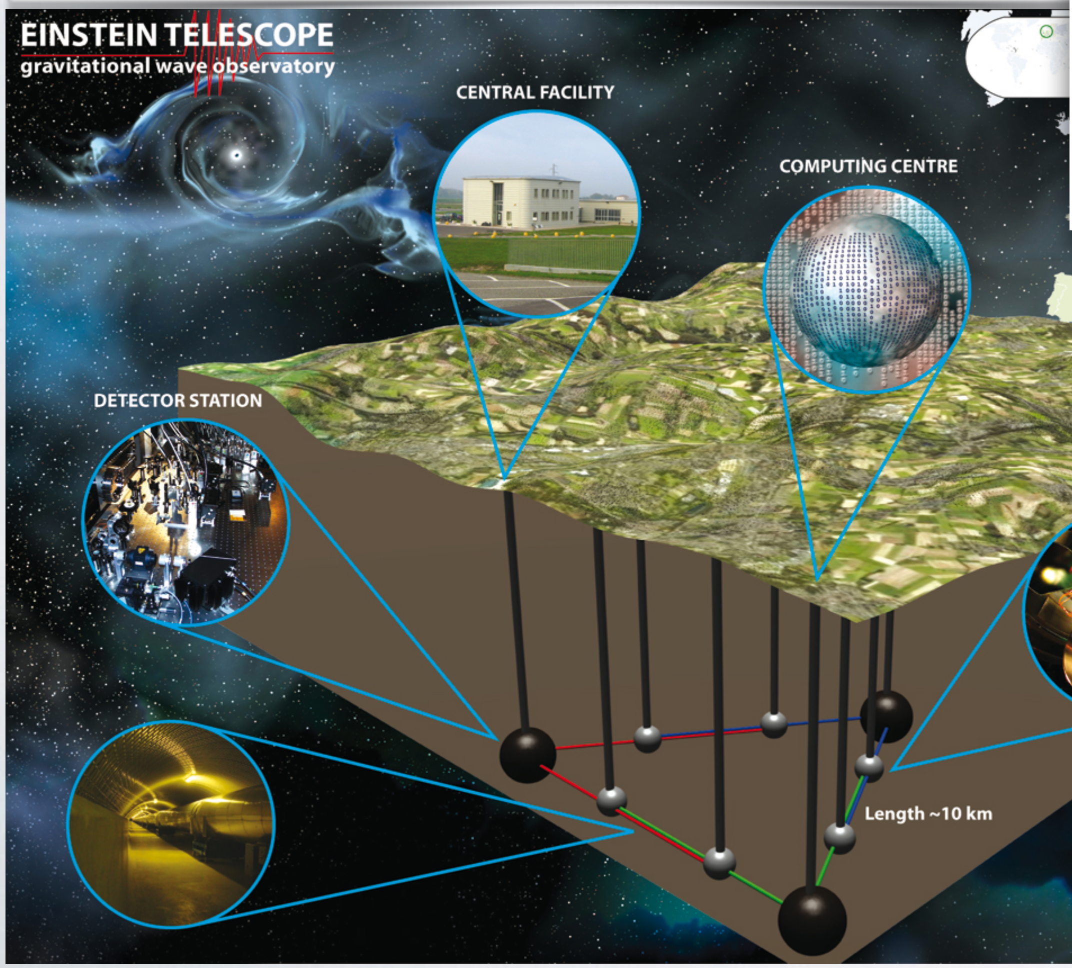
VIRGO @CASCINA



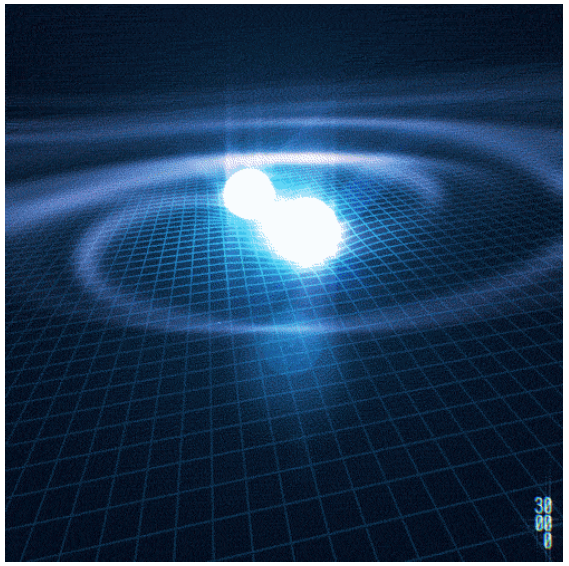
FUTURE GW DETECTORS







GW SOURCES



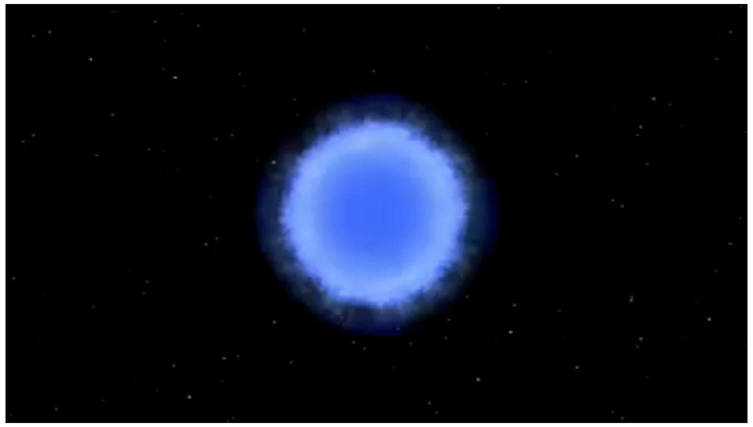
A. Coalescing Binary NS/BH systems

$$E_{kin} \sim \frac{1}{2} U_{grav} = \frac{1}{2} \frac{G M_1 M_2}{R_1 + R_2}$$

NS-NS: $\frac{1}{2} \frac{G M^2}{R} \sim 0.015\, M^2$

BH-BH: $\frac{1}{2} \frac{G M_1 M_2}{2 G (M_1 + M_2)} \sim \frac{M_1}{8} \frac{q}{1+q}$

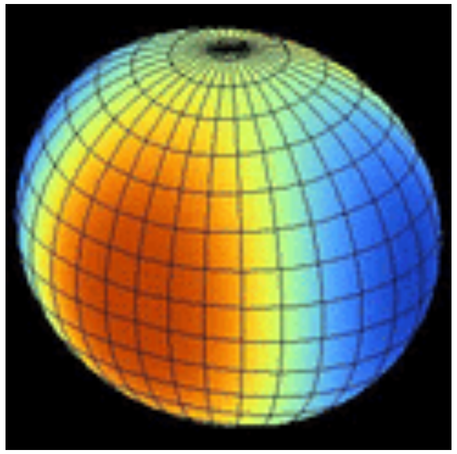
$$h \sim 10^{-20-23} \quad for \quad D \sim 1-200\, Mpc \quad - \quad \nu \quad 0.1-2\, kHz$$



B. Core-Collapse Supernovae

$$E_{kin} \sim 10^{-4} - 10^{-8} M_{sun} c^2$$

$$h \sim 10^{-20 \div -26} \quad for \quad D \sim 10\, Kpc \quad - \quad \nu \quad 0.2-1\, kHz$$



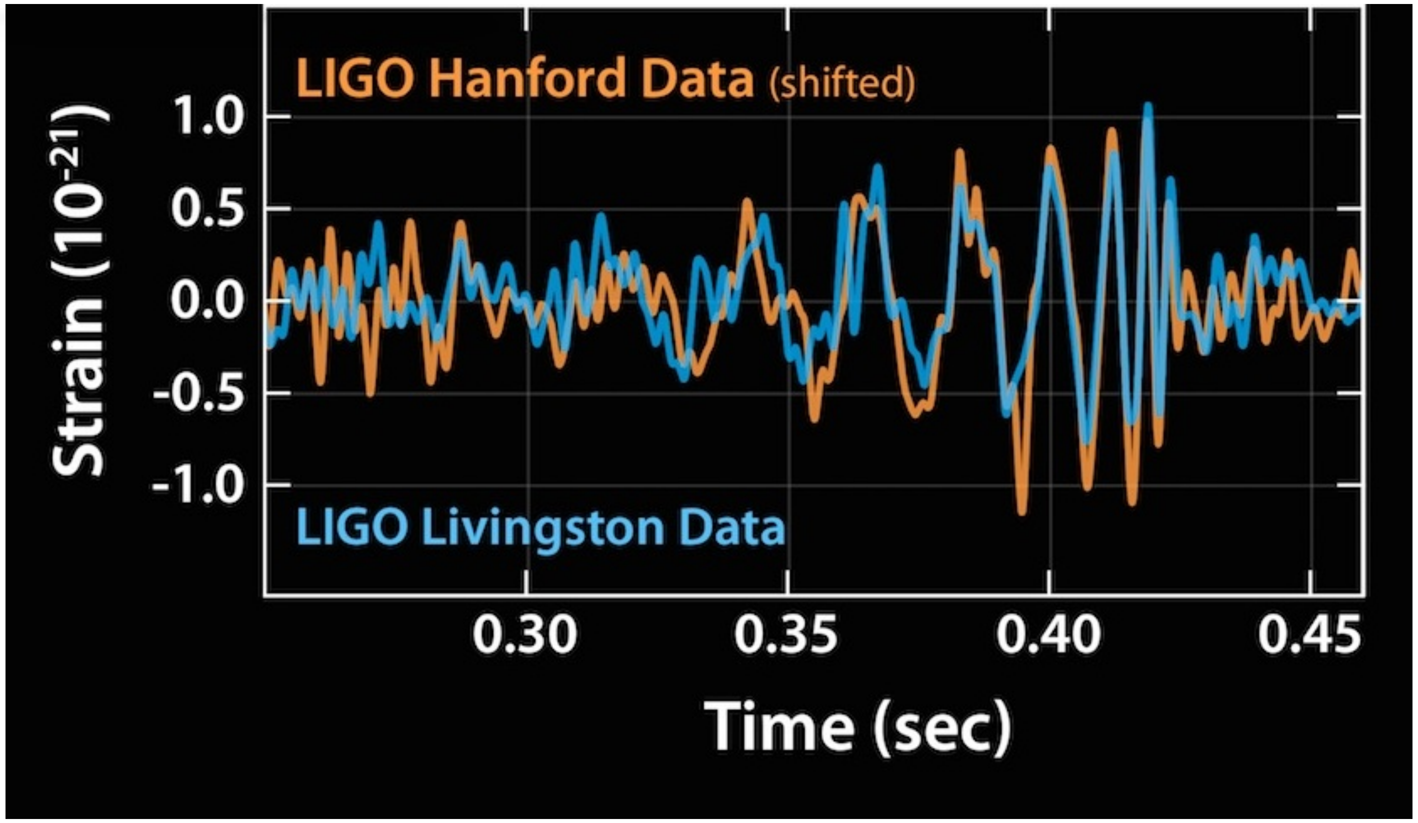
C. Fast spinning NS with “mountains”

$$E_{kin} < 10^{-10} M_{sun} c^2$$

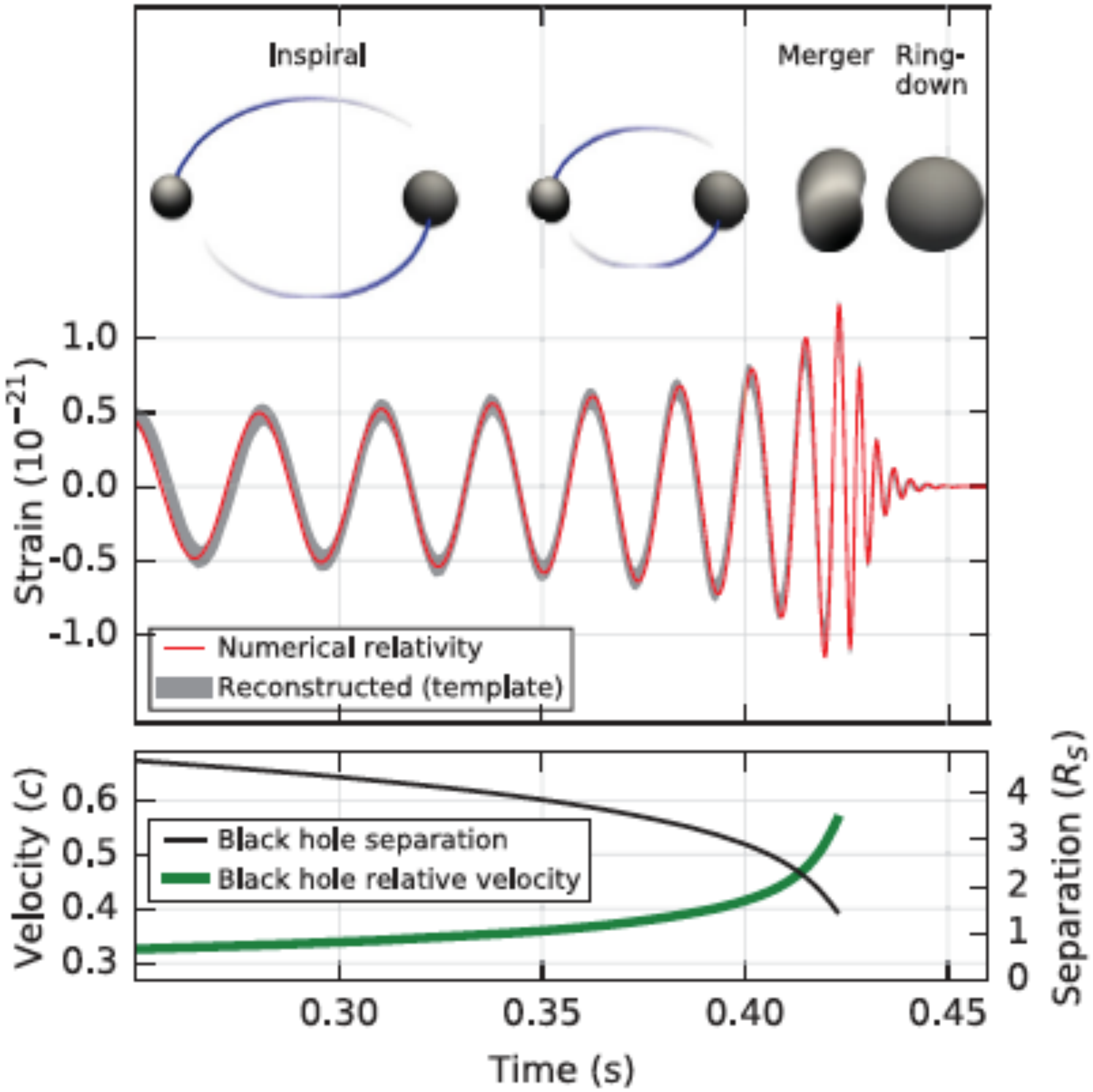
$$h \; < \; 10^{-26} \quad for \quad D \sim 10\, Kpc \quad - \quad \nu \quad 10-600\, kHz$$

GRAVITATIONAL WAVE DISCOVERIES

Abbott et al. 2016

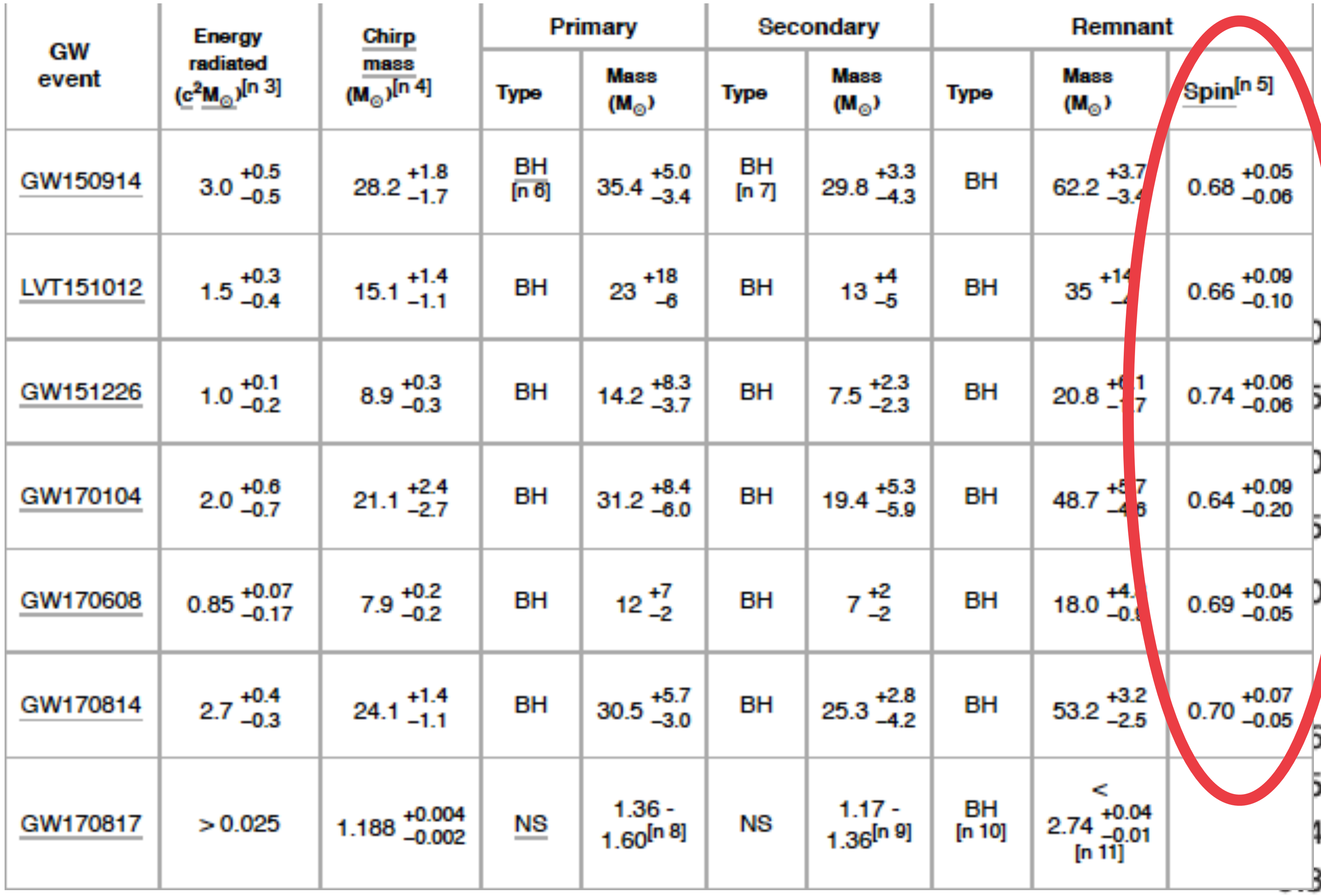


GW 150914

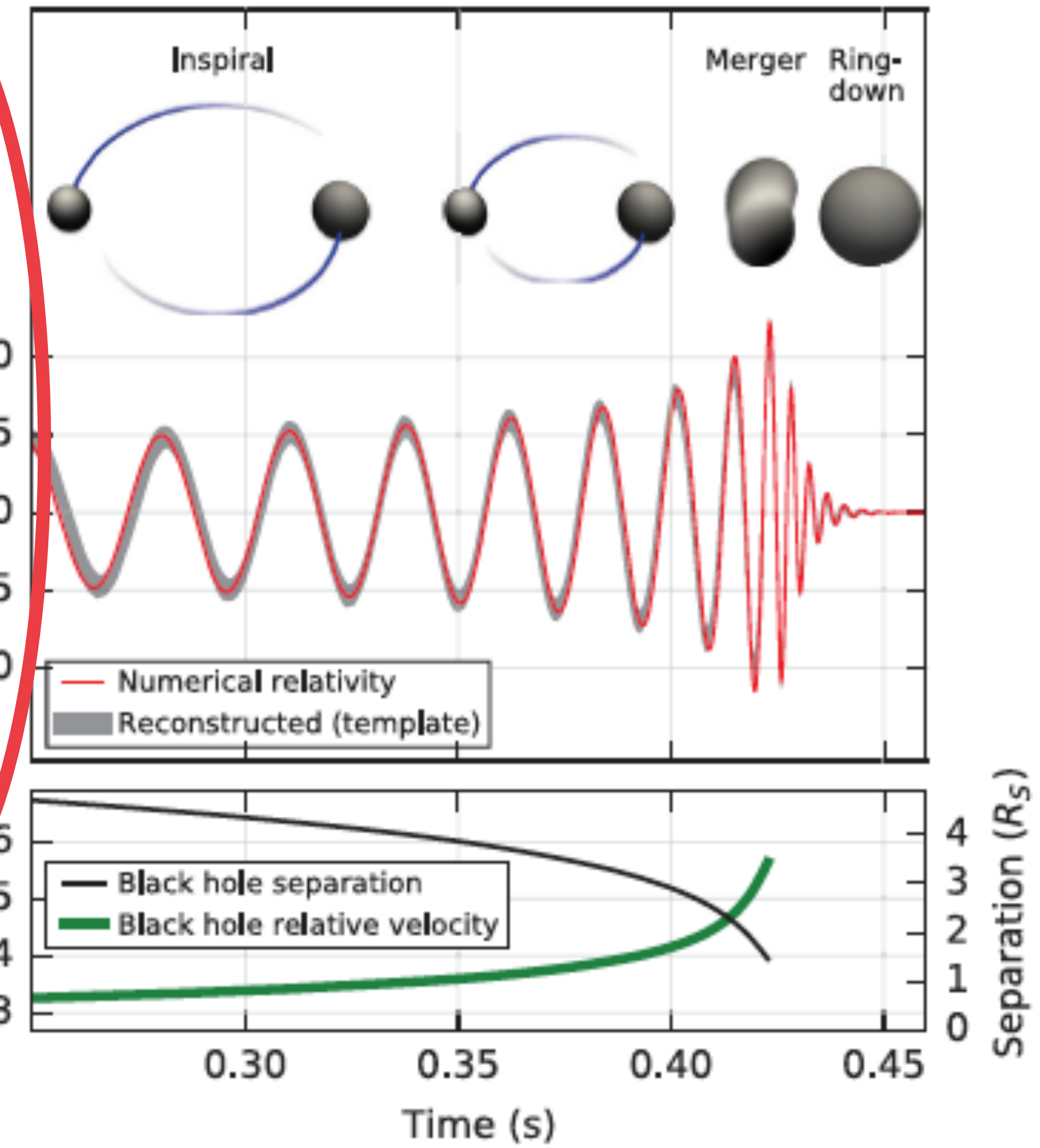


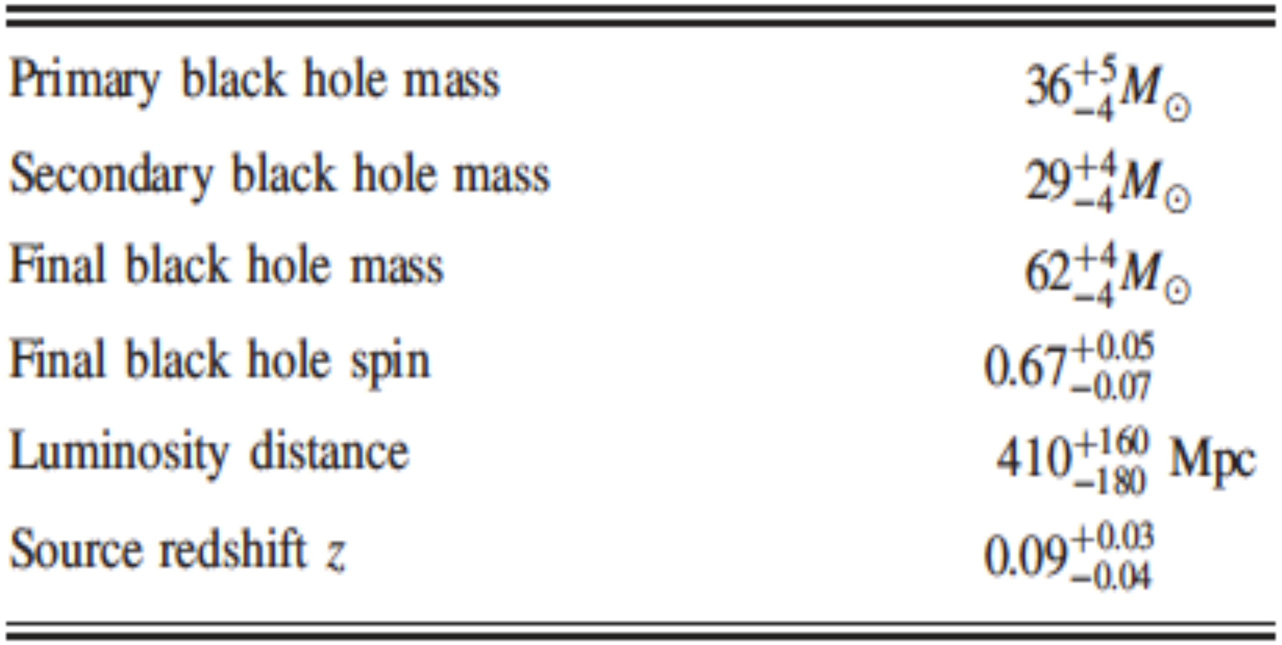
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

GRAVITATIONAL WAVE DISCOVERIES



GW event	Energy radiated ($c^2M_\odot$)[n 3]	Chirp mass ($M_\odot$)[n 4]	Primary		Secondary		Remnant		
			Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Spin[n 5]
GW150914	$3.0^{+0.5}_{-0.5}$	$28.2^{+1.8}_{-1.7}$	BH [n 6]	$35.4^{+5.0}_{-3.4}$	BH [n 7]	$29.8^{+3.3}_{-4.3}$	BH	$62.2^{+3.7}_{-3.4}$	$0.68^{+0.05}_{-0.06}$
LVT151012	$1.5^{+0.3}_{-0.4}$	$15.1^{+1.4}_{-1.1}$	BH	23^{+18}_{-6}	BH	13^{+4}_{-5}	BH	35^{+14}_{-4}	$0.66^{+0.09}_{-0.10}$
GW151226	$1.0^{+0.1}_{-0.2}$	$8.9^{+0.3}_{-0.3}$	BH	$14.2^{+8.3}_{-3.7}$	BH	$7.5^{+2.3}_{-2.3}$	BH	$20.8^{+6.1}_{-1.7}$	$0.74^{+0.06}_{-0.06}$
GW170104	$2.0^{+0.6}_{-0.7}$	$21.1^{+2.4}_{-2.7}$	BH	$31.2^{+8.4}_{-6.0}$	BH	$19.4^{+5.3}_{-5.9}$	BH	$48.7^{+5.7}_{-4.6}$	$0.64^{+0.09}_{-0.20}$
GW170608	$0.85^{+0.07}_{-0.17}$	$7.9^{+0.2}_{-0.2}$	BH	12^{+7}_{-2}	BH	7^{+2}_{-2}	BH	18.0 [illegible]	$0.69^{+0.04}_{-0.05}$
GW170814	$2.7^{+0.4}_{-0.3}$	$24.1^{+1.4}_{-1.1}$	BH	$30.5^{+5.7}_{-3.0}$	BH	$25.3^{+2.8}_{-4.2}$	BH	$53.2^{+3.2}_{-2.5}$	$0.70^{+0.07}_{-0.05}$
GW170817	> 0.025	$1.188^{+0.004}_{-0.002}$	NS	1.36 - 1.60[n 8]	NS	1.17 - 1.36[n 9]	BH [n 10]	$< 2.74^{+0.04}_{-0.01}$ [n 11]	





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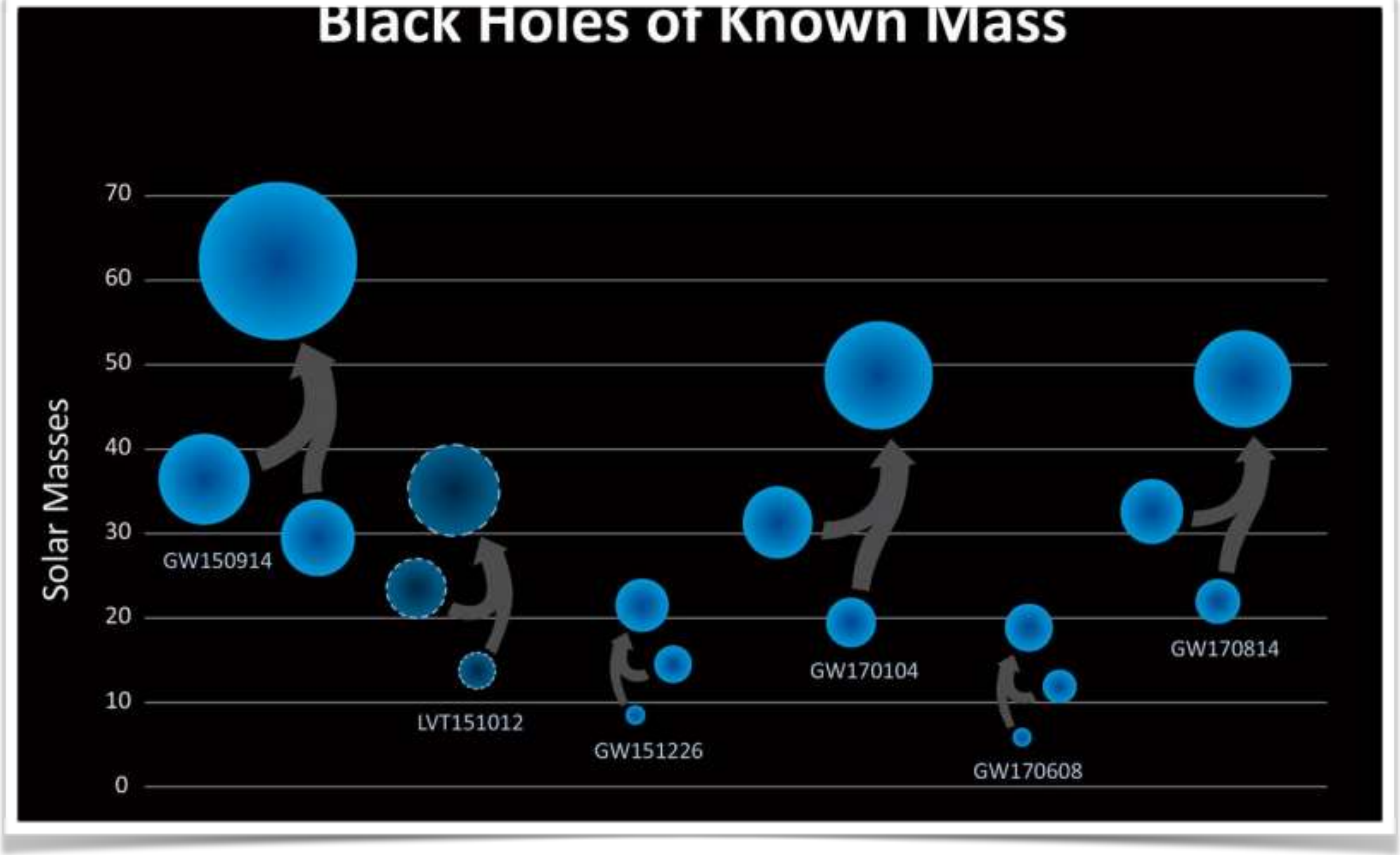
GRAVITATIONAL WAVE DISCOVERIES

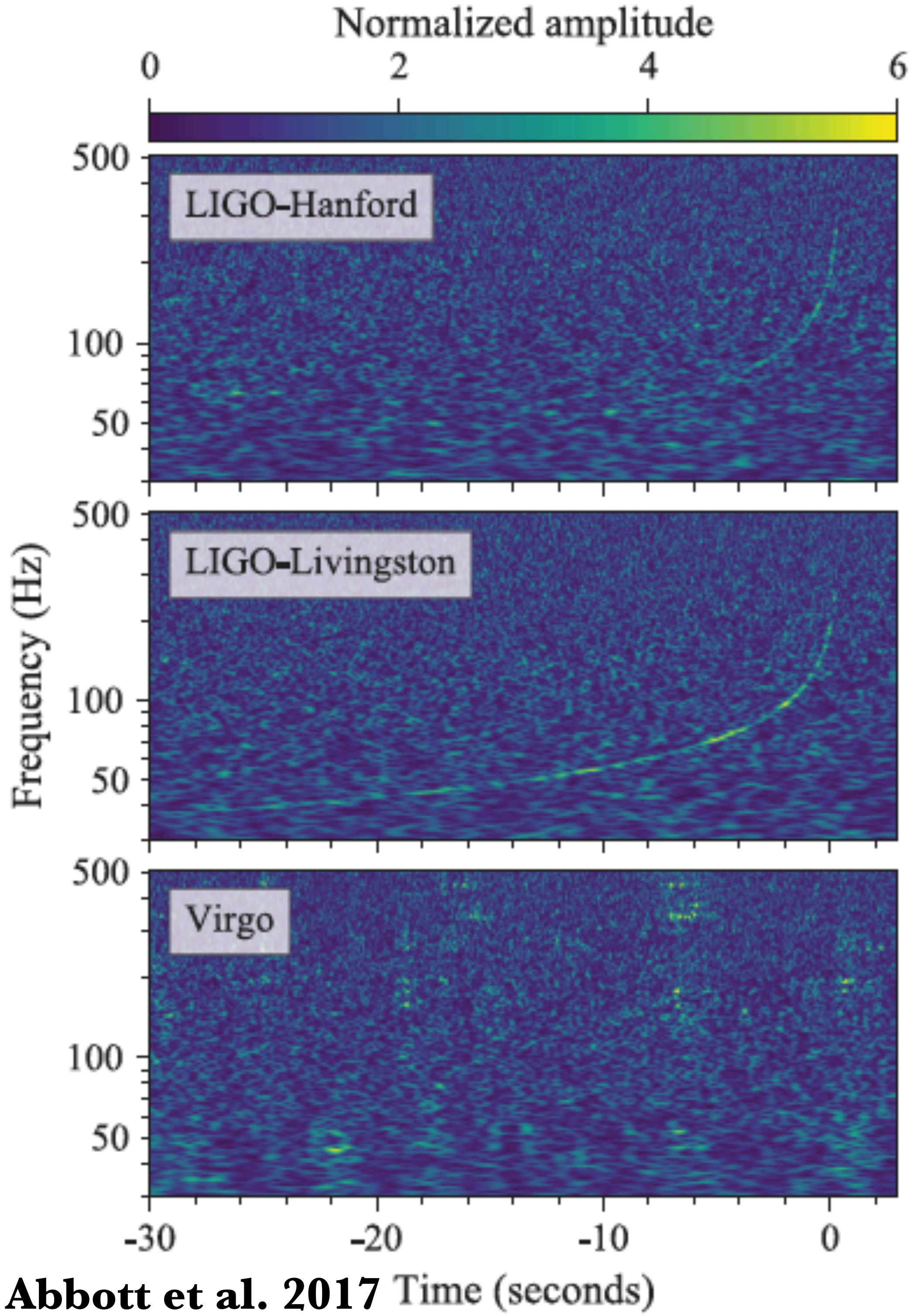
Credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)



Binary Black Holes

1. First direct detection of GWs
2. First direct detection of BHs
3. First direct detection of binary BHs
4. First direct measurement of BH spin

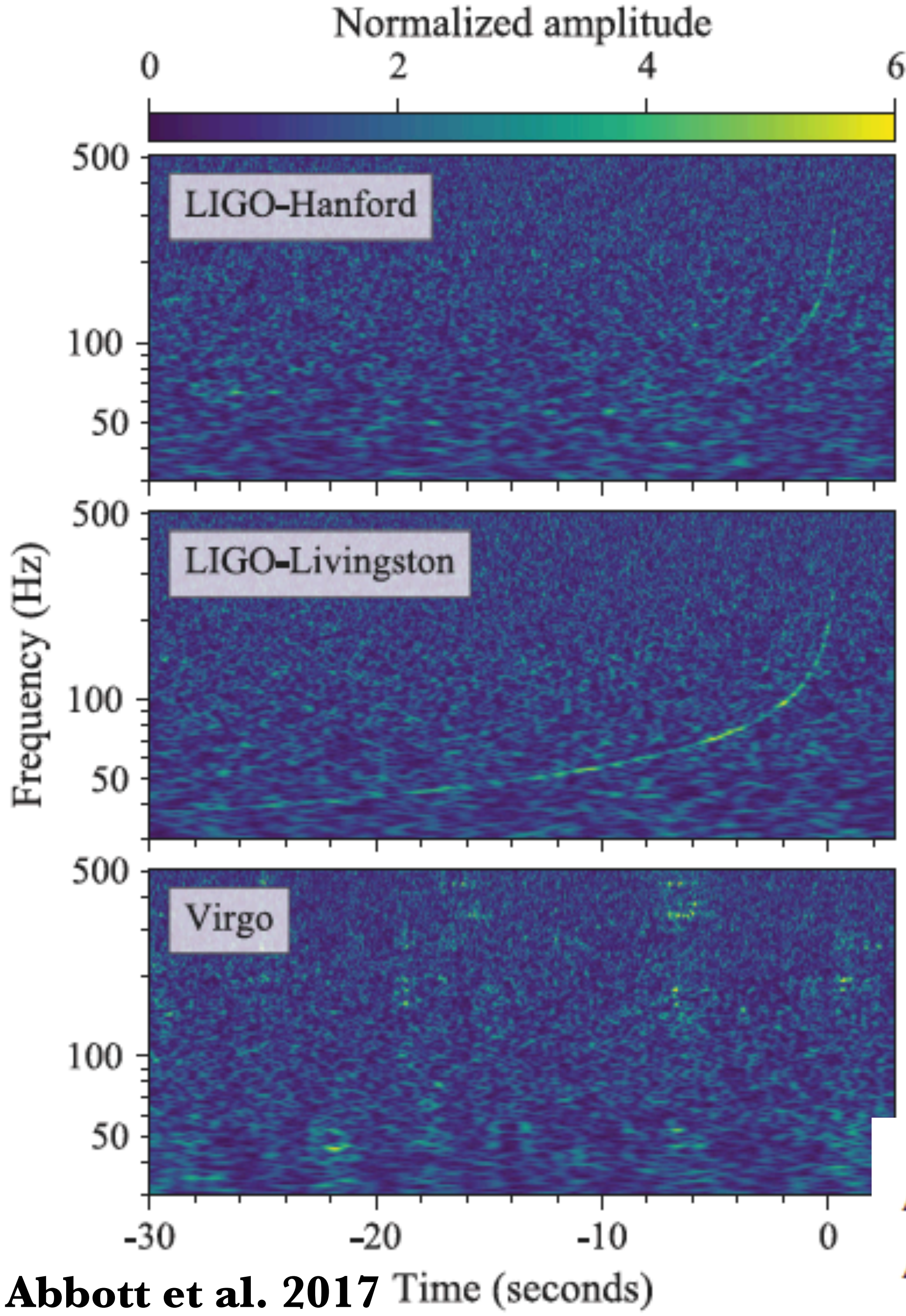
GRAVITATIONAL WAVE DISCOVERIES



Abbott et al. 2017

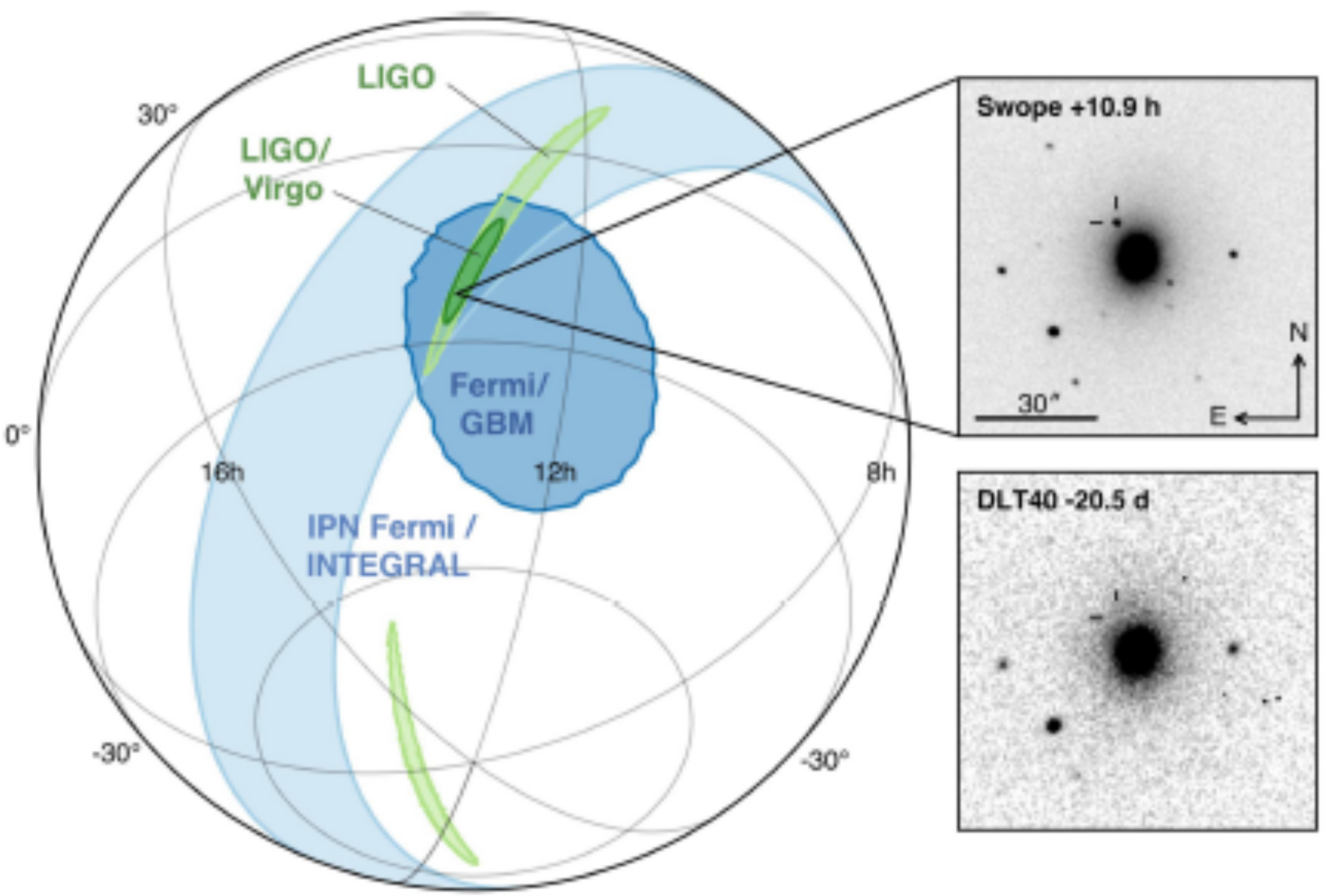
GW 170817

GRAVITATIONAL WAVE DISCOVERIES



Abbott et al. 2017

GW 170817

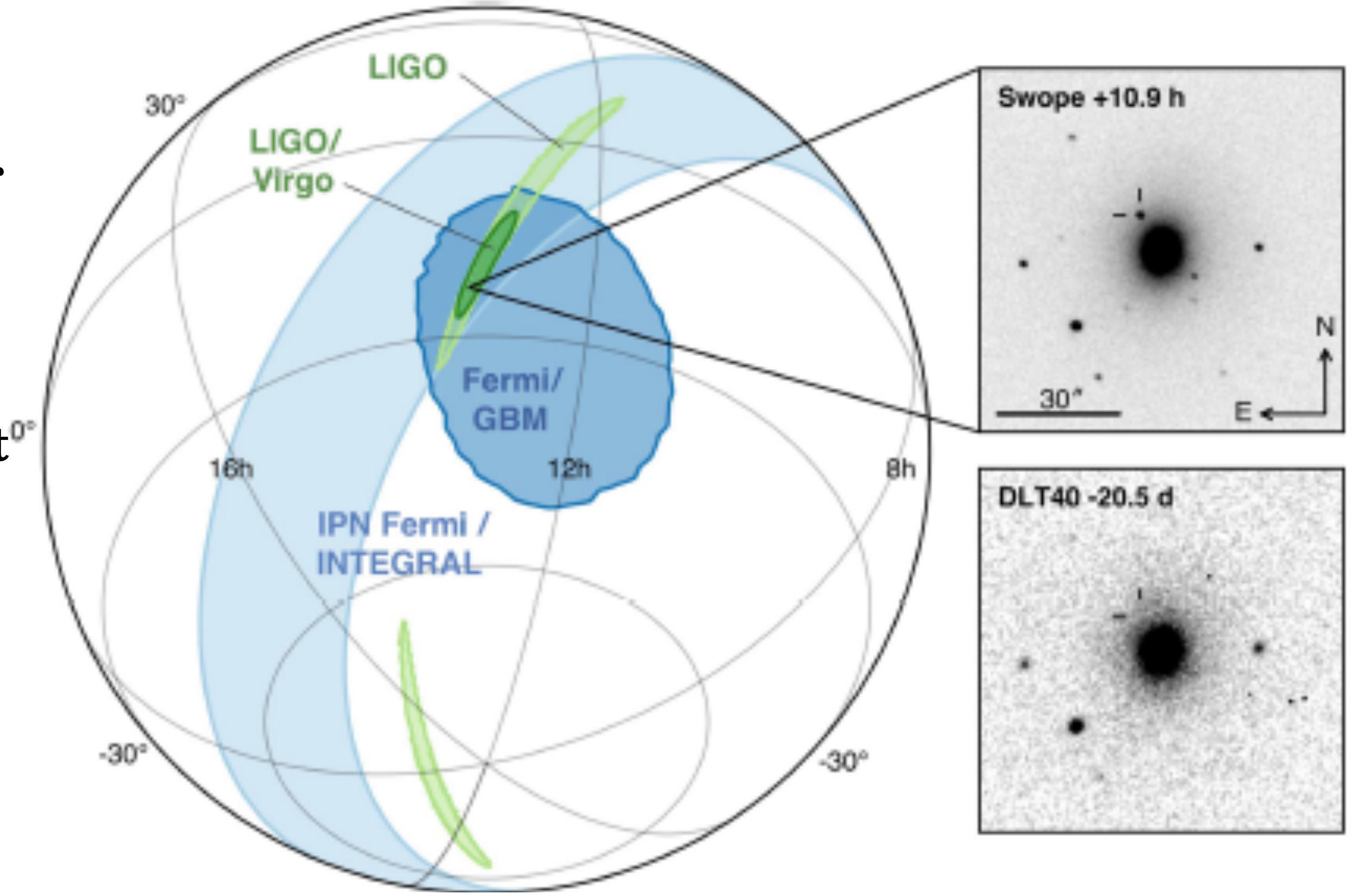


LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT

GRAVITATIONAL WAVE DISCOVERIES

1. **First joint detection of a GW source and its EM counterpart**
2. **First direct detection of a NS merger**
3. **First direct confirmation that NS mergers are progenitors of (at least a class of) short gamma-ray bursts**
4. **First observation of a kilonova associated to dynamically ejected material from the merger**
5. **Confirmation of binary NS mergers as the production sites for the *r*-process elements.**

GW 170817



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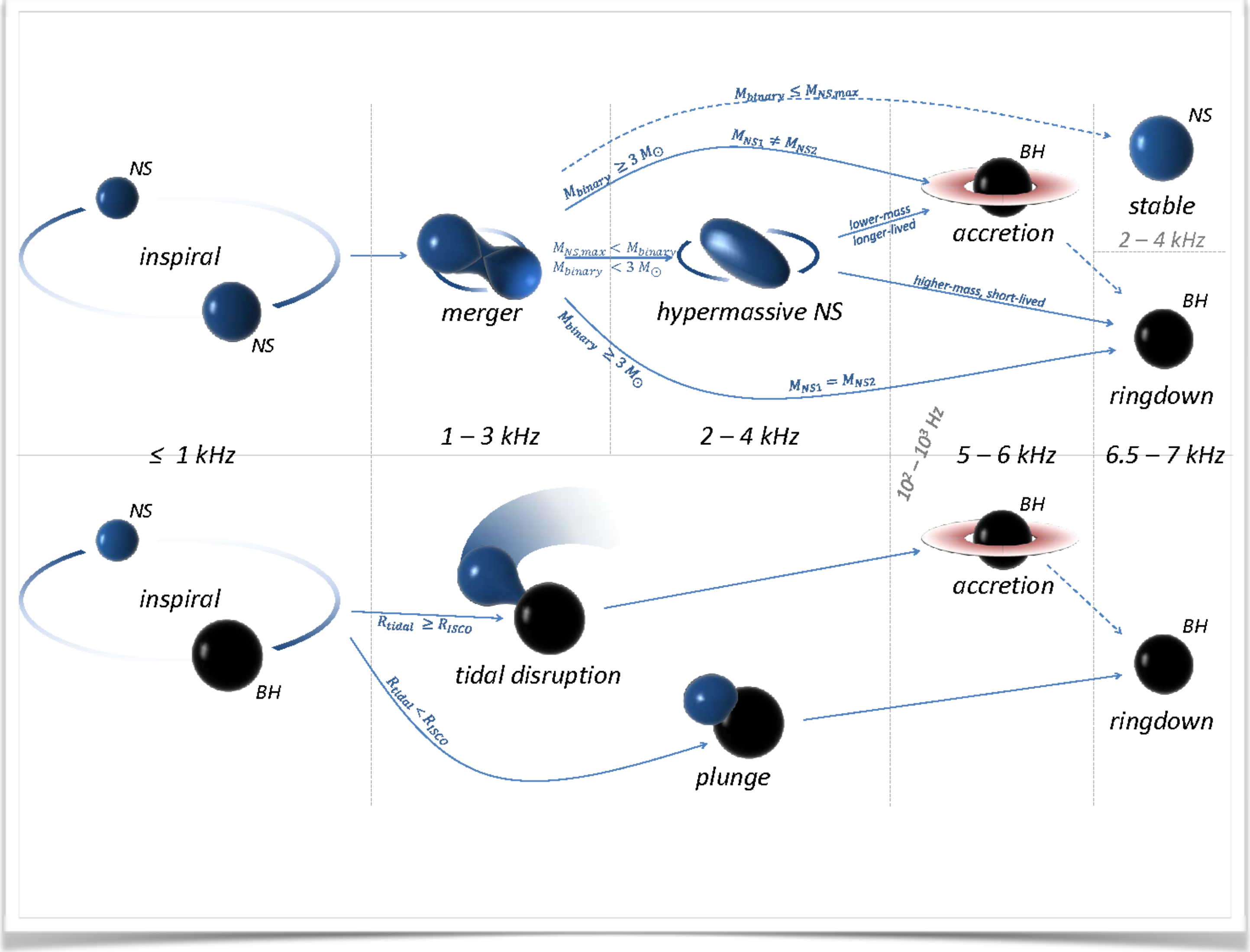
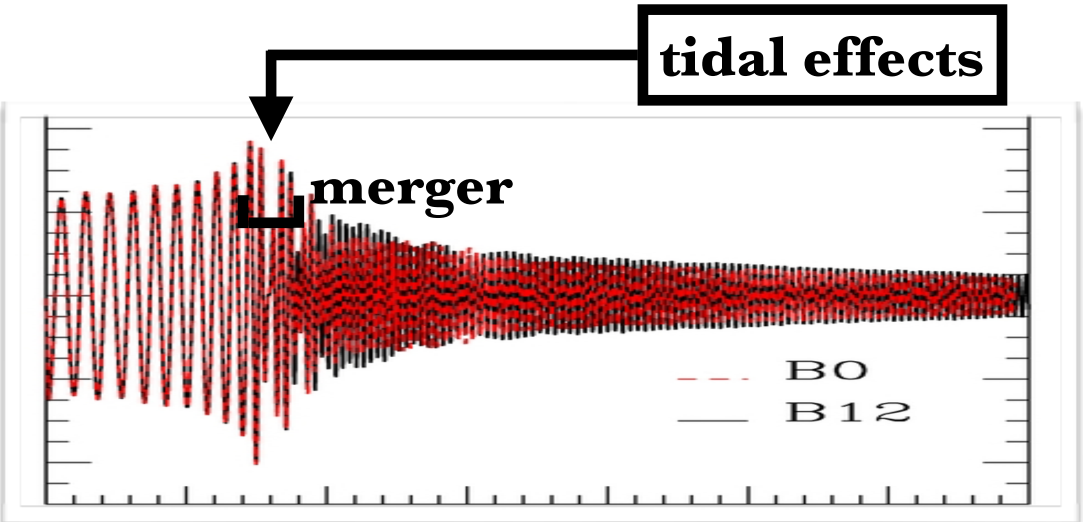
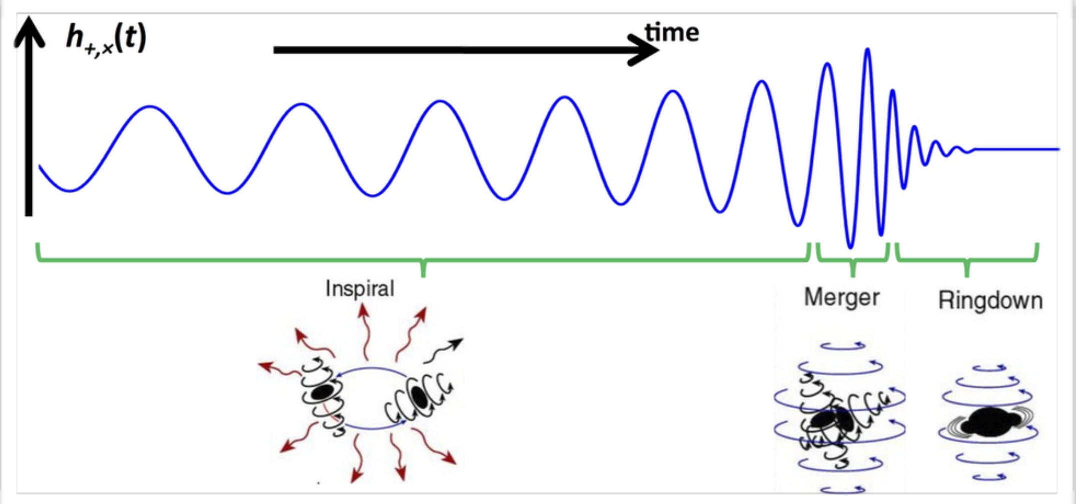




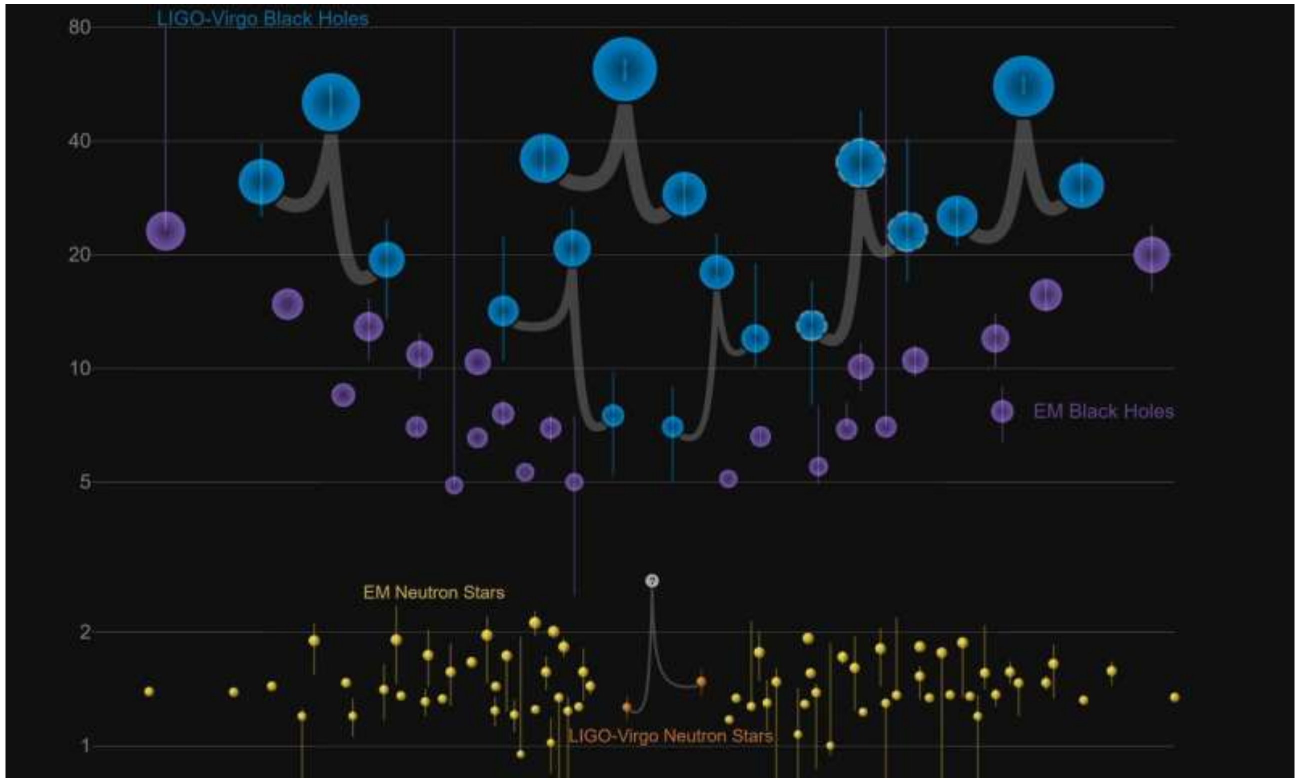


Bartos et al. 2013

Three possible outcomes:

1. stable NS, if $M < M_{max}$ requires $M_{max} > 2.35\,M_\odot$ (e.g., **Dall'Osso** et al. 2015, Piro et al. 2017)
2. hypermassive (centrifugally supported) NS: collapse after some spindown
3. collapse to a BH: ring down gives mass and spin of the BH

GRAVITATIONAL WAVE DISCOVERIES



Open problems:

1. Component masses in the pre-merger system suggest the gravitational mass of the remnant

$$M \lesssim 2.4\ \mathrm{M}_\odot$$

Collapse likely but there are EoS's that can support a stable NS with this mass.

2. The ejecta mass $M_{\mathrm{ej}} \gtrsim 0.05\ \mathrm{M}_\odot$ exceeds the maximum mass that was expected in *ALL* pre-discovery models/numerical simulations $M_{\mathrm{ej,exp}} \leq 0.01\ \mathrm{M}_\odot$

3. The lack of a clear EM signature of a highly energy NS in the early day after the merger suggests there was no energetic NS. However, models are still based on over-simplified assumptions: need to develop more realistic scenarios, also in perspective (more discoveries expected in the future).

4. If the gamma-ray counterpart of GW170817 was actually a short-GRB then it was a very ``unlikely” event (*a priori* a chance) $\lesssim$ a few percent at most.

MAGNETARS

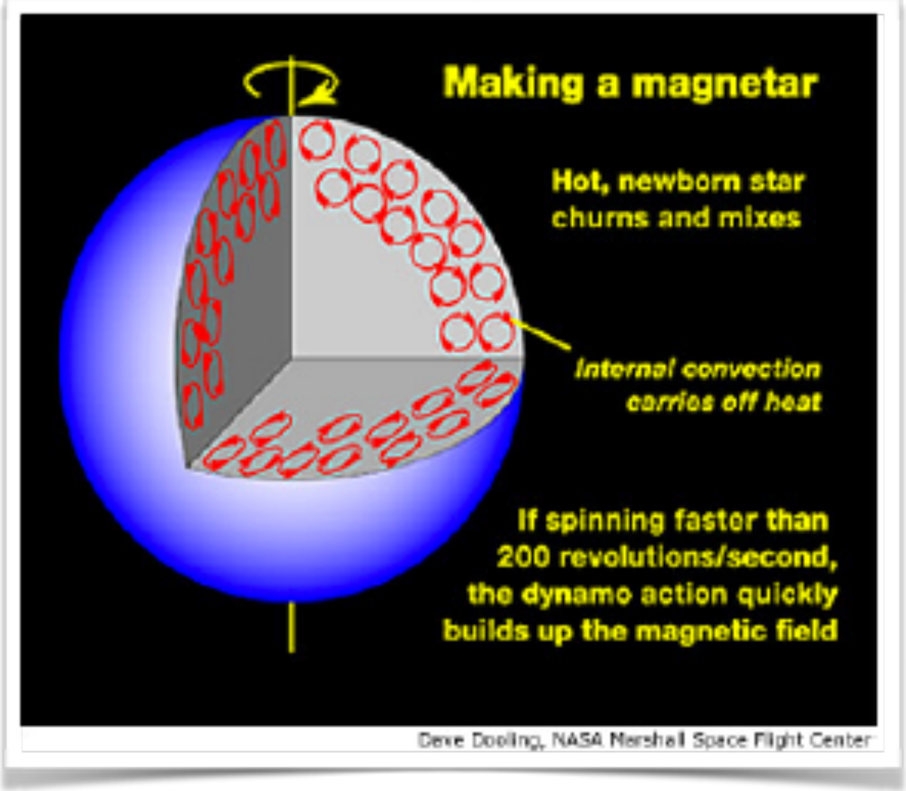
ULTRA-MAGNETIZED NEUTRON STARS

ms-spinning proto-NS

differential rotation ⟷ *toroidal* magnetic field B~10^{16}G

magnetic energy dissipation powers high-energy emission from here on

Thompson & Duncan 1993 ⟶ 2001



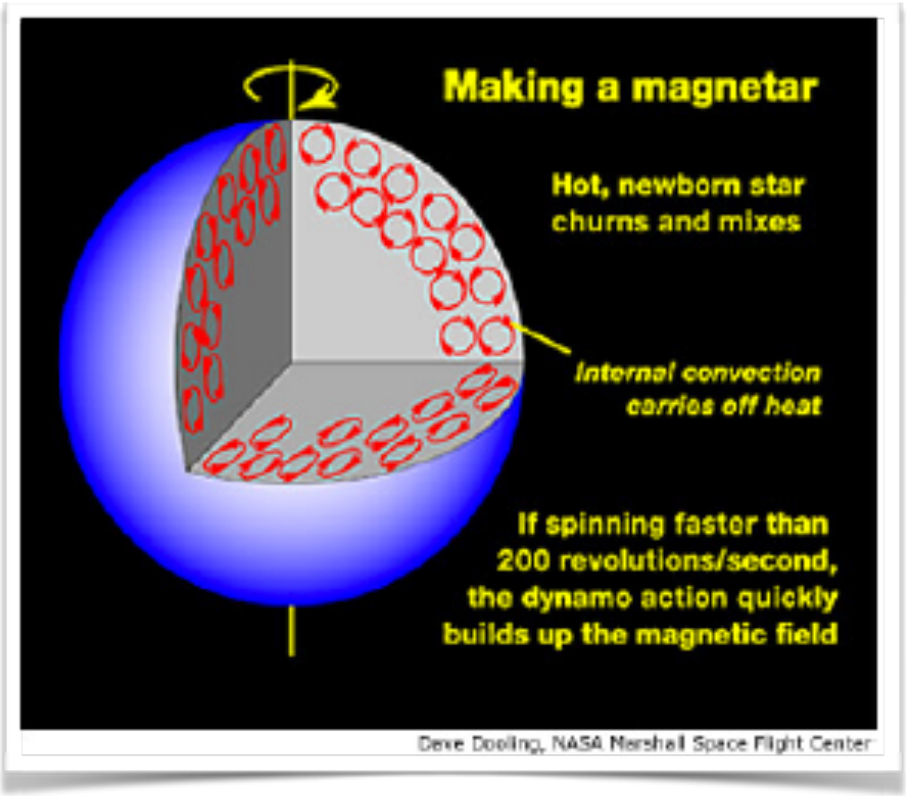
Dave Dooling, NASA Marshall Space Flight Center

The lack of isolated magnetars with spin period longer than ~ 12 s implies that the magnetic dipole must decay on timescale < 10^4 yrs.

The bright X-ray emission that is observed at ages > 10^4 yrs implies requires a stronger magnetic field in the interior

(e.g. **Dall'Osso**, Granot & Shaviv 2012; Vigano', Pons & Perna 2013; Beloborodov 2016)

ULTRA-MAGNETIZED NEUTRON STARS



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ms-spinning proto-NS

differential rotation ↔ *toroidal* magnetic field B~10^{16}G

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Thompson & Duncan 1993 ⟶ 2001

FORMATION SITE

core-collapse **(M > 30 $M_\odot$?)**

Long GRBs
Zhang & Meszaros (2001)
Dall'Osso et al. (2011)
Metzger et al. (2011)

Super-Luminous SNe
Kasen & Bildsten (2010)
Mazzali et al. (2014)
Metzger et al. (2016)

binary NS merger
Giacomazzo & Perna (2013)
Ciolfi et al. (2017) - cf. **Dall'Osso** & Rossi (2013)

Short GRBs
Rowlinson et al. (2013)
Rezzolla & Kumar (2015)

Possible Electromagnetic Counterparts

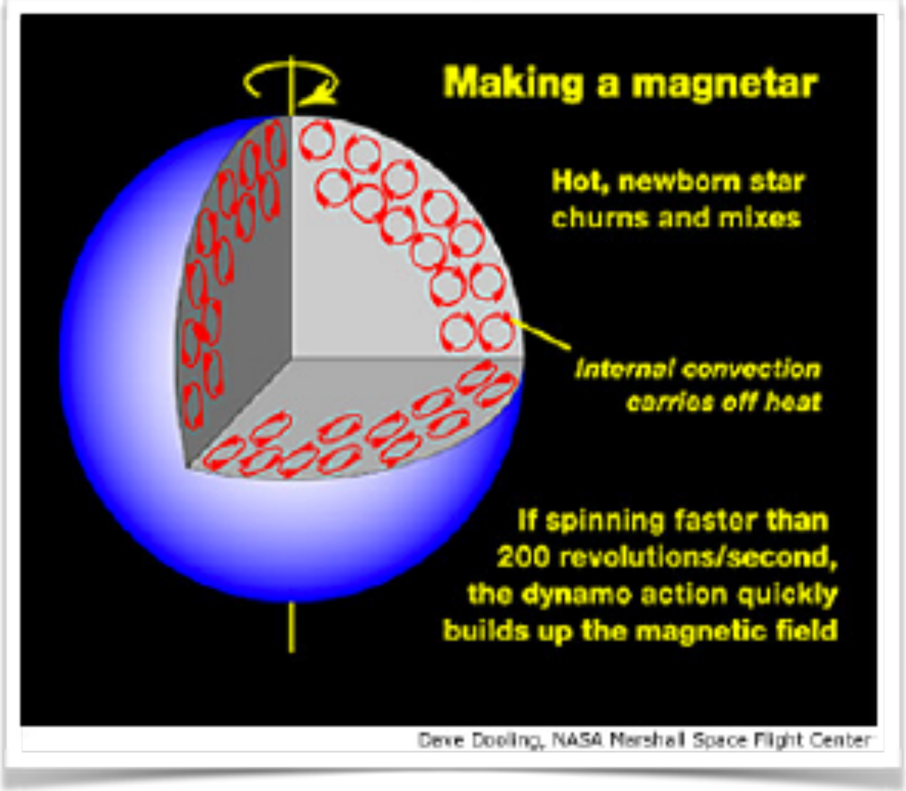
ULTRA-MAGNETIZED NEUTRON STARS

ms-spinning proto-NS

differential rotation ↔ *toroidal* magnetic field B~10^{16}G

magnetic energy dissipation powers high-energy emission from here on

Thompson & Duncan 1993 ⟶ 2001



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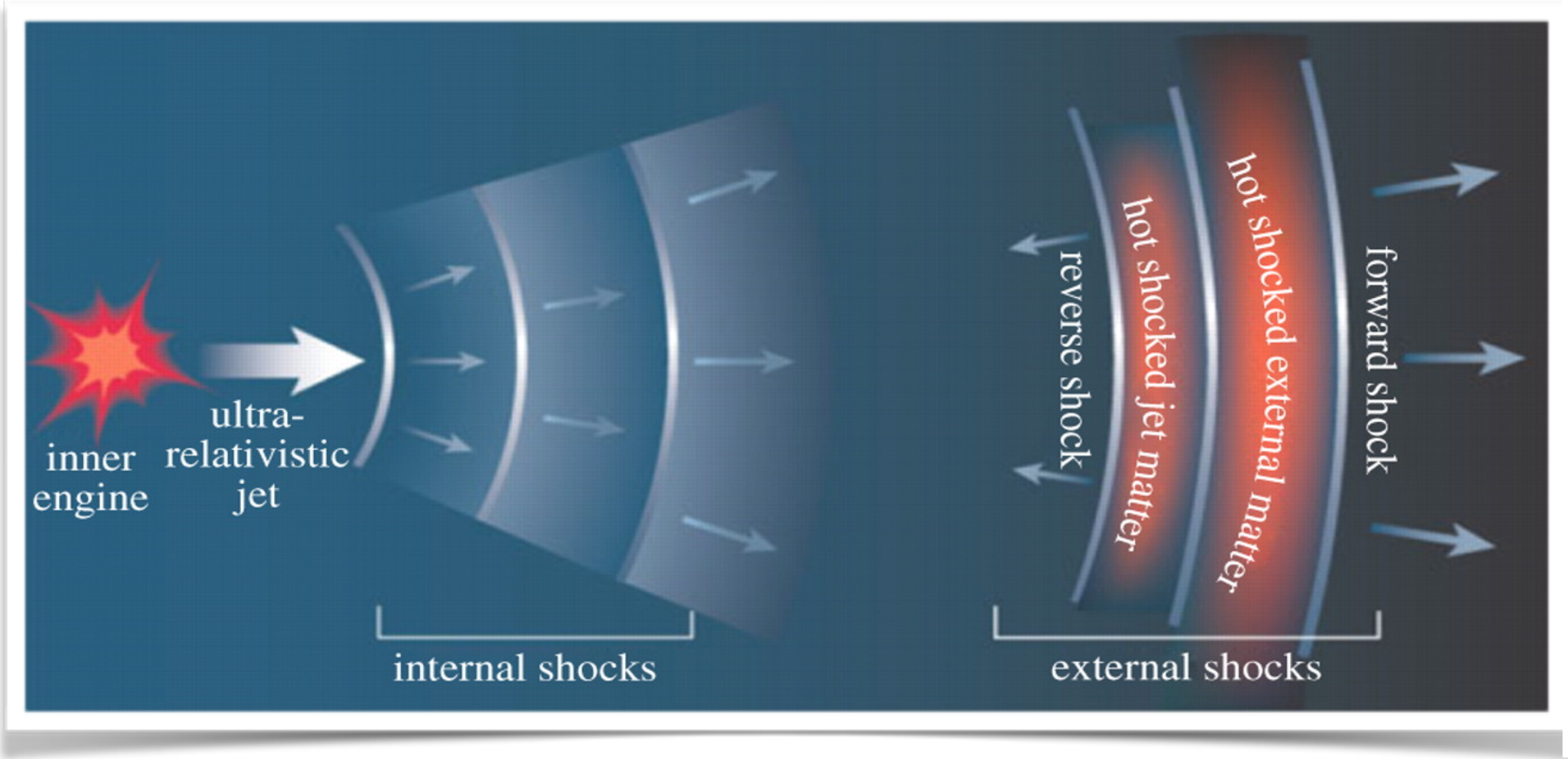
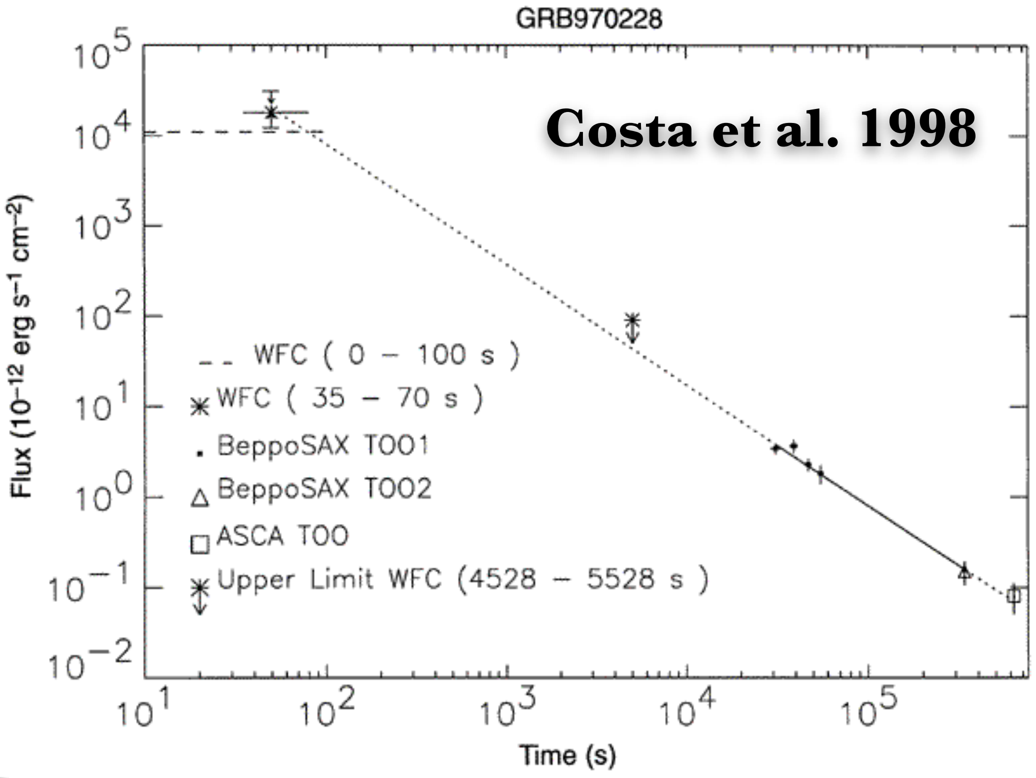
PARADIGM

↓

A ms-spinning, highly magnetized NS radiates its huge spin energy to magnetic dipole radiation - or similar - in (much) less than 1 day.





Costa et al. 1998

ULTRA-MAGNETIZED NEUTRON STARS

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differential rotation ↔ *toroidal* magnetic field B~10^{16}G

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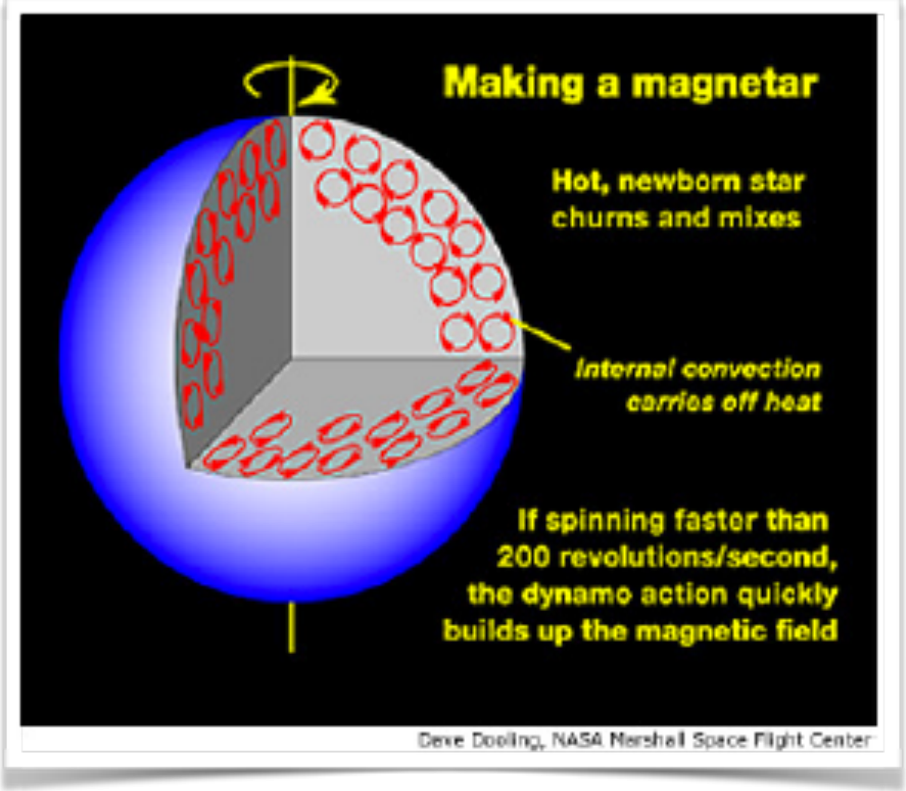
Thompson & Duncan 1993 ⟶ 2001



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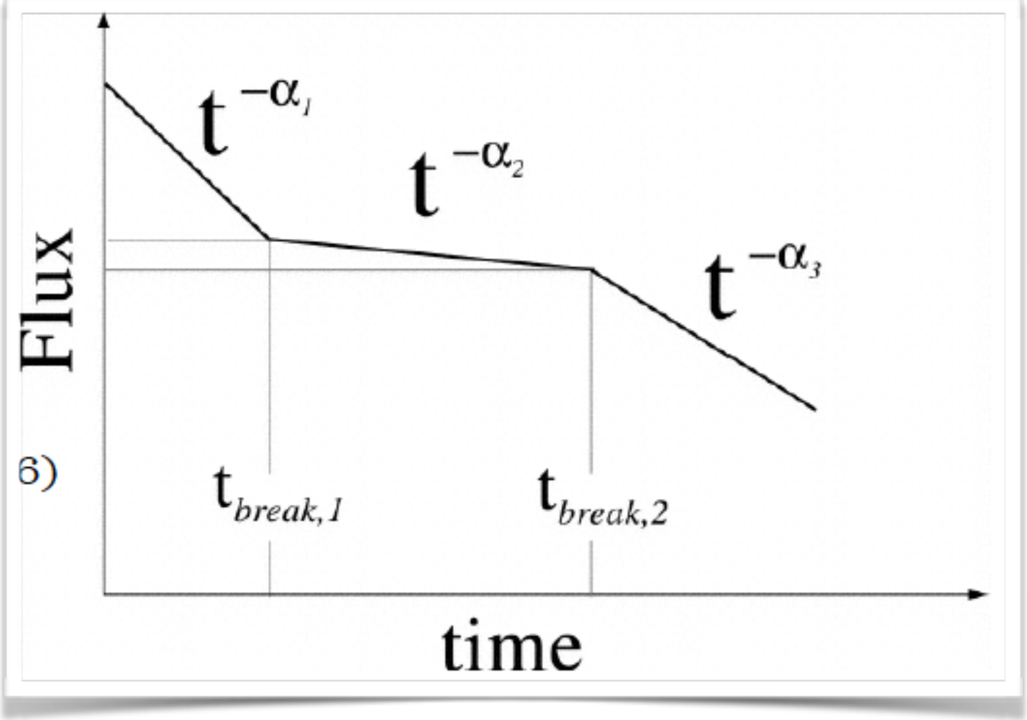
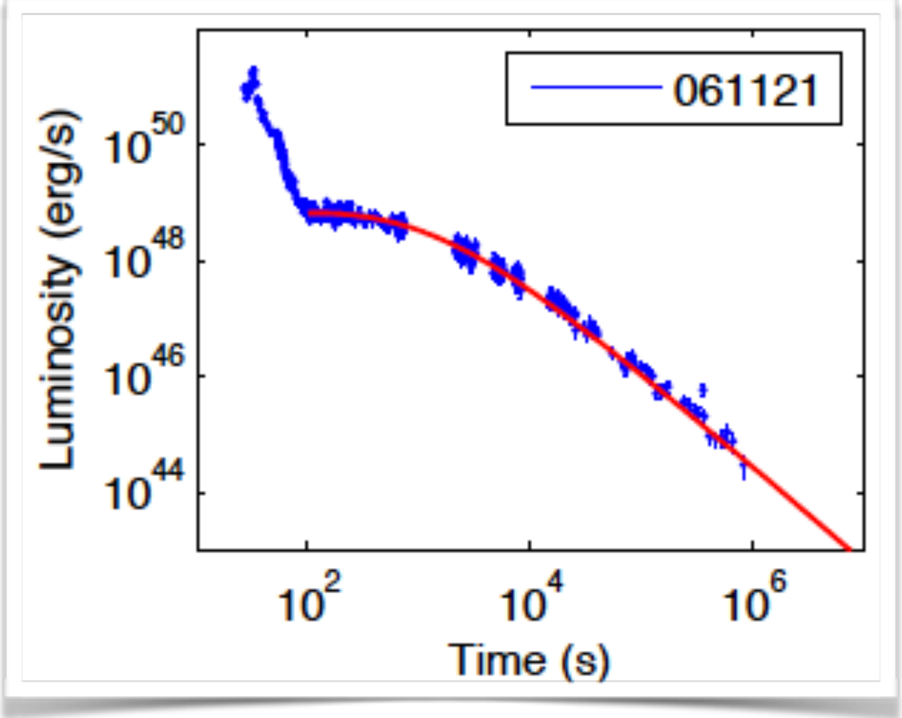
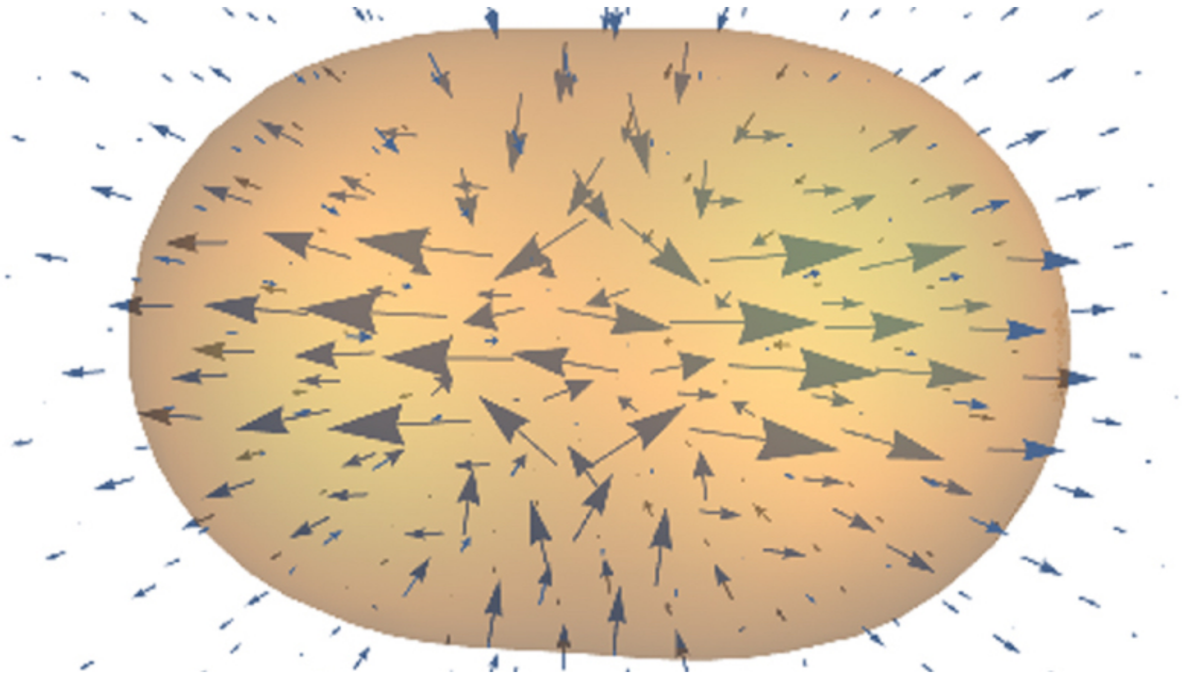


Nousek et al. 2006



Dall'Osso et al. 2011

GWS FROM NEWLY BORN MAGNETARS

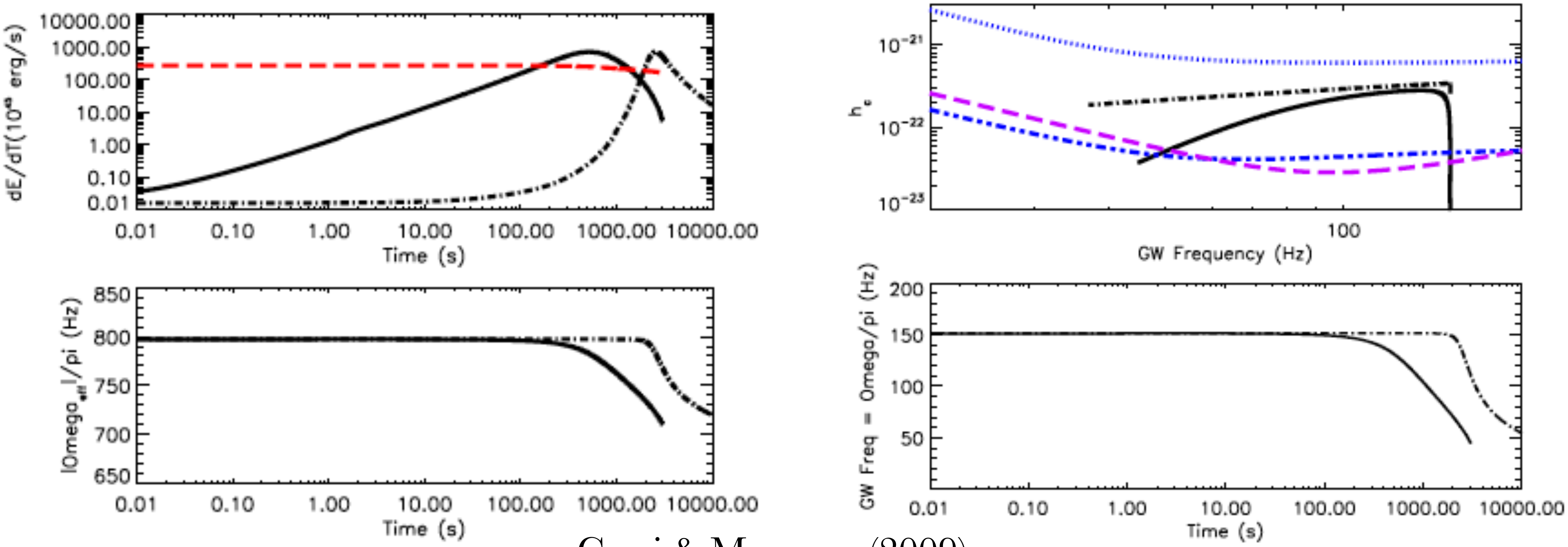


secular bar-mode instability

$$\frac{T}{|W|} \gtrsim 0.14 \Rightarrow T \lesssim 2 \times 10^{52}\ \text{erg s}^{-1}$$

growth time $\sim 10^2 - 10^3$ s

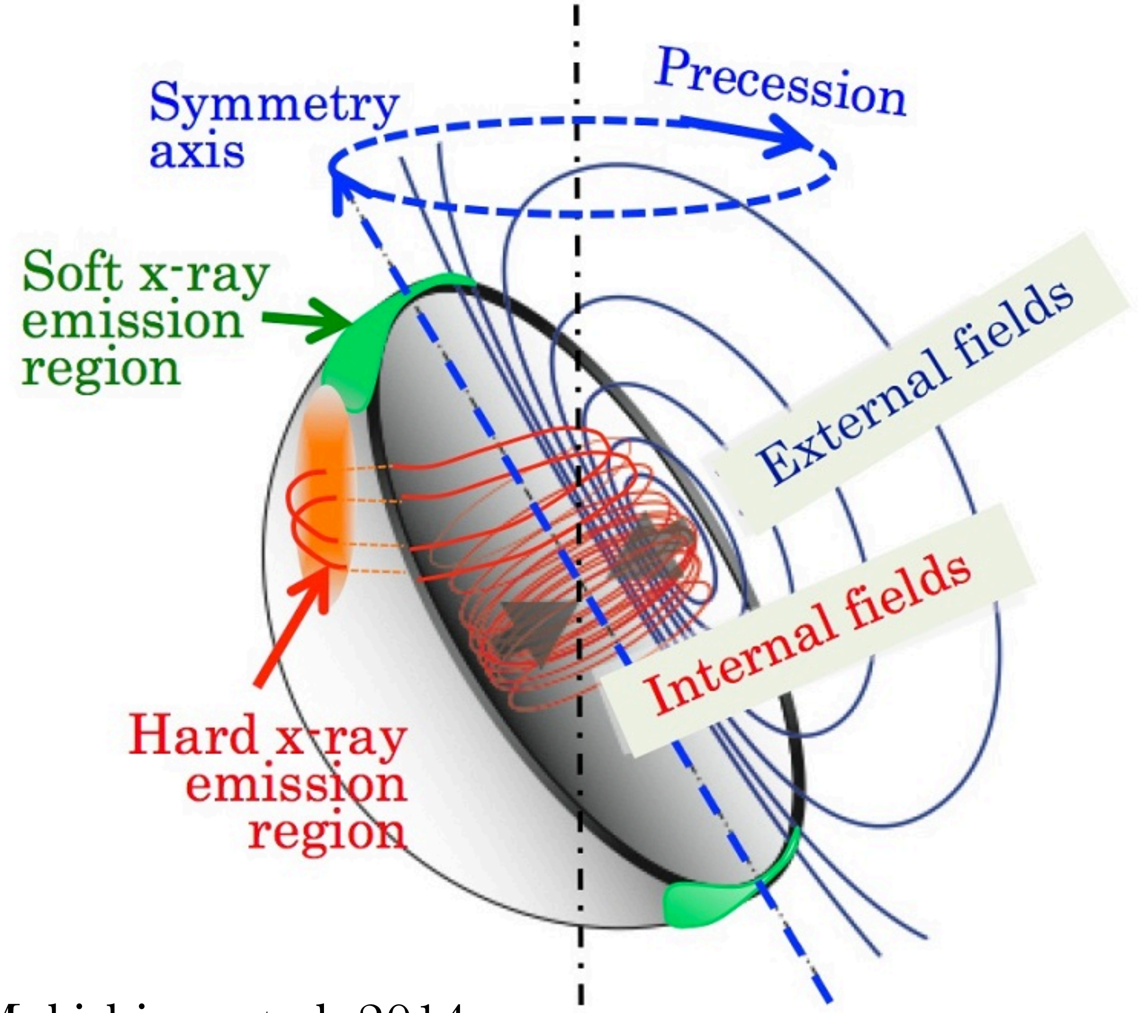
The non-axisymmetric NS spins down sweeping the LIGO/Virgo range from ~200 Hz to ~30 Hz



Corsi & Meszaros (2009)

GWS FROM NEWLY BORN MAGNETARS

TOROIDAL B-FIELD → **PROLATE DISTORTION**



Makishima et al. 2014

? $\epsilon_B \sim 10^{-4}$ **4U 0142+61**

$\chi \neq 0$ **Excites free body precession**

$\omega = \epsilon_B \Omega \cos\chi$ Mestel & Takhar (1972)

$\epsilon_B \sim 10^{-3} B_{16}^2$

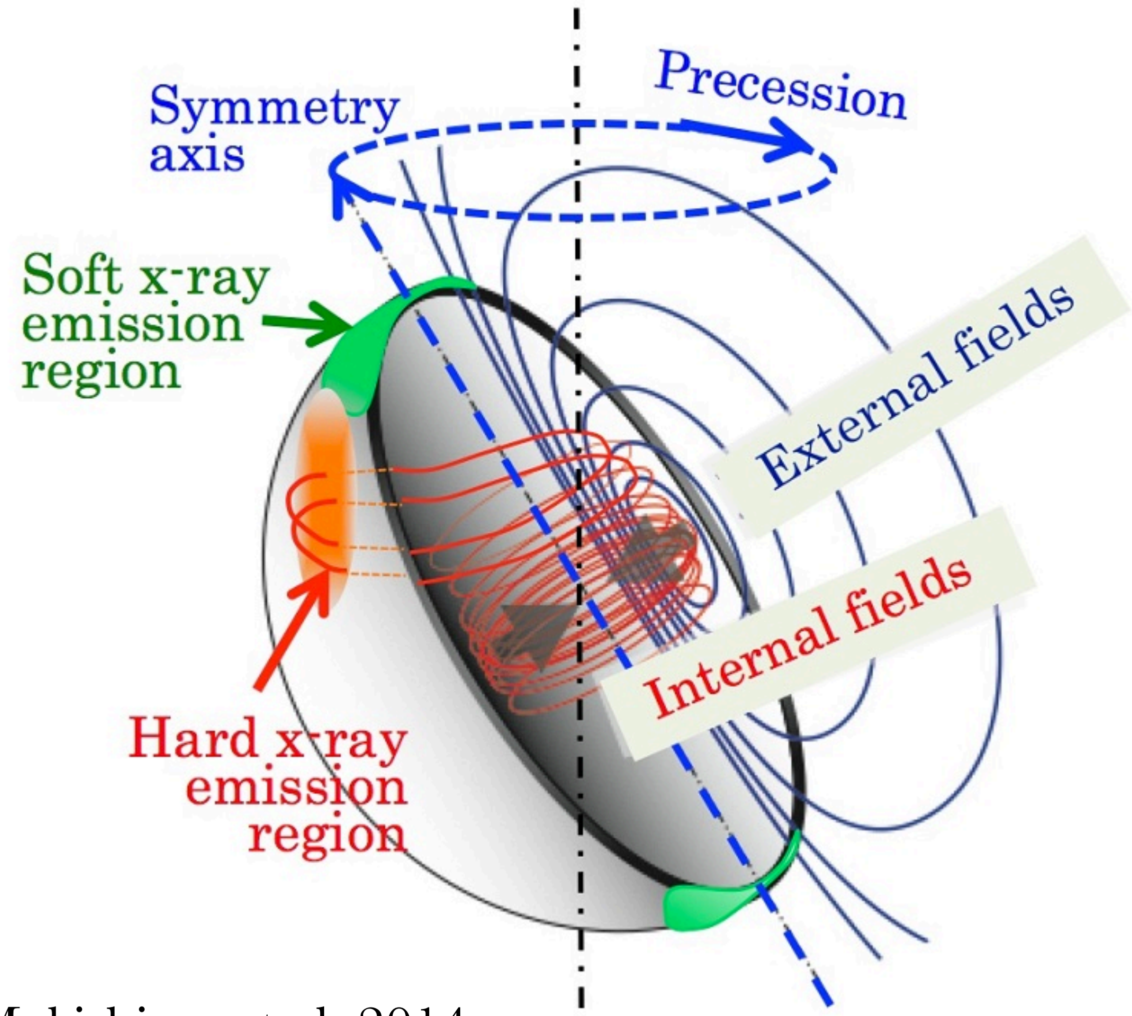
cf. Cutler (2002)

Dall'Osso et al. 2009, 2015,2017

$E_{spin} \sim (2\text{-}10)\ 10^{52}$erg $\sim 0.015\ P^{-2}_{ms} M_\odot c^2$

GWS FROM NEWLY BORN MAGNETARS

TOROIDAL B-FIELD → **PROLATE DISTORTION**



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Dall'Osso et al. 2009, 2015,2018

$E_{spin} \sim (2\text{-}10)\ 10^{52}\,\mathrm{erg} \sim 0.015\ P^{-2}_{ms}\ M_{\odot} c^2$

External (dipole) B ~ 10^{14}-10^{15} G

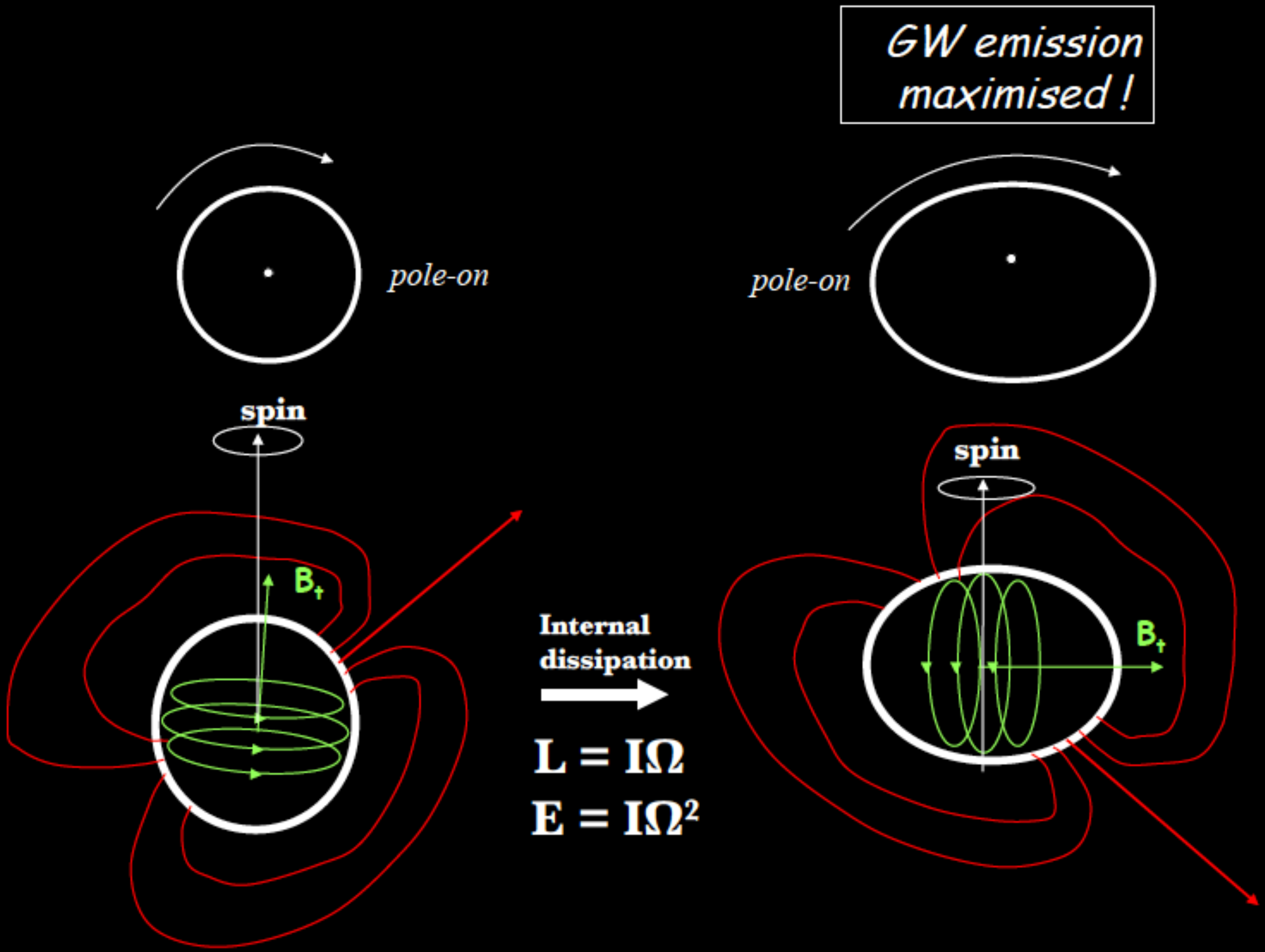
Internal (toroidal) B ~ 10^{16} G

→

Magnetic dipole spindown ~ 10^3-10^5 s

GW emission in ~ 10^2-10^4 s

GWS FROM NEWLY BORN MAGNETARS



GW emission maximised !

Internal dissipation

$$L = I\Omega$$

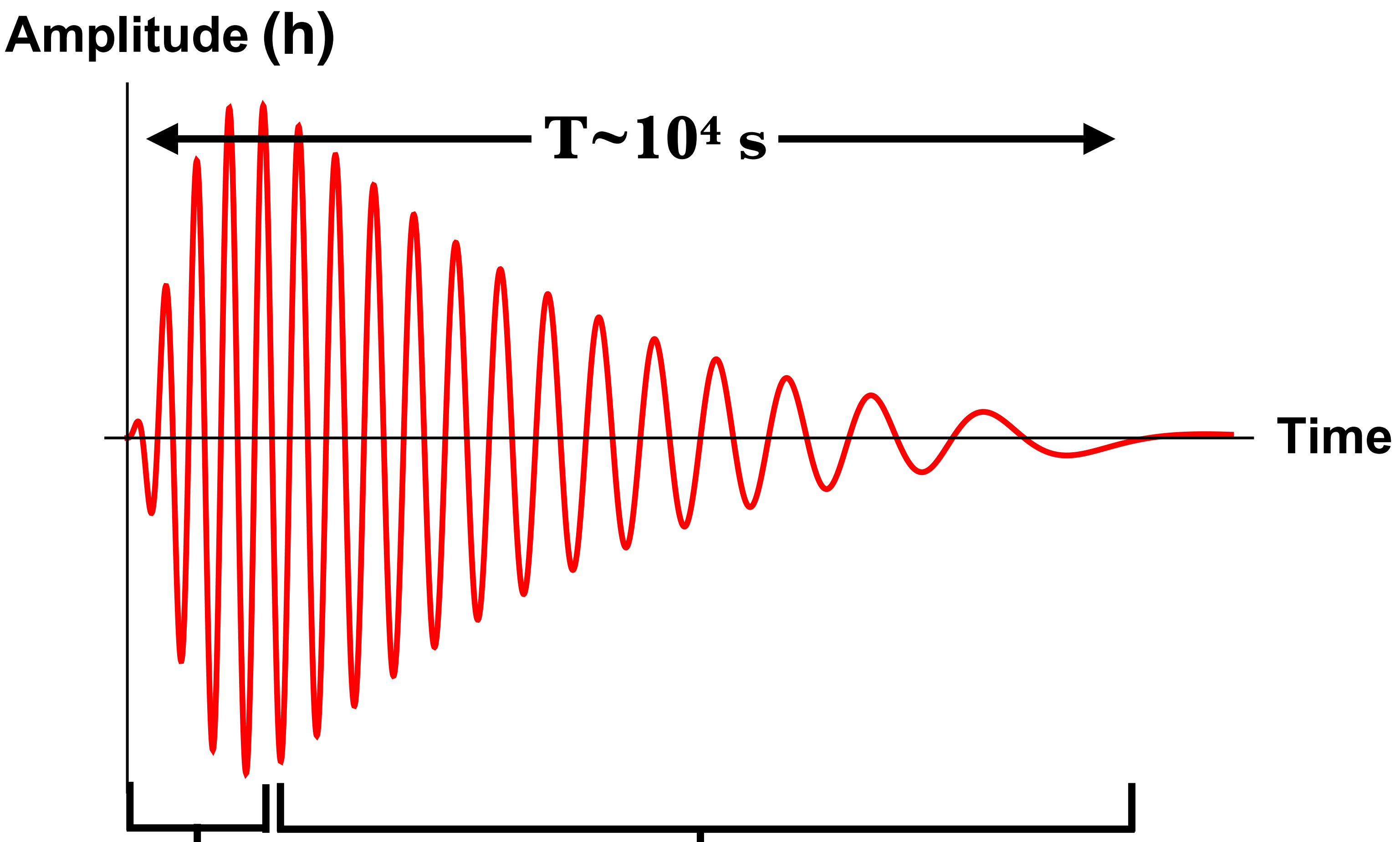
$$E = I\Omega^2$$

BULK VISCOSITY:

depends on chemical composition and EoS

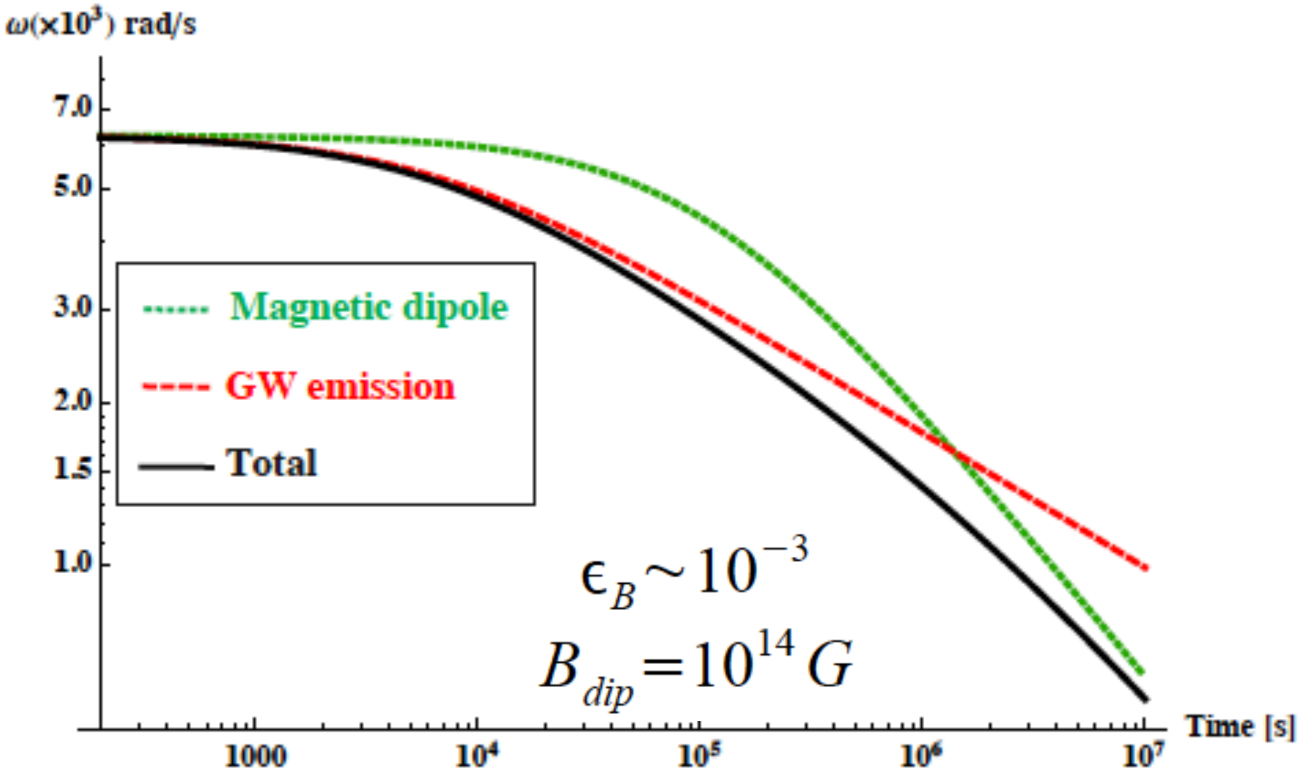
(Prakash 1998, Haensel et al. 2001; **Dall'Osso,** Stella & Palomba 2018)

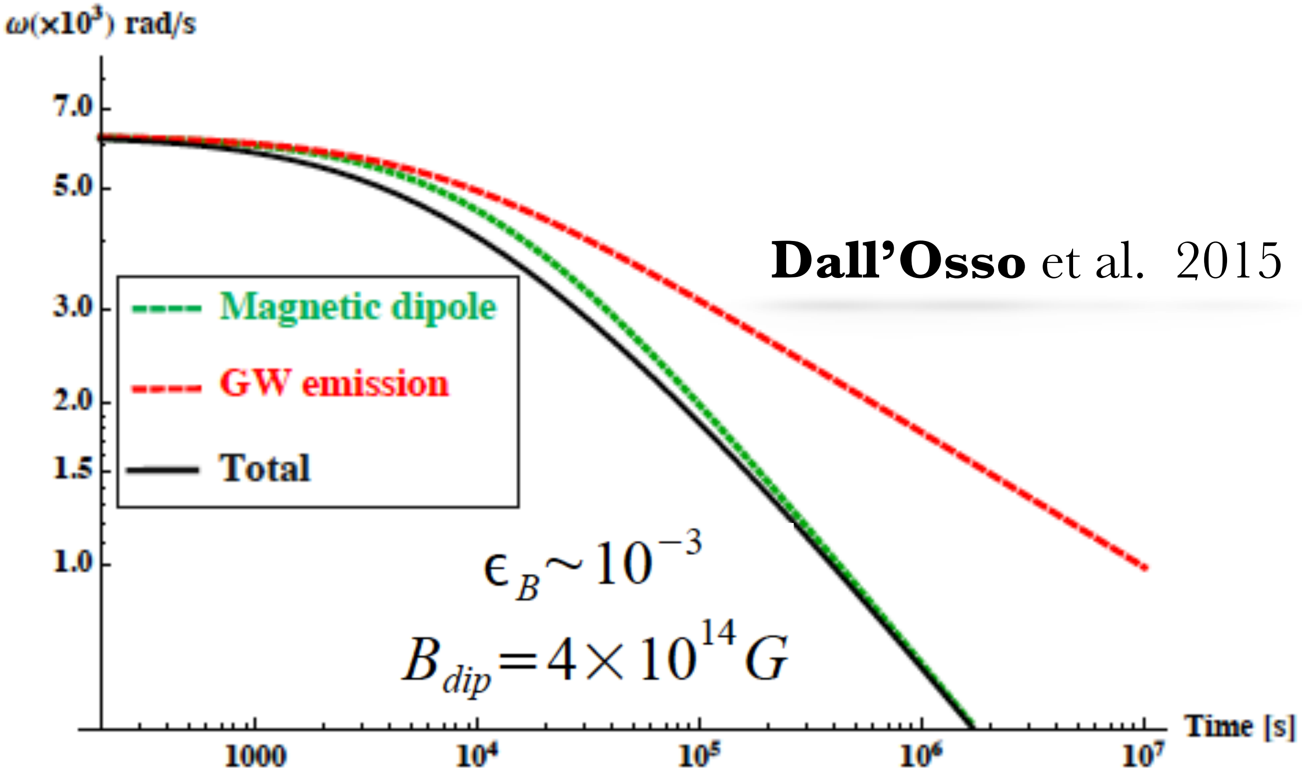
GWS FROM NEWLY BORN MAGNETARS



growth of tilt angle

spin down driven by EM+GW torque





Dall'Osso et al. 2015

GWS FROM NEWLY BORN MAGNETARS

EVENT RATE

core-collapse

Optimistic: $\lesssim 0.5$ **year from Virgo Cluster**

``Realistic": $\lesssim 1$ **every ~30-50 yrs within 5 Mpc (Dall'Osso et al. 2018)**

TO BE DONE:

a. **characterize magnetar population based on EM properties (GRBs SLSNe) and theory**

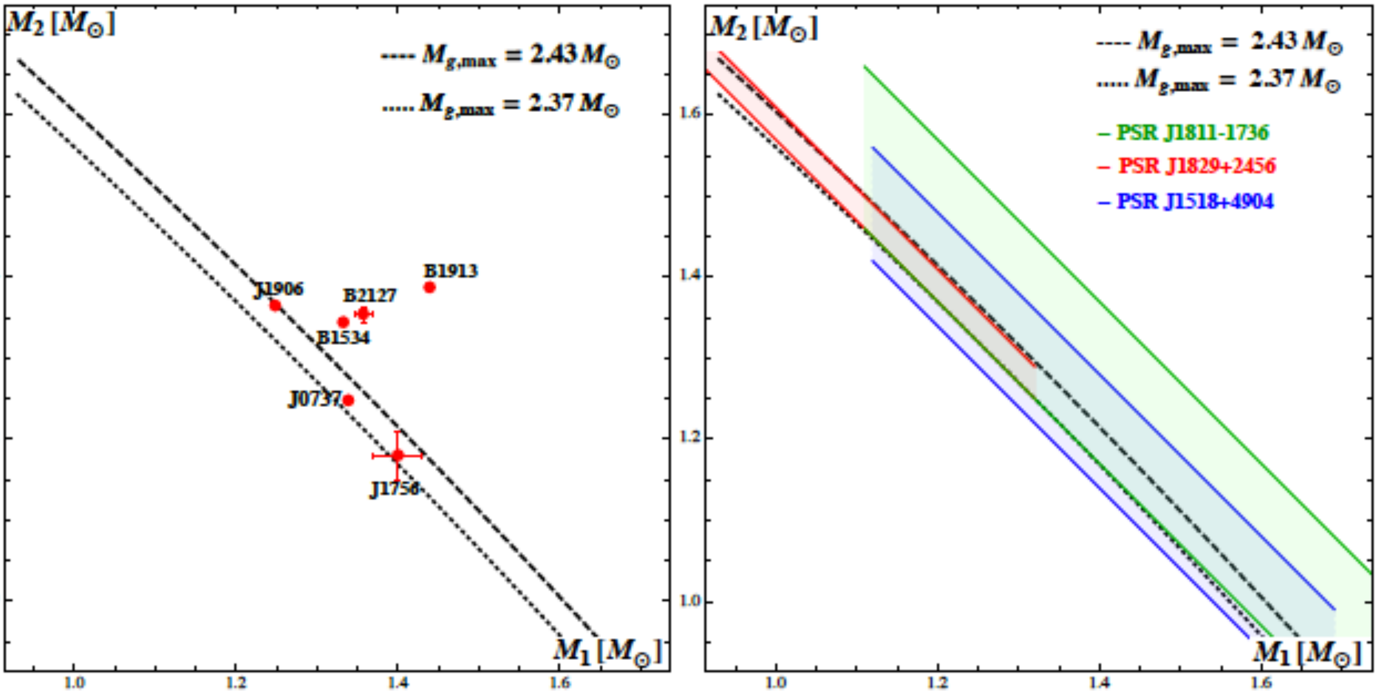
b. **develop effective strategies to detect the expected GW signals from nearby starburst (adv LIGO/Virgo) or from within ~ 30 Mpc (ET)**

c. **develop effective strategies to reveal the expected EM counterparts (SN, KN, shock break-out).**

NS mergers

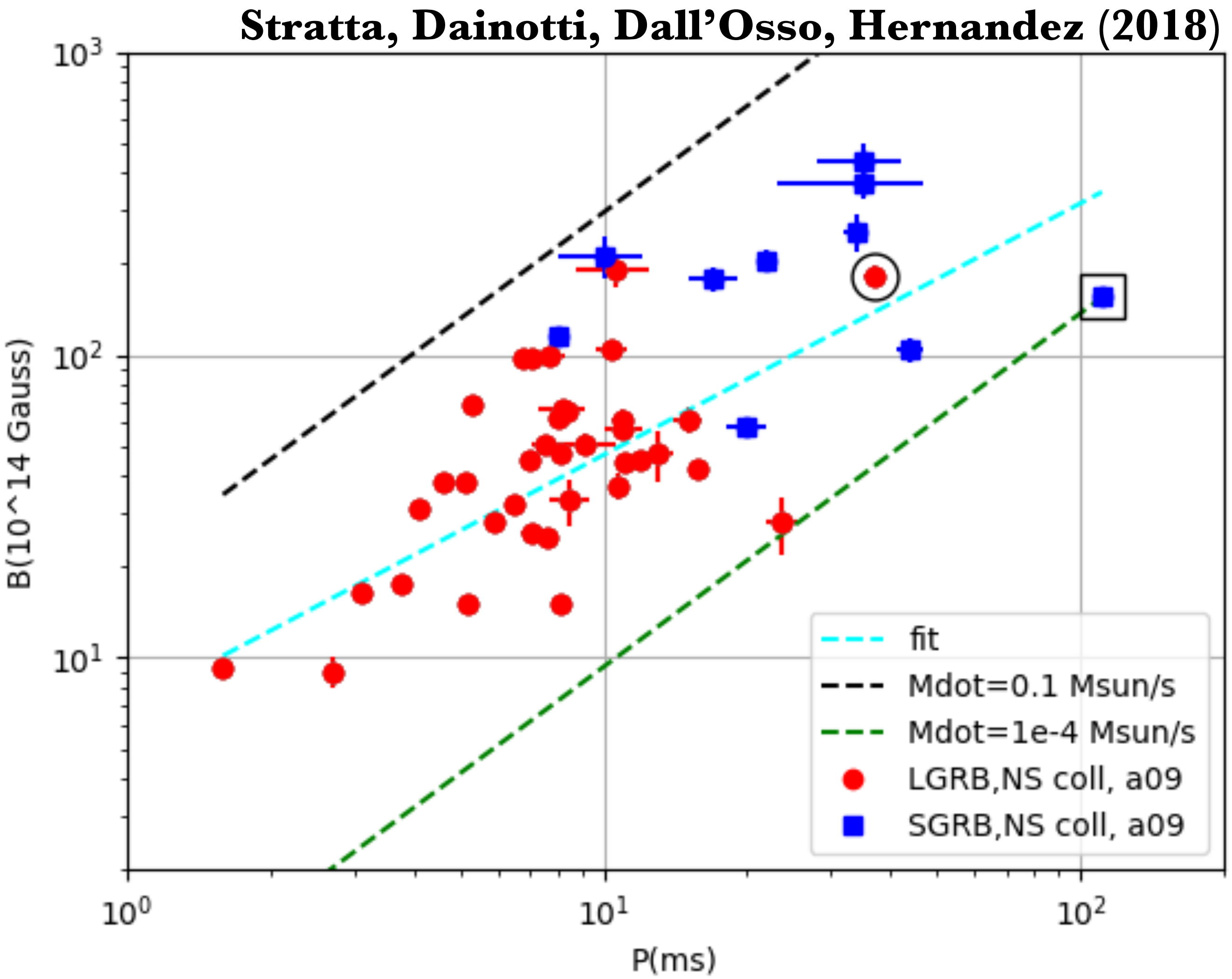
Stable: ~(0.1-0.3)/yr if M_{max} >2.35 $M_\odot$

unstable: will need 3G detectors

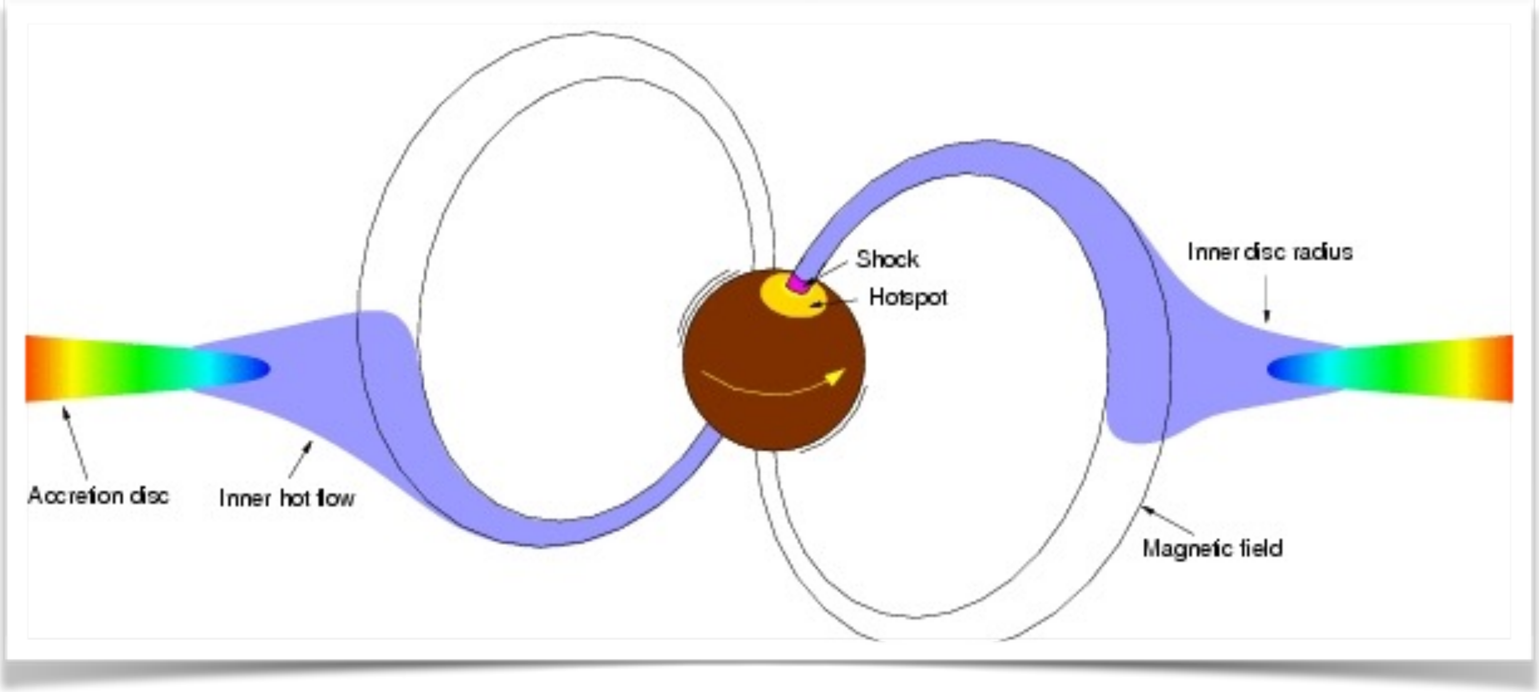


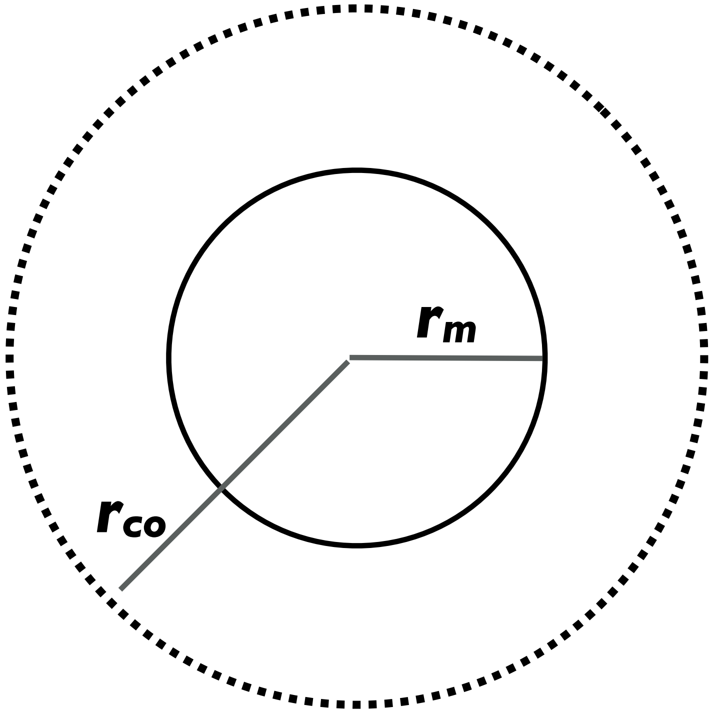
Dall'Osso et al. 2015

EM SIGNATURE OF NEWBORN MAGNETARS



ACCRETION ONTO MAGNETISED NS





Accretion/spinup

$$r_m \sim r_A \propto \dot{M}^{-2/7} B^{4/7}$$
$$N_{mat} \sim \dot{M} (G M r_m)^{1/2}$$

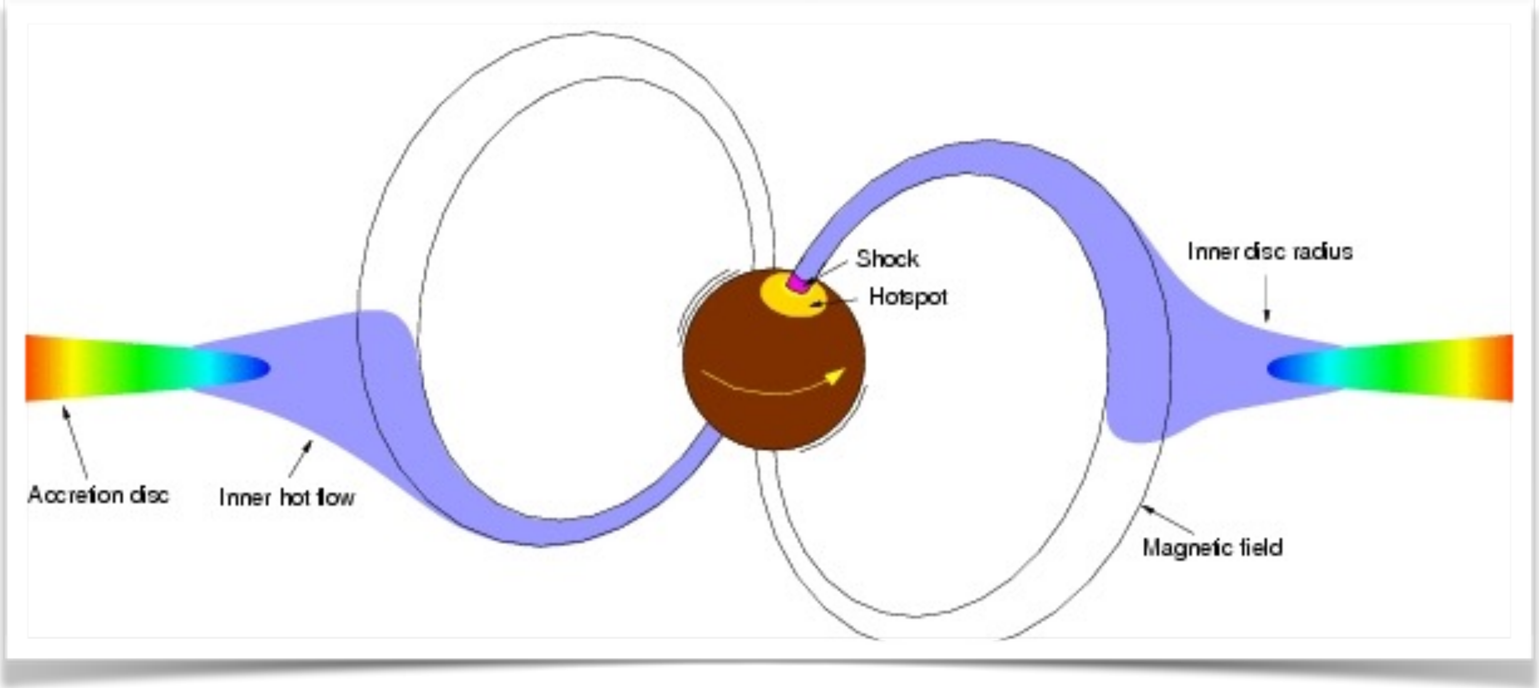
→ Material torque: specific angular momentum at r_m

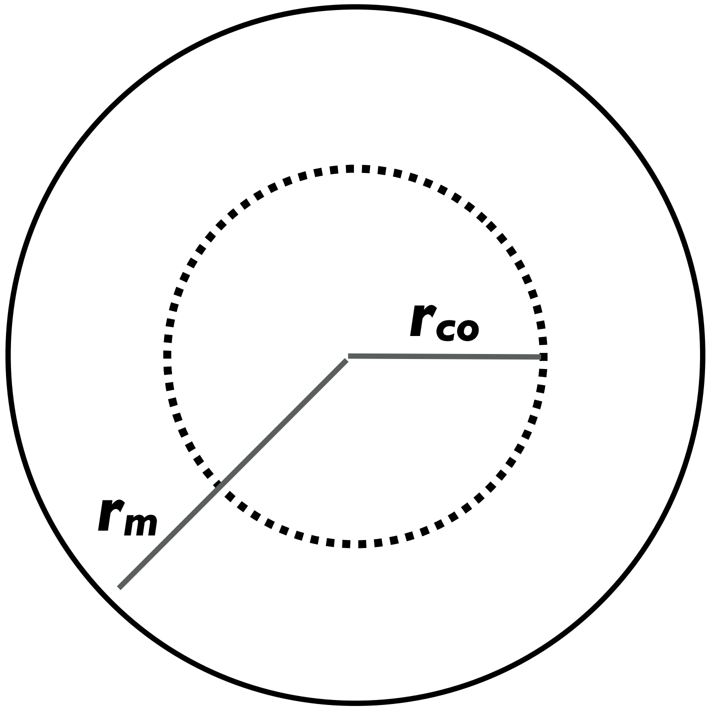
$$r_{co} = \left(\frac{G M}{\Omega^2} \right)^{1/3} \sim 2 \times 10^8 \, cm \left(\frac{P_{spin}}{1.37 \, s} \right)^{2/3} M_{1.4}^{1/3}$$

→ **accretion** if $r_m < r_{co}$ (NS spin-up, r_{co} moves in)

if $r_m > r_{co}$ → **propeller phase:** the NS spins down, r_{co} moves outwards

ACCRETION ONTO MAGNETISED NS





No accretion/spindown

$$\boxed{\begin{array}{l} r_m \sim r_A \propto \dot{M}^{-2/7} B^{4/7} \\ N_{mat} \sim \dot{M}\left(G M r_m\right)^{1/2} \end{array}}$$

⟶ Material torque: specific angular momentum at r_m

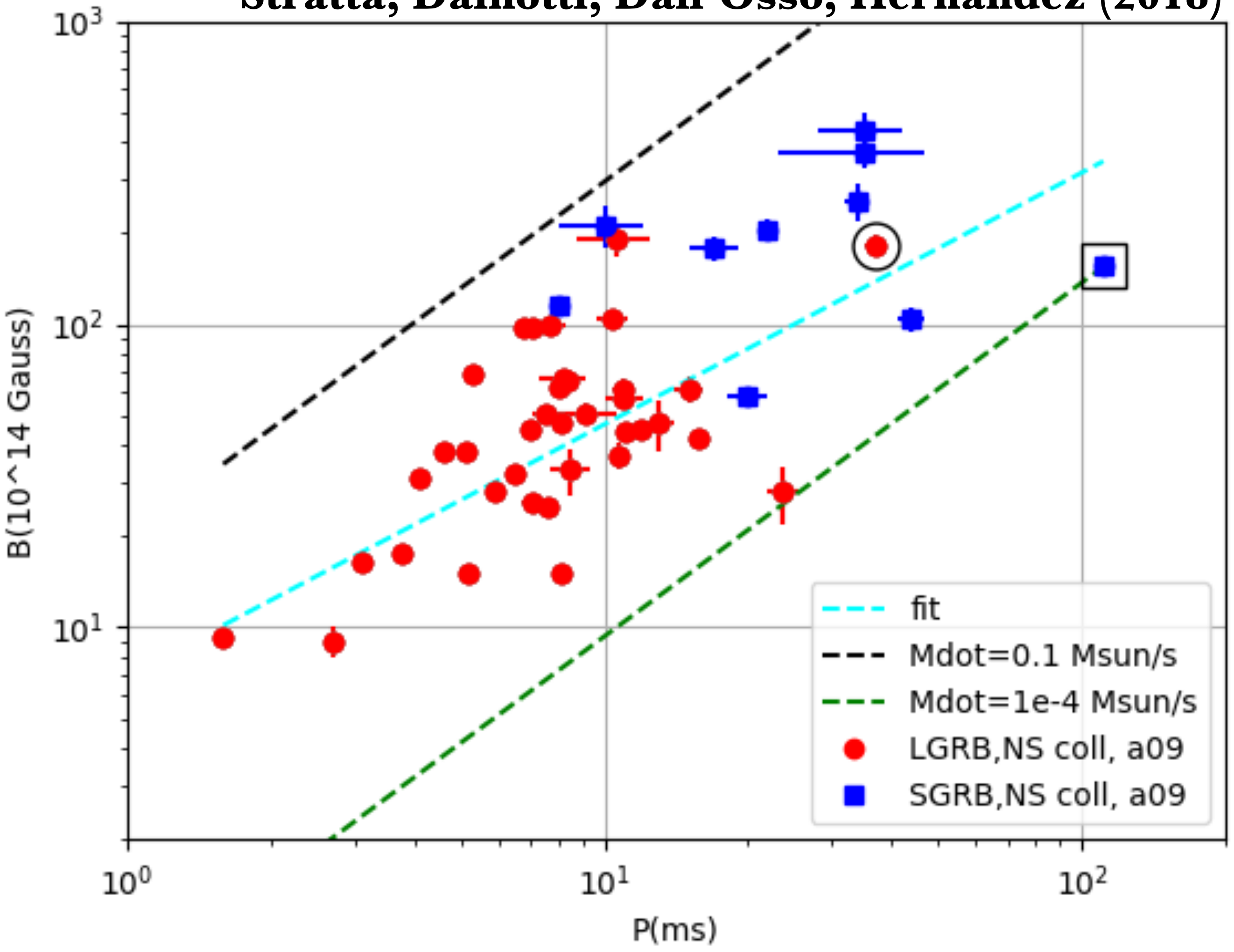
$$\boxed{r_{co} = \left(\frac{GM}{\Omega^2}\right)^{1/3} \sim 2\times10^8\,cm \left(\frac{P_{spin}}{1.37\,s}\right)^{2/3} M_{1.4}^{1/3}}$$

⟶ **accretion** if $r_m < r_{co}$ (NS spin-up, r_{co} moves in)

if $r_m > r_{co}$ ⟶ **propeller phase:** the NS spins down, r_{co} moves outwards

EM SIGNATURE OF NEWBORN MAGNETARS

Stratta, Dainotti, Dall’Osso, Hernandez (2018)



equilibrium at $r_m = r_{co}$

$$\frac{B}{10^{14}G} \approx 15 \left(\frac{P_{\rm eq}}{1{\rm ms}}\right)^{7/6} \left(\frac{M}{1.4M_\odot}\right)^{5/6} \left(\frac{\dot{M}}{0.01M_\odot/{\rm s}}\right)^{1/2} \left(\frac{R}{12\ {\rm km}}\right)^{-3}$$

The model allows to infer the main characteristics of the prompt emission based *only* on the observed plateau’s.

UNDER WAY: furthert investigation of the scenario and comparison with the available data

CONCLUSIONS & OUTLOOK

1. **Future runs of Adv. LIGO/Virgo might be able to detect for the first time the signal from a newborn NS in a nearby starburst Galaxy**

2. **These will have robust and easy-to-detect EM counterparts (a SN, or a kilonova). In addition, there may be additional - and brighter - EM signatures (e.g., a GRB, a SLSN, a shock break-out, etc).**

3. **Top priority at this stage: observation and data analysis efforts, in order to be ready to reveal both the GW and EM transients associated to the newborn NS.**

4. **Theoretical work: developing more realistic models, urged to correctly extract physics information from multi-messenger observations**

5. **Theoretical work II: need for investigating specific signatures of a newborn magnetar in other channels (neutrino, cosmic rays).**