Exploring the Universe with gravitational waves

Enrico Barausse

(Institut d'Astrophysique de Paris & CNRS, France)

27th International Symposium on Lepton Photon Interactions at High Energies

Plan of the talk

- The world's shortest introduction to GWs
- Indirect evidence for Gws
- Present and future GW detectors
- GW astrophysics, physics and cosmology

General Relativity in a nutshell

- Generalizes both $\vec{F} = m\vec{a}$ and Poisson's equation to v ~ c and strong gravitational fields
- Gravity is no more a force, but geometrical effect encoded in 4D metric $ds^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$ describing a spacetime

Einstein equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G T_{\mu\nu}}{c^4}$$

spacetime curvature (generalizes Laplacian of Poisson's equation)

Stress-energy tensor: depends on matter (on its density, pressure, velocities, etc)

Equations of motion (geodesics equation and energy/momentum conservation) follow from the Einstein equations, like electric charge conservation from Maxwell's equations!

Causality and gravitational waves

- No signal/body can travel faster than light
- In suitable coordinates (”gauge”) Einstein equations become ”wave equation”

$$\Box_{\text{flat}} \bar{H}^{\alpha\beta} = -16\pi\tau^{\alpha\beta} \qquad \Box_{\text{flat}} = -\frac{1}{c^2}\frac{\partial}{\partial t^2} + \nabla^2$$

$$\bar{H}^{\mu\nu} \equiv \eta^{\mu\nu} - (-g)^{1/2} g^{\mu\nu} \qquad \tau^{\alpha\beta} = (-g)T^{\alpha\beta} + (16\pi)^{-1}\Lambda^{\alpha\beta}$$

”Perturbation” away from Minkowski metric

Matter stress-energy

”Gravitational stress-energy”
= non-linearities of gravitational field

- Perturbations of gravitational field travel at speed of light: gravitational waves!

GWs vs EM waves

- EM: no monopolar radiation because electric charge is conserved → dipolar radiation
- GR:

  - no monopolar radiation because mass is conserved

  - no dipolar radiation because linear momentum is conserved

  - Quadrupolar radiation allowed!

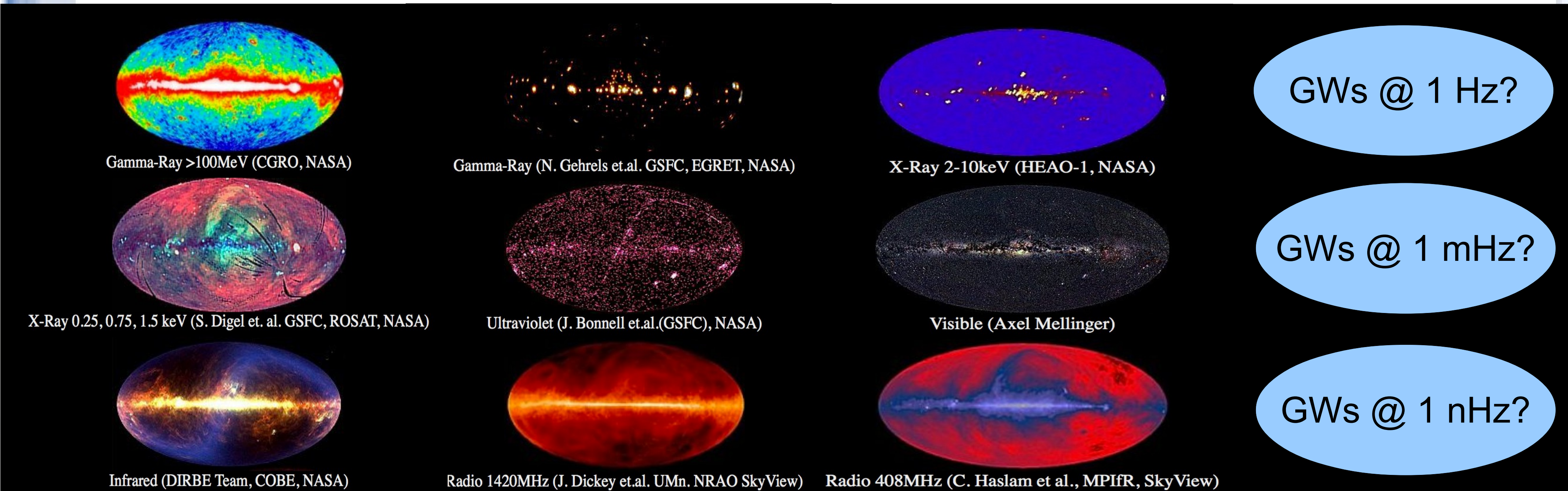
$$L_{\text{mass quadrupole}} \equiv \frac{1}{5}\frac{G}{c^5}\langle\, \dddot{\boldsymbol{I}}\,\rangle^2 = \frac{1}{5}\frac{G}{c^5}\langle \dddot{I\!\!\!-}_{jk}\dddot{I\!\!\!-}_{jk}\rangle^2$$ "Quadrupole formula"

$$\dddot{I\!\!\!-}_{jk} \sim \frac{(\text{mass of the system in motion}) \times (\text{size of the system})^2}{(\text{time scale})^3} \sim \frac{MR^2}{\tau^3} \sim \frac{Mv^2}{\tau}$$

$G/c^5 \sim 10^{-59}$ Conversion of any type of energy into GWs is inefficient, unless large masses and/or v ~ c

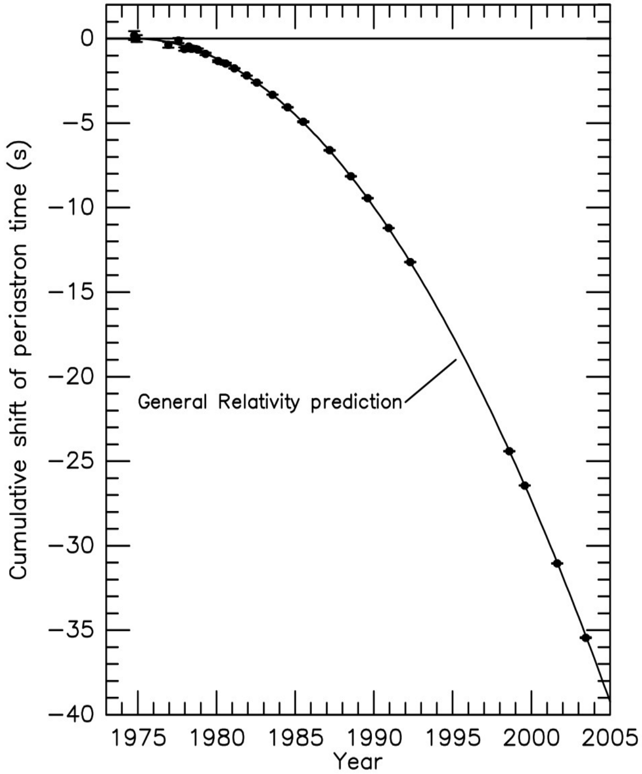
GWs vs EM waves

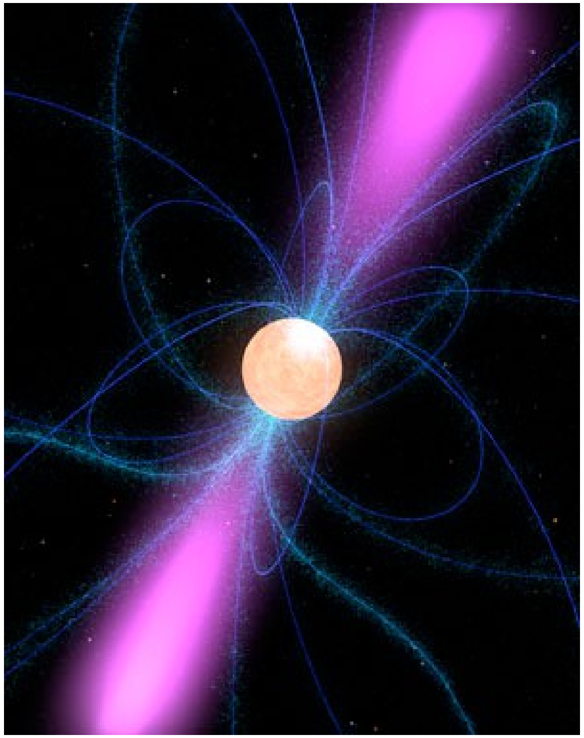
- GW wavelength $\gtrsim$ size of astrophysical sources (similar to sound, can't be used for imaging, i.e. generally poor localization)
- EM waves produced by accelerated charges/atomic processes: wavelength $\lesssim$ size (can be used for imaging)
- EM luminosity decays as $1/r^2$, GWs decay as $1/r$
- GWs interact very weakly with matter



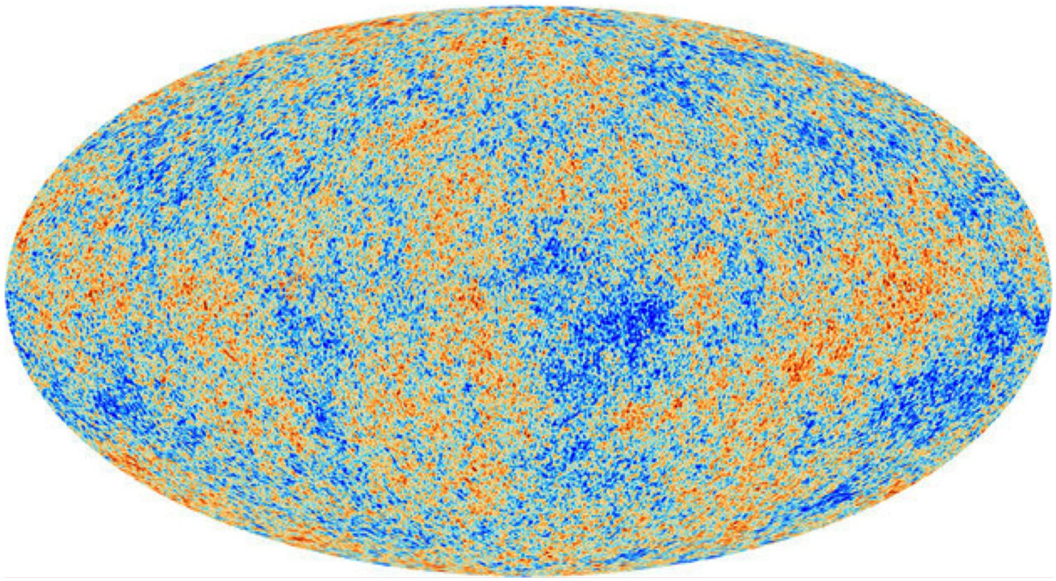
Indirect detection of GWs

- Binary system of stars in circular orbits has time changing mass quadrupole ⟹ GW emission
- GWs carry energy and angular momentum away from system ⟹ binding energy gets more and more negative and binary shrinks
- Indirect detection by binary pulsar systems (e.g. Hulse-Taylor pulsar)





GWs in the CMB?



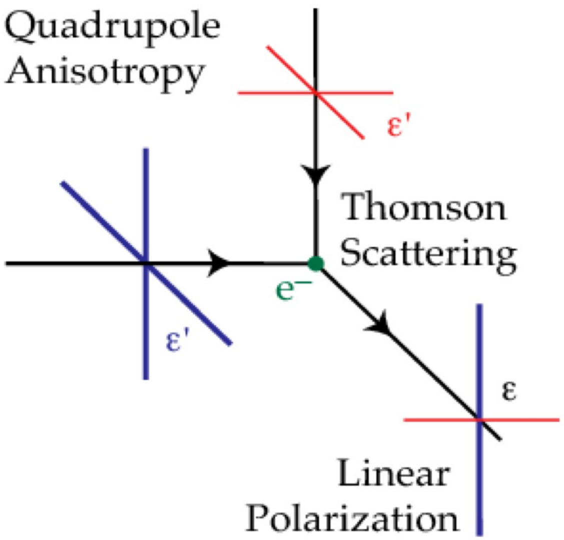
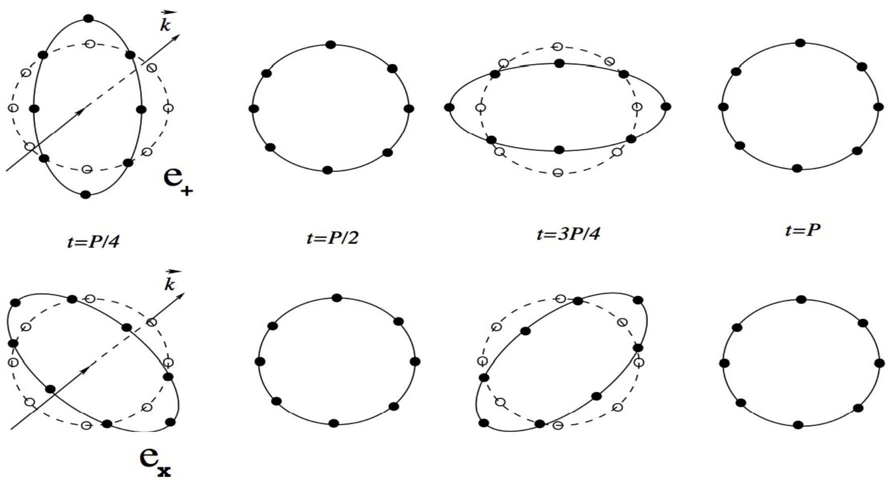


Figure from Hu & White

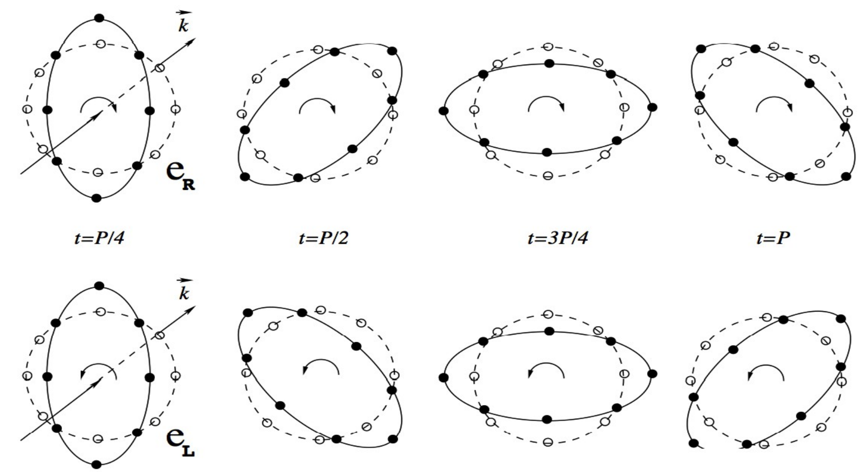
No evidence so far, but possibility of detection depends on energy scale of inflation

Direct effect of GWs

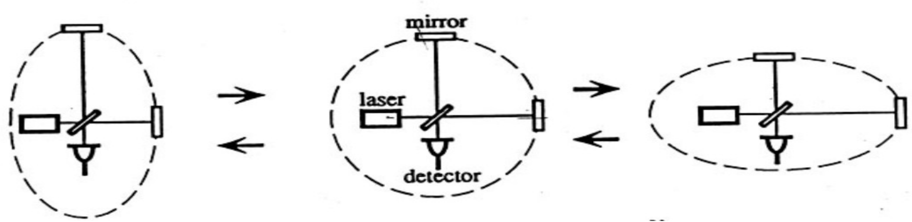
- Passing GW changes distance between particles: h ~ ΔL/L
- Effect on a ring of particles: quadrupolar pattern



Linearly polarized GWs

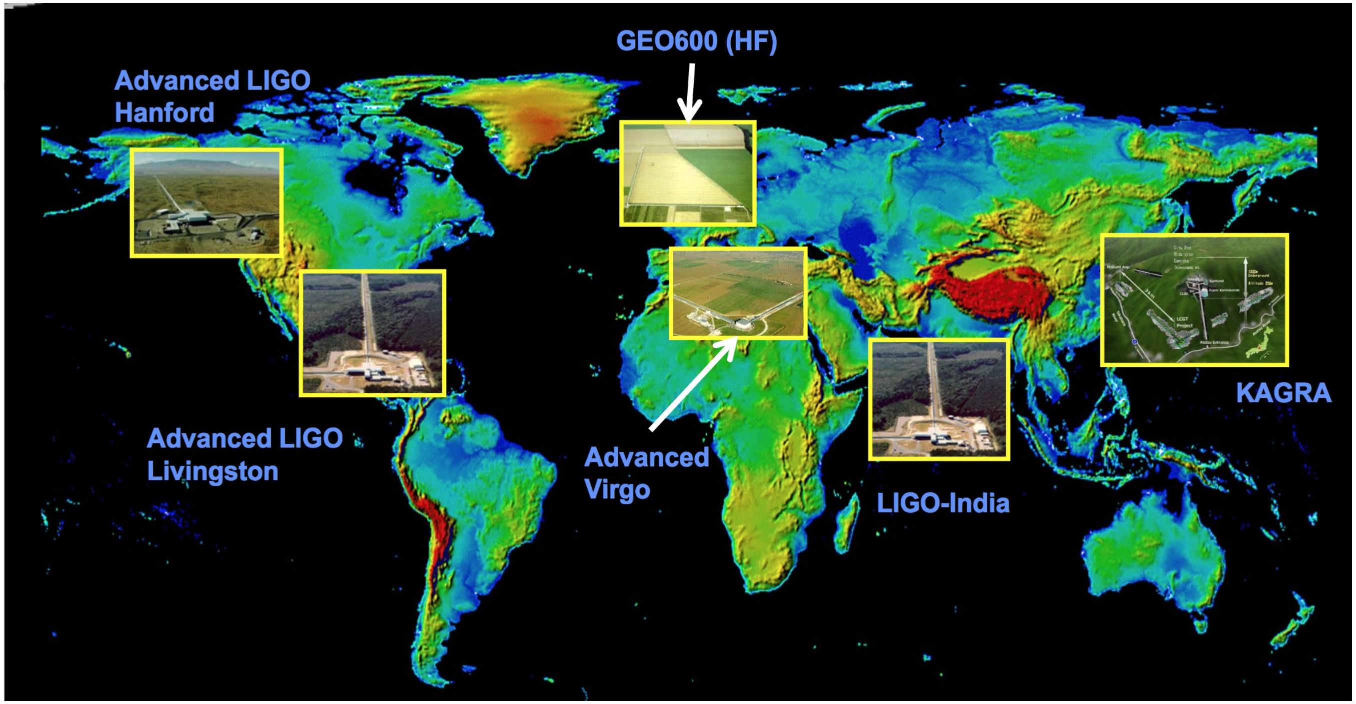


Circularly-polarized GWs



- For fixed ability to measure ΔL, make L as large as possible!

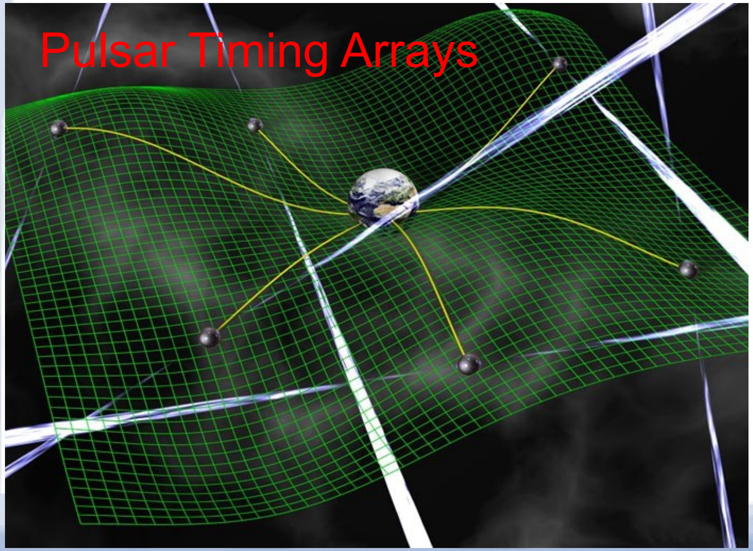
A direct detection before 2020?

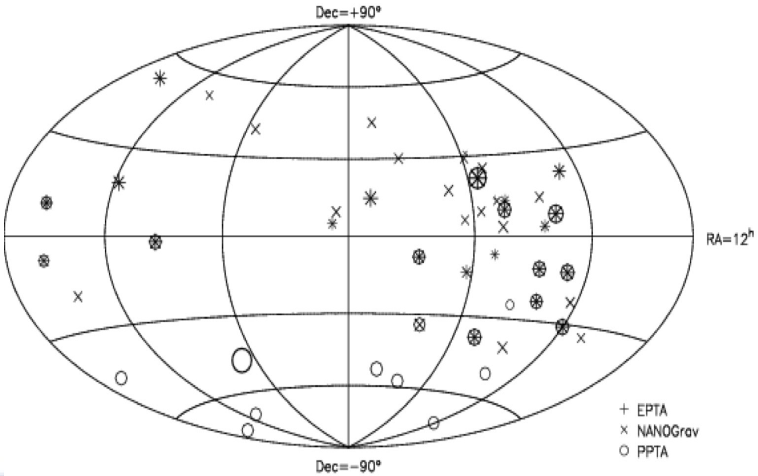


Armlength $\lesssim$ 4 km

- Commissioning for Advanced LIGO under way (ER8), first science near...

- Advanced Virgo commissioning in 2016

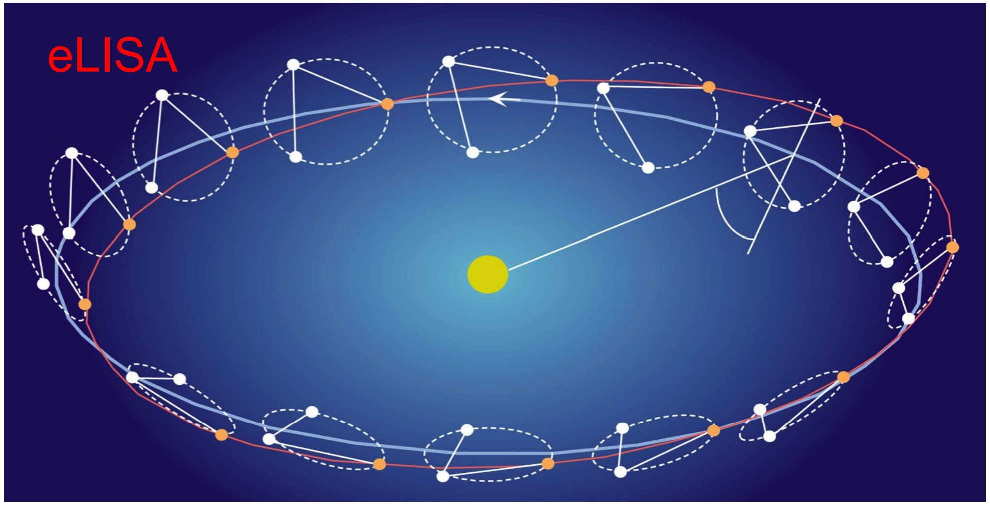


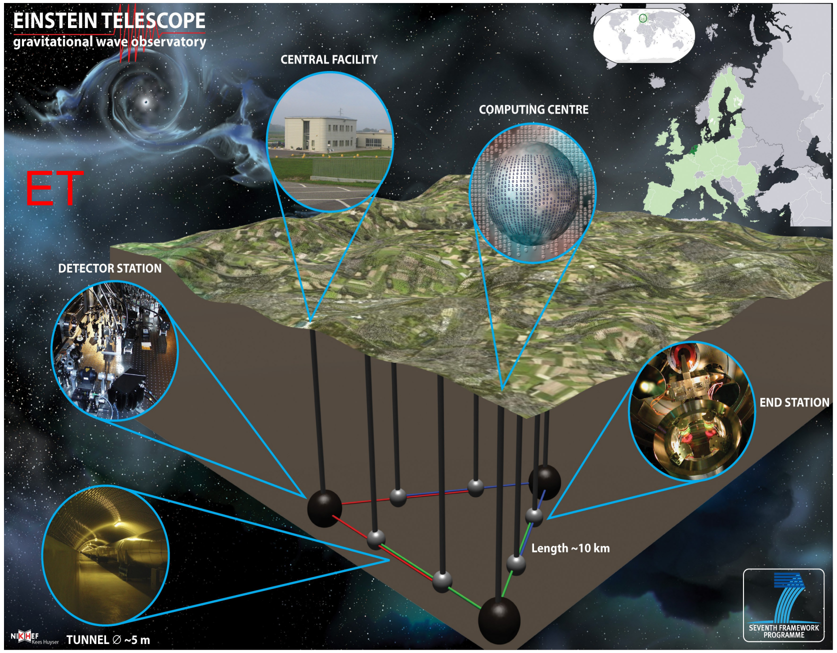


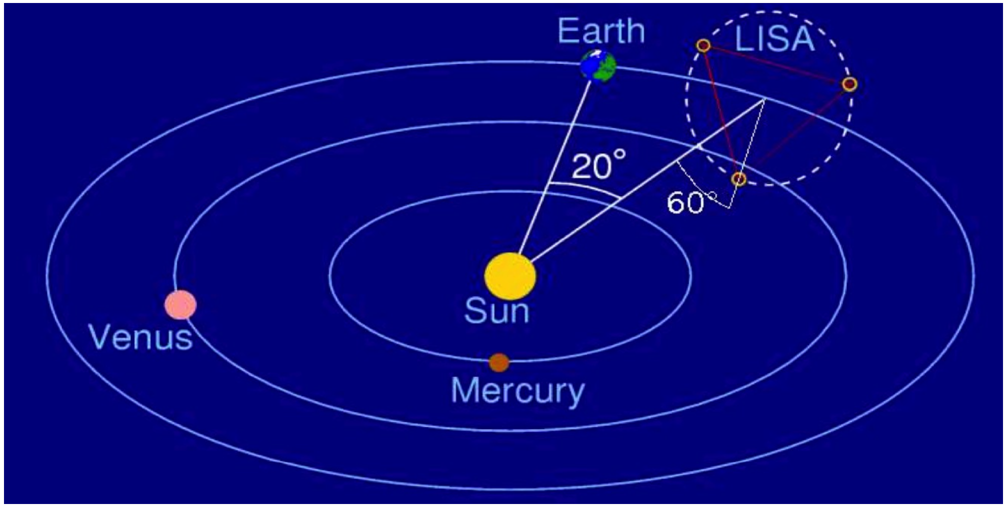
Existing!

Looks for pattern in time of arrival of observed pulsars

Future detectors







L ~ 10 km, design studies funded

ESA mission, to be launched in 2034 (but earlier date may be considered)

Baseline currently under study, but L $\lesssim 10^6$ km

"Pathfinder" mission's launch in fall 2015!

Frequency ranges

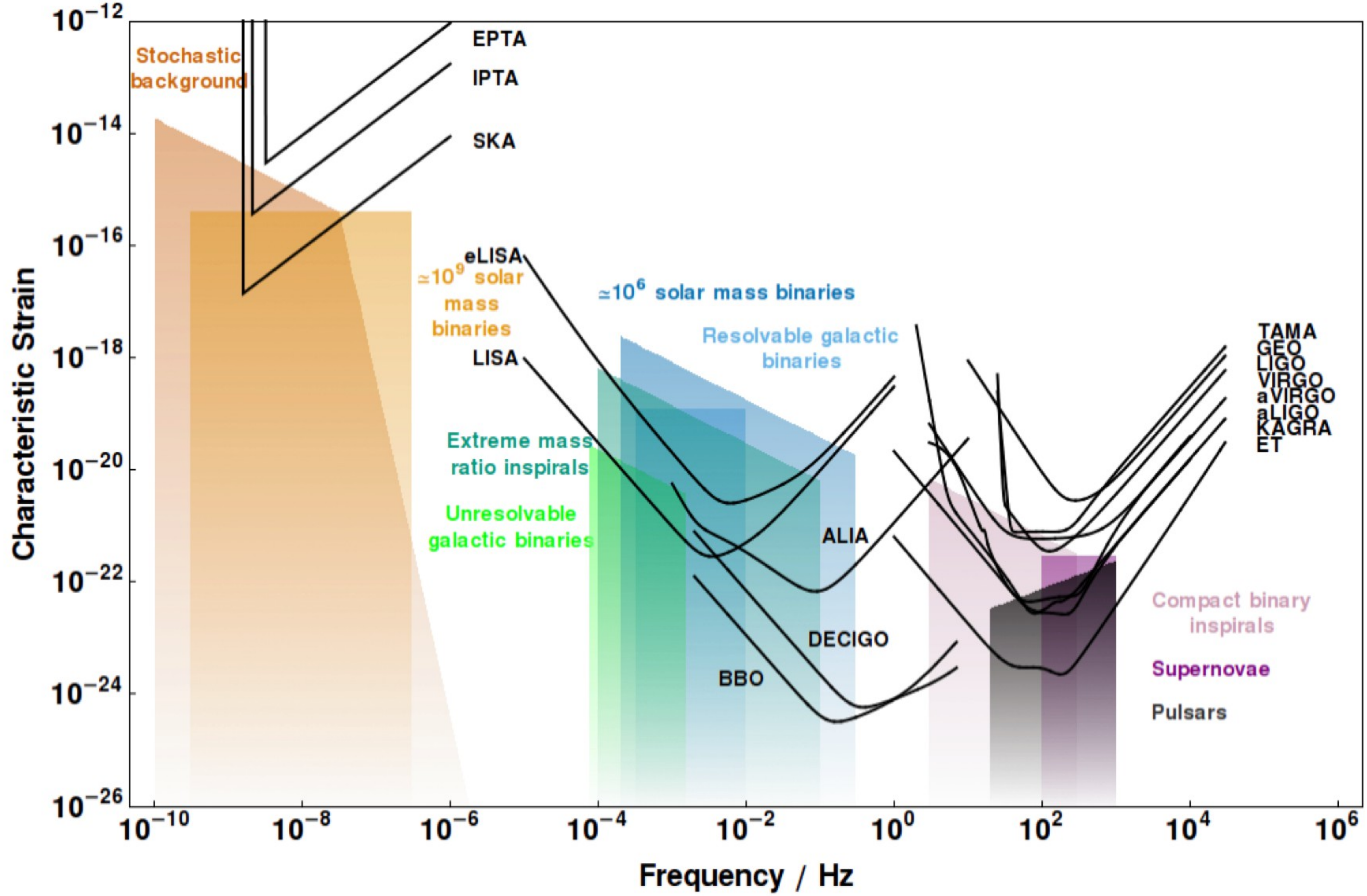


Figure from Moore, Cole and Berry 2015

GWs from binary systems

$$f_{\rm GW} = \frac{6\times 10^4}{\tilde{m}\tilde{R}^{3/2}}{\rm Hz} \qquad \begin{aligned}\tilde{R} &= R/(Gm/c^2)\\ \tilde{m} &= m/M_\odot\end{aligned}$$

Advanced terrestrial detectors

1) Late inspiral of NS-NS: from few to 100s/yr

NSs in binaries have mass ~ 1.4 M_{sun}, but isolated NS have masses $\gtrsim$ 2 M_{sun}

2) BH-NS and BH-BH late inspiral and merger: up to 100s/yr

BH candidates with mass $\gtrsim$ 10 M_{sun} observed in isolation

3) If intermediate mass BHs exists, IMBH-BH/NS/WD and IMBH-IMBH observable up to total masses ~ 300 M_{sun}

Pulsar Timing Arrays:

SMBH-SMBH at 0.2 < z < 1.5, with masses $\gtrsim$ 5 x 10^8 M_{sun} and separations of hundreds gravitational radii

GWs from binary systems

eLISA

Supermassive BHs observed in center of galaxies with masses
$\sim 10^5 - 10^9\ M_{sun}$; believed to merge when galaxies merge

1) Inspiral and merger of SMBH-SMBH (with masses $\sim 10^5 - 10^6\ M_{sun}$): from a few to 100s per year

2) Inspiral and merger of SMBH – BH/NS/WD (aka Extreme Mass Ratio Inspirals, EMRIs): rates uncertain, from a few to 100s/1000s per year

3) IMBH-SMBH: rates uncertain

4) WD-WD at separations of a few star radii ($\sim 10^5$ km): 1000s of resolved sources, a few guaranteed sources in the Galaxy

GWs from isolated systems

- Rotating axisymmetric star/spherical collapse do not emit GWs
- Core collapse supernovae (type II) produce burst of GWs if instabilities develop due to high rotational velocities, or if asymmetries are present:

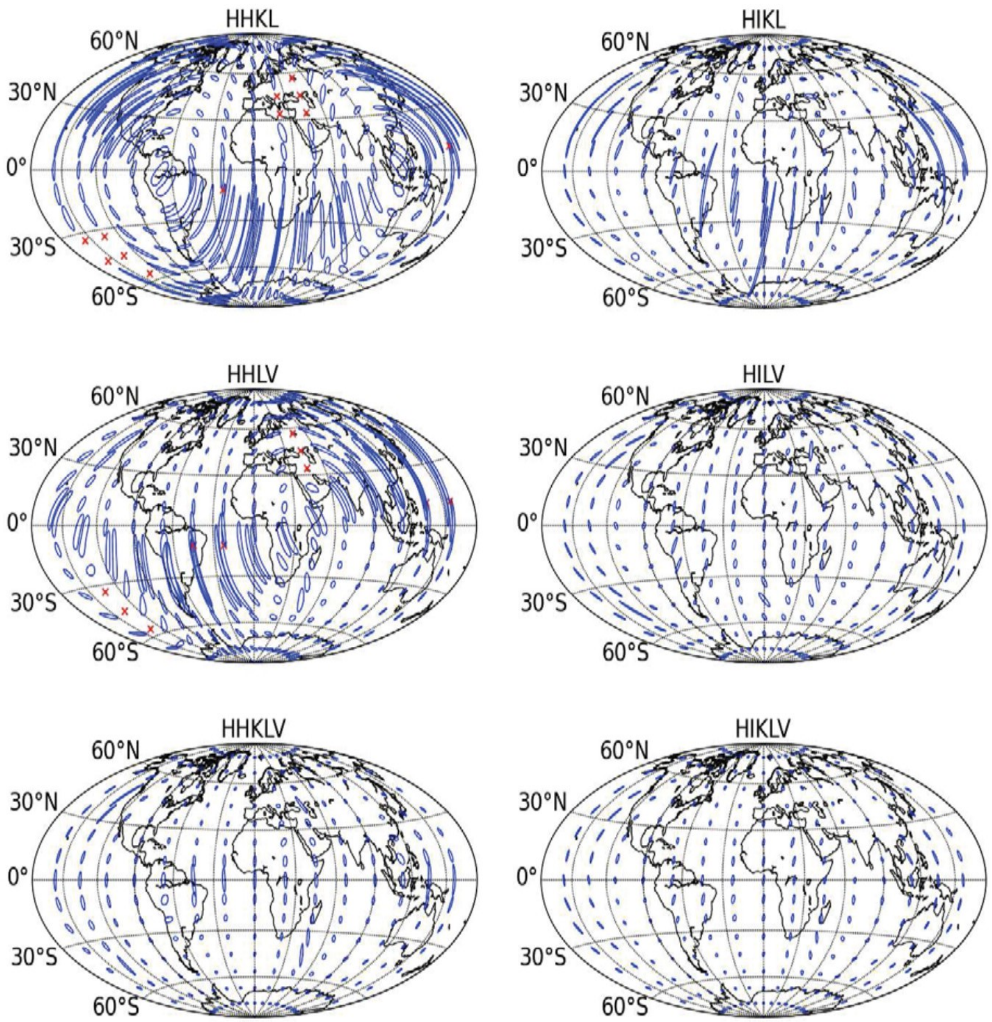
  possible sources for terrestrial detectors
- Rotating pulsar can radiate monochromatically if rotation deviates from axisymmetry: possible sources for terrestrial detectors but no good model for ϵ

$$h \sim \frac{G}{c^4}\frac{I f^2 \epsilon}{r} \qquad \epsilon = (I_{xx} - I_{yy})/I$$

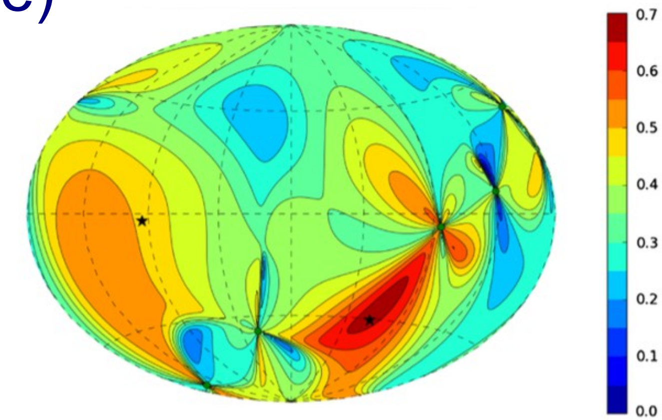
Advanced detectors will constrain $\epsilon < 10^{-7}$

GWs alone have poor sky localization

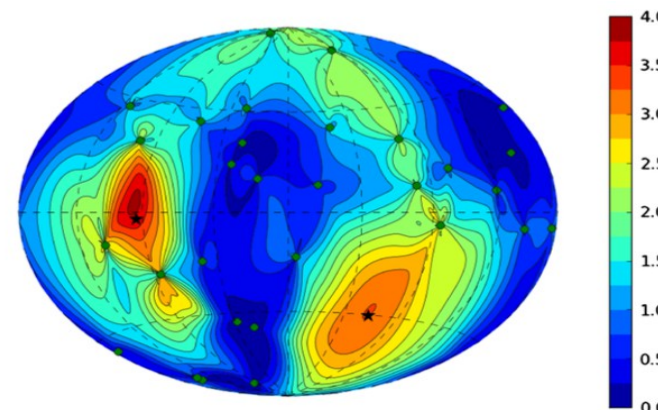
Need network of detectors/many pulsars (also to enhance detection confidence and minimize downtime)



BH-NS face-on at 160 Mpc (Fairhurst 2014)



2 sources, 5 pulsars



2 sources, 30 pulsars

Babak & Sesana (2012)

PTAs: to estimate sky location of N sources, 3 x N pulsars are needed

EM counterparts to GW sources?

- Would allow: - sky localization and detection confidence enhanced

  - redshift measurement, unavailable with GWs alone (no intrinsic energy scale in GR)

- Main suspect: short GRBs

  - Duration < 2s, energy up to 10^{54} erg, large Lorentz factor $\Gamma \gg 2$

  - Burst interaction with interstellar gas gives ”afterglow” → localization to arcmin (in X-rays) and to sub-arcsec (in optical and radio) scale → redshift measurements from optical spectroscopy of the afterglows and host galaxies → cosmological origin

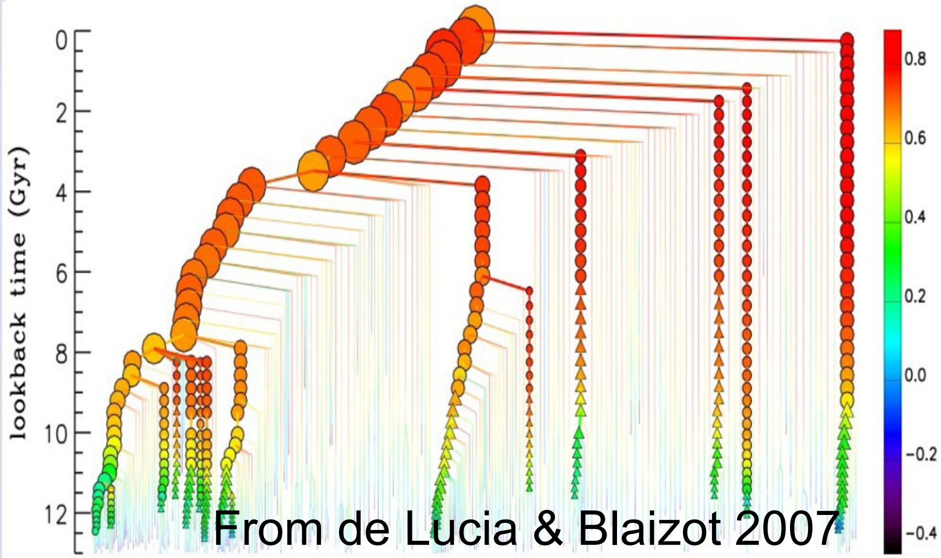
  - High-energy neutrino's production expected at same time as gamma

  - Possible models: NS-NS or NS-BH mergers, magnetar

- Goals: - GRB as triggers for GW searches (e.g. GRB 051103)

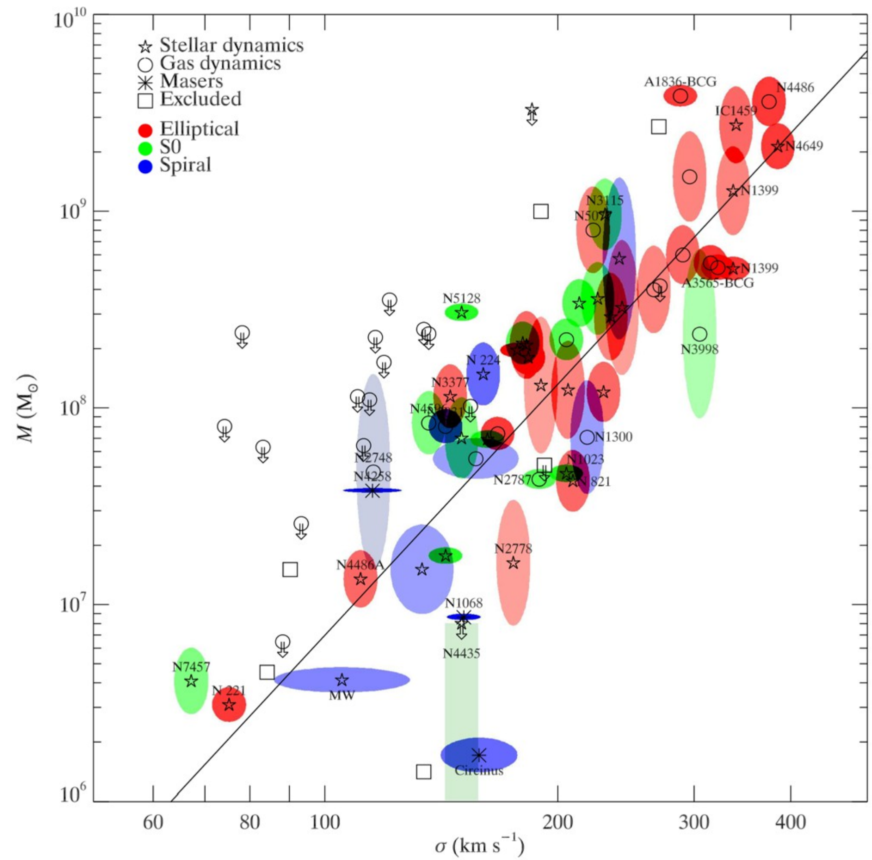
  - generate GW triggers to point telescopes in 10-100 sec to observe optical prompt emission, 100 sec-days for afterglow

Galaxy formation with PTAs and eLISA



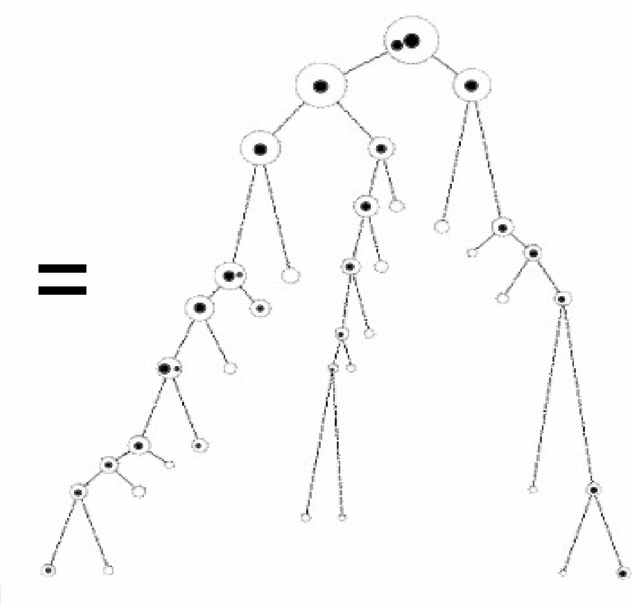
From de Lucia & Blaizot 2007

+



Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

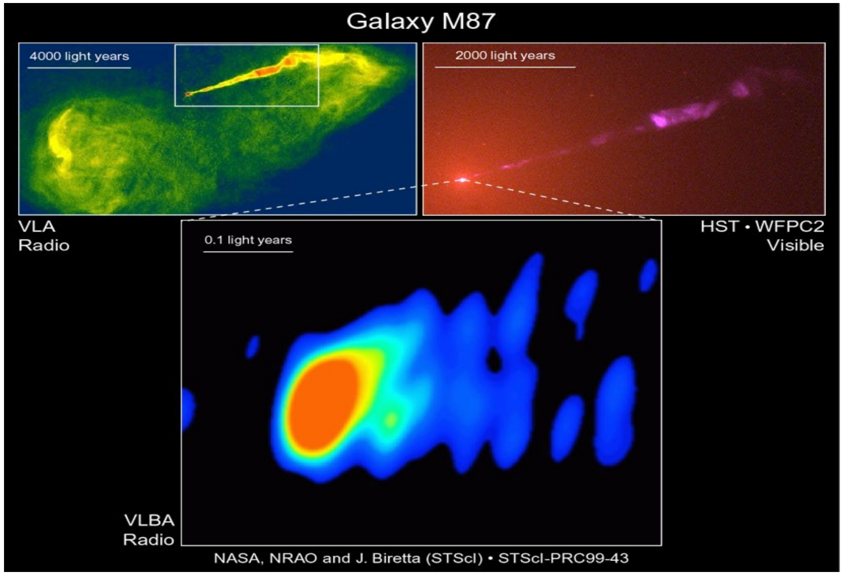
=

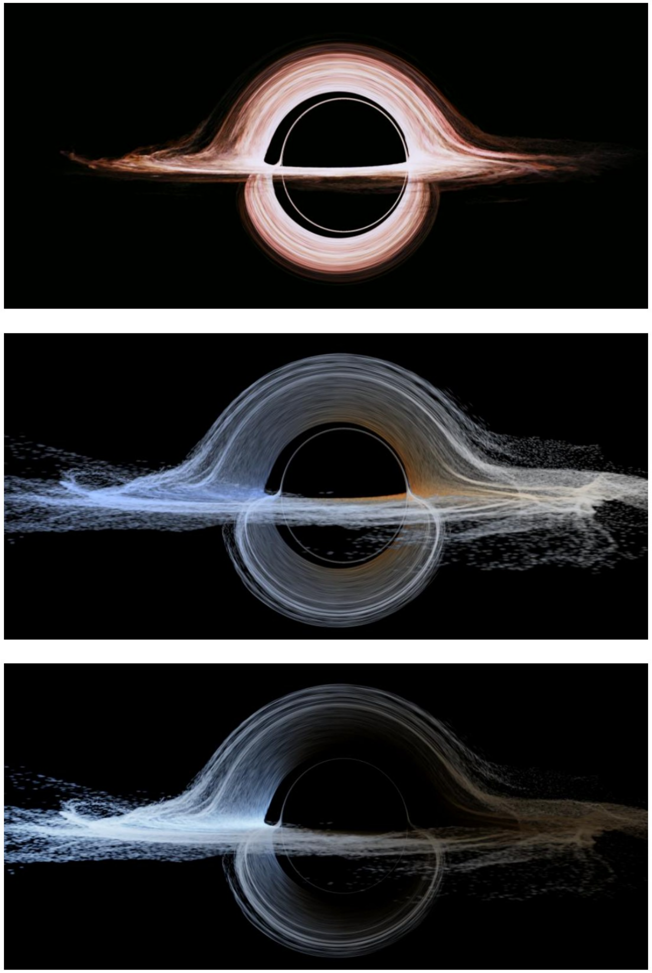


Credits: Marta Volonteri

What links galaxy ($\gtrsim$kpc) and SMBH ($\lesssim$pc) physics?

- Small to large: BH jets or disk winds transfer kinetic energy to the galaxy and keep it “hot”, quenching star formation (”AGN feedback”)

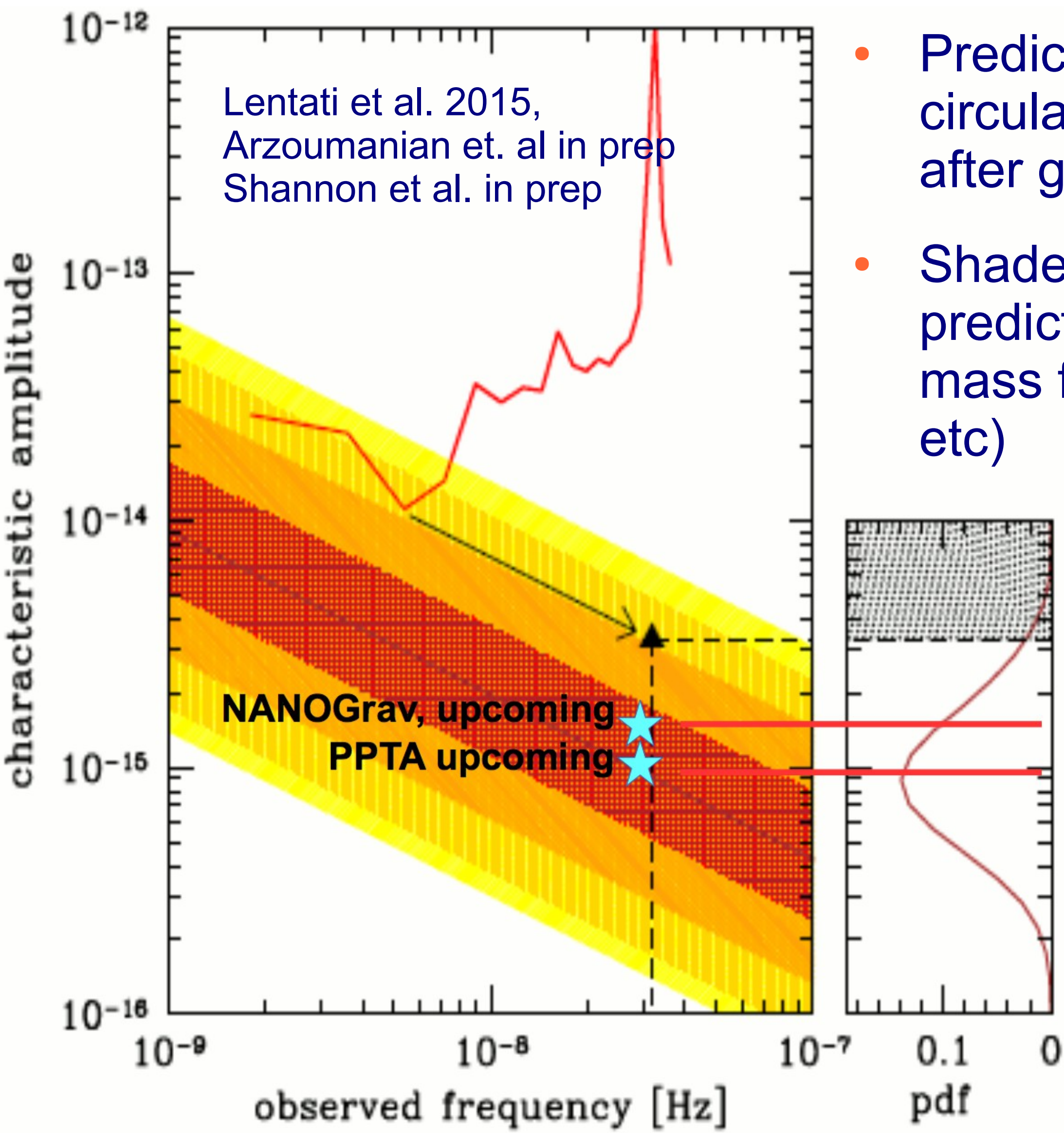




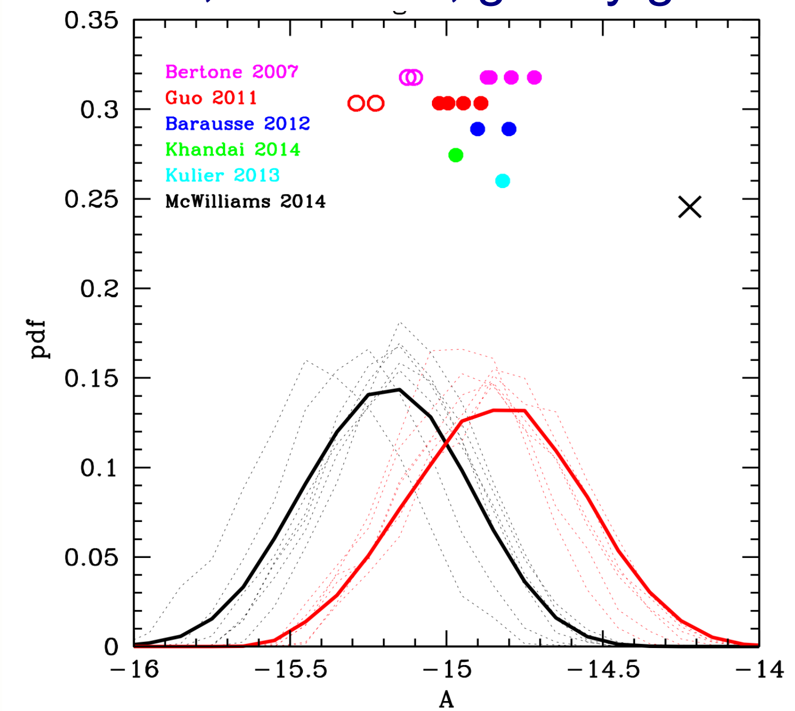
- Large to small: galaxies provide fuel to BHs to grow (”accretion”)

Figures from James at al 2015 (cf movie ”Interstellar”)

PTA limits on SMBH mergers



- Predictions (Sesana 2013) assume: circular orbits, efficient SMBH mergers after galaxy mergers
- Shades areas = confidence region of predictions (account for uncertainties on mass functions, accretion, galaxy growth etc)



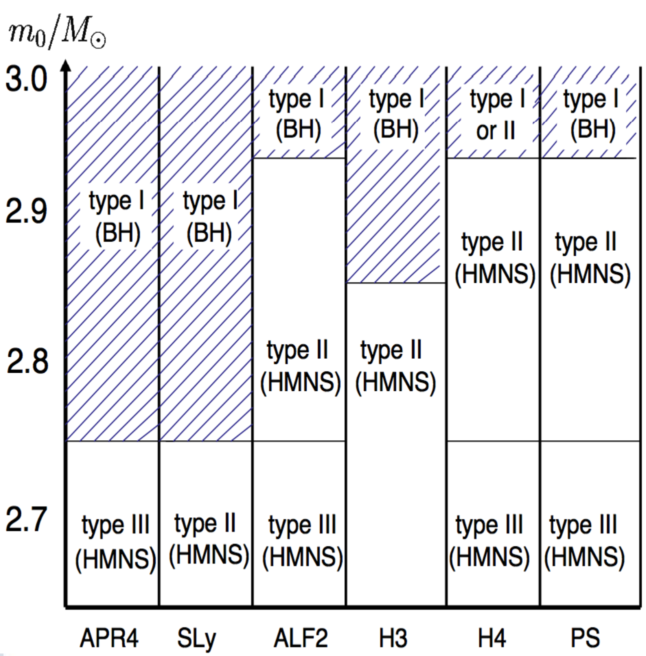
Figures courtesy of A. Sesana

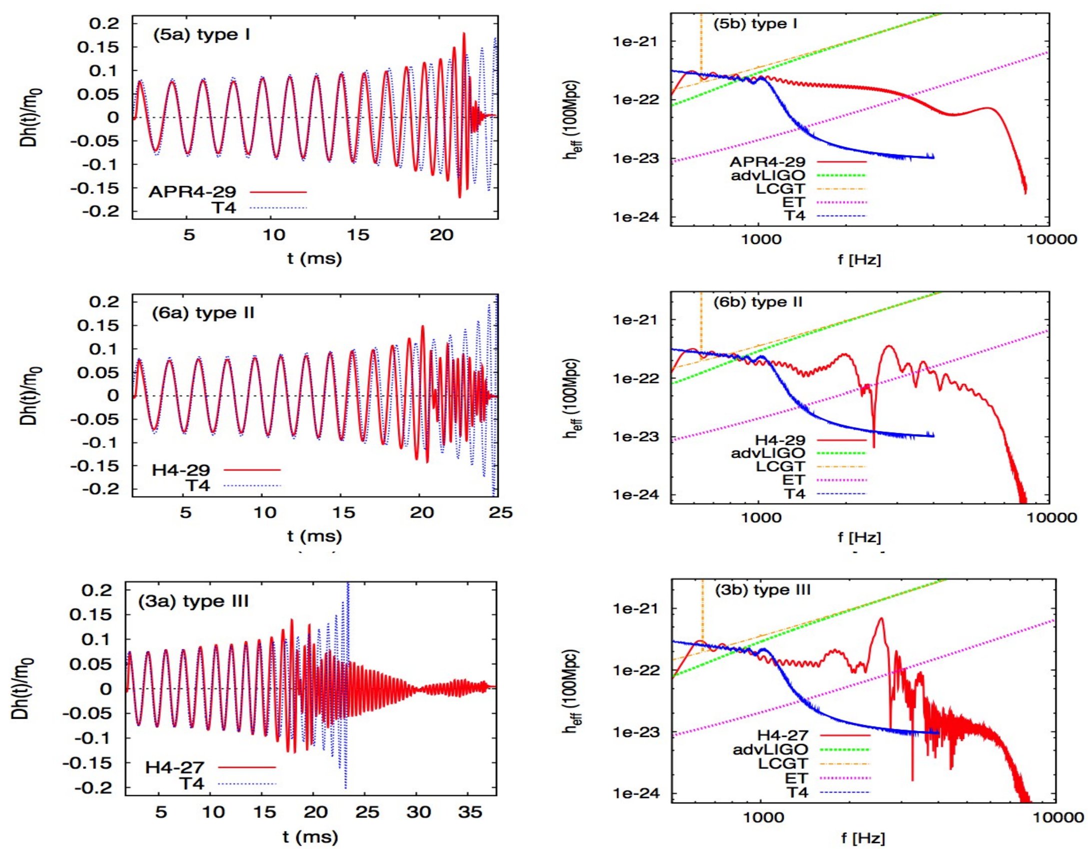
Exotic physics with GW detectors

- Measure nuclear matter EOS with NS mergers advanced detectors/ET)
- 3 possible outcomes: - BH is promptly formed (type I)

  - short-lived (< 5 ms) hypermassive NS (type II)

  - long-lived (> 5 ms) hypermassive NS (type III)

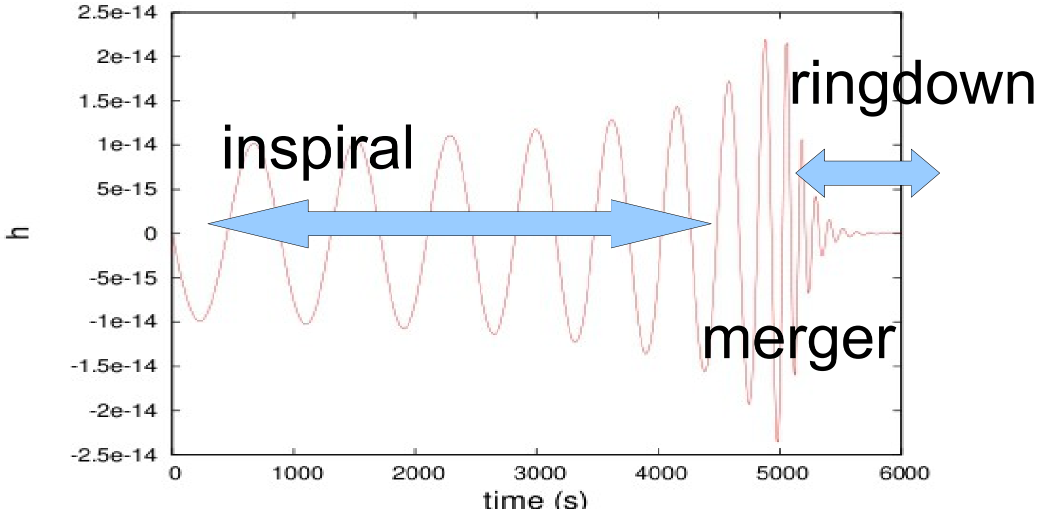




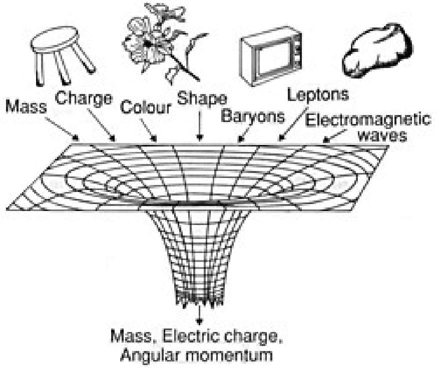
Figures from Hotokezaka et al (2011)

Exotic physics with GW detectors

- First order phase transitions (PTAs) and cosmic strings (eLISA)
- We believe we understand BH mergers and spin effects (analytically and numerically), but do we?



- Tests of the no hair theorem with BH ringdown...

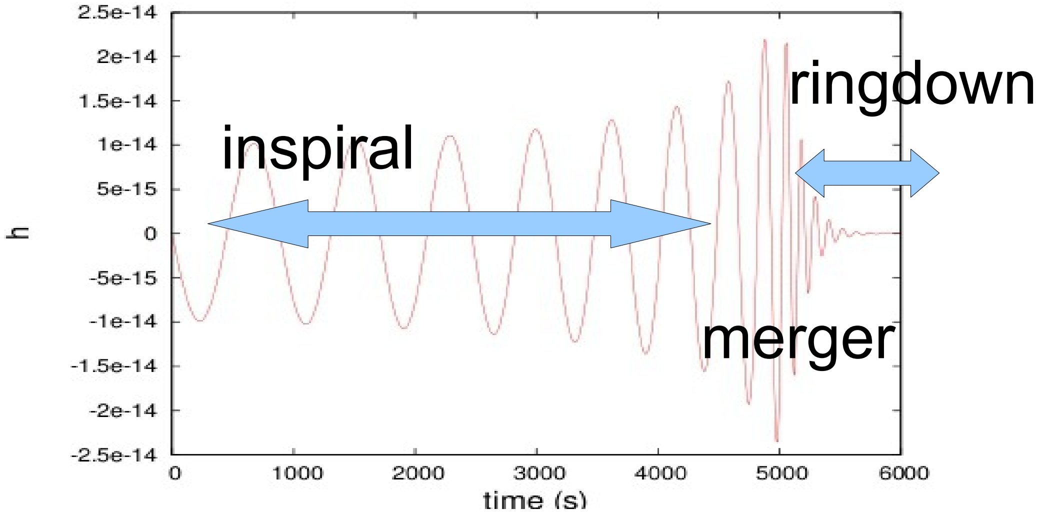


http://nonlocal.com/hbar/blackholes.html

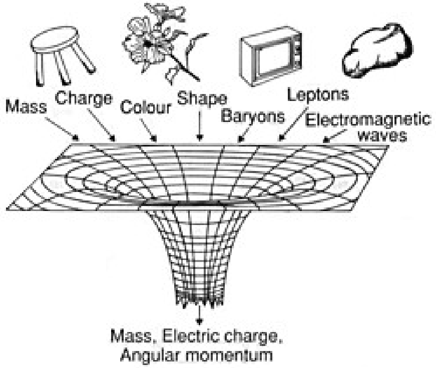
… or spacetime mapping (with eLISA)

Exotic physics with GW detectors

- First order phase transitions (PTAs) and cosmic strings (eLISA)
- We believe we understand BH mergers and spin effects (analytically and numerically), but do we?

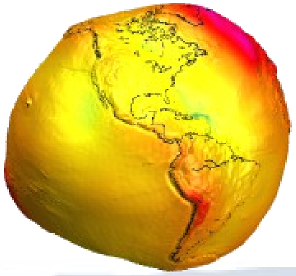


- Tests of the no hair theorem with BH ringdown...



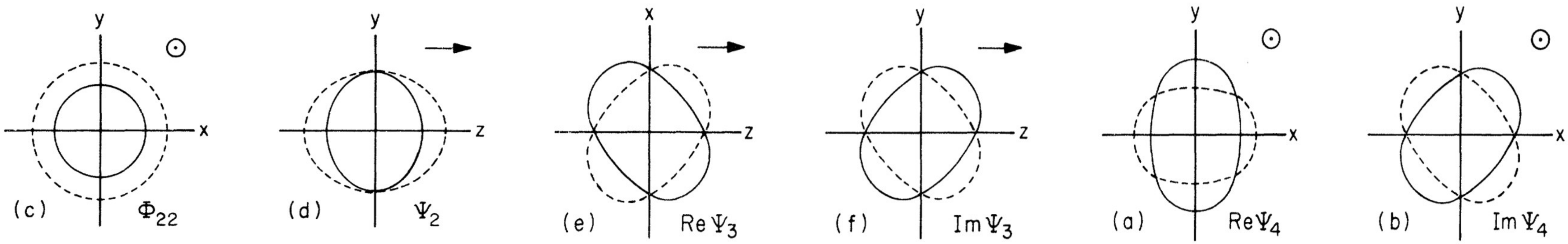
http://nonlocal.com/hbar/blackholes.html

… or spacetime mapping (with eLISA)



Beyond GR: more polarizations?

$$\Psi_2(u) \quad (s=0), \quad \Phi_{22}(u) \quad (s=0) \quad \Psi_3(u) \quad (s=\pm 1), \quad \Psi_4(u) \quad (s=\pm 2)$$



Figures from Eardley, Lee and Lightman 1973

e.g. dipolar emission if equivalence principle is violated (Brans-Dicke, scalar tensor theories, Lorentz-violating gravity, etc)

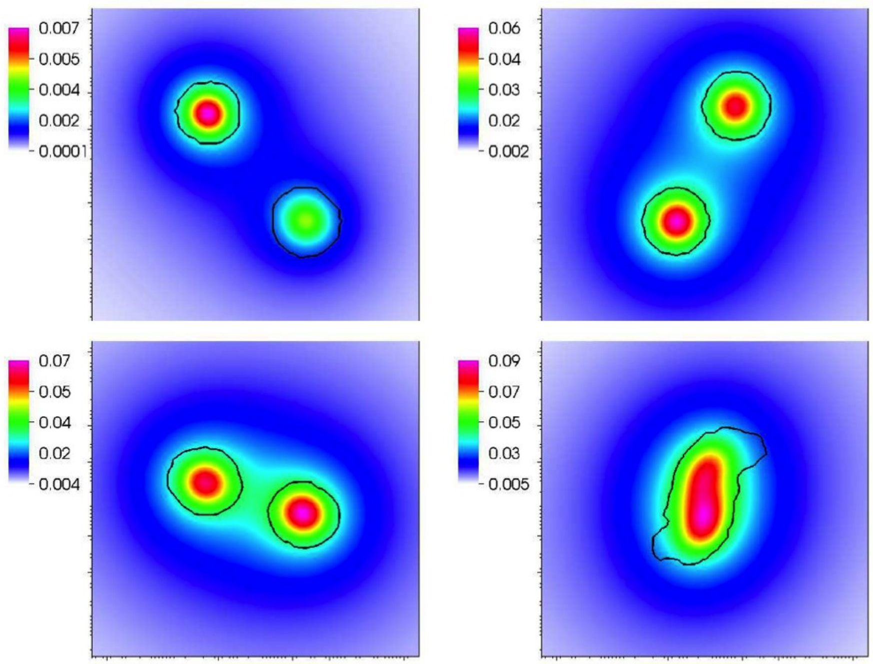
- Constraints from binary pulsars and PTAs.
- Testable with network of advanced detectors

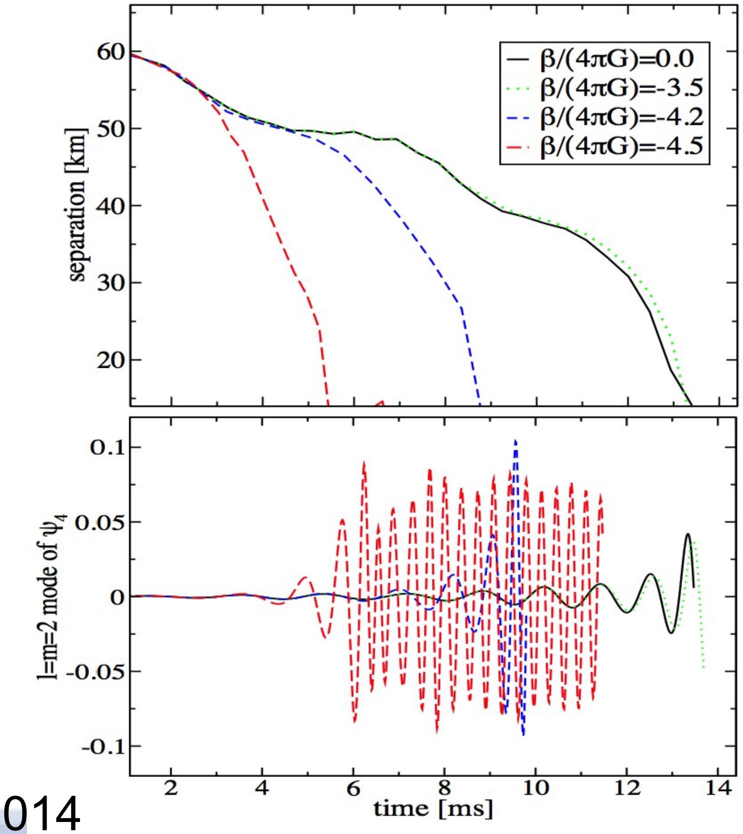
Beyond GR

- Test PN expansion during inspiral

$$\tilde{h}_{\rm ppE}(f) = \tilde{h}_{\rm GR}(f)\,(1+\alpha u^a)\,e^{i\beta u^b} \qquad u = (\pi\mathcal{M}f)^{1/3}$$

- Look for smoking-gun deviations (e.g. in some scalar tensor theories)





From EB, Palenzuela, Ponce and Lehner 2013, 2014

Conclusions

- GWs are a generic prediction of relativistic gravity theories (including GR!) because they follow from casual structure of such theories (nothing can propagate faster than light)
- GWs have been observed indirectly, and direct detection is imminent (terrestrial interferometers or PTAs)
- Existing and future detectors will cover complementary windows of the GW spectrum allowing for

  - Test of the strong field/highly relativistic dynamics of GR

  - Coincident detection with EM and neutrino telescopes

  - Tests of stellar physics and galaxy formation models

  - Test of gravitational theories beyond GR

Conclusions

- GWs are a generic prediction of relativistic gravity theories (including GR!) because they follow from casual structure of such theories (nothing can propagate faster than light)
- GWs have been observed indirectly, and direct detection is imminent (terrestrial interferometers or PTAs)
- Existing and future detectors will cover complementary windows of the GW spectrum allowing for

  - Test of the strong field/highly relativistic dynamics of GR

  - Coincident detection with EM and neutrino telescopes

  - Tests of stellar physics and galaxy formation models

  - Test of gravitational theories beyond GR

Most of all, expect surprises!

Thank you!

Problem: SMBHs are tiny!

SMBH ~ 10^{-6} – 10^{-7} pc

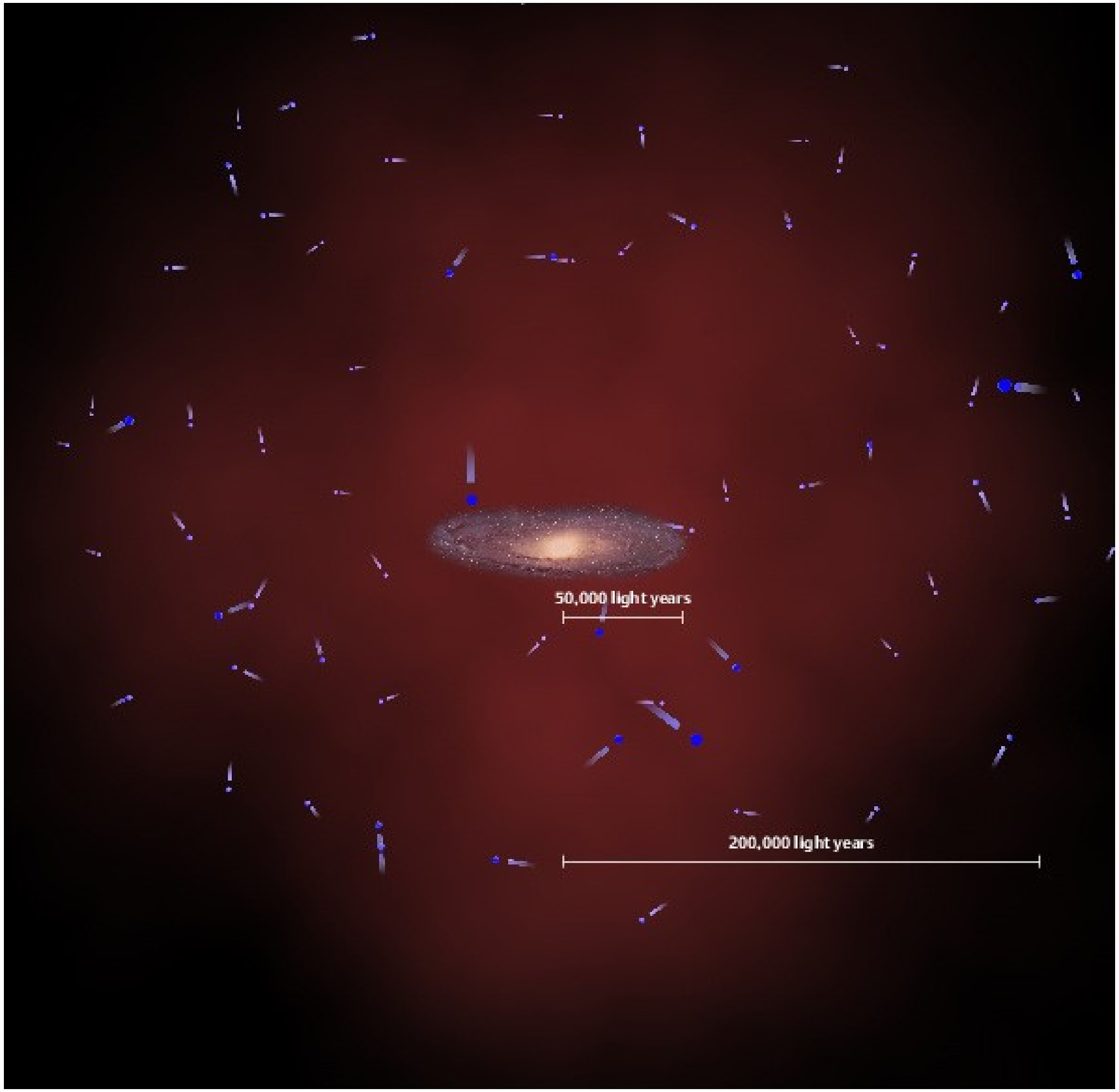
SMBH accretion disk ~ pc

Circumbinary disk ~ 100 pc

Galactic bulge ~ kpc

Galactic disk ~ 10 kpc

Dark-matter halo ~ Mpc



Synergy with EM astronomy

- If EM counterparts exist, they will dramatically improve sky localization and enhance detection confidence
- Main suspect given by short GRBs (duration < 2 s)

  - Isotropic equivalent energy up to 10^{54} erg

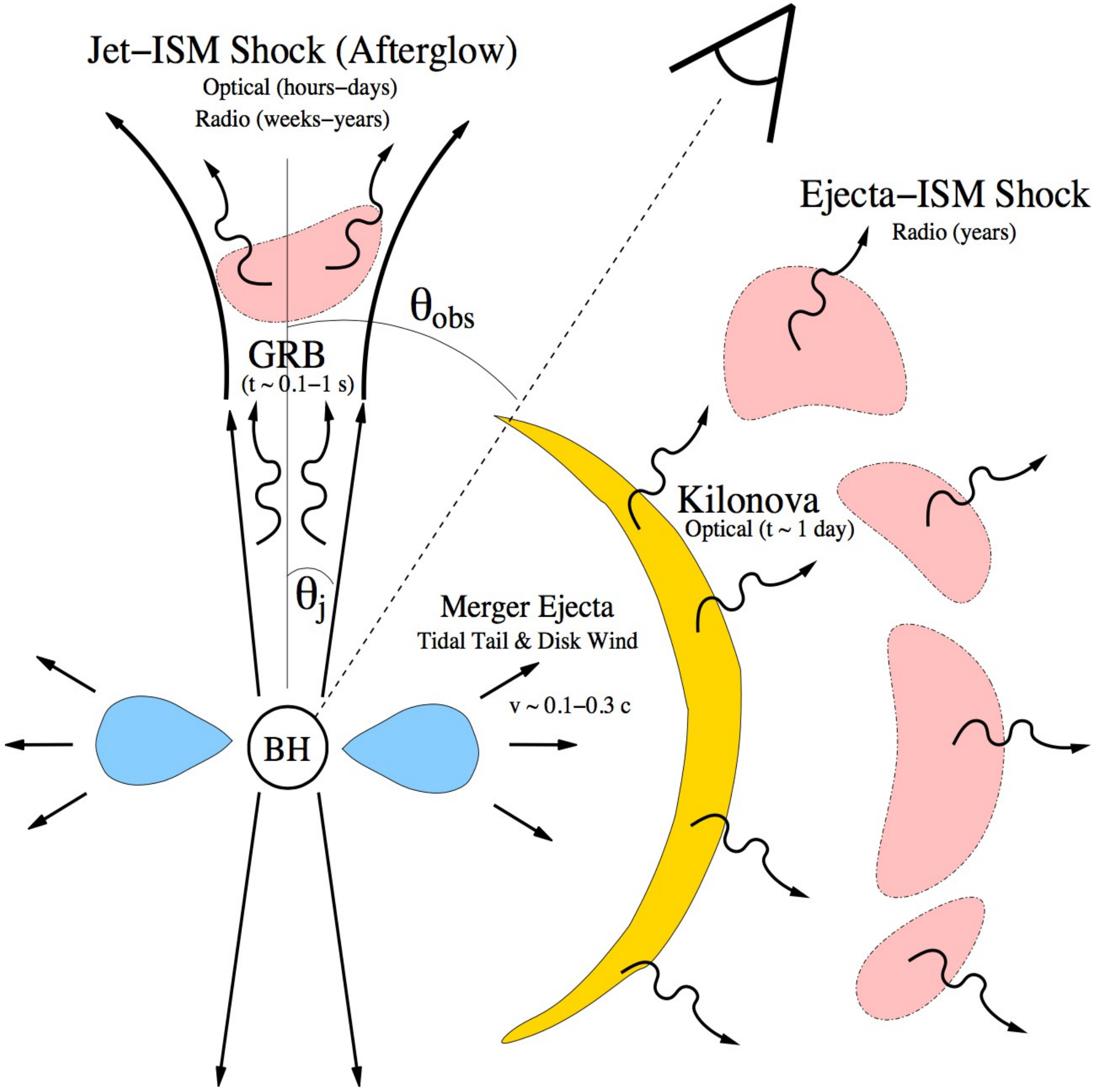
  - Large Lorentz factors ($\Gamma \gg 2$) to explain spectrum

  - Afterglow $\Rightarrow$ localization to arcminute (in X-rays) and to sub-arcsecond (in optical and radio) scale $\Rightarrow$ redshift measurements from optical spectroscopy of the afterglows and host galaxies $\Rightarrow$ cosmological origin

  - High-energy neutrino's production expected

  - Possible models: NS-NS or NS-BH mergers, magnetar

A sGRB's anatomy



From Metzger and Berger (2012)

- GRB as triggers for GW searches (e.g. GRB 051103)

- Goal: generate GW triggers to point telescopes within 10-100 sec to to observe optical prompt emission, 100 sec-days for afterglow

- EM counterpart will allow redshift measurement, which is not obtainable with GWs alone (no intrinsic energy scale in GR, unlike in atomic emission lines)

- GWs will measure luminosity distance → cosmography?

SMBH mergers with eLISA

Arm	Noise	Links	Config ID	Precession+ HH						restricted 2PN					
				popI		Q3-nod		Q3-d		popI		Q3-nod		Q3-d	
				all	$z > 10$	all	$z > 10$	all	$z > 10$	all	$z > 10$	all	$z > 10$	all	$z > 10$
A1	N1	L4	L4A1M5N1	28.4	0.0	90.6	0.7	11.9	0.0	35.4	0.1	193.5	11.2	24.0	0.1
		L6	L6A1M5N1	48.8	0.2	132.5	2.7	16.6	0.0	56.1	0.2	262.0	23.9	29.2	0.0
	N2	L4	L4A1M5N2	97.2	1.5	441.2	91.5	36.7	0.5	96.3	1.5	519.1	164.3	39.1	0.5
		L6	L6A1M5N2	157.6	6.7	485.9	131.6	39.2	0.6	152.4	5.7	570.5	193.9	40.4	0.7
A2	N1	L4	L4A2M5N1	70.6	0.6	179.4	8.3	21.1	0.1	69.5	0.4	316.7	49.9	31.1	0.1
		L6	L6A2M5N1	118.7	3.3	243.8	20.7	26.6	0.2	120.3	2.5	398.2	80.7	36.8	0.3
	N2	L4	L4A2M5N2	233.1	20.2	493.0	140.9	38.9	0.5	223.4	17.6	557.5	188.6	39.9	0.7
		L6	L6A2M5N2	356.8	51.8	548.6	176.0	40.2	0.6	359.3	50.8	593.8	211.9	40.4	0.7
A5	N1	L4	L4A5M5N1	153.9	6.8	333.0	52.3	32.8	0.3	149.1	6.5	470.8	128.6	38.7	0.6
		L6	L6A5M5N1	246.6	23.0	406.4	83.1	36.4	0.4	245.9	22.1	533.0	164.5	39.9	0.7
	N2	L4	L4A5M2N2	510.7	112.3	555.6	183.8	40.0	0.7	507.6	112.6	602.4	219.0	40.4	0.7
		L6	L6A5M2N2	657.4	177.0	589.0	207.4	40.4	0.7	665.8	179.4	610.2	224.9	40.4	0.7

- Armlength:
  - 1 million kilometer (A1)
  - 2 million kilometer (A2)
  - 5 million kilometer (A5)
- Low frequency acceleration noise
  - LISA original requirement (N2)
  - 10 times worse than LISA original requirement (N1)

A. Klein, EB et al in prep.

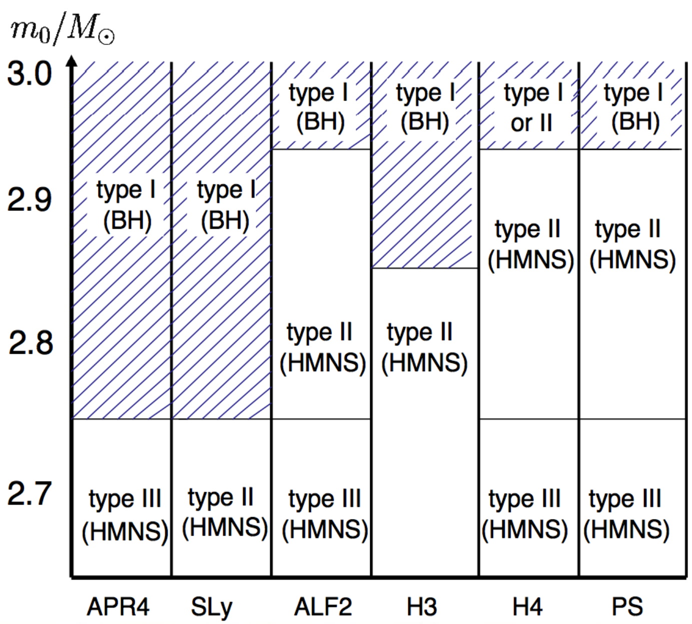
Exotic physics with GW detectors

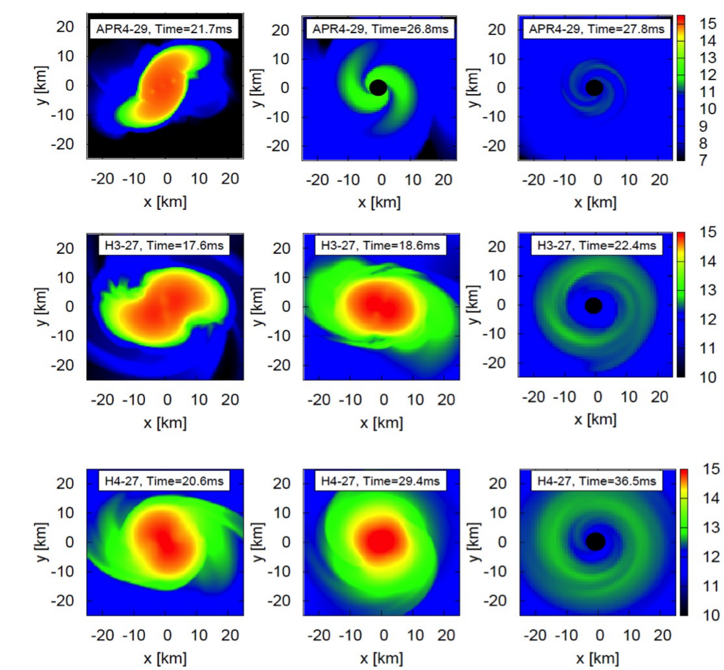
- Measure nuclear matter EOS with NS mergers (with advanced detectors, but most likely with ET)
- 3 kinds of NS mergers:

  - Type I: BH is promptly formed

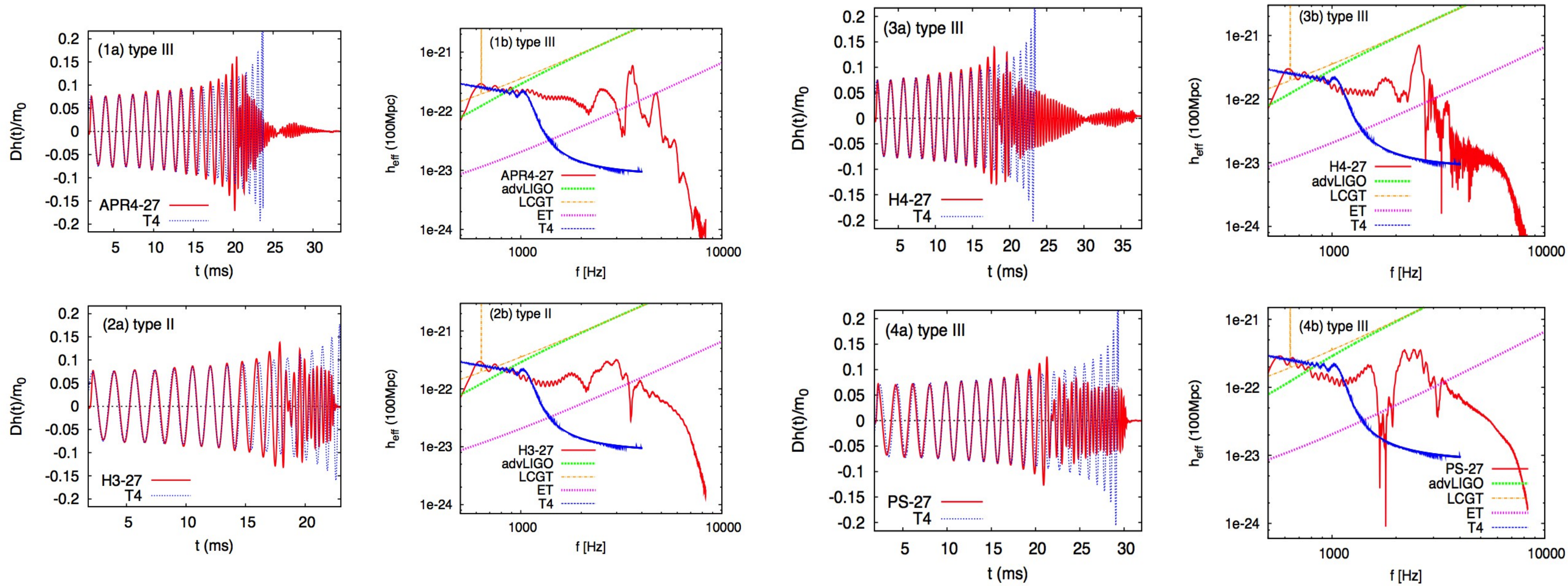
  - Type II: short-lived (< 5 ms) hypermassive NS

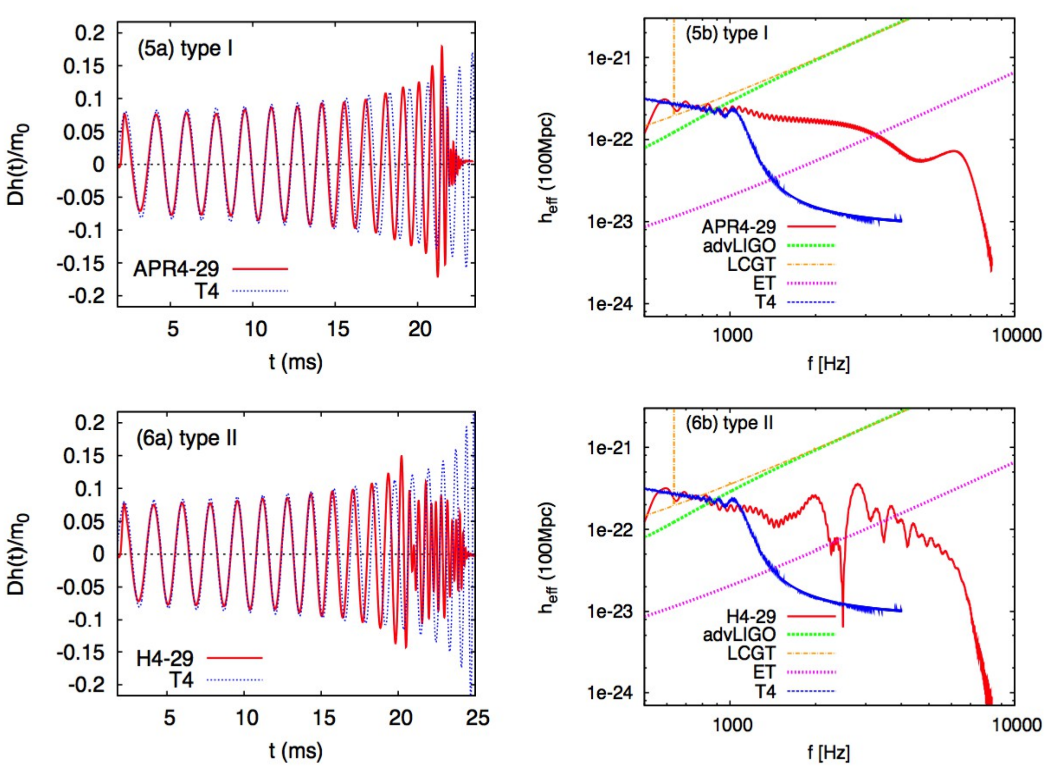
  - Type III: long-lived (> 5 ms) hypermassive NS





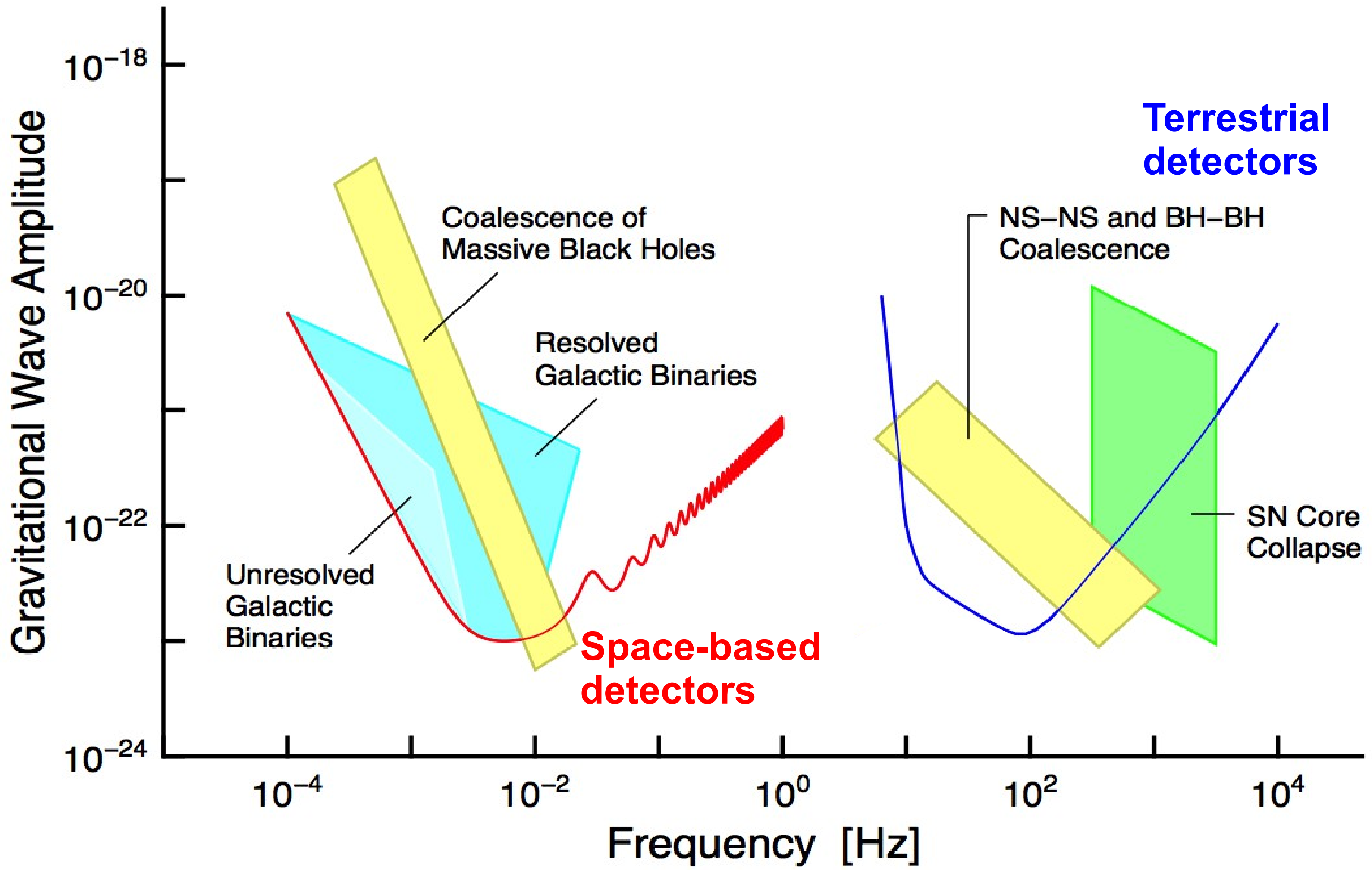
Figures from Hotokezaka et al, PRD 83 124008 (2011)





Figures from Hotokezaka et al, PRD 83 124008 (2011)

Binaries as GW sources



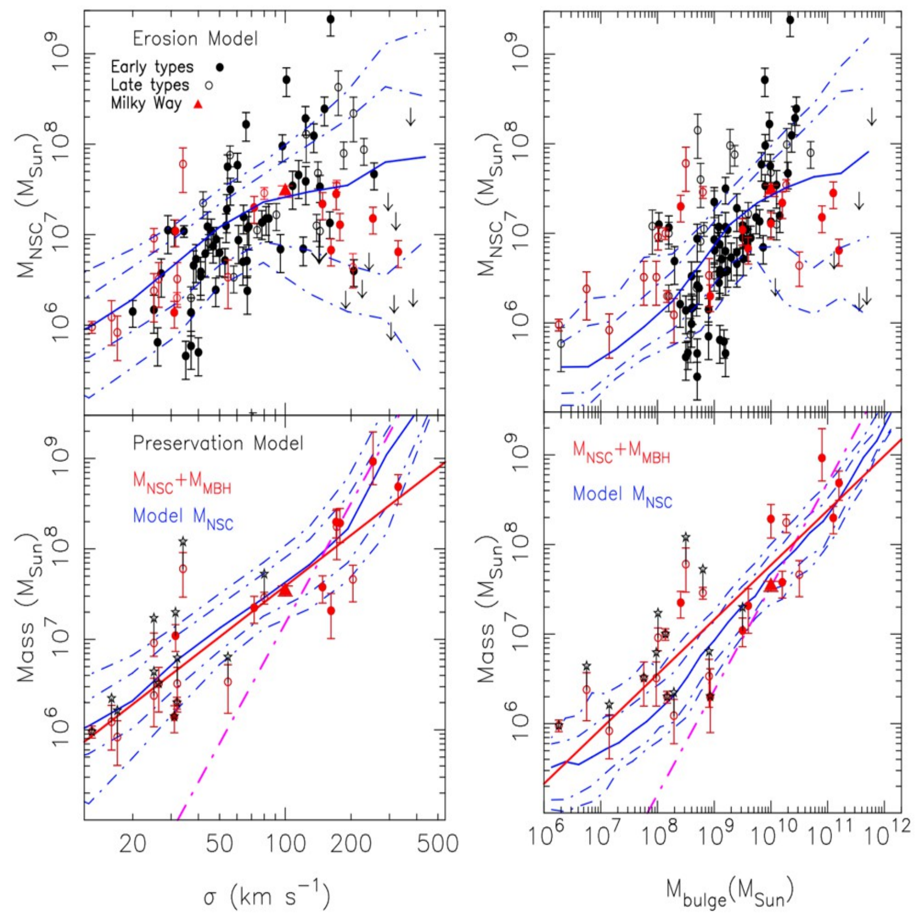
Hints of SMBH binaries in observations

- Dual AGNs (but separation ~ kpc)
- Scaling relations of nuclear star clusters ($M \sim 10^7\,M_{sun}$, r ~ pc)

SMBH binaries erode nuclear star clusters by ejecting hypervelocity stars

Mass deficit comparable to binary mass

$$M_{ej} \approx 0.7 q^{0.2} M_{bin} + 0.5 M_{bin} \ln\left(\frac{a_h}{a_{gr}}\right) + 5 M_{bin} \left(V_{kick}/V_{esc}\right)^{1.75} ,$$



Antonini, EB, Silk 2015

Why GW source modelling?

- GWs typically buried in noise: to dig it out, we must know what it sounds like
- Technique is called matched filtering: cross correlate detector's output with bank of templates describing possible sources with all possible parameters

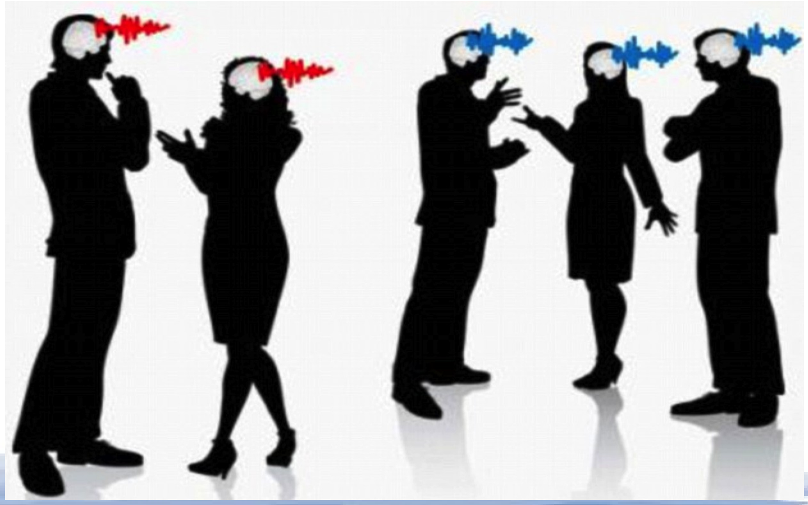
⟶ need good templates!

Why GW source modelling?

- GWs typically buried in noise: to dig it out, we must know what it sounds like
- Technique is called matched filtering: cross correlate detector's output with bank of templates describing possible sources with all possible parameters

  → need good templates!

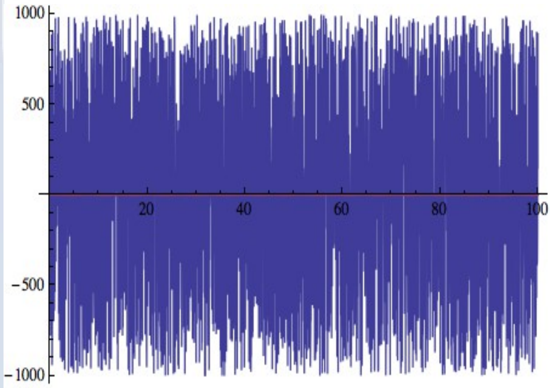
- Human brain is great at match filtering sounds! ("cocktail party problem")

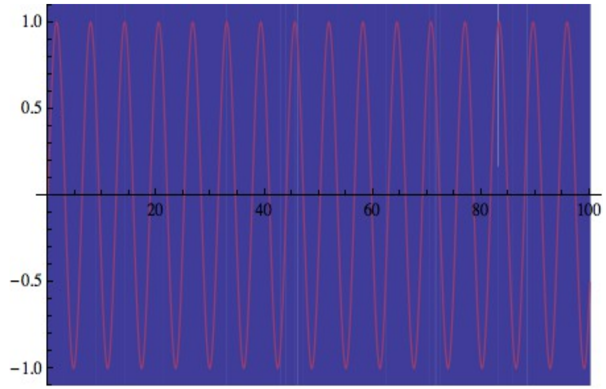


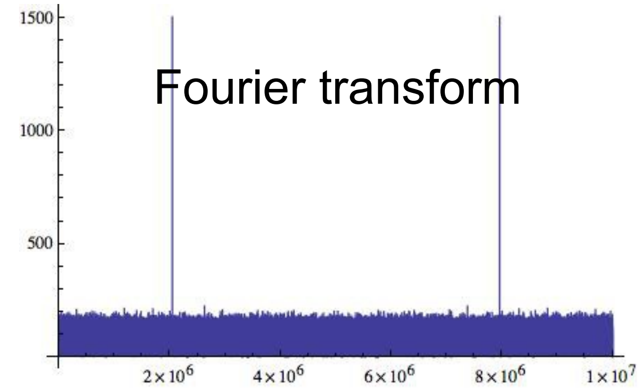
How to dig signal out of noise?

Matched filtering: cross correlate detector's output with bank of templates describing possible sources with all possible parameters

Elementary example







$$(h_1, h_2) \equiv 2\int_0^\infty \frac{\tilde{h}_1^*(f)\tilde{h}_2(f) + \tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)} df$$

$$= \int \int h_1(t) h_2(\tau) w(t-\tau) dt\, d\tau ,$$

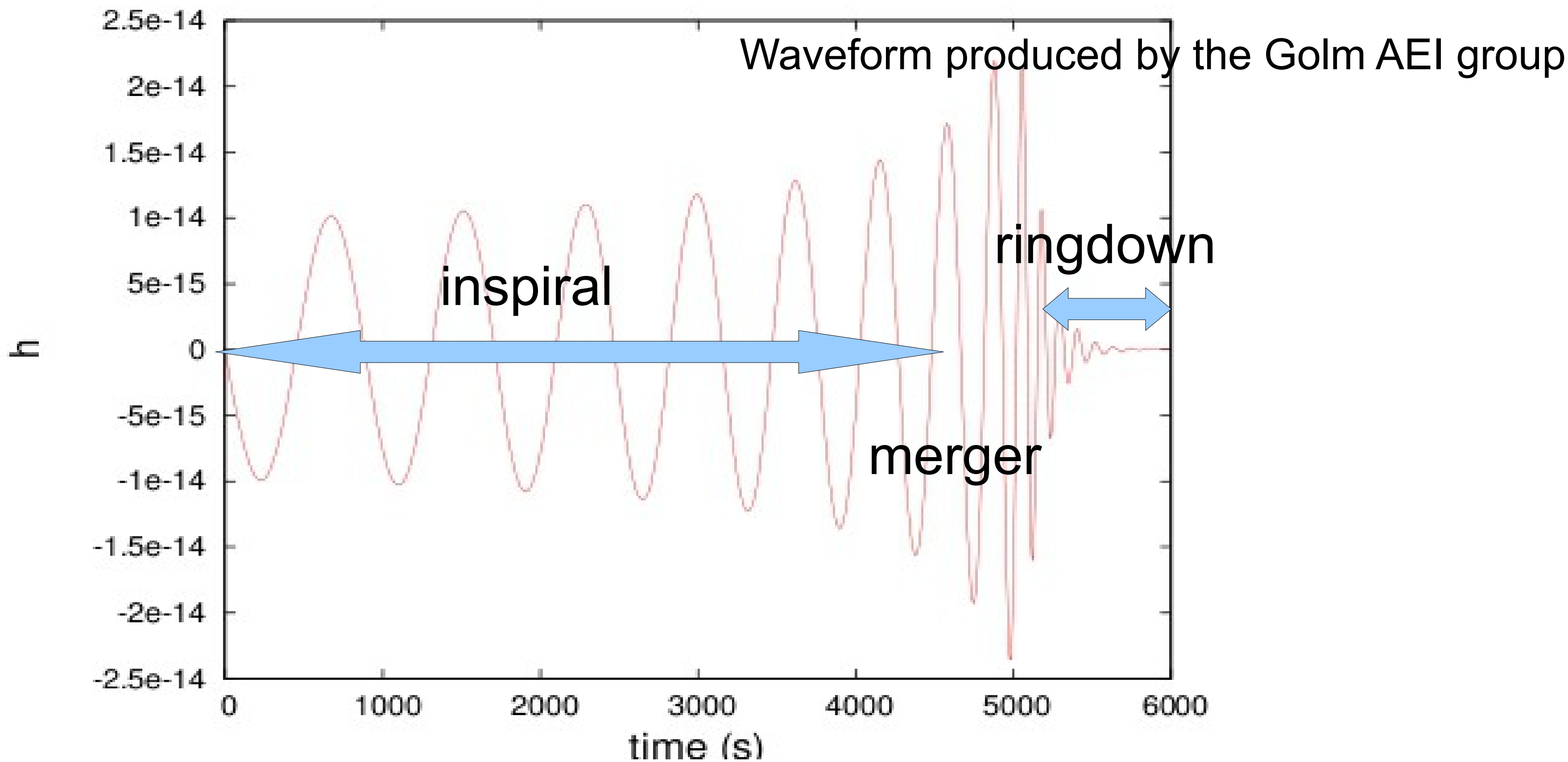
$$\text{with} \quad \tilde{w}(f) = 1/S_n(f)$$

Look for template h(t) that maximizes overlap with signal s(t) [ideally, *O(s,h)=1*]

$$O(s,h) = \frac{(s,h)}{(h,h)}$$

Need good templates!

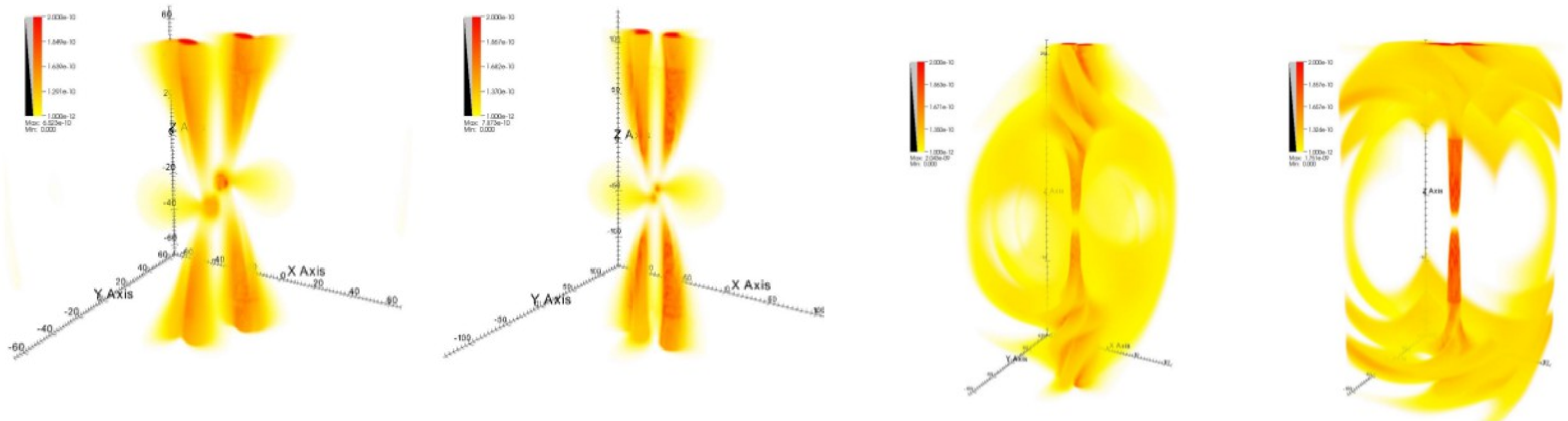
Binary BHs on a computer (aka numerical relativity)



It takes weeks/months to generate numerical-relativity (NR) waveforms: too slow for data analysis!

Jets are produced produced by BHs!

- Jets can be produced by isolated spinnning BHs in a magnetic field anchored to accretion disk (Blandford & Znajek 1977)...
- … or by BHs (even non spinning ones) moving a magnetic fields anchored to circumbinary disk (Palenzuela, Lehner and Liebling 2010)



(a) $-11.0\, M_8$ hrs (b) $-3.0\, M_8$ hrs (c) $4.6\, M_8$ hrs (d) $6.8\, M_8$ hrs