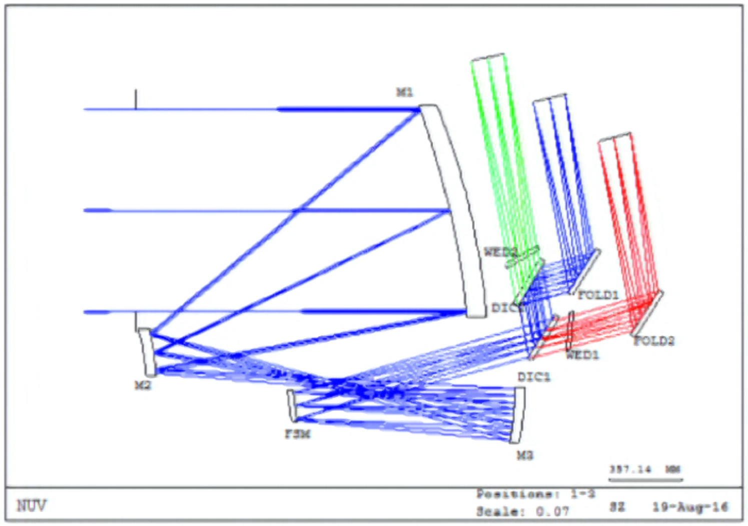
Title: Challenges and opportunities in Gravitational Wave Astronomy

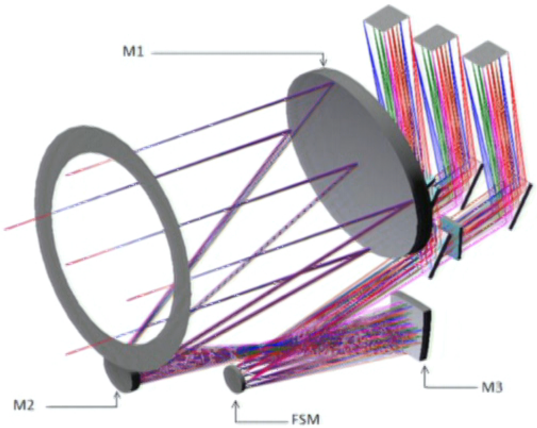
Date: May 08, 2018 03:00 PM

URL: http://pirsa.org/18050048

Abstract:

Optical Design





- Input aperture: 1 m
- FOV: 0.473 deg x 0.473 deg
- Image Size: 165.3 mm x 165.3 mm
- Common input optics, including a fine steering mirror located at the pupil
- Three spectral bands
  - NUV-band: 150-303 nm
  - U-band: 337-411 nm
  - G-band: 414-559 nm
- Common FOV for all three bands
- Three separate focal planes
- Band separation via two dichroics
- Band definition via interference filters for the U and g bands and reflective coating for NUV band
- Custom broadband coating on the TMA mirrors to reduce red signal

Cosmic messengers

- Electromagnetic waves

- Neutrinos (e.g SN1987a), high energy cosmic rays

- *Gravitational waves*

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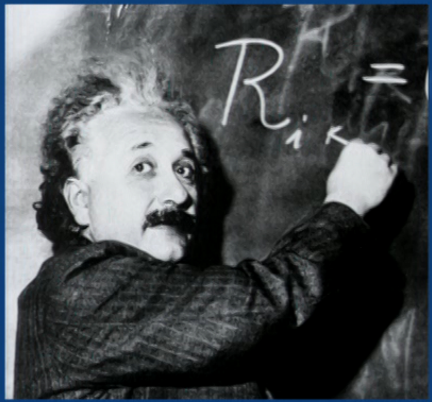
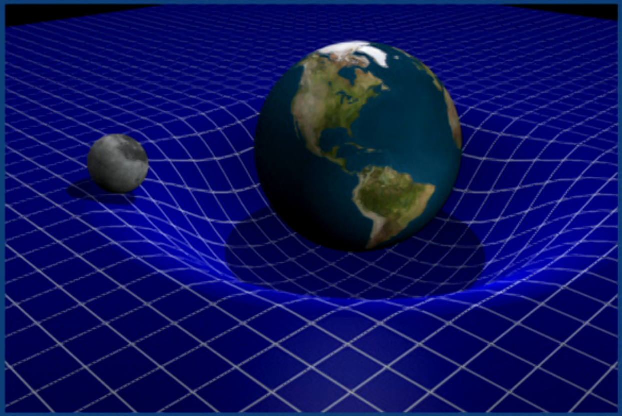
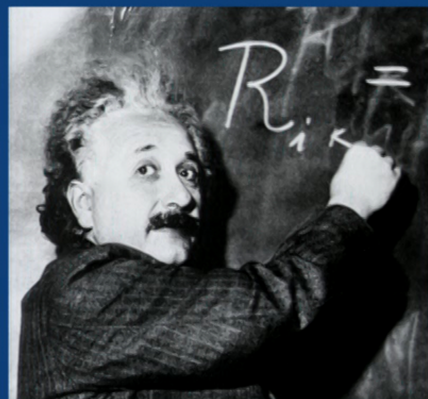
Einstein (1915) goes rogue

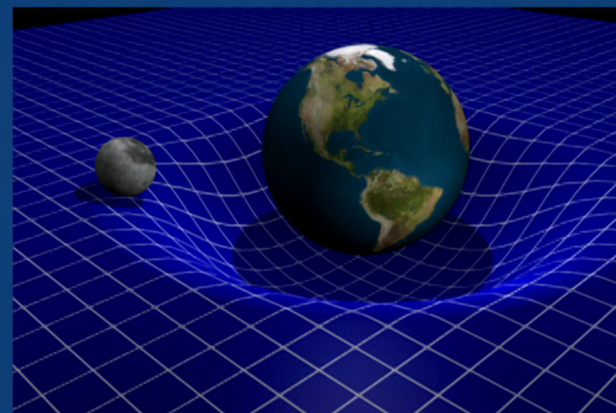




- Mass/energy curve spacetime. Higher densities → stronger curvatures

Einstein (1915) goes rogue





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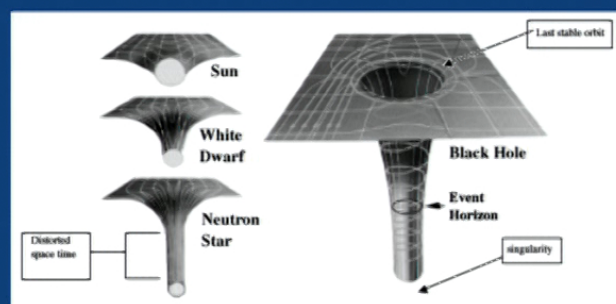
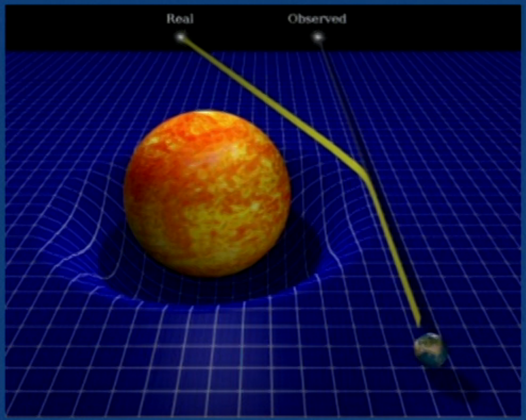
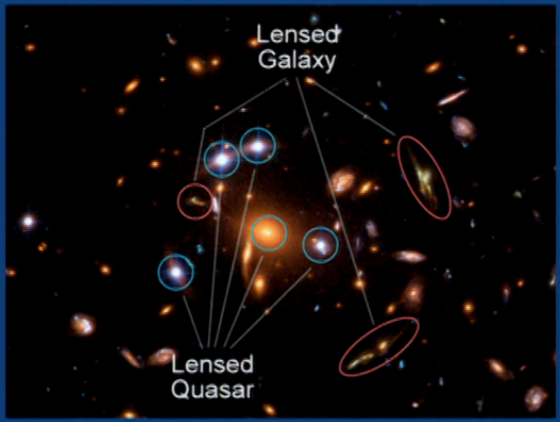


Exploiting gravity to learn about our universe

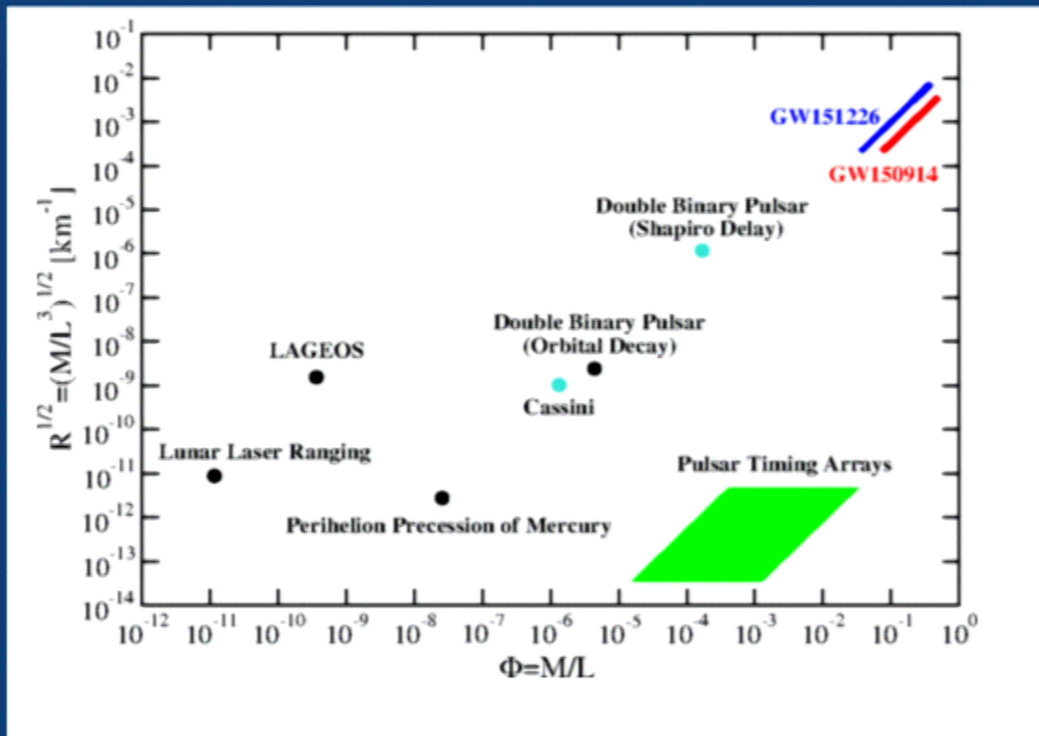
- An early prediction of GR : curved spacetime → bending of light: 'gravitational lens'





- E.g. 'Dark Matter' and more recently exoplanets are inferred through lensing observations.
- *"practical" and "fundamental" qns adressed*

Constraints for GR

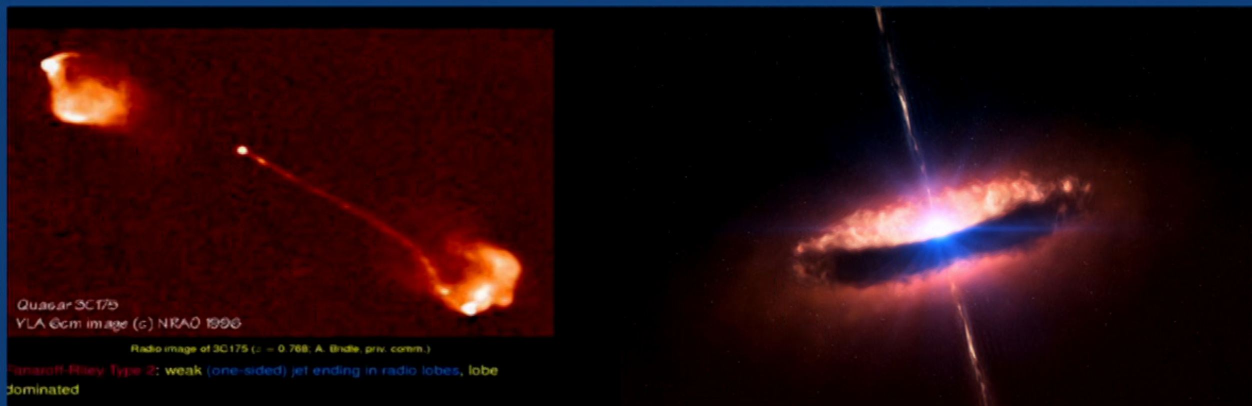


[figure from Yunes,Yagi,Pretorius'16]

Black hole basics [in GR!]

- Stationary BHs are uniquely described by 2 parameters: mass (M) and angular momentum parameter (a).
- 1-way membrane at R = 2M (a=0), R=M (a/M=1)
- No stable circular orbits if $r < R_{ISCO}$
- Max energy extractable from a rotating BH: 29%M
- Stable.... *for massless perturbations,* and all modes tightly defined in terms of (M,a)

- *Black holes in astrophysics*: as key ingredients of AGNs, GRBs, modulating galaxy behavior....



- *But much beyond...* : holography (AdS/CFT), CMT, quantum information, turbulence, chaos....

- *Black holes in astrophysics*: as key ingredients of AGNs, GRBs, modulating galaxy behavior….

- *But much beyond…* : holography (AdS/CFT), CMT, quantum information, turbulence, chaos….

‘numerology’: energetic events in the universe

- Sun: ~ 4 10^{33} ergs/s [fusion H→ H_e]
- Supernovae: ~ $10^{42\text{-}44}$ erg/s [fusion/collapse-binding energy] (~ 1 galaxy, $10^{10\text{-}11}$ L_{sun})
- GRB : ~ (?) $10^{49\text{-}51}$ ergs/s [? binding energy?] (~ whole universe, ~ 10^{16} L_{sun}). 1 NS → energy ~ 10^{54} erg

---- even more radical: Planck luminosity: c^5/G ~ 10^{59}erg/s

can BH collisions tap itss?

General Relativity: Gravity waves

At weakly curved regionsg = flat + h

G_{ab} → Box(h) = -16π T (with T: stress energy tensor)

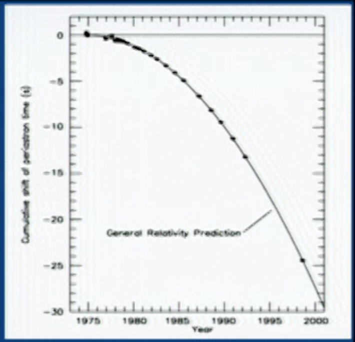
- Far from ‘source’ (T=0) → solutions are travelling waves, which are transversal to propagating direction (only 2 polarization modes [massless graviton]

- Generation? Assume an expansion on *(v/c) & M/r* and arrive at: $h \sim G/c^4\, Q_{,tt}$ with Q the source quadrupole: [mass & momentum are conserved in GR]

Why go after gravitational waves?

- Is GR consistent in systems with M/R ~ 1, v/c ~ 1?
- Population (and existence) of black holes, NSs. *masses, spins, location*
- Behavior of cold (and hot) matter at supra nuclear densities
- Combine & complement astro-observations with EM and particle efforts (sGRB origin?)
- *Surprises!* [Exotic objects? Non-standard gravity?...]

Source estimation

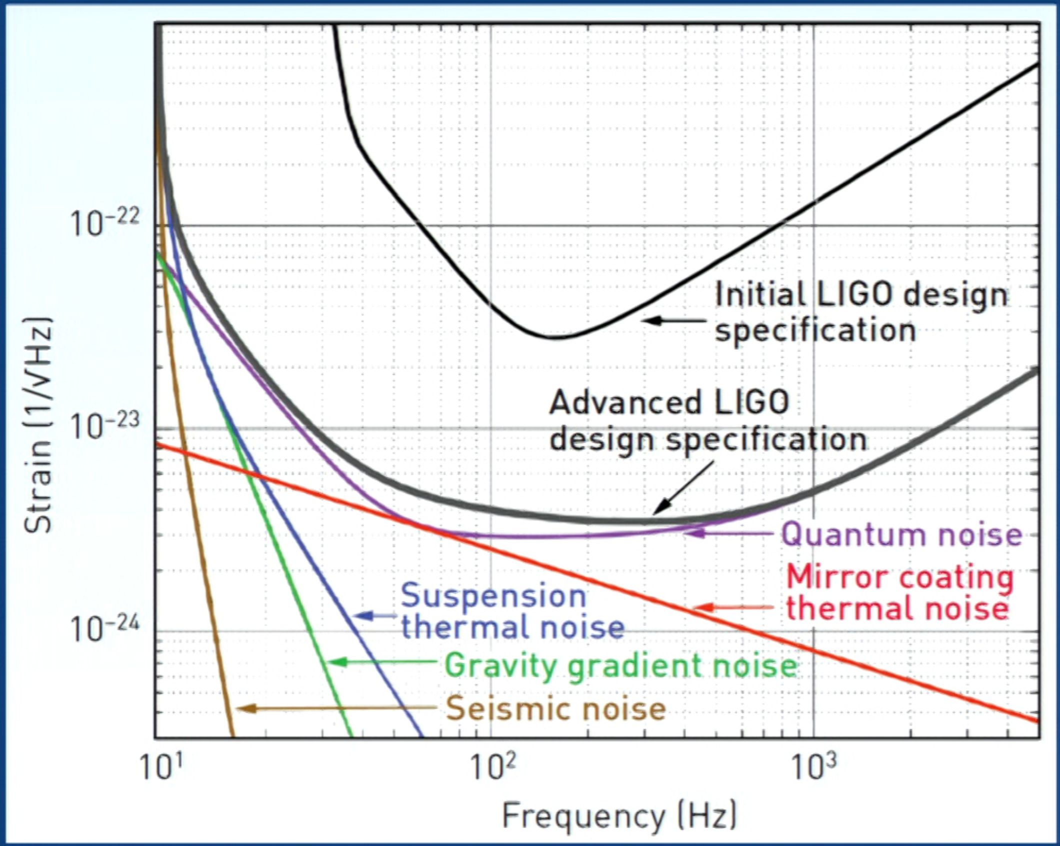


- Characteristic strain:
  - $h \sim (GM/Rc^2)\ (GM/rc^2)$
  - (h ~ grav potential from source x grav pot at observer)

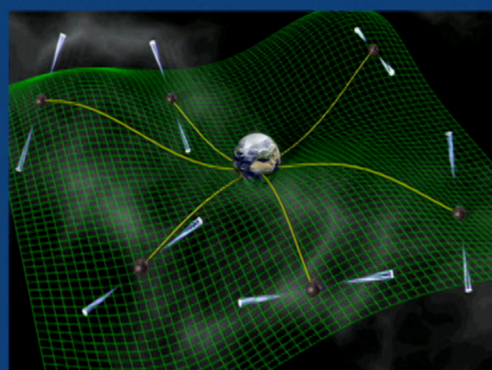
- Luminosity: $L \sim (c^5/G)\ (G\ M/Rc^2)^5$
  - (ie. Planck luminosity times 'source compaction')

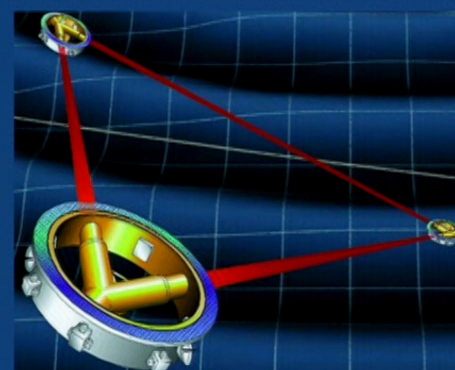
- Example: equal mass *NS binary*
  - $h \sim 10^{-21}\ (15\text{Mpc}/r)\ (M/2.8M_O)^2\ (90\text{km}/R)$
  - $f \sim (M/2.8M_O)^{1/2}\ (90\text{km}/R)^{3/2}\ 100\ \text{Hz}$

LIGO's noise curve



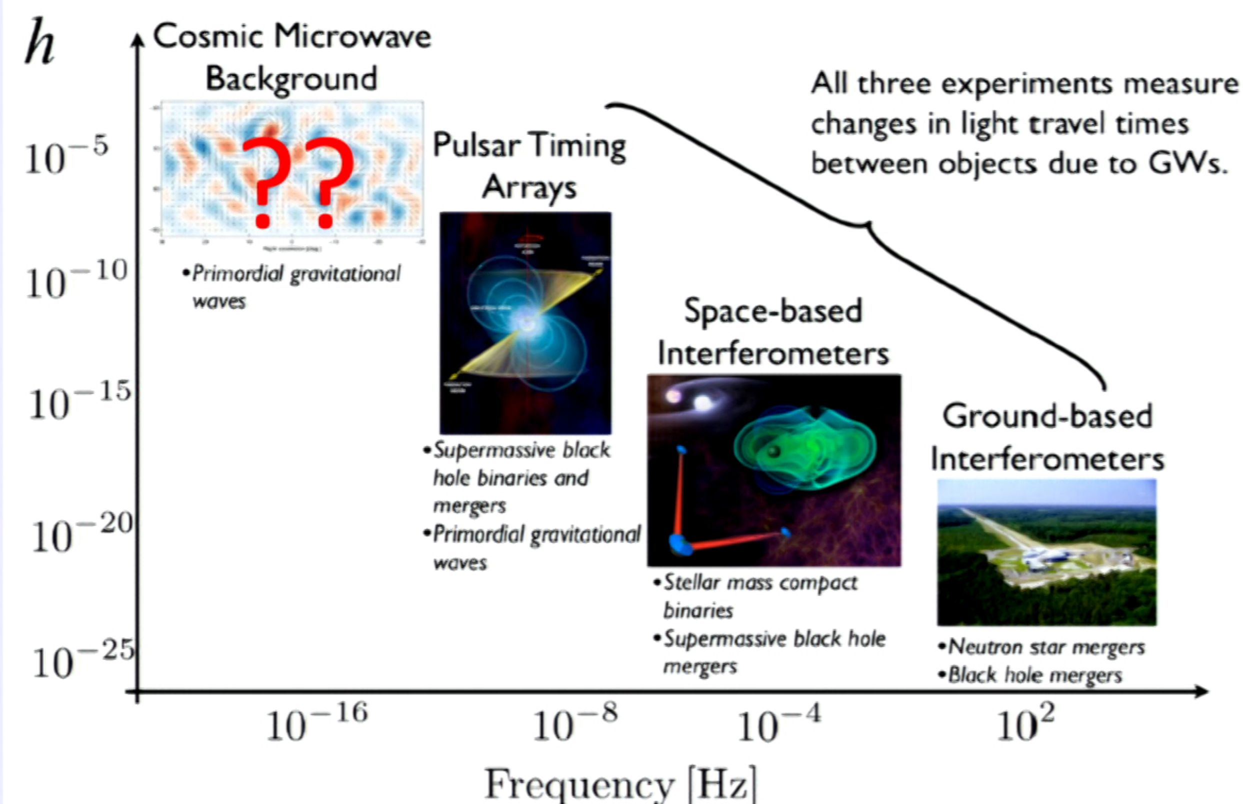
Opening gravity wave 'bands'





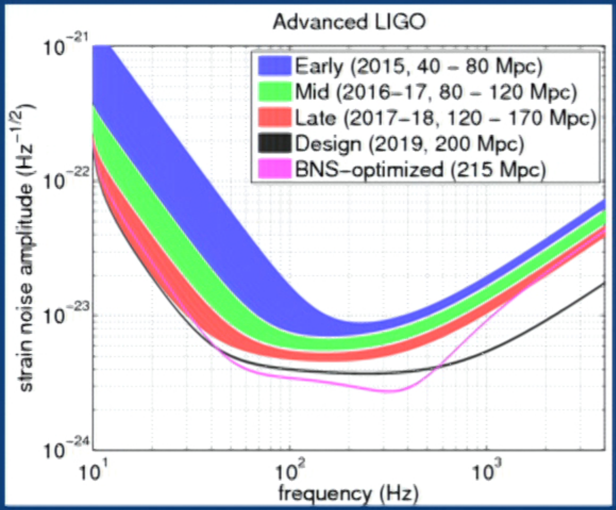
- And others in concept stages... (e.g. atomic interferometry)

The gravitational wave spectrum:



[Image: Nanograv]

Detection strategies

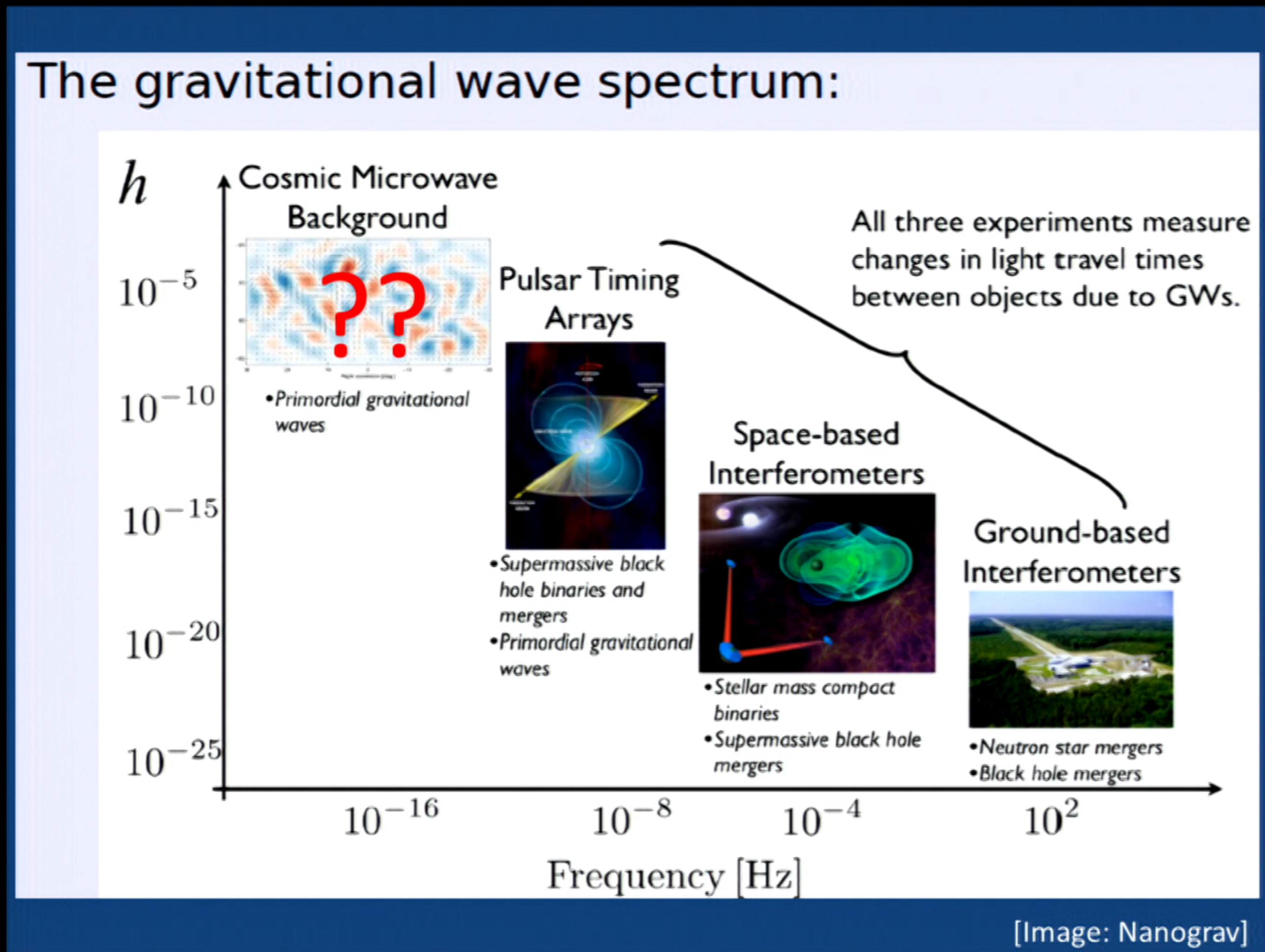


- Matched filtering

$$< d|h > = \int \frac{dh^* + c.c.}{Noise} df$$

  - Intimately requiring models → higher SNR & source-theory knowledge

- Other options: 'burst search', etc


The gravitational wave spectrum:
h
Cosmic Microwave Background
•Primordial gravitational waves
Pulsar Timing Arrays
•Supermassive black hole binaries and mergers
•Primordial gravitational waves
Space-based Interferometers
•Stellar mass compact binaries
•Supermassive black hole mergers
Ground-based Interferometers
•Neutron star mergers
•Black hole mergers
All three experiments measure changes in light travel times between objects due to GWs.
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-16}
10^{-8}
10^{-4}
10^{2}
Frequency [Hz]
[Image: Nanograv]

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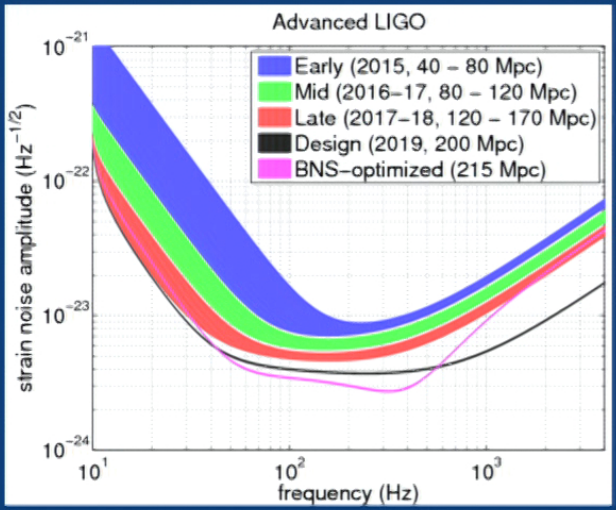

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Anatomy of a binary merger

4 stages: newtonian, inspiral, plunge/merger, after-merger

Newtonian: $t_M < t_H$: *other physics is needed to induce merger*: dynamical friction, n-body encounters, etc.

Inspiral: energy/ang. mom. Loss through GWs is the dominant mechanism.

Perturbation techniques. Rely on: separation of scales! (v/c), M/R, etc

$a_i \sim$ *Newt + {SpinOrbit} +....+ RADN* $(M/R)^5$ *+.... + tidal_effects* $(M/R)^{10}$

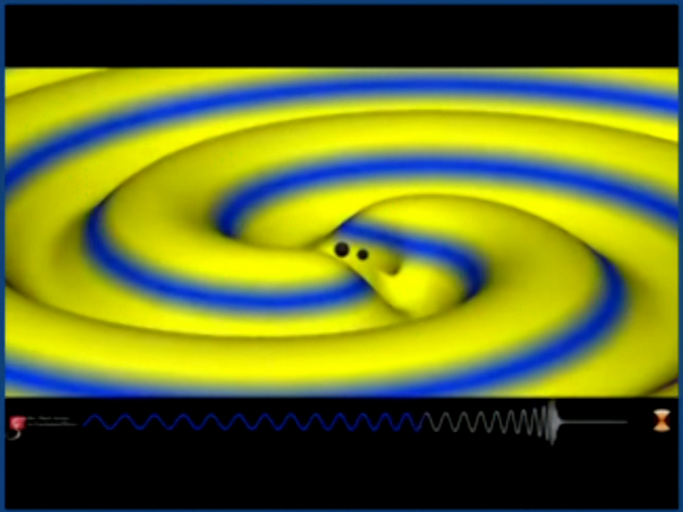
Perturbative to nonlinear and back

- During merger, v/c ~ 1 and objects have M/R ~ 1

→ Full solutions required, and in turn numerical simulations

- Access the truly non-linear regime of GR

- *Merger/plunge:*
  - 2 black holes merge into one *if cosmic censorship holds.*
  - 2 NS will form another one which may collapse to a BH
  - BH-NS. The BH will disrupt or swallow the NS depending on typical radii involved



- *After merger:* use BH perturbation → decaying oscillations

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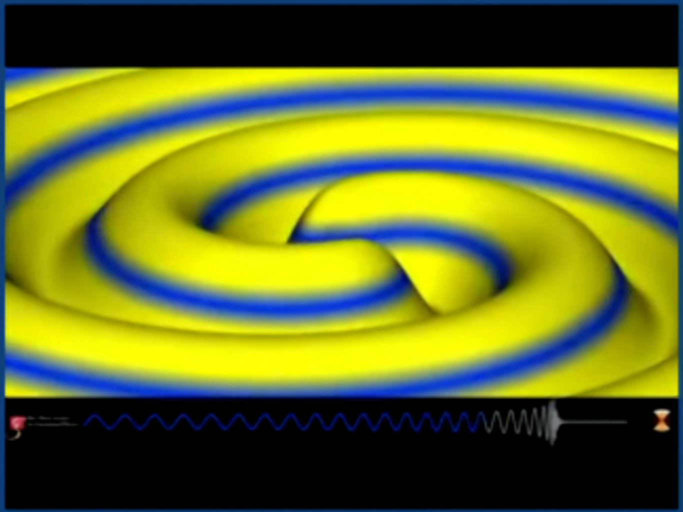

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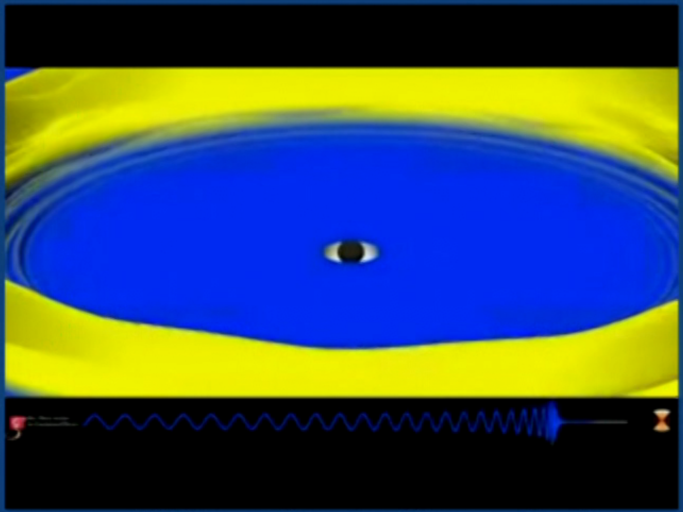

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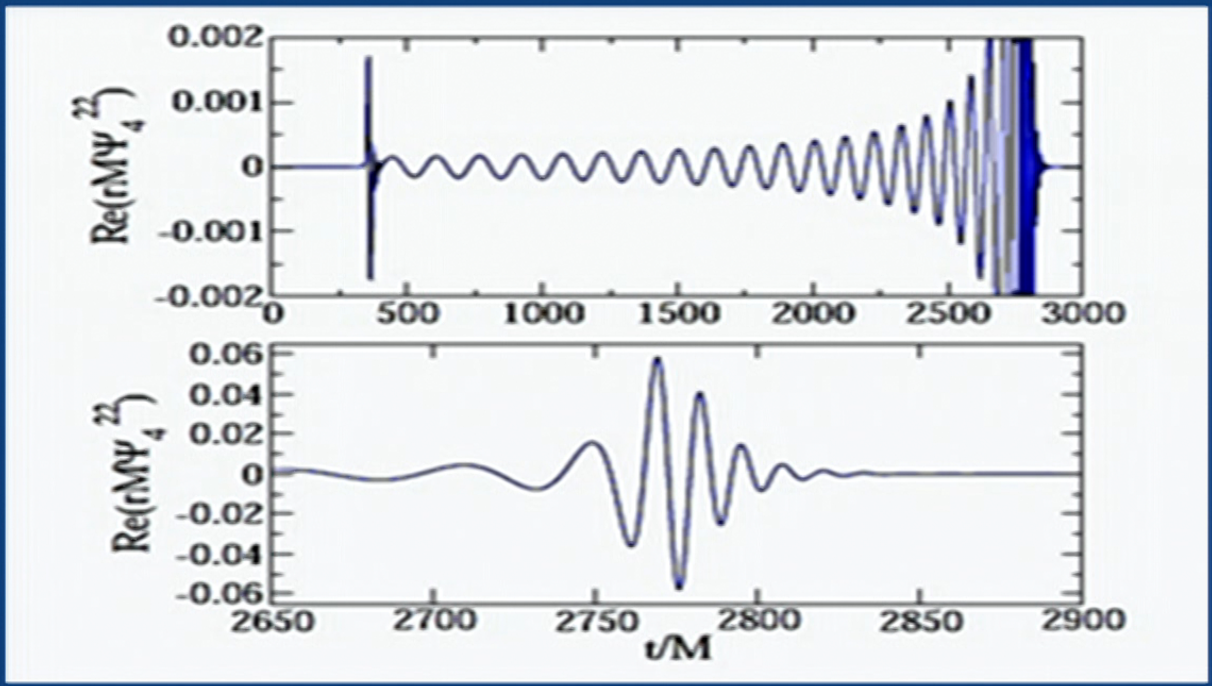
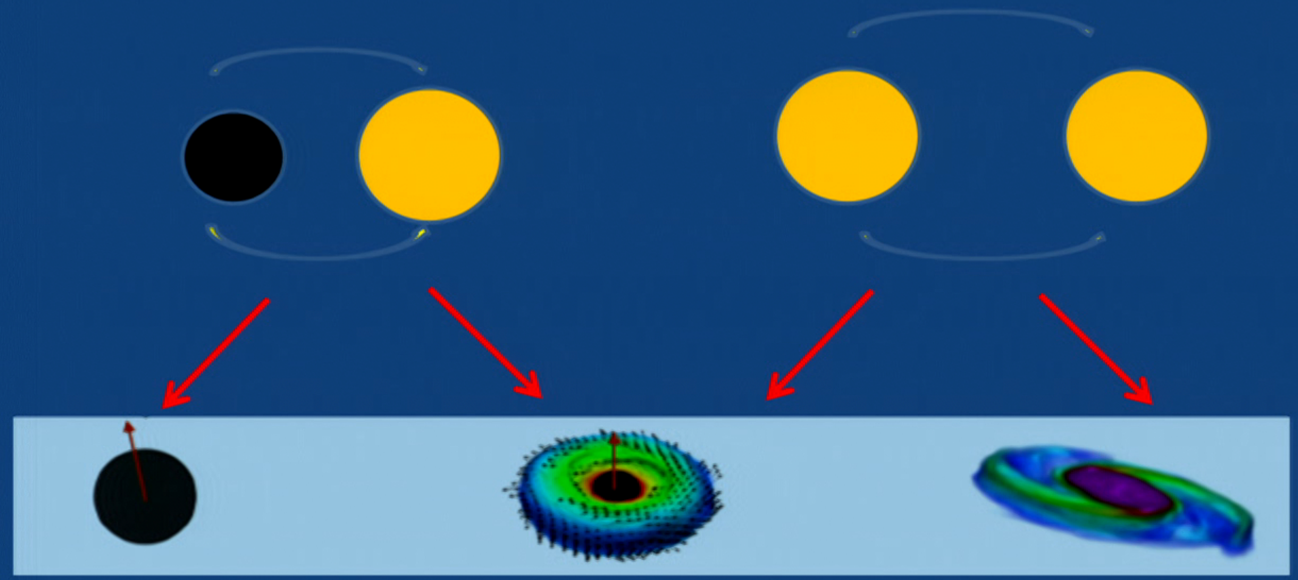
Anatomy of 'theoretical' BBH signal



Energy radiated ~ 3- 12 % of total mass

What's the possible outcome? (sGRB motivated)

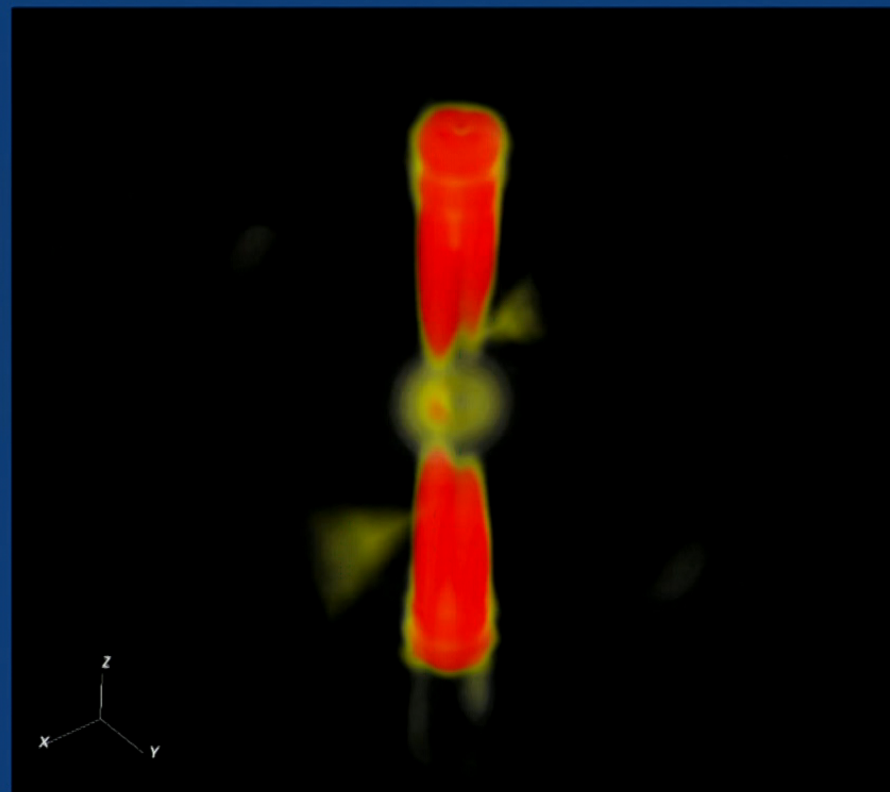


Low spin/high mass, small radius → direct plunge.
No sGRB, but could still shine?

BHNS: High spin/low mass, large radius → disruption.
NSNS: $M_{tot} > 1.3\text{-}1.5\ M_{max}$
'comfortable' disk mass
GW: with a clear cutoff

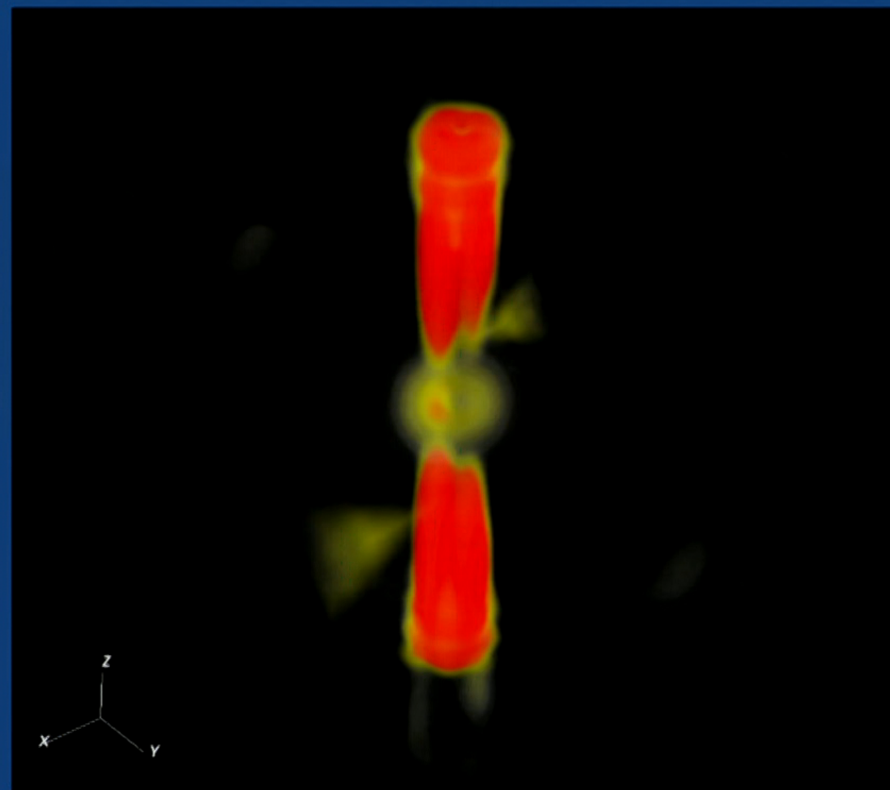
NSNS: $M_{tot} < 1.3\text{-}1.5\ M_{max}$
GW: postmerger signal
sGRB from 'sufficiently' magnetized MNS?

‘indirect impact’ on EM



[Palenzuela + ‘10]

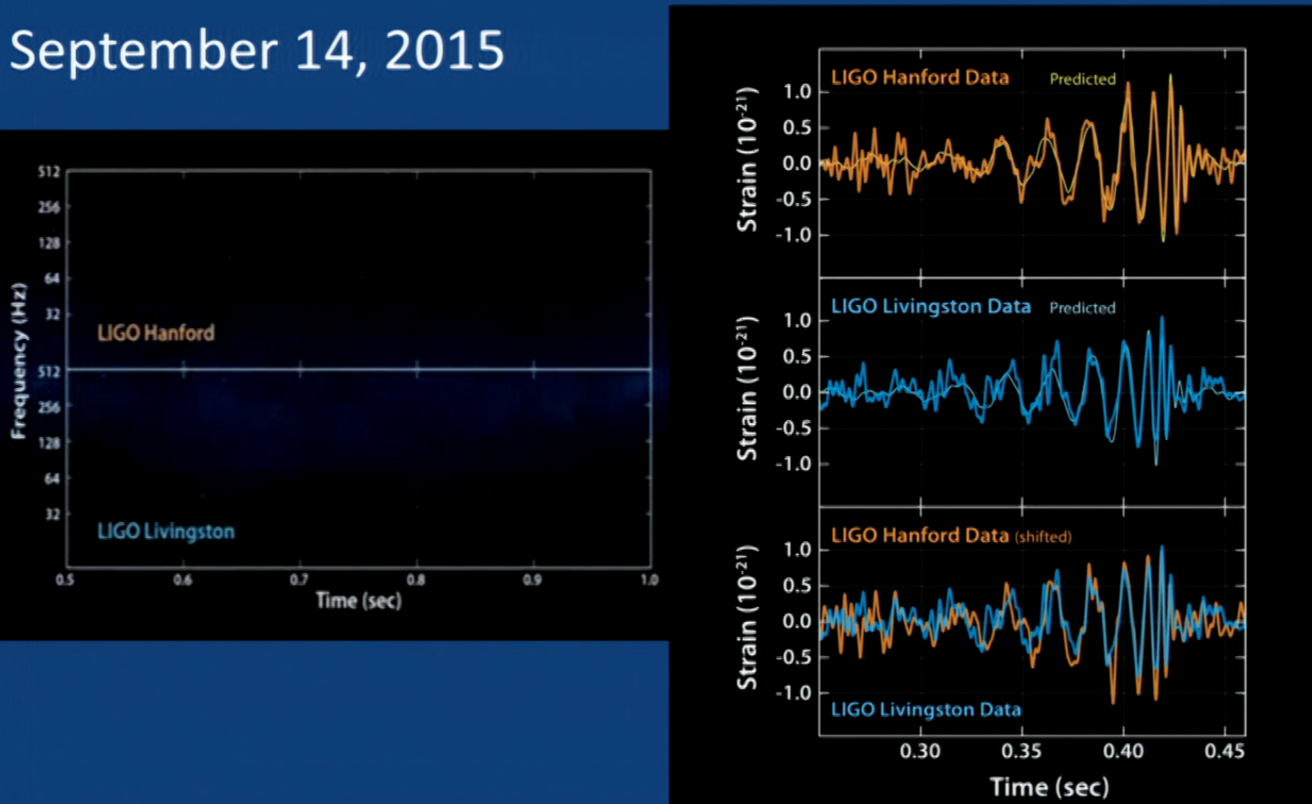
‘indirect impact’ on EM



[Palenzuela + ‘10]

But finally…

September 14, 2015



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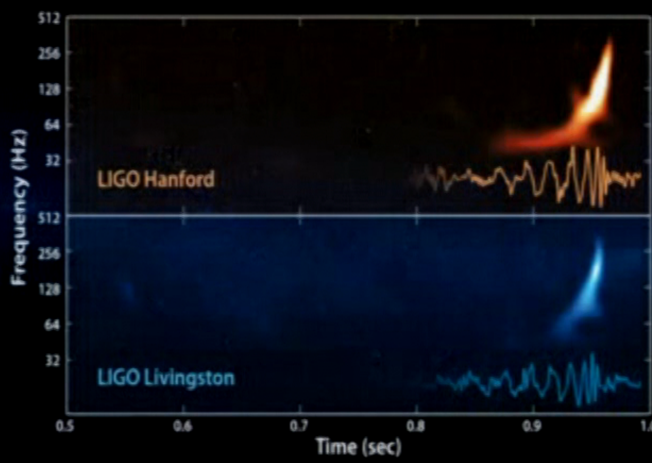
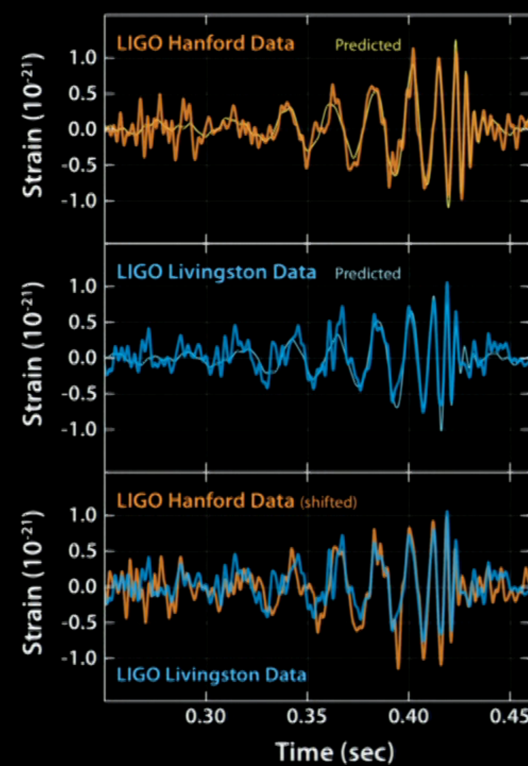
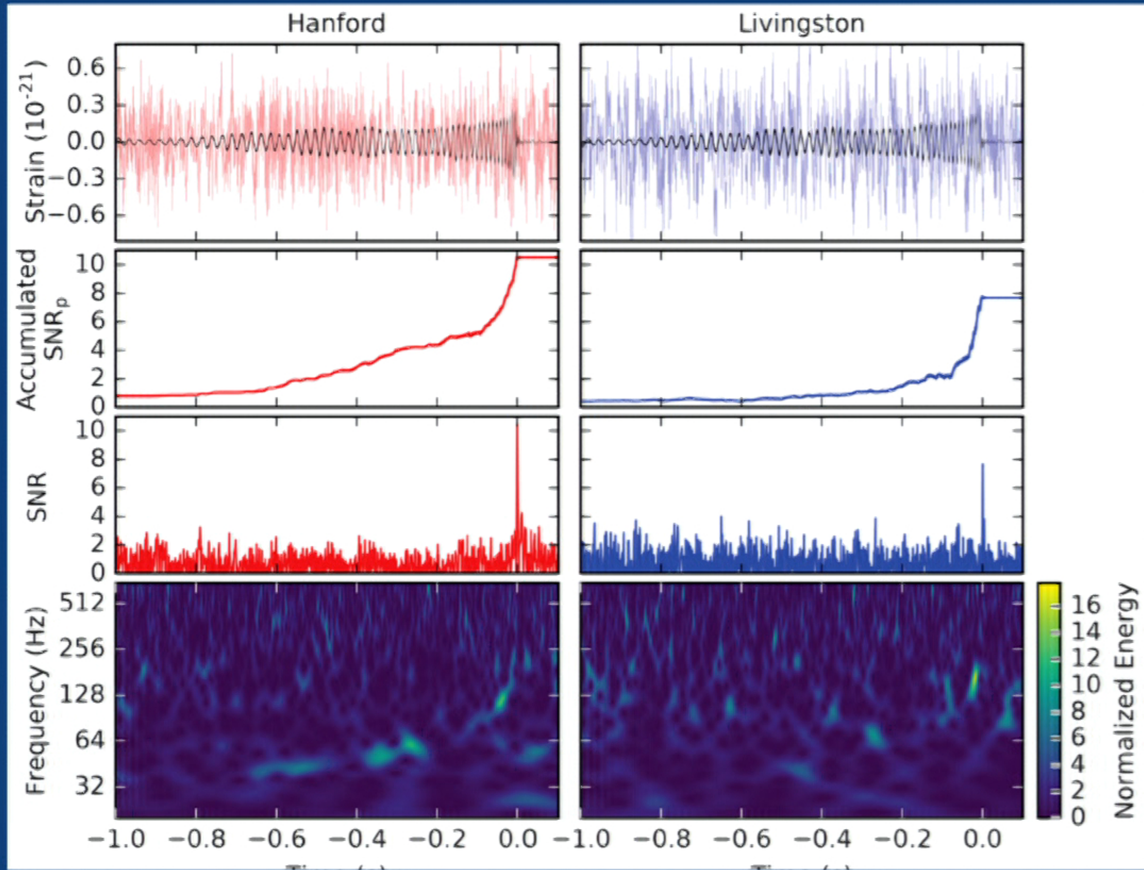




GW151226



Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR$_p$
10
8
6
4
2
0
SNR
Frequency (Hz)
512
256
128
64
32
Normalized Energy
16
14
12
10
8
6
4
2
0
−1.0 −0.8 −0.6 −0.4 −0.2 0.0

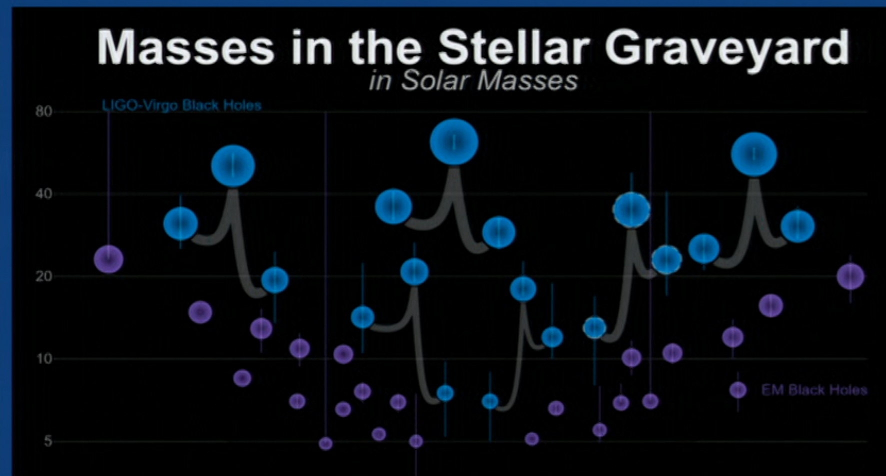
Event	Prob	m1 (M_O)	m2 (M_O)	χ_{eff}	D_L (Mpc)	Mrad (M_O)
GW150914	> 5.1σ	36^{5}_{4} (5,-4)	29^{4}_{-4} (4,-4)	$-0.06^{0.17}_{-0.18}$ (0.17, -0.18)	410^{160}_{-180}	3
LVT151012	2.1σ	23	13	$0.0^{0.3}_{-0.2}$	1100^{500}_{-500}	2
GW151226	> 5σ	$14.2^{8.3}_{-3.7}$	$7.5^{2.5}_{-2.3}$	0.2 (…1 with spin)	440^{180}_{-190}	1
GW170104	~ 4.5σ	$31.2^{8.4}_{-6}$	$19.4^{5.3}_{-5.9}$	$-0.12^{0.21}_{-0.3}$	880^{450}_{-390}	2
GW170608	SNR 13	12^{7}_{-2}	7^{2}_{-2}	$0.07^{0.23}_{-0.09}$	340^{140}_{-140}	0.85
GW170814	SNR 18	$30.5^{5.7}_{-3}$	$25.3^{2.8}_{-4.2}$	$0.06^{0.12}_{-0.12}$	540^{130}_{-210}	2.7

- Rate: ~ [12-213] Gpc^{-3} yr^{-1}
- DM candidate? Still few to make an argument [peak in distribution?]
- Large masses in GW150914 not 'first bet' → population implication?
- $m_g < 10^{-22}$ ev/c^2

Black hole puzzles

- Spin?

(superradiance with axions? [Arvanitaki -Dimopoulos +])

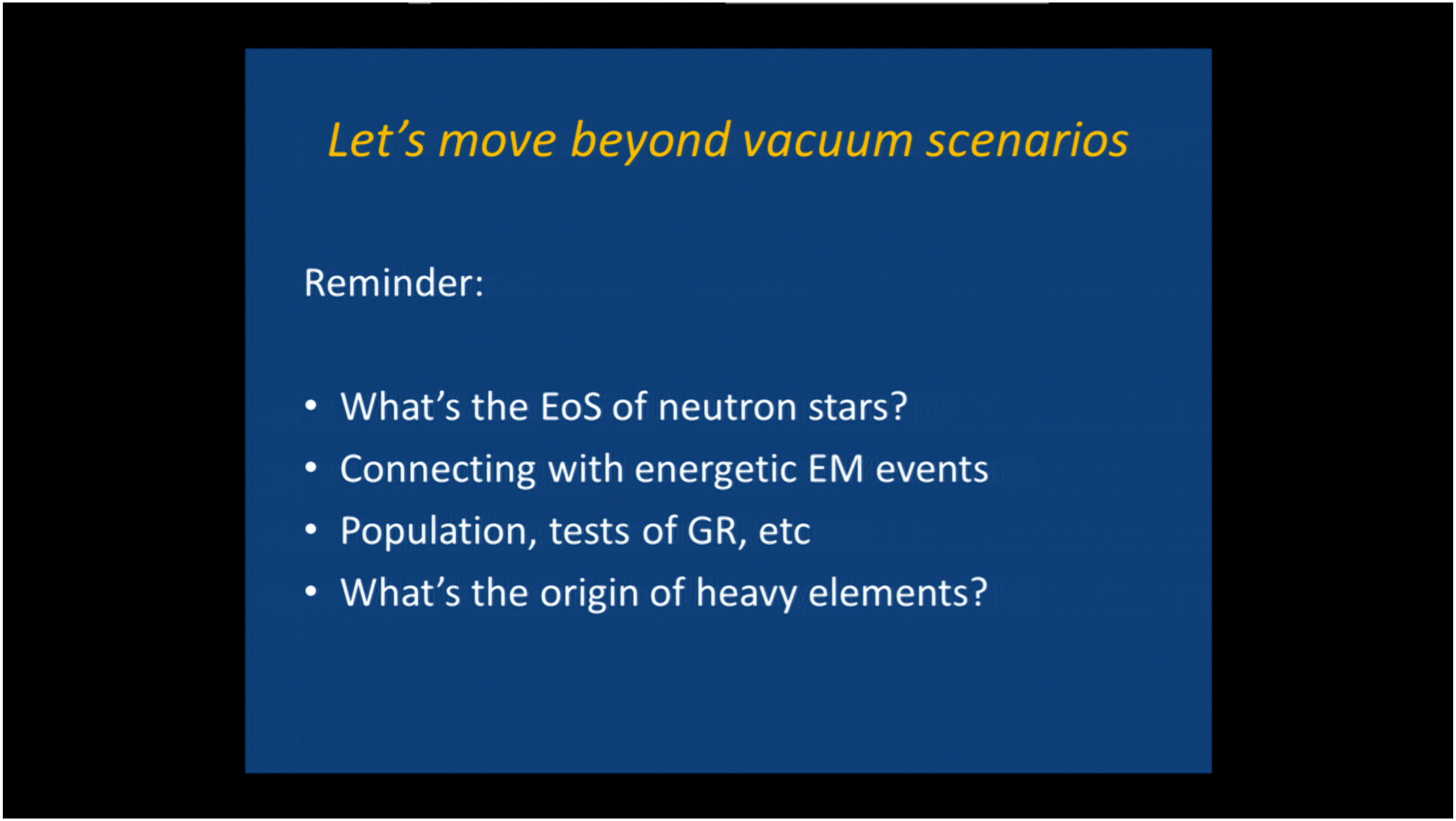


- Formation?

- Really a BH?

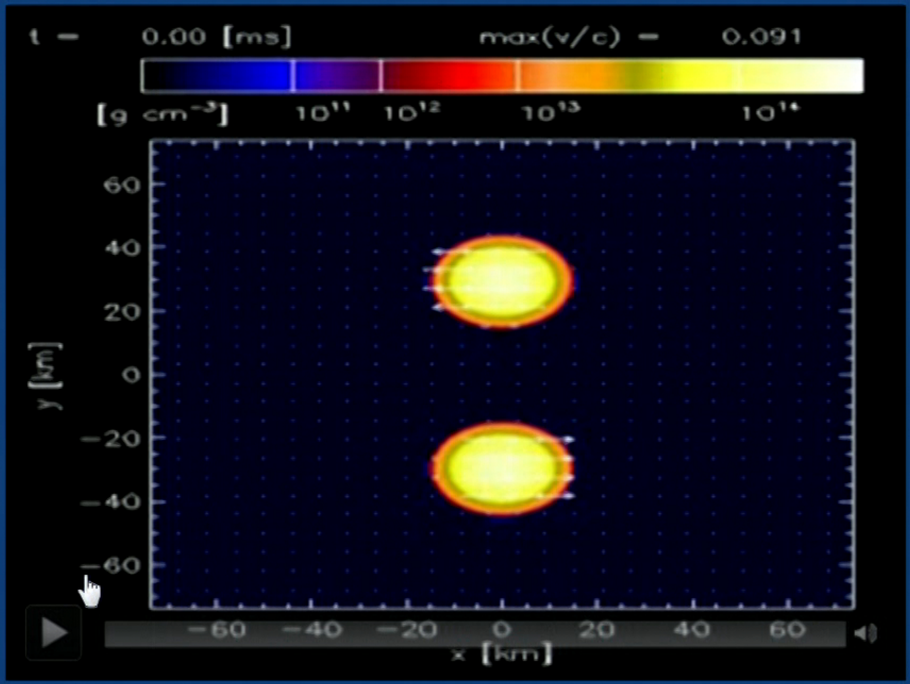
- Really as in GR/Kerr BH?

[Yang +]


Let's move beyond vacuum scenarios
Reminder:
• What's the EoS of neutron stars?
• Connecting with energetic EM events
• Population, tests of GR, etc
• What's the origin of heavy elements?

Non-vacuum binaries

- No-rescaling of mass possible, though constrained masses
- Tidal effects -ie EOS- → $F \sim (R_s/M)^5 (M/R)^{10}$



Non-vacuum binaries

- No-rescaling of mass possible, though constrained masses
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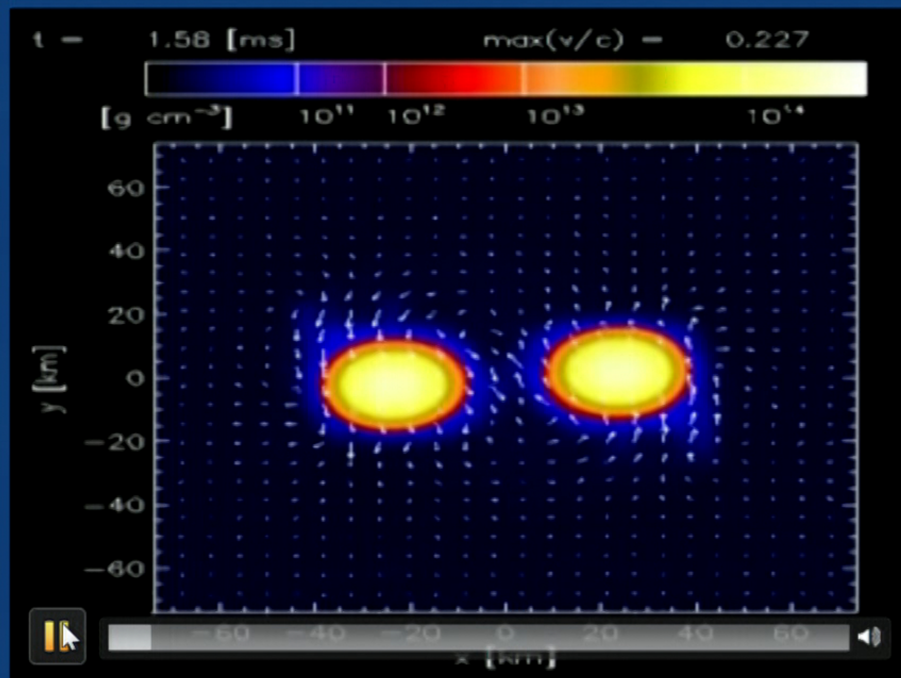

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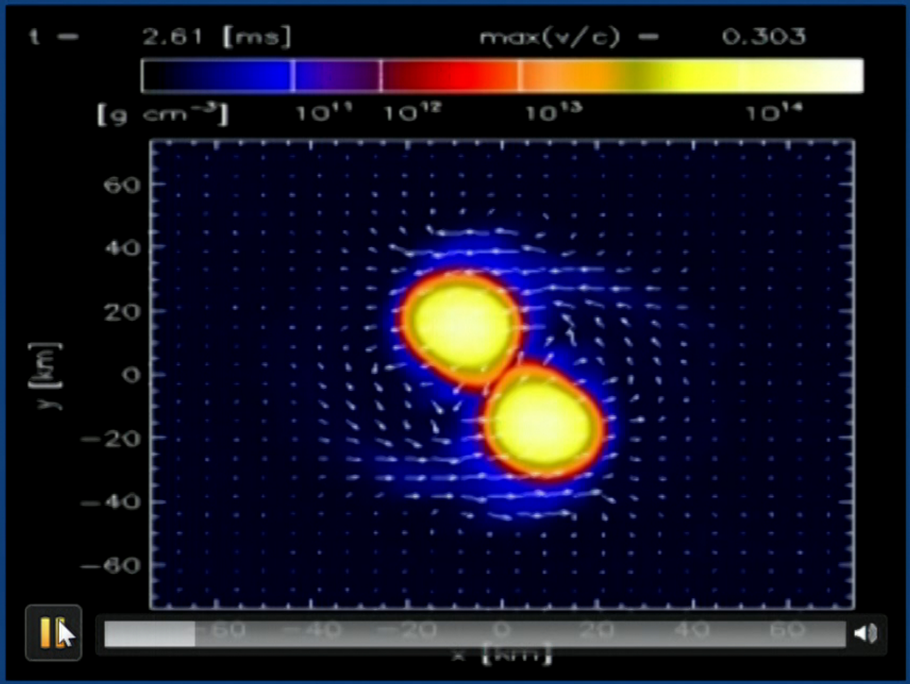

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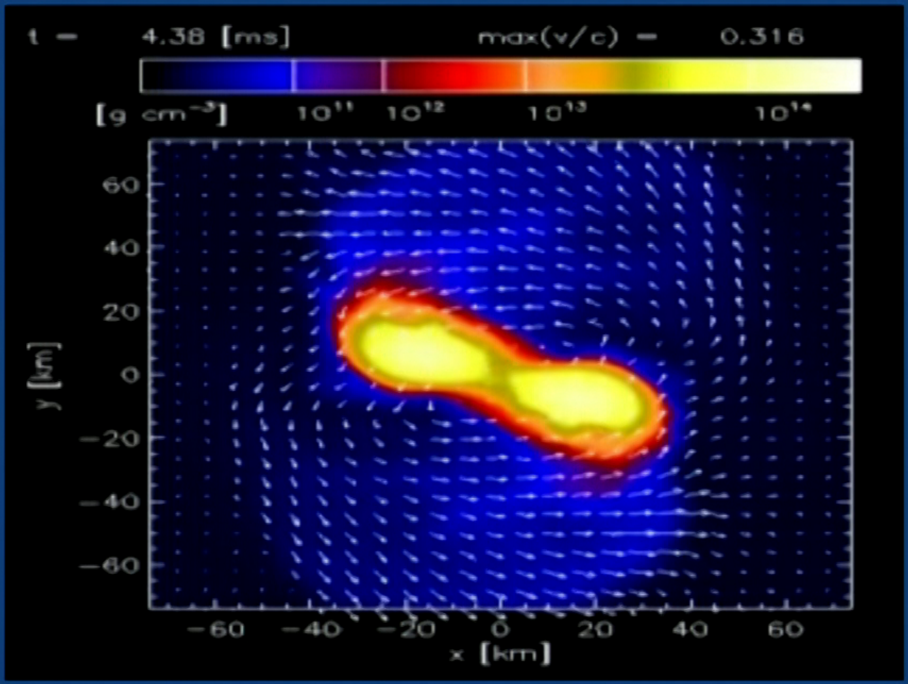

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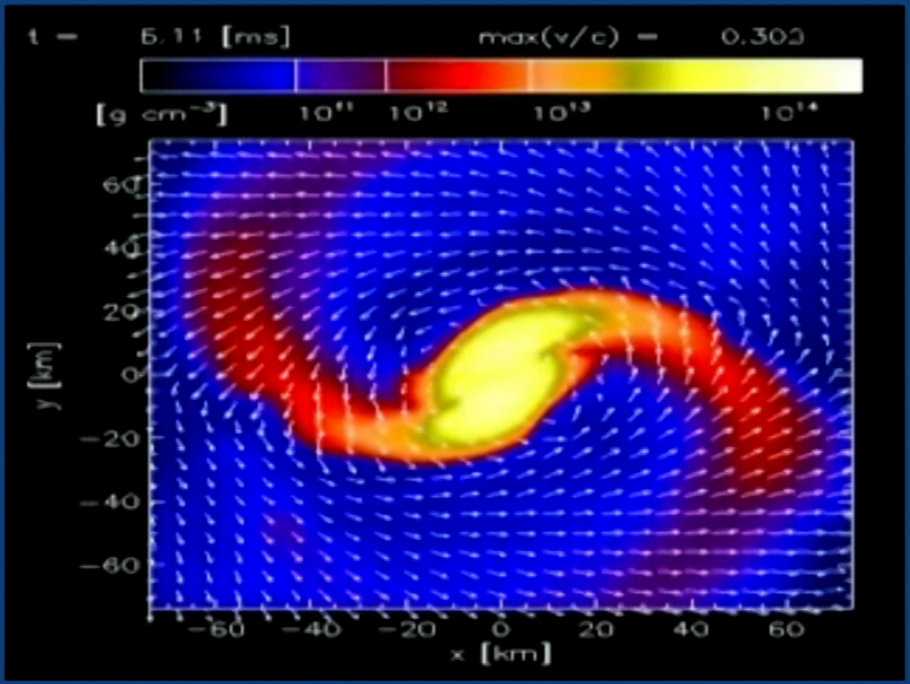

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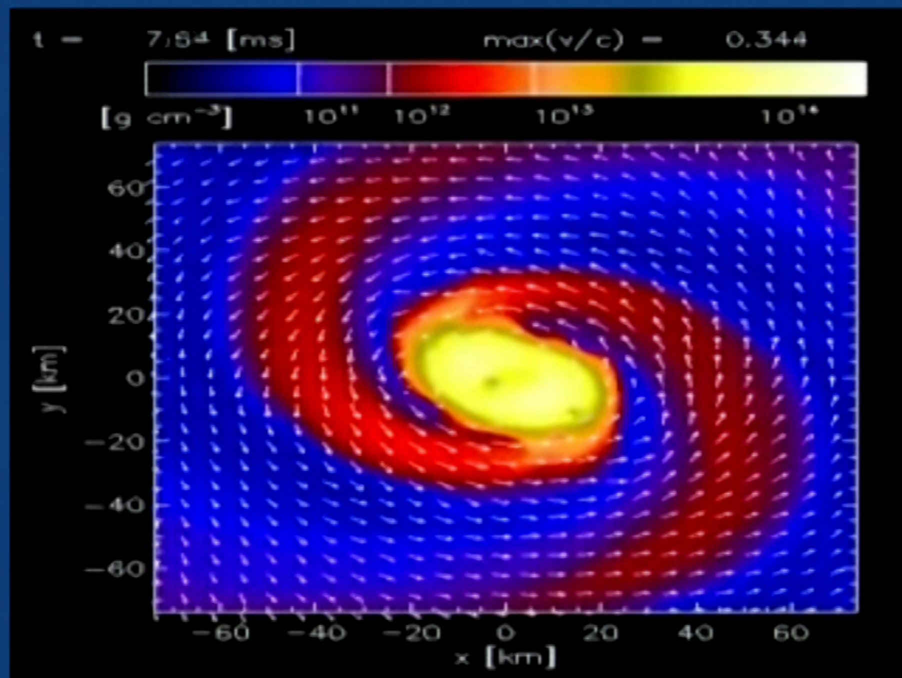

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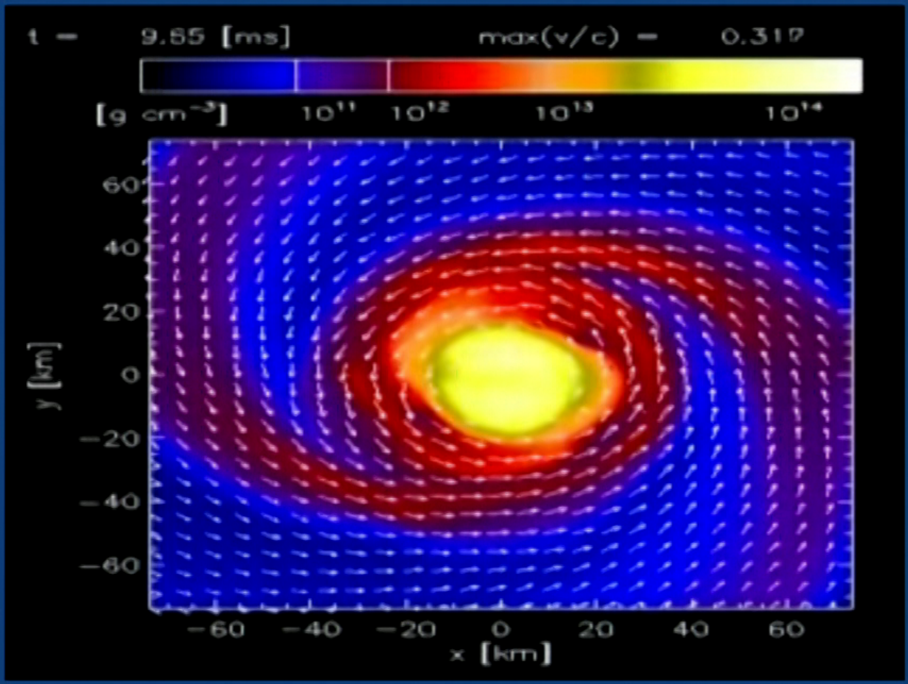

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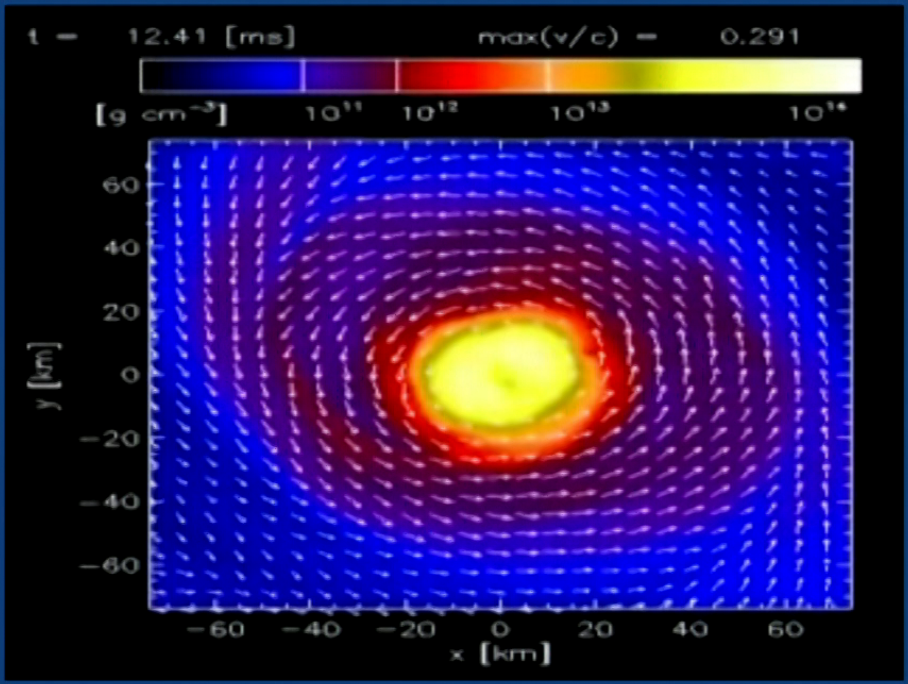

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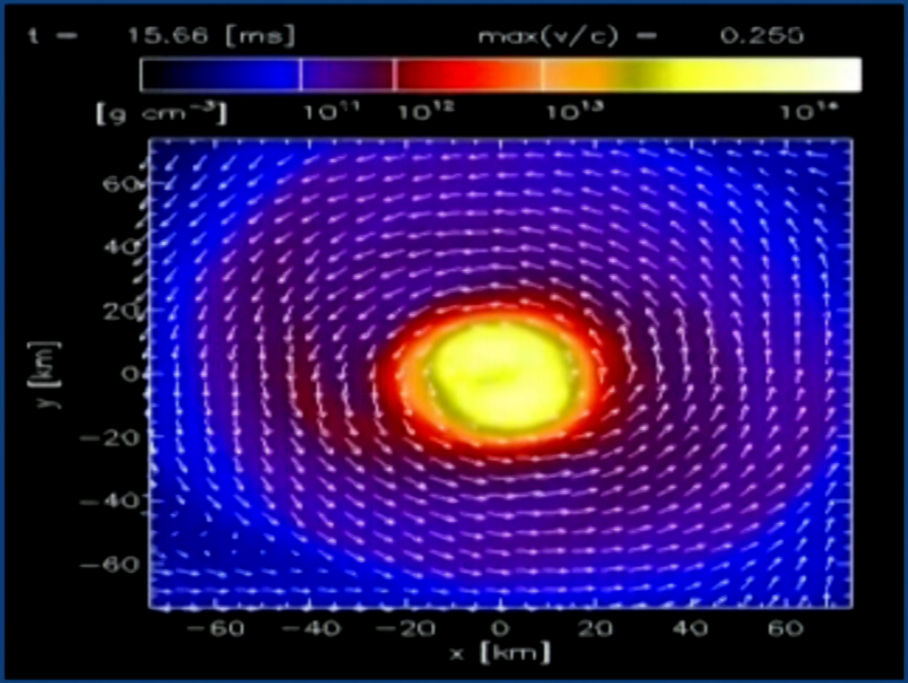

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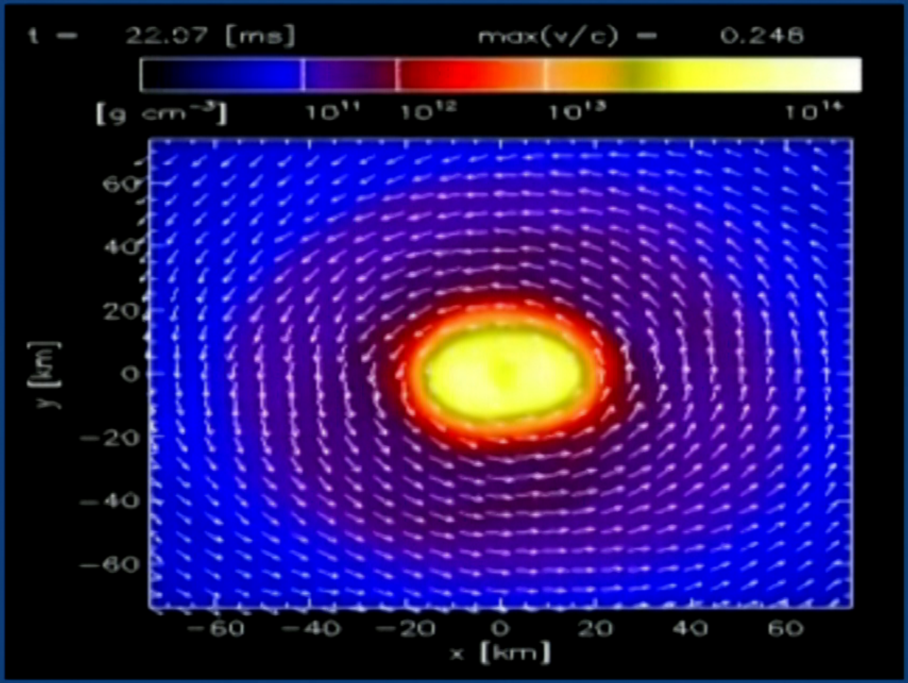

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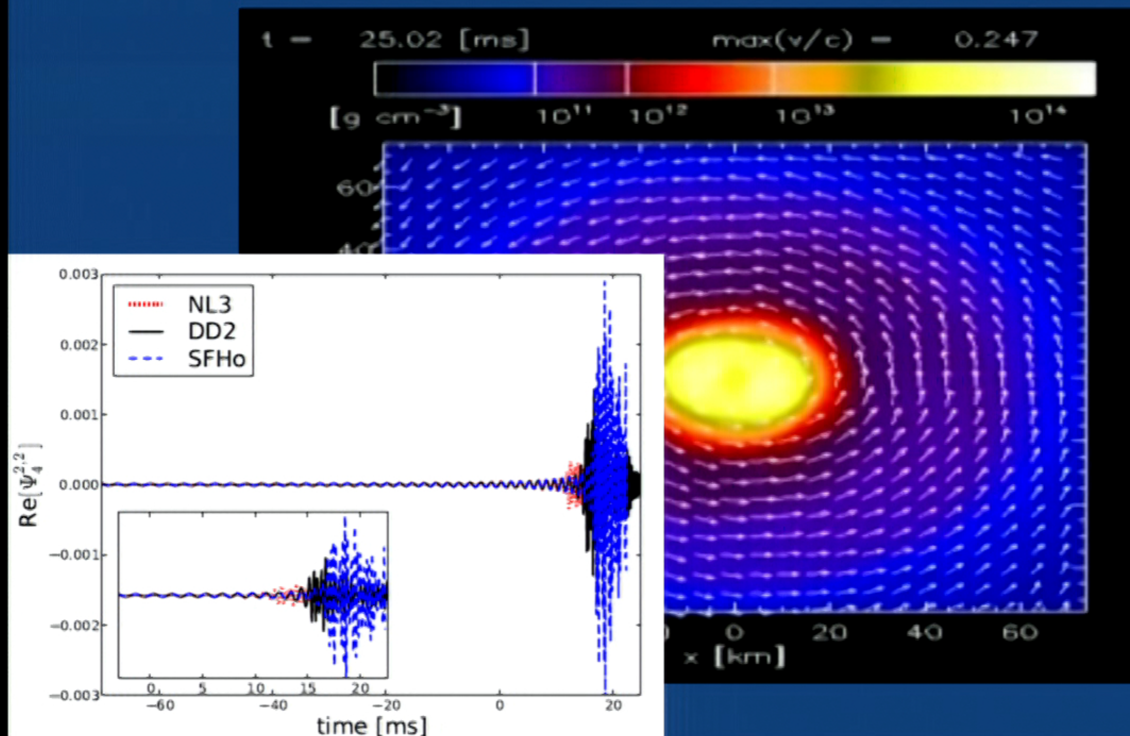
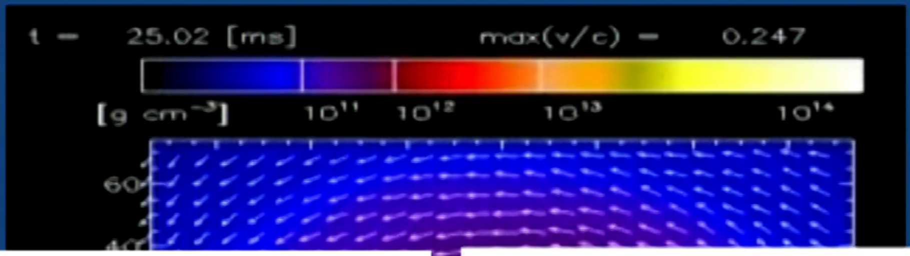
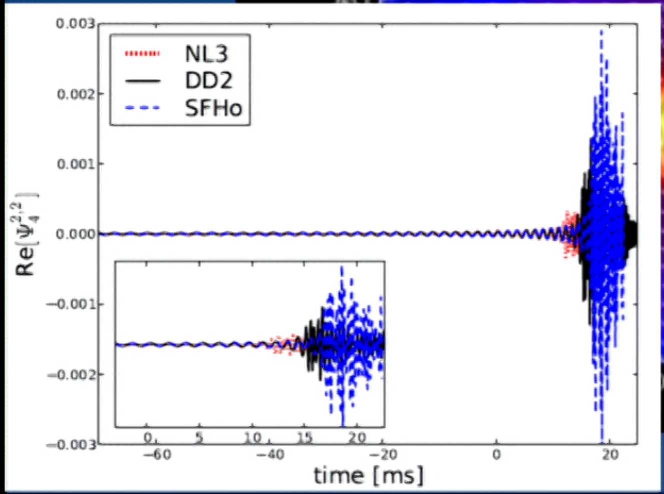
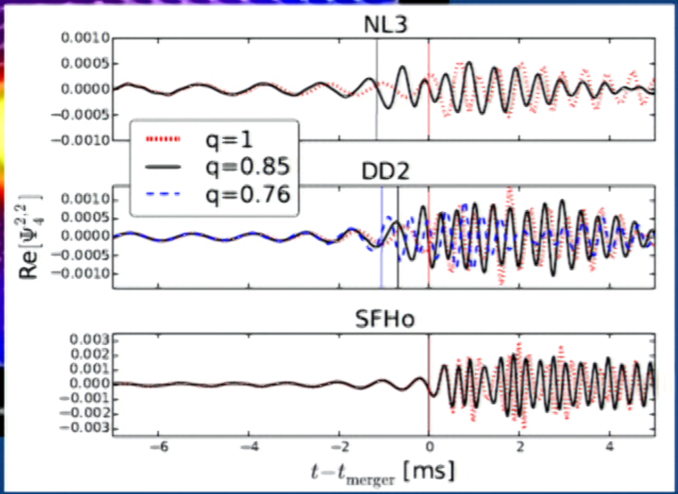


Non-vacuum binaries

- No-rescaling of mass possible, though constrained masses
- Tidal effects -ie EOS- → $F \sim (R_s/M)^5\,(M/R)^{10}$





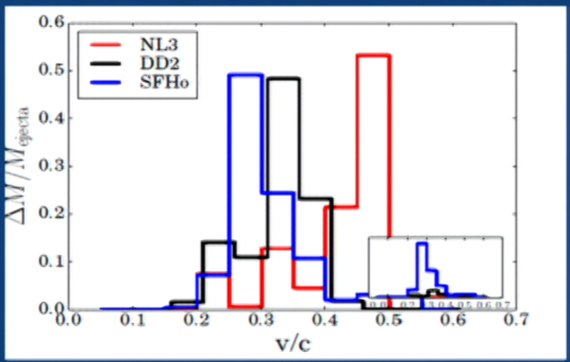


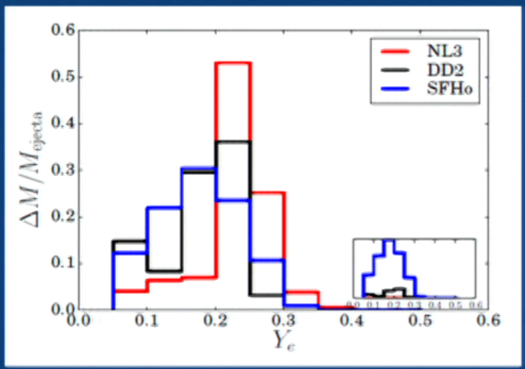
Far and away…

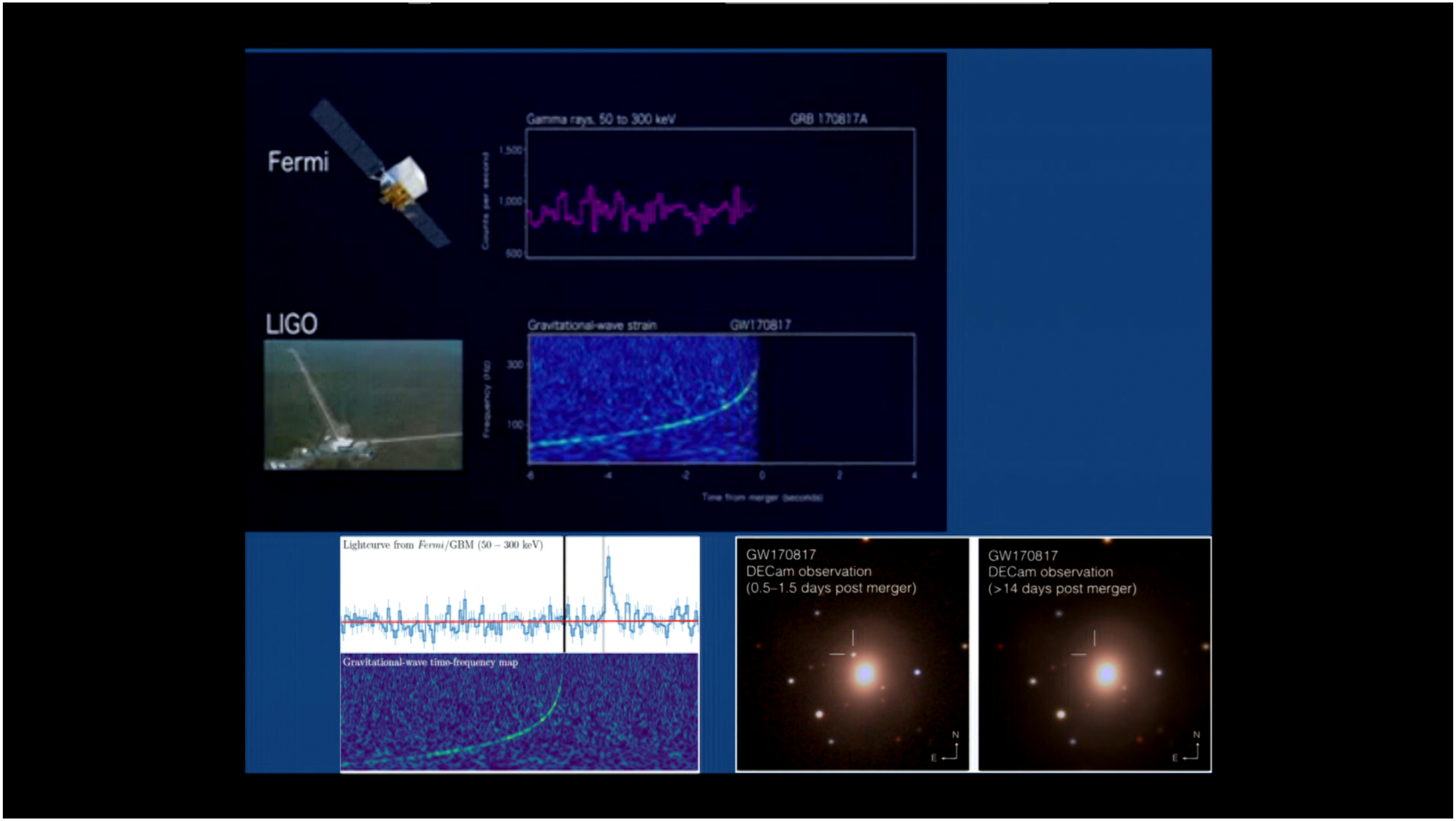
'kilonovae' → driven by radiactive decay of r-processes. Features are tied to how neutron rich the material ejected is. Produces high atomic mass elements, e.g. *Lanthanides*

'old' suspect: supernovae… but simulations point to ejecta not sufficiently neutron rich & measurements in sediments → lower rates in source events

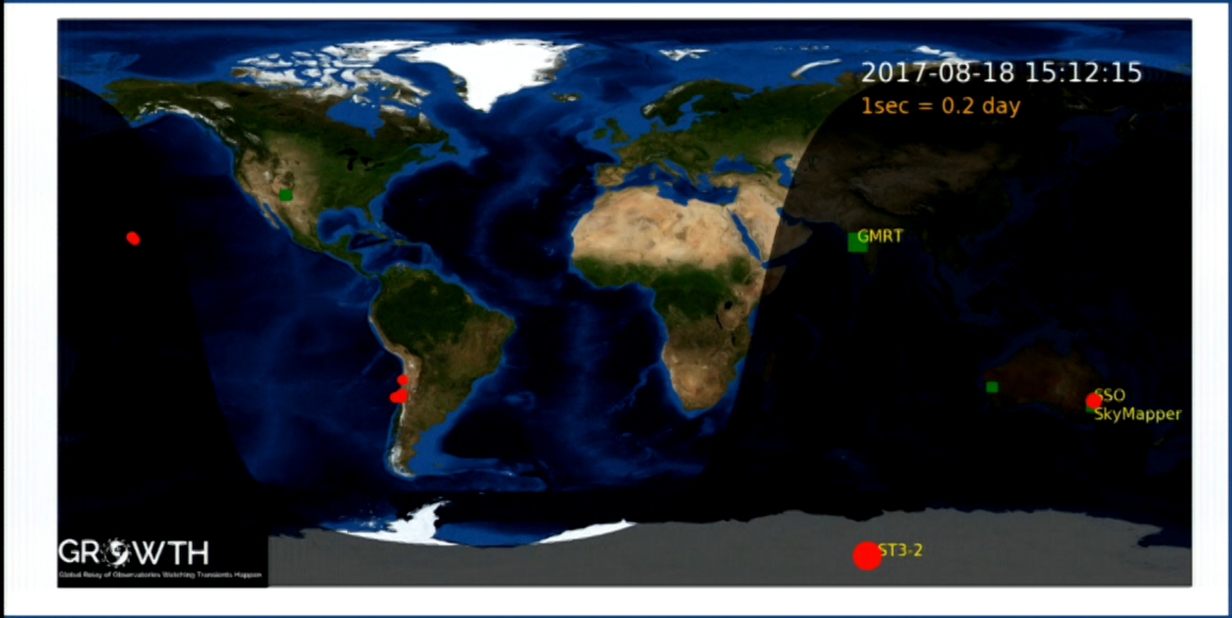
NS-NS & BH-NS collisions? Amount/characteristics in the right ballpark

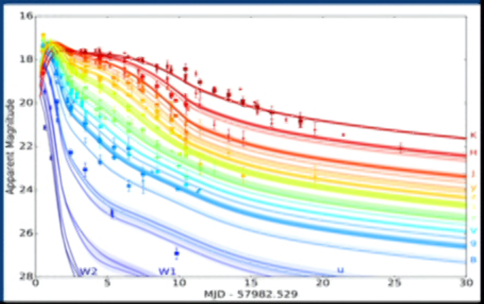




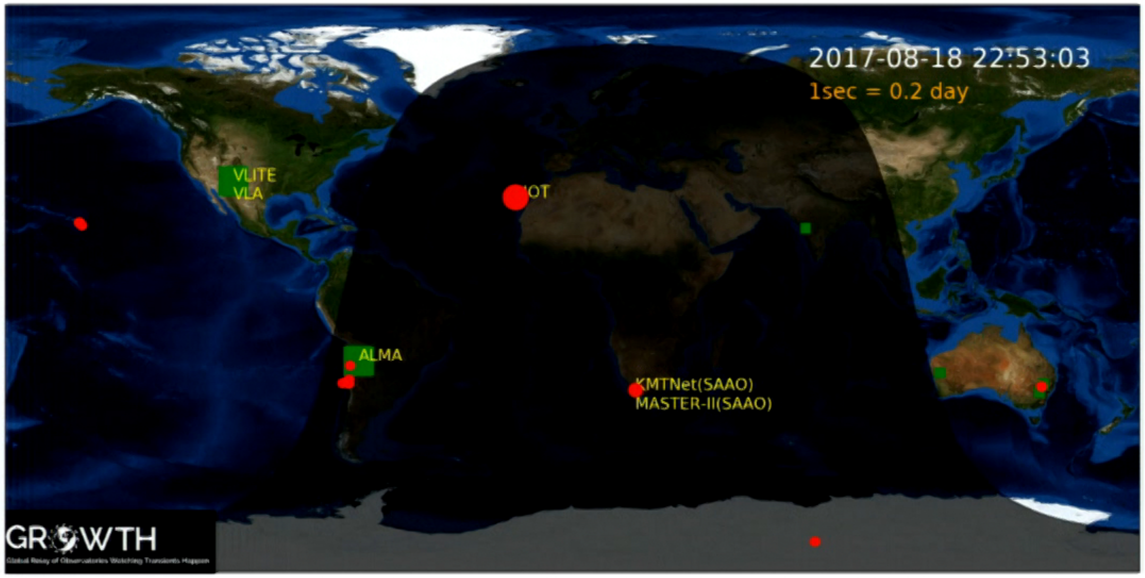

Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
LIGO
Gravitational-wave strain
GW170817
Lightcurve from Fermi/GBM (50 – 300 keV)
Gravitational-wave time-frequency map
GW170817
DECam observation
(0.5–1.5 days post merger)
GW170817
DECam observation
(>14 days post merger)

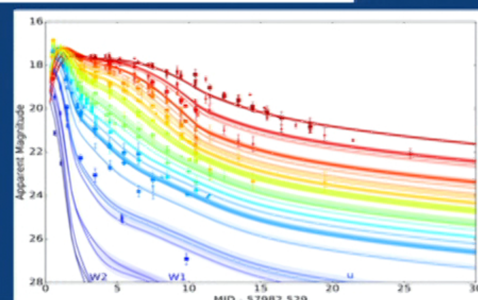
And then...


2017-08-18 15:12:15
1sec = 0.2 day
GMRT
SSO
SkyMapper
ST3-2
GROWTH

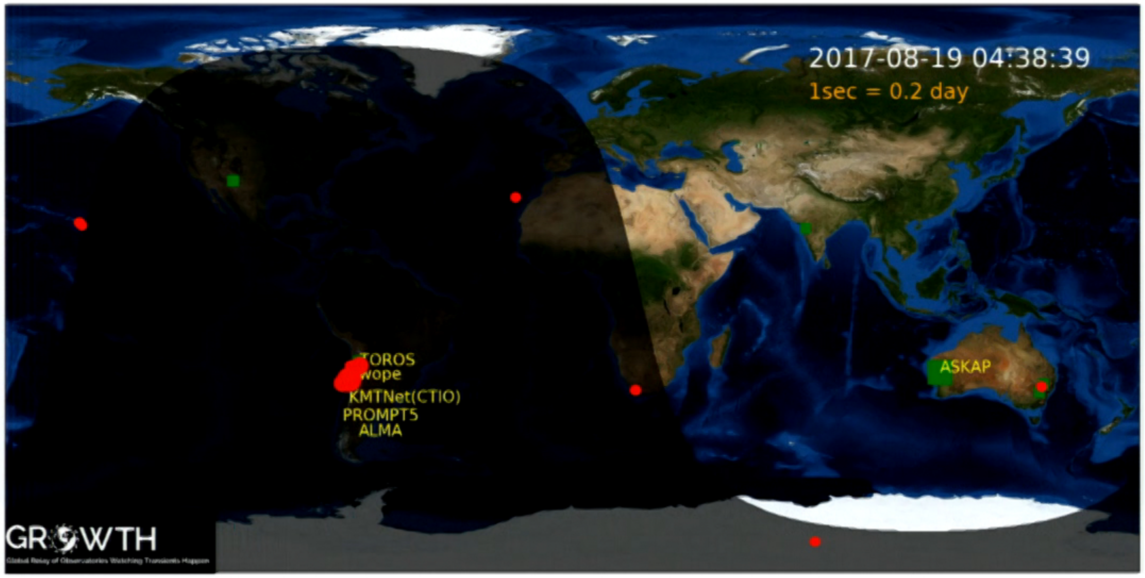

Apparent Magnitude
MJD - 57982.529
W2
W1

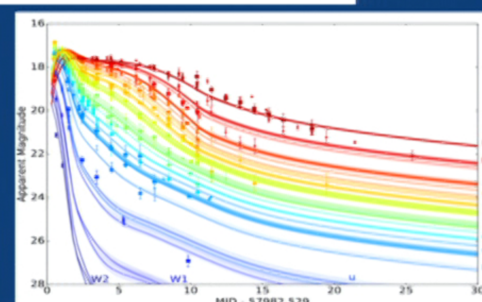
And then...


2017-08-18 22:53:03
1sec = 0.2 day
VLITE
VLA
ALMA
KMTNet(SAAO)
MASTER-II(SAAO)
GROWTH

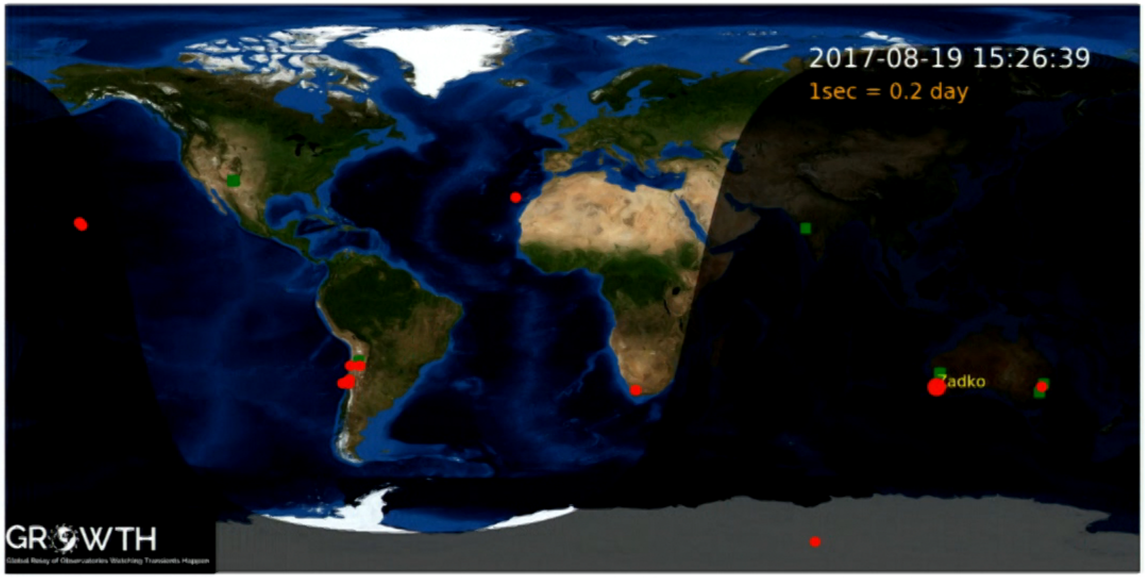

Apparent Magnitude
MJD - 57982.529
W2
W1

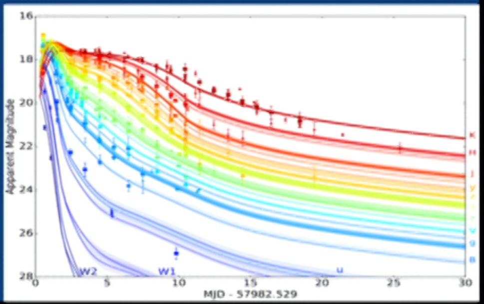
And then...


2017-08-19 04:38:39
1sec = 0.2 day
TOROS
wope
KMTNet(CTIO)
PROMPT5
ALMA
ASKAP
GROWTH


Apparent Magnitude
MJD - 57982.529
W2
W1

And then...


2017-08-19 15:26:39
1sec = 0.2 day
Zadko
GROWTH


Apparent Magnitude
MJD - 57982.529
W2
W1

Parameters

	m1 (M_o)	m2 (M_o)	Rad energy (M_o)	Distance (Mpc)
GW170817	1.36-1.6 (1.36-2.26)	1.17-1.36 (0.86-1.36)	> 0.25	40^{8}_{-14}

From GWs alone → EoS can't be too stiff [no modulations detected]
can't say it isn't a BH-BH or a BH-NS and what the final object is

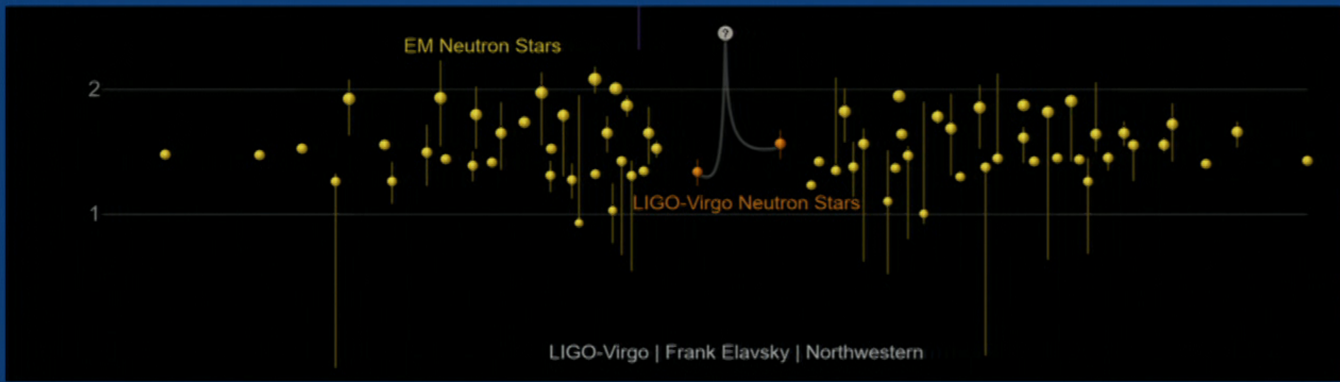
With EM counterparts:

- One must be a NS
- EM/GW propagation: $-3\ 10^{-15} < (v_{GW}-v_{EM})/v_{EM} < 7\ 10^{-16}$
- minimal coupling of EM: $-2.6\ 10^{-7} < \gamma_{GW} - \gamma_{EM} < 1.2\ 10^{-6}$

With EM counterparts + 'reasonable' models:

- final object is a BH [e.g. Siegel-Metzger]
- propagation took place in D = 3+ 1 dimensions [Pardo+]

NS data…



First NS in the ~ 2.7 M_{O} ?

First BH in the mass gap ?

Site of heavy element production

NS puzzles

- EoS?
- Final State?
- BH-NS?
- Ejecta characteristics?
- GR theory?

Final thoughts

- Gravitational wave astronomy is on
  - A solid and complementary new tool for astrophysics. Ripe time to think new ideas and explore new prospects

- It's taken lots of efforts through ~ 4 decades to get to this point. Important to think what else can GWs (and the technology to get us here) can do for physics/astronomy

- Future detectors will reach z → 20, SNRs ``ridiculously high''…


Final thoughts