Progress in Gravitational Wave Astrophysics

Blois, 2010

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for the LIGO Scientific Collaboration and the Virgo Collaboration

Nikhef, Amsterdam

20 July 2010

LSC

EGO European Gravitational Observatory

A GRAVITATIONAL WAVES ANTENNA VIRGO

Gravitational Wave Astrophysics

- **Introduction**
- **Status of Interferometer GW detectors**
- **Different types of signals:**
  - **bursts;** **(coalescence, supernovae, magnetars)**
  - **cw ;** **(neutronstars)**
  - **stochastic;**
- **Multi-Messenger Astronomy and Future**
- **Conclusion**

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Gravitational Waves

basic ingredient to General Relativity (1915) ;

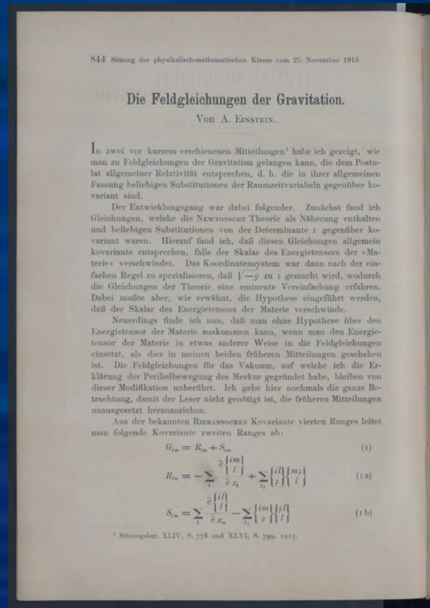
active research since 1955 ;

pioneer : Joseph Weber

indirect evidence : strong;

direct evidence so far: still negative ...

nevertheless: physics results .



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten Riemannschen Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

$$G_{im} = R_{im} + S_{im} \qquad (1)$$

$$R_{im} = -\sum_{l} \frac{\partial \begin{Bmatrix} im \\ l \end{Bmatrix}}{\partial x_l} + \sum_{l\rho} \begin{Bmatrix} il \\ \rho \end{Bmatrix} \begin{Bmatrix} m\rho \\ l \end{Bmatrix} \qquad (1a)$$

$$S_{im} = \sum_{l} \frac{\partial \begin{Bmatrix} il \\ l \end{Bmatrix}}{\partial x_m} - \sum_{l\rho} \begin{Bmatrix} im \\ \rho \end{Bmatrix} \begin{Bmatrix} \rho l \\ l \end{Bmatrix} \qquad (1b)$$

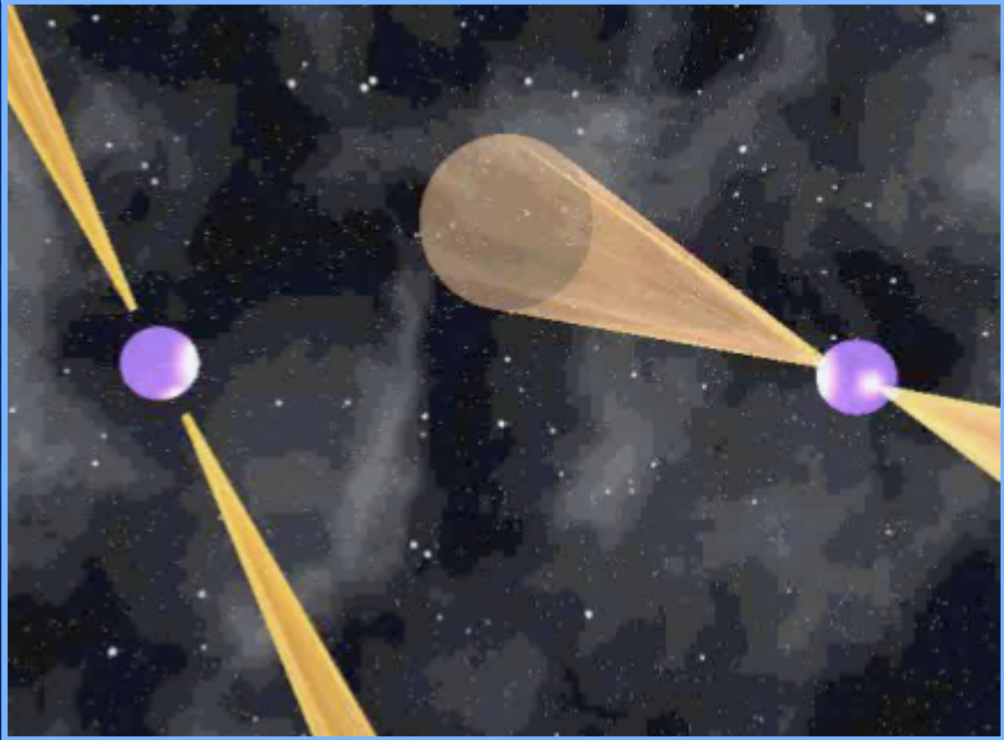
[1] Sitzungsber. XLIV, S. 778 und XLVI, S. 799, 1915.

Gravitational waves exist:

time dependent quadrupole moment → grav.waves

$$h_{\mu\nu} = \frac{2\,G}{R\,c^4}\,\ddot{I}_{\mu\nu}$$

best example: Hulse – Taylor:
binary neutron star:



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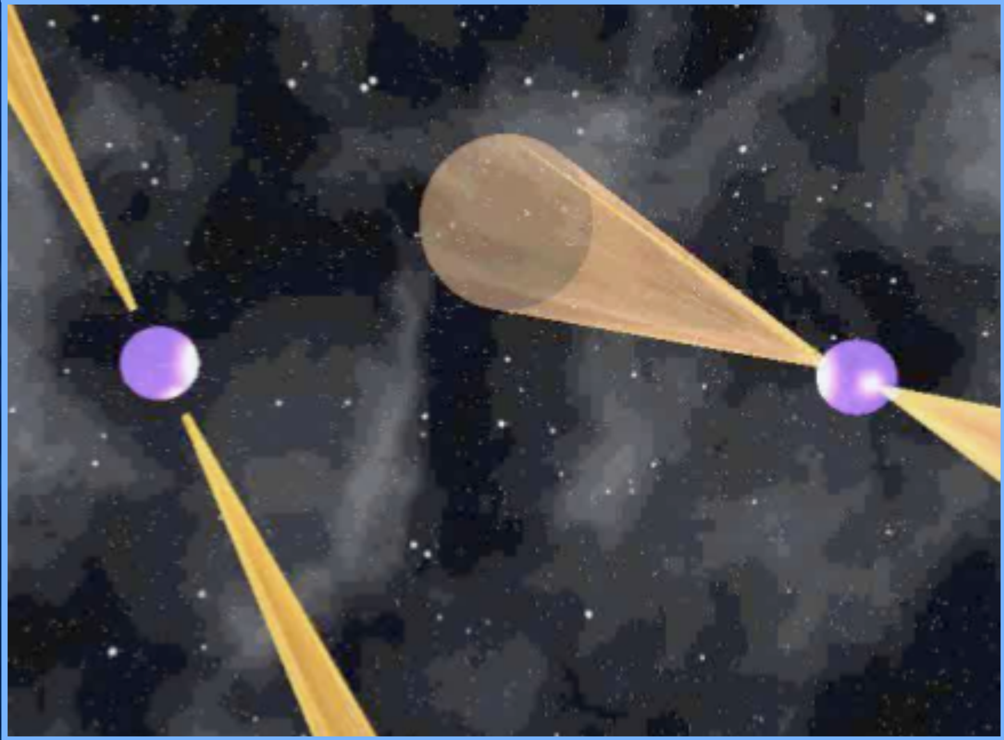

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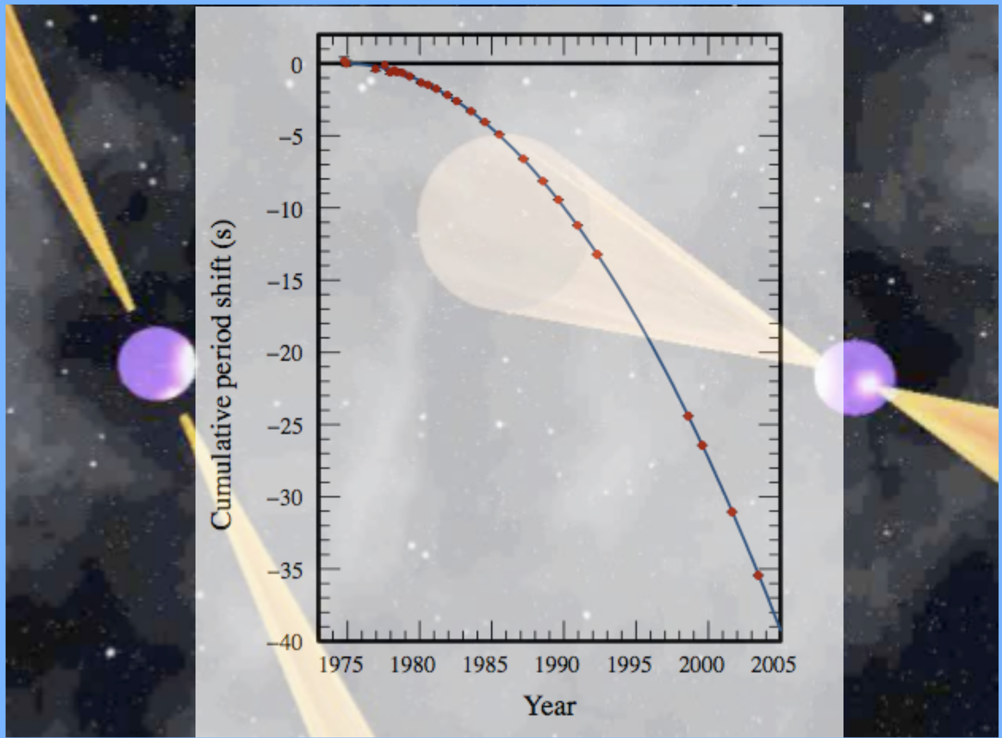

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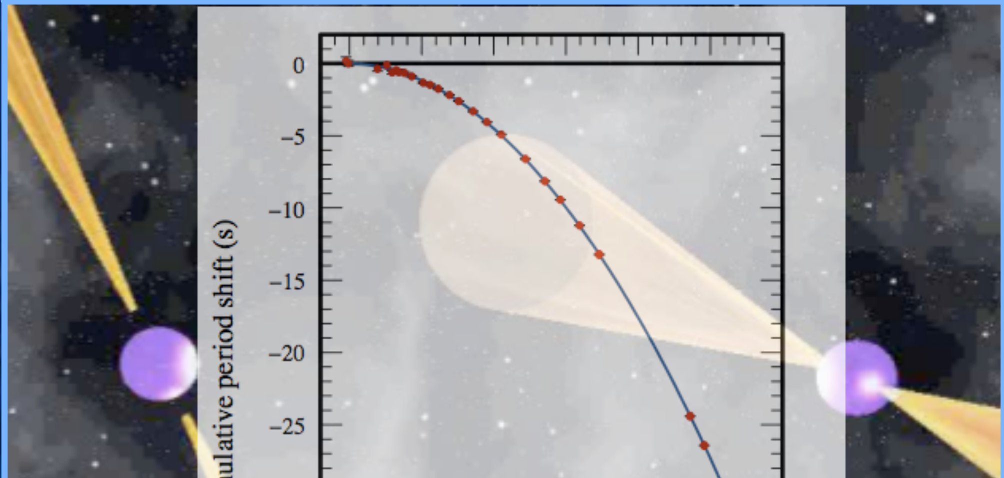


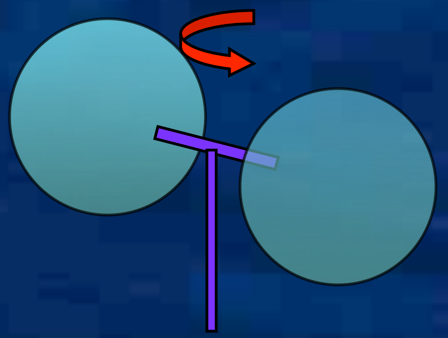
Orbit shrinks due to GW emission;
f_{gw} = 1/8 hrs

can we produce strain in laboratory ?

$$h_{\mu\nu} = \frac{2\,G}{R\,c^4}\,\ddot{I}_{\mu\nu}$$

$$|h| \approx \frac{r_{S1} * r_{S2}}{r_0 * R}$$

$\ddot{I}_{\mu\nu}$: red. quadr. moment ;
R : distance of observer ;
r_0 : Kepler radius
r_S : Schwarzschild-radii :
$r_S = 2\,G\,m/c^2$
$= 1.5\ 10^{-27} * m$



"man-made" :

2 spheres of 1 ton each, hold at 2 m distance ,
rotating at 1 kHz:

$$|h| \approx 10^{-42}$$

for interferometer of 10 km length,
this is change in arm length of 10^{-38} m ...

can we produce strain in laboratory ?

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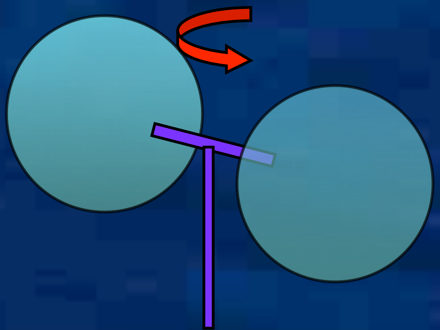

$$|h| \approx 10^{-42}$$

thus : need astrophysical sources !

possible sources :

	$\|h\|$ (galactic)	
• Supernova ;	$< 10^{-20}$	
• coalescence of binary compact system ;	$< 10^{-18}$	
• other burst sources (e.g. magnetars) ;	??	
• fast spinning deformed neutron stars ;	$< 10^{-27}$	cw

some sources are rare :

Supernovae: ≈ 1/(100 y * galaxy)

coalescence: ≈ 1/(1000 y * galaxy)

$|h| = \delta L / L$

possible sources :

$|h|$

- Supernova ; $< 10^{-20}$
- coalescence of binary compact system ; $< 10^{-18}$
- other burst sources (e.g. magnetars) ; ??

- fast spinning deformed neutron stars ; $< 10^{-27}$ cw

Note: better sensitivity ⟶ larger horizon D_{horiz}
⟶ larger rate ($\propto D_{horiz}^3$!)

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Note: better sensitivity → larger horizon D_{horiz}
→ larger rate ($\propto D_{horiz}^3$!)

I'll come back to expected rates

$|h| = \delta L / L$

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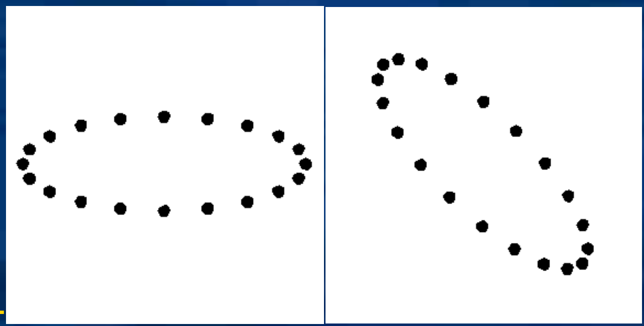
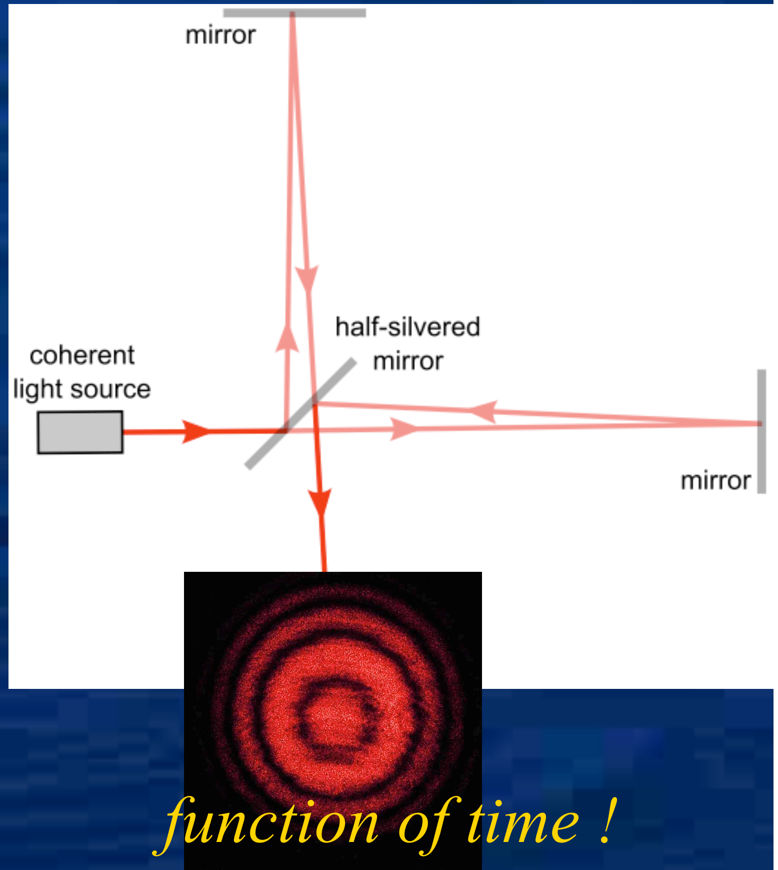
Grav. waves and ITF

h ≈ 0.5

polarizations:



h_+ h_x



function of time !

strength of GW: $|h| = \delta L / L$

Note: $|h| \propto {}^{1}/_{r}$!

Interferometric GW detectors: **A world-wide effort**

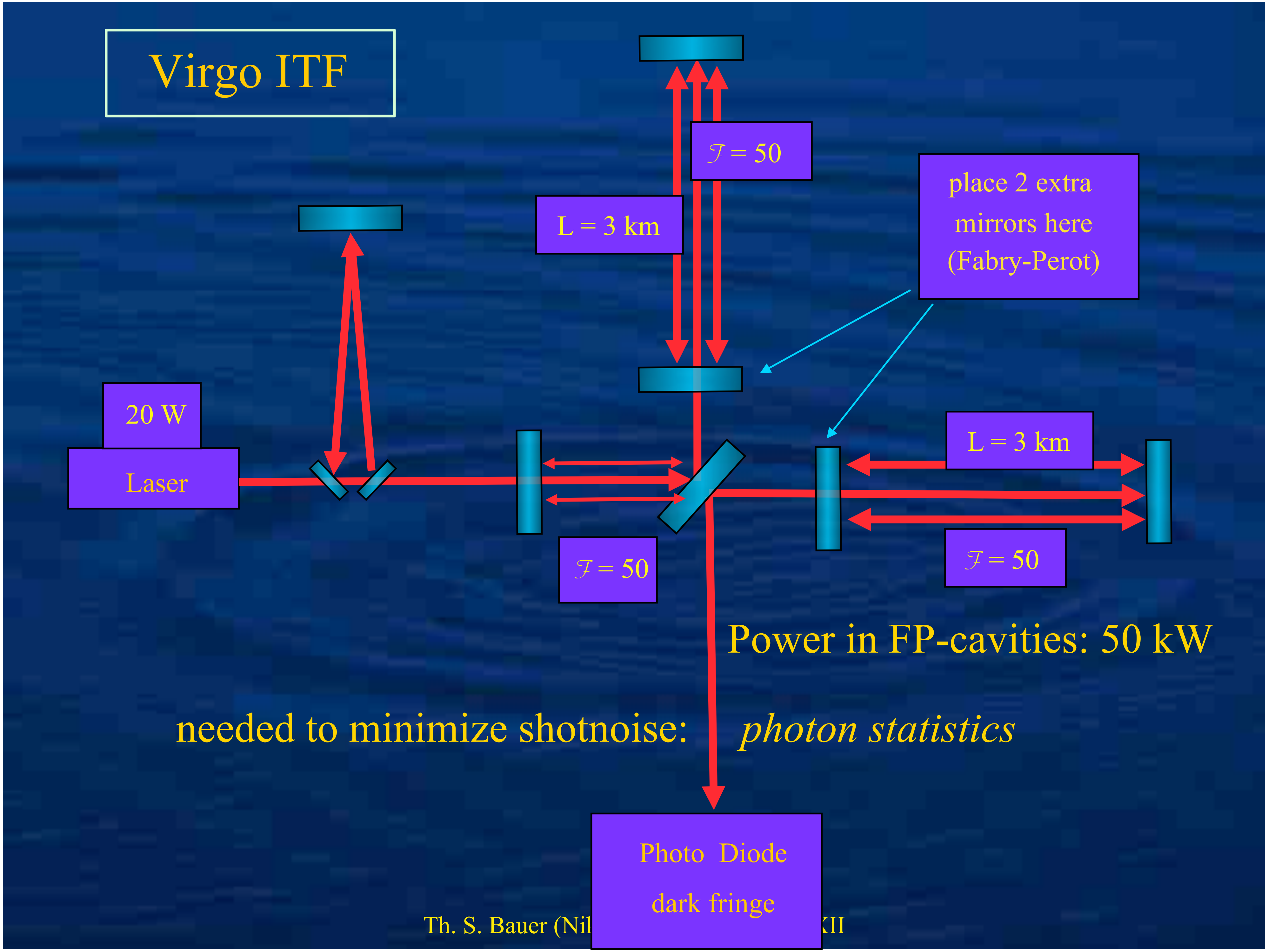
GEO600 (British-German)
Hanover, Germany

LIGO (USA)
Hanford, WA and Livingston, LA

TAMA300 (Japan)
Mitaka

AIGO (Australia),
Wallingup Plain, 85km north of Perth

VIRGO (French-Italian-
Netherlands, Cascina, Italy


Virgo ITF
$\mathcal{F}$ = 50
L = 3 km
place 2 extra
mirrors here
(Fabry-Perot)
20 W
Laser
L = 3 km
$\mathcal{F}$ = 50
$\mathcal{F}$ = 50
Power in FP-cavities: 50 kW
needed to minimize shotnoise: *photon statistics*
Photo Diode
dark fringe
Th. S. Bauer (Nil
XII

actual GW-detection sensitivity

What are the current sensitivities ?

(How far can we look ?)

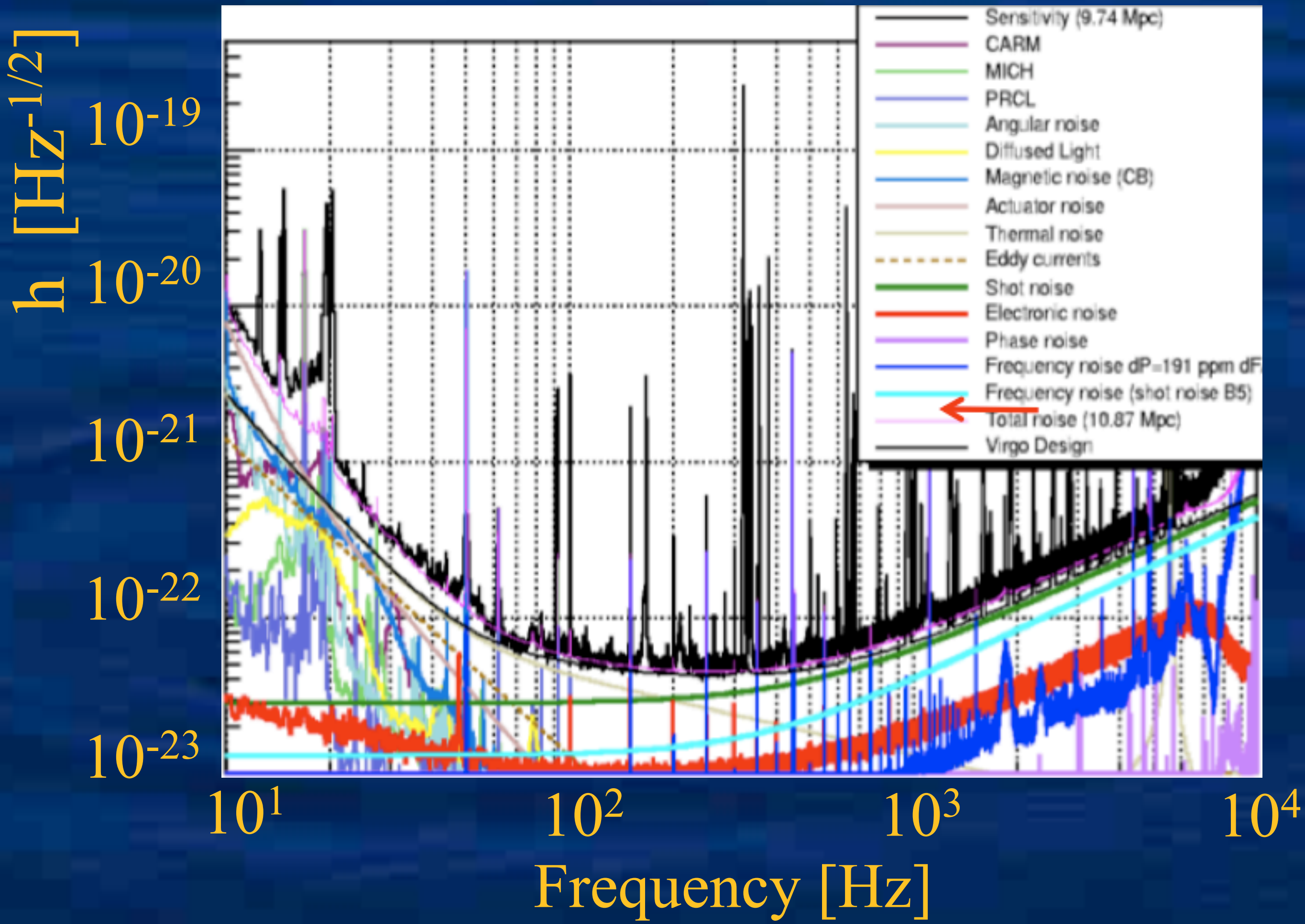
LIGO (USA) : 2 ITF, arm length : 4 km

(+ 1 ITF arm length 2 km)

Virgo (It + Fr + NL) : 1 ITF, arm length : 3 km

actual GW-detection sensitivity:

Virgo



actual GW-detection sensitivity:

LIGO

h [Hz$^{-1/2}$]

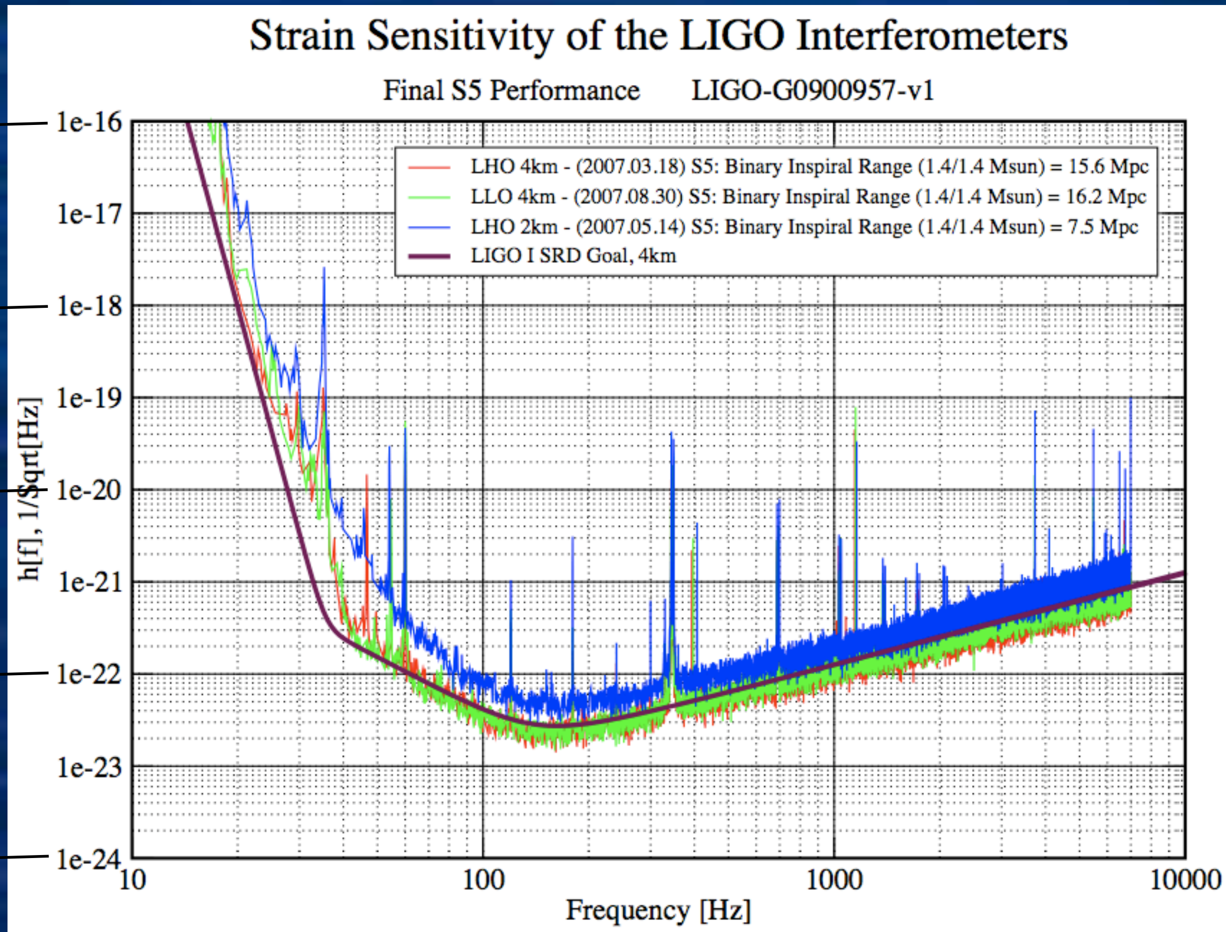
10^{-16}

10^{-18}

10^{-20}

10^{-22}

10^{-24}



10^{1} 10^{2} 10^{3} 10^{4}

Frequency [Hz]

actual GW-detection sensitivity

How far can we look ?

note: sensibility of ITF ***not*** isotropic, values given here are ***averaged*** over sensitivity pattern .

LIGO at present typically 15 – 20 MPc

Virgo (Jan. 2010): typically ~ 9 MPc

Note: this is for NS-NS-coalescences

actual GW-detection sensitivity

Did we see anything ???

actual GW-detection sensitivity

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no ... not yet

actual GW-detection sensitivity

Did we see anything ???

no ... not yet

actual GW-detection sensitivity

but ... what would we expect ?

actual GW-detection sensitivity

but ... what would we expect ?

coalescence of compact binaries :

Rates:	(MWe * Myr)$^{-1}$		Detections / year (2010)		
NS-NS:	1 ...	4000	10^{-4}	0.02	0.6
BH-BH	0.01 ...	30	10^{-4}	0.004	0.5
			pessimistic	realistic	optimistic

arXiv: 1003.2480v2

there is a *tiny* chance, that we might see

1 event in a year . . .

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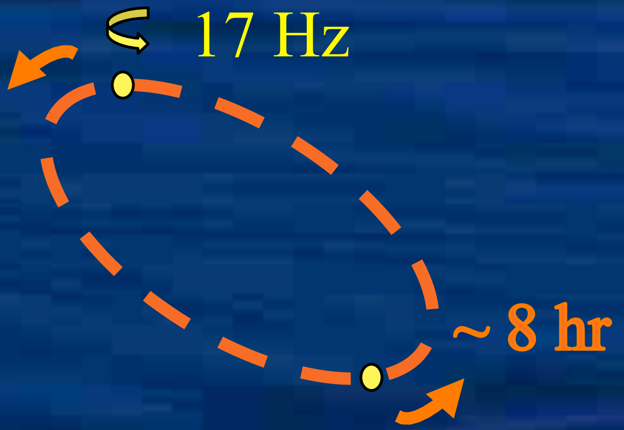
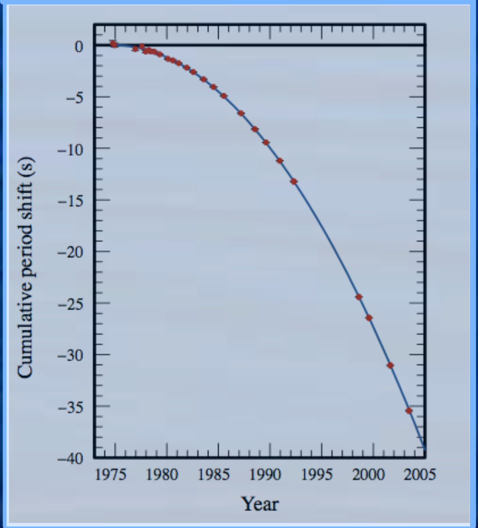
Bursts

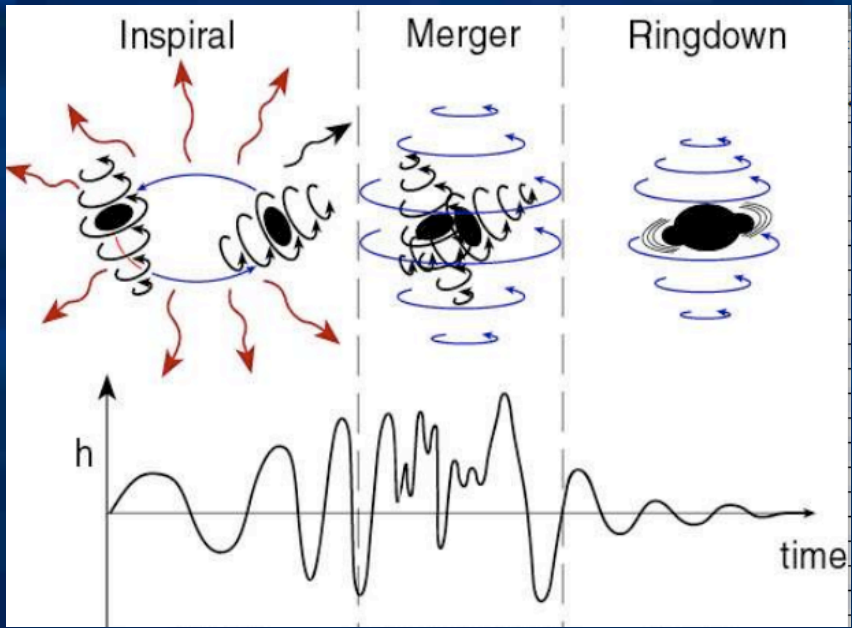
Bursts



Hulse – Taylor

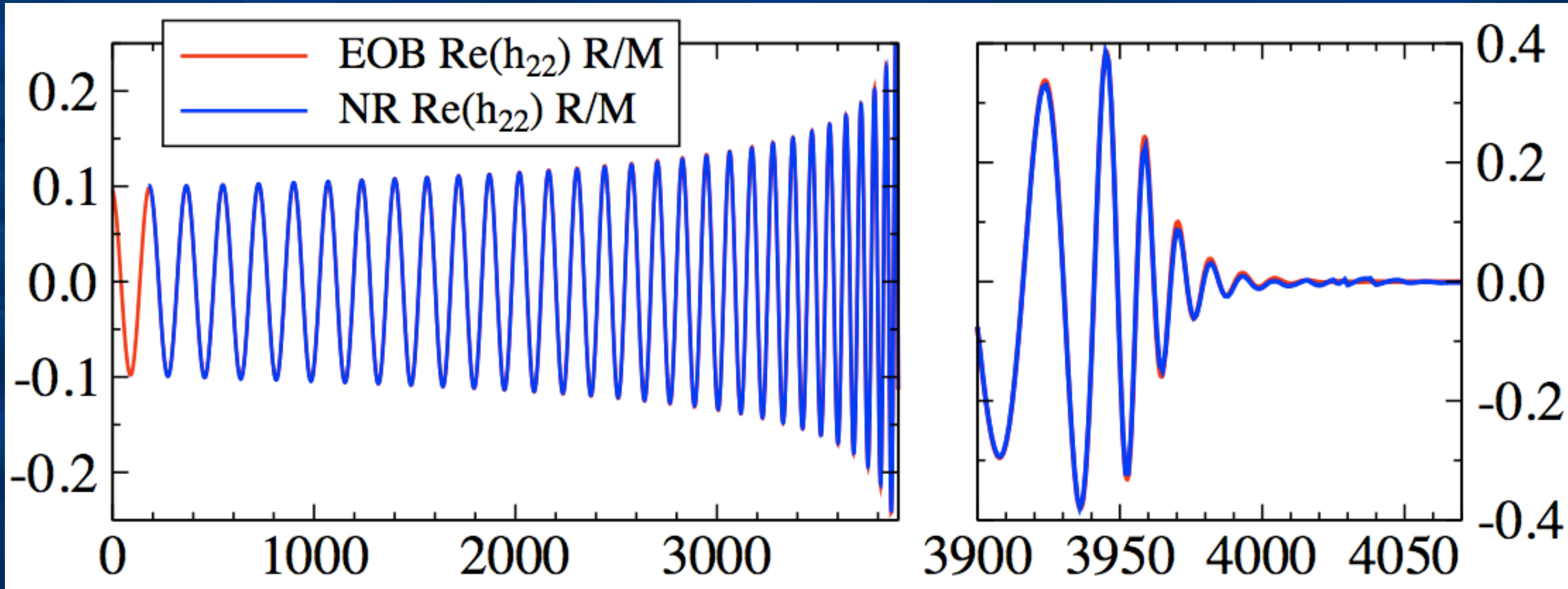


easy prediction:
the system inspirals
(crash in ~ 300 My)



Burst

Inspiral:
characteristic "chirp"



A. Buonanno et al, arxiv:0902.0790v2

sweeps fast through frequency band
(~ few sec ... < min)

Burst

2. Merger

present understanding, (but *unconfirmed*) :

Merger process *) is source of **GRB *and* GW**

→ **use GRB** to trigger

*) NS-NS and NS-BH

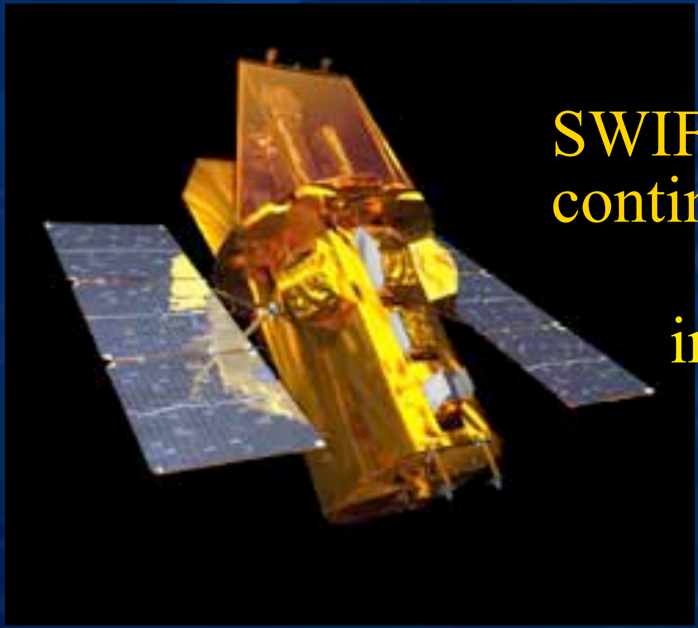
Burst

2. Merger

present understanding, but *unconfirmed* :

Merger process is source of **GRB** and **GW**

→ **use GRB** to trigger

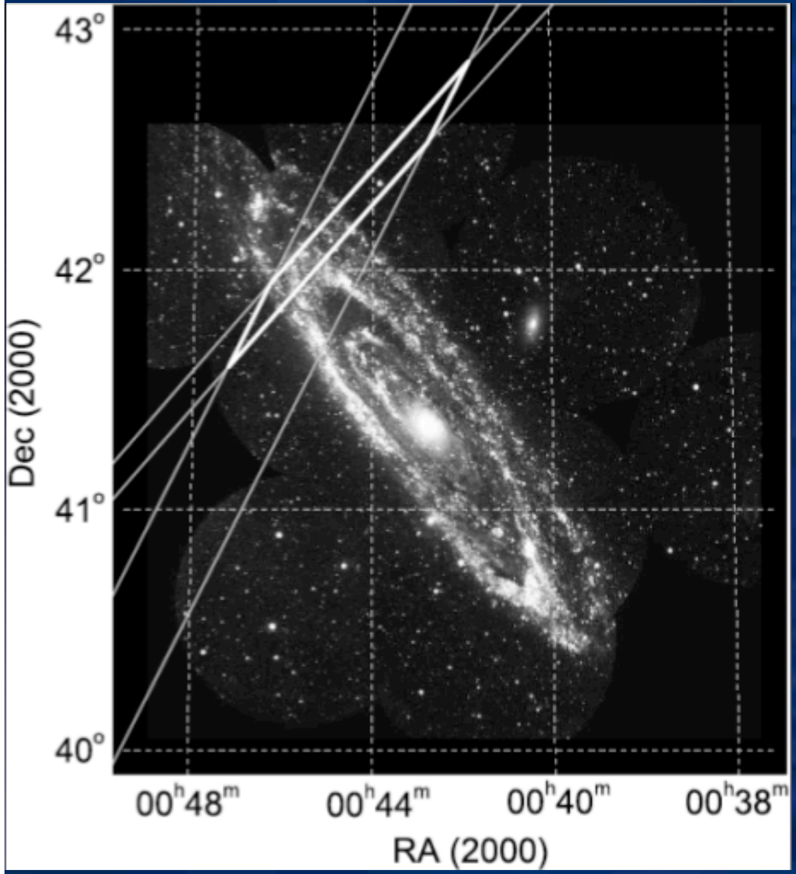


SWIFT (and other) satellites continuously hunt for GRBs

interesting case:

GRB 070201

Results : "GRB 070201 Event"

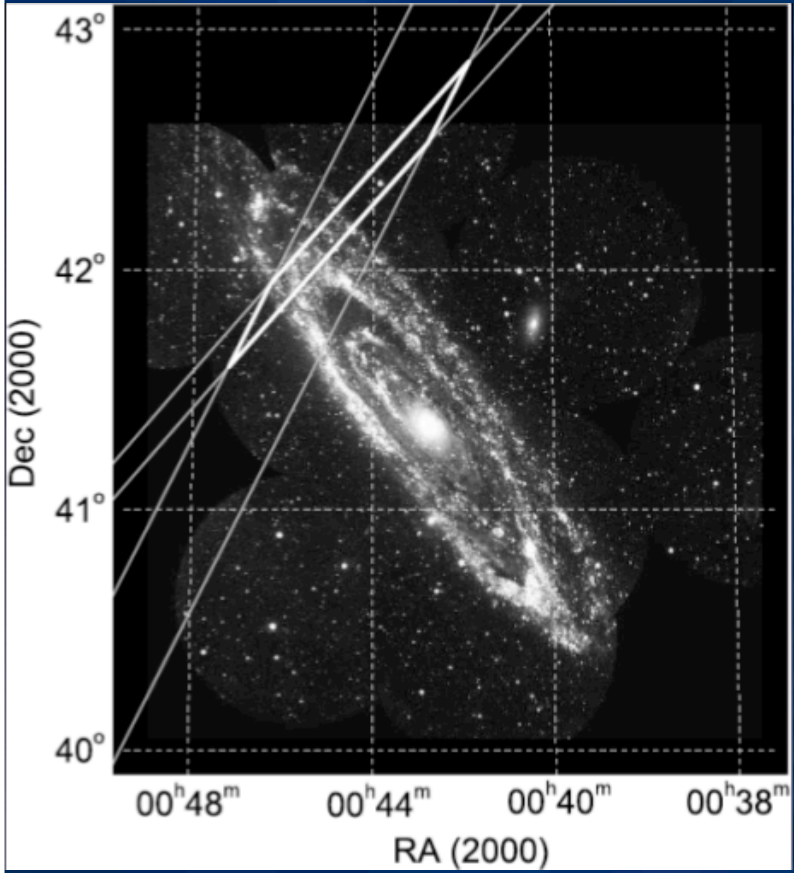


- Intense short (0.15 s) hard GRB;
- seen by 5 satellites
- position coincides with M31 (0.8 Mpc);
- only 2 detectors (LIGO) online

LIGO Analysis

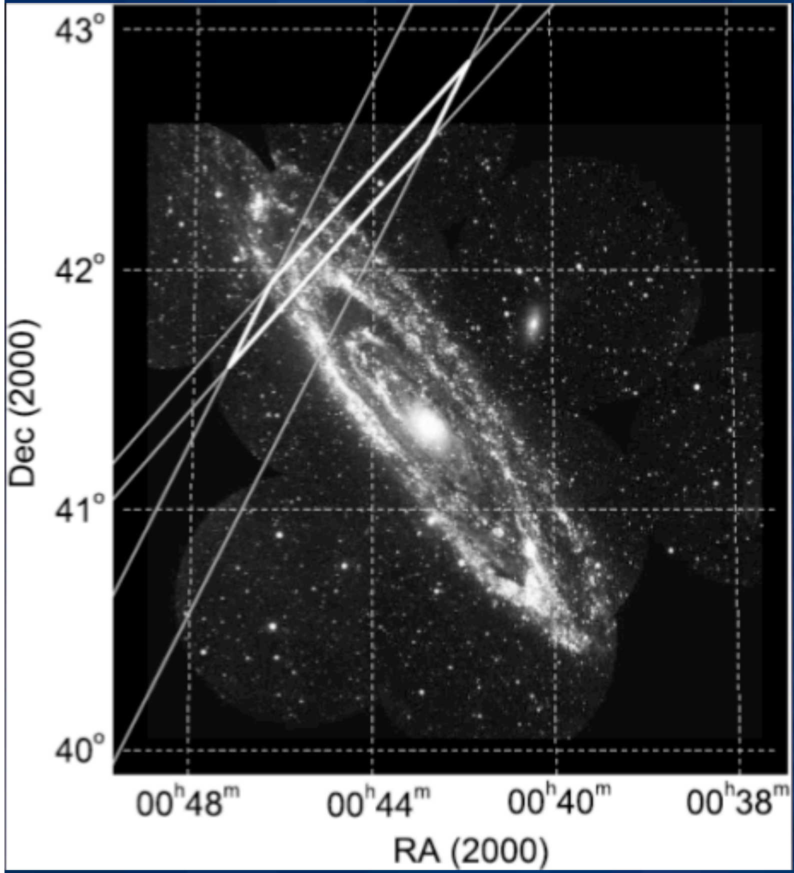
- analyze 3 minutes around trigger;
- understand background (few hrs around event)
- take mass and orbital possibilities into account

Results : "GRB 070201 Event"



- no signal found ...
- EXCLUDE :
  - compact binary with
  - $m_1 < 3\ M_s$, $m_2 < 40\ M_s$
  - $D < 3.5$ Mpc (90 % CL)
  - CBC in M31 (>99 % CL)
- need alternative explanation ...
- most likely: extragalactic SGR
- LIGO measurements are compatible with such a scenario

Results : "GRB 070201 Event"



GRB 070201 is quite an interesting event:

- it combines information of different detector types : "Multi-Messenger approach"
- a non-detection can also be a physics result .

if 070201 Event was not a GRB – what then?

possibly a Soft Gamma Repeater –

- 3 pulsars at same direction as SGRs
- repeated outbursts ← → starquakes;
- correlate with rotations frequency;
- very strong magnetic fields : 10^{10} Tesla
- name: "Magnetar".

"Little is known about the physical structure of a magnetar"

absence of GW is physics information;
simultaneous observation with different messengers is very important . . .

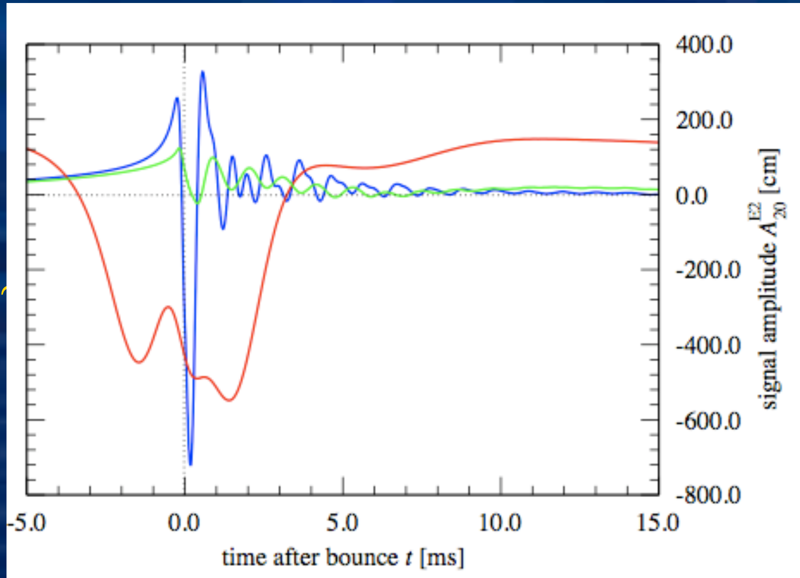
Supernovae

SN 1994 D in NGC 4526, ~ 17 MPc

Supernovae

several types, need core collapse ; ≈ 1/(100 y * galaxy) *)

signal strength: estimated $h \sim 10^{-20}$



let's look beyond our own galaxy:

next neighbour: **Magellanic Clouds**

next step : **Andromeda** (group)

next problem:

wave form not really known, but definitely *very short*: 10 ms ...

*) Note: SN collapse must be "<u>non-axi-symmetric</u>"

cw sources:

fast spinning *deformed* Neutron Stars

Remnant of a Supernova ;

ca 1.4 sun-masses

~ 10 km diameter;

strong magnetic field;

maximum deformation 10^{-5};

numerous

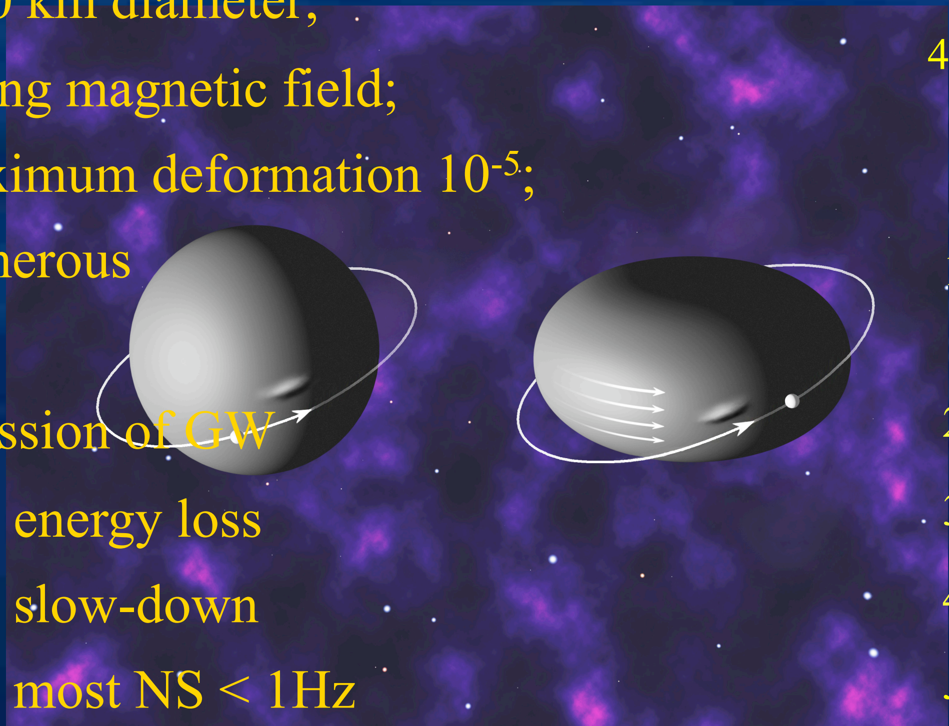
but:

emission of GW

→ energy loss

→ slow-down

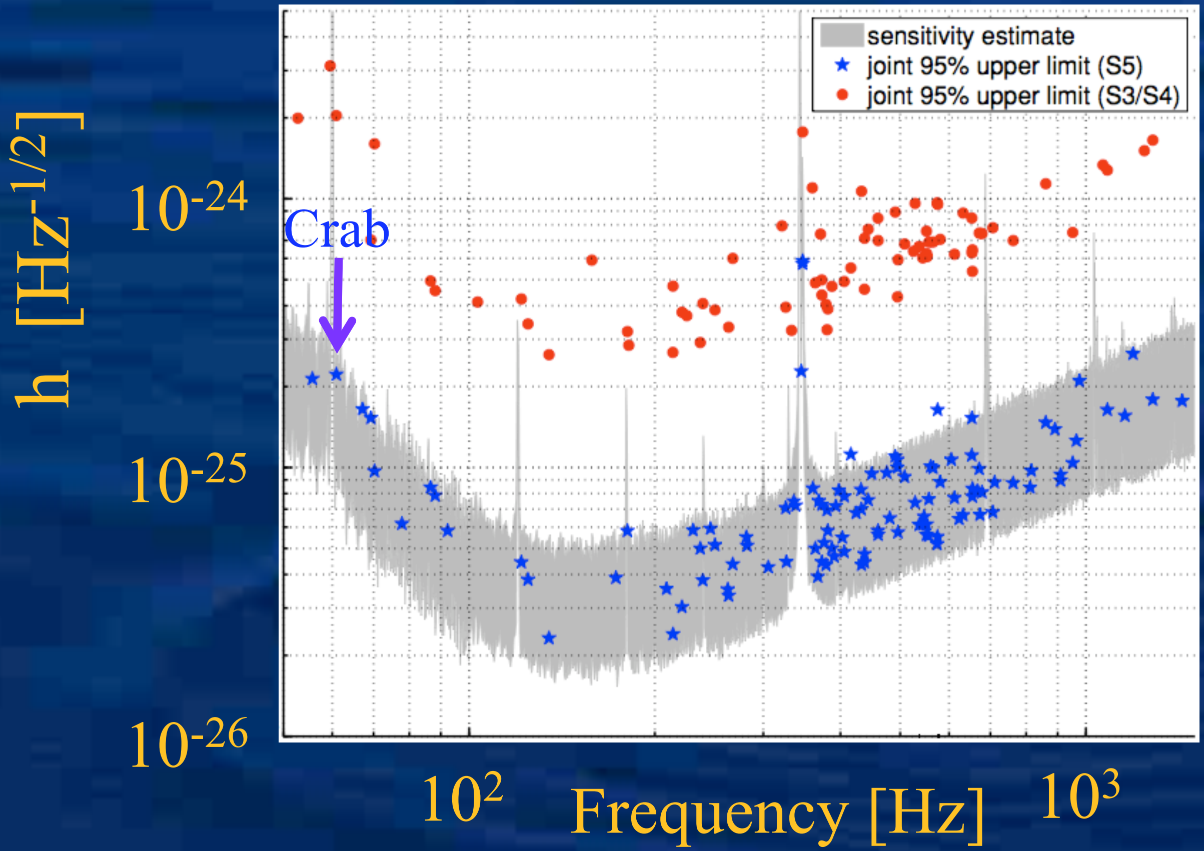
→ most NS < 1Hz



1. highly constant frequency
2. integrate over long period
3. $-10^{-10} < df/dt < 0$
4. Doppler shift due to Earth motion

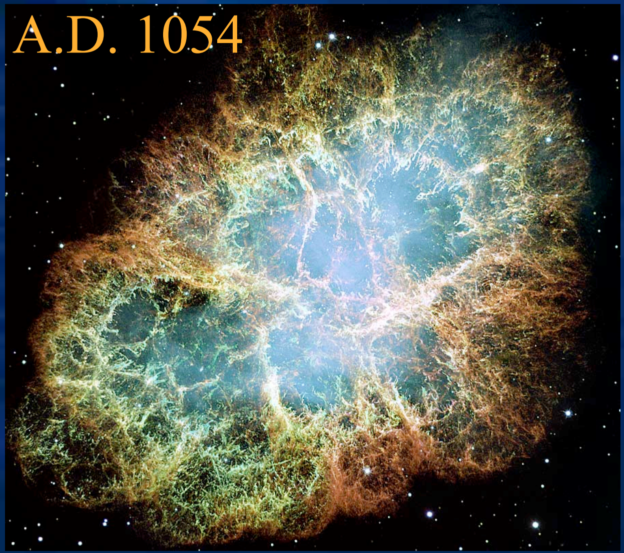
1. Filtering the data to find these orbits in a *huge* parameter space
2. target *known* NS
3. or
4. Blind all-sky search
5. *extremely computing intensive*

Results : "fast spinning *known* Neutron Stars"

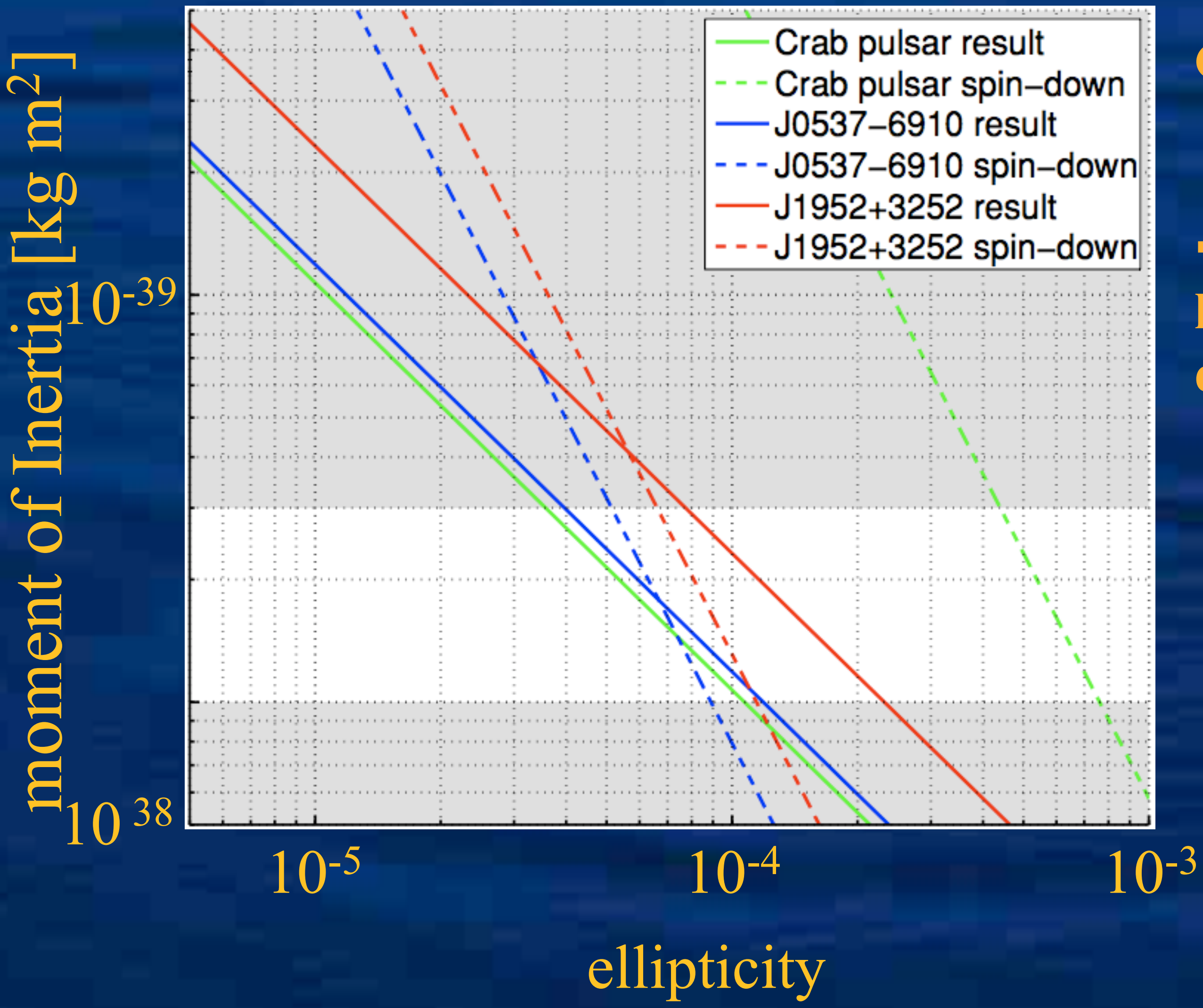


take care of Doppler effect due to known position of pulsar;
note: $f_{gw} = 2 * f_{pulsar}$

Crab: 30.2 Hz



Crab result:



Crab pulsar:

➔ GW-result > 10 times lower than classical spin-down limit

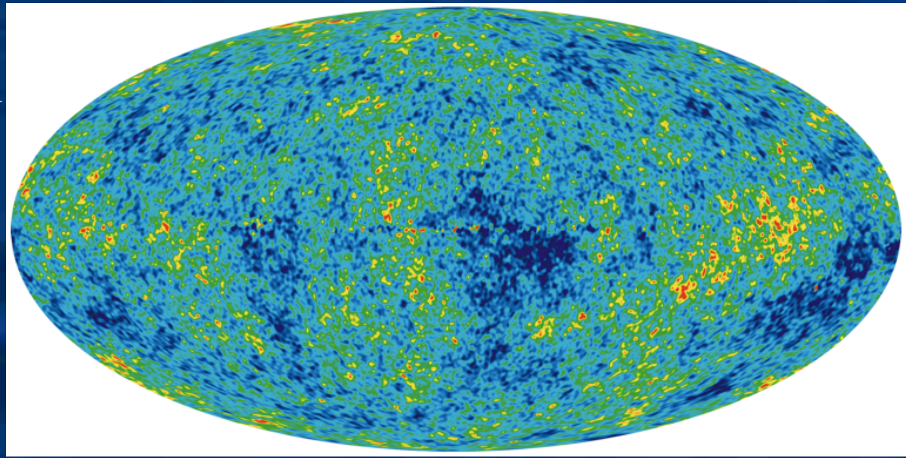
(ApJ, 2008, 683, L45)

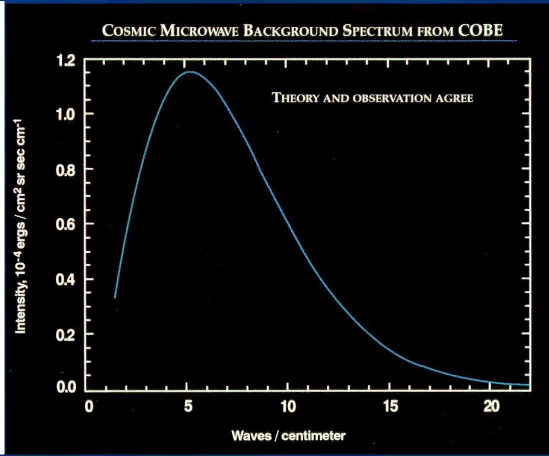
Stochastic

Results : "stochastic Background"

well-known picture:
CMB, shows temperature anisotropies of sky
from WMAP

mean: 2.725 K
blue: colder
red: warmer
by 0.0002°

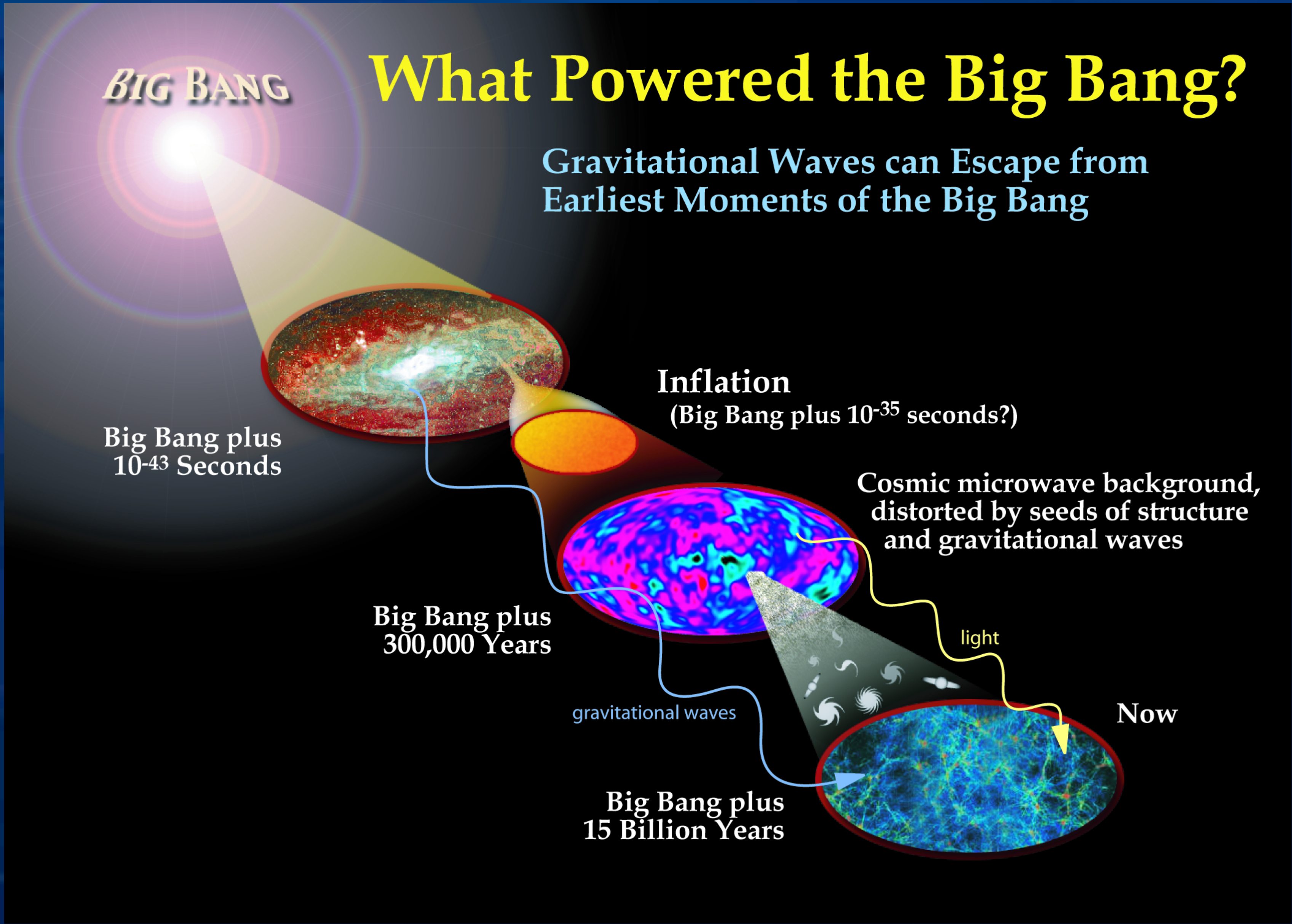




Picture says: - *inflationary Big Bang;*
- *can learn a lot about Universe from stochastic background;*

NB: Universe became transparent to photons only at the age of 379 000 years . . .

Results : "stochastic Background"



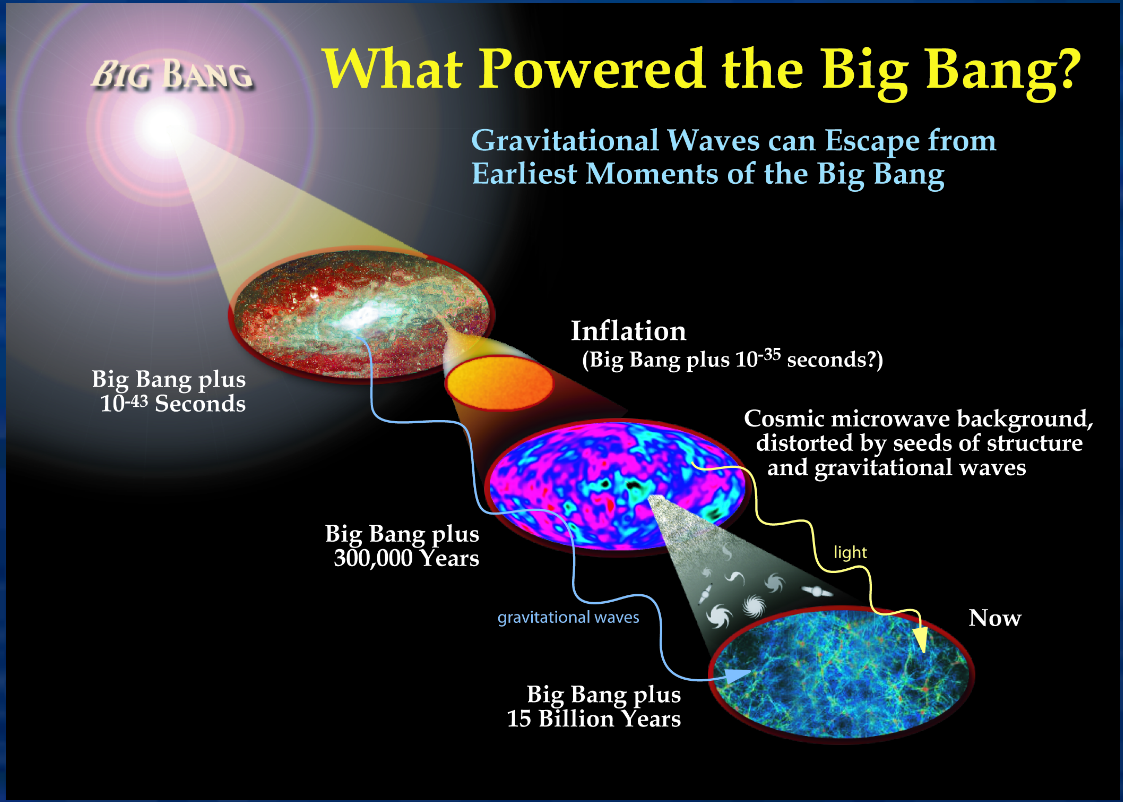
from: http://science.nasa.gov

Results : "stochastic Background"

Big Bang represents the biggest acceleration of the biggest amount of mass of the Universe alltogether ...

Grav. waves interact extremely weakly with matter;

the Universe is *transparent* for grav. waves *right* from the Big Bang.



Grav. waves carry *direct* information about the Big Bang (in contrast to other messagers)

Results : "stochastic Background"

it seems rather crazy to try to analyze GW data
in the same way as CMB ;

however:

- the ITF's give at least an *upper limit* for GW radiation;

- we may try to analyze the implications of the data and check whether they are compatible with different scenarios

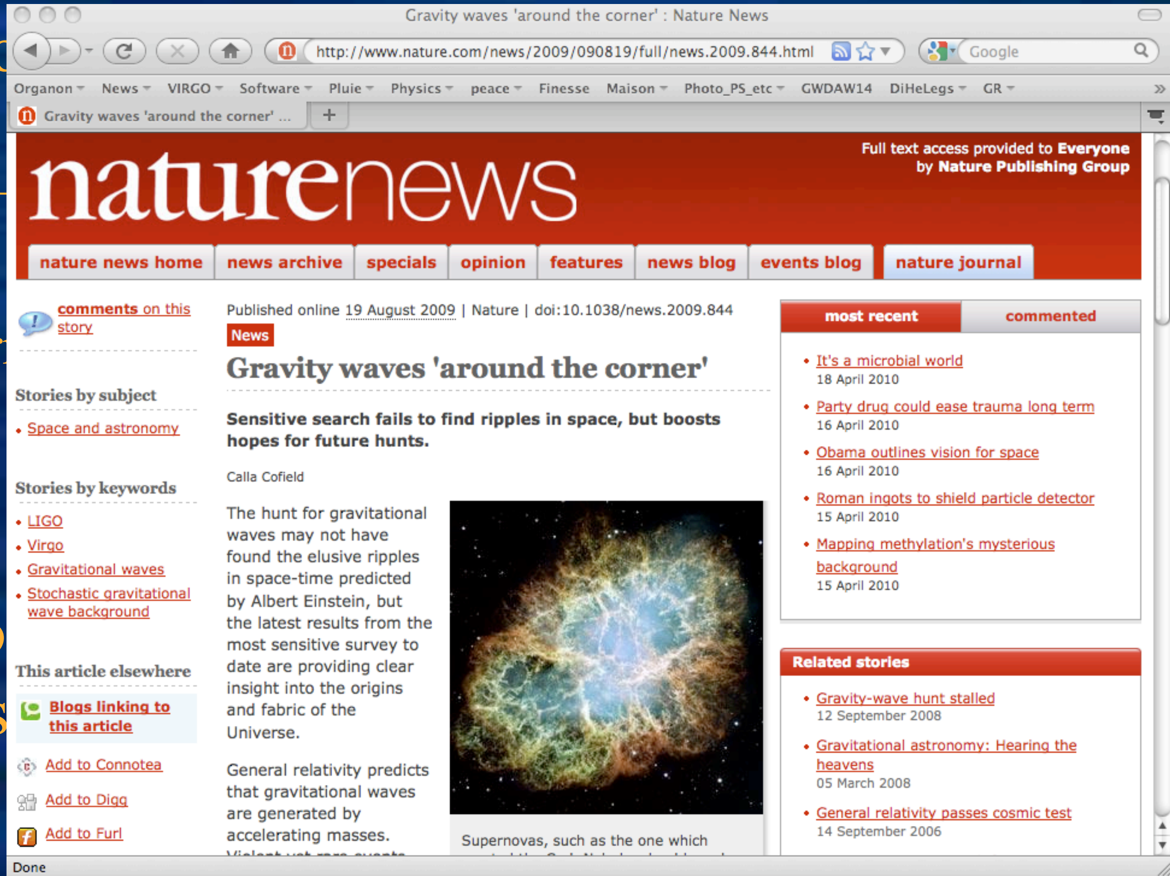
Results : “stochastic Background”

Result :

1) Energy density o

$< 6.9 \times 10^{-}$

(around 100 Hz, nor)


Gravity waves 'around the corner' : Nature News

http://www.nature.com/news/2009/090819/full/news.2009.844.html

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Gravity waves 'around the corner' ...

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Published online 19 August 2009 | Nature | doi:10.1038/news.2009.844

News

Gravity waves 'around the corner'

Sensitive search fails to find ripples in space, but boosts hopes for future hunts.

Calla Cofield

The hunt for gravitational waves may not have found the elusive ripples in space-time predicted by Albert Einstein, but the latest results from the most sensitive survey to date are providing clear insight into the origins and fabric of the Universe.

General relativity predicts that gravitational waves are generated by accelerating masses.

Supernovas, such as the one which

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  15 April 2010

Related stories
- Gravity-wave hunt stalled
  12 September 2008
- Gravitational astronomy: Hearing the heavens
  05 March 2008
- General relativity passes cosmic test
  14 September 2006

Done

2) rules out
- large equation-o
- small string tens
- improves limits

The LIGO Scientific Collaboration &
The Virgo Collaboration.
Nature 460, 990-994 (2009).

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Multi Messenger Approach

- SWIFT (and others) hunt for GRBs ;
- in case of a detection, an "*alarm*" goes at Virgo and LIGO ;
  Goal: essentially to keep detectors running ;
  alarm not really needed since data are recorded .

- if Virgo and LIGO detect an "potential event",
  SWIFT (x-ray), TAROT and QUEST (optical)
  are notified for immediate follow-up;
- must be in *real time* in order to point the EM telescopes
  → need small latency !

- NOTE: only limited number or notifications allowed !

Multi Messenger Approach

depending on the sources, different particles or waves are emitted:

- Supernovae: ν, γ
- CBC: GRB (of different characteristics)
- Pulsars: el-mag,
- …

useful for coincidences:

- GRBs (SWIFT (and others) satellites);
- High-energy Neutrinos (KM3Net);
- low-energy neutrinos ;
- optical;
- rf-signals (pulsars!)

Science from Grav. Waves observation

- Merger rates, structure formation
- GRB progenitors
  short, hard: CBC
- SGR progenitors

- Neutron-star equation of state
- Magnetars

- Test GR in strong field regime
- Test or constrain non-GR theories

- "Standard sirens" : Hubble constant

The Future

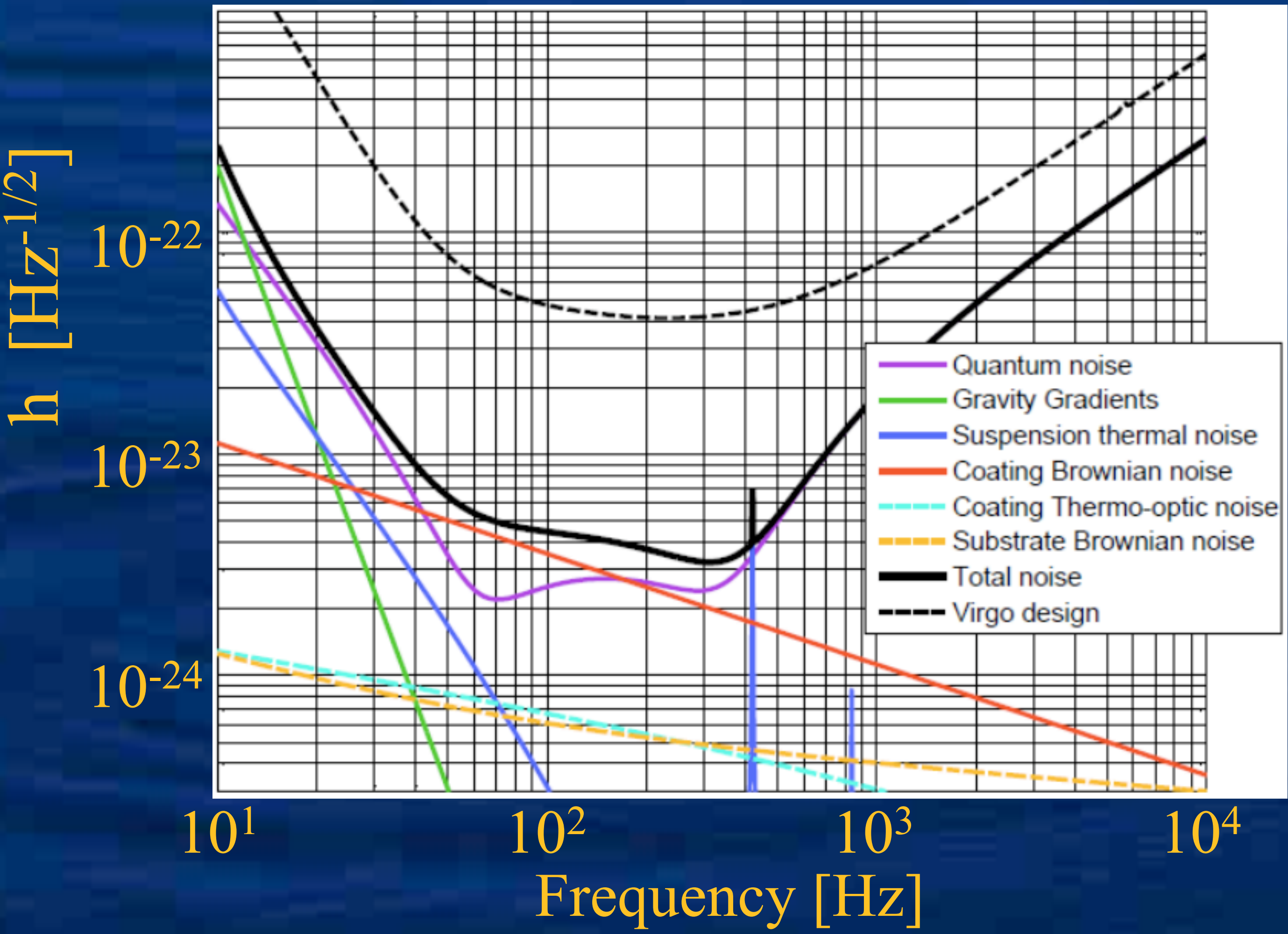
Advanced Virgo, and LIGO

funded,
activities started,
commissioning ~ 2014

BNS range: **121** Mpc
BBH range: **856** Mpc
1 kHz sens.: $6\ 10^{-24}/\sqrt{Hz}$

Comparison	Virgo ←	→Advanced Virgo:	
Power recycling:	yes	yes	
Signal recycling:	no	yes	
Laser	25	>160	W
Suspension:	steel	fused silica	
mirror losses:	250	37.5	ppm
vacuum:	$2*10^{-7}$	$2*10^{-9}$	mbar

Advanced Virgo



Horizon:
BNS range: **121** Mpc

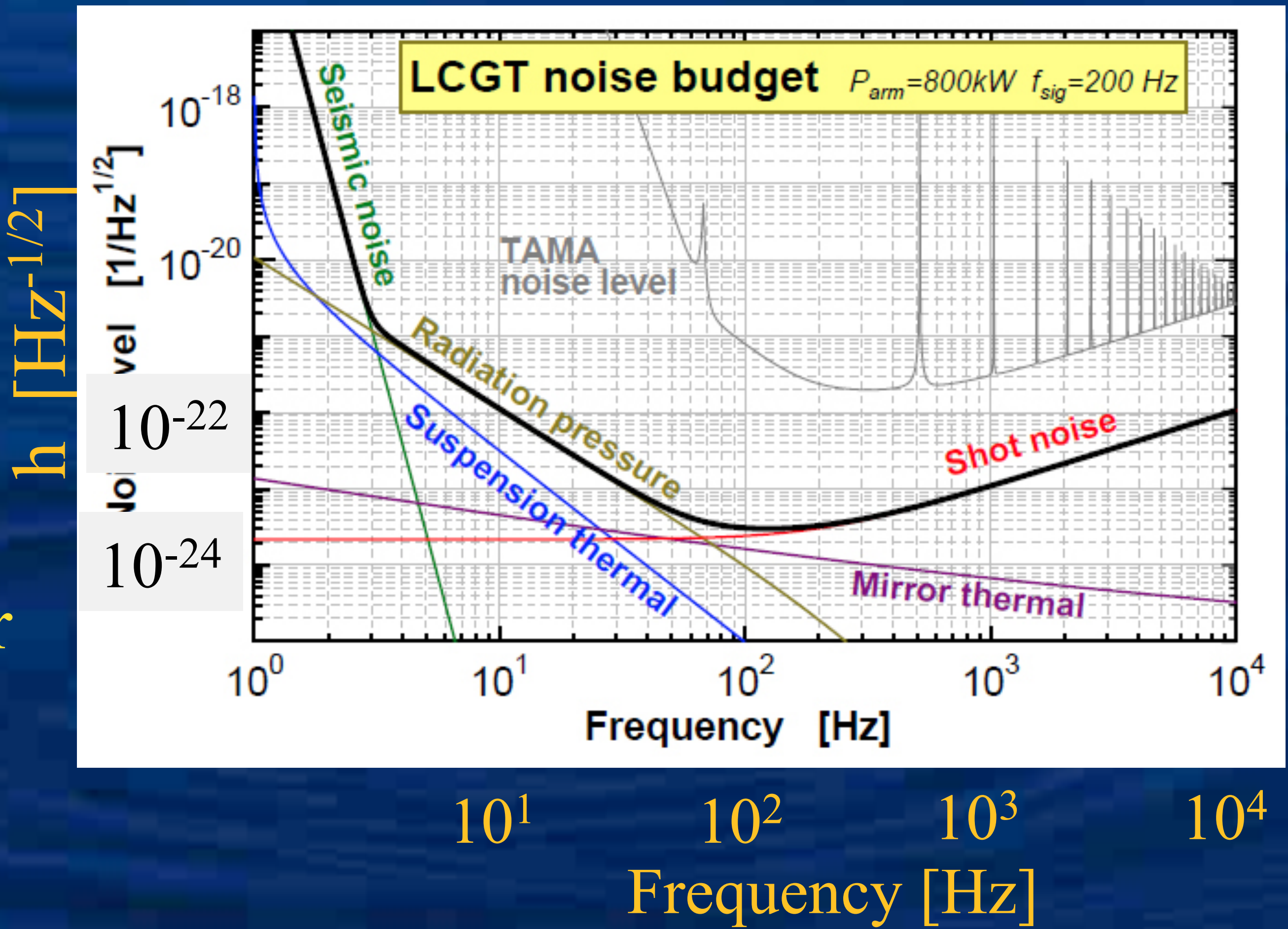
Advanced LIGO rather similar to AdV

LCGT – Japan (Kamioka)

just approved

cryogenic,

somewhat better than AdV



Event rates AdV (2014)

Detection rates for compact binary coalescence sources.

Source[a]	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm re}$ $\rm yr^{-1}$	$\dot{N}_{\rm pl}$ $\rm yr^{-1}$	$\dot{N}_{\rm up}$ $\rm yr^{-1}$
NS-NS	0.4	40	400	1000
NS-BH	0.2	10	300	
BH-BH	0.4	20	1000	

realistic

plausible

Ref.: Rates paper arXiv:1003.2480v2

the near future AdV (2010 - 2011)

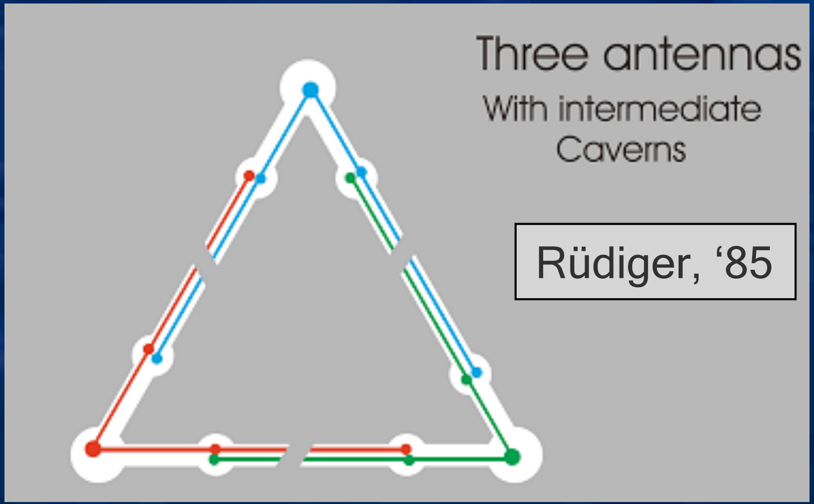
		horizon	
Virgo		9 MPc	2010
Virgo+MS	new mirrors, fused silica suspension :	50 MPc	being installed
AdV	better mirrors, vacuum,...	150 MPc	~ 2014

The third generation ...

Third generation detector ET

Preparation: since 2008
Start: 2016 ??

1. Two orders of magnitude compared to initial Virgo $\sim < 10^{-23}$
2. underground → less seismic noise
3. Multiple interferometers:
   1. 3 Interferometers; triangular configuration?
   2. 10 km long
   3. 2 polarization + redundancy
4. Design study part of ILIAS & FP7
5. Construction: > 201x ?



Space based Interferometers ?

Sciencefiction ??

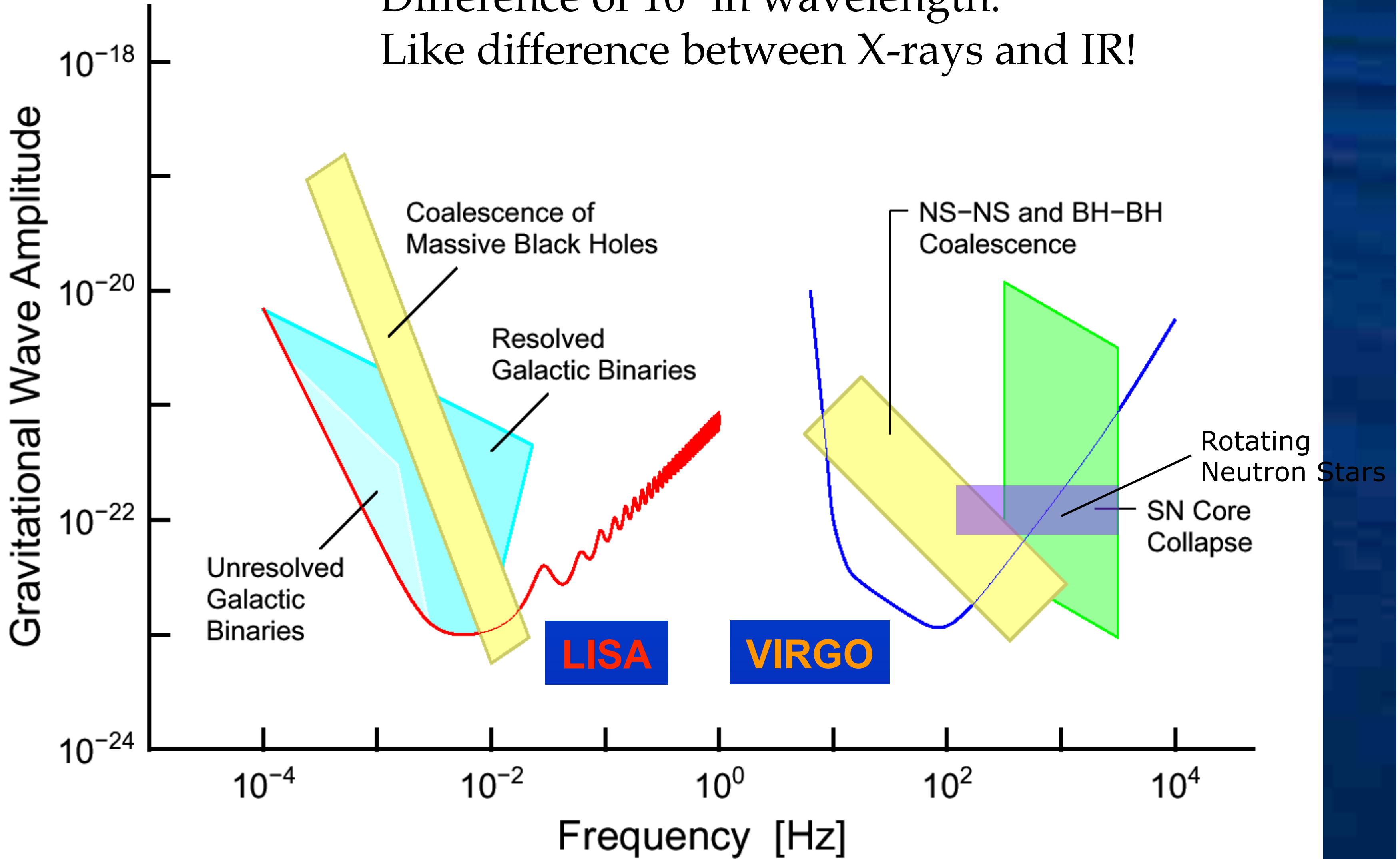
ESA-NASA Project with
Highest priority!! ("Flagship")
Start: 2018 (??)

go away from seismic noise
i.e. go into space

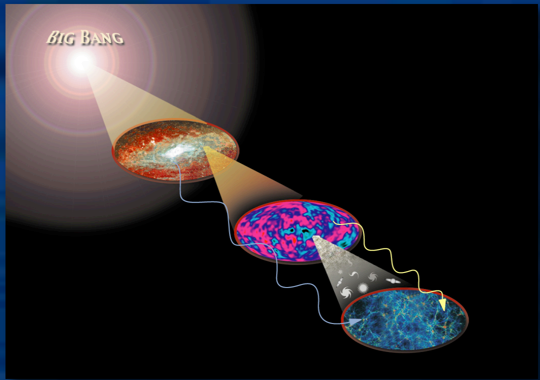
put 3 satellites on Earth orbit around Sun
at 60° behind Earth (50 Gm from Earth)
forming stable triangle
baseline 5 Gm
use satellites as corners of 3 ITFs
Due to long baseline, very low frequency
due to absence of seismic, very good sensitivity

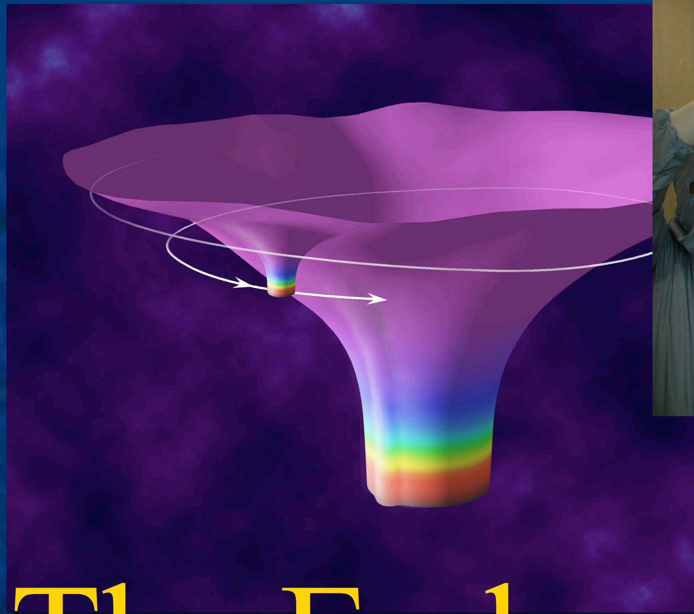
Complementarity of Space- & Ground-Based Detectors

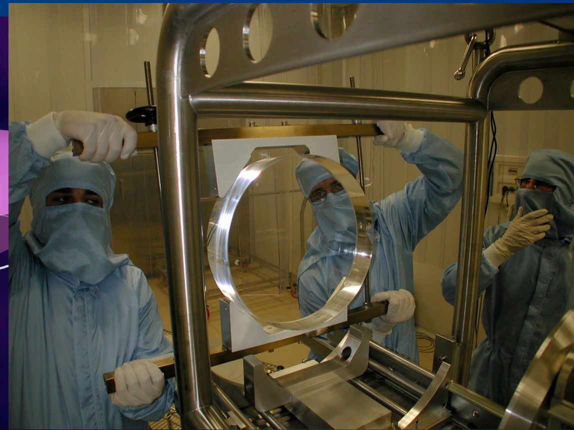
Difference of 10^4 in wavelength:
Like difference between X-rays and IR!



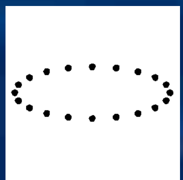
LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy (Schutz)

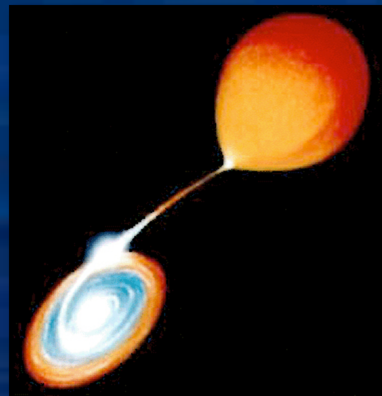


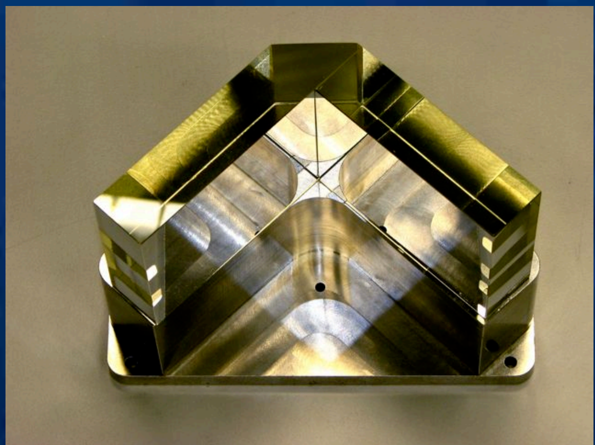




The End







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Backup slides