Astrophysics with LISA

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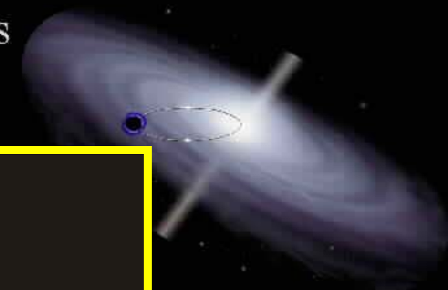
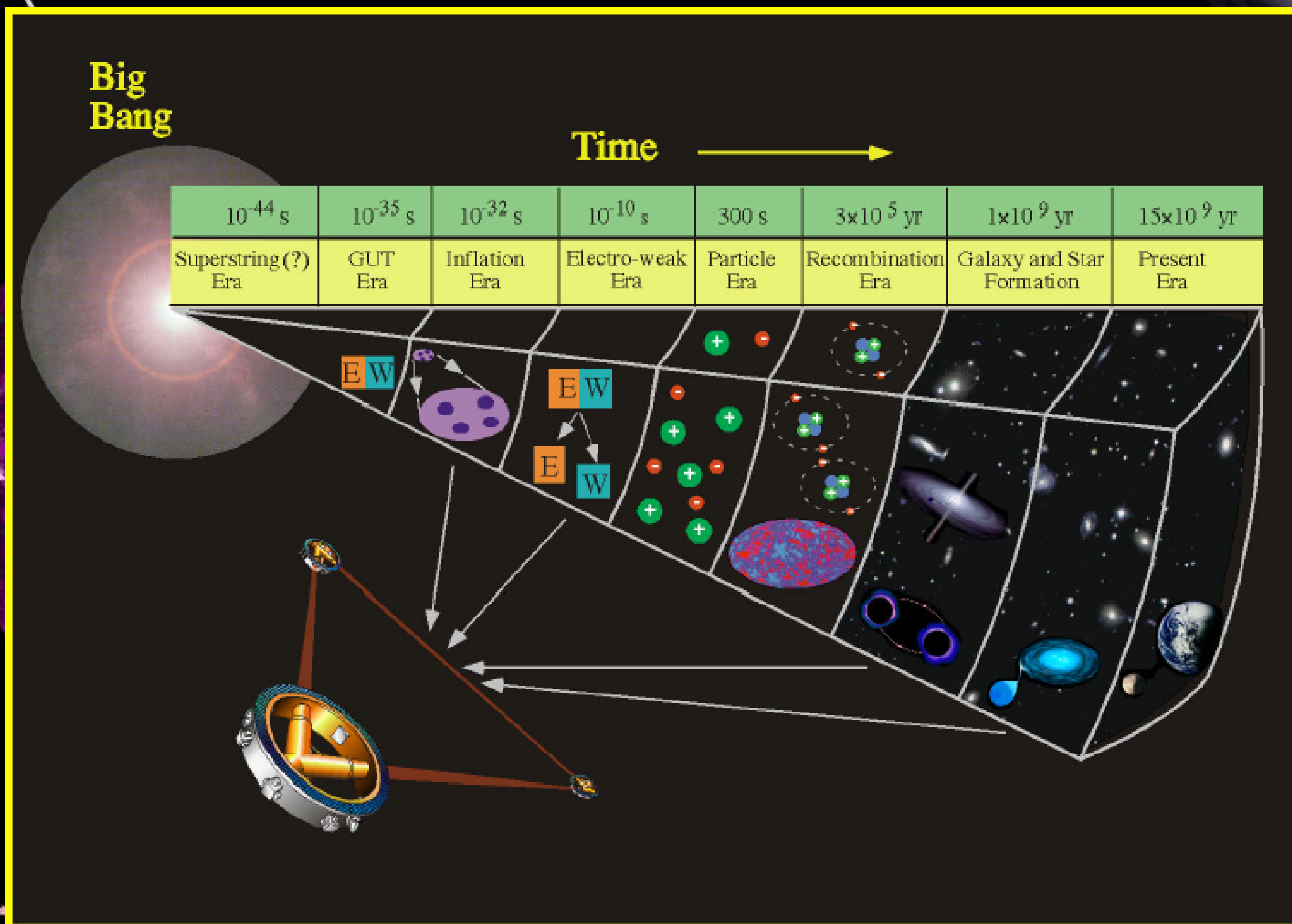
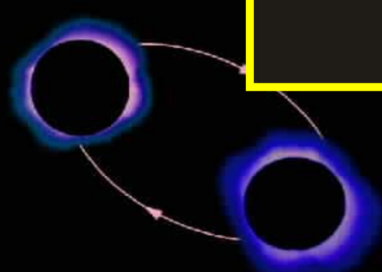
Galactic Binaries:
(Including future
Ia supernovae)

Compact Objects Orbiting
Massive Black Holes
(High-precision probes
of high-field gravity)







Formation of
Massive Black Holes
(Quasar Cores)
Before Star Formation

Fluctuations from
Early Universe
(before recombination
formed 3° background)

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LISA: GW telescope

- LISA is an all-sky monitor:
  - All sky surveys are for free
  - "Pointing" is done in software
- Signals are (for the vast majority) long lived
- Information about sources are reconstructed through structure of signal
  - Intrinsic in the waveform
  - Induced by instrument motion and response
- Each signal depends (with a few exceptions) on 7-to-17 parameters

- One yr of LISA data contain:
  - A dozen of known solar mass binaries (verification sources)
  - ~ 10000 WD binaries (a few with NS companion)
  - ~ 100 EMRIs
  - ~ 10 I/M/SMBH binaries
  - Some short lived burst events
  - Stochastic foregrounds and backgrounds

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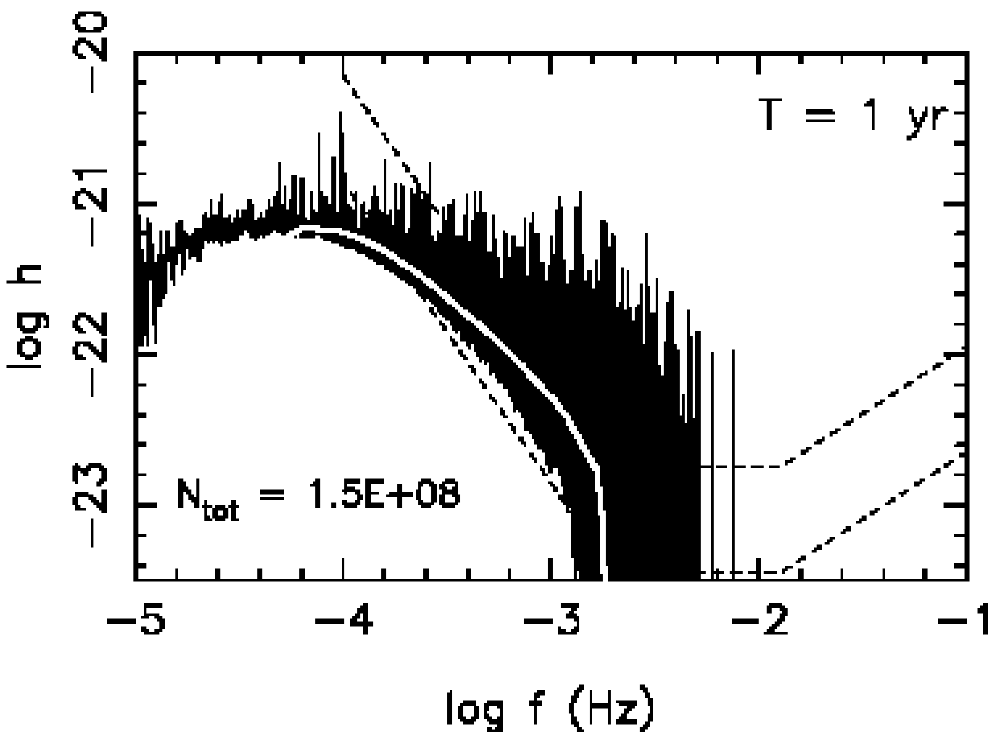
Astrophysics and cosmology

- (Compact) stars:
  - Primarily white dwarfs
  - But also neutron stars
  - And possible main-sequence and/or super-massive stars
- Star formation rate
- Black hole demographics (from 1 to 10^8 Msun)
  - Our galactic centre
  - Stellar mass BHs
  - Intermediate mass BHs
  - Massive BHs
  - Super-massive BHs
- Dynamics in
  - Star clusters
  - Galactic nuclei
- Hierarchical clustering
  - The very first structures
  - Structure formation
  - Galaxy merger history
- Cosmology:
  - Dark energy
  - Early-Universe:The first second of cosmic time

Galactic WD binaries



(Nelemans et al, 2001)

- LISA is expected to provide the largest observational sample of white dwarfs (WDs)
  - Very large number in frequency space

$$\frac{dN}{df} = 2 \times 10^{8}\, Hz^{-1} \left(\frac{0.001\, Hz}{f} \right)^{11/3}$$

- WDs are detected as
  - Individual deterministic signals (primarily for f > 3 mHz)
  - Astrophysical foreground (for f < 3 mHz large number of sources per frequency bin)

Galactic WD (/NS) binaries

Type	Birth rate (year^{-1})	Resolved systems	With frequency change
(wd, wd)	2.9×10^{-2}	12 163	560
AM CVn	1.8×10^{-3}	10 117	49
(ns, wd)	1.4×10^{-4}	21	3
(ns, ns)	3.2×10^{-5}	1	0
(bh, wd)	3.8×10^{-5}	1	0
(bh, ns)	1.0×10^{-5}	0	0
Total		22 303	614

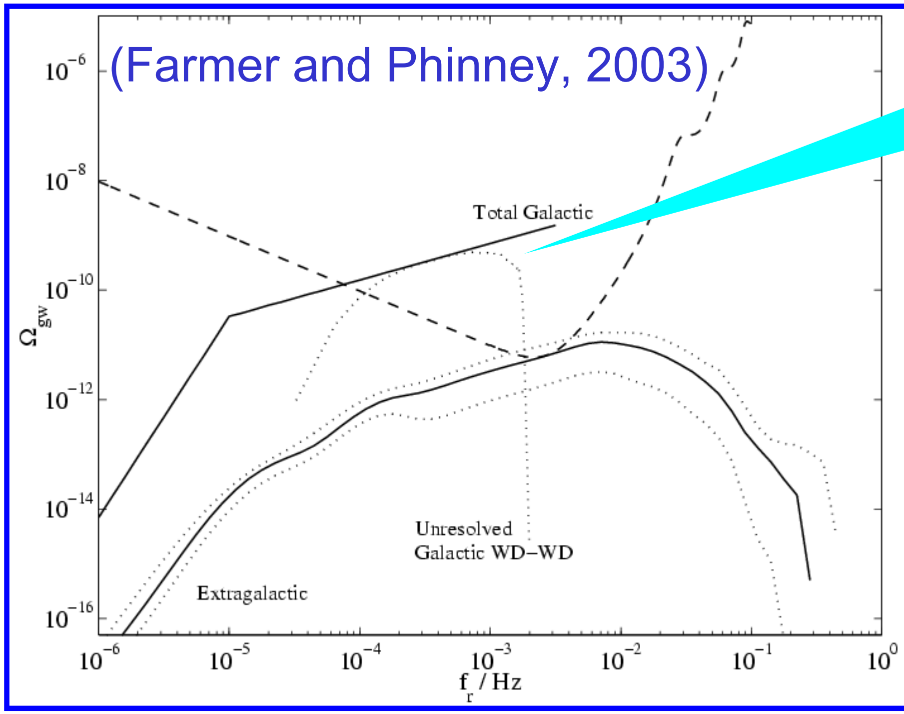
(Nelemans et al, 2001; Nelemans, 2002)

Main challenge for data analysis: identify, measure parameters, and remove "lines"

- Map (partially 3D) of WDs in the galaxy
- For ~100 systems, studies of:
  - Tidal interaction
  - Mass transfer
- If follow-on optical observations are available (for some objects):information on M-R relation (Cooray and Seto, 2004)

Galactic WD foreground

Foreground from galactic WD binaries

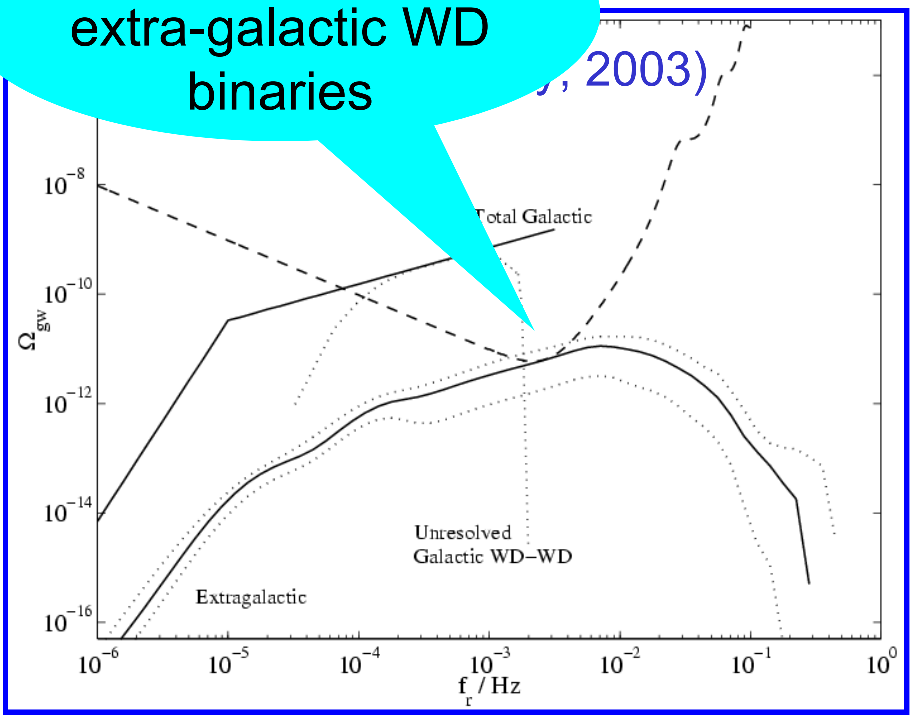


$$\frac{\rho_{gw}(f)}{\rho_{critical}} = \int \Omega_{gw}(f)\, d(\ln f) \qquad S_{gw}(f) = \frac{3H_0^2}{10\pi^2 f^3}\Omega_{gw}(f)$$

- Dominates instrumental noise: detectable at high SNR (Tinto et al, 2000; Hogan and Bender, 2001)
- Anisotropic (Giampieri and Polnarev; 1997)
  - A few moments of the distribution are detectable (Cornish, 2001; Ungarelli and AV, 2001; Seto and Cooray, 2004)
  - Source number density (and formation rate)
  - Angular distribution and map

Extra-galactic WD foreground

Foreground from extra-galactic WD binaries



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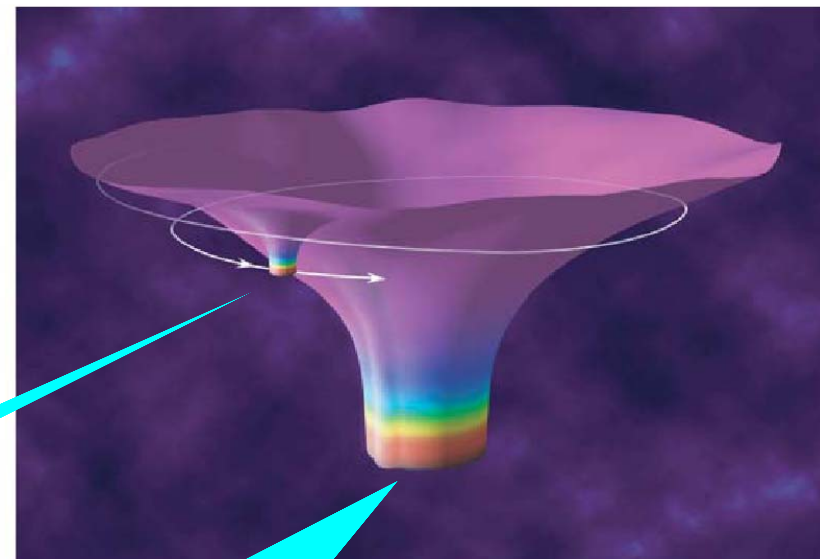
- **If** detectable:
  - High redshift (z ~1) distribution of sources
  - Evolution of star formation rate as a function of z
- LISA noise floor is essentially set by brightness of sky

Stars in galactic centres

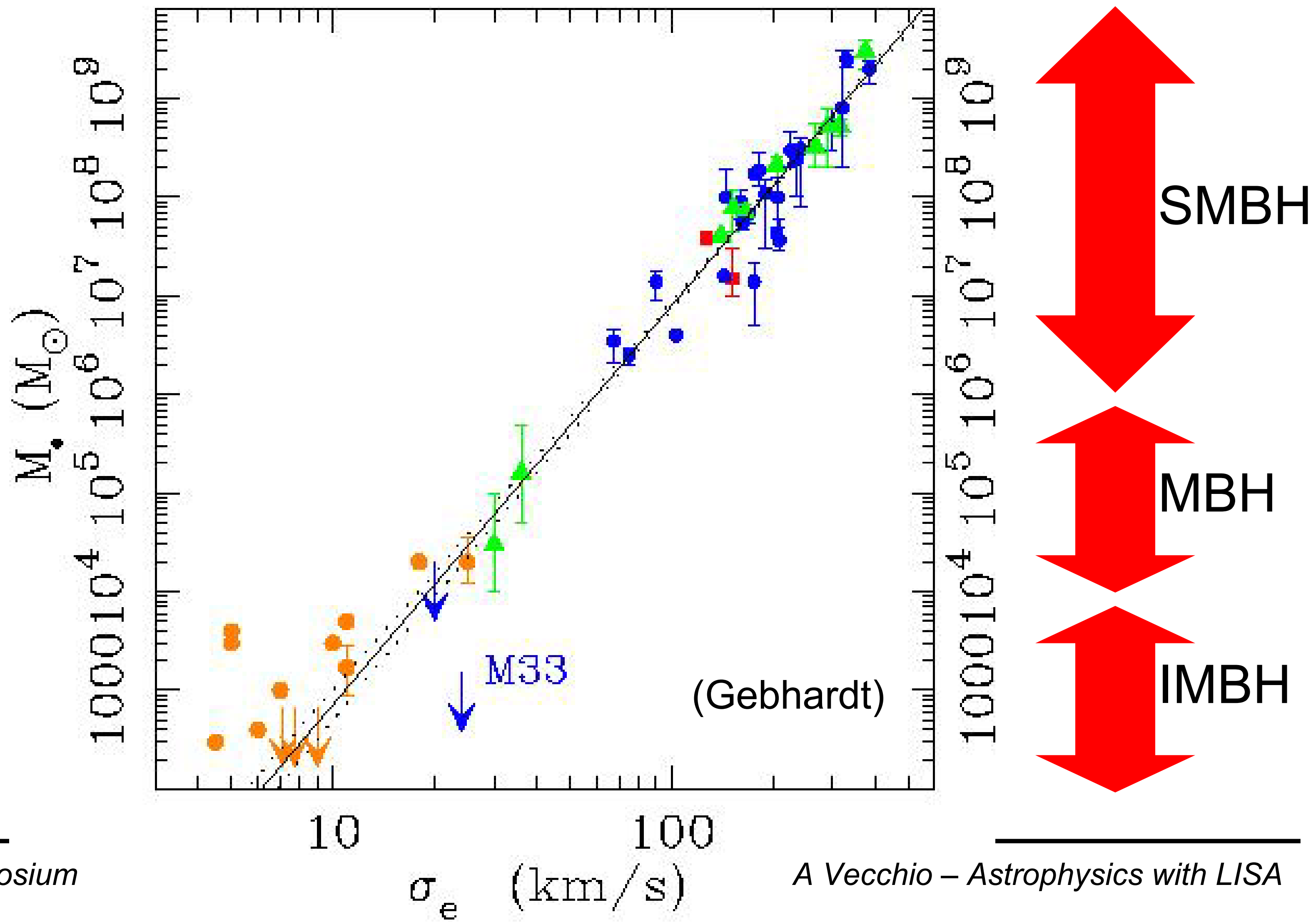
- Low mass (a few x 0.l Msun) main sequence star orbiting Sgr A* (Freitag, 2001, 2003; Barack and Cutler, 2004)
- Super-massive stars in quasar disks (Goodman and Tan, 2004)



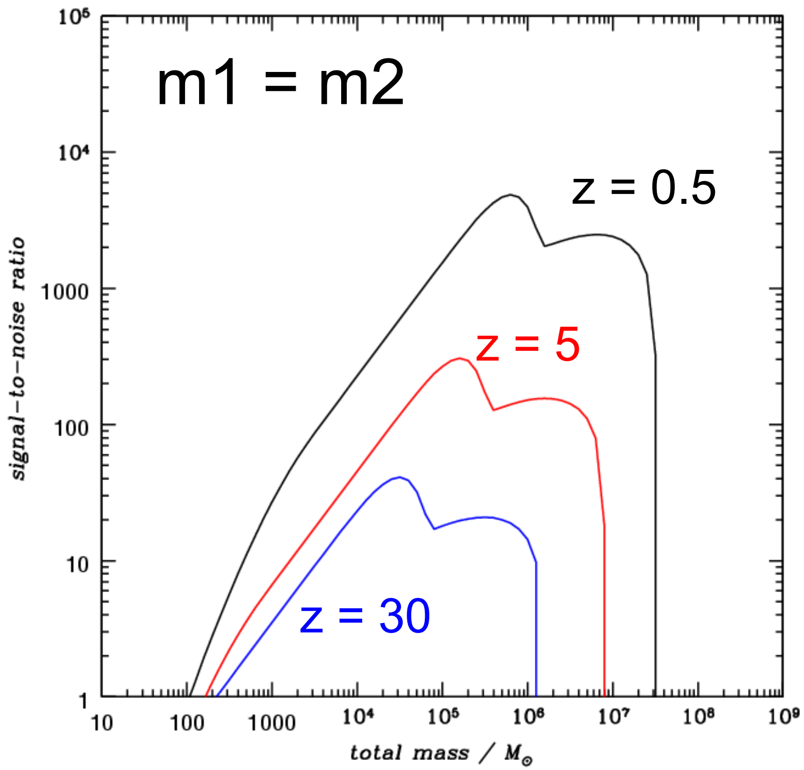
Star

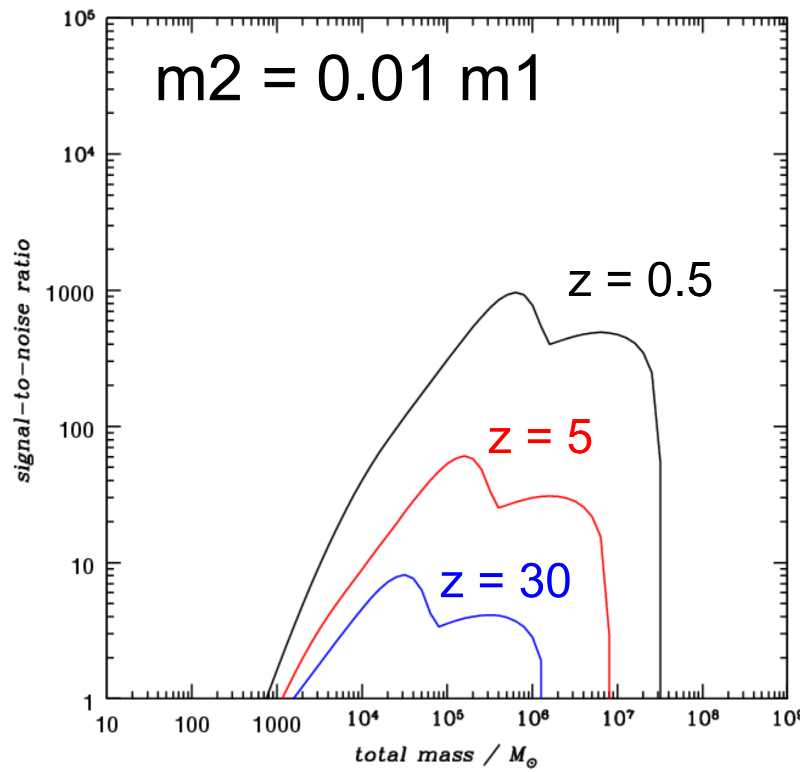
Massive black hole (~ 10^6 Msun)

Black holes demographics



LISA Sensitivity





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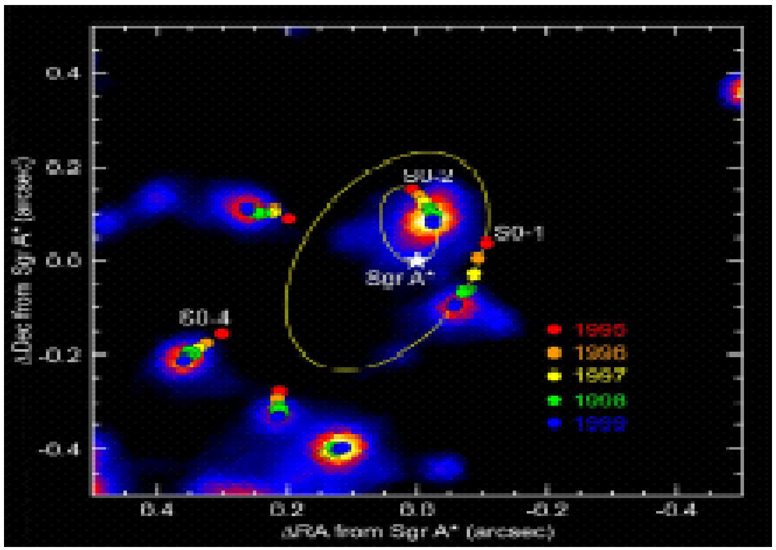
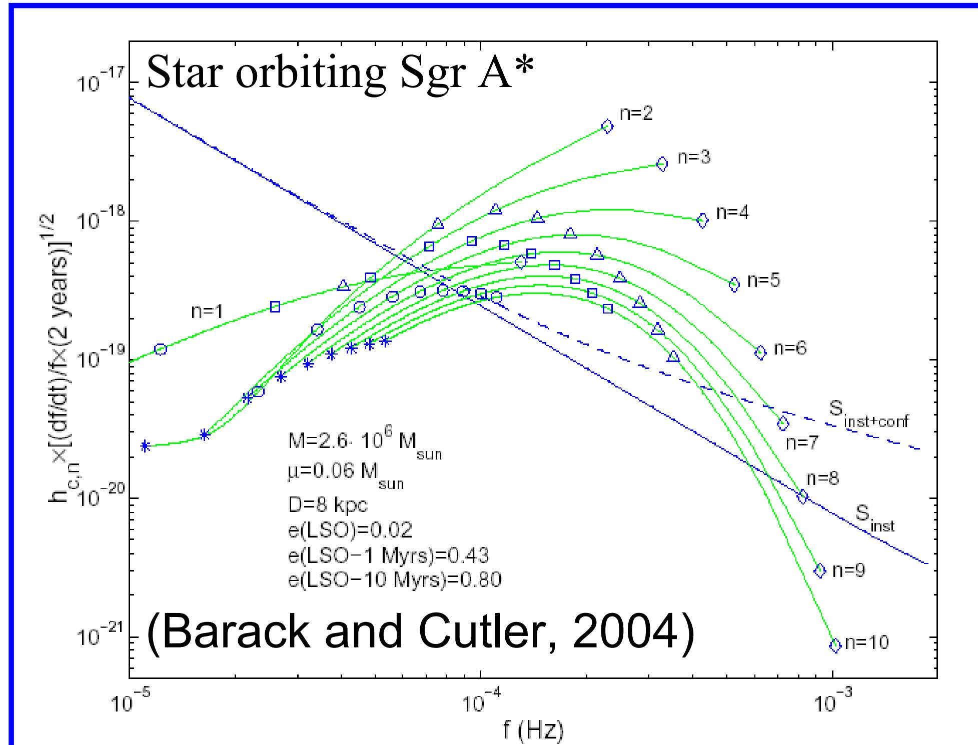
Our galactic centre



Mass of the 2.6 x10^6 Msun BH in Sgr A* measured to ~0.005 – 0.2 accuracy



Very accurate measurement of spin (error ~ 0.005)

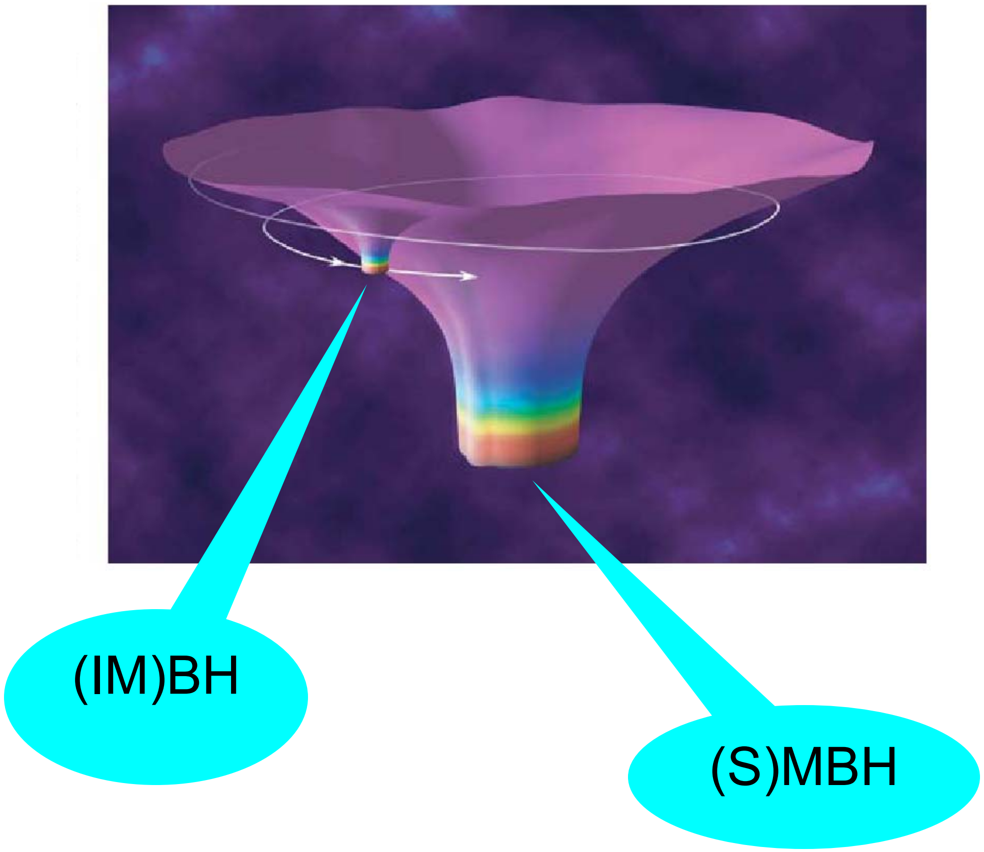
Event rate: ~ a few (possibly optimistic) during mission lifetime

Extreme mass ratio in-spiral: EMRI = (IM)BH + (S)MBH

Detection rate

$M_\bullet$	m	LISA Optimistic	LISA Pessimistic
300 000	0.6	8	0.7
300 000	10	700*	89
300 000	100	1*	1*
1 000 000	0.6	94	9
1 000 000	10	1100*	660*
1 000 000	100	1*	1*
3 000 000	0.6	67	2
3 000 000	10	1700*	134
3 000 000	100	2*	1*

(Gair et al, 2004)



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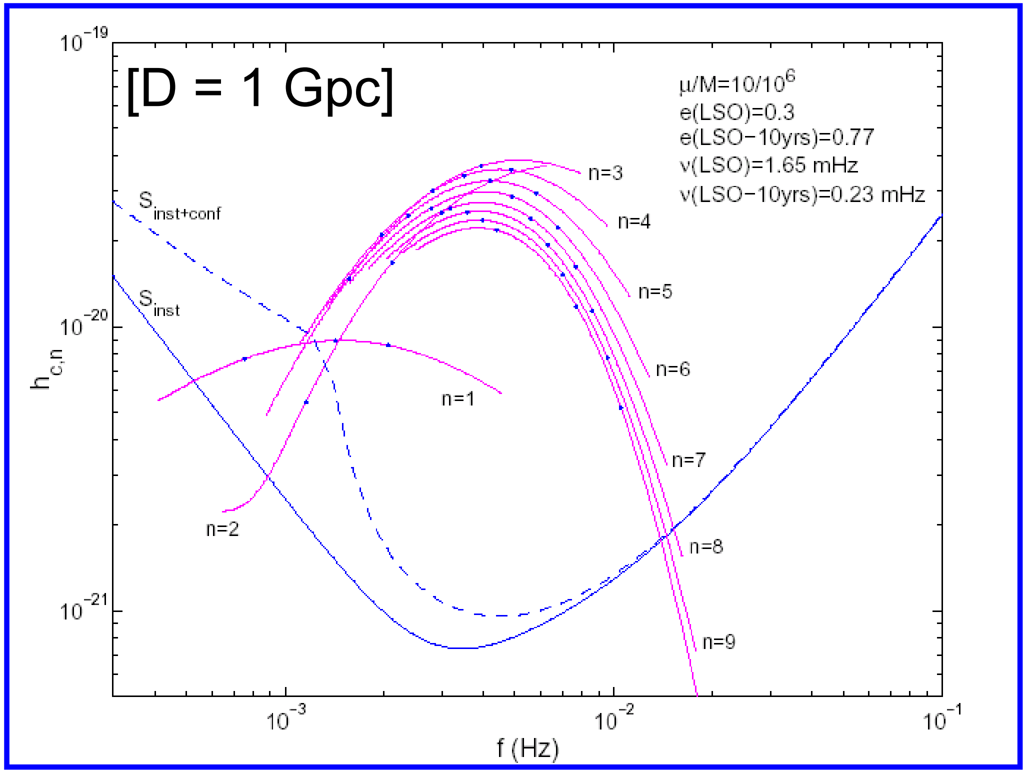
Extreme mass ratio in-spirals

$$(\mathrm{SNR_I})_n^2 = \int (h_{c,n}/h_n)^2 \, d(\ln f)$$

- Extremely complicated signals:
  - Highly eccentric orbits
  - Non-equatorial orbits
  - (Rapidly) spinning black holes
- Major challenge for
  - Waveform computation
  - Data analysis



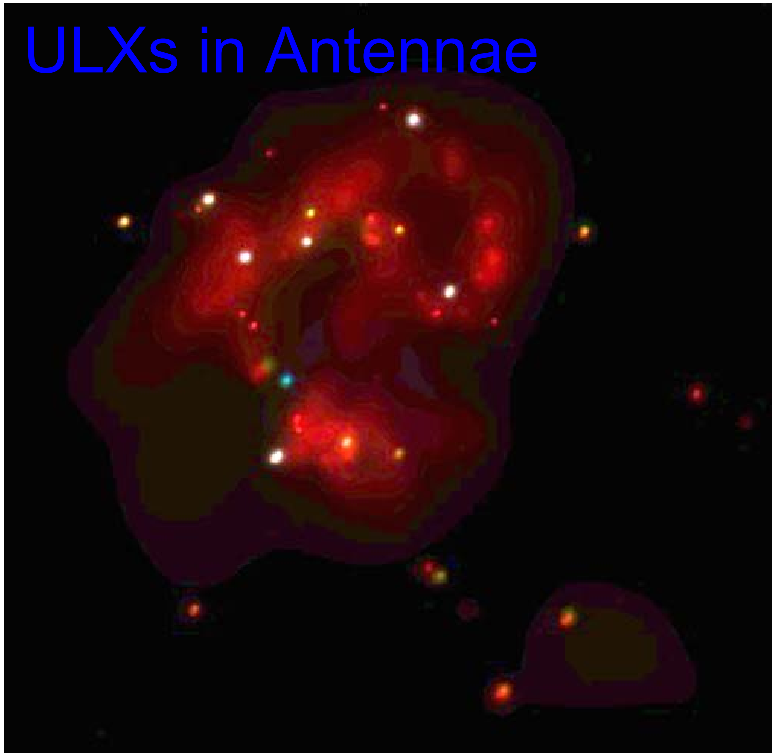
(Barack and Cutler, 2004)

Astrophysics with EMRI

- Demographics (up to z ~1) of:
  - (Super-)Massive black holes in the centre of galaxies
  - Compact stars (e.g. WDs) and stellar-to-intermediate mass BHs
- Measure:
  - Masses with relative error 10^{-4} – 10^{-3}
  - Spin magnitude with error 10^{-4} and direction within error ~ 0.02 srad
  - Distance with relative error ~ 0.1

- Detection rate and physical parameters provide information on:
  - Populations of compact stars and BHs inside galactic nuclei
  - Dynamics in galactic cores
  - Multiple body interactions
  - Loss cone
  - Mass segregation

Intermediate mass BHs



- (S)MBH – IMBH
  - Event rate: >1 for whole mission
  - Possibly IMBH formation from accretion disk fragmentation (Levin, 2003)
- IMBH – IMBH/BH in local/low-redshift universe
  - Event rate possibly too low for LISA
- IMBH – IMBH at very high redshift ($10 < z < 20$)
  - Event rate: ~ 10 / yr

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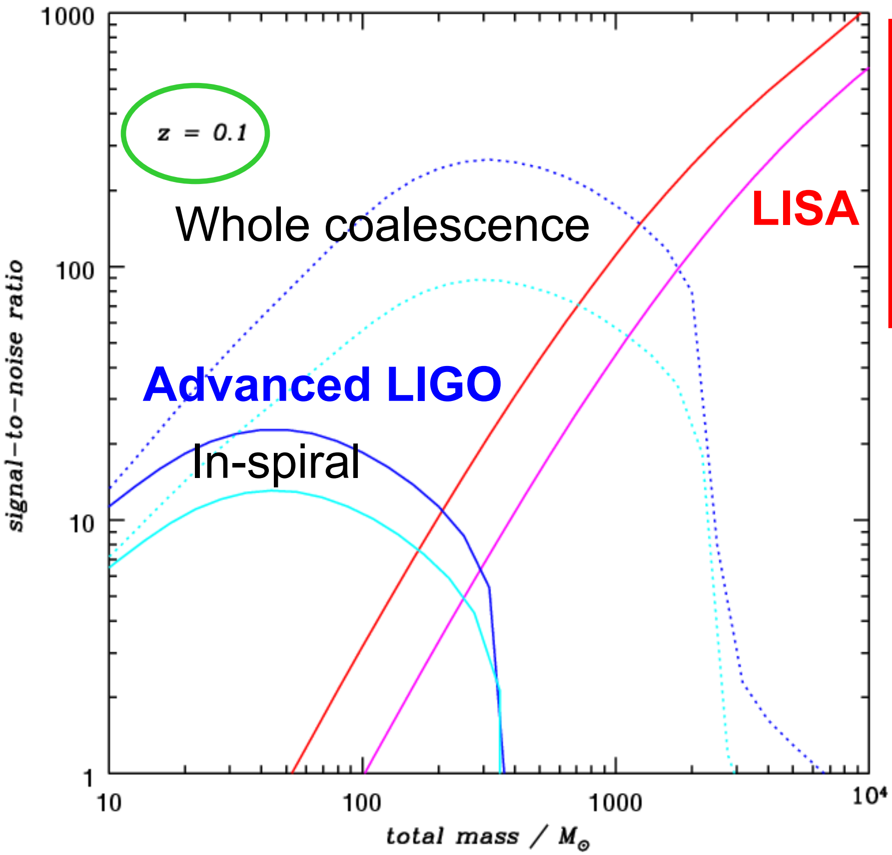
IMBH – IMBH/BH (z < 1)



$$R \approx 1.0\times10^{-6}\left(\frac{h}{0.7}\right)^3\left(\frac{f_{\rm tot}}{0.1}\right)\left(\frac{\mu}{10M_\odot}\right)^{19/8} \times\left(\frac{M_{\rm max}}{100M_\odot}\right)^{13/4}\left(\ln\frac{M_{\rm max}}{M_{\rm min}}\right)^{-1}{\rm yr}^{-1}\,.$$

(Will 2004; Miller, 2002)

If sources are detected:

- Unequivocal confirmation of existence of IMBHs
- However: unlikely study of relation between IMBH and its environment (error box is too big for EM counterpart)

Frequency range **0.01 – 1 Hz** is crucial

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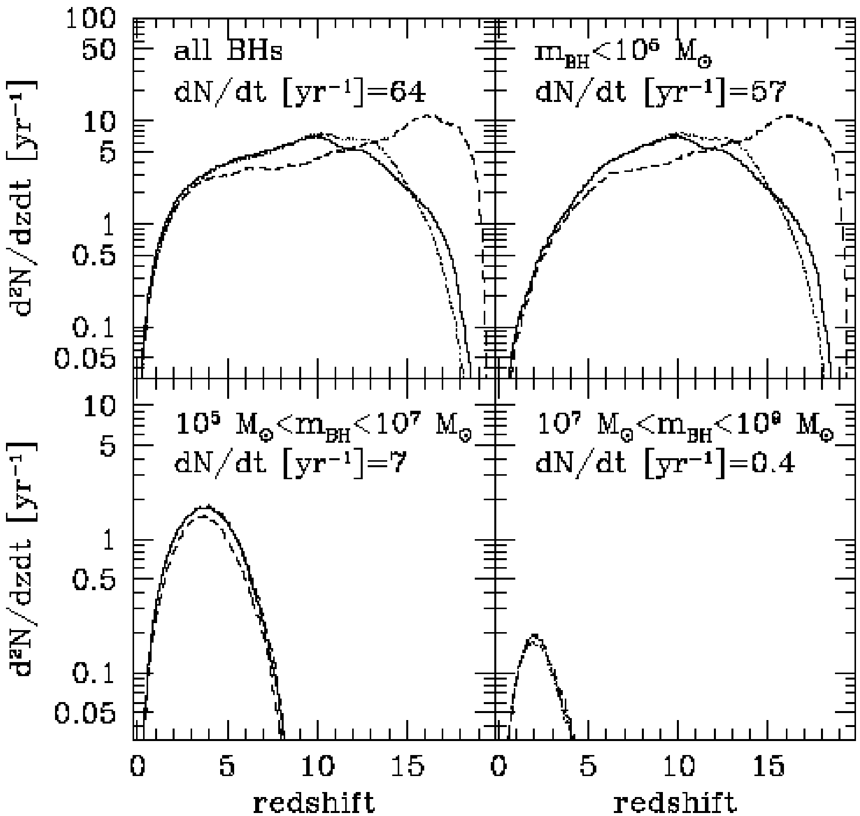
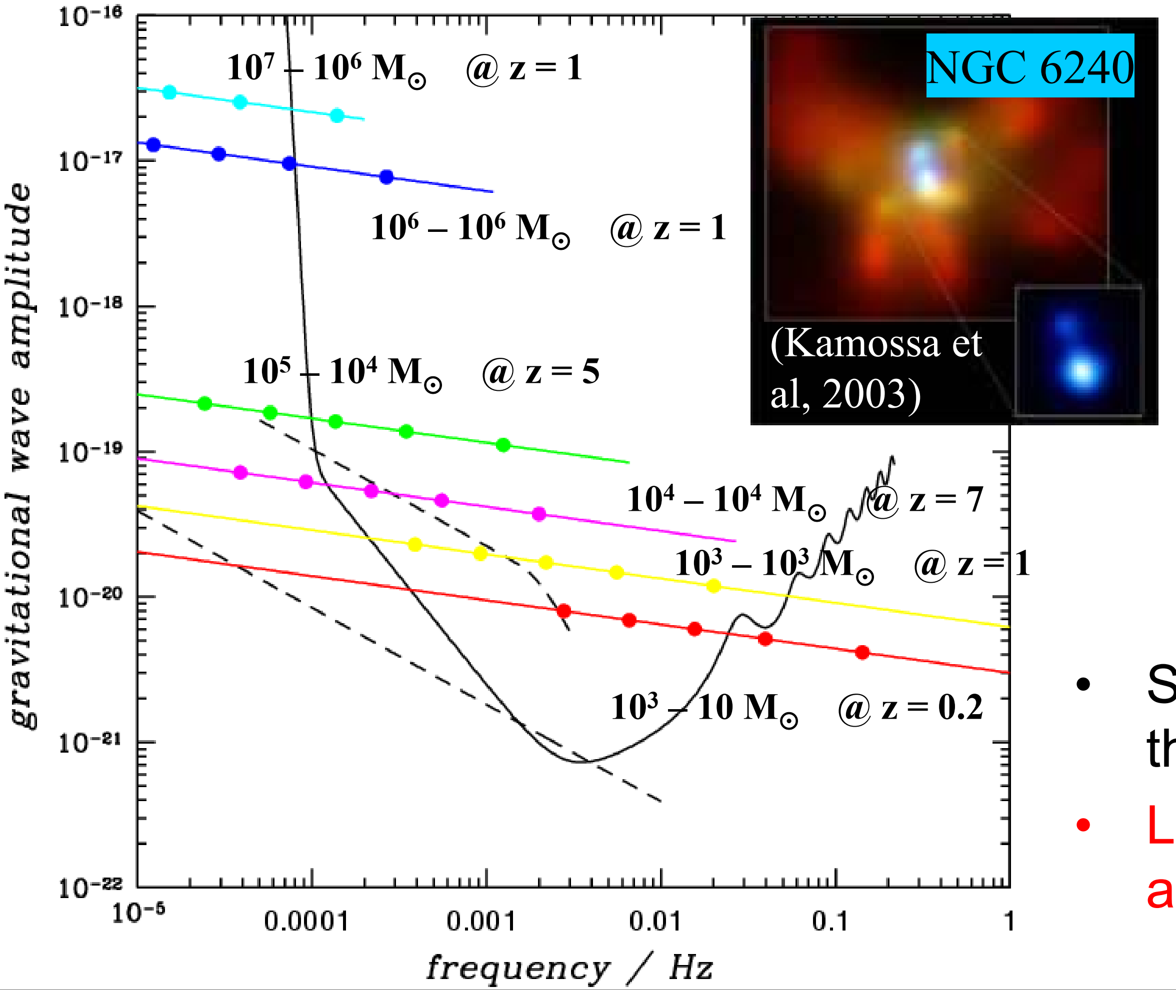
IMBH – IMBH (z >> 1)

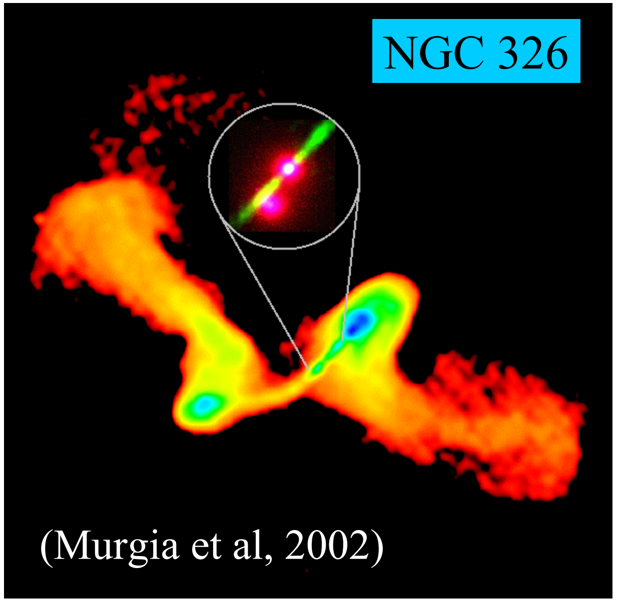


(Sesana et al, 2004; cf also Islam et al, 2004)

- Demographics of the first generation(s) of black holes:
  - Masses with fractional error ~ $10^{-4} – 10^{-2}$
  - Spin with error ~ 0.01
  - Distance with fractional error ~ 10% – 30 %
- Detection rate and physical parameters provide "orthogonal" trace of structure formation:
  - Merger history of galaxies

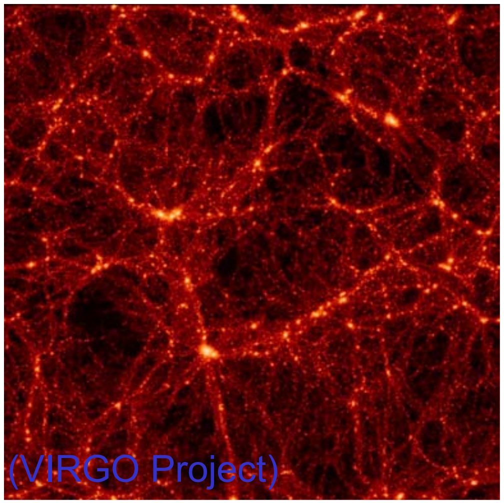
(Super) Massive black holes

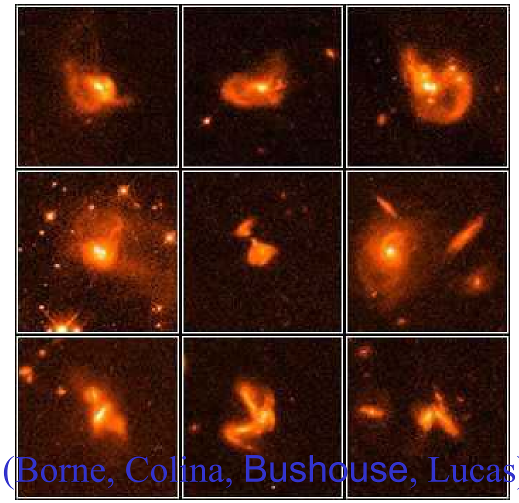


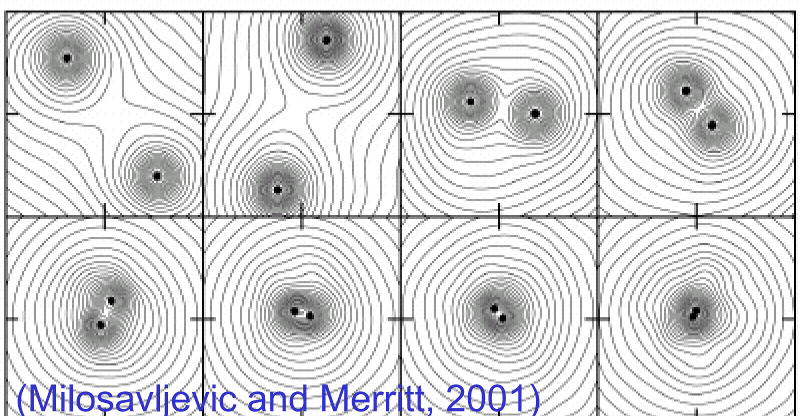


- Systems visible throughout the whole universe (z < 30)
- Low-frequency is crucial for astronomy (not detection)

Astrophysical Scenario


(VIRGO Project)


(Borne, Colina, Bushouse, Lucas)


(Milosavljevic and Merritt, 2001)

- BH commons in galaxy centres
- Hierarchical clustering: galaxies merge and BH pair forms
- Stages in binary evolution
  1. Dynamical friction (efficient)

$$t_{\rm df} = \frac{4\times10^6\,{\rm yr}}{\log N}\left(\frac{\sigma_{\rm c}}{200\,{\rm kms^{-1}}}\right)\left(\frac{r_{\rm c}}{100\,{\rm pc}}\right)^2\left(\frac{10^8 M_{\rm sun}}{m}\right)$$

  2. Hard binary

$$a \le \frac{Gm_2}{4\sigma_{\rm c}^2} = 2.8\,{\rm pc}\left(\frac{m_2}{10^8 M_{\rm sun}}\right)\left(\frac{200\,{\rm kms^{-1}}}{\sigma_{\rm c}}\right)^2$$

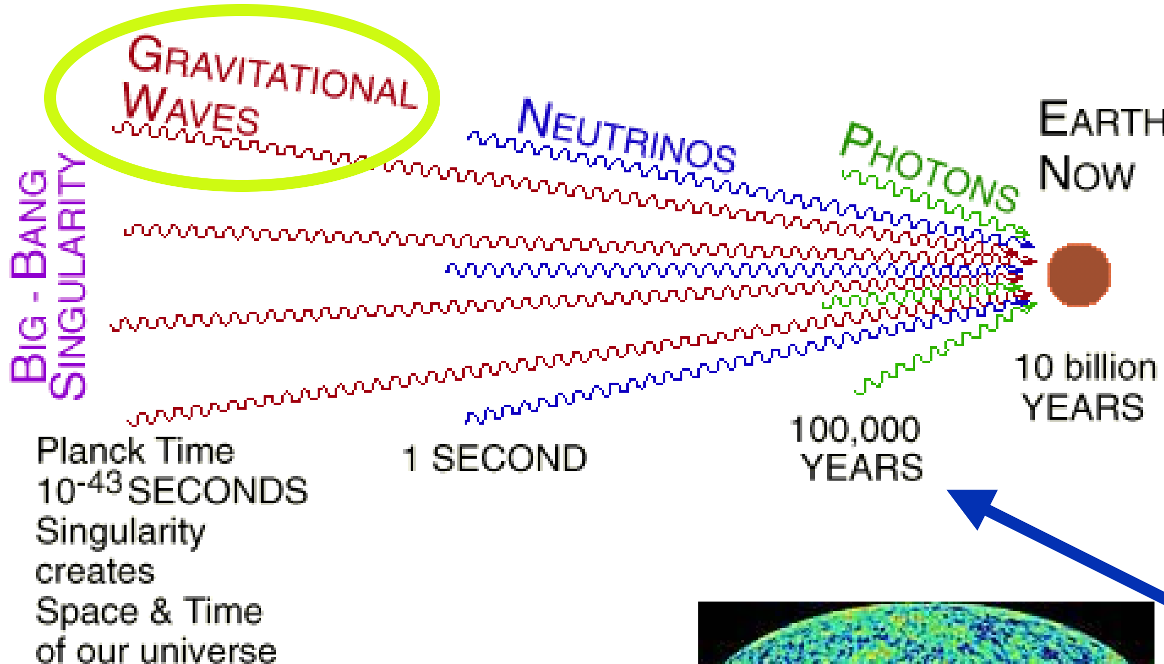
  3. Radiation reaction takes over

$$t_{\rm gr}(a) = 5.8\times10^6\,{\rm yr}\left(\frac{a}{0.01\,{\rm pc}}\right)^4\left(\frac{10^8 M_{\rm sun}}{m_1}\right)^3\frac{m_1^2}{m_2(m_1+m_2)}$$

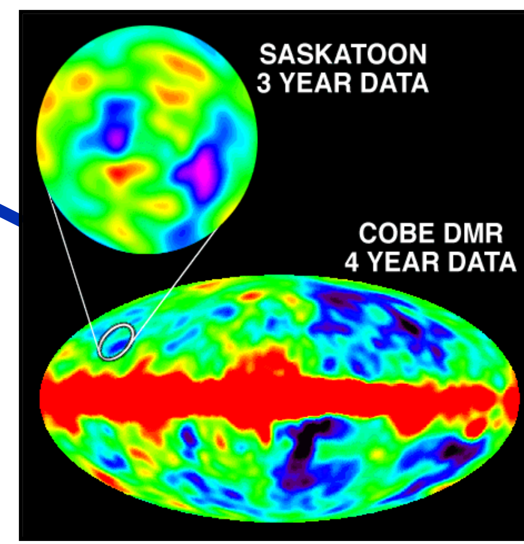
Astrophysics with (S)MBHs

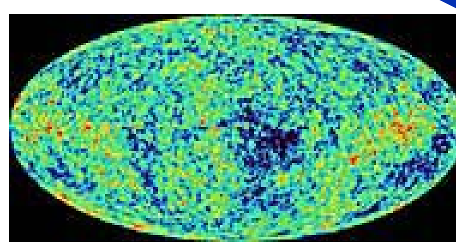
- Event rate:
  - One event out to z ~ 5 (Merritt and Eckers, 2002)
  - Possibly more at higher redshift
- Very accurate demographics (Cutler, 1998; Hughes, 2002; Seto 2003, 2004; Moore and Hellings, 2003; AV, 2004):
  - Masses known with fractional error ~ 10^{-4} or better
  - Spins with error ~ 10^{-3}
  - Fractional error on distance 1% - 0.1%
- Can we use them as standard candles? D(z) and dark energy
  - Easy to alert astronomers (merger time can be predicted with error < a few min), but error box possibly too big
  - Weak lensing makes things worse (Holz and Hughes, 2004)
- Dynamics and structure in the central (sub-) parsec region of galactic nuclei
  - Stellar dynamics, loss cone
  - Gas dynamics
  - Triaxiality

Early-Universe cosmology



Cosmic microwave background





WMAP 2003

The Universe became transparent to GWs at the Planck epoch: $t \sim 10^{-43}$ sec and $T \sim 10^{19}$ GeV

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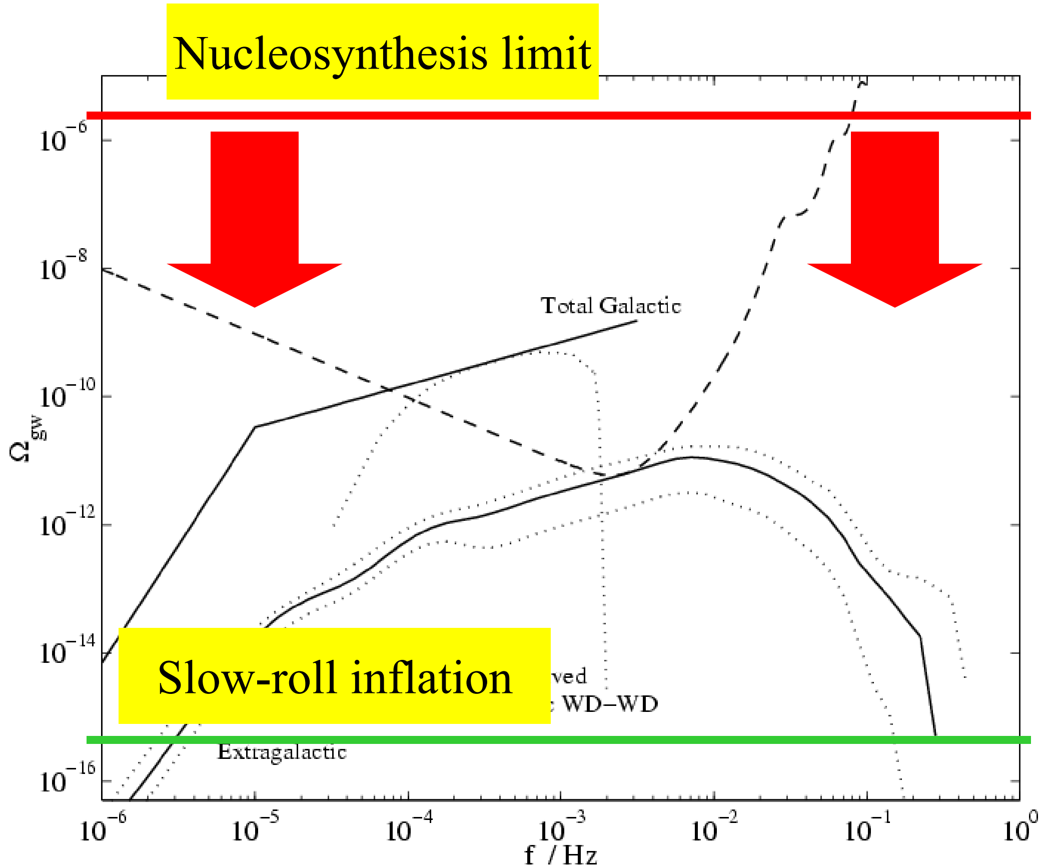
Cosmic GW background



Strongest scientific motivation behind LISA follow-on mission: **Big Bang Observer**

- Slow-roll inflation is not detectable (sky is too bright; Ungarelli and AV, 2001)
- Speculative models, but exciting possibilities
  - First-order phase transitions (Apreda et al, 2001), $\Omega \sim 10^{-11}$
  - Extra-dimensions (as strong as $\Omega \sim 10^{-7}$; Hogan, 2000)
  - Kinks/Cusps in cosmic strings (Damour and Vilenkin, 2000), still well above the noise

Conclusions

- LISA will have a major impact on astrophysics and cosmology
- We have a much better understanding of **<u>what</u>** we can learn from LISA
- … but we do not know yet **<u>how</u>**:
  - Effort (waveforms, data analysis strategies, …) is needed to secure optimal science exploitation of the LISA data
  - The way in which we approach GW astronomy from space is <u>very</u> different form the way we approach it from ground