Angular resolution of mid-frequency GW detectors

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Works to appear soon, with Peter W. Graham

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Takeaway messages

- Single-baseline measurement of mid-frequency GW contains directional information!
  - The mid-frequency band (~0.01-5 Hz) has ideal and natural properties for good localization.
  - Single-baseline can be a good precision detector.

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- Single-baseline measurement of mid-frequency GW contains directional information!
  - The mid-frequency band (~0.01-5 Hz) has ideal and natural properties for good localization.
  - Single-baseline can be a good precision detector.

NB: We use Atom Interferometers as a typical single-baseline detector to demonstrate these messages.

Why localization?

- Among many reasons already discussed in this conference, two most important are:

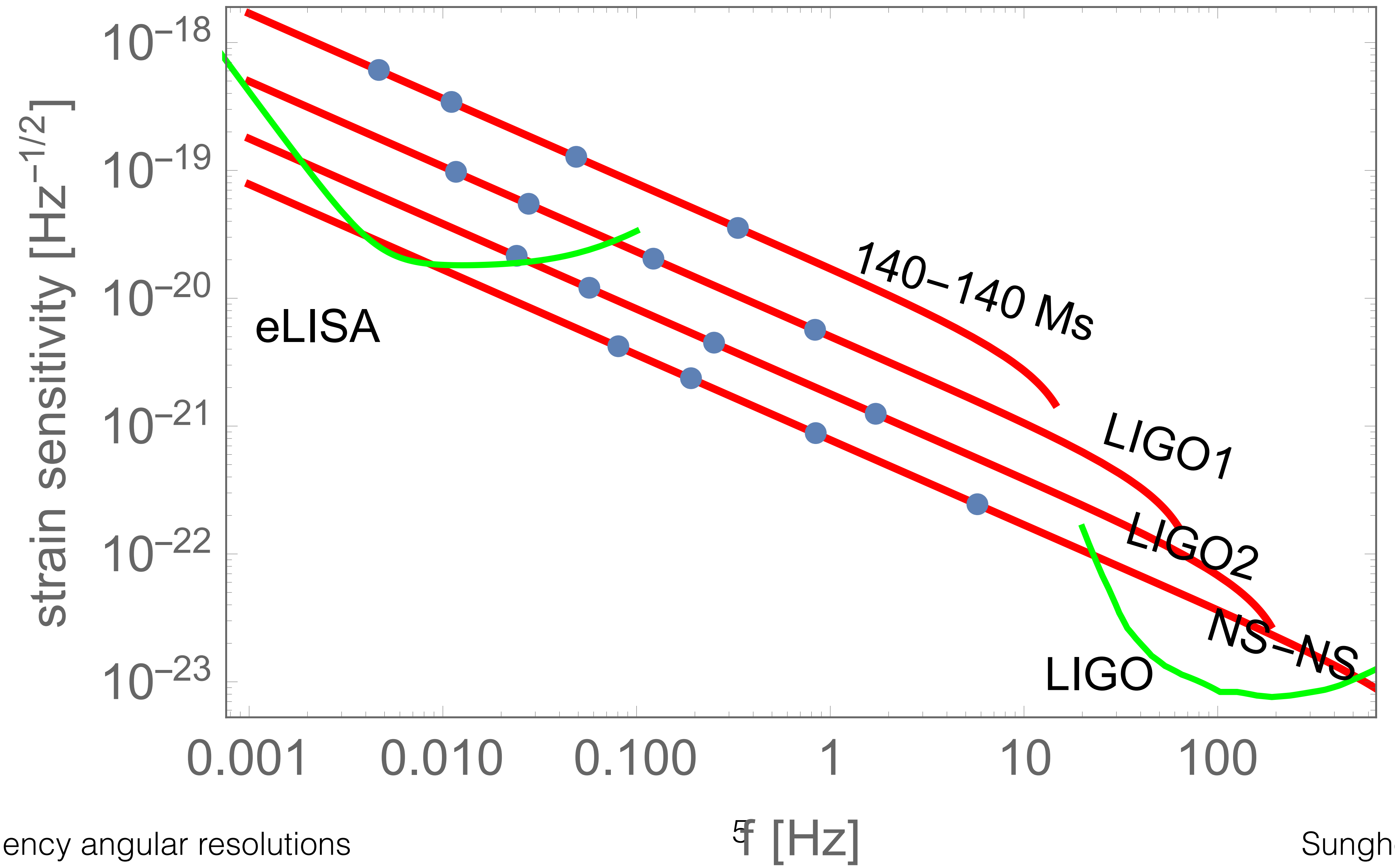
- Multi-messenger observations & standard siren

- Precision measurement of GW and its source

NB: A good first target would be ground-based telescope FOVs ~1 deg

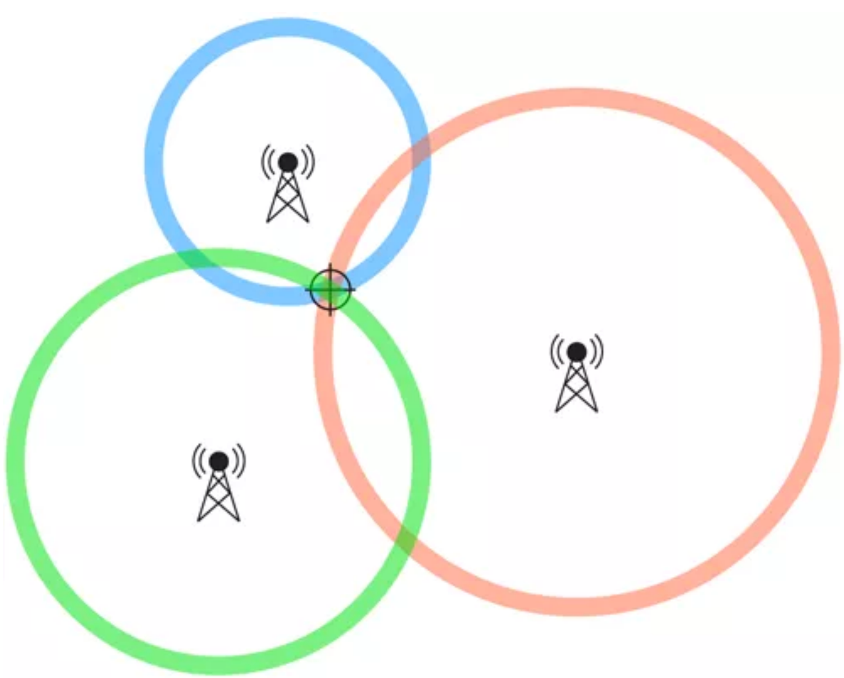
How do LIGO/LISA localize?

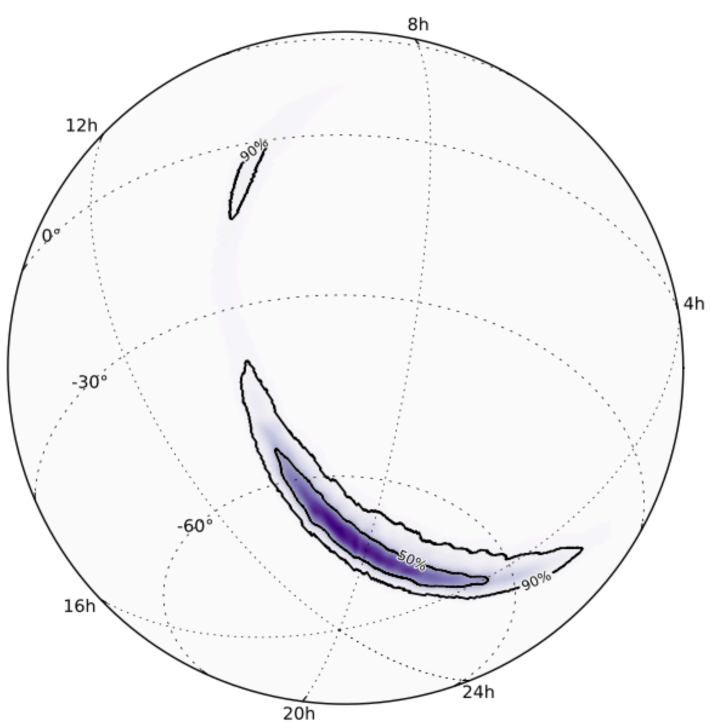
- One main difference of LIGO vs LISA is GW lifetimes (and frequencies).

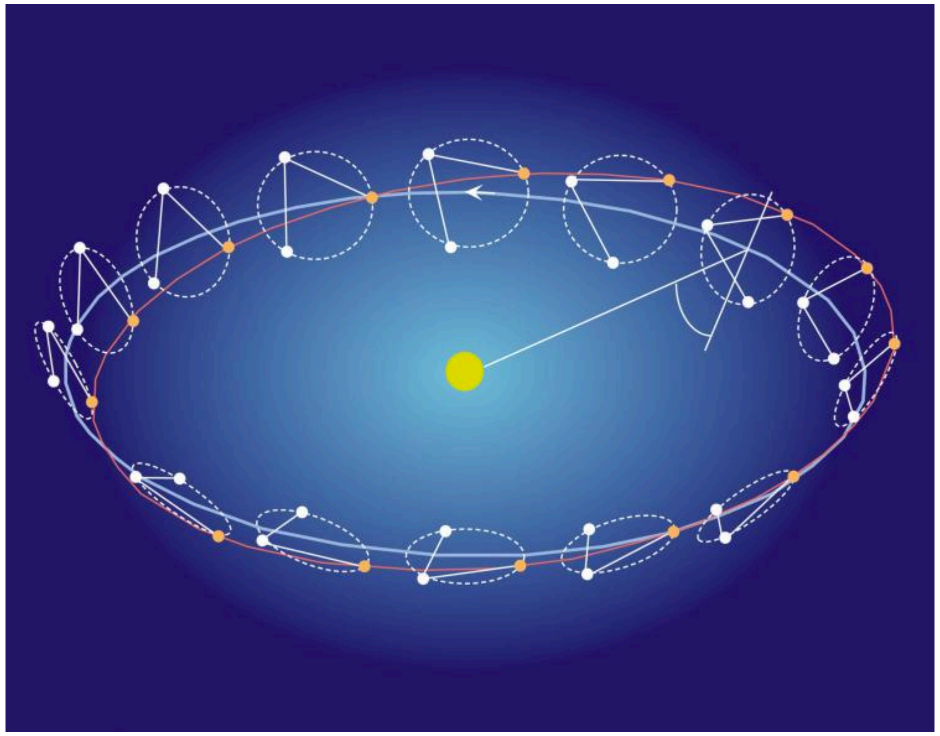


How do LIGO/LISA localize?

- LIGO : triangulation from multiple detectors (practically may need >~3 detectors; short duration)
- LISA : signal modulation over annual orbit around the Sun (relative angle btwn baseline and source direction)

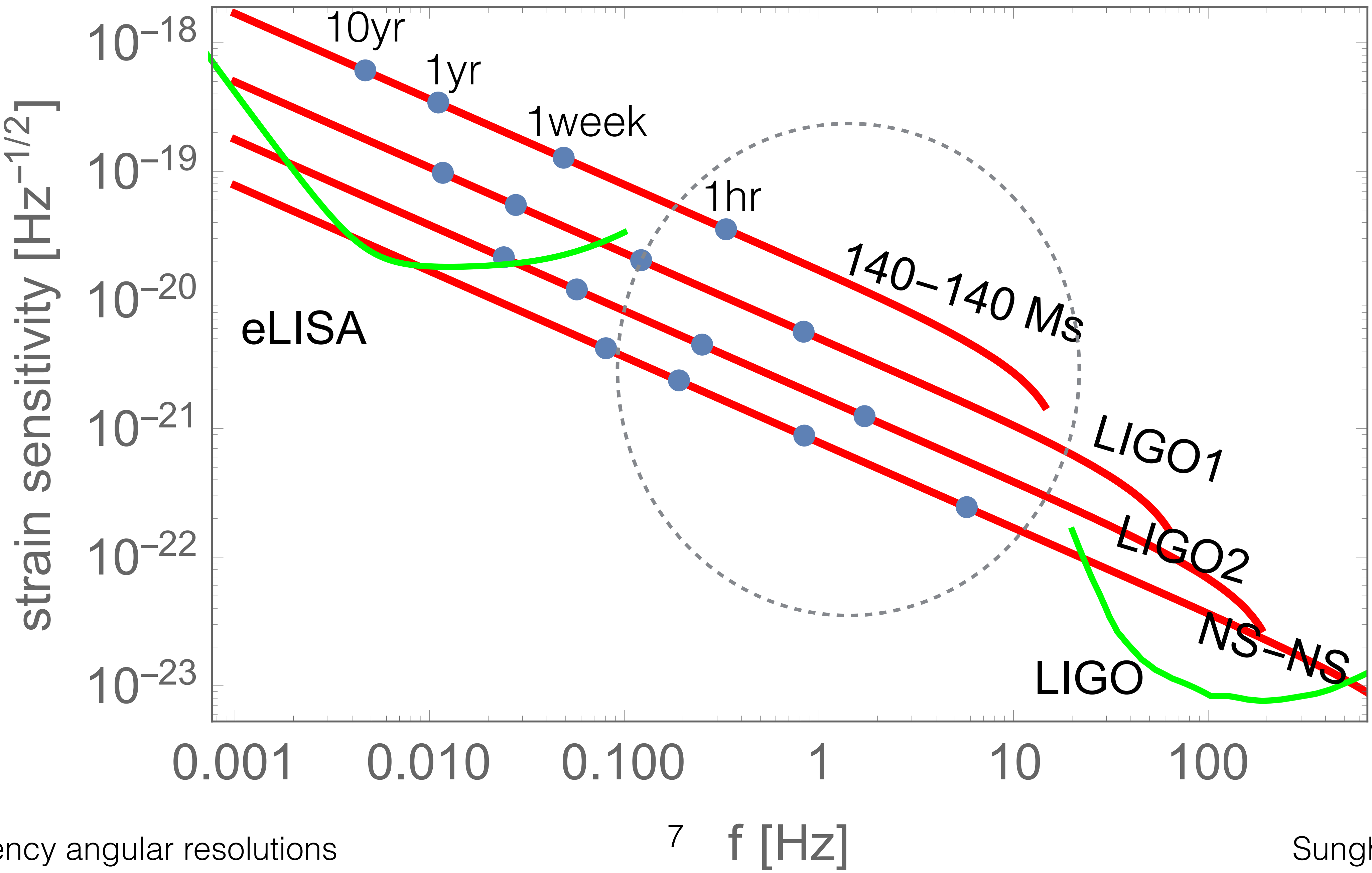






Mid-frequency band

- Is it just an interpolation btwn LIGO and LISA?



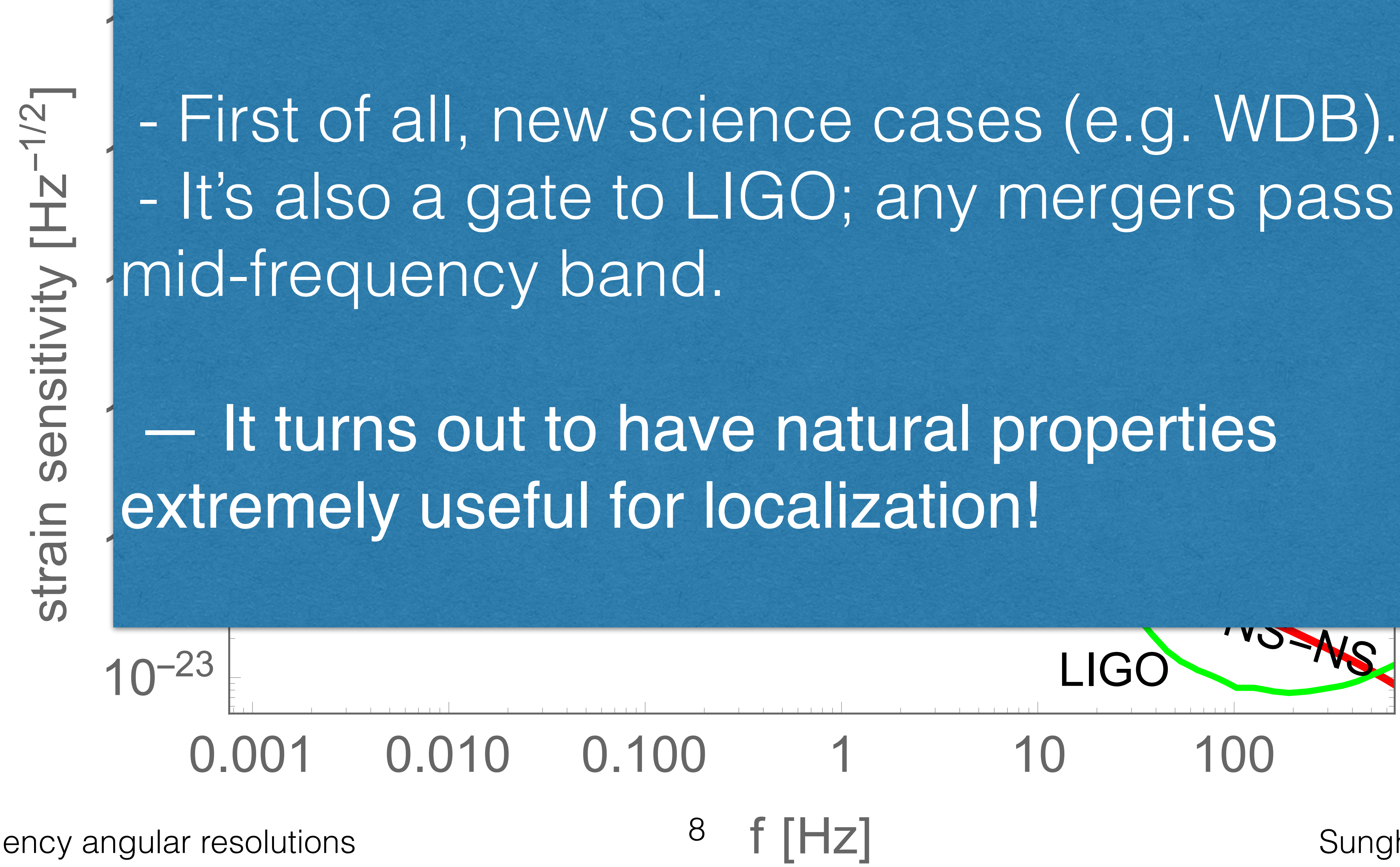
Mid-frequency band

- Is it just an interpolation btwn LIGO and LISA?

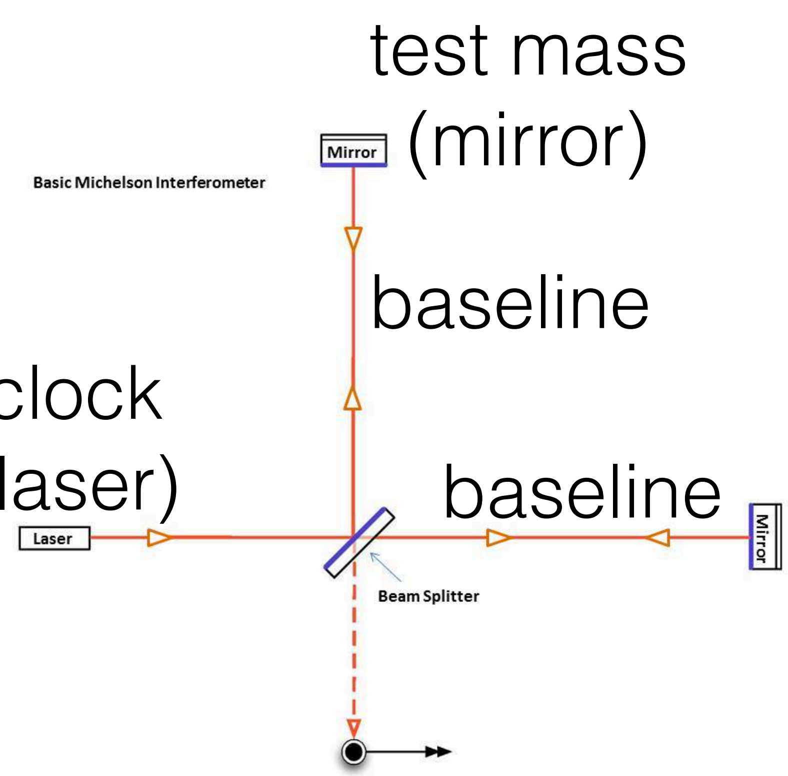
No!

- First of all, new science cases (e.g. WDB).
- It's also a gate to LIGO; any mergers pass mid-frequency band.

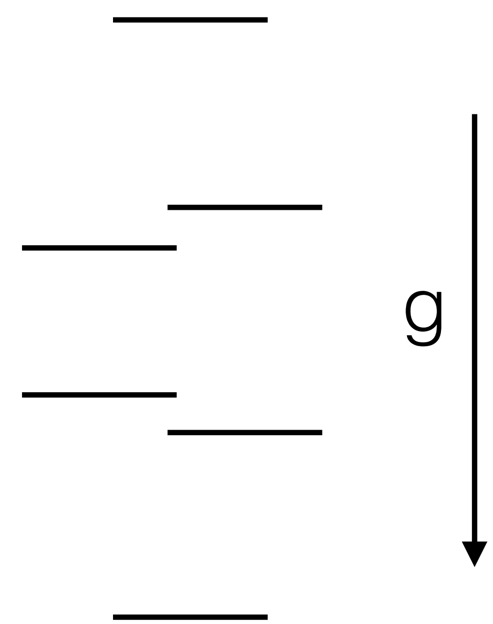
— It turns out to have natural properties extremely useful for localization!



Atom Interferometer (AI)

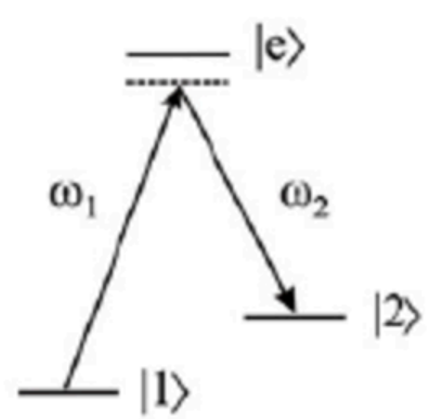


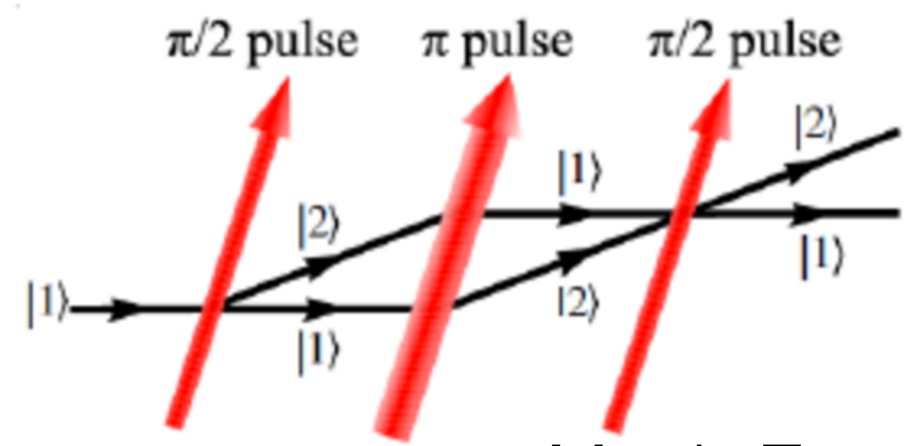
Michelson interferometer



Atom clouds
free fall.

Atom clouds are both
test mass and clock.

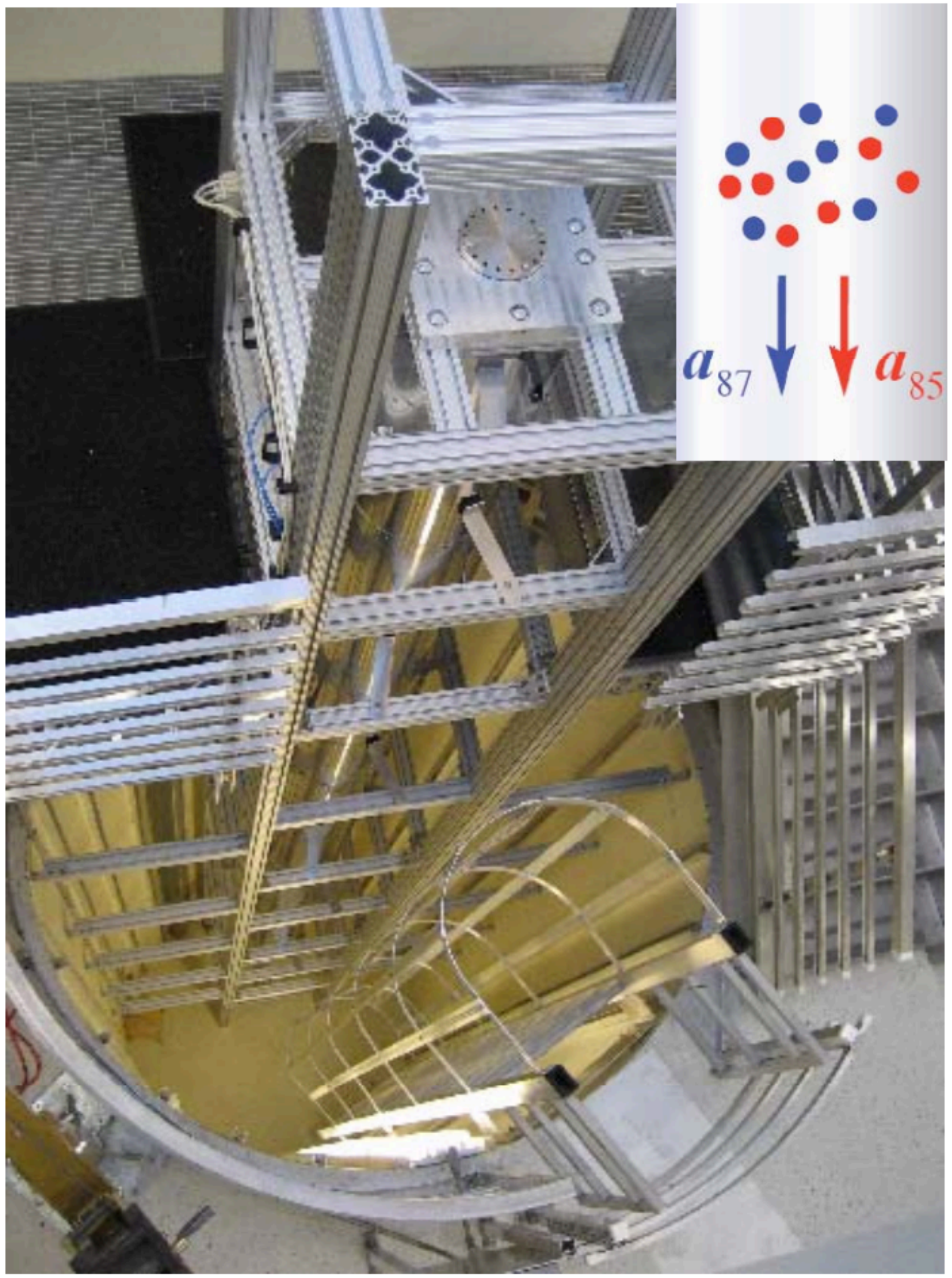




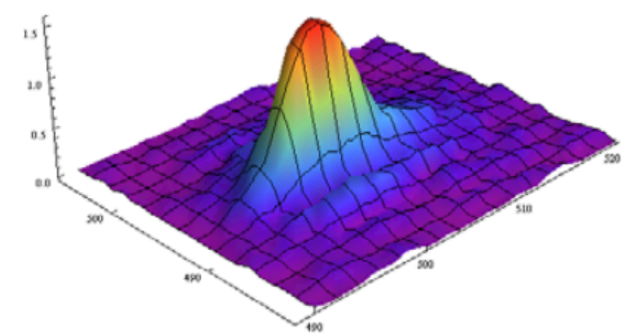
Mach-Zender

Energy-dependent phase accumulation

Atom Interferometer (AI)



10m drop tower at Stanford campus

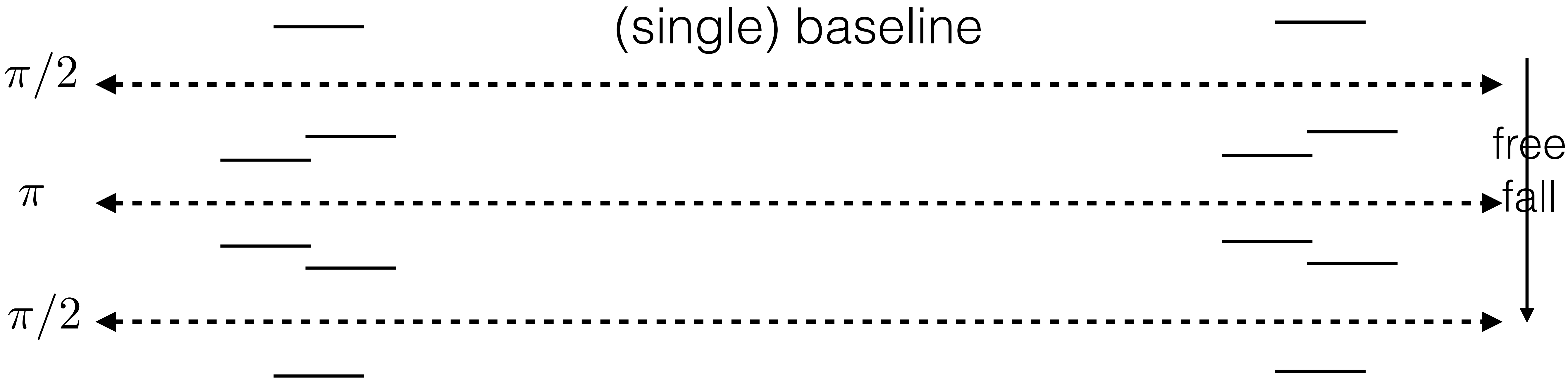


Evaporatively cooled atom source

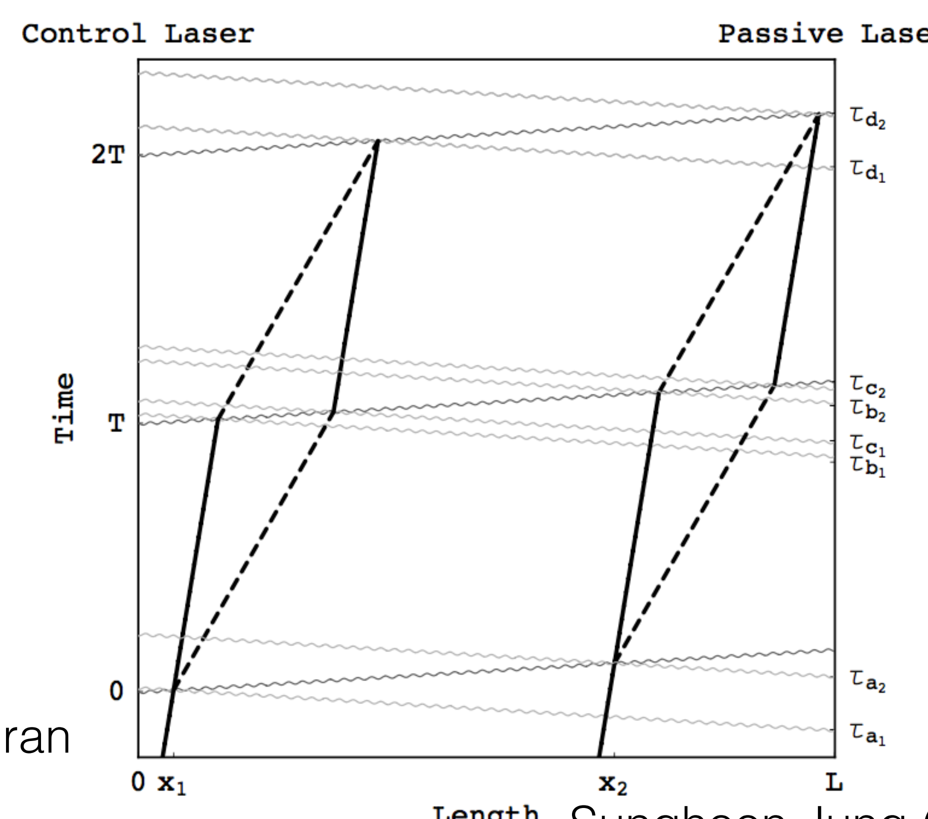
one of the most precise measurement of the gravity constant on the Earth.

picture credit: M.Kasevich

Differential measurement



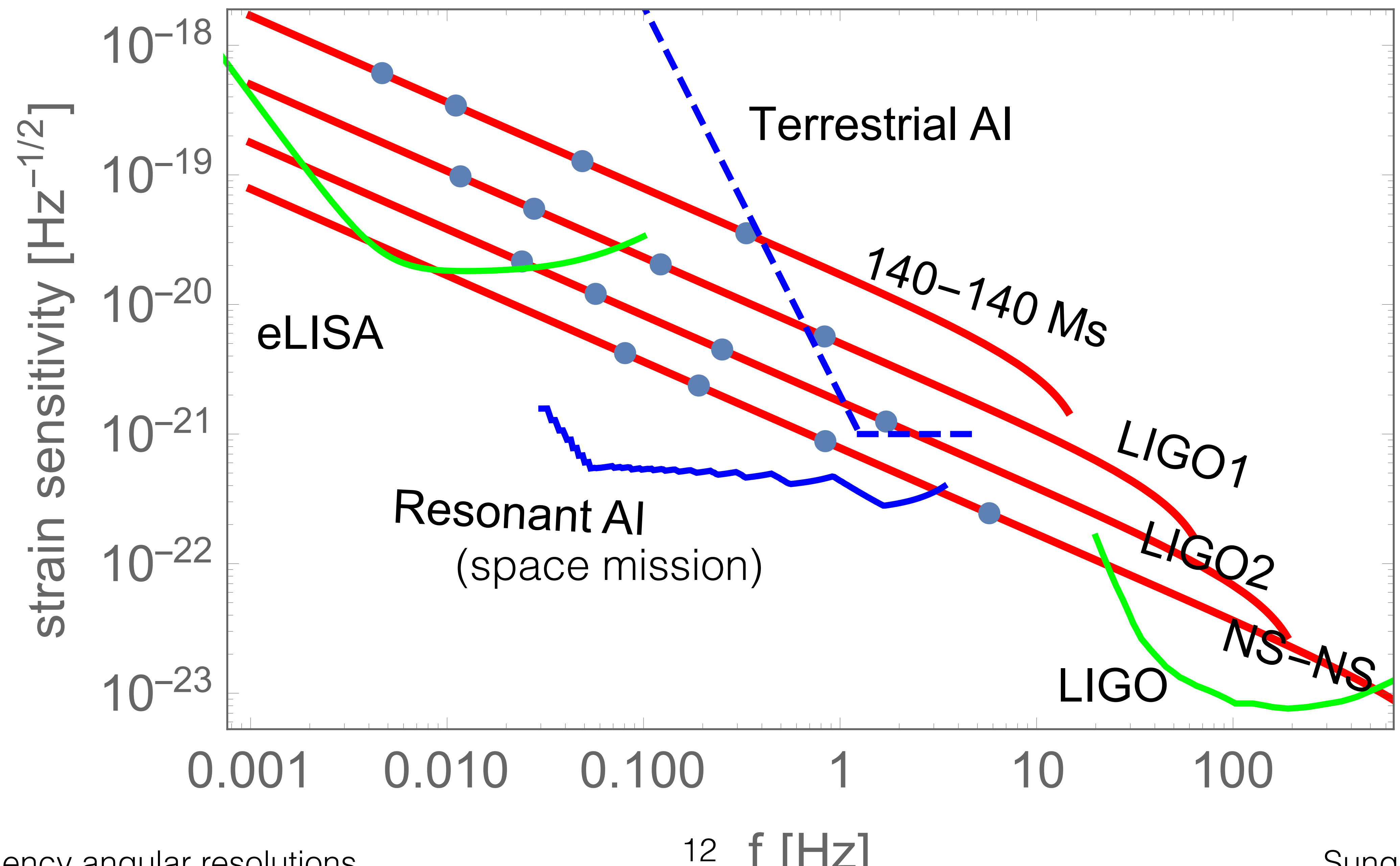
Differential phase can measure (space-time oscillating) GW signal.



Ref: S.Dimopoulos, P.W.Graham, J.Hogan, M.Kasevich, S.Rajendran

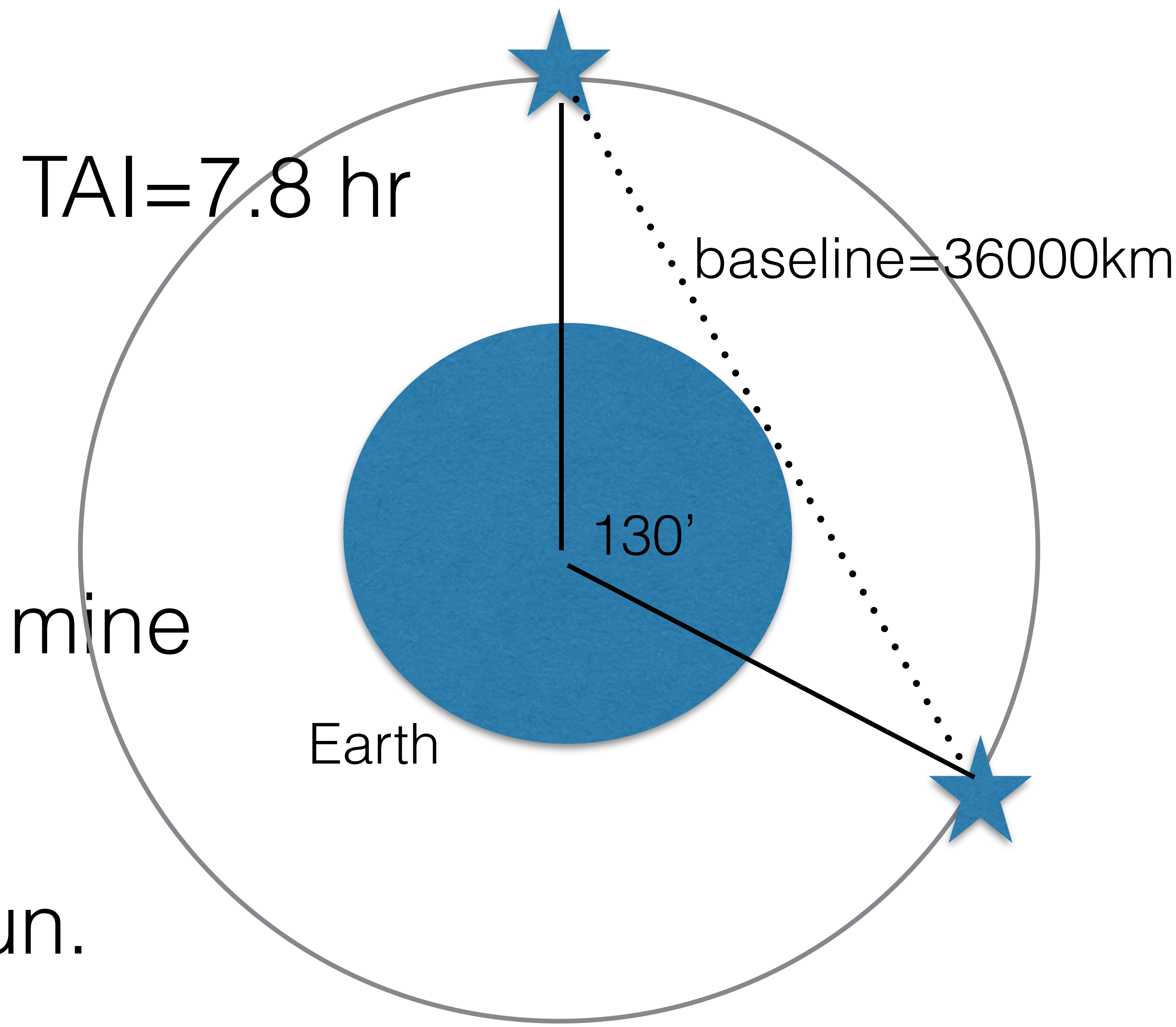
AI in mid-frequency band

- sensitive to f = 0.03~5 Hz; both space and terrestrial missions are considered for each design/protocol studies (also illuminating some underlying physics).



Space & Terrestrial AI

- Space AI orbits the Earth every 7.8 hrs.
- Terrestrial AI in underground mines. Maybe near future. ex) ~km shaft in Homestake mine
- But after all, they orbit the Sun.



Two underlying physics

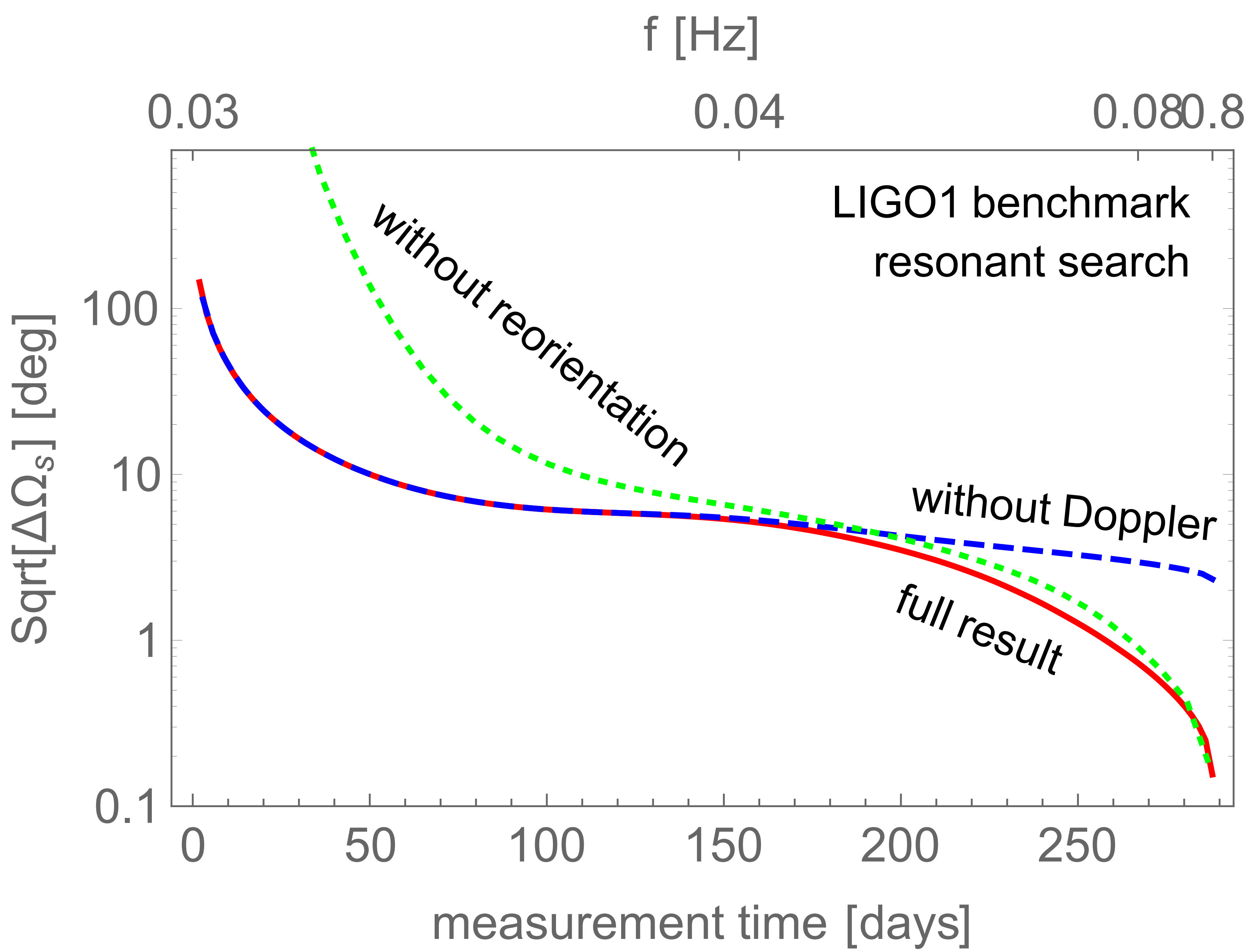
- “Reorientation” of baselines —
  modulation of signal strength and phase (rapid, O(1)-size)

- periodic change of “Doppler” shift —
  around the Sun. Modulation of phase (slow, but can be large in proportion to the frequency)

GW150914 by space AI

GW150914 (36-29 Ms) spends
9.6 months in the AI band.

$$\Delta\Omega_s \equiv 2\pi \sin\theta \sqrt{\Gamma^{-1}_{\theta\theta}\Gamma^{-1}_{\phi\phi} - (\Gamma^{-1}_{\theta\phi})^2}.$$

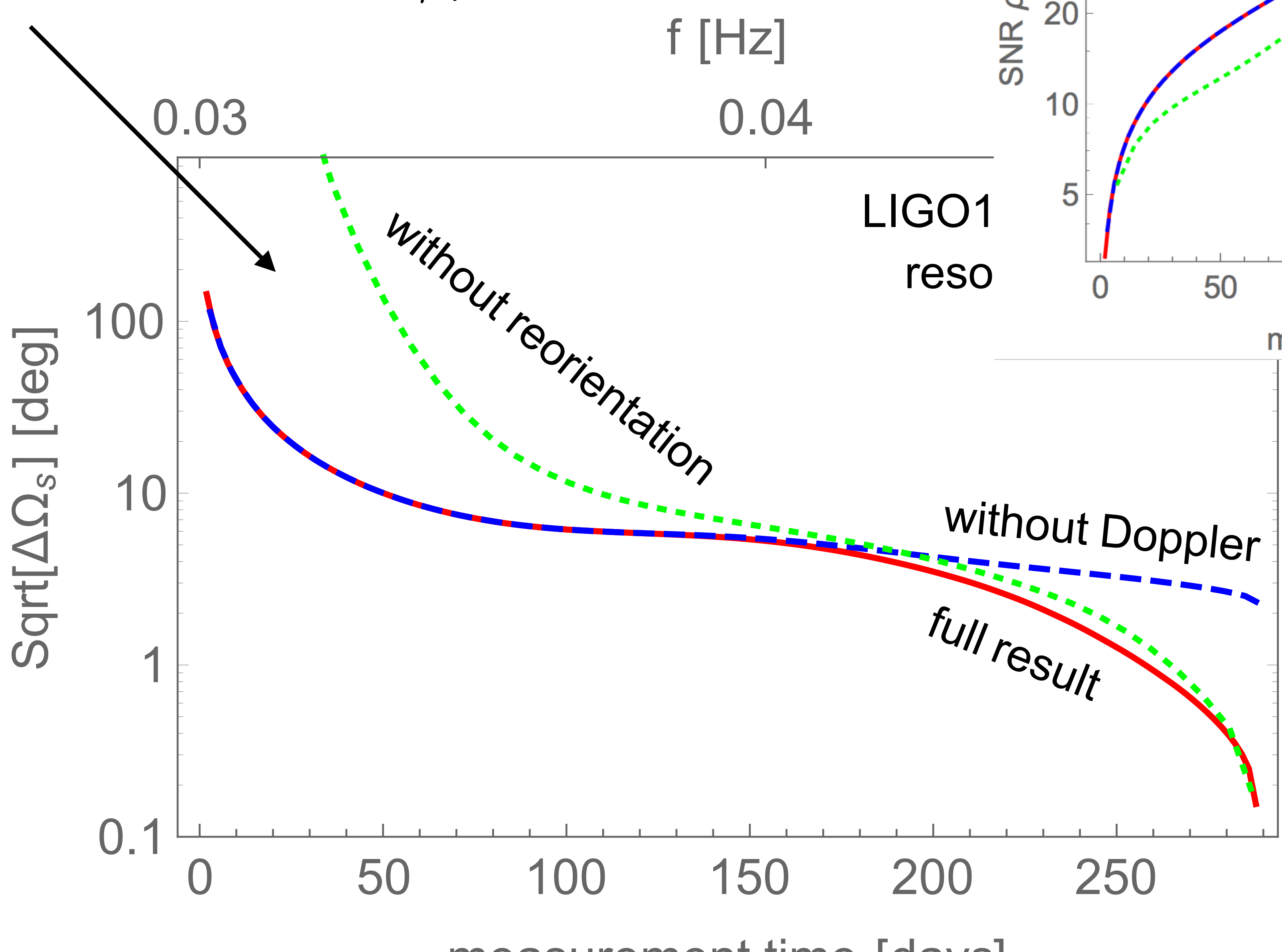


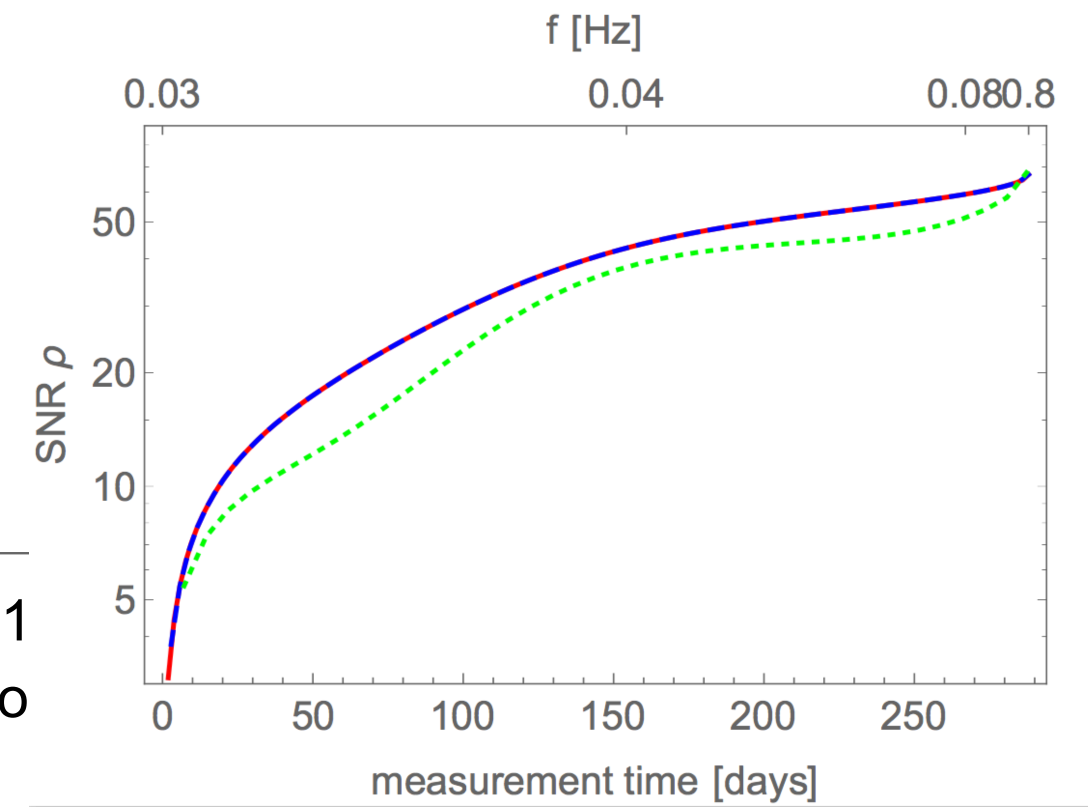
space AI
resonant-mode

Fisher matrix
method
(10 parameters)

Reorientation

Quick reorientation from TAI=7.8 hr dominates early.
growing as $\sim 1/\rho$



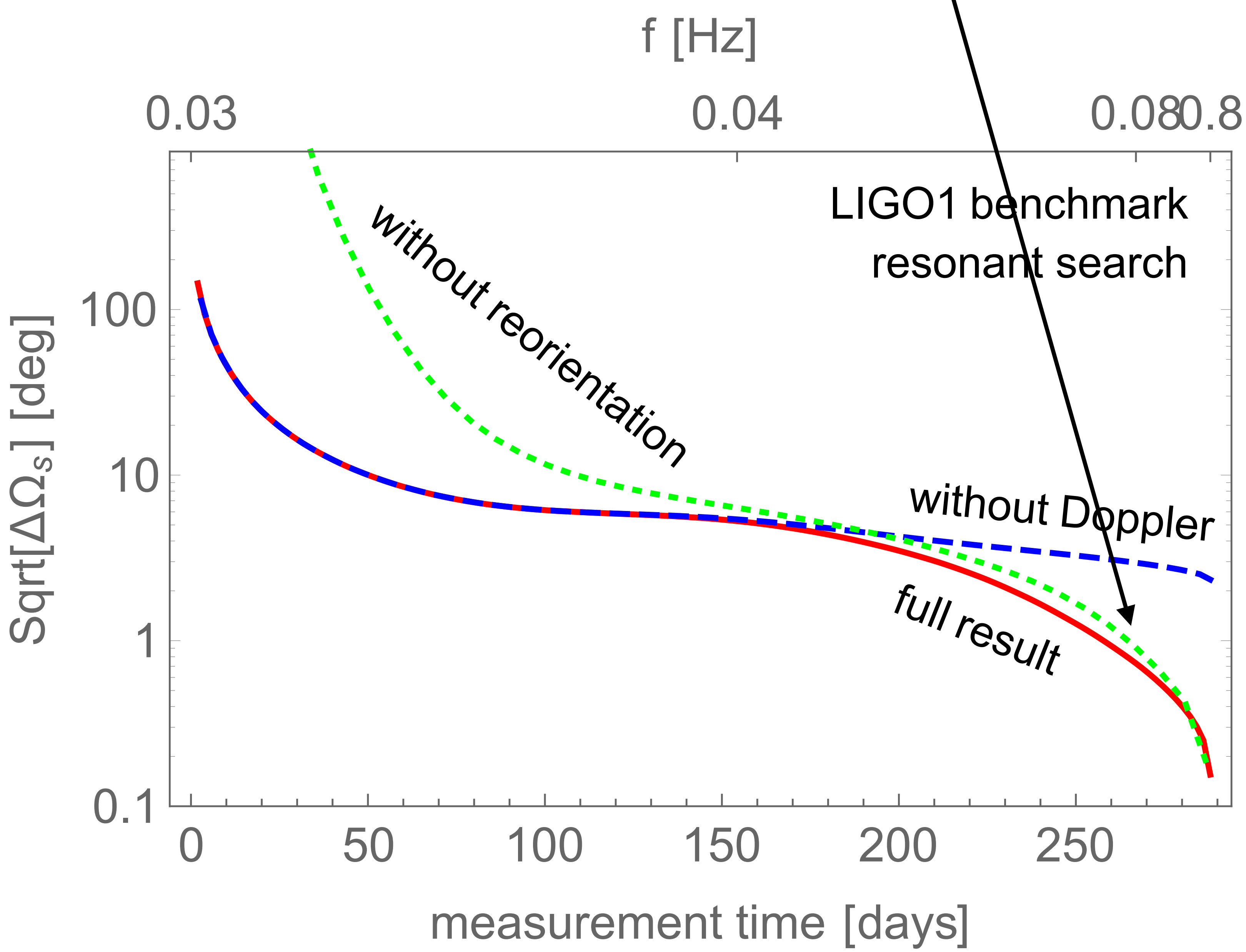


Doppler

Earth-Sun Doppler improves much further (only) after a few months.

$\sim 1/\rho/(2\pi f R/c) \ll 1/\rho$

Doppler phase-shift grows with f and R.



Change of Doppler is appreciable only after months.

Improving quickly as frequency chirps.

Final Angular Resolution

- Space AI usually O(0.1)deg, good enough for most ground-based telescopes, but not for the Hubble.
- Need multiple terrestrial AIs. Maybe useful for Fermi.

	resonant	terrestrial	lifetime
LIGO1	0.16 deg (ρ=67)	400 deg (ρ=1.8)	9.6 months
LIGO2	0.20 deg (ρ=16)	450 deg (ρ=0.94)	5.5 years
NS-NS	0.27 deg (ρ=3.6)		140 years
Short signal	0.75 deg (ρ=190)	710 deg (ρ=1.4)	25 days

Last 1 yr
or
full lifetime

TABLE II. Angular resolution $\sqrt{\Delta\Omega_s}$ and SNR ρ of an atom interferometer. Errros can be scaled linearly with 1/distance.

Aside: Angular Resolution vs SNR

In this band:
SNR 10-100 for O(0.1)deg

	resonant
LIGO1	0.16 deg (ρ=67)
LIGO2	0.20 deg (ρ=16)
NS-NS	0.27 deg (ρ=3.6)
Short signal	0.75 deg (ρ=190)

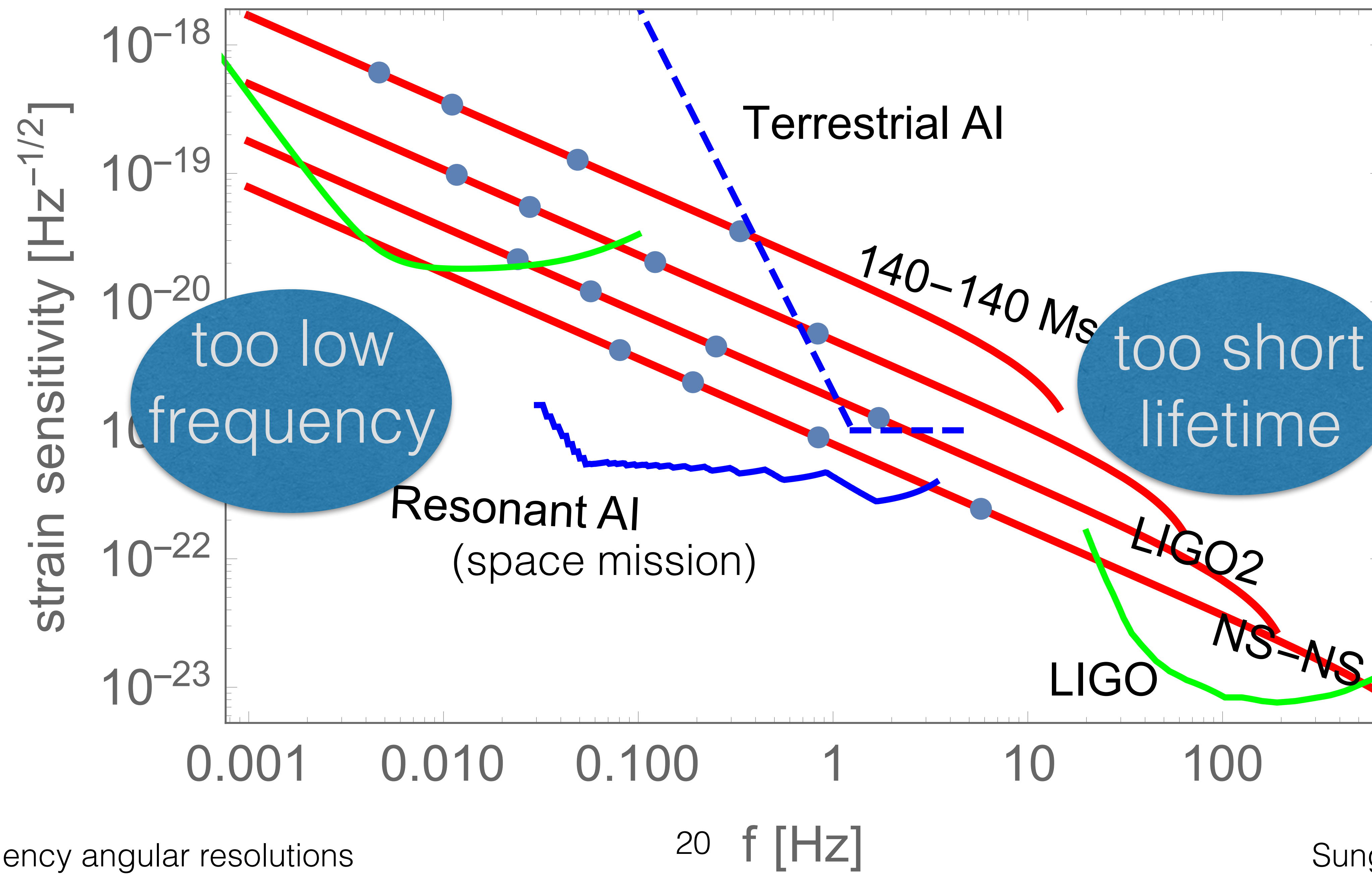
TABLE II. Angular resolution $\sqrt{\Delta\Omega_s}$
interferometer. Errros can be scaled li

S_I/N	S/N	$\Delta\Omega_{S,I}$ (10^{-5} str)	$\Delta\Omega_S$ (10^{-5} str)
975	1336	153	1.52
1435	2085	256	15.5
3150	4907	148	29.1
2505	3361	234	24.5
4610	6715	53.8	13.0
2386	3940	164	38.8
3411	3984	457	78.7
469	641	125	1.53
687	1001	188	12.4
1483	2310	104	20.9
1182	1589	154	18.1
2193	3188	42.3	9.61
1125	1853	[illegible]	[illegible]
1612	1884	[illegible]	[illegible]
2774	3806	[illegible]	[illegible]
4091	5935	[illegible]	[illegible]
9016	14041	[illegible]	[illegible]
7165	9607	104	13.8
13152	19172	27.5	6.93
6826	11280	76.8	20.8
9749	11385	220	39.8
1318	1809	152	1.67
1943	2820	164	16.6
4280	6666	99.5	25.3
3402	4561	135	23.8
6246	9104	43.0	10.5
3241	5355	109	34.5
4628	5405	289	60.0
667	913	294	4.54
982	1425	331	42.4
2157	3359	238	62.4
1715	2301	312	61.5

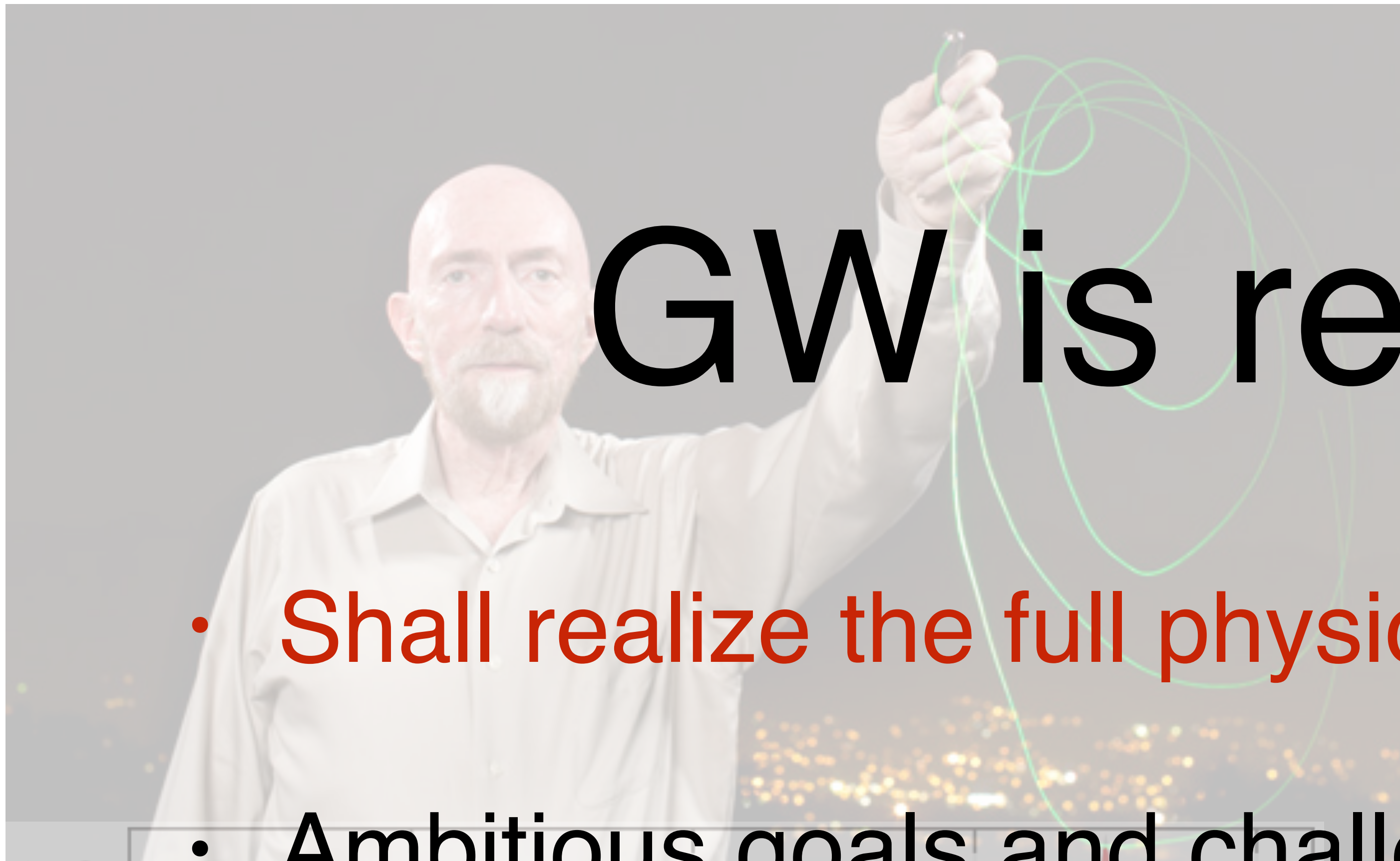
LISA: SNR 10^3-4
for O(0.1)deg

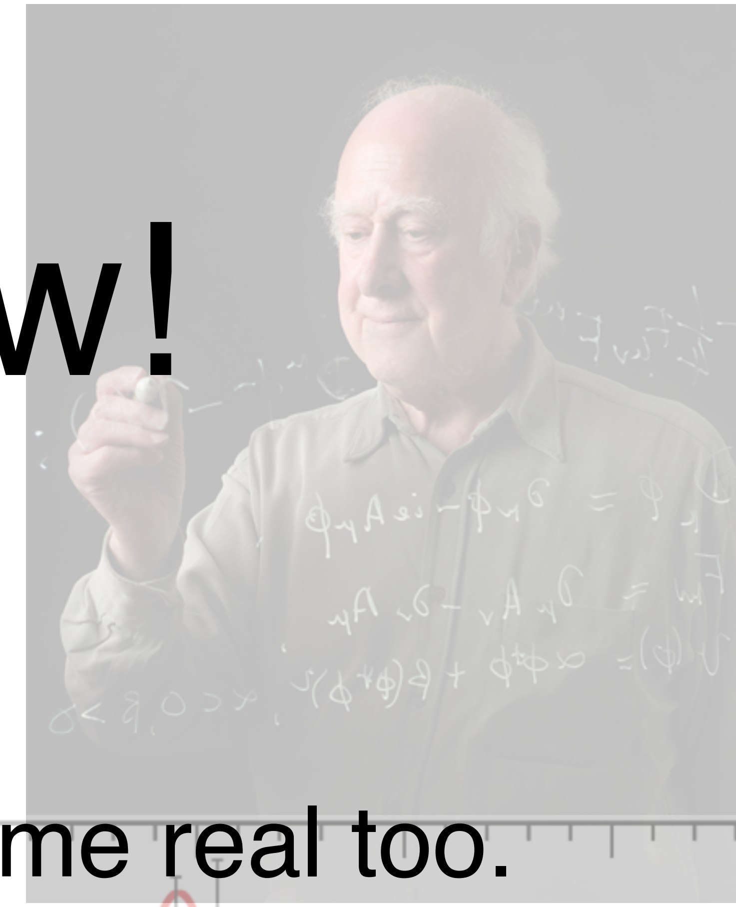
Ref: C.Cutler, 9703068

Thus, this mid frequency band 0.01~5 Hz is ideal for
(1) sub-degree angular resolution,
(2) to warn merger follow-ups.

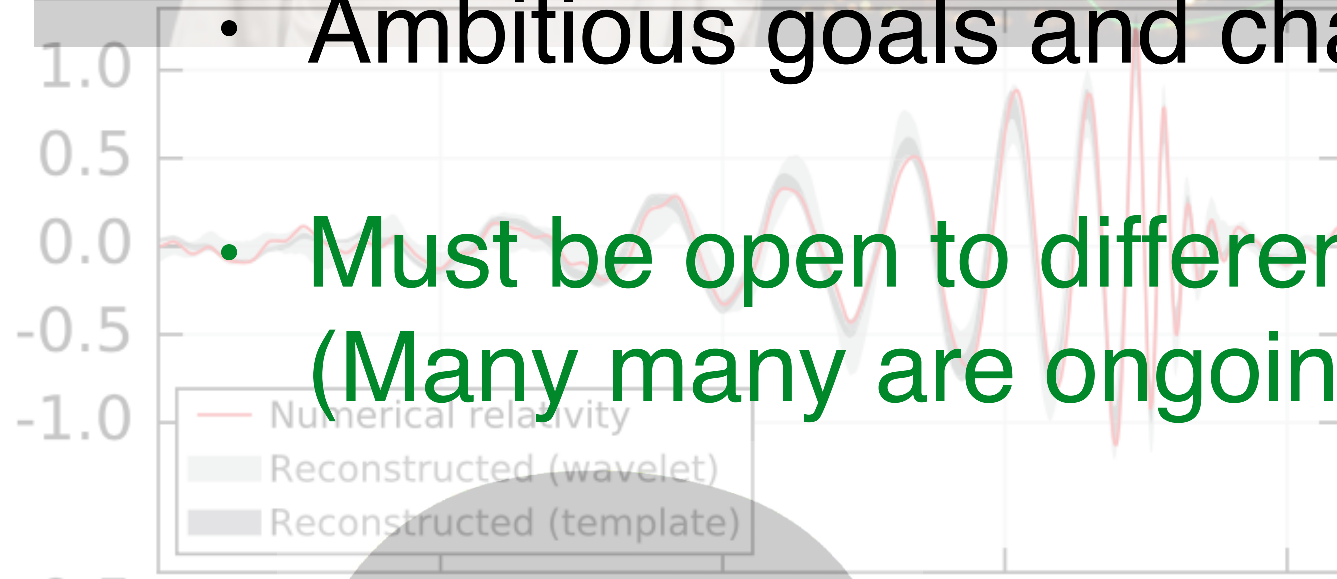


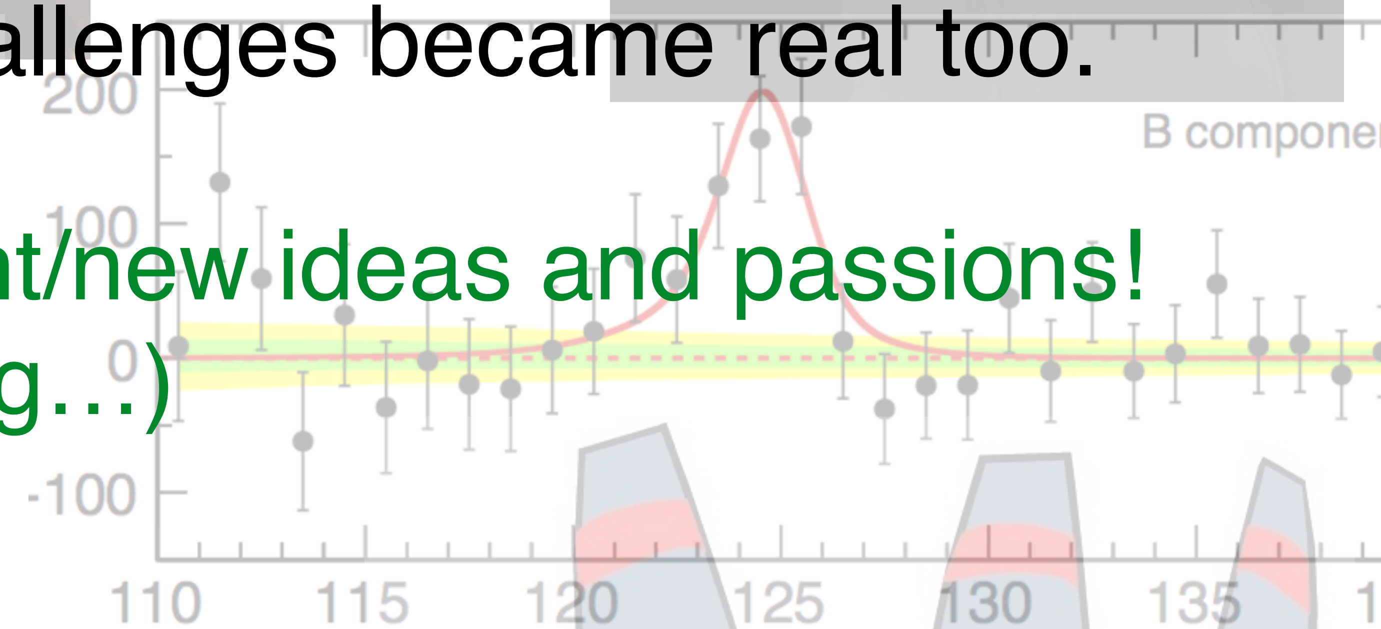
GW is real now!





- Shall realize the full physics potential.
- Ambitious goals and challenges became real too.
- Must be open to different/new ideas and passions! (Many many are ongoing…)





- Natural good localization in the mid-f band (and AI inputs) should greatly help understand the Universe.

Thank you

But (quick) reorientation still essential

- DL, polarization, inclination can *only* be measured by reorientation. Doppler doesn’t contribute directly.

- Localization of short signals spending less than months.

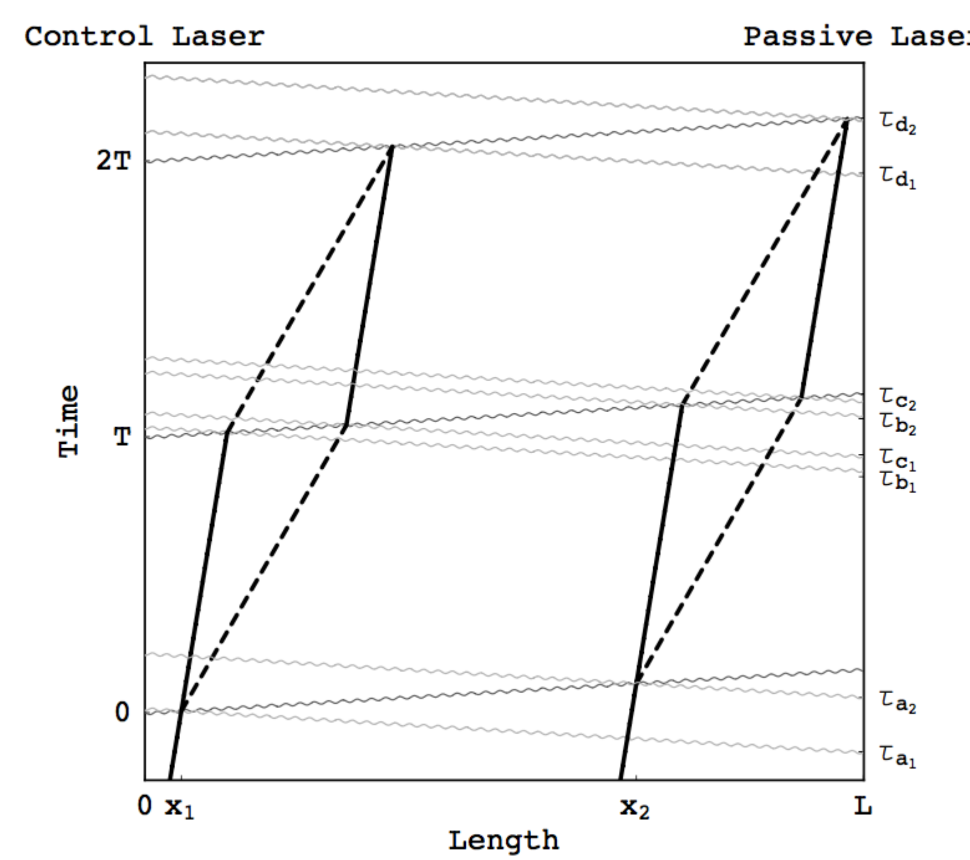
Technical aside: enhancing sensitivities

- Large Momentum Transfer (LMT):

  Repeating pulses/atom transitions can give larger momentum kick —> larger energy and higher sensitivity.

- Resonant-mode:

  Tuning $\pi/2$ - π pulse interval T to the GW frequency, the phase-shift is (resonantly) maximized.



AI noise curves