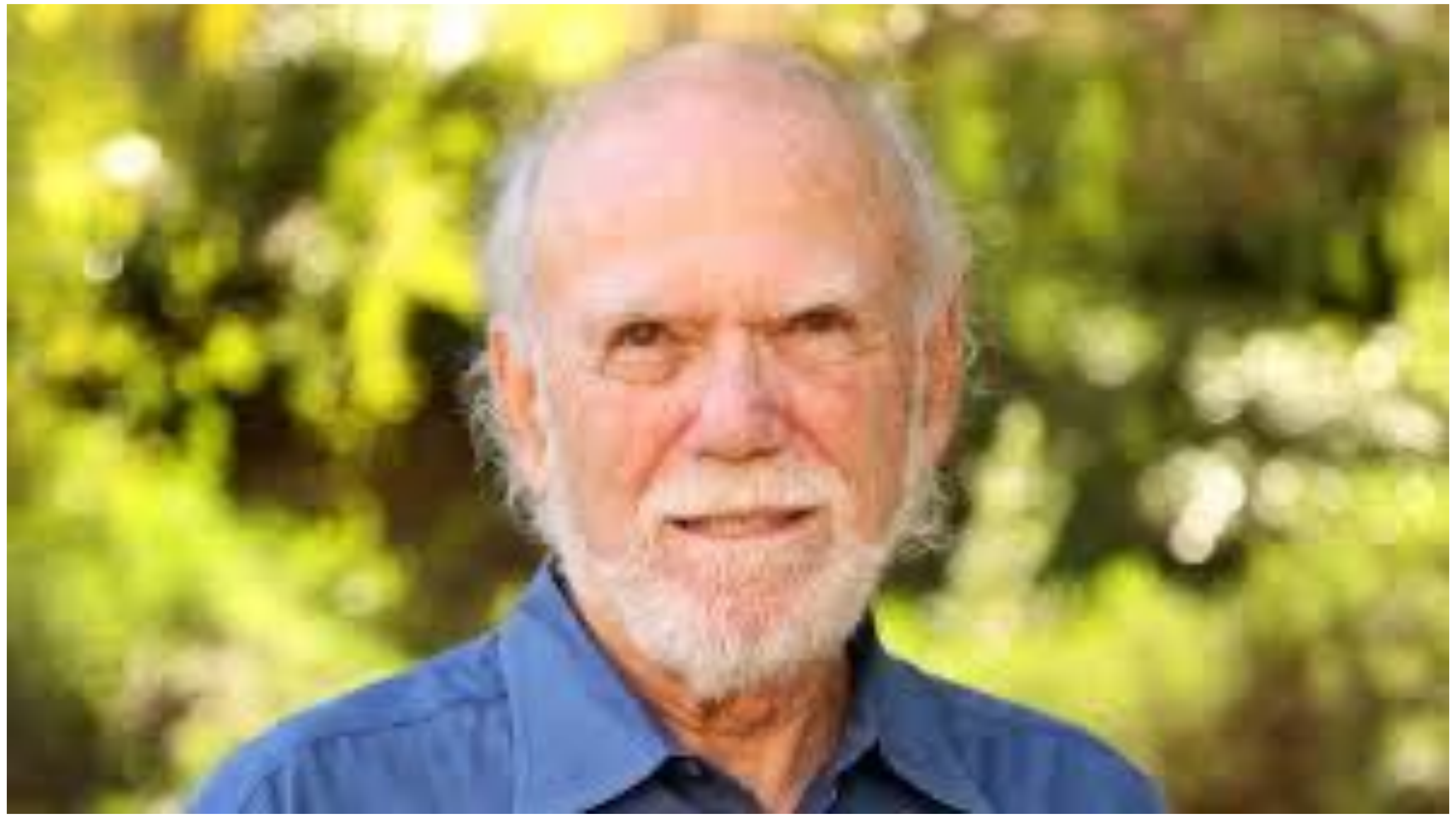
The Impact of a Midband Gravitational Wave Experiment On Detectability of Cosmological Stochastic Gravitational Wave Backgrounds

Yanou Cui
University of California,
Riverside

arXiv: 2012.07874 YC w/Barry Barish and Simeon Bird

My Collaborators

- A Highly Interdisciplinary work



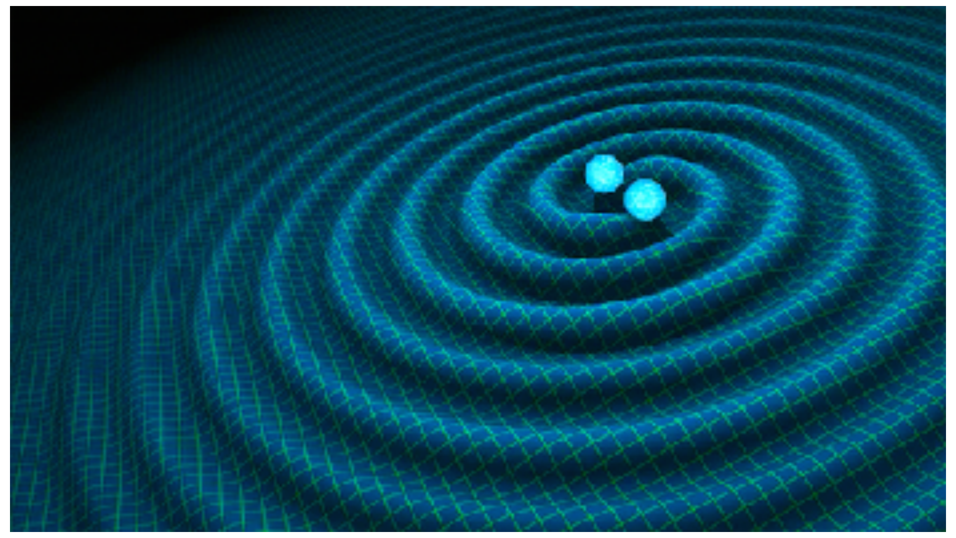
Barry Barish (UCR/Caltech): GW experimentalist, LIGO leader

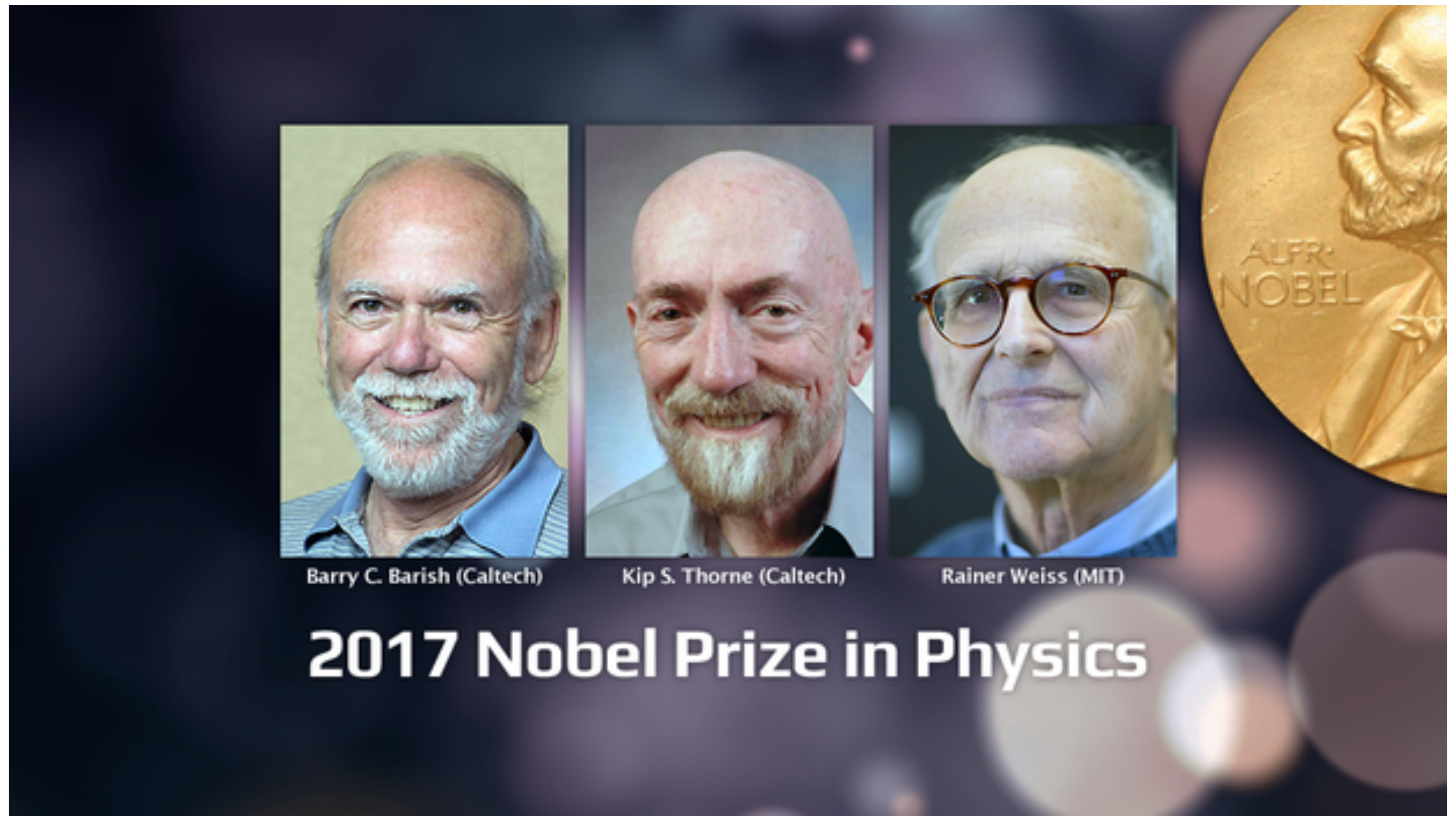
Simeon Bird (UCR): theoretical astrophysicist
An author on the original paper on LIGO detecting PBH

Gravitational Waves: An Unprecedented Window to New Physics?

- LIGO discovery 2016:

  A new era of observational astronomy
  (blackholes, neutron stars…)





- New opportunities for probing

  new particle physics/early universe cosmology?

Cosmological Sources of Stochastic GW Background

— BSM particle physics meets GWs

- Inflation
- 1st order phase transition: EWPT/EWBG, dark sector
- Cosmic strings: e.g. a spontaneous U(1) symmetry-breaking (γ', Z', $U(1)_{B-L}$, axion…) or superstring theory, "cosmic archaeology" (pre-BBN primordial dark age)

—my personal focus so far (arXiv: 1711.03104, 1808.08968, 1910.04781,1912.08832) + other work in prep

★ Rising interest in recent years!

★ Primary targets of LIGO-Virgo, LISA

arxiv: 1712.01168, 2101.12248 by LIGO-Virgo collaboration;
arxiv: 1909.00819, 1910.13125 by LISA cosmology working group + LISA science book (in prep)

Cosmological Sources of Stochastic GW Background
— BSM particle physics meets GWs

- The potential rewards: HUGE!

  Shed light on big questions:
  The electroweak hierarchy problem, matter-antimatter asymmetry, dark matter, unification of forces, inflation, primordial dark age…

  E.g. Geller, Hook, Sundrum, Tsai 2018; Buchmuller, Domcke, Murayama, Schmitz 2019; Dror, Kohri, Hiramatsu, Murayama, White 2019; YC, Chang 2019; Dunsky, Hall, Harigaya 2019; Gouttenoire, Servant, Simakachorn 2019 (2); YC, Lewicki, Morrissey 2019; Kumar, Sundum, Tsai 2020…

- May not be "futuristic"!

  Active searches @ LIGO, the recent NANOGrav excess signal can be readily addressed by a SGWB…

  E.g. Ellis, Lewicki 2020; Blasi, Brdar, Schmitz 2020

Emerging field!

The Practical Challenges:
Astrophysical Sources of SGWB

- SGWB can also originate from astrophysics!

e.g. With modeling assumptions LIGO/Virgo expect to detect stochastic GW bkg from unresolved binary BH/NS mergers, possibly overwhelms/confuses with cosmogenic signals in the LIGO f range…
- Ongoing searches for inclusive SGWB (astro+cosmo)@LIGO *(arXiv: 2101.12130)*

A real challenge for discovery of BSM physics:

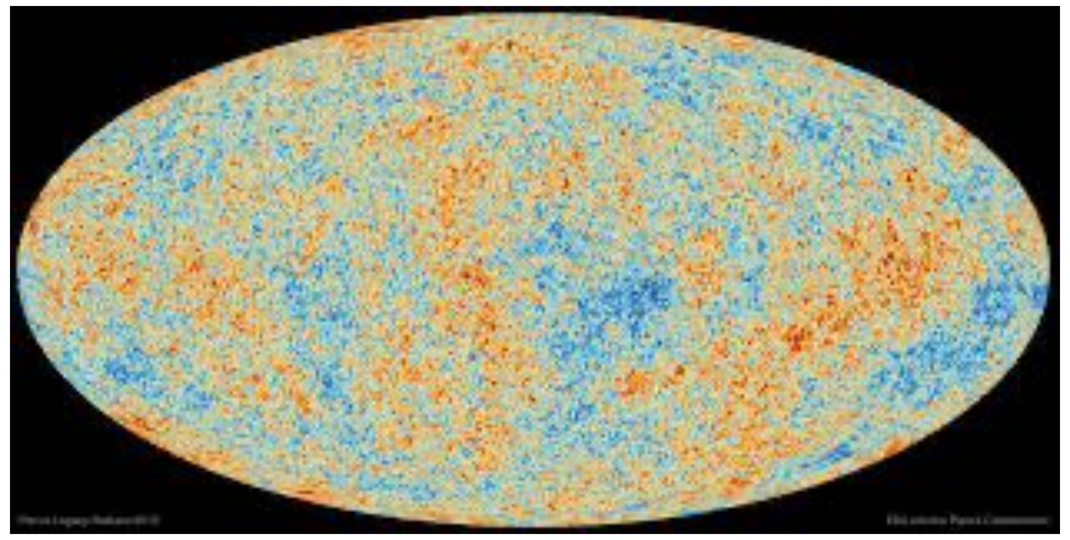
Can we/How can we distinguish/separate cosmological SGWB from astrophysical SGWB?

Facing the Challenge of Astrophysical Sources of SGWB

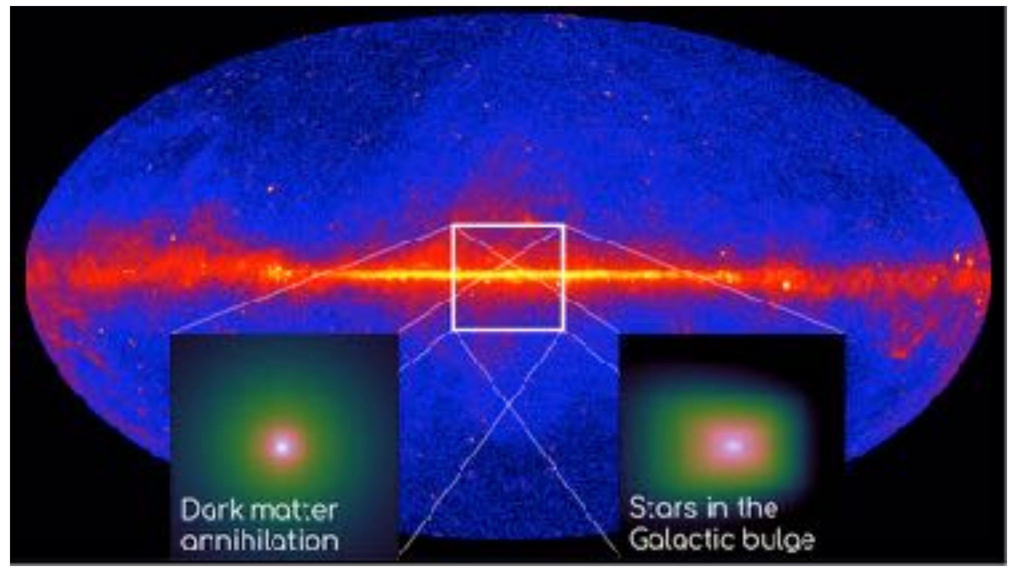
- A pessimist's view: too hard, hopeless, not worth the effort…

✔

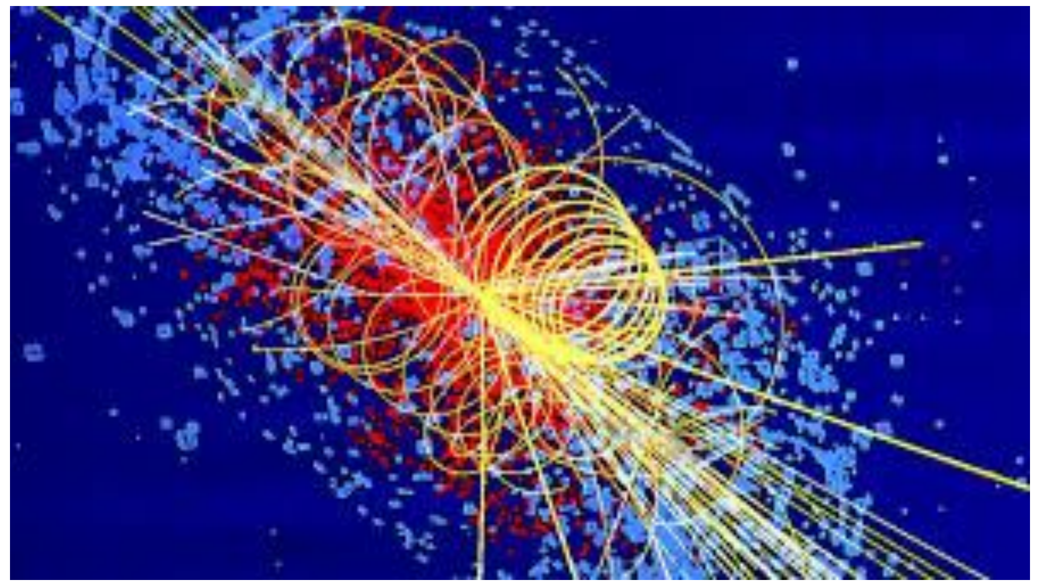
- An optimist's view: creative efforts required, but many reasons to be optimistic!
  - Remember: the potential reward is HUGE! → Worth the effort!
  - Large cosmological signal→Obvious excess over astro bkg (easy/lucky scenario)
  - This is a signal vs. background problem, we have successful histories/inspirations!



CMB foreground subtraction

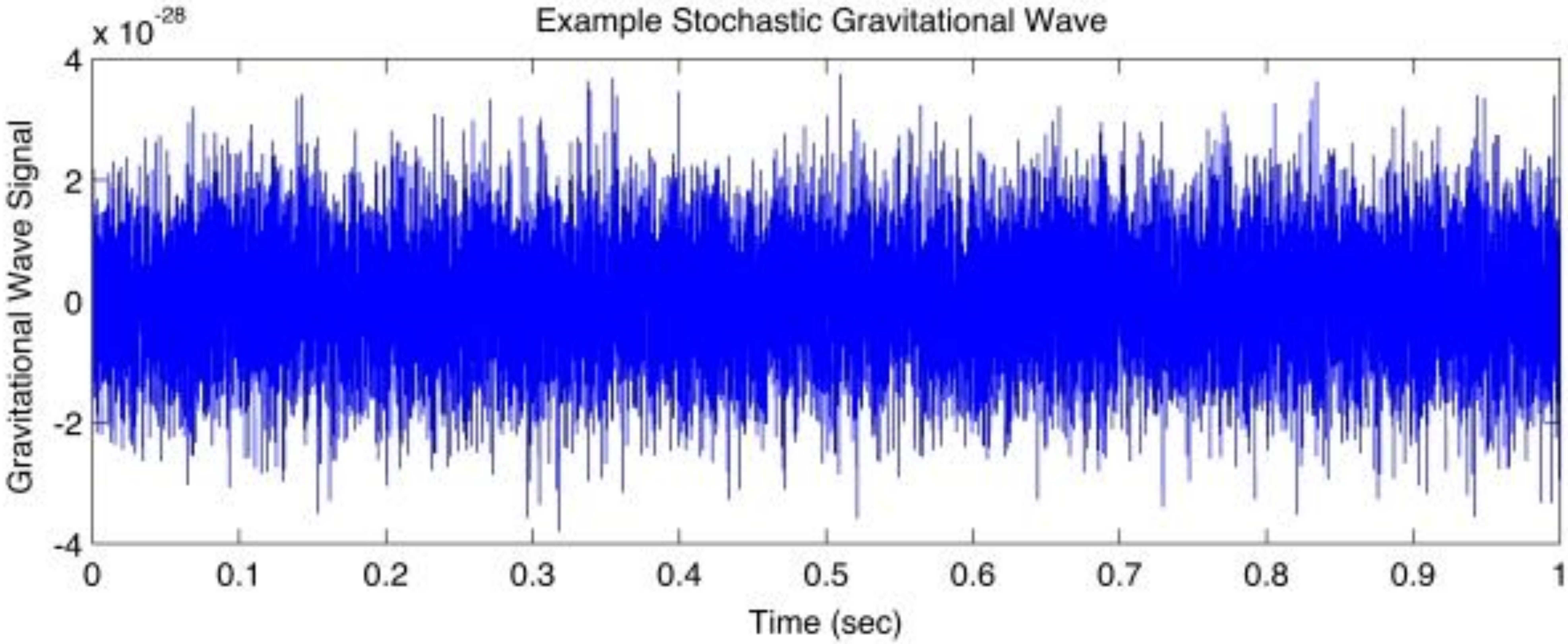


DM indirect detection



LHC (Higgs!)

Confronting the Challenge of Astrophysical Sources of SGWB



—SGWB signals in time domain: they look similar, difficult to tell apart!

(Instrumental noises reduced by cross-correlation of >1 detectors)

Confronting the Challenge of Astrophysical Sources of SGWB

What are possible solutions?

— An important newly developing research area!

- Optimize statistical analysis in time domain: identify astro bkg with fine patterns, e.g. (non-/quasi-)Gaussianity *e.g. arXiv:1712.00688*
- Resolve the "unresolved": subtract astro bkg by identifying them with future observations/detectors (e.g. + LISA, ET/CE, BBO) *e.g. arXiv: 1611.08943*

✔ • **Utilize information in frequency domain:** astro and cosmo SGWB generally have different shapes in frequency spectrum

e.g. binary mergers $f^{2/3}$ *with a cutoff* $\sim 10^3 Hz$*, inflation/cosmic strings* f^0 *at high* f*, PT split power-law with a peak at characteristic* f*… More later.*

A Muti-Frequency Band Approach

- SGWB: typically broadband in f

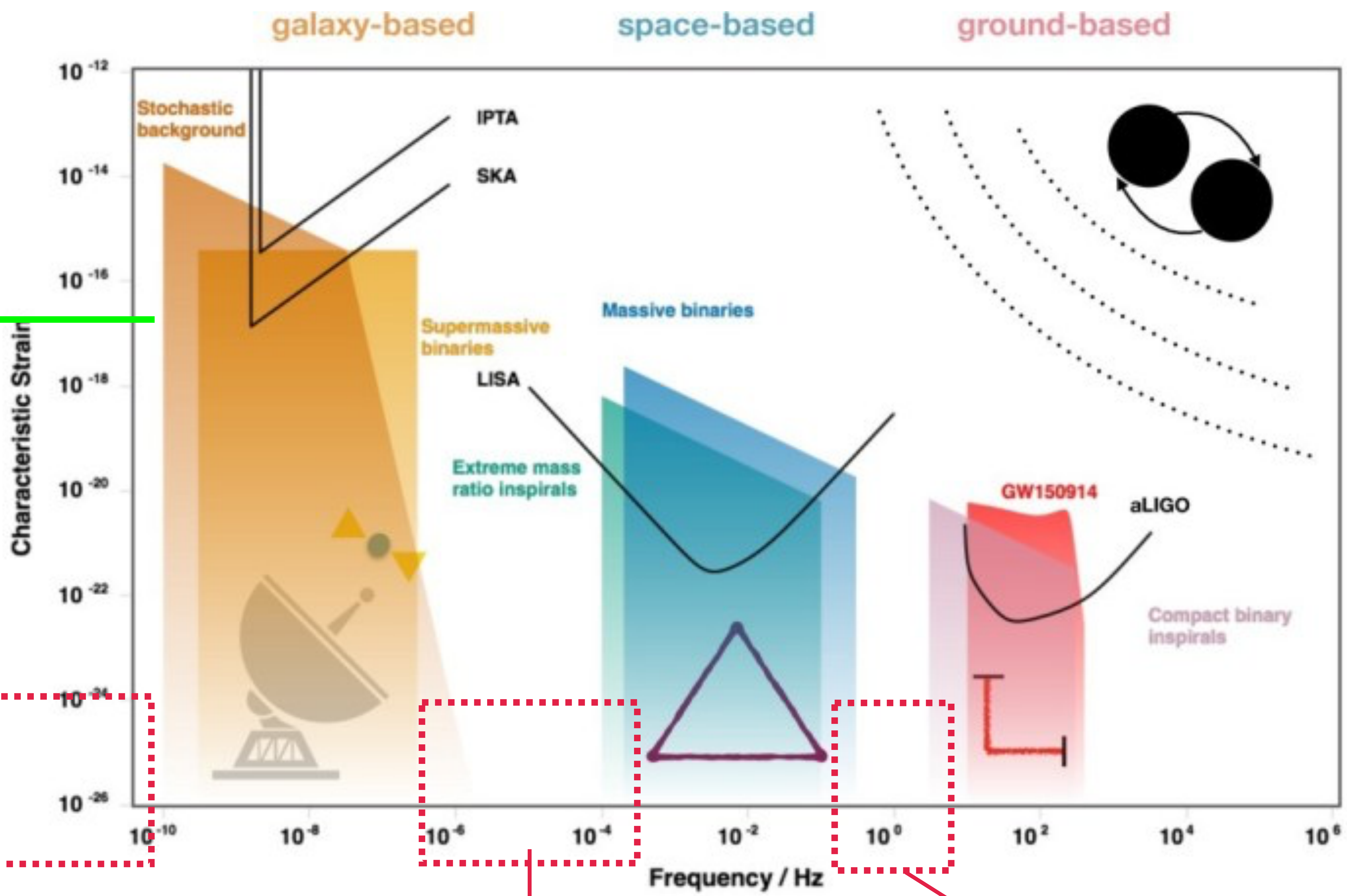
  → effective reconstruction/characterization of f spectral shape helps separating astro vs. cosmo sources

- But, individual GW experiments focus on a relatively narrow f band → limited info!

☞ **Utilize information from different GW experiments across a wide f range**

We are at the dawn of multi-band GW astronomy (cosmology)!

The Landscape of GW Experiments in Frequency Bands



+ CMB
$\sim 10^{-16} Hz$

?

Arxiv: 1908.11391 (μAres),
2010.02218(astrometry)

The "Midband": most studied, many proposals

- The gaps!

✔ **Midband** proposals: (B-)DECIGO, TianGo, TianQin, MAGIS, AEDGE, BBO…

- + further developments in LIGO band: KAGRA, ET, CE…

- The designs mostly driven by astrophysics targets; Cosmology/HEP drivers?

Designs for Midband/Deci-Hz GW Experiments

$$(f \sim 10^{-2} - 10Hz)$$

★ *Laser-interferometer based: (B-)DECIGO, TianGo, TianQin, BBO…*

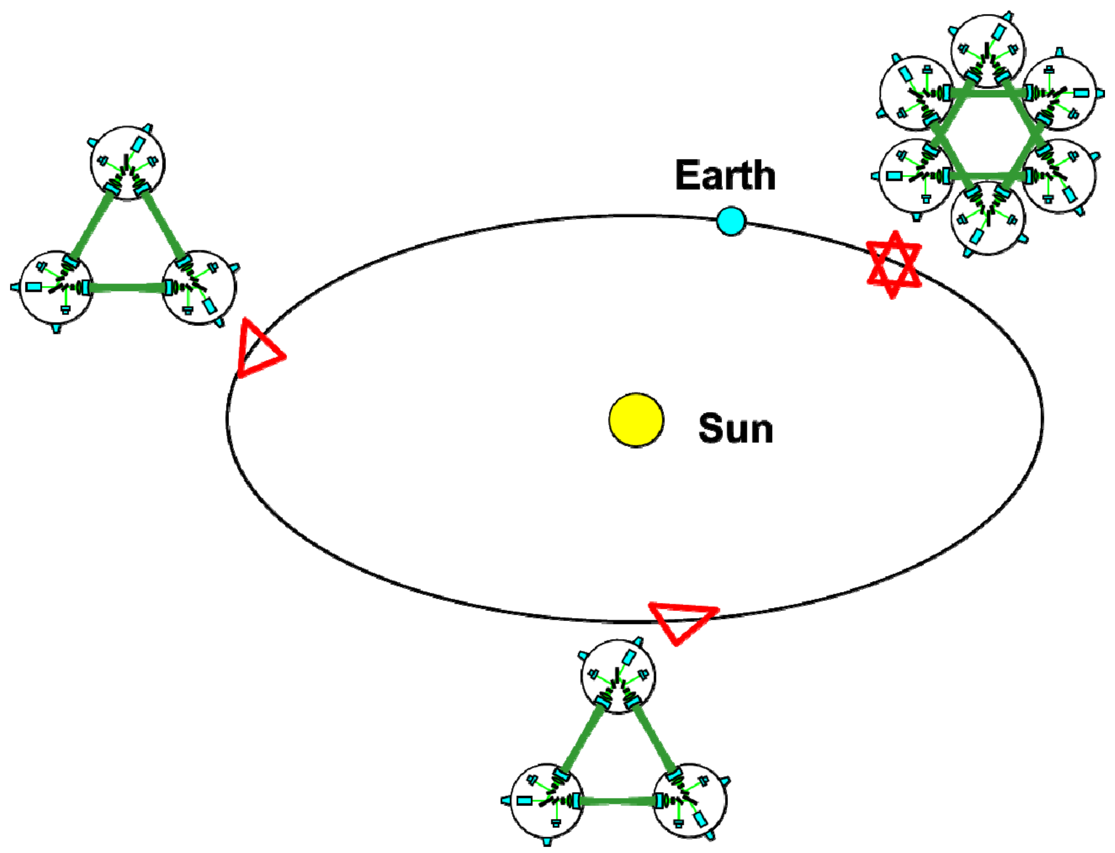


Fig. 1. Orbit of DECIGO. Four clusters of DECIGO are put in the heliocentric orbit: two at the same position and the other two at different positions.

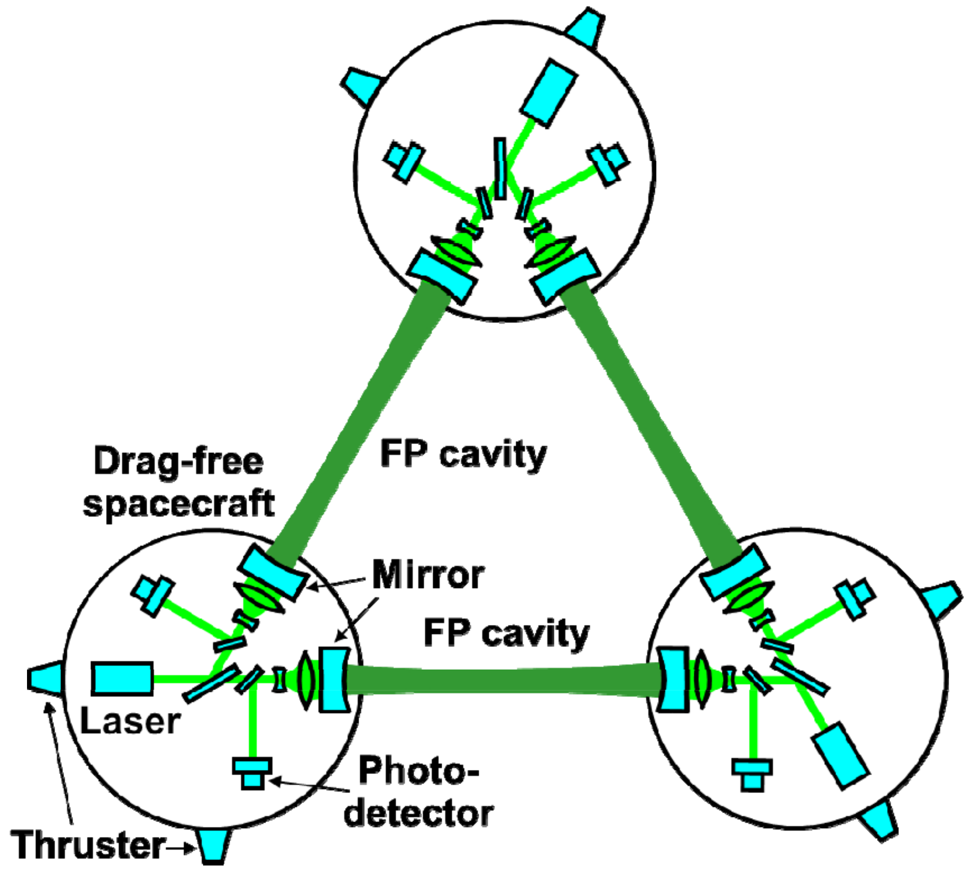
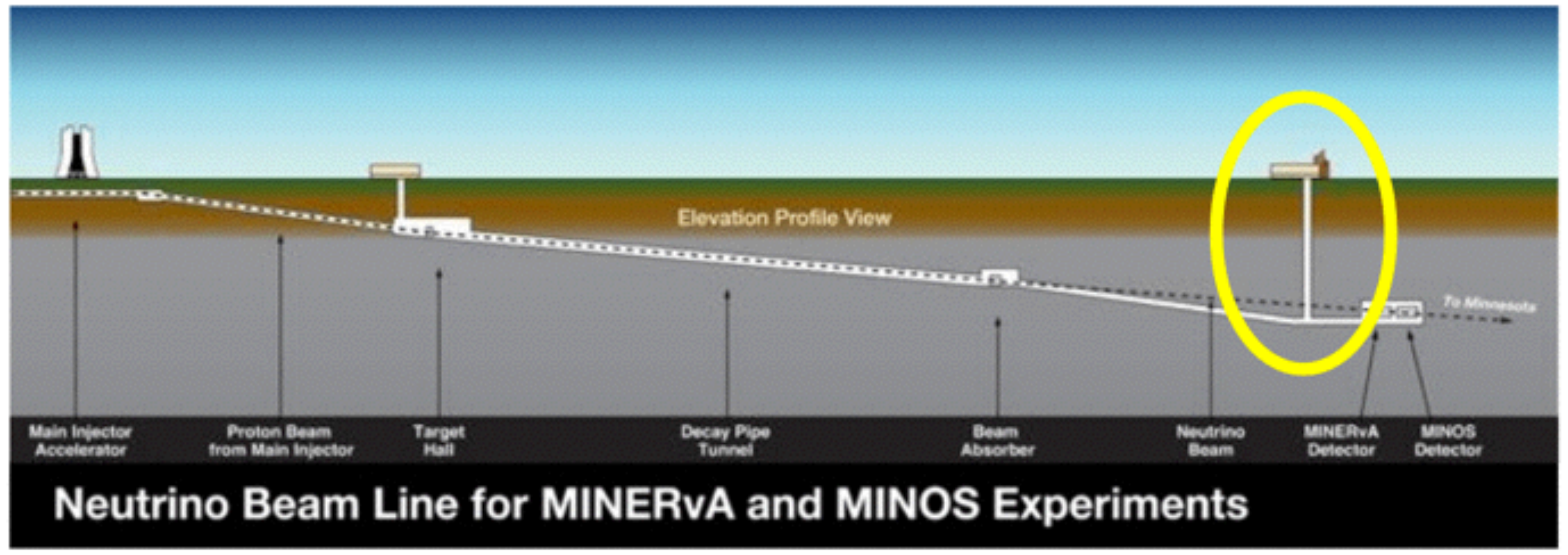


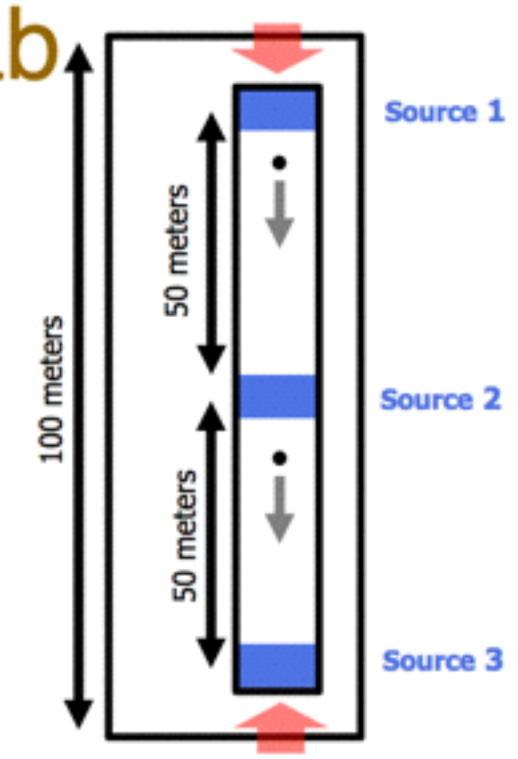
Fig. 2. Conceptual design of DECIGO. One cluster of DECIGO consists of three drag-free spacecraft. FP cavities are used to measure a change in the arm length.

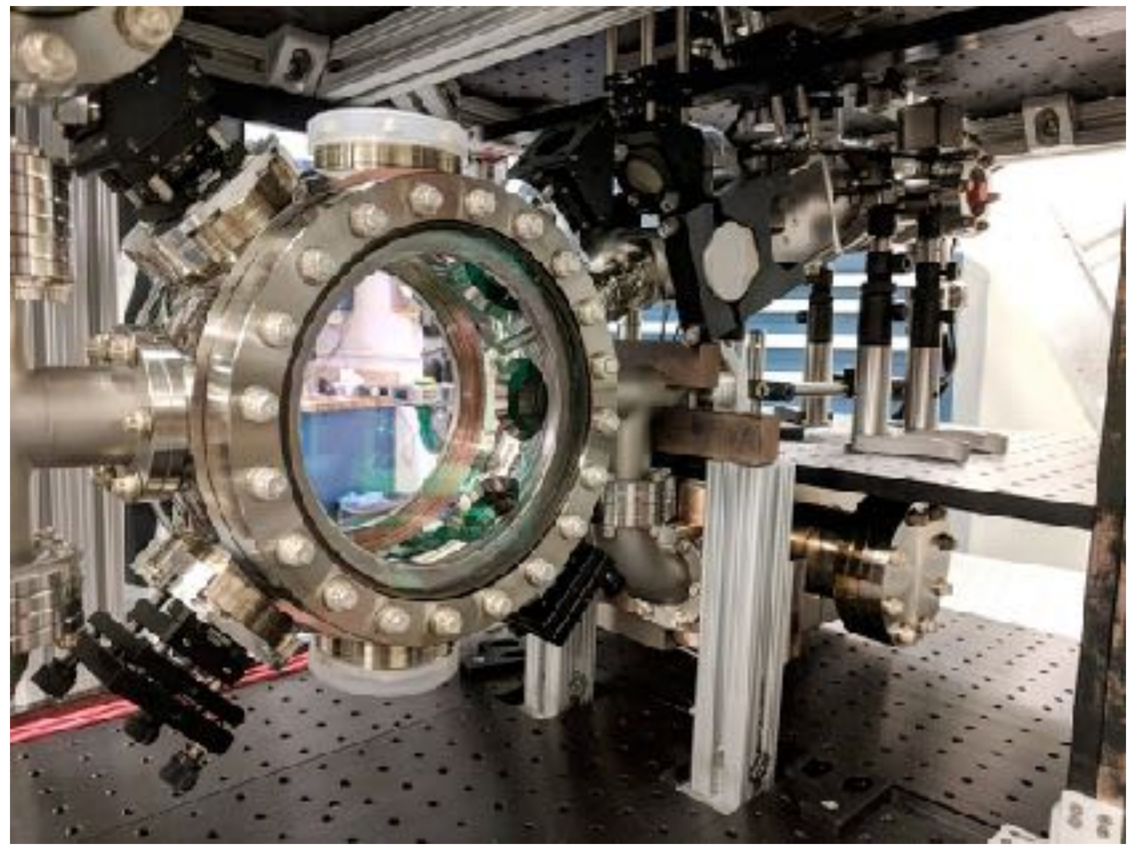
Current status of DECIGO: arXiv:2006.13545

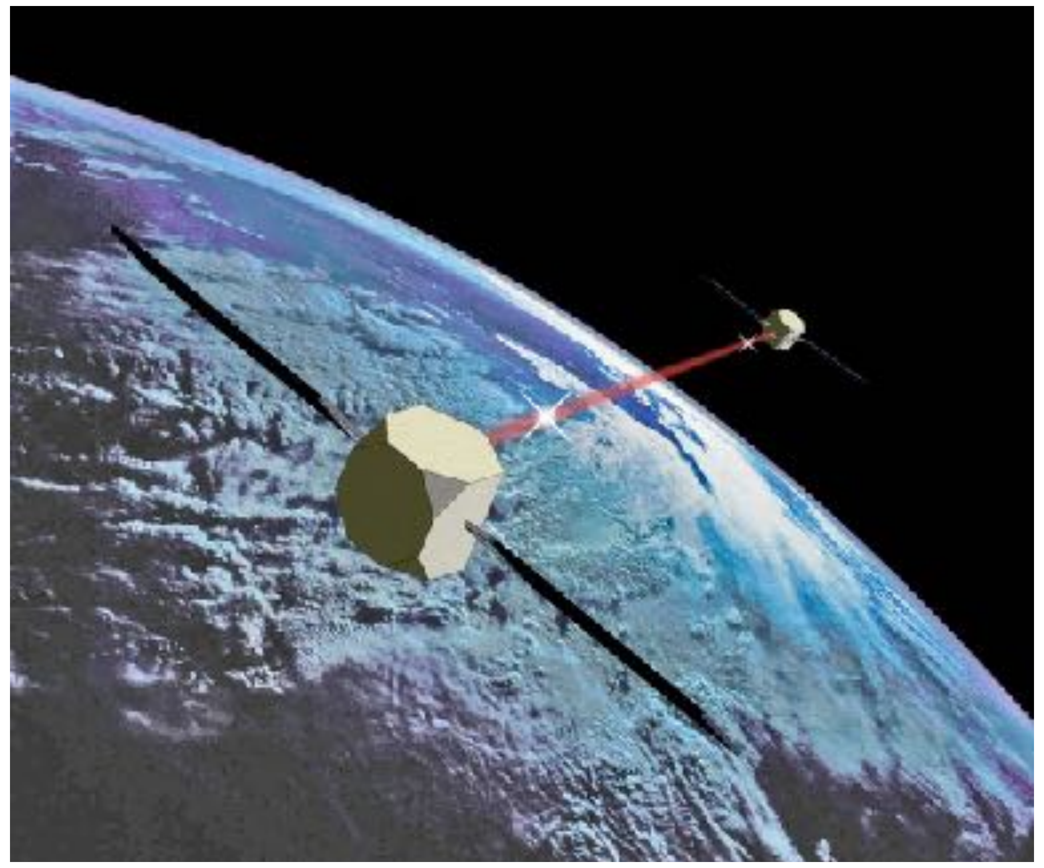
★ *Atomic-interferometer based: MAGIS, AEDGE…*

MAGIS-100 detector at Fermilab









Original concept (2008): by Dimopoulos, Graham, Logan Kasevich, Rajendran; AEDGE: arXiv: 1908.00802

Key motivations

- Dedicated quantitative study: how a future midband GW experiment complements LIGO + LISA for improving sensitivity to cosmo SGWB
- Interdisciplinary: HEP + astro, theory + experiment
- Boost the science case for midband GW experiments from HEP/cosmo motivation

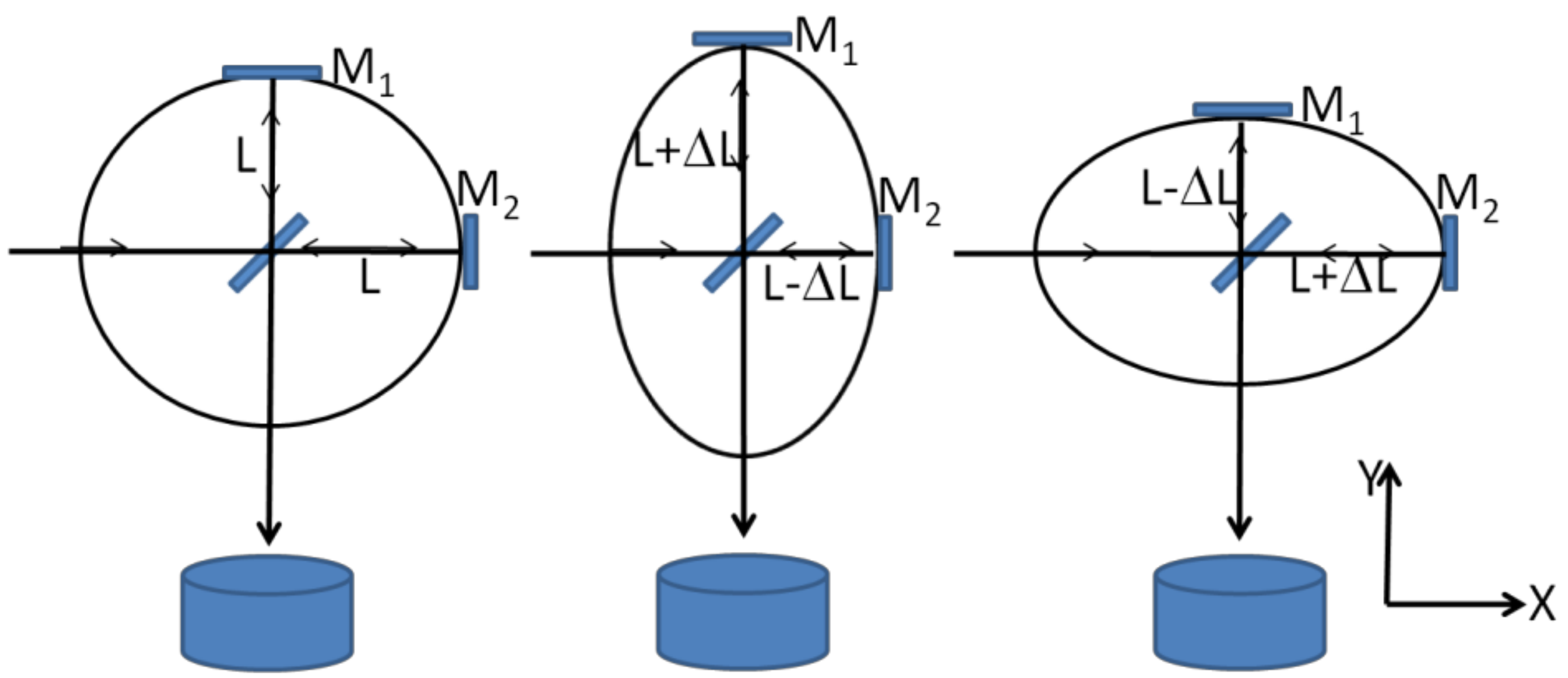
Outline

- Improvement for inclusive SGWB (astro+cosmo) vs. noise: combined power law integrated sensitivity curve (CPLS)
- Benchmark sources for cosmo SGWB and astro bkg sources, parametrization
- Likelihood analysis, forecast results
- Conclusion/Outlook

Power-law Integrated Sensitivity Curve (PLS)

- An individual GW experiment: effective strain noise $h_n(f)$, strain noise spectral density $S_n(f) = h_n^2(f)/f$. Commonly used for SGWB searches is the noise energy density sensitivity:

$$\Omega_s(f) \equiv \frac{4\pi^2}{3H_0^2} f^3 S_n(f)$$



GW strain $h = \Delta L/L$

- SGWB signal (cosmo or astro):

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f} = \frac{1}{3H_0^2 M_p^2}\frac{d\rho_{\rm GW}}{d\ln f}$$

Naive sensitivity curve: $\Omega_{\rm GW}(f) > \Omega_s(f)$ → SNR>1

Power-law Integrated Sensitivity Curve (PLS)

- We can do better! Signal generally broad band in f and static over observation time T

  ☞ Integrate over T and f band width Δf to boost SNR by $\sim \sqrt{T\Delta f}$!

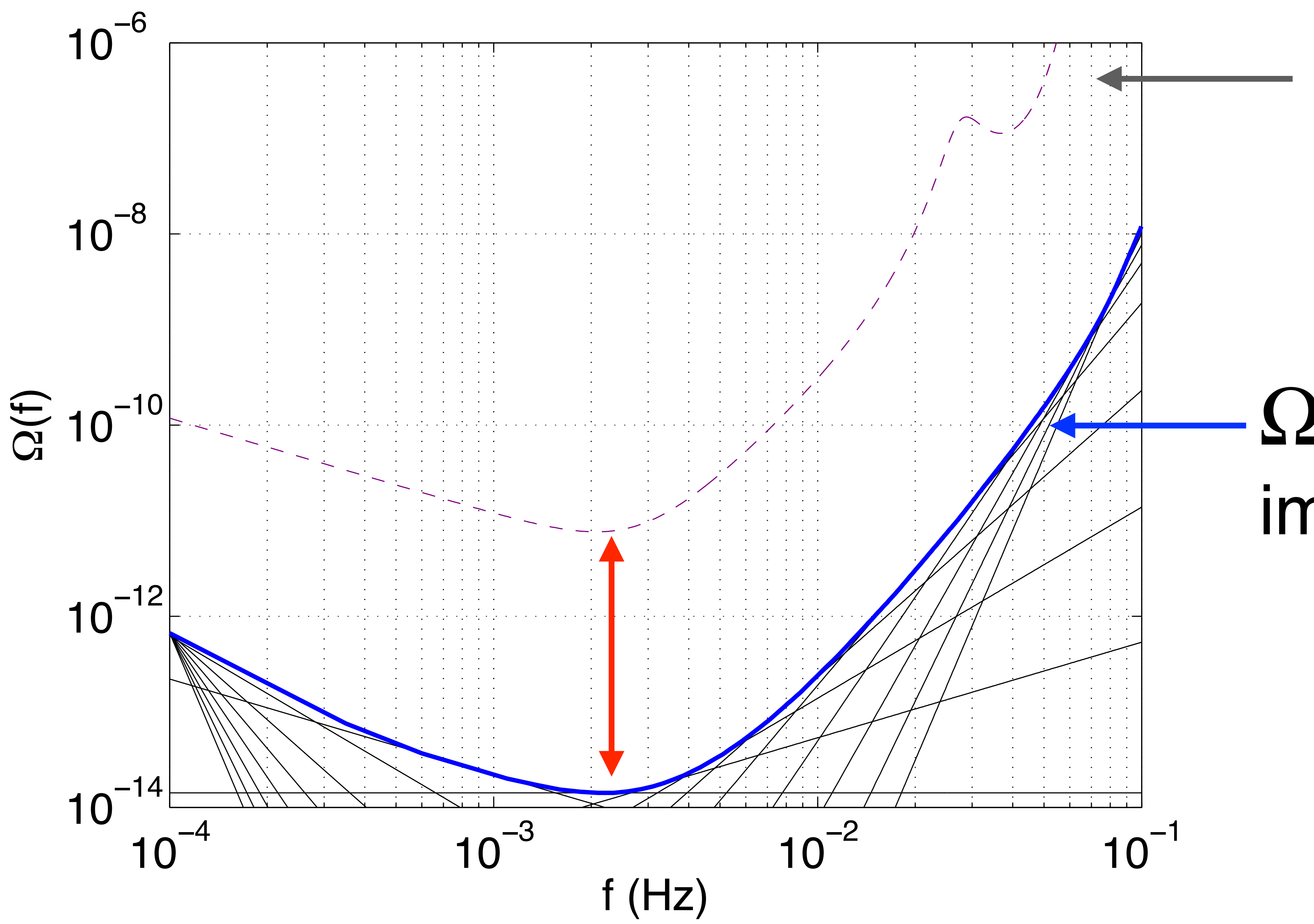
- **Power-law Integrated Sensitivity Curve** (for individual experiment)

  (Thrane and Romano 2013):

$$\mathrm{SNR} = \sqrt{T\int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\rm GW}(f)}{\Omega_s(f)}\right)^2}$$

$$\Omega_{\rm GW}(f) \;=\; (f/f_{\rm ref})^B$$

$$\Omega_{PLS}(f) = \max_B \left[\left(\frac{f}{f_{\rm ref}}\right)^B \frac{\mathrm{SNR}^{\rm thr}}{\mathrm{SNR}(f,B)}\right]$$



Ω_s : the naive sensitivity curve

Ω_{PLS} : PLS, significant improvement!

Combined PLS Curve

— Barish, Bird and YC 2020

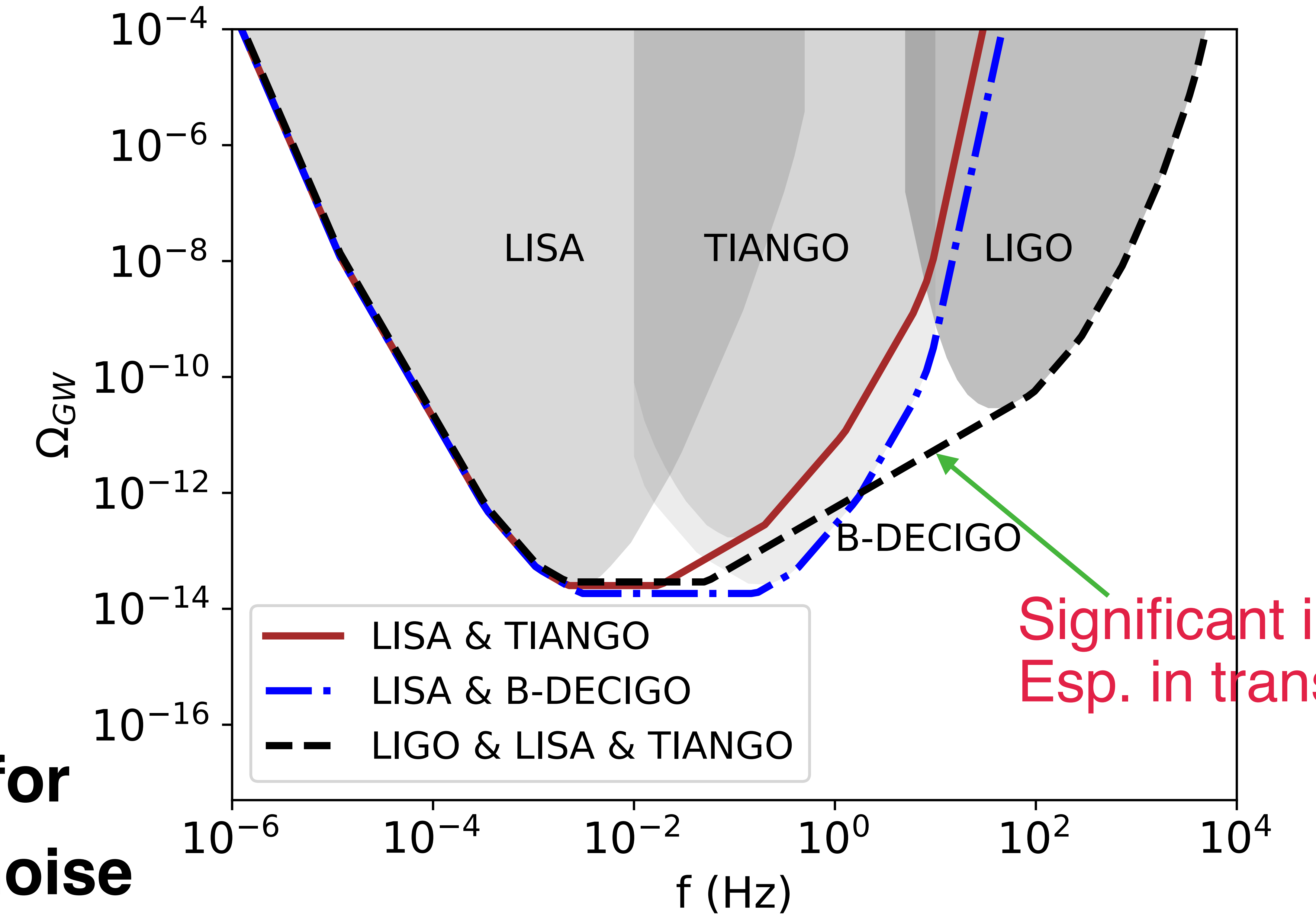
What about combine different GW experiments as one big multi-band experiment?

- We focus on: Midband (e.g. TianGo/B-DECIGO) + LISA+LIGO—continuous coverage over a wide f range

Combined PLS:

$$\mathrm{SNR}^{\mathrm{comb}} = \sqrt{\sum_i T_i \int_{f^i_{\min}}^{f^i_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega^i_s(f)}\right)^2}$$

i : label different experiment



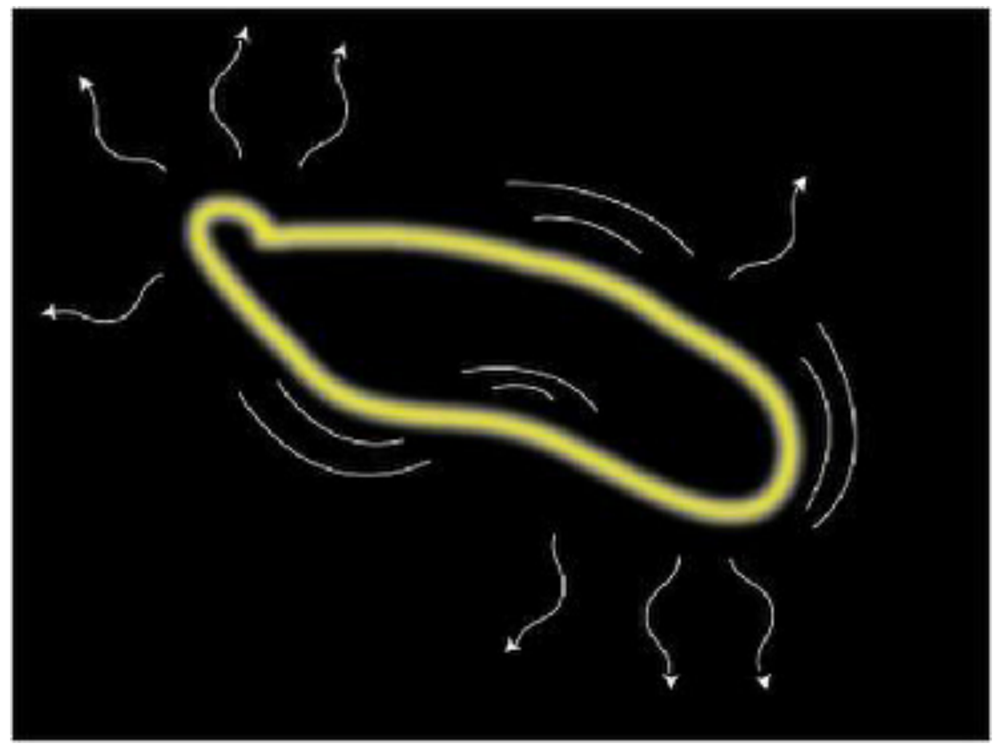
Significant improvement, Esp. in transitional regions!

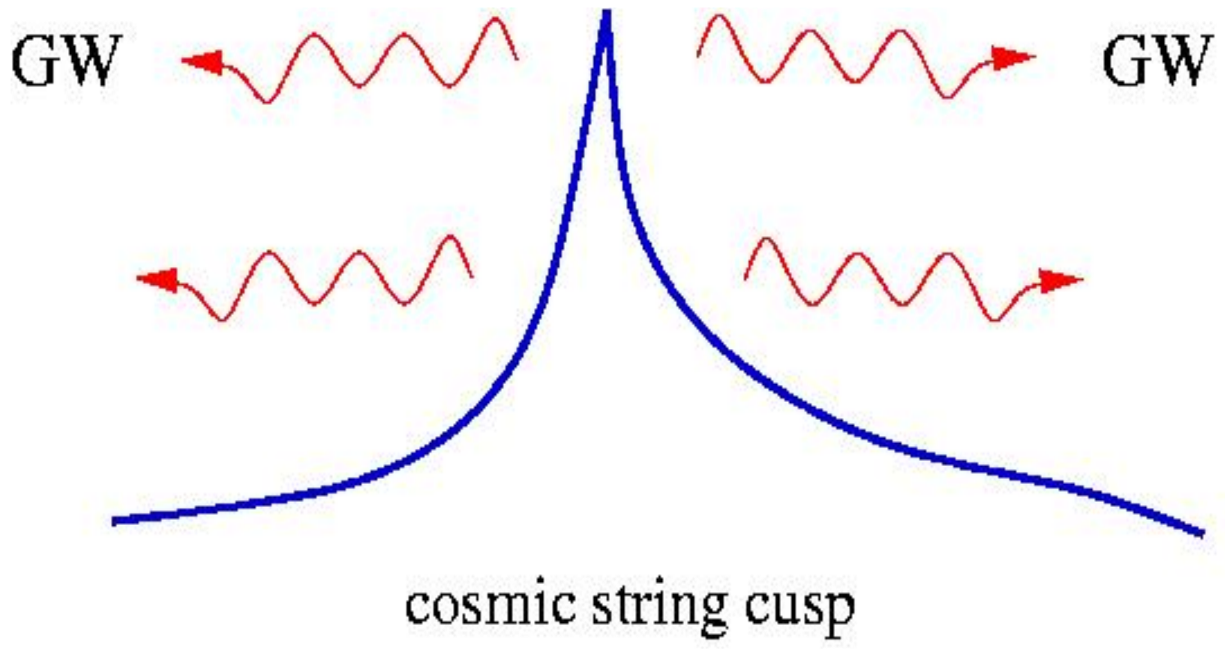
★ **This shows generic improvement for inclusive SWGB (<u>astro+cosmo</u>) vs. noise**

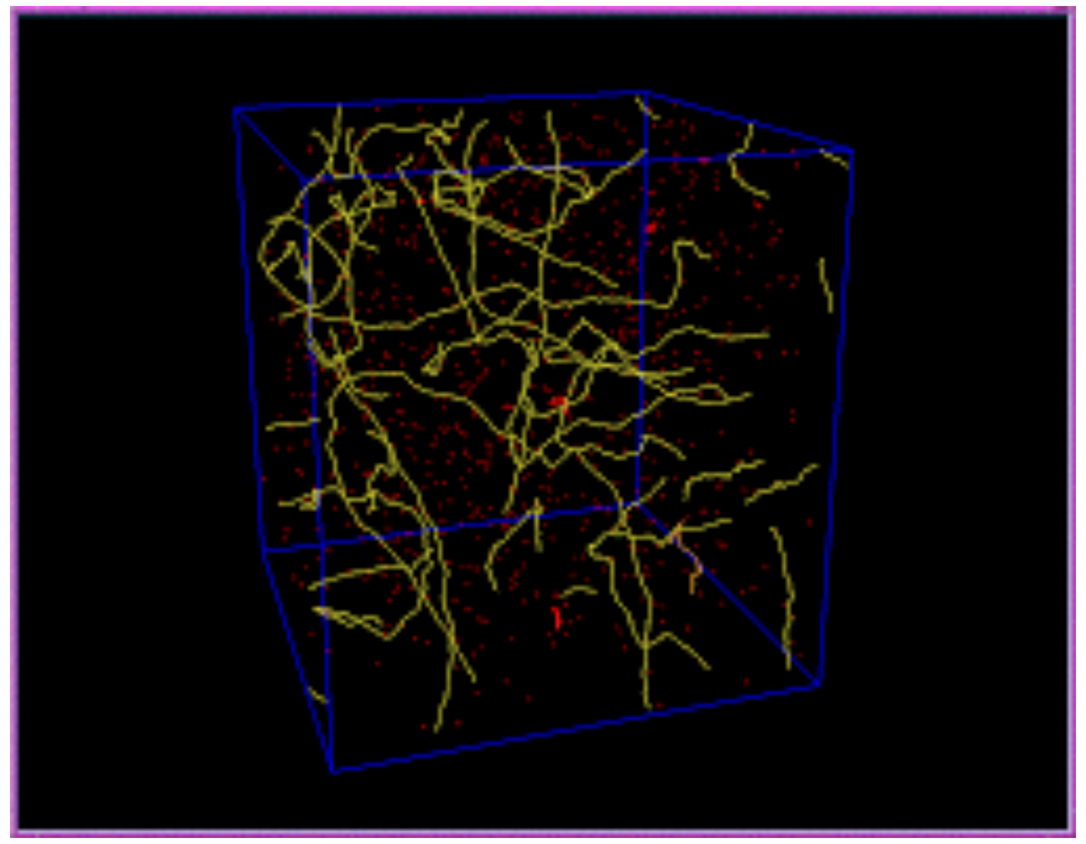
Benchmark Cosmological Sources of SGWB

1. Cosmic Strings

- The origin of cosmic strings: stable 1-dim field theory topological defects from certain symmetry breaking in the early Universe (e.g U(1)'), or superstring theory
- Horizon-sized long strings inter-commute on collisions → sub-horizon loops
- GW bursts from decays of oscillating string loops throughout cosmic history







- Accumulation of unresolvable (high redshift) GW bursts → SGWB from strings!

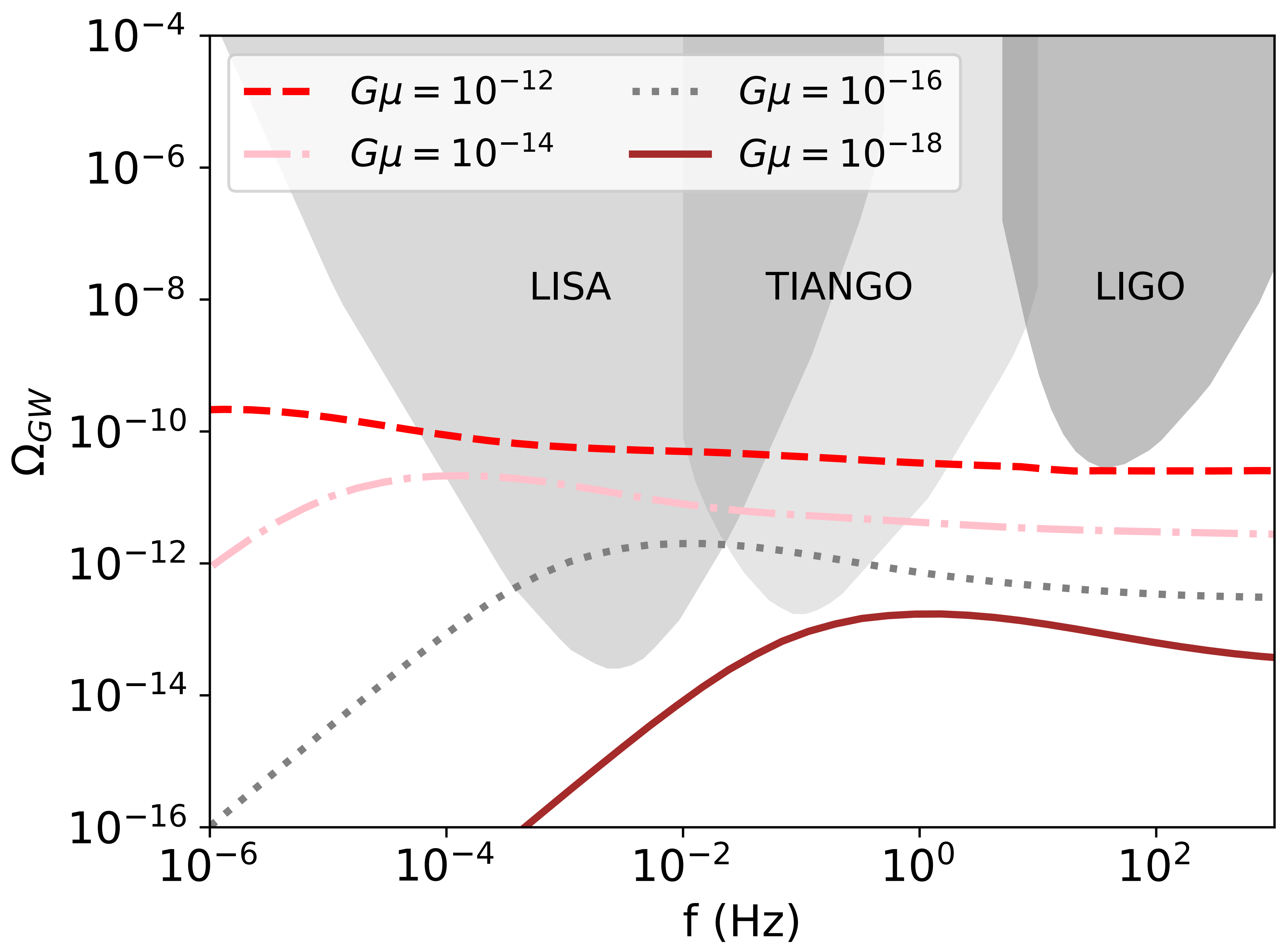
Benchmark Cosmological Sources of SGWB

1. Cosmic Strings

Factors to determine the SGWB spectrum from a cosmic string network & our choices

- NG or local/gauge strings ✔ (vs. global): GW is the dominant radiation mode
- Loop size distribution: $\ell_i \sim \alpha t_i, \alpha \sim 0.1$ ✔— widely used simulation results
- Cosmic history: ✔ standard cosmology (long epoch of RD) (vs. non-standard)
- String tension $G\mu$: $\mu \sim v^2$ (v : symmetry breaking scale)

✤ SGWB from strings: a nearly flat plateau at high f (RD), bump/declination at low f

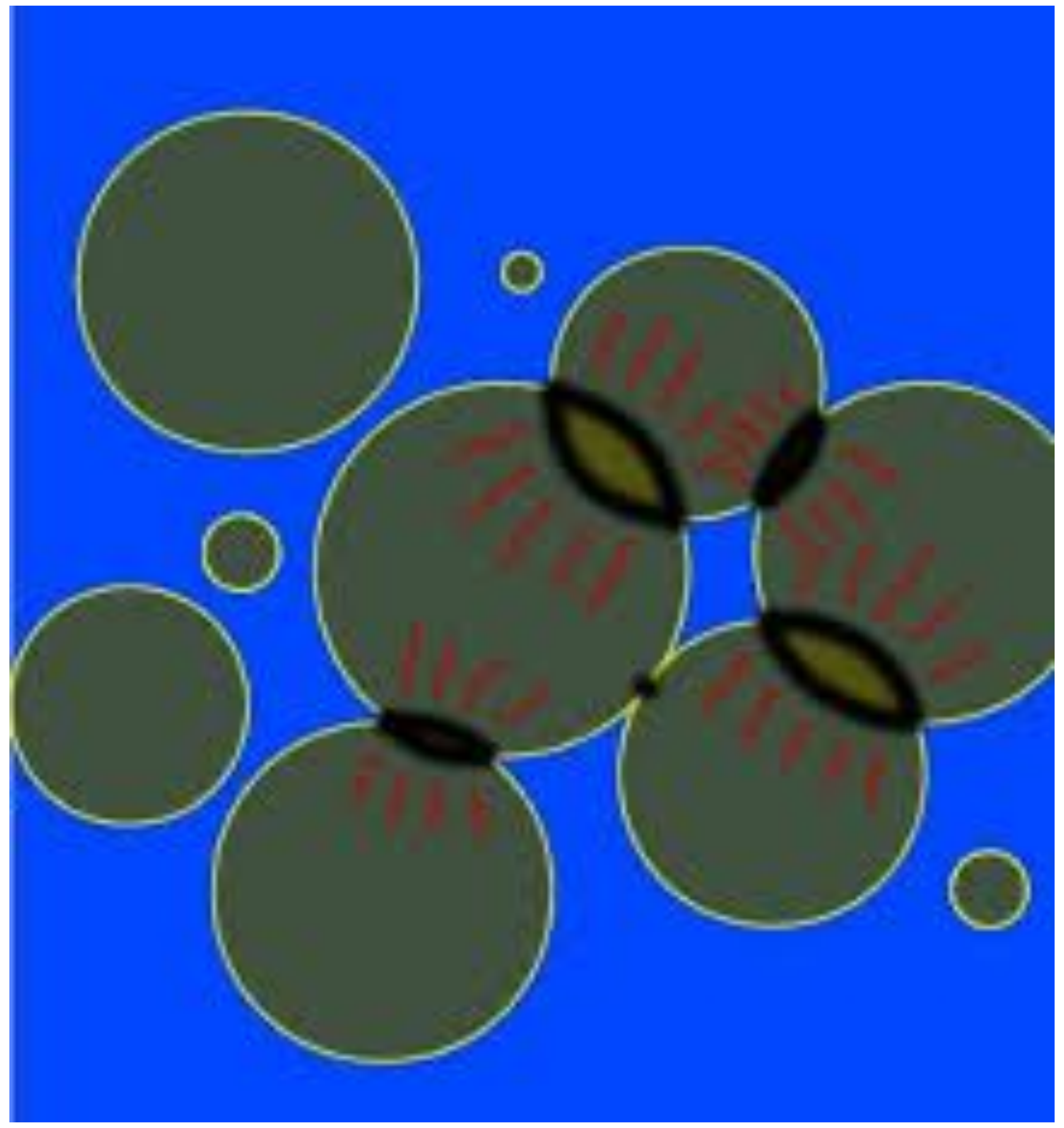


Benchmark Cosmological Sources of SGWB

2. Phase Transitions

- Strong 1st order phase transition in the early Universe: EWPT, EWBG, dark sectors
- GW produced during the PT due to 3 effects: bubble collisions, sound waves ✔, turbulence;

  Recent studies→ sound wave contribution typically dominates *(our focus)*



Benchmark Cosmological Sources of SGWB

2. Phase Transitions

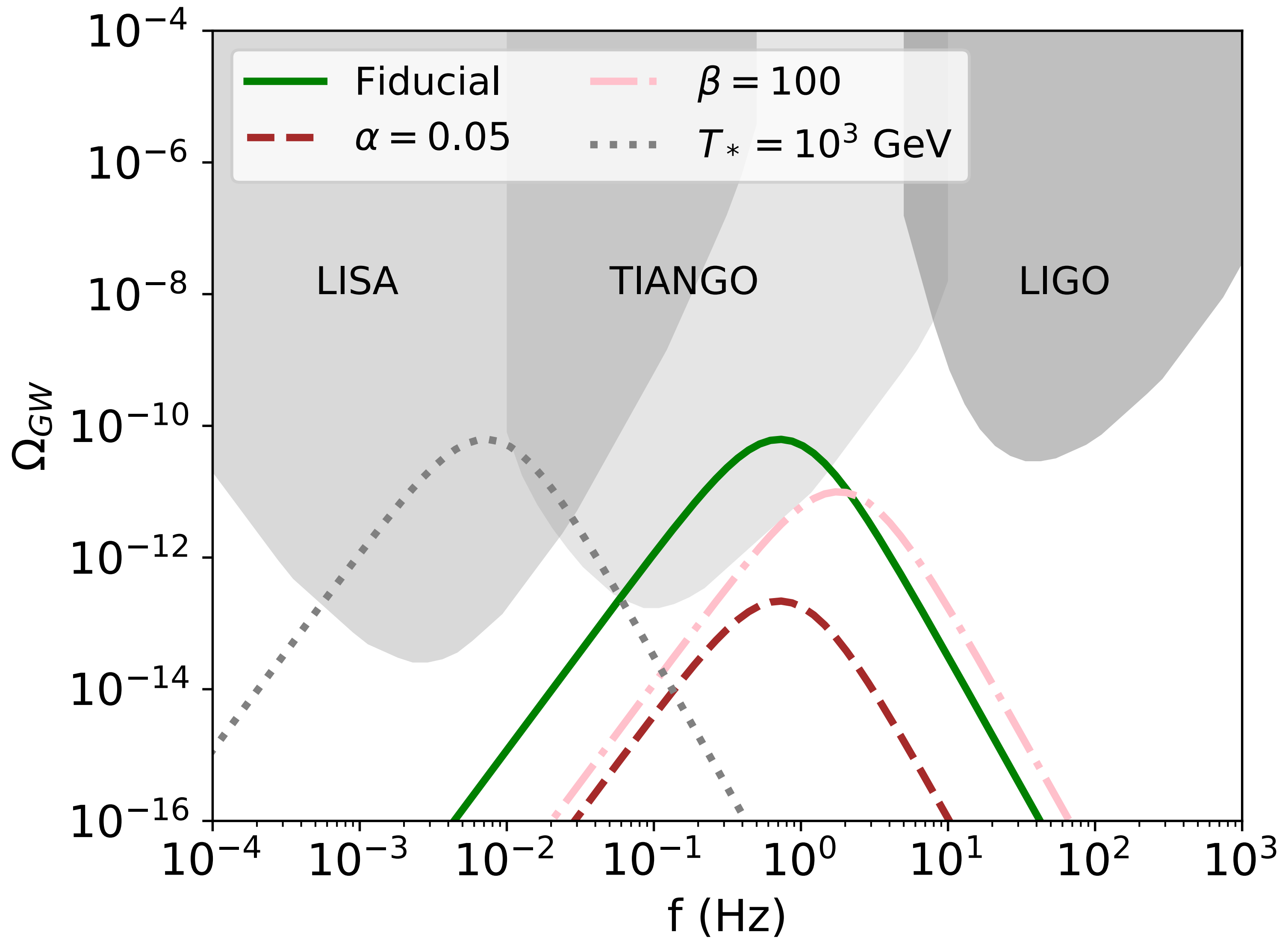
Factors to determine the SGWB spectrum from a PT & our choices

- Source: sound wave ✔
- Temperature at which the PT occurs: T_*, we scan in the relevant range of (100 GeV, 10^7 GeV)
- Bubble wall velocity: v_w—simulation determines, we choose benchmark $v_w = 0.5$
- The strength of the PT: α , the duration of the PT: β/H_* —correlated for a given particle physics model, we scan over $\alpha < 0.8$ (safe for the PT to complete) and marginalize over β

✤ SGWB from a PT: a peak at a characteristic f with $\sim f^{\pm 3}$ power law at two sides (SW)

$$f_{p,0} = \frac{2.6 \times 10^{-5}}{H_* R_*} \left(\frac{T_*}{100\ \mathrm{GeV}} \right) \left(\frac{g_*}{100} \right)^{1/6} \ \mathrm{Hz}$$

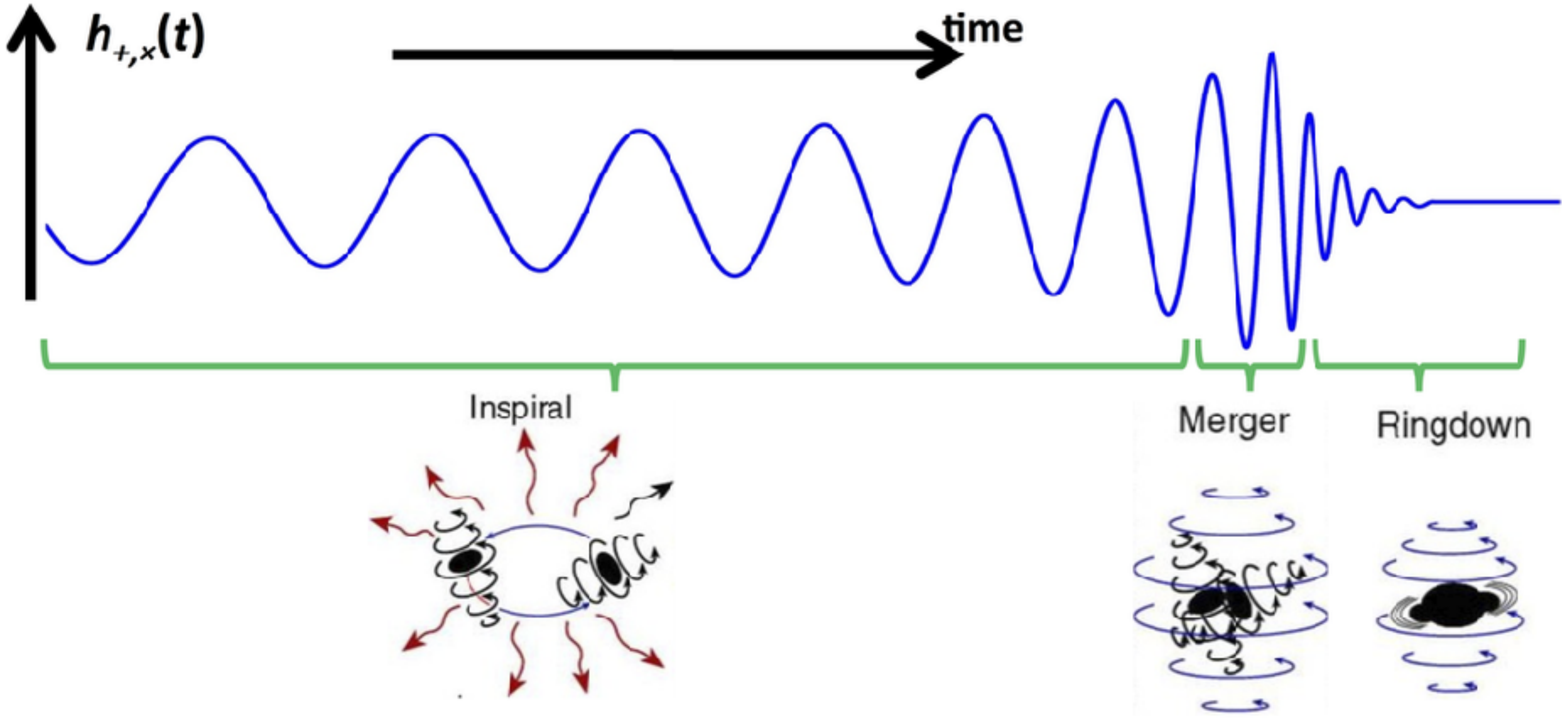
$$R_* = \frac{(8\pi)^{1/3}}{H_* \beta v_w}$$



Astrophysical Sources of SGWB

- Mergers of compact astrophysical objects (BH, NS) → transient GW chirps/bursts that LIGO has observed

- These mergers, if unresolved → SGWB! Unresolved:
  - Too far away to be detectable
  - Early inspiral phase of ultimately observable merger (weak, long-lasting signals)



★ For stellar mass BH/NS: mergers are important only in the LIGO band, low-f inspirals dominates LISA band

Astrophysical Sources of SGWB

General formula:

$$\Omega_{\rm GW}(f_{\rm obs}) = \frac{f_{\rm obs}}{\rho_c}\frac{d\rho_{\rm GW}}{df_{\rm obs}}$$
$$= \frac{f_{\rm obs}}{c^2\rho_c}\int_0^{10} dz\, \frac{R_m(z)}{(1+z)H(z)}\frac{dE}{df_{\rm s}}$$

- $R_m(z)$: merger rate, assumed to follow an empirical fit to star formation rate, we scan over the overall normalization factor

$$R_m(z) \sim \frac{a \exp\left[b(z-z_m)\right]}{a + b\left(\exp\left[a(z-z_m)\right]-1\right)}$$

- f_s : frequency in the source frame $f_{\rm obs} = f_{\rm s}/(1+z)$

- dE/df_s: Spectral energy density of the source (depends on coalescing masses)

Astrophysical Sources of SGWB

- The most important astro sources for our consideration

- **Stellar mass BH binary mergers (StMBBH)** (NS mergers subdominant and degenerate with overall merger rate)

$$\frac{dE_{\rm insp}}{df_{\rm s}} = \frac{1}{3}\left(\frac{\pi^2 G^2}{f_{\rm s}}\right)^{1/3} \frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

$$f_{\rm merg}^{\rm StBBH} = 0.04\frac{c^3}{G(m_1+m_2)}$$

$$\frac{dE_{\rm merg}}{df_{\rm s}} = \frac{1}{3}\left(\pi^2 G^2\right)^{1/3} \frac{f_{\rm s}^{2/3}}{f_{\rm merg}^{\rm StBBH}} \frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

We consider $5 < m_1, m_2 < 50 M_\odot$

- **Intermediate Mass Ratio Inspirals (IMRI):** IMBHs with $10^2 - 10^4 M_\odot$, hypothetical until the first (and the only) discovery of LIGO GW290521 (2020!);

☞ We know little about them now but potentially important for LISA and midband!

— We take a simplistic modeling of IMRI SGWB based on limited current literature + dE/df_s formulae for StMBBH: best we can do now, future observations will clarify

Astrophysical Sources of SGWB

- The most important astro sources for our consideration

- **Extreme mass ratio inspirals (EMRIs):** mergers between stellar mass and supermassive BHs (SuMBH), $M_{\rm SuMBH} \gtrsim 10^6 M_\odot$ (galaxy M33)

$$f_{\rm merg}^{\rm EMRI} = 0.01 \left(\frac{M_{\rm SuMBH}}{10^6} \right)^{-1} \ {\rm Hz}$$

— relevant for LISA band, faint but detectable.

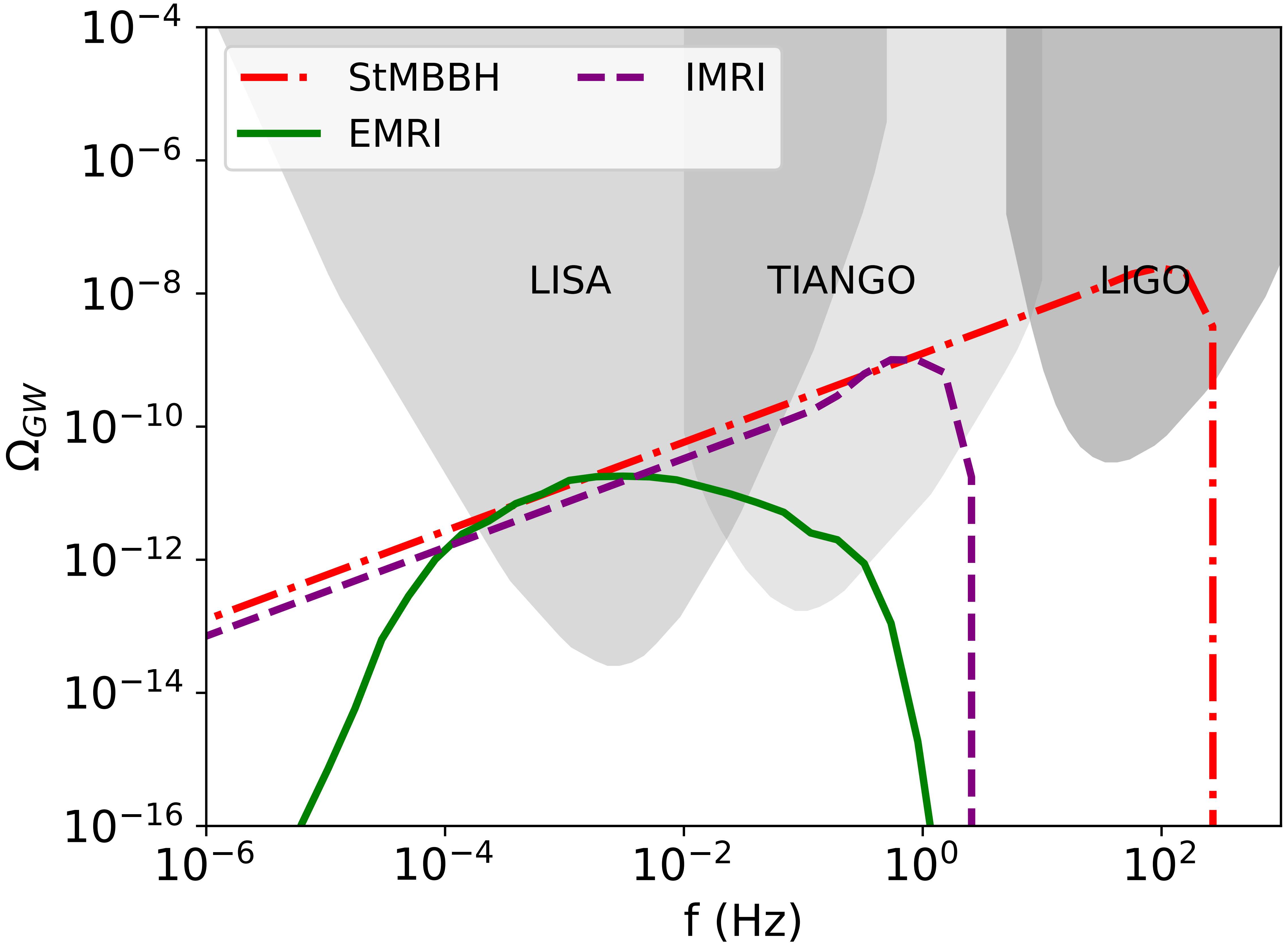
Modeling: complex, depends on many params—BH masses, eccentricity, spin;
We use available EMRI population model (e.g. Bonetti and Sesana 2020) to extract the characteristic EMRI strain $h_c(f)$, and calculate SGWB as:

$$\Omega_{\rm GW}(f) = \frac{4\pi^2 f^2}{3H_0^2} h_c(f)^2$$

— The overall merger rate is a parameter in our scan

Astrophysical Sources of SGWB

- Putting the three leading astro sources together



- StMBBH and IMRI: $\sim f^{2/3}$ till the cutoff
- EMRI: complex: $\sim f^{-1/3}$ between $3 \times 10^{-3} - 3 \times 10^{-2}\text{Hz}$

Caveats on uncertainties:

- StMBBH: best known, amplitude uncertainty O(1)
- EMRI: shape less certain, amplitude uncertainty up to 1 order of magnitude
- IMRI: shape/amplitude uncertain, power law should be between EMRI and StMBBH

★ Our assumptions are based on current best understanding, a great amount of new data will become available in the next decade to better constrain astro SGWB

Astrophysical Sources of SGWB

- The *less* important astro sources for our consideration

- **Supermassive BH mergers:** LISA can resolve all such mergers with $10^4 M_\odot - 10^7 M_\odot,\ z < 8$
  Higher redshift: number exponentially reduced, $M > 10^7 M_\odot$: rare very brief transients, more like glitches than SGWB ☞ We do not consider these in our analysis

- **White dwarf mergers:** relevant for LISA band, but the signal very weak unless occurring in the Milky Way → highly anisotropic, can be reduced by decomposing into angular harmonics (discard all but isotropic component) ☞ We assume they can be neglected

- **Slowly rotating neutron stars:** non-axisymmetric NS can produce GWs, may be marginally detectable by LIGO, limited to Milky Way, so can be reduced like for WD mergers

- **Type 1A Supernovae:** white dwarfs reaching the Chandrasekhar mass by accretion, peak around $0.5 - 1\text{Hz}$ (unique to midband), but very faint SGWB due to lack of inspiral phase (all GW energy released in 1-2 sec)—$\Omega_{GW} \sim 10^{-21}$☞ too small!

Our Analysis: Forecast Generation

- We simulate signals with astro SGWB sources + with (for evidence/discovery) and without (for constraints) a cosmo SGWB (from strings or PT), using MCMC

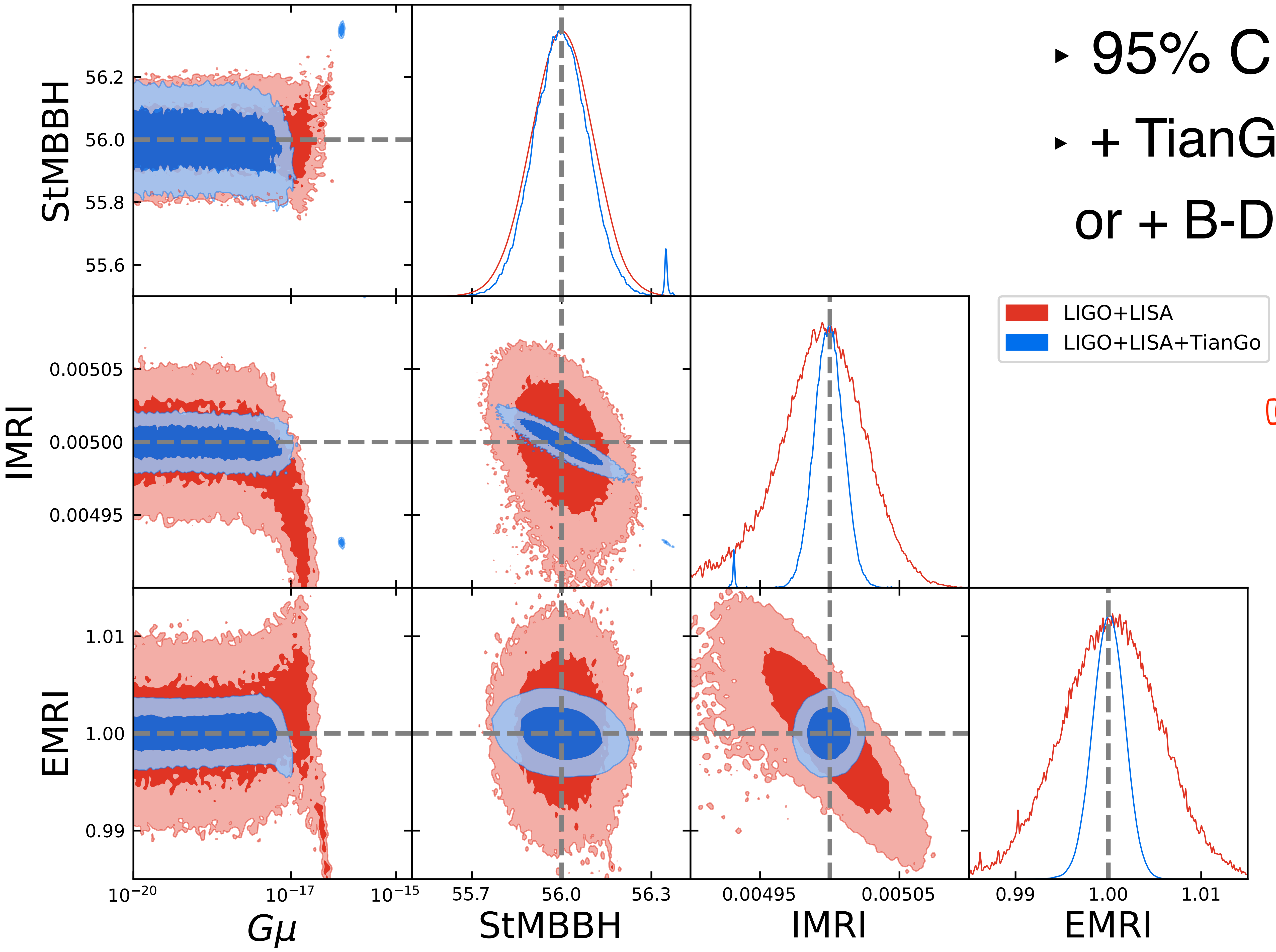
- Our likelihood function:

$$\log \mathscr{L}(p) = -\Sigma_i T_i \int df \left(\frac{M_i(f,p) - D_i(f)}{S_n^i(f)} \right)^2$$

  - Σ_i : sum over i experiments *(recall: the power of combining!)*, we compare $i = (\mathrm{LISA}, \mathrm{LIGO})$ vs. $i =$ (LISA, LIGO, + B-DECIGO or TianGo)
  - T_i: observation time duration of each experiment, $S_n^i(f)$: noise spectral density
  - $M_i(f,p)$: model prediction with parameters p
  - $D_i(f)$: mock data, with default astro model only for constraints, adding cosmo SGWB for discovery forecast

Results: Cosmic Strings

- **Constraints**: mock data with astro sources only



- 95% C.L. with LIGO+LISA only: $G\mu < 2.7 \times 10^{-17}$
- + TianGo: $G\mu < 9 \times 10^{-18}$,

  or + B-DECIGO: $G\mu < 2.5 \times 10^{-18}$

☞Up to an order of magnitude improvement in $G\mu$ sensitivity!

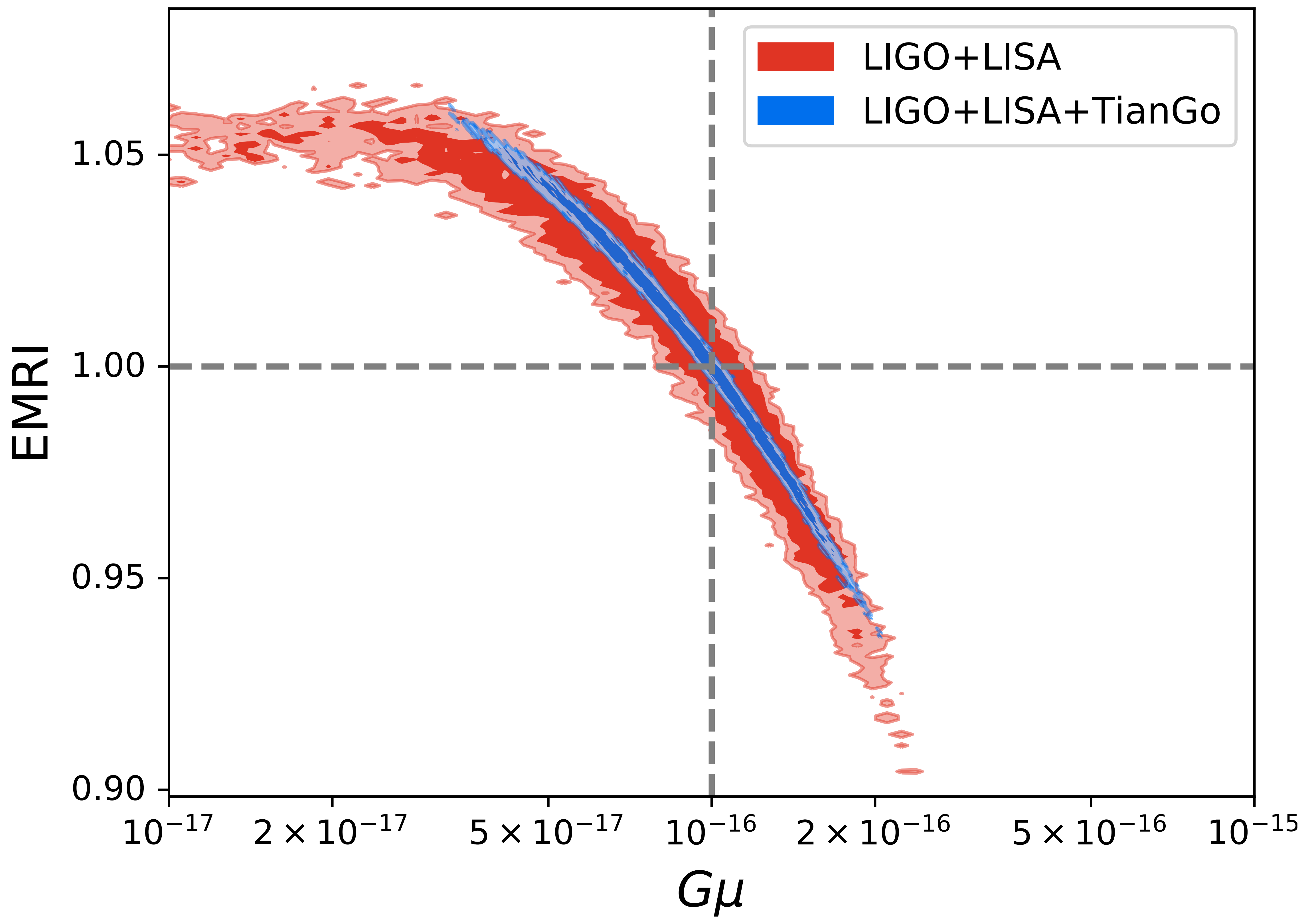
- cosmic string signal flat in $10^{-3} - 1\text{Hz}$, so LISA dominates signal sensitivity

- With midband improvement primarily driven by better constraints on EMRI and IMRI

(StMBBH already well constrained by LIGO)

Results: Cosmic Strings

- **Discovery**: mock data adding cosmo source with $G\mu = 10^{-16}$ (near LISA threshold)



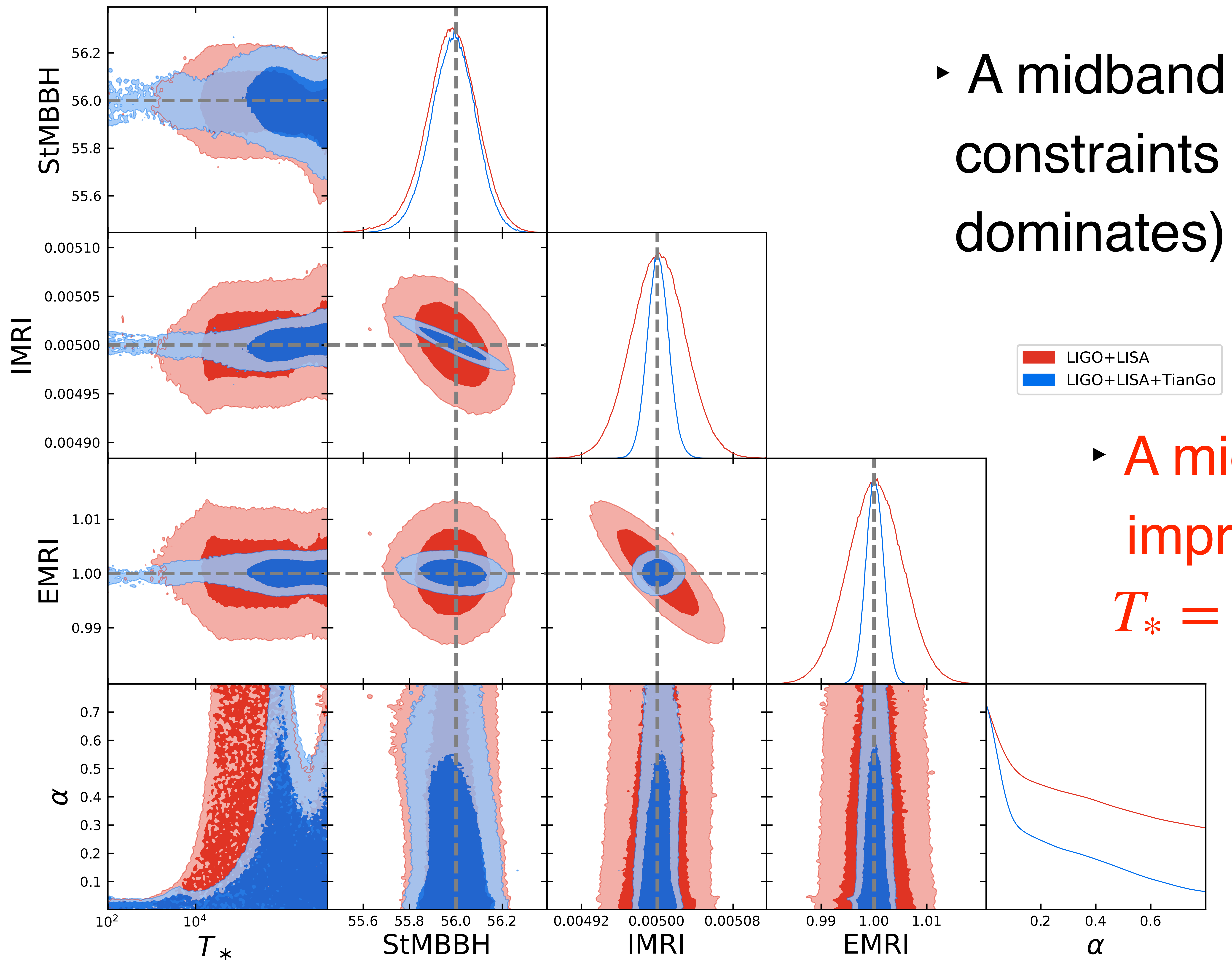
- Strong curving degeneracy between string signal and EMRI
- LISA alone not able to correctly separate cosmo vs. astro SGWB
- Extra info from midband: greatly improves separation

+TianGo: $G\mu = 4\times10^{-17} - 1.7\times10^{-16}$

+ B-DECIGO: $G\mu = 6\times10^{-17} - 1.65\times10^{-16}$

Results: Phase Transitions

- **Constraints**: mock data with astro sources only



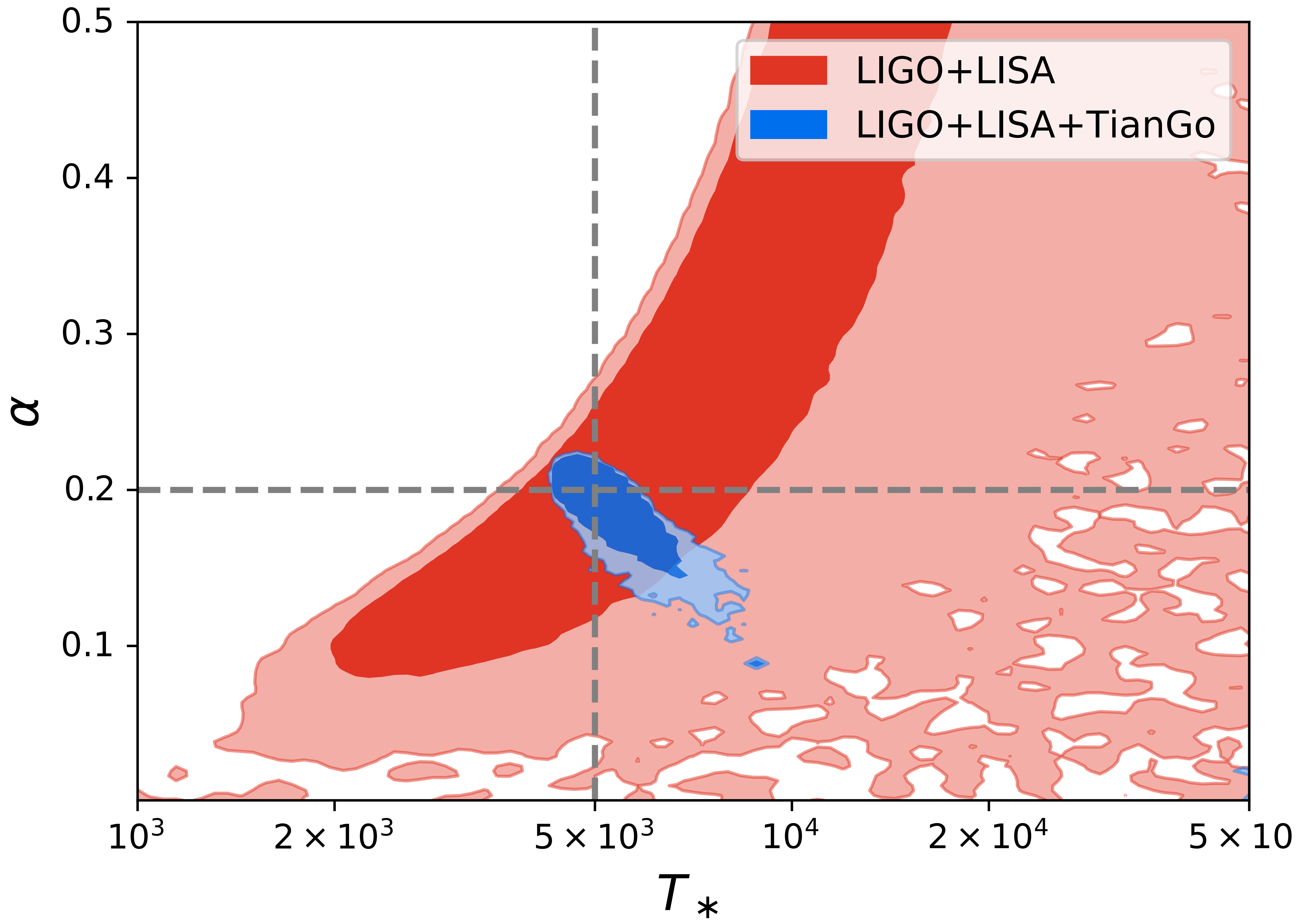
- A midband experiment does not improve constraints for PT with $T_* > 10^6\mathrm{GeV}$ (LIGO dominates) or $T_* < 10^4\mathrm{GeV}$ (LISA dominates)

- A midband experiment substantially improves constraints for PT with $T_* = 10^4 - 10^6\mathrm{GeV}$

- The reason: the f peak in SGWB spectrum from PT ⟷ T_*

Results: Phase Transitions

- **Discovery**: mock data adding cosmo source with $T_* = 3 \times 10^3 \mathrm{GeV},\ \alpha = 0.2$



- With LISA+LIGO only: can only constrain $T_* > 10^3 \mathrm{GeV}, \alpha > 0.1$
- Extra coverage from midband data: $T_* = 4.7 \times 10^3 - 10^4 \mathrm{GeV},\ \alpha = 0.1 - 0.22$

☞Signal parameters much better localized with midband data!

- LISA may capture the signal but do not have enough information in f band to characterize the shape…

Conclusion/Outlook

- To discover BSM with GWs (exiting new frontier!), we need to confront the potential challenges from astro sources with creative, dedicated approaches

- We forecast how a midband GW experiment (e.g. TianGo, B-DECIGO, AEDGE) can impact the detection of cosmo SGWB → potentially substantial improvements

- We propose CPLS curve: up to 2 orders of magnitude improvement in inclusive $\Omega_{\rm GW}$

- Likelihood analysis for benchmark cosmological SGWB (cosmic strings, PT) vs. astro SGWB (explicit modeling of leading sources) → strings: $G\mu$ improvement up to ~ 10; PT: covers $T_* \sim 10^4 - 10^6 {\rm GeV}$, facilitates shape info for $T_* \sim {\rm TeV}$

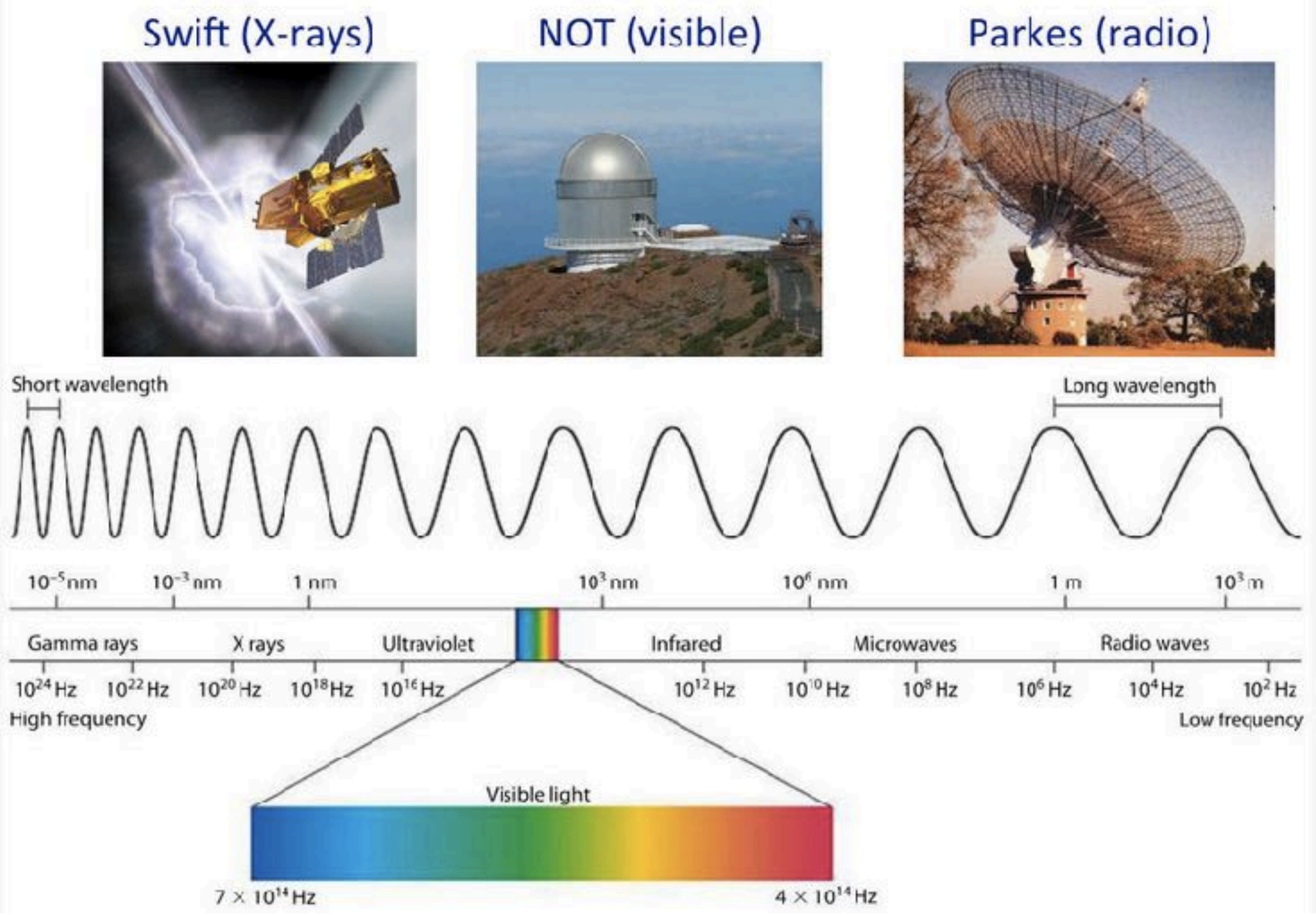
- Our study helps to propel the science case of a midband GW experiment (from cosmology/HEP motivations) + Showcase the advantages for probing BSM physics with a well-coordinated multi-band GW program *(an exciting new era!)*

The Multi-band GW Astronomy/Cosmology

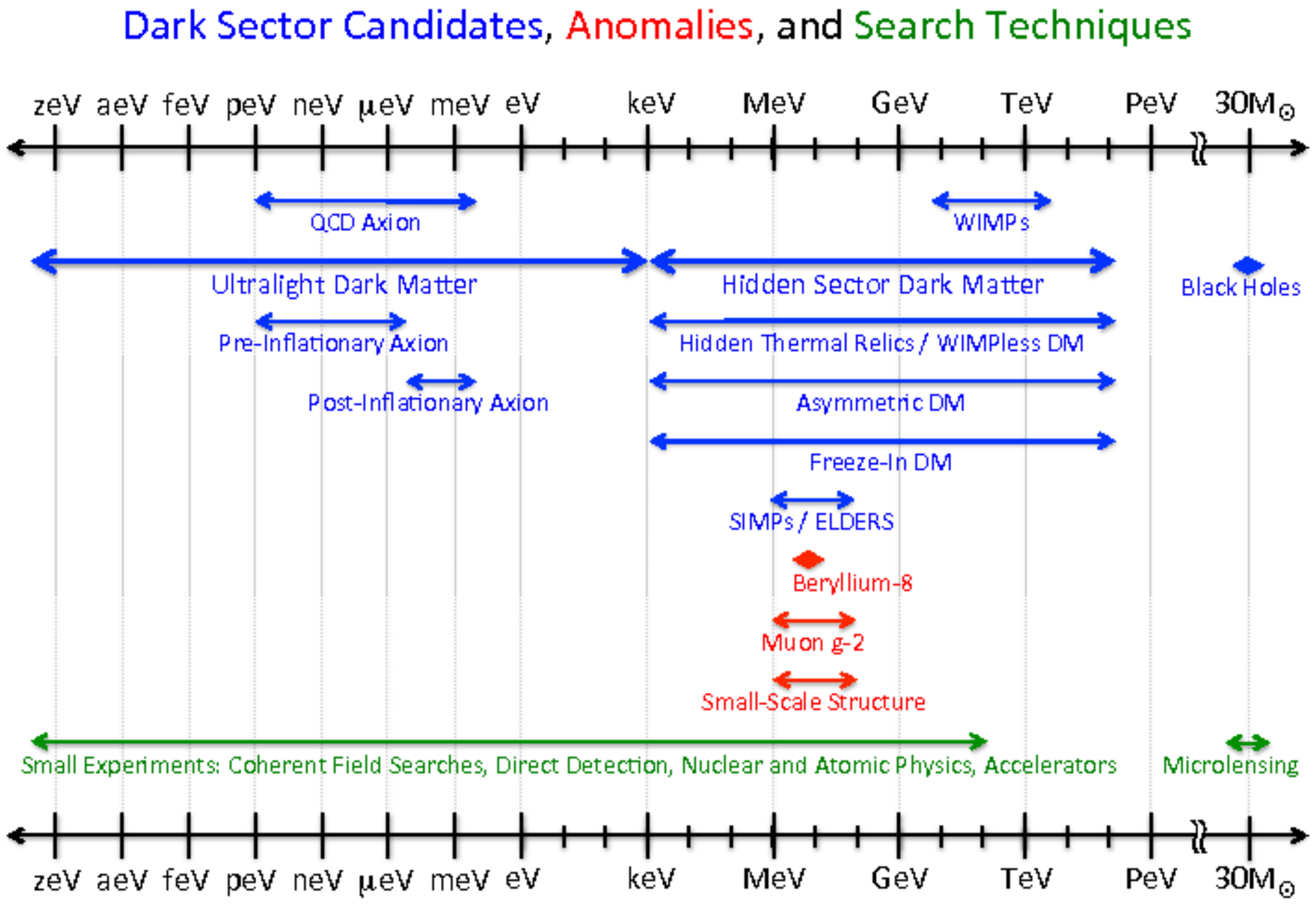
- The Exciting Future

- Intriguing/inspiring analogies:

Observatories for EM radiation



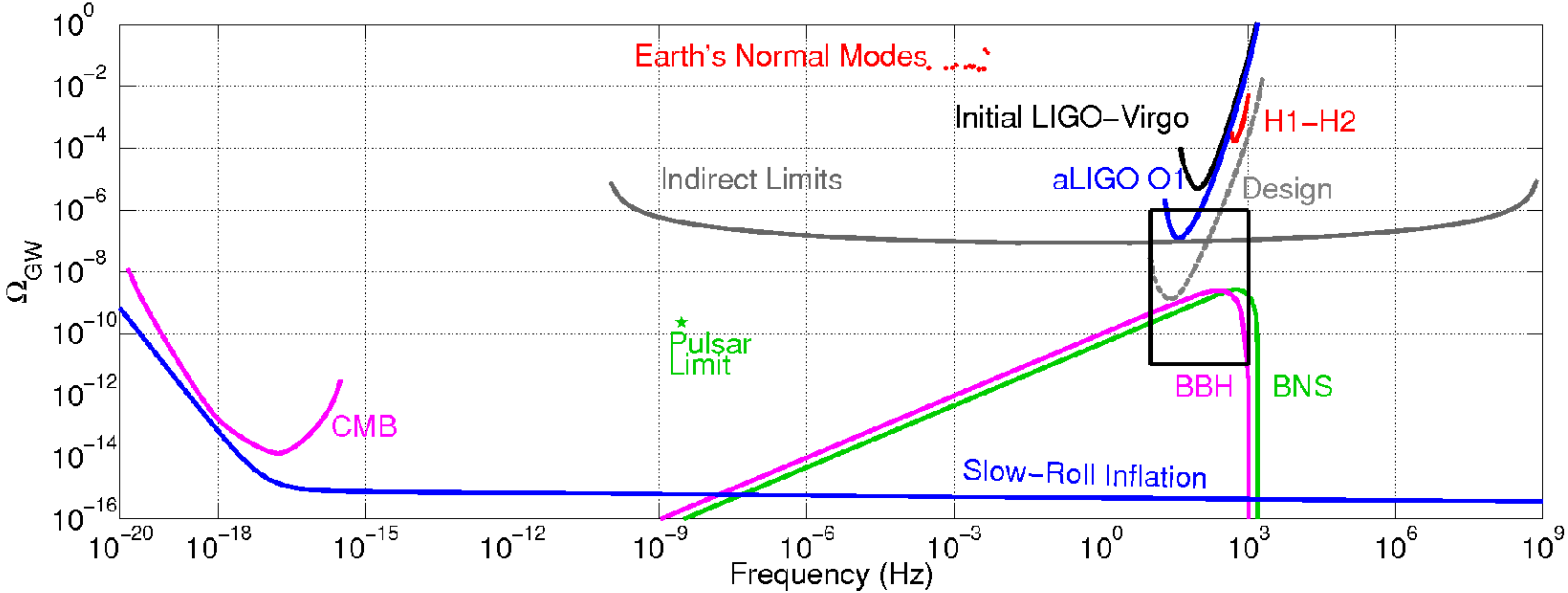
DM searches over wide mass ranges



- Multi-band GW program: will take decades to build, but ample opportunities for discovery, rewarding!

Thank you!

Backup Slides



Earth's Normal Modes
Initial LIGO−Virgo
H1−H2
Indirect Limits
aLIGO O1
Design
Pulsar
Limit
BBH
BNS
CMB
Slow−Roll Inflation
Ω_{GW}
Frequency (Hz)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-20}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}