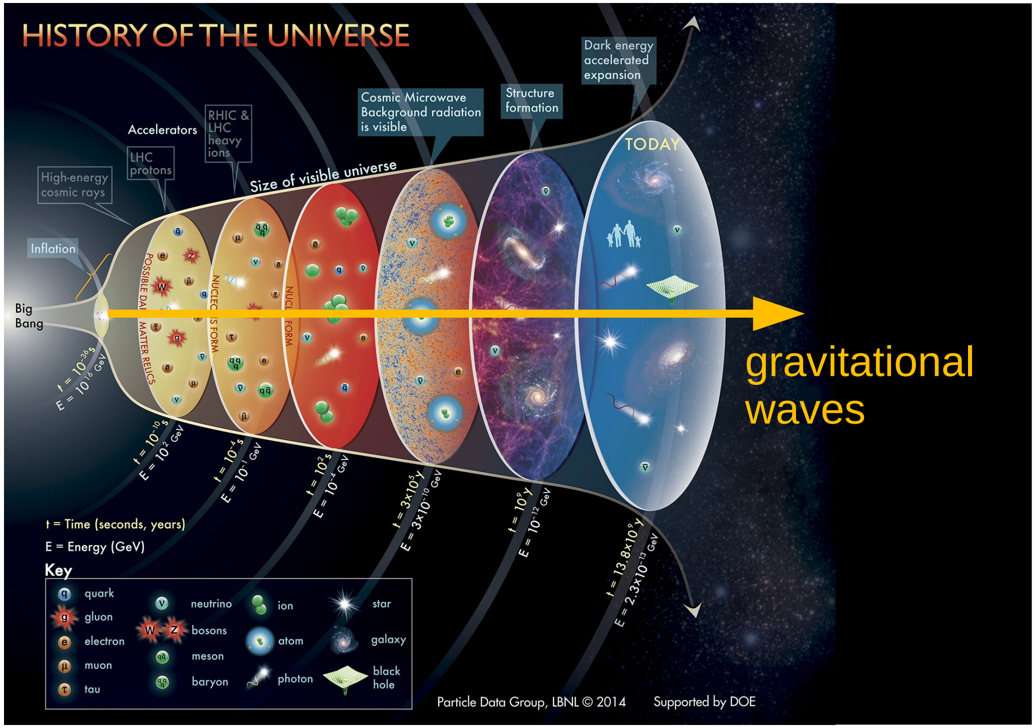
Gravitational wave searches:

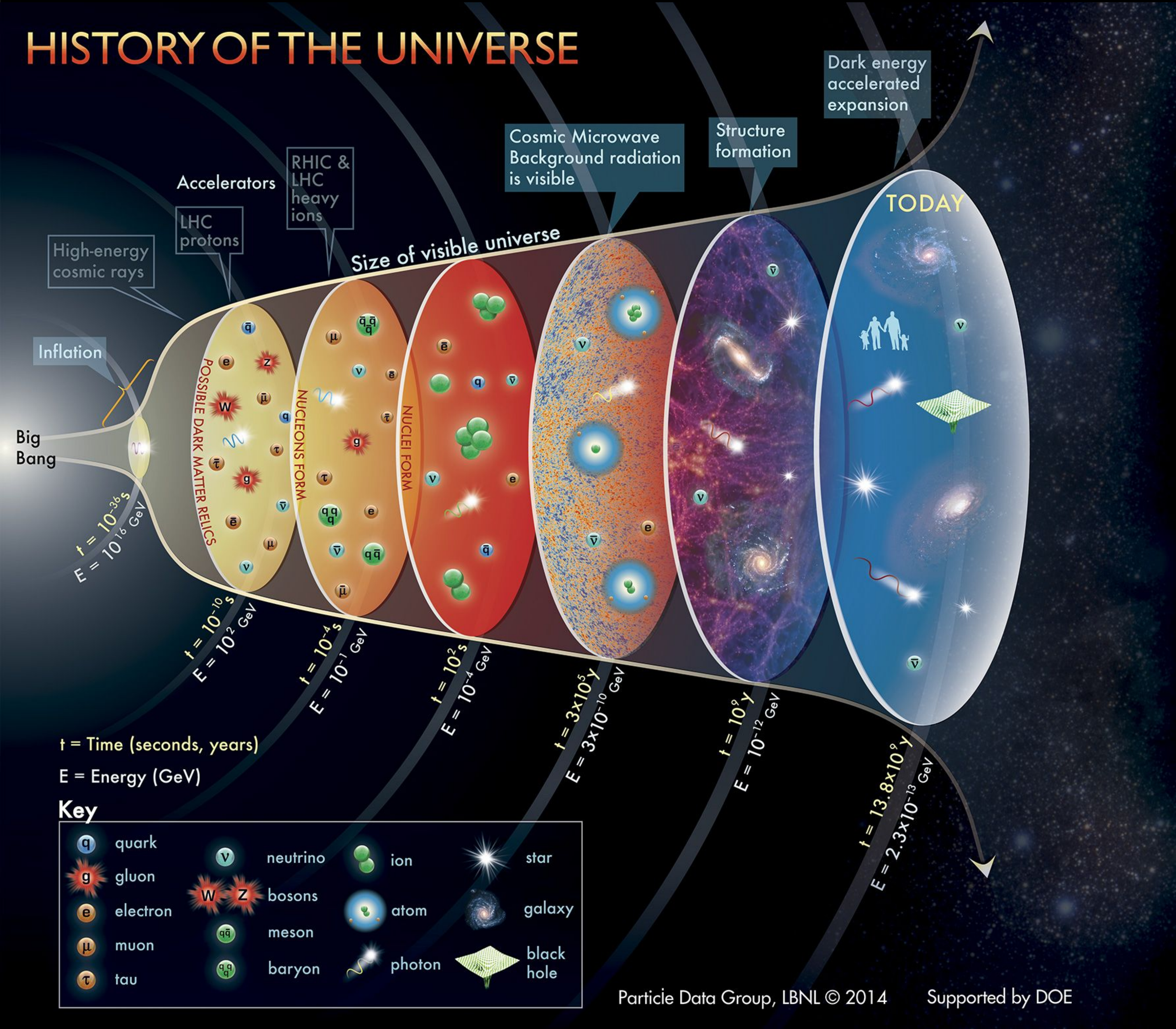
milestones and challenges

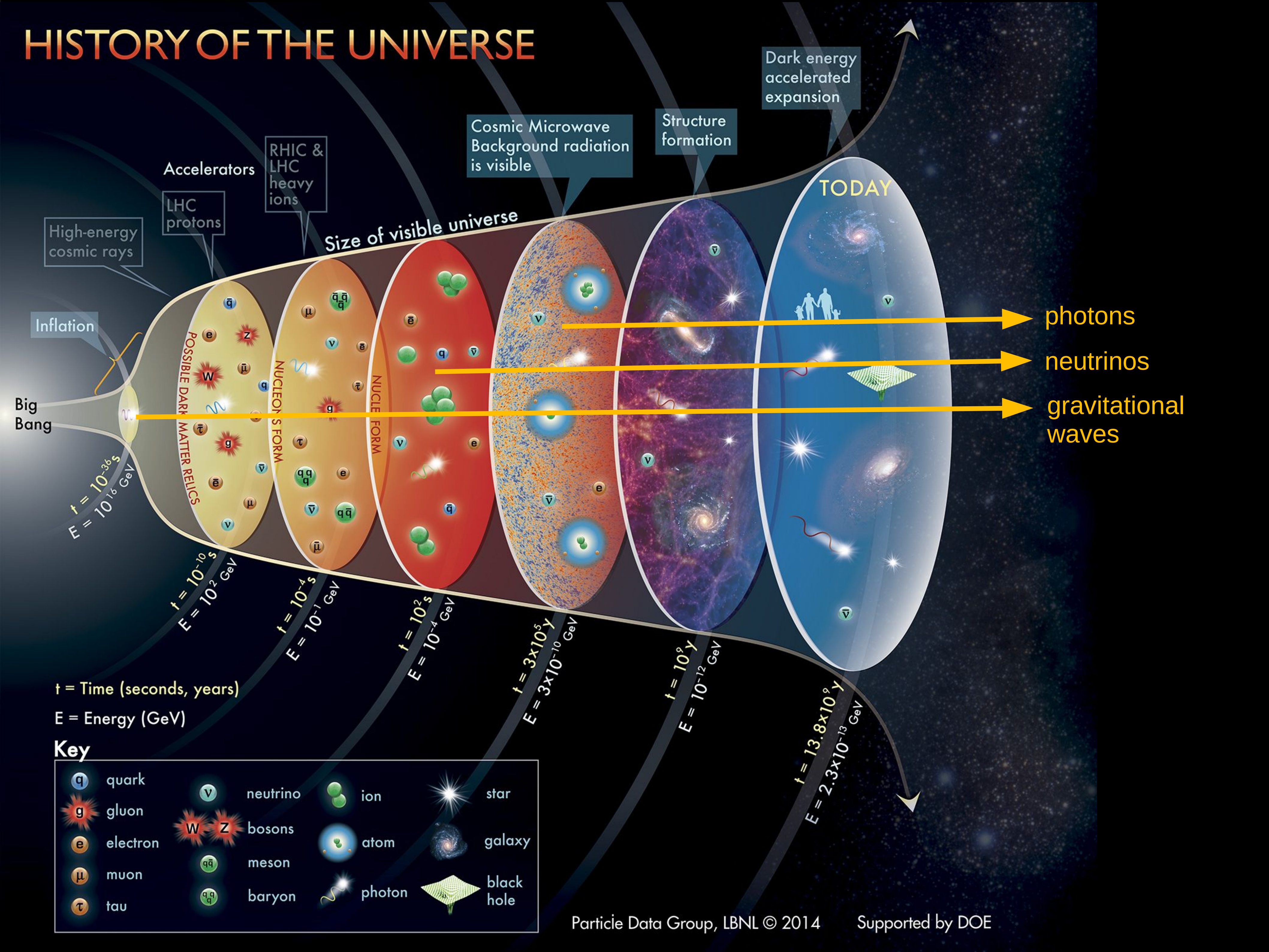


Valerie Domcke
CERN

Planck 2025
Padua, Italy

May 30, 2025


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE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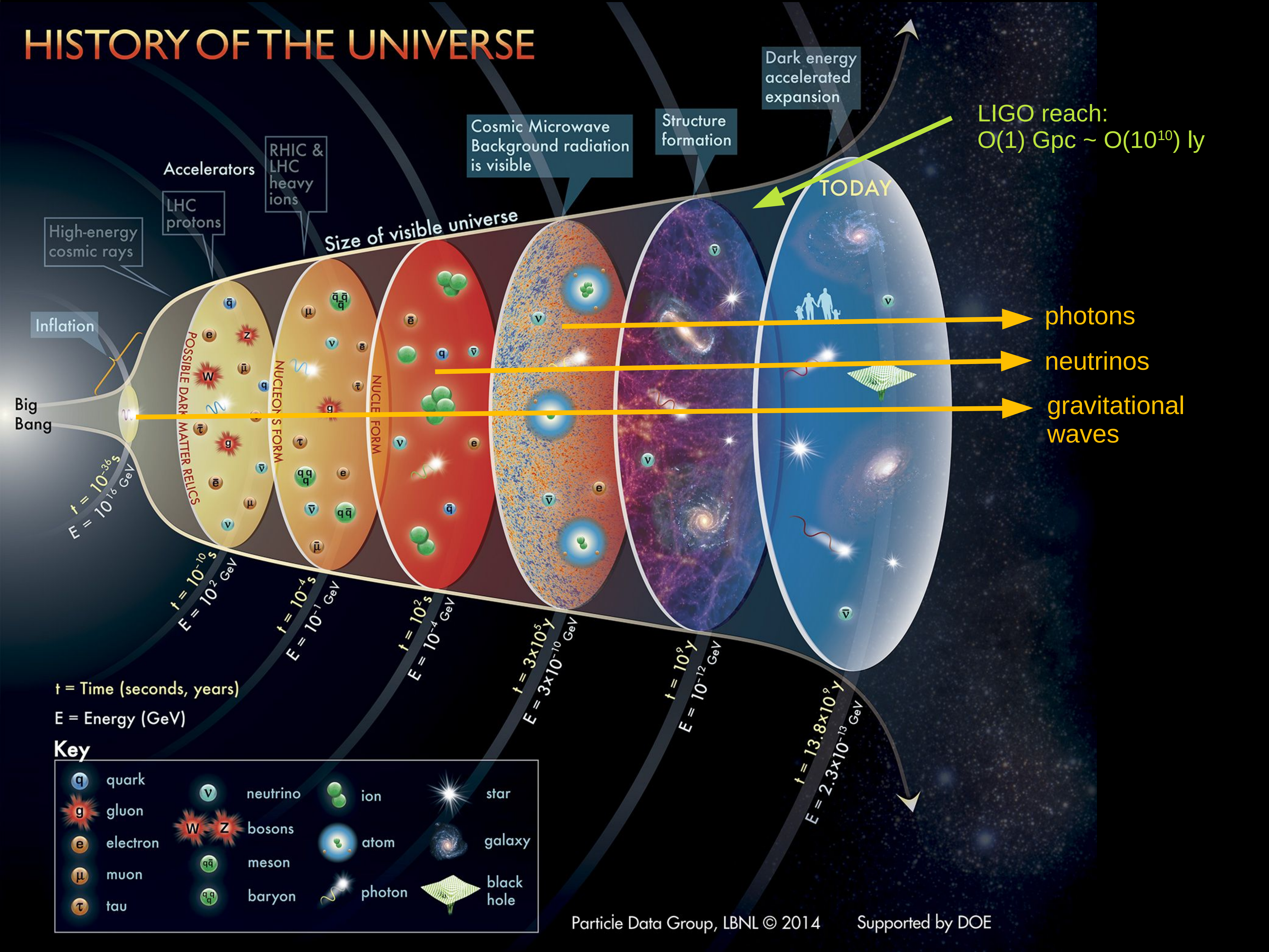
photons
neutrinos
gravitational waves


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
LIGO reach:
O(1) Gpc ~ O(10^10) ly
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
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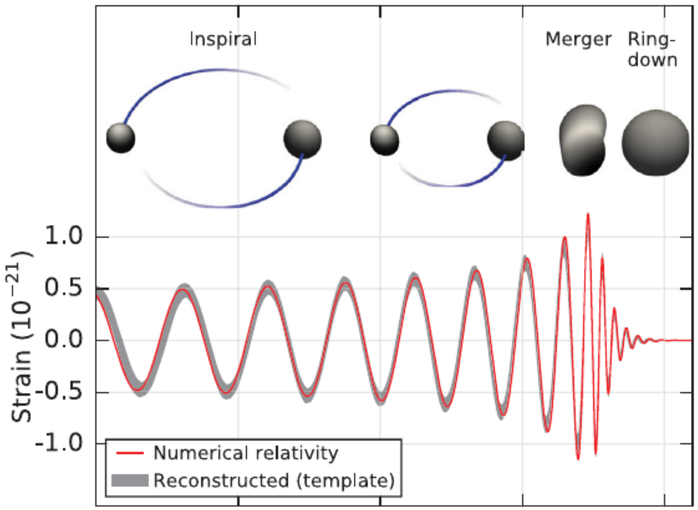
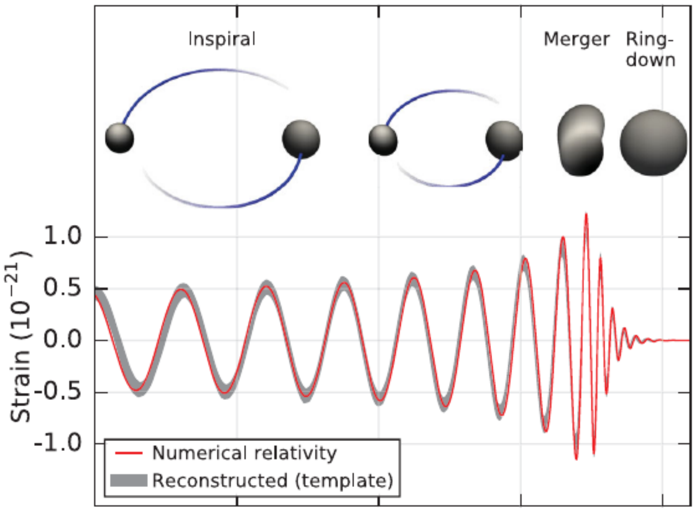
transient and stochastic signals



LIGO Livingston, USA

2015: first direct observation of GWs, collision of two black holes a billion years ago

transient and stochastic signals



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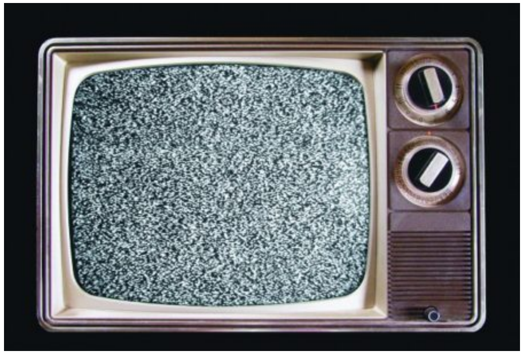
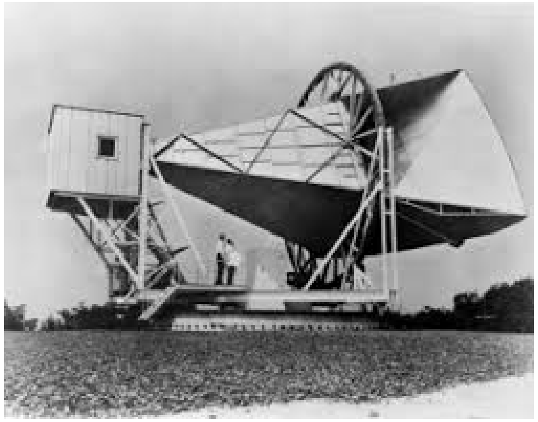


stochastic gravitational wave background

analagous to CMB

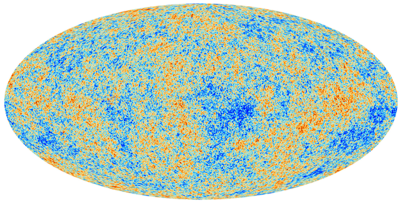


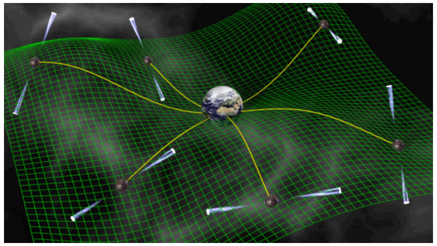
Penzias, Wilson `64

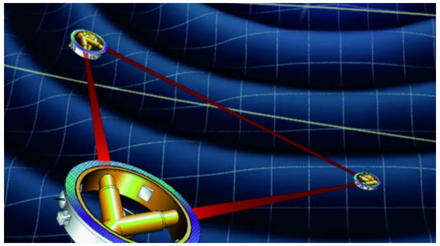
astrophyscial and cosmological contributions

possible detection by PTAs

The GW sky







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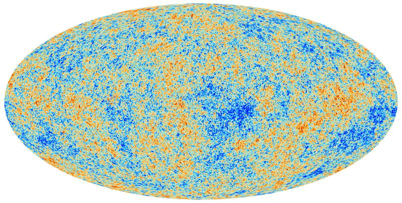
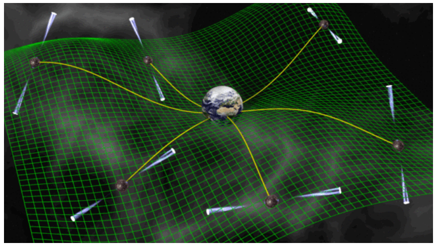
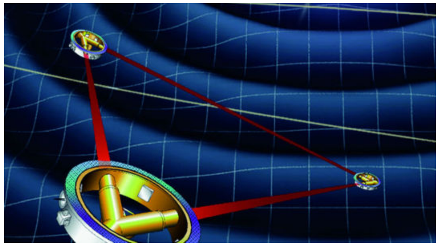
CMB B-modes			
BICEP/KEK,.. Lightbird			
$r < 0.04$			
$\Omega_g h^2 < 10^{-16} (f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz			

nHz mHz kHz

frequency

The GW sky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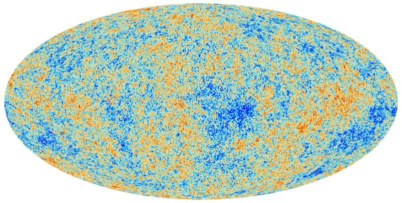
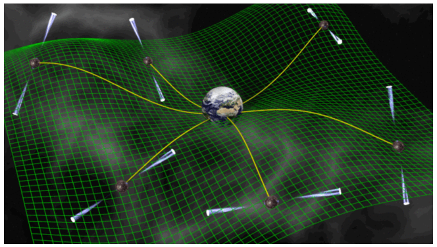
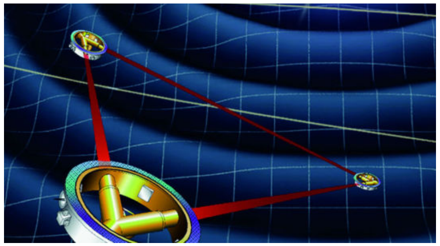
CMB B-modes	Pulsar timing arrays
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA
$r < 0.04$	evidence for GW signal, HD correlation
$\Omega_g h^2 < 10^{-16} (f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz	$\Omega_g h^2 \sim 10^{-9}$

nHz mHz kHz

frequency

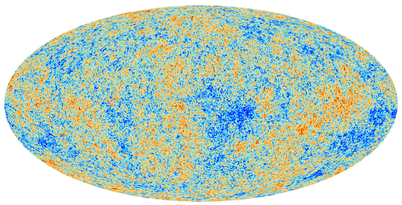
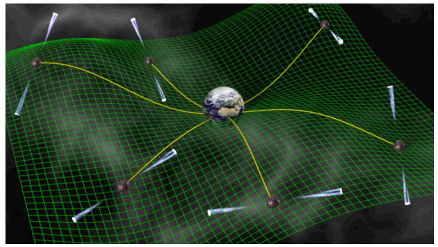
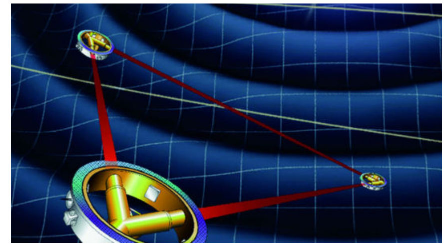
    ?

CMB B-modes	Pulsar timing arrays	Space interfometers
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA	LISA
$r < 0.04$	evidence for GW signal, HD correlation	ESA/NASA mission launch ~ 2030s
$\Omega_g h^2 < 10^{-16} (f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz	$\Omega_g h^2 \sim 10^{-9}$	exp. sensitivity: $\Omega_g h^2 \sim 10^{-13}$

nHz mHz kHz

frequency

The GW sky

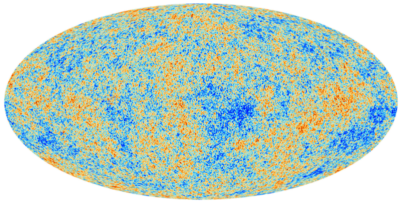
    ?

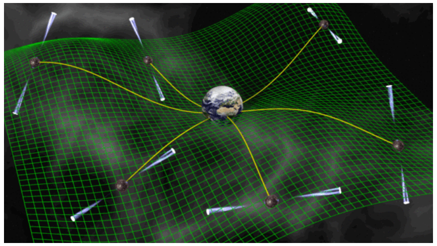
CMB B-modes	Pulsar timing arrays	Space interfometers	Ground-based interferometers
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA	LISA	LIGO/Virgo/Kagra ET / Cosmic Explorer
$r < 0.04$	evidence for GW signal, HD correlation	ESA/NASA mission launch ~ 2030s	GW detection, O(100) CO mergers
$\Omega_g h^2 < 10^{-16} (f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz	$\Omega_g h^2 \sim 10^{-9}$	exp. sensitivity: $\Omega_g h^2 \sim 10^{-13}$	$\Omega_g h^2 \lesssim 10^{-9}$

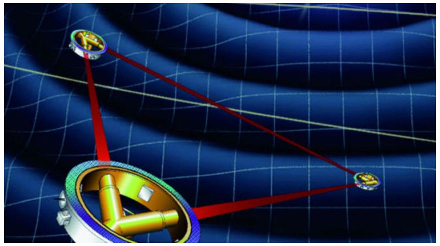
nHz mHz kHz

frequency

Testing fundamental physics with GWs







?

Cosmic inflation

New physics impacting star formation and evolution

Precision tests of GR, test of cosmological standard model

Unknown unknowns ...

1st order QCD phase transition?

1st order electro-weak phase transition?

Phase transitions above 100 GeV

Topological defects (cosmic strings) from GUT scale phase transitions?

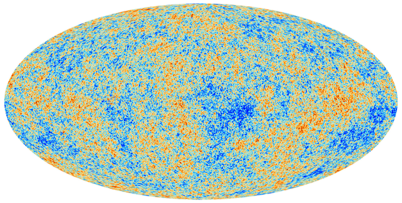
nHz

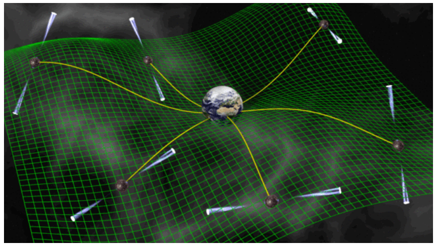
mHz

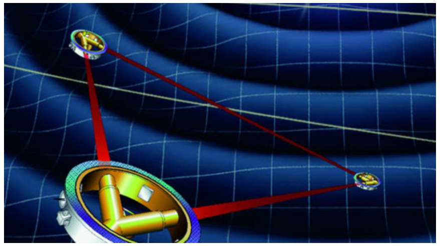
kHz

frequency

The GW sky – challenges and open questions







?

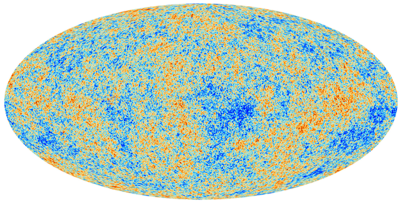
Foregrounds, lensing

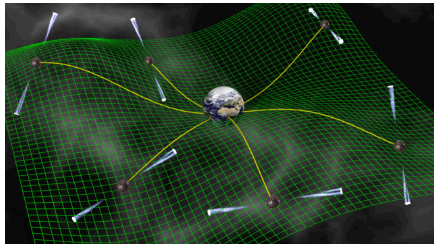
goal: reach $r \sim 10^{-3}$ (Starobinsky inflation)

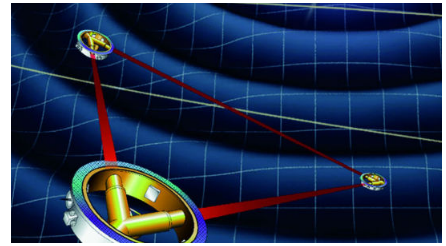
nHz mHz kHz

frequency

The GW sky – challenges and open questions







?

Foregrounds, lensing

goal: reach $r \sim 10^{-3}$ (Starobinsky inflation)

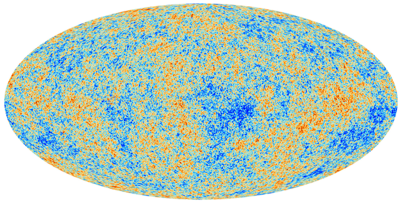
Confirm HD signature.
Single source or SGWB?
Spectral shape?
Origin?

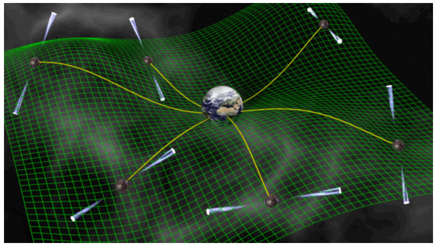
some answers expected in the next few years

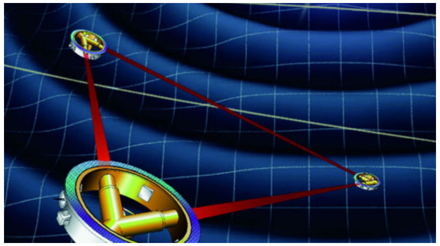
nHz mHz kHz

frequency

The GW sky – challenges and open questions







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Foregrounds, lensing

goal: reach r ~ 10^{-3} (Starobinsky inflation)

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Spectral shape?

Origin?

some answers expected in the next few years

Data analysis challenge:

signal dominated (many overlapping signals)

→ „global fit“ program

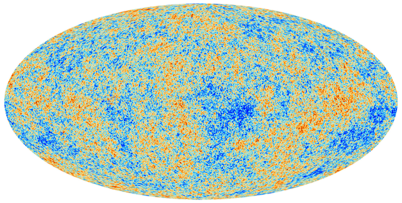
High requirements for accuracy of waveforms.

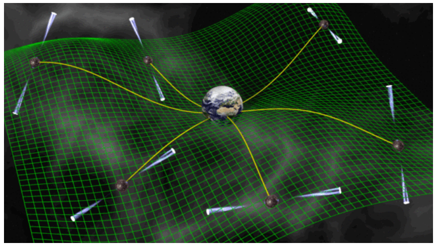
EMRIs.

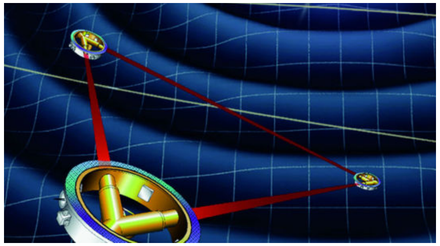
nHz mHz kHz

frequency

The GW sky – challenges and open questions







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Foregrounds, lensing

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Data analysis challenge:
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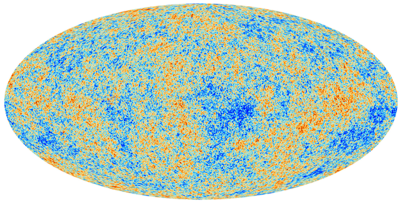
EMRIs.

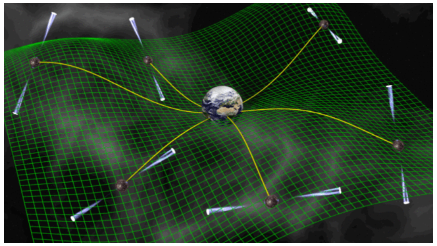
Noise dominated
→ signal dominated

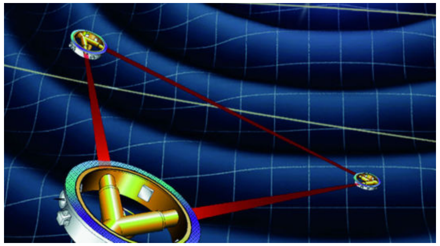
nHz mHz kHz

frequency

The GW sky – challenges and open questions







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Foregrounds,
lensing

goal: reach
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Confirm HD signature.
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Data analysis challenge:
signal dominated (many overlapping signals)
→ „global fit“ program

High requirements for accuracy of waveforms.

EMRIs.

Noise dominated
→ signal dominated

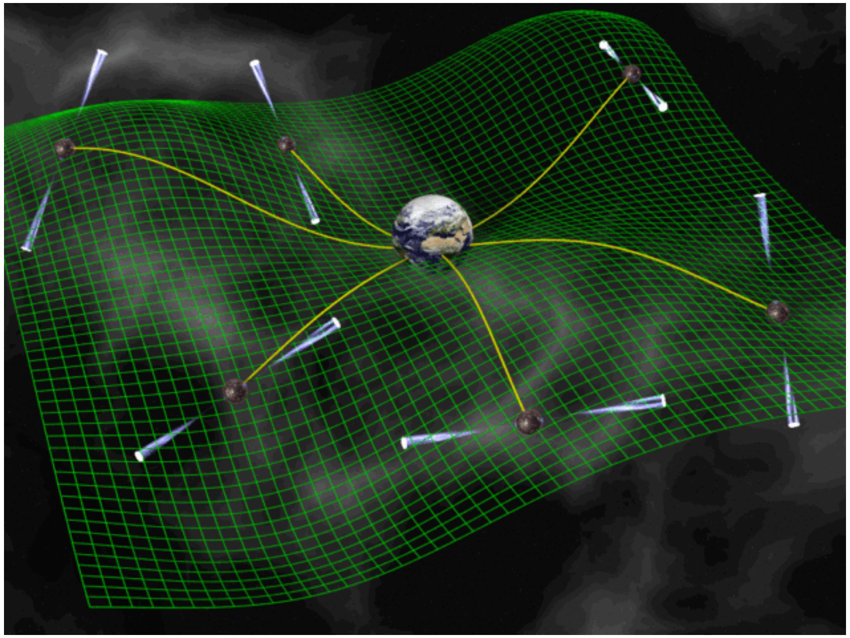
Investigation of
detector concepts.

nHz mHz kHz

frequency

Pulsar timing arrays

- search for delays in pulse arrivals: EPTA, NanoGrav, PPTA, InPTA, CPTA, Meerkat
- 2020: evidence for common stochastic noise component across all pulsars
- 2023: evidence for Hellings-Down correlation (i.e. gravitational waves)



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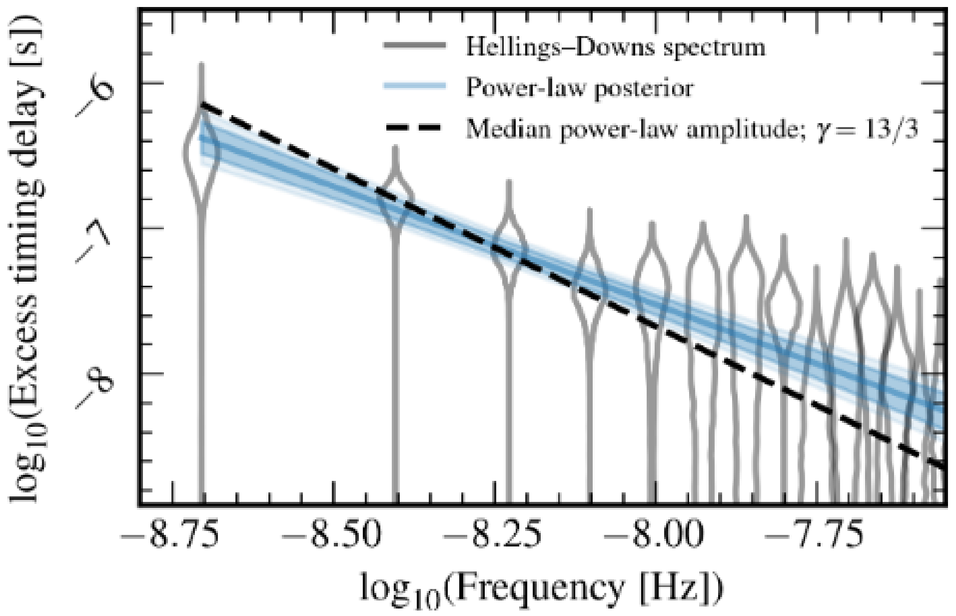

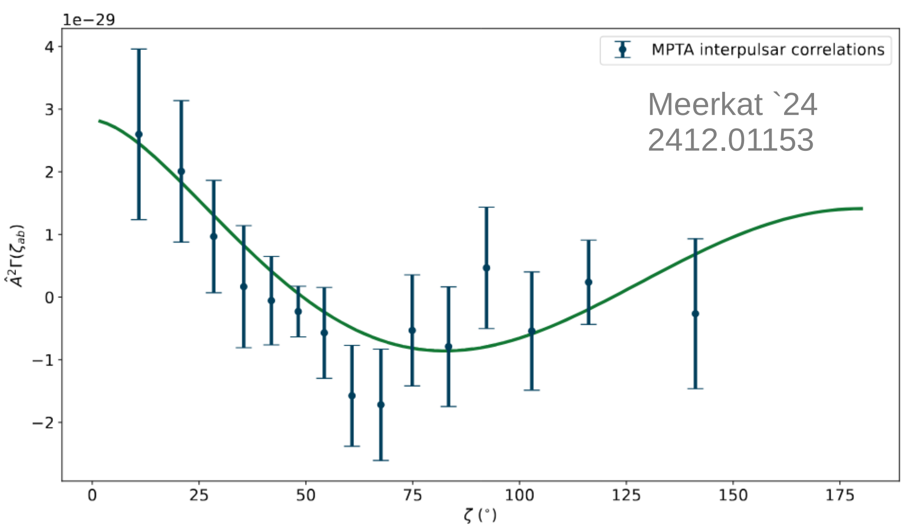

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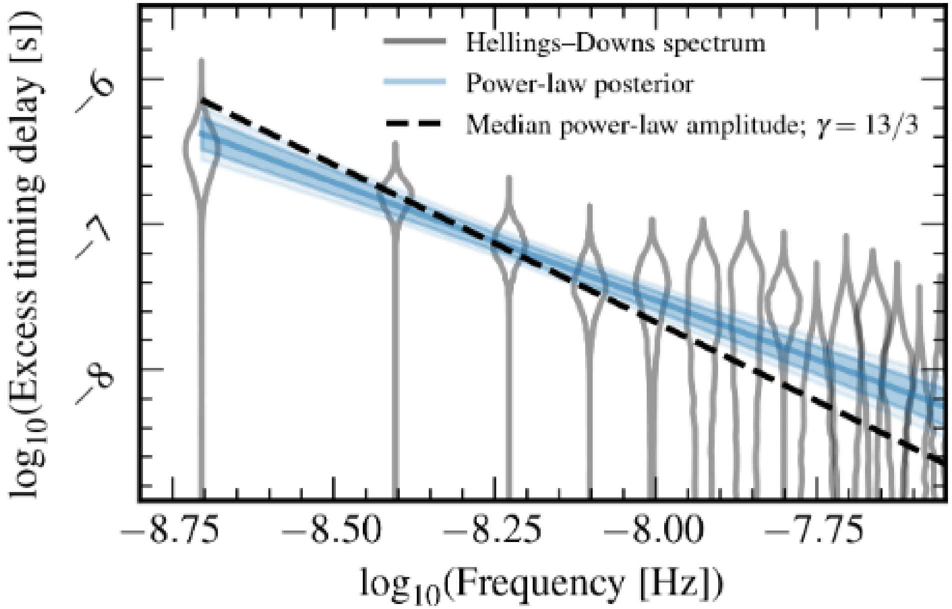
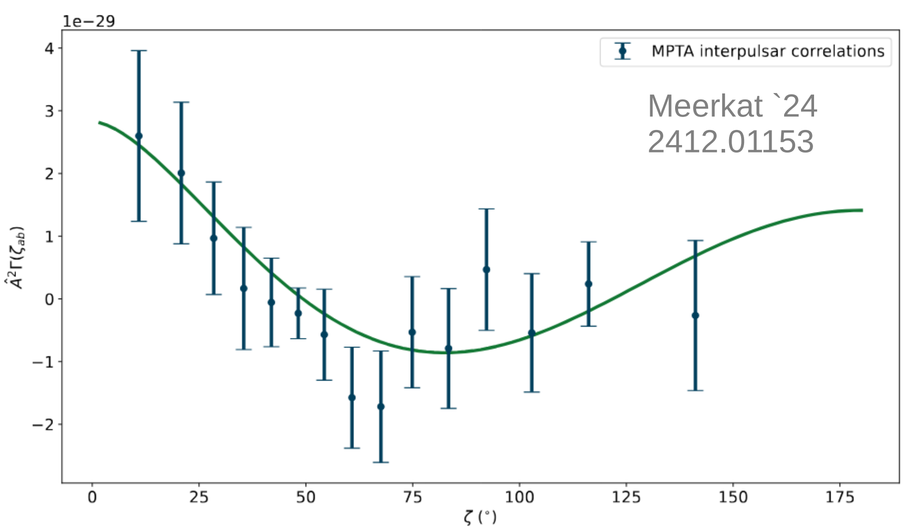
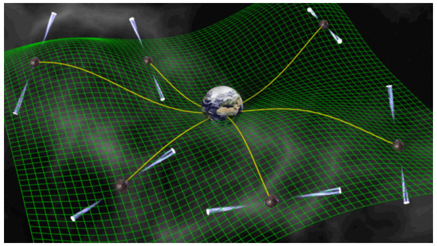




- likely origin: supermassive BH binaries
- SGWB or individual source?
- cosmological or astrophysical?

Measuring anisotropies with PTAs



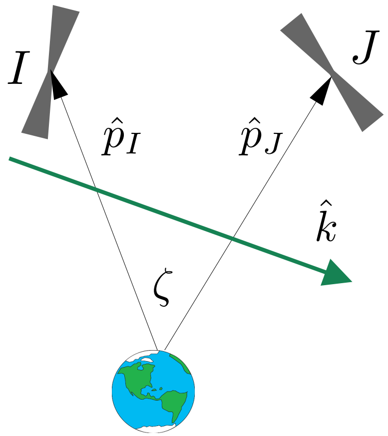
Stochastic gravitational wave background (SGWB)

$$\langle \tilde{h}_P(f,\hat{k})\tilde{h}^*_{P'}(f',\hat{k}')\rangle = \frac{1}{4} S_h(f) P(\hat{k}) \delta(f-f')\delta_{PP'}\delta^2(\hat{k},\hat{k}')$$

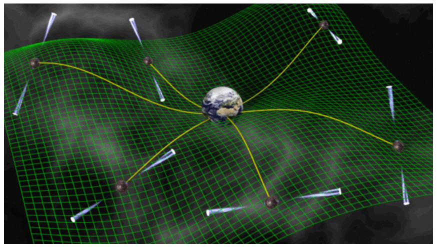
$$\langle \Delta t_I \Delta t_J \rangle = \int_{-\infty}^{\infty} \mathrm{d}f \frac{S_h(f)}{24\pi^2 f^2} \frac{3}{2}\sum_P \int d^2\hat{k}\, F^P_{\hat{p}_I}(\hat{k}) F^P_{\hat{p}_J}(\hat{k})\, P(\hat{k})$$

instrument response
anisotropic GW background

[Mingarelli et al `13 (th), NANOGrav `23 (exp)]



Measuring anisotropies with PTAs



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instrument response
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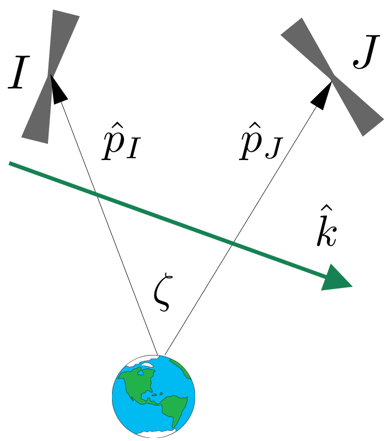
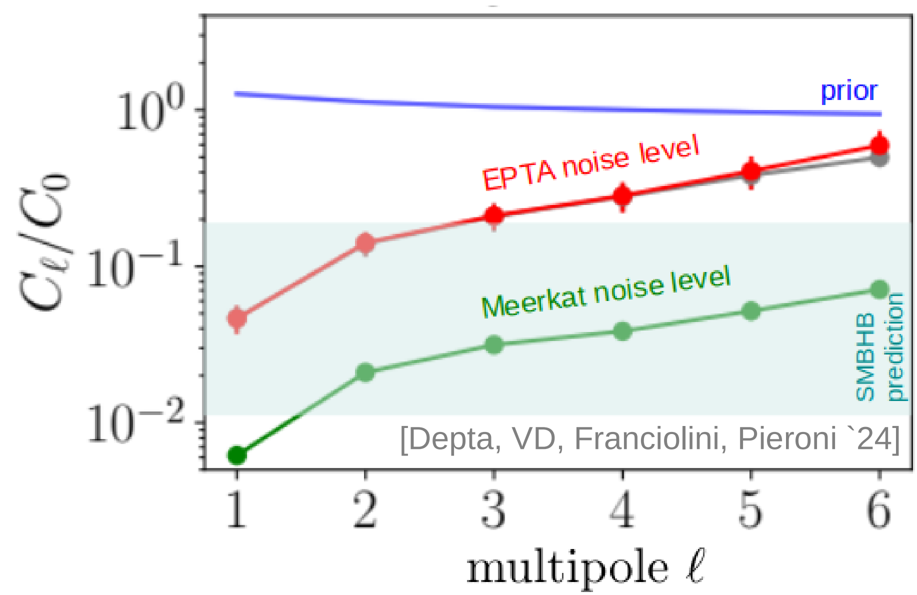
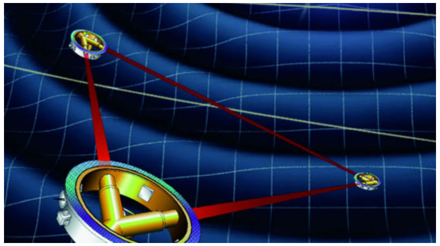


Upcoming PTA data: distinguish cosmological vs astroph. source

projection for 140 pulsars

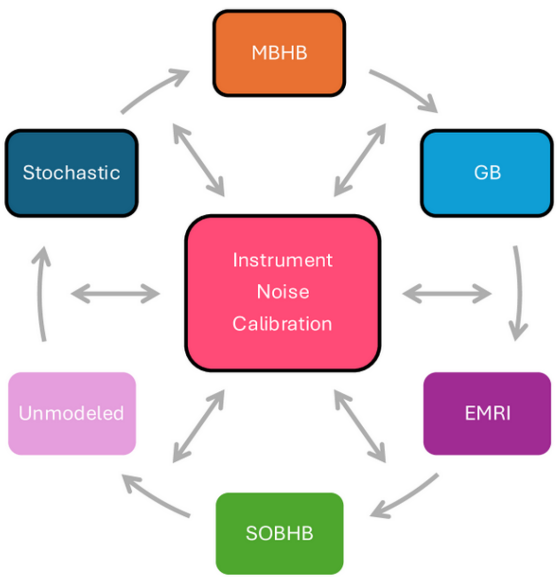


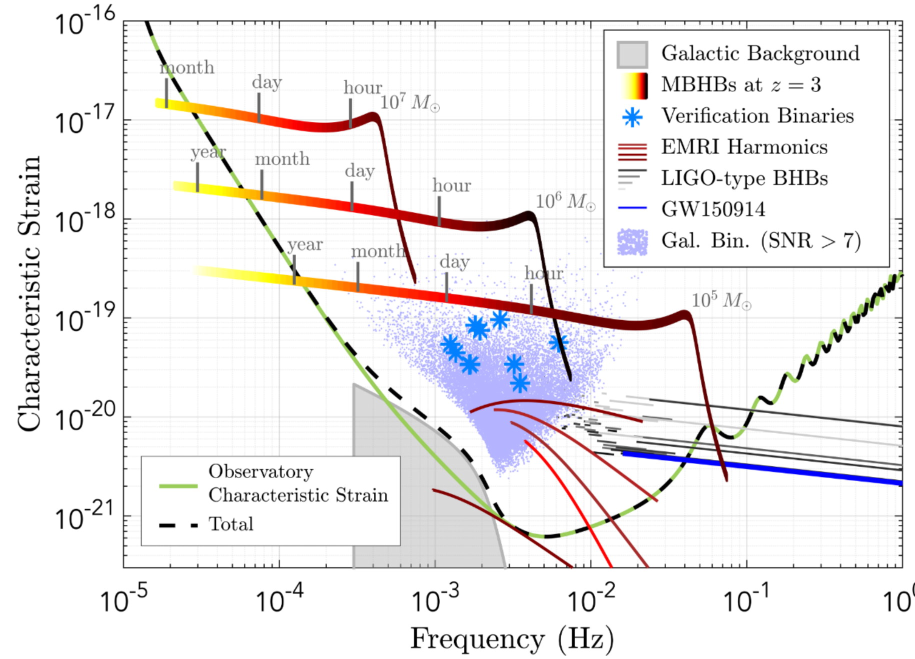
Laser interferometer space antenna (LISA)



Overlapping signals
→ LISA Global Fit

Littenberg, Cornish et al `20..`23
Strub et al `24
Katz et al `24





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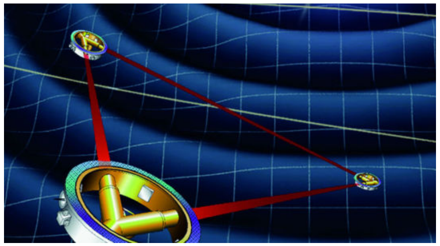

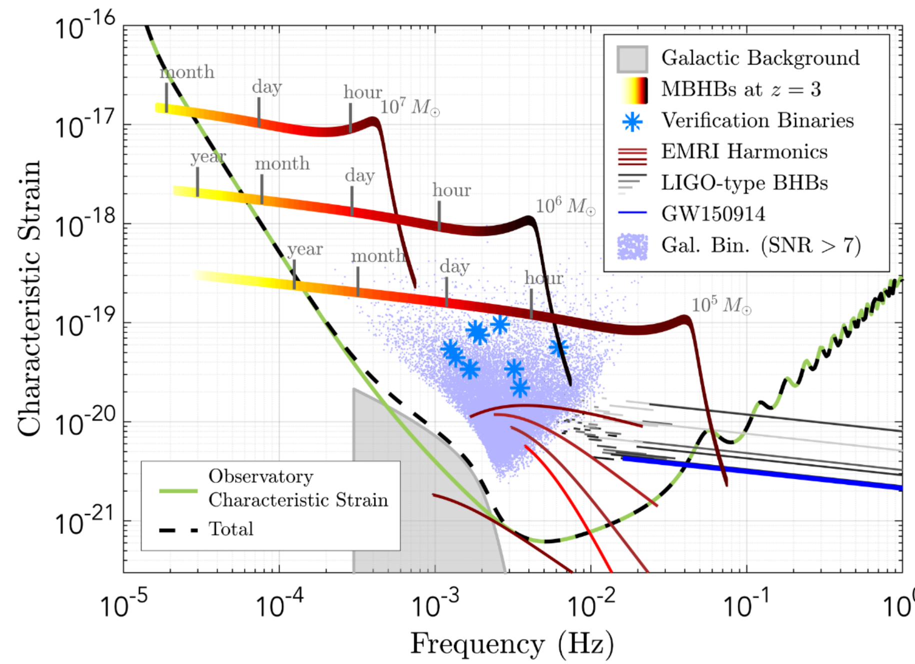

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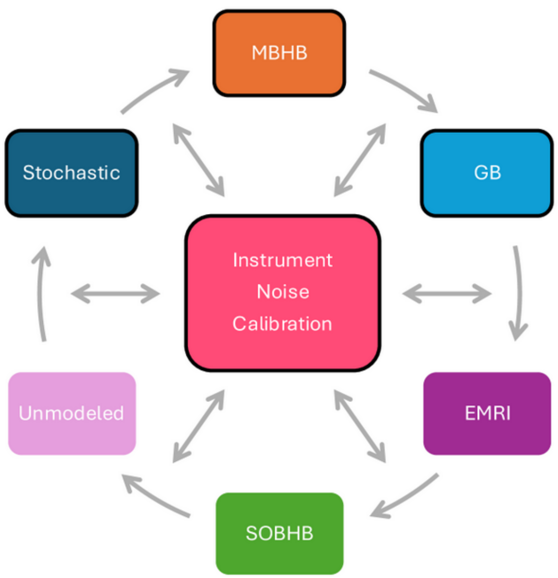


Exploring new techniques: Simulation Based Inference (SBI) :

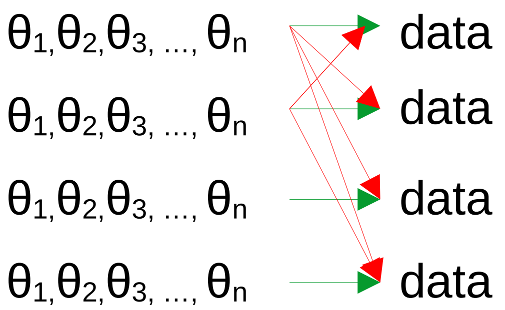
- Forward simulation is fast
- Marginalization over nuisance parameters
- Likelihood-free (life is not Gaussian)

For SGWBs:
Alvey, Bhardwaj, VD, Pieroni, Weniger `23 + `24
Dimitriou, Figueroa, Zaldivar `23

SBI for LISA data analysis

Marginalization

- Many(!) nuisance parameters, e.g. unresolved sources
  Alvey, Bhardwaj, VD, Pieroni, Weniger `23
- Train network directly on relevant parameters



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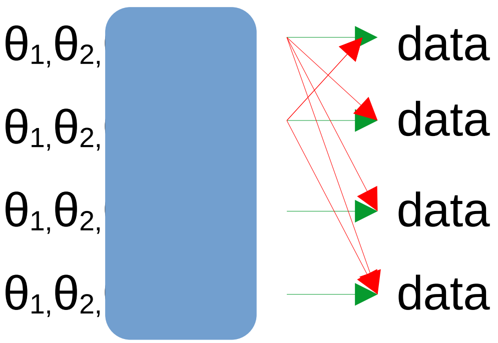

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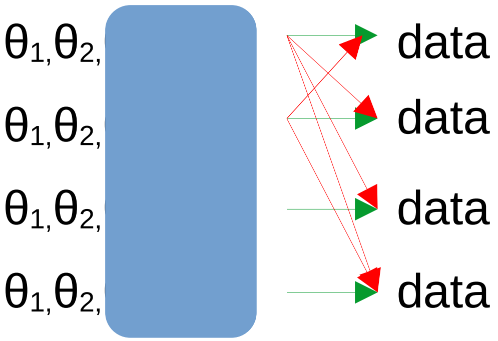
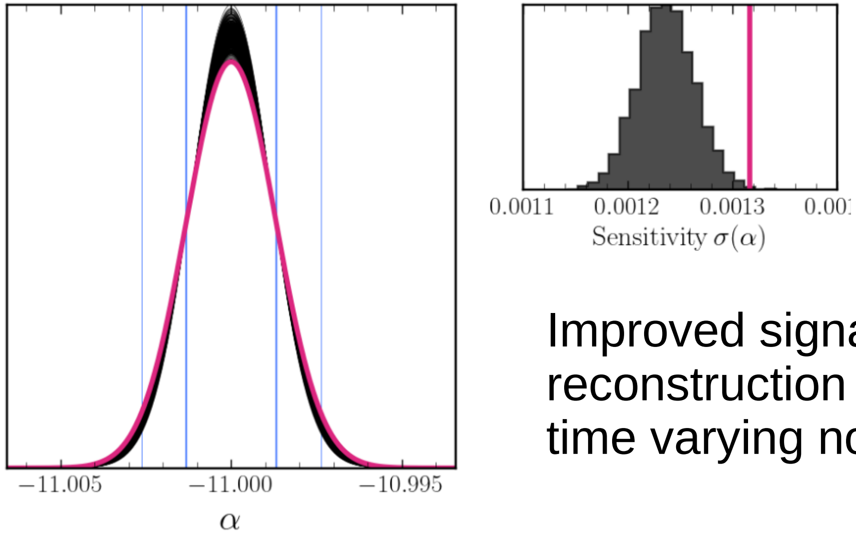


Likelihood-free
Life is not Gaussian

- Marginalization
- Limited statistics: pop-corn noise, low-frequency bins, ...



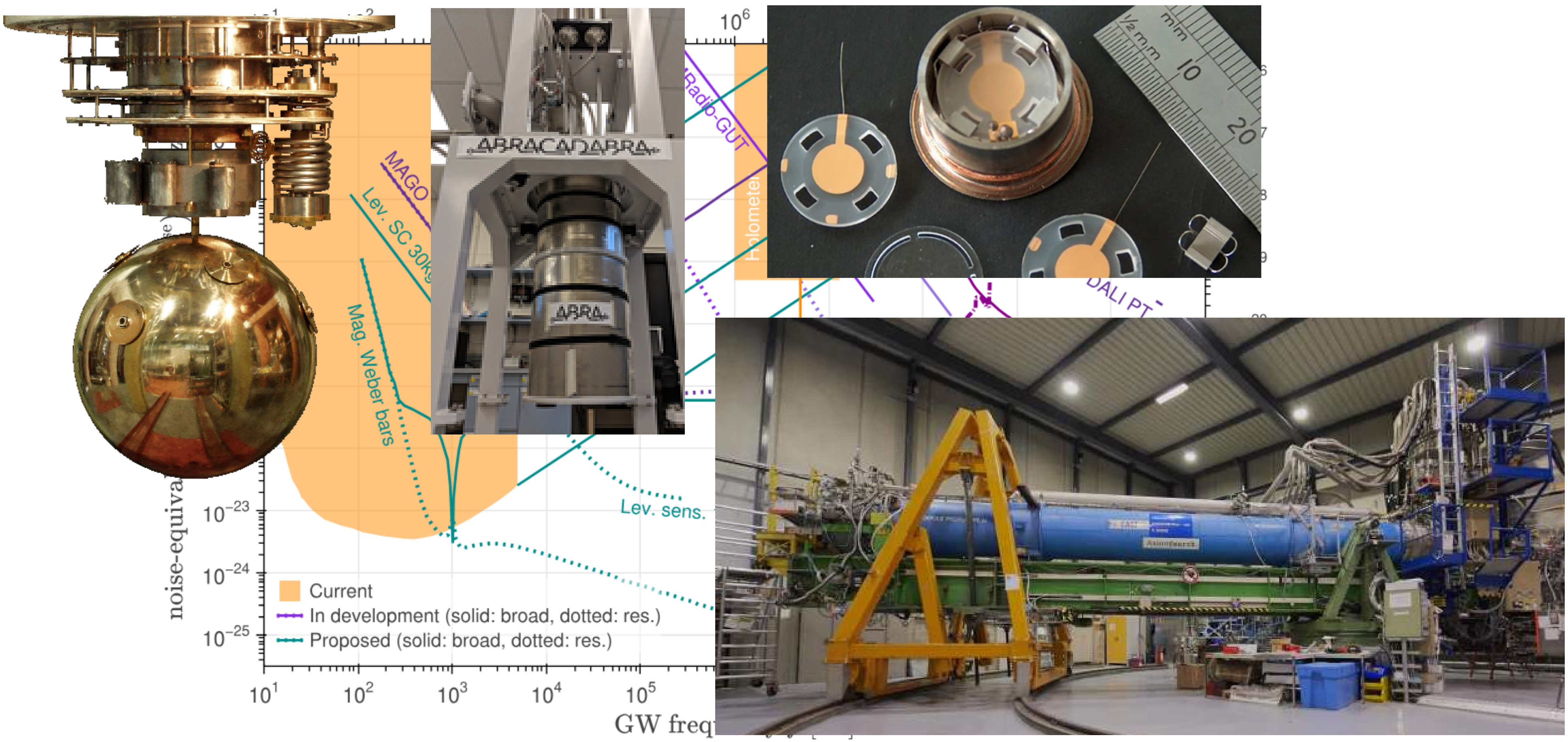
Improved signal reconstruction for time varying noise

Alvey, Bhardwaj, VD, Pieroni, Weniger `24

High frequency GW searches

Very early Universe, subsolar compact objects ⟶ GWs > kHz (BSM search!)

Suitable detector concept? Synergies with DM searches, precision experiments.



Challenges and Opportunities of Gravitational Wave searches above 10 kHz, Living Review Relativity 24 (2021) 1, v2: 2501.11723

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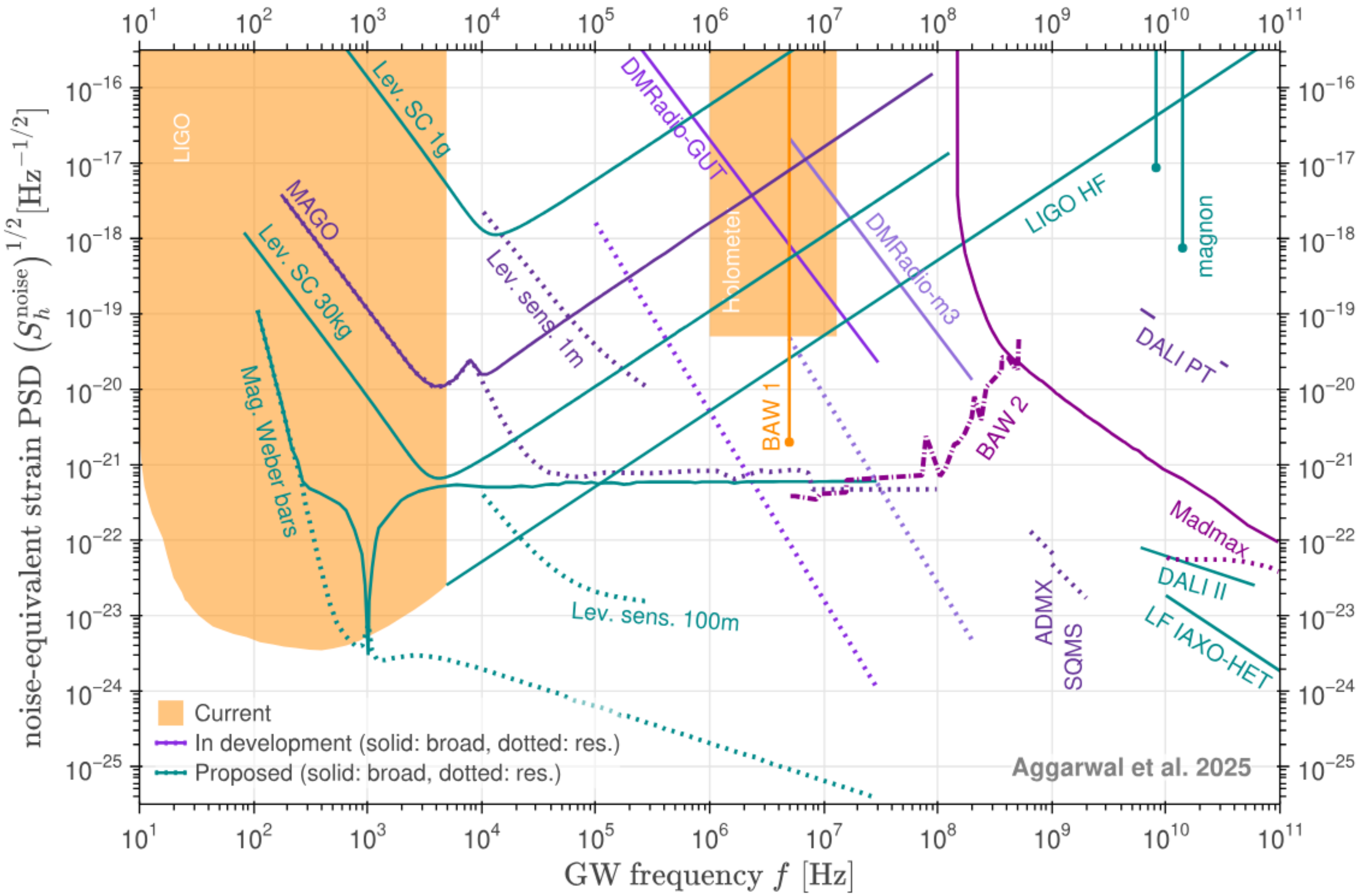
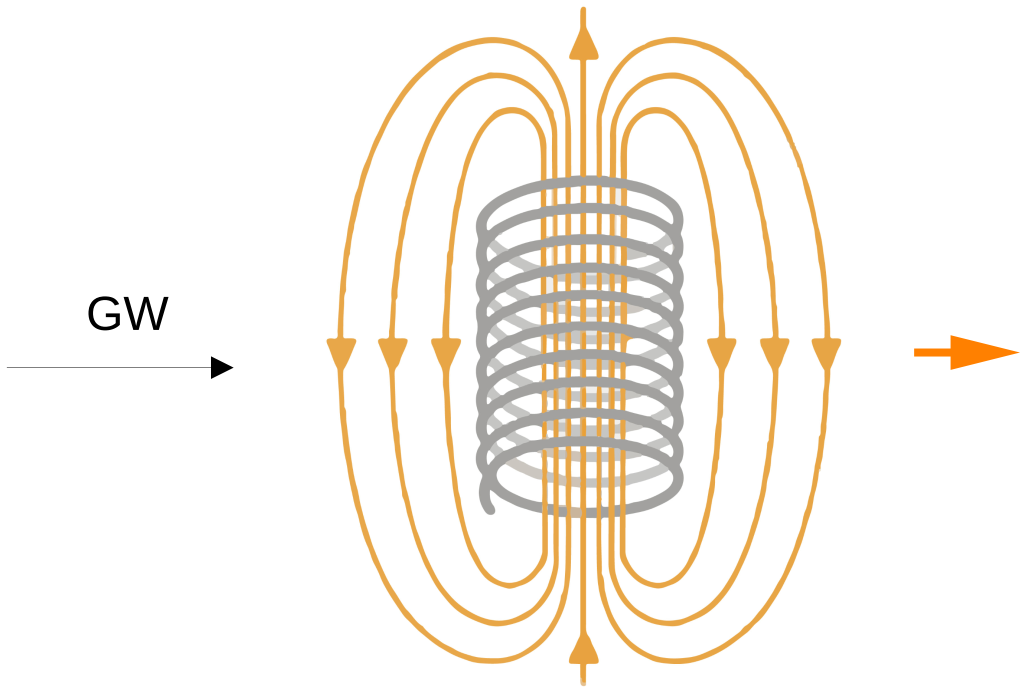


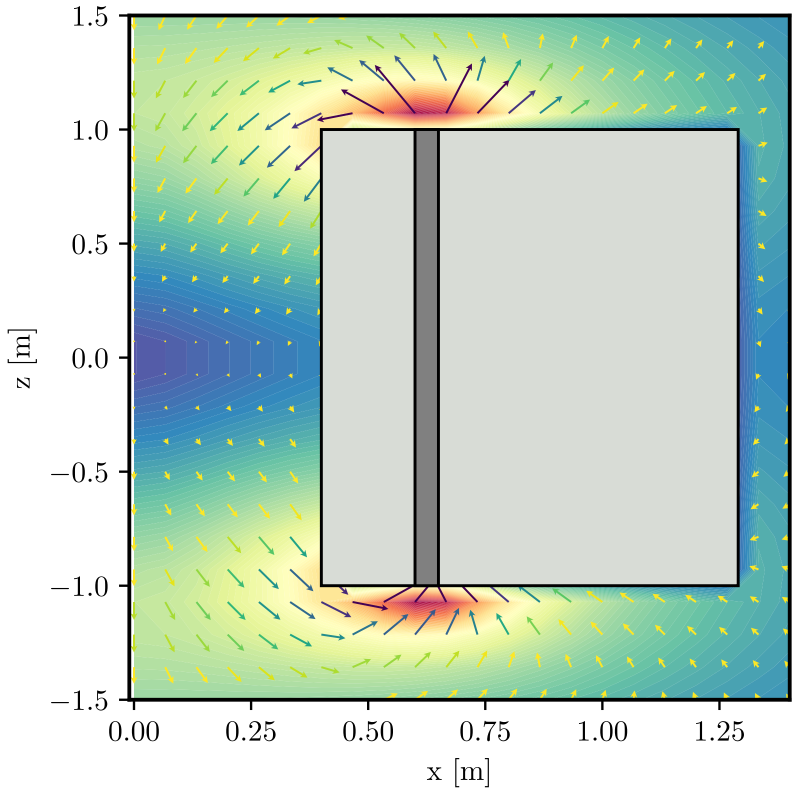
Challenges and Opportunities of Gravitational Wave searches above 10 kHz, Living Review Relativity 24 (2021) 1, v2: 2501.11723

Magnetic Weber Bar

VD, Ellis, Rodd `24

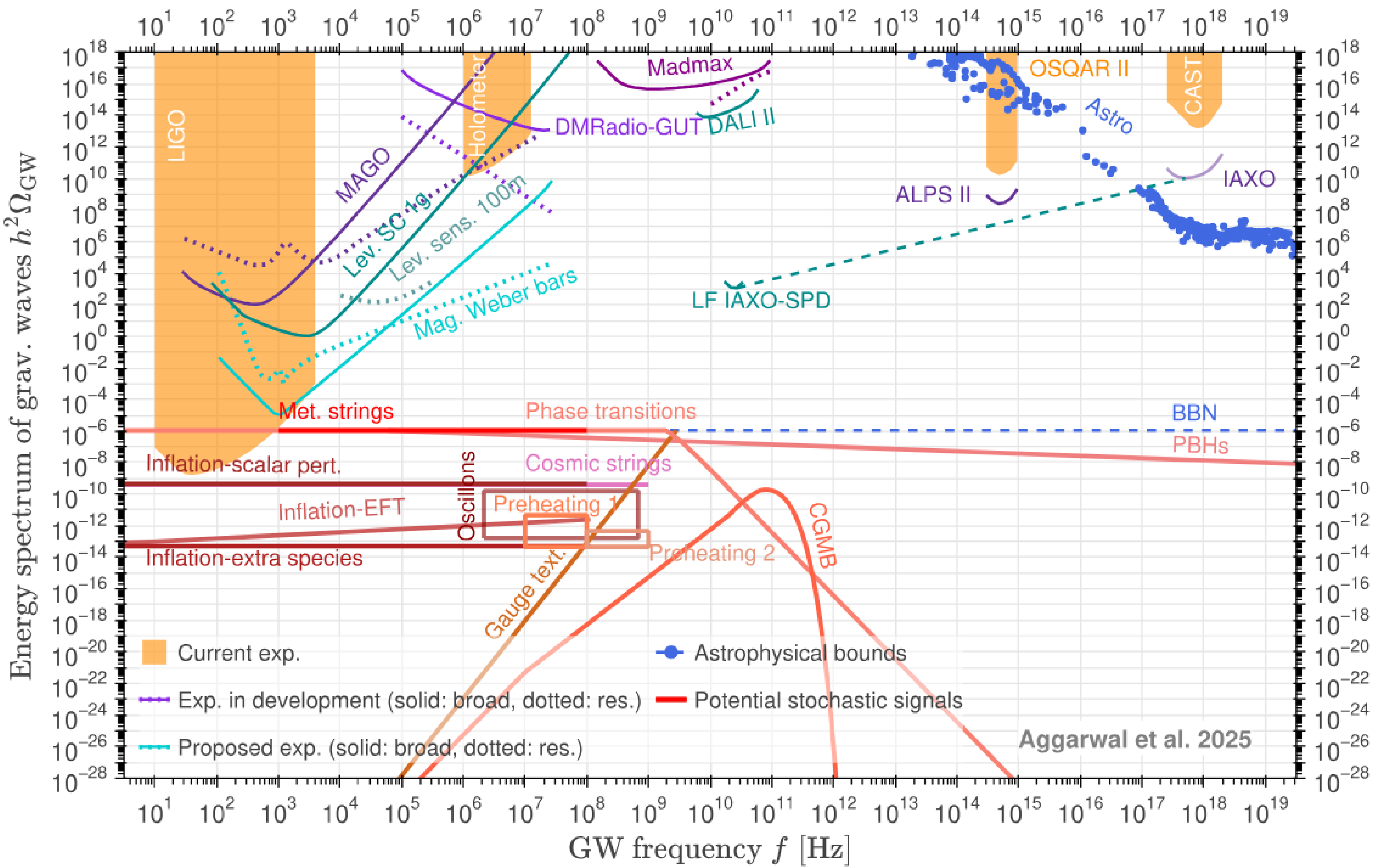
GW acts as a mechanical force on (current-carrying) wires:





Induced AC magnetic field, read out with pickup loop + SQUID

Reaching SGWBs is extremely(!) challenging



Conclusions and Outlook

The future GW sky looks bright

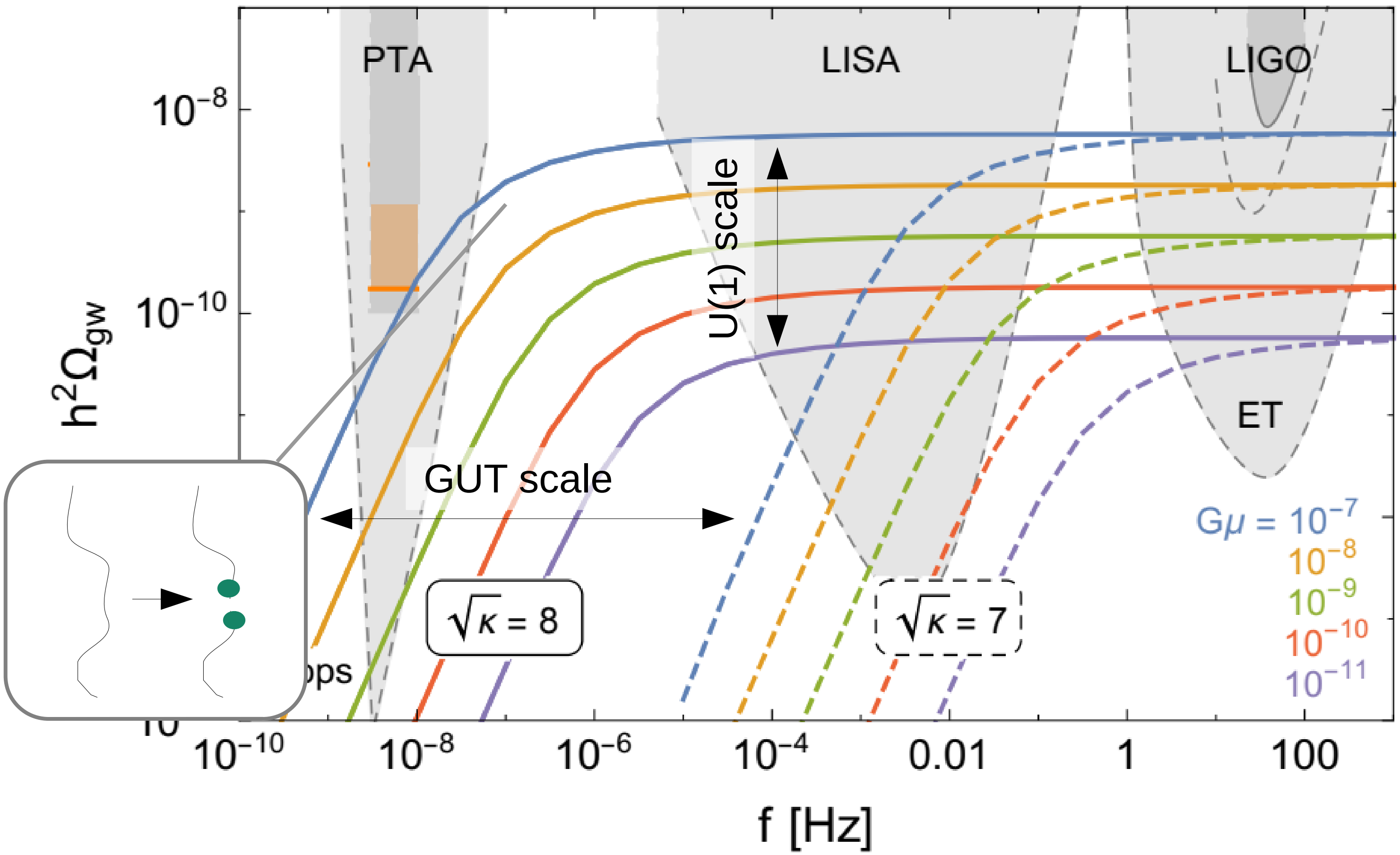
- Data is coming. Across decades in frequency.
- Synergies with particle physics:
  - Testing BSM models (1st order EWPT, topological defects, DM …)
  - Data analysis and detector development

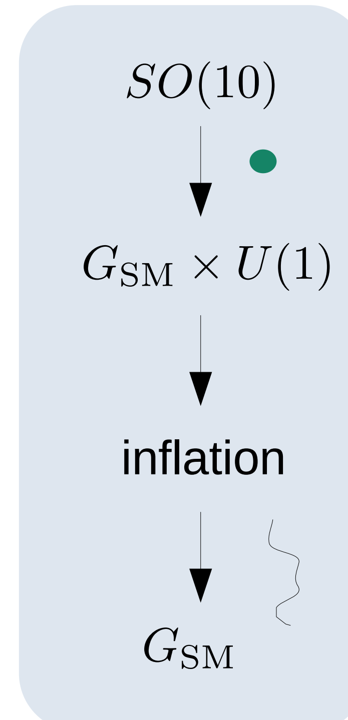
Upcoming challenges in GW searches

- nHz : origin of the signal? (sub)dominant cosmological contribution?
- mHz – kHz : from first detection to ‘pile up’ challenges
- > kHz : most promising detector concept yet to be identified

backup slides

Buchmüller, VD, Schmitz `21,`23



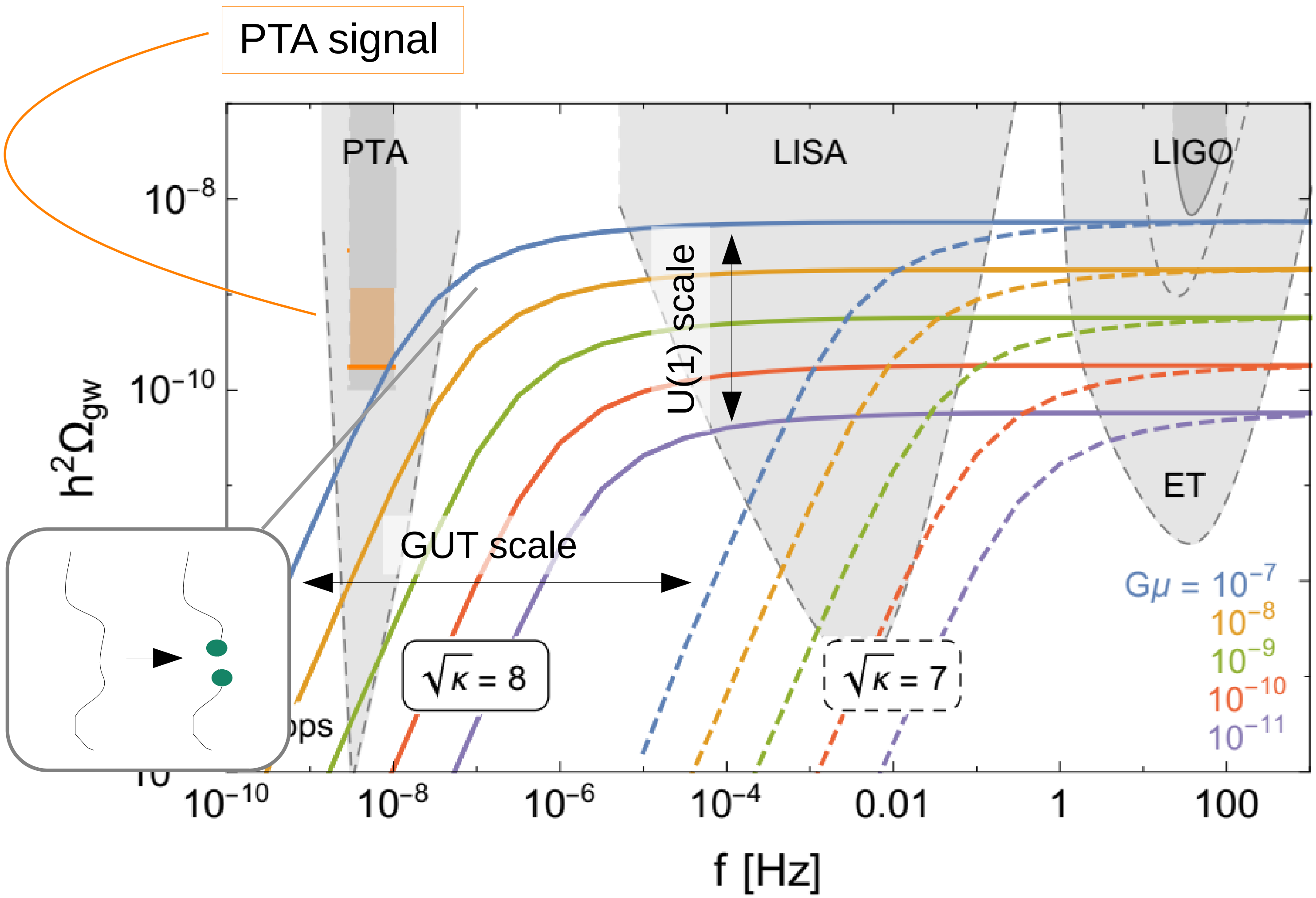


GUT-scale U(1) phase transition can be tested with GWs

$$\sqrt{\kappa} \sim v_{\rm SO(10)}/v_{U(1)}$$
$$G\mu \sim (v_{U(1)}/M_P)^2$$

example: metastable cosmic strings

Buchmüller, VD, Schmitz `21,`23



$SO(10)$

$\downarrow$

$G_{\mathrm{SM}} \times U(1)$

$\downarrow$

inflation

$\downarrow$

G_{SM}

GUT-scale U(1) phase transition can be tested with GWs

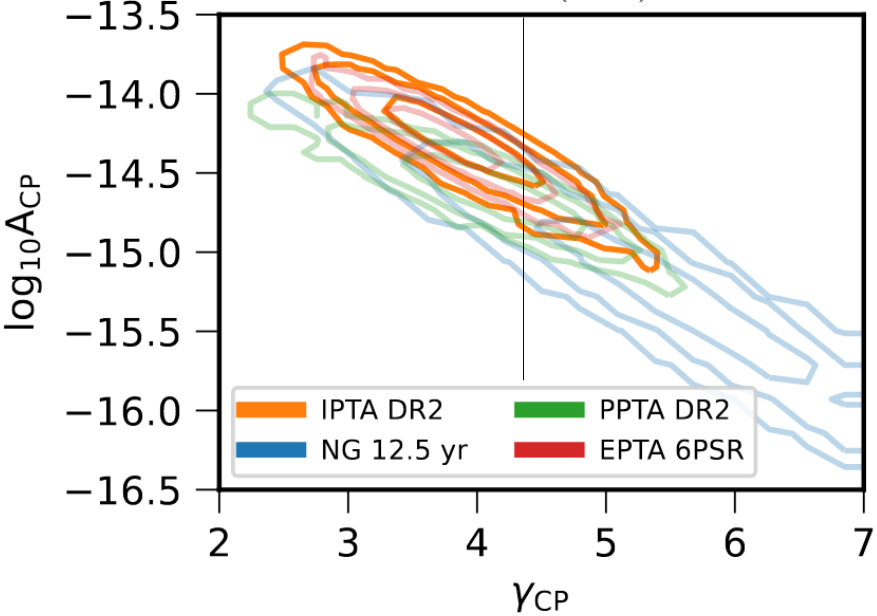
$\sqrt{\kappa} \sim v_{\mathrm{SO(10)}}/v_{U(1)}$

$G\mu \sim (v_{U(1)}/M_P)^2$

PTAs: Information on spectral shape

power-law fit $h_c(f) = A_{\rm CP}\left(\frac{f}{f_{\rm yr}}\right)^{(3-\gamma_{\rm CP})/2}$

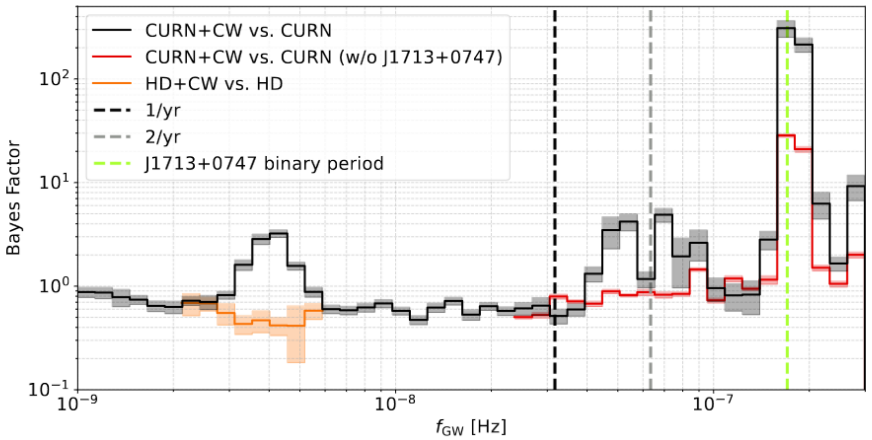
IPTA DR 2 (2022), 2201.03980



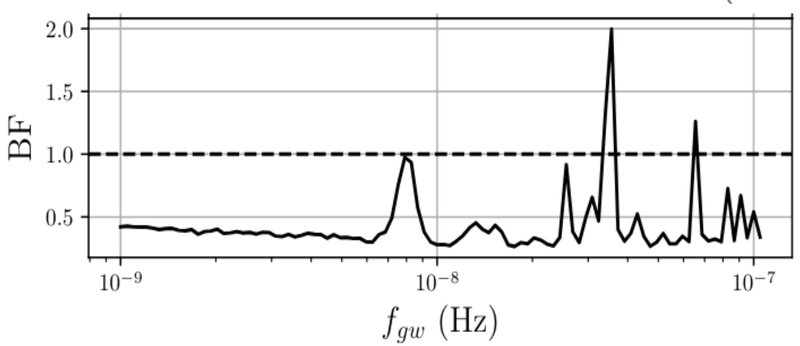
No conclusive indication of origin of GW signal

search for individual source

NANOGrav 15 individual source search (2023)

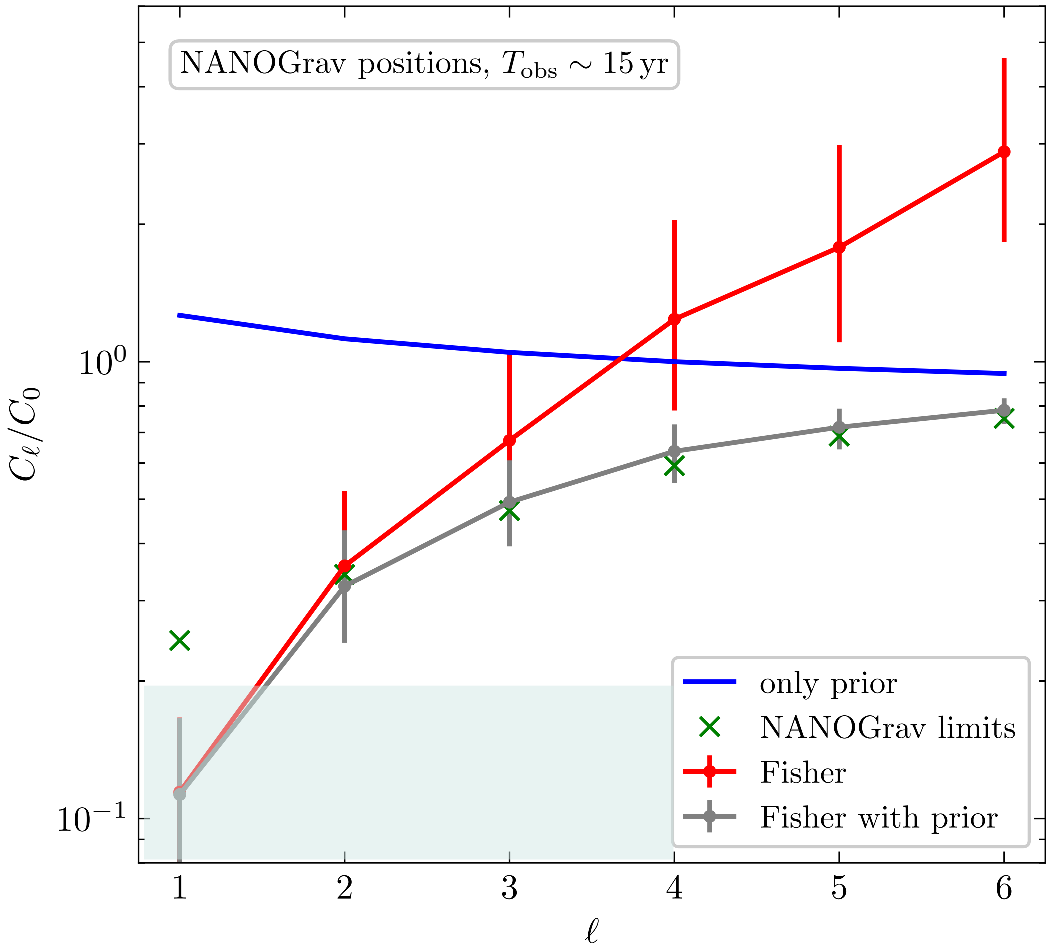


IPTA DR2 individual source search (2023)



Cross-check against NG15 results

[Depta, VD, Franciolini, Pieroni `24]



$$C_\ell = \frac{1}{2\ell+1}\sum_m |c_{\ell m}|^2.$$

Estimated sensitivity with 70 pulsars

Estimated reconstructed limits imposing NG prior

NG15 results

SMBHB background:

$$C_\ell/C_0 \sim 1 - 20\%$$

[Mingarelli et al `13]

(weakly) informative constraints only for low multipoles