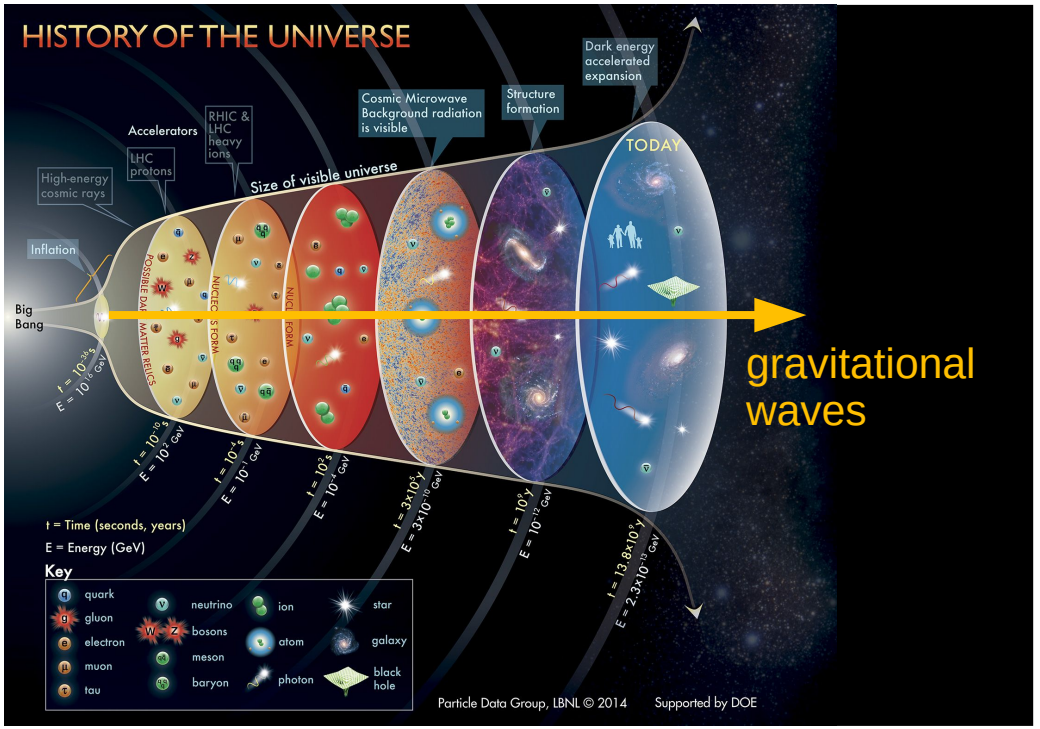
Gravitational Waves:

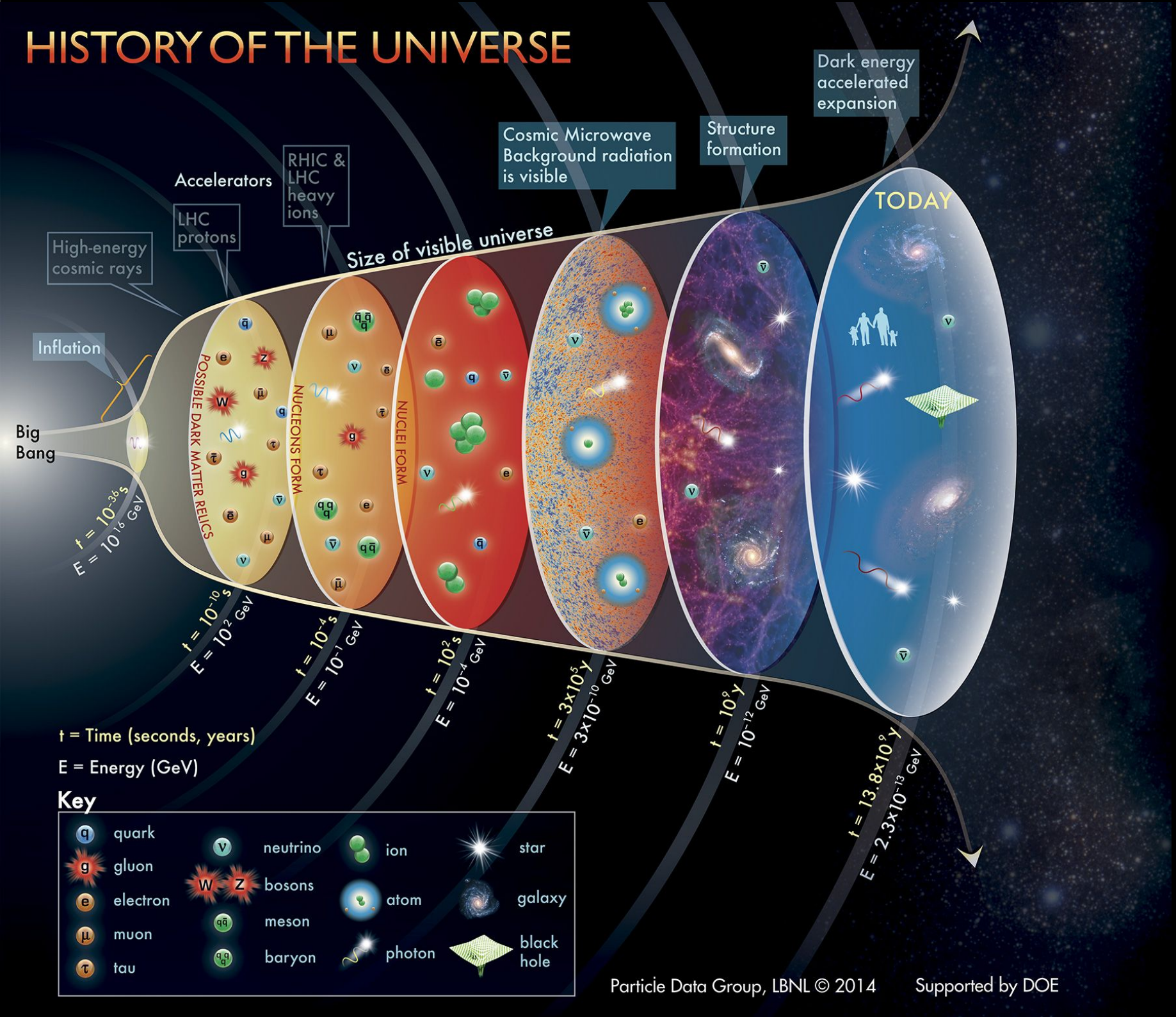
present and future

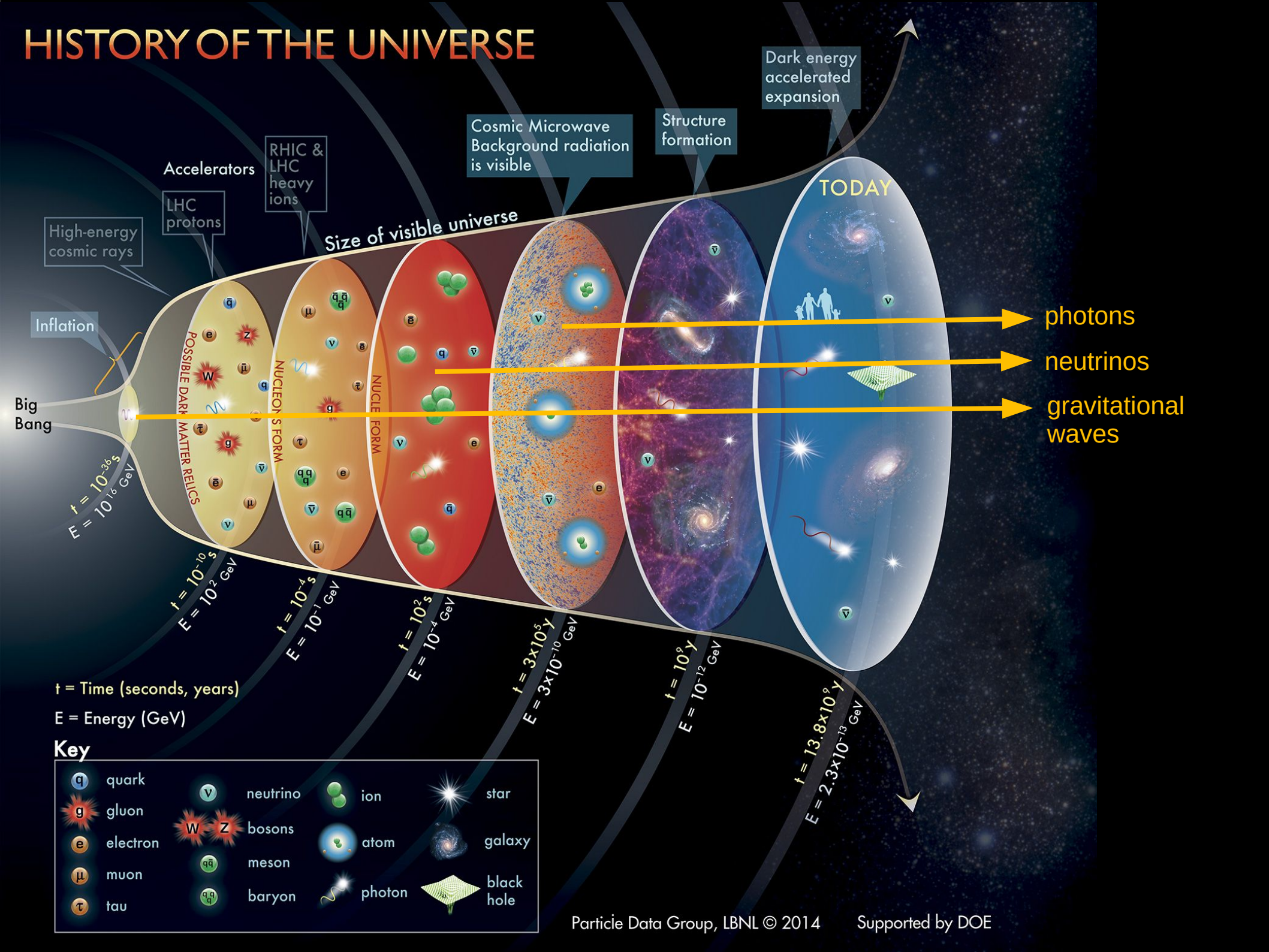


Valerie Domcke
CERN

Moriond 2025
Electroweak interactions & unified theories

March 28, 2025


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
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 = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-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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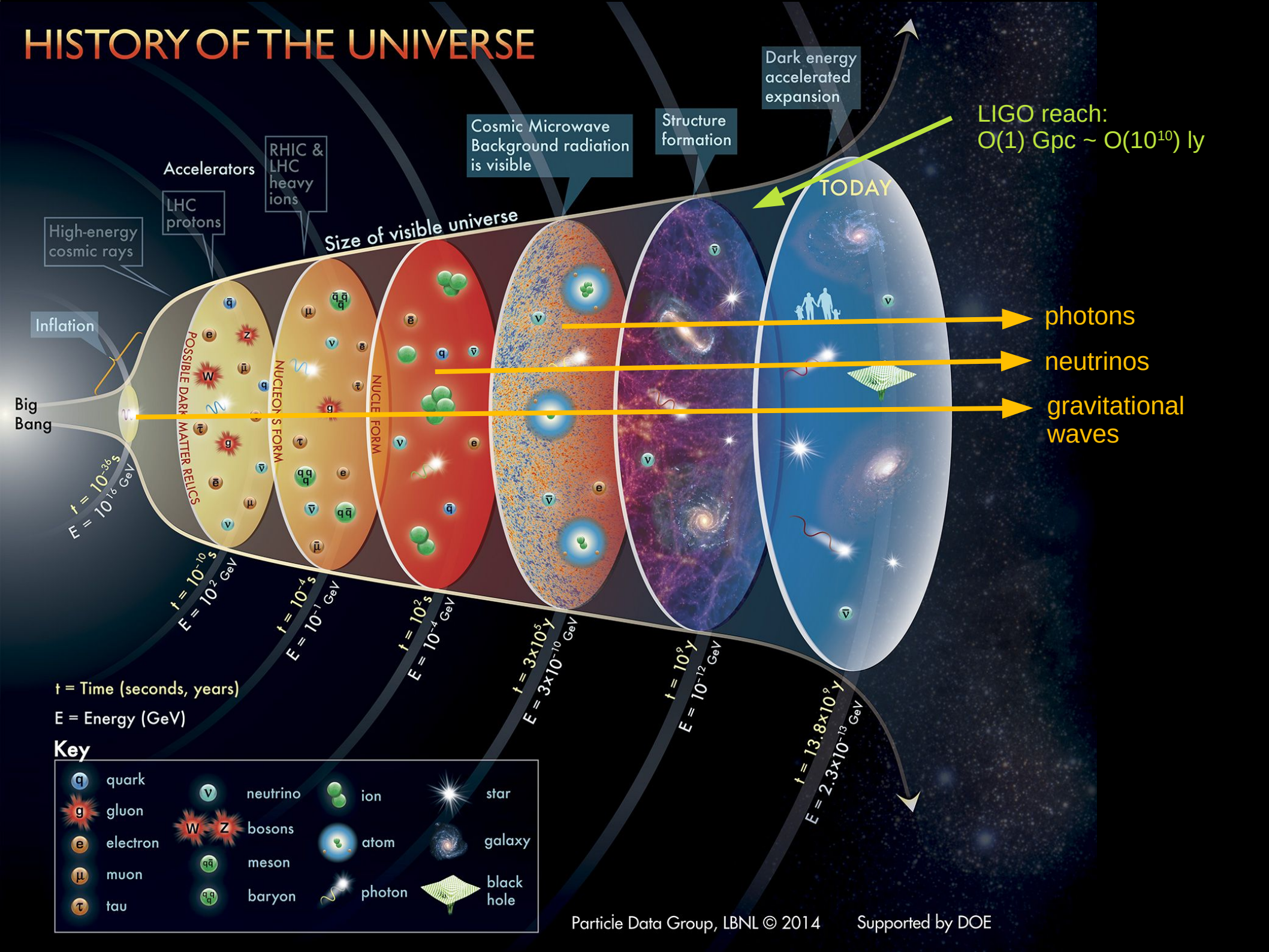
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Dark energy accelerated expansion
LIGO reach:
O(1) Gpc ~ O(10^10) ly
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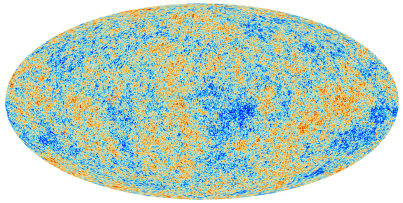
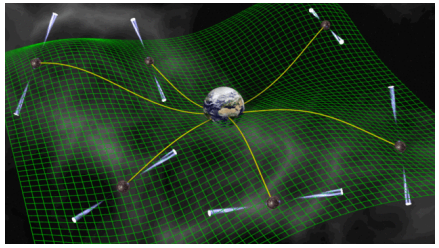
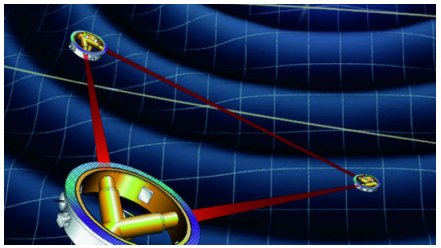
The GW sky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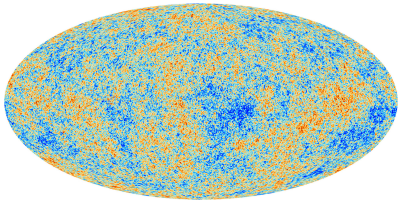
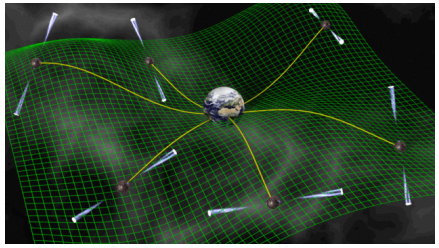
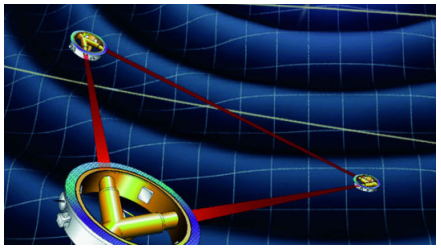
CMB B-modes		
BICEP/KEK,.. Lightbird		
$r < 0.04$		
$\Omega_g h^2 < 10^{-16}(f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz		

nHz mHz kHz

frequency

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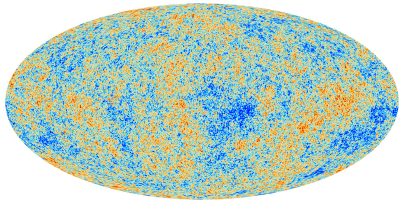
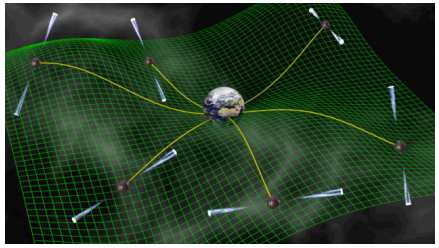
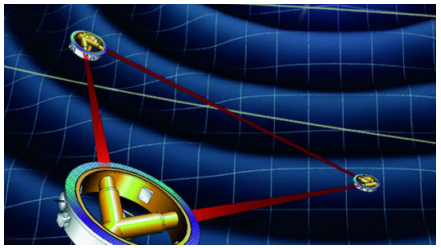
CMB B-modes	Pulsar timing arrays
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA
$r < 0.04$	evidence for GW signal, HD correlation
$\Omega_g h^2 < 10^{-16}(f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz	$\Omega_g h^2 \sim 10^{-9}$

nHz mHz kHz

frequency

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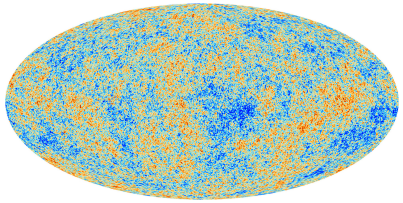
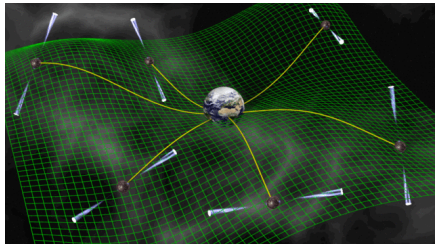
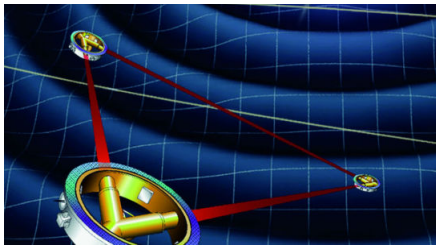
CMB B-modes	Pulsar timing arrays	Space interfometers
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA	LISA
$r < 0.04$	evidence for GW signal, HD correlation	ESA/NASA mission launch ~ 2030s
$\Omega_g h^2 < 10^{-16}(f_{\rm eq}/f)^2$ $f_{\rm eq} \sim 10^{-17}$ Hz	$\Omega_g h^2 \sim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

The GW sky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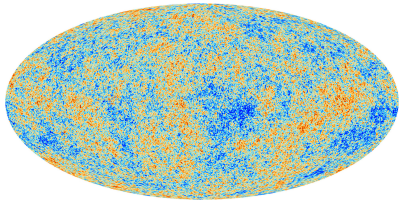
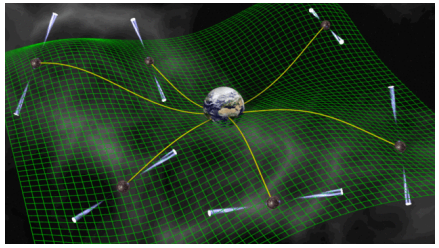
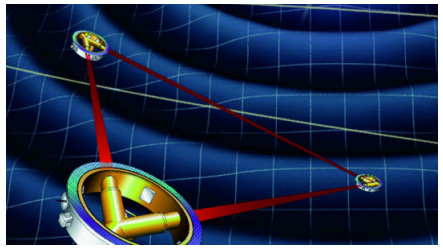
CMB B-modes	Pulsar timing arrays	Space interfometers	Ground-based interferometers
BICEP/KEK,.. Lightbird	EPTA, NANOgrav, PPTA, INPTA, CPTA, Meerkat, SKA	LISA	LIGO/Virgo/Kagra ET / Cosmic Explorer
$r < 0.04$	evidence for GW signal, HD correlation	ESA/NASA mission launch ~ 2030s	GW detection, O(100) CO 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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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?

s. talk by M. Mühlleitner

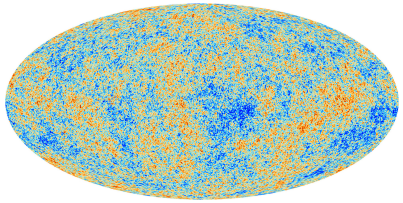
Phase transitions above 100 GeV

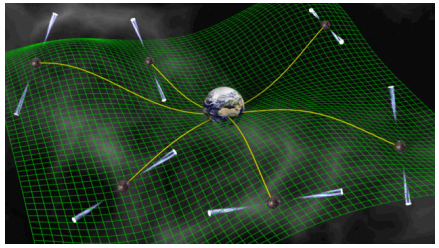
Topological defects (cosmic strings) from GUT scale phase transitions?

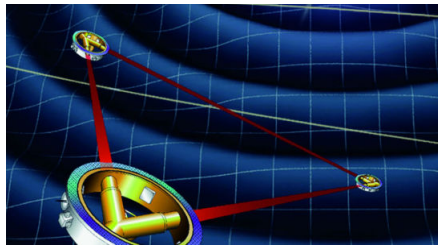
nHz mHz kHz

frequency

The GW sky – challenges and open questions







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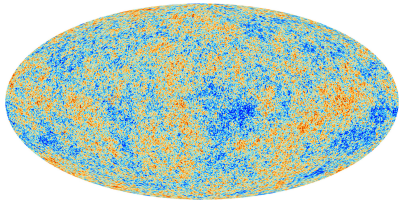
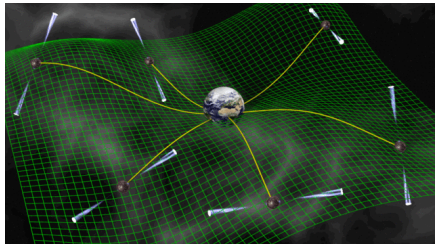
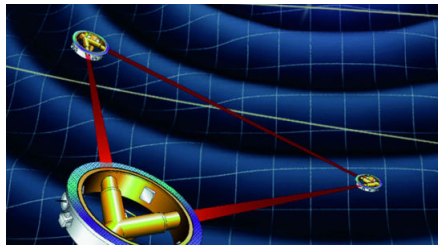
Foregrounds, lensing

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

The GW sky – challenges and open questions







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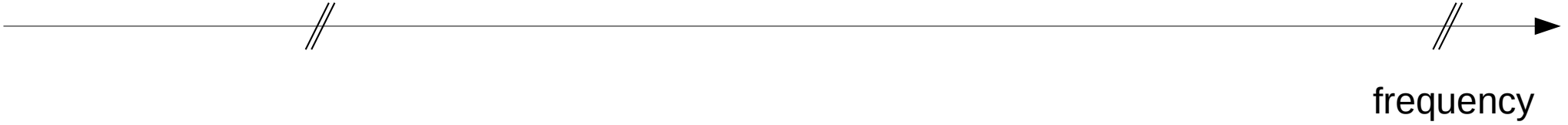
Foregrounds, lensing

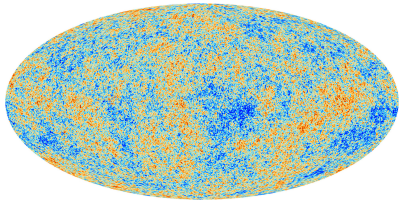
goal: reach $r \sim 10^{-3}$ (Starobinsky inflation)

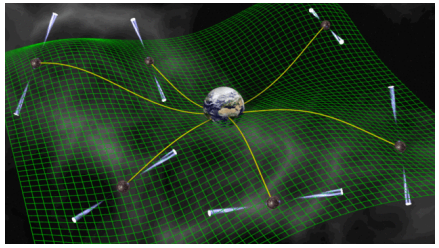
Confirm HD signature
Single source or SGWB?
Isotropic or anisotropic?
SMBHs or primordial?
Spectral shape?

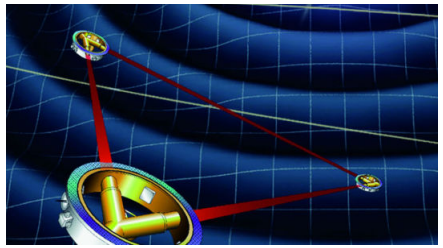
some answers expected in the next few years



The GW sky – challenges and open questions







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signal dominated („pile-up“ of many overlapping signals)
→ „global fit“ program

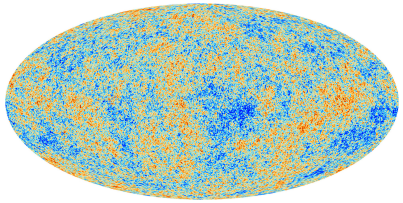
High requirements for accuracy of waveforms.

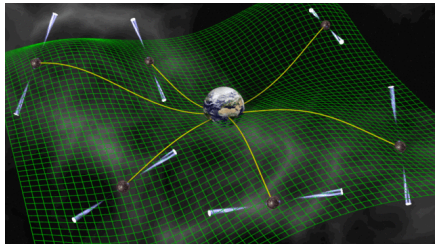
EMRIs.

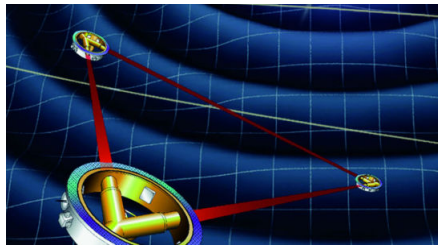
nHz mHz kHz

frequency

The GW sky – challenges and open questions







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Noise dominated
→ signal dominated

nHz mHz kHz

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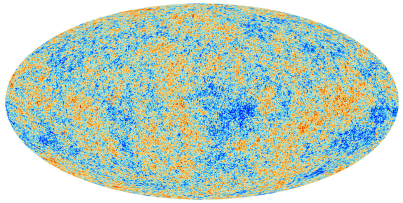
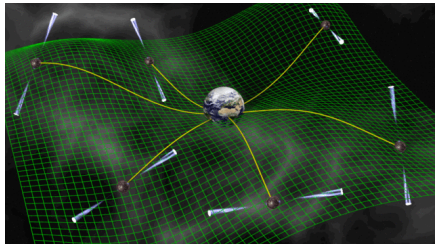
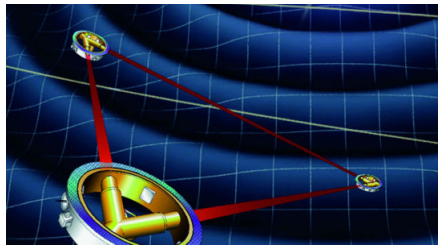
The GW sky – challenges and open questions







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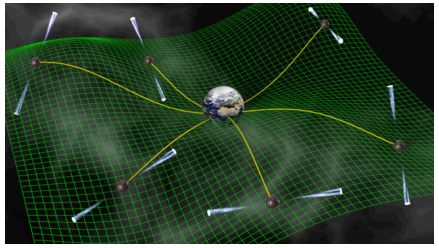
Noise dominated
→ signal dominated

Investigation of detector concepts.
High-precision “table-top“ experiments ?
Strong magnets?

nHz mHz kHz

frequency

Measuring anisotropies with PTAs



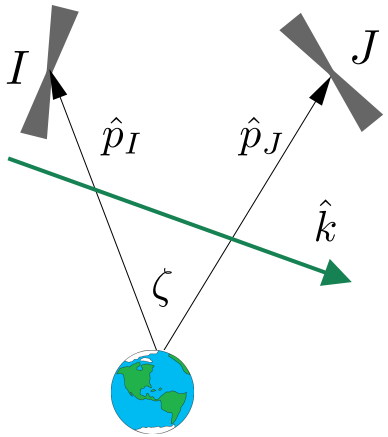
Stochastic gravitational wave background (SGWB)

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

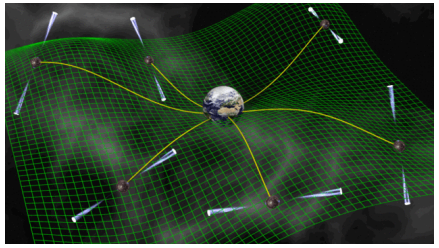
$$\langle \Delta t_I \Delta t_J\rangle = \int_{-\infty}^{\infty} \mathrm{d}f \frac{S_h(f)}{24\pi^2 f^2} \frac{3}{2}\sum_P \int d^2\hat{k}\, F^P_{\hat{p}_I}(\hat{k}) F^P_{\hat{p}_J}(\hat{k})\, P(\hat{k})$$

instrument response
anisotropic GW background

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



Measuring anisotropies with PTAs



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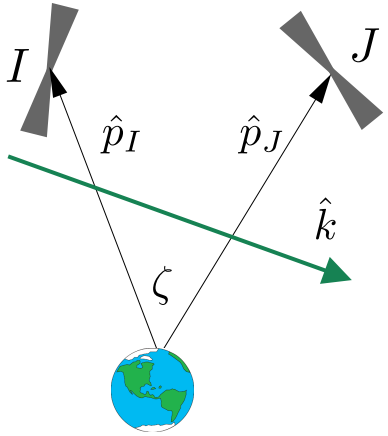
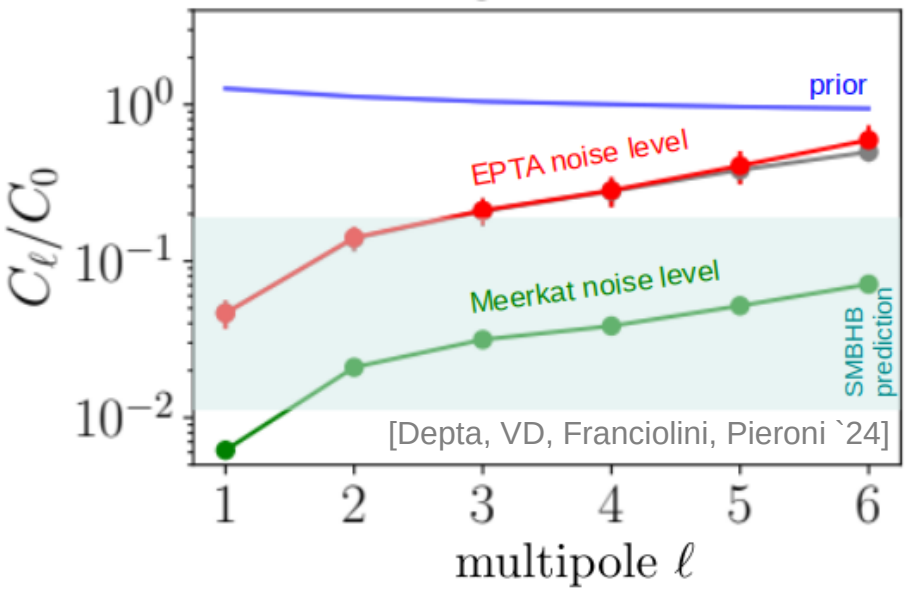
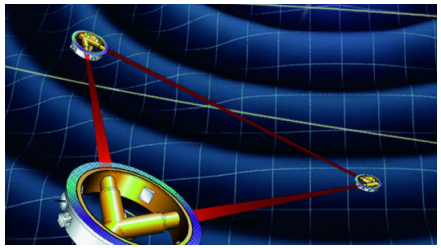


Upcoming PTA data: distinguish cosmological vs astroph. source

projection for 140 pulsars

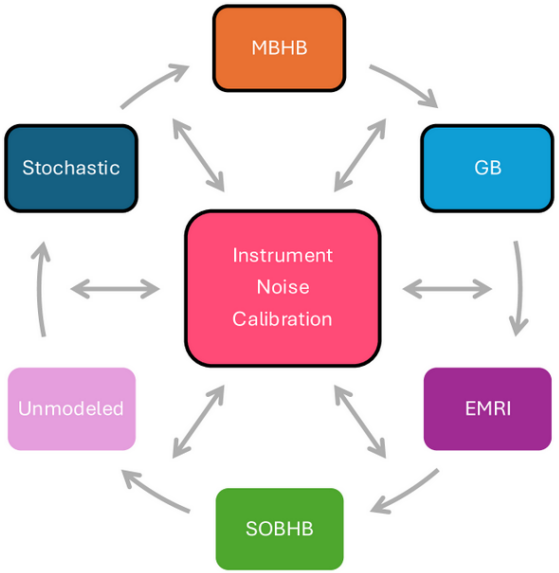


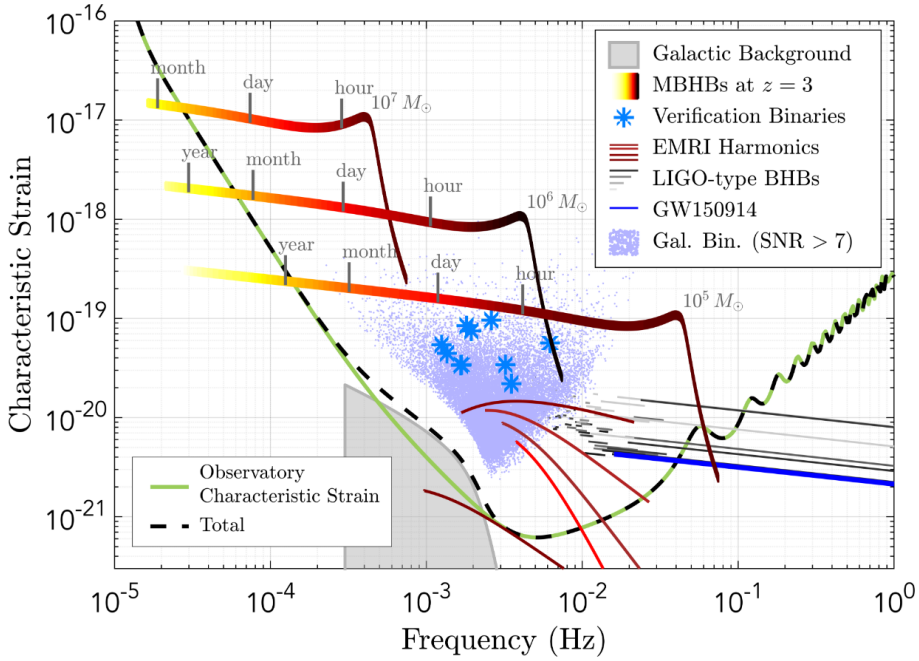
Laser interferometer space antenna (LISA)



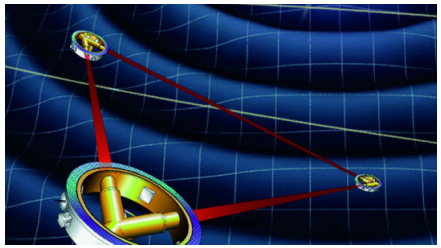
Overlapping signals
→ LISA Global Fit

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



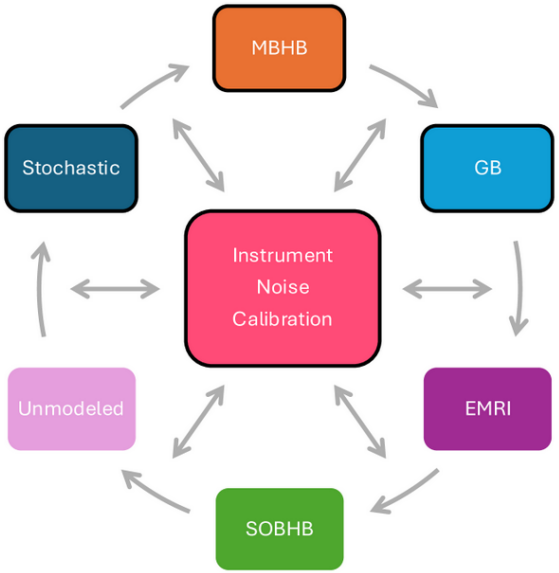


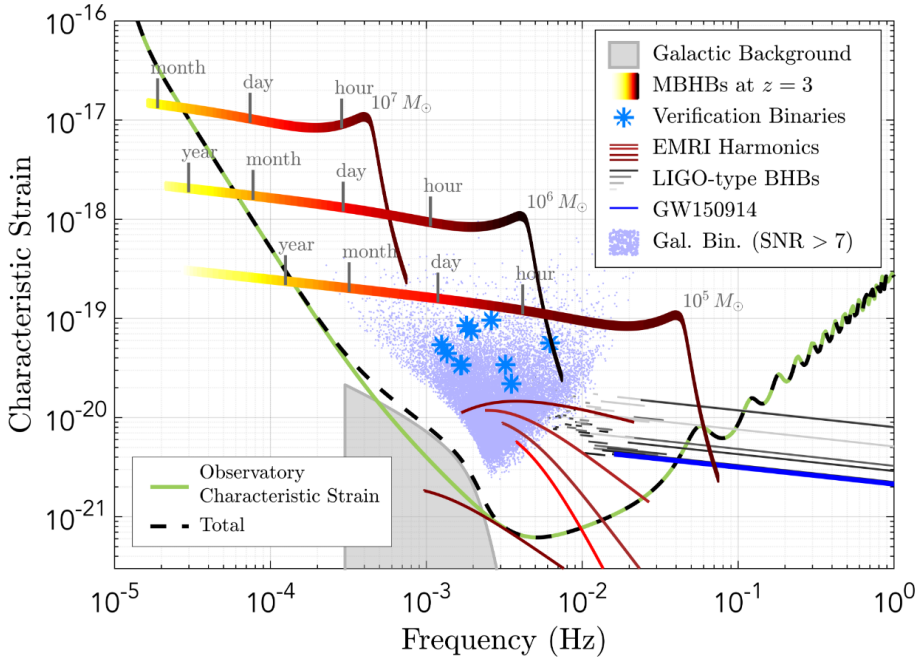
Laser interferometer space antenna (LISA)



Overlapping signals
→ LISA Global Fit

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





Exploring new techniques: Simulation Based Inference (SBI) :

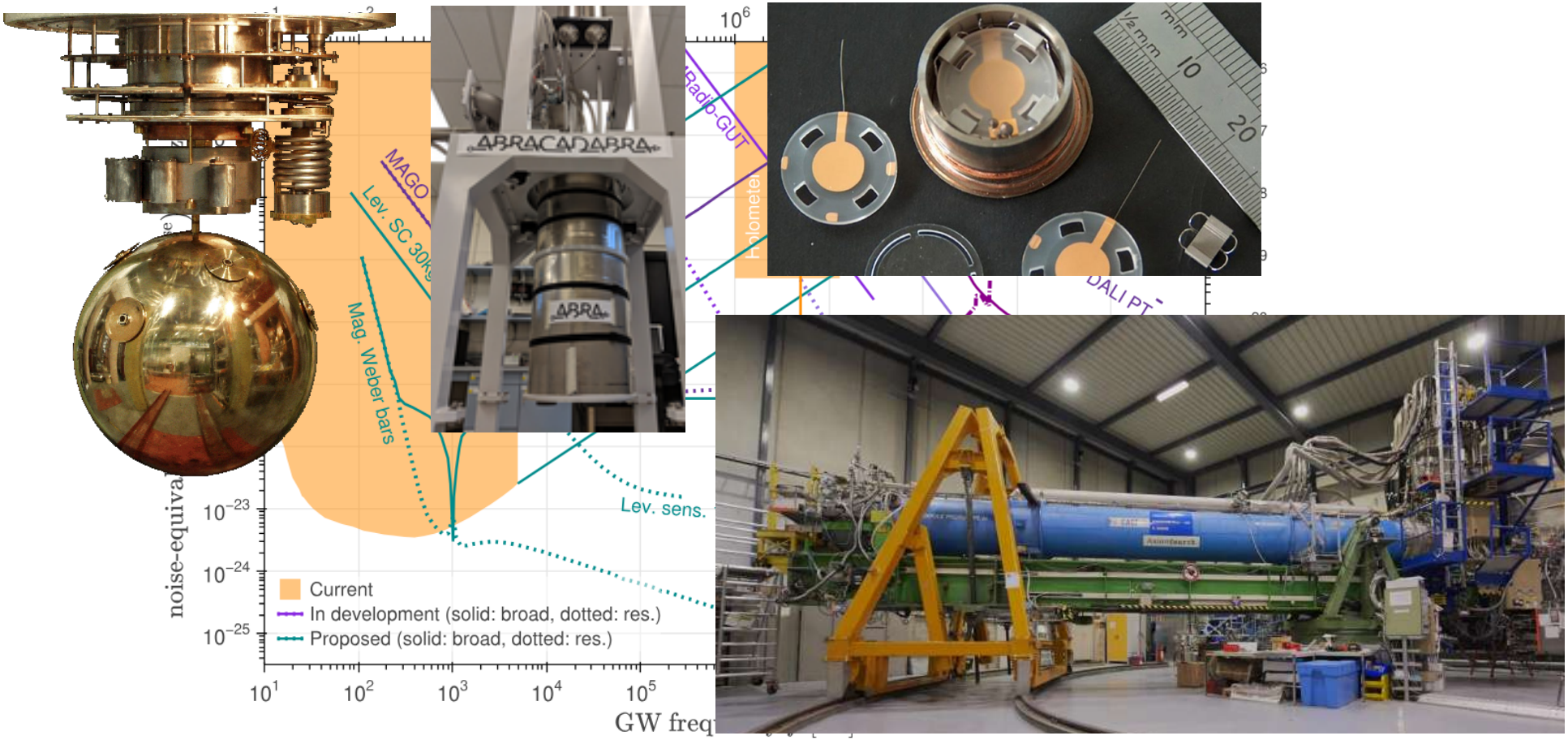
- Forward simulation is fast
- Marginalization over nuisance parameters
- Likelihood-free (life is not Gaussian)

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

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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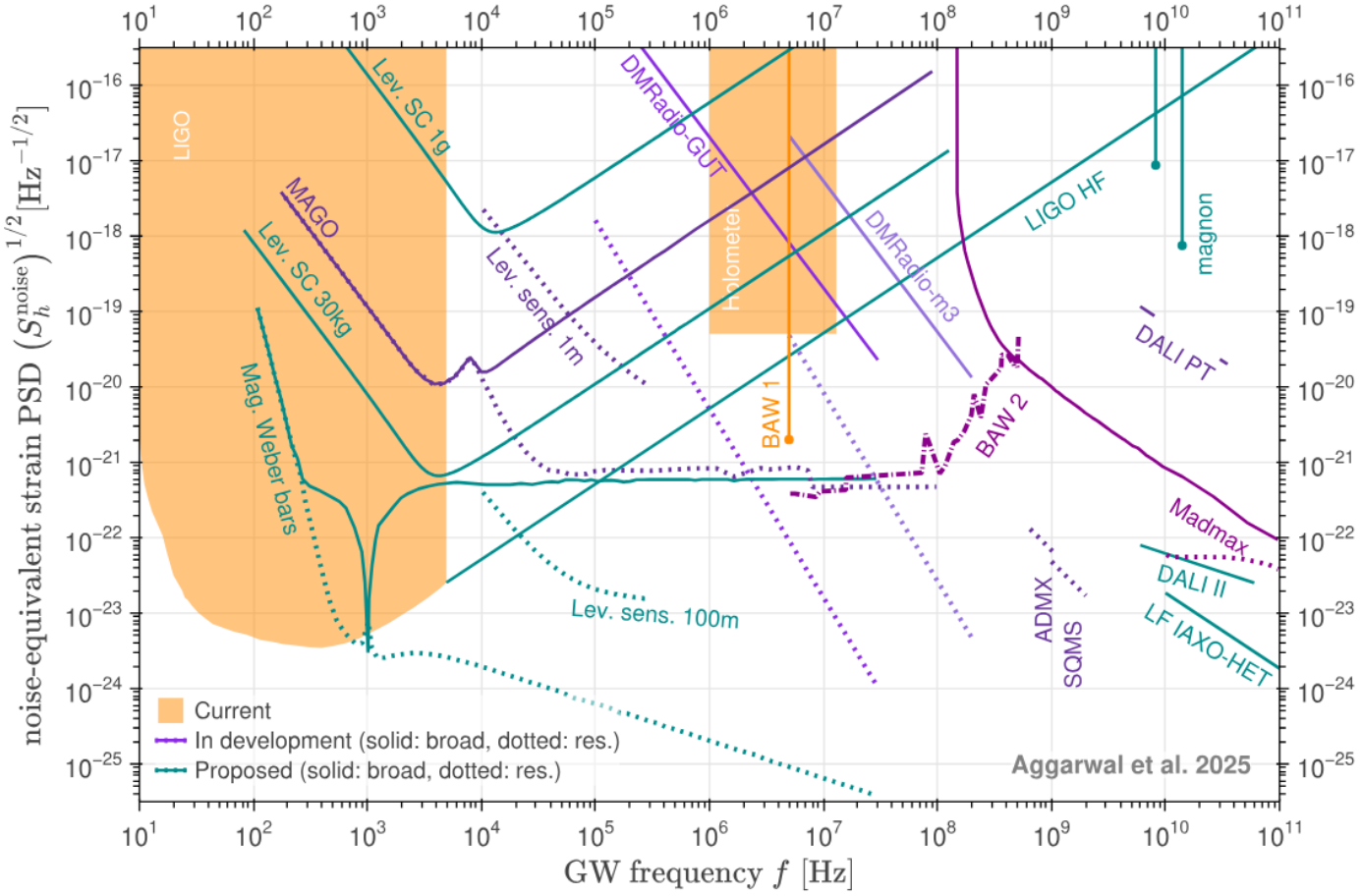

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Conclusions and Outlook

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

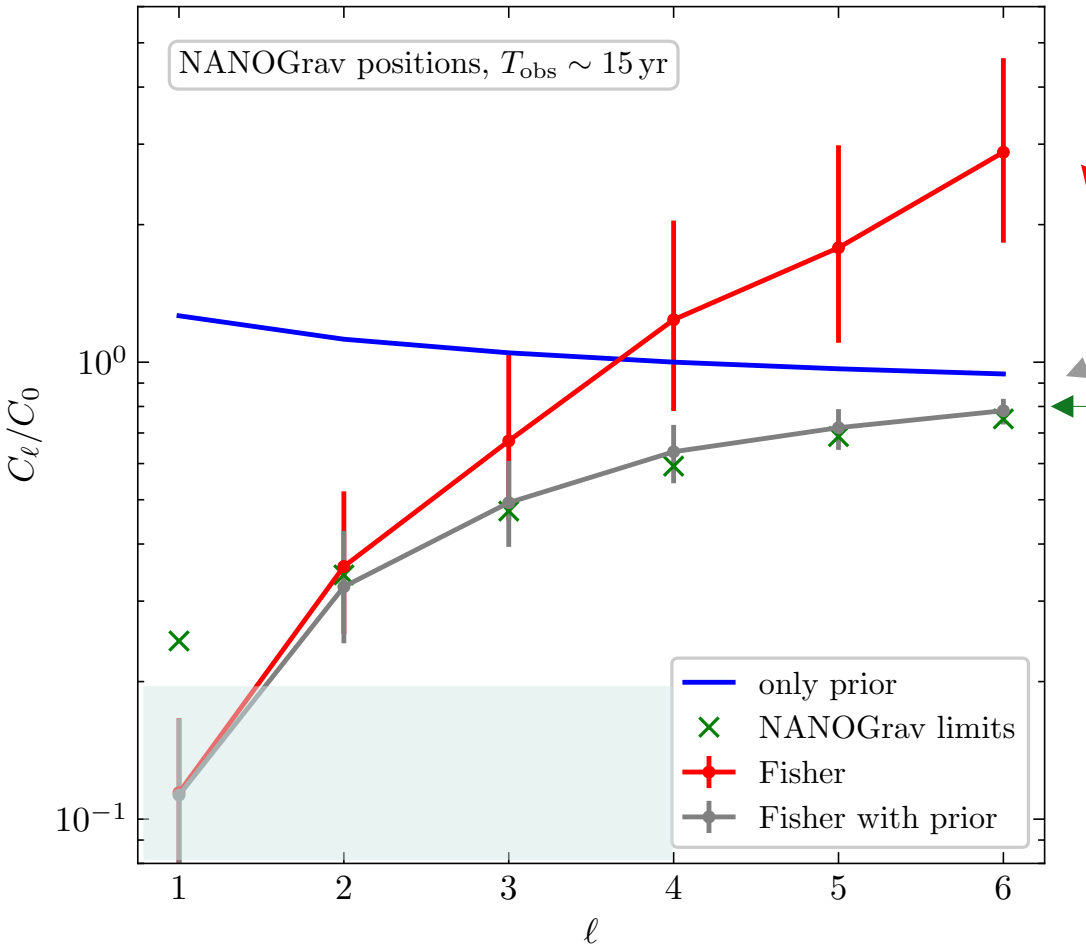
Upcoming challenges in GW searches

- 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

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

HFGW searches - SGWB