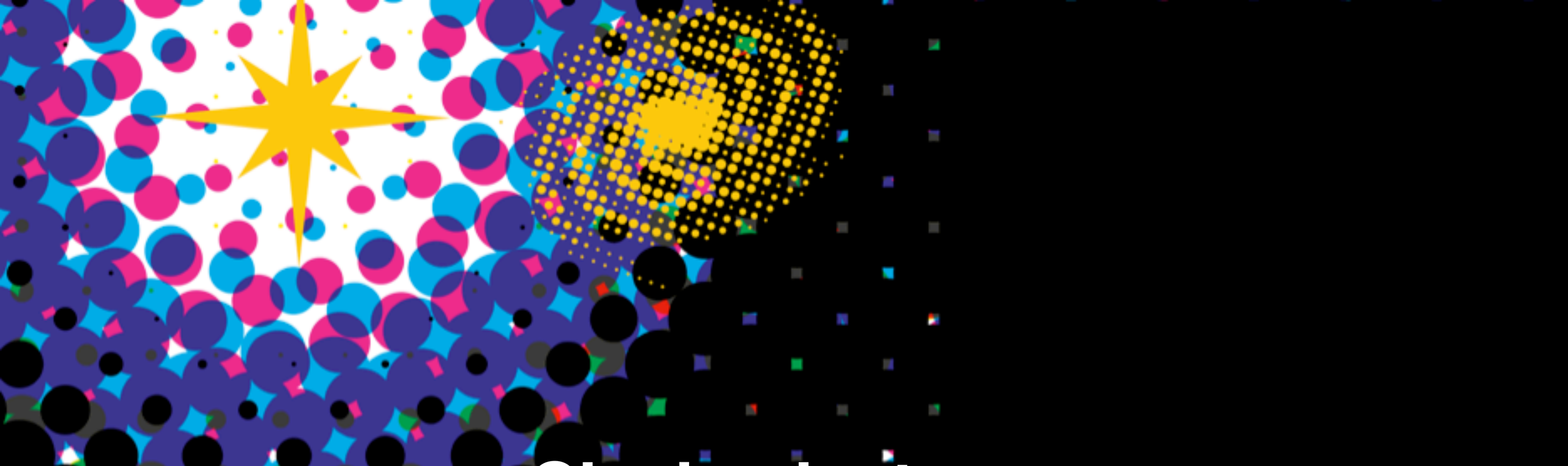


Closing lecture:
the path behind and the road ahead

Diego Blas

UAB Universitat Autònoma de Barcelona
IFAE
BIST Barcelona Institute of Science and Technology
Ayuda Beatriz Galindo Senior
BG20/00228
GOBIERNO DE ESPAÑA
MINISTERIO DE UNIVERSIDADES
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

Particle Physics

Astroparticles in Cosmology

Fundamental Physics w/ CMB

DE Th&Observation

Fundamental Physics w/ LSS

Fundamental Physics w/ galaxies

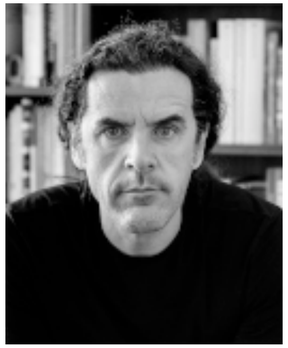
Early Universe & Inflation

DM Th&Observation

Fundamental Physics w/ C-rays & γ-rays

Neutrinos in Cosmo&astroph

Gravitational waves



Distinguished lecturer

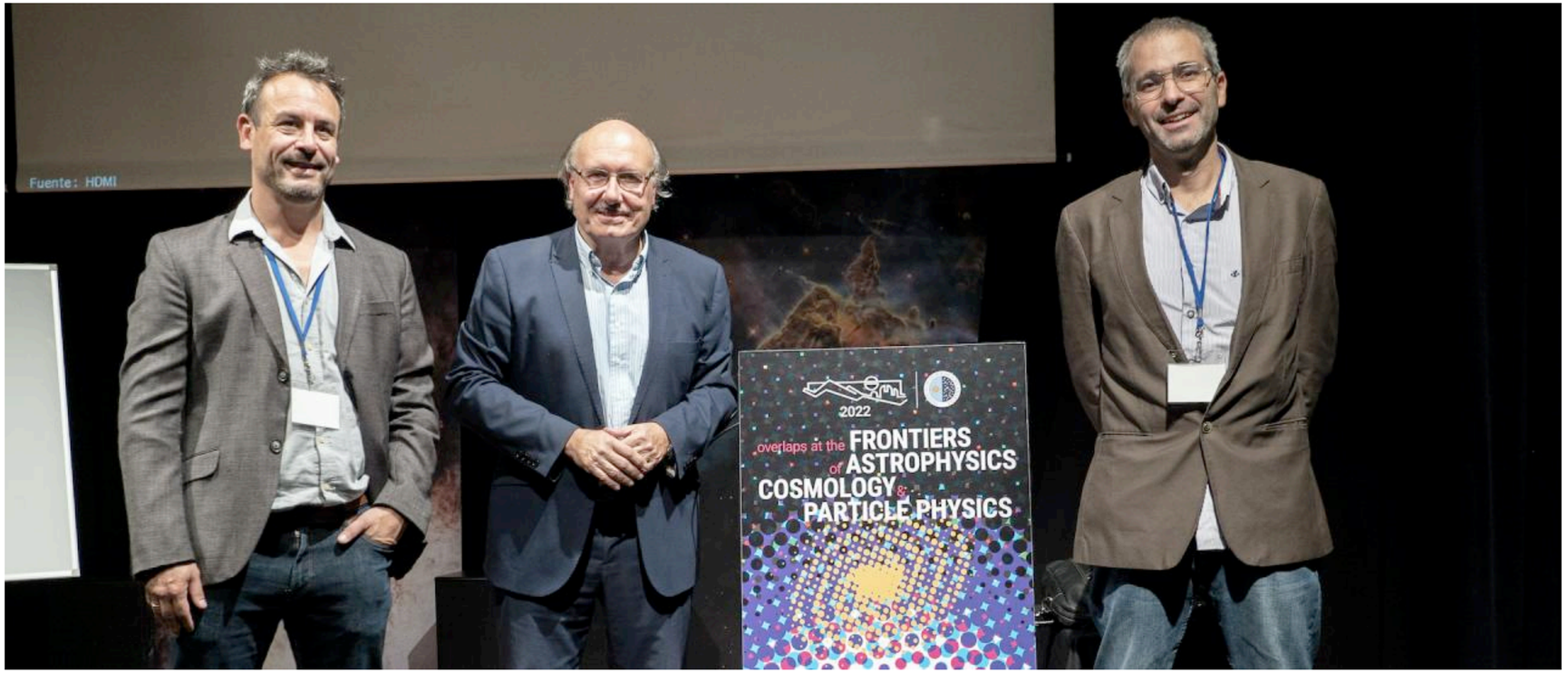
Cosmological DM Sims

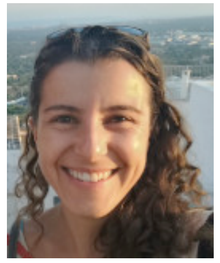
Galaxy Simulations

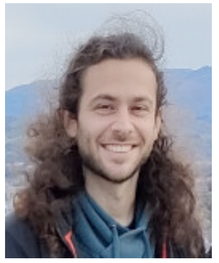
Reconstruction Initial Conditions

Art & Science: Scientific Outreach

Big thanks!


Fuente: HDMI
2022
overlaps at the FRONTIERS of ASTROPHYSICS COSMOLOGY & PARTICLE PHYSICS



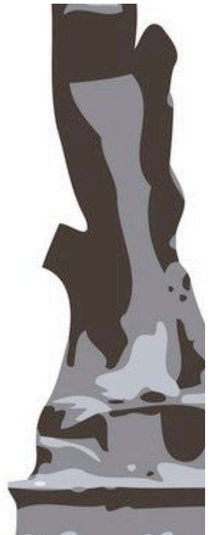


How do we unveil the mysteries of Nature?

observations

theory

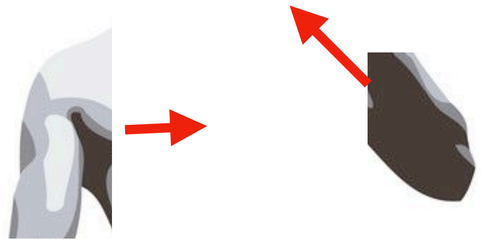
data analysis



phenomenology

instrumentation

How do we unveil the mysteries of Nature?



observations

More data

theory

data analysis

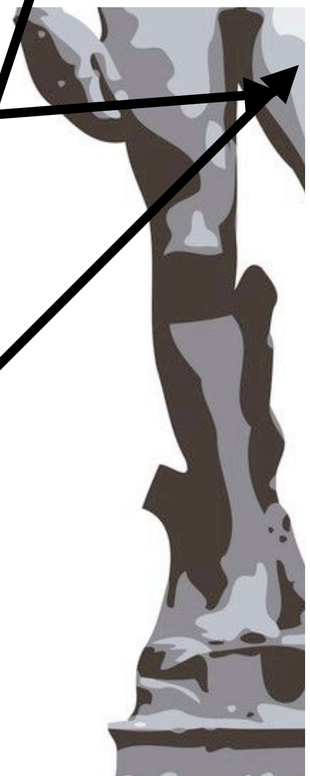
phenomenology

instrumentation

How do we unveil the mysteries of Nature?

This can’t be an headless body. Bodies need a head! **Look** here.

observations



theory

data analysis

This seems very unstable. **Look** for what stabilises it.

phenomenology

instrumentation

How do we unveil the mysteries of Nature?

This can't be an ugly headless body. **Look** here.

theory

This seems very unstable. **Look** for what stabilises it.

phenomenology

observations

data analysis

instrumentation

Y. Zel’dovich

the Universe is the ‘poor* man's accelerator’

Y. Zel’dovich

the Universe is the ‘poor* man's accelerator’

Y. Zel’dovich

*once you build the detector

Theory recap

Particle physics on a leg

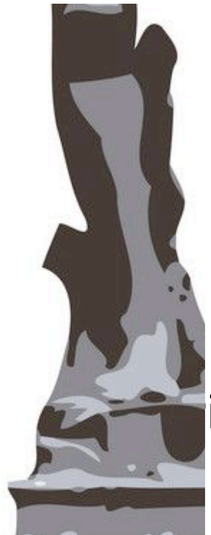
Astro Laguna School

Benjamin Grinstein - Nov 2022

Theory recap

Particle physics on a leg

Astro Laguna School



instein - Nov 2022

Theory recap

Q: Do I need to understand all about theory?

?

Find the level that makes you confortable and enjoying it, but this is important!

Causality

Quantum physics

AMO

Quantum field theory

Statistical physics

Locality

Unitarity

Particle physics

Dynamics friction

Many body physics

Simulations

Fokker-Planck

Relativity (Special and General)

…

Gravitation

Electroweak theory

Data analysis

Radiative processes

Statistics

Galactic dynamics

Electrodynamics

Nuclear physics

What's known?

What's new?

Where are the cracks?

How do I answer X?

Where do I start?

Theory recap

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What's known?

What's new?

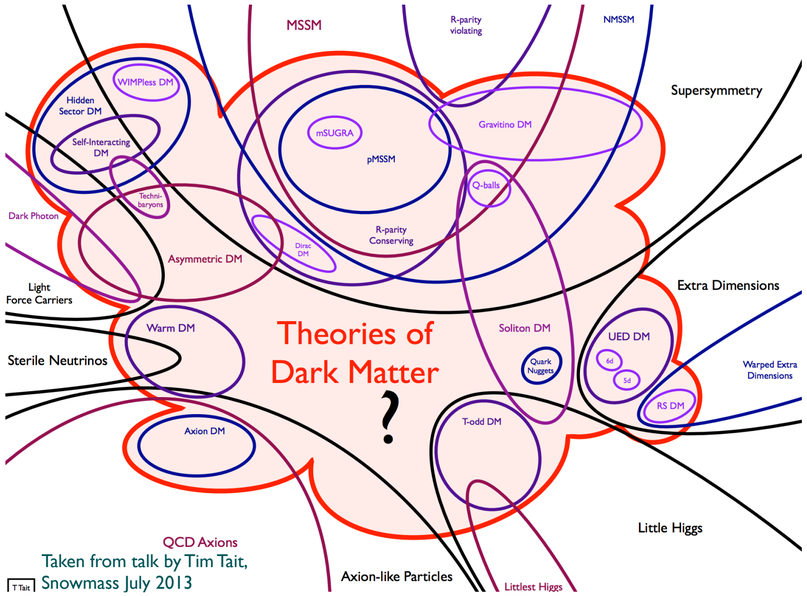
Where are the cracks?

How do I answer X?

Where do I start?

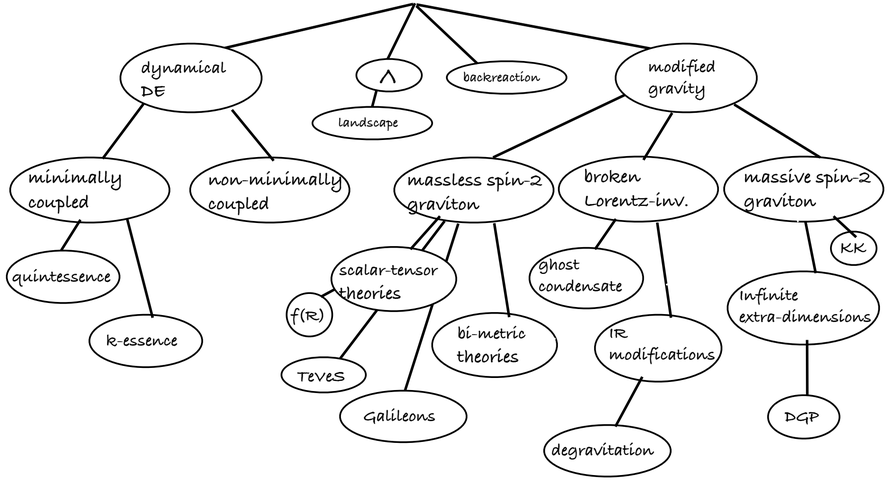
You know a lot +
you have time to learn!

Theory recap



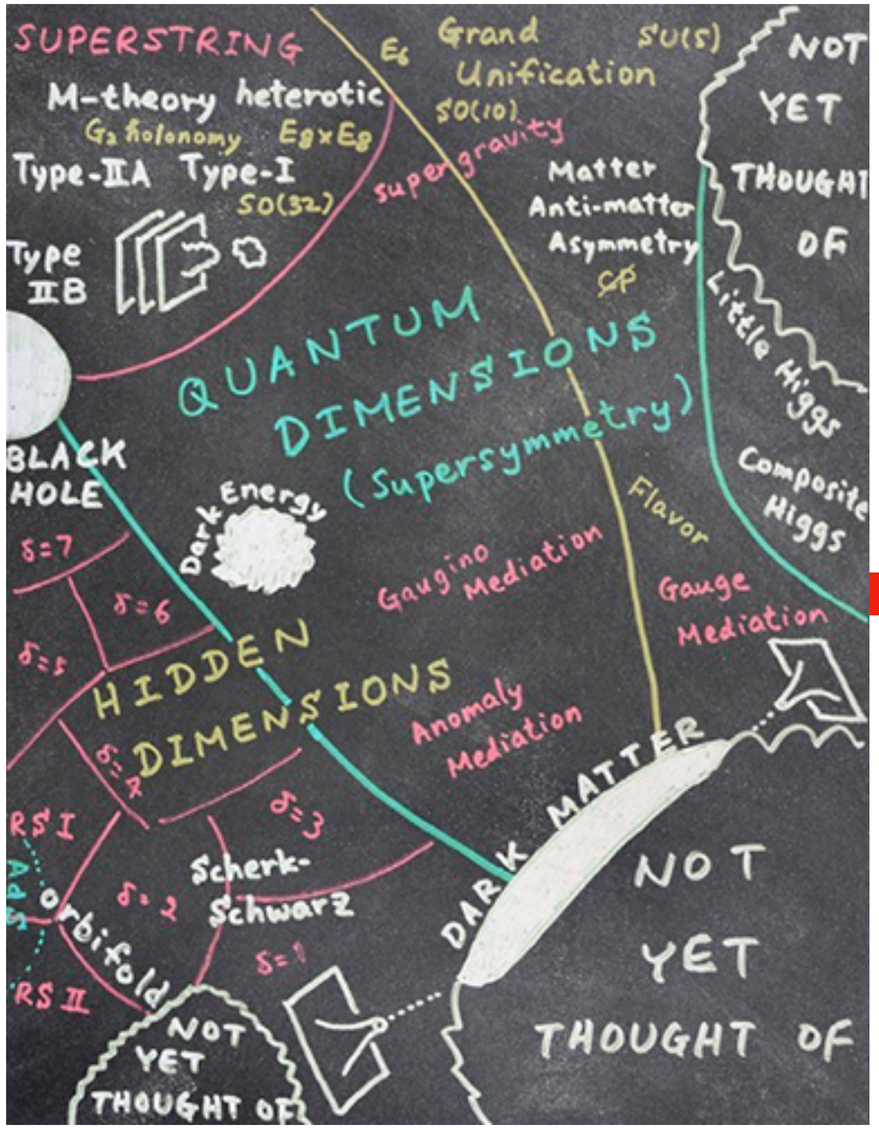
Taken from talk by Tim Tait, Snowmass July 2013

The theoretical landscape



Courtesy Alessandra Silvestri

CERN courier, H. Muroyama

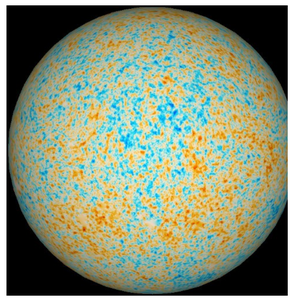


Everyone is confused

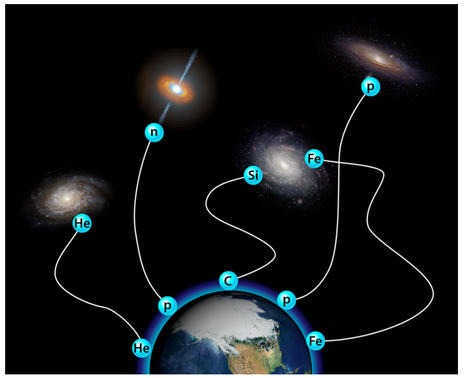
Messengers recap

How do we unveil the mysteries of Nature?

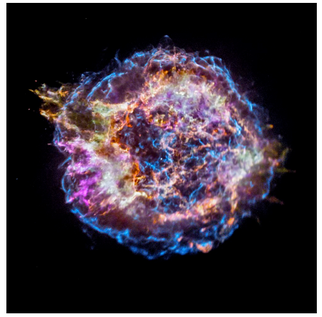
Light



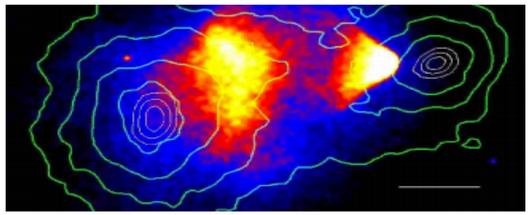
Cosmic-rays



Neutrinos



Dark matter

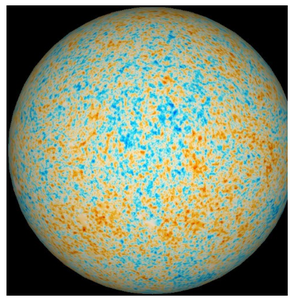


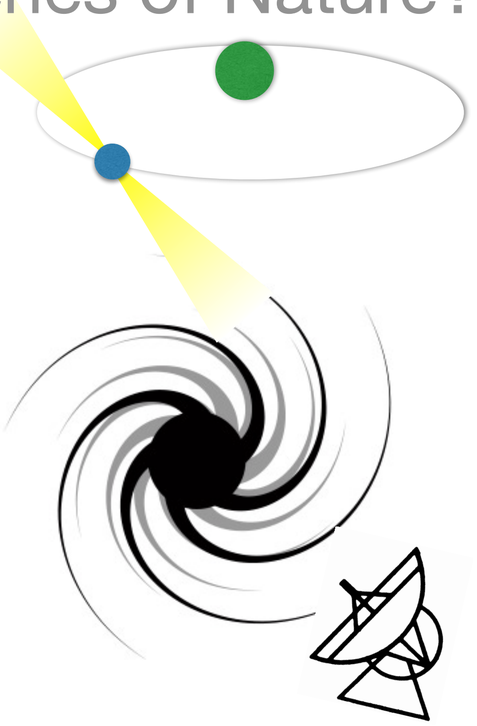
Gravitational waves

Messengers recap

How do we unveil the mysteries of Nature?

Light





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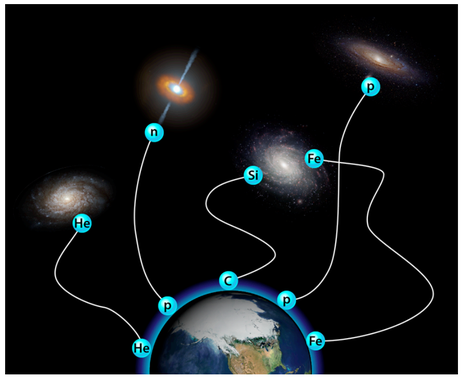

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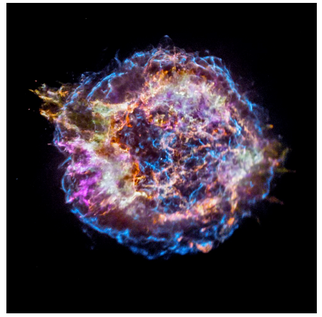

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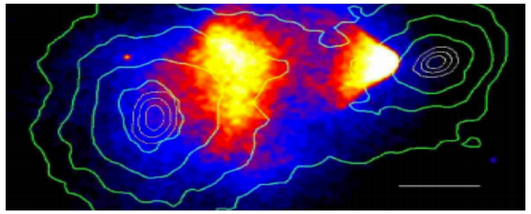


Gravitational waves

Messengers recap

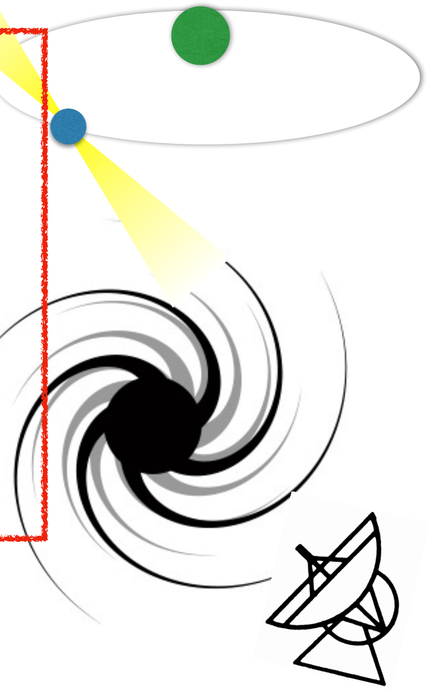
How do we unveil the mysteries of Nature?

What creates them (ic)?

With which properties?

How do they propagate?

How are they detected?



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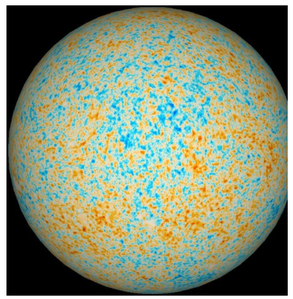

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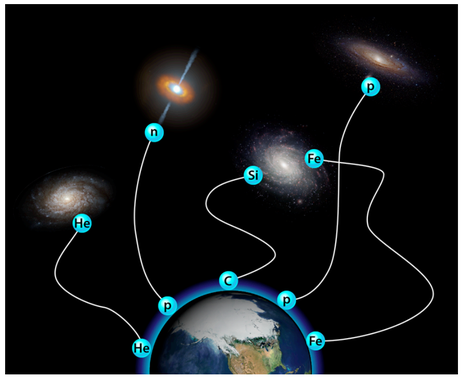

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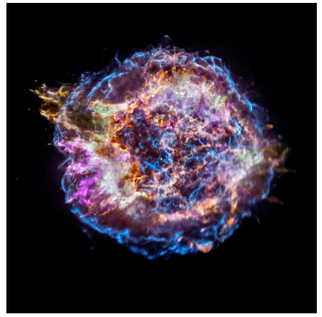

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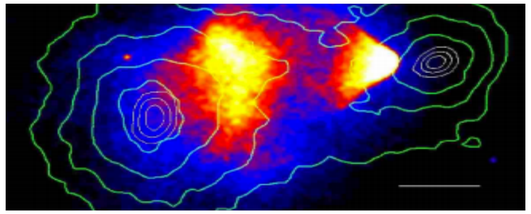

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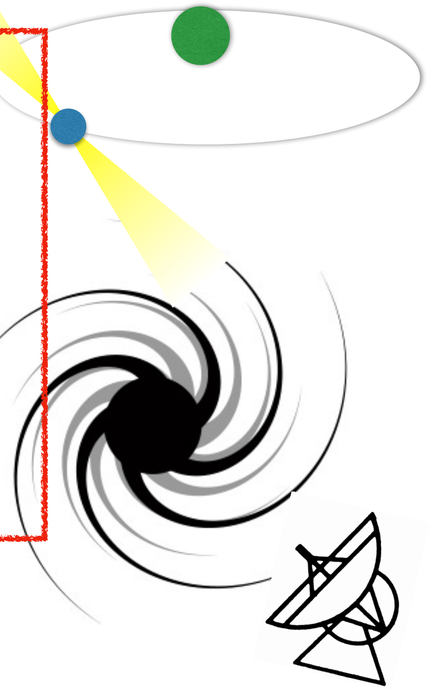

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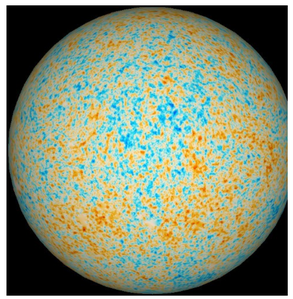

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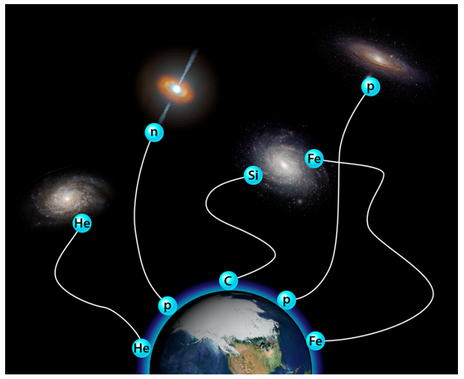

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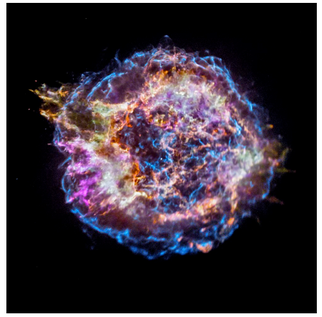

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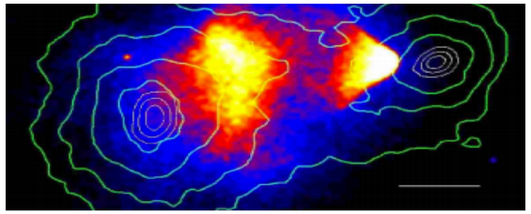


Gravitational waves

+ multiband aspect

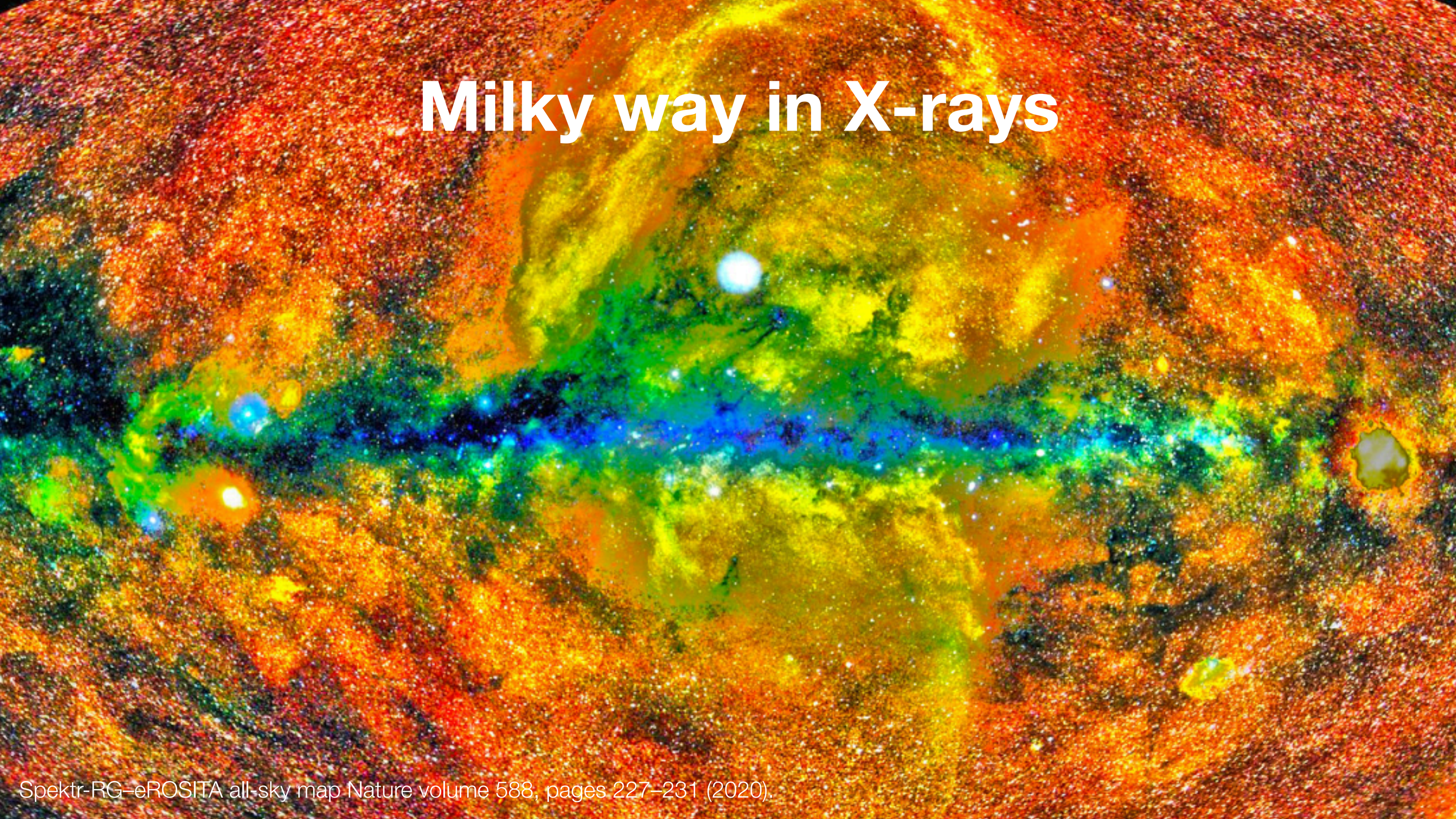
Milky way in radio band

http://www.chromoscope.net/

Milky way in ‘visible’ light

http://www.chromoscope.net/

Milky way in X-rays



Spektr-RG–eROSITA all-sky map Nature volume 588, pages 227–231 (2020).

Taxonomy of objects for fund. physics

BBN	Globular clusters
CMB	Supernovae
Large scale structure	Families of stars
Intergalactic medium	Neutron stars
Galaxy clusters	Pulsars
Galaxies	Black holes
AGN	…

What's the standard picture?

Is there a 'clean' observable?

e.g. mass of neutron stars

Can it be modified by a new model?

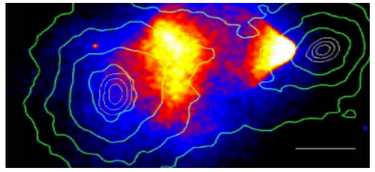
Will it be degenerate with some standard physics?

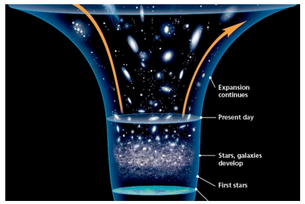
Are there cross correlations?

List of open questions

Fundamental

Observational



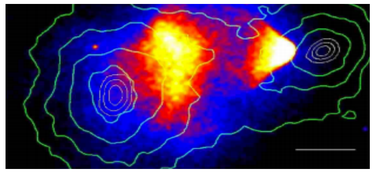


List of open questions

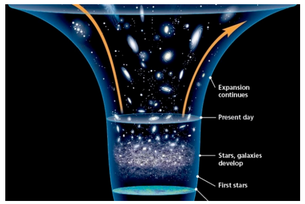
Fundamental

Neutrinos: What's the mass?
What mechanism? Why their flavour structure?
How do they interact?

Why are there baryons in the Universe? Mass of the Higgs?
Are there new forces? Why are we in a metastable Universe?
What happens in dense media?



Dark matter: What's its mass?
What's its spin? How is it produced?
How does it interact? How do we feel it locally?



Dark energy: Why so small? Is it constant?
Coincidence problem (why now)? What is it?
Does it interact? Can we feel it locally?

Observational

Gravitation: Can we test quantum gravity?
Can we modify gravity for a good purpose?
Are we seeing black holes? GWs pheno?

List of open questions

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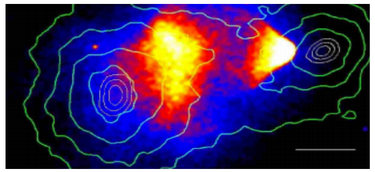

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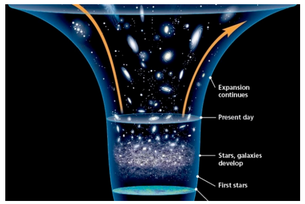

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Observational

H0 tension

ΛCDM model:
small scales problems?

Reionization data

Larger volumes

...

Are we living boring times?

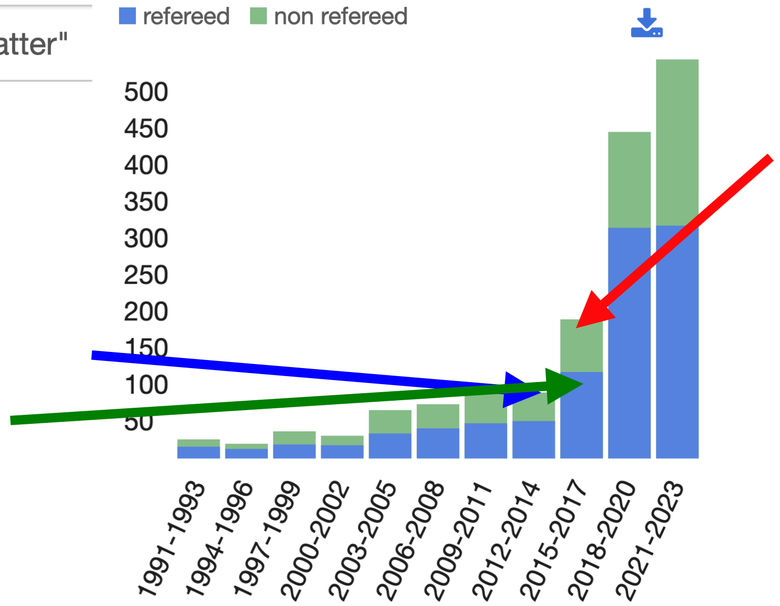
One counterexample

Are we living boring times?

One counterexample

abs:"gravitational waves" and abs:"dark matter"

Your search returned **1,631** results



i) LIGO/Virgo

ii) LISA gets approved

"Dark sector fever"

i) + ii) + lack of results for traditional searches

Are we living boring times?

One counterexample

ads

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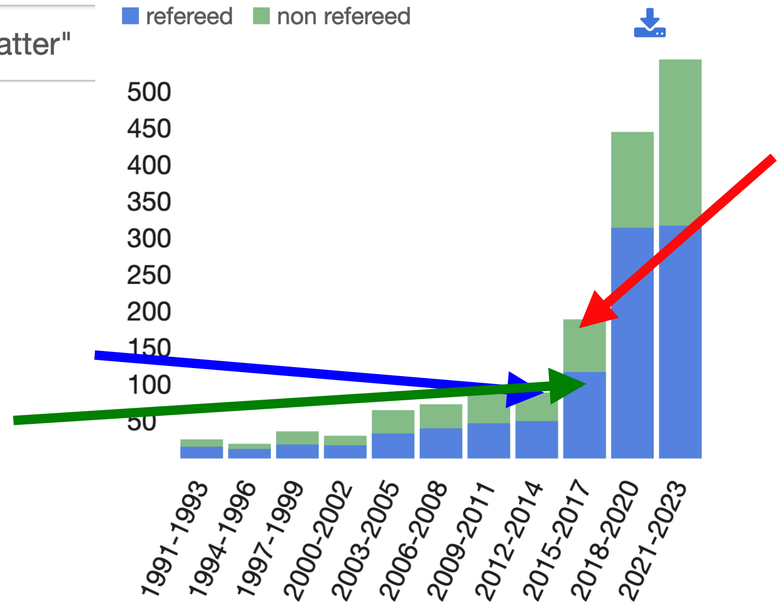

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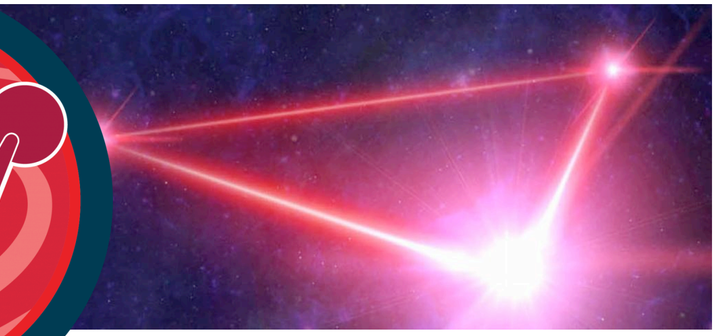
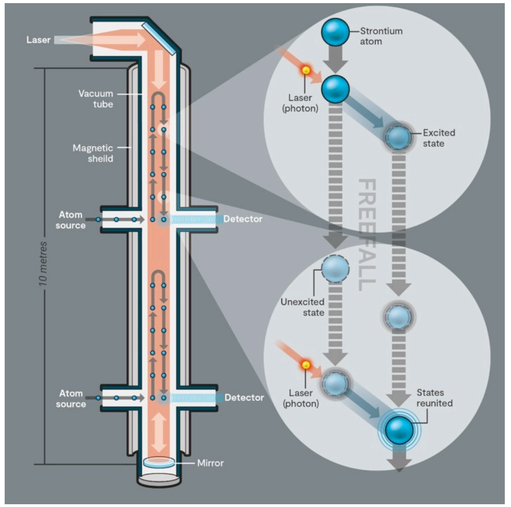
ESA | NASA

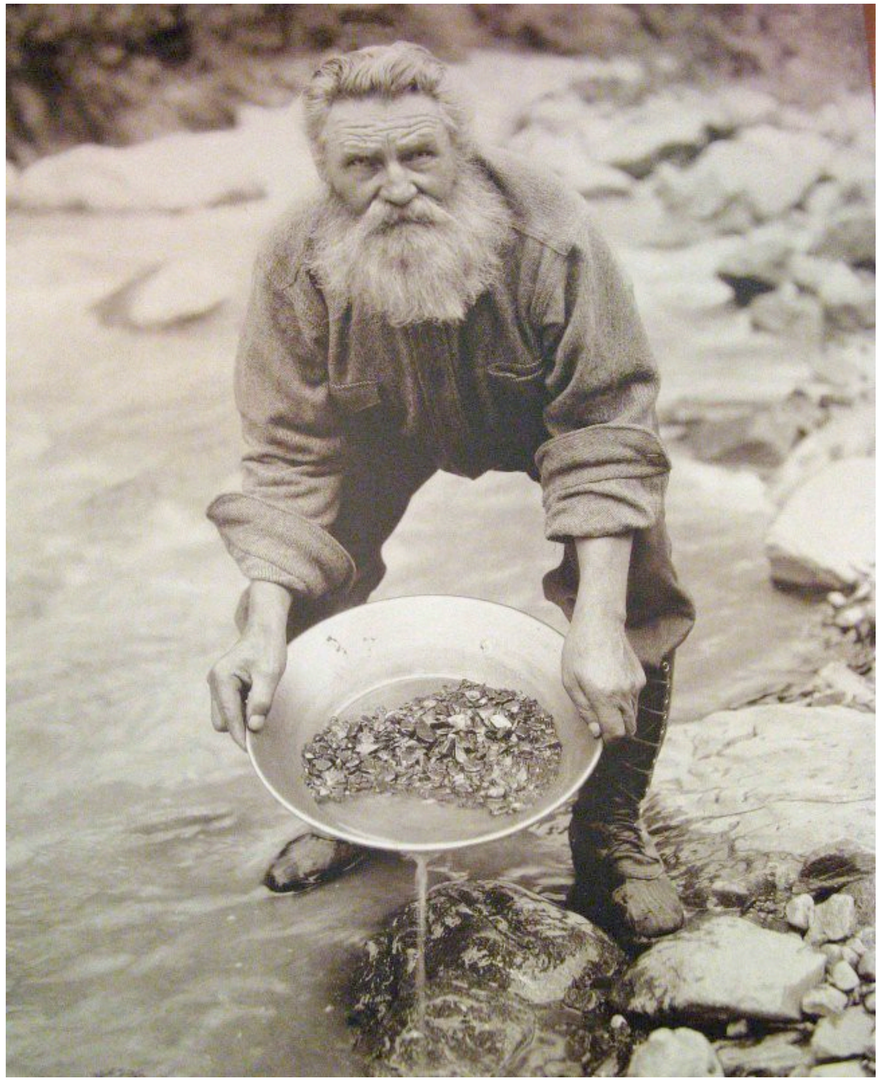
lisa



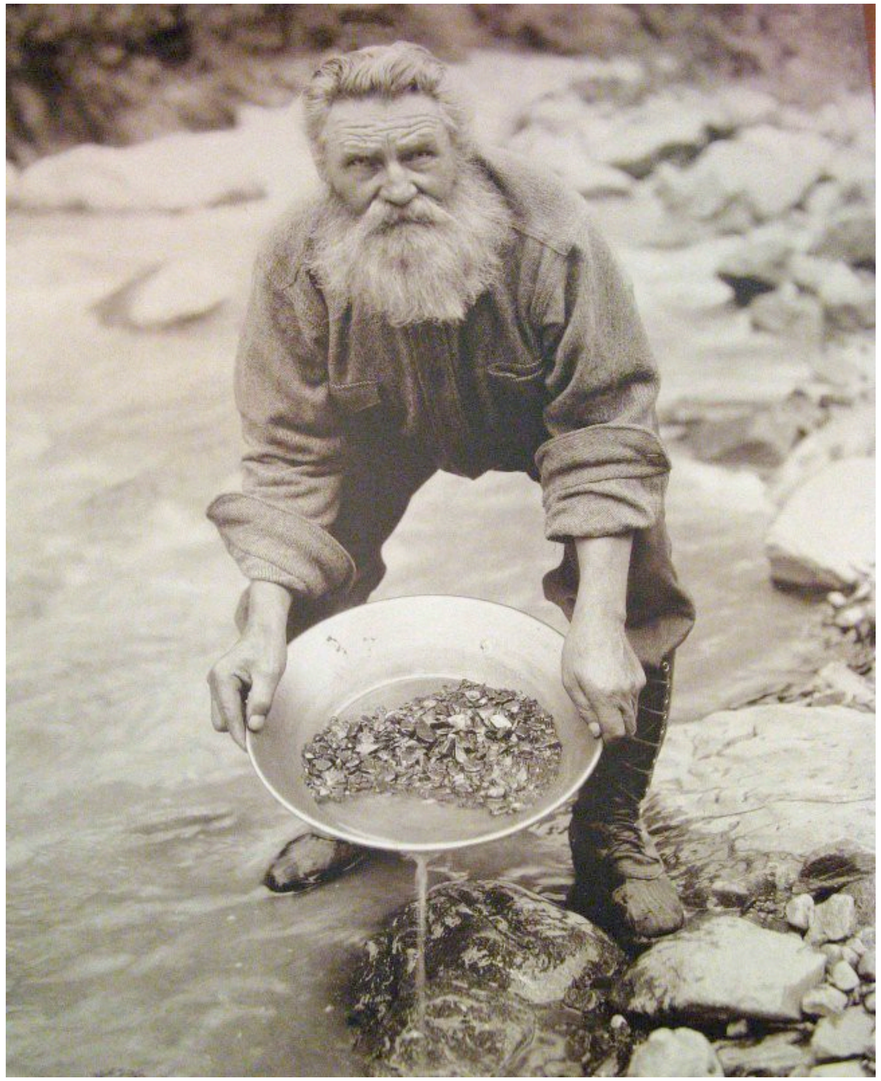
AION



Remark on opportunities



Remark on opportunities



Particle Physics

Astroparticles in Cosmology

Fundamental Physics w/ CMB

DE Th&Observation

Fundamental Physics w/ LSS

Fundamental Physics w/ galaxies

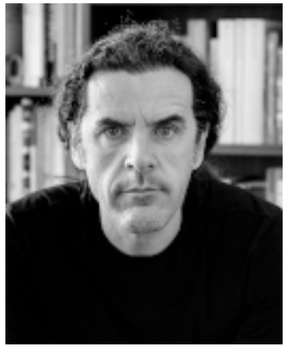
Early Universe & Inflation

DM Th&Observation

Fundamental Physics w/ C-rays & γ-rays

Neutrinos in Cosmo&astroph

Gravitational waves



Distinguished lecturer

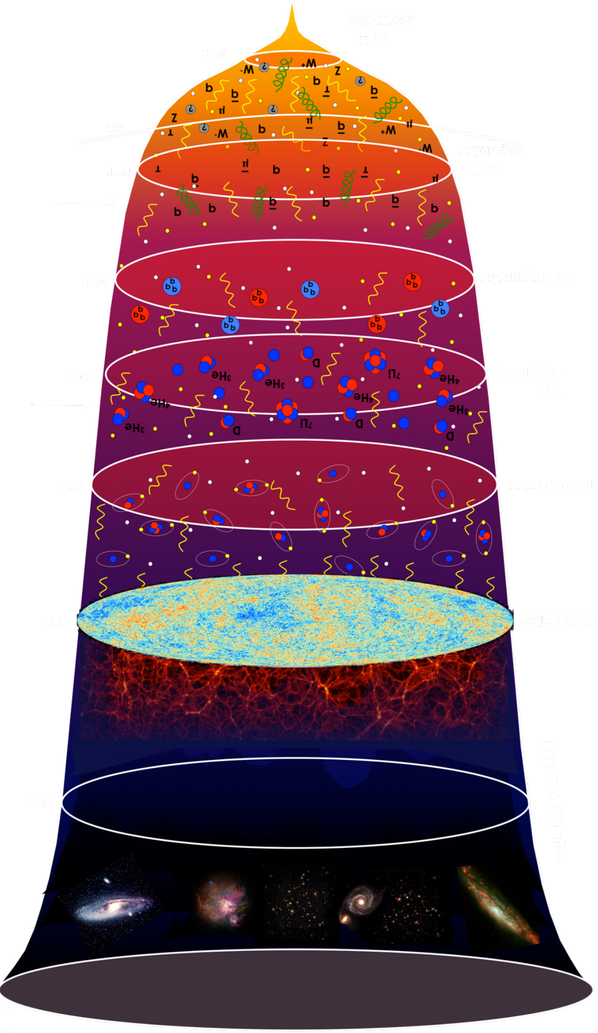
Cosmological DM Sims

Galaxy Simulations

Reconstruction Initial Conditions

Art & Science: Scientific Outreach

Anything else?



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EW phase transition	20 ps	10^{15}	100 GeV
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Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

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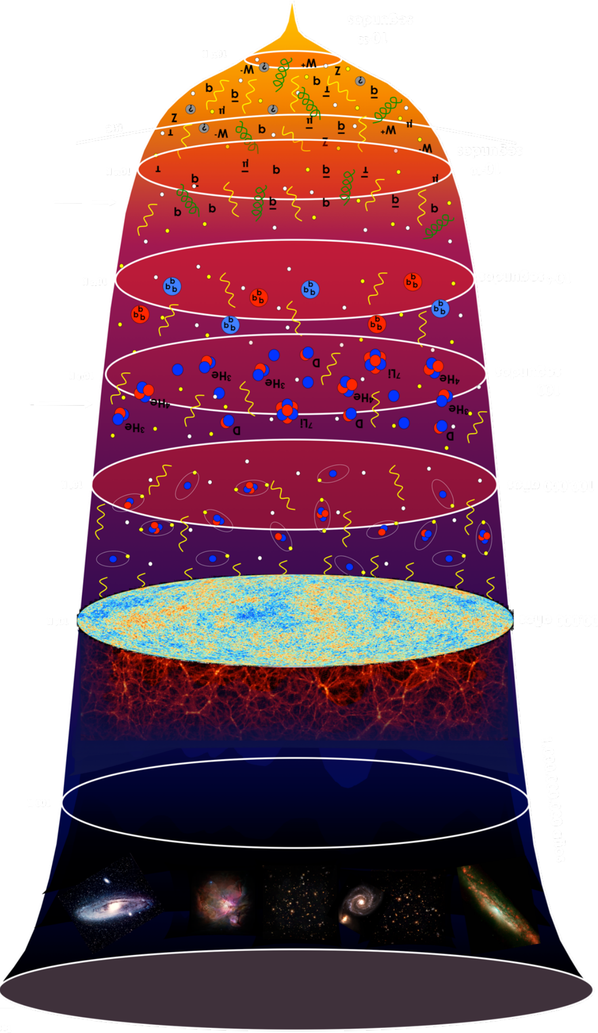

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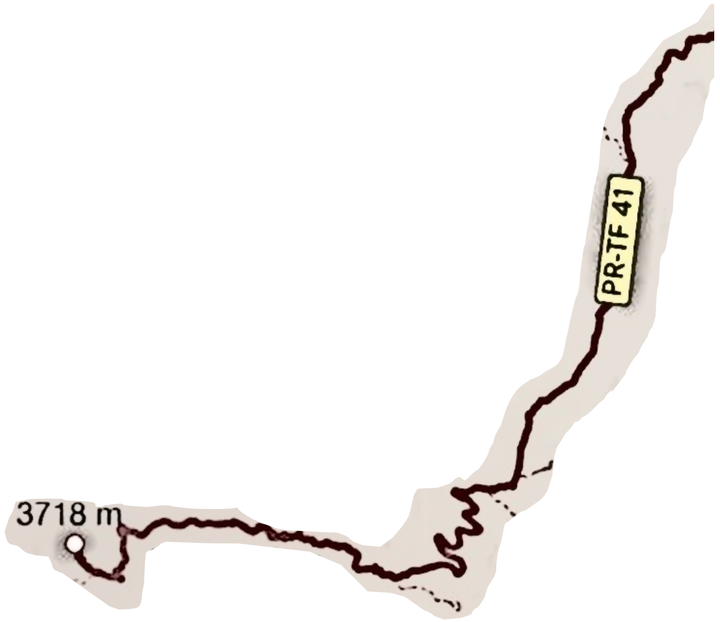

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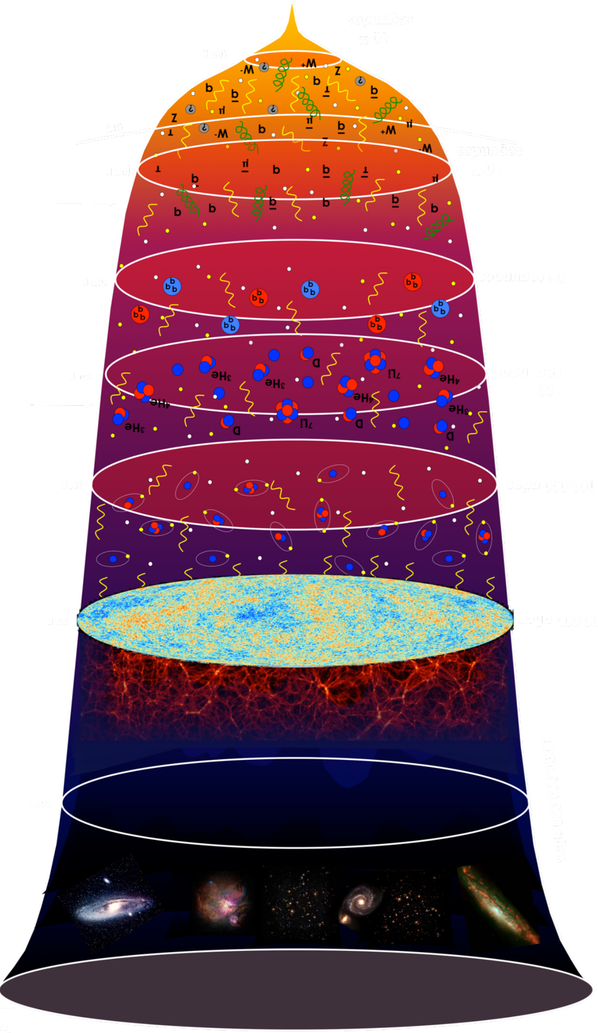

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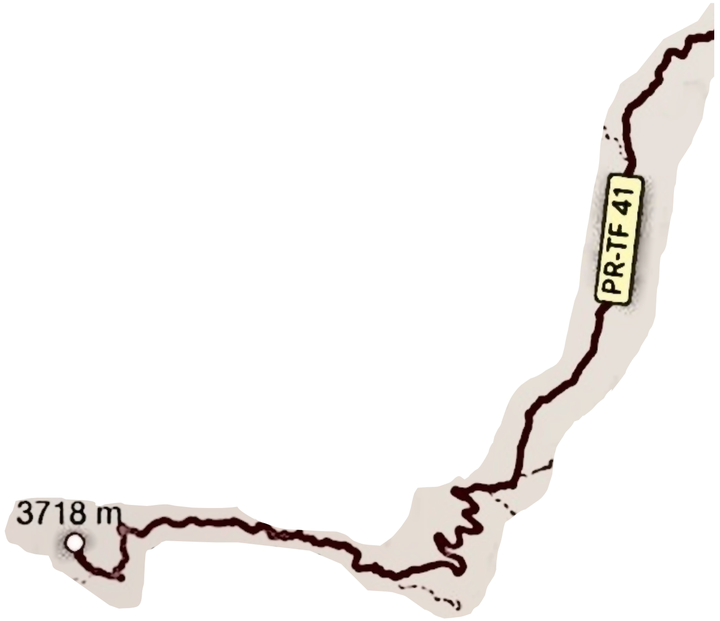

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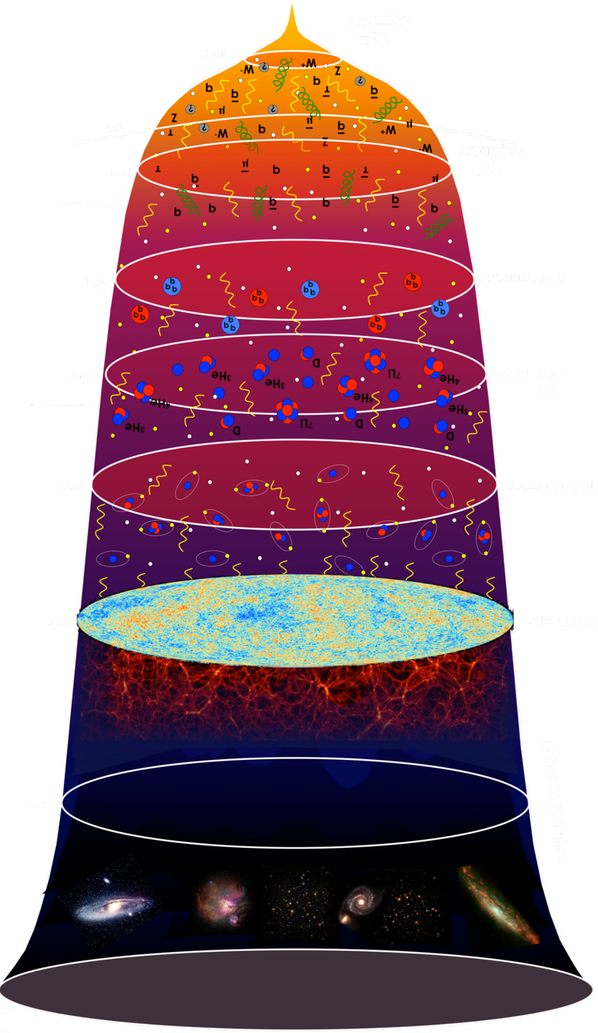

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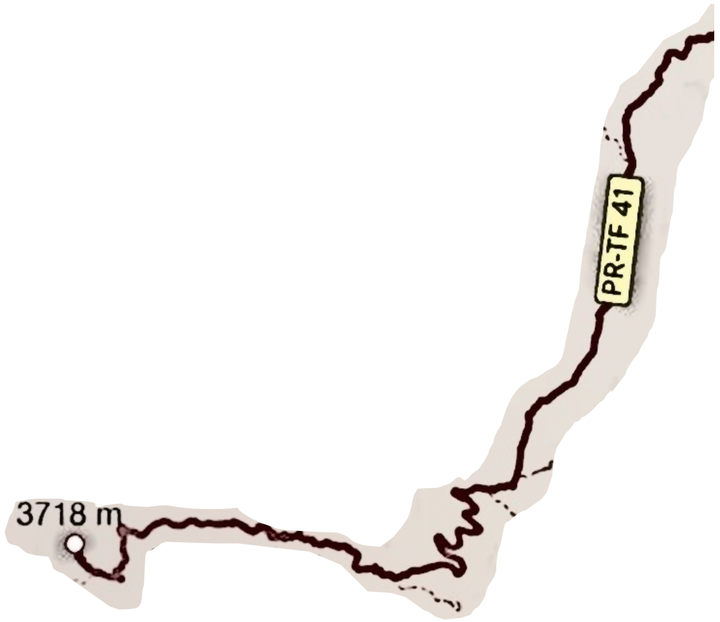

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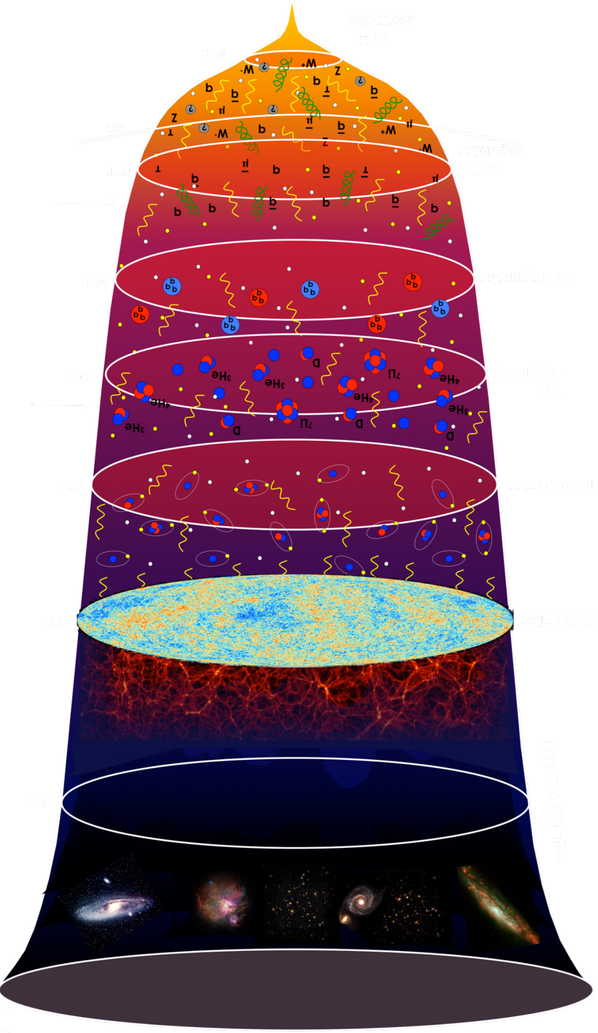

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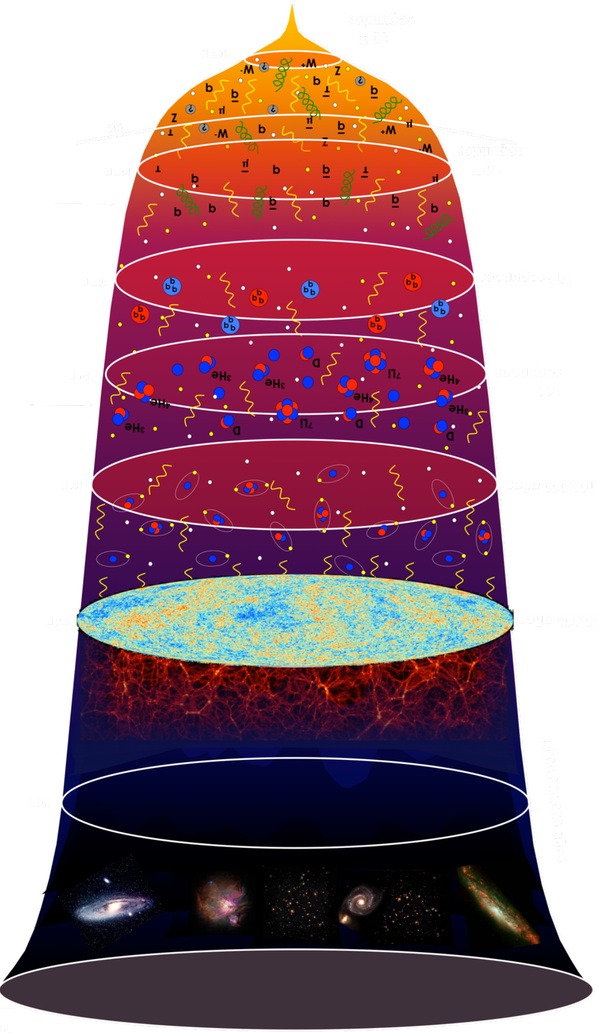
iii) Precision frontier

...

Anything else?



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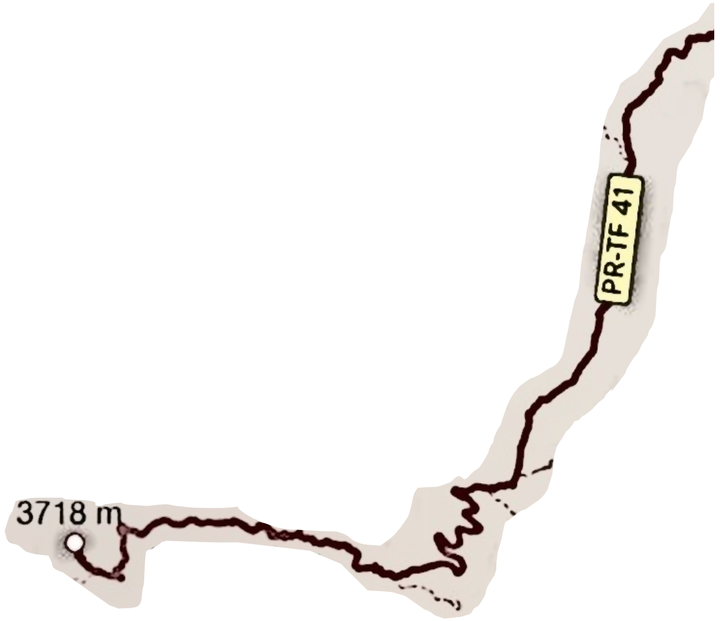
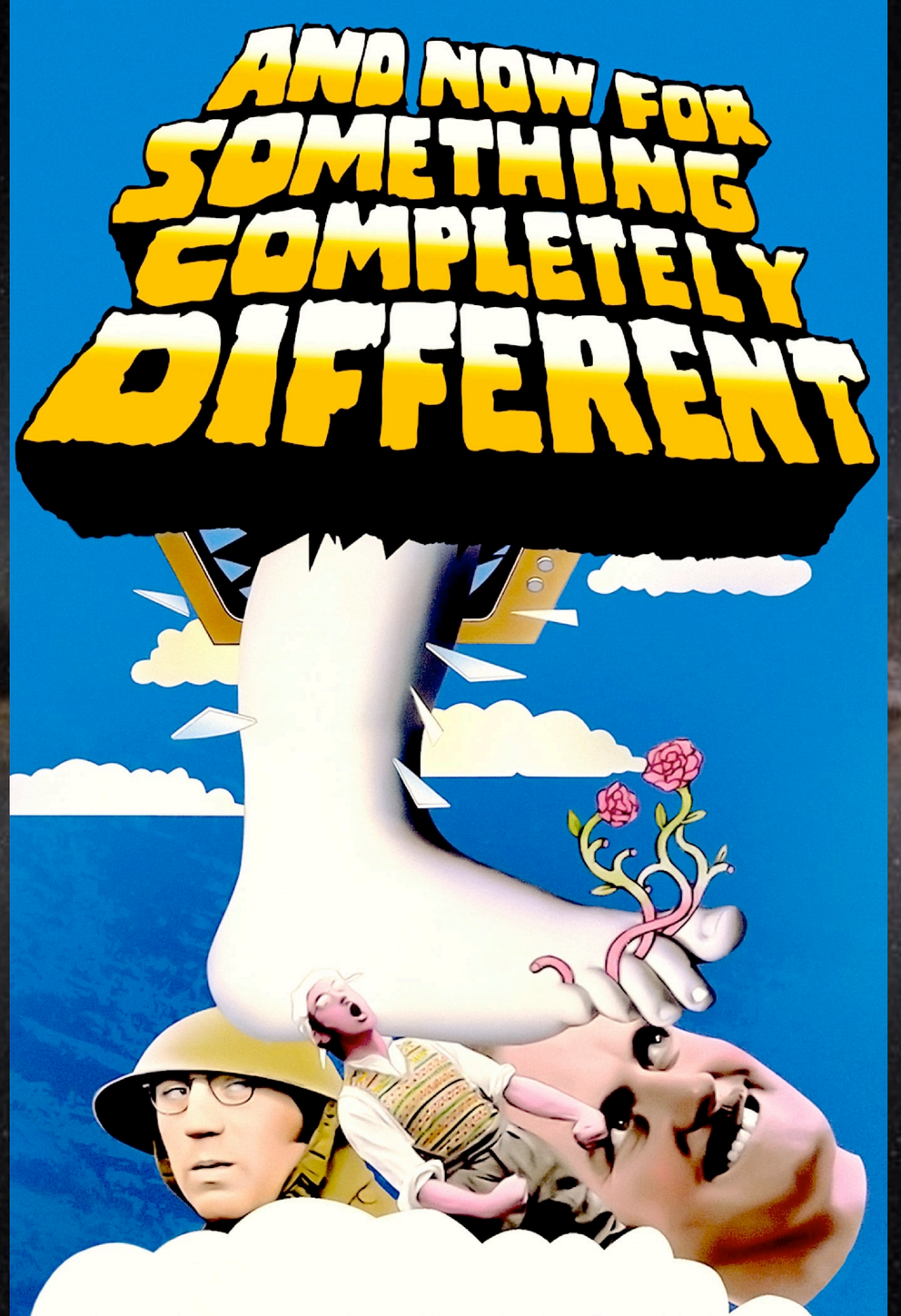
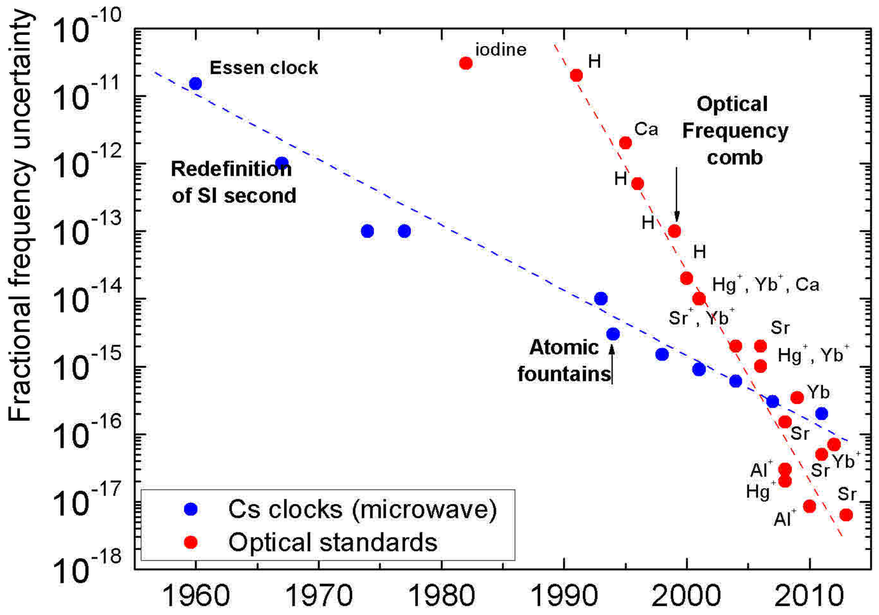


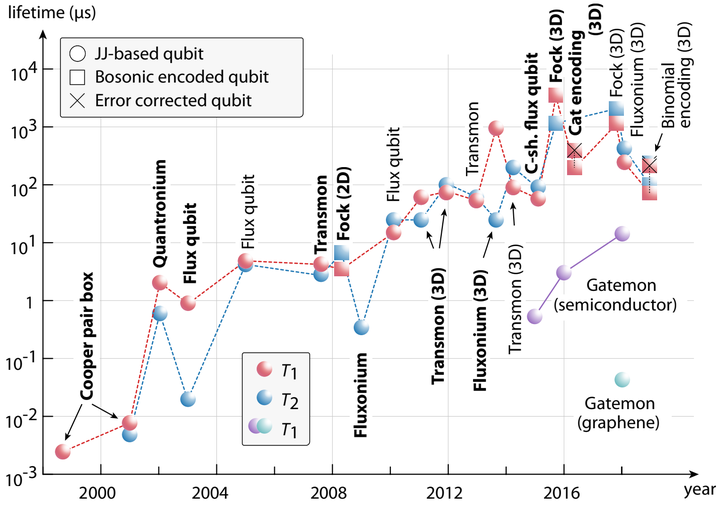

AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

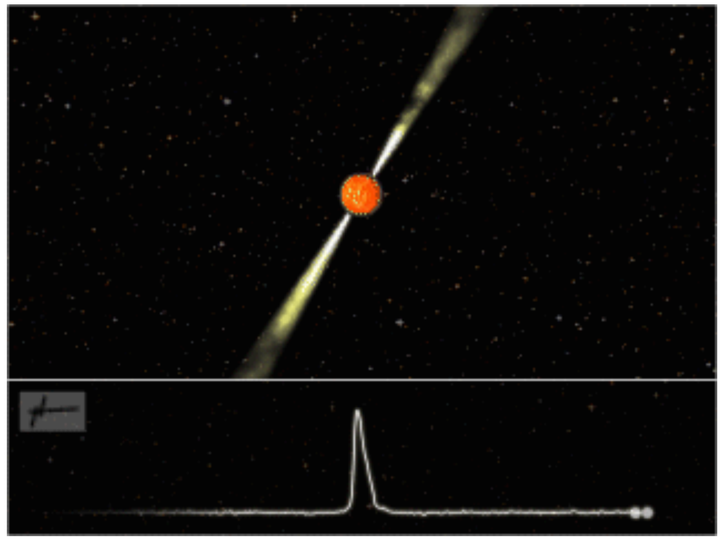
Two examples of the precision frontier

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$



1905.13641





Pulsar timing

PSR J0437-4715 (mass similar to that of the Sun)

Ps = 5.757451924362137(2)ms

J1903+0327

$$\dot{P}_b = (-53 \pm 33) \times 10^{-12}$$

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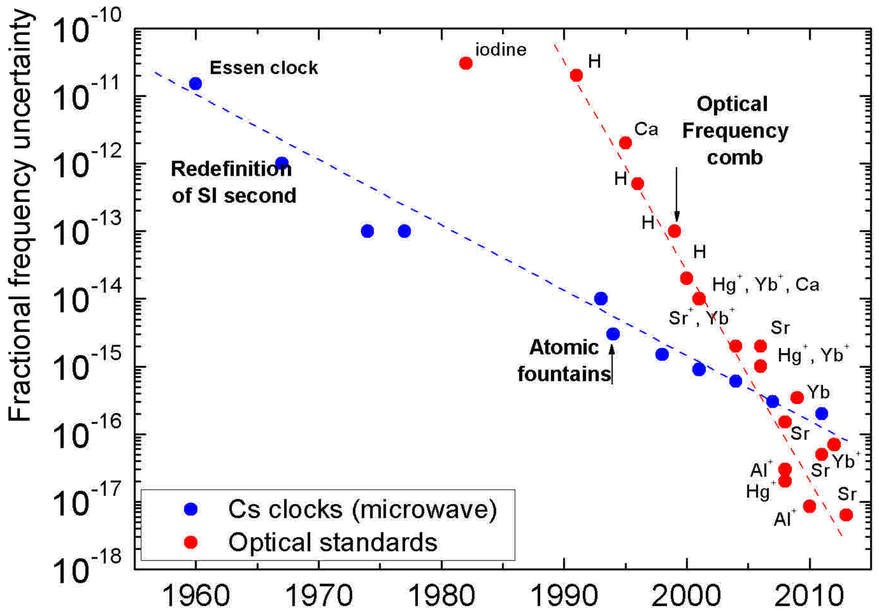
$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$



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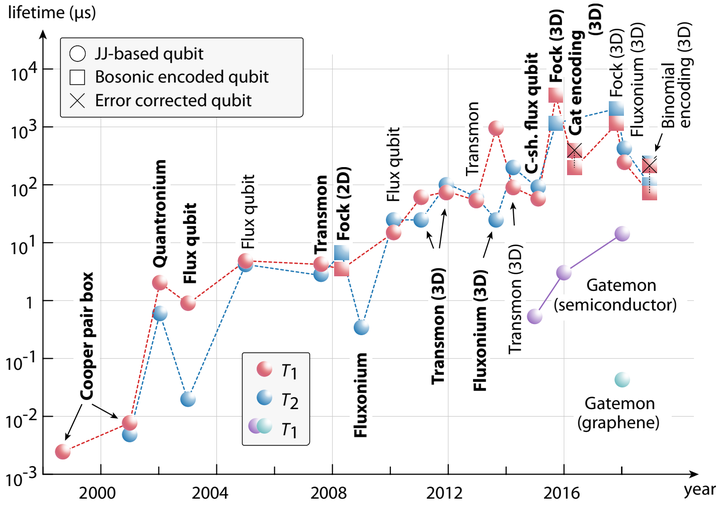

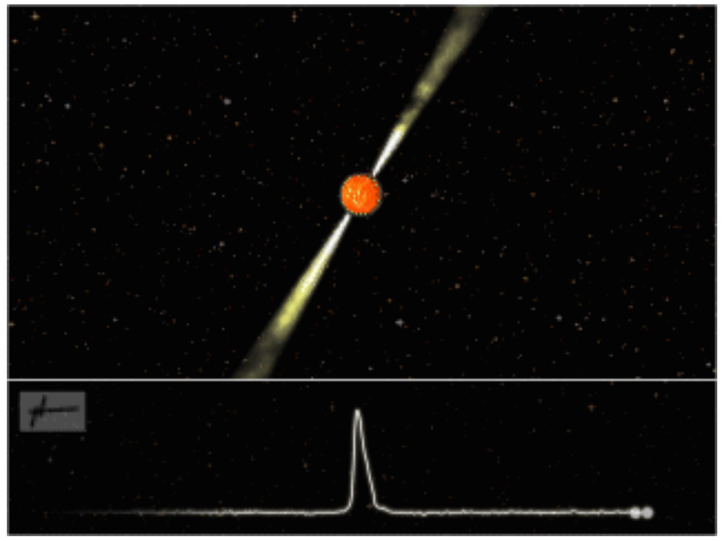

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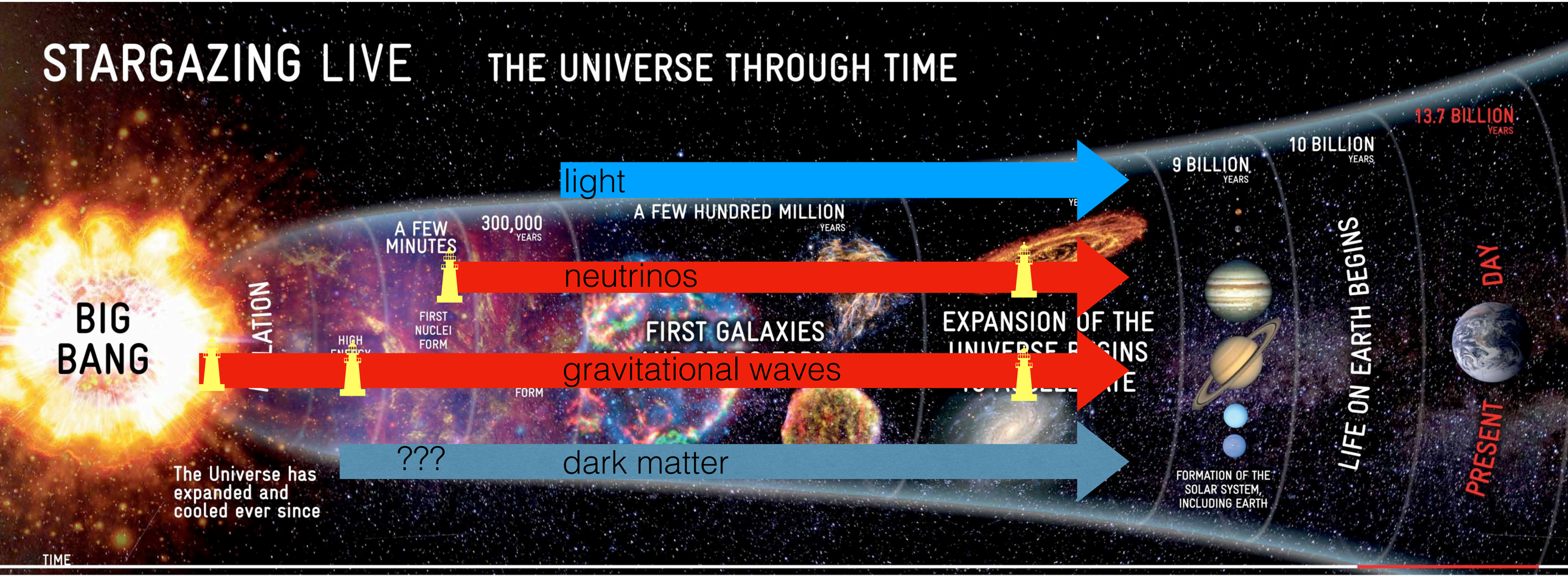
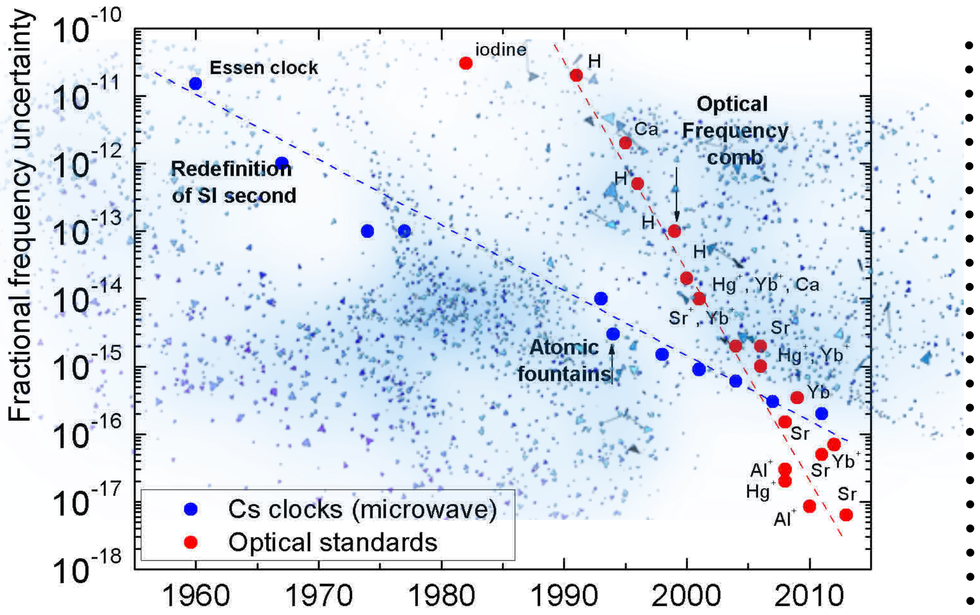
Fundamental cosmological backgrounds



very weak backgrounds, of fundamental origin, permeate the Universe…

Two examples of the precision frontier

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$



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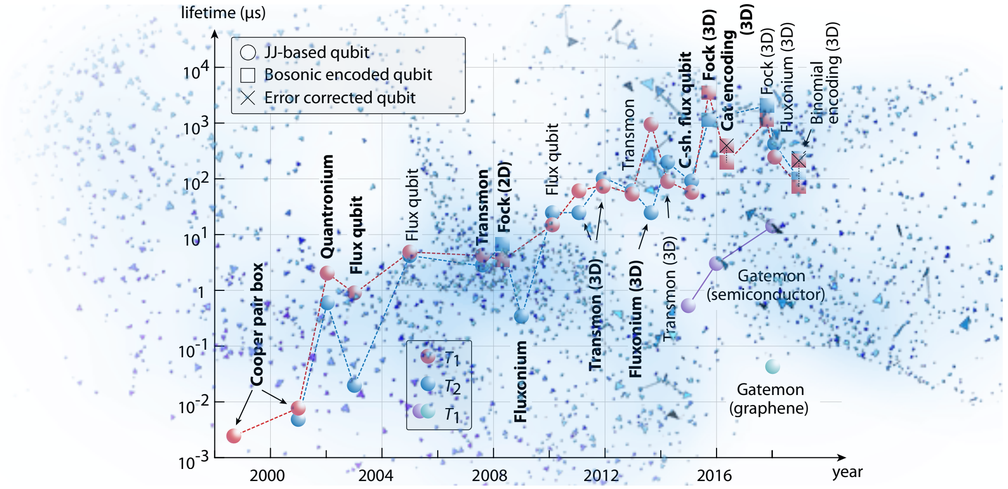

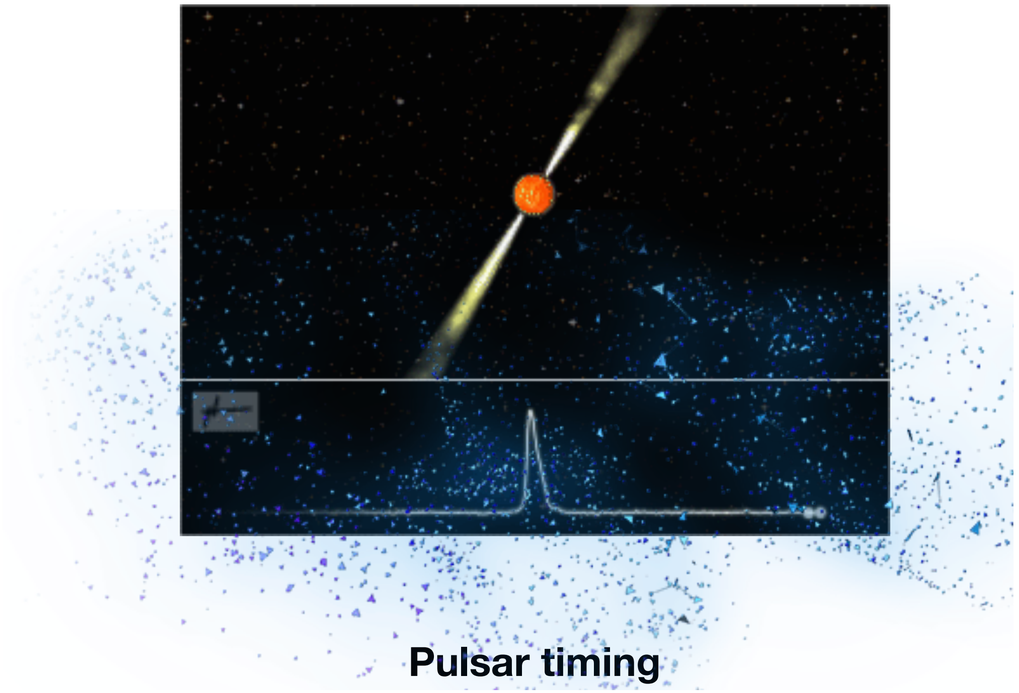

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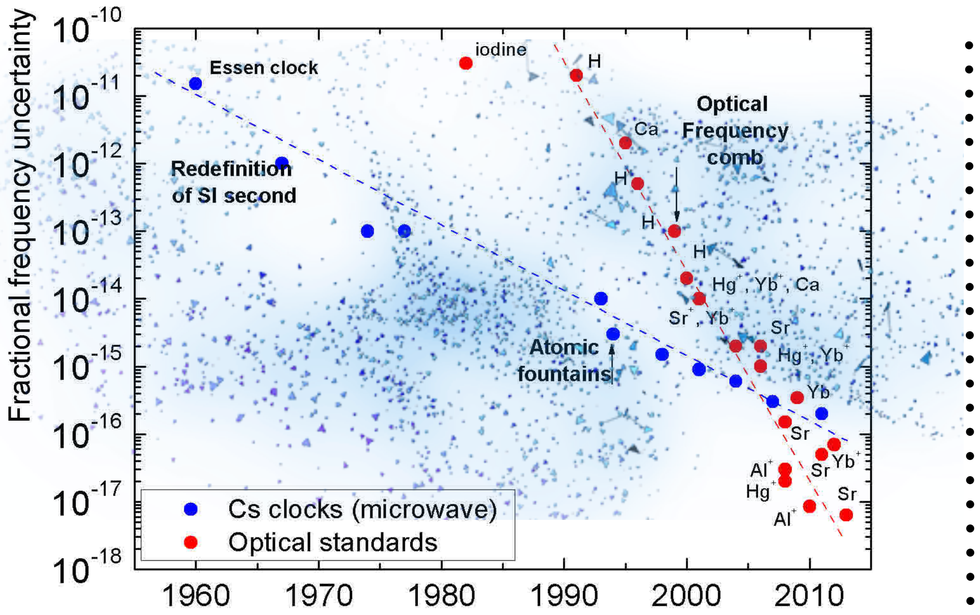

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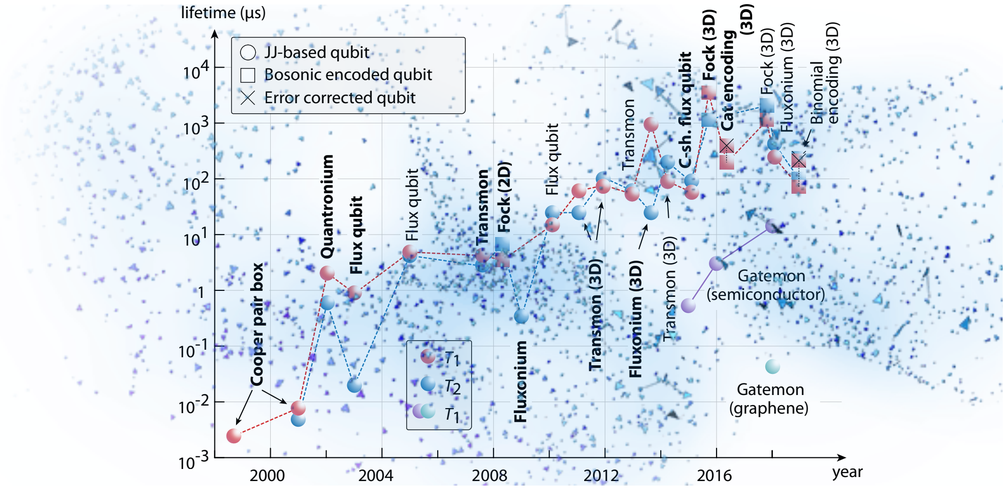

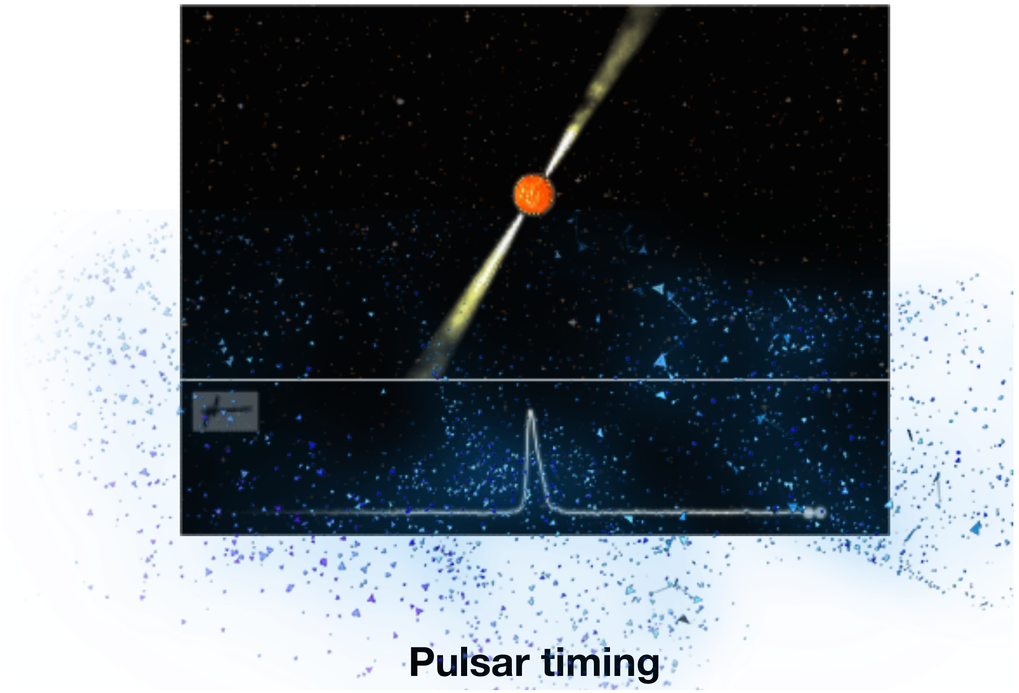

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How does an atomic clock feel dark matter?

Me 2015-2017

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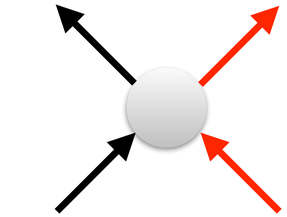
Me 2015-2017

‘Traditional’ Direct Detection

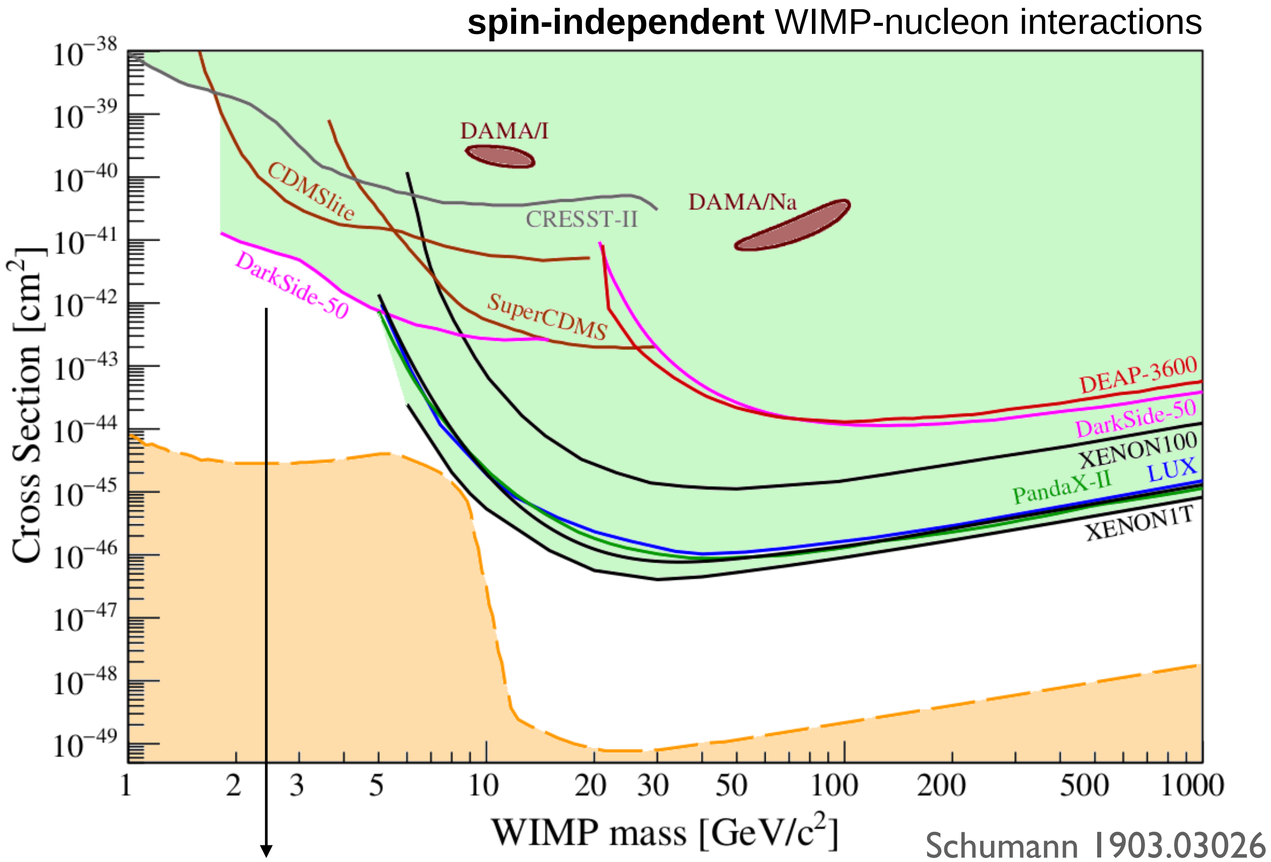
scattering



DM nucleus

$$E_R^{\max} \sim \left(\frac{m_\chi}{\text{GeV}}\right) \text{keV}$$

$$\vec{q} = \vec{p}_1 - \vec{p}_2$$



Schumann 1903.03026

low-energy threshold

dramatic loss of sensitivity at low mass
(still ‘high’ mass in the DM landscape)

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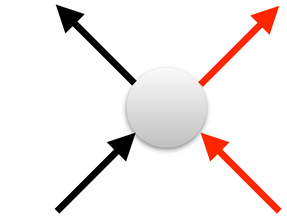

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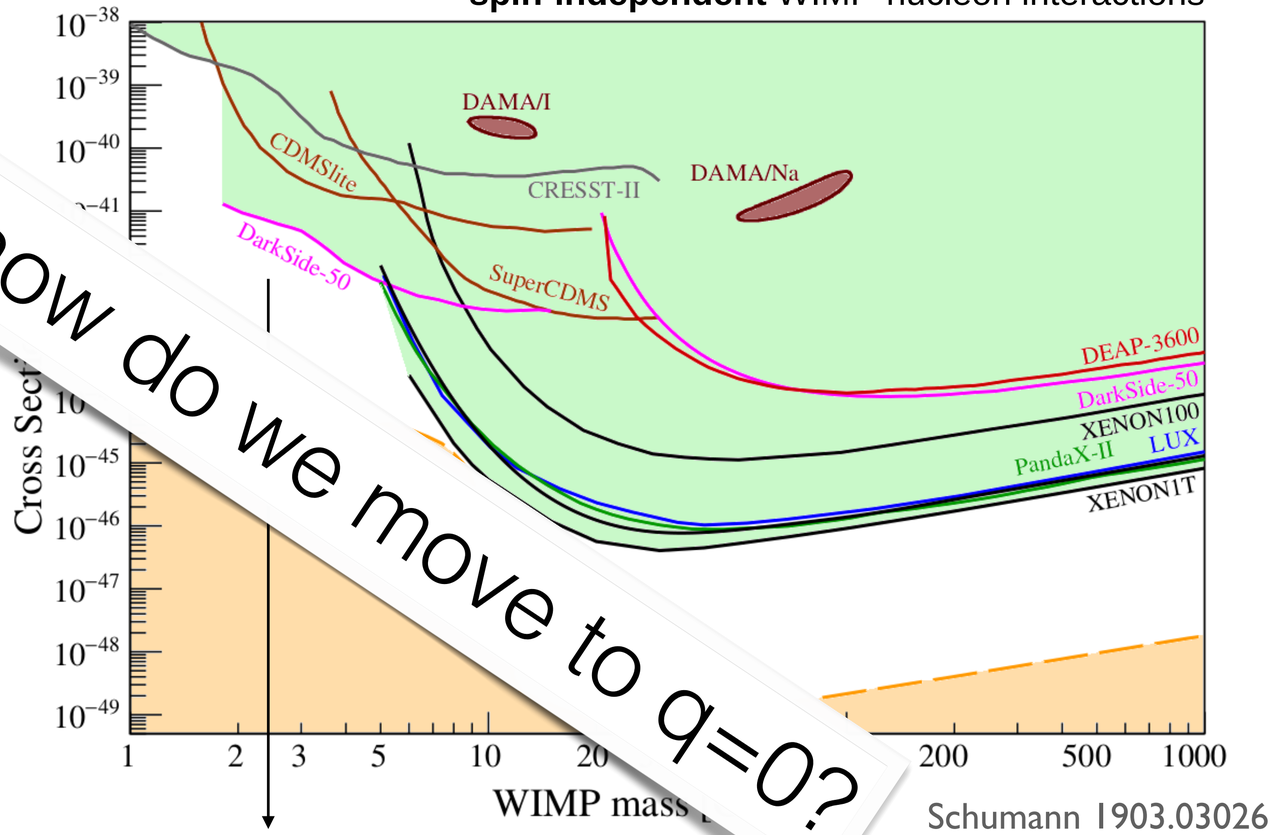
spin-independent WIMP-nucleon interactions



how do we move to q=0?

Schumann 1903.03026

low-energy threshold

dramatic loss of sensitivity at low mass
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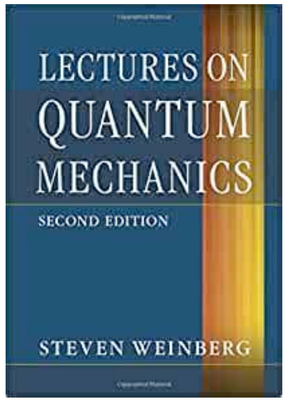
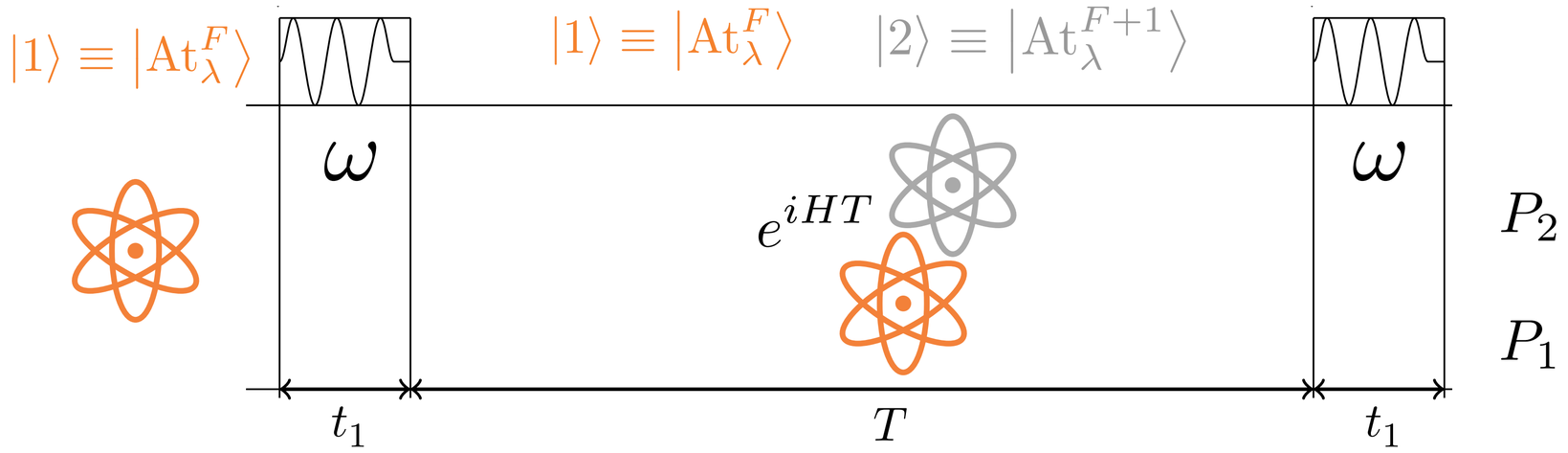
Very active field! See e.g. Alexander et al 1608.08632

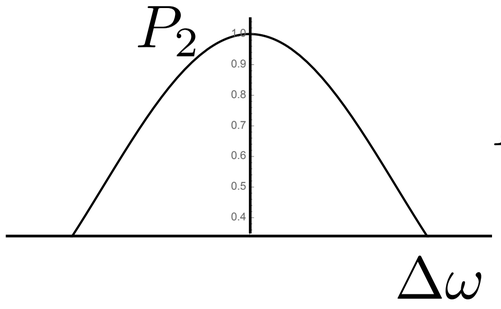
How does an atomic clock feel dark matter?

R. Alonso, DB and P. Wolf
1810.00889 & 1810.01632

Ramsey sequence (this uses only QM!)







$$P_2 = \cos[\Delta\omega\, T/2]^2 \quad \text{with} \quad \Delta\omega \equiv \omega - (E_2 - E_1)$$

$$\partial P_2 = 0 \;\Rightarrow\; \omega_{\max} = \Delta E$$

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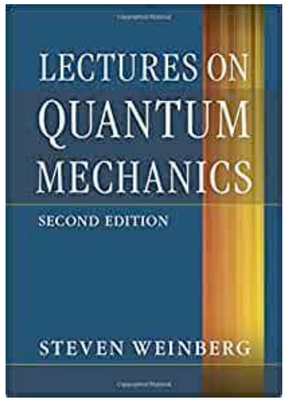
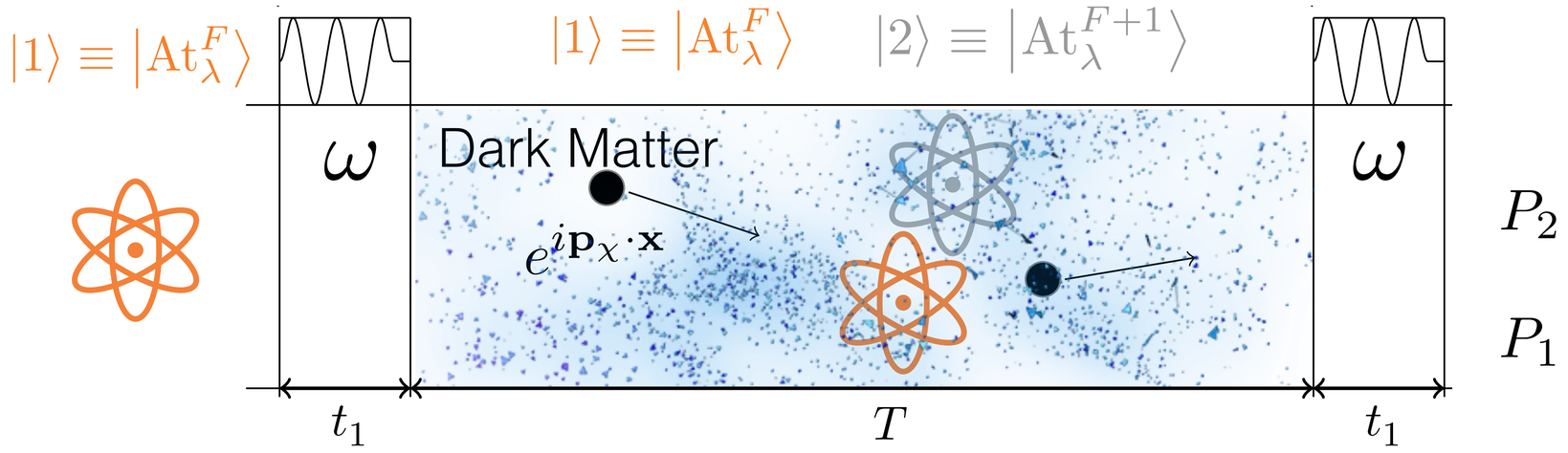
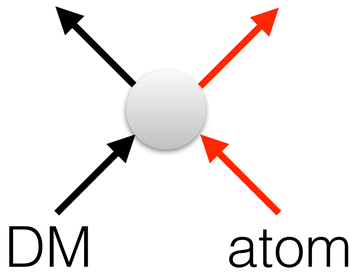
Ramsey sequence in the presence of DM







$m_{\mathrm{DM}} \ll m_{\mathrm{atom}}$

scattering amplitude at $q = 0$

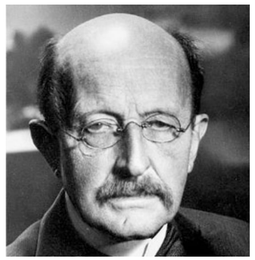
$$P_2 = \cos[\Delta\omega\, T/2]^2 + \frac{\pi n_\chi v\, T}{p_\chi}\mathrm{Re}[\bar{f}_1(0) - \bar{f}_2(0)]\,\mathrm{sin}[\Delta\omega T]$$

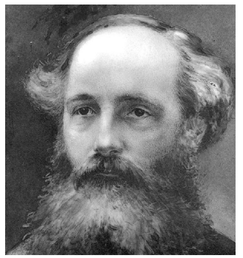
$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\mathrm{max}} = \Delta E + \delta_{\mathrm{DM}}$$

QM allows us to measure at $q = 0$ and hence move to **low DM masses**!

Why is ultralight DM so different?

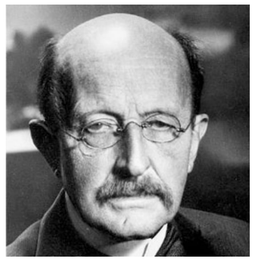
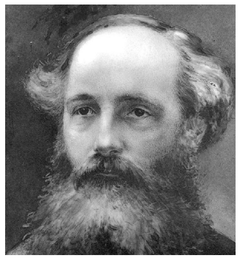
$\hbar\omega$

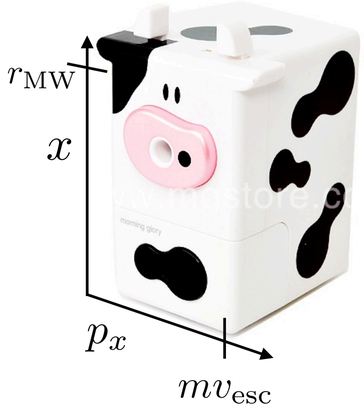




$F_{\mu\nu}$

Why is ultralight DM so different?

$\hbar\omega$   $F_{\mu\nu}$



i) escape velocity $\sim 2\times10^{-3}c$ ii) size $100\ \mathrm{kpc}$

$$\Delta x\Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75}\left(\frac{m}{\mathrm{eV}}\right)^3$$

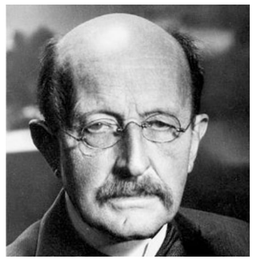
$$N_p = \frac{M_{MW}}{N_s m} \sim 10^3\left(\frac{\mathrm{eV}}{m}\right)^4$$

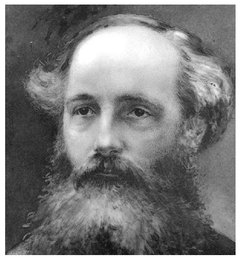
For ULDM, field has huge occupation numbers with random phases:

it can be treated as a classical field (all the quantum properties are suppressed)

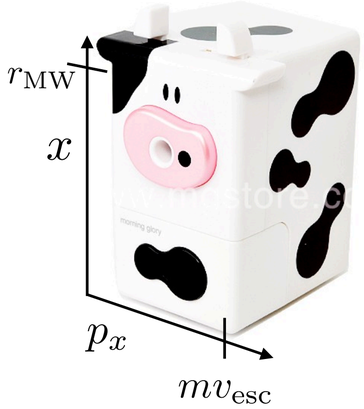
Why is ultralight DM so different?

$\hbar\omega$





$F_{\mu\nu}$



i) escape velocity $\sim 2\times10^{-3}c$ ii) size 100 kpc

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For ULDM, field has huge occupation numbers with random phases:

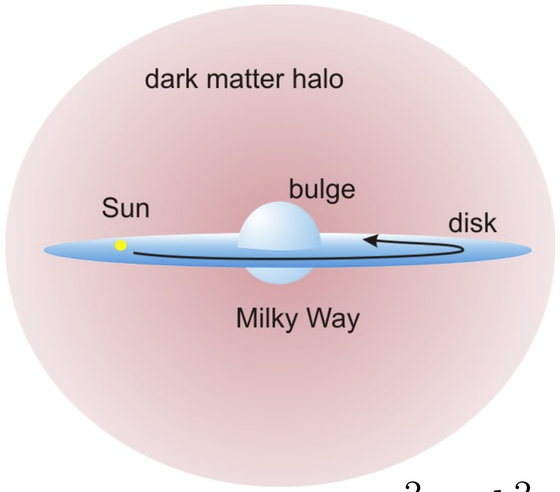
it can be treated as a classical field (all the quantum properties are suppressed)

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu\phi)^2 - m^2\phi^2\right] \rightarrow \phi_k \sim e^{i(\omega t - kx)}$$

in a virialized halo

Q: fermions?

‘Coherent’ effects of ULDM in the MW



Virialized collection of waves $\phi_k \sim e^{i(\omega t - kx)}$

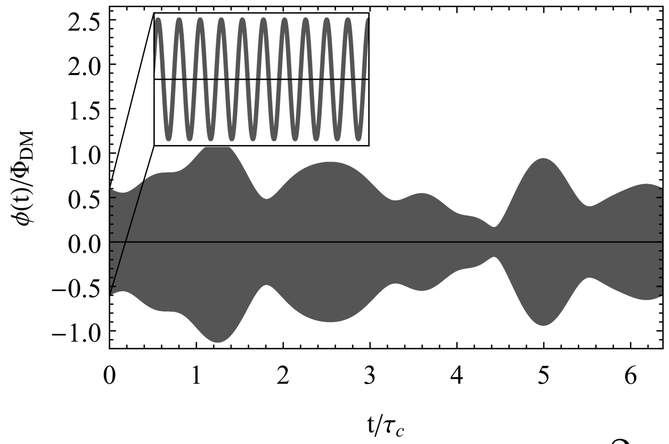
$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

distribution: $\sigma_0 \sim 10^{-3} c$ in the MW

$$\omega^2 = k^2 + m^2 \approx m^2(v^2+1)$$

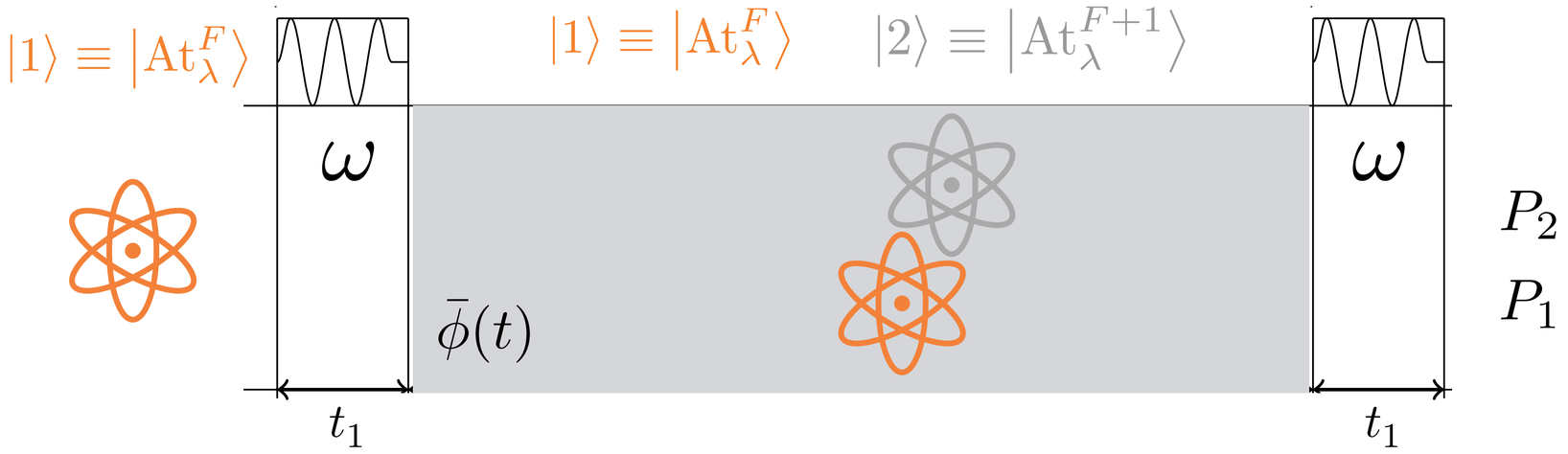
since $v \sim \sigma_0 \ll 1$ → $\omega_v \approx m$ → $\phi \propto \phi_0 \cos(mt + f)$

$\omega_0 \approx m$



$$\tau_c \sim 8\,\mathrm{months} \left(\frac{10^{-3}}{V_0}\right)^2 \left(\frac{10^{-15}\mathrm{eV}}{m_\Phi}\right)$$

‘Coherent’ effects of ULDM in the MW

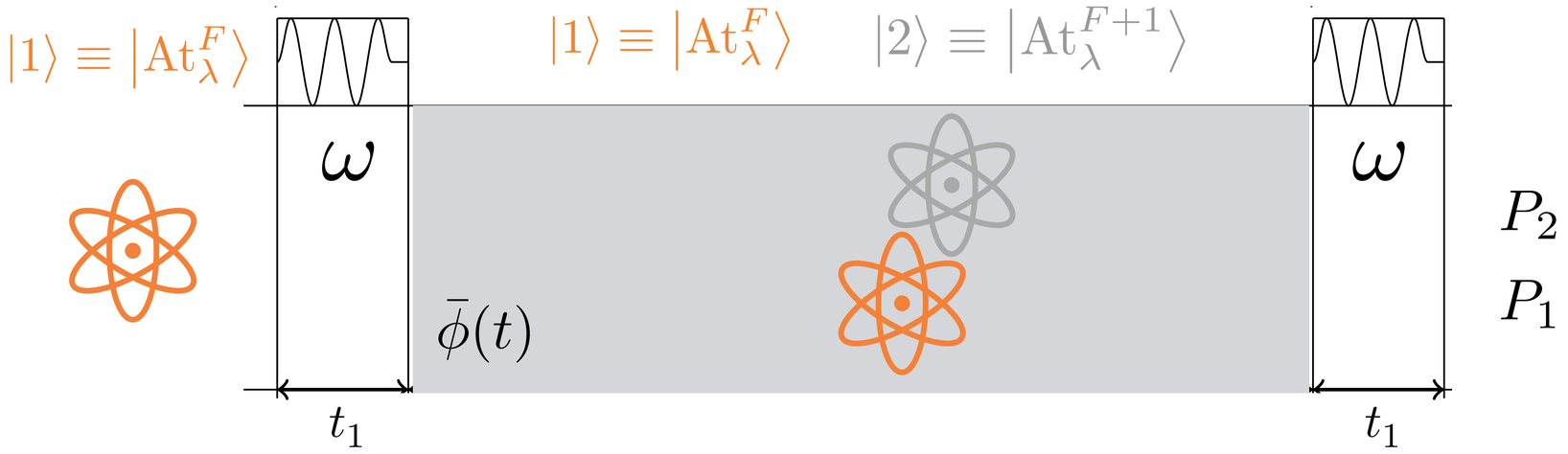


$$e^{iHT} \quad \text{with} \quad E_i = E_i^0 + V_i$$

The atoms live in a background with some coherent features and for certain dark matter models

$$V_2 - V_1 \neq 0$$

‘Coherent’ effects of ULDM in the MW



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The atoms live in a background with some coherent features and for certain dark matter models

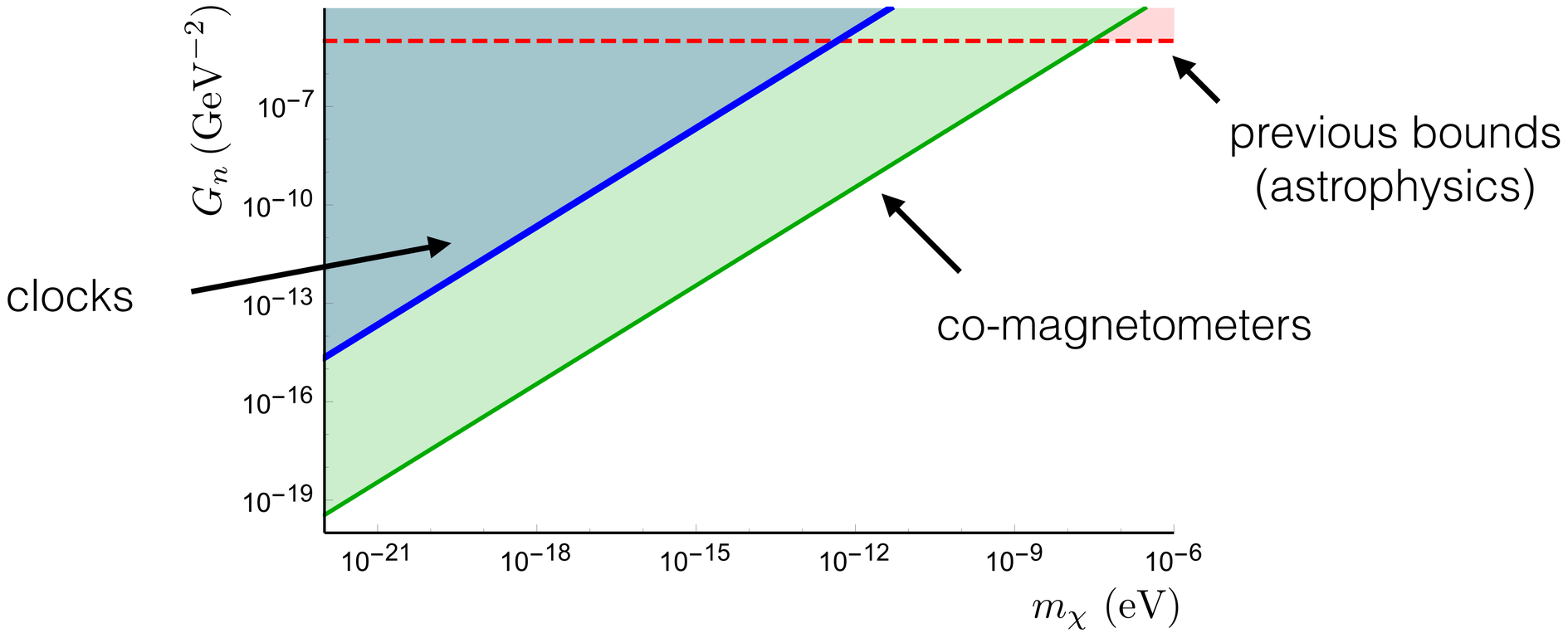
$$V_2 - V_1 \neq 0$$

One possible model

Alonso, DB, Wolf 1810.00889

nucleons DM

$$L_{\rm int} = -G_n \int {\rm d}^3x \, (\bar{n}\gamma^\mu\gamma_5 n) \, (i\chi^\dagger\partial_\mu\chi + {\rm h.c.}) \quad \Rightarrow \quad \vec{S}_n \cdot \vec{v}_\chi$$



How do pulsar signals feel dark matter/GWs?

2015-2022

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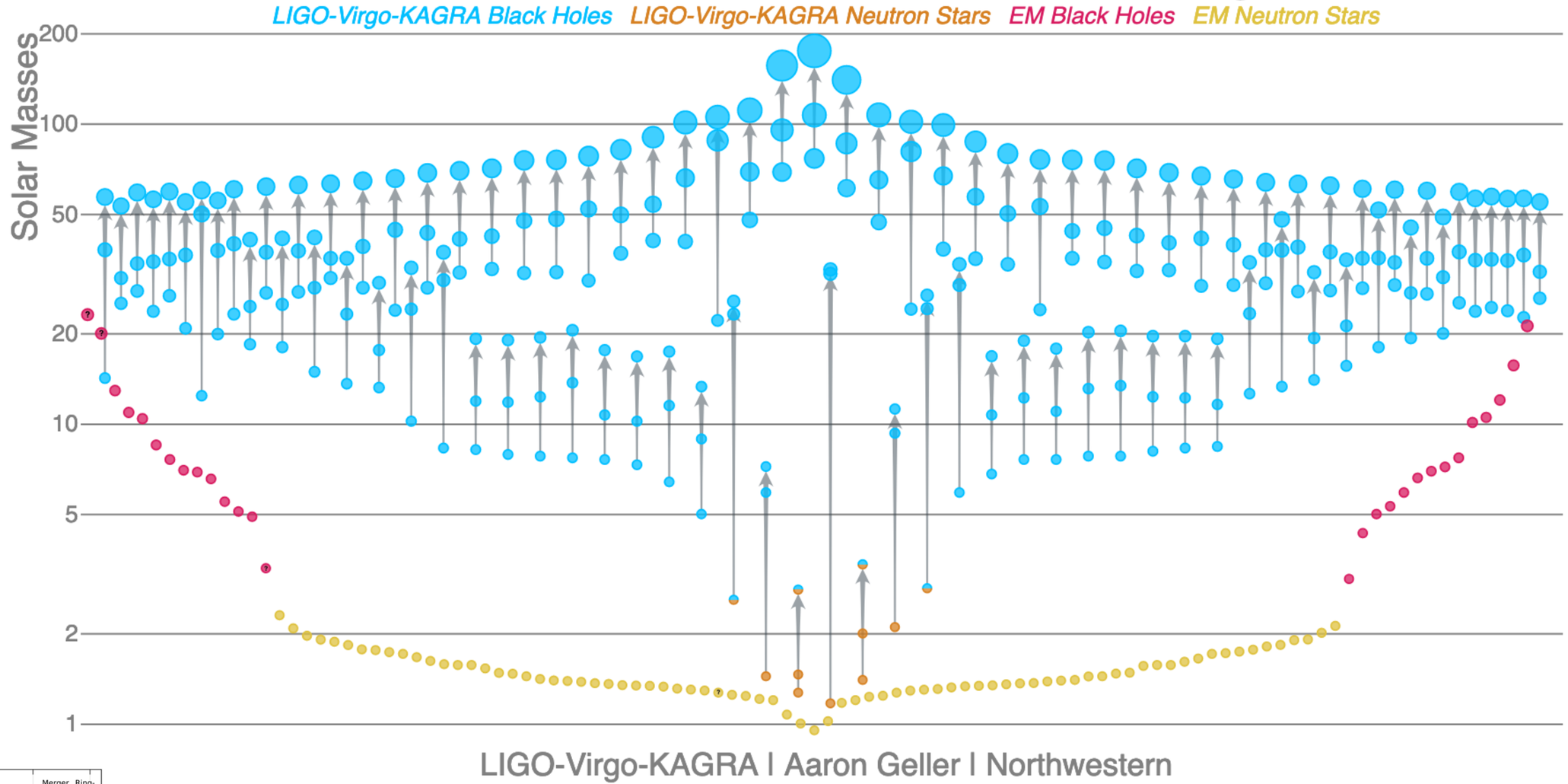
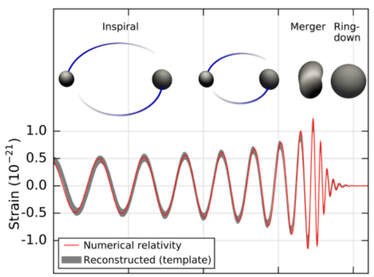
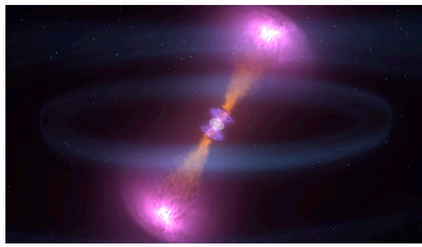
2015-2022

A bit more on pheno of GWs

Masses in the Stellar Graveyard

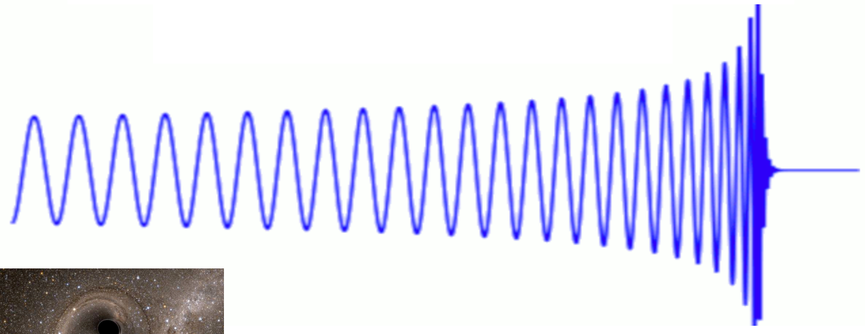
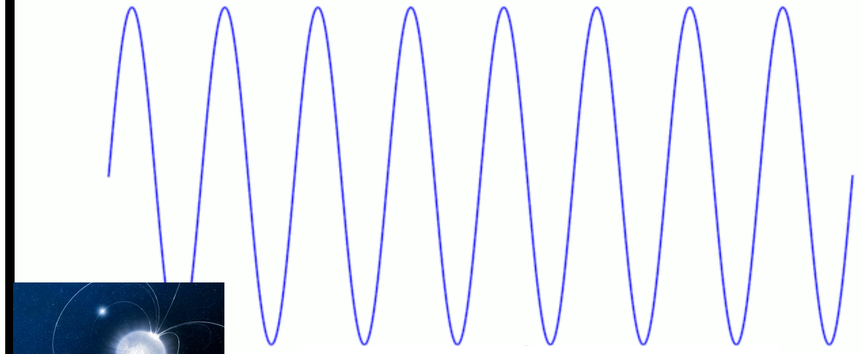
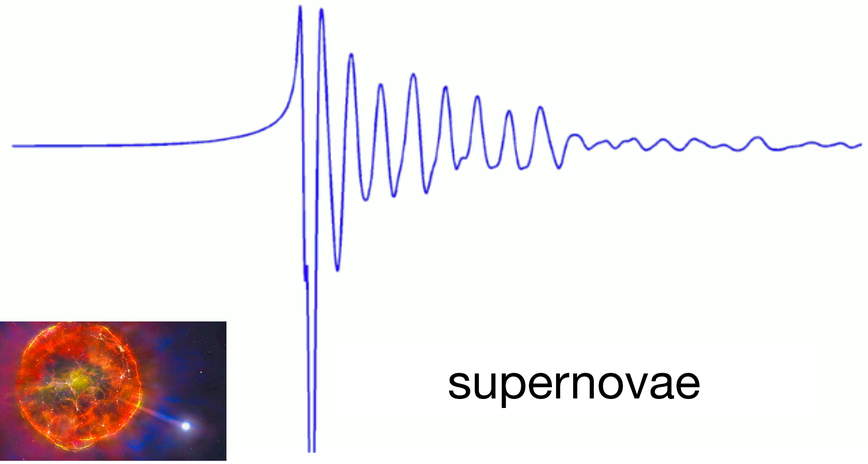
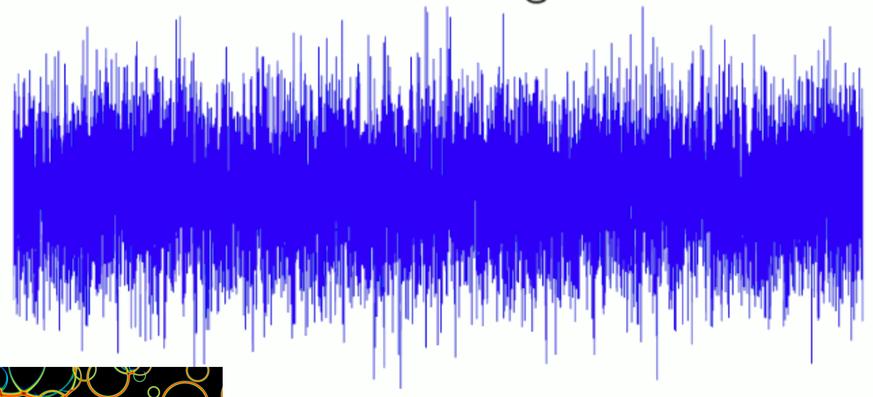


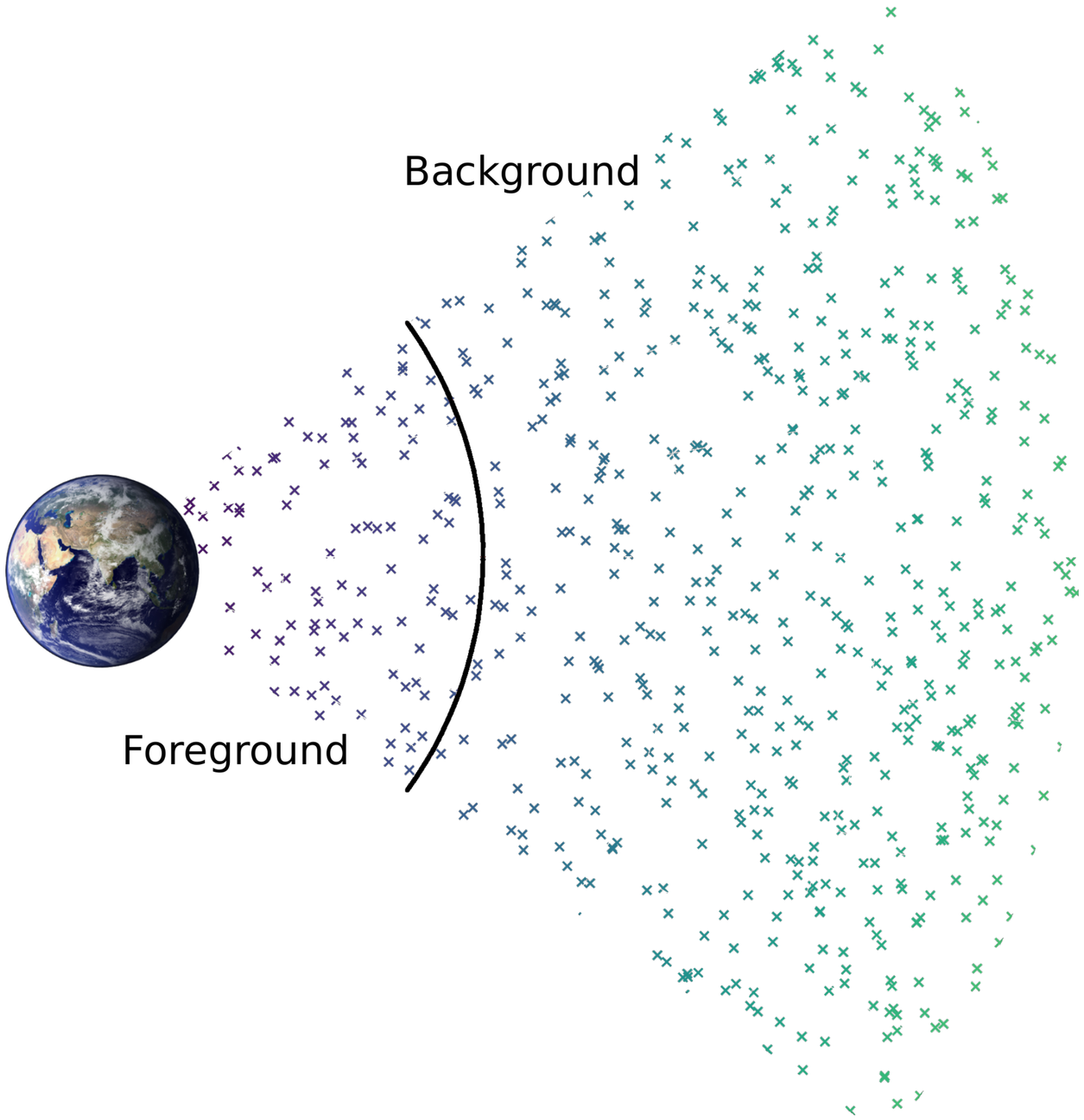




Taxonomy of GWs

$h(t)$

	transient	persistent
phase modelled	 BH binaries	continuous waves  pulsars
phase unmodelled	bursts  supernovae	stochastic backgrounds  phase transitions



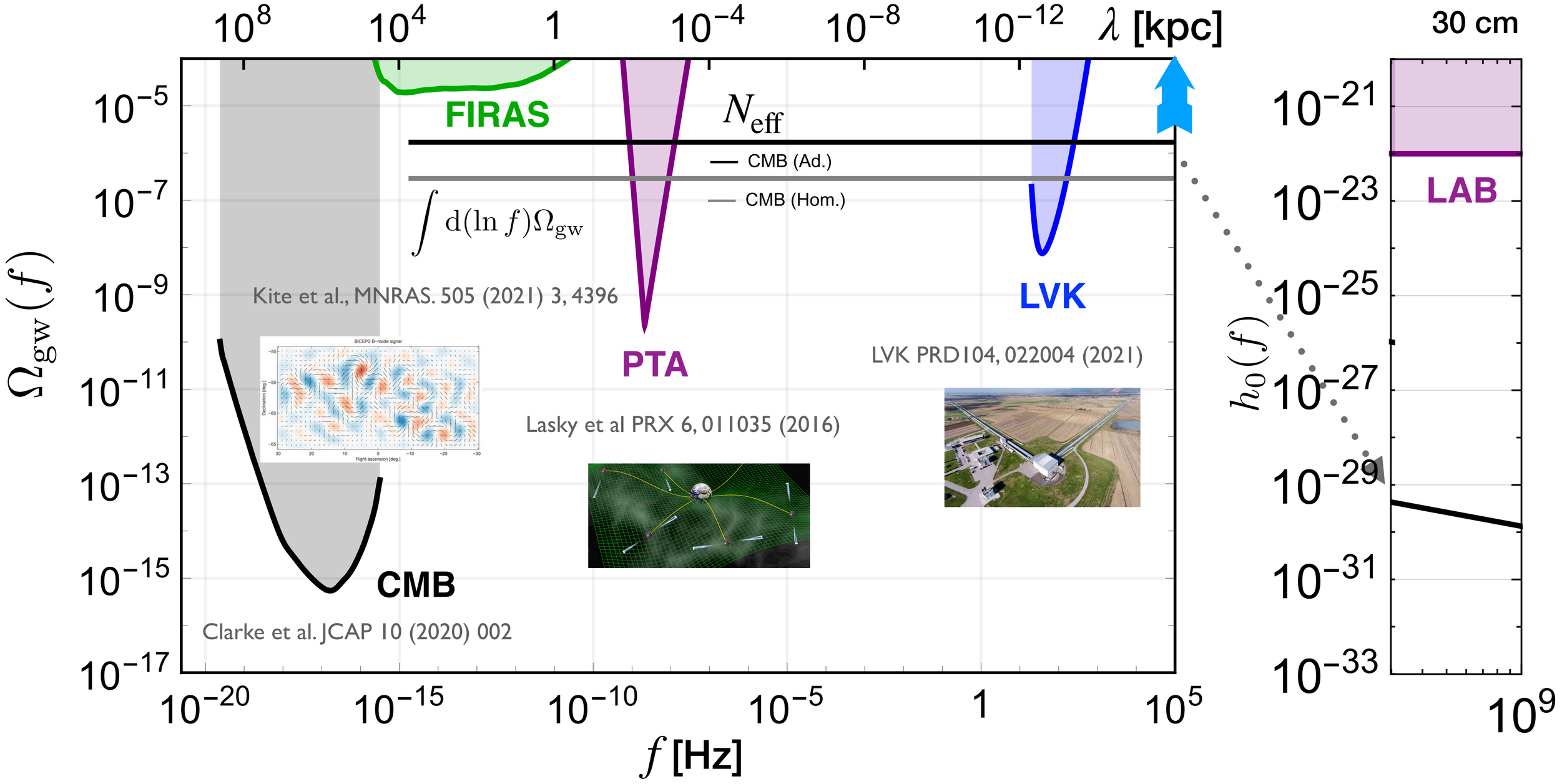
$$h_{+,\times} \approx h_0 \cos\left(2\pi f(t-z)+\phi\right)$$

$$\rho_{\rm gw} = \frac{1}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$$

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}(\ln f)}$$

$$\rho_c = 1.2\times 10^{11} M_\odot {\rm Mpc}^{-3}$$

Today soundscape



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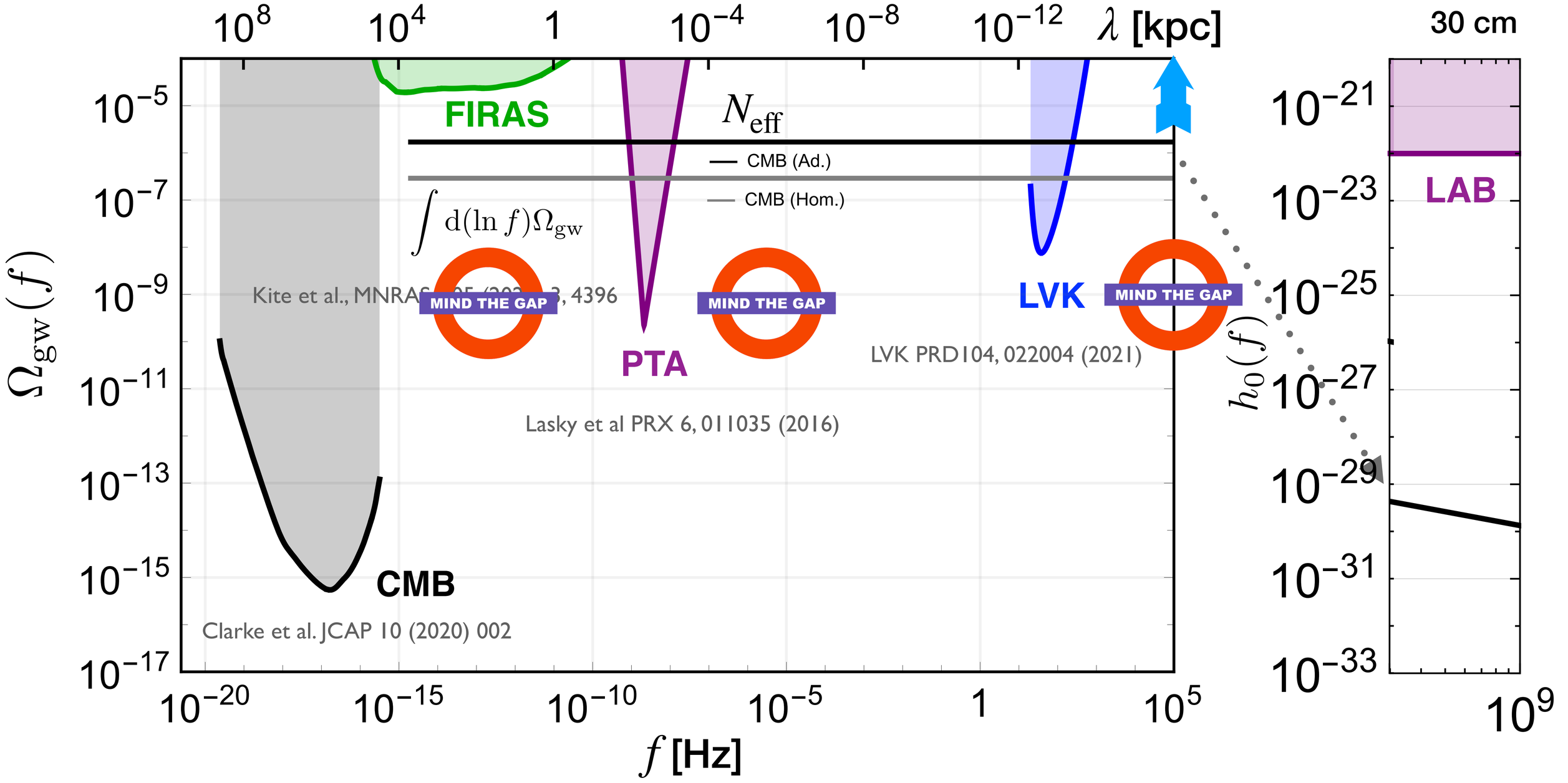
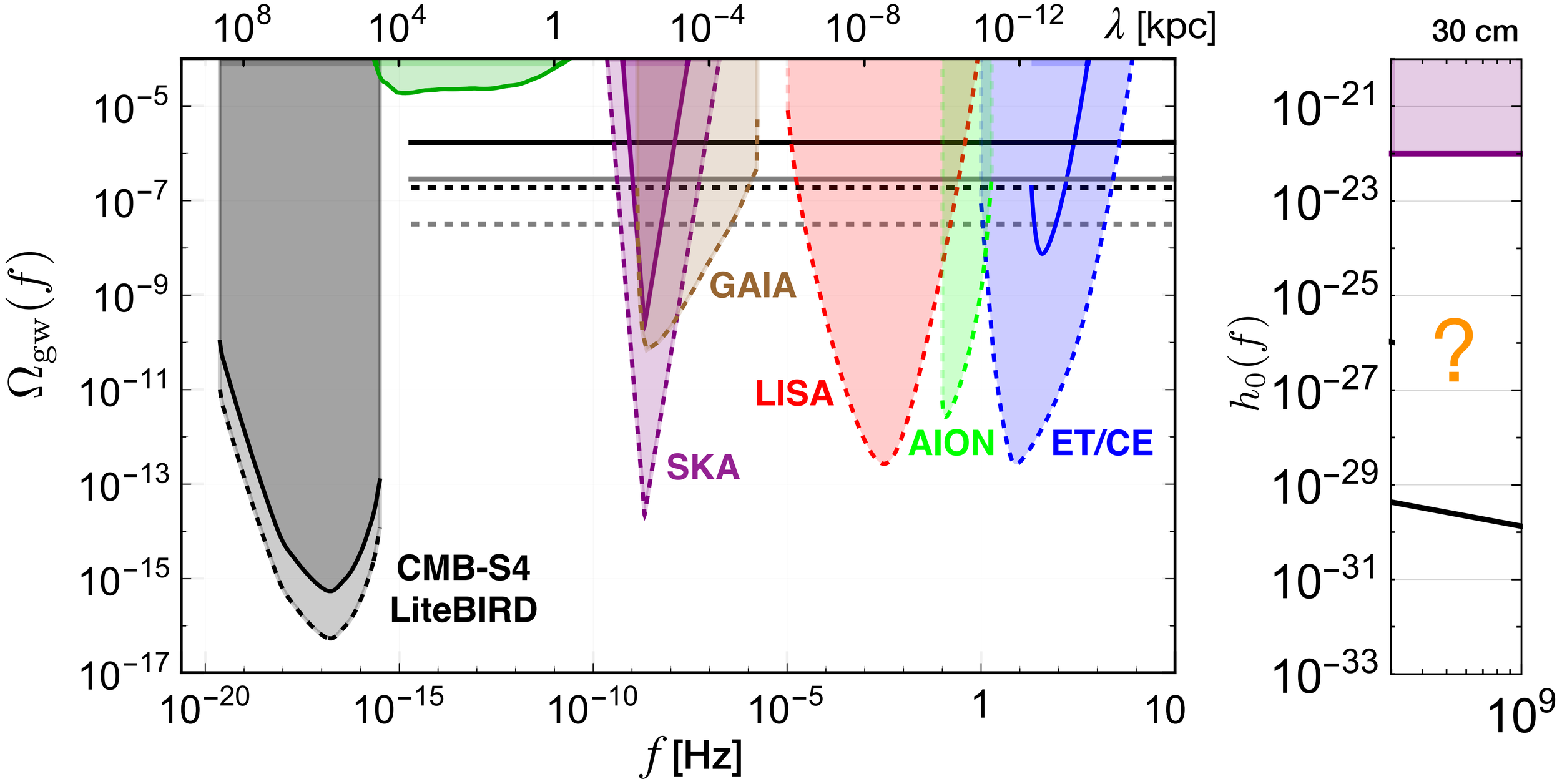


What's the future of GWs (maybe 2040)?



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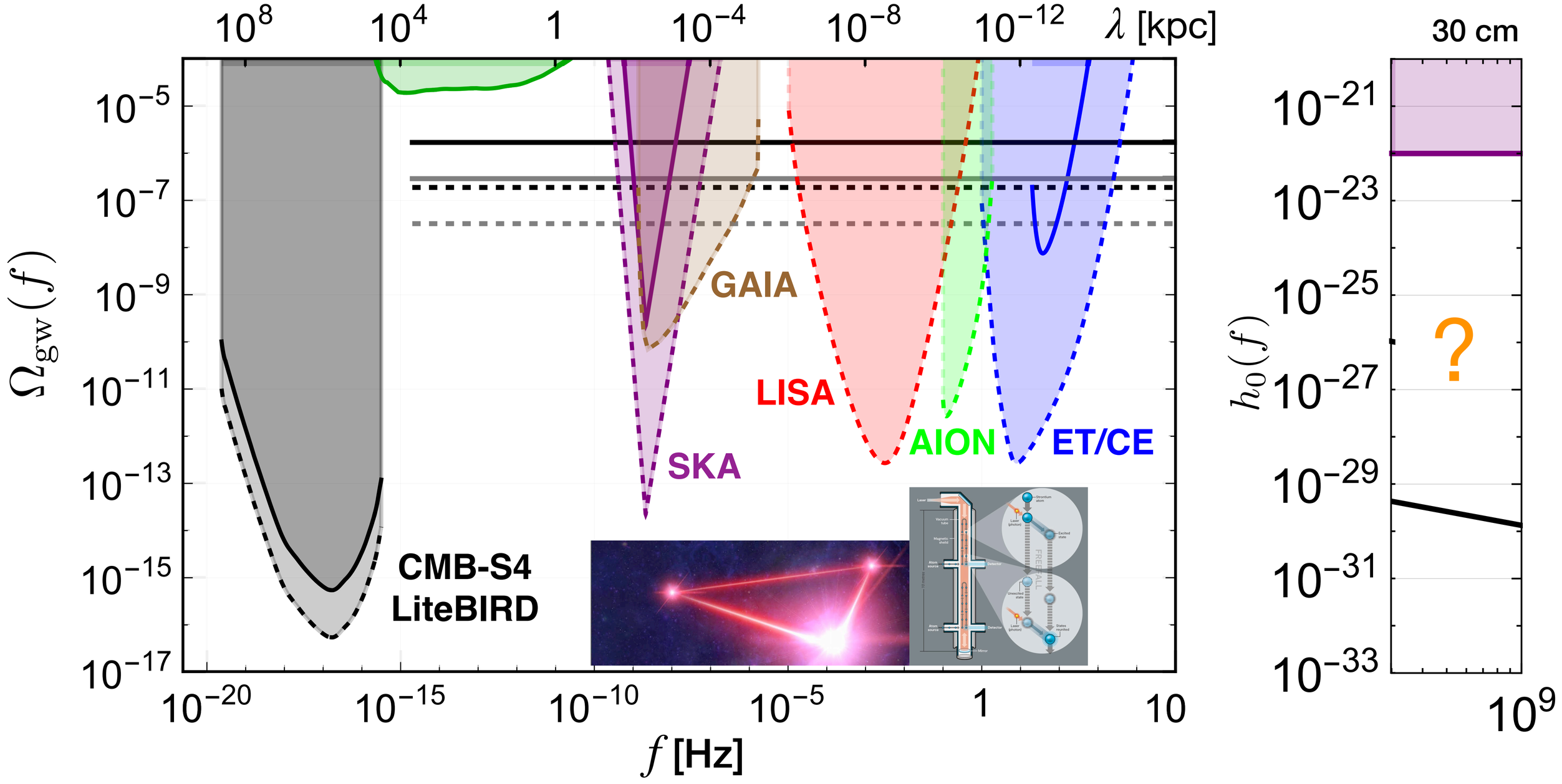

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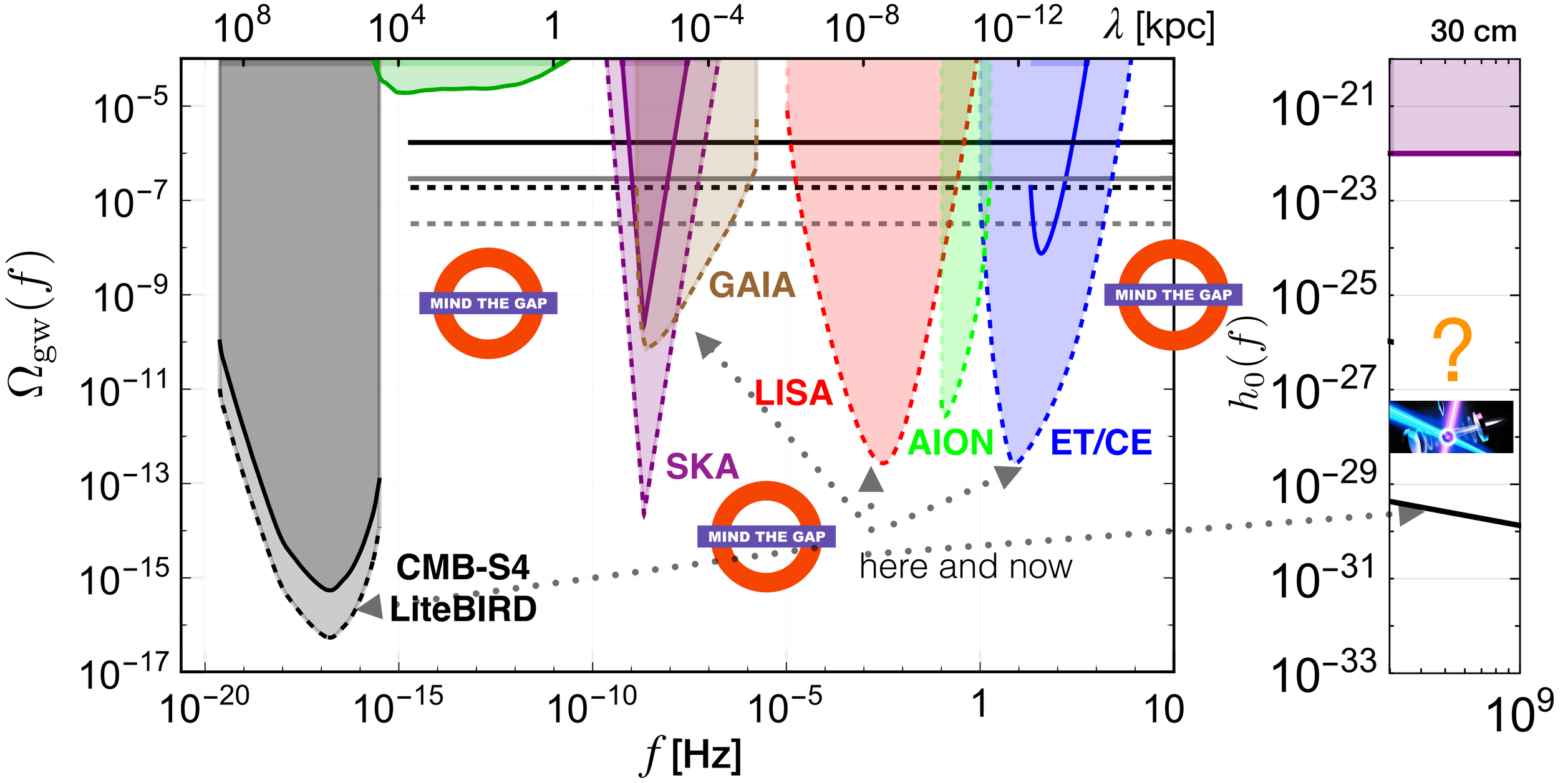
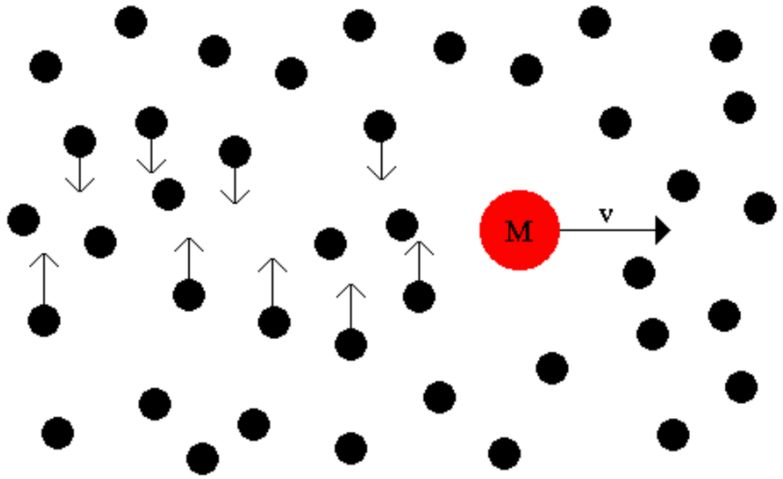


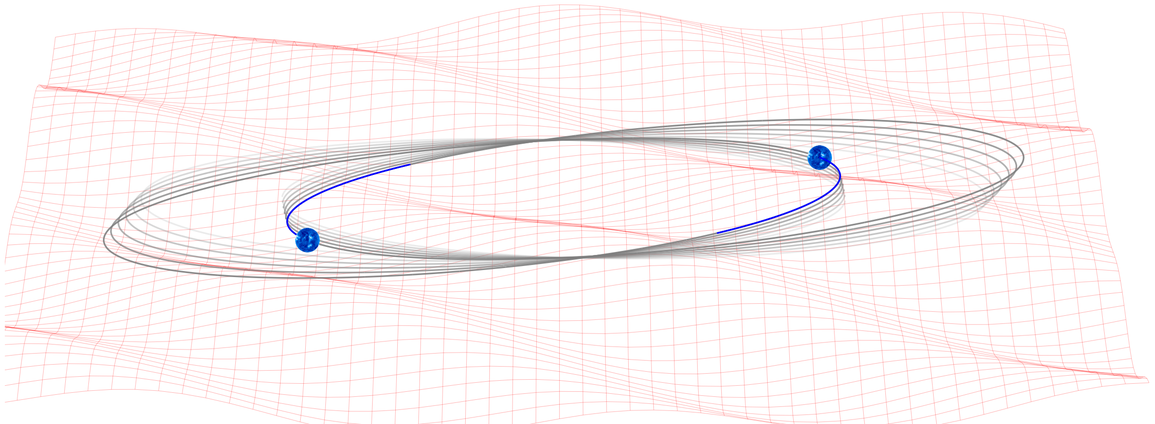
Can we use precision physics?

How do pulsar signals feel dark matter/GWs?

i) Pulsar travels in a medium. Does it lose momentum? Dynamical friction?



ii) Pulsar travels in a medium. Does it get energy? Heating?



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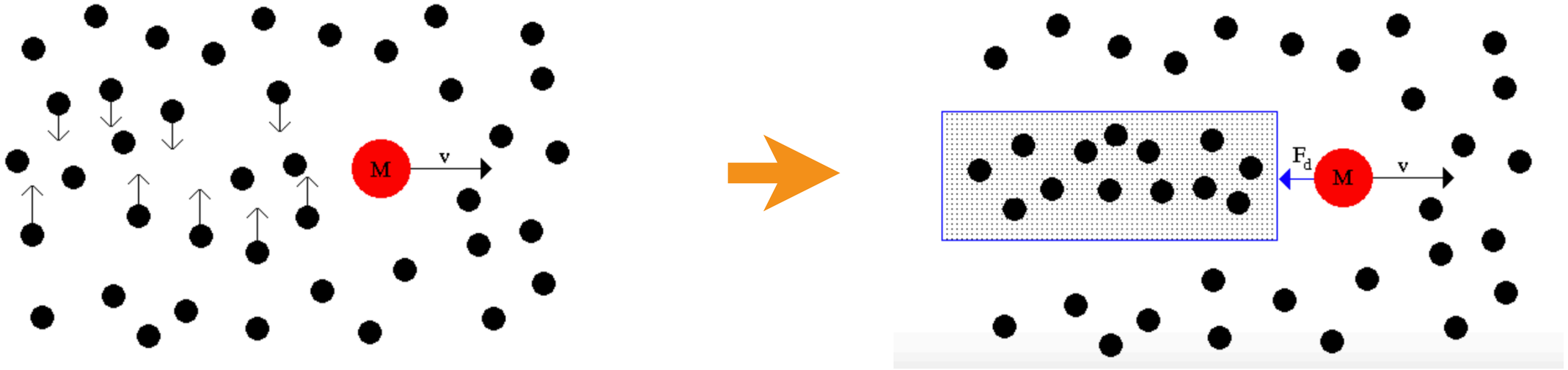

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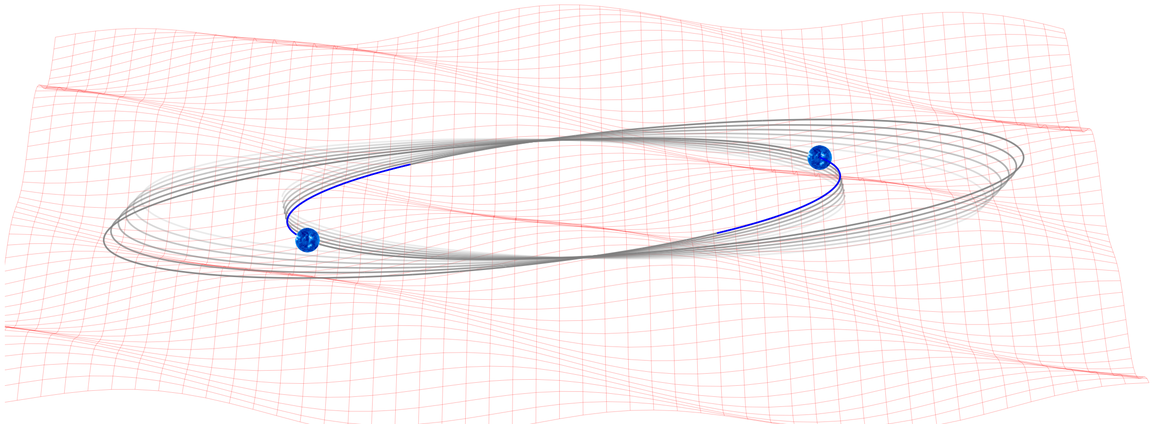
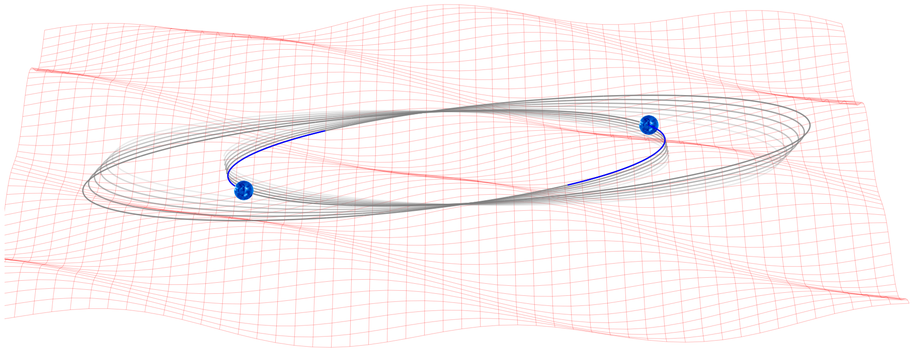
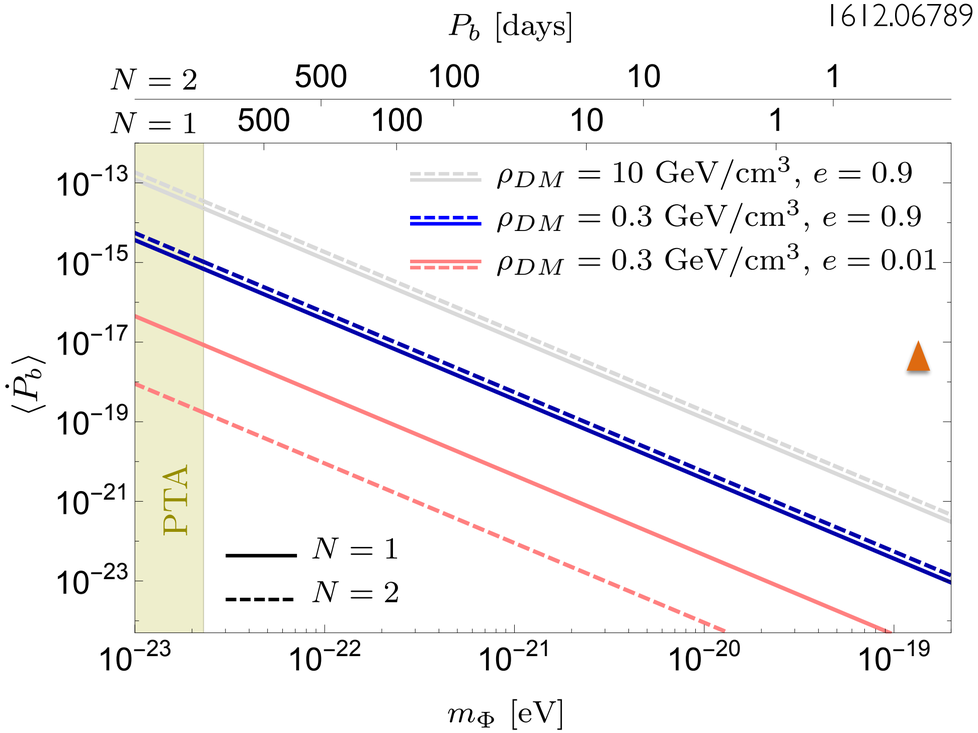


How do pulsar signals feel dark matter/GWs?

i) When DM is ultralight, it has a wave behaviour: one can absorb them efficiently if

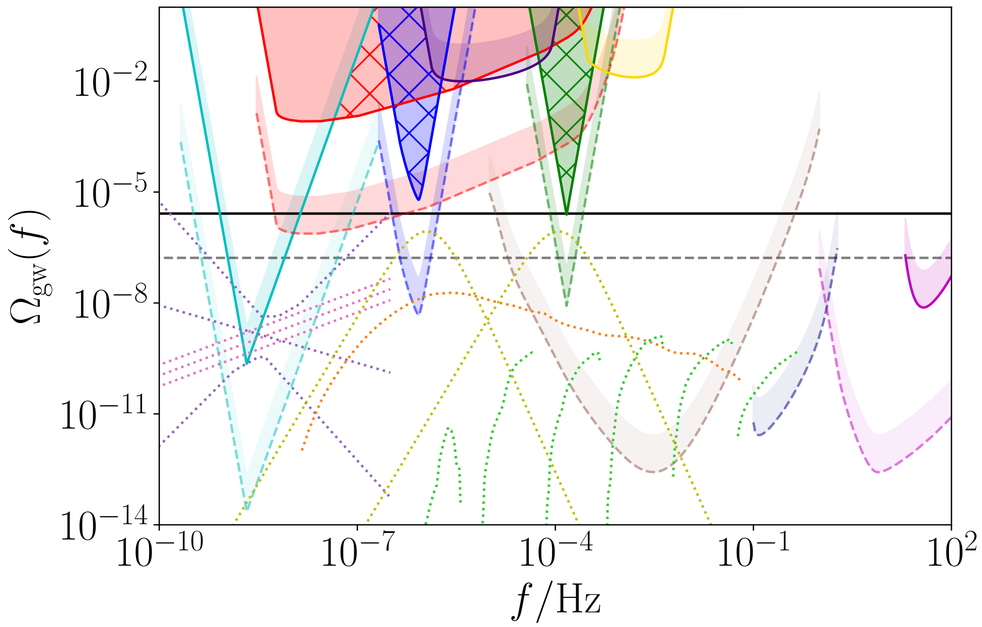


1612.06789



ii) For GWs such that $P_b = n/f$

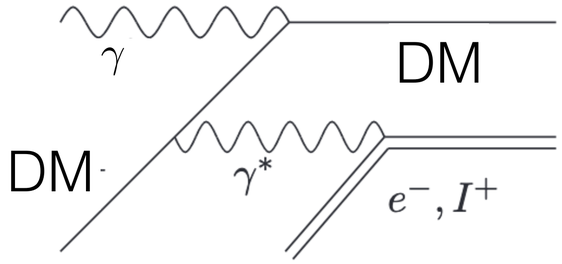
2107.04063

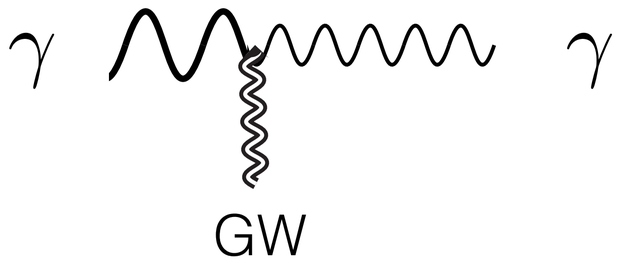


$$P_b \approx 2\pi n/m_\Phi$$

How do pulsar **signals** feel dark matter/GWs?

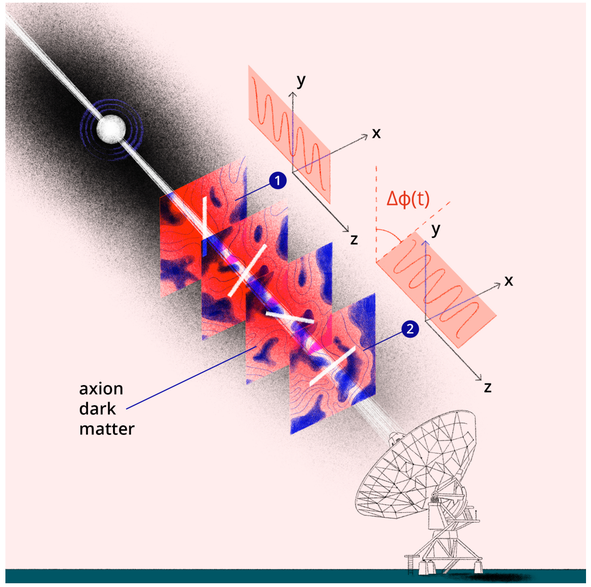
i) It travels in a medium. Is it absorbed?

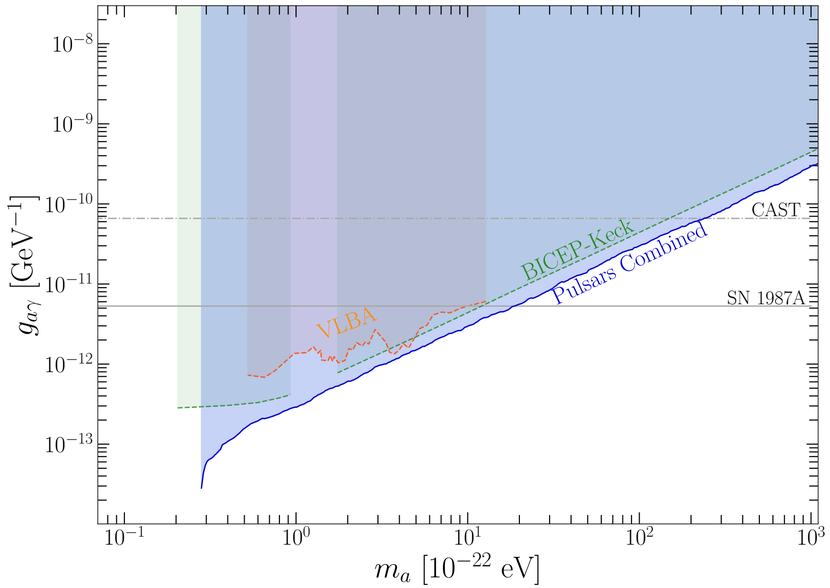




ii) It travels in a medium. Is it modified? (polarization/speed/spectrum)

Andrés Castillo, Jorge Martin-Camalich. Jorge Terol-Calvo. et al JCAP 06 (2022) 06, 014

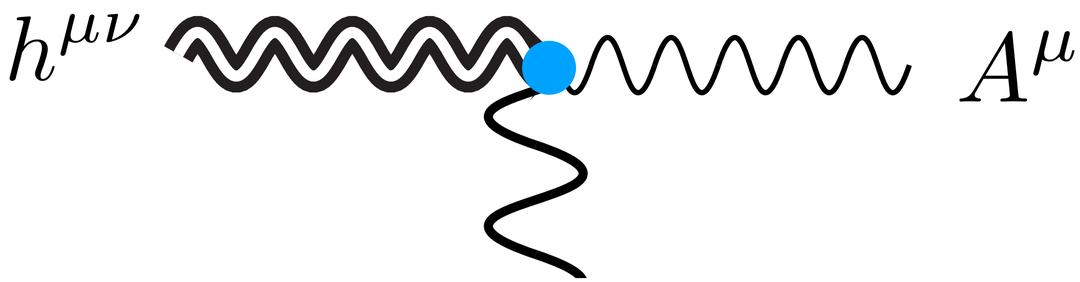




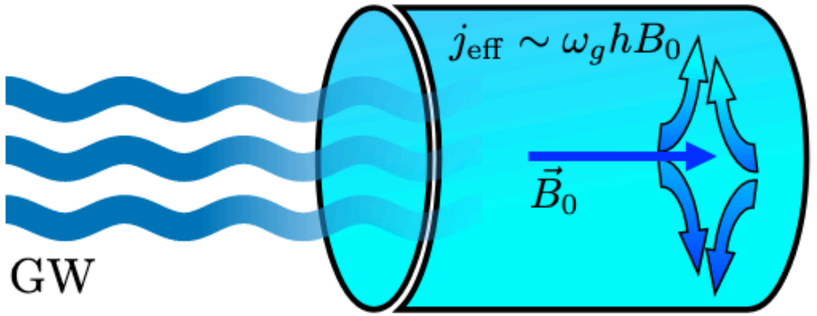
What about the quantum frontier for GWs?

$$\mathcal{L} \approx \frac{1}{2} A_\mu j^\mu_{\rm eff}(h) + \eta^{\mu\alpha}\eta^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} \,.$$

gravitational wave + EM field = current!

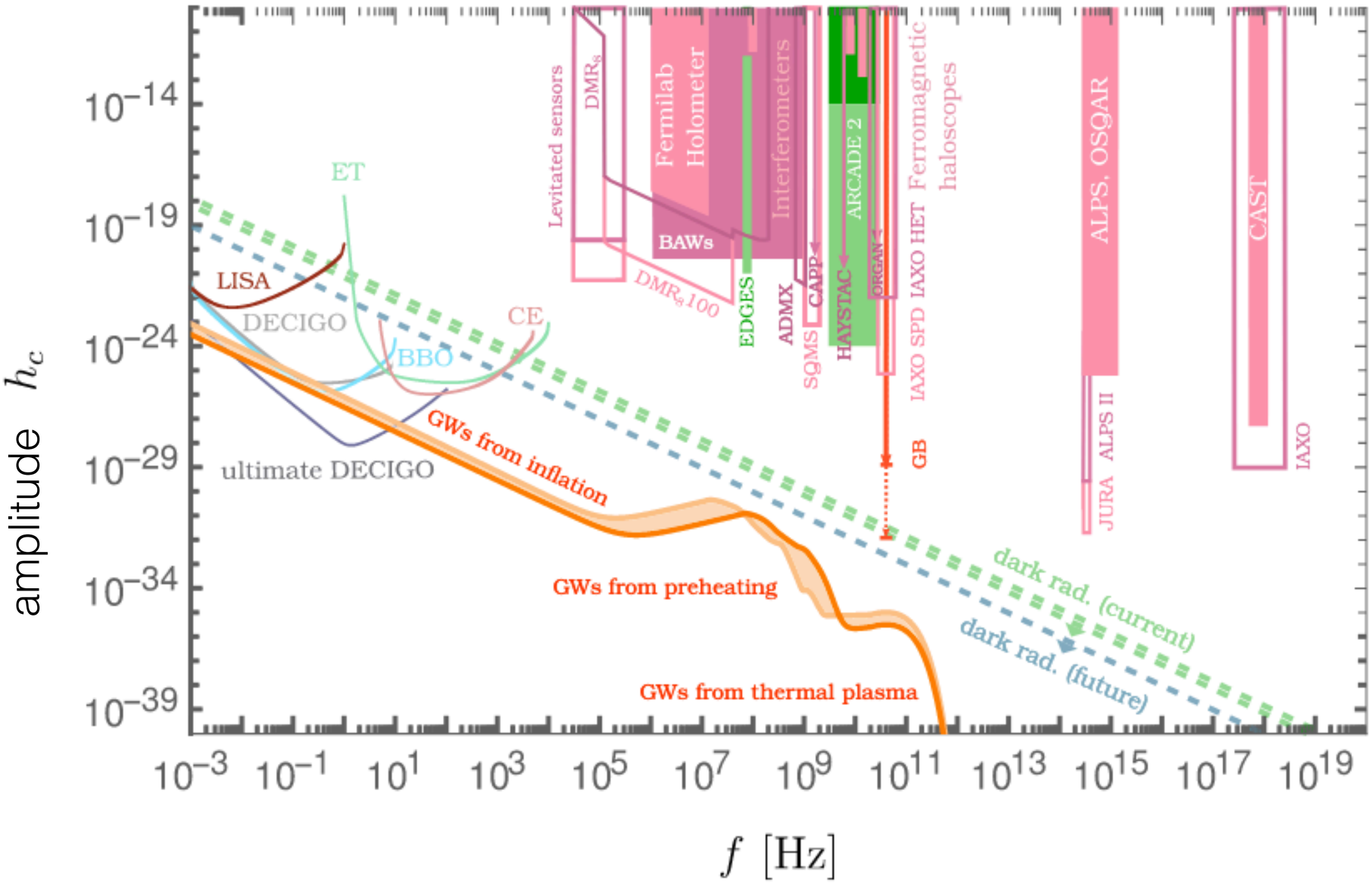


gravitational wave + Magnetic field = Generates photons that accumulate in cavities



How do we read out this? We need the best ways to store and detect photons.

What about the quantum frontier for GWs?



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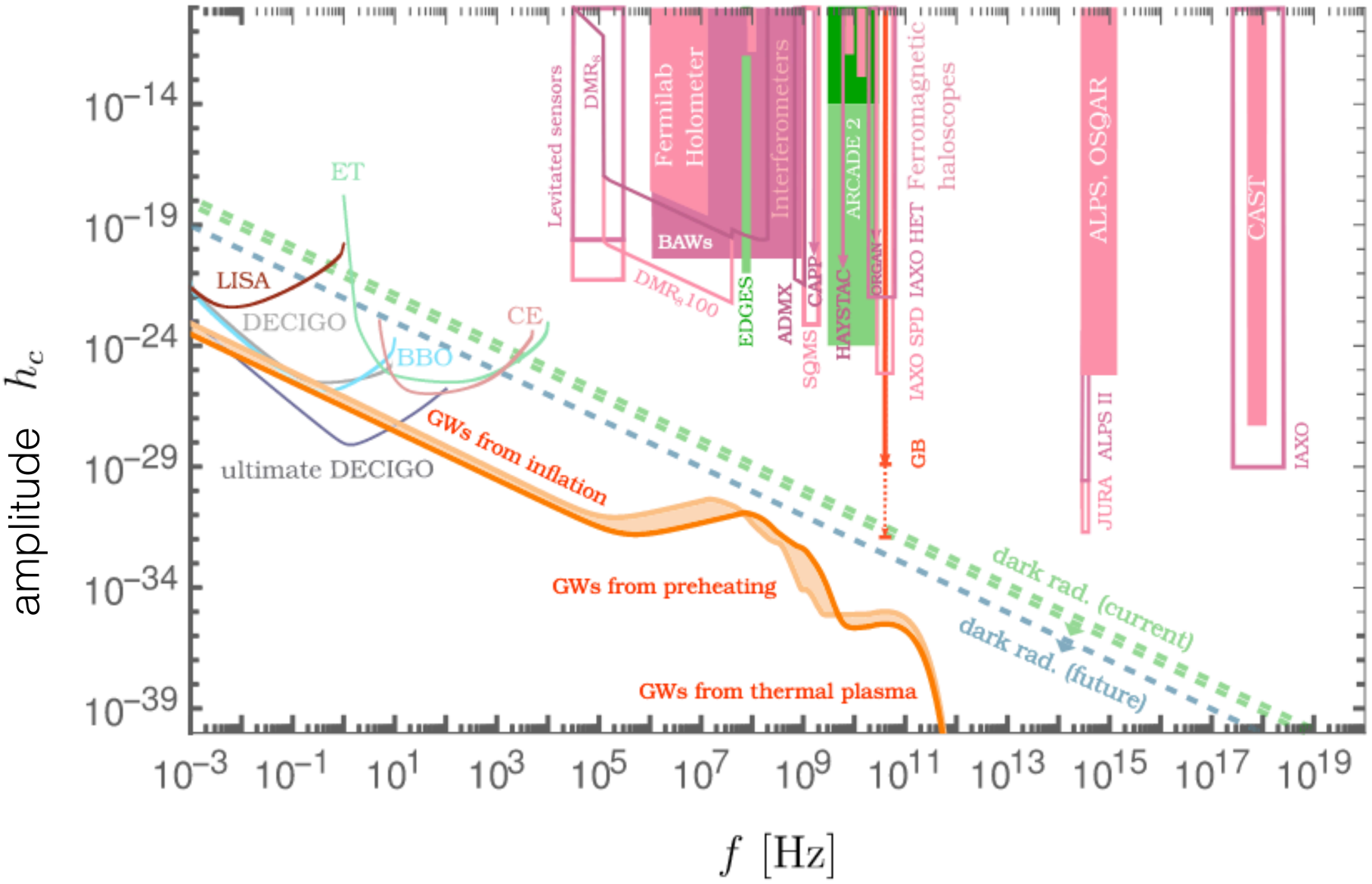

How do we unveil the mysteries of Nature?

Theory recap

Taxonomy of objects

Messengers recap

List of open questions

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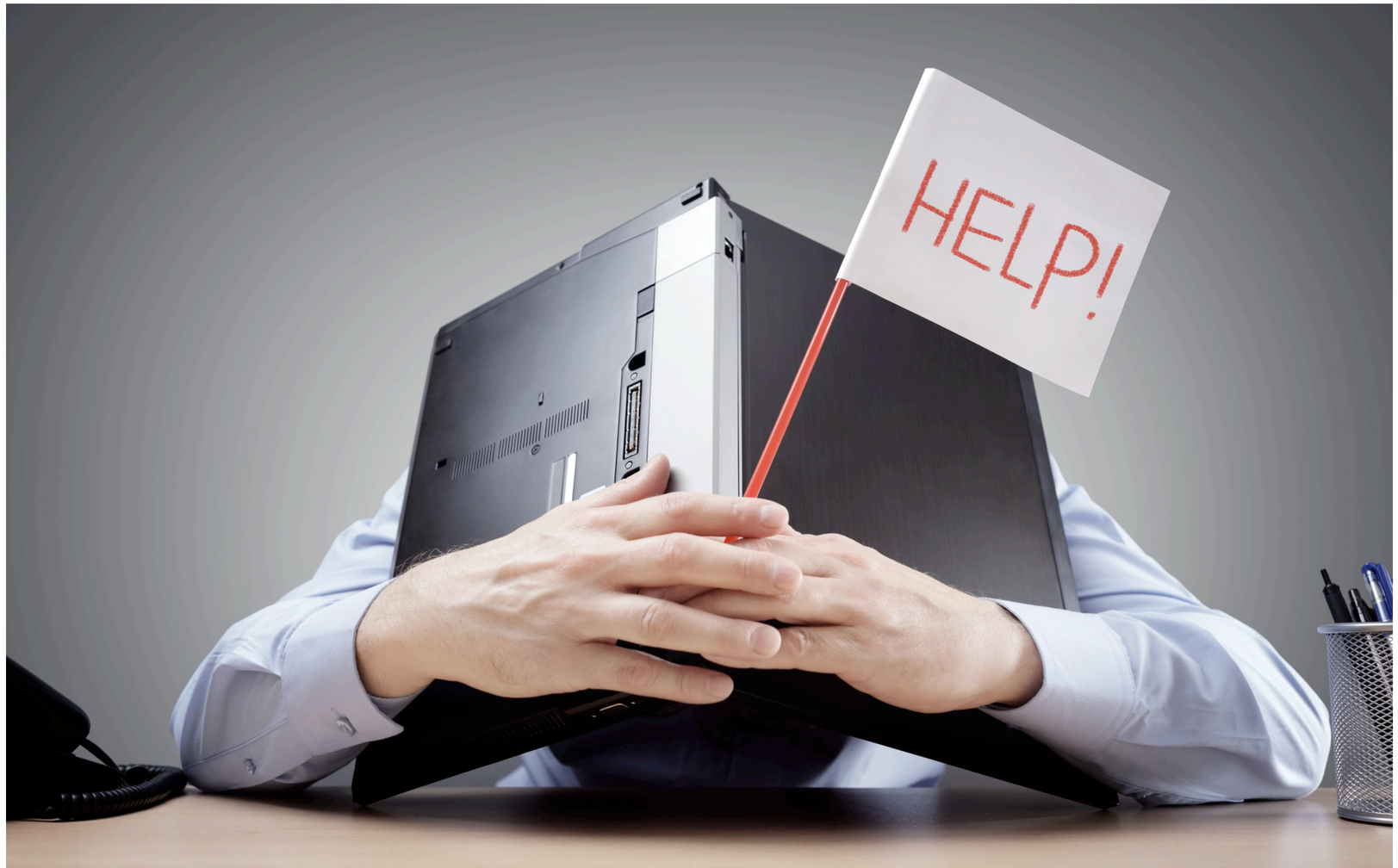


How do we unveil the mysteries of Nature?

Theory recap

Messengers recap

Taxonomy of objects

List of open questions

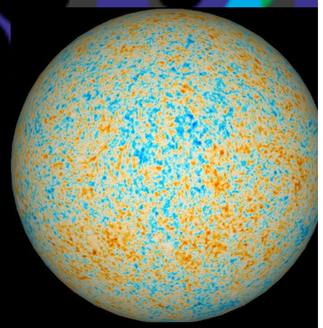
observations

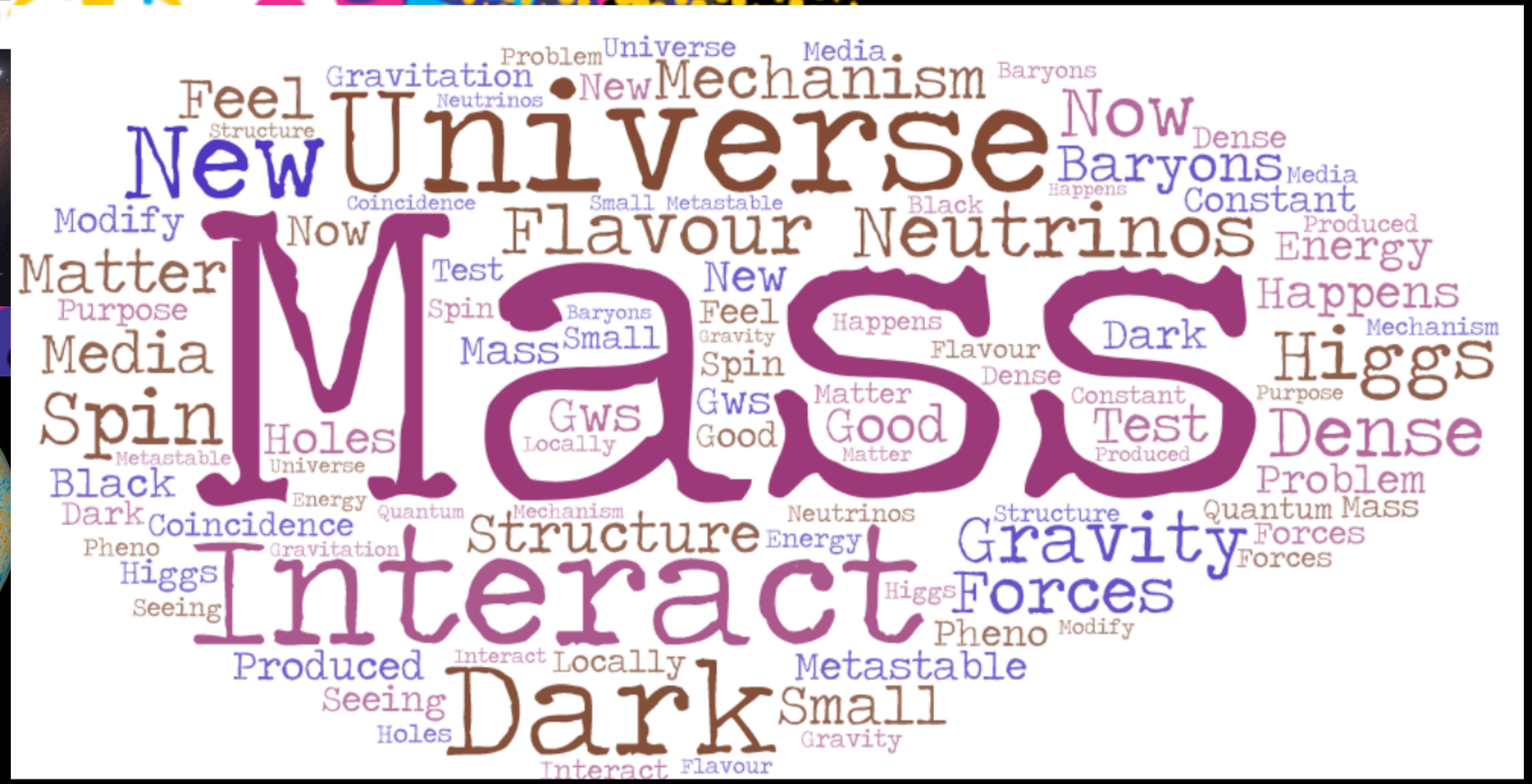
theory

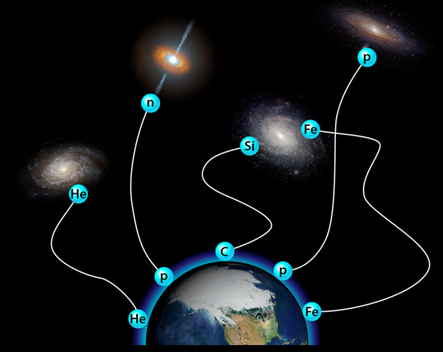
data analysis

phenomenology

instrumentation




Problem Universe Media
Gravitation New Mechanism Baryons
Feel Neutrinos
Structure
New Universe Now Dense
Baryons Media
Happens
Coincidence Small Metastable Black Constant
Modify Now Flavour Neutrinos Produced
Energy
Matter Test New Happens
Purpose Spin Baryons Feel Happens Mechanism
Media Mass Small Gravity Flavour Dark Higgs
Spin Spin Dense
Gws Gws Matter Constant Purpose
Holes Locally Good Good Test Dense
Metastable Universe Matter Produced
Black Problem
Dark Energy Quantum Mechanism Neutrinos Structure Quantum Mass
Coincidence Structure Energy Gravity Forces
Pheno Gravitation Forces
Higgs Interact Higgs Forces
Seeing Pheno Modify
Produced Interact Locally Metastable
Seeing Dark Small
Holes Gravity
Interact Flavour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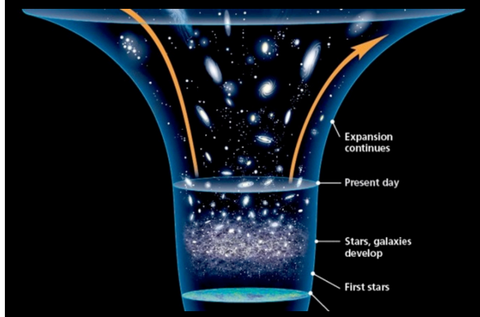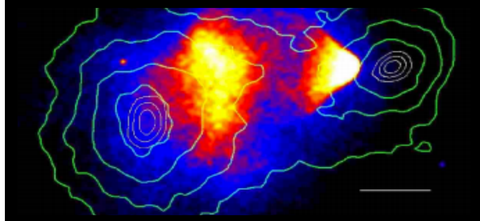
Expansion continues
Present day
Stars, galaxies develop
First stars