Credit: Sandbox Studio, Chicago

Axion-like particle dark matter and gravitational waves from topological defects

APEC Seminar,
Kavli IPMU (online),
October 6, 2021

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UCLA

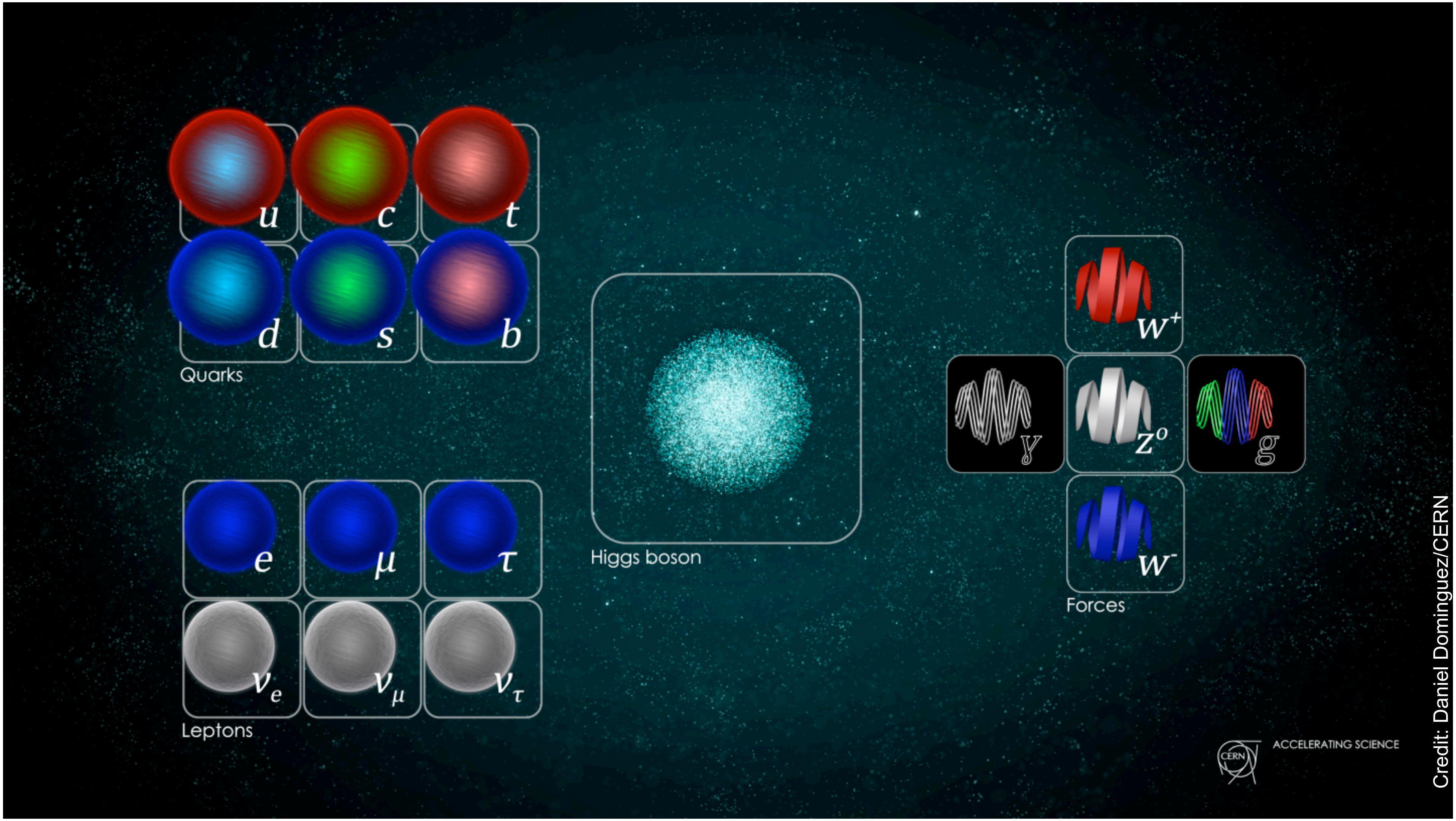
Based on arXiv:2103.07625

Prologue

Known unknowns

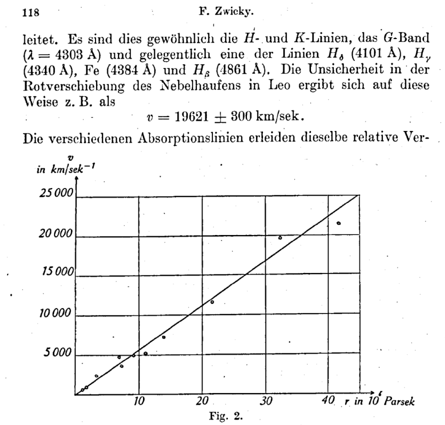
UCLA

Particle physics in the 20th century has been incredibly successful



Credit: Daniel Dominguez/CERN

What is dark matter?



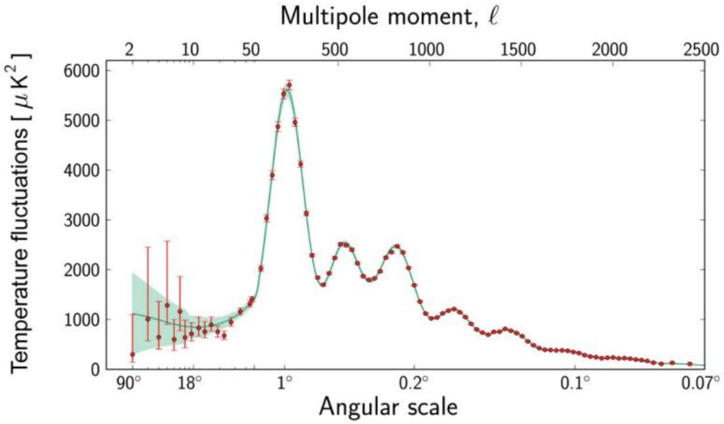
118 F. Zwicky.

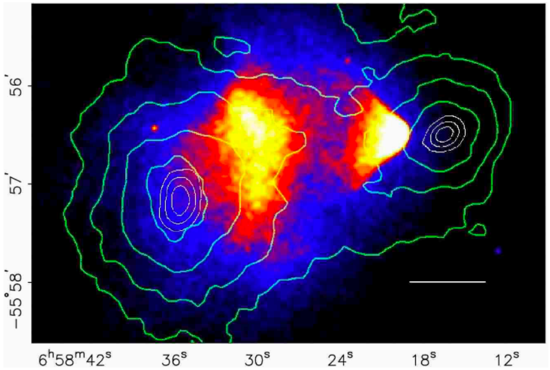
leitet. Es sind dies gewöhnlich die *H*- und *K*-Linien, das *G*-Band ($\lambda = 4303$ Å) und gelegentlich eine der Linien H_δ (4101 Å), H_γ (4340 Å), Fe (4384 Å) und H_β (4861 Å). Die Unsicherheit in der Rotverschiebung des Nebelhaufens in Leo ergibt sich auf diese Weise z. B. als

$$v = 19621 \pm 300 \text{ km/sek}.$$

Die verschiedenen Absorptionslinien erleiden dieselbe relative Ver-

Fig. 2.

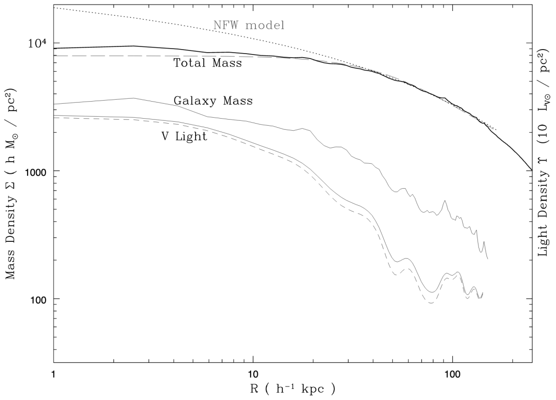


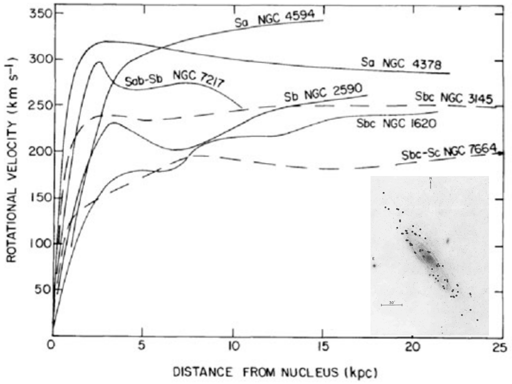


Coma cluster

Cosmic Microwave Background

Bullet Cluster





Lensing

Galactic rotation curves

Plus a bunch of other gravitational interaction proofs

(A nice historical and philosophical account:
de Swart et al. 1703.00013)

ALPs and GWs from string-walls

I. How to produce and detect topological defects

- Gravitational waves
- Symmetry breaking and topological defects

II. Particle physics model(s)

- From the QCD axion to axion-like particles
- ALP cosmology

III. From theory to observations

- Present GWs
- Present ALPs
- Detection perspectives

Conclusions

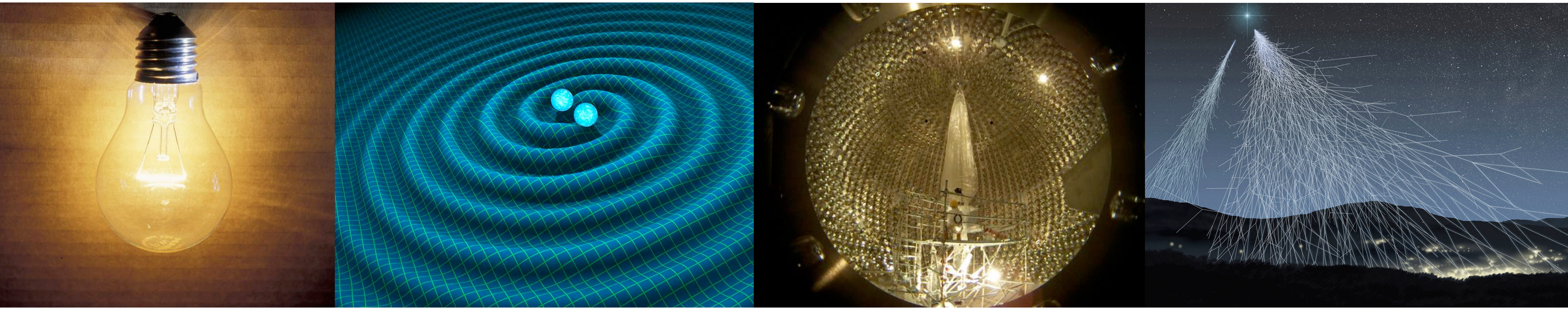
How to produce and detect topological defects

Dawn of multi-messenger astronomy

From Wikipedia…

Multi-messenger astronomy is astronomy based on the coordinated observation and interpretation of disparate "messenger" signals. The four extrasolar messengers are ***electromagnetic radiation****,* ***gravitational waves****,* ***neutrinos****, and* ***cosmic rays****. They are created by different astrophysical processes, and thus reveal different information about their sources.*

https://en.wikipedia.org/wiki/Multi-messenger_astronomy

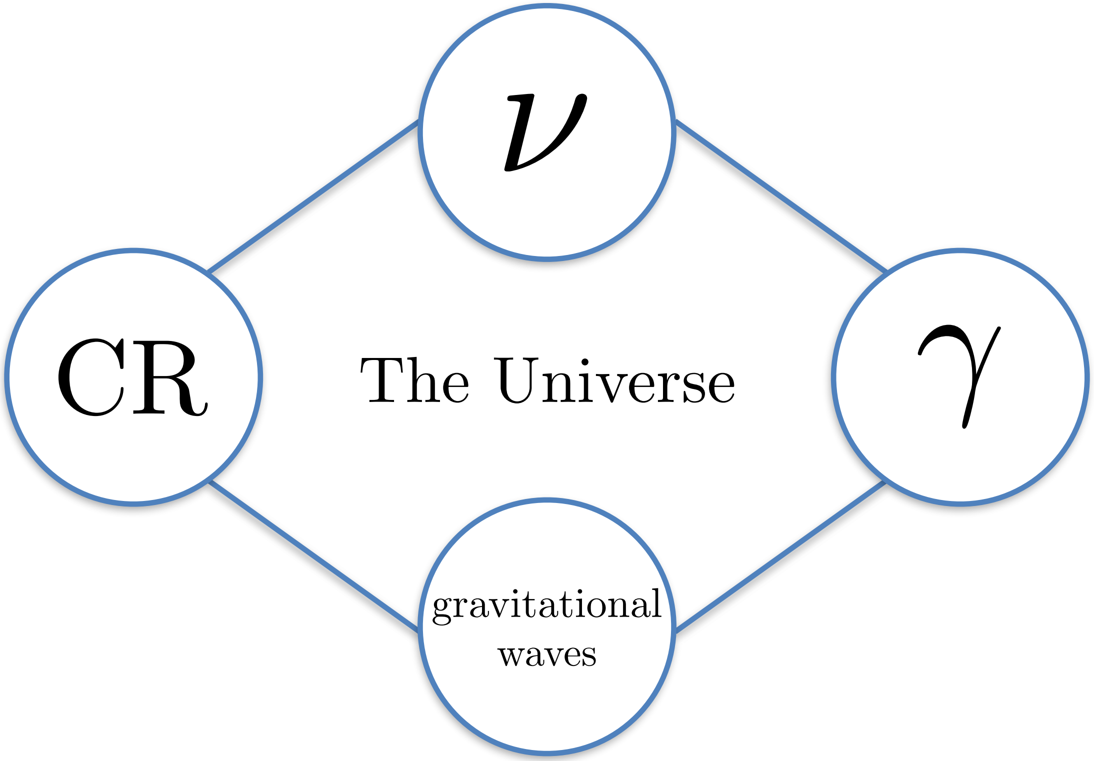


Images credits: Rex, R. Hurt/Caltech-JPL/EPA, Virginia Tech Physics, ASPERA/Novapix/L. Bret

A new way to explore the universe

The universe is no longer explored with electromagnetic radiation alone.

In particular, **gravitational waves** are becoming crucial astrophysical probes



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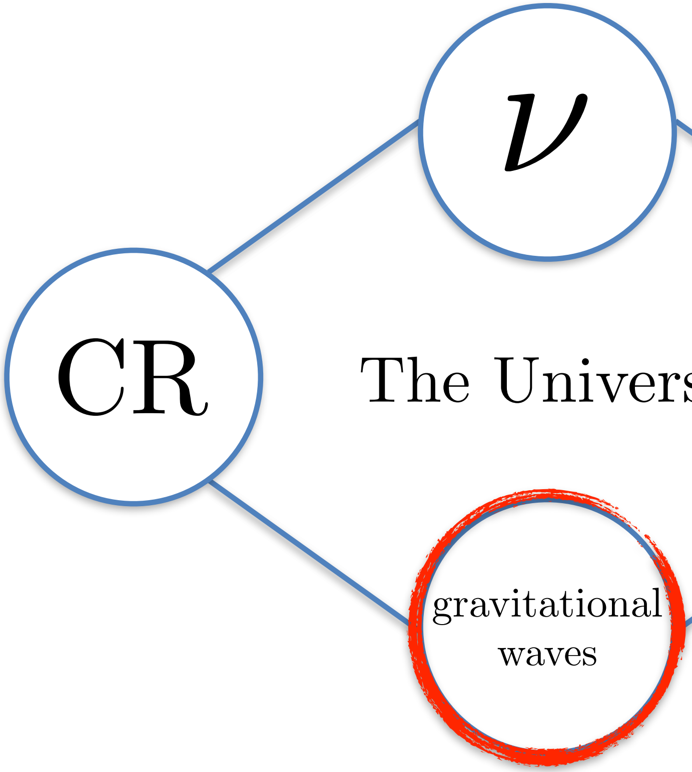


This talk

Gravitational wave detection

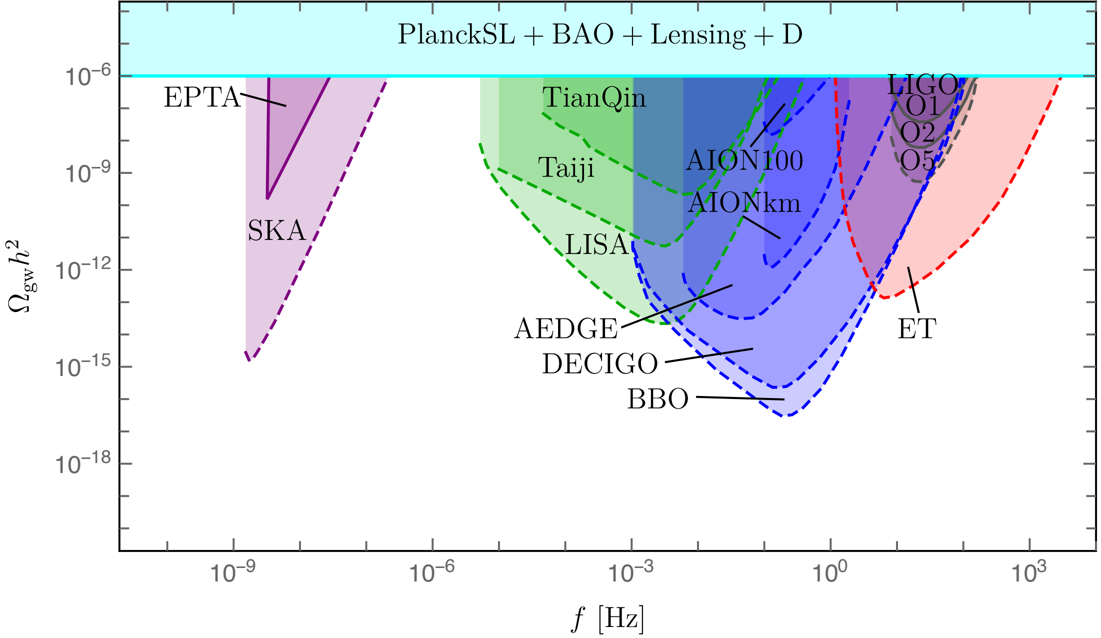
Direct detection

- Ground and space-based interferometers
- Particularly suitable for astrophysical events
- Useful for stochastic gravitational wave background (SGWB) depending on the spectrum

Pulsar timing

- GWs affect the time of flight of light from pulsars, so radio telescopes can probe supermassive black holes (well before they merge) and early universe signals

Adapted from Gelmini, Pascoli, **EV**, Zhou 2009.01903



Gravitational wave detection

Astrometry (e.g. Very Long Baseline Array)

- GWs cause an apparent distortion of the position of background sources on the celestial sphere

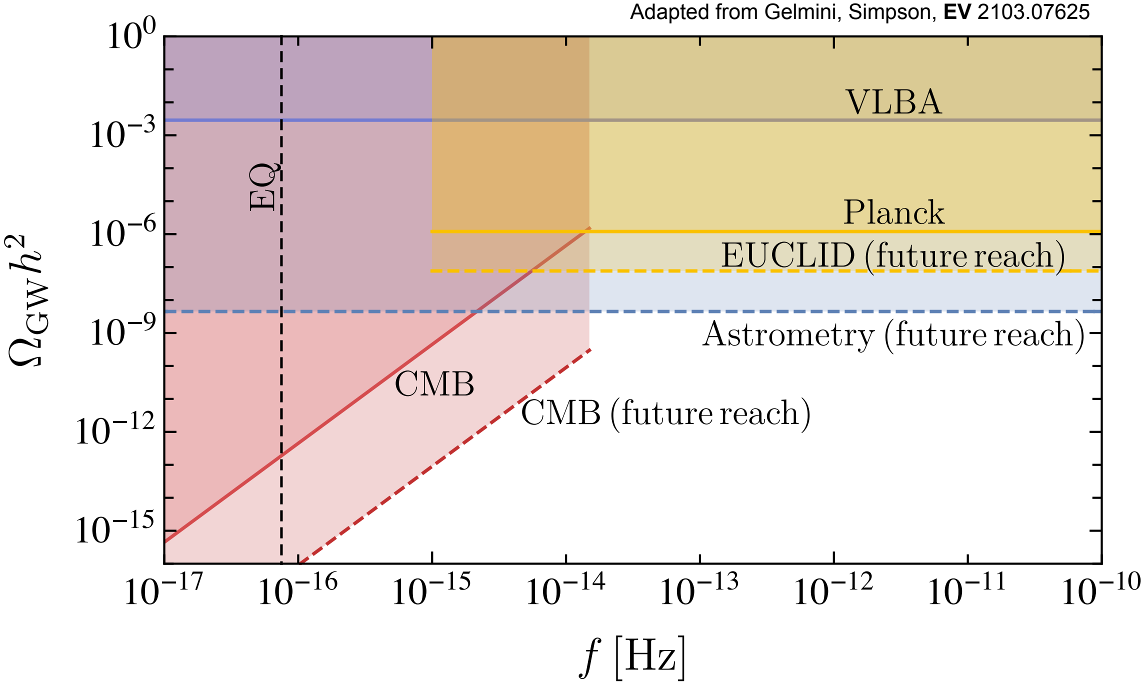
Cosmology (N_{eff})

- GWs contribute to the effective number of neutrinos

Cosmology

- GWs affect both temperature and polarization anisotropies in the CMB

Adapted from Gelmini, Simpson, **EV** 2103.07625



Pagano et al. 1508.02393, EUCLID 1110.3193,
Darling et al. 1804.06986, Arvanitaki et al. 1909.11665,
Namikawa et al. 1904.02115

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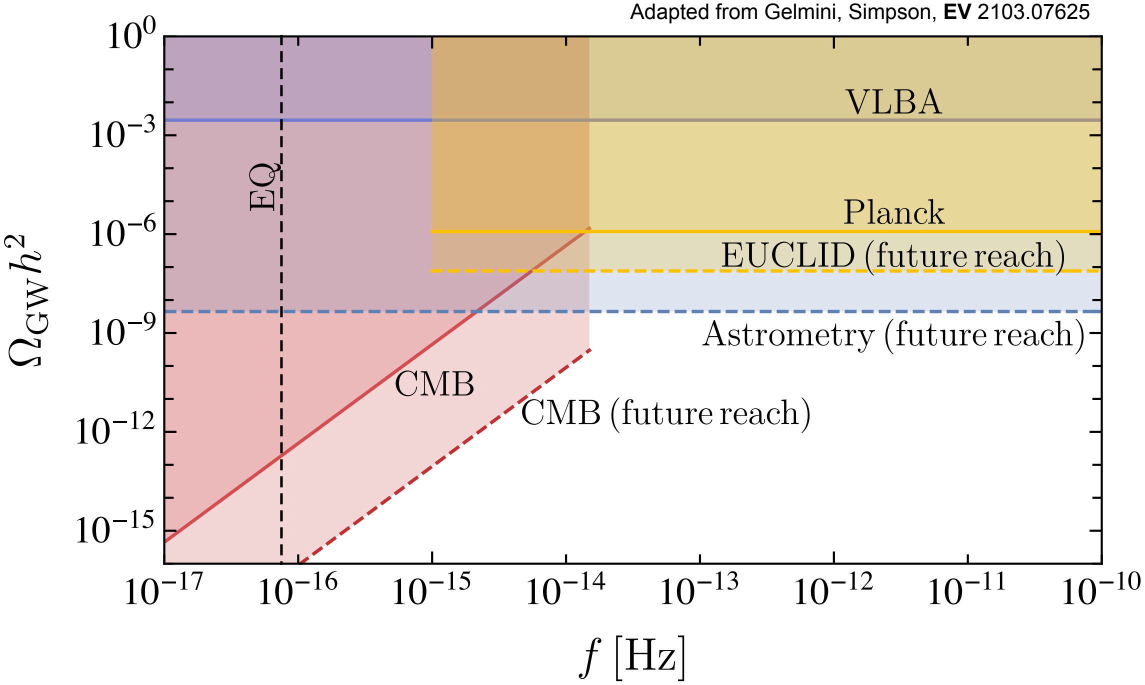

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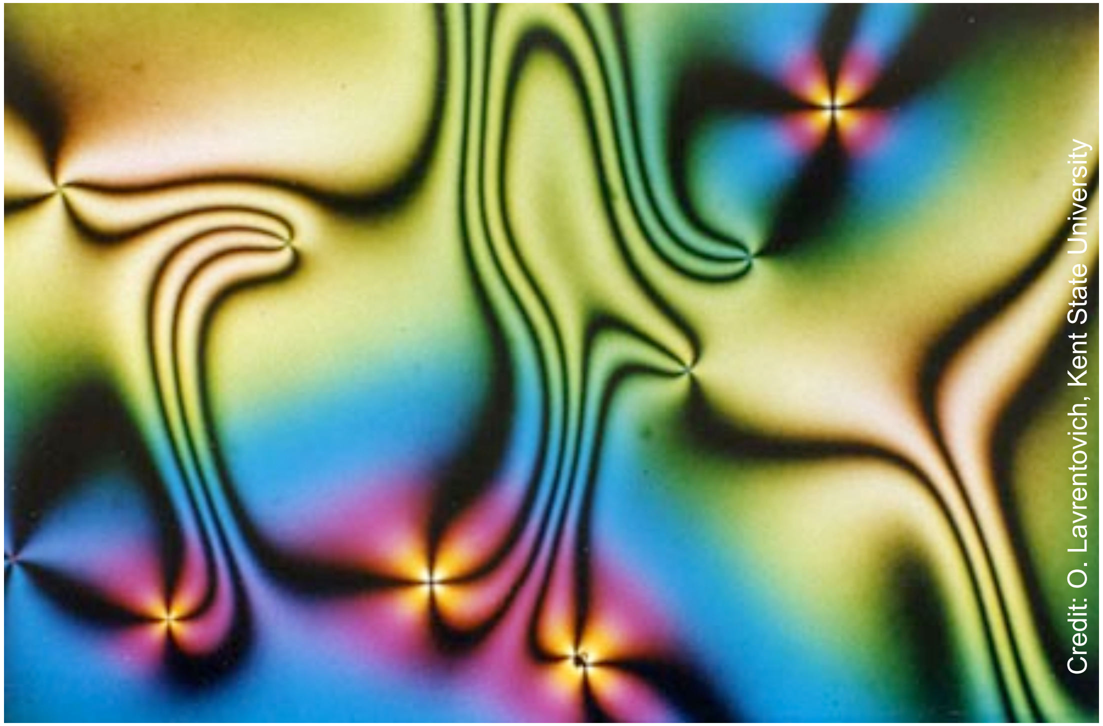
Large objects moving in the early universe produce GWs

Topological defects

Kibble mechanism (Kibble 1976, Zel’dovich 1974, Everett 1974): different patches of the universe develop different VEVs of the same scalar field

Several types of topological defects are possible depending on the pattern of the symmetry breaking:

- monopoles
- strings
- domain walls
- textures


Credit: O. Lavrentovich, Kent State University

Spontaneous symmetry breaking
- Occurrence of primordial phase transitions followed by the formation of topological defects (Kibble 1976)
- Dark matter production (Sikivie 1982)
- Gravitational wave emission (Vilenkin and Shellard 2000 for a review)

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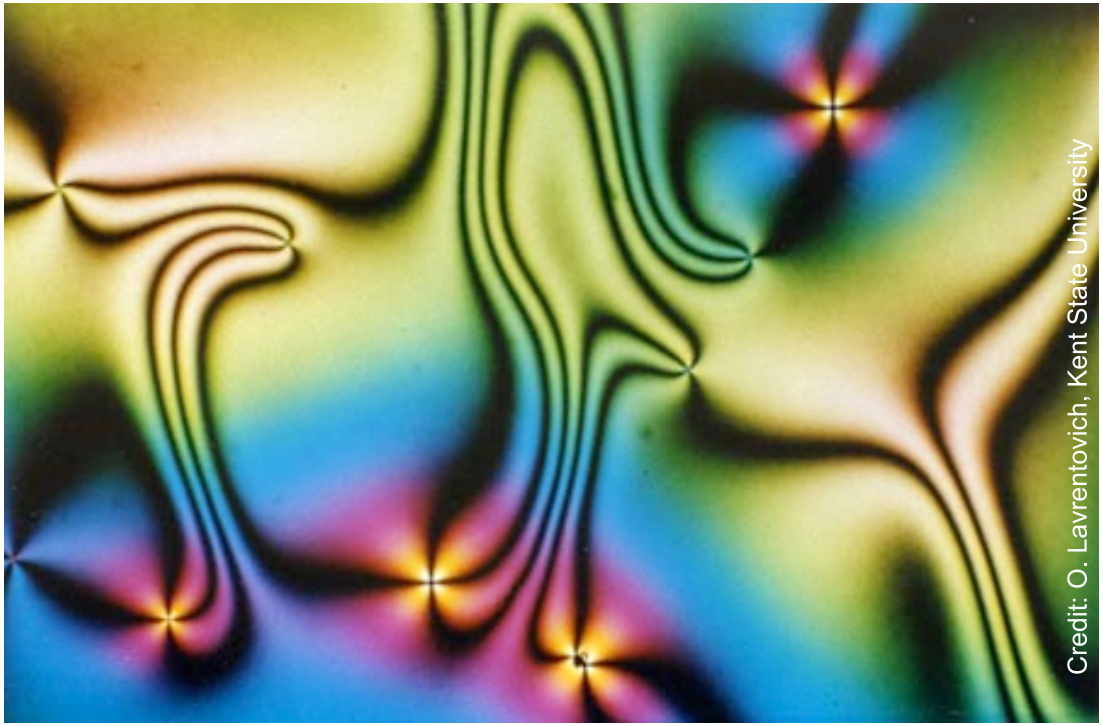

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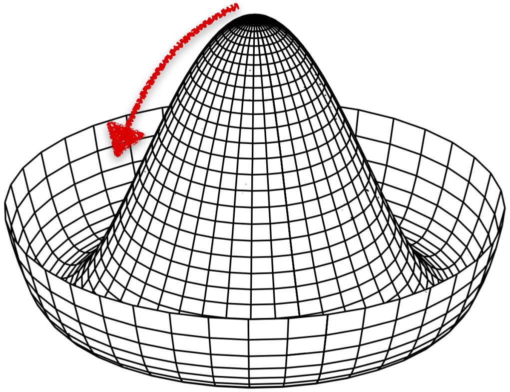
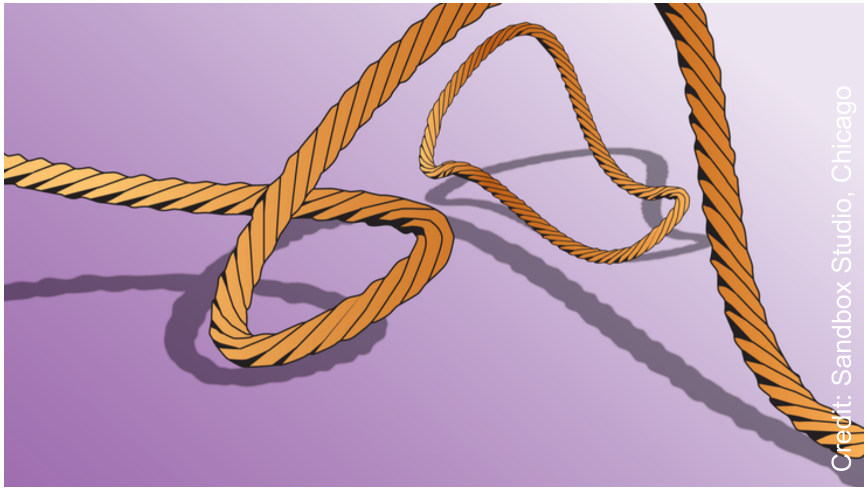
Cosmic strings



Many models include an axial symmetry which is spontaneously broken (e.g. $U(1), O(N)$)

- Cosmic strings: winding number different from zero
- String recombination together with Hubble expansion lead the string network to a scaling regime ($\mathcal{O}(1)$ string per Hubble volume)



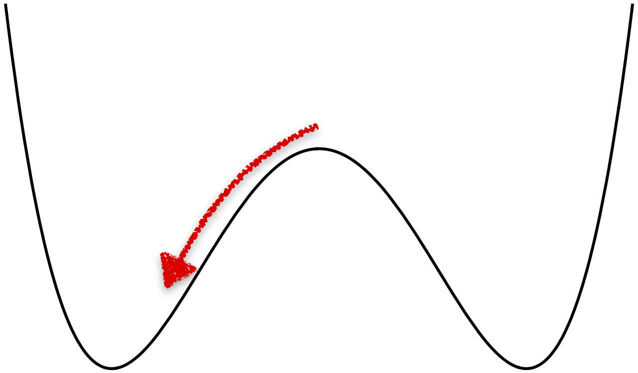
Credit: Sandbox Studio, Chicago

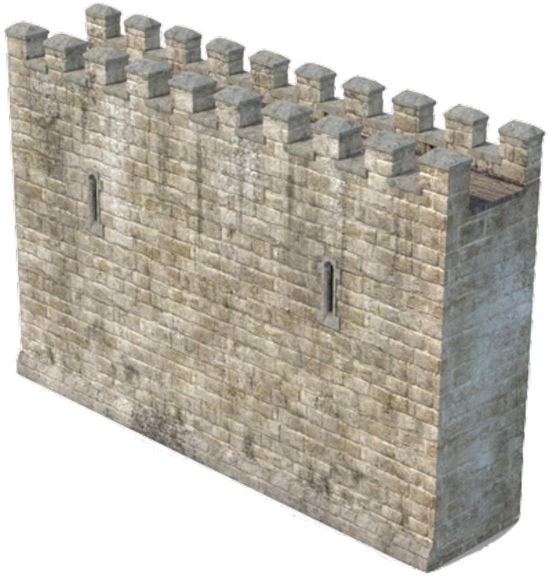
Domain walls

Domain walls form due to a spontaneously broken discrete symmetry (e.g. Z_N)

Different regions of space at different vacua are bounded by walls

- Like strings, domain walls reach a scaling solution in which the energy density evolves with cosmic time σ / t





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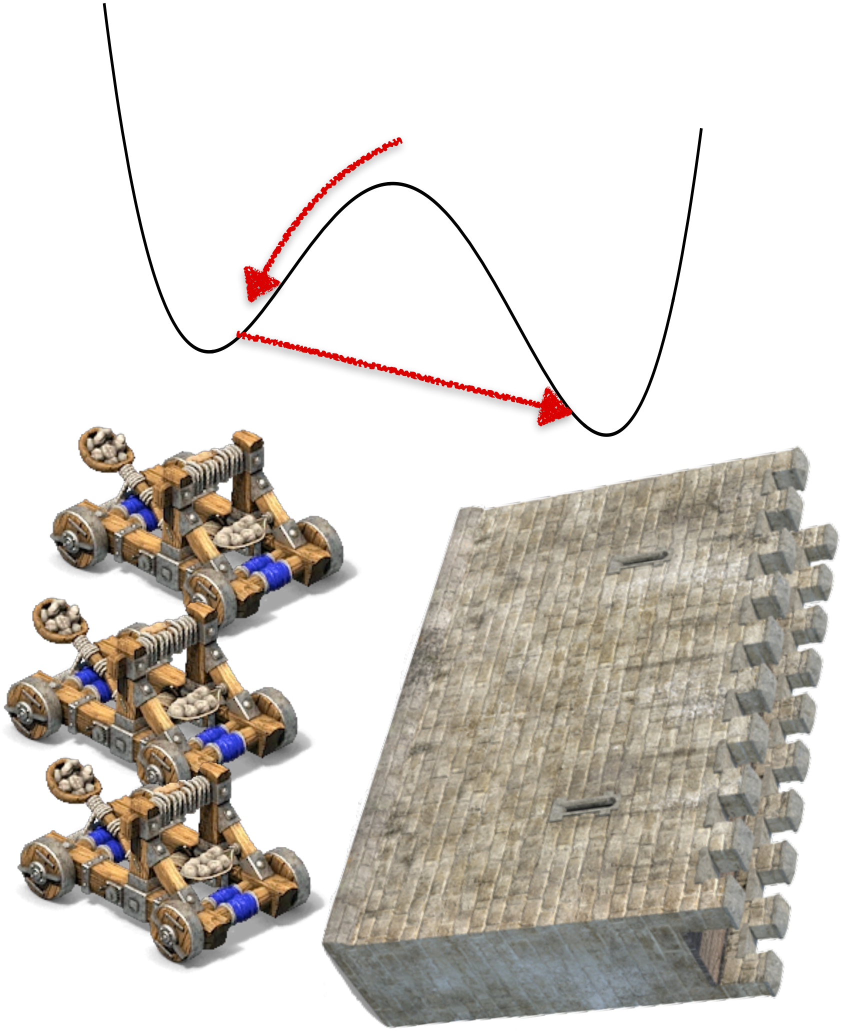
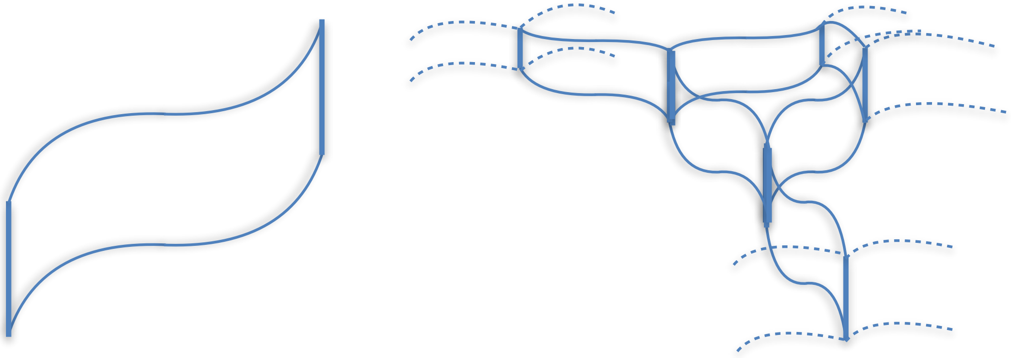
- A wall dominated universe undergoes a power law inflation, which must be prevented by introducing a tilt in the potential, a bias

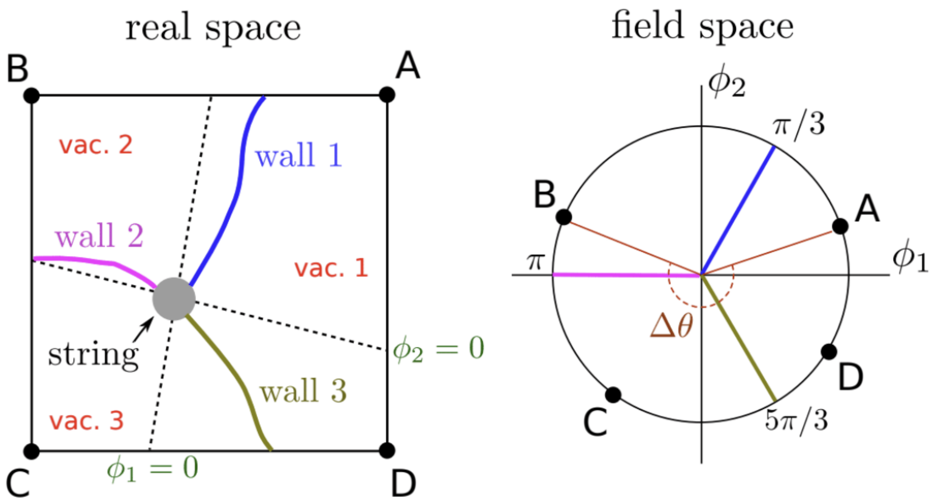


Walls bounded by strings

Formation of walls after strings leads to string wall networks

- N: number of vacua along orbit of minima
- $N = 1$: unstable ribbons collapsing shortly after formation
- $N > 1$: stable network held up by wall tension
- String-wall networks eventually dominated by wall energy density, leading to power law inflation





Adapted from Hiramatsu et al. 1207.3166

Particle physics model(s)

Strong CP ~~problem~~ hint

CP violation in neutrons: electric dipole moment

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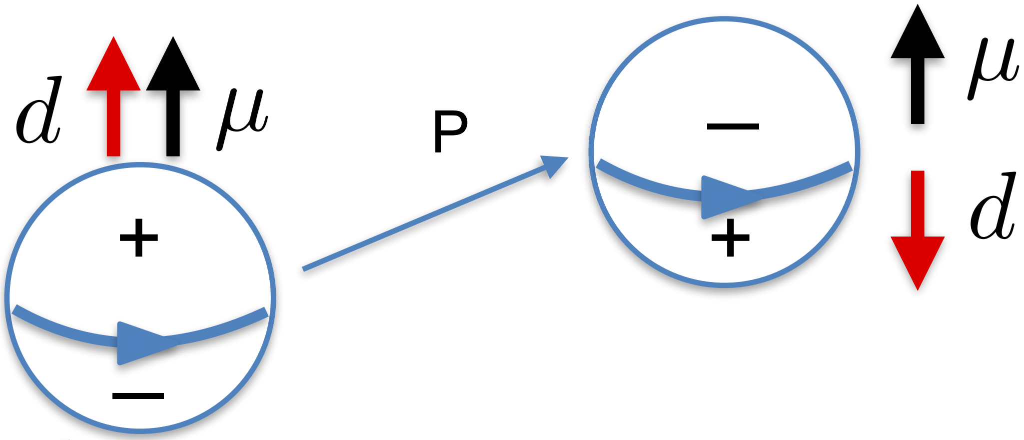
CP violation in neutrons: electric dipole moment

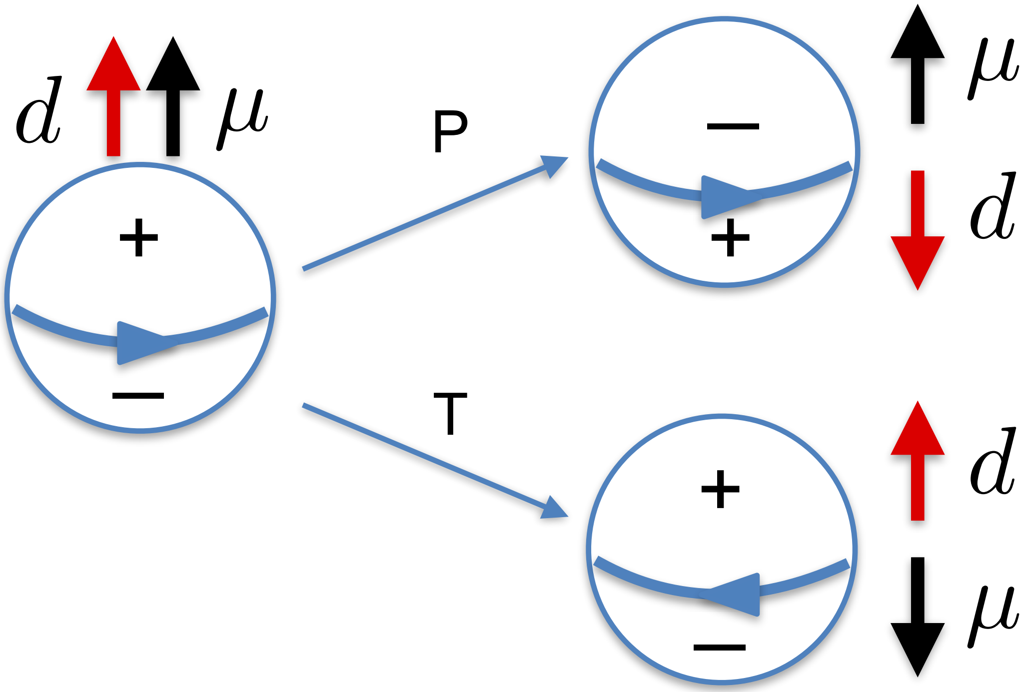


EDM would violate P…

this is a neutron

Strong CP ~~problem~~ hint

CP violation in neutrons: electric dipole moment



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But also T (i.e. CP)

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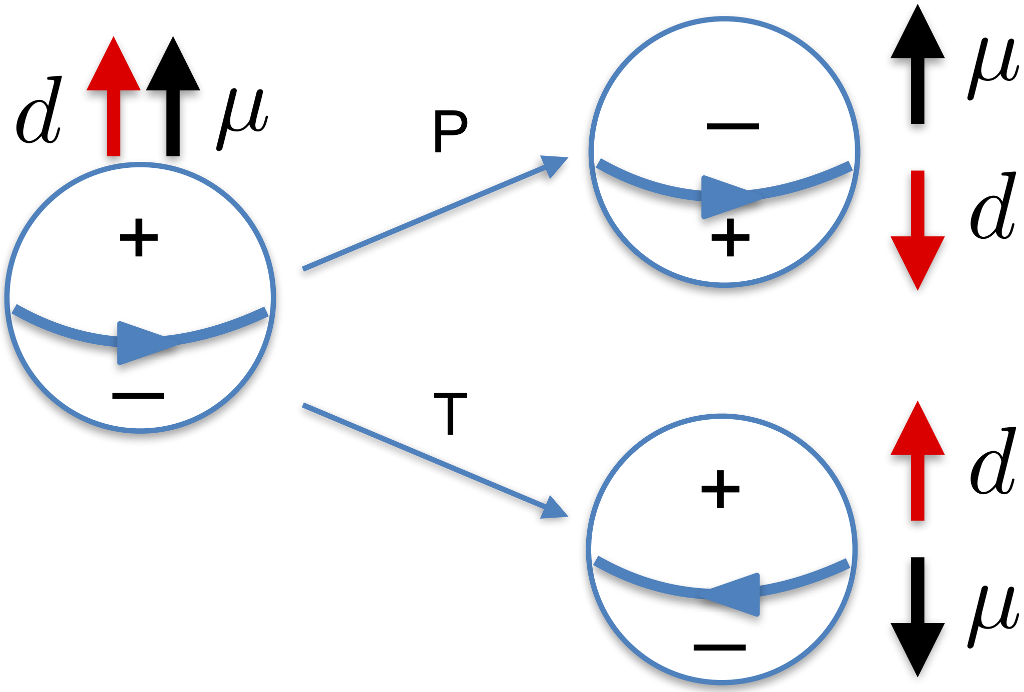

EDM would violate P…

But also T (i.e. CP)

$$|d_n| < 3 \times 10^{-26} q\,\mathrm{cm}$$

It is small. Perhaps because it is not allowed…

Strong CP ~~problem~~ hint, cont'd

The Lagrangian describing hadrons is

$$\tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}G_{\rho\sigma}$$

$$\mathcal{L}_{QCD} = \sum_q \overline{\psi}_q (i\not{D} - m_q e^{i\theta_q})\psi_q - \frac{1}{4}G^2 - \theta\frac{\alpha_s}{8\pi}G\tilde{G}$$

Real mass

Yukawa phase

CP odd

Strong CP ~~problem~~ hint, cont'd

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Why?

A detour: the QCD axion

Introduce a global symmetry spontaneously broken at some high scale V, the Peccei-Quinn symmetry

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Lesson 1

After the SSB, we have a pseudo Goldstone boson rotating the angle away

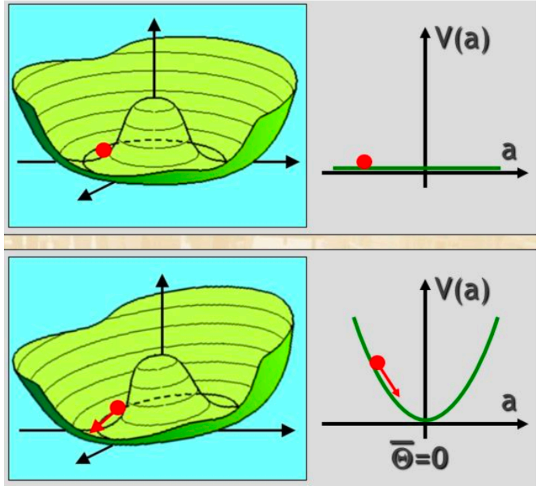
STRONG CP PROBLEM SOLVED ✓

A detour: the QCD axion

Lesson 1, cont'd
The same rotation gives a mass to the axion (w/ two quarks)

$$m_a^2 = \frac{m_u m_d}{m_u + m_d} \frac{\langle \bar{u} u \rangle}{V^2}$$

In other words, give enough time to the universe and it relaxes to a CP conserving QCD Lagrangian*



Credit: G.Raffelt

*your mileage may vary

QCD Axion cosmology in a nutshell

Suppose PQ is broken before inflation. The axion field is homogeneous

$$\ddot{a} + 3H\dot{a} + \frac{\partial U}{\partial a} = 0$$ where $$H = \frac{\dot{R}}{R} \qquad U = m_a^2 a$$

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After being a damped harmonic oscillator, it becomes

$$\ddot{a} \simeq -m_a^2 a \quad \longrightarrow \quad a \simeq \left[\frac{R(H \sim m_a)}{R(t)}\right]^{3/2} a_0 \cos m_a t$$

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Including an additional temperature dependence

$$a \simeq \theta_0 f_a \sqrt{\frac{m_a(T_C)}{m_a(T)}} \left[\frac{R(H \sim m_a)}{R(t)}\right]^{3/2} a_0 \cos m_a t \qquad \rho_a = \frac{1}{2} m_a^2 a^2$$

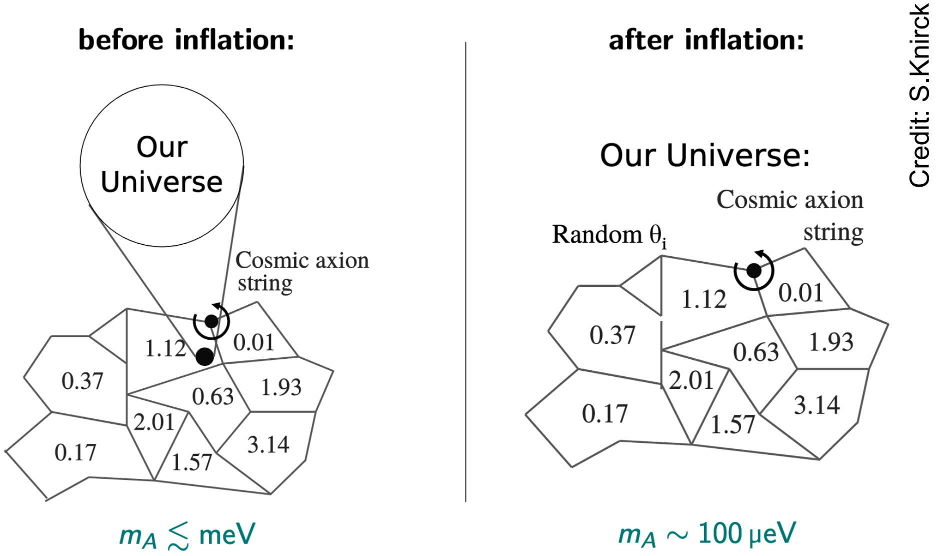
Lesson 2

Axion can be a dark matter candidate

DM MISTERY SOLVED ✓

QCD Axion cosmology in a nutshell

(If broken after inflation, more axions produced from cosmic strings and domain walls)



On QCD axion GW and axion production: Sikivie 1982, Chang et al. hep-ph/9808302, hep-ph/9807374, Hiramatsu et al 1002.1555, 1309.5001, 1207.3166. Ask for additional bibliography on the topic of axions from strings
On N=1 ALPs: Gorghetto et al. 2101.11007

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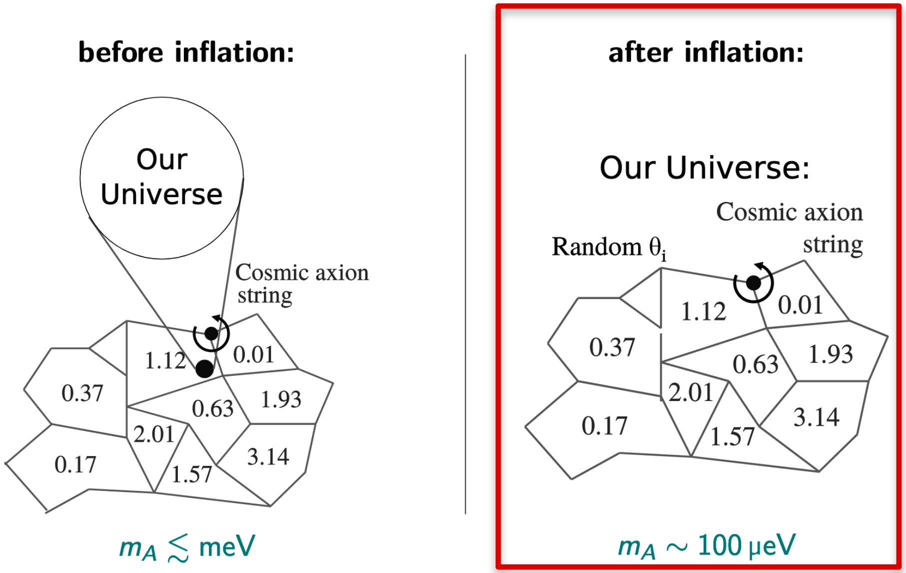

Credit: S.Knirck

New QCD axion detection ideas!

Examples:

- MADMAX (*Phys.Rev.Lett.* 118 (2017) 9, 091801)
- Plasma haloscope (Lawson, Millar, Pancaldi, **EV**, Wilczek), *Phys.Rev.Lett.* 118 (2017) 9, 091801

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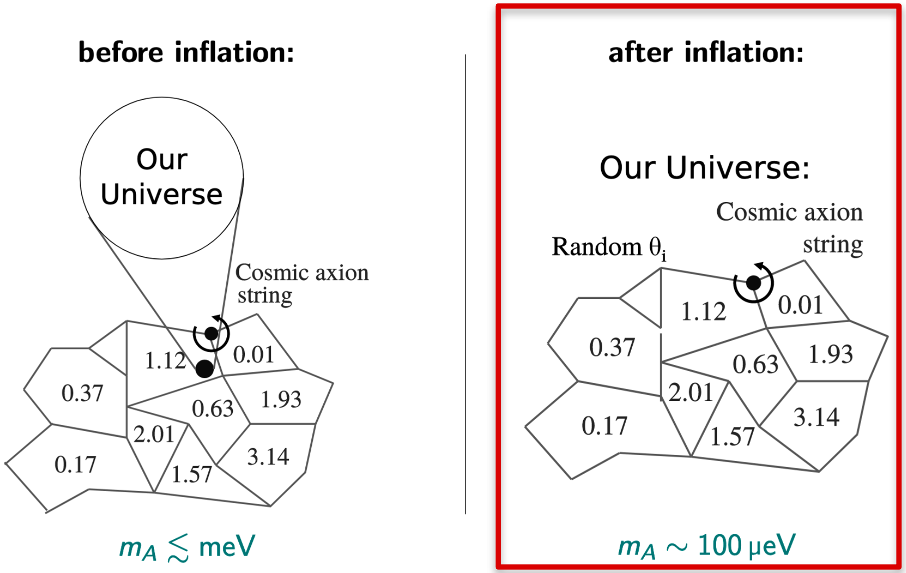

Credit: S.Knirck

Main differences: m_a independent from T and $m_a \not\propto \frac{1}{V}$

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ALPs: a definition

Axion-like particles are pseudo-Nambu-Goldstone bosons corresponding to the spontaneous breaking of a symmetry at high scale V and whose mass is generated by an additional breaking at a smaller scale v. They include

- majorons
- possibly string theory-inspired ALPs

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A simple toy model:

$$V(\phi) \supset \underbrace{\frac{\lambda}{4}(|\phi|^2 - V^2)^2}_{\text{Nambu-Goldstone bosons}} + \underbrace{\frac{v^4}{2}\left(1 - \frac{|\phi|}{V}\cos(N\theta)\right)}_{\text{Mass generation}} \underbrace{- \epsilon_b v^4 \frac{|\phi|}{V}\cos\left(\theta - \delta\right)}_{\text{Bias}}$$

As the temperature lowers, each term becomes important

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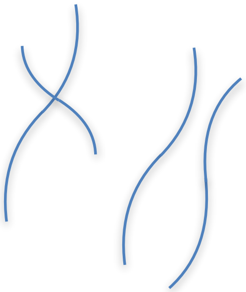
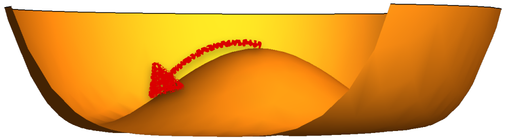
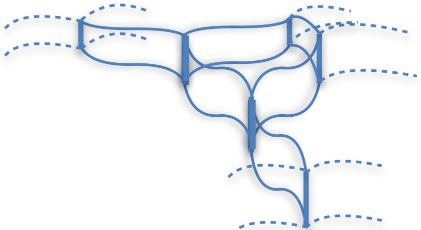
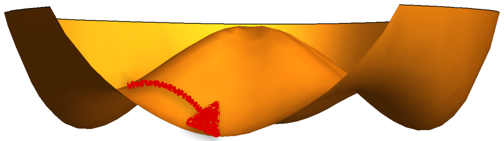


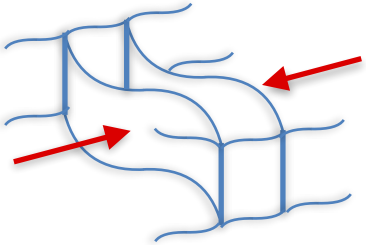
Strings form



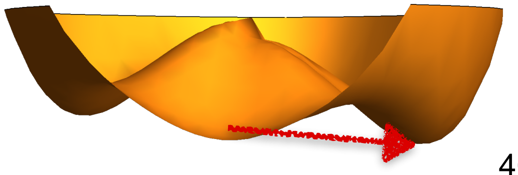


Walls formation+misalignment





Walls annihilate



Spontaneous symmetry breaking

$$V(\phi) \supset \underbrace{\frac{\lambda}{4}(|\phi|^2 - V^2)^2}_{\text{Nambu-Goldstone bosons}} + \underbrace{\frac{v^4}{2}\left(1 - \frac{|\phi|}{V}\cos(N\theta)\right)}_{\text{Mass generation}} - \underbrace{\epsilon_b v^4 \frac{|\phi|}{V}\cos\left(\theta - \delta\right)}_{\text{Bias}}$$

- When $T \simeq V$ (assuming that the field has initially the same temperature as the visible sector), spontaneous symmetry breaking occurs

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- The string mass per unit length is

$$\mu \simeq 2\pi V^2 \ln\left(\frac{t}{\sqrt{\xi}\, d_{\text{st}}}\right)$$

strings/volume

Explicit breaking

$$V(\phi) \supset \underbrace{\frac{\lambda}{4}(|\phi|^2 - V^2)^2}_{\text{Nambu-Goldstone bosons}} + \underbrace{\frac{v^4}{2}\left(1 - \frac{|\phi|}{V}\cos(N\theta)\right)}_{\text{Mass generation}} - \underbrace{\epsilon_b v^4 \frac{|\phi|}{V}\cos(\theta - \delta)}_{\text{Bias}}$$

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$$T_w \simeq \frac{5.1 \times 10^4 \mathrm{GeV}}{[g_\star(T_w)]^{1/4}} \left(\frac{m_a}{\mathrm{eV}}\right)^{1/2}$$

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- Walls attached to the strings form with tension

$$\sigma = f_\sigma v^2 \frac{V}{N}$$

Model-dependent dimensionless parameter

Bias

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- The volume pressure $p_V = \text{Bias}$ tends to accelerate the walls towards their lower energy adjacent vacuum (detonation)
- Walls annihilate when $p_T \simeq p_V$,

$$H(T_{\rm ann}) \simeq \epsilon_b v^4/2\sigma = \frac{\epsilon_b m_a}{\sqrt{2} f_\sigma}$$

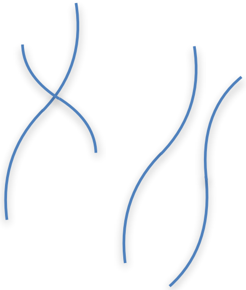
$$\longrightarrow T_{\rm ann} \simeq \frac{0.73 \times 10^5 \ \text{GeV}}{[g_\star(T_{\rm ann})]^{1/4}} \sqrt{\frac{\epsilon_b \ m_a}{f_\sigma \ \text{eV}}}$$

From theory to observations

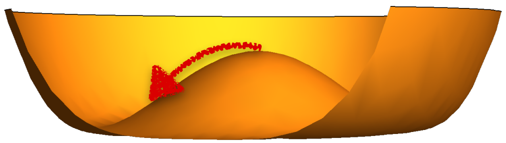
Present ALP energy density

There are **three** mechanisms to produce ALPs in our scenario:

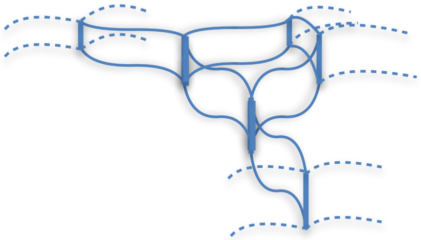
- Misalignment mechanism
- String decay
- Walls annihilation



Strings form



$$T \simeq V$$



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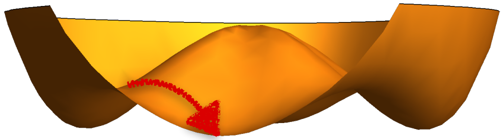
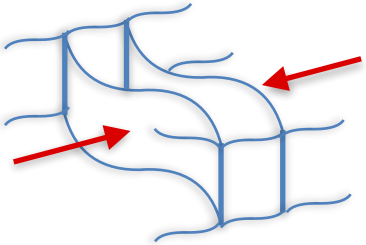


$$3H(t_w) \simeq m_a = \frac{v^2 N}{\sqrt{2}V}$$



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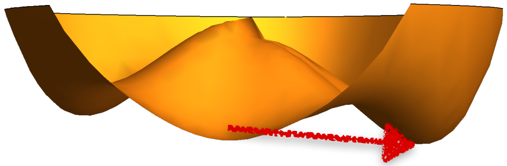

$$p_T(T_{\rm ann}) \simeq p_V(T_{\rm ann})$$

ALPs at present: misalignment

- The dark matter abundance due to the misalignment mechanism is immediately obtained. At wall formation (when $3H \simeq m_a$)

$$\rho_{a,0}(t_w) = \frac{1}{2} m_a^2 a^2 = \frac{1}{2} m_a^2 \theta_w^2 V^2$$

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- Including the redshift

$$\rho_{a,0}(t_0) = \rho_{a,0}(t_w) \left(\frac{R(t_w)}{R(t_0)} \right)^3 \qquad \left(\frac{R(t_w)}{R(t_0)} \right)^3 = \frac{\frac{2\pi^2}{45} g_0^* T_0^3}{\frac{2\pi^2}{45} g_w^* T_w^3}$$

- Which gives

$$\Omega_a^{\text{mis}} h^2 = \frac{\rho_{a,0}(t_0)}{\rho_c} h^2 \simeq 0.77 \times 10^{-19} \underbrace{\langle \theta_w^2 \rangle}_{\simeq \pi^2/3} \frac{V^2 m_a^{1/2}}{\text{GeV}^{5/2}} \frac{[g_\star(T_w)]^{3/4}}{g_{s\star}(T_w)}$$

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UCLA

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- The number density is found as (see e.g. 1012.5502)

$$n_a \simeq \int_{t_*}^{t_w} dt \left[R(t)^3 \left(\frac{d\rho_{\rm strings}}{dt}\frac{1}{H(t)}\right)\right]$$

$$E_a \simeq H(t)$$

- After the formation of walls, the number density simply redshifts and one finds

$$\Omega_a^{\rm st} h^2 \simeq 0.95 \times 10^{-23}\,\xi\;\ln\left(\frac{3V}{\sqrt{2\xi}\;m_a}\right)\left(\frac{V}{\rm GeV}\right)^2\left(\frac{m_a}{\rm eV}\right)^{1/2}\frac{[g_\star(T_w)]^{3/4}}{g_{s\star}(T_w)}$$

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ALPs at present: walls

- Most of energy stored in walls is lost in the emission of ALPs at annihilation, therefore

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$$m_a/\langle E_a \rangle \simeq 1/\sqrt{2}$$

- The density parameter from walls is

$$\Omega_a^{\rm walls} h^2 \simeq \frac{2.4 \times 10^{-24}}{\epsilon_b^{1/2}} \left(\frac{f_\sigma^{3/4} V}{N {\rm GeV}}\right)^2 \left(\frac{m_a}{\rm eV}\right)^{1/2} \frac{[g_\star(T_{\rm ann})]^{3/4}}{g_{s\star}(T_{\rm ann})}$$

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ALPs at present: take home

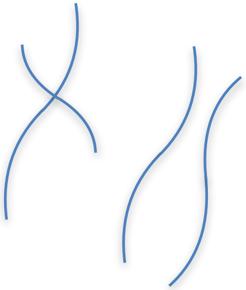
- String decay can be more important than misalignment mechanism (subject to simulation uncertainties)

- Wall annihilation gives most of the contribution to ALPs for a small enough bias ϵ_b (walls decay later and they are less redshifted)

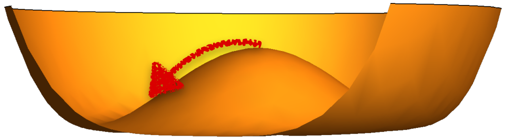
Present GW energy density

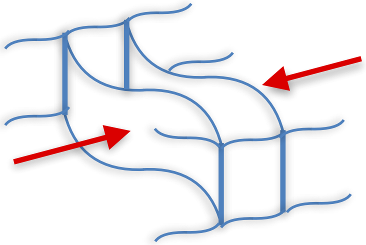
There are **two** mechanisms to produce GWs in our scenario:

- String decay
- Walls annihilation

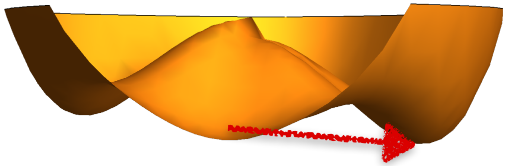


Strings form



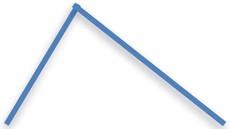


Walls annihilate



Present GW energy density: walls

Wall annihilation gives a spectrum which scales like f^3 at low frequencies (because of causality) and f^{-1} at high frequencies (a bit more uncertain)



We expect therefore a peaked spectrum. The peak amplitude is evaluated through the quadrupole formula,

$$P \simeq G \dddot{Q}_{ij} \dddot{Q}_{ij}$$

where

$$\dddot{Q}_{ij} \simeq \sigma t$$

(Because)

$$Q_{ij} \simeq \; E_w t^2 \qquad\qquad E_w \simeq \sigma t^2$$

Present GW energy density: walls

So the GW energy density is

$$\Delta\rho_{\rm GW}(t) \simeq G\sigma^2 \frac{\Delta t}{t}$$

Which including the redshift is

$$\rho_{\rm GW}\big|_{\rm peak} \simeq G\sigma^2 \left(\frac{R(t_{\rm ann})}{R_0}\right)^4$$

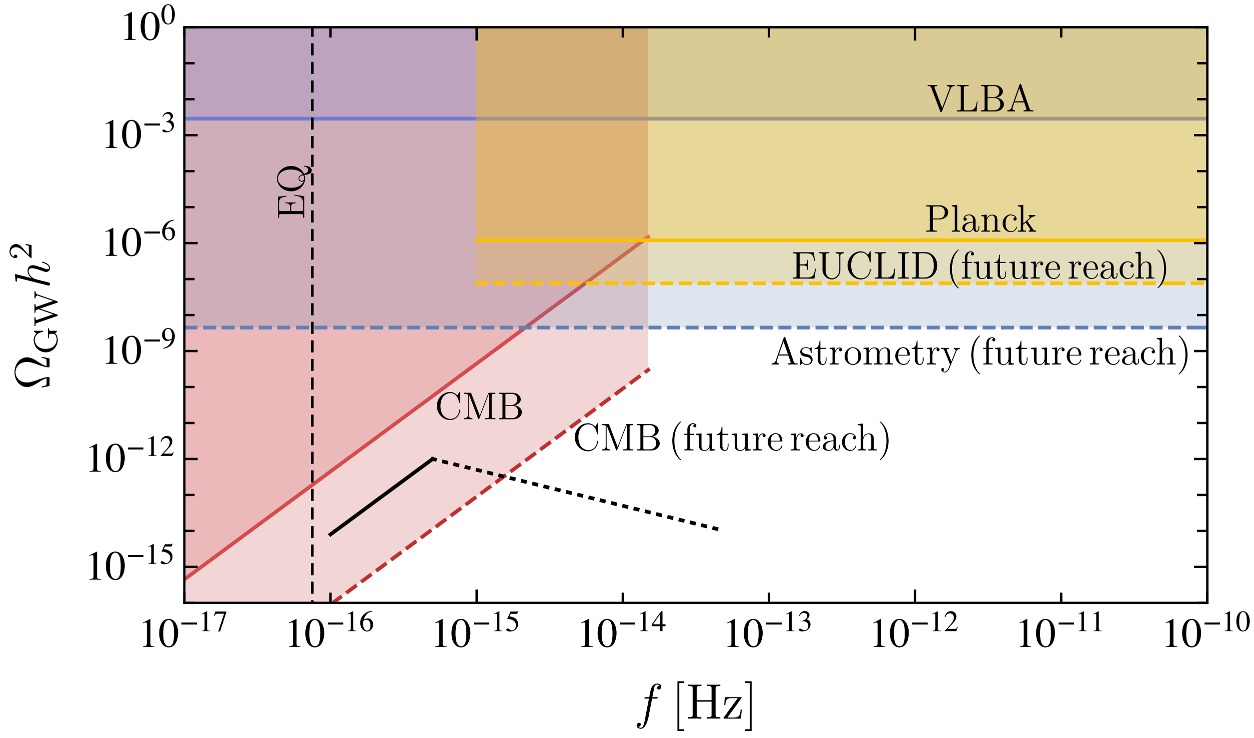
$$\Omega_{\rm GW}h^2\big|_{\rm peak} \simeq \frac{1.2\times 10^{-79}\epsilon_{gw}\ g_\star(T_{\rm ann})}{\epsilon_b^2\ \left[g_{s\star}(T_{\rm ann})\right]^{4/3}} \left(\frac{f_\sigma V}{N{\rm GeV}}\right)^4$$

The peak frequency is

$$f_{\rm peak} = R(t_{\rm ann})H(t_{\rm ann}) \simeq 0.76\times 10^{-7}{\rm Hz}\ \frac{T_{\rm ann}}{\rm GeV}\ \frac{\left[g_\star(T_{\rm ann})\right]^{1/2}}{\left[g_{s\star}(T_{\rm ann})\right]^{1/3}}$$

Present GW energy density: walls

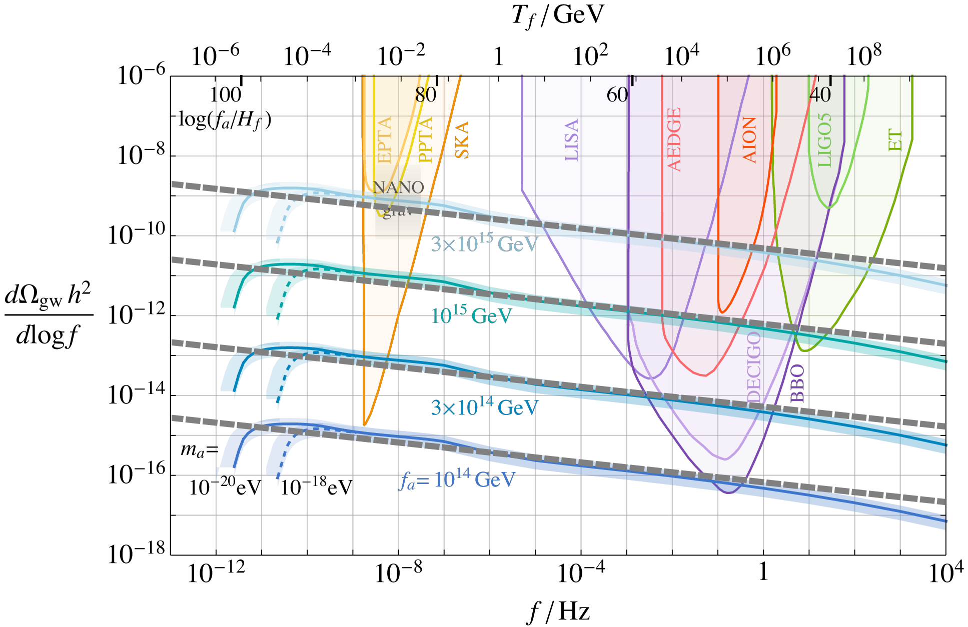
An example of GW spectrum from walls is this



(assuming $f_\sigma/N = 1$, $T_{\rm ann} = 5\,{\rm eV}$ and $\Omega_{\rm GW}h^2|_{\rm peak} = 10^{-12}$)

Present GW energy density: strings

- The GW emission from string is $\mathcal{O}(1)$ the same as in the $N=1$ case computed in the literature (see e.g. 2101.11007)



Adapted from Gorghetto et al. 2101.11007

- We find that a good semi-analytical fit is

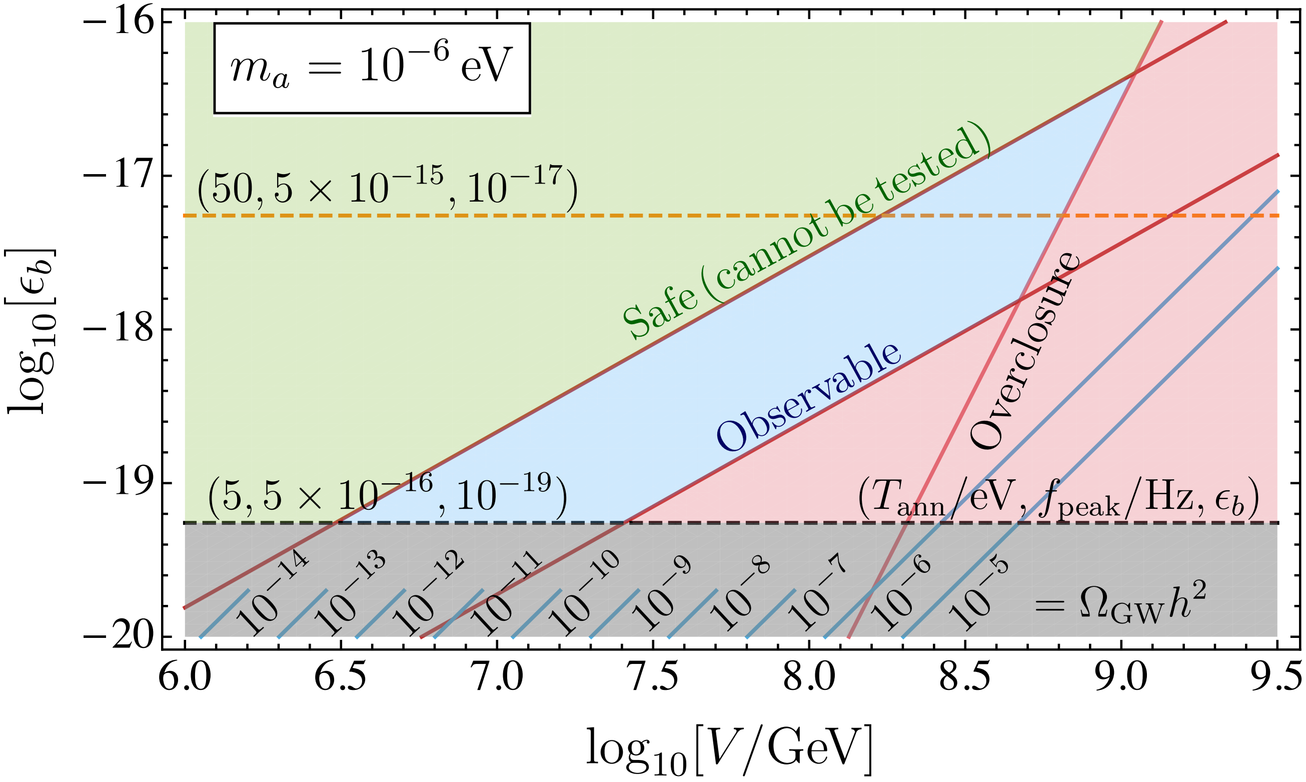
$$\Omega_{\rm GW}^{\rm st}h^2 \simeq 2\times10^{-15}\left(\frac{10^{-12}\ \mathrm{Hz}}{f}\right)^{1/8}\left(\frac{V}{10^{14}\ \mathrm{GeV}}\right)^{4}$$

Present GW energy density: strings

As far as $V \lesssim 10^{14}\,\mathrm{GeV}$, GWs from walls dominate the signal

Observational perspectives

The observable region preserves its shape as $\epsilon_b \propto 1/m_a$



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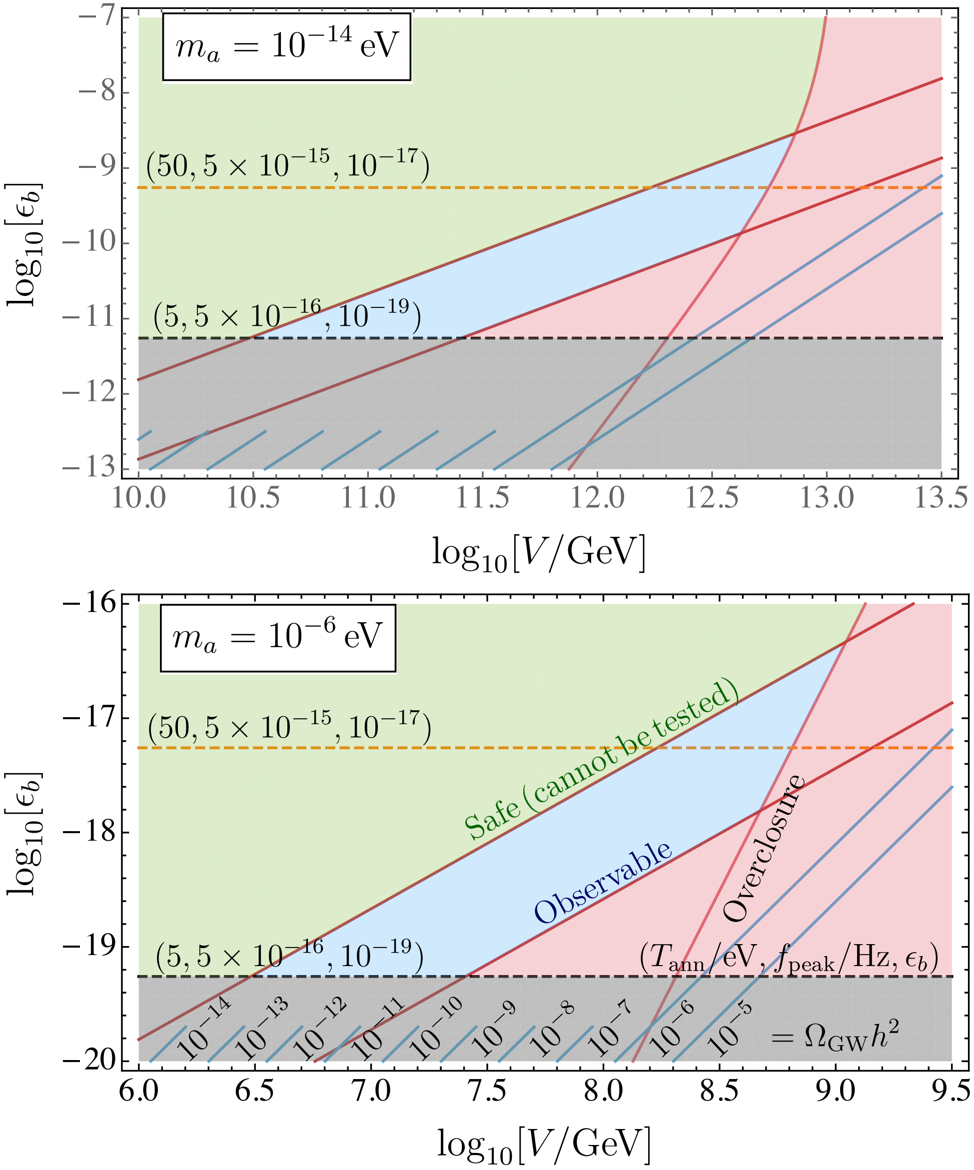
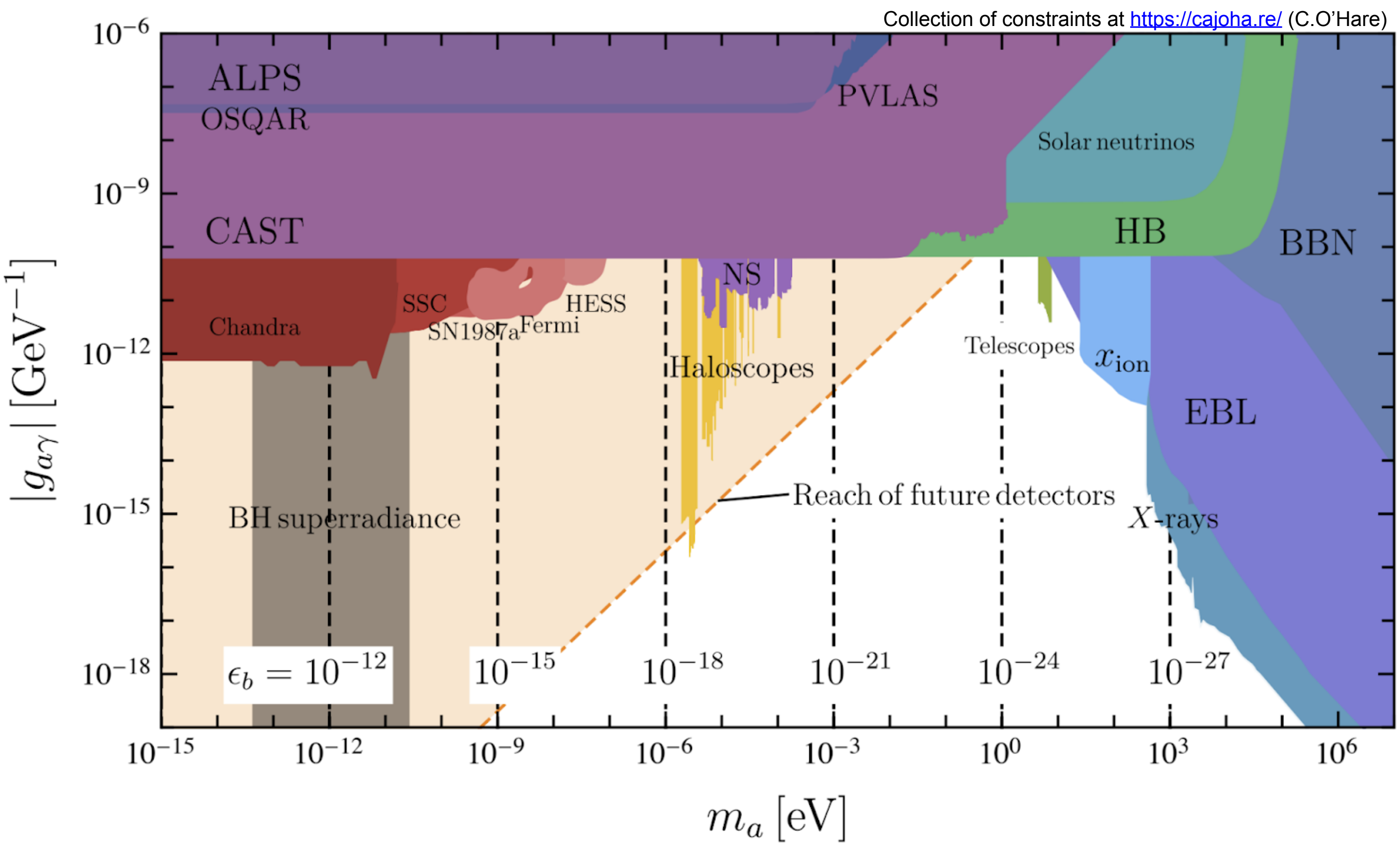


Coupling to photons

Collection of constraints at https://cajoha.re/ (C.O'Hare)



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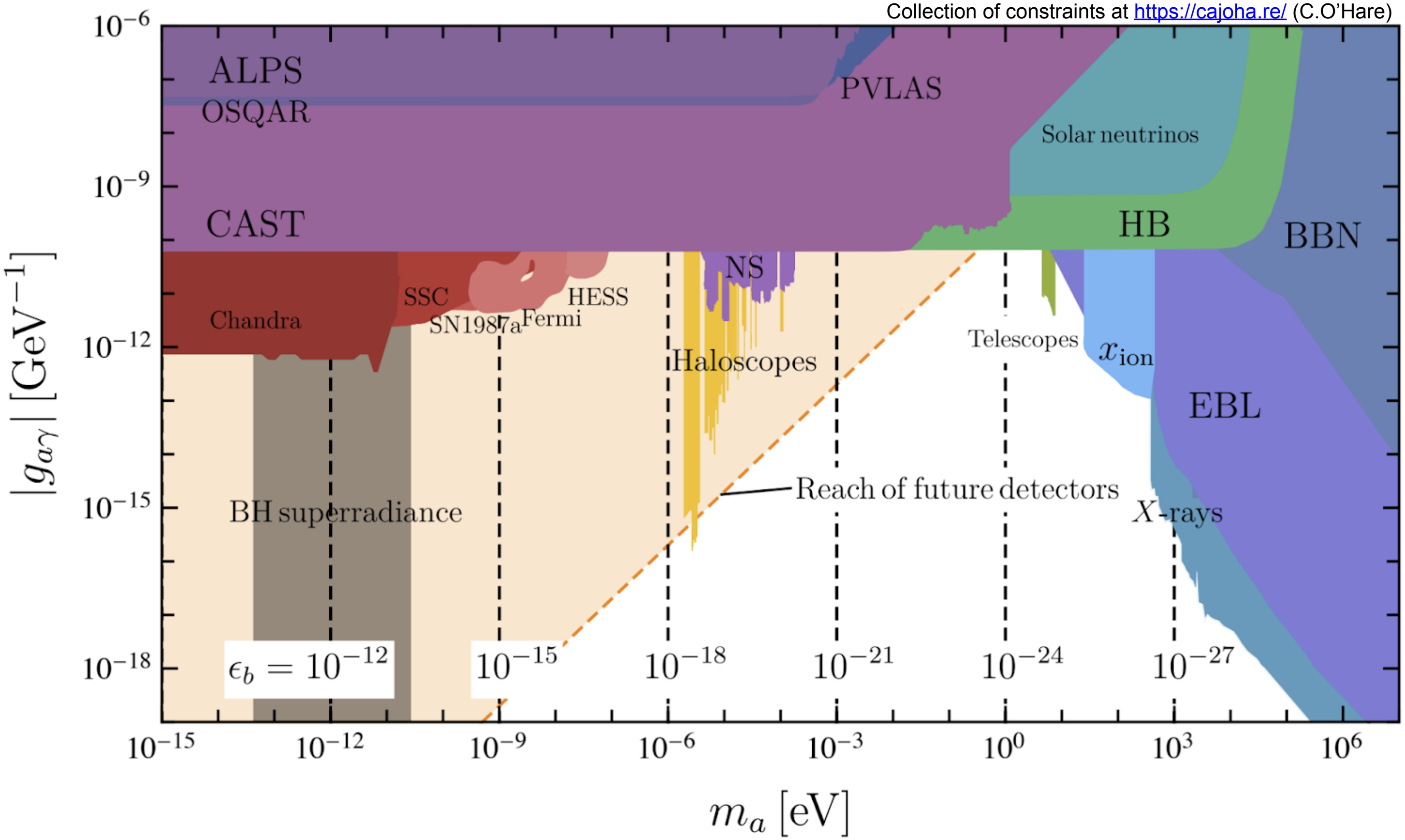

Asking for $\Omega_{\rm GW}^{\rm wall} \gtrsim \Omega_{\rm GW}^{\rm strings}$

$$m_a > 5 \times 10^{-16} \text{ eV}$$

Asking for $v < 10^{-2} V$

$$\begin{cases} V > 2.5 \text{ GeV} \\ m_a < 1.5 \text{ MeV} \end{cases}$$

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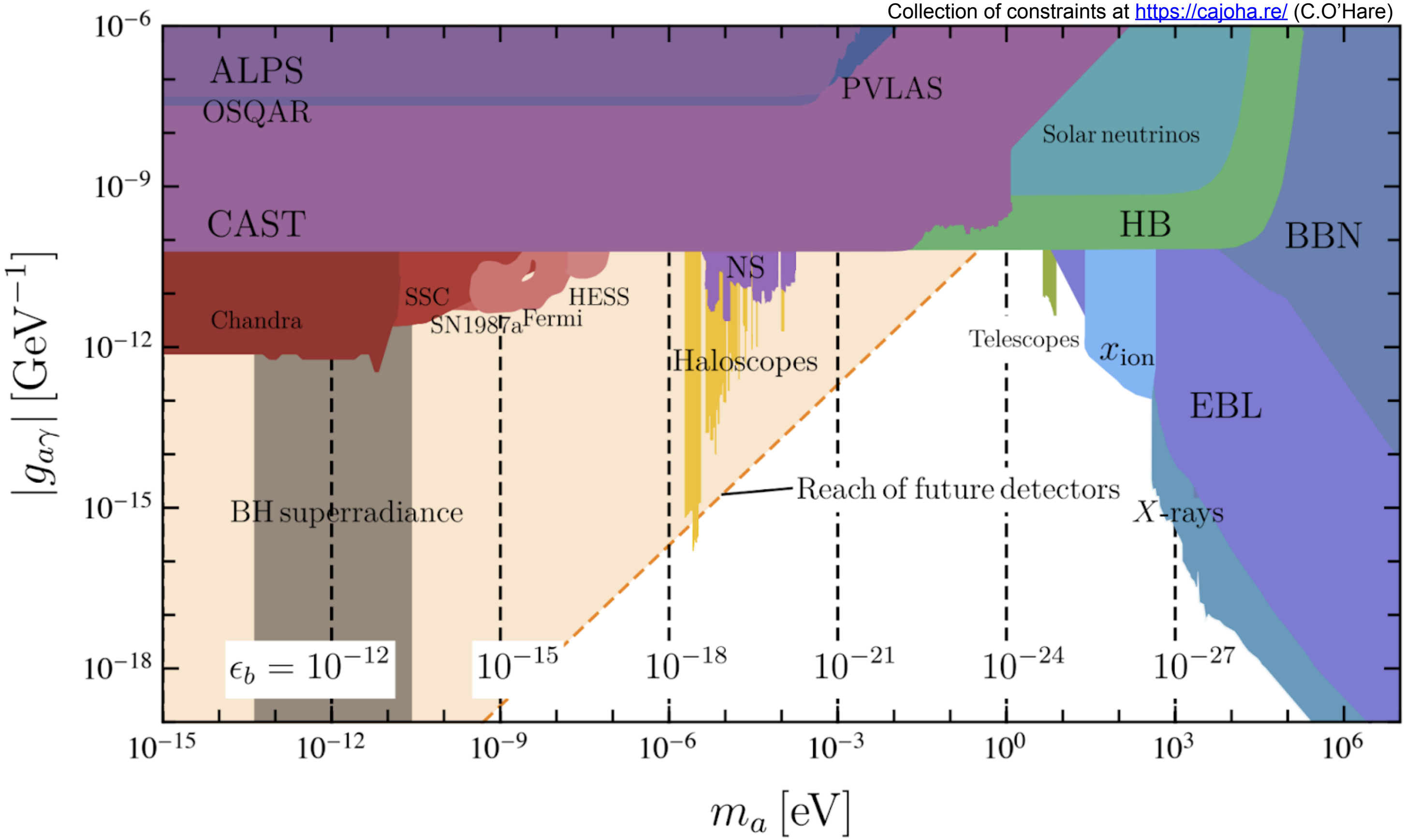

If we are lucky, we could discover barely interacting ALPs

Conclusions

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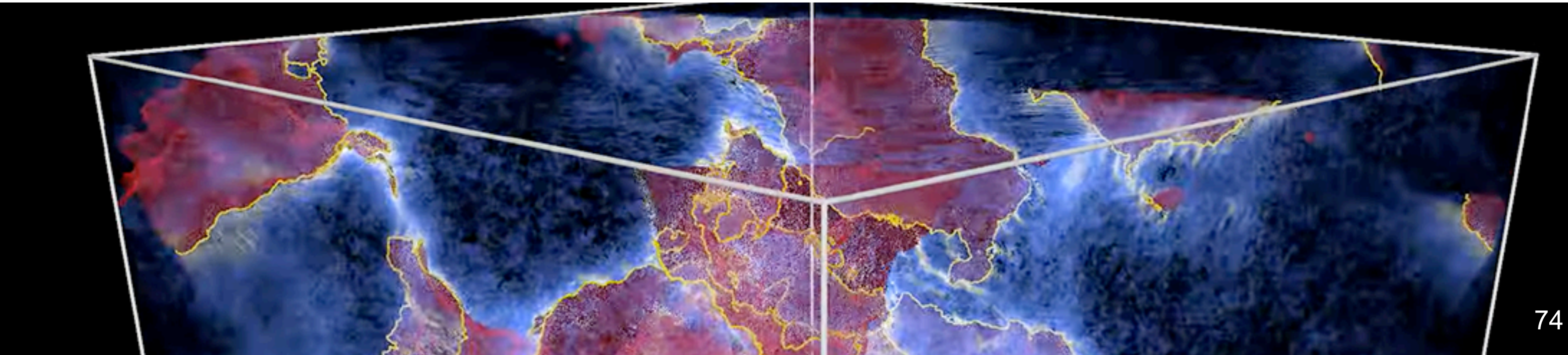

Credit: M. Buschmann

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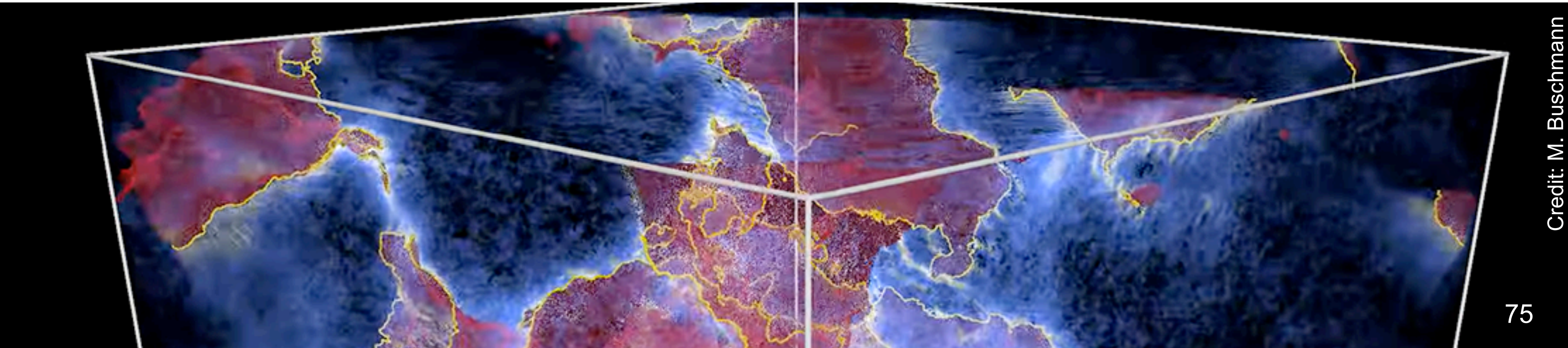

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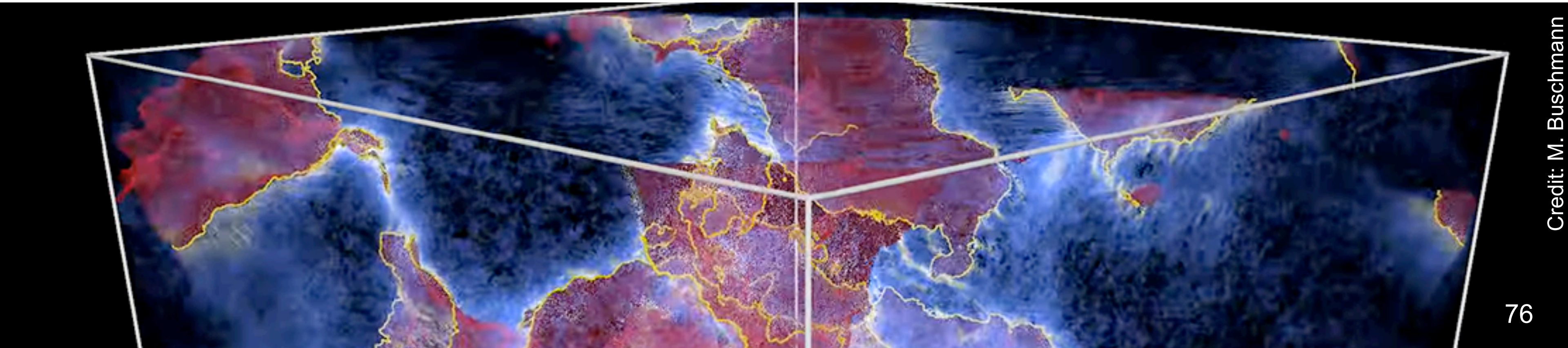
- The presence of ALPs leads to the formation of topological defects, i.e. **cosmic strings and domain walls**
- For $N > 1$ domain walls produce most of ALP dark matter and gravitational waves
- There is a window in which the gravitational wave background from domain walls would be **observable** with cosmological and astrometric data



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Thank you

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*like