Les candidats au-delà du Modèle Standard: WIMPs versus Axions

avantages et inconvénients

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Introduction

- DM is a key part of our SM of cosmology.
- ΛCDM predicts the evolution of the Universe since the Big Bang at large scales, and depends on a few number of assumptions.
- Without DM, it is not possible to reconcile data with observations.

Why do you need to know about DM?

- As physicist exploring the frontiers of the SM of particle physics: it is important to know which BSM candidates are well motivated.

needed BSM: neutrino masses, baryogenesis, DM and quantum gravity, etc.

Goal of this talk:

- Understand the link between DM and the weak scale (WIMP paradigm).
- However, the **WIMPs** are showing some of their limits, prompting efforts to explore candidates with varying masses and cross-sections (**Axions**).

Earlier DM crisis

Before modern evidence for DM (early of the last century) :

- 1840's: astronomical data faced a DM crisis: orbits of the planets in the Solar System was not consistent with the mass observed.

Uranus anomalous orbit:

- 31/**08/1846**: Le Verrier predicted a new source of matter (new planet) that hadn't been detected before.
- 23/**09/1846**: Neptune was found.

Mercury anomalous orbit:

- 1860: Le Verrier predicted an inner planet (Vulcan).
- 1916: Einstein showed that theory of gravity was failing
  i.e Newtonian dynamics need to include GR corrections

Lesson:

- Newtonian gravity was not being accurate in 2 situations with two very different gravitational potentials $\phi_N \sim GM_\odot/r$
- The solution to one of the problem couldn't fix the other one.
  GR corrections are very small for outer planets.

In the case of DM: a multi-scale phenomenology can be explained by 1 hypothesis!

Dark matter evidence: **galactic curves**

- Circular gravitational orbits satisfy:

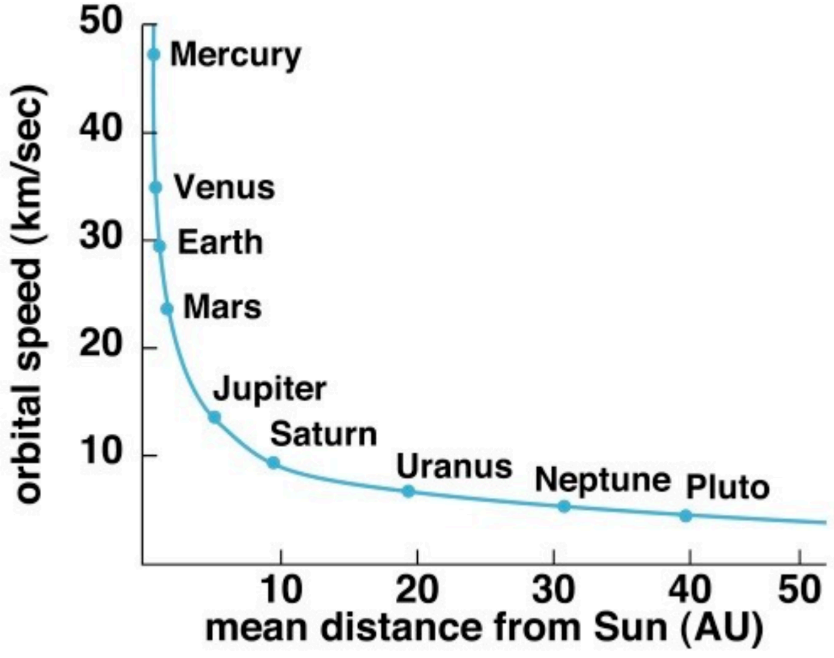
spherical mass

$$v^2(r) = \frac{GM(<r)}{r} \quad \text{(Newton's law)}$$

all the mass is at the center: $r^{-1/2}$ law →

(Newton's second theorem)

In the Solar System:

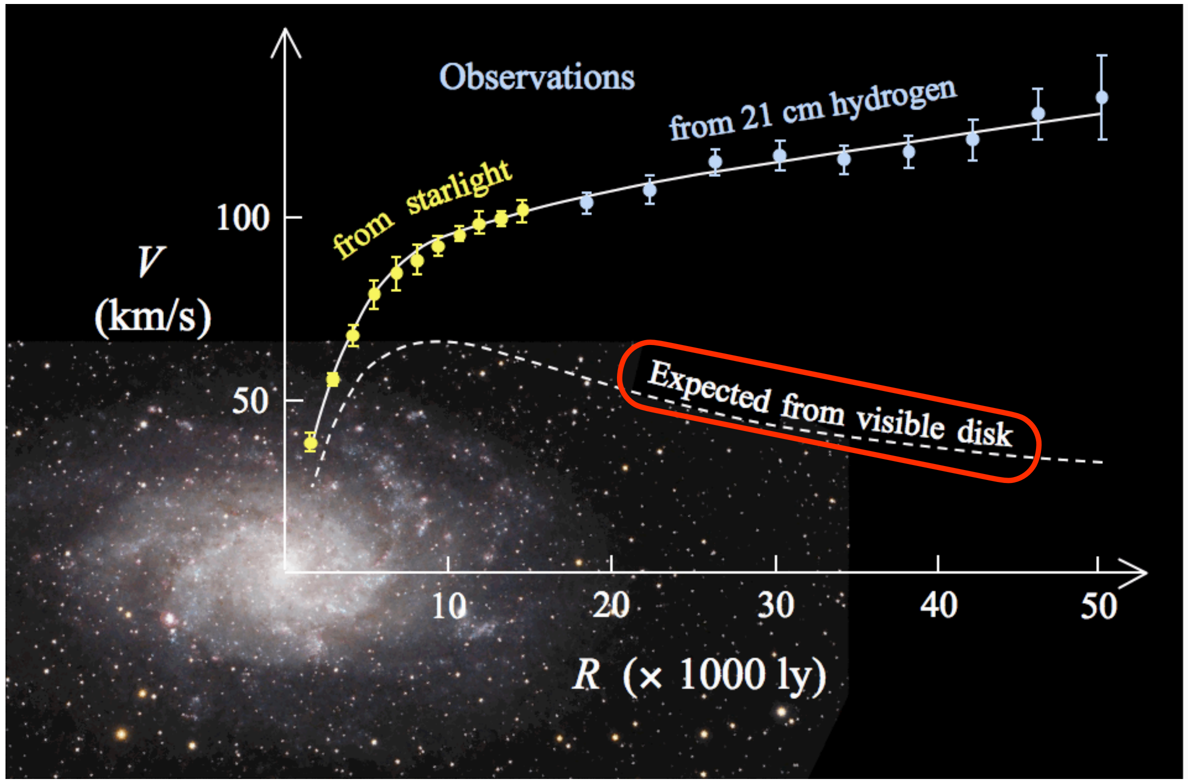


- Rotation curves in galaxies:

(axisymmetric objects of constant density)

Inside of matter distribution:

$$M(r) \propto \rho r^3$$
$$v(r) \propto r$$



one needs

⊳ $\rho(r) \propto r^{-2}$

spherical 'halo' of matter extending disk of observed galaxies

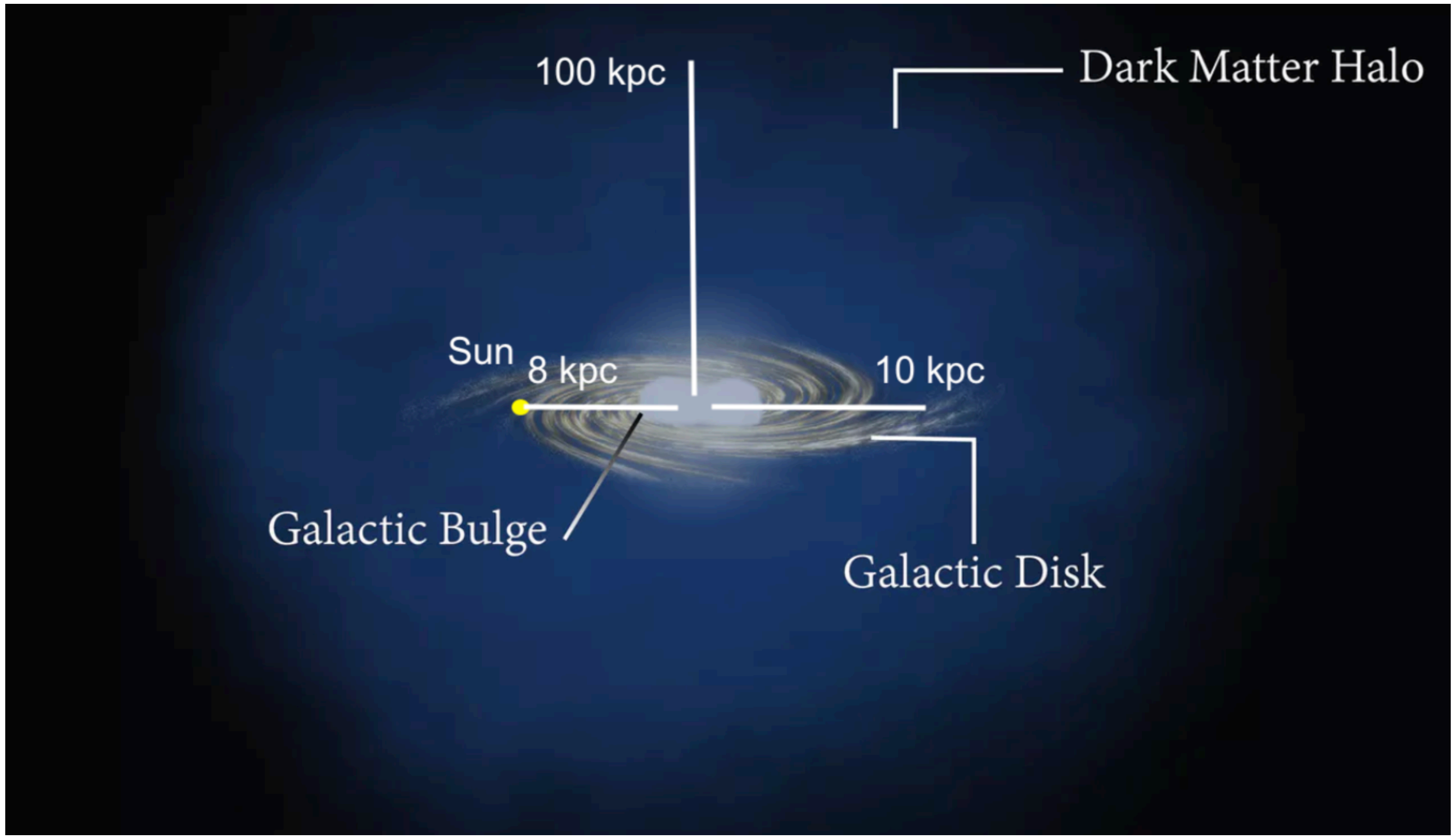
Outside of matter distribution:

$$M(<r) = cst$$
$$v(r) \propto r^{-1/2}$$

Assuming Newtonian gravity is correct ⇒ galaxies are surrounded by the extended halos of invisible dark matter

What DM can not be

Milky Way : most of the visible galaxy is confined into a flat **disk**



Why does SM matter prefer to form disks rather than spherical configurations?

Cooling of the primordial halos due to emission of photons.

If DM can cool efficiently, it can not be distributed as a sphere.

→ DM can not be charged as much as SM particles.

Dark matter evidence: **dynamics of galaxy clusters**

- Galaxies are large structures (radius of the DM halo in the Milky Way is 100 kpc).

- **Clusters** of galaxies: several galaxies are interacting with each other and form a gravitationally bound structure (typical size of 10 Mpc)

If the cluster of galaxies is in a stationary configuration, the **virial theorem** teaches us:

$$2\langle T\rangle = -\langle V\rangle$$

1933: F. Zwicky analyses the data from the Coma cluster and realized that the virial theorem was not satisfied.

(galaxies were too fast)

⟶ galaxies must be held together by 'dunkle Materie'

The analysis yields consistent results across various galaxy clusters, **indicating a deficit of matter necessary to explain systems in stable configurations**.

(which satisfy the virial theorem)

Dark matter evidence: **lensing of galaxy clusters**

- Gravitational potentials influence light propagation

→ one can measure the gravitational potential (gravitational lensing).

Light is lensed by an intervening gravitation potential

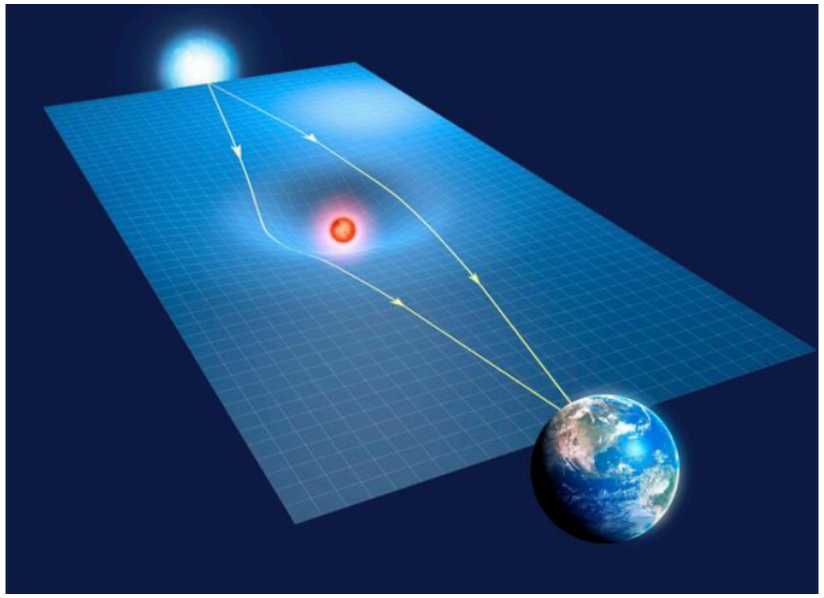
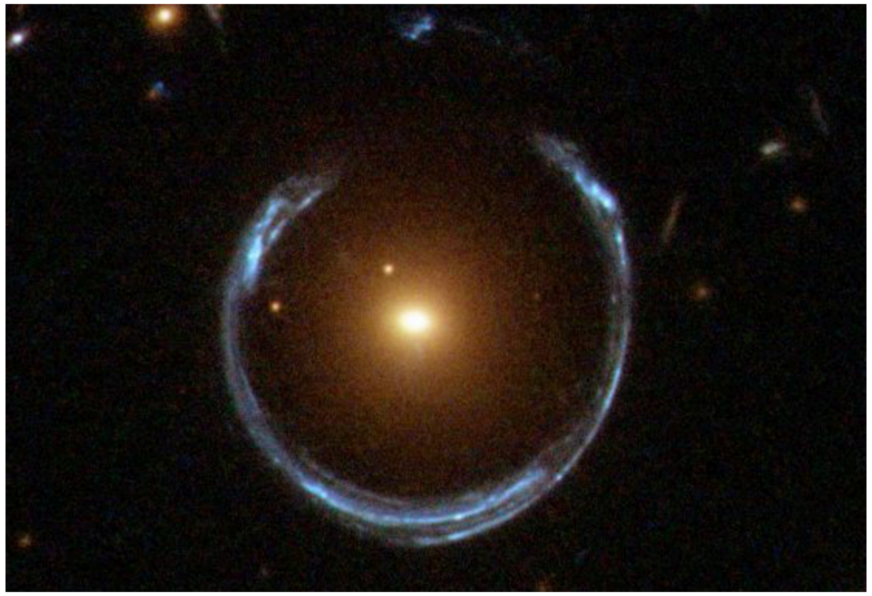
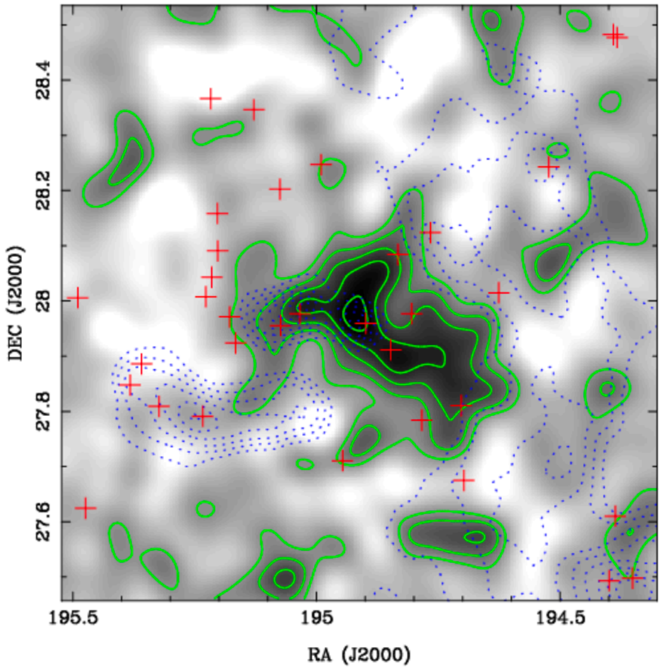


Image of a strongly lensed field



- Matter in the Coma cluster:



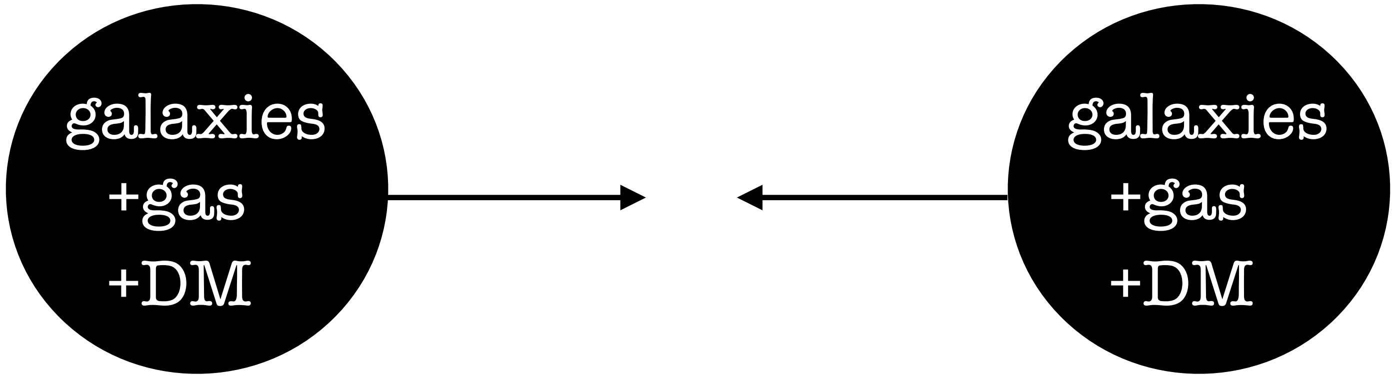
+ visible matter

— matter responsible for gravitational fields

Conclusion is the same as F. Zwicky's:

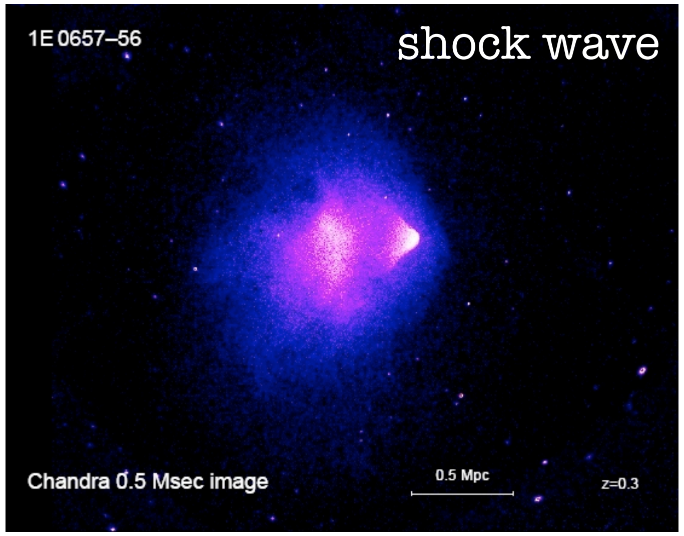
one needs more matter diffused in the cluster than what is observed in galaxies.

Dark matter evidence: **collisions of galaxy clusters**



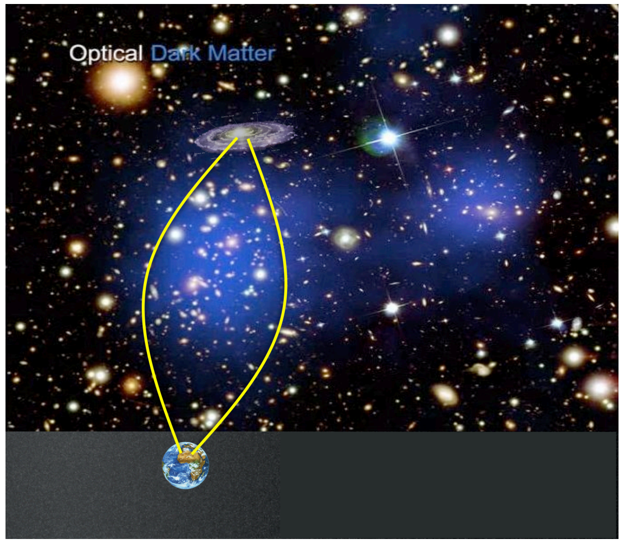
The bullet cluster:

gas interacts with
SM cross-sections



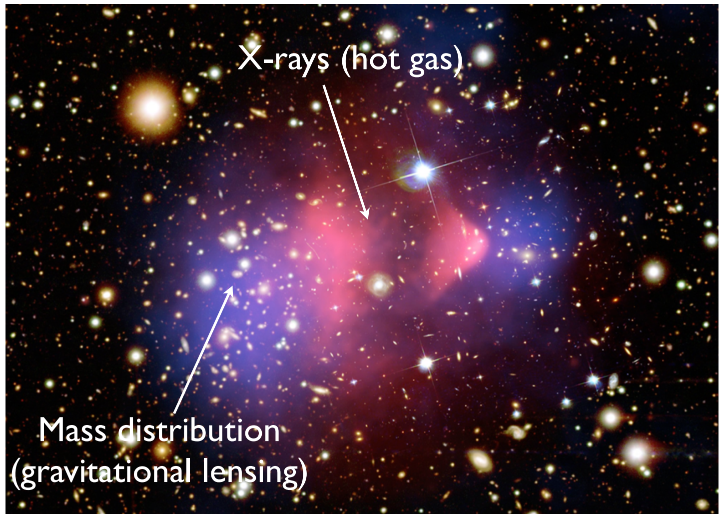
(hot due to the collision)
X-ray image

DM interacts gravitationally



weak lensing mass contours
optical image

composite image



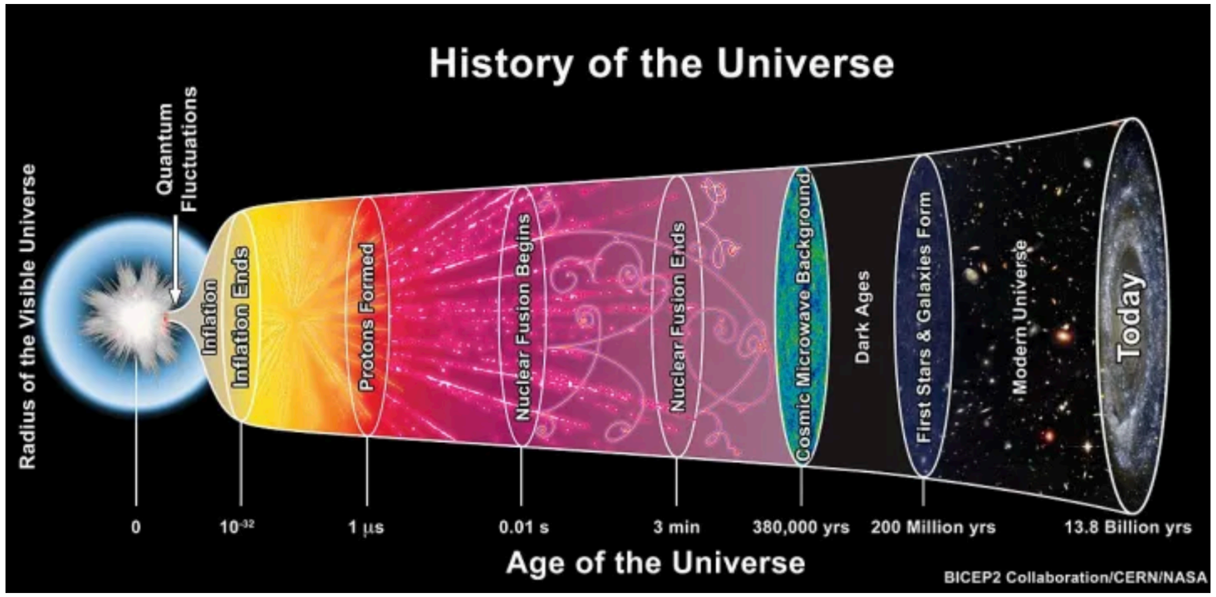
asymmetric configuration:
gas in the middle & DM in the outskirts

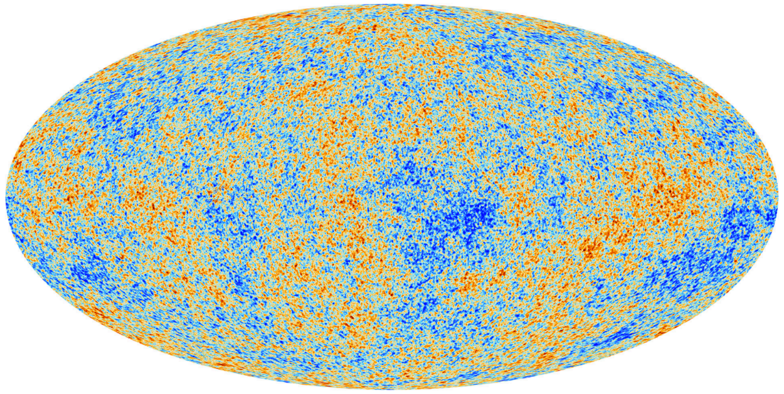
Comparing the matter across different components suggests a greater proportion of collision-affected matter than gas or stars ⟶ **dark matter**

This also informs us about the self-coupling of DM particles.

Dark matter evidence: **cosmological probes**

The current cosmological SM precisely describes the evolution of the observed universe.





- Our universe was very homogeneous and isotropic in the past. Indeed, we know this with high precision from the detection of the CMB.

(a picture of the universe from ~ 13 billion years ago)

- After the Big Bang, the primordial universe was made of a plasma of protons, electrons and photons. During cooling, when T ~ 0.1 eV, the electrons and protons recombine: then light propagates freely, and this is the radiation that we detect today.

- This picture shows some irregularities in the energy density: $\delta\rho/\rho \sim 10^{-5}$

There is not enough baryonic matter in the early universe to make the primordial perturbations evolve into the dense matter environment that we see today.

$$\longrightarrow \boxed{\Omega_{DM} \sim 5\Omega_b}$$

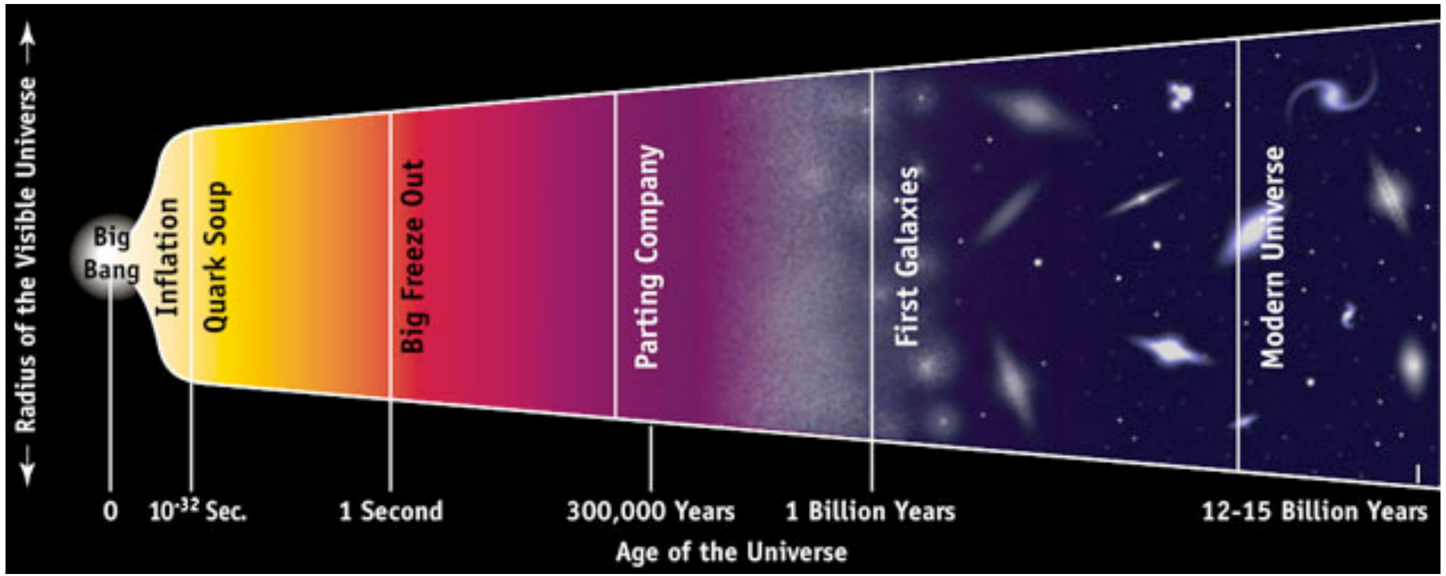
DM particle solution at very different scales

- **What about modified gravity?**

All the evidence of dark matter to date comes from its gravitational effects

Newton’s laws have been tested to high accuracy on terrestrial scales. The laws of gravity could, in principle, be different on astronomical/cosmological scales.

The dark matter paradigm is the only successful framework for understanding the entire range of observations from the time the Universe is 1 seconde old.



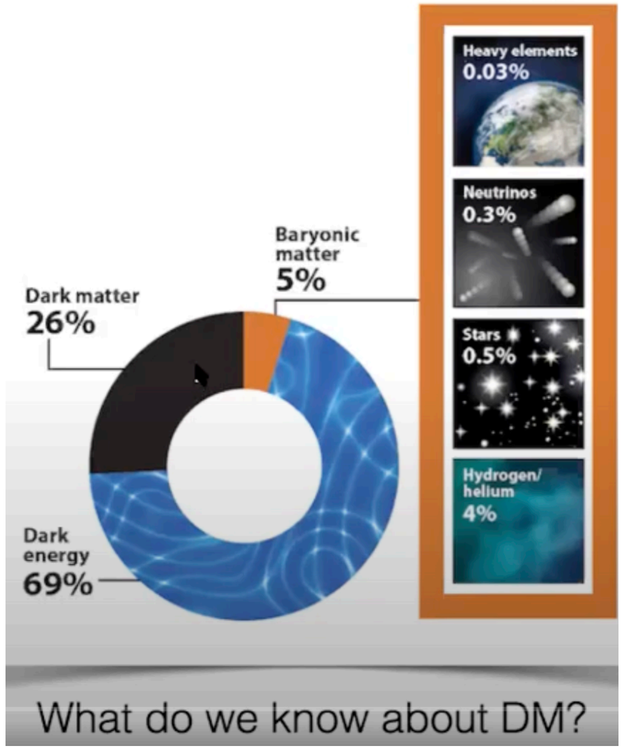
↑ BBN (baryons)

↑ CMB (curvature)

↑ LSS (matter)

↑ Supernovae (DE)

↑ Galaxy curves (matter)



Dark matter properties

All the evidences point towards the existence of a single new component. This is remarkable!

Here is a list of the **'knowns'** about what this new component should be:

- **Darkness :** i.e its interaction with SM particles should be small.

  DM must be neutral to high degree: EM charge: $q_{DM} \lesssim 10^{-4} \left(\frac{m_{DM}}{\text{TeV}}\right)^{1/2}$ charge quantization?

- **Coldness:** i.e non-relativistic

  DM should have clustered for a large period of time.

  To generate the growth of the small perturbations of the CMB ⟶ **DM can't be massless**

  Any thermally produced DM candidate: $m_{DM}^{thermal} \gtrsim \text{keV}$

- **Collisionless:**

  DM can't have large collision cross-section because this would lead to a different phenomenology in the collision of clusters.

  The distribution of DM in the galactic halos should be close to spherical.

Self-interactions and possibility to dissipate into lighter species typically imply a loss of sphericity in the halos.

Dark matter properties

- **Stability:**

The traces of dark matter are observed from ~ 13 billion years ago to the present day.

$\longrightarrow$ if it decays, its decay rate must be very slow: $\Gamma_d \times (13 \text{ Gyrs}) \gtrsim 1$

Indeed, that's a way to look for DM :

stable DM candidates are common in models in which a new discrete symmetry is imposed by ensuring that the DM particle is the lightest with an exotic charge.

(Ex: R-parity in Supersymmetry)

- **Non-baryonic:**

We also know the amount of baryonic matter in the universe from CMB and BBN.

The BB paradigm includes a mechanism of generation of different relics (H, D, He, Li,...) whose final amount depends on the amount of baryonic DM.

The current measurements agree very well with: $\Omega_b \approx \Omega_c/5$

BBN happens in the very early Universe, where the influence of DM is negligible and hence DM could be generated afterwards. But doing it within SM degrees of freedom is tricky.

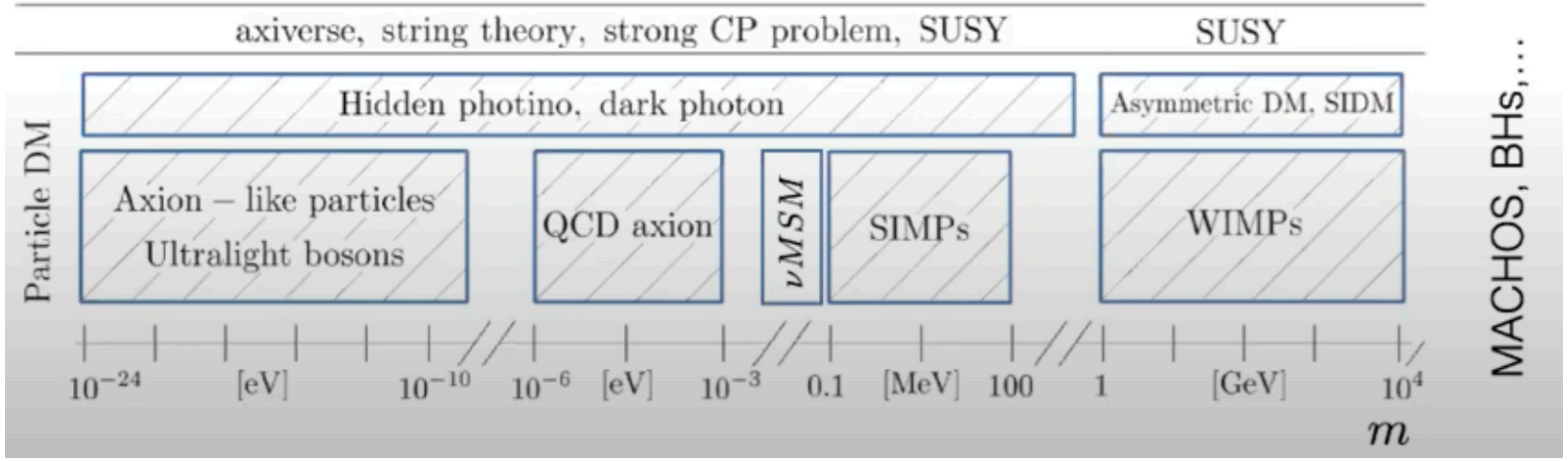
A fashionable possibility is that DM is made of BHs.

Is it enough to select a candidate?

No.

- The previous phenomenology can be reproduced by many models.
- We don't know anything about the fundamental properties of DM: the mass, the spin, the charges…

Take the mass: it can be anything from $10^{-22} eV - M_{\odot}$. (compact objects)



$1\ M_{\odot} \sim 10^{57}$ GeV

Some robust bounds:

- for thermally produced : $m_{DM} \gtrsim \mathrm{keV}$
- if DM is a fermion : $m_{DM} \gtrsim 400\,\mathrm{eV}$

DM candidate should be able to generate halos of a certain size.

- if DM is a boson : $m_{DM} \gtrsim 10^{-22}\,\mathrm{eV}$

de Broglie wavelength of the candidate should be smaller than the radius of the halo

WIMP dark matter candidate from the SM?

Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

None of the known particles can be cold DM.

The relic density

Does cosmology give us any hints towards underlying particle physics scenarios?

The one thing we do know precisely is the dark matter's relic density:

$\Omega_{\mathrm{DM}} h^2 = 0.1200 \pm 0.0012$ Planck Collaboration (2018)

What can we learn from this about dark matter's particle properties?

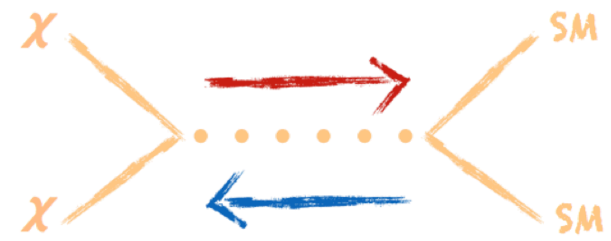
– Generically: **nothing**

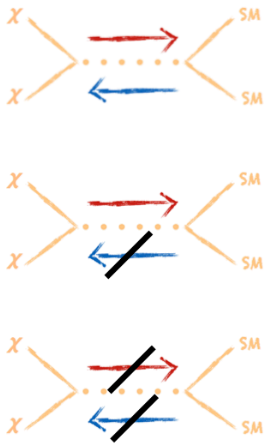
– But if the dark matter now is a surviving relic of the hot Big Bang and have been in **thermal equilibruim**: a lot!

Thermal freeze-out & the WIMP miracle

Physics in an expanding Universe: annihilation rate, Boltzmann equation, equilibrium density, temperature of Universe

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle \left[n_\chi^2 - n_\chi^{eq2} \right]$$



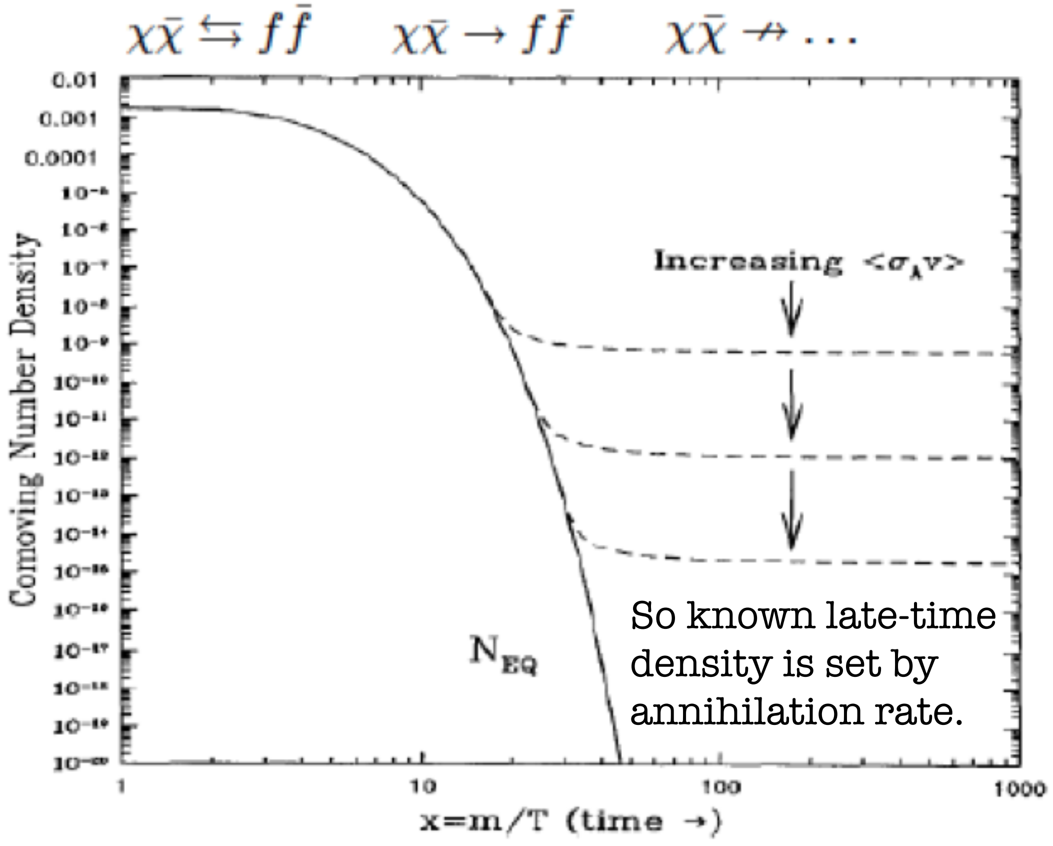


- χ (CDM) is initially in thermal equilibrium
- universe cools down $\Rightarrow \chi$ only decreases by pair annihilation
- universe expands: $\langle \sigma v \rangle n_\chi(T) < H(T) \Rightarrow \chi$ decouples from the SM

$$\Omega_{DM} h^2 \approx 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_{DM}}{100\,\mathrm{GeV}}\right)^2$$

$\Omega_{DM} \approx 26\% \Rightarrow M_\chi \approx 100$ GeV with EW couplings

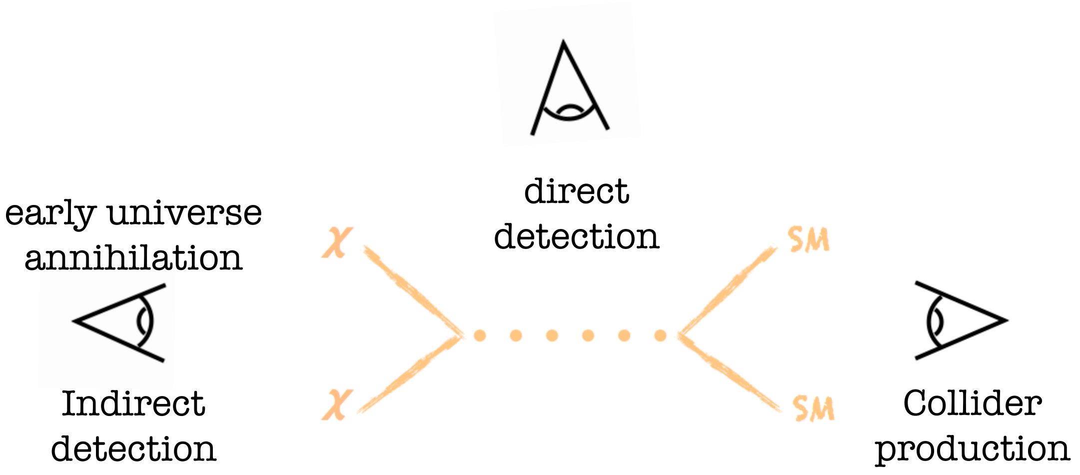
⟶ **the WIMP miracle!**



So known late-time density is set by annihilation rate.

If new physics is responsible for the weak scale, it may come with a related DM candidate.

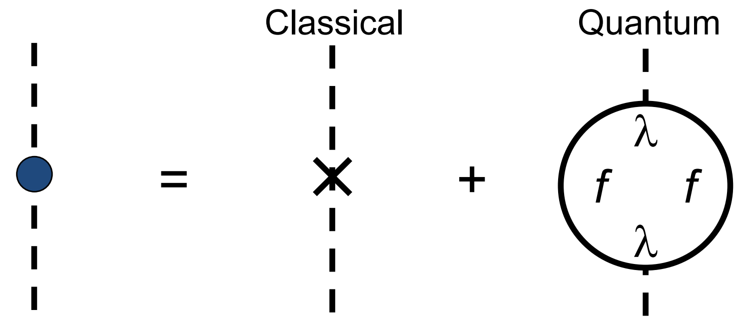
Through this, cosmology provides a strong motivation for **direct**, **indirect** and **collider searches** :



Supersymmetry

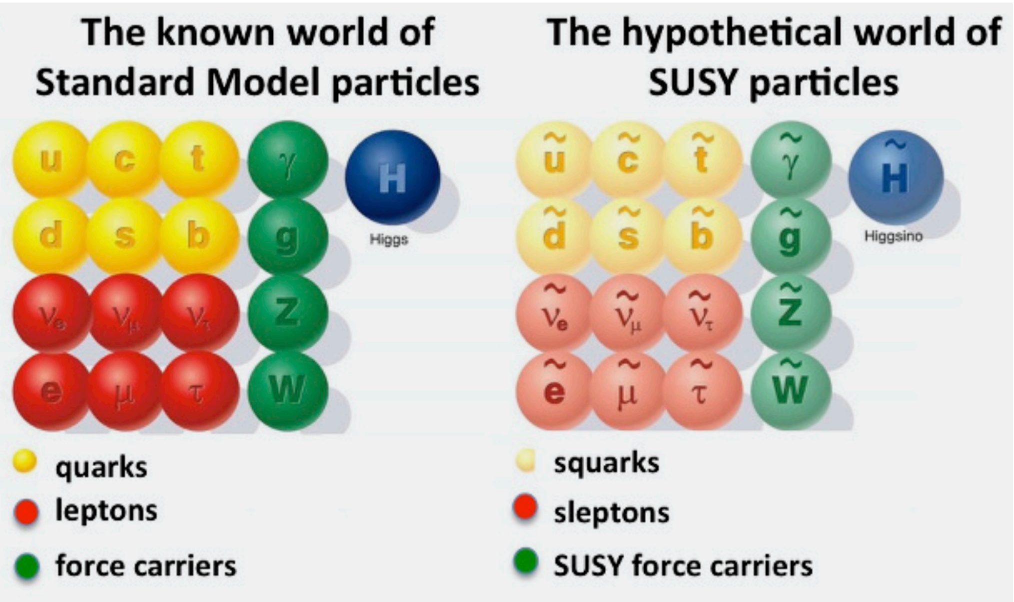
Why $\vec{F}_{EM} \gg \vec{F}_G$?
$M_h \ll M_{Planck}$?

hierarchy problem :



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- In supersymmetric theories, every particle has a superpatner:



- Fermions have boson superpartners and vice versa.

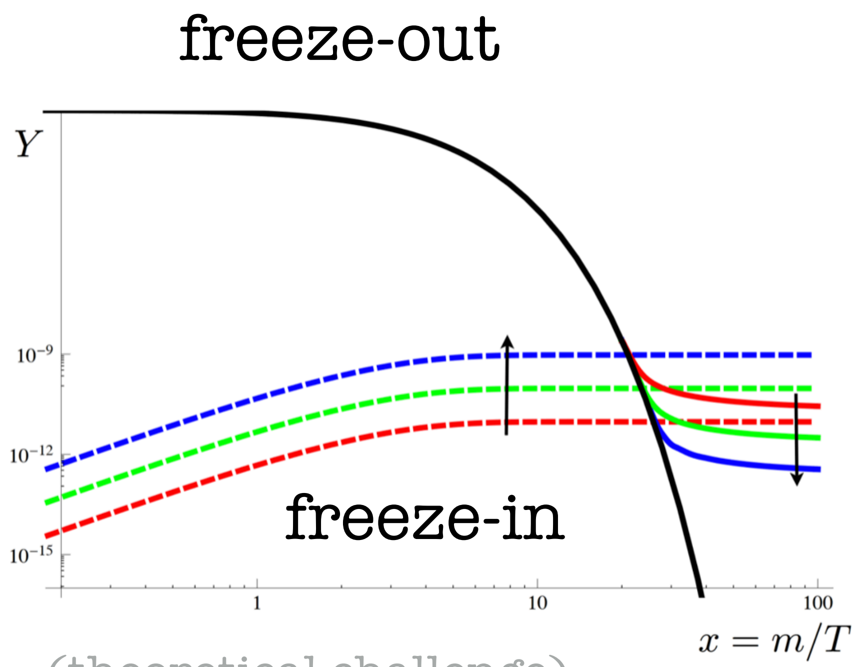
- Neutral fermionic superpartners = superpartners of the neutral gauge bosons.

  Neutralino physical state corresponds to mixture of Higgsino/Wino/Bino.

- The neutralino is the LSP (lightest particle with R-parity odd i.e cannot decay)

Alternatives: non-thermal freeze-**in**

For a given dark matter candidate, on can trace the cosmological history from early times to present day, **even if DM never in equilibruim**



→W(eakly)-IMP

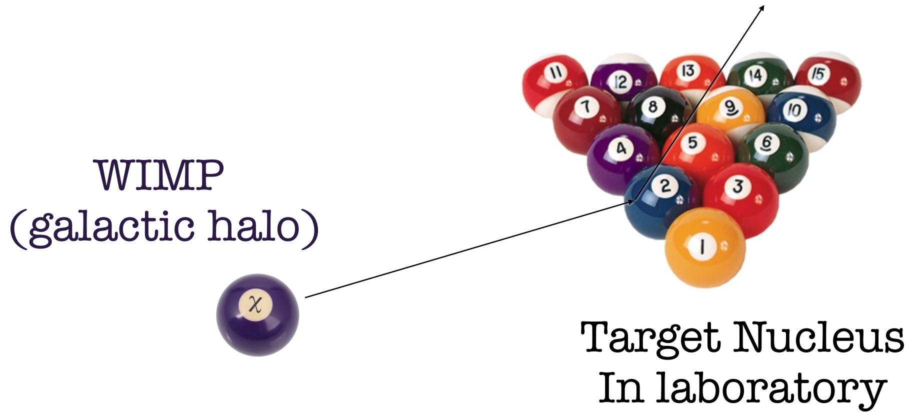
→F(eably)-IMP

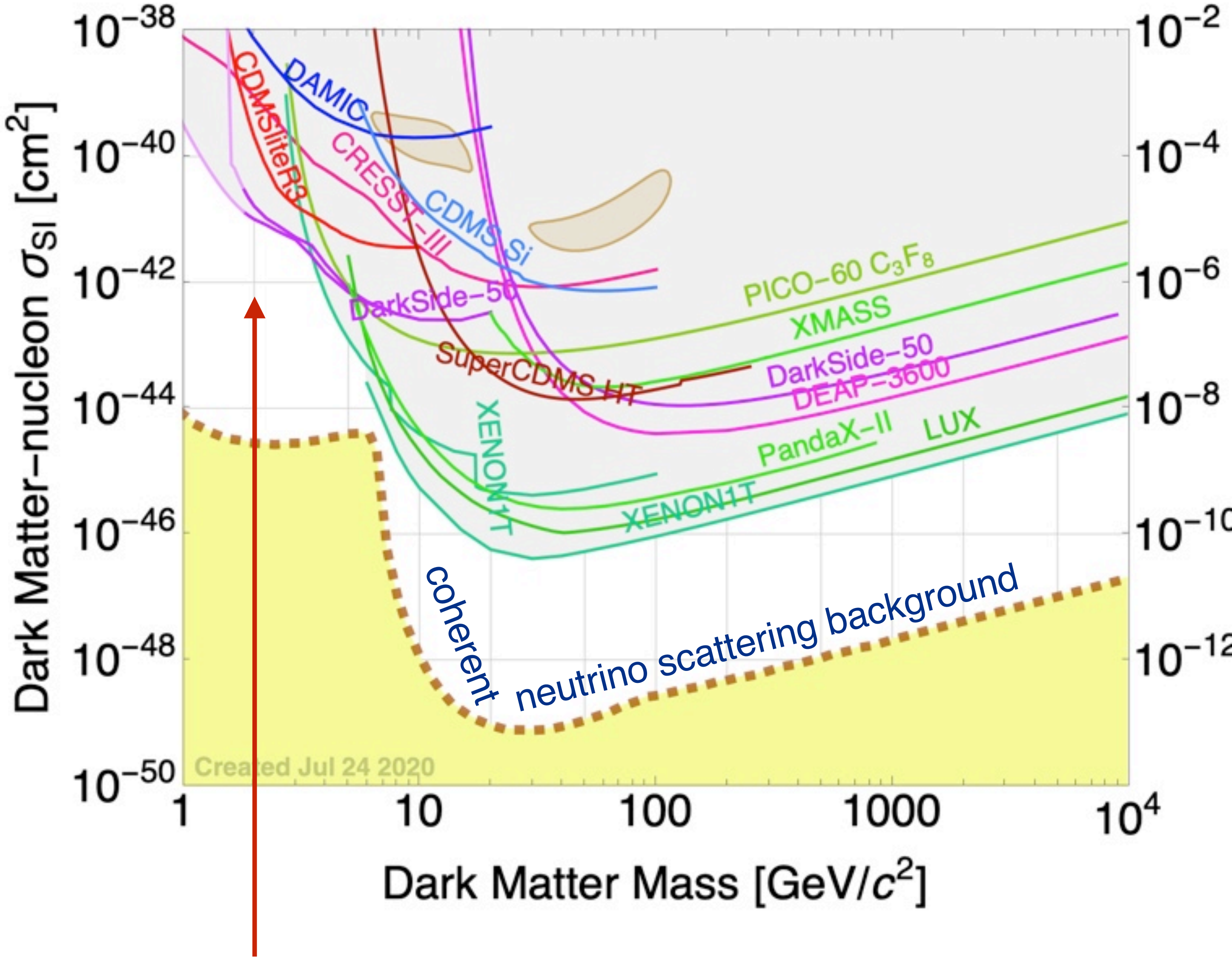
(theoretical challenge)

For a given postulated **feeble** interaction form, one can calculate the amount of dark matter left over

WIMP direct detection searches

- **Good news:** speed of progress is tremendous! Experimental sensitivity has increased by several orders of magnitude in past decade
- **Bad news**: no confirmed dark-matter signal yet. Are WIMPs dead? No, not yet at least
- Target is still WIMPs, but now looking fo those that couple via Higgs; expected signal is elastic scatter from target nuclei and with tiny cross section
- Marching down to the neutrino floor



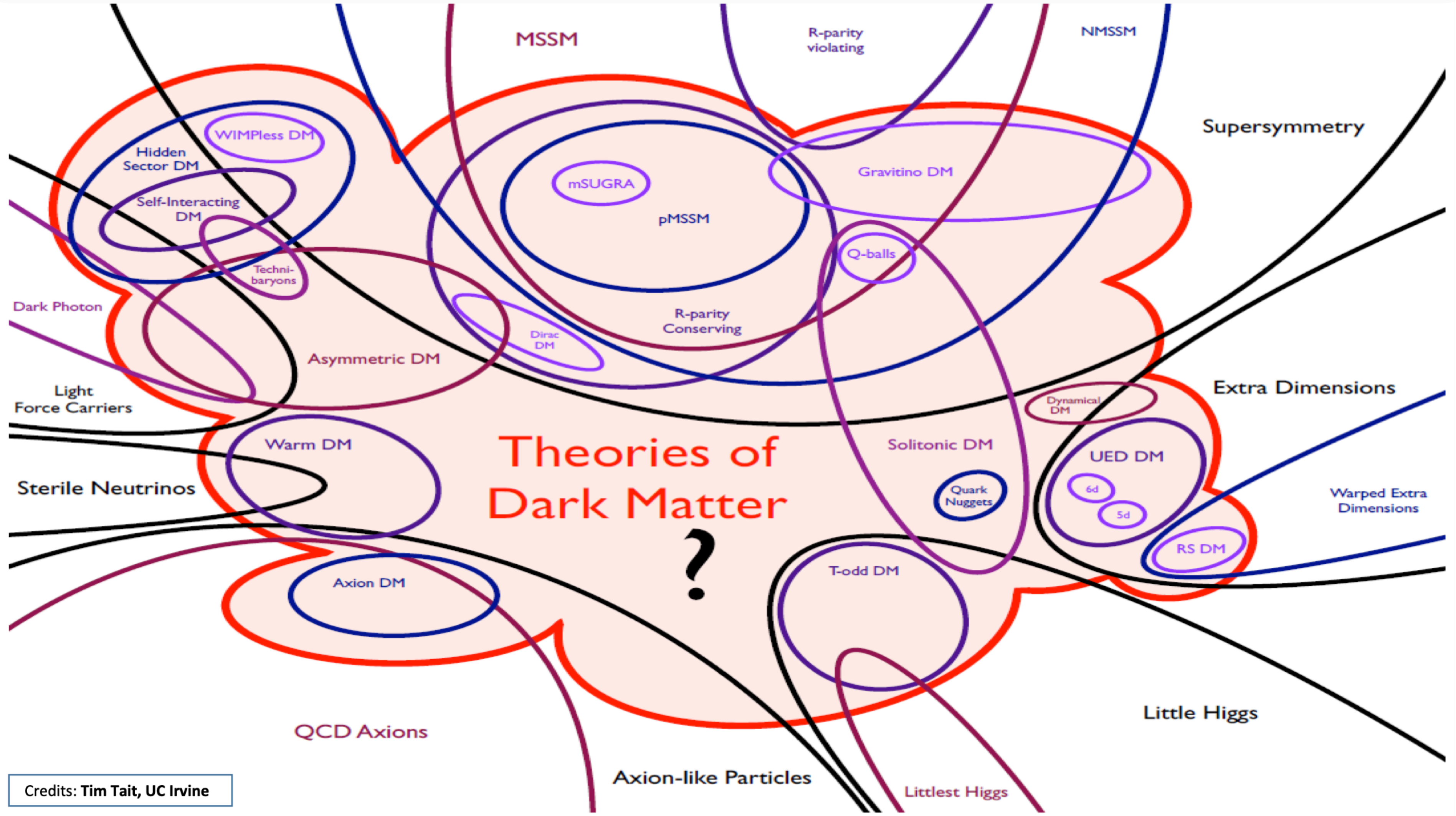


dramatic loss of sensitivity at low mass
(still 'high' mass in the DM landscape)

From predictive models to **simplified models**

use in moderation

Starting point: « well, we don't know because
dark matter possibilities is vast »



Credits: **Tim Tait, UC Irvine**

Simplified models are constructed to capture the relevant phenomenology, but should not be stretched too far. Details matter, and complete models may have different relic density, direct detection…

Dark-matter Higgs portal models

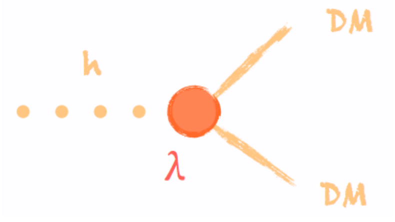
$$\Delta\mathcal{L}_S \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_{hSS}\underline{H^\dagger H}S^2$$

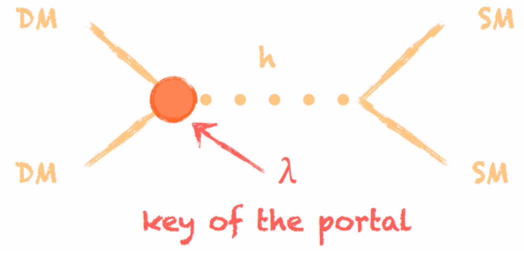
lowest dimension SM singlet

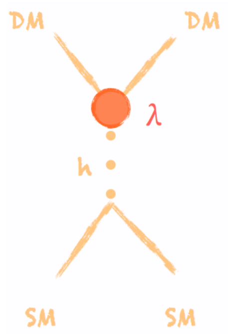
$$\Gamma^{\mathrm{inv}}_{h\to SS} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h}$$ (LHC)

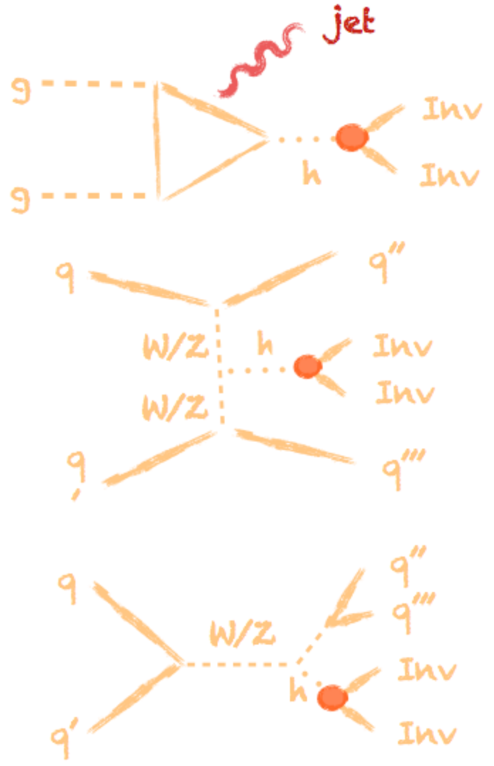
$$\langle\sigma^S_{\mathrm{ferm}} v_r\rangle = \frac{\lambda_{hSS}^2 m_{\mathrm{ferm}}^2}{16\pi}\frac{1}{(4M_S^2 - m_h^2)^2}$$ (PLANCK)

$$\sigma^{SI}_{S-N} = \frac{\lambda_{hSS}^2}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S + m_N)^2}$$ (XENON)

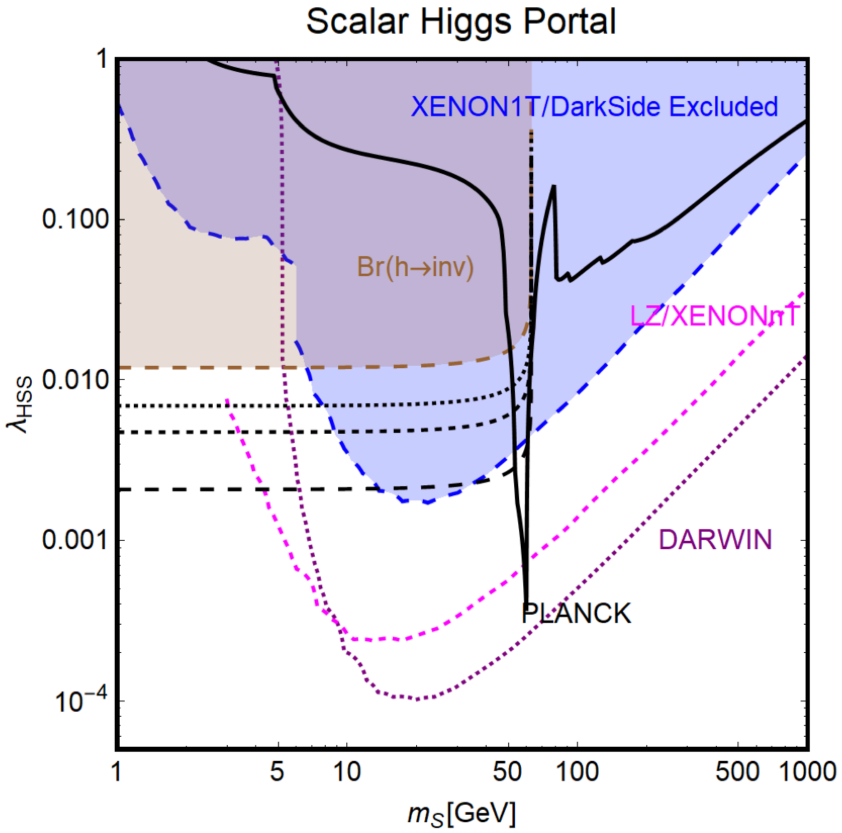


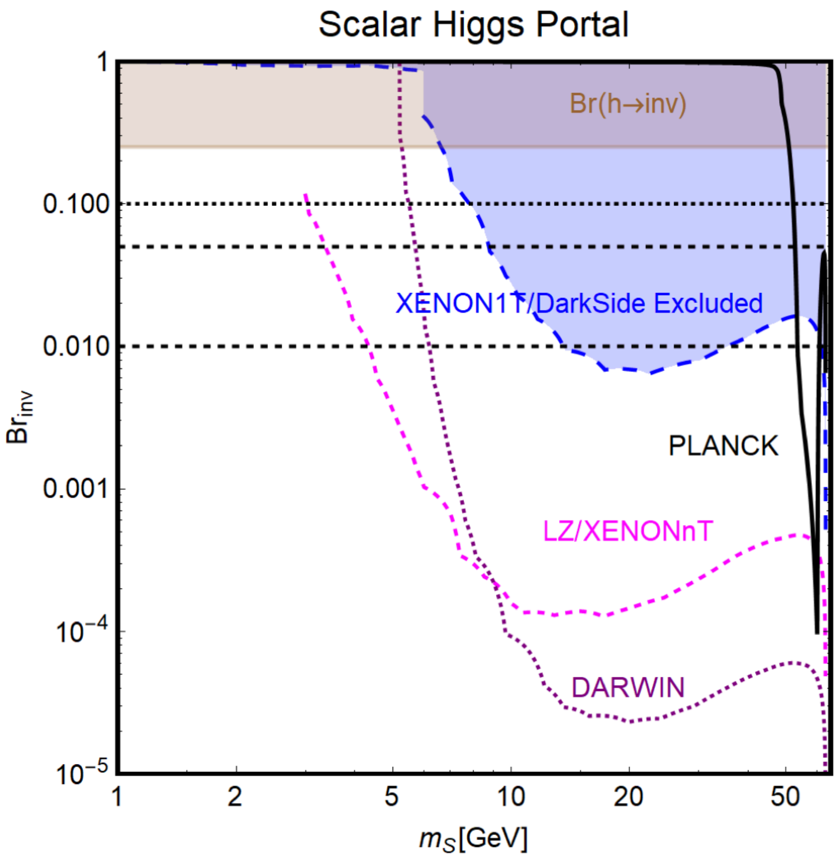






LHC is a great DM detector apparatus!





Key word: complementarity

Supercolliders

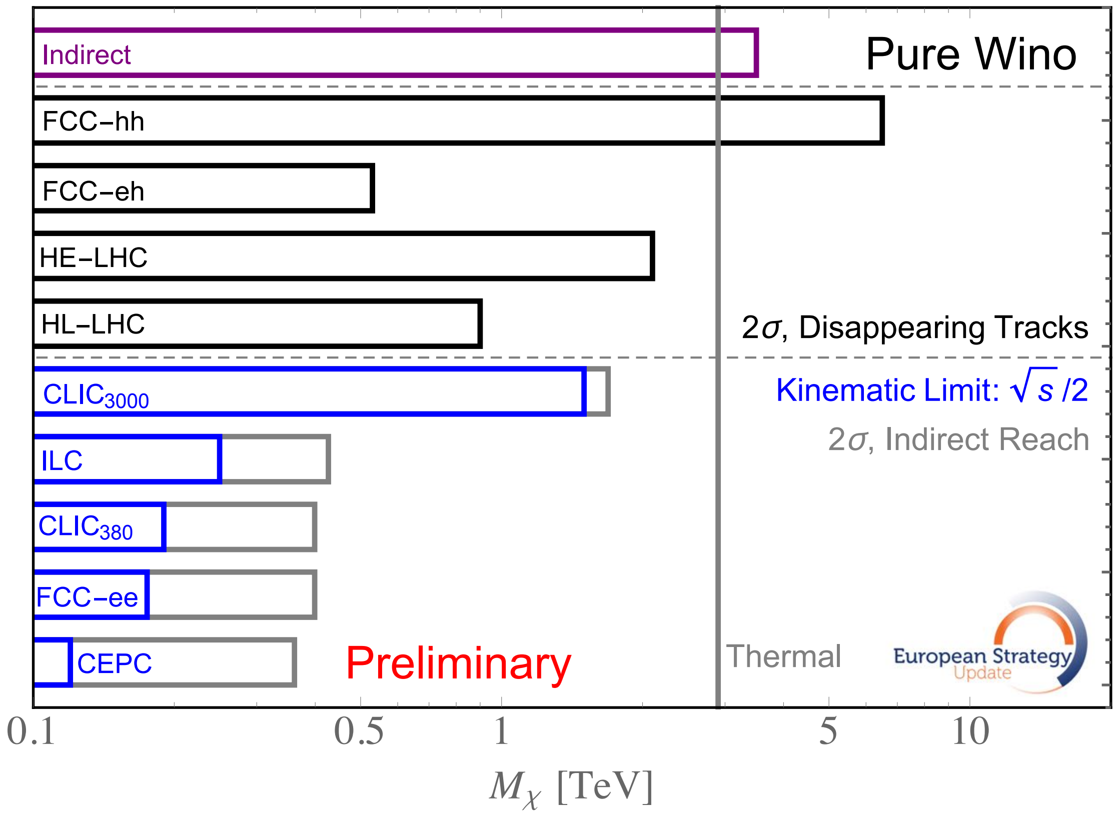
Thermal paradigm is very much still viable and there are many thermal freeze-out models

One class is electroweak-charged massive particles (∈ WIMPs)

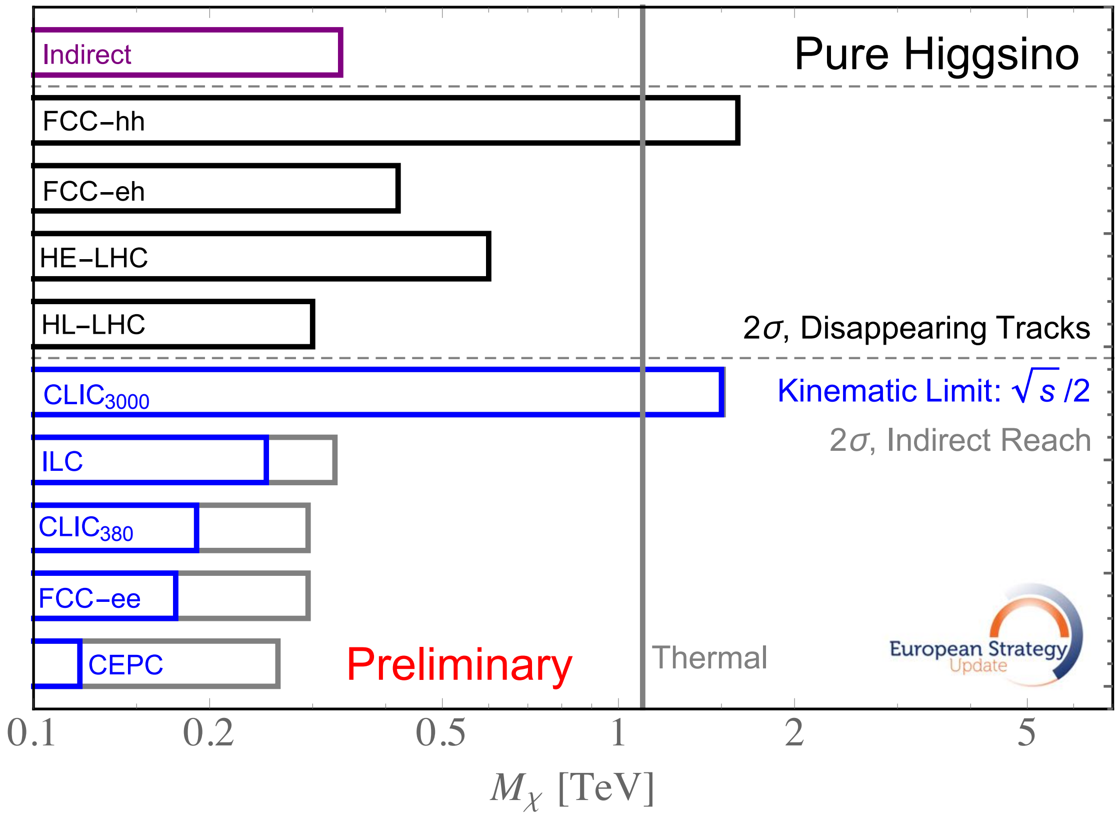
Standard candle, the supersymmetric:

- Wino:
- Higgsino:

Projected sensitivity of colliders:



For Winos, obtaining the abundance this way requires a mass in the ballpark of **2.9 TeV**

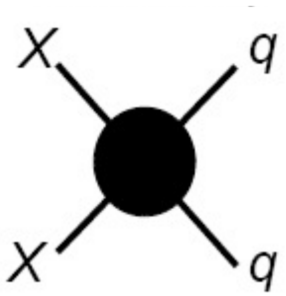


For Higgsinos, obtaining the abundance this way requires a mass in the ballpark of **1.1 TeV**

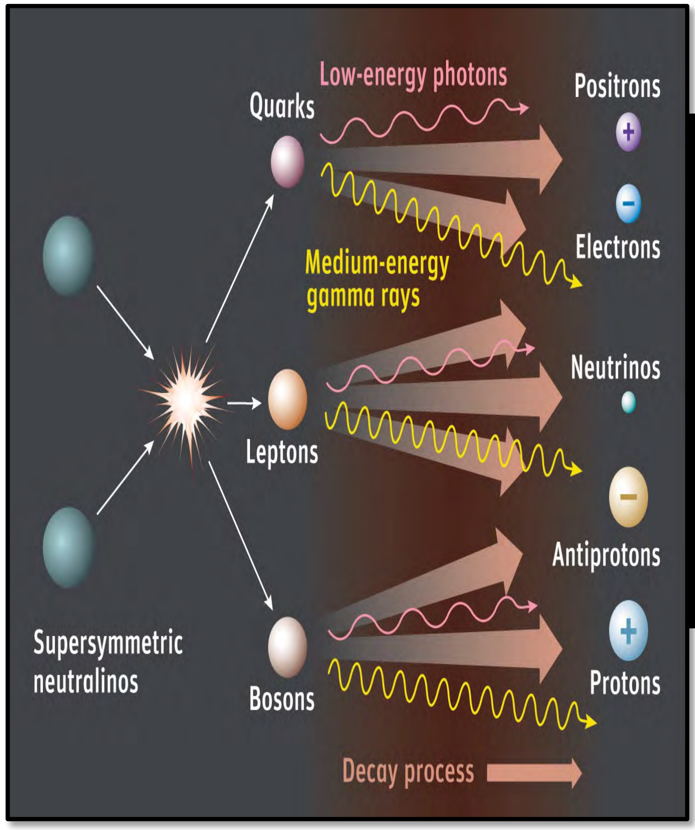
Indirect detection

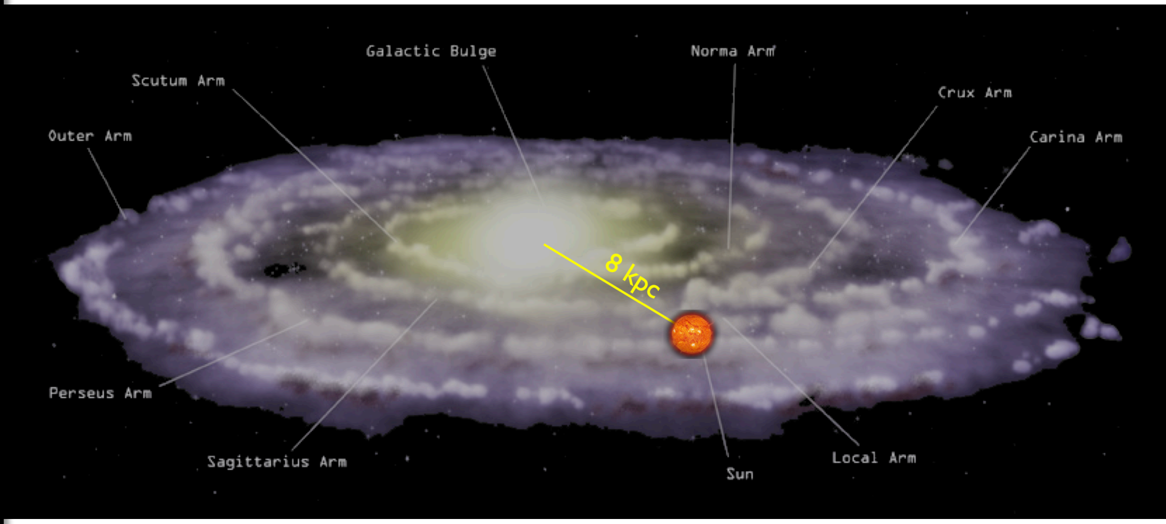
tries to find DM in astrophysical processes beyond the gravitational phenomenology.

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons



- The relic density provides a target annihilation cross section $\langle \sigma_A v \rangle \sim (2 \text{ to } 3) \times 10^{-26}\ \mathrm{cm^3/s}$





- **No conclusive signals from indirect DM searches so far**
  - But slow and steady progress being made on indirect searches in many fronts:

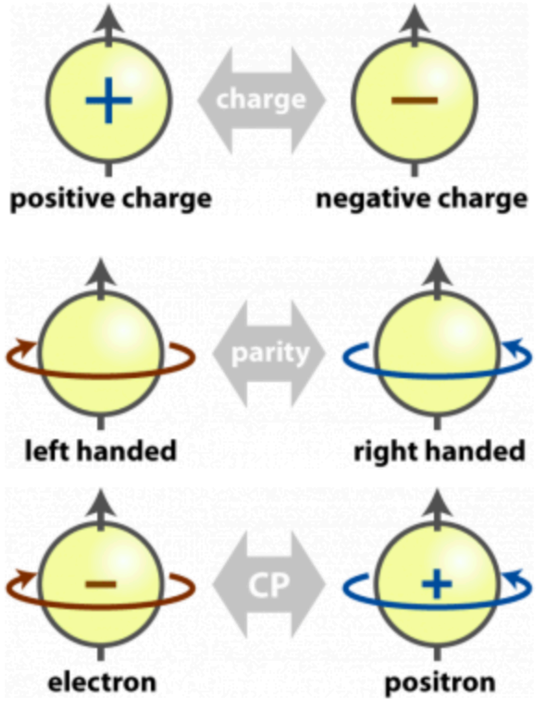
    Diffuse gamma rays, e.g galactic center GeV excess

    Antiproton excess from cosmic rays

    Neutrinos from DM annihilation in the Sun
  - It is possible that in the future it will be a convincing signal from one or more indirect DM searches
  - This will have a large impact on direct detection and accelerator bases DM searches

Axions

Why matter and not anti-matter in our universe?

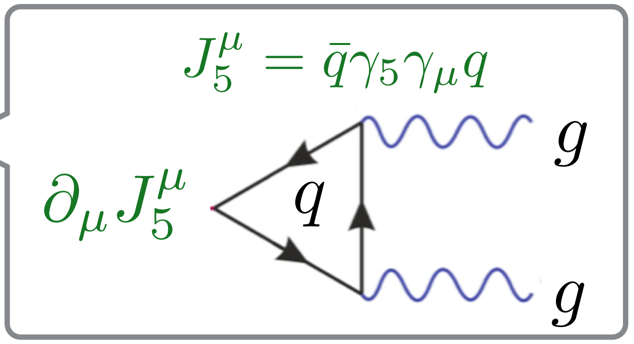


The strong CP puzzle in particle physics

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q \underset{\text{CPV}}{e^{i\theta_{EW}}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}\underset{\text{CPV}}{G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}}$$

4-component Dirac field

$U(1)_A$ chiral transformation: $q \to e^{i\gamma^5\theta_{EW}}q$ anomalous symmetry (so not a symmetry!)



$J_5^\mu = \bar{q}\gamma_5\gamma_\mu q$

axial anomaly shifts quark mass phase to QCD vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - (\overbrace{\theta_{QCD} - \underset{\neq 0}{\theta_{EW}}}^{\bar{\theta}})\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Yukawa coupling to the Higgs are complex $\theta_{CKM} \neq 0$ from K and B physics

Why is this strong CP-violation term so puzzling? $\mathcal{L}_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

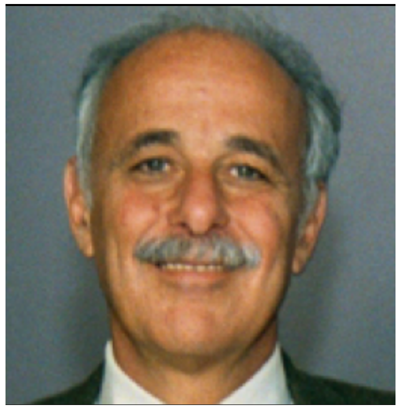
The strong CP problem
=Why is $\bar{\theta}$ so small?

The strong CP problem is really why the combination of QCD and EW parameters make up should be so small…

The QCD

$$\mathscr{L}_{QCD}^{\cancel{CP}} \supset \bar{\theta}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

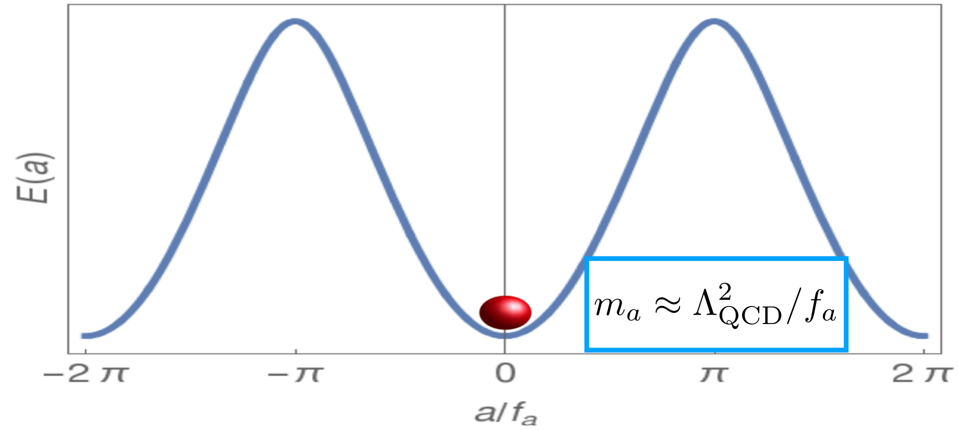
1977



Roberto Peccei

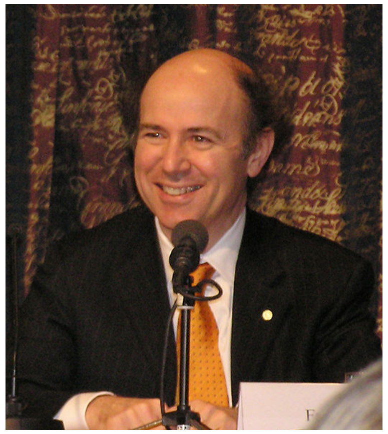
Helen Quinn

Promote $\theta \rightarrow \theta(x)$ to a field, which rolls dynamically to zero



1978

Steven Weinberg



Frank Wilczek

The theory can be quantized, leading to a new particle:

The QCD **axion**

$$\mathscr{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axion energy scale

A shift of paradigm

- **Supersymmetry** : -enlarges Poincaré algebra (new energy scale)
  -needs many new particles
  -can preserve SM gauge group

- **'Peccei-Quinn' theory :** -enforces CP-symmetry
  -needs a new global 'no symmetry'
  (anomalous+spontaneously broken)
  (new energy scale)
  -entangled with SM gauge group :
  (careful!)

$$[SU(3)_c \otimes SU(2)_L \otimes U(1)_Y]_{local} \times [U(1)_{\mathcal{B},\mathcal{L},PQ}]_{global}$$

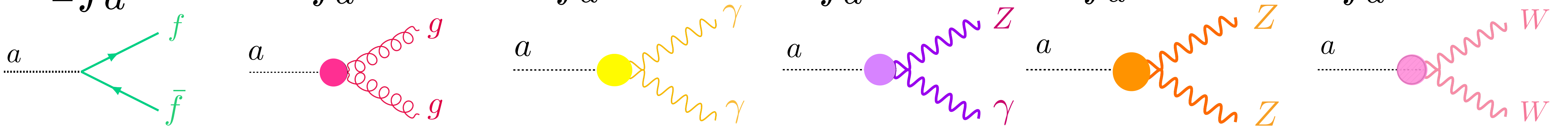
the axion: Goldstone bosons combination $\perp Z_L$

Axion couplings

Energy

At energies below f_a (SSB):

$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2 f_a} j_a^\mu + \# \frac{a}{f_a} G\tilde{G} + \# \frac{a}{f_a} F\tilde{F} + \# \frac{a}{f_a} Z\tilde{F} + \# \frac{a}{f_a} Z\tilde{Z} + \# \frac{a}{f_a} W\tilde{W}$$



electroweak couplings recently computed
do not follow the expected pattern

At energies below $\Lambda_{QCD} : a - \eta' - \pi^0 - \eta - \ldots$ mixing

axion mass: $m_a = m_\pi \frac{f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim \frac{\Lambda_{QCD}^2}{f_a}$

axion couplings to electrons, nucleons, mesons, photons, ...

(EDMs)

mostly explored:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\boxed{\frac{E}{N}} - \boxed{1.92}\right)$$

model dep.

model indep.
below confinement

Symmetry breaking in cosmology

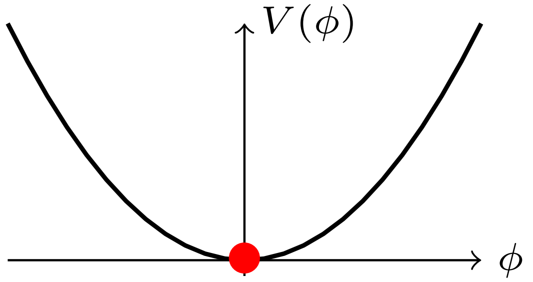
Temperature

$\delta\phi \sim T$

$$V_{\text{PQ}}(\phi) = \frac{\lambda}{4}(|\phi|^2 - f_a^2)^2$$

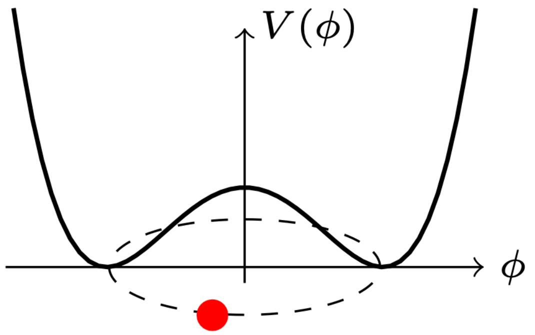
$T > f_a$

T determines the PQ vev: $< \phi >= 0$



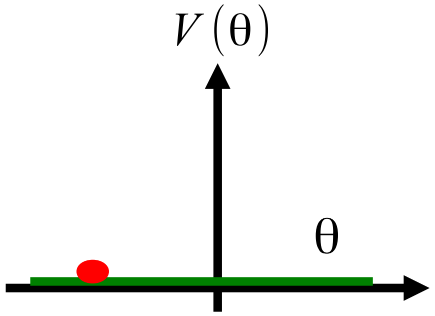
$T \sim f_a$

PQ symmetry is spontaneously broken: $< \phi >= f_a e^{i\frac{a(x)}{f_a}}$



The axion is born:

Relic of symmetry breaking



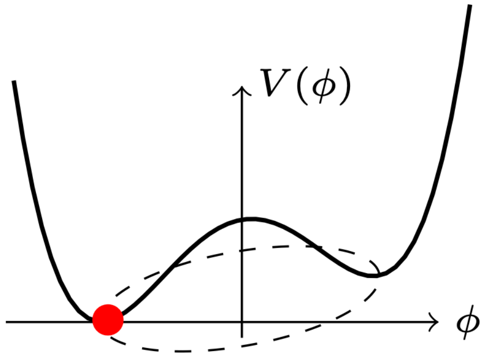
$$\theta = \frac{a}{f_a} \in [-\pi, \pi]$$

$T \sim \Lambda_{QCD}$

PQ symmetry is explicitly broken

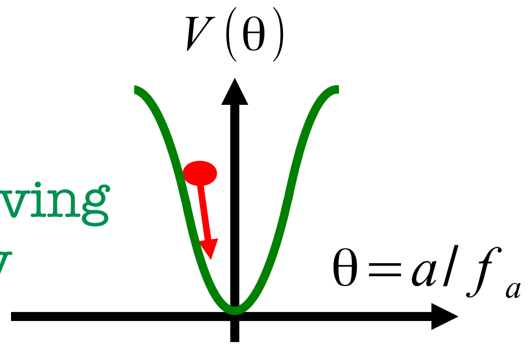
$$m_a^2(T) \begin{cases} \propto T^{-n} & T \gtrsim 100 \text{ MeV} \\ = m_a(T=0) & T \lesssim 100 \text{ MeV} \end{cases}$$

Instanton effects



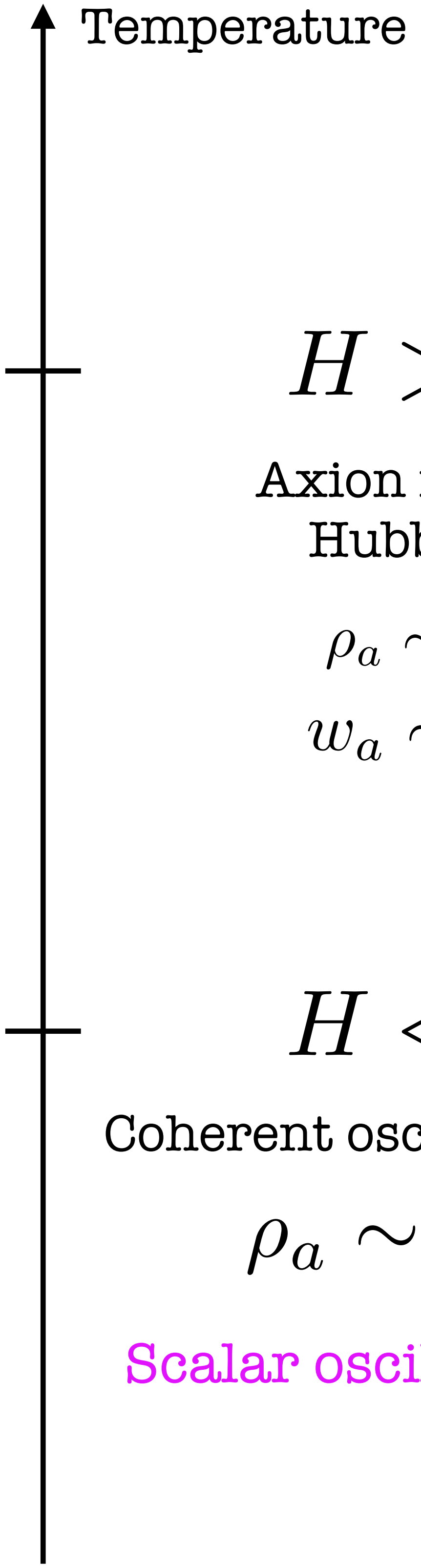
$$+V_{QCD}^{\text{Non-Pert.}} = f_a^2 m_a^2(T)(1 - cos(N_{DW}\theta))$$

CP-concerving theory



Crucial role played by inflation...

Dark matter from vacuum realignment



Equation of motion:
(Klein-Gordon)

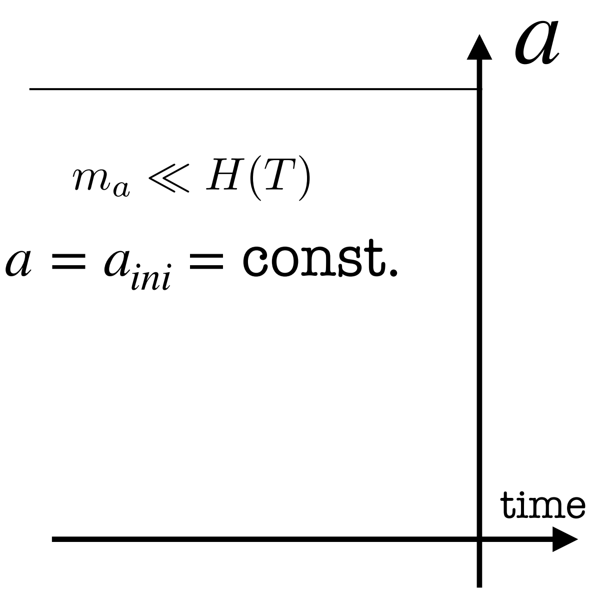
$$\ddot{a} + 3\boxed{H}\,\dot{a} + \boxed{m_a(T)}^2\, a = 0$$

$$H \gg m_a$$

Axion is 'frozen' by
Hubble friction

$$\rho_a \sim \text{const}$$

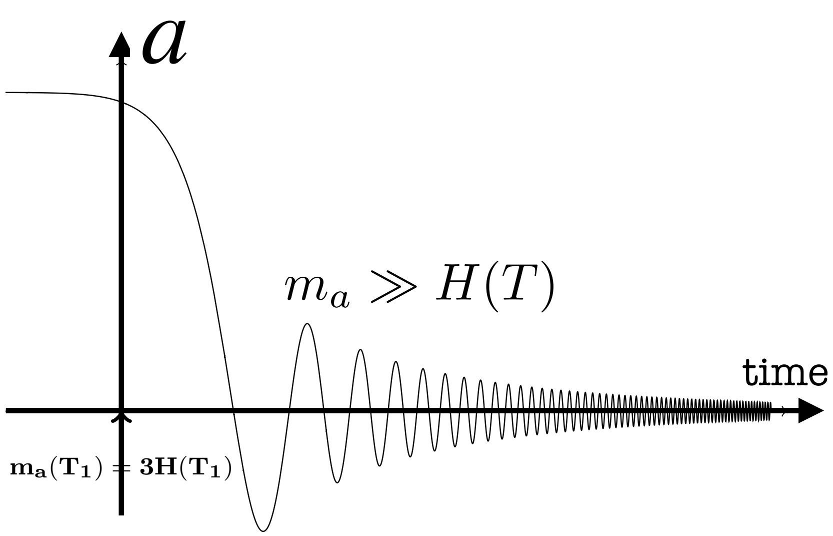
$$w_a \sim -1$$



$$H \ll m_a$$

Coherent oscillations of axion field

$$\rho_a \sim \rho_a(\boxed{a_{\rm osc}})\,a^{-3}$$



Scalar oscillations behave as matter

$$\boxed{\Omega_a h^2 \approx 0.195 \left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^{1.184} \boxed{\theta_{\rm ini}^2}}$$

← 2 scenarios

- Cold Dark Matter!
- Axions are born as non relativistic, classical field oscillations

Initial conditions and inflation

Crucial question: did SSB occur before or after inflation?

$$\boxed{\Omega_a h^2 \approx 0.195 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.184} \theta_{\mathrm{ini}}^2}$$

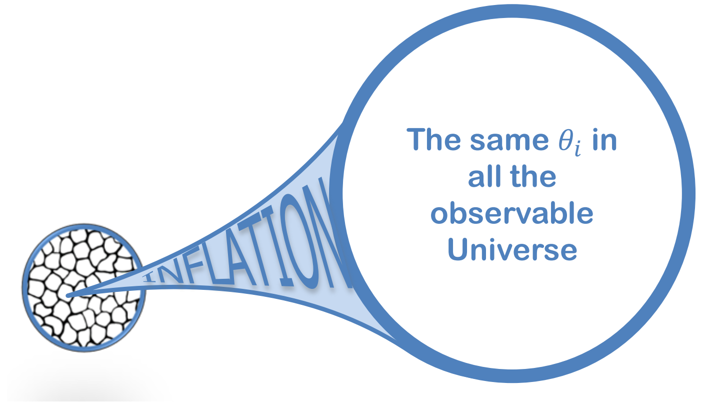
← 2 scenarios

Pre-inflation scenario

$f_a \gtrsim 10^{13}\mathrm{GeV}$

PQ symmetry is broken during inflation and not restored afterwards

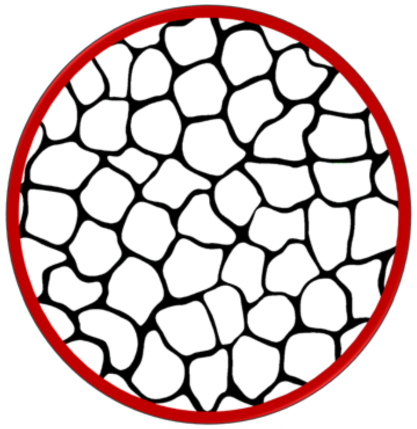
Inflation « selects » one θ_{ini} that is now constant across the observable Universe



Post-inflation scenario

May occur for low f_a

PQ symmetry is broken after inflation



- Many different $-\pi \leq \theta_{ini} \leq \pi$ in the visible « patches » of the universe,

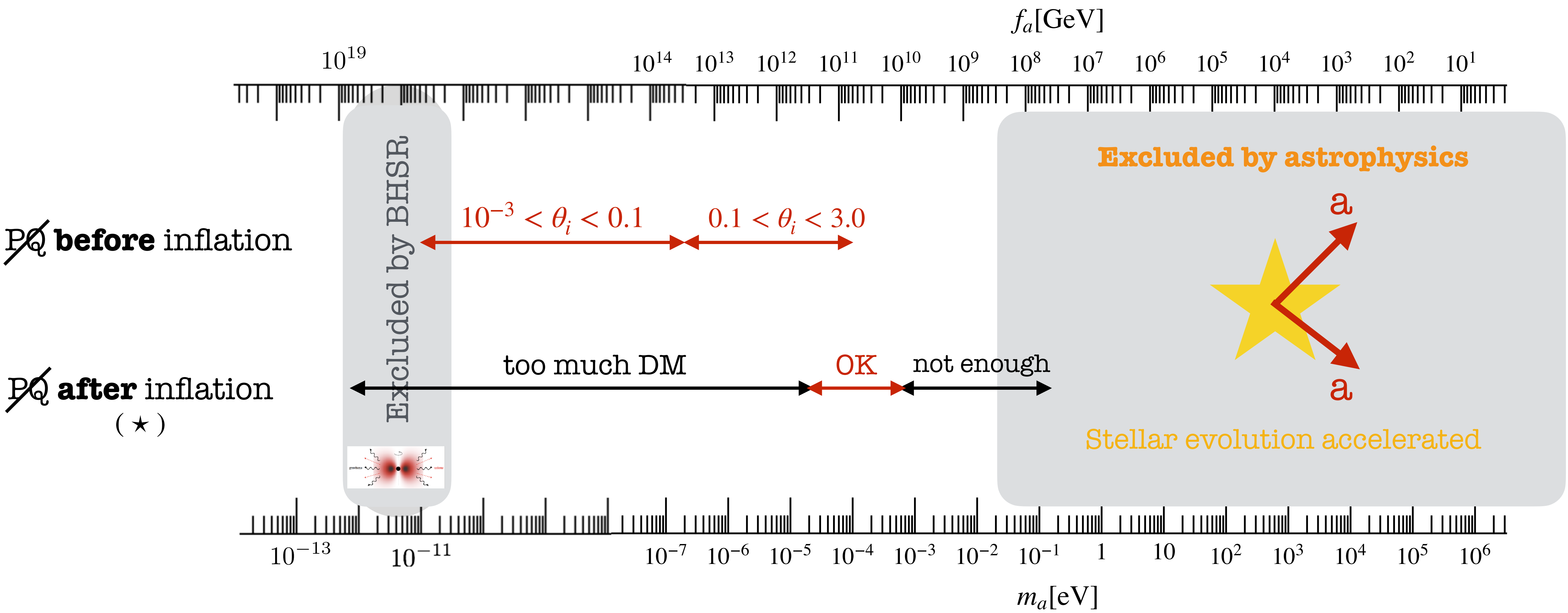
  average field value fixed: $\langle \theta_{\mathrm{ini}}^2 \rangle = \frac{1}{2\pi} \int_{-\pi}^{\pi} \theta^2 \, d\theta = \frac{\pi^2}{3}$

$\longrightarrow$ Ω_a independent of initial conditions

DM relic density, narrow mass window: $\Omega_c h^2 = 0.12$ → $50 \lesssim \frac{m_a}{\mu\mathrm{eV}} \lesssim 200$

Landscape

Axions should be very light and feebly interacting



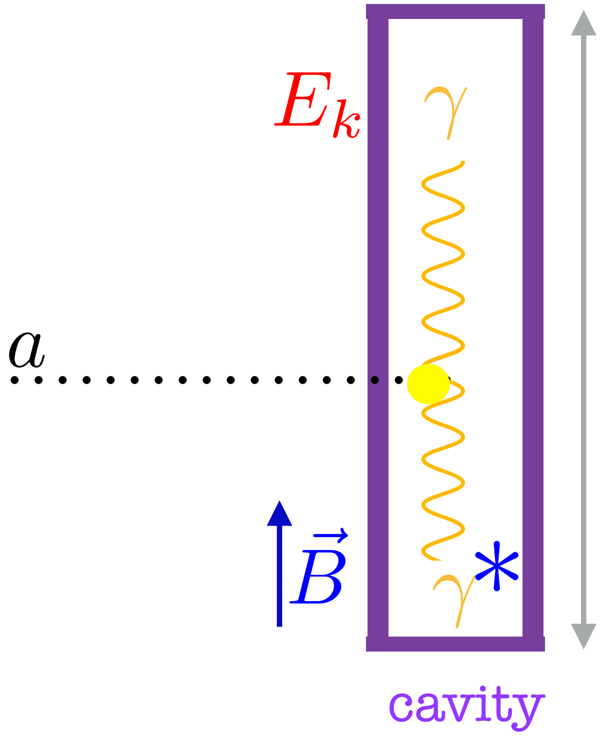
(⋆) for $N_{DW} > 1,$ predictions spoiled by topological defects

Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

Axion haloscope

Amplify resonantly the EM field in a resonant cavity

(forced oscillator)



$\lambda/2 = 0.62\ \text{cm}\ (100\,\mu\text{eV}/m_a)$

Power extracted from a cavity: $P_{signal} \propto g_{a\gamma}^2 B^2 QV$ to amplify

$P_{noise} \propto T_{sys}\delta\omega$

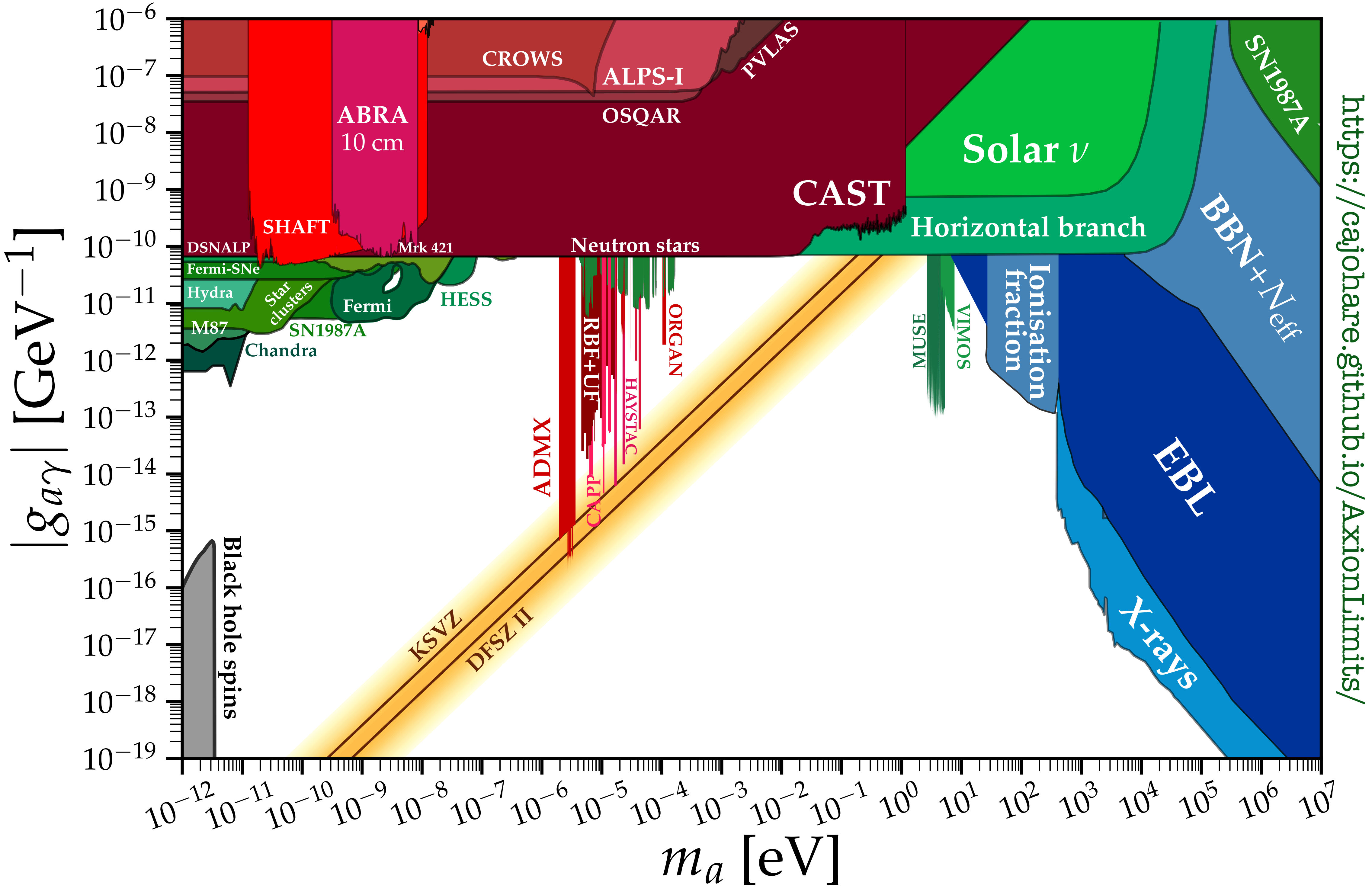
GrAHal : the Grenoble Axion Haloscope

1. Hybride Magnet 43 T (34 mm), 40 T (50 mm), 27 T (170mm), 9 T (800 mm) **LNCMI**
2. $T_{sys} \sim 20\text{mK}$ **Institut Néel**
3. quantum amplifiers SQUID &JPA **Institut Néel**

$$g_{a\gamma\gamma}^{\text{1st point}} = 25 \times g_{a\gamma\gamma}^{\text{KSVZ}}$$
$$m_a = 23\mu\text{eV}$$

- New ideas : **‘reactoscope’** = haloscope + nuclear plant

Axion limits



Axion miniclusters

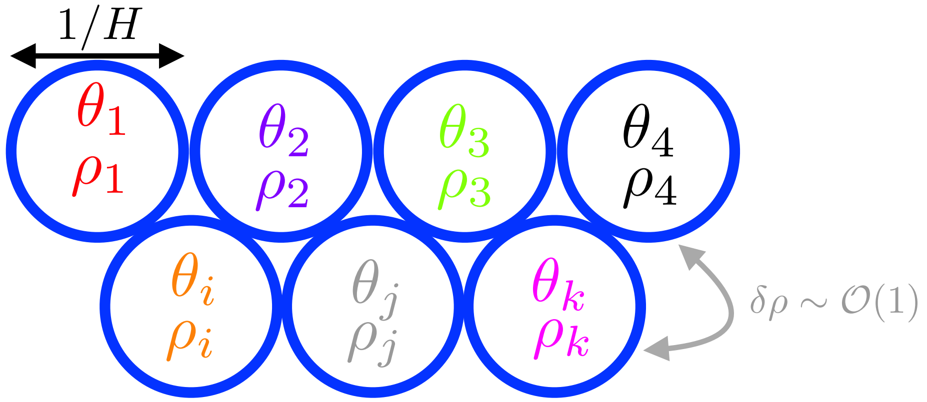
Temperature

...Inflation occurred already

$T \sim f_a$ SSB of PQ

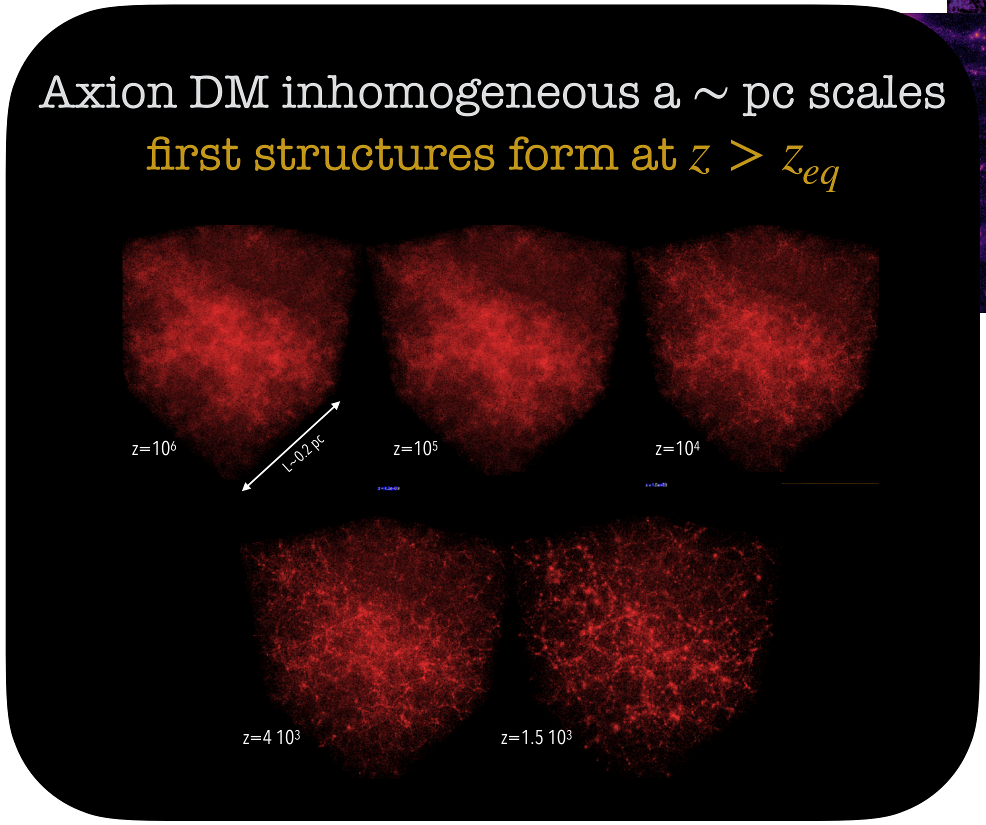
$T \sim \Lambda_{QCD}$ $m_a \neq 0$

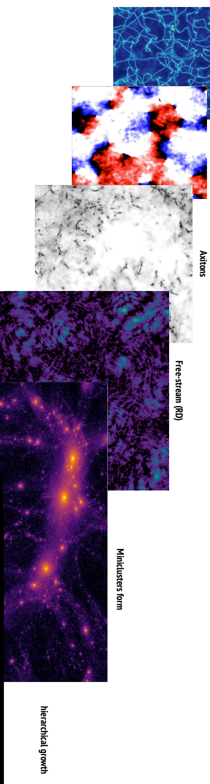
$T_{\rm osc}$ $H(T_{\rm osc}) \sim m_a$:



Axion DM inhomogeneous a ~ pc scales

first structures form at $z > z_{eq}$





- density perturbations grow under gravity as usual
- collapsing into gravitationally bound objects known as **miniclusters**
- total axion mass contained within the horizon at $t_{\rm osc}$ sets the characteristic minicluster mass at $z_{\rm eq}$:

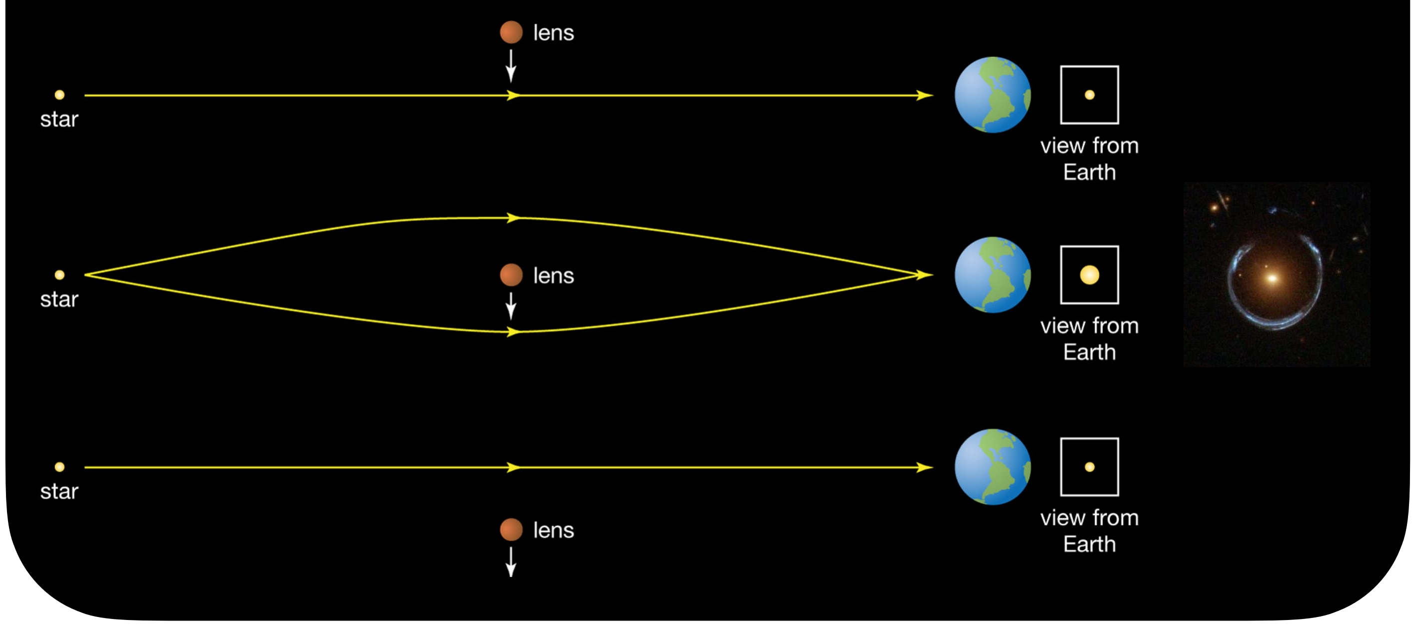
Hogan & Reese (1988)

$$M_0 = \overset{\text{today}}{\bar{\rho}_a}\frac{4}{3}\pi\left(\frac{\pi}{a(T_0)H(T_0)}\right)^3 \begin{cases} M_0 \sim 10^{-12} M_\odot \\ \text{size } \sim 10^7 \text{ km} \\ \sim 10^{25} \text{ in the Galaxy} \\ \text{through the Earth every } \sim 10^5 \text{ years} \end{cases}$$

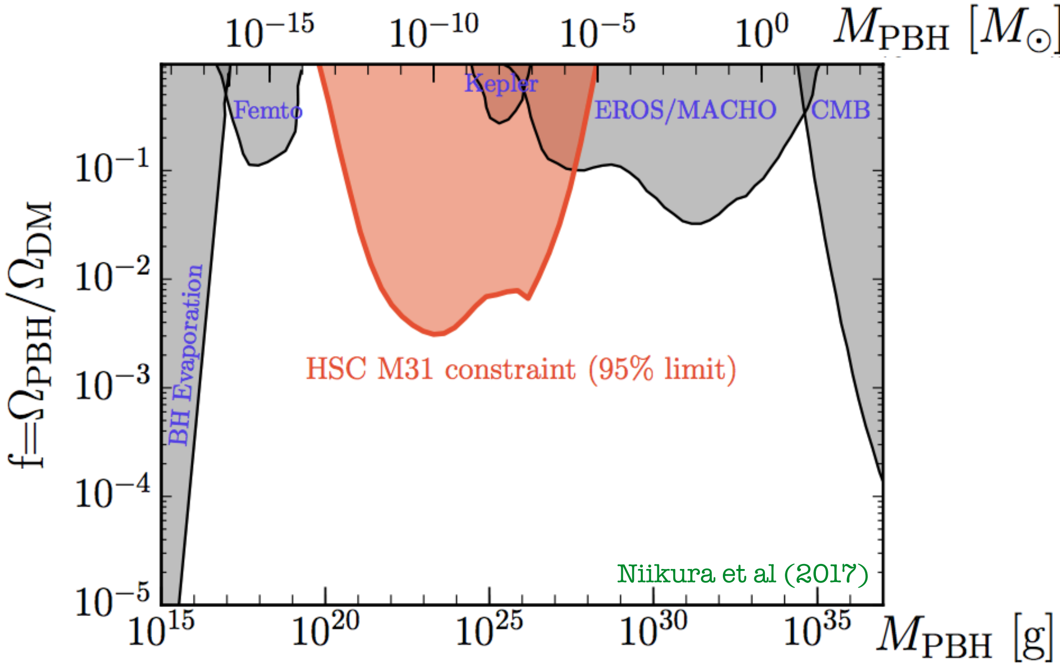
Smaller than smallest WIMP structures ($\sim 10^{-6} M_\odot$)

Detecting axion miniclusters with gravitational microlensing

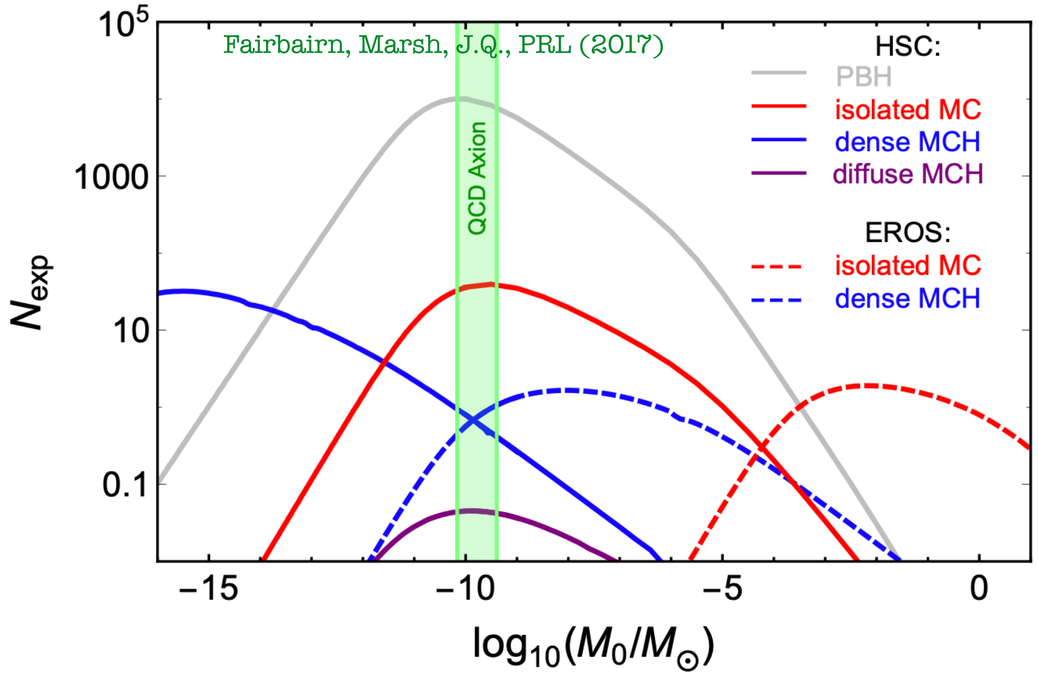
Microlensing: fugitive amplification of a background star which occurs when a compact object passes close to the line of sight to that star.

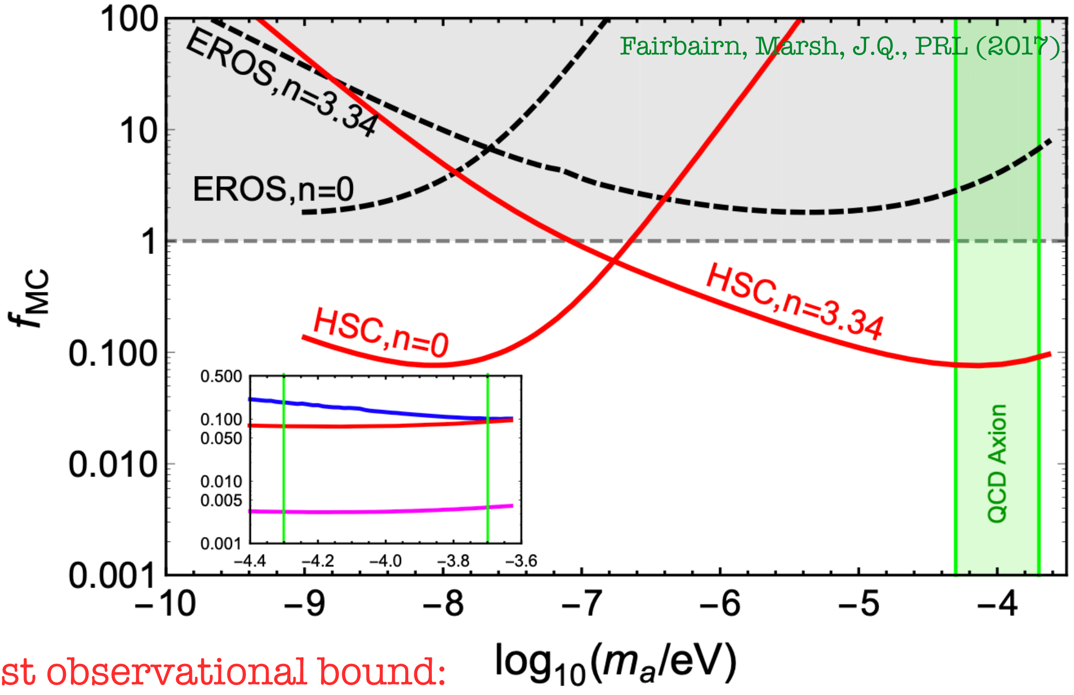


For PBH (point masses), the amount of DM in compact objects is strongly constrained:



Expected microlensing events:





Place the first observational bound:

$$\boxed{f_{\rm MC} \;<\; 0.083(m_a/100\,\mu{\rm eV})^{0.12}}$$

If $f_{\rm MC}$ is high, rare MC encounters → axion DM detection is limited.

Conclusion

- The dark matter puzzle is a serious and real challenge for fundamental physics.
- Whether dark matter interacts with the Standard Model particles continues to be one of the great unresolved questions of modern physics.

The WIMP hypothesis:

- WIMP with their thermal freeze-out motivates a bare-minimum target mass range and phenomenology for collider searches (few GeV-TeV).
- Direct detection experiments searching for WIMP-like dark matter have excluded significant parameter space using ton-scale detectors and unprecedented low background levels.
- WIMP paradigm is not dead, but it's under enormous pressure
- Freeze-out provides a useful target, however nature need not be so simple and a broad programme is required to cover all phenomena

The axion hypothesis:

- Lack of evidence for WIMP has given rise to renewed interest in axion including more robust theoretical predictions and new ideas for probes
- Vast majority of axion parameter space still unprobed.
  New experiments, new experimental ideas & technics along with alternative DM scenarios
- Axion physics is a mature field but new fundamental properties are expected
- Axions are multidisciplinary: a chance/challenge

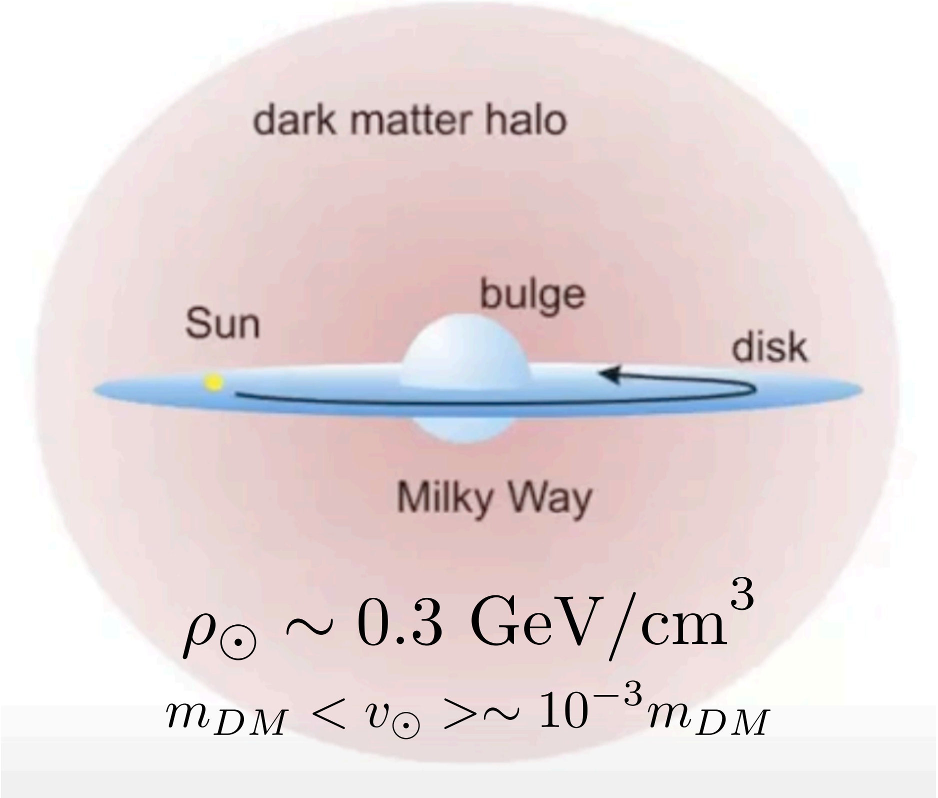
Spare slides

Local DM and direct detection of WIMPs

‘miracle’: the local abundance of DM has little to do with the generation mechanism or with the technologies of the XXIst century.

To understand the prospects for direct detection, we need:

- the flux of DM on Earth:



$\rho_\odot \sim 0.3\ \mathrm{GeV/cm}^3$

$m_{DM} < v_\odot > \sim 10^{-3} m_{DM}$

$\longrightarrow$ flux: $10^{10}\dfrac{MeV}{m_{DM}}cm^{-2}s^{-1}$

- the experimental sensitivities.

DM scattering on Earth

- The kinetic energy of DM in the lab frame $E_{DM} = \frac{1}{2} m_{DM} v^2 \sim 10^{-6} m_{DM}$

if $m_{DM} \lesssim$ GeV: E_{DM} is smaller than the binding energy in nuclei (MeV)

⟶ elastic scattering

- One can compute the recoil energy of the nucleus: $E_R^{max} \sim \frac{m_{DM}}{GeV} \; keV$

This amount of energy per nucleus needs to leave a trace in the detector.

For the standard detector (e.g. Xenon) there is a threshold for signals below keV.

⟶ These detectors do not see anything below ~ GeV masses.

Shall we build a DM detector?

For typical interactions, $N \sim 10^{-2} \mathrm{events/kg/day}$

key: how to reduce background

Two main models for Cold Dark Matter

WIMPs :	Axions :
Predicted $\sim$ 1970's	Predicted $\sim$ 1970's
Naturally come from SUSY	Come from strong-CP
Heavy (nucleon mass)	very light (sub-neutrino mass)
Thermal	Non-thermal (classical scalar field)
'Traditional' search strategies	'Non Traditional' search strategies
Cold due to small thermal velocities	'Cold' due to coherence and small λ
Collisions necessary for production	Interactions via wave equations

Axions/ALPs are just a type of CDM, with different initial conditions & dynamics than thermal DM

Symmetry breaking leading to axion relic density:

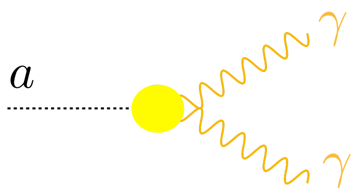
⟶ Lightest DM particle
⟶ Dense DM relics
⟶ 'Miniclusters'
⟶ Smallest DM structures

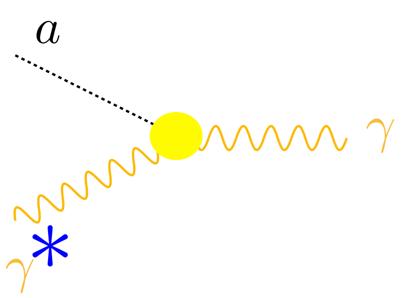
$\Bigg\}$ (linear fluctuations grow like WIMPs but might differ during non linear structure formation?)
[cf. delicate N-body simulations]

Axion conversion to photon

$$\mathcal{L}_{axion} \supset \# \frac{a}{f_a} F\tilde{F} \longleftrightarrow \# \frac{a}{f_a} \vec{E}.\vec{B}$$

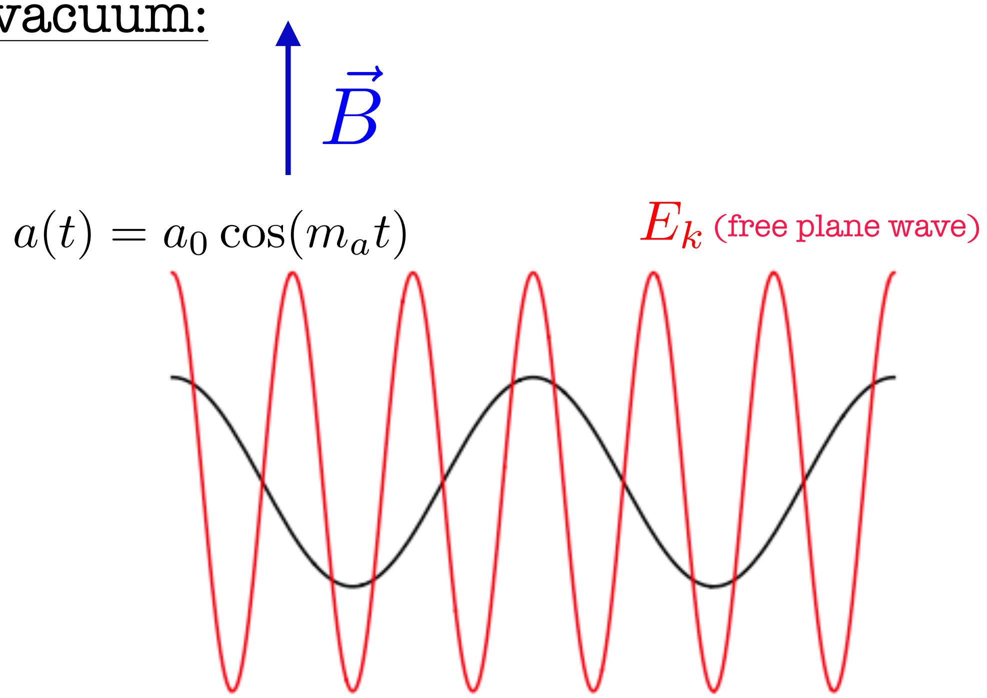
in an external B-field
the axion sources an E-field





Matrix element given by the **overlap** of the **axion** and **virtual photon** wave functions

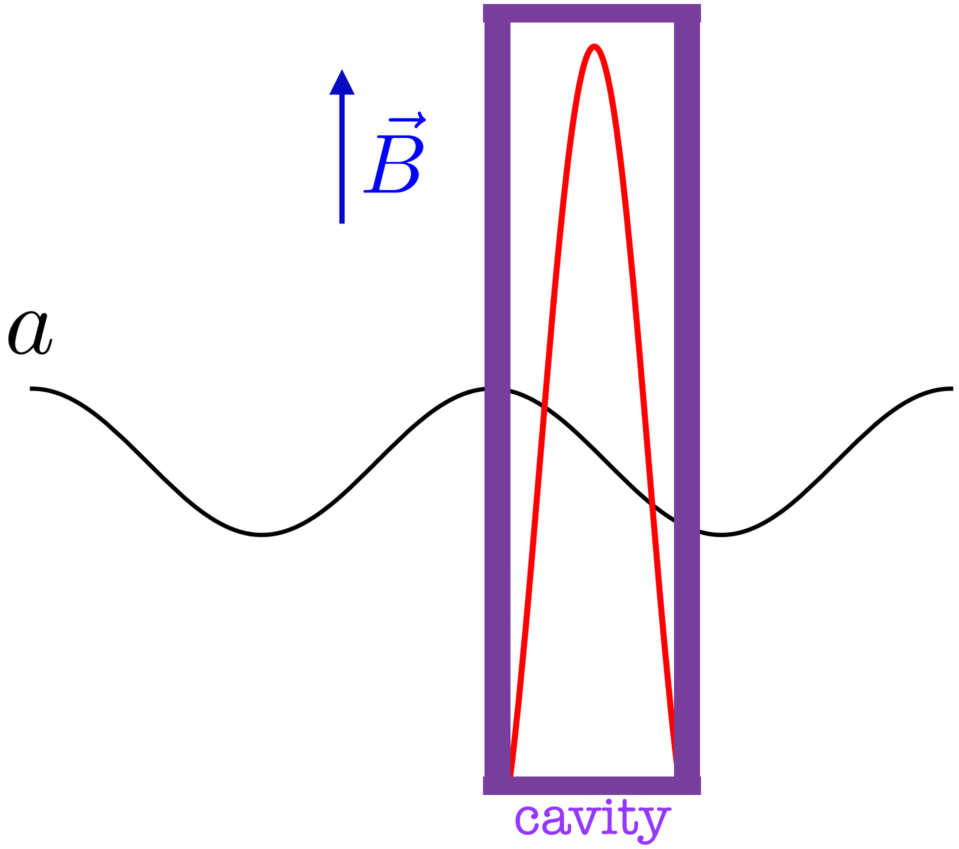
In vacuum:



Oscillatory integral vanishes (moment conservation)
⟶ **no** axion-photon conversion

One needs to modify the free wave function

Inside a cavity: E_k becomes the cavity modes



⟶ axion-photon conversion is allowed

The Peccei-Quinn axion solution

axial anomaly: $\theta_{EW}^{\text{CPV}} \longleftrightarrow \theta_{QCD}^{\text{CPV}}$

Solution to the strong CP problem of QCD: add fields such that rotate $\bar{\theta}$ to the phase of a complex SM-singlet scalar who gets a VEV and dynamicaly drives $\bar{\theta} \to 0$

Peccei & Quinn

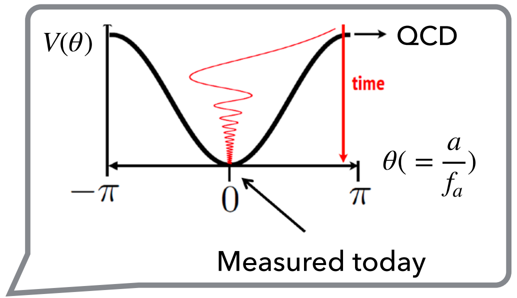
$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q e^{i\theta_{EW}})q - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{\mu\nu}^a$$

1. Introduce a new global anomalous axial $U(1)_{PQ}$ symmetry S.B. at high scale
   ⟶ the low-energy theory has a **Goldstone boson** (the **axion** field)

cf. global vector $U(1)_{\mathcal{B},\mathcal{L}}$

2. Design $\mathcal{L}_{axion}$ such that $Q(q_L) \neq Q(q_R)$ ⟶ this makes the $U(1)_{PQ}$ **anomalous** : $\partial_\mu J^\mu \sim G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$

   net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{a}{v}G_{\mu\nu}\tilde{G}^{\mu\nu} + \ldots$



3. Non-perturbative QCD effects induce:

$$\mathcal{L}_{axion} = \mathcal{L}_{ChPT}(\partial_\mu a, \pi, \eta, \eta', \ldots) + V_{eff}(\bar{\theta} + \frac{a}{v}, \pi, \eta, \ldots)$$

$$\sim -\Lambda_{QCD}^4 cos(\bar{\theta} + \frac{a}{v})$$

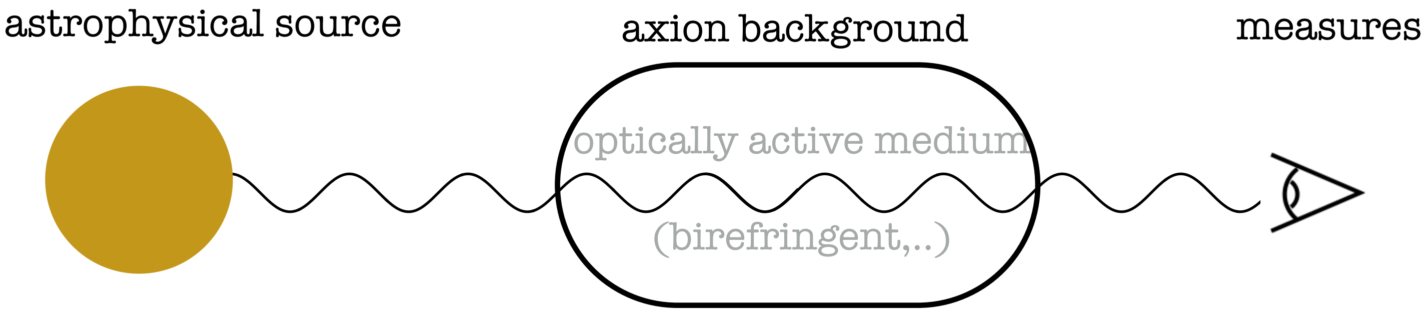
minimum of the potential: $\bar{\theta} + \frac{<a>}{v} = 0$

new energy scale!

CP-violating term cancels!

CP symmetry is dynamically restored!

How do photons propagate through axion background?



axion electrodynamics:

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a\,,$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma\gamma}\dot{a}\mathbf{B} + g_{a\gamma\gamma}\nabla a \times \mathbf{E}\,,$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\dot{\mathbf{B}} + \nabla \times \mathbf{E} = 0\,.$$

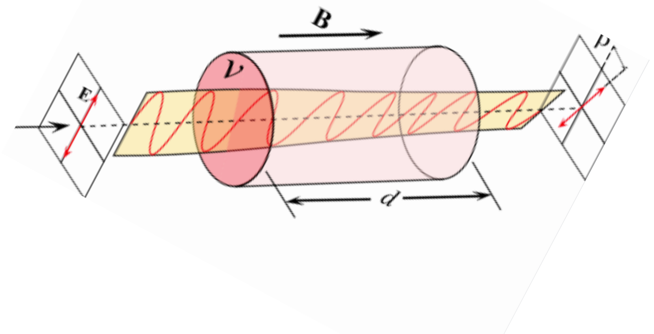
dispersion relation:

$$\omega_\pm \sim k \pm \frac{g_{a\gamma\gamma}}{2}(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a) \mp g_{a\gamma\gamma}\omega_p^2\frac{\partial_t a}{4k^2} + \mathcal{O}(g_{a\gamma\gamma}^2)$$

Apply carefully Hamilton's optic

$$v^\pm_{phase} = \frac{\omega^\pm}{k}$$

The Faraday rotation



axion induces photon **polarisation rotation**: Harrari-Sikivie (1992)

$$\theta = \frac{1}{2}\int_{t_i}^{t_f}(\omega_+ - \omega_-)dt$$
$$\theta = \frac{1}{2}\int_{t_i}^{t_f} g_{a\gamma\gamma}(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a)dt$$

VLT observations of neutron star

$$v^\pm_{group} = \frac{d\omega^\pm}{dk}$$

Group velocity splitting between L/R polarisations:

$$v_g^+ - v_g^- = \pm\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_p^2}{k_0^2}\left[a' - \dot{a}\right]$$

time delay

$$\Delta t_p = \mp\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_p^2}{k_0^2}\int_0^{t_f} dt'\left[a' - \dot{a}\right]$$

Constraints from :

-Gamma-ray burst

-radio waves from pulsars & fast radio bursts

No refraction at $\mathcal{O}(g_{a\gamma\gamma})$ in absence of plasma

Blas et al. 'No chiral bending of light by axion clumps' (2019) cf. Weinberg (1962)

$$\Delta k^i = \pm\frac{g_{a\gamma\gamma}}{2}\partial_i[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$
$$\Delta\omega = \mp\frac{g_{a\gamma\gamma}}{2}\partial_0[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$

Suggests a new way to use atomic clocks to constraints axion DM:

$$\frac{\Delta\omega}{\omega} \sim 10^{-16}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)\left(\frac{1\,\mathrm{GHz}}{\omega}\right)\sqrt{\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm}^3}}$$

-optical effects should be examined further in specific axion backgrounds

-investigate precision terrestrial optical experiments to probe axion backgrounds

From theoretical topological defects to cosmological astrophysical objects

Physics left invariant by a $U(1)_{\mathrm{PQ}}$ rotation only if it rotates the QCD angle of $G\tilde{G}$

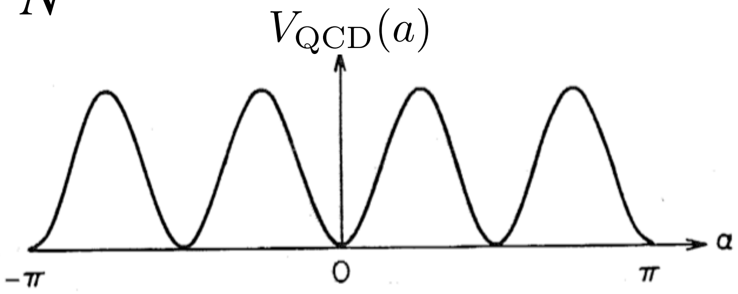
$$\phi \rightarrow e^{i\alpha}\phi \qquad \theta_{QCD} \rightarrow \theta_{QCD} + \boxed{N}\alpha$$

model dependent

Strong interaction effects break $U(1)_{\mathrm{PQ}}$ but are 2π periodic $\Rightarrow \alpha = \mathbb{Z}\dfrac{2\pi}{N}$ still a good symmetry

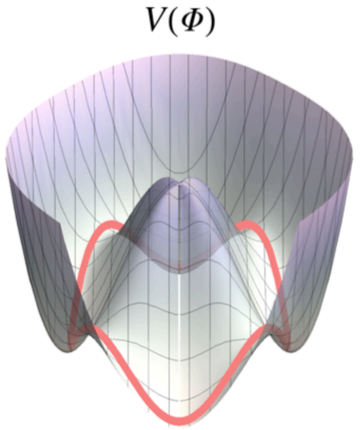
$$\boxed{U(1)_{PQ} \xrightarrow{\text{QCD instantons}} \mathbb{Z}_N}$$

Ex: $N = 4$ axion model
(4 degenerate minima)

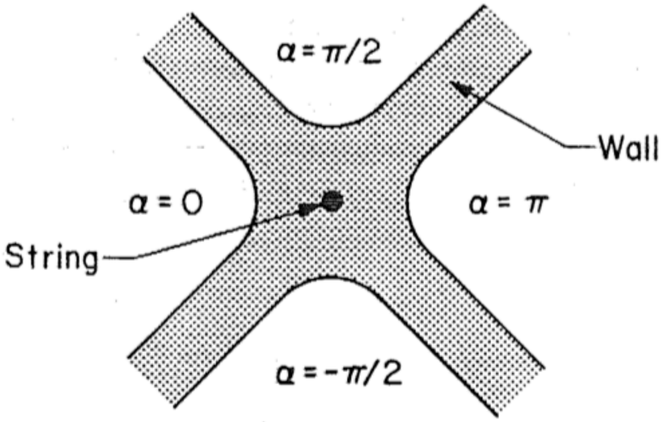


In QFT:

$T << T_{\mathrm{QCD}}$

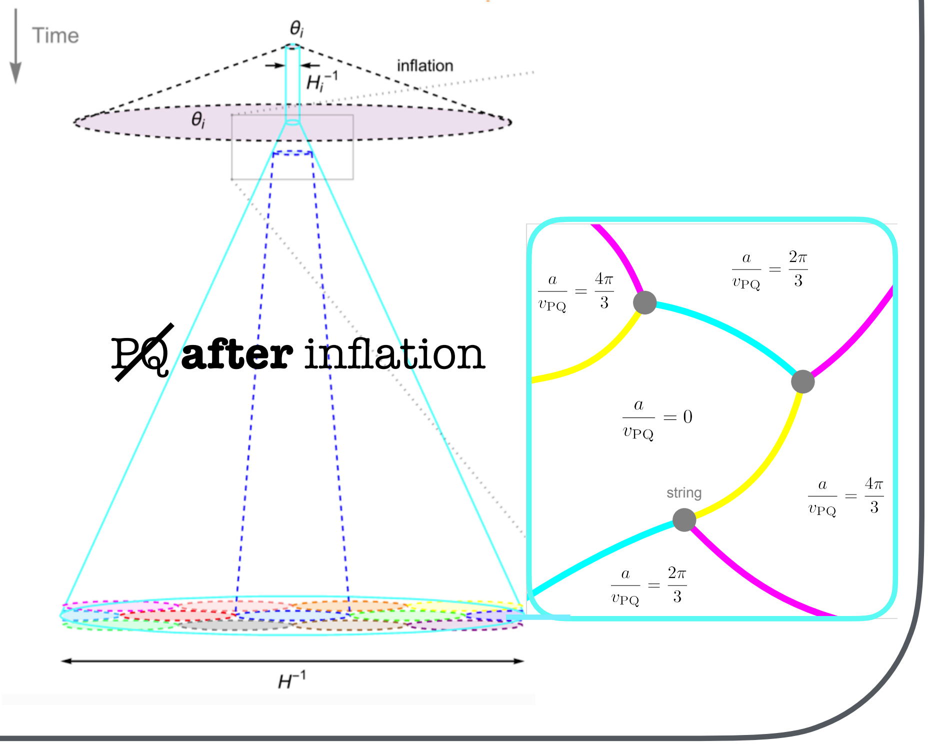


In position space:



$N = 4$ domain walls meet in a string

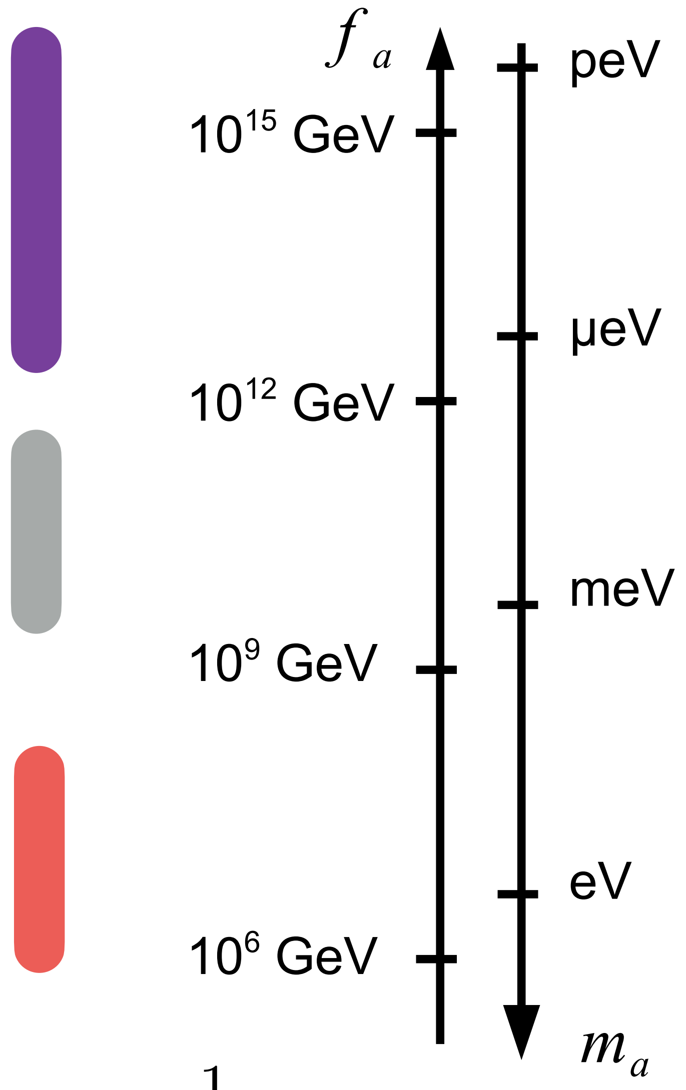
In the early universe:



$\cancel{\mathrm{PQ}}$ **after** inflation

Three main ways to get a cosmological axion population

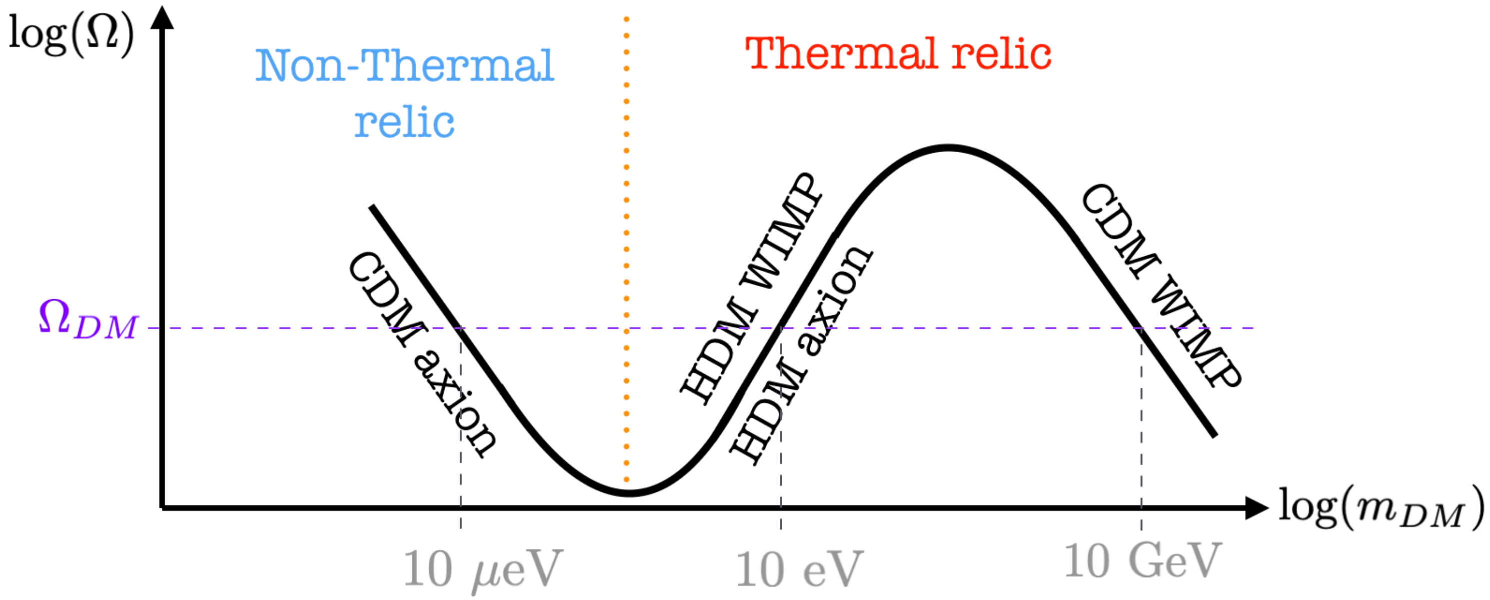
Populations of axions can be hot or cold, particles or coherent fields



- Misalignment mechanism [Cold Field]
- Decay from topological defects (axion strings, DW) [Cold Particles]
- Thermal production (neutrino-like) [Hot Particles]

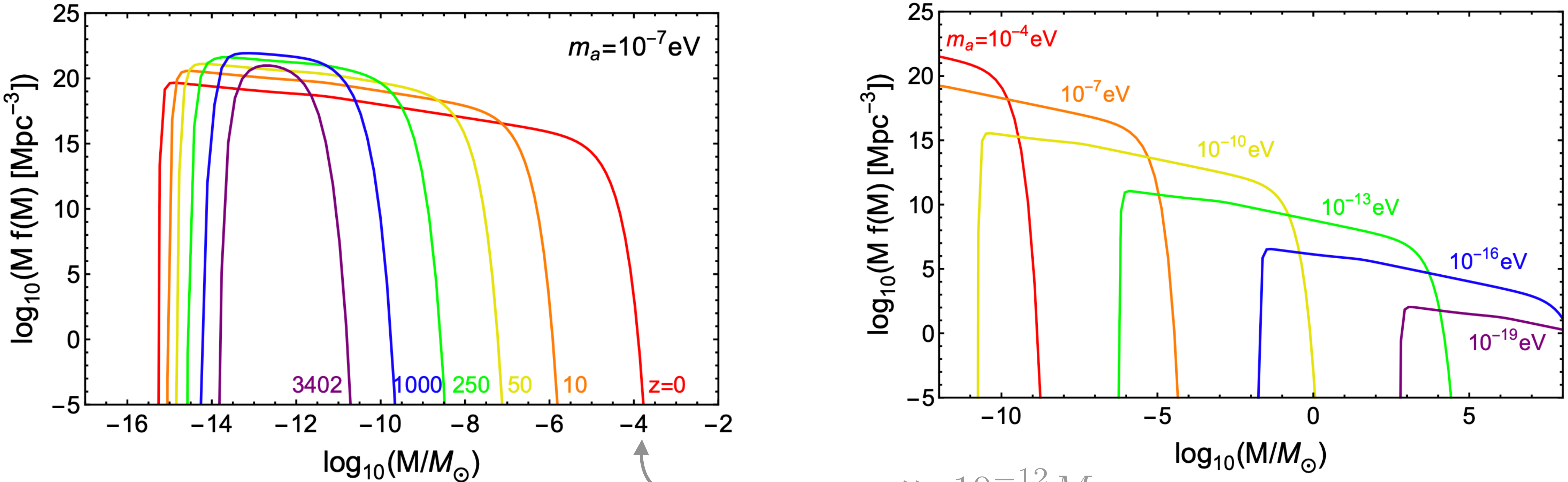
Production in the early universe via scattering with the cosmic plasma : $\pi + \pi \leftrightarrow \pi + a$

Main process governing thermalisation/decoupling depends on: $c_{\text{axion-X}} \propto \dfrac{1}{f_a}$



Axion miniclusters ‘nowadays’

- **initial conditions** for the axion field on **small scales** caused by SSB lead to the **collapse of objects** of mass M_0 around matter-radiation equality.
- once initially formed, go on to **merge into larger bound structures**, which we term “minicluster **halos**”
- behaviour is quite **different from CDM**: the initial conditions are **isocurvature**, structure formation begins much earlier, and the **power spectrum is truncated**.
- We consider the **formation of gravitationally bound structures** from linear density perturbations using the analytic **Press-Schechter formalism**
- Miniclusters halos formed on small scales. Contribute to the **substructure mass function** in the Milky Way.



Reach masses $\gg 10^{-12} M_\odot$

More than 10 orders of magnitude

How can we search for miniclusters halos? Like MACHOs?

Fairbairn, Marsh, J.Q., Rozier, PRD (2017)