Particle dark matter candidates

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Observational evidences for dark matter

Observational evidences for dark matter

in **Galaxies**

Rotation curves:

Stars and neutral hydrogen gas in spiral galaxies, move in circular orbits due to the force of gravity

Speed measured from Doppler shift of hydrogen 21cm line

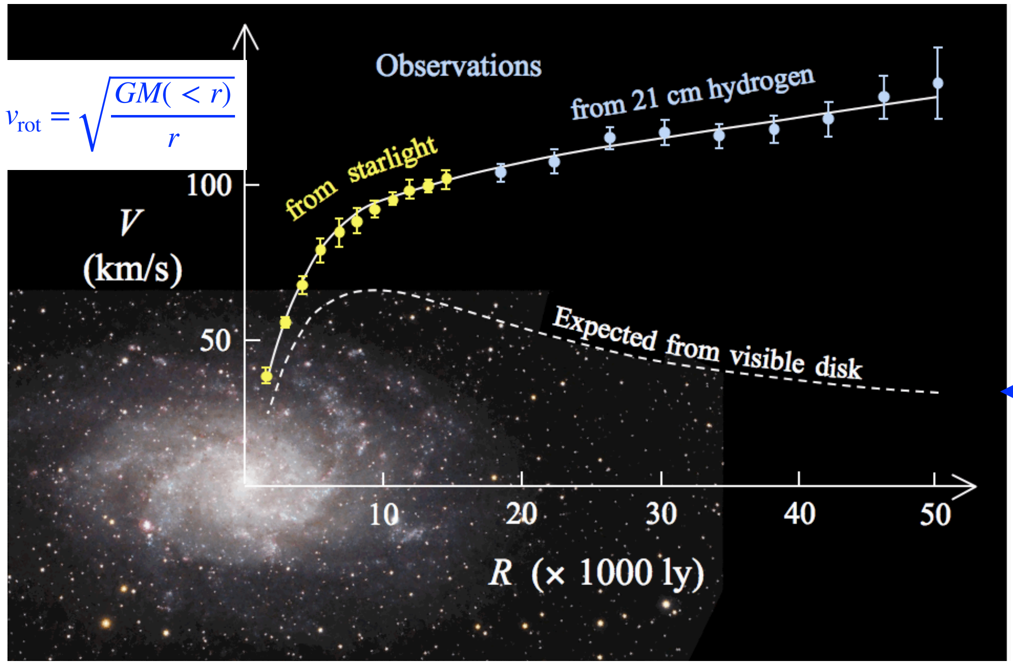
Using Newton's law of gravity: $\frac{v_{rot}^2}{r} = \frac{GM(<r)}{r^2}$

Newton's second theorem:

the gravitational force outside a closed spherical shell of matter is the same as if all the matter were concentrated at the point at its centre

$M(<r)$ = mass enclosed within a radius r.

$$= \int_0^r 4\pi r^2 \rho(r)\,\mathrm{d}r$$



Outside of matter distribution:

$M(<r)$ is constant and $v_{\rm rot} \propto r^{-1/2}$ 'Keplerian fall-off'

$v_{\rm rot} \sim \text{const} \;\rightarrow\; M(<r) \propto r \;\rightarrow\; \rho(r) \propto r^{-2}$

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

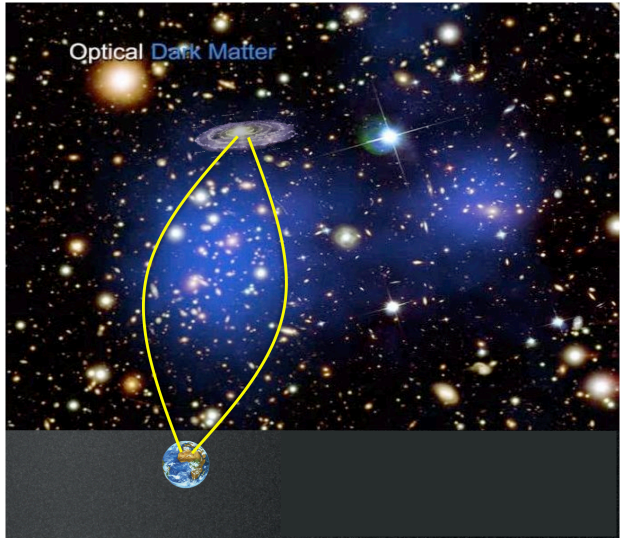
Observational evidences for dark matter

in **Galaxy clusters** (100s or 1000s of galaxies plus hot X-ray emitting gas)

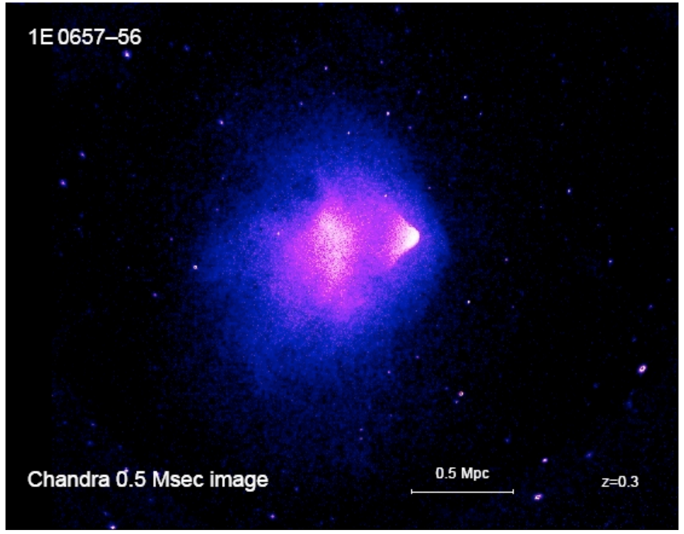
Largest gravitational bound objects in Universe, therefore expect that the material they contain is roughly representative of the Universe as a whole

The bullet cluster:

optical image

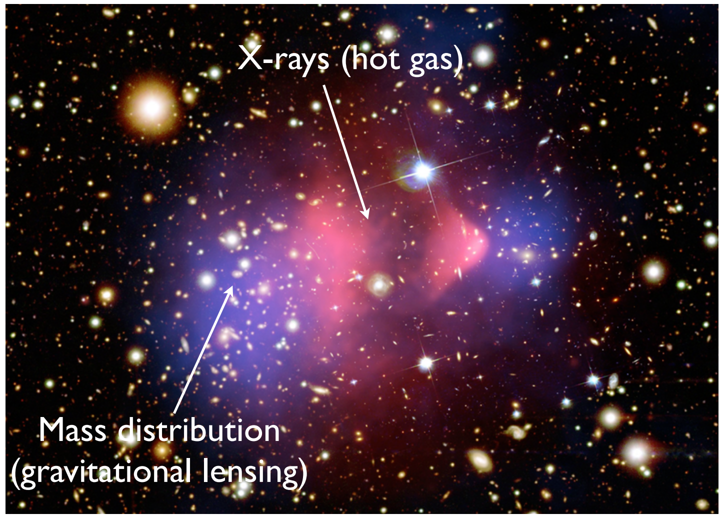


X-ray image

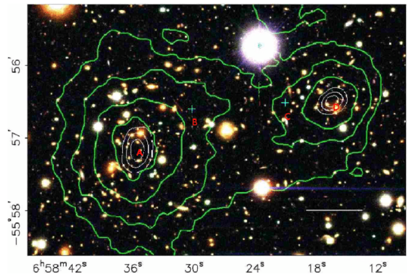


→

composite image



weak lensing mass contours



lensing analysis assumes GR, however explaining these observations is a big challenge for modified gravity theories

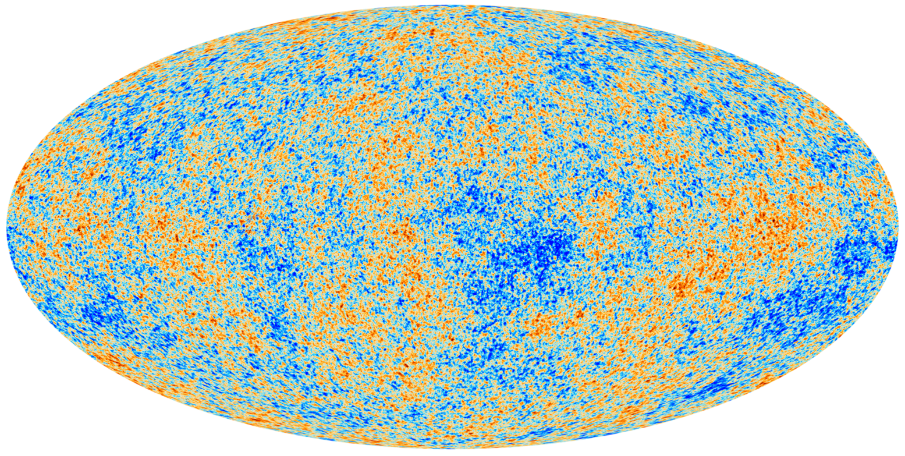
Separation of gravitational potential (reconstructed from weak lensing obs.) & dominant baryonic mass component (hot gas, X-ray emission imaged by Chandra)

⇒ dark matter

Observational evidences for dark matter

from **Cosmic Microwave Background** anisotropies

Relic of electromagnetic radiation:



Amplitude of perturbations:

On large angular scales: $\frac{\Delta T}{T} \sim 10^{-5}$

density fluctuations

↓

fluctuations in gravitational potential $\nabla^2(\delta\Phi) = 4\pi G\delta\epsilon$

↓

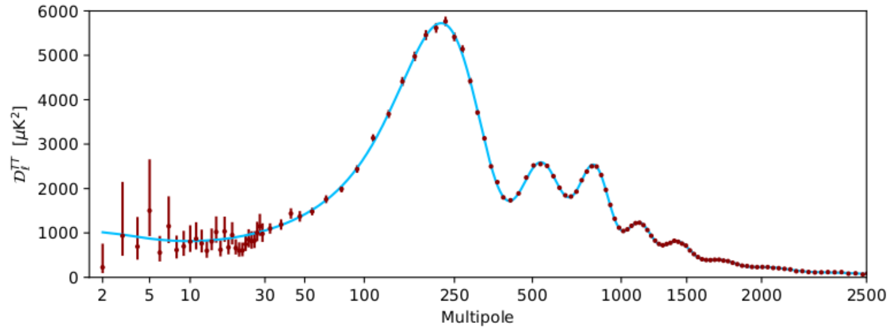
red/blue shift of photons $\frac{\delta T}{T} = \frac{1}{3}\delta\Phi$

- Baryons are tightly coupled to photons until decoupling ($t \sim 0.4$ Myr) and perturbations in baryons can only grow after decoupling
- Therefore in a universe without non-baryonic DM initial perturbations have to be large ($\Delta T/T \sim 10^{-4}$) to explained structure formation
- Density perturbations in dark matter grow $\propto a$ from radiation-matter equality ($t \sim 0.05$ Myr)

$\Rightarrow$ For perturbations to grow sufficiently from initial measured amplitudes **requires non-baryonic DM**

Heights of peaks:

depends on baryon and matter densities:

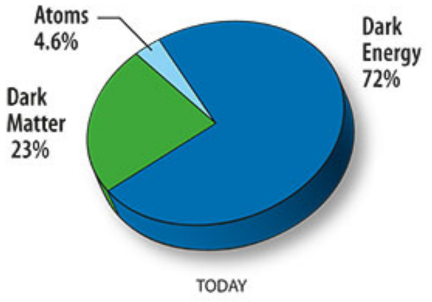


Planck 2018

From temperature, polarisations and (CMB) lensing data:

$$\Omega_b h^2 = 0.02237 \pm 0.00015$$

cold dark matter ⟶ $$\Omega_c h^2 = 0.1200 \pm 0.0012$$



What about modified gravity?

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

Could the observations be explained by instead modifying the laws of gravity?

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. But hard to explain all of the diverse (nature and scale) evidences

In this paradigm how to accommodate the observed galaxies without DM?

Paradigm: a particle dark matter candidate

WIMP dark matter candidate from the SM?

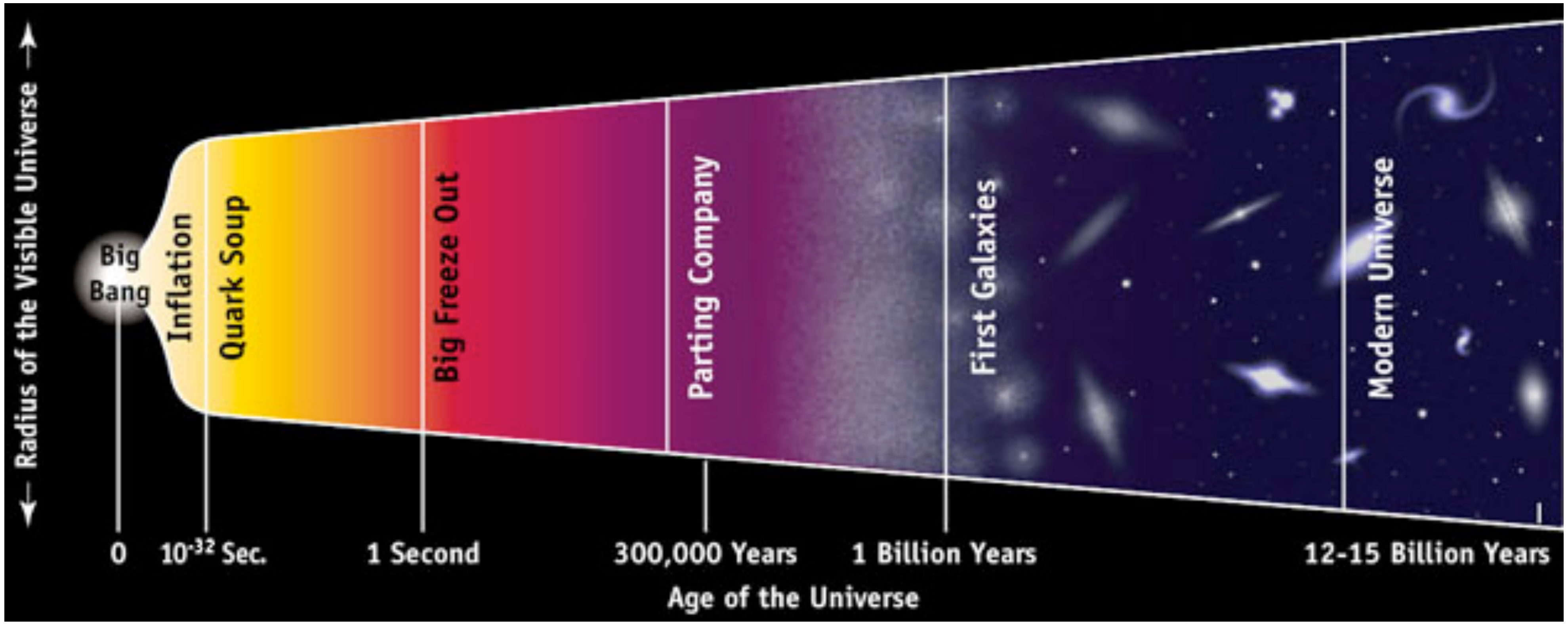
Known DM properties

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

None of the known particles can be cold DM.

Why new particle physics?

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)

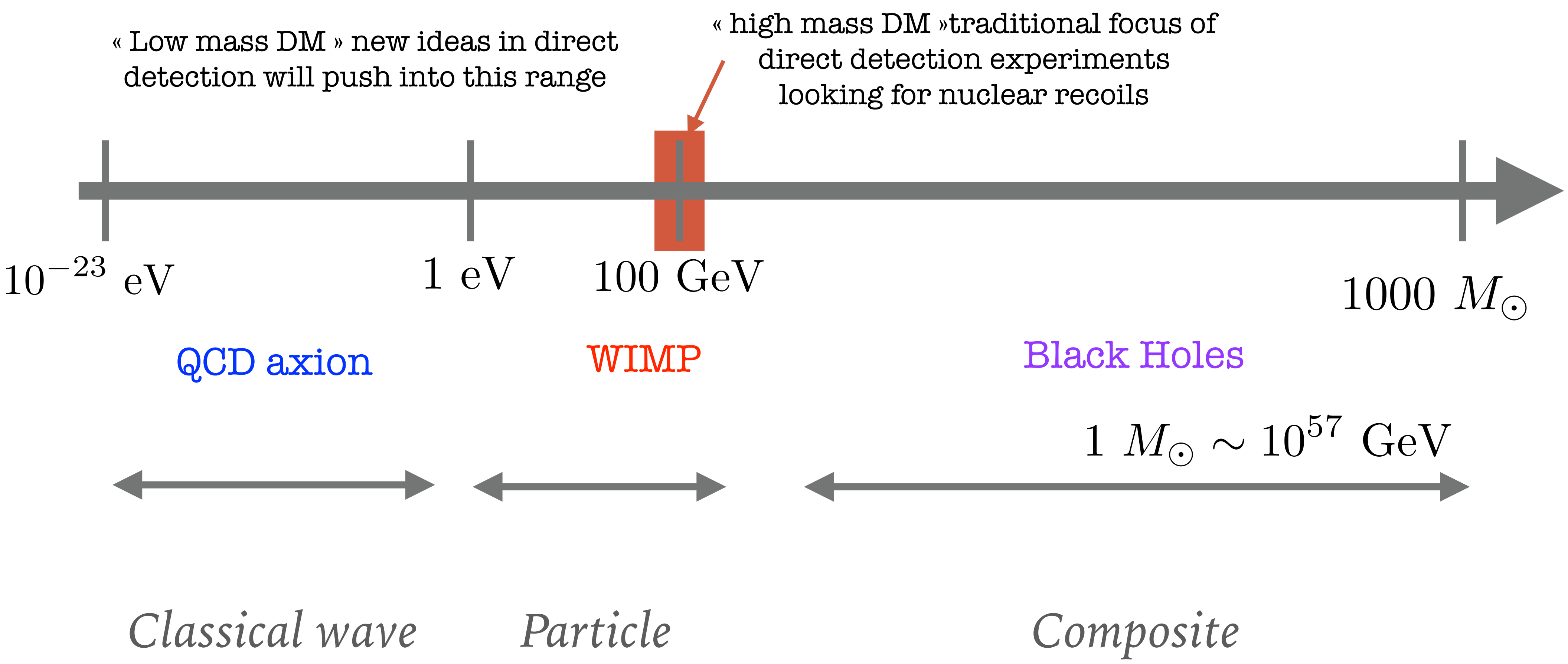
LSS (matter)

Supernovae (DE)

Galaxy curves (matter)

Dark matter candidates

- Dark matter is one of the most concrete clues of physics beyond the Standard Model
- The mass scale for dark matter spans many orders of magnitude
- Large range of parameter space that requires particular search strategy
- For masses below eV, the dark matter has to be bosonic, non-thermal and can be described by a classical field



« Low mass DM » new ideas in direct detection will push into this range

« high mass DM »traditional focus of direct detection experiments looking for nuclear recoils

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

The relic density

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

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

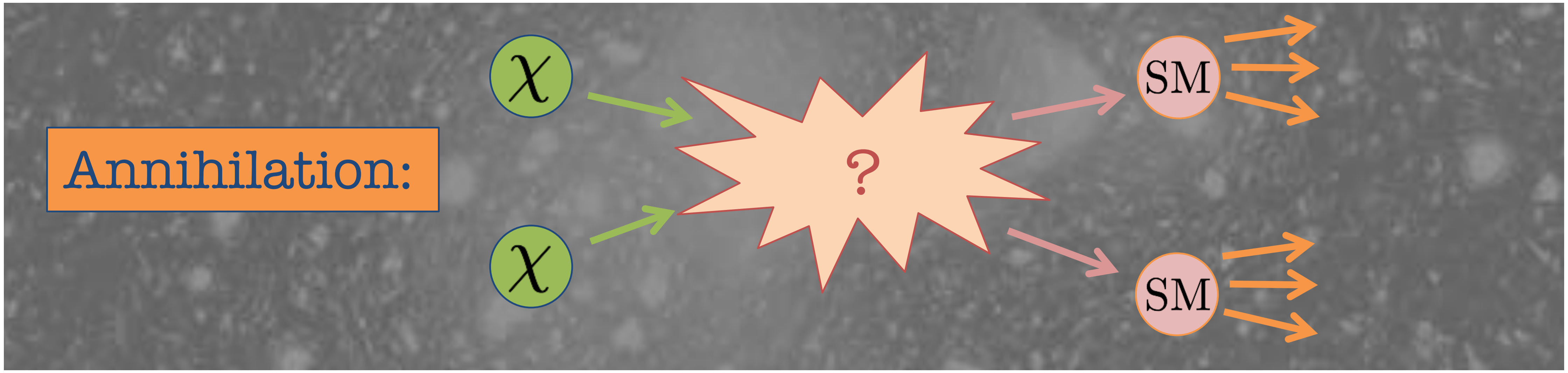
What can we learn from this about dark matter's particle properties?

— 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

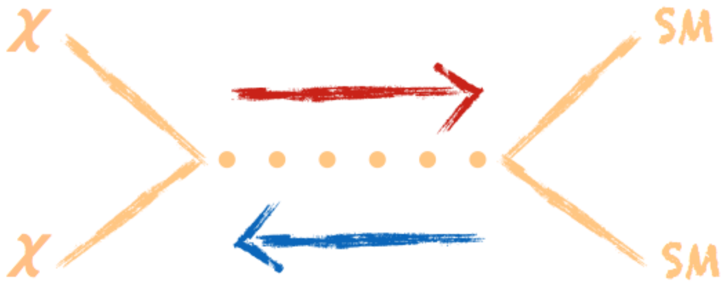
For a given dark matter candidate, on can trace the cosmological history from early times to present day



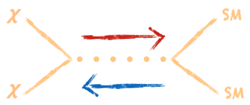
For a given postulated interaction form, one can calculate the amount of dark matter left over

The WIMP miracle

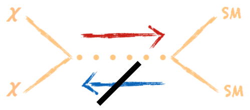
Boltzmann equation and Freeze-out



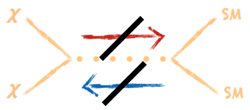
$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma v\rangle \left[n_\chi^2 - n_\chi^{eq2}\right]$$



- χ (CDM) is initially in thermal equilibrium



- universe cools down $\Rightarrow \chi$ only decreases by pair annihilation

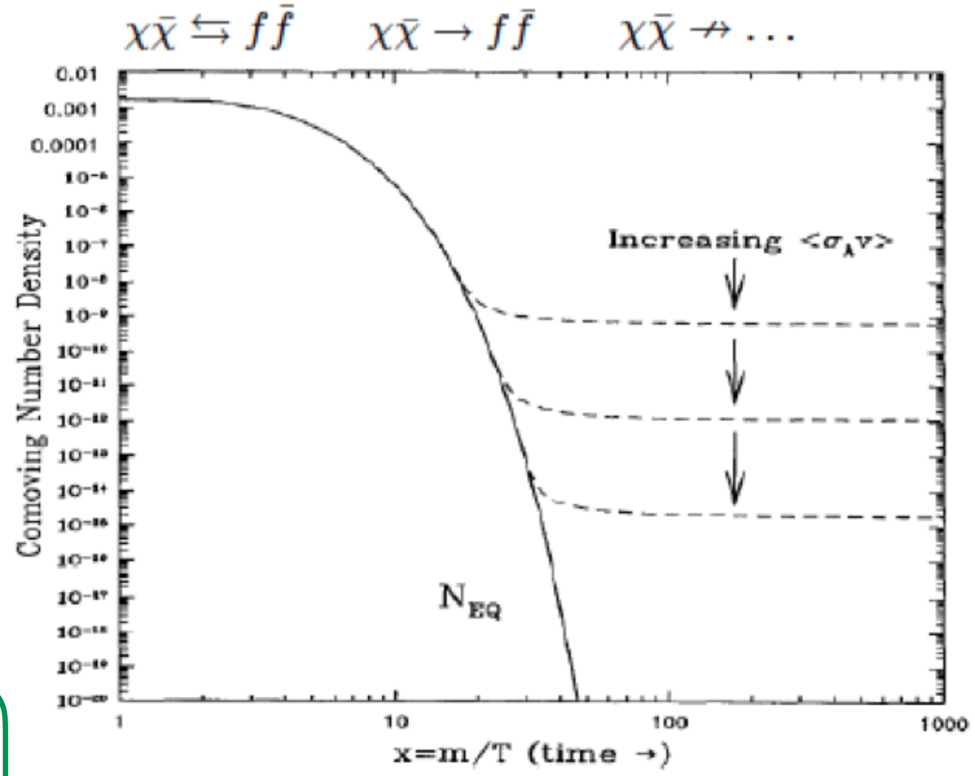


- universe expands: $\langle\sigma v\rangle n_\chi(T) < H(T) \Rightarrow \chi$ decouples from the SM

$$\Omega_{DM} h^2 = \frac{2 m_\chi Y_\chi^0}{3.6 \times 10^{-9} \text{GeV}} = \frac{3.10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle} \sim 0.1$$

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

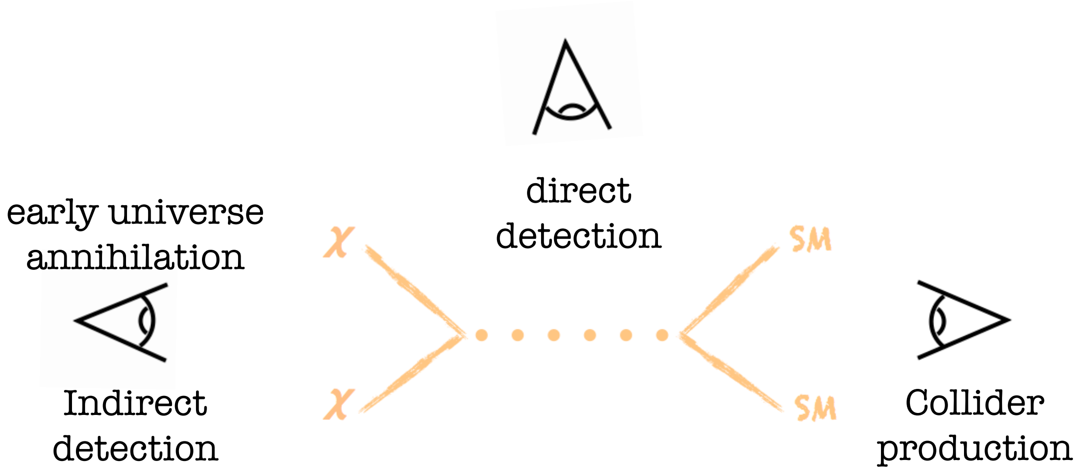
→ The WIMP miracle!



A remarkable coincidence: particles with the right thermal relic density are now at the energy frontier! The LHC is a big DM search experiment.

The WIMP miracle is not a precise coincidence. But it is tantalizing, and it is our strongest quantitative hint that our attempts to understand the universe on the largest and smallest scales may be related.

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



early universe annihilation

direct detection

Indirect detection

Collider production

The weak scale

- Fermi's constant G_F was introduced in the 1930s to describe nuclear beta decay

$$n \to p\, e^- \bar{\nu}\ .$$

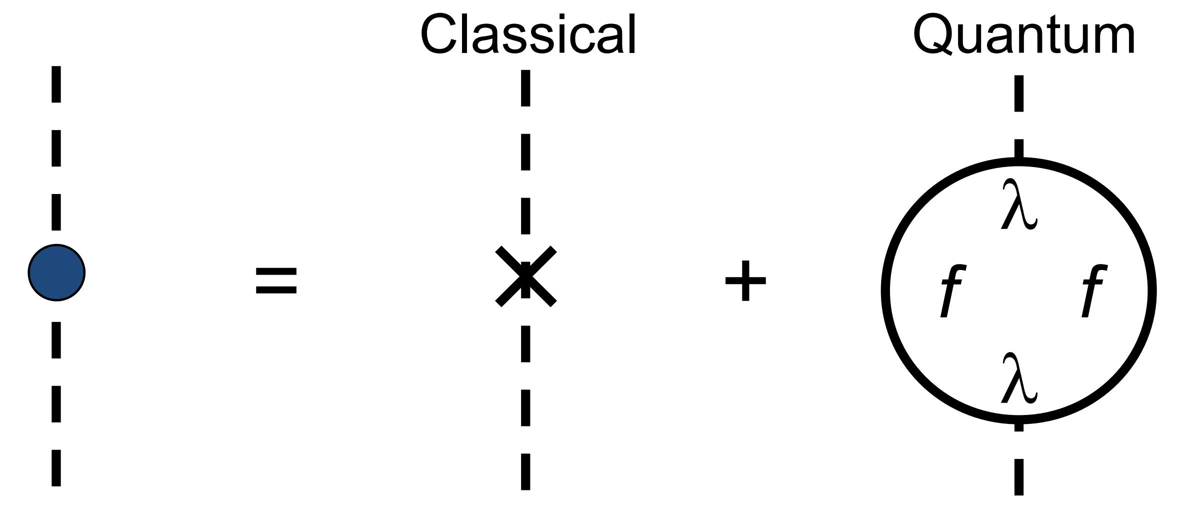
- The measured value, $G_F \sim 10^{-5}\ \mathrm{GeV}^{-2}$, introduces a new mass scale in nature, the weak scale:

$$m_{\mathrm{weak}} \sim 100\ \mathrm{GeV}\ .$$

- We still don't understand the origin of this mass scale, but every reasonable attempt so far introduces new particles at the weak scale.

The naturalness issue

- We have now discovered a particle that looks like a fundamental scalar with a mass $m_h \simeq 125$ GeV: the Higgs boson. Scalars are different:



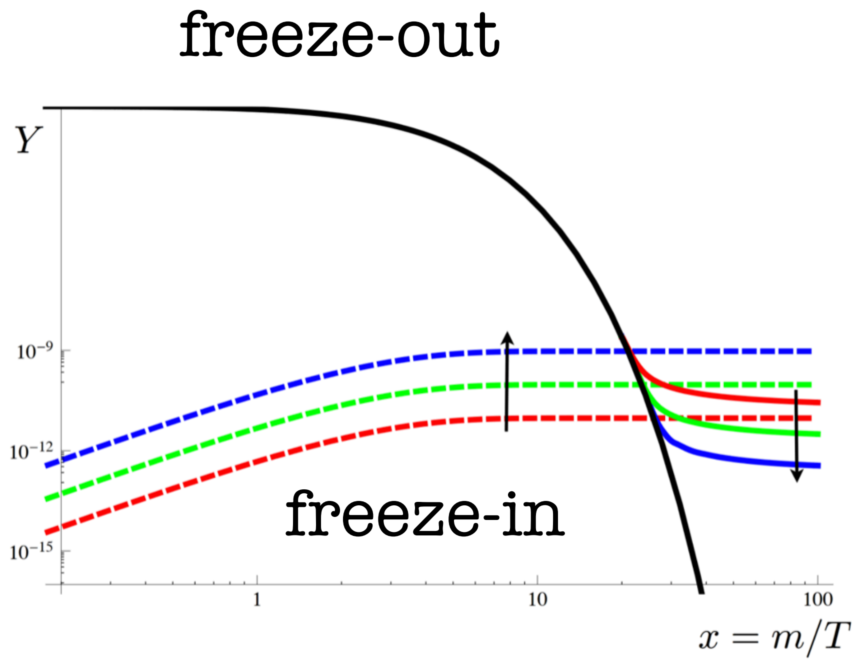
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- For $\Lambda \sim m_{\text{Planck}} \sim 10^{19}$ GeV, and f = top ($\lambda \sim 1$), the classical and quantum contributions must cancel to 1 part in 10^{32} to yield the physical Higgs mass.

- This is the naturalness, fine-tuning, or gauge hierarchy problem of the Standard Model. Its resolution likely requires new particles at the weak scale that introduce new quantum contributions to cancel the existing ones.

Alternatives: 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

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

Dark matter classification

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

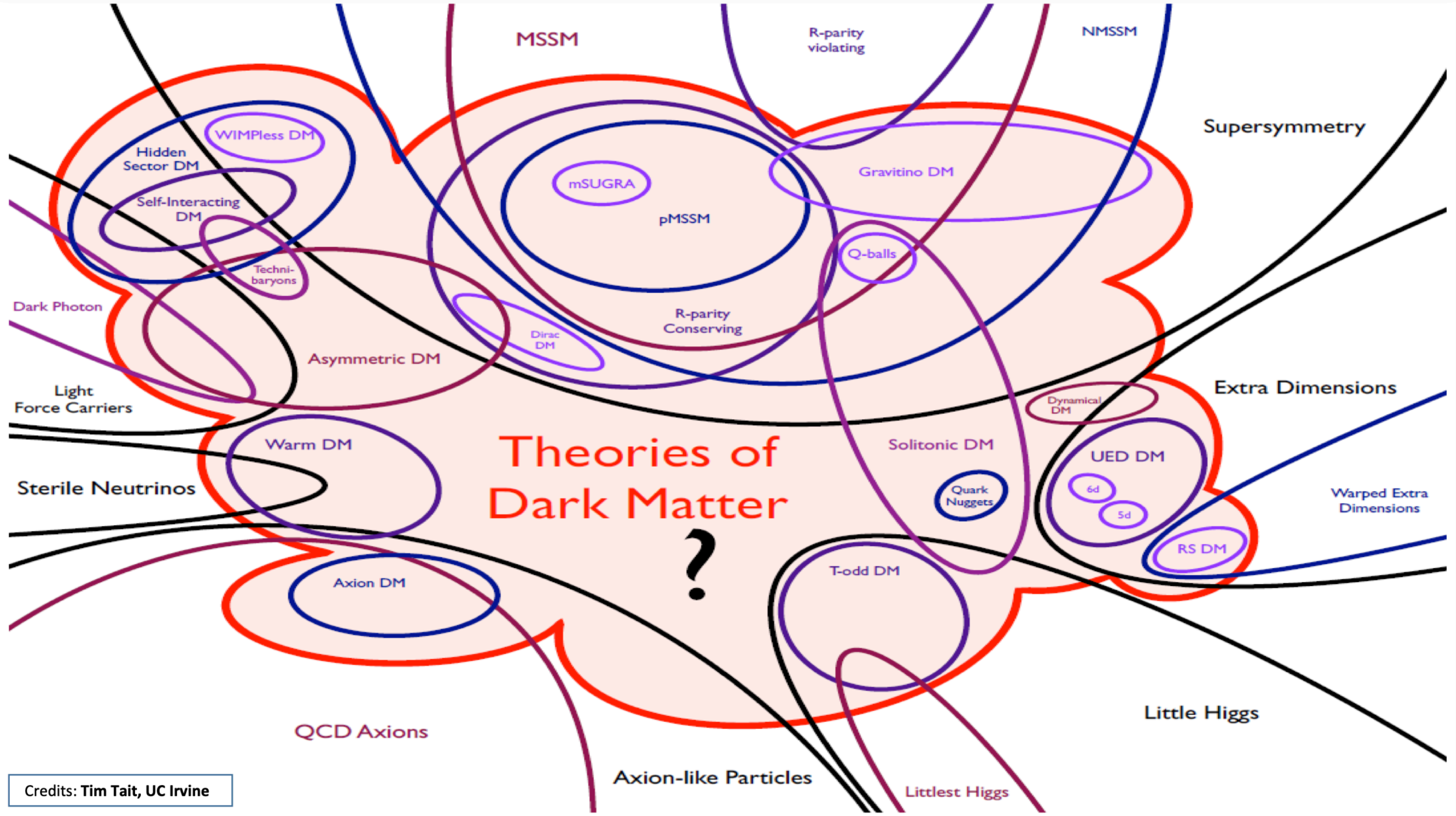
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other “feeble” creatures – call them **superweakly interacting MPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim 10^{10}$. “Super-cool DM”. Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

From predictive models to **simplified models**

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 sector

What is meant by a dark sector ?
A Hidden sector, with Dark matter, that talks to us through a Portal

Standard Model → Portal → Dark Sector

Portal can be the Higgs boson itself or New Messenger/s

Dark sector has dynamics which is not fixed by Standard Model dynamics
→ New Forces and New Symmetries
→ Multiple new states in the dark sector, including Dark Matter candidates

Ex: Higgs portal

Does the Higgs boson interact with a Hidden-Sector?

Motivation: $|H|^2$ is lowest dimension SM singlet, so SM singlet dark matter may naturally couple to SM via this operator

Higgs-portal models : [Silveira,Zee(1985); Shabinger,Wells(2005);Patt,Wilczek(2006)]

- Scalar DM: $\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$
- Vectorial DM: $\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu$
- Fermion DM (not renormalizable): $\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi$

(DM stability ensured by a Z_2 parity)

→ 2 parameter model: phenomenology fully determined by the mass m_{DM} and coupling λ_{DM}

Z' portal

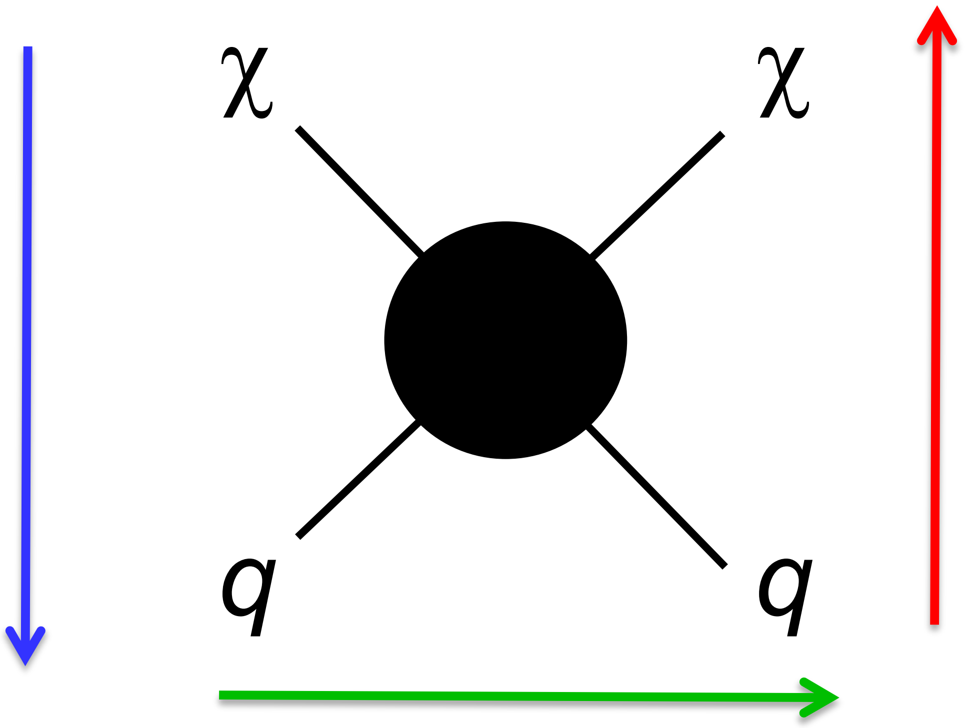
$$\mathscr{L} = -g_{SM} Z'^{\mu} \bar{f}\gamma_\mu\gamma_5 f - g_{DM} Z'^{\mu} \bar{\chi}\gamma_\mu\gamma_5\chi$$

...

How to directly detect WIMPs?

WIMP detection

Correct relic density → Efficient annihilation then



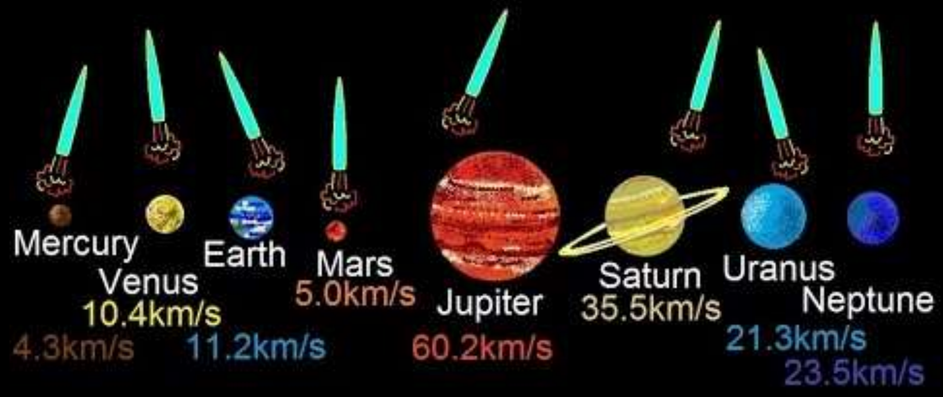
Efficient annihilation now
(Indirect detection)

Efficient production now
(Particle colliders)

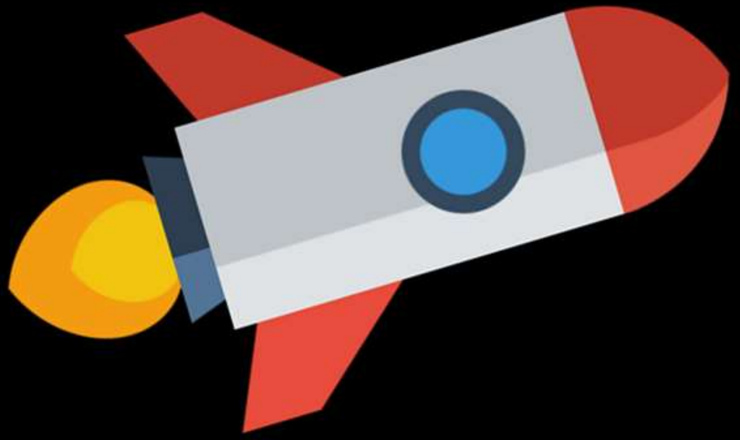
Efficient scattering now
(Direct detection)

What about dark matter velocity?

Planet escape velocities:



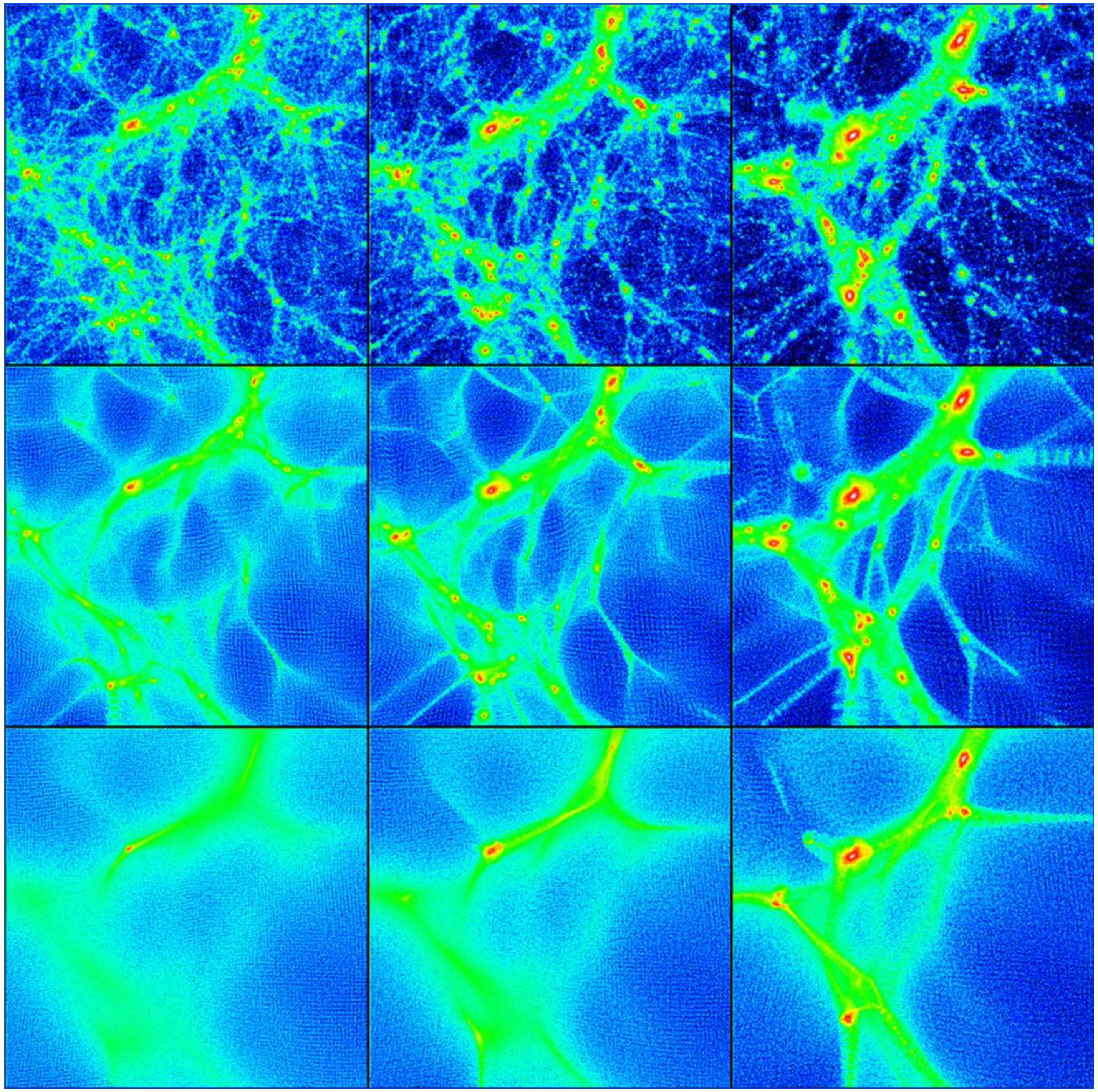
Milky Way Escape velocity



~ 500 km / s

We know dark matter must be travelling less quickly than this, since we know it is present in galaxies like the Milky Way

How quickly was the dark matter moving in the early universe?



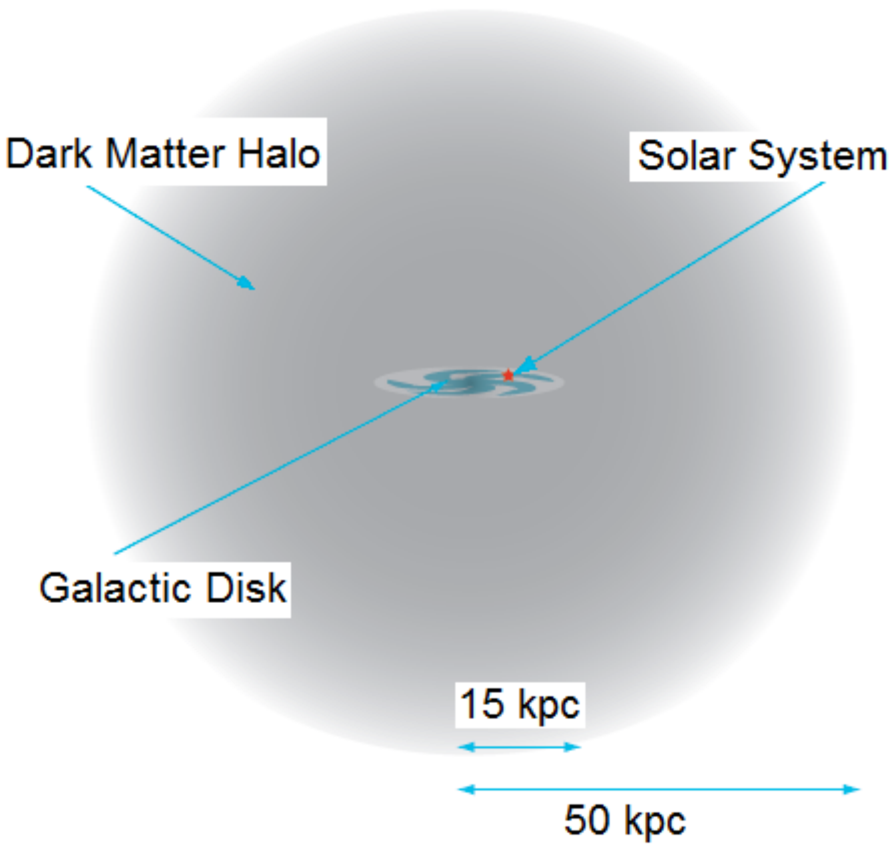
Slow moving dark-matter

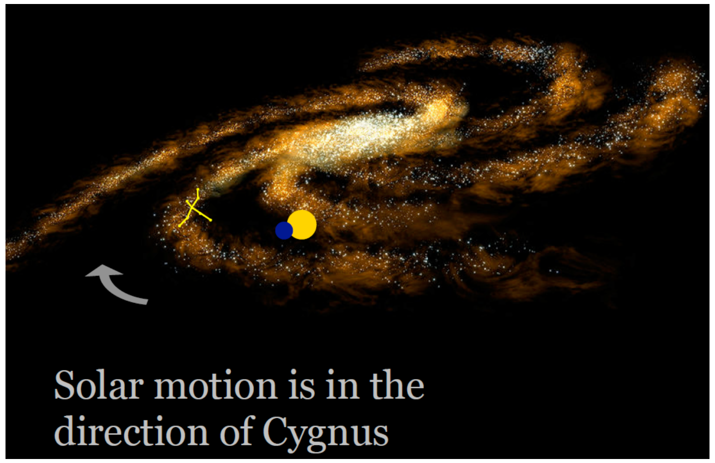
(computer simulations)

Fast moving dark-matter

Different initial dark-matter velocities lead to different amounts of substructure

How WIMPs are distributed?




Solar motion is in the direction of Cygnus

- WIMPs are distributed in isothermal spherical halos with Gaussian velocity distribution (Maxwellian)

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{|\vec{v}|^2}{2\sigma^2}}$$

- The speed dispersion is related to the local circular speed by

$$\sigma = \sqrt{\frac{3}{2}} v_c \quad where \quad v_c = 220\ km/s$$

- The density profile of the sphere is

$$\rho(r) \propto r^{-2} \quad and \quad \rho_0 = 0.3\ GeV/c^2$$

- Particles with speeds greater than v_{esc} are not gravitationally bound. Hence, the speed distribution needs to be truncated.

$$v_{esc} = 650\ km/s$$

Density of WIMPs

- The local dark matter density is

$$\rho_0 = 0.3\ GeV/cm^3$$

- Pick your favored mass for the dark matter particle

$$m = 5\ GeV/c^2$$

$$m = 60\ GeV/c^2$$

- What is the number density?

$$60{,}000\ particles/m^3 \longrightarrow for\ 5\ GeV/c^2$$

$$5{,}000\ particles/m^3 \longrightarrow for\ 60\ GeV/c^2$$

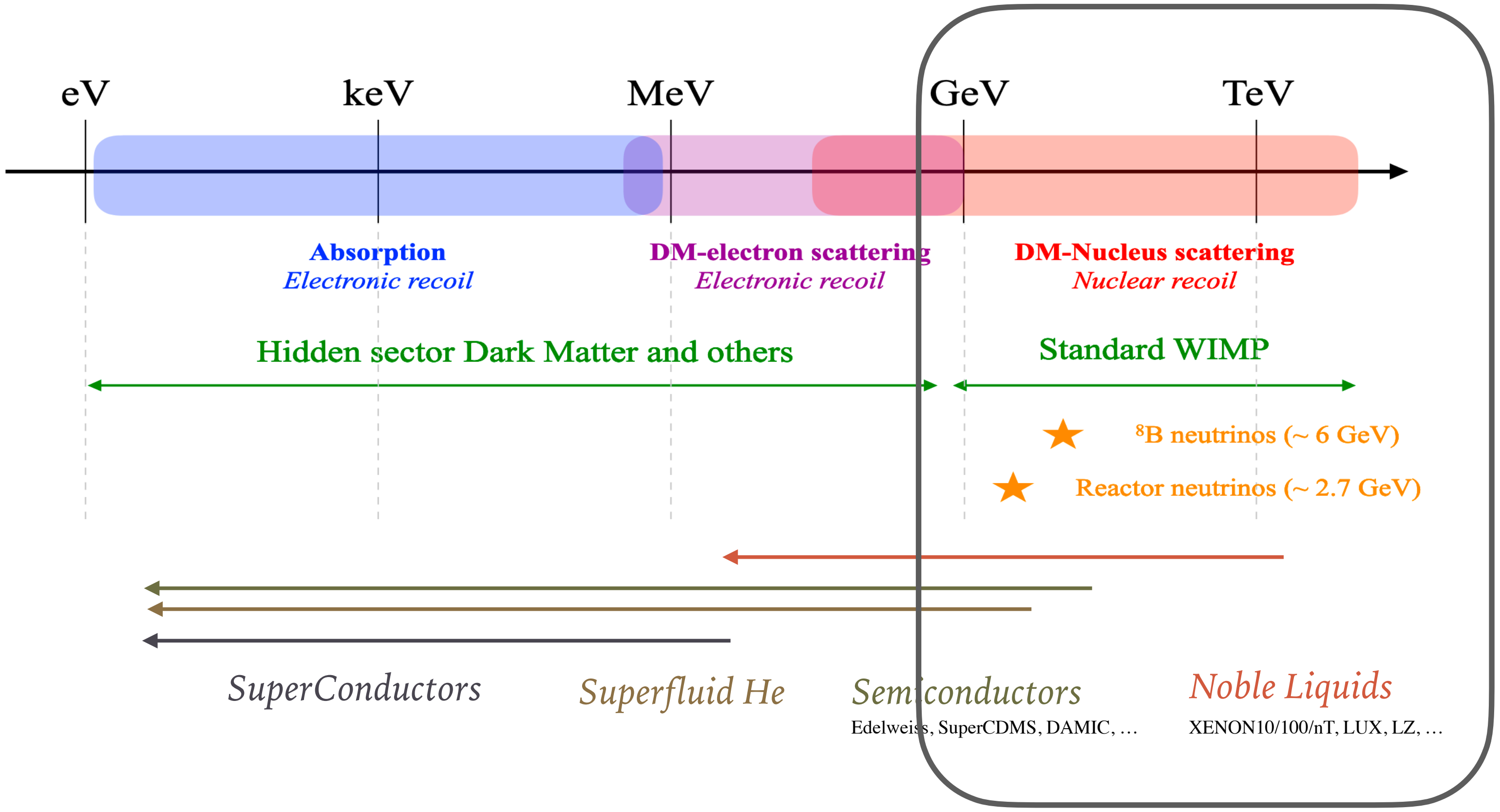
- How many dark matter particles in a 2 liter bottle?

$$recall\ that\ 1\ liter = 0.001\ m^3$$

$$120\ particles \longrightarrow for\ 5\ GeV/c^2$$

$$10\ particles \longrightarrow for\ 60\ GeV/c^2$$

Detection dark-matter via nuclear scattering



eV keV MeV GeV TeV

Absorption
Electronic recoil

DM-electron scattering
Electronic recoil

DM-Nucleus scattering
Nuclear recoil

Hidden sector Dark Matter and others

Standard WIMP

★ ^{8}B neutrinos (~ 6 GeV)

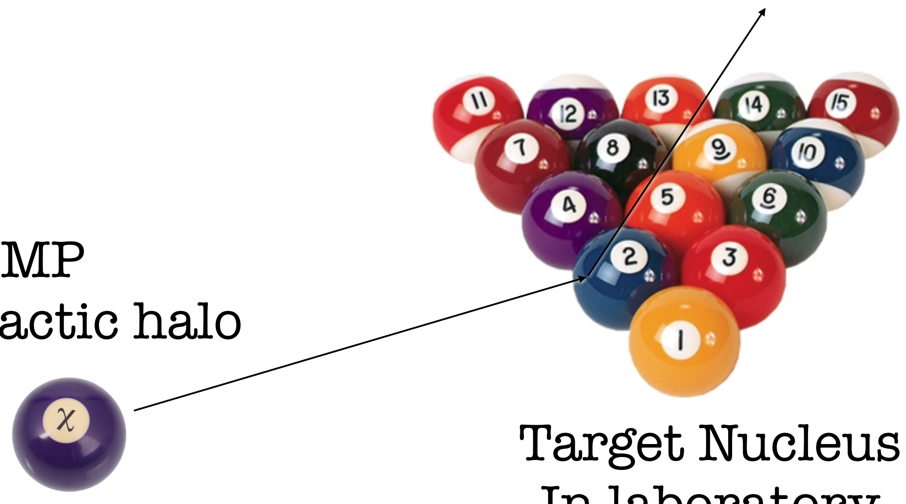
★ Reactor neutrinos (~ 2.7 GeV)

SuperConductors

Superfluid He

Semiconductors
Edelweiss, SuperCDMS, DAMIC, …

Noble Liquids
XENON10/100/nT, LUX, LZ, …



WIMP
from galactic halo

Target Nucleus
In laboratory

elastic collision

$v \sim 220$ km/s

$v \sim 0$ km/s

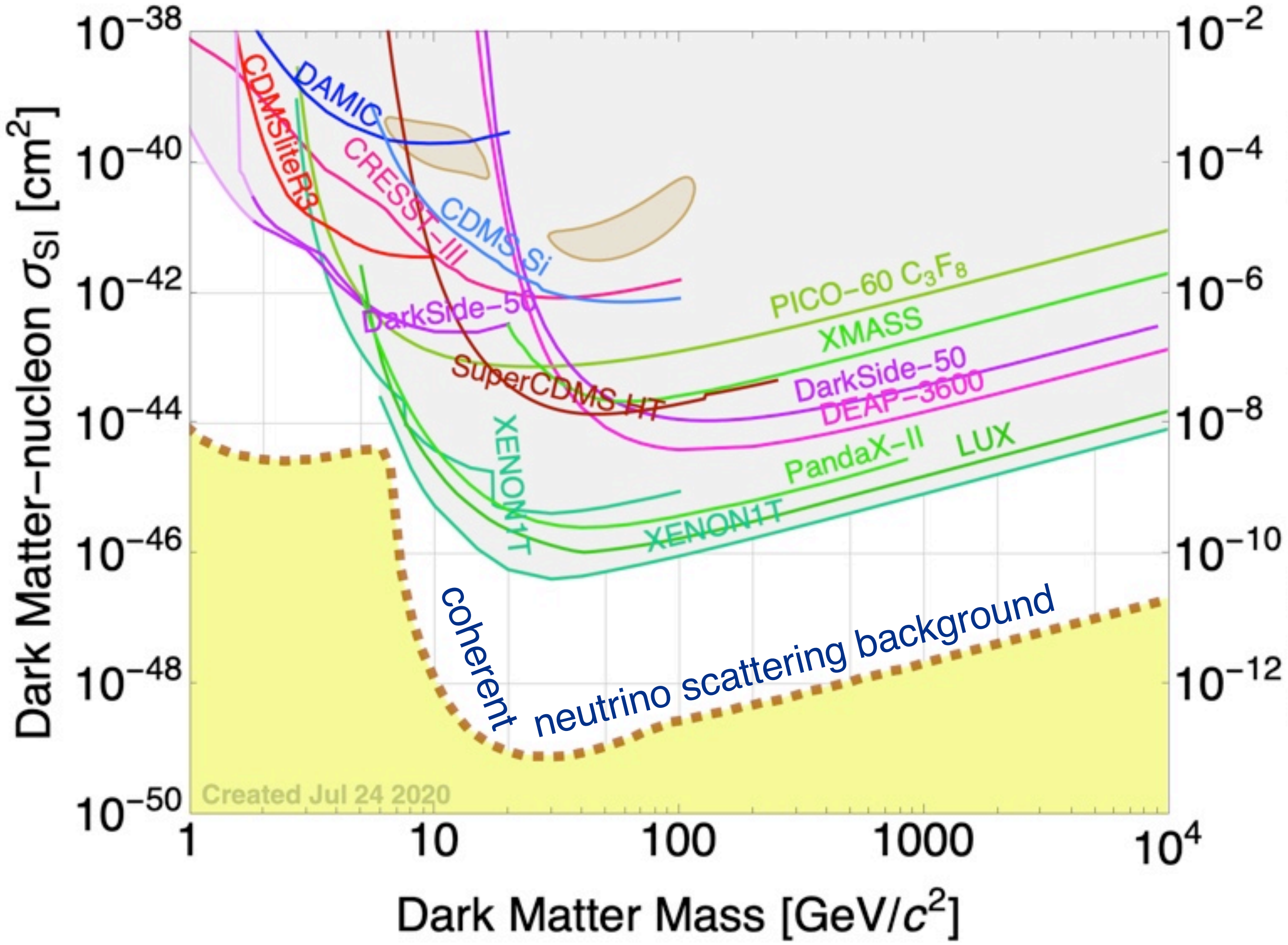
WIMP direct detection searches

- **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 for those that couple via Higgs; expected signal is elastic scatter from target nuclei and with tiny cross section

- Marching down to the neutrino floor



Direct dark-matter searches at colliders

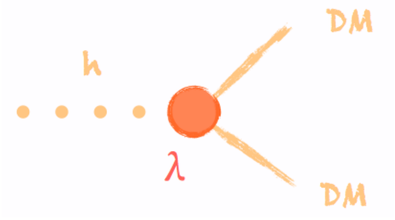
Dark-matter Higgs portal models

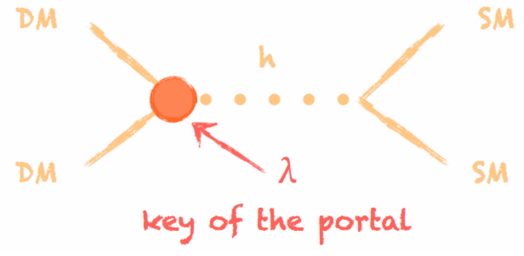
$$\Delta\mathcal{L}_S \supset -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$$

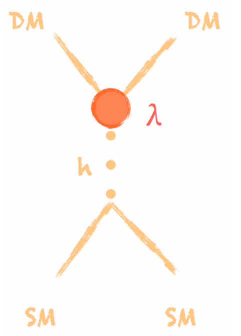
$\Gamma^{\rm inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h}$ (LHC)

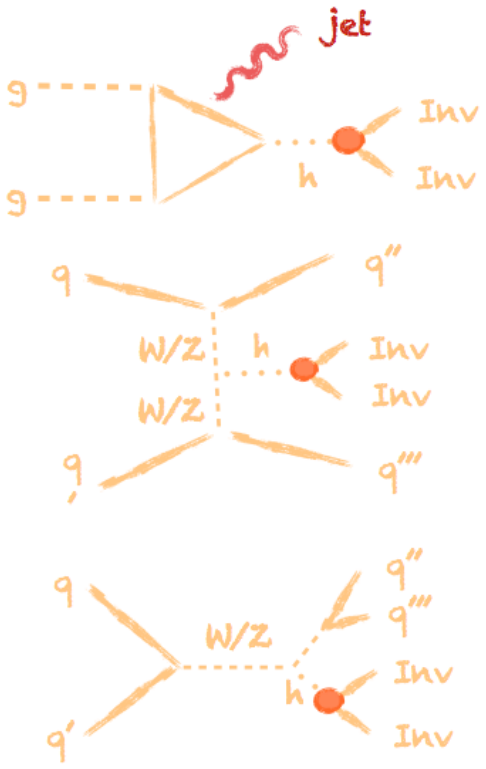
$\langle\sigma^S_{\rm ferm} v_r\rangle = \frac{\lambda^2_{hSS} m^2_{\rm ferm}}{16\pi}\frac{1}{(4M_S^2-m_h^2)^2}$ (PLANCK)

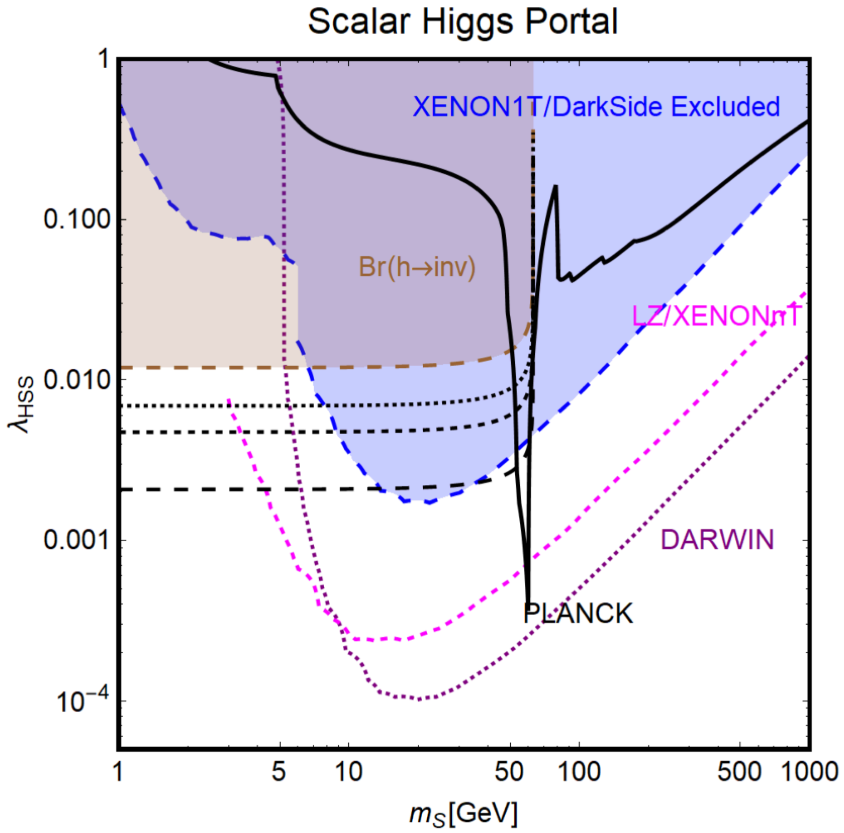
$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S+m_N)^2}$ (XENON)

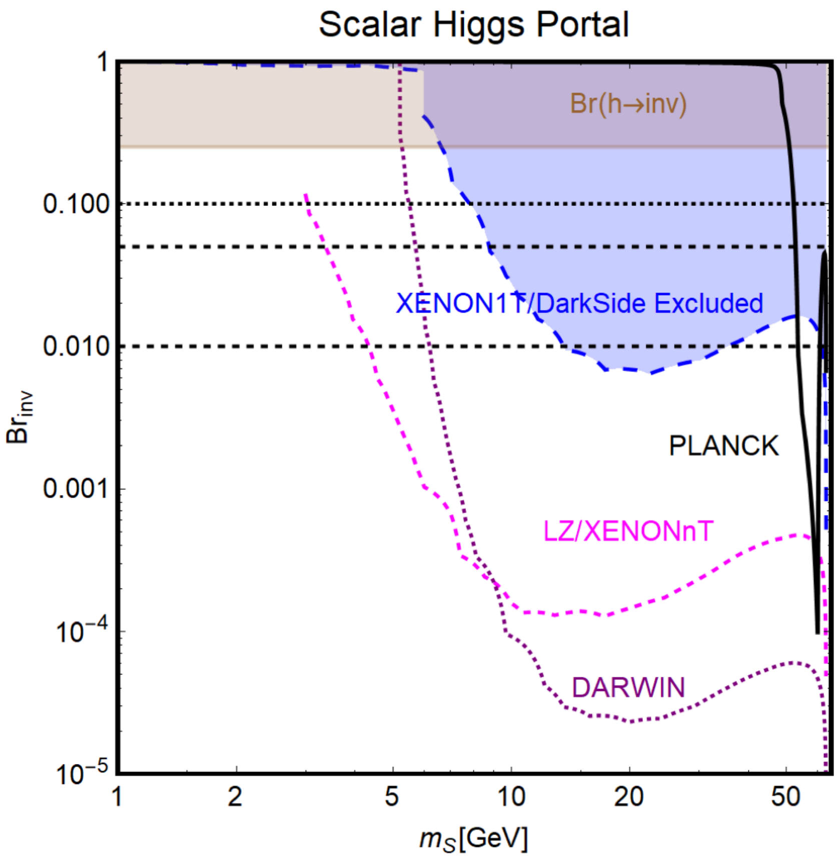












Key word: complementarity

Supersymmetric DM candidates

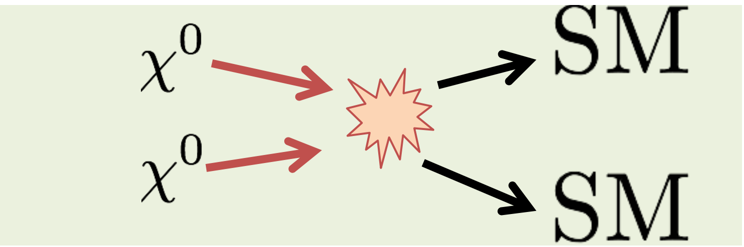
Thermal paradigm is very much still viable and there are many thermal freeze-out models

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

Standard candle, the supersymmetric WINO: $\mathcal{L} = \frac{1}{2} W^c \not{D} W - \frac{1}{2} M_W W^c W$

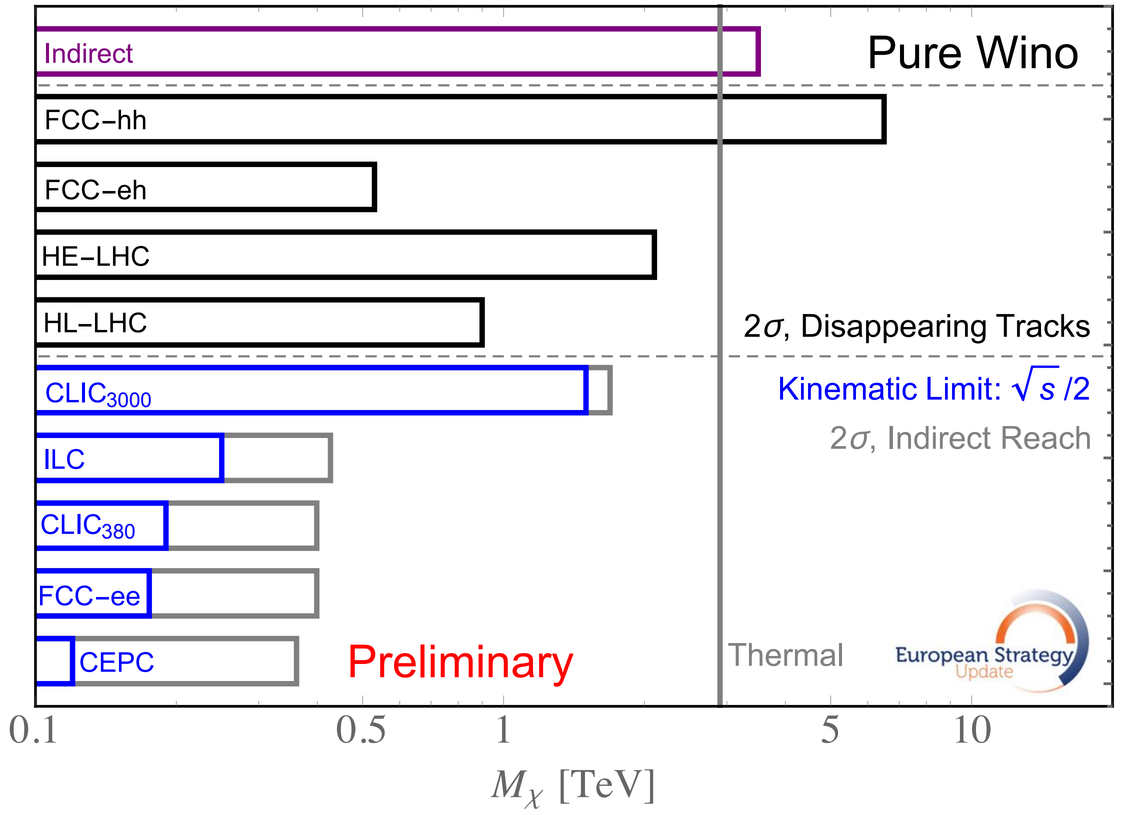
Thermal abundance

Annihilation in the early Universe determine, under some assumptions, the relic abundance:



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

Projected sensitivity of colliders:



Supersymmetric DM candidates

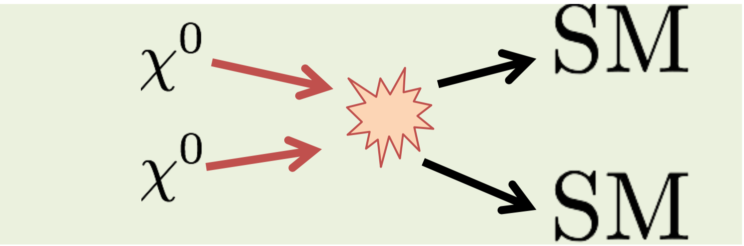
Thermal paradigm is very much still viable and there are many thermal freeze-out models

One class is electroweak-charged massive particles ($\in$ WIMPs)

Another standard candle, the supersymmetric HIGGSINO: $\mathcal{L} = \overline{H}\,\not{D}H - M_H \overline{H}\,H$

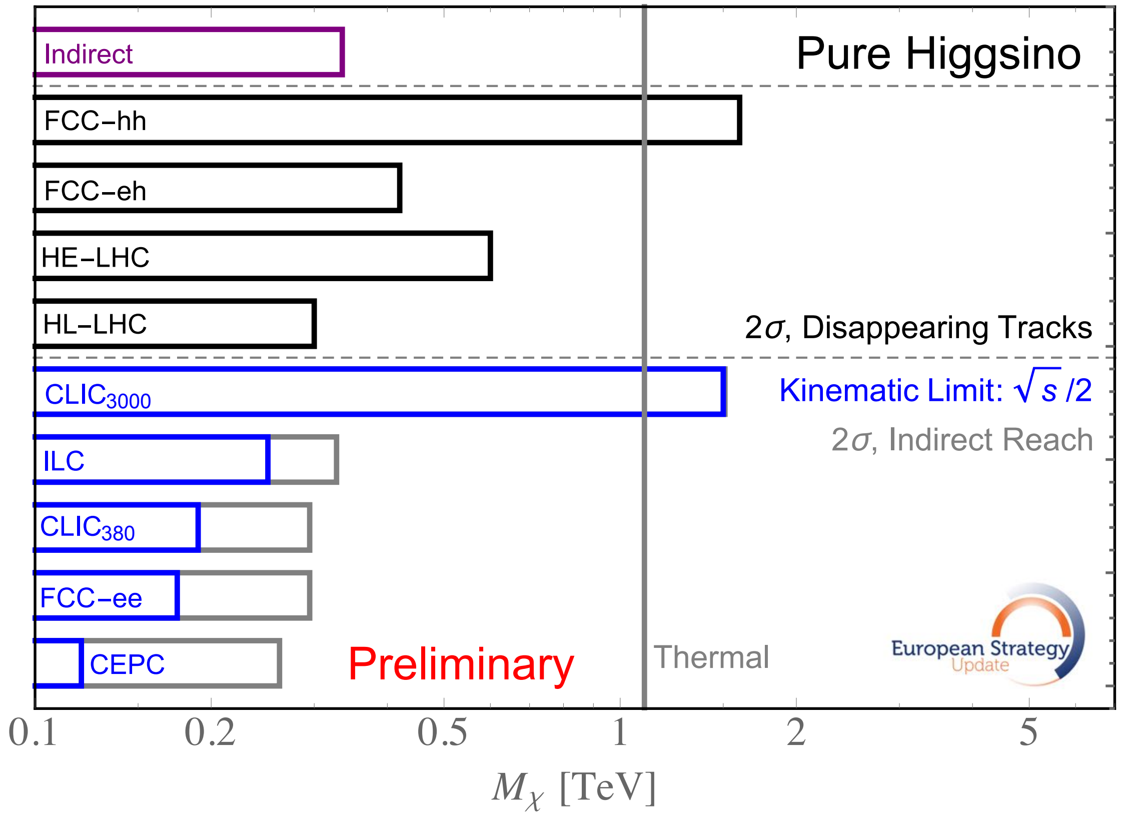
Thermal abundance

Annihilation in the early Universe determine, under some assumptions, the relic abundance:



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

Projected sensitivity of colliders:



Ultimate collider kinematic reach

First things first,

You will never discover a dark matter particle directly if its mass is greater than:

- CEPC: 125 GeV
- FCC-ee: 185 GeV
- ILC: 250 GeV
- CLIC: 1.5 GeV

For lepton colliders: for reasonable couplings one often saturate the kinematic reach of half the collider energy

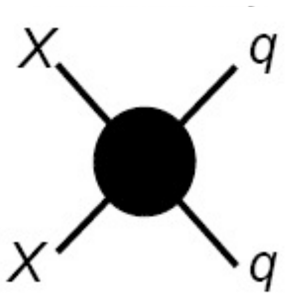
- HL-LHC: 7 TeV
- HE-LHC: 13.5 TeV
- FCC-hh: 50 TeV

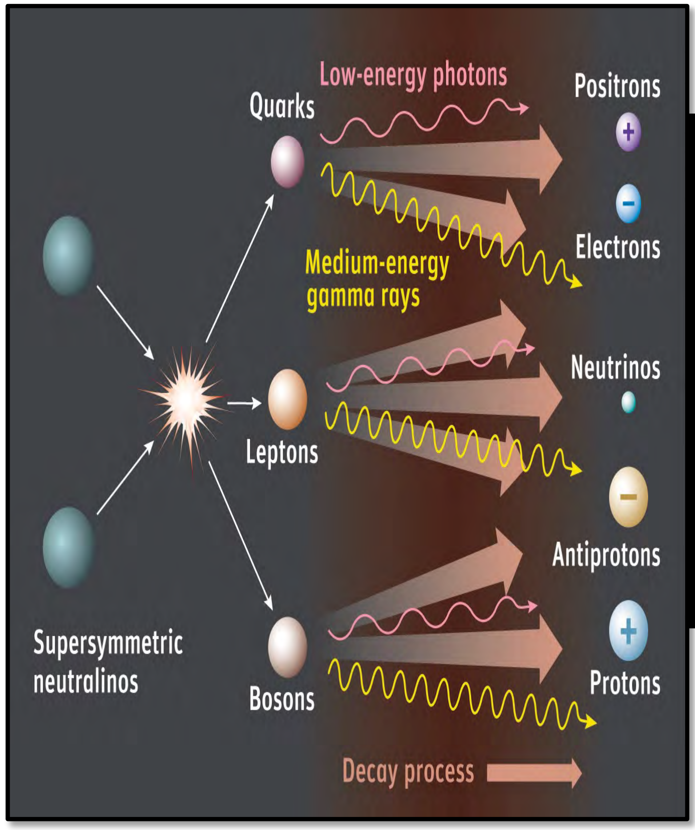
For hadron colliders: one will never reach this kinematic limit, however one can get close for large couplings

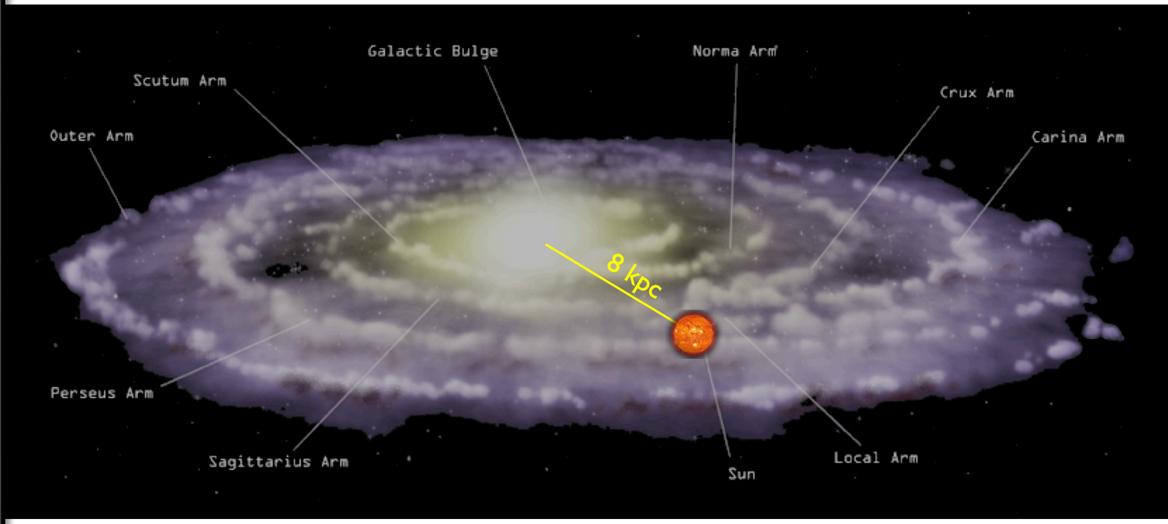
Of course details always matter but these are hard kinematic limits

Indirect detection

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







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

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

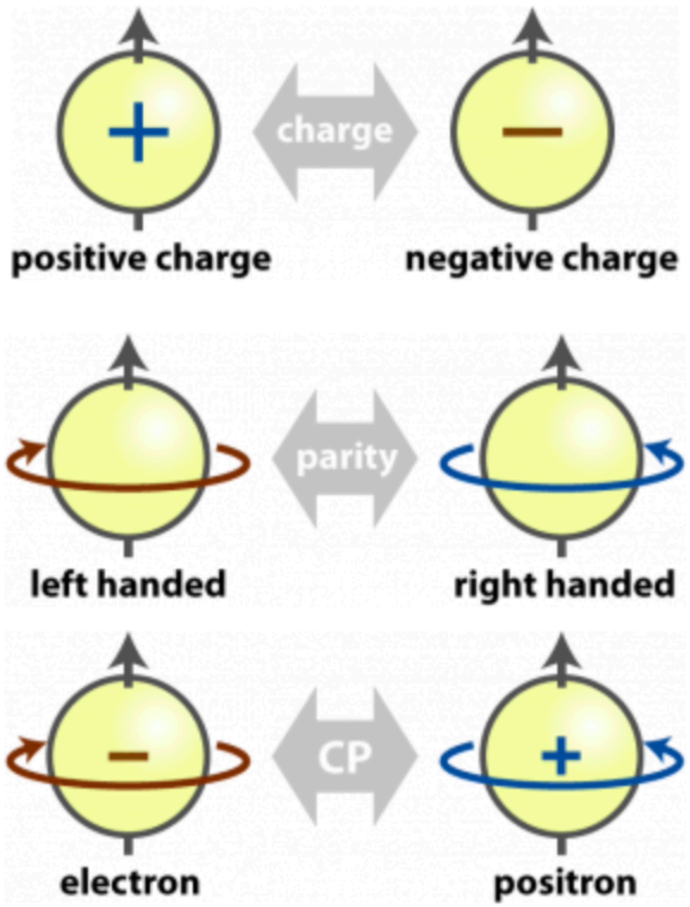
    Diffuse gamma rays, e.g galactic center GeV excess

    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

Axion dark matter

The CP symmetry & matter-antimatter asymmetry



Strong force coupling

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

EM counterparts of gluon field

The value $\bar{\theta}$ controls the matter-antimatter asymmetry in QCD

Why matter and not anti-matter in our universe?

A similar θ term arises from electroweak sector:

$$\theta = \bar{\theta} + \theta_{weak} \sim \mathcal{O}(1)$$

No observation of C and CP violation in Nature, $|\theta| \lesssim 10^{-10}$

(No neutron EDM so far...)

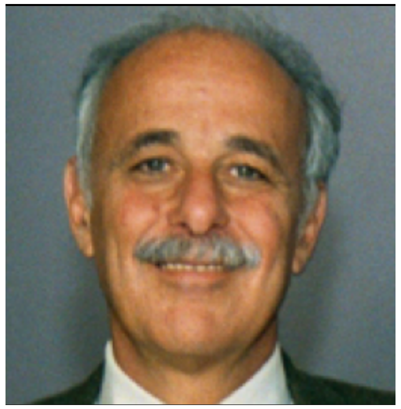
The strong CP problem
=Why is θ so small?

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

The QCD

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

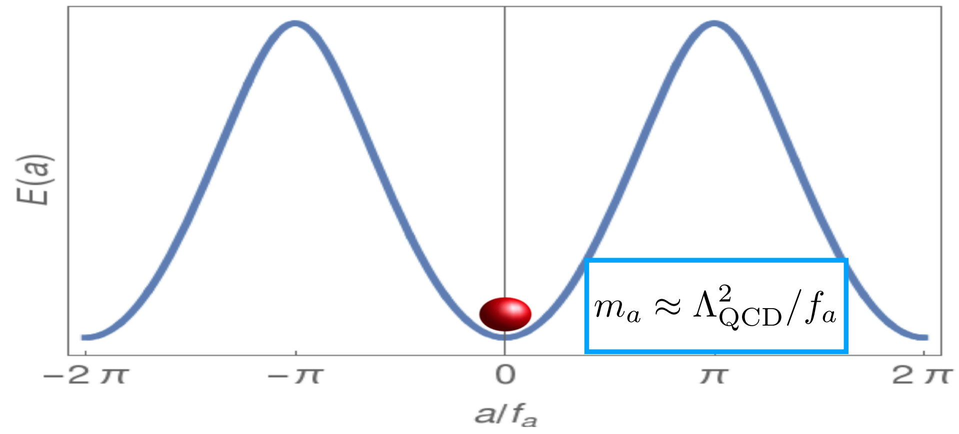
1977



Roberto Peccei

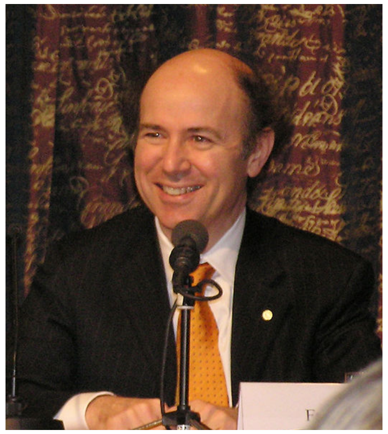
Helen Quinn

Promote $\theta \to \theta(x)$ 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**

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

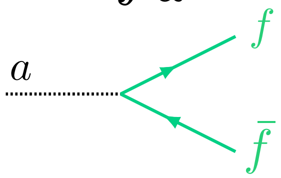
Axion energy scale

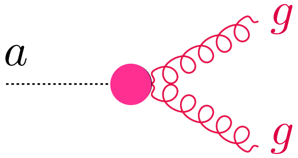
Axion couplings

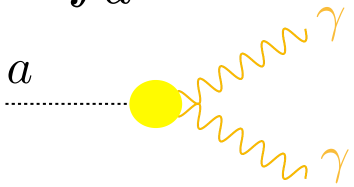
Energy

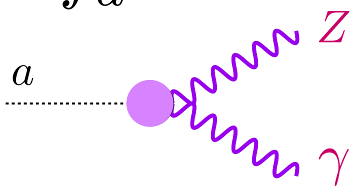
At energies below f_a (SSB):

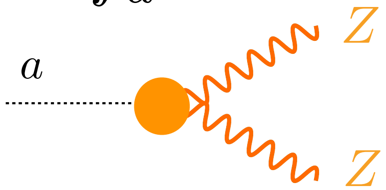
$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2f_a} j_a^\mu + \#\frac{a}{f_a} G\tilde{G} + \#\frac{a}{f_a} F\tilde{F} + \#\frac{a}{f_a} Z\tilde{F} + \#\frac{a}{f_a} Z\tilde{Z} + \#\frac{a}{f_a} W\tilde{W}$$

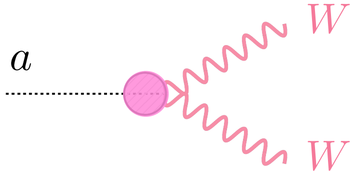












electroweak couplings recently computed
do not follow the expected pattern
(J.Q. and C. Smith, arXiv:1903.12559)

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

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

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

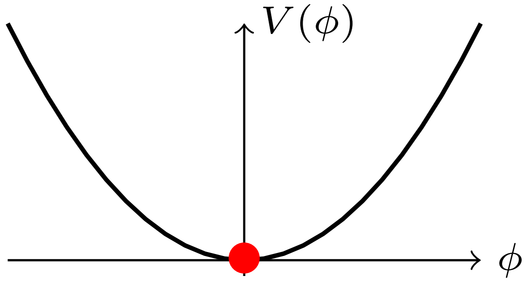
$$\delta\phi \sim T$$

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

$T > f_a$

T determines the PQ vev:

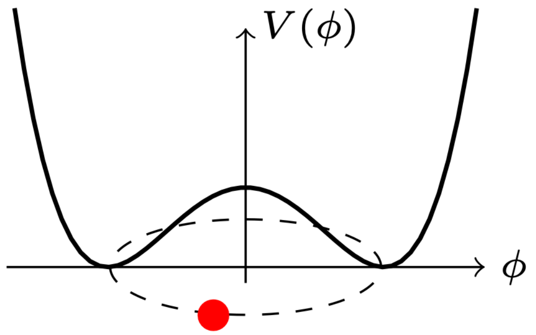
$$<\phi>= 0$$



$T \sim f_a$

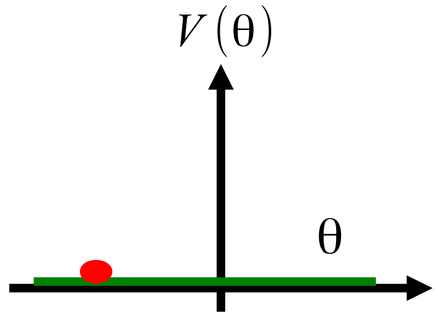
PQ symmetry is spontaneously broken:

$$<\phi>= f_a e^{i\frac{a(x)}{f_a}}$$



The axion is born:

Relic of symmetry breaking



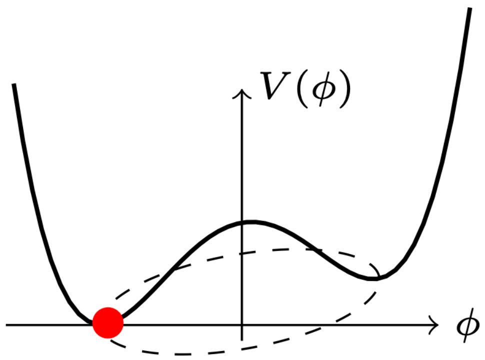
$$\theta = \frac{a}{f_a} \in [-\pi,\pi]$$

$T \sim \Lambda_{QCD}$

PQ symmetry is explicitly broken

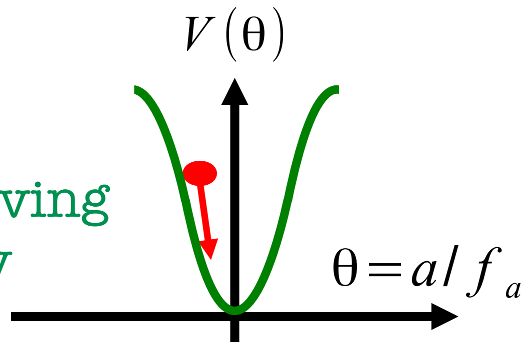
$$m_a^2(T)\begin{cases}\propto T^{-n} & T \gtrsim 100\ \text{MeV}\\ = m_a(T=0) & T \lesssim 100\ \text{MeV}\end{cases}$$

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

Temperature

Equation of motion:
(Klein-Gordon)

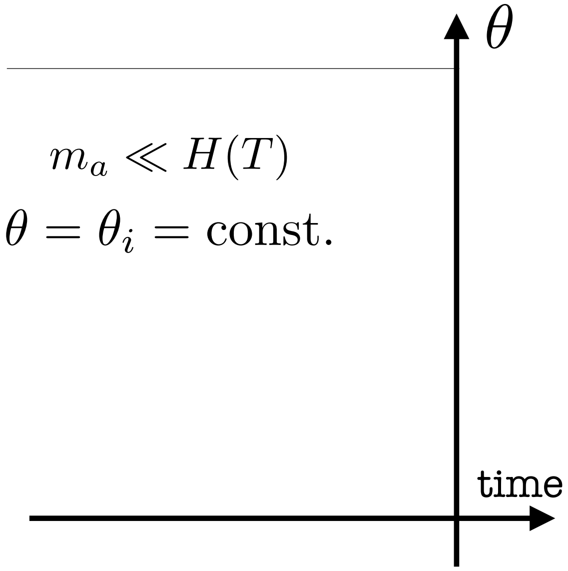
$$\ddot{\phi} + 3\boxed{H}\dot{\phi} + \boxed{m_a(T)}^2\phi = 0$$

$$H \gg m_a$$

Axion is 'frozen' by
Hubble friction

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

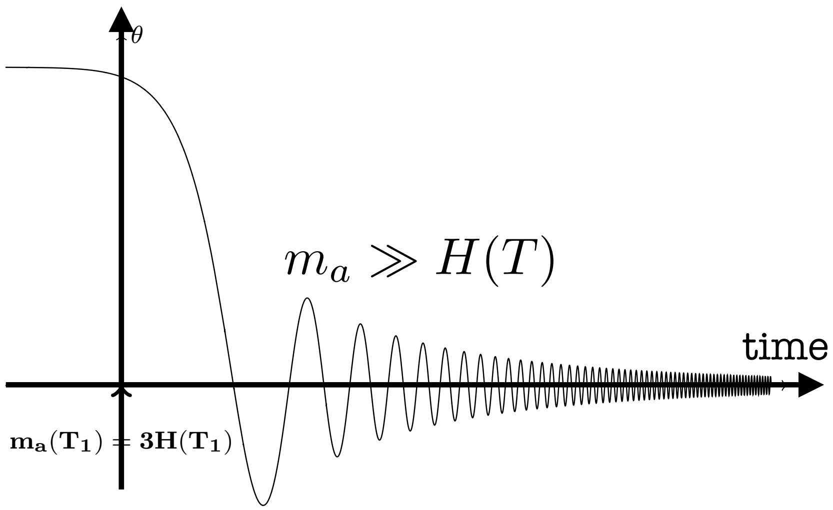
$$w_a \sim -1$$



$$H \ll m_a$$

Coherent oscillations of axion field

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



Scalar oscillations behave as matter

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

← 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?

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

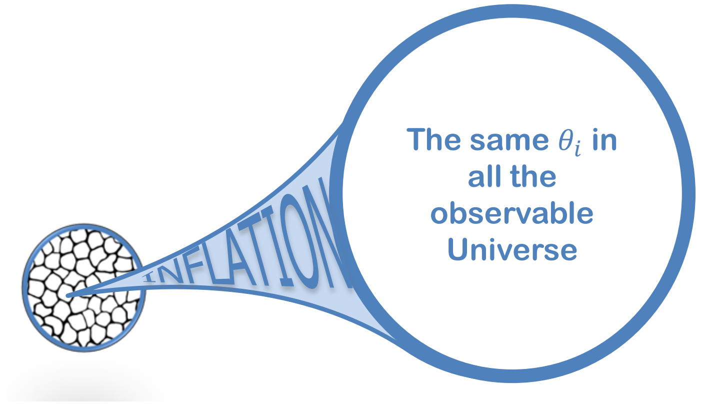
2 scenarios

Pre-inflation scenario

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

PQ symmetry is broken during inflation and not restored afterwards

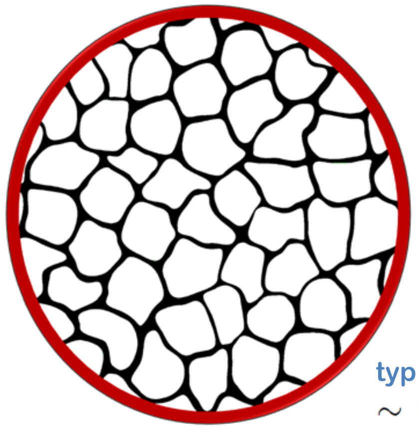
Inflation « selects » one θ_{ini} that is now constant across the observable Universe



Post-inflation scenario

May occur for low f_a

PQ symmetry is broken after inflation



typical size of single patch nowadays: $\sim 0.001(m_A/10\ \mu\mathrm{eV})^{1/2}\ \mathrm{pc}$

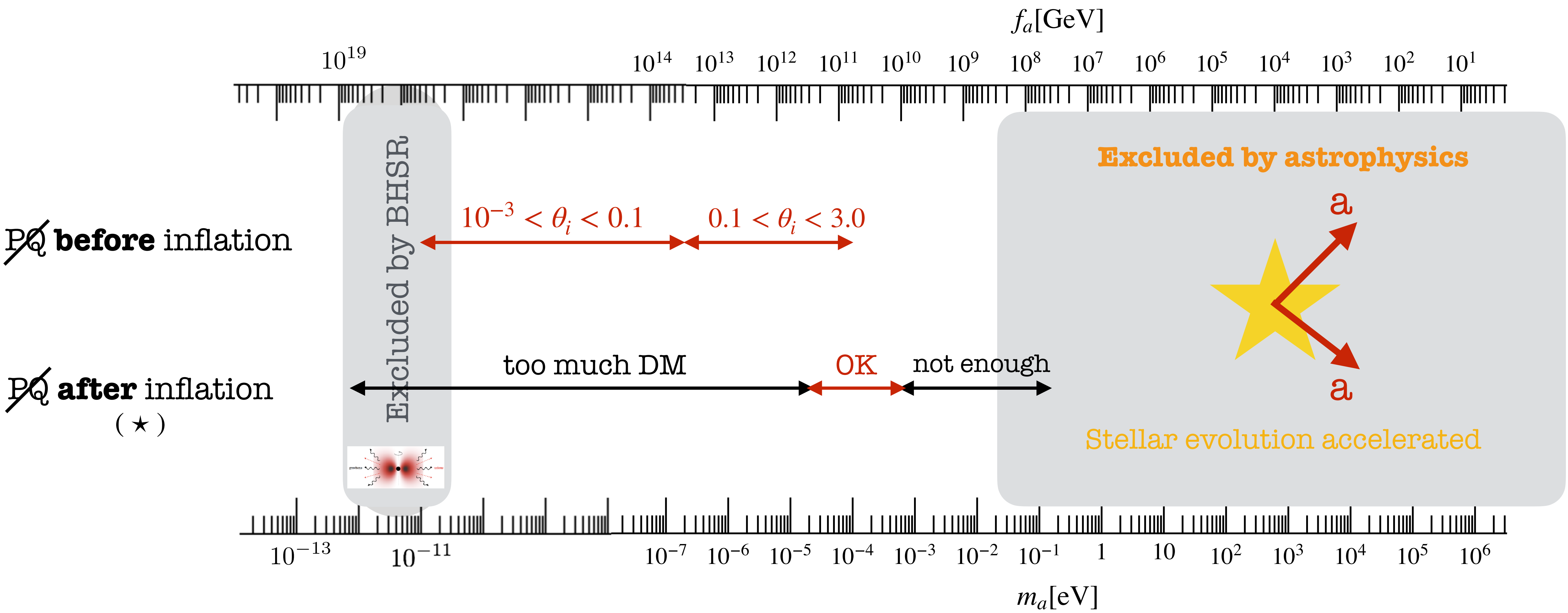
- Many different $-\pi \le \theta_{ini} \le \pi$ in the visible « patches » of the universe,
  average field value fixed: $\langle \theta_{\mathrm{ini}}^2 \rangle = \frac{1}{2\pi}\int_{-\pi}^{\pi} \theta^2 d\theta = \frac{\pi^2}{3}$

$\longrightarrow$ Ω_a independent of initial conditions

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

Landscape

Axions should be very light and feebly interacting



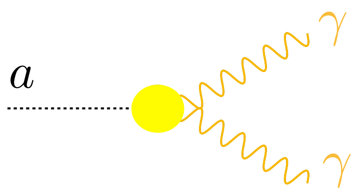
(⋆) for $N_{DW} > 1$, predictions spoiled by topological defects

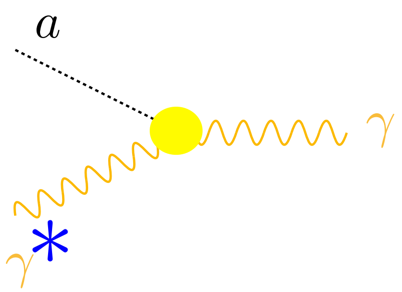
Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

Axion conversion to photon

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

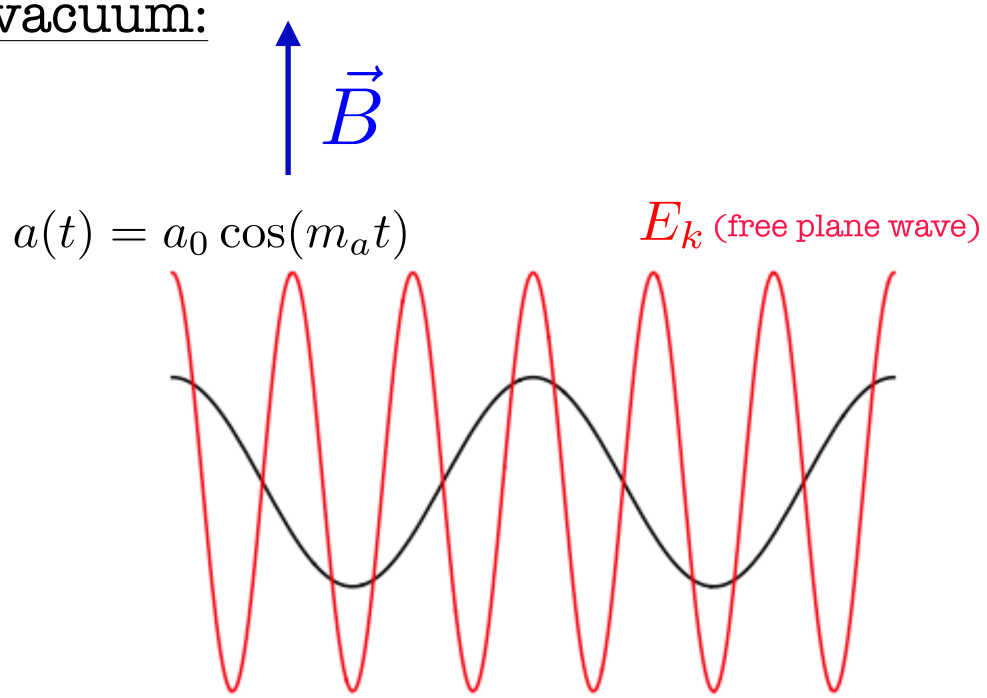
in an external B-field
the axion sources an E-field





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

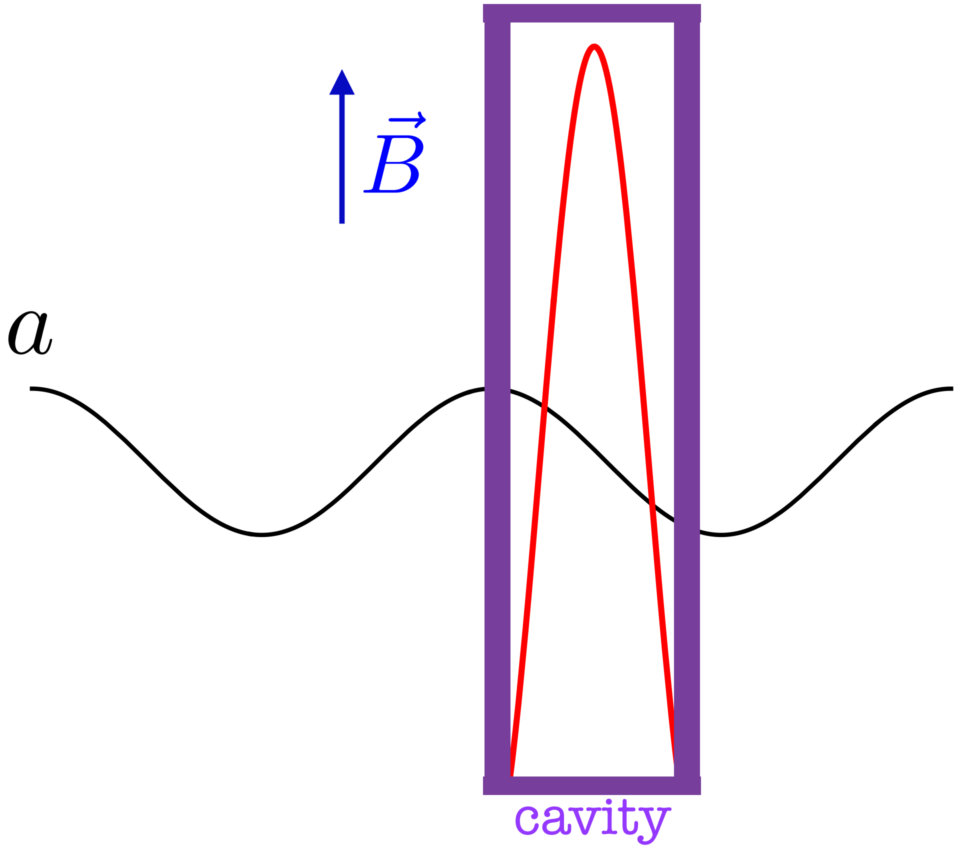
In vacuum:



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

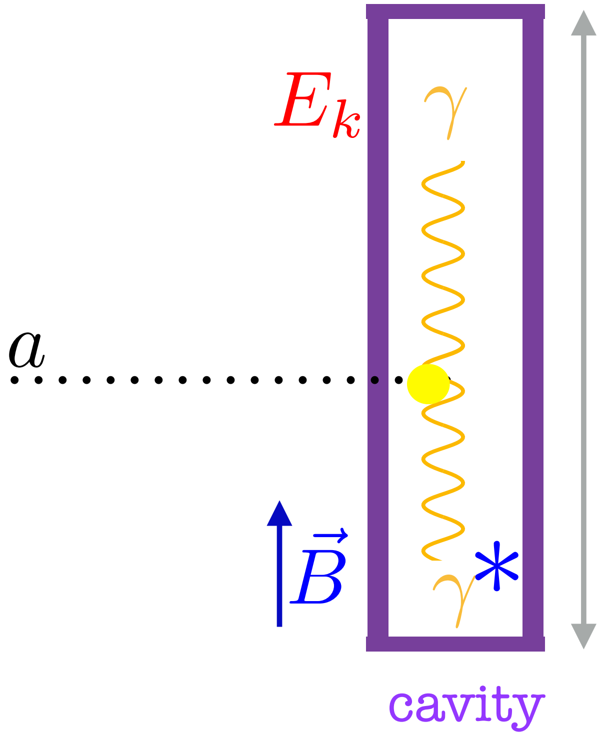


⟶ axion-photon conversion is allowed

Axion haloscope

Amplify resonantly the EM field in a resonant cavity

(forced oscillator)



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

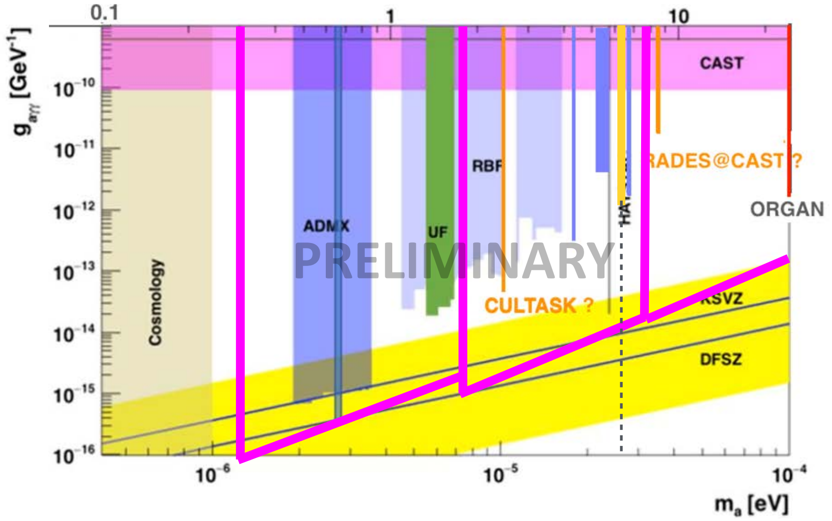
Power extracted from a cavity: $P_{signal} \propto g_{a\gamma}^2 B^2 QV$ to amplify

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

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**

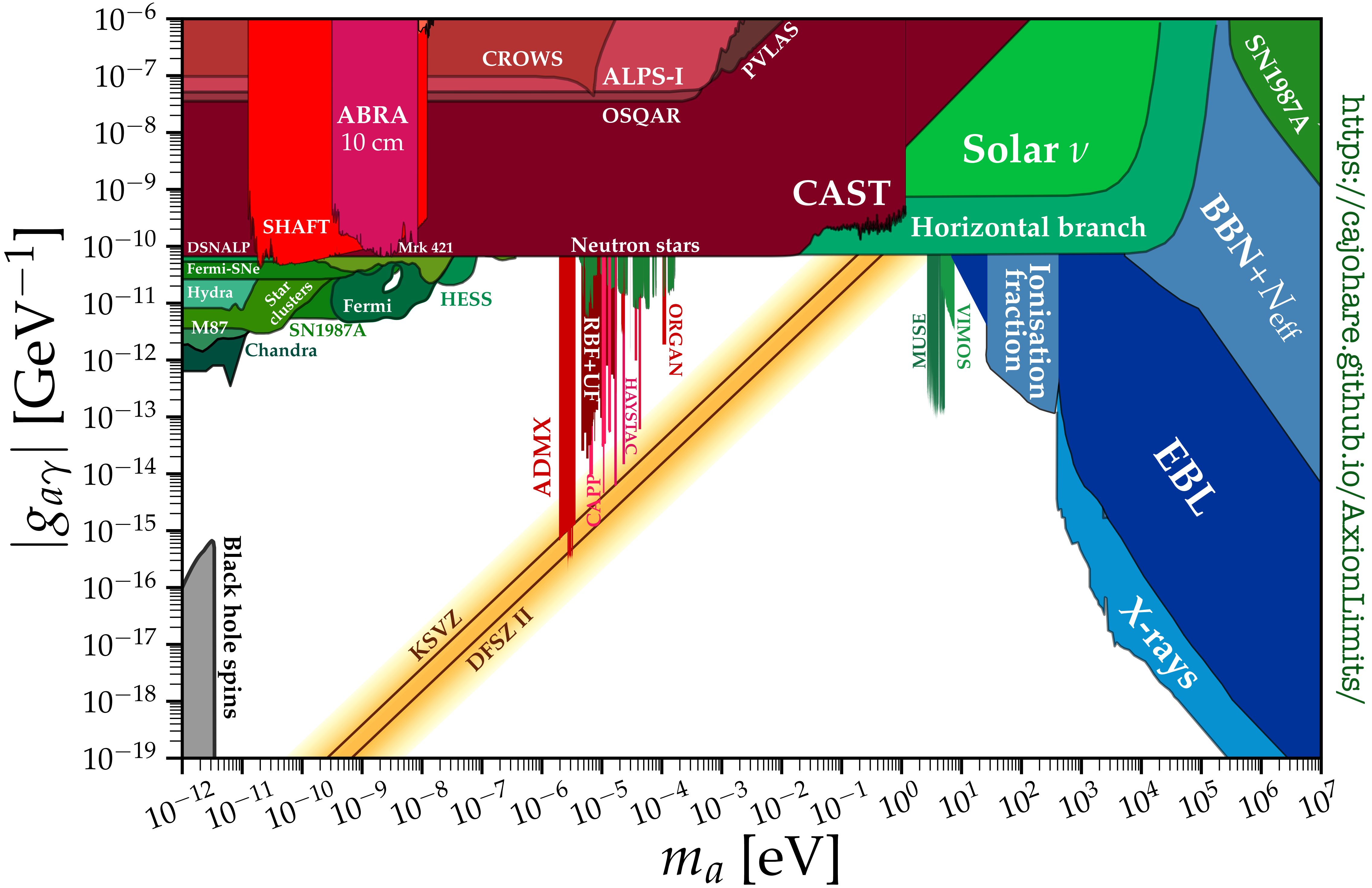
$$g_{a\gamma\gamma}^{\text{1st point}} = 25 \times g_{a\gamma\gamma}^{\text{KSVZ}}$$
$$m_a = 23\mu\text{eV}$$



- New interesting idea : **'plasmon haloscope'** :

-resonance when the **axion** and **plasma** frequencies match
-thin wire metamaterials (~cm spacing ⇒ ~ GHz plasma frequency)
-tuneable with wire spacing ⇒ haloscopes not anymore V limited?

Axion limits



From theoretical topological defects to cosmological astrophysical objects

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

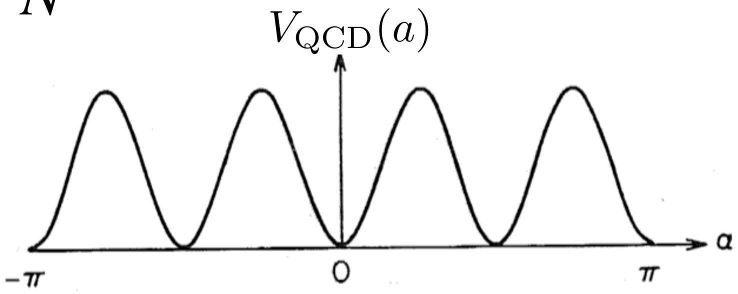
$$\phi \to e^{i\alpha}\phi \qquad \theta_{QCD} \to \theta_{QCD} + \boxed{N}\alpha$$

model dependent

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

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

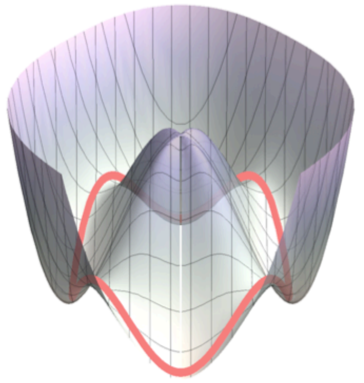
Ex: $N = 4$ axion model (4 degenerate minima)



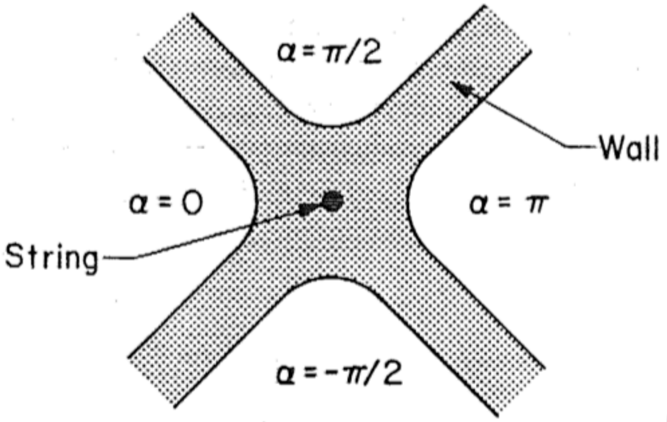
In QFT:

$T << T_{\rm QCD}$

$V(\Phi)$

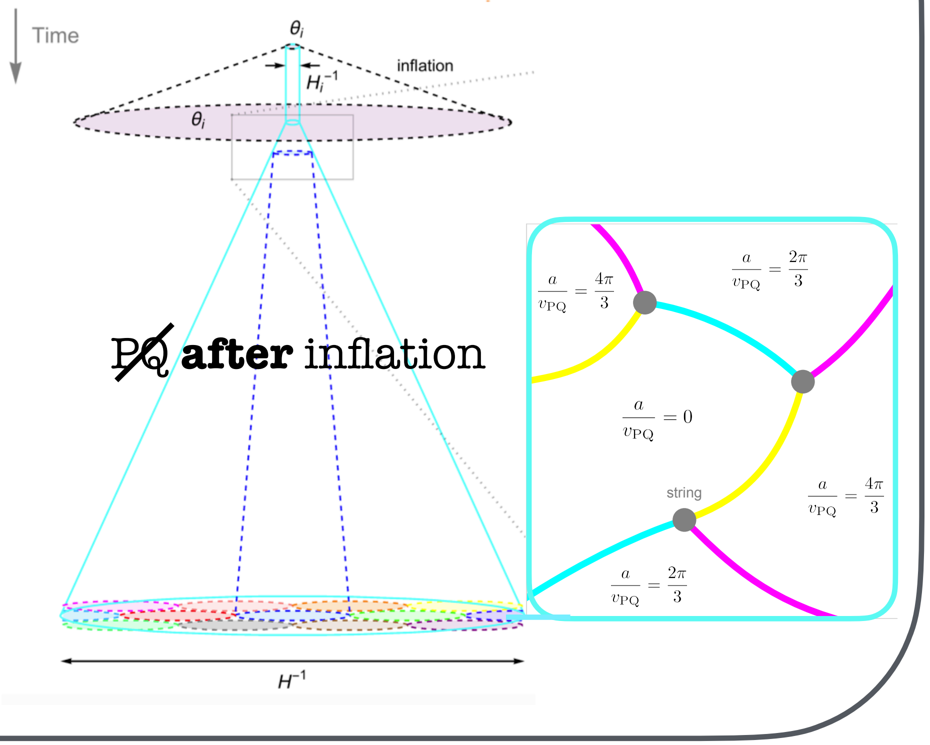


In position space:



$N = 4$ domain walls meet in a string

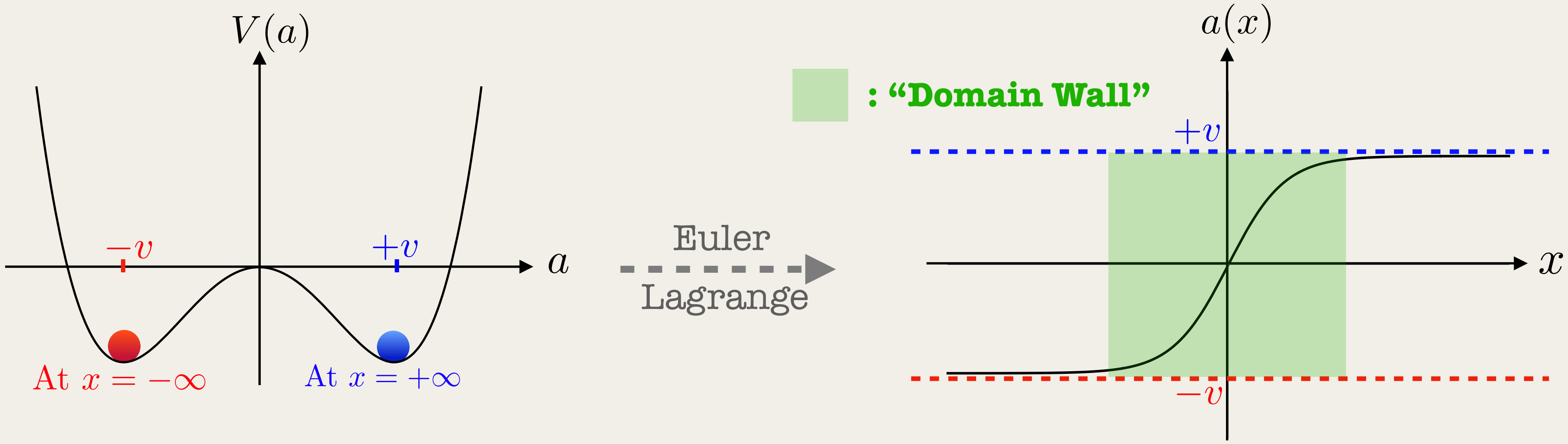
In the early universe:



~~PQ~~ **after** inflation

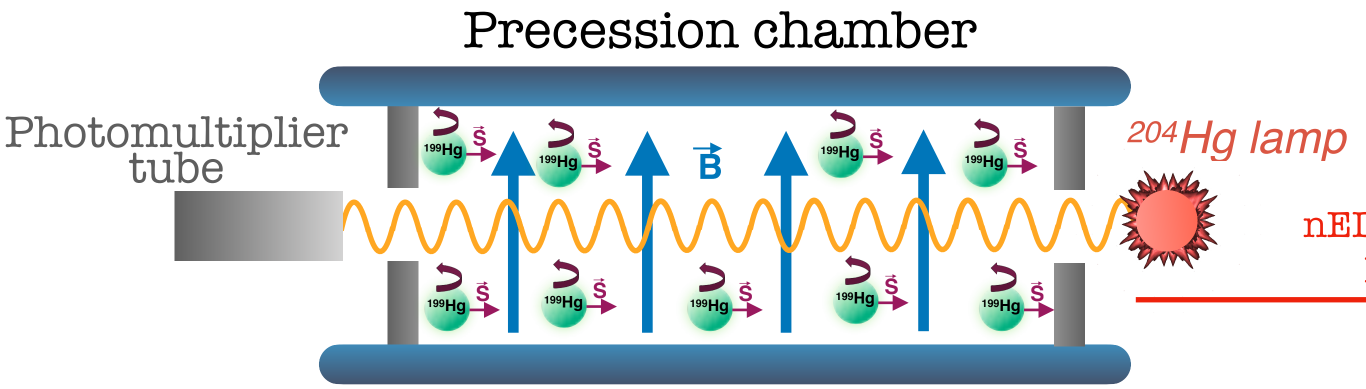
Detecting axion transient with nEDM

Example : $V(a) = -\mu^2 a^2 + \lambda a^4$

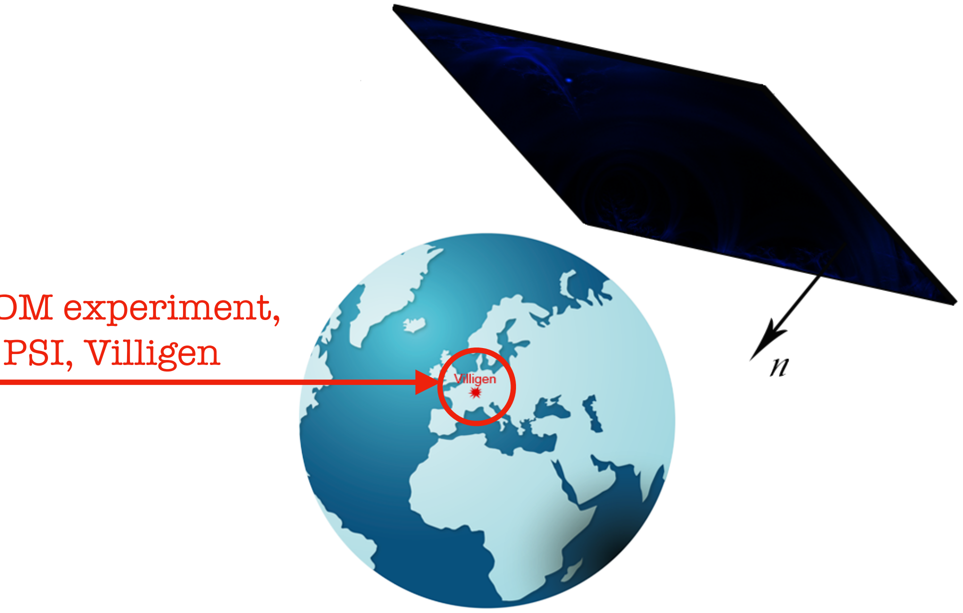


$$\mathcal{L}_{\rm int} = \bar{\psi}\gamma^\mu\gamma^5\psi \times \frac{\partial_\mu a}{f_a} \xrightarrow[\text{limit}]{\text{Non relativistic}} H_{\rm int} = \sum_{i=e,n,p} 2\vec{s}_i . \left(f_i^{-1}\vec{\nabla}a\right)$$

Pseudo-magnetic field

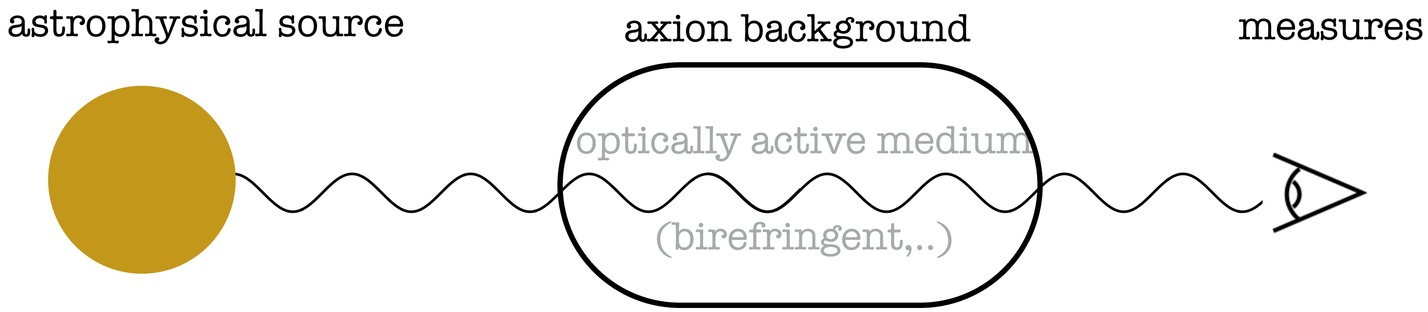


nEDM experiment's mercury co-magnetometry



work in progress at the LPSC

How do photons propagate through axion background?



axion electrodynamics:

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

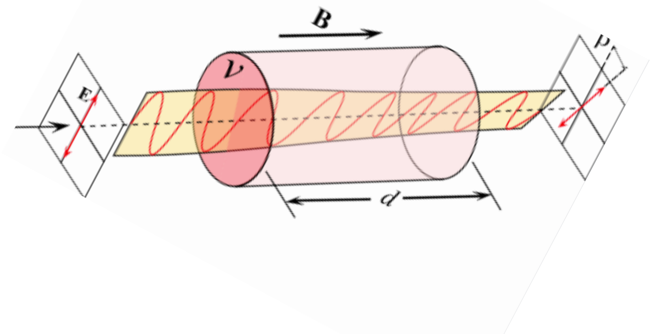
dispersion relation:

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

Apply carefully Hamilton's optic

$$v_{phase}^{\pm} = \frac{\omega^\pm}{k}$$

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

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

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:

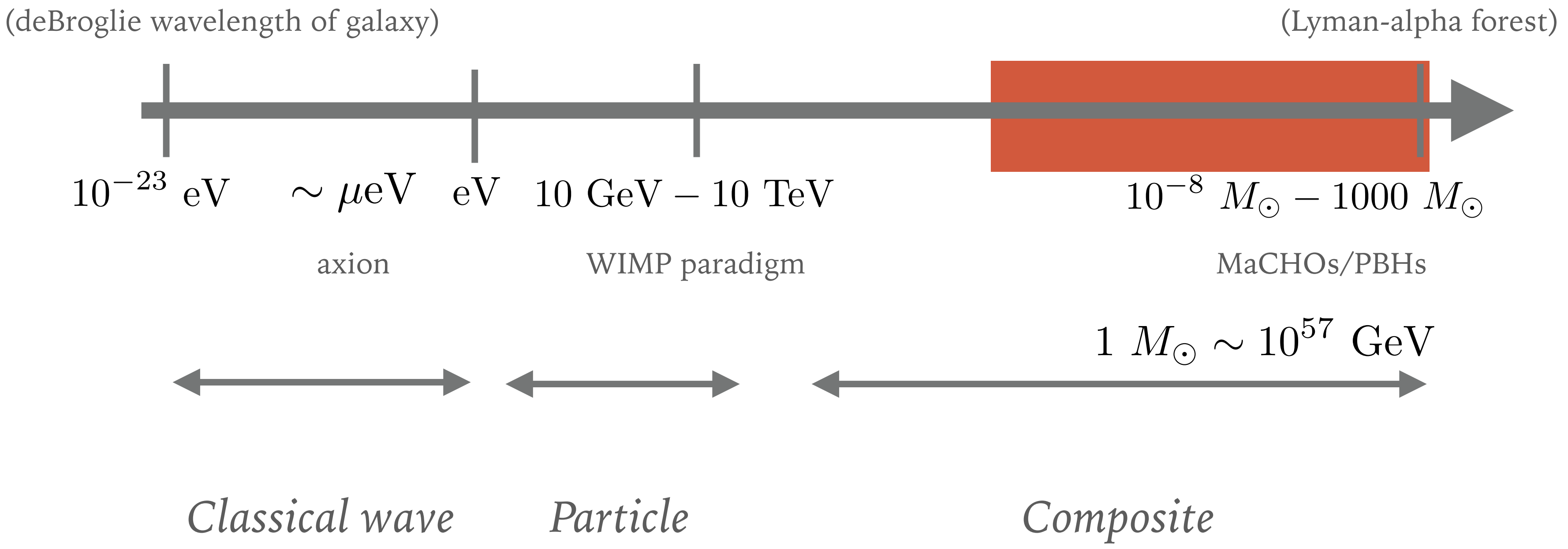
$$\frac{\Delta\omega}{\omega} \sim 10^{-16} \left(\frac{g_{a\gamma\gamma}}{10^{-10} \mathrm{GeV}^{-1}} \right) \left(\frac{1\,\mathrm{GHz}}{\omega} \right) \sqrt{\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm}^3}}$$

-optical effects should be examined further in specific axion backgrounds

-investigate precision terrestrial optical experiments to probe axion backgrounds

Super heavy DM candidate

Super heavy dark matter candidate



(deBroglie wavelength of galaxy)

(Lyman-alpha forest)

10^{-23} eV

$\sim \mu$eV

eV

10 GeV – 10 TeV

$10^{-8}\ M_\odot - 1000\ M_\odot$

axion

WIMP paradigm

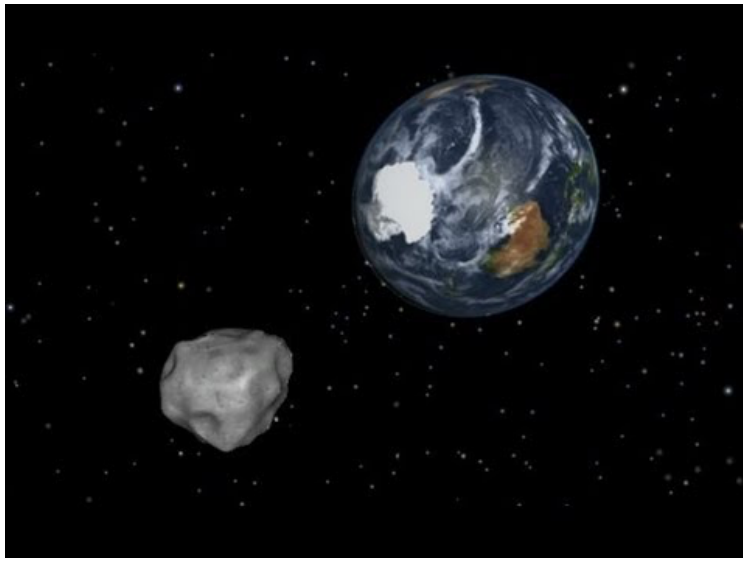
MaCHOs/PBHs

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

Classical wave

Particle

Composite



- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging
- At heavier masses, detection through Standard Model interactions is (generally) not motivated by abundance
- Look for gravitational means to detect structure
- Above $10^{-13}\ M_\odot$ e.g. pulsar timing may be effective
- Project of the (far) future to use laboratory clocks to detect small gravitational redshift effects

Axion miniclusters

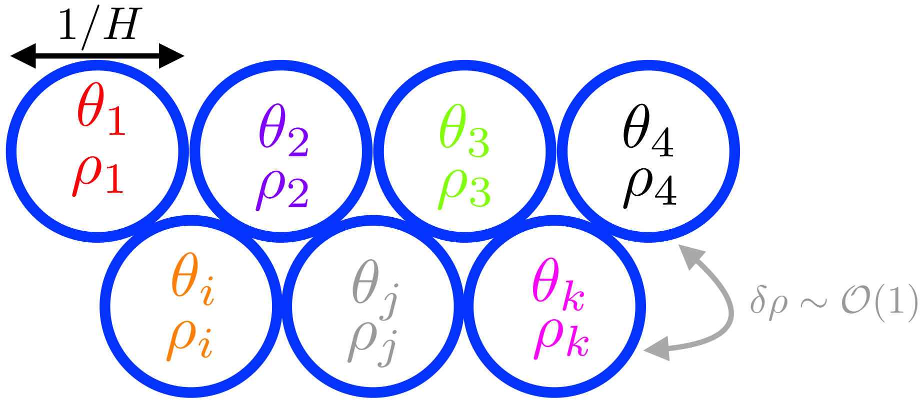
Temperature

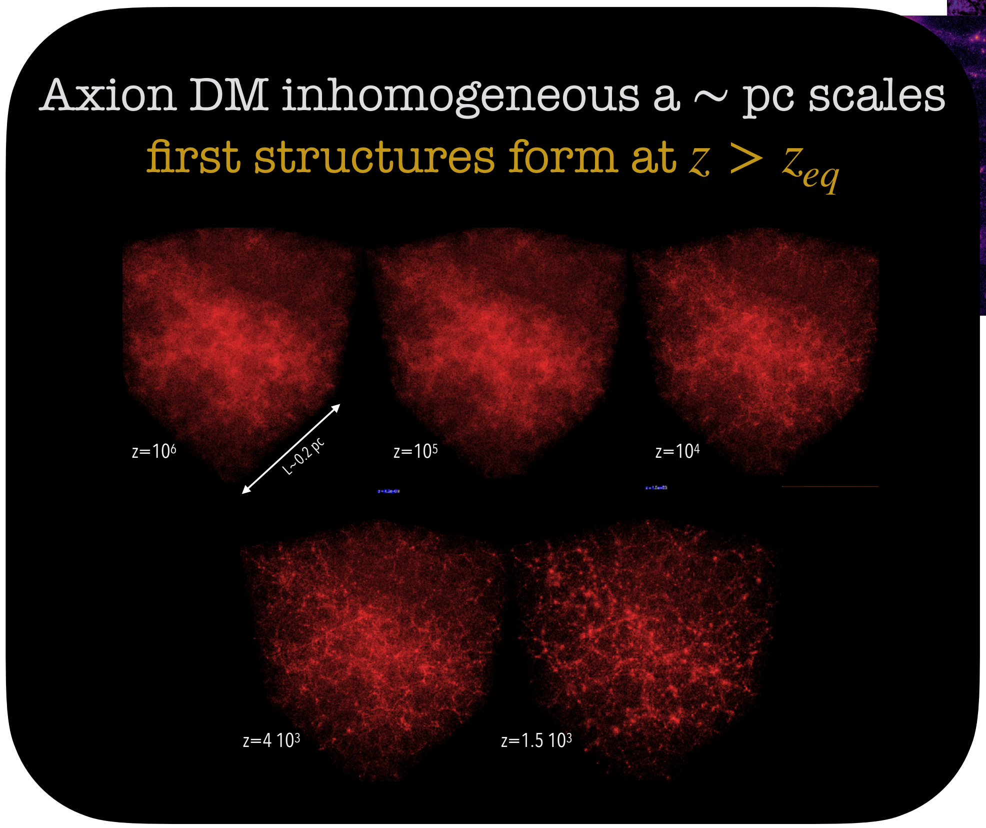
...Inflation occurred already

$T \sim f_a$ SSB of PQ

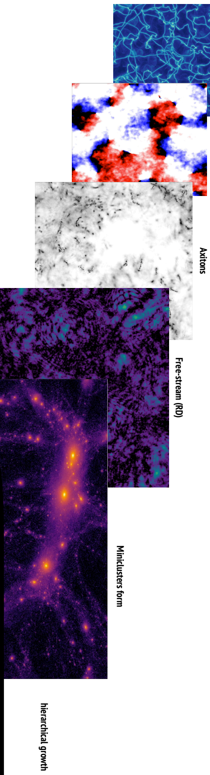
$T \sim \Lambda_{QCD}$ $m_a \neq 0$

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




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 $z_{\rm eq}$:

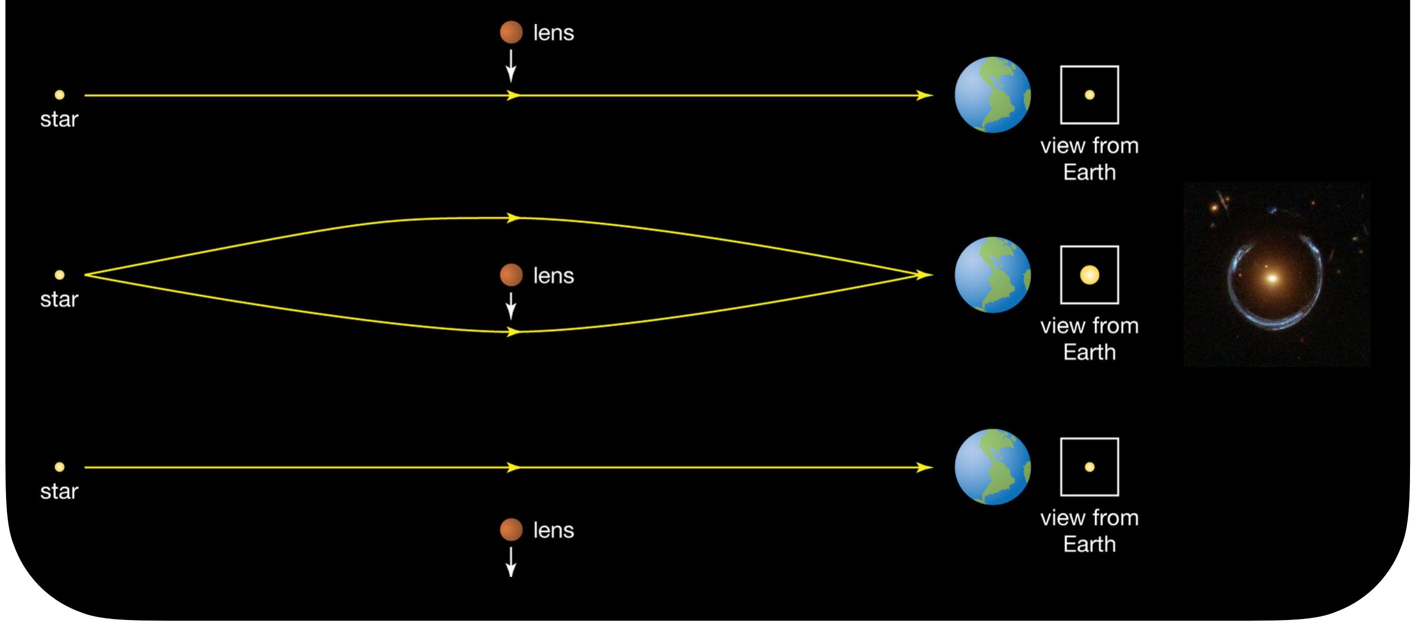
Hogan & Reese (1988)

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

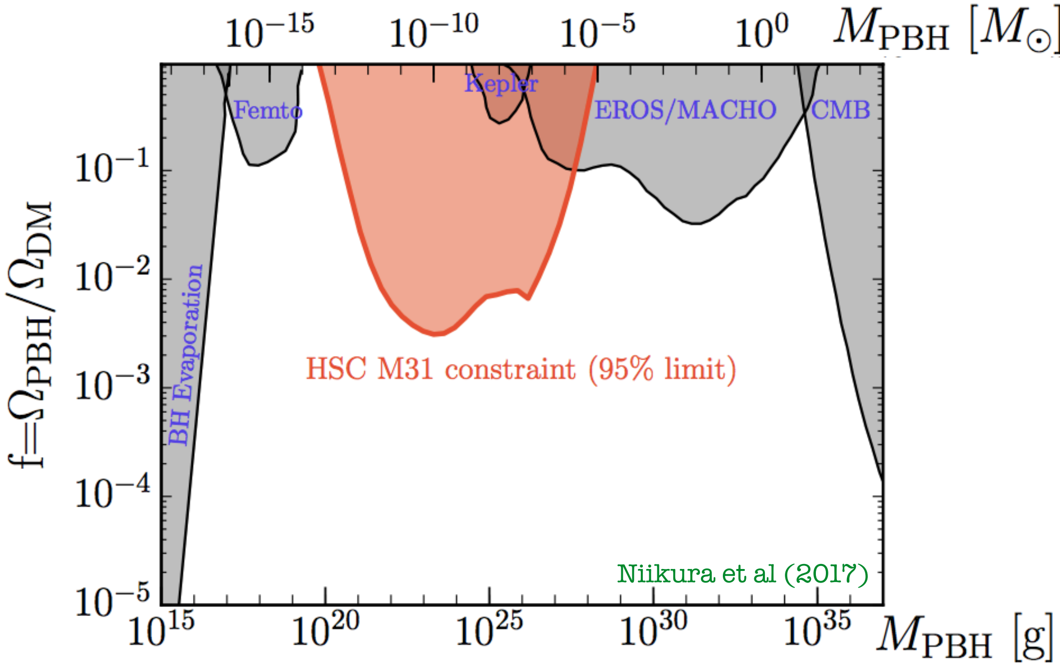
Smaller than smallest WIMP structures ($\sim 10^{-6} M_\odot$)

Detecting axion miniclusters with gravitational microlensing

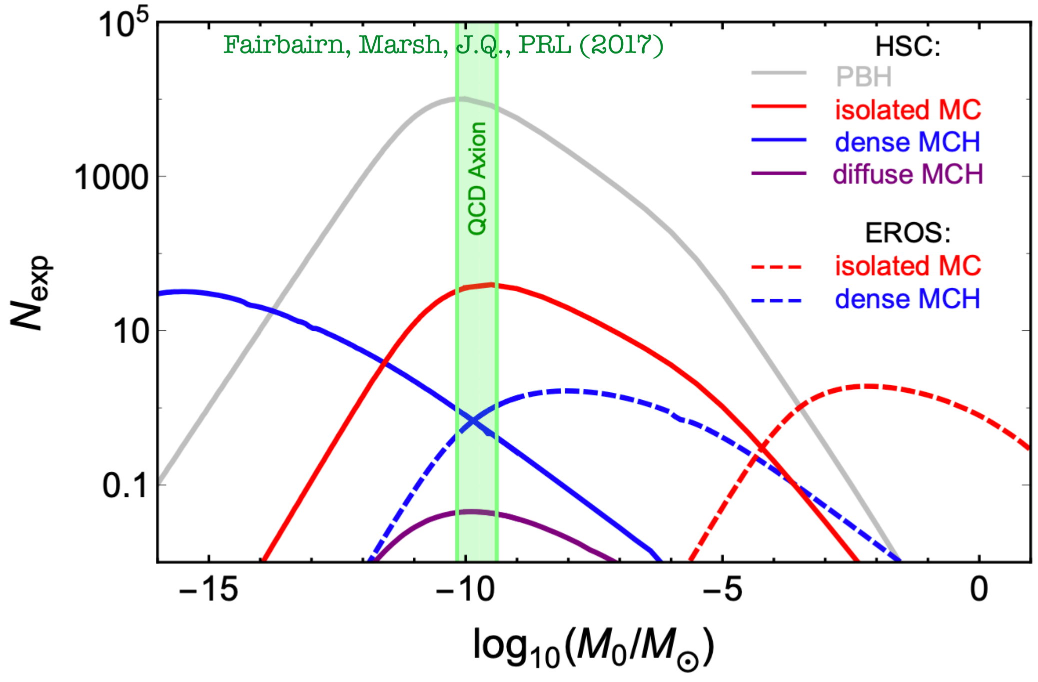
Microlensing: fugitive amplification of a background star which occurs when a compact object passes close to the line of sight to that star.

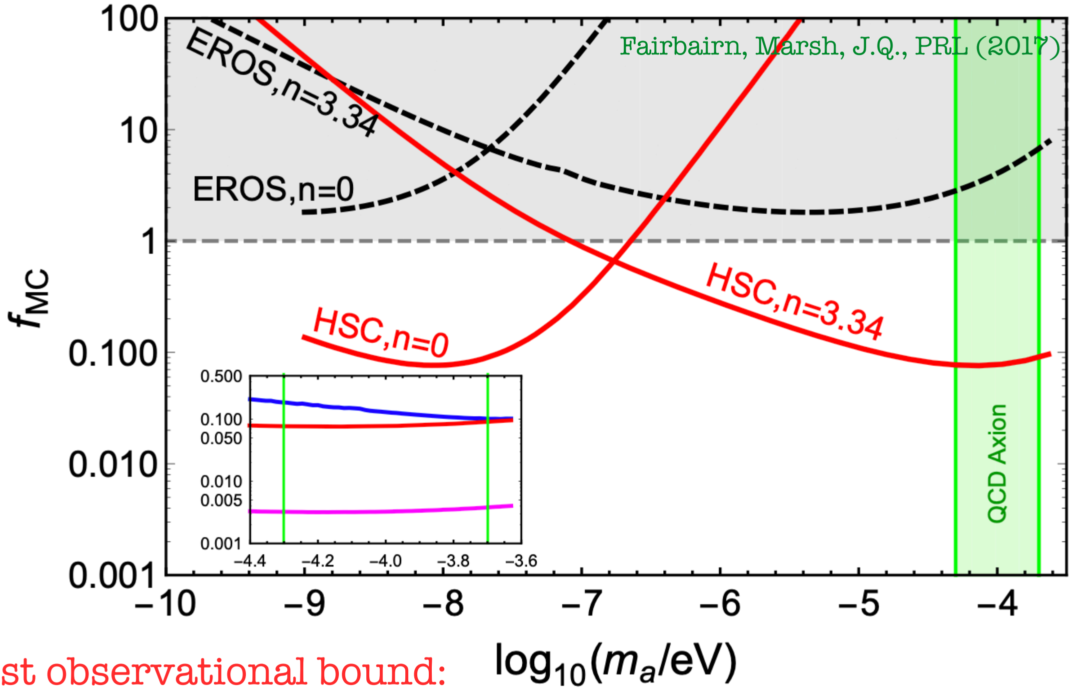


For PBH (point masses), the amount of DM in compact objects is strongly constrained:



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

Conclusion

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

  cf. **GrAHal** collaboration

- Axion physics is a mature field but new fundamental properties are expected

- Axions are multidisciplinary: a chance/challenge

The 100% gravity hypothesis:

- Whether dark matter interacts with the Standard Model particles continues to be one of the great unresolved questions of modern physics
- Dark matter may interact only gravitationally. Probes of dark matter substructure may still tell us about underlying theory
- Optical effects & precision terrestrial experiments should be examined further in specific DM backgrounds