Universität Zürich[UZH]

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PHY213 Kern- und Teilchenphysik II
(FS 2020)

Cosmic Frontier: Dark Matter candidates and direct searches

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Overview

- Evidence for dark matter
  - Galactic rotation curves
  - Gravitational lensing
  - Bullet cluster
  - CMB temperature power spectrum
  - Structure growth
  - Big bang nucleosynthesis
- Dark matter abundance
- Candidates for dark matter
  - Baryonic matter
  - Neutrinos
  - WIMPs
  - Axions

Galactic rotation curves

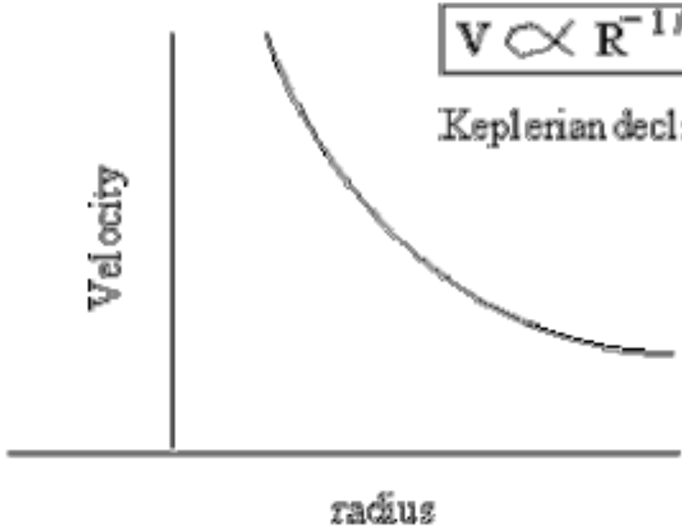
The rotation curve of a galaxy is the rotational velocity about the center [km/s] plotted as a function of radius [km/s or arc seconds]. The curve, if from true circular velocity, is a tracer of the force (~$1/r^2$) and therefore the mass distribution in a galaxy.

Measurement of radial velocity, distance to each star

Keplerian rotation: $$\frac{mv_r^2}{r} = G\frac{M_r m}{r^2}$$

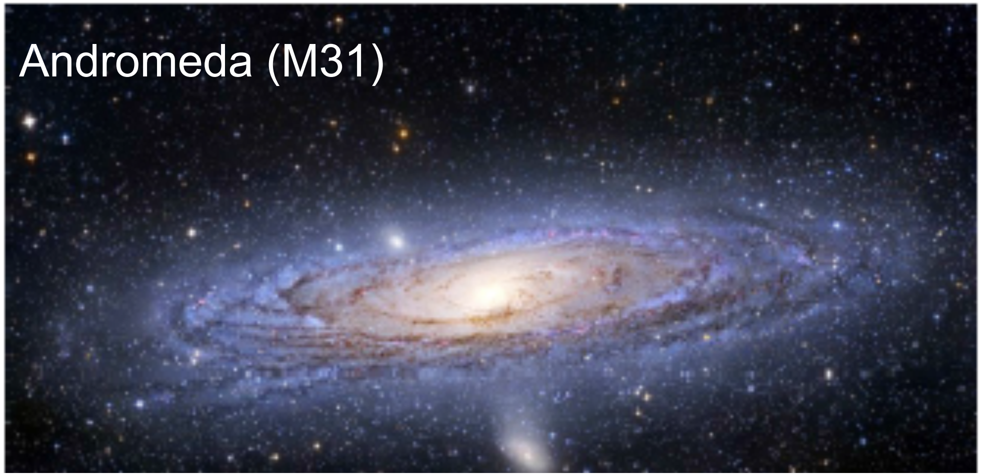
$$\boxed{V \propto R^{-1/2}}$$

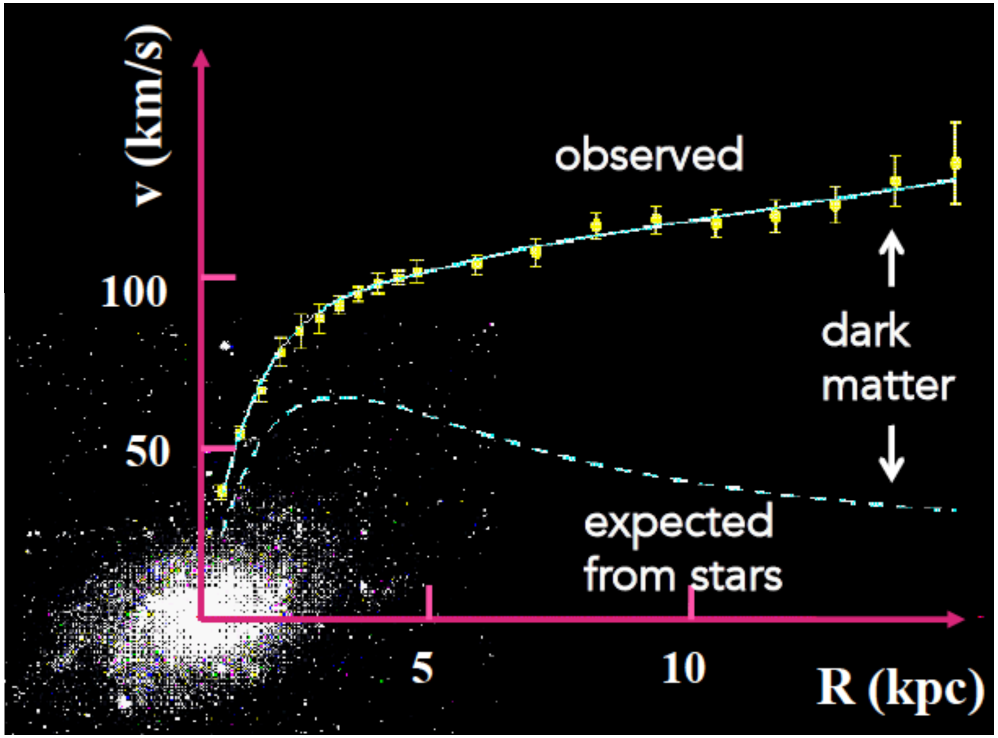
Keplerian decline



Galactic rotation curves

Vera Rubin (1928-2016)

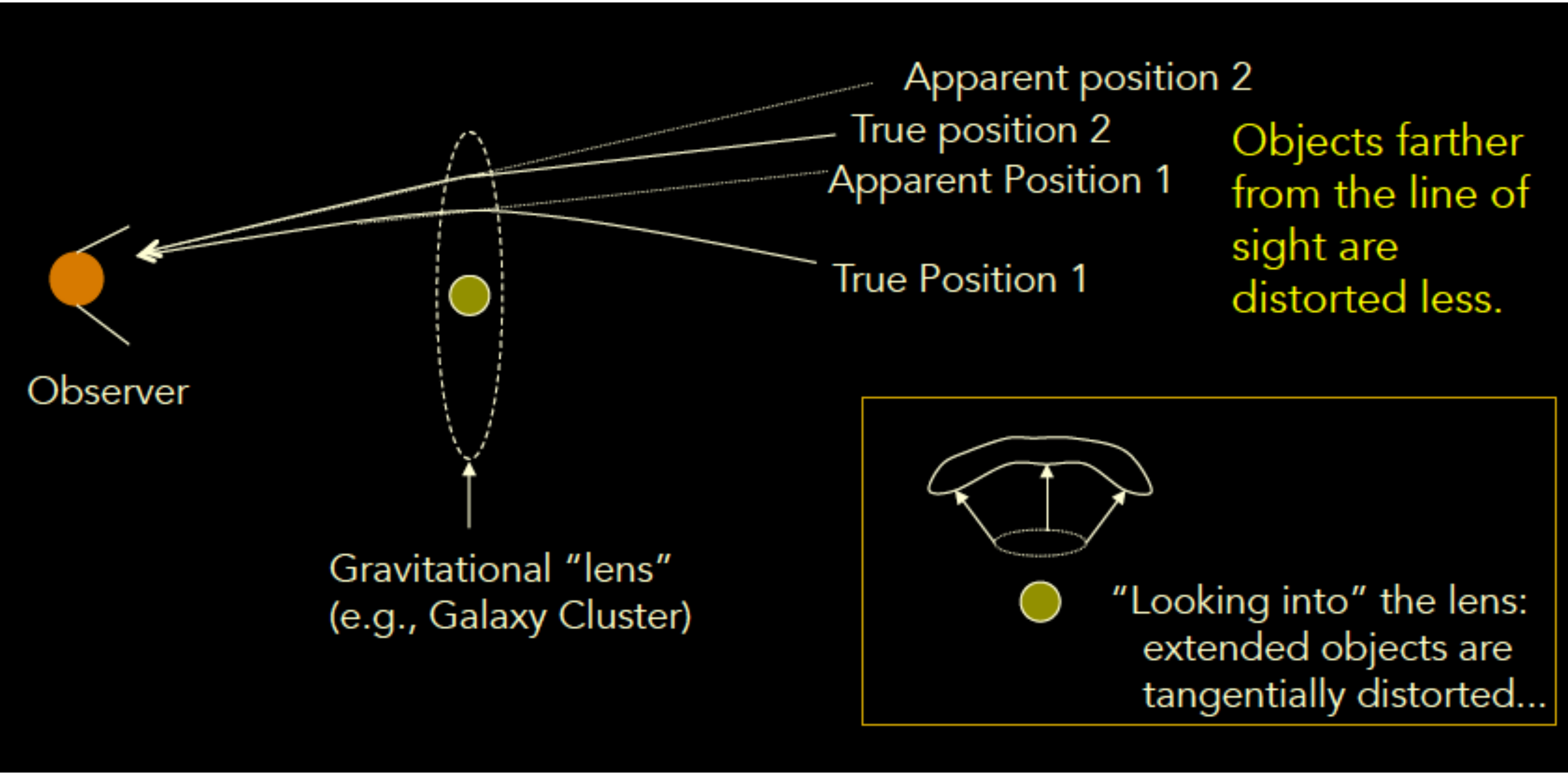




Expected: $v_r \propto \frac{1}{\sqrt{r}}$

Observed: velocity at large radii nearly constant (enclosed mass must increase with radius).

Gravitational lensing



Gravitational lensing

Strong lensing: 2 or more images form.
Weak lensing: luminous objects are not multiply imaged, but rather tangentially distorted (drawn into elongated arc shapes).

Einstein Ring (Cosmic Horseshoe) of distant (blue) galaxy behind a Luminous Red Galaxy (strong lensing)

Weak lensing of distant (blue) galaxy behind galaxy cluster CL0024+17 and dark matter (Massey, 2010)

Colliding galaxies

For dark matter, strongest evidence from lensing observations comes from collisions between galaxies

Bullet Cluster

Non-equilibrium systems:
Main cluster and sub-cluster separated by 720 kpc, at z~0.3

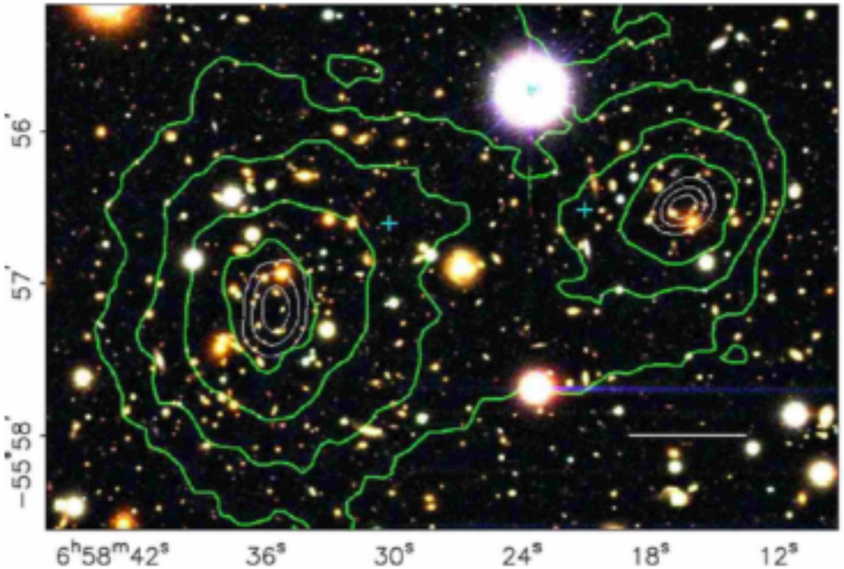
Snapshot of galaxy collision

Observed with both X-ray imaging (baryonic component) and lensing (center of mass)

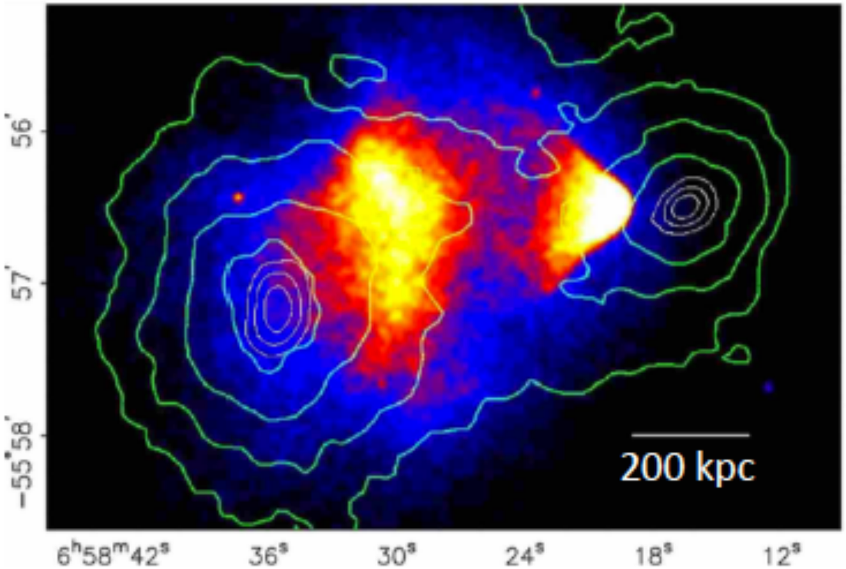
Chandra x-ray telescope

- NASA space telescope launch aboard the Space Shuttle in 1999
- Designed to detect X-ray emission from very hot regions of the universe (exploded stars, galaxy clusters, matter around black holes)
- Placed above earth atmosphere to avoid absorption
- Four nested mirrors focusing on CCD detectors

Bullet cluster



Lensing contours in green (Magellan) map mass distribution, CoM in white: galaxies mostly pass through

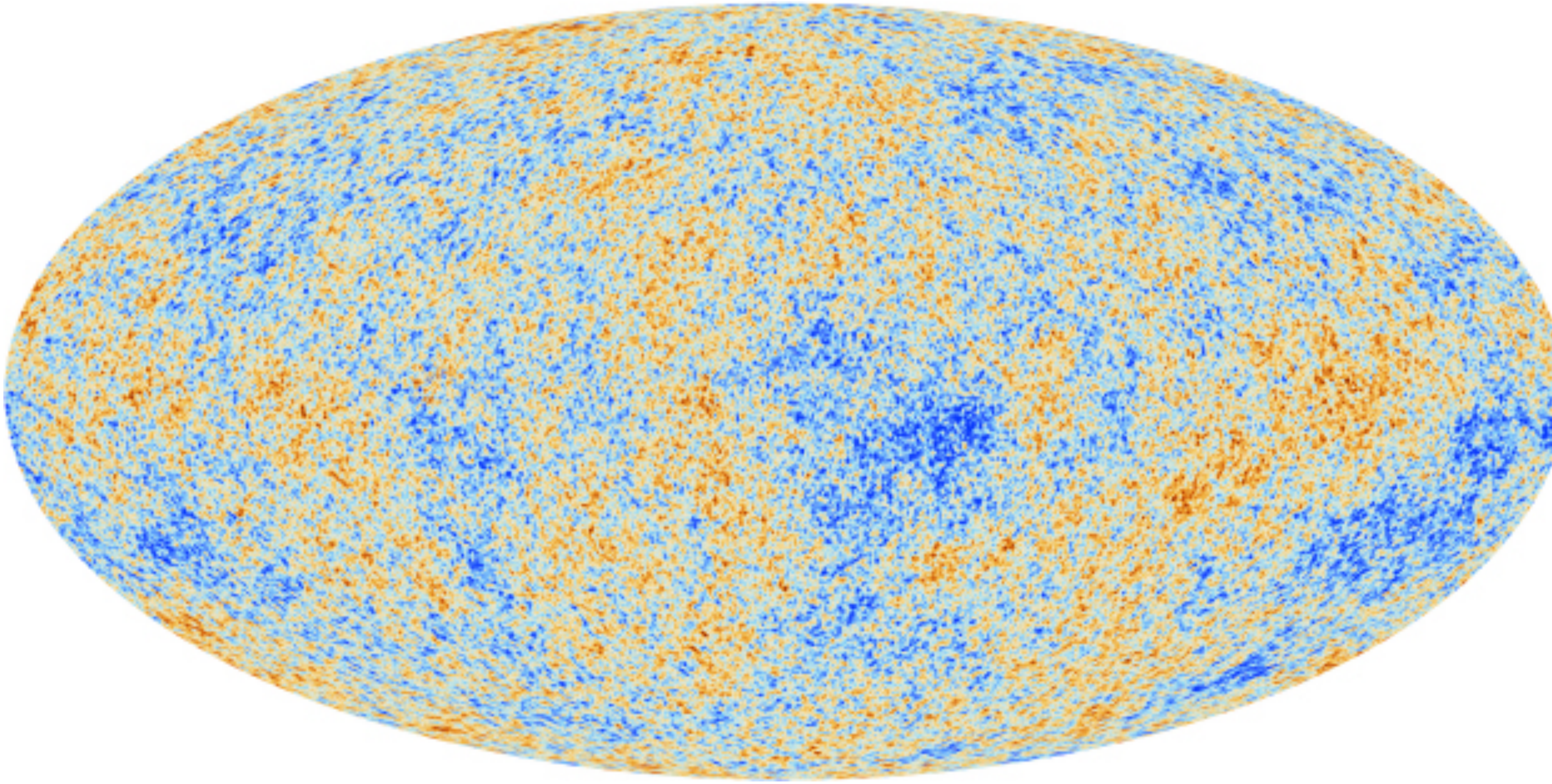


X-ray (CHANDRA) main baryonic components (fluid-like plasma) collide and decelerate subcluster has supersonic bow: 4000 km/s

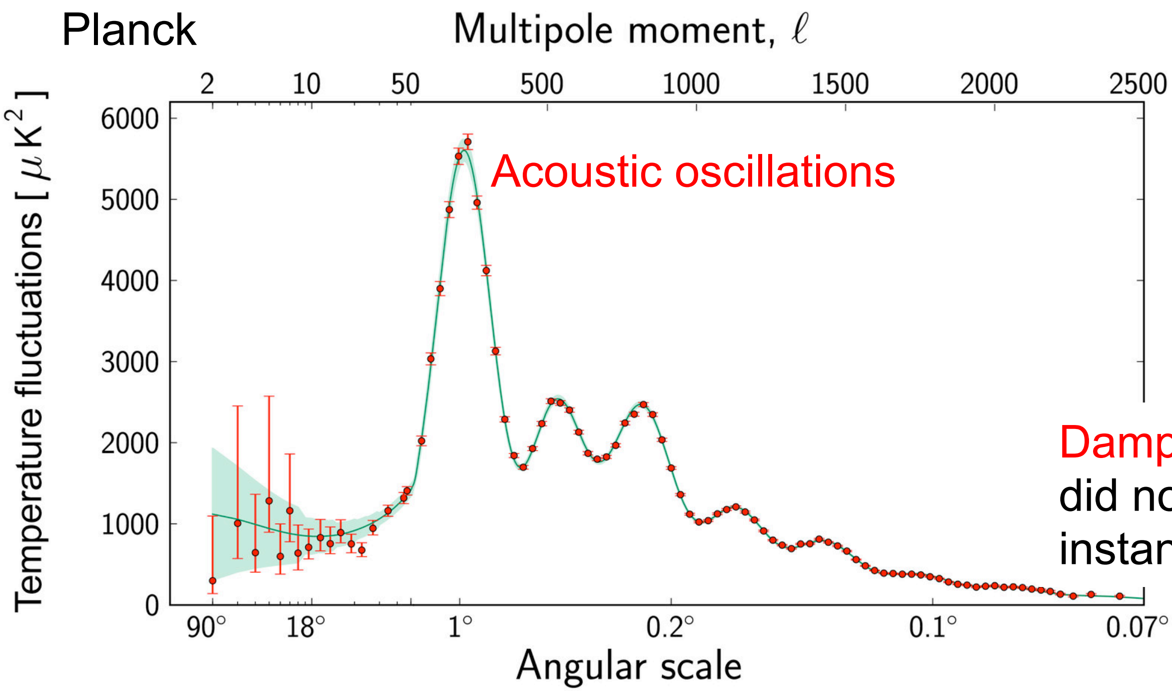
Clowe et al, 2006
Arxiv:0608407

→ Center of mass and center of baryons are separated
→ weakly interacting dark matter, constrains self-interaction cross section

Cosmic Microwave background (CMB)



Temperature power spectrum of CMB



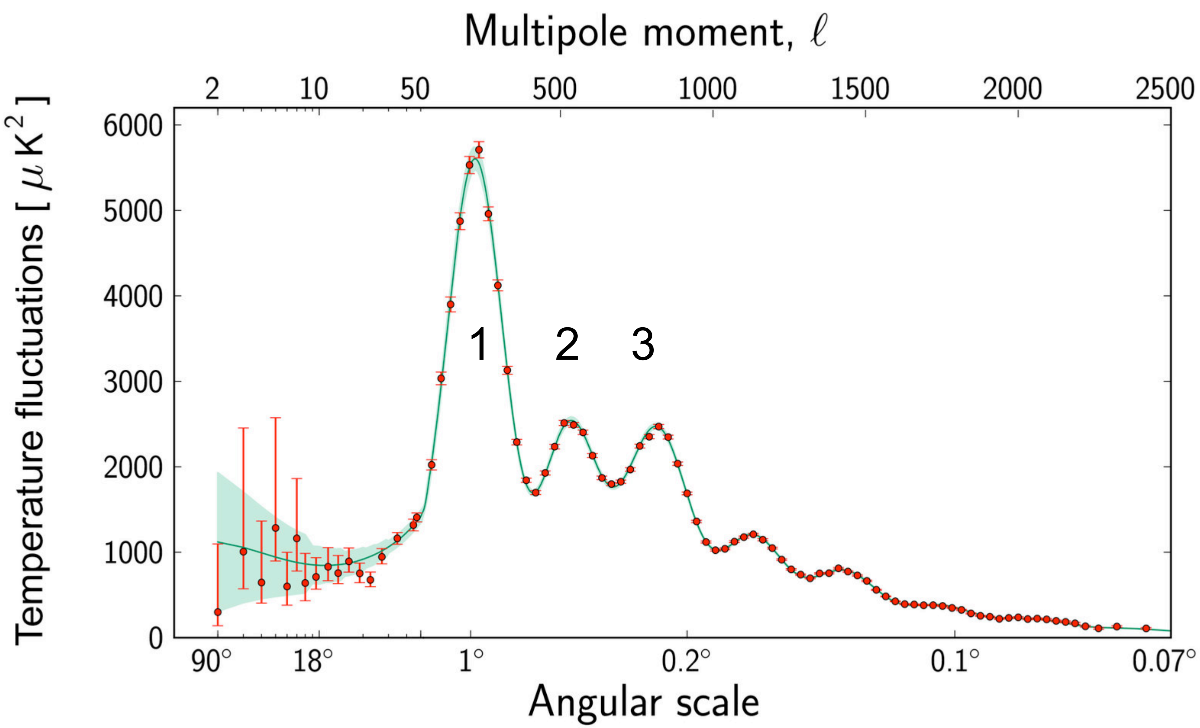
- Spherical harmonic transforms
- Correct for effect of earth and solar motion and other sources

Damping tail since universe did not become transparent instantaneously

- Matter density after inflation is not completely homogeneous. Regions with more dark matter gravitationally attract baryonic matter. Density of baryons increases. Photon pressure increases and counter acts the increase in baryon density → baryonic acoustic oscillations

→ Position of peaks gives information about matter distribution

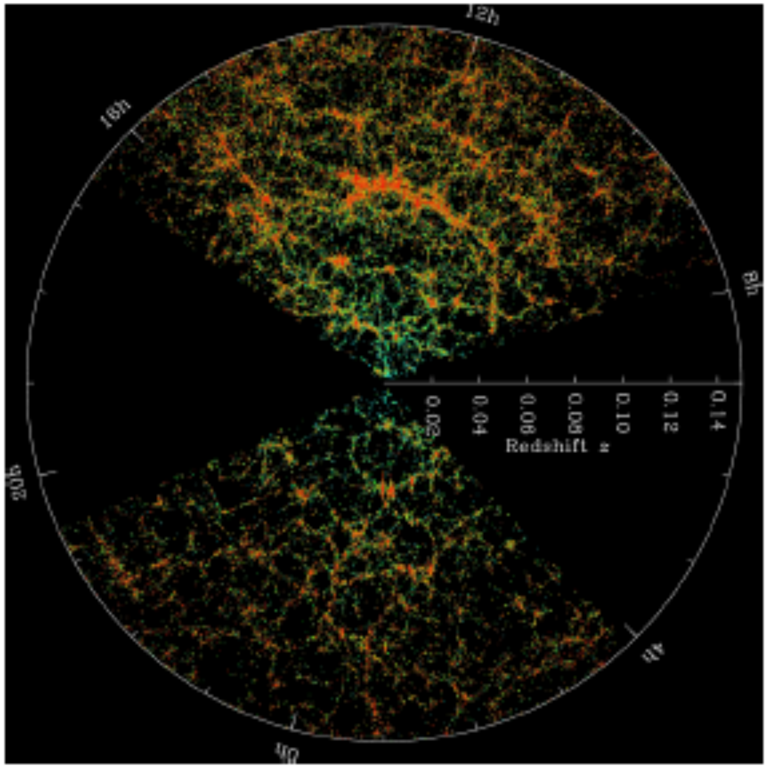
Temperature power spectrum of CMB



- Angular scale of first peak determines curvature of universe
  - shift to the right open universe, shift to the left closed universe
- Relative height of odd and even peaks related to relative density of baryonic and dark matter
  - higher baryon density would enhance peak 1 and 3

Structure growth

- Period after the Big Bang when density perturbations collapsed to form stars, galaxies and clusters (t>200 million years)
- Small anisotropies in the universe grew and condensed into large scale structures
- Matter is affected by radiation → perturbations are washed out in the early universe → structures would not form
- Dark matter not affected by radiation → density perturbations can grow → act as potential well for ordinary matter
- Can trace density perturbations by counting galaxies in different volumes of the universe



Sloan Digital Sky Survey (SDSS)

Closer to Truth with George Smoot
"Why does dark matter really matter?"
https://www.youtube.com/watch?v=al4b4EWBzCg

Dark matter abundance

- From Friedmann equation:

$$\Omega_R + \Omega_M + \Omega_\Lambda + \Omega_k = 1$$

Ω_R – radiation density
Ω_M – non-relativistic matter density (baryonic + dark)
Ω_Λ – cosmological constant (vacuum density)
Ω_k – spatial curvature density

- At the present time:

- Ω_R is negligible compared to $\Omega_M = 0.308 \pm 0.012$
- Luminous baryonic matter is $\Omega_{lum} = 0.01$
- Spatial curvature very close to zero: $|\Omega_k| < 0.005$
- Major contribution from Ω_Λ → related to dark energy

Hypotheses

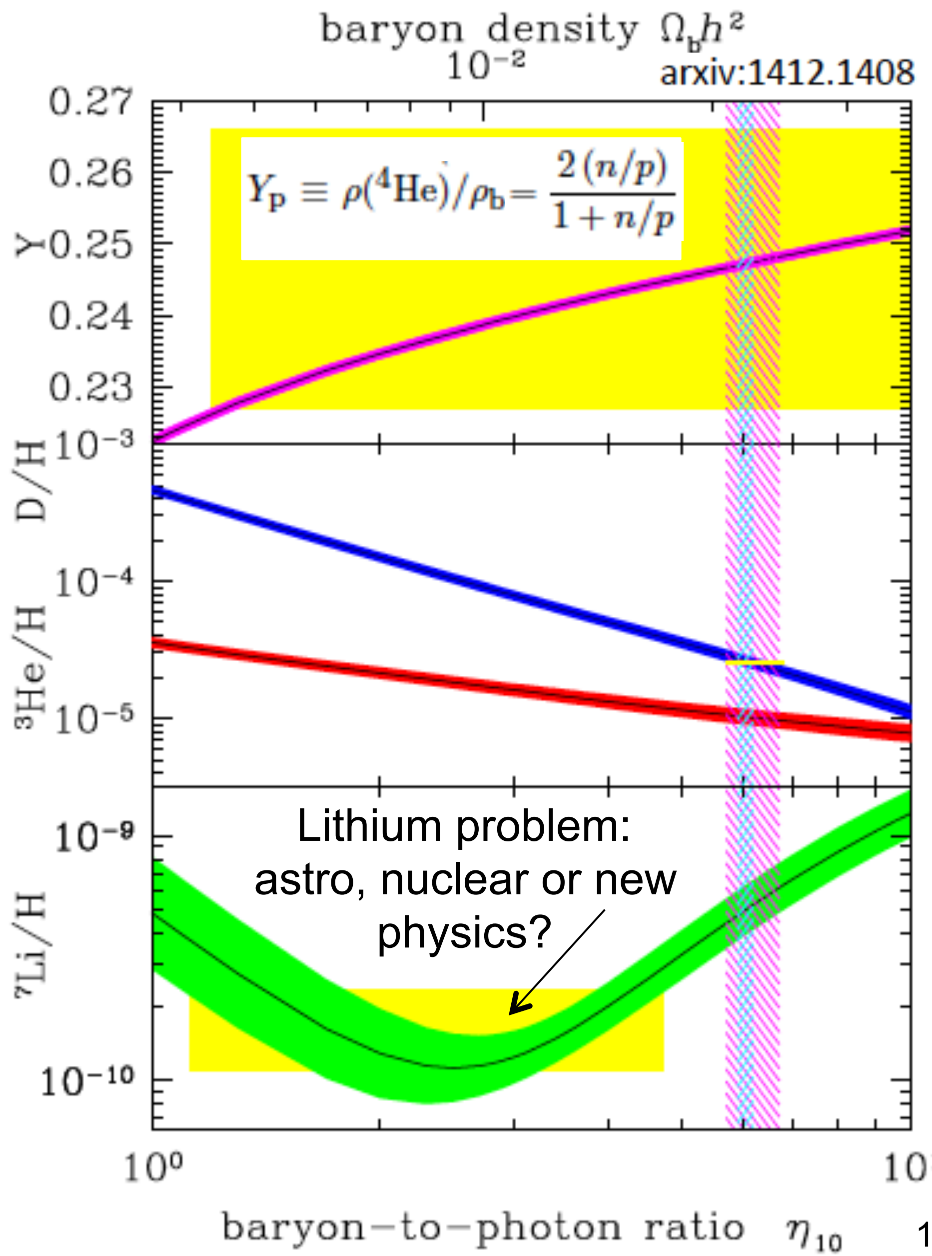
1) Laws of gravity to not apply on largest scales → Modified Newtonian Dynamics (MOND) theories

2) Dark matter – a new kind of matter

Since this is a particle physics lecture → focus on 2) and examine different dark matter candidates

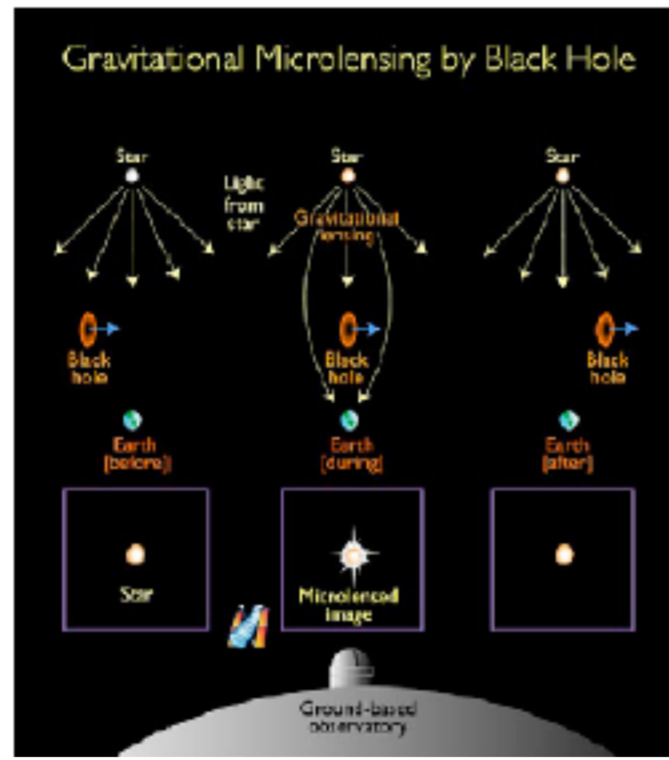
Is dark matter baryonic matter?

- Using the Big Bang Nucleosynthesis model, the abundance of light elements (^4He, ^3He, D, H) are predicted as a function of the baryon density
  - The prediction is compared to the observed abundances (yellow boxes)
  - The concordance range (magenta band) is in agreement with the baryon density obtained from CMB measurements (blue band)
- $\Omega_b \approx 0.05$
- Compared to $\Omega_{lum} \approx 0.01$ → some of the invisible (dark) matter is baryonic



MACHOs

- Massive compact halo objects (MACHOs) were the most popular dark matter candidates in ~1970-1980
- Searched for using so-called microlensing technique:
  - Gravitational lensing of individual stars do not produce distinct separated clusters (resolution of optical telescopes too poor)
  - However, can observe fluctuations in light intensity

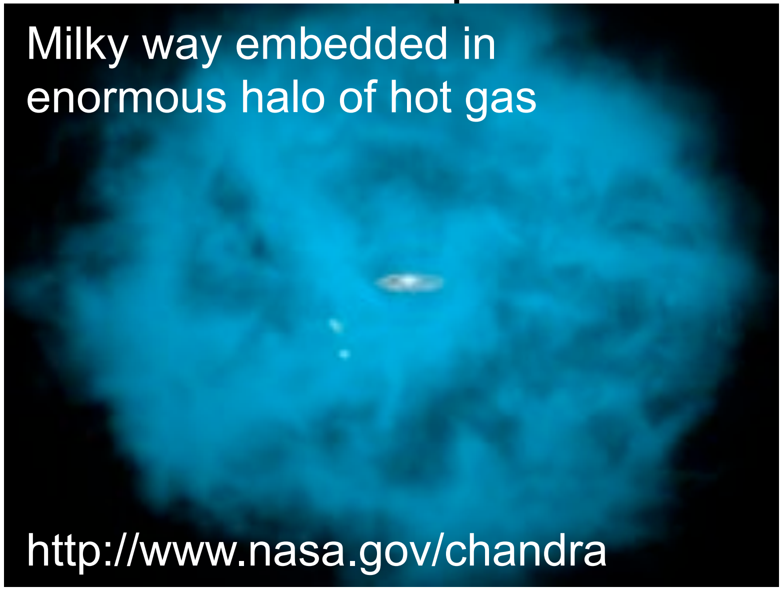


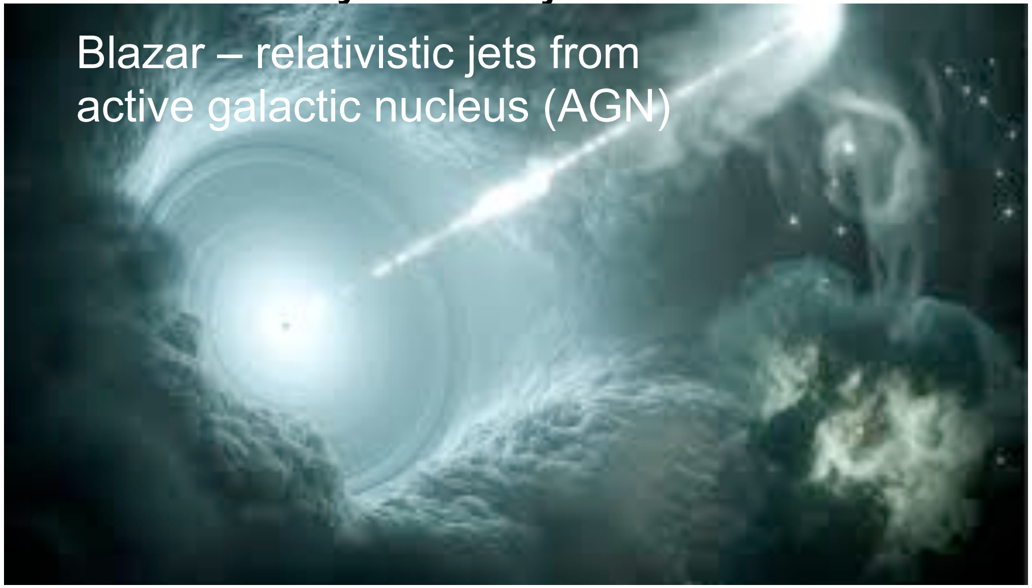
- Lensing of an individual source star is a rare event → need to observe many million stars over years (computerized search techniques)
  - Sensitive to masses as small as 10^{-8} m_{solar}
  - Experimental results find fraction of about 20% of MACHOs in the galactic halo (uncertainty in detection efficiency

→ not enough to account for all dark matter

Other sources of non-luminous baryonic matter

- X-ray studies of galaxy clusters revealed vast amount of gas present between galaxies → can account for almost half of the baryonic matter in the universe
- Other sources of missing baryons are attributed to long filaments of gas associated with blazars
- No indication for presence of more exotic baryonic objects

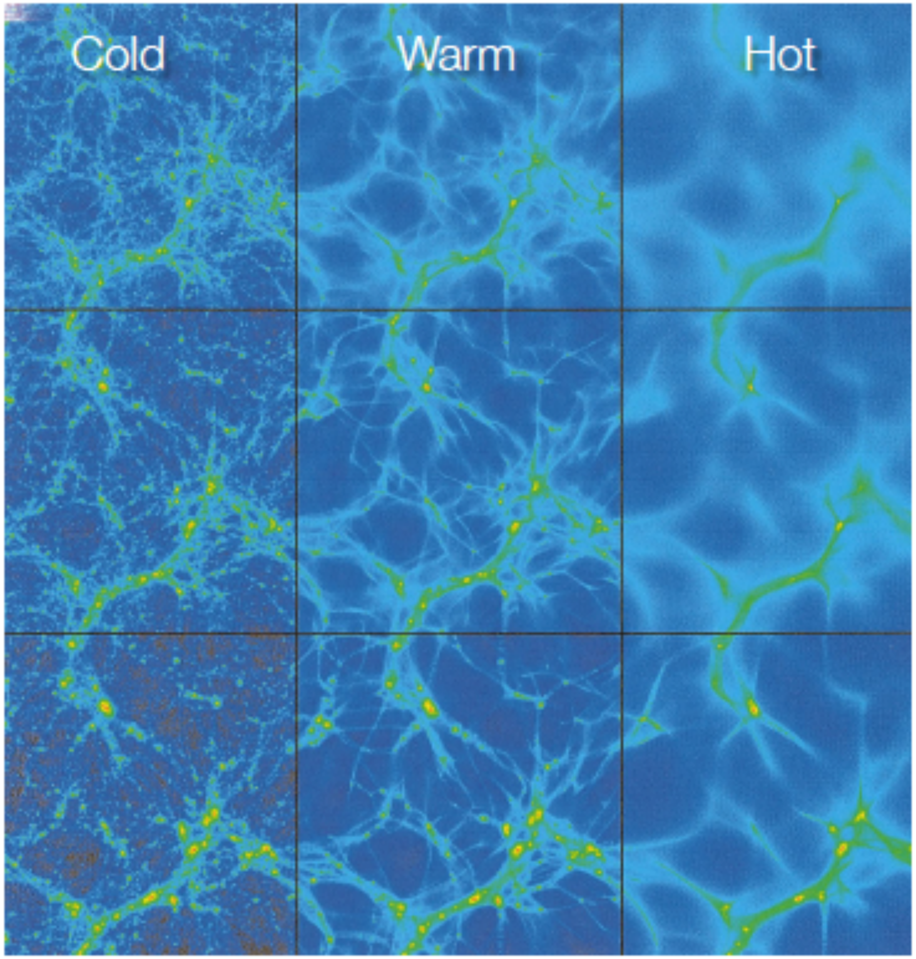




→ Thus: Baryonic matter makes only a small contribution in the universe, less than 15% of estimated dark matter density

What particle could dark matter be?

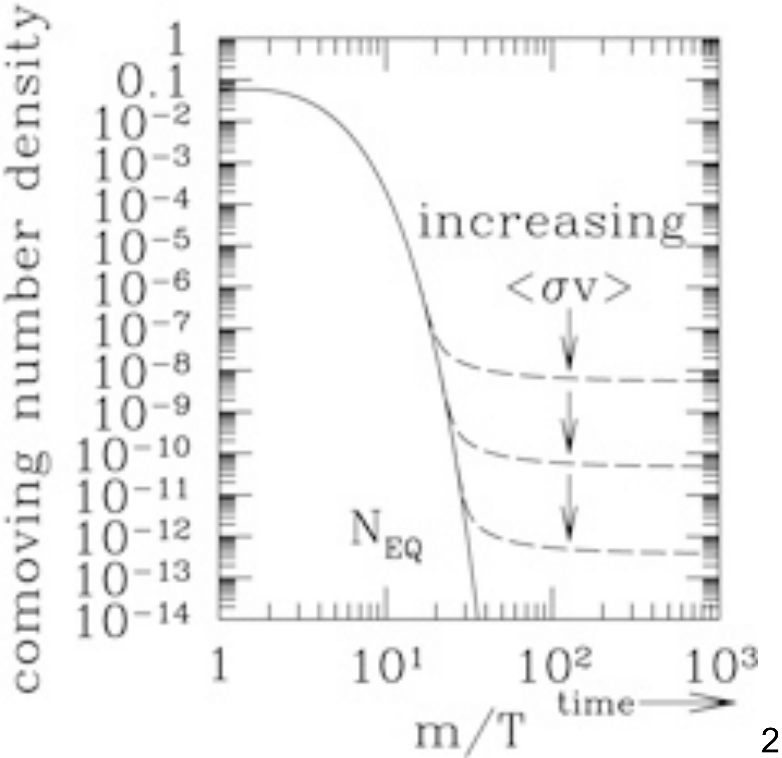
- Exists today and in the early universe → dark matter is stable or very long-lived
- Constraints from astrophysics and searches for new particles:
- No (or very small) electric charge
  - structure formation → no coupling to photons
- No strong self-interaction
  - additional interaction would facilitate momentum transfer through halo → would make them round
- Slow moving (non relativistic) when large-scale structure were forming



Probing dark matter through gravity

Relic density

- Leading hypothesis: Dark matter is a 'thermal relic' from an early period in our universe
  - average temperature T ~ 10^{15} K ~ 100 GeV
  - hot enough to create new massive particles
- As the universe expands, production and annihilation rates become longer than the (current) Hubble time → freeze out
- Number of particles first decreases due to the Boltzmann factor $e^{-m/T}$
- Reaches a constant value after freeze out
- Larger annihilation cross sections lead to smaller densities



Neutrinos

- (Conventional) neutrinos were the most popular dark matter candidates in ~1980-1990
- Neutrinos were produced productively in the very early universe

$$\gamma \leftrightarrow e^{+} + e^{-} \leftrightarrow \nu_i + \bar{\nu}_i$$

- Freeze-out at kT < 3 MeV

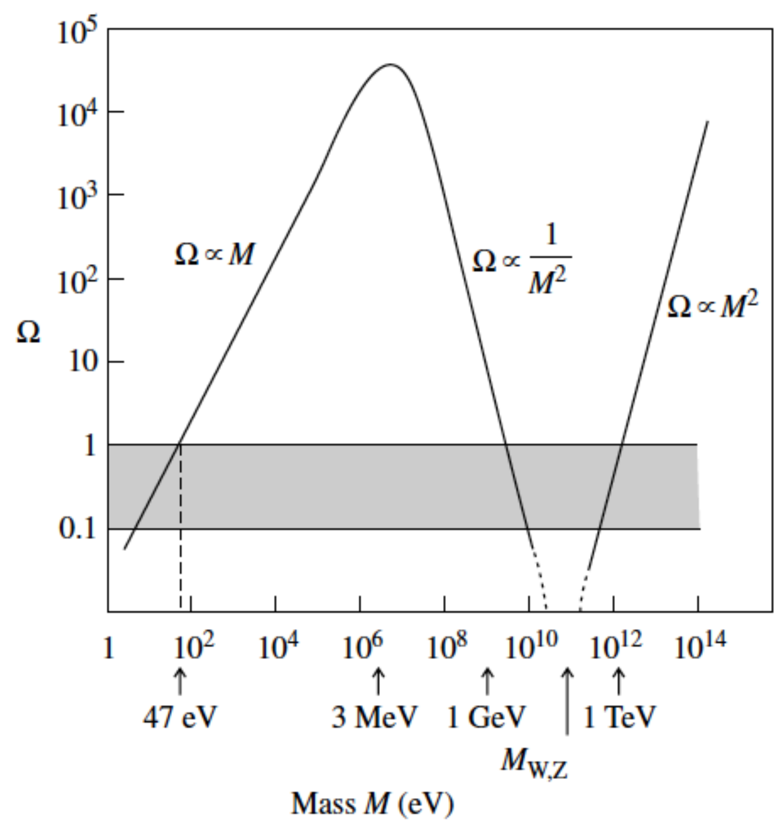
$$N_\nu = \left(\frac{3}{11}\right) N_\gamma = 113\,\mathrm{cm}^{-3}$$

- Neutrino masses would have to be in the few eV range to make significant contribution to dark matter → contradicts observation
- Also neutrinos are hot dark matter as they were still relativistic at the time of freeze-out → cannot explain structure formation

→ Conventional neutrinos ruled out as dark matter candidates, more exotic versions (sterile, massive) still possible

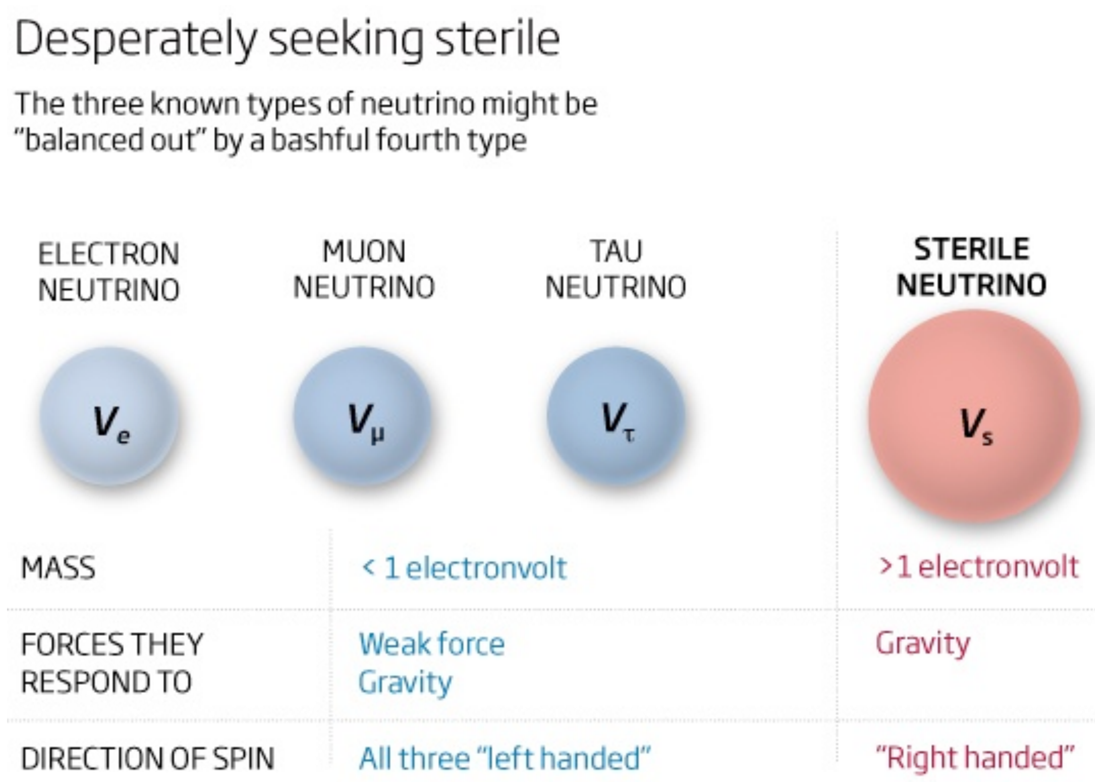
Heavier neutrinos

- Looking at more massive neutrinos
- as long as these neutrinos move with relativistic velocities at the time of freeze-out, the density parameter Ω increases linearly with the neutrino mass m_ν
- For higher masses, neutrinos become non-relativistic and the dependence of Ω goes with $1/m_\nu^2$
- LEP measurement of Z width → no additional neutrinos with masses $m_\nu < m_Z/2 \approx 45$ GeV
- For heavier masses contribution to Ω too small to explain dark matter
- For even higher masses → weak cross section falls rapidly because of propagator effects → WIMPs in TeV range as dark matter candidates



Sterile neutrinos

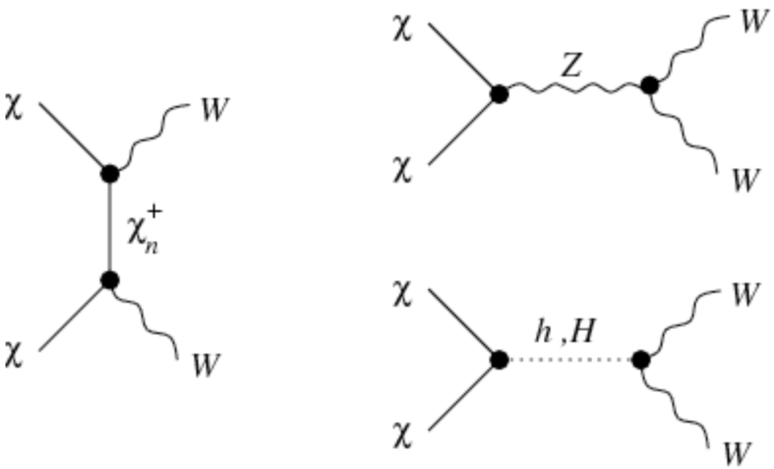
- Hypothetical right-handed neutrinos that are not charged under the weak interaction
- Provide explanation for tiny masses of ν_e, ν_μ, ν_τ:
- Pure left-handed neutrino state has zero mass, but gains a tiny mass through mass mixing with the heavy right-handed neutrino via small mixing angle
- very hard to find experimentally. Only through their interaction with left-handed neutrinos



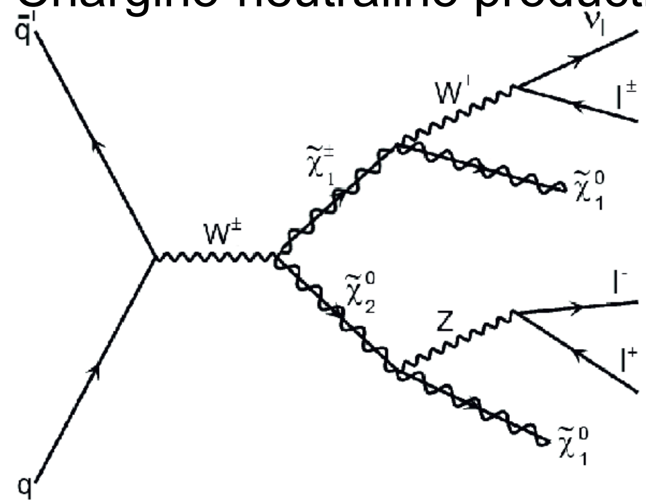
WIMPs

- Weakly interacting massive particles (WIMPs), moving with non-relativistic velocities at the time of freeze-out → cold dark matter
- An example would be the neutralino in SUSY models with a neutral lightest stable particle (LSP)
  - no electromagnetic charge, no strong charge, only weak charge
  - can disappear through annihilation with their antiparticles
  - can be produced in high-energy collisions

Neutralino annihilation



Chargino-neutralino production



- Due to large number of SUSY parameters → mass, cross-section and abundance can vary over wide ranges

WIMP miracle

- Freeze-out occurs when rate of WIMP annihilation falls below expansion rate:

$$N \langle \sigma v \rangle \leq H$$

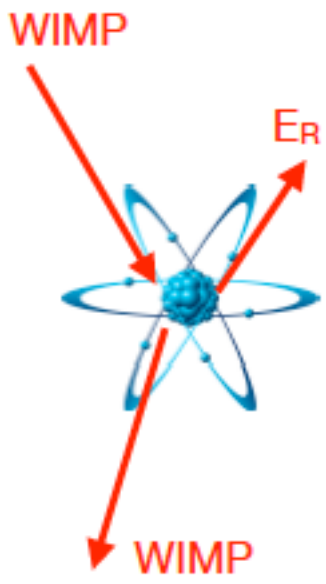
- N: WIMP number density, v: relative velocity, σ: annihilation cross section, H: Hubble parameter at the time of freeze-out
- Obtaining the correct abundance of dark matter today requires an annihilation cross section of

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \ \mathrm{s}^{-1}$$

- This is roughly what is expected for a new particle in the 100 GeV mass range (like a neutralino) that interacts via the weak force

→ This apparent coincidence make WIMPs to very attractive targets in the dark matter searches

Direct detection of WIMPs

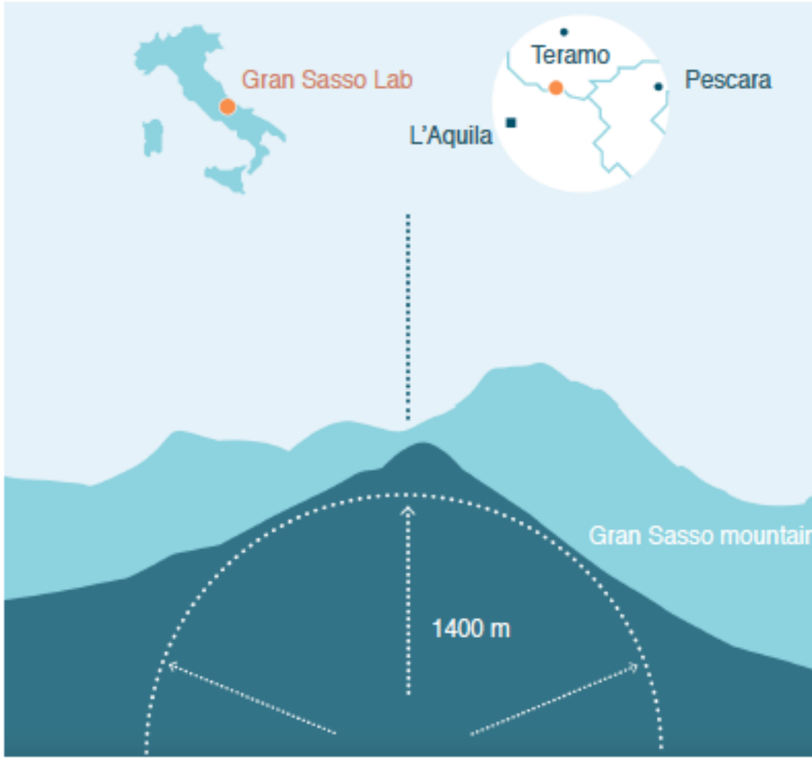


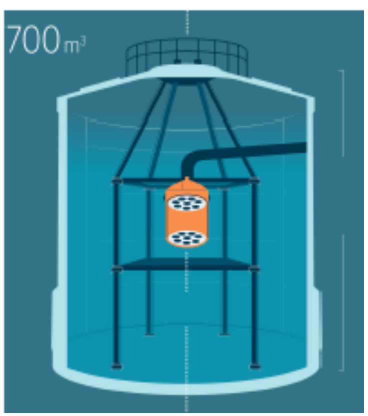
- Search for collisions of WIMPs with atomic nuclei
- Measure the recoil of the scattering nucleus
- Detection method depends on target material, e.g.:
  - ionization in silicon
  - scintillation light in liquid gas (like Argon or Xenon)
  - phonons from lattice vibrations at cryogenic temperatures
- Recoil energy is small ~few 10 keV → need low detection threshold
- Scattering events are rare → need large scale detectors
- Need to suppress background from radioactive decays and cosmic rays → use pure materials, go deep underground and use active shielding

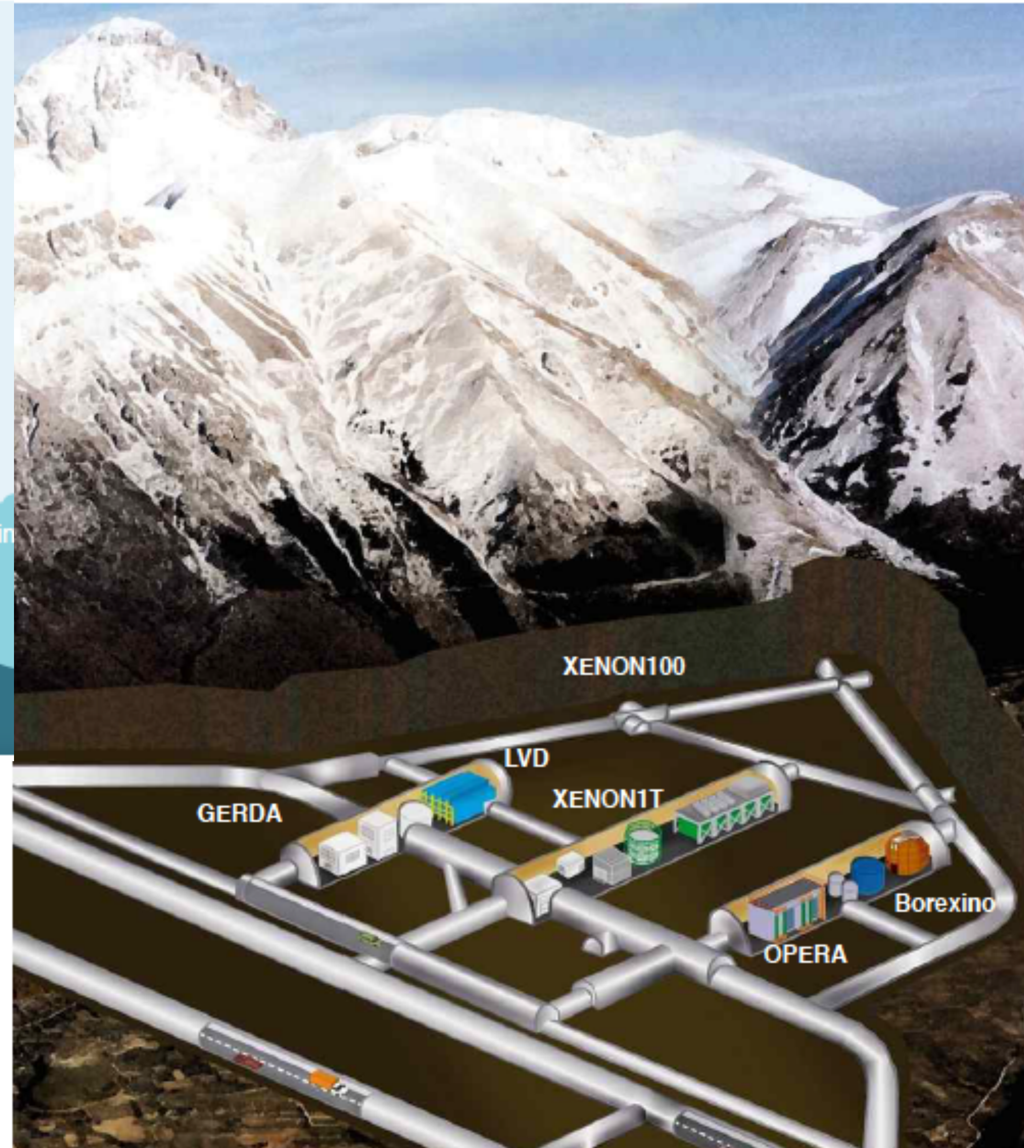
Direct detection of WIMPs

- Many underground laboratories around the world hosting different experiments

Xenon 1T at Gran Sasso laboratory

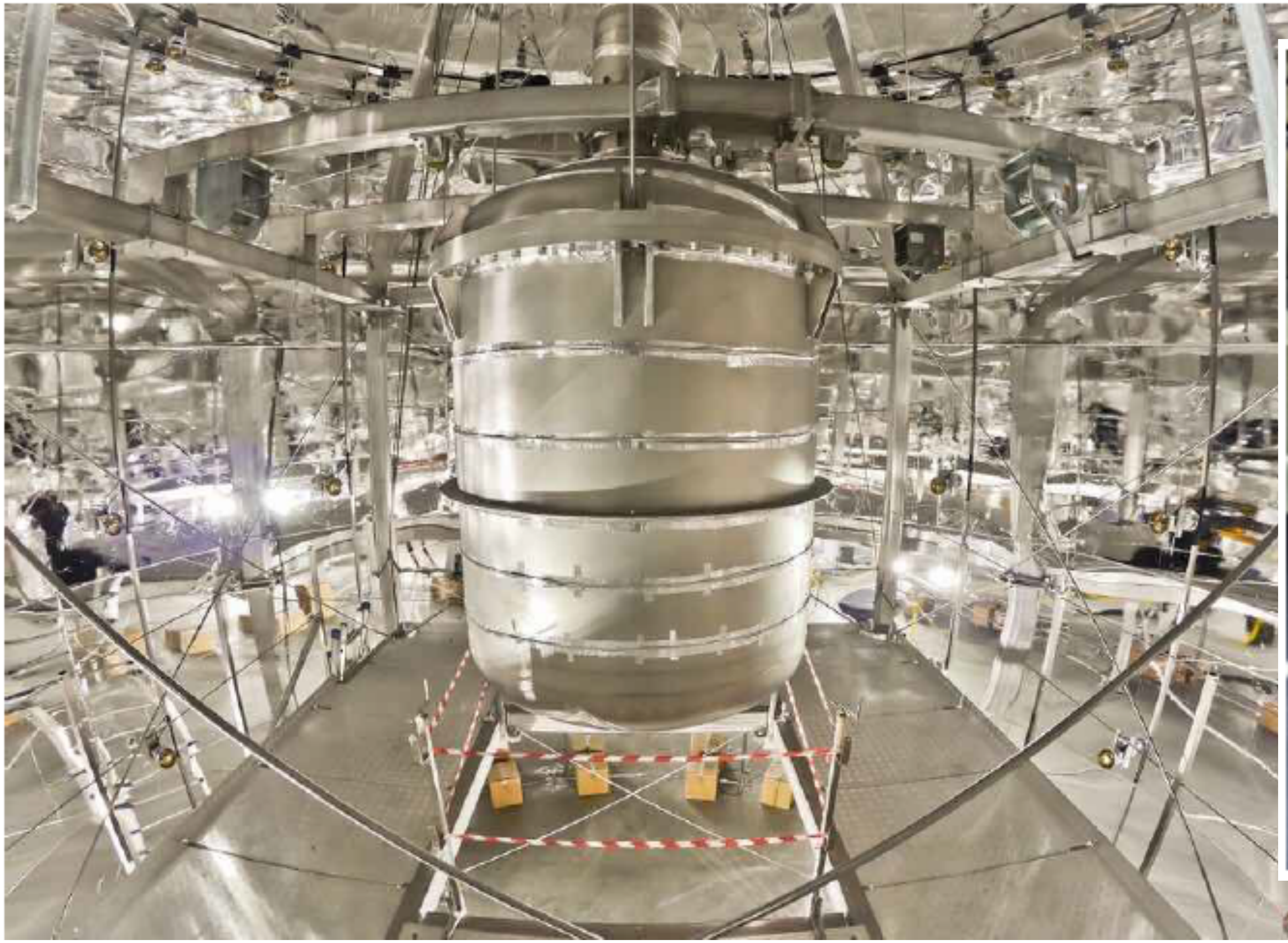




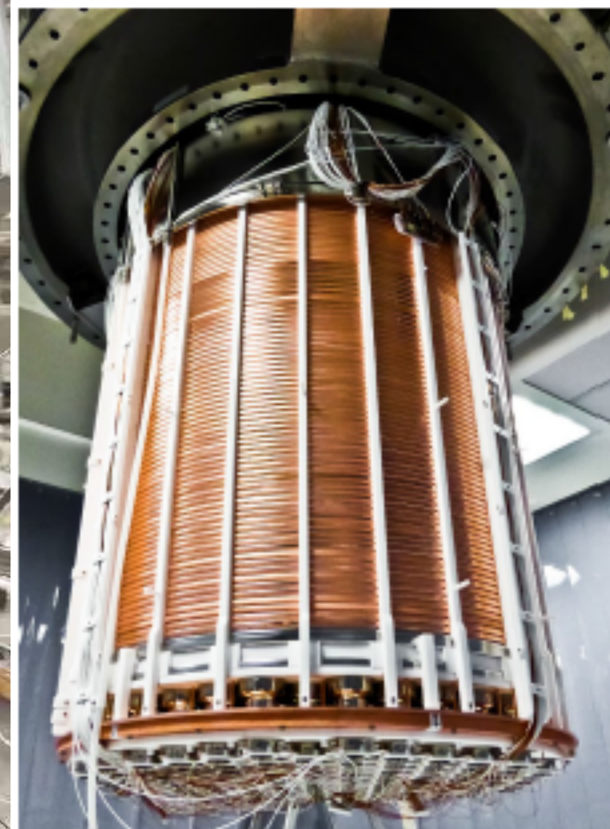


Xenon 1T

Cryostat and water shielding

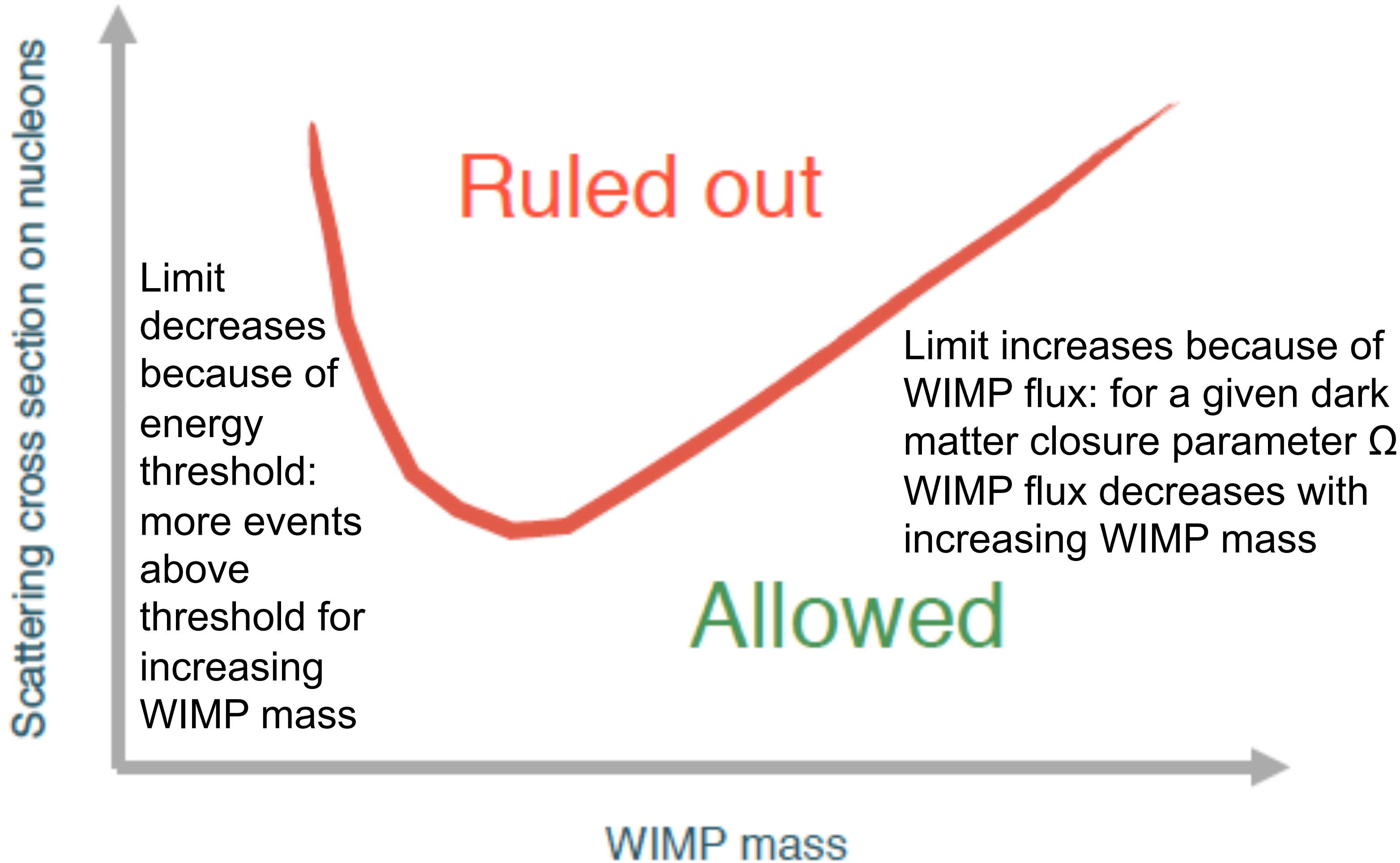


Time projection chamber (TPC)



Results of direct dark matter searches

- Scan parameter space of WIMP mass and scattering cross section



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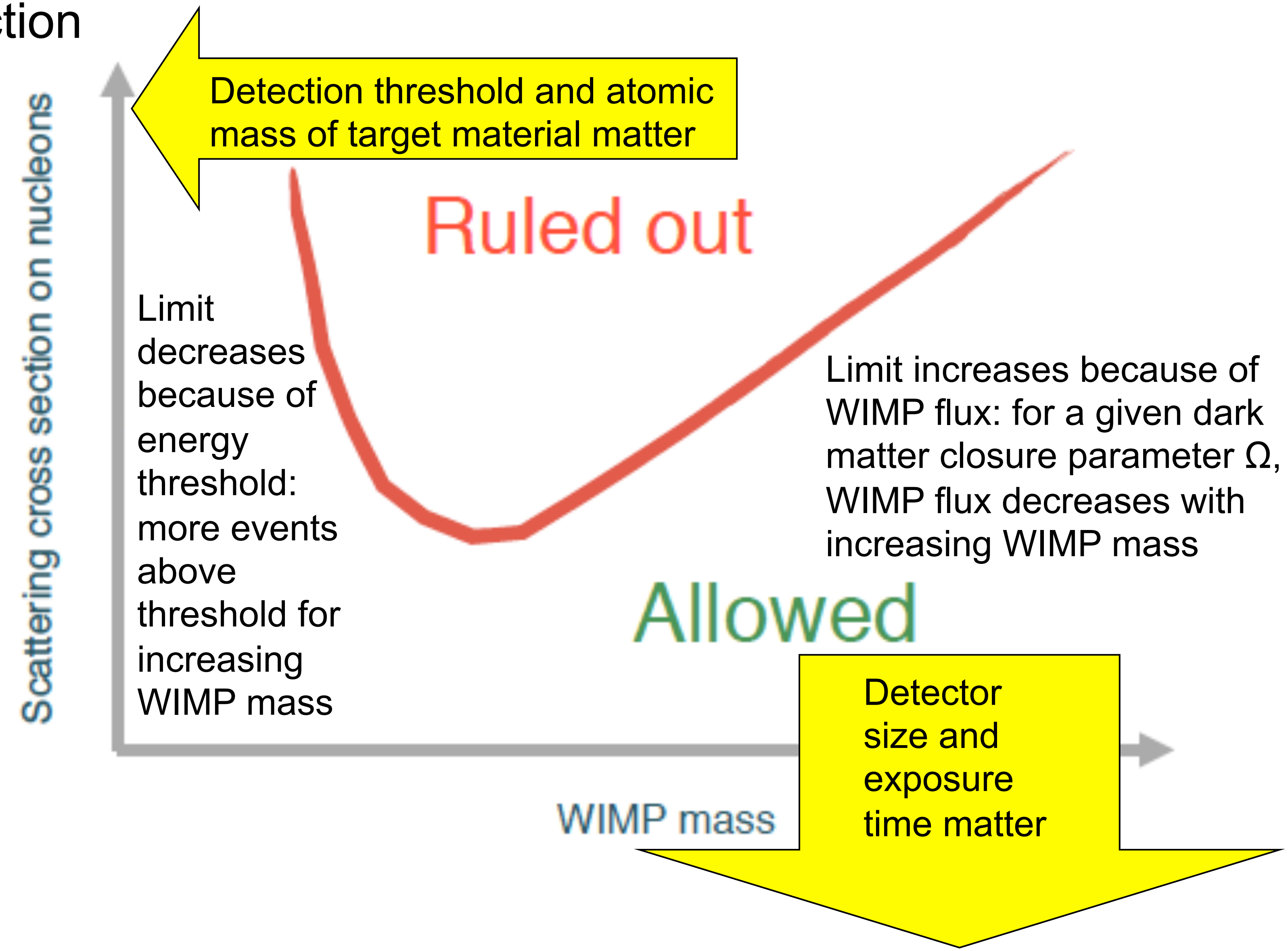
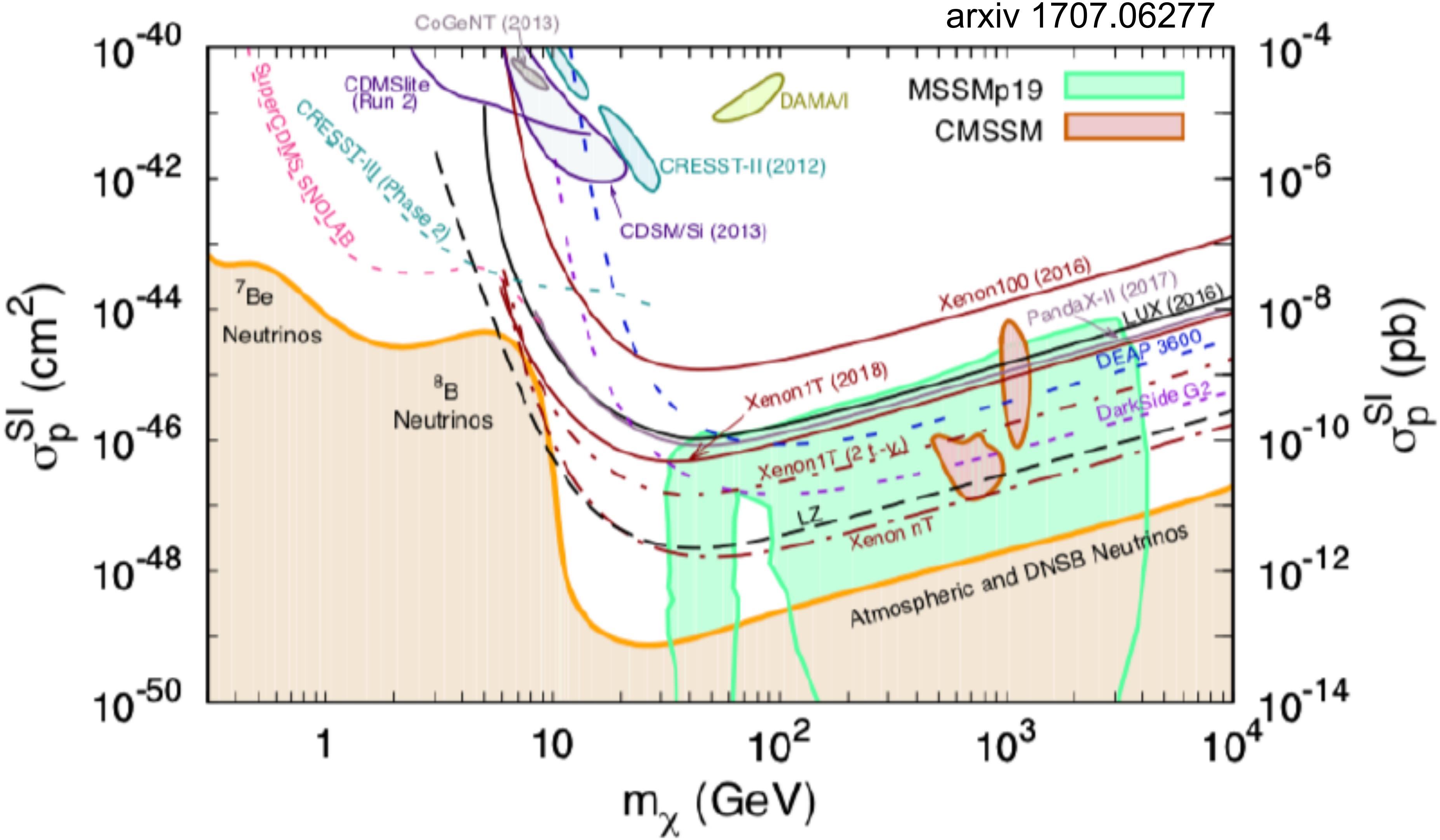


Results of direct dark matter searches

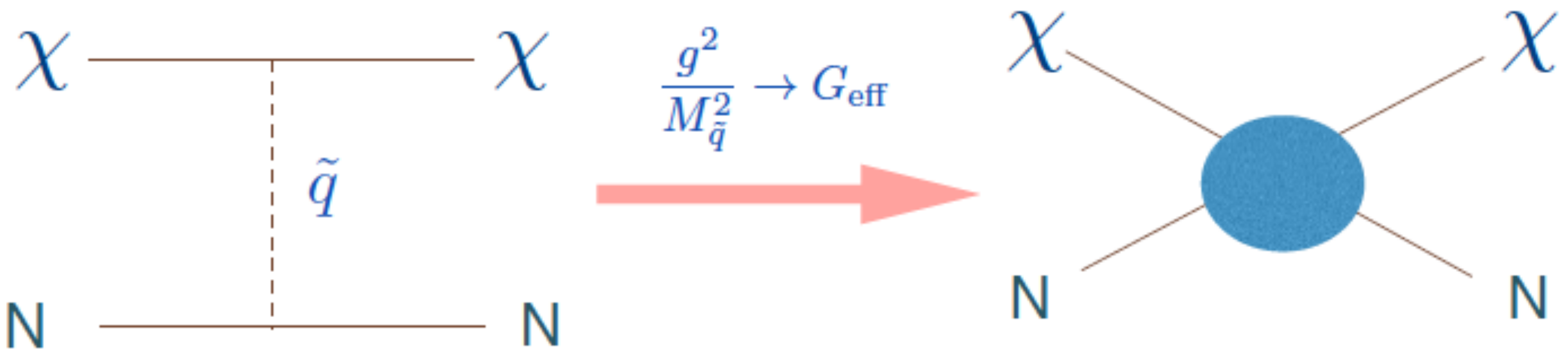
arxiv 1707.06277



→ Experiments are closing in on SUSY phase space

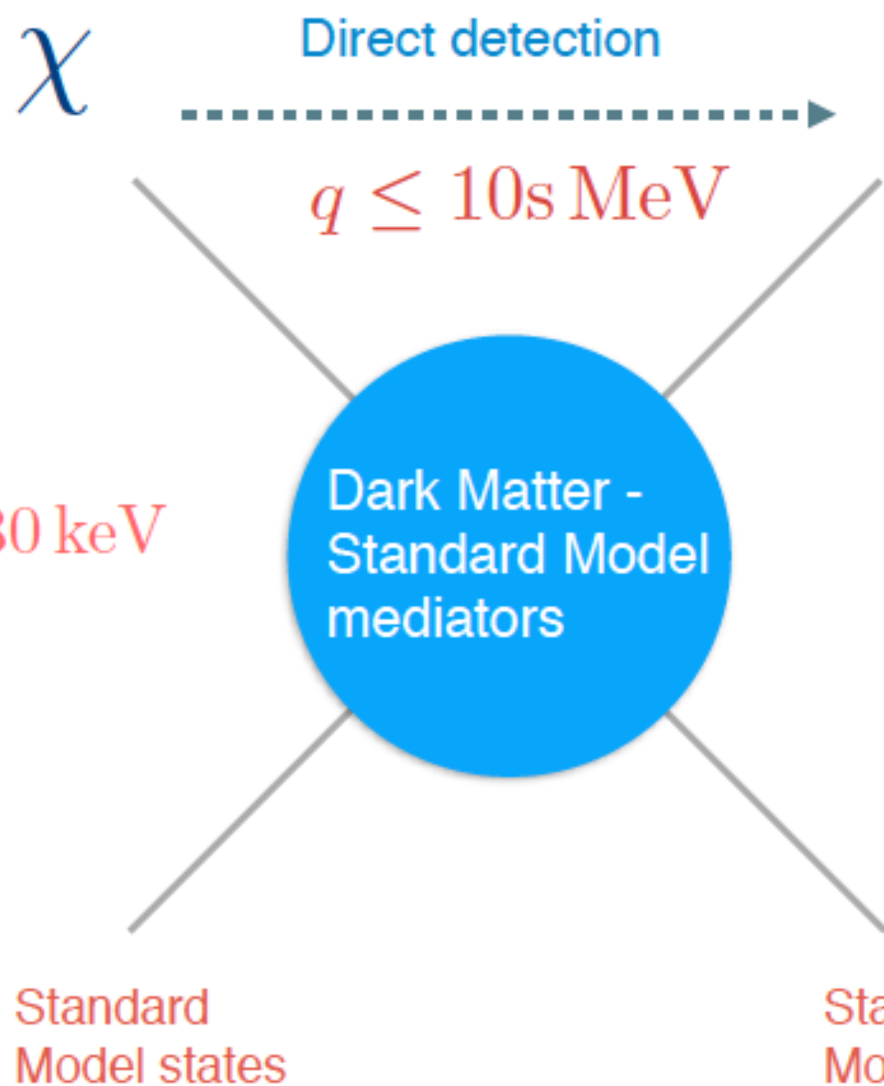
WIMPs

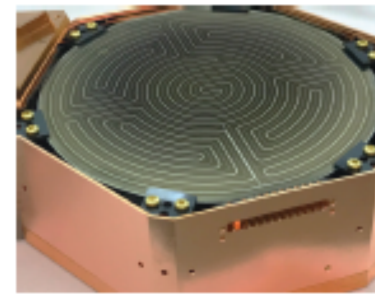
- More general definition of a WIMP is a new elementary particle that interacts via gravity and any other force (or forces), potentially not part of the Standard Model itself, which is as weak or weaker as the weak force
- Interaction happens through dark matter mediator and can be parameterized as effective coupling



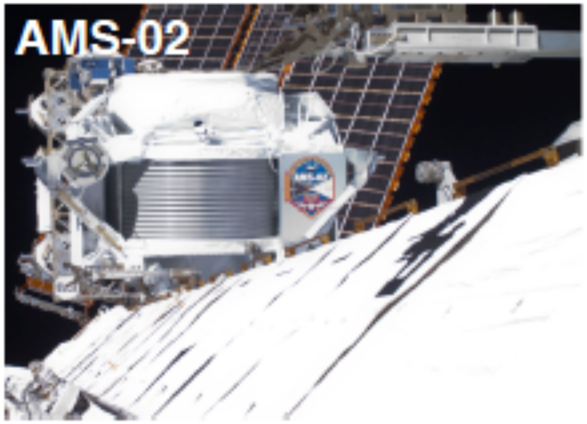
WIMP search program

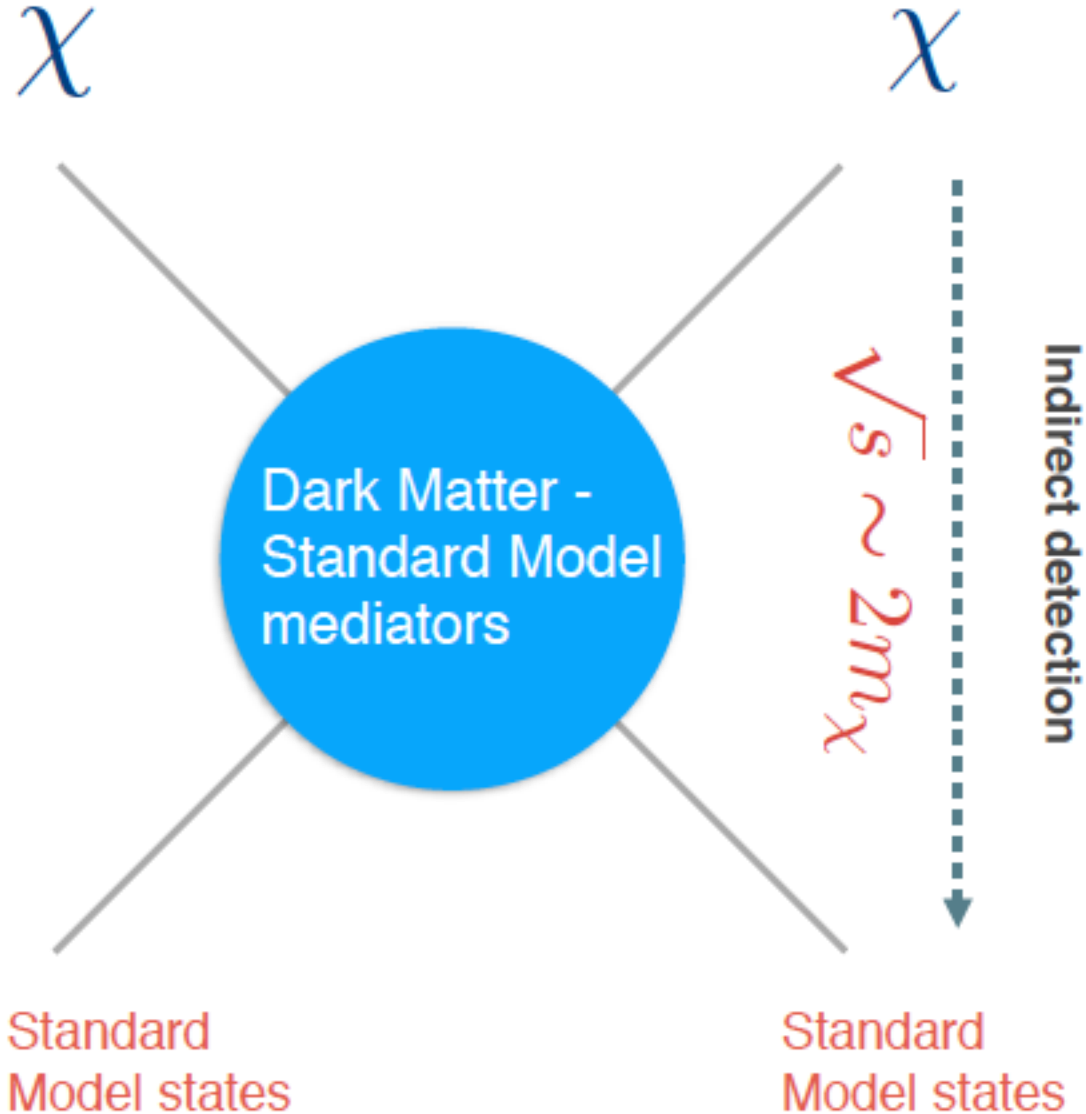
$$E_R = \frac{q^2}{2m_{Xe}} < 30\,\mathrm{keV}$$



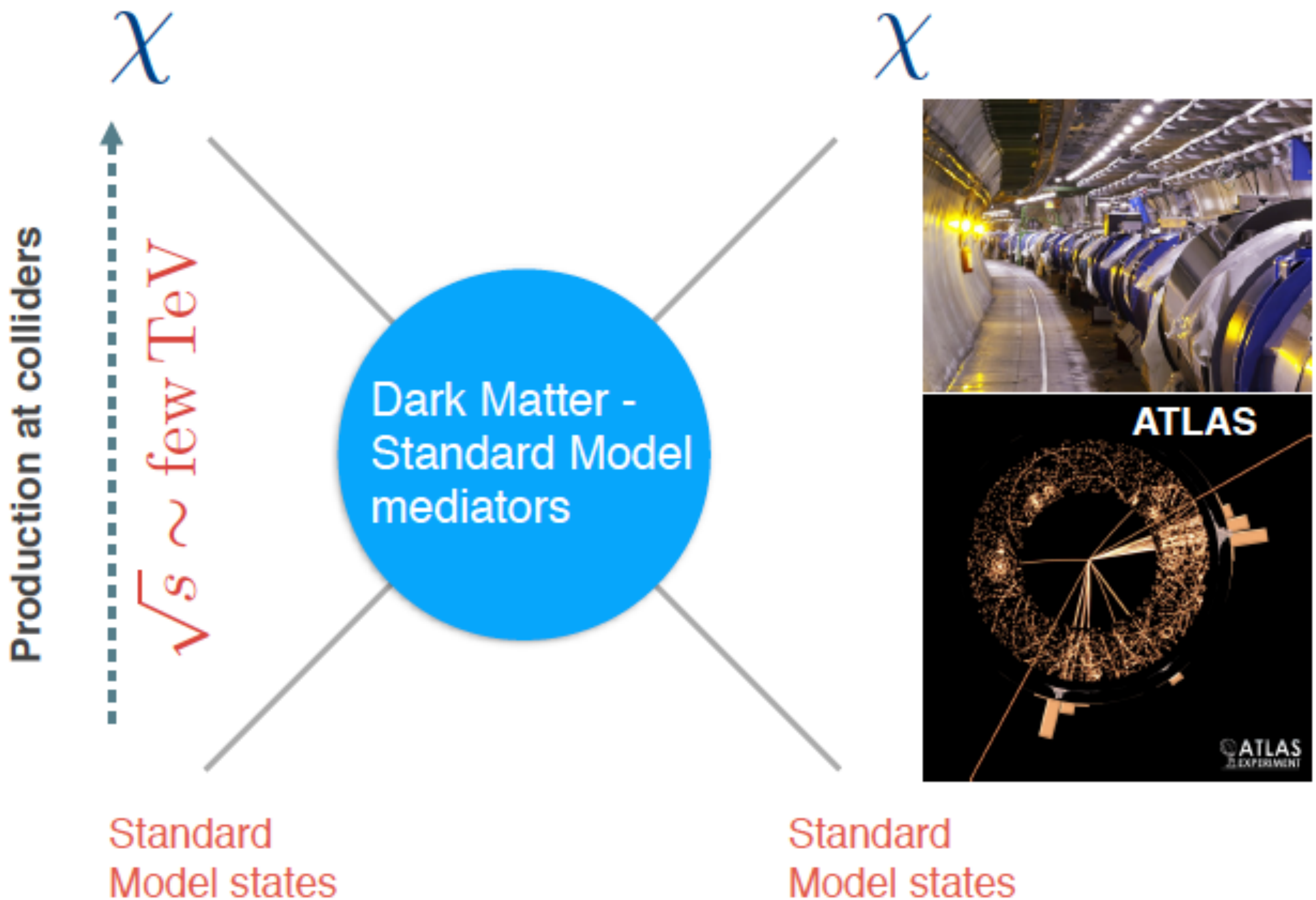


WIMP search program





WIMP search program

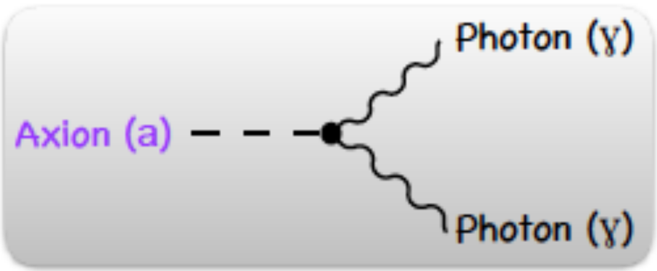


Axions as dark matter candidates

- Axion is a very light pseudoscalar particle (spin-parity 0^-) proposed to solve the strong CP problem:
  - Complex CP violating phase can occur in QCD wavefunctions, however strong CP violation not observed experimentally (and thus not in SM)
- Peccei and Quinn (1977) proposed a new global U(1) symmetry, spontaneously broken at some very high energy scale
- Gives rise to Goldstone boson → the axion
  - receives small mass through non-perturbative effects at QCD scale (200 GeV)

Axions as dark matter candidates

- Like the neutral pion π^0, axion can decay to two photons with rate $1/f_a$ (f_a: Peccei-Quinn energy scale)



- Axion mass given by:

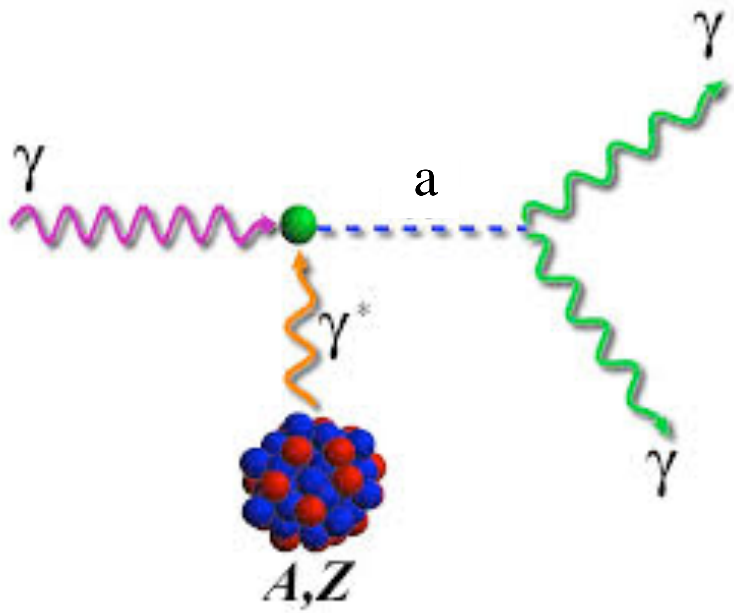
pion mass pion decay constant

$$m_a \approx 0.5 \frac{m_\pi f_\pi}{f_a} \approx \frac{6\,\mathrm{eV}}{[f_a/(10^6\,\mathrm{GeV})]}$$

- Lifetime proportional to $1/m_a^5$ → larger than the age of the universe for $m_a < 10$ eV → would survive as relics from the Big Bang
- Axions never got into thermal equilibrium in early universe → freeze-out arguments for density parameter do not apply

Axions: Constraints from cosmology

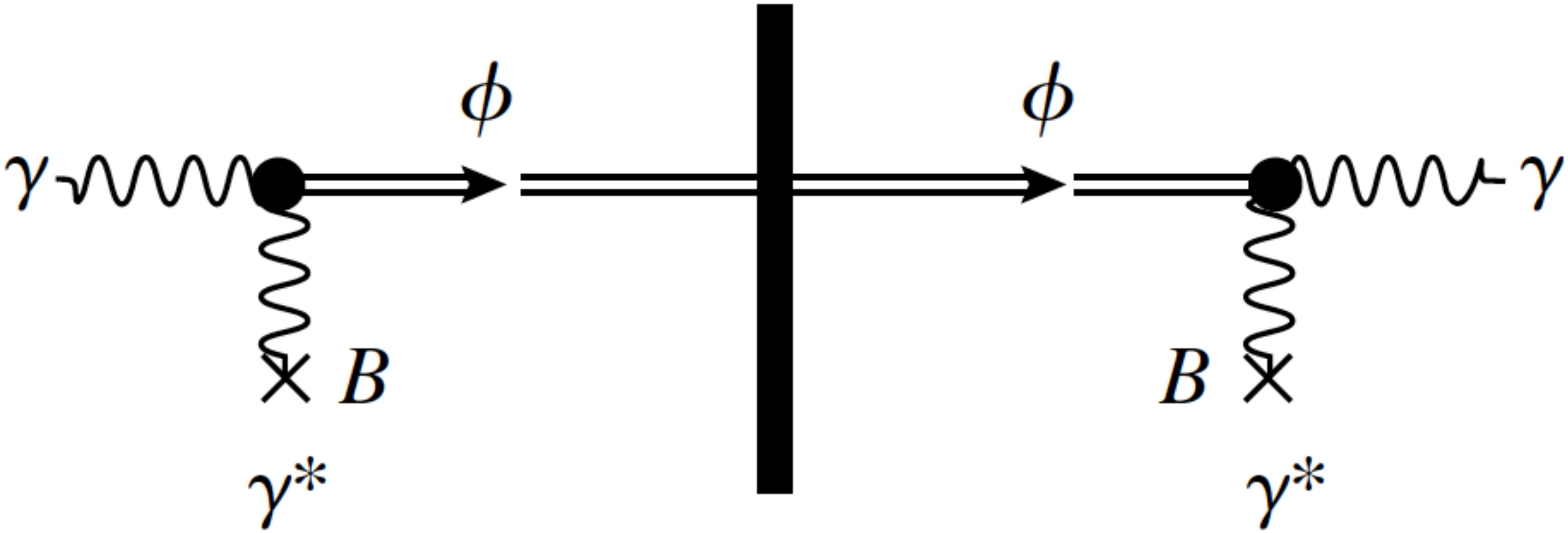
- Axions could be produced in stars by scattering of photon on Coulomb field of a nucleus (Primakoff effect)



- Due to very weak coupling, axions would be emitted from stars and contribute to cooling rate → upper limit on $m_a < 0.01$ eV

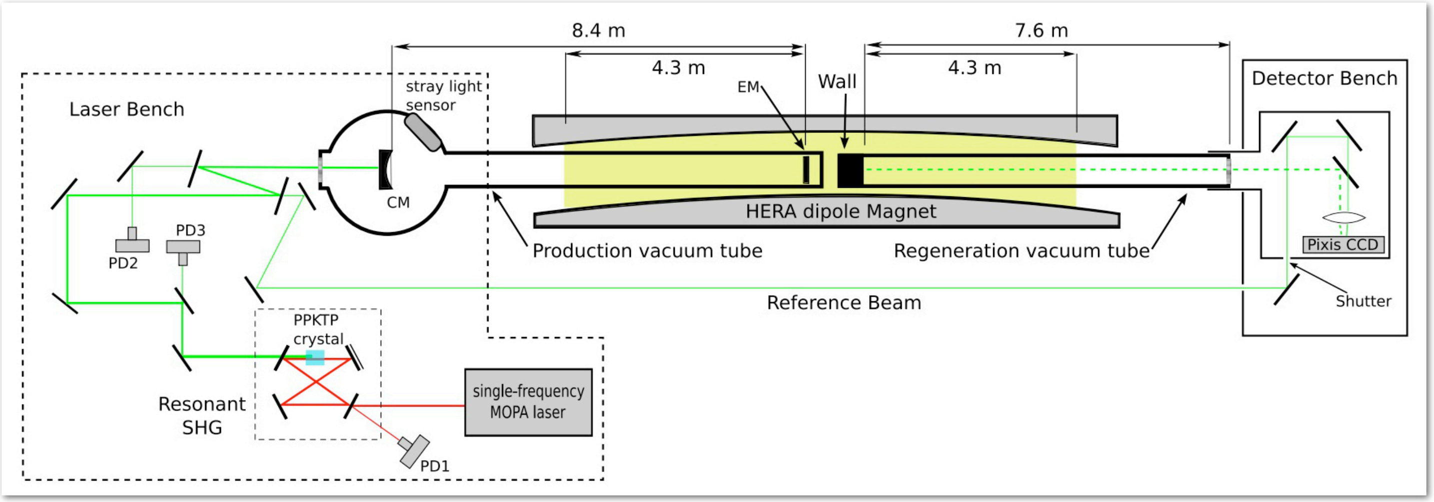
Search for axions: Photon through a wall

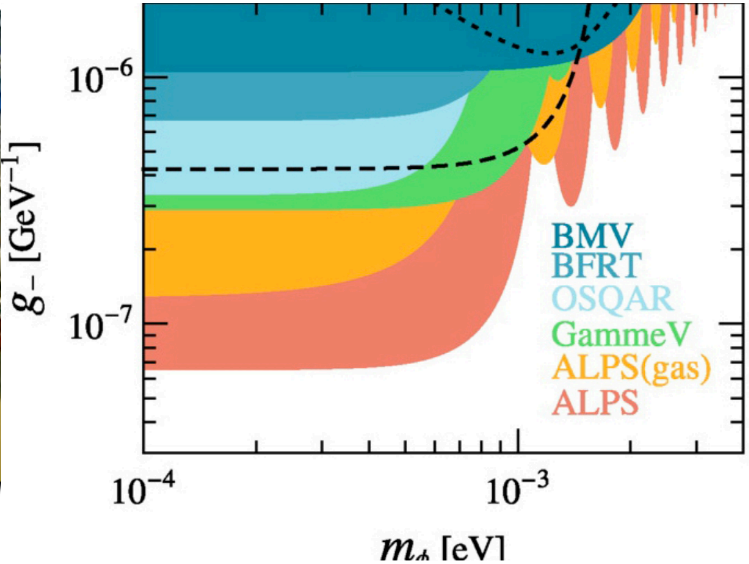
- Incoming photon from a laser interacts with a photon of a very strong magnetic field to produce an axion
- Axion can pass through the wall
- After the wall converts back into a photon in another magnetic field



ALPS experiment at DESY

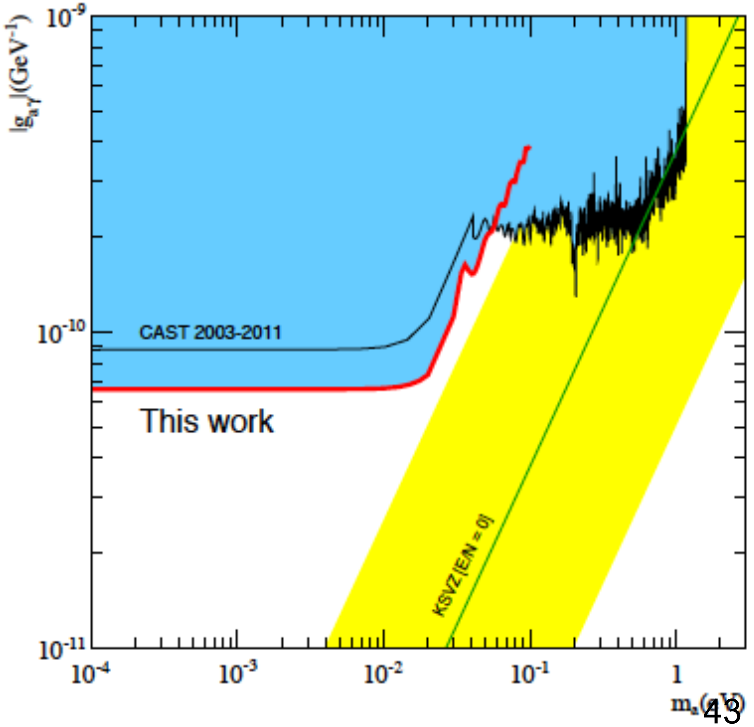
- ALPS – Any light particle search
- Using one of the HERA dipole magnets (5T)





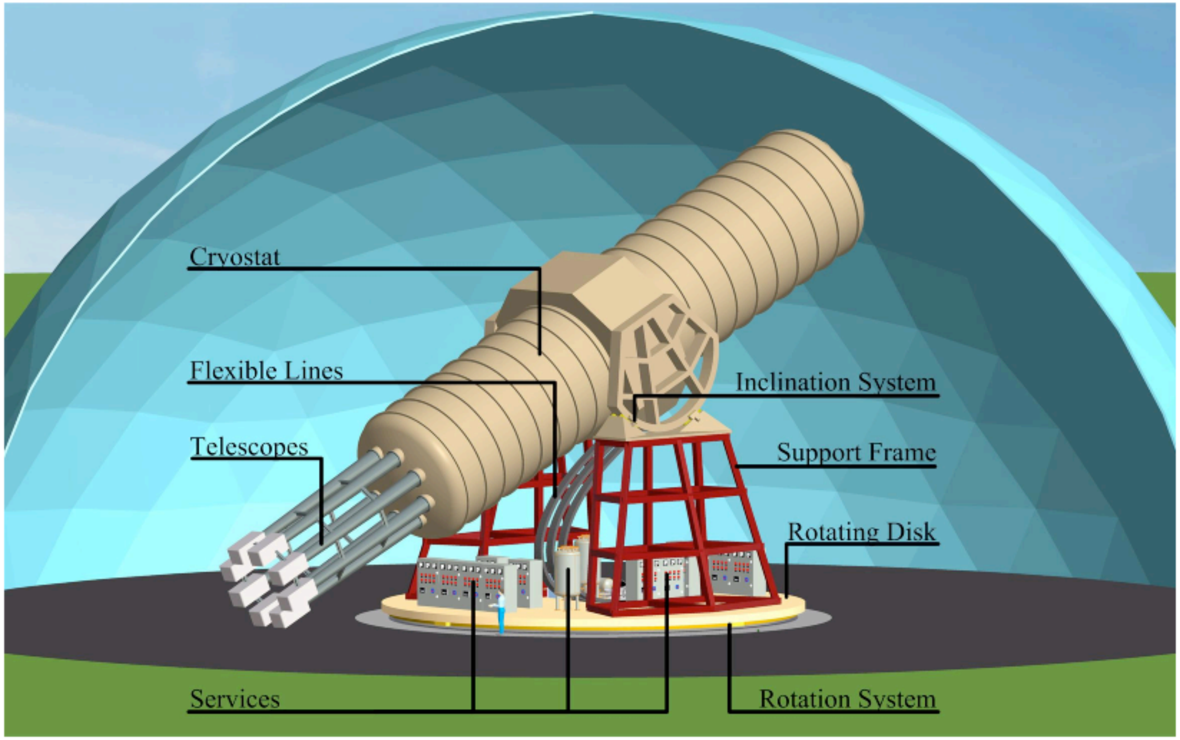
Search for axions: Solar axions

- Look for the decay of axions produced in the sun by the Primakoff effect (excess of x-ray photons)
- Helioscope: Detector that consists of a dipole magnet with bore steered in the direction of the sun and x-ray detectors at the end
- CAST: CERN Axial Solar Telescope – built from 9T LHC magnet
- Set limits on axion mass depending on photon-axion coupling



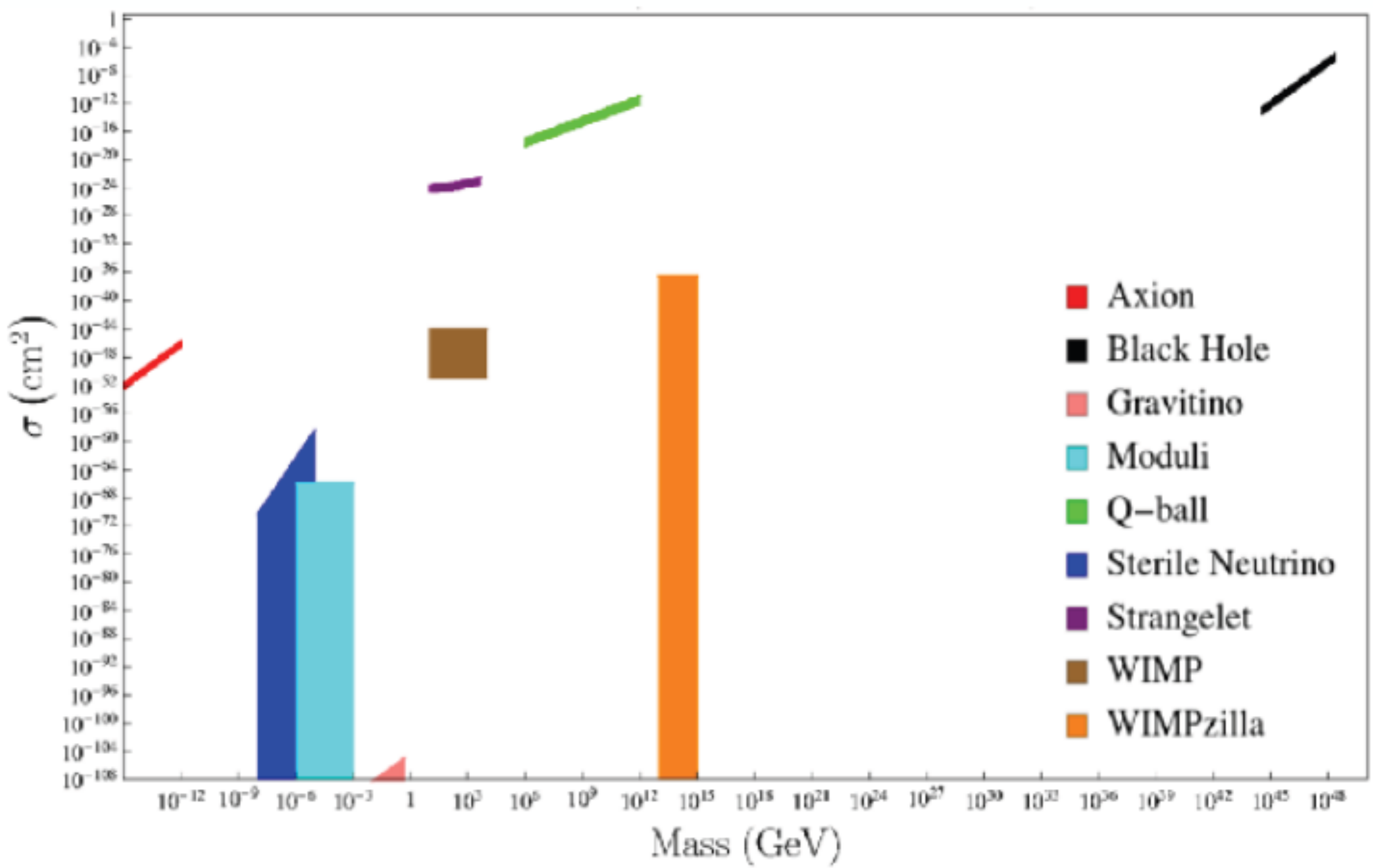
Search for axions: Status

- QCD axion has well bounded parameter space of mass and couplings
- Several models propose axion-like particles (ALP) with slightly different properties → vast and largely unexplored search space
- New experiments proposed: International Axion Observatory IAXO



Summary

- Evidence for dark matter from cosmological observations
- Nature of dark matter is still unknown
- Dark matter might be due to new particles – many proposals – lots of experimental searches to explore the different options



Closer to Truth with Lee Smolin

"Why does dark matter really matter?"

https://www.youtube.com/watch?v=Go0_2e870Vk

References

- Lecture includes material prepared by L. Baudis, J. Frieman, M. Galloway, A. Kish, F. Pauss, D. Perkins

Backup

Evolution of the universe

Basic effect: Competition between equilibrium (thermal, kinetic, chemical) and expansion

- State of equilibrium described by Γ: rate of reactions
- Expansion described by H: Hubble constant

- As long as $\Gamma/H > 1$: interactions between particles strive towards equilibrium
- As the temperature decreases → Γ decreases
- At some point $\Gamma/H < 1$ → Deviation from equilibrium: "freezing" of reactions

→ Today's abundances are very close to the primordial abundances at the time of freezing

Friedmann equation

$$\Omega_R + \Omega_M + \Omega_\Lambda + \Omega_k = 1$$

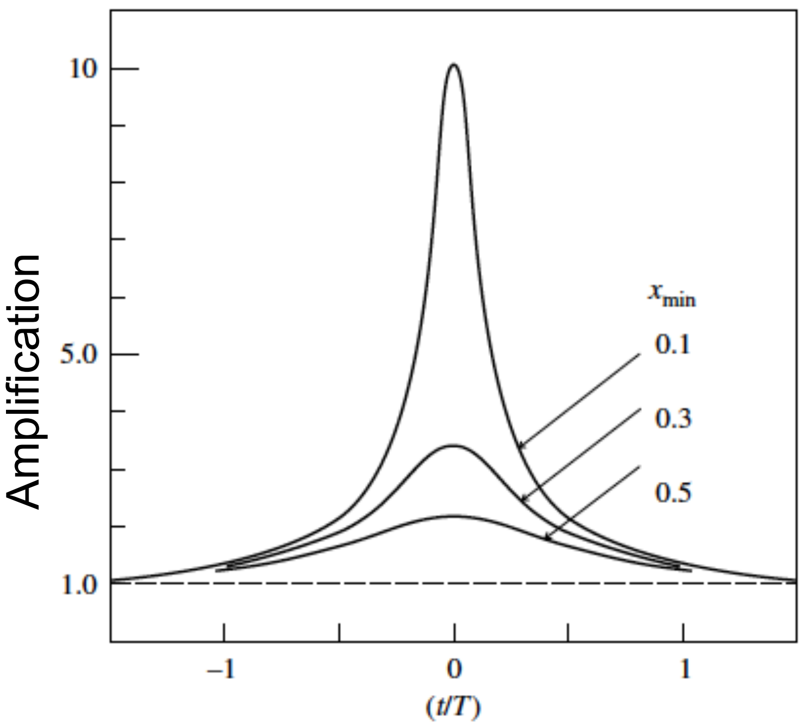
Ω_R – radiation density
Ω_M – non-relativistic matter density (baryonic + dark)
Ω_Λ – cosmological constant (vacuum density)
Ω_k – spatial curvature density

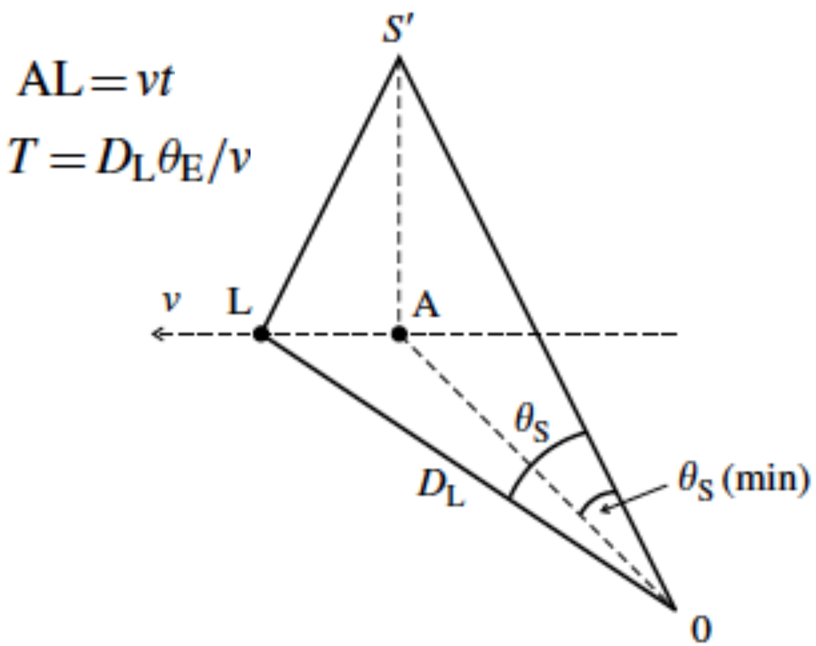
- At the present time:

- Ω_R is negligible compared to $\Omega_M = 0.308 \pm 0.012$
- Luminous baryonic matter is $\Omega_{lum} = 0.01$
- Spatial curvature very close to zero: $|\Omega_k| < 0.005$
- Major contribution from $\Omega_\Lambda \rightarrow$ related to dark energy

Microlensing

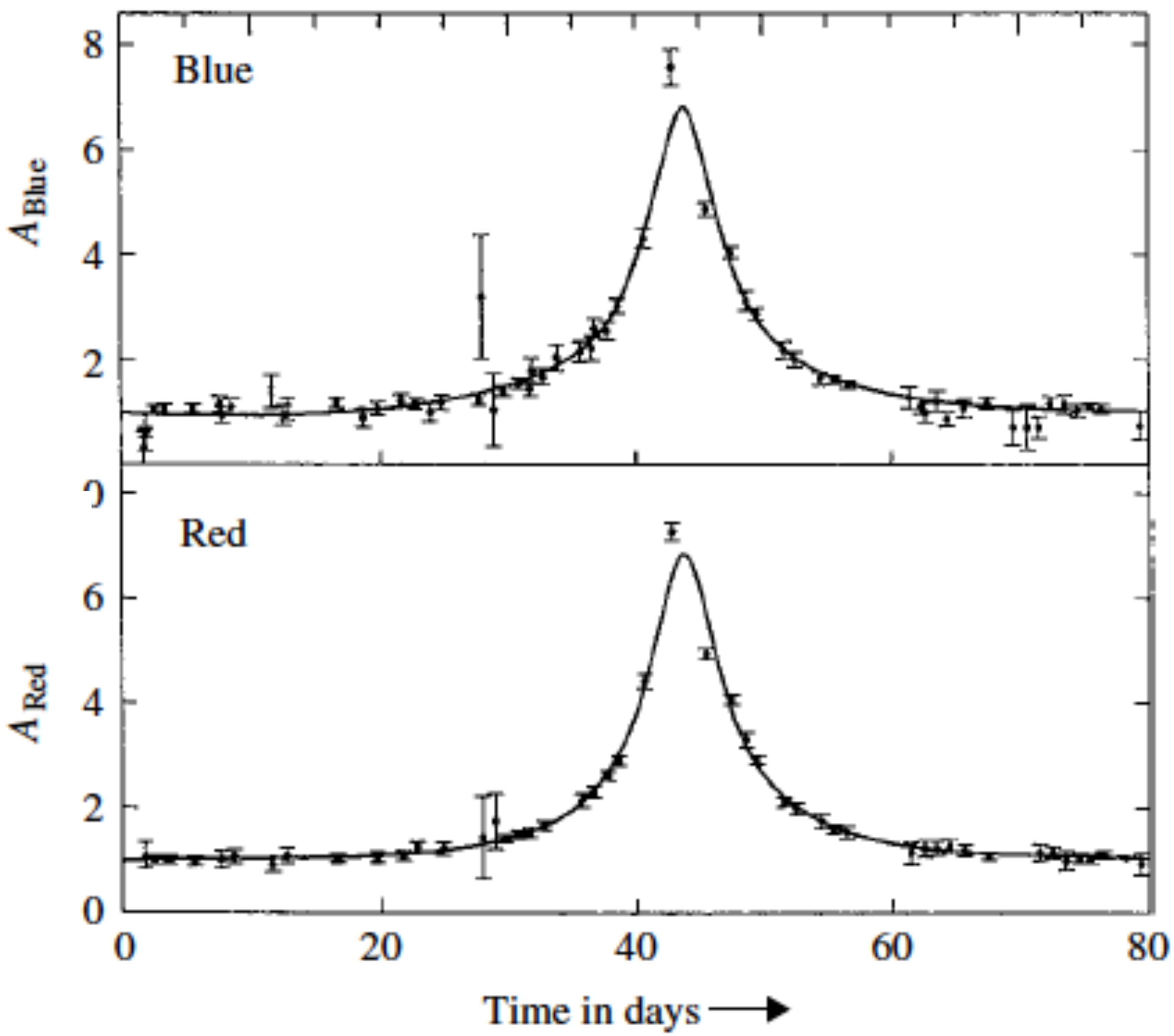
- Gravitational lensing commonly observed for massive objects (galaxies or clusters)
- Individual stars do not produce distinct separated clusters (resolution of optical telescope too poor)
- However, fluctuation in intensity can be observed → micro-lensing





Microlensing

- Example of microlensing event of a star in the Magellanic cloud
- Characterized by same amplification at different wavelength



Photon with momentum p
has gravitational mass p/c
receives transverse momentum Δp α p from gravitational field

→ deflection Δp/p independent of wavelength h/p

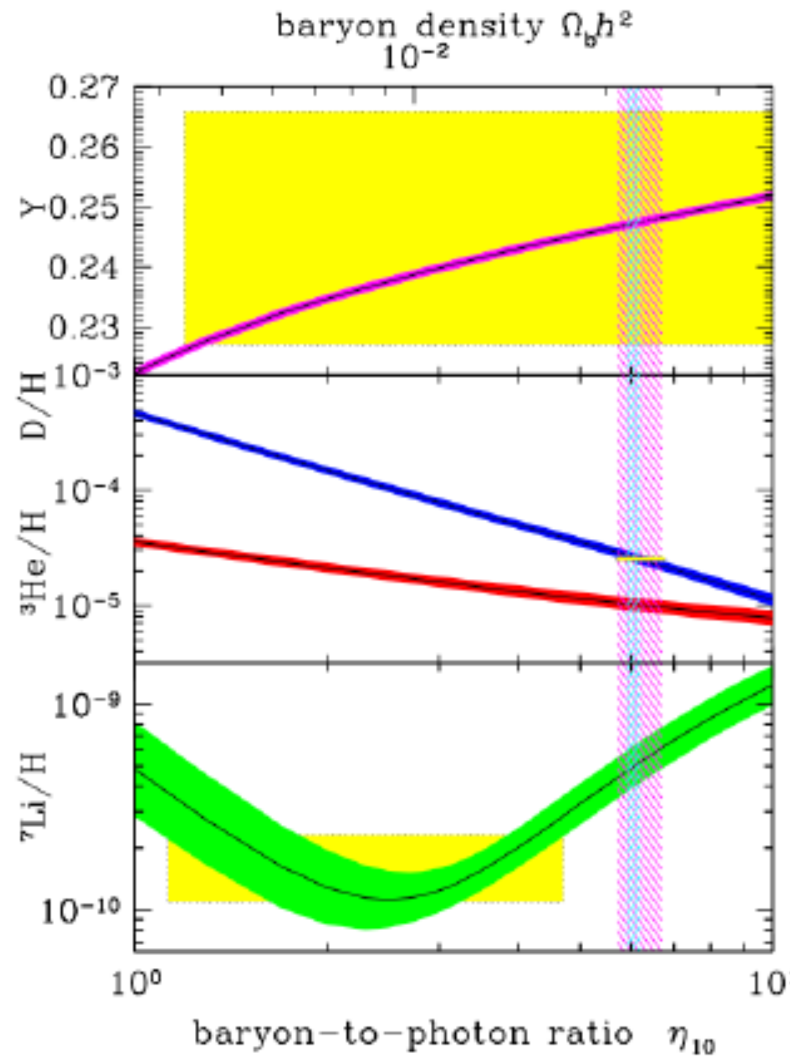
Big Bang Nucleosynthesis

- A few seconds to minutes after big bang, neutrons and protons fuse to form light elements (D, He, Li)
- Largest source of deuterium is from BBN (observed abundance is lower limit)
- Using nuclear reactions and cross sections, can predict elemental abundances

→ BBN predicts Ω_b~0.05 (consistent with observed light-element abundances)

→ Observations Ω_m~0.2-0.3

→ Baryonic matter only ~20%



Fields, Molaro, Sarkar, 2014
arxiv:1412.1408

CMB and structure growth

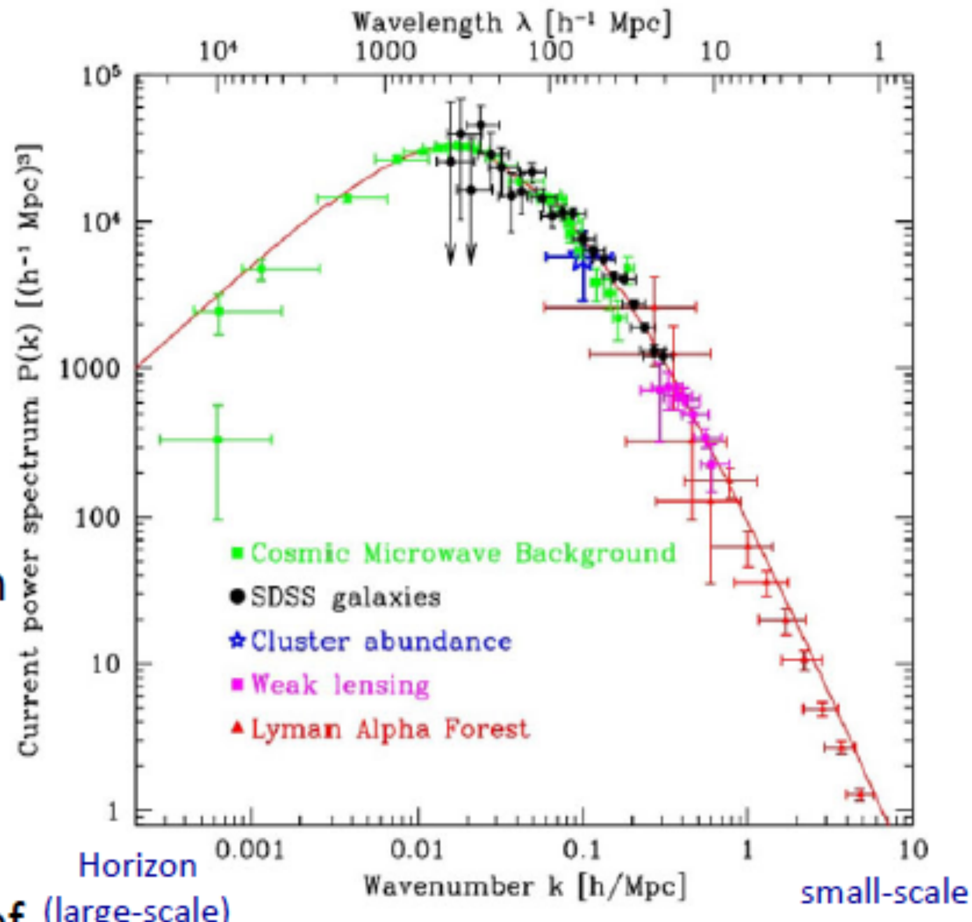
Primordial power spectrum tells how amplitude fluctuations grow in time, i.e. clustering at different scales

- Matter-radiation equality ~ 1eV
- Recombination (turnover in spectrum) ~0.3 eV, baryonic infall only: not enough time to form structures

→Need electrically neutral matter in early Universe for structure formation to be consistent with observed anisotropies

→Warm DM suppresses small-scale structure, can set constraints

→Active area of simulations, variety of mass functions



Tegmark et al, 2003
arxiv:0310723