What are we?
Where do we come from?
Where are we going?

The aim of particle physics:
What is matter in the Universe made of?

John Ellis

KING'S College LONDON

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

The Rotation Curves of Galaxies

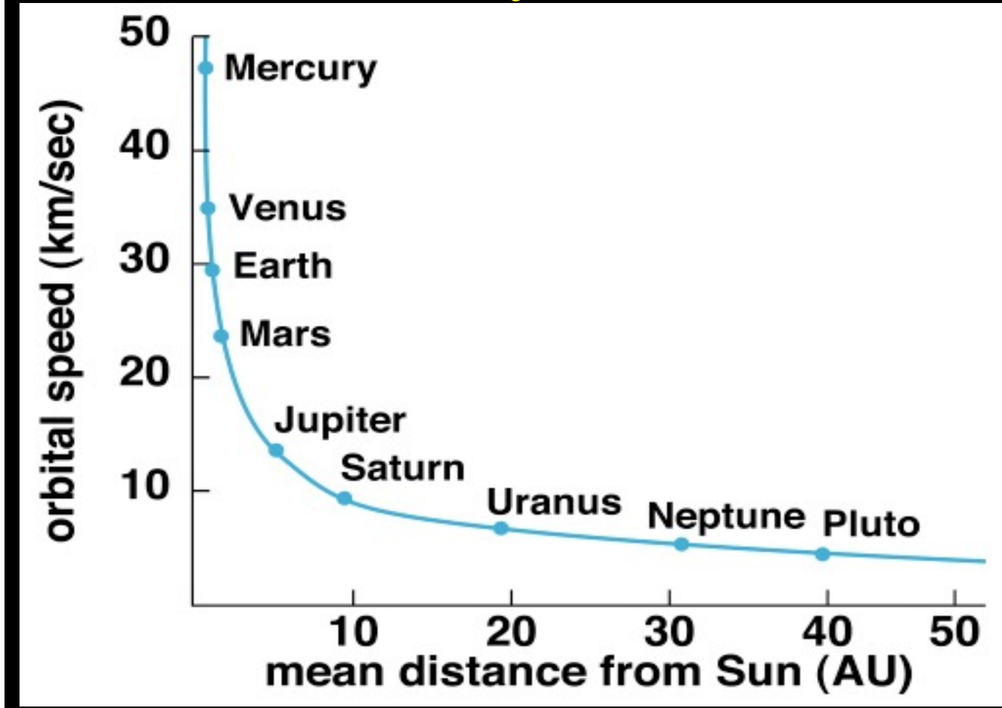
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

- **Further strong evidence for dark matter**
- Also:
  - Structure formation, cosmic background radiation, …

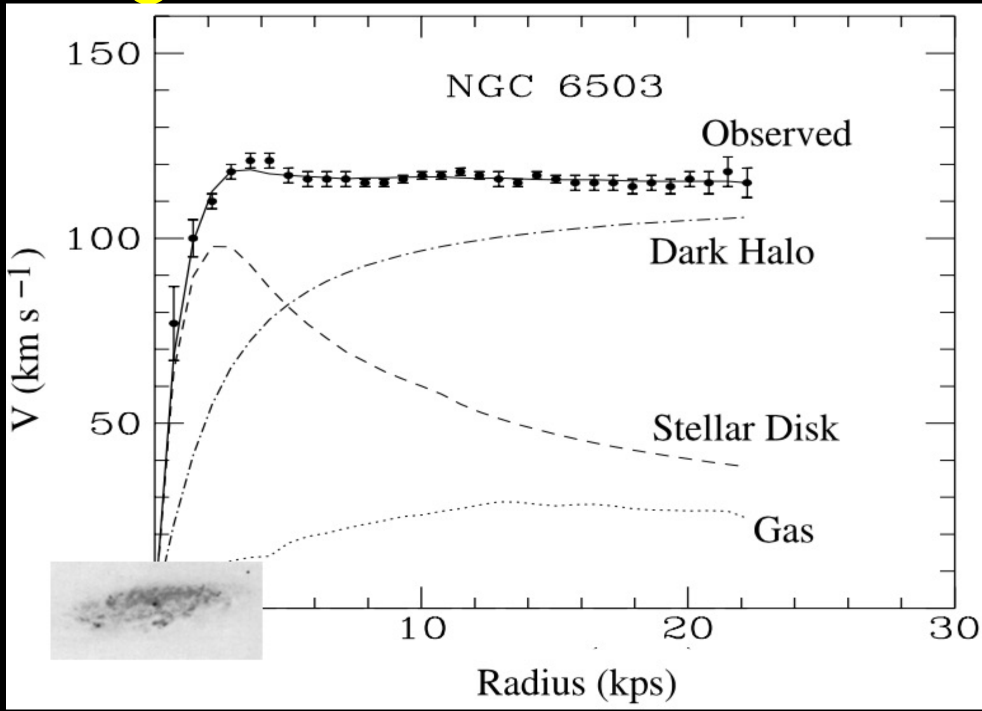
Galactic Rotation Curves

- In the Solar System



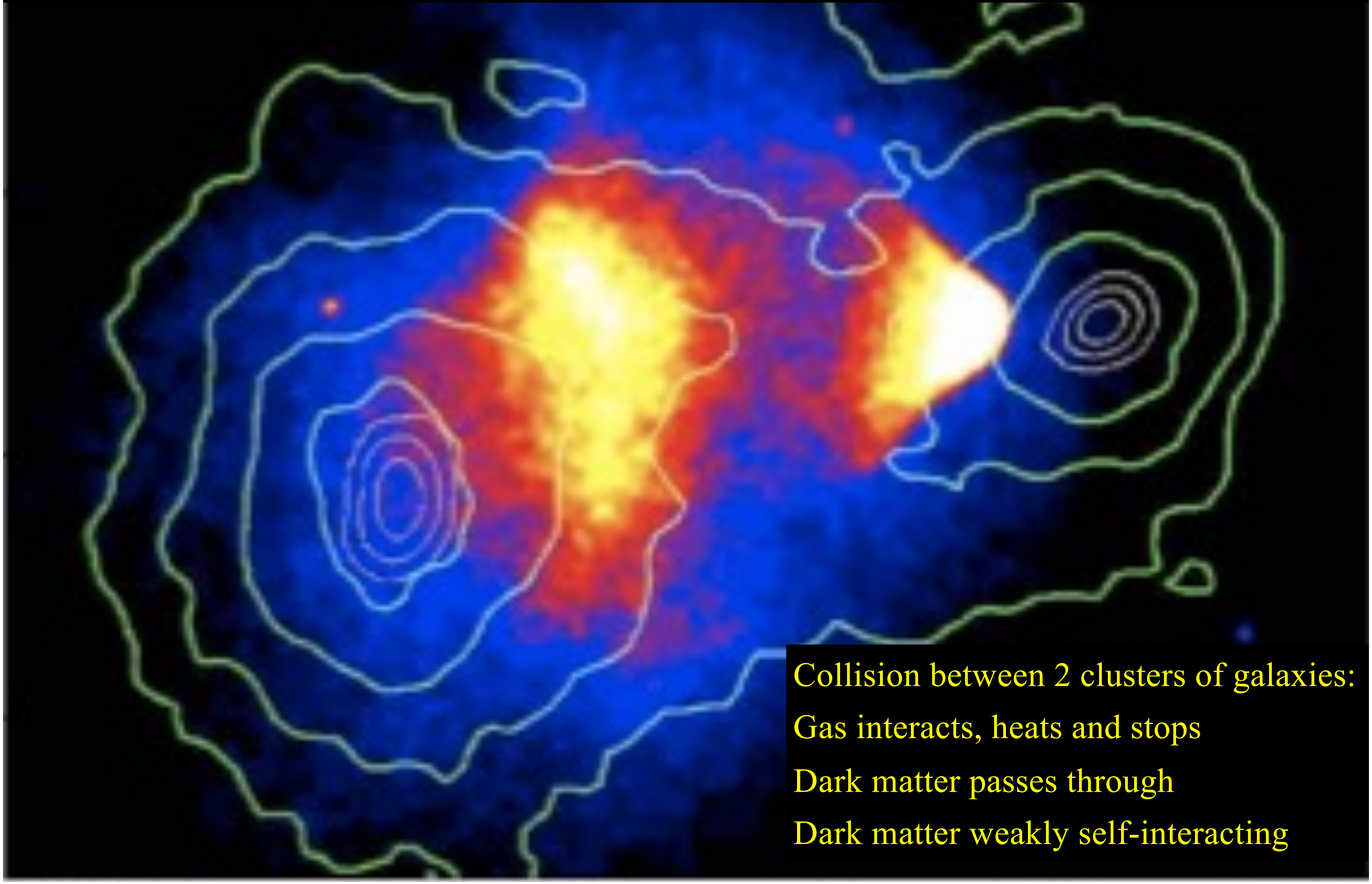
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



- The velocities do not decrease with distance
- Dark matter spread out

Biggest Collider in the Universe?



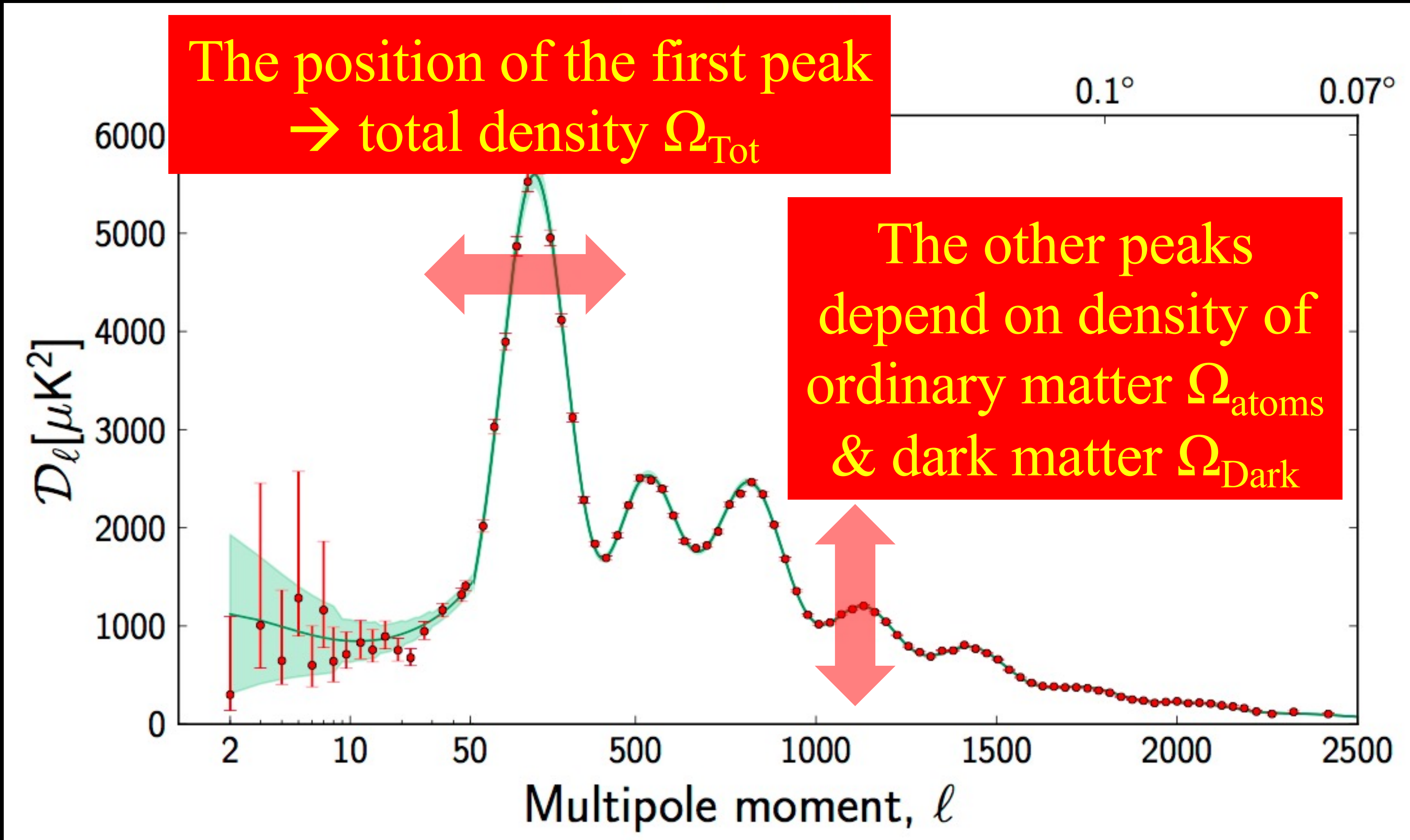
Collision between 2 clusters of galaxies:

Gas interacts, heats and stops

Dark matter passes through

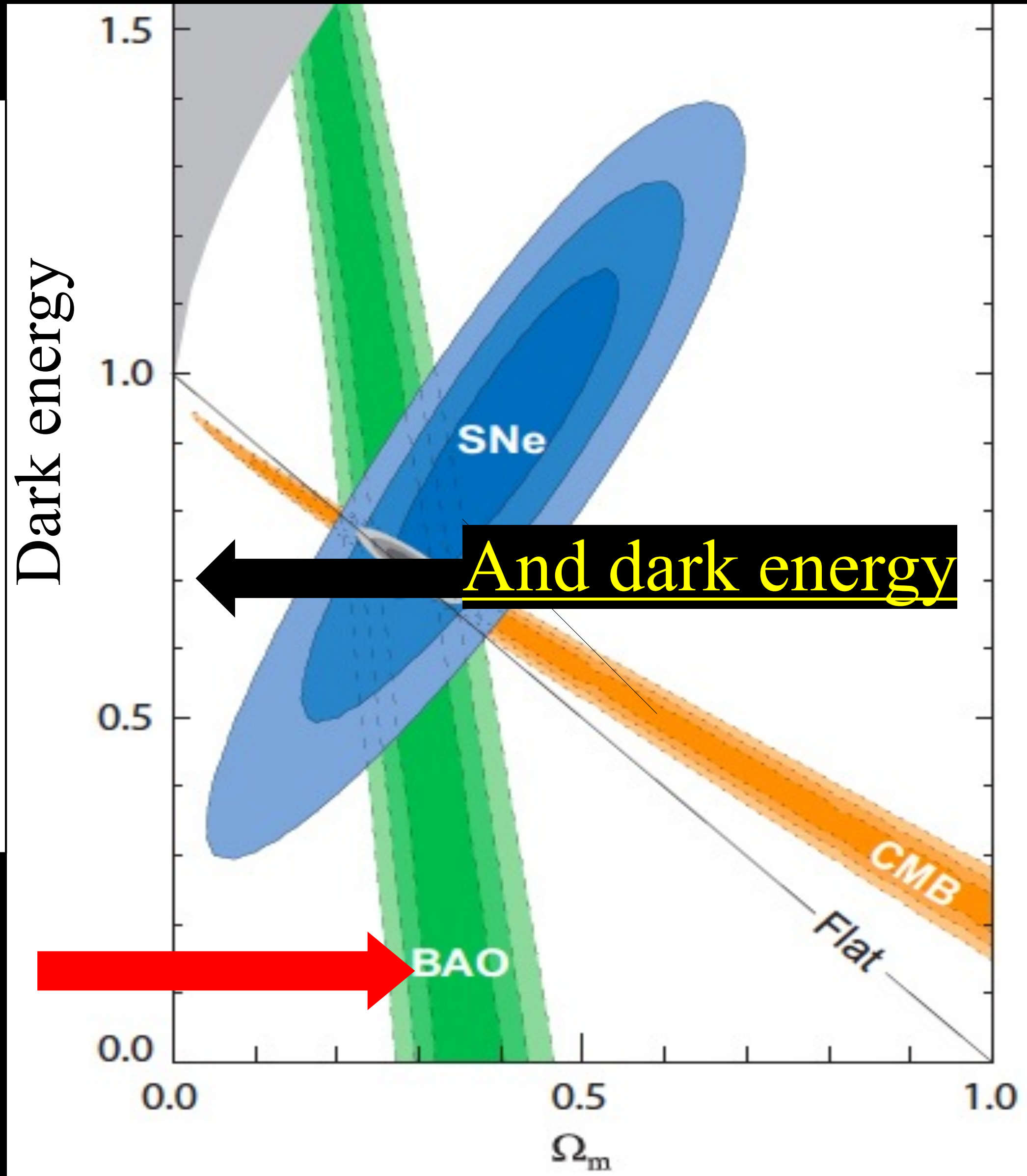
Dark matter weakly self-interacting

The Spectrum of Fluctuations in the Cosmic Microwave Background



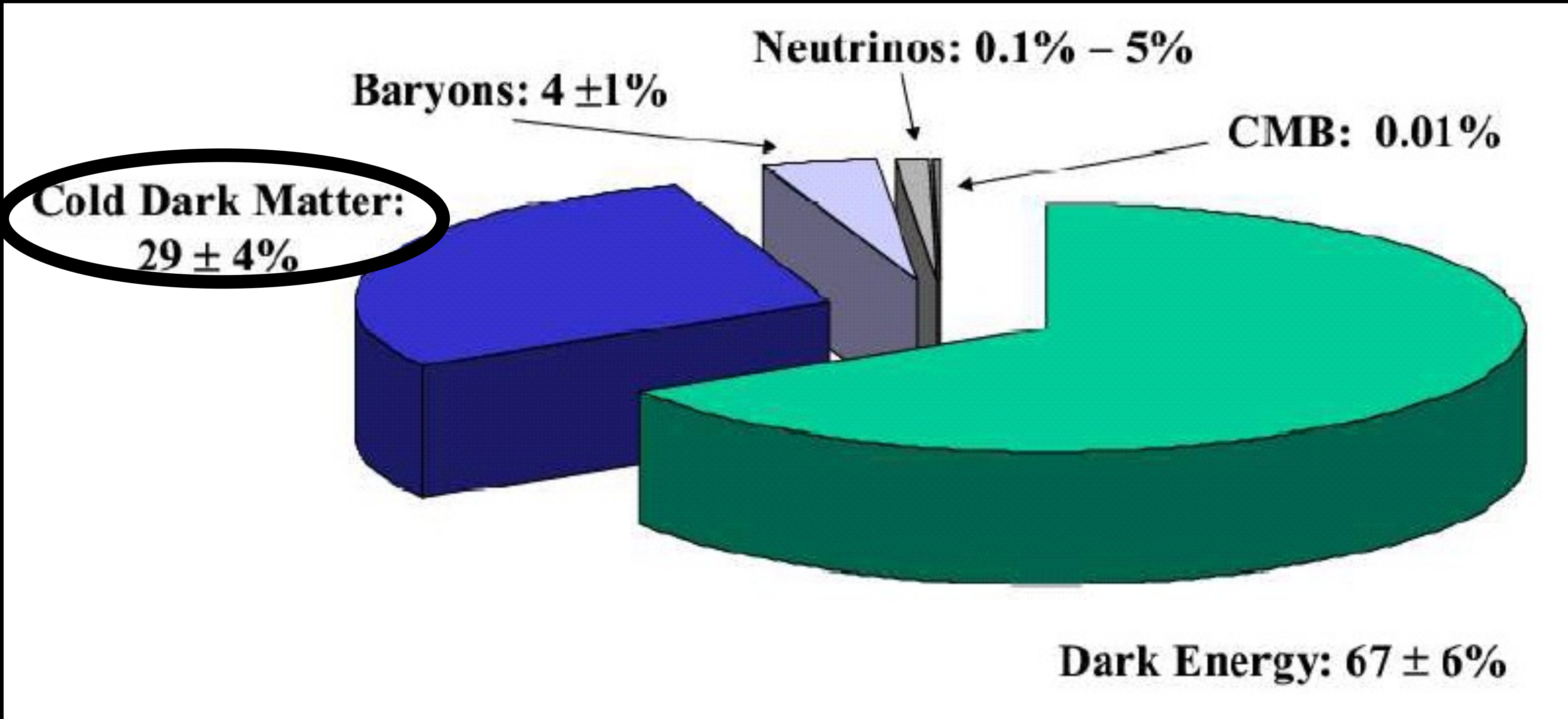
The Content of the Universe

- According to
  - Microwave background
  - Supernovae
  - Structures (galaxies, clusters, …) in the Universe



There is dark matter

Strange Recipe for a Universe

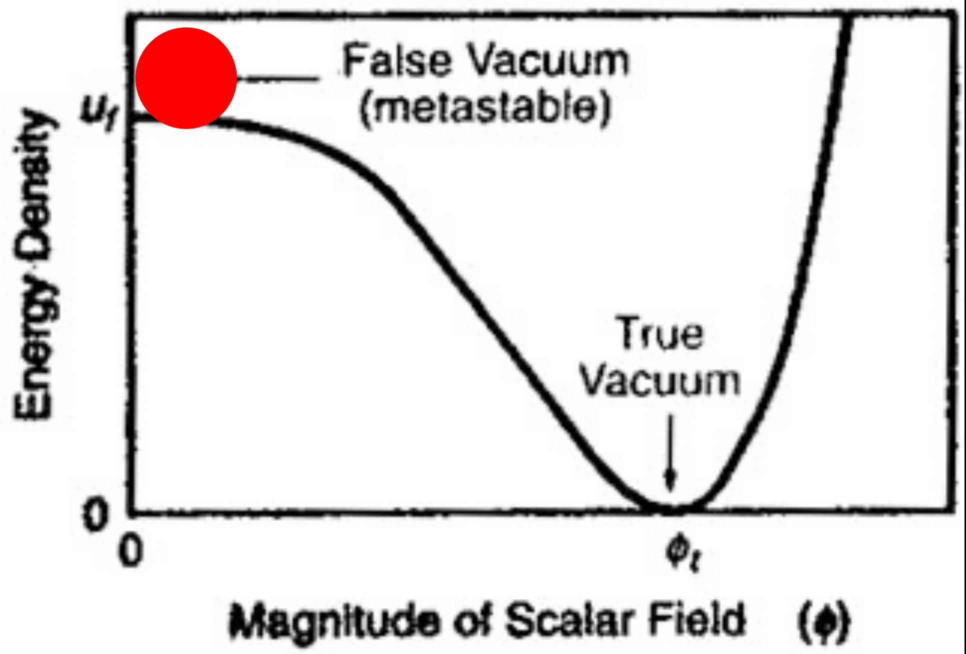


The 'Standard Model' of the Universe indicated by astrophysics and cosmology

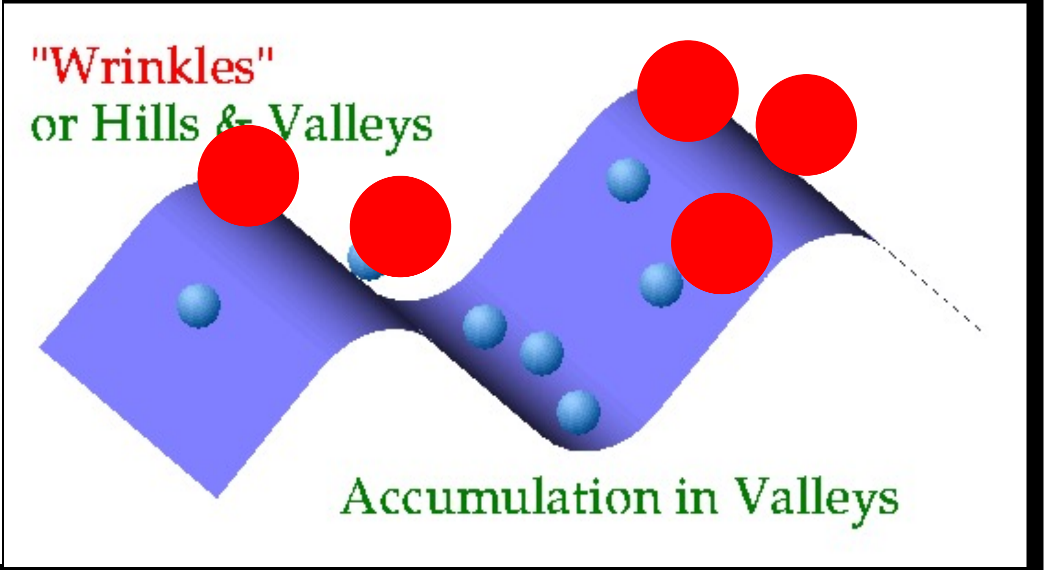
The Origin of Structures in the Universe

Small primordial quantum fluctuations: ~ $1/10^5$

Gravitational instability: dark matter falls into the gravitational potential wells, visible matter follows

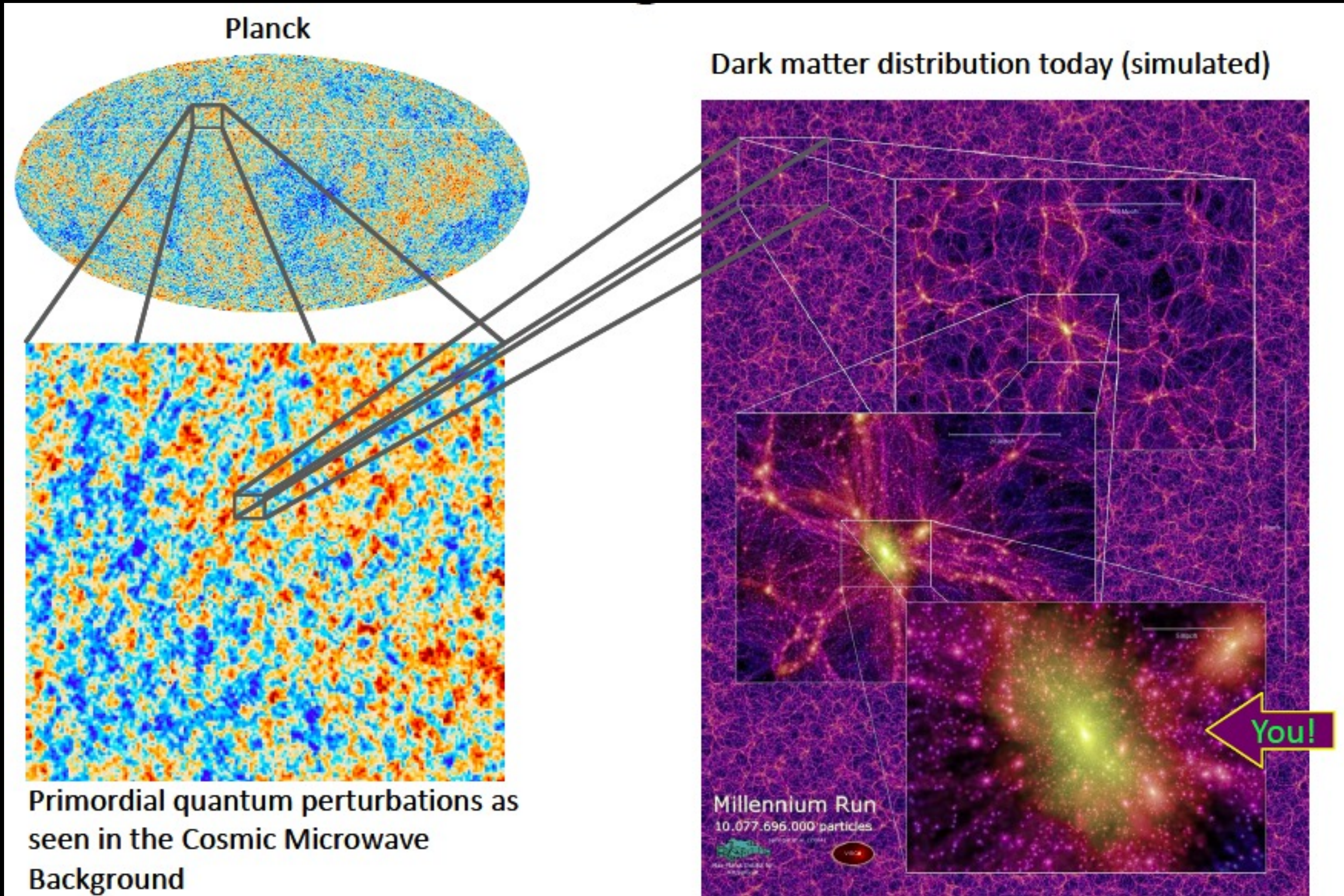


Become density fluctuations



Become structures in Universe

Dark Matter Generated Structures



A Successful Theory of the Formation of Structures in the Universe

Dark matter:

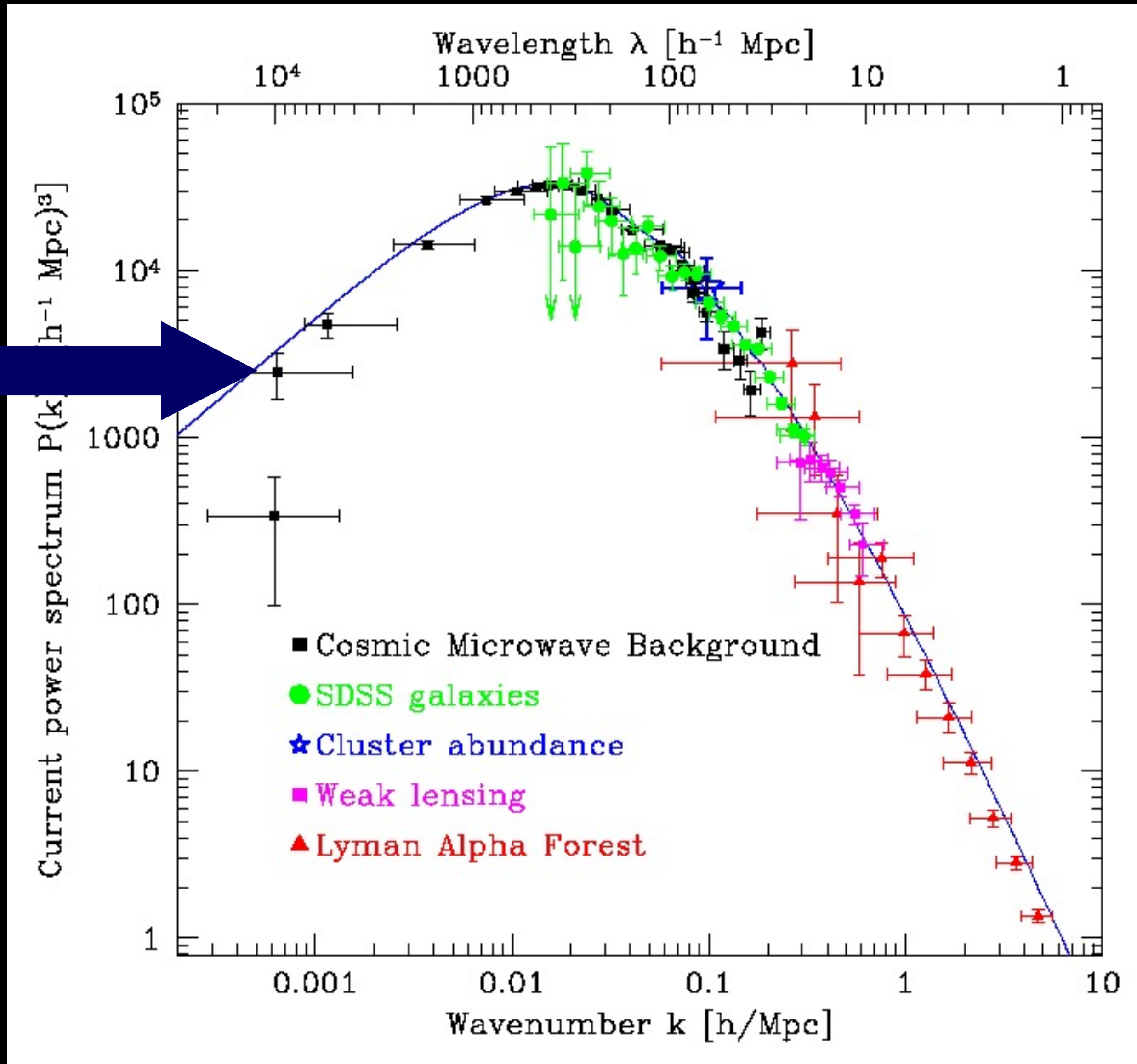
$\Omega_{CDM} \sim 0.25$,

Visible matter:

$\Omega_b \sim 0.05$,

Dark energy:

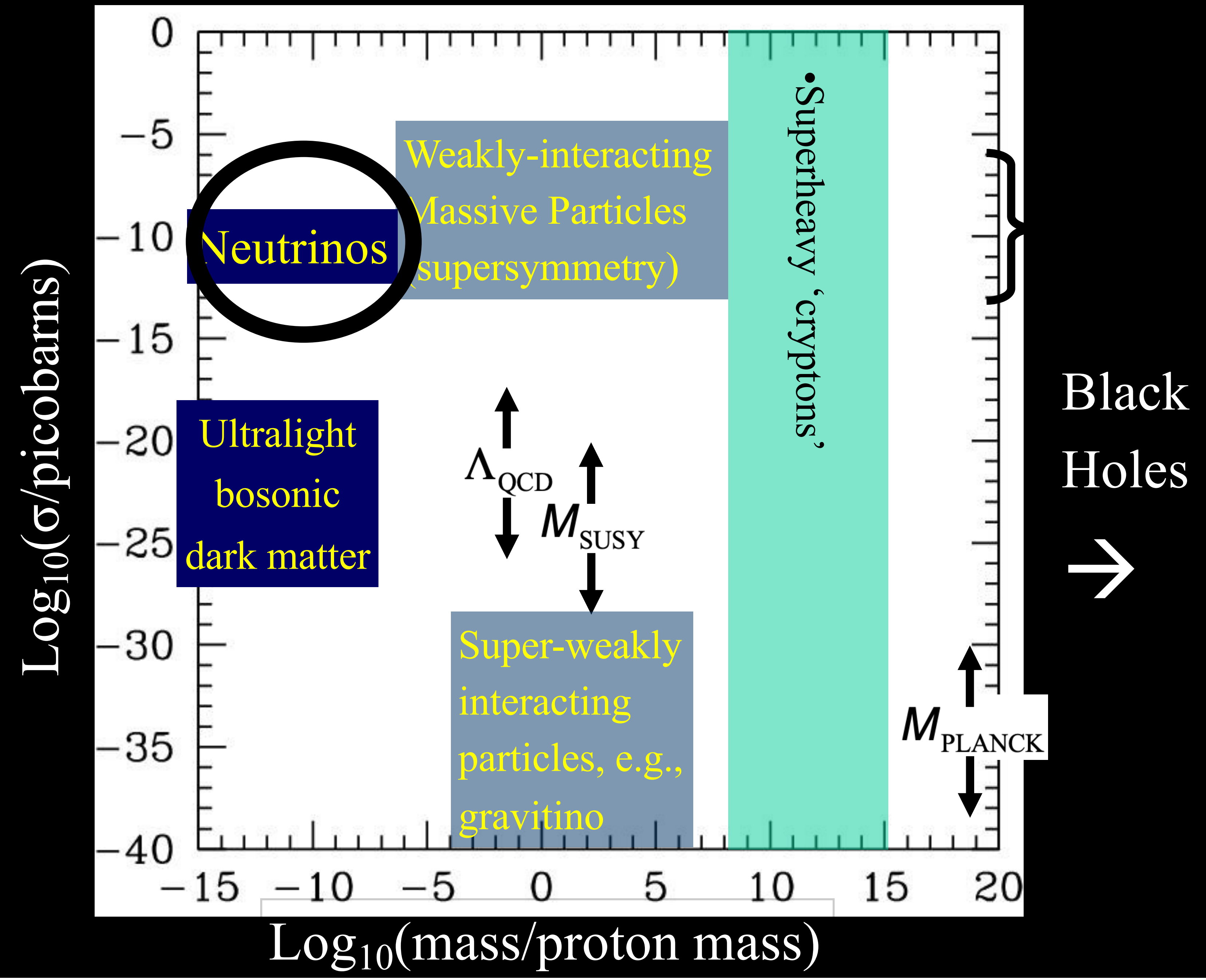
$\Omega_\Lambda \sim 0.7$



Properties of Dark Matter

- Should not have (much) electric charge
  - Otherwise we would have seen it
- Should interact weakly with ordinary matter
  - Otherwise we would have detected it, either directly or astrophysically
- Should not be too light
  - Needed for forming and holding together structures in the Universe: galaxies, clusters, …

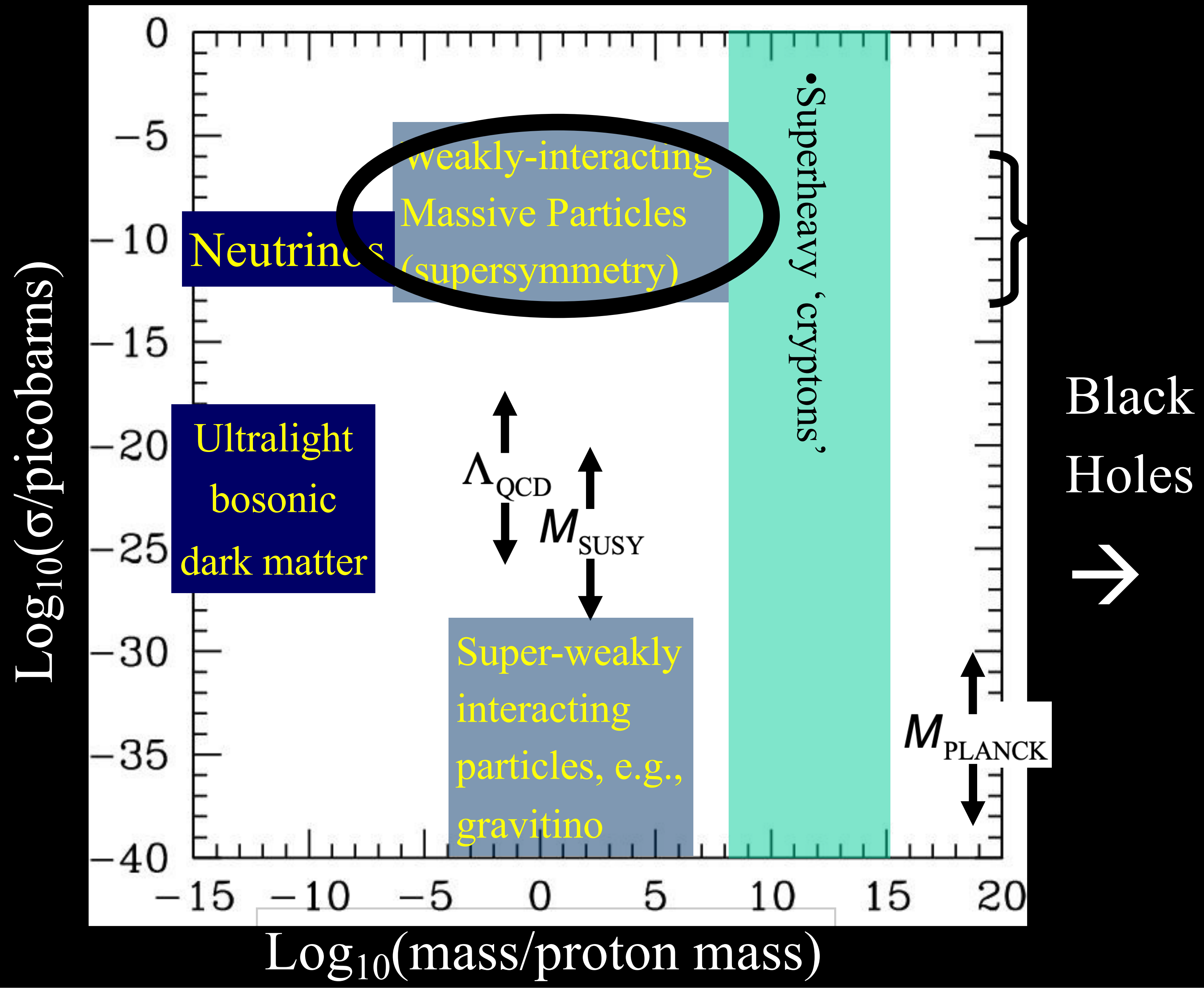
Particle Dark Matter Candidates



Neutrinos

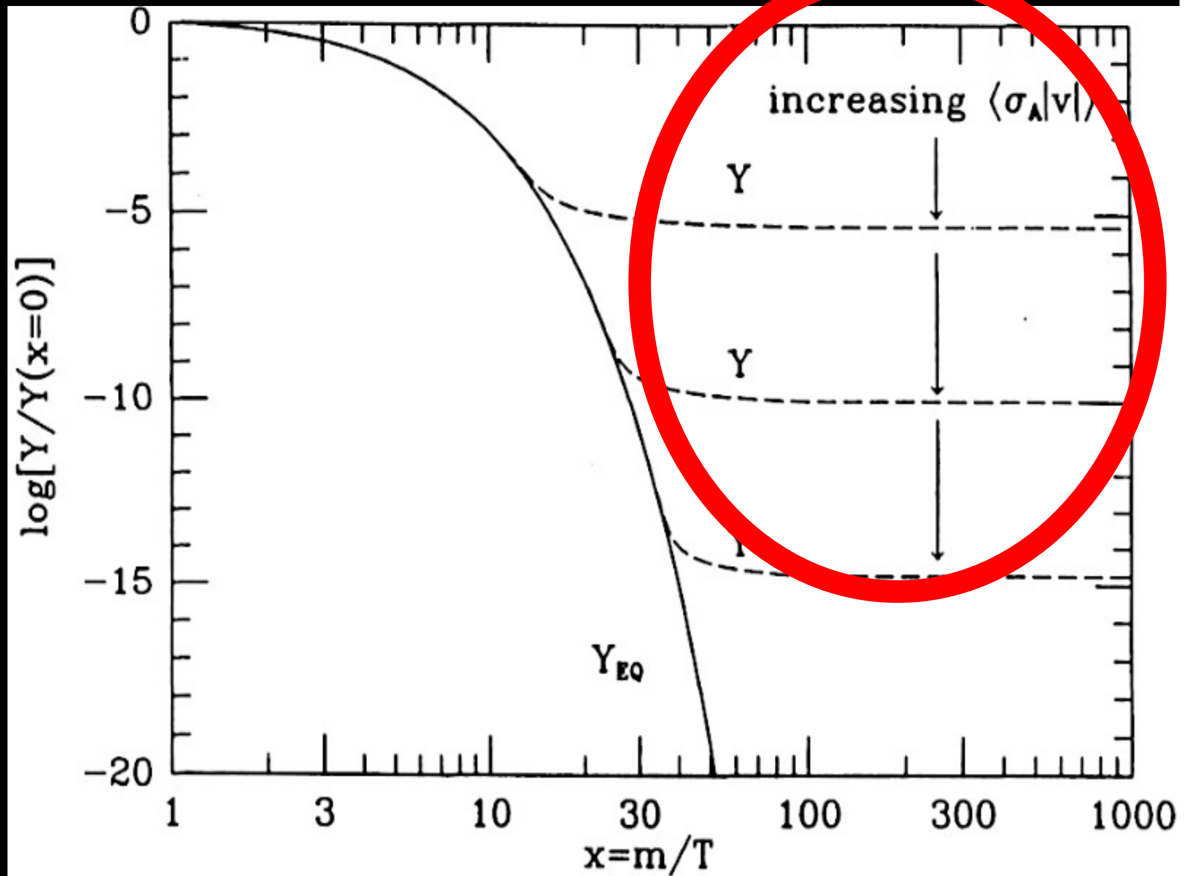
- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe some other neutrinos beyond the Standard Model? **Sterile neutrinos?**

Particle Dark Matter Candidates

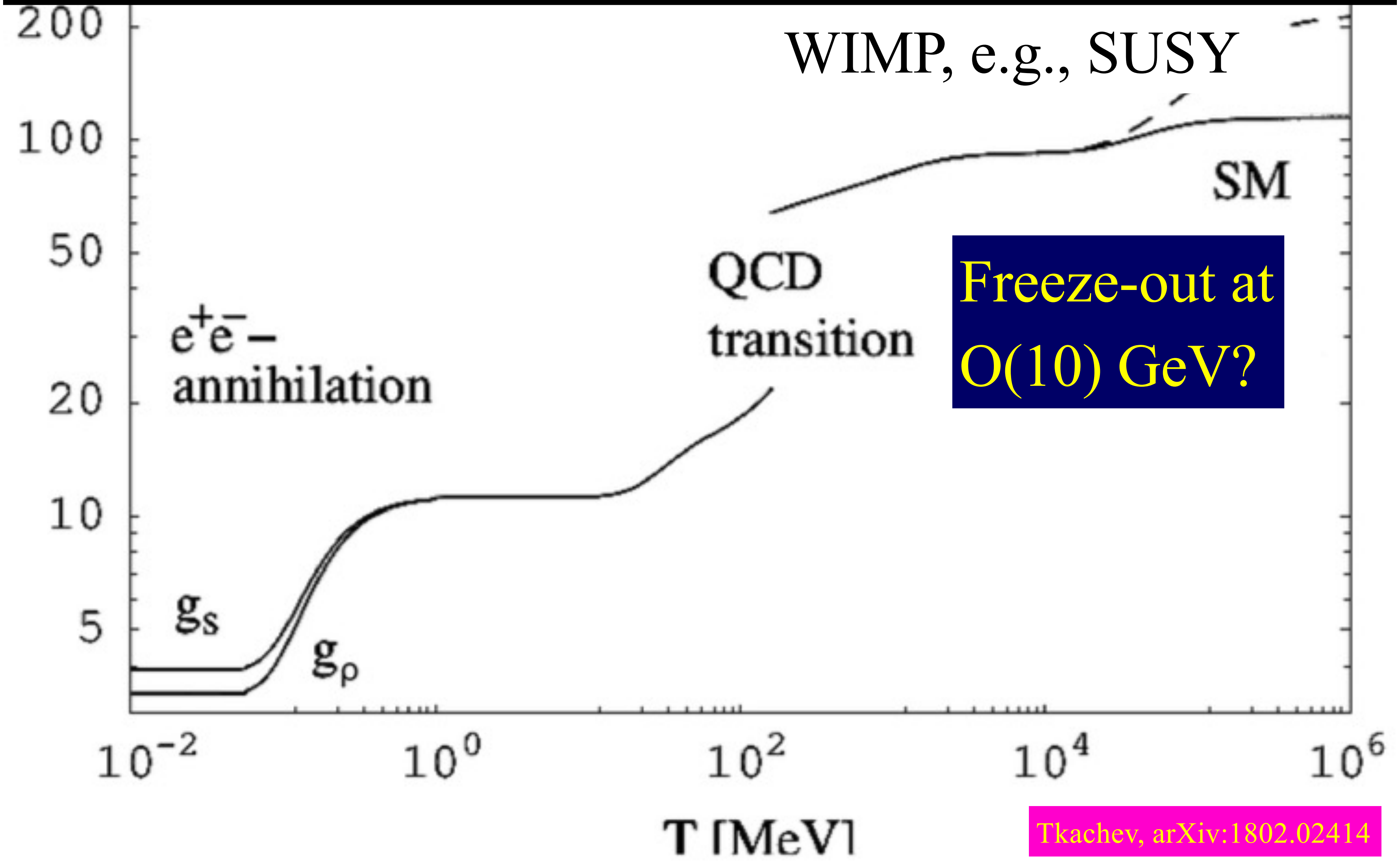


Weakly-Interacting Massive Particles (WIMPs)

- Expected to have been numerous in the primordial Universe when it was a fraction of a second old, full of a primordial hot soup
- Would have cooled down as Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter
- "Freeze-out"
- Larger σ → lower Y



‘Standard’ Thermal History of Early Universe



Freeze-out at O(10) GeV?

Tkachev, arXiv:1802.02414

The WIMP 'Miracle'

- The TeV scale from cosmology:

$$\mathrm{TeV} \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}$$

- Generic density from freeze-out:

$$\Omega_X h_0^2 \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}} \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{\mathrm{TeV}^2}$$

- Generic annihilation cross-section:

$$\sigma v \simeq \frac{c \alpha^2}{m^2}$$

- Generic relic mass:

$$m \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}\; 16\alpha \sqrt{C} \sqrt{\frac{\Omega_X h_0^2}{0.25}}$$

$$\simeq \mathrm{TeV}\; 16\alpha \sqrt{C} \sqrt{\frac{\Omega_X h_0^2}{0.25}} .$$

- Putting the numbers in:

$$m \lesssim \tfrac{1}{2} \sqrt{10C}\,\mathrm{TeV} \lesssim 5\,\mathrm{TeV}$$

Dimopoulos, PLB246, 347 (1990)

WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry**

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

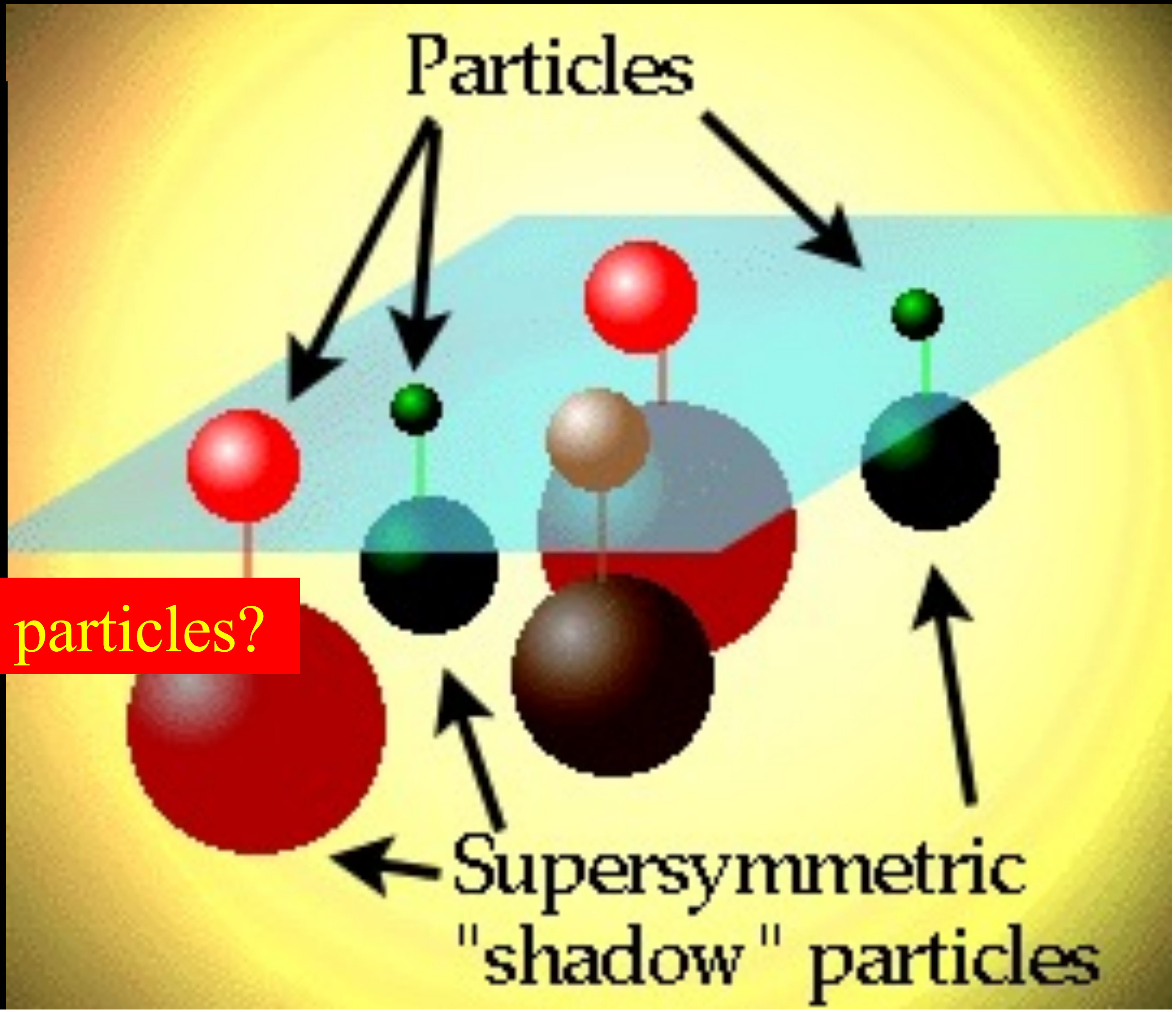
- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  – Should be < 130 GeV in simple models
- Successful predictions for couplings
  – Should be within few % of SM values
- Naturalness, GUTs, string, …, **dark matter**

What is the Dark Matter in the Universe?

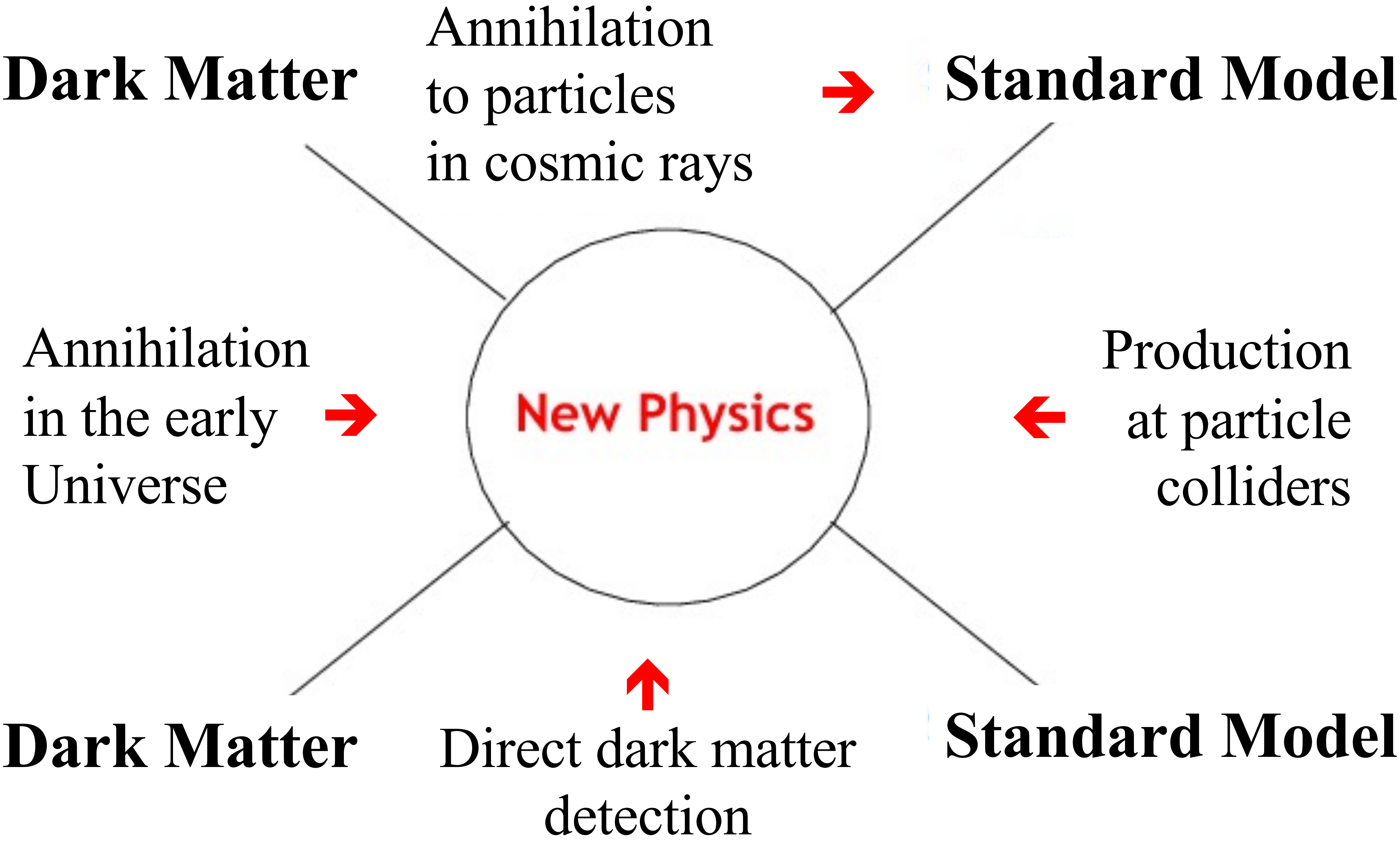
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Made of unknown particles?

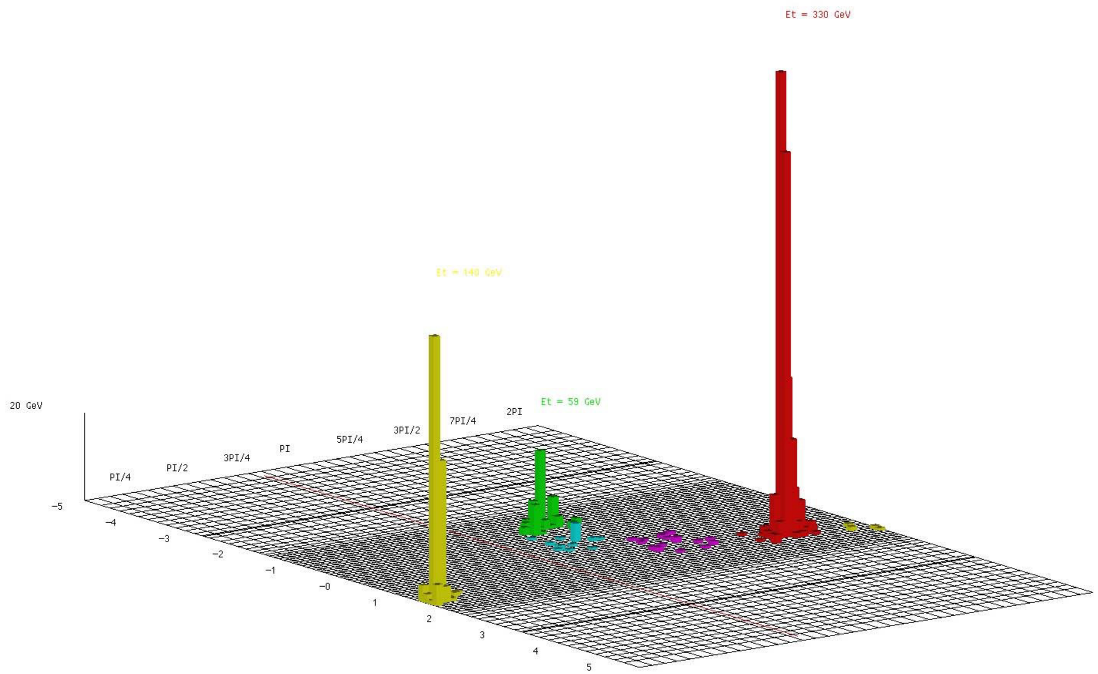
We are searching for them at the LHC

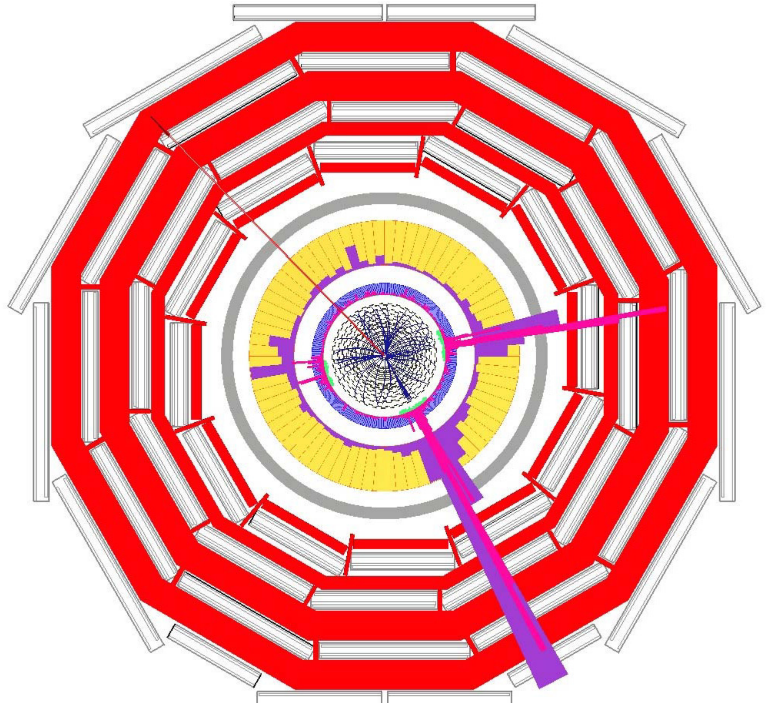


Searches for Dark Matter



Classic Dark Matter Signature

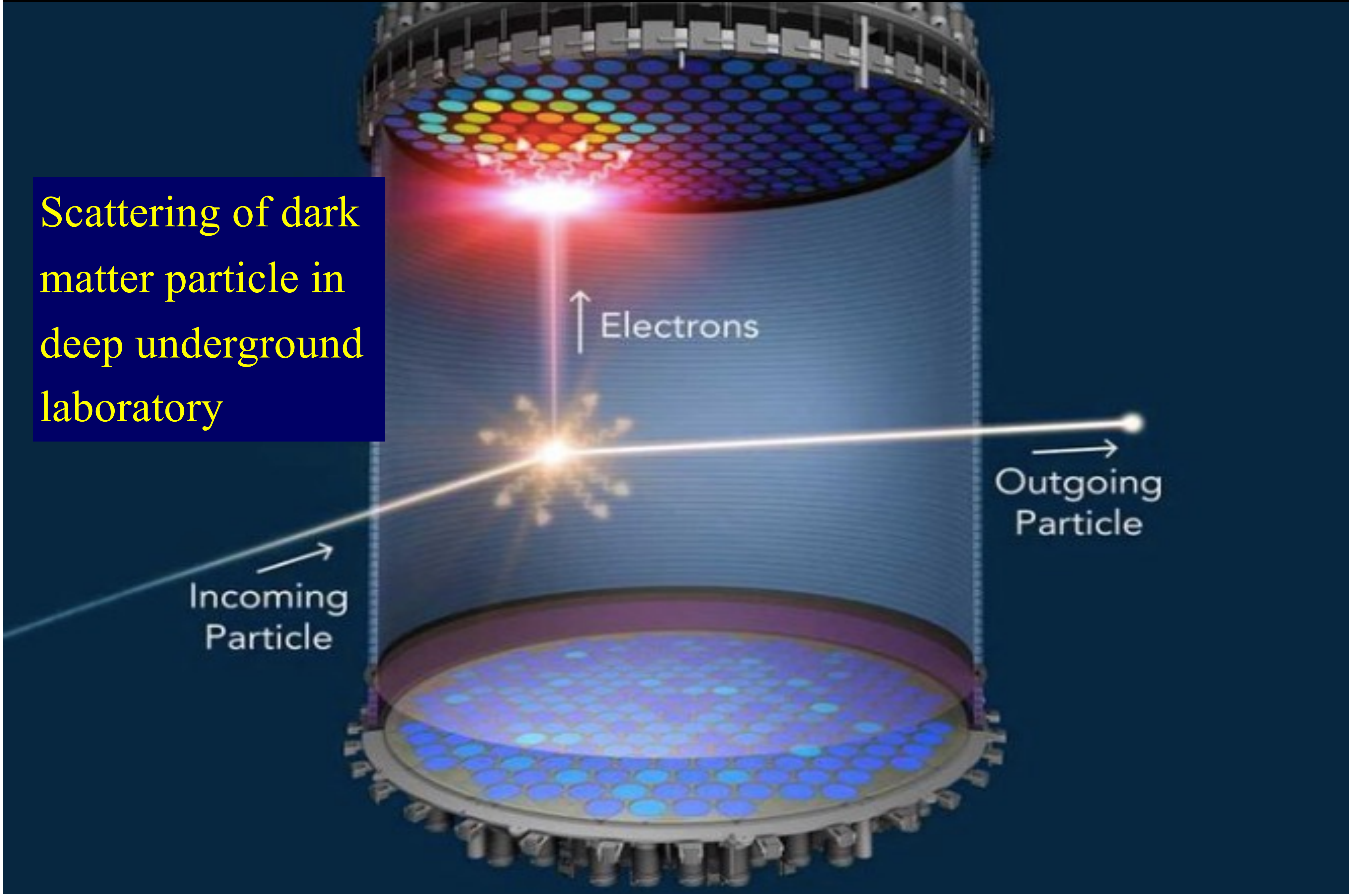




Missing transverse energy
carried away by dark matter particles

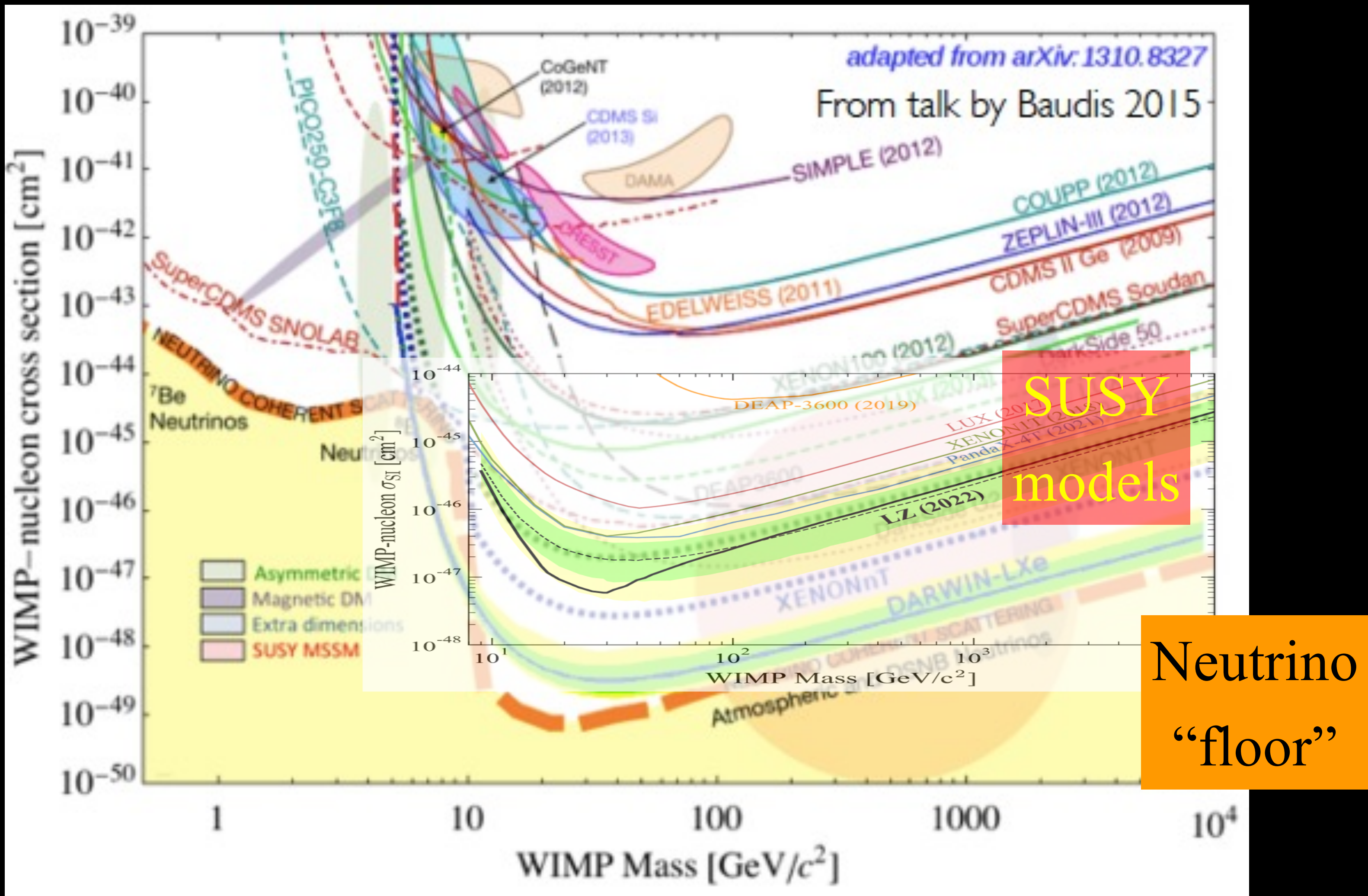
Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory



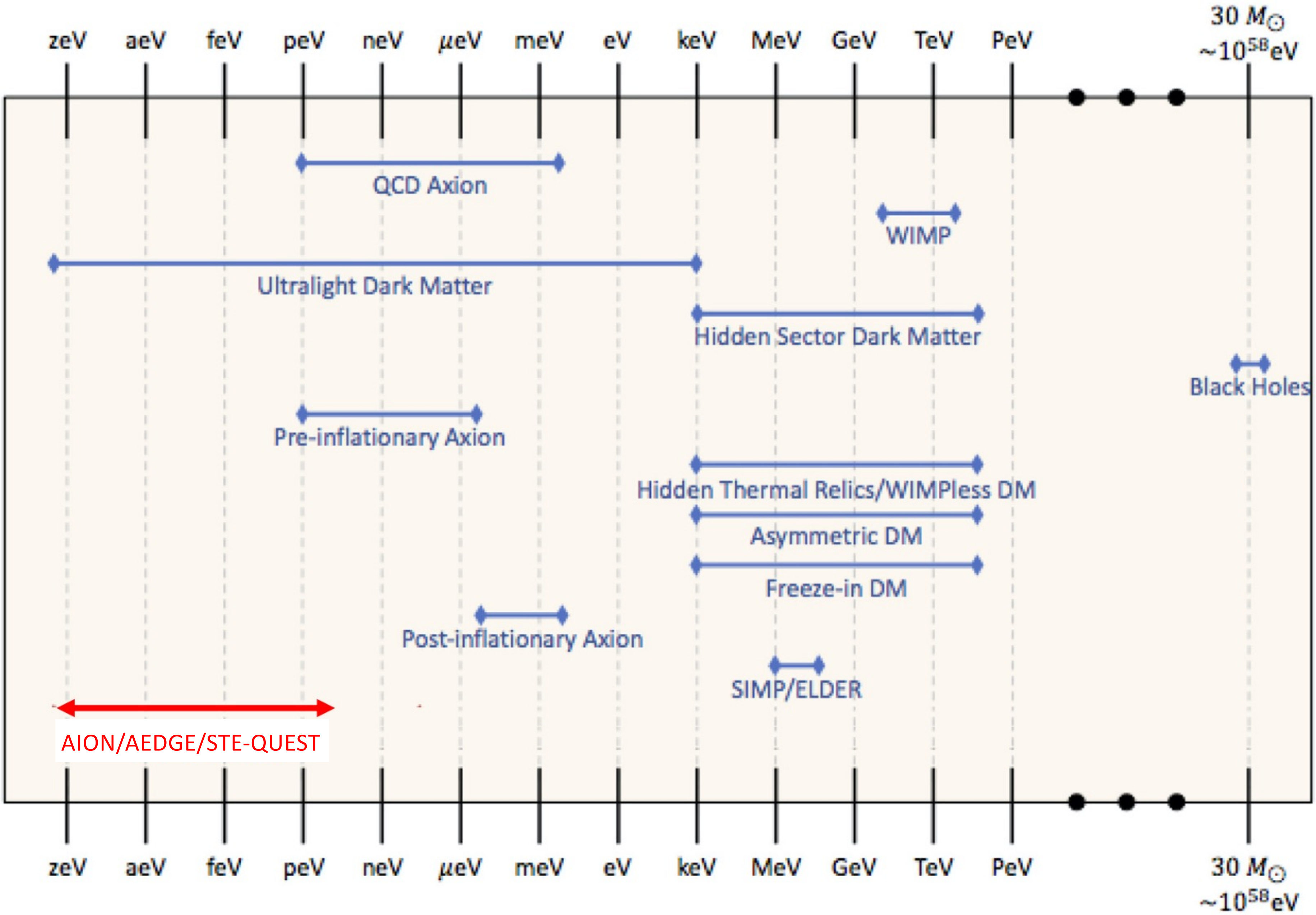
Direct Dark Matter Searches

- Compilation of present and future sensitivities



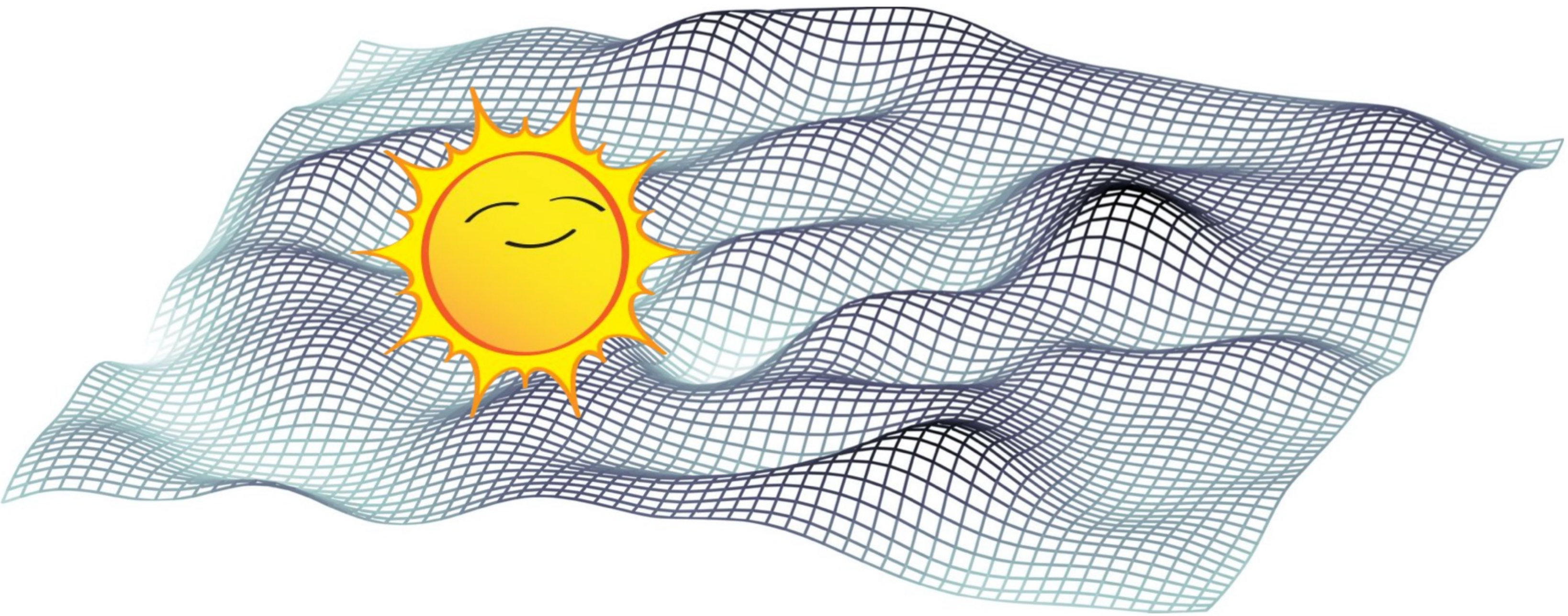

We still believe in supersymmetry
You must be joking

Search for Ultralight Dark Matter



Ultralight Dark Matter

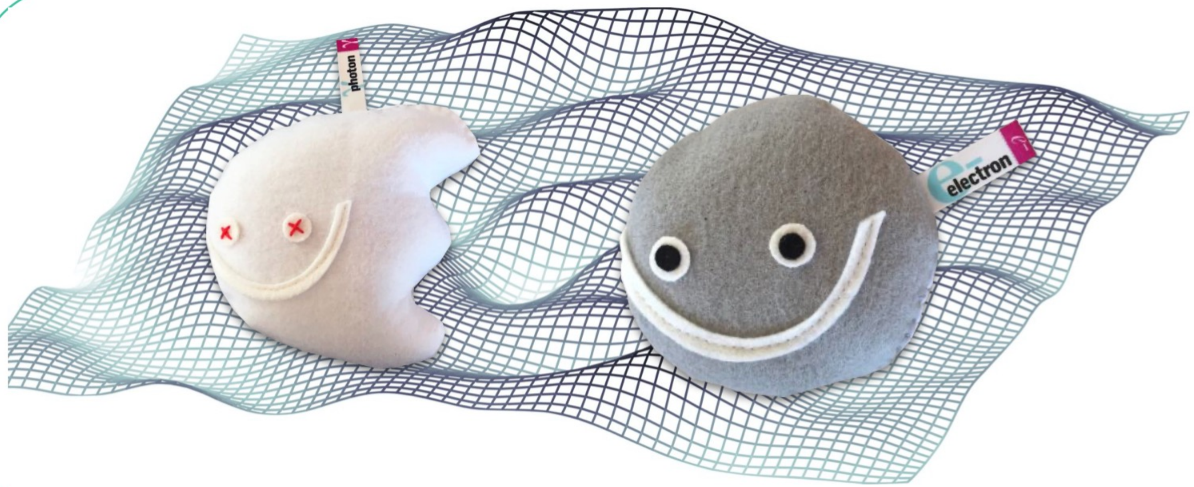
A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System



The wavelength depends on the ULDM mass: $$\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$$

Ultralight Dark Matter

Interactions with the ULDM field lead to oscillations in fundamental 'constants'



Time-dependent electron mass:

$$m_e(t, \mathbf{x}) = m_e \left[1 + \frac{d_{m_e}}{M_{\mathrm{Pl}}} \phi(t, \mathbf{x}) \right]$$

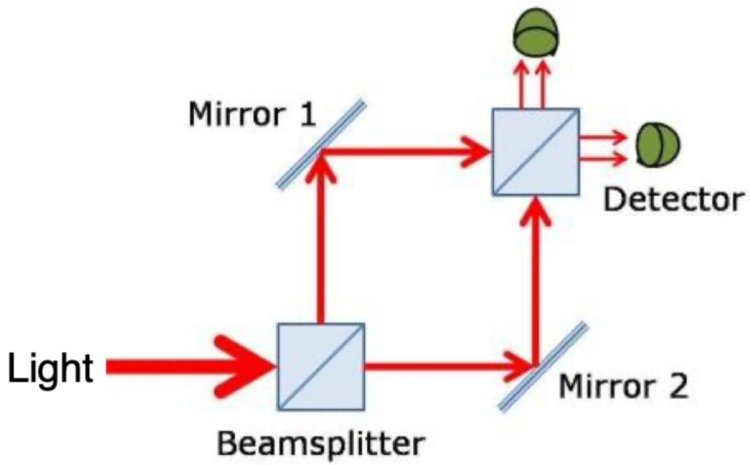
Time-dependent electromagnetic fine structure constant:

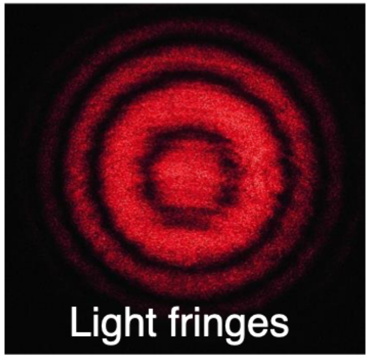
$$\alpha(t, \mathbf{x}) = \alpha \left[1 + \frac{d_e}{M_{\mathrm{Pl}}} \phi(t, \mathbf{x}) \right]$$

Tiny oscillations induced in transition energies: $$\frac{\delta\omega_{\mathrm{Sr}}}{\omega_{\mathrm{Sr}}} = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\mathrm{DM}}} \frac{(d_{m_e} + \xi d_e)}{M_{\mathrm{Pl}}} \cos(m_{\mathrm{DM}} t)$$

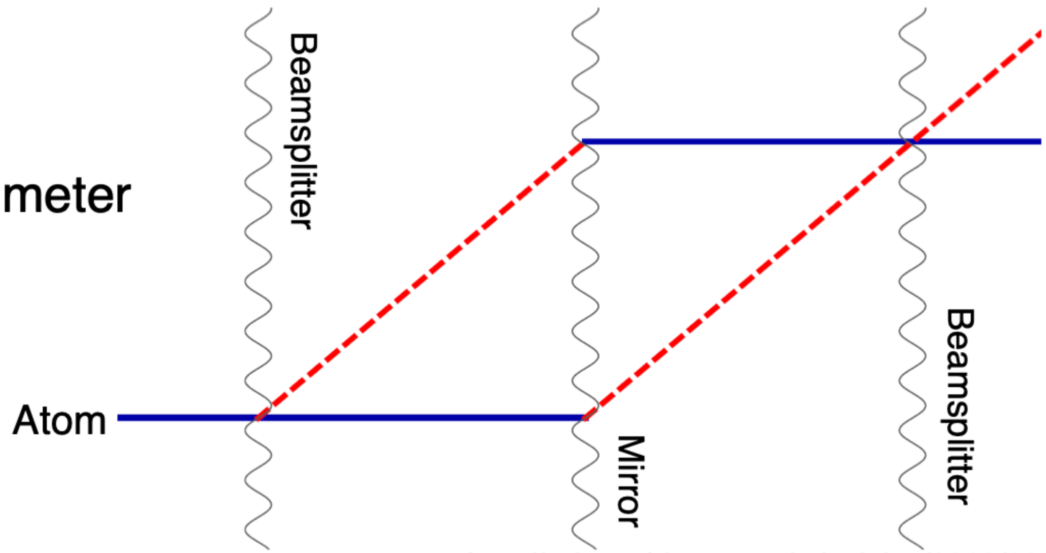
Principle of Atom Interferometry

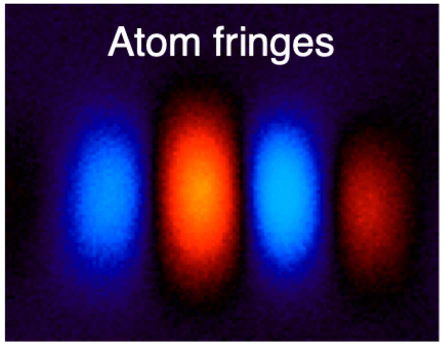
Light interferometer





Atom interferometer



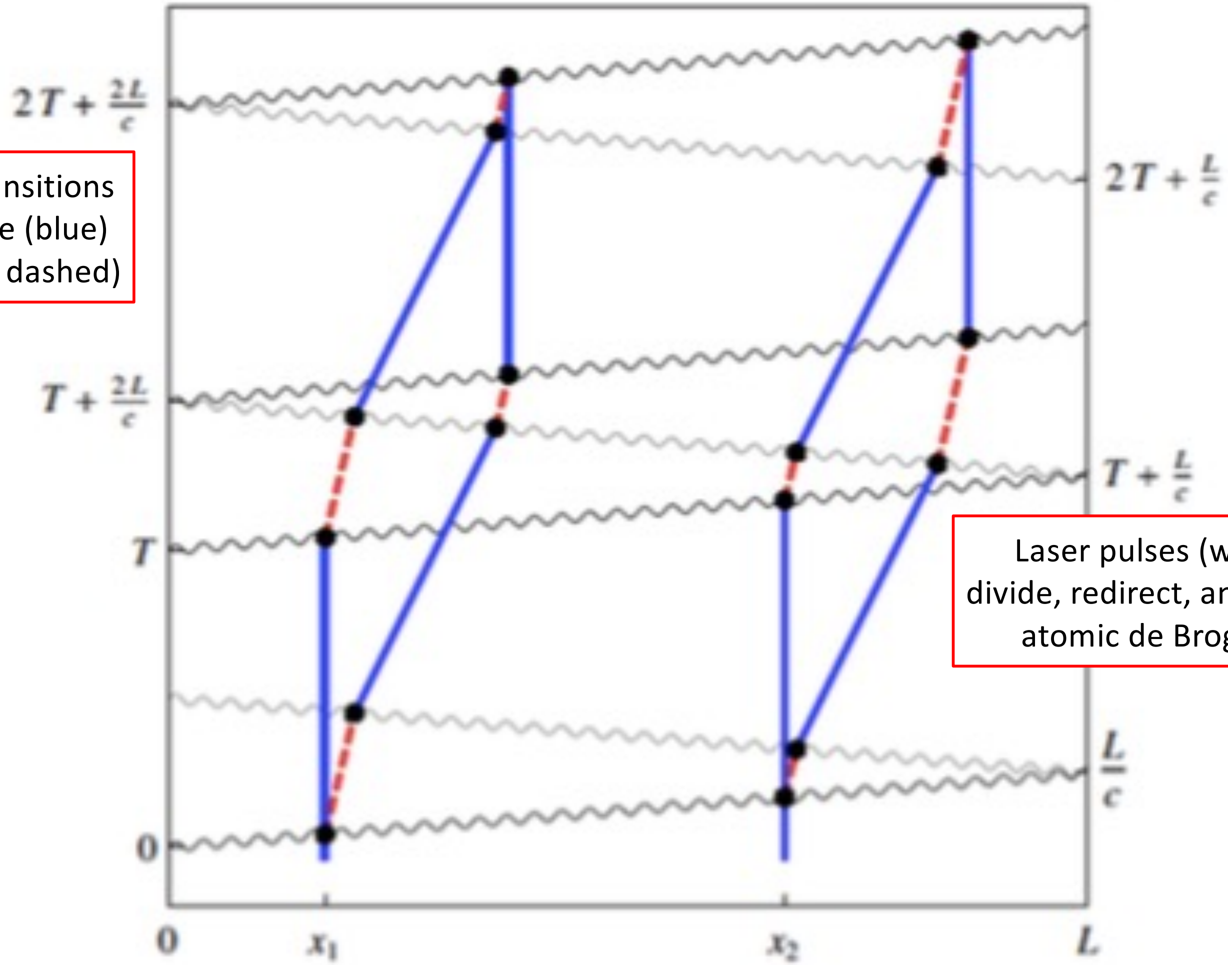


http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Principle of Atom Interferometry

Space-time diagram of operation of pair of cold-atom interferometers

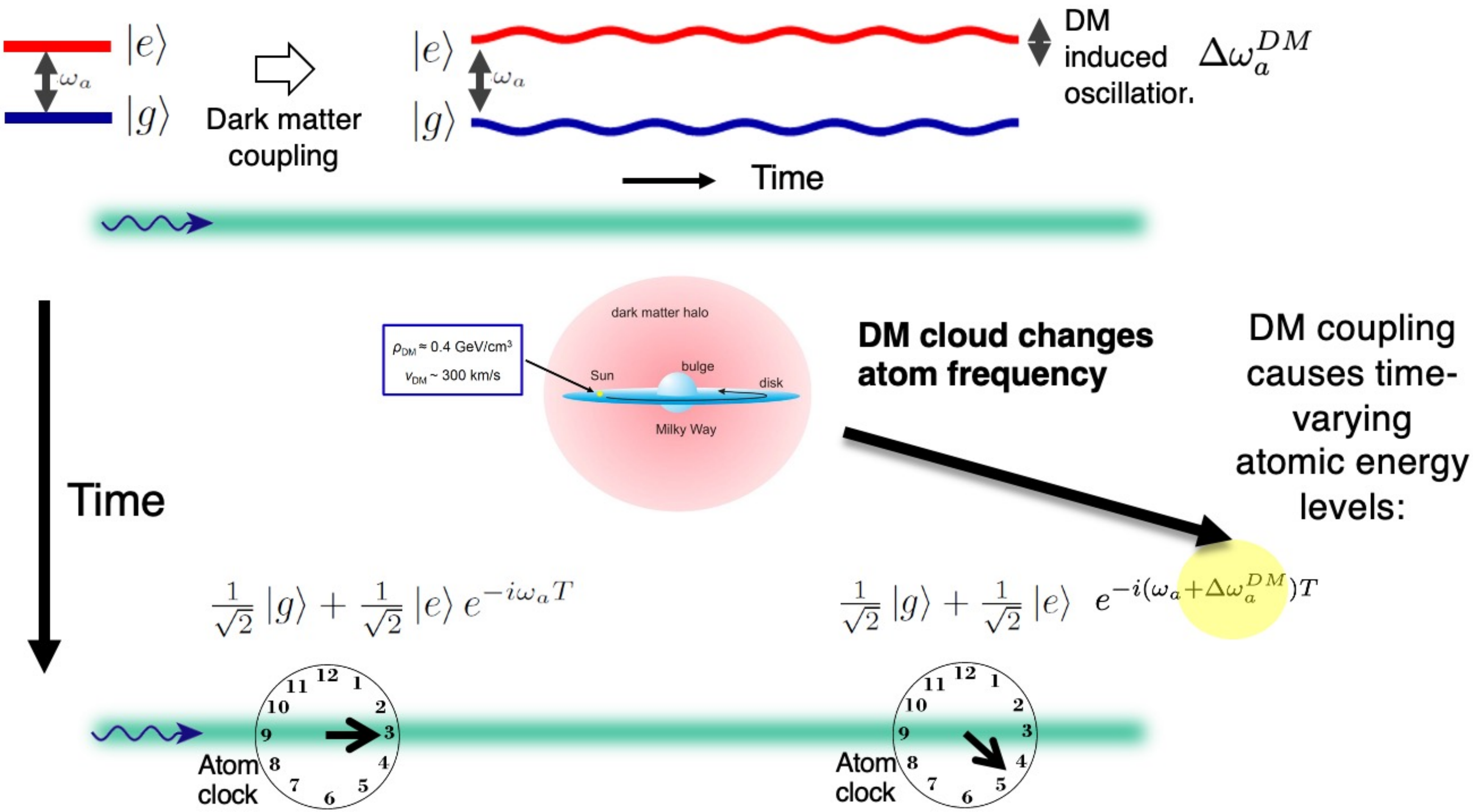
Use single-photon transitions between ground state (blue) and excited state (red dashed)



Laser pulses (wavy lines) divide, redirect, and recombine atomic de Broglie waves

Interference patterns sensitive to interactions with dark matter & modulation of light travel time caused by GWs

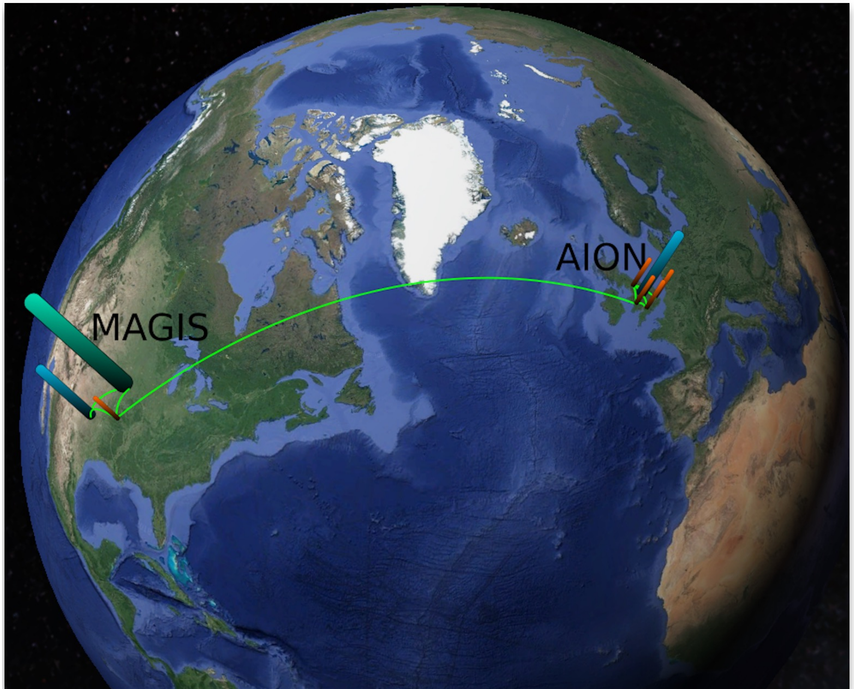
Effect of Dark Matter on Atom Interferometer



AION Collaboration

L. Badurina, S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1]
D. Bort... ...wcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Colema... J. Carlton
G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
M. Holynski..., A. Khazov[2], M. Langlois[4], S. ...[4], Y.H. Lien[4], R. Maiolino[7],
P. Majewski[2], S. Malik[6], J. March-Russell, C. McCabe, D. Newbold[2], R. Preece[3],
B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. ..., M. Tarbutt[6], M. A. Uchida[7],
T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7],
J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

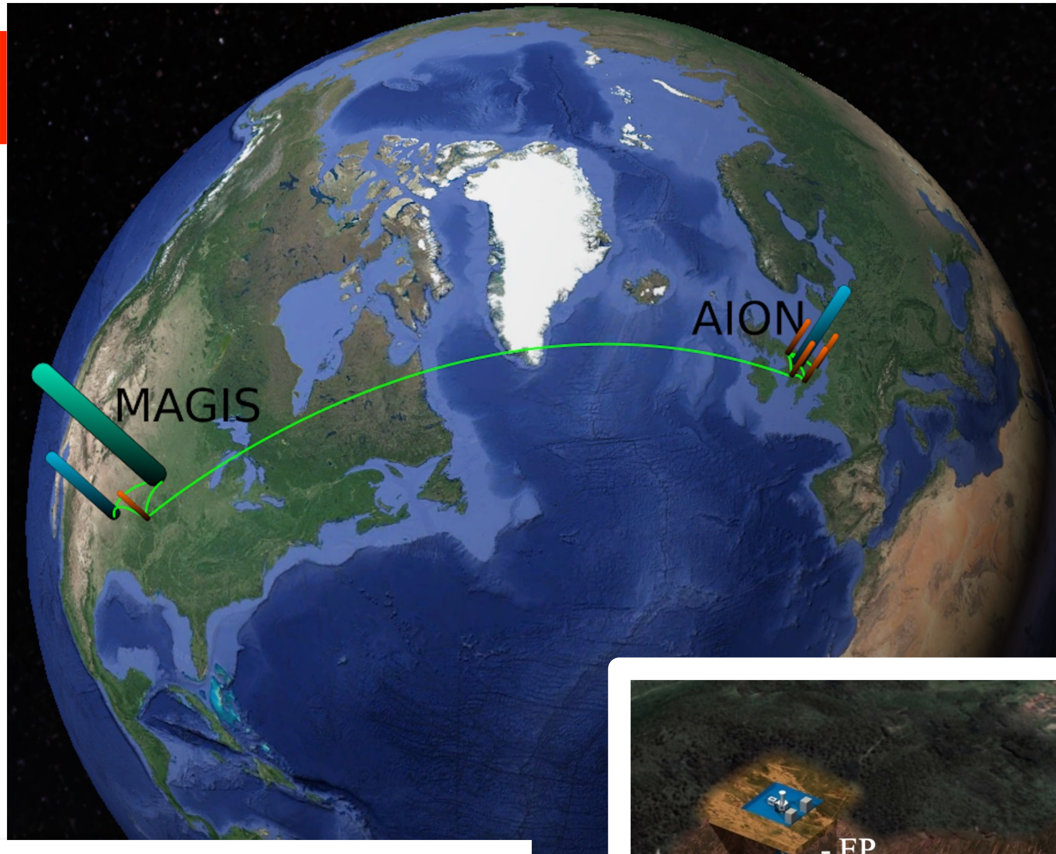


Network with MAGIS project in US

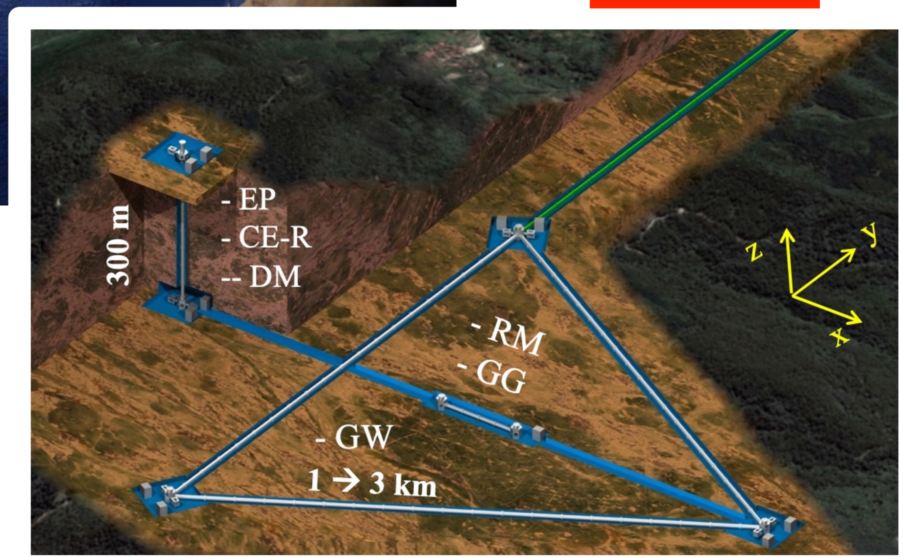
MAGIS Collaboration (Abe et al): arXiv:2104.02835

Atom Interferometer Observatory & Network

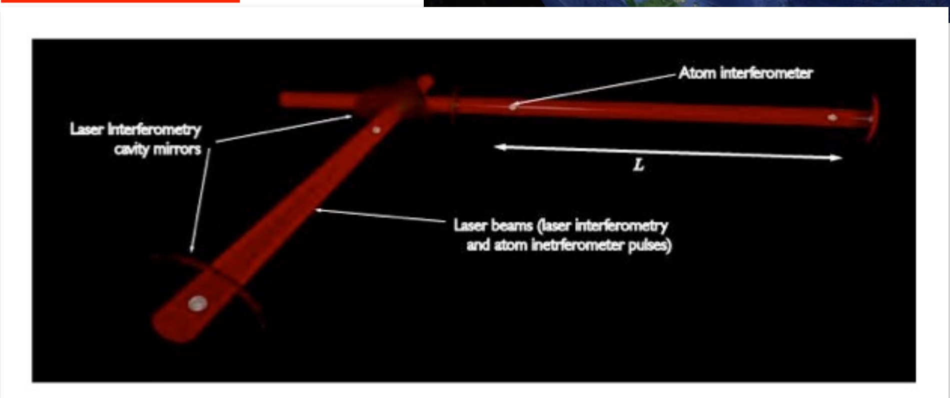
Partnership with MAGIS could be extended



ZAIGA (China)



MIGA (France)



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Quantum Science Program

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  - Skipper CCDs for quantum imaging
  - **MAGIS-100**
- Quantum networking
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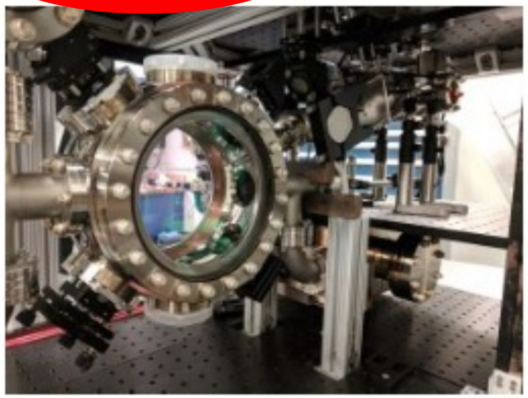
MAGIS-100



Fermilab seeks to host MAGIS-100 — the 100-meter Matter-wa Gradiometer Interferometric Sensor — which will test quantum macroscopic scales of space and time.

The laboratory is developing a sensitive prototype detector tha precisely measure properties of the cosmos.

One of these is dark matter. Physicists have offered a number models describing dark matter, a mysterious substance that m quarter of the universe. Some of these models suggest that da made of ultralightweight particles. MAGIS-100 will be used to particular those that predict varying atomic energy levels.

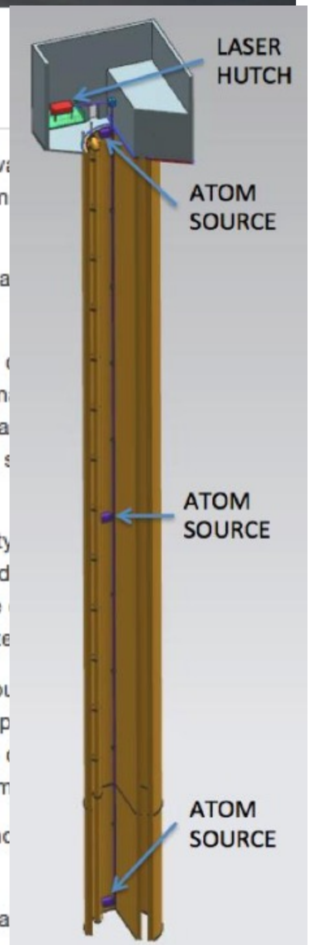
A longer-term goal for MAGIS-100 is to establish the sensitivity technique to gravitational waves in the frequency range around 1 hertz, where there are few existing or proposed d waves, predicted by Einstein a century ago but discovered for the first time only in 2015, are ripples in space-time accelerating masses, such as stars and galaxies. MAGIS-100 creates atom matter waves in superposition separate

The MAGIS-100 prototype would make use of an existing vertical shaft on the Fermilab site that leads to undergrou will perform precision quantum measurements using clouds of ultracold falling atoms, whose phases can be manip using lasers, aiding in the test for lightweight dark matter particles. The length of the 100-meter drop expands the technology by about a factor of 10 and provides opportunities for significant advances in the systematics of this im

MAGIS-100 combines the unique physical features of the Fermilab site with the laboratory expertise in vacuum anc

MAGIS Collaboration (Coleman et al): arXiv:1812.00482

Northern Illinois University, Stanford University, University of California, Berkeley and University of Liverpool are pa



AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

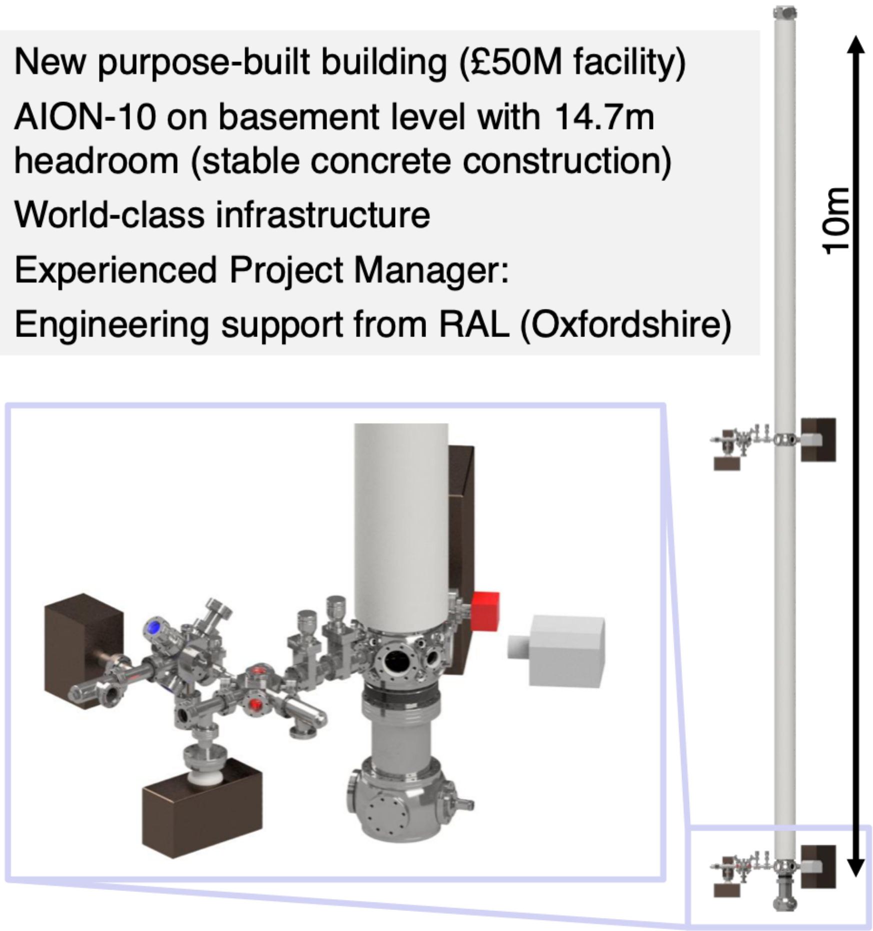
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

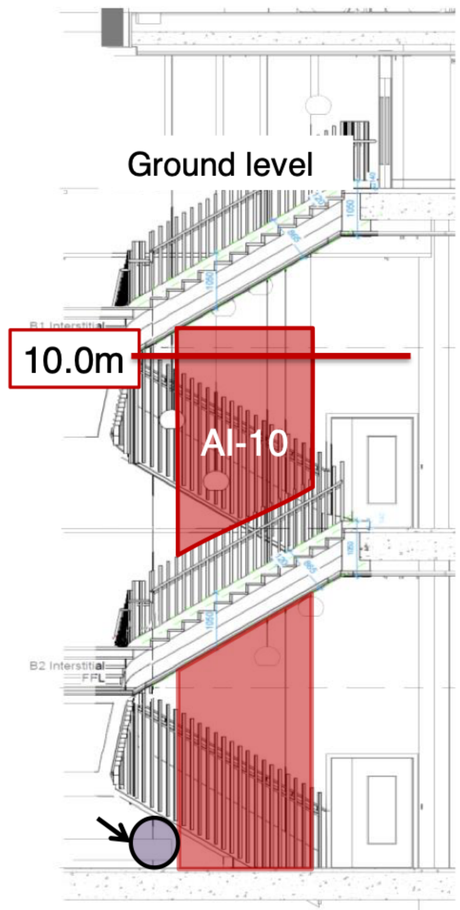
Planned Location of AION-10m

AION

AION-10 @ Beecroft building, Oxford Physics

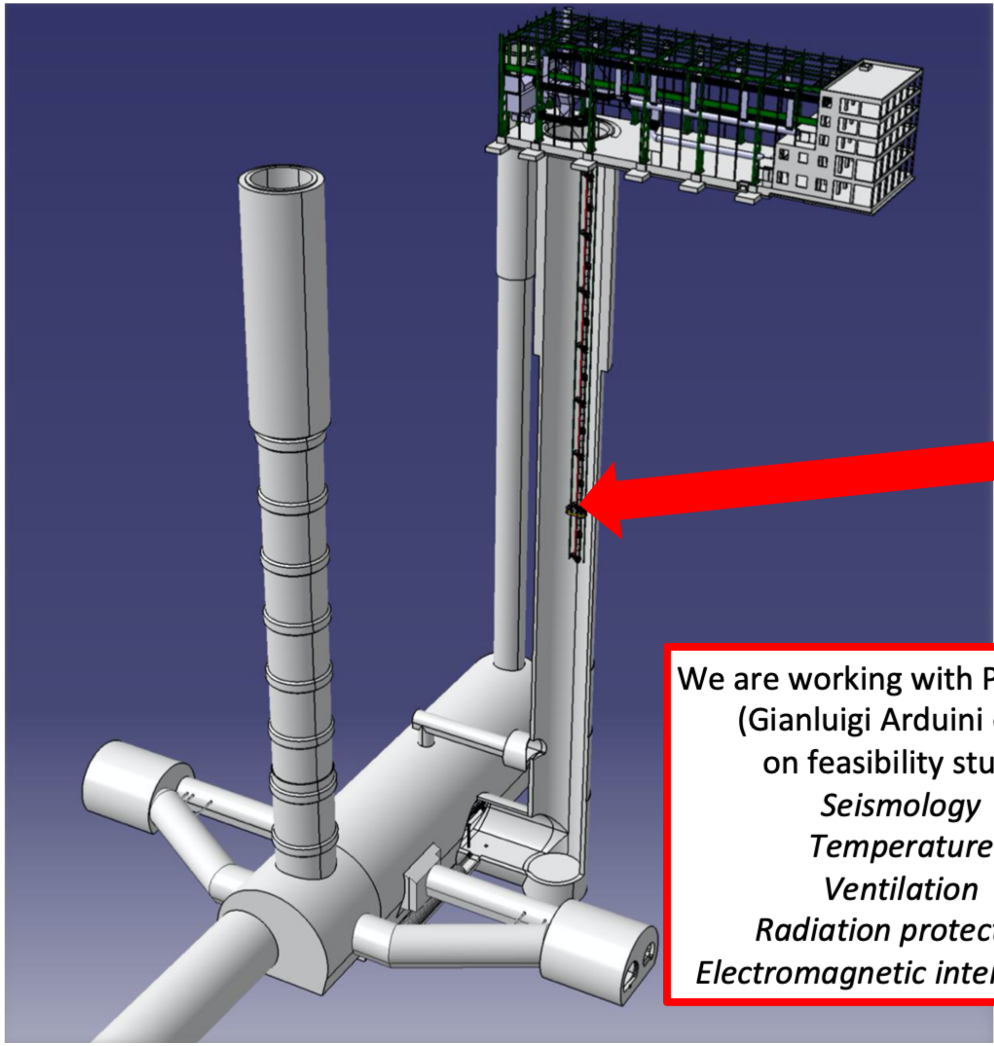
- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)



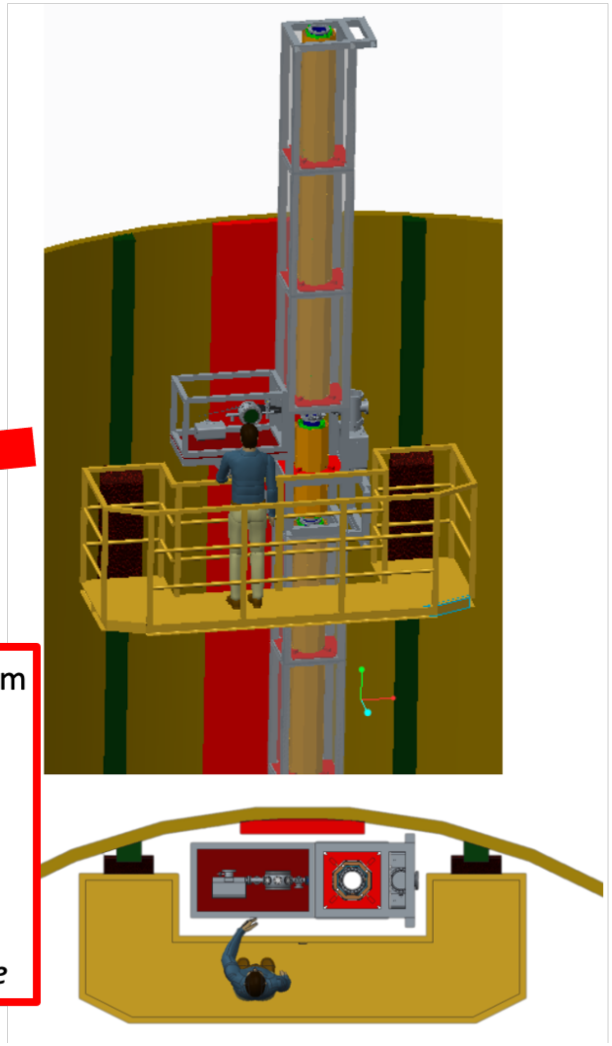


Possible CERN Location of AION-100m

General view of LHC Point 4



Possible layout in PX46 shaft



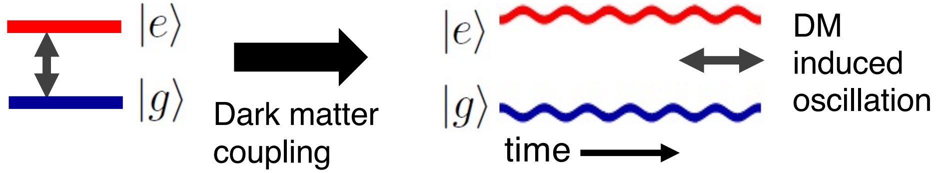
We are working with PBC Team
(Gianluigi Arduini et al)
on feasibility study:
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference

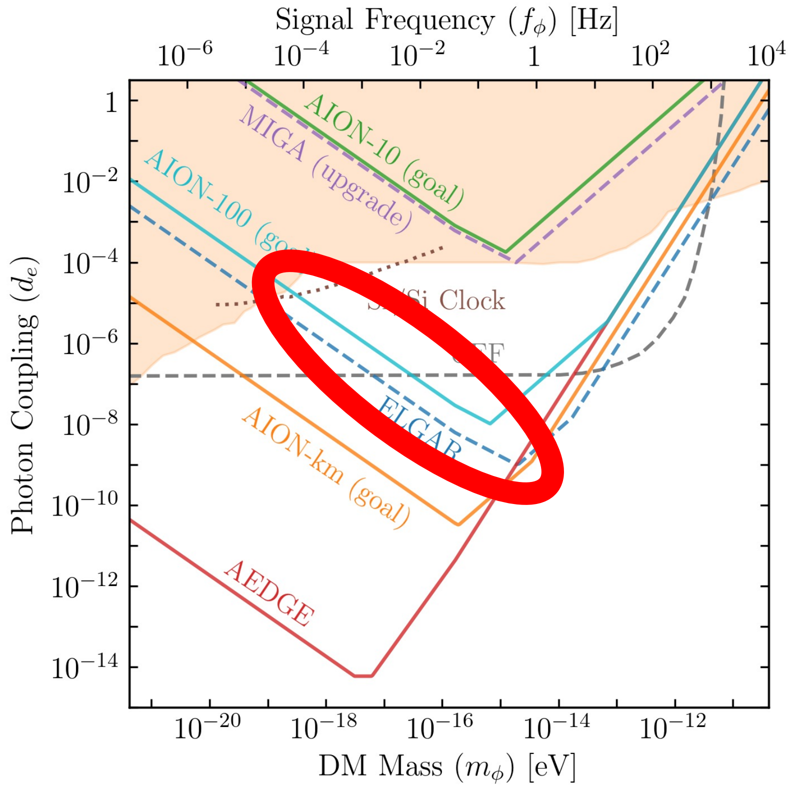
Searches for Ultralight Dark Matter

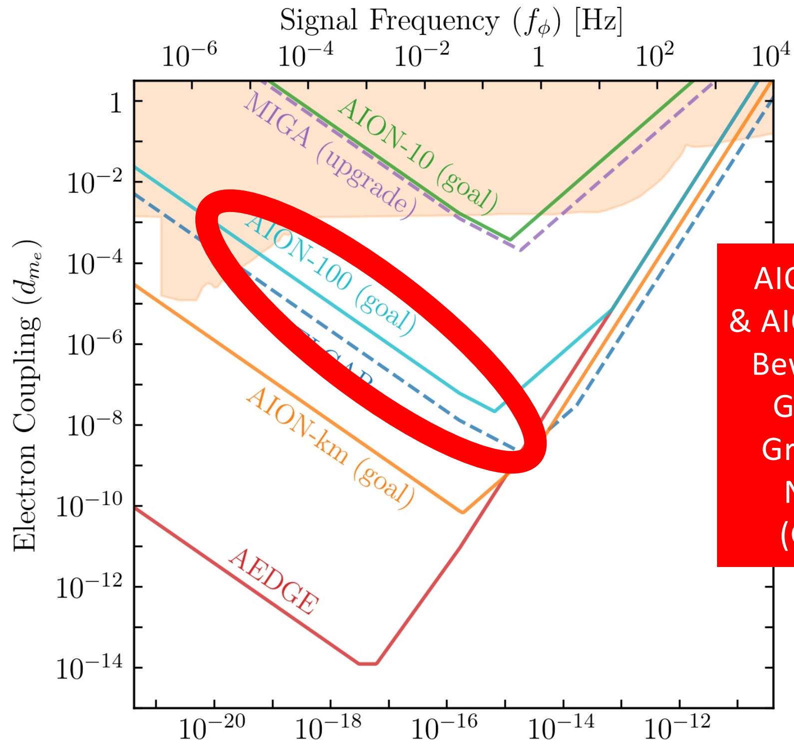
AION

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$







AION-100 & AION-1km: Beware of Gravity Gradient Noise (GGN)

Abou El-Neaj, …, JE et al:, arXiv:1908.00802

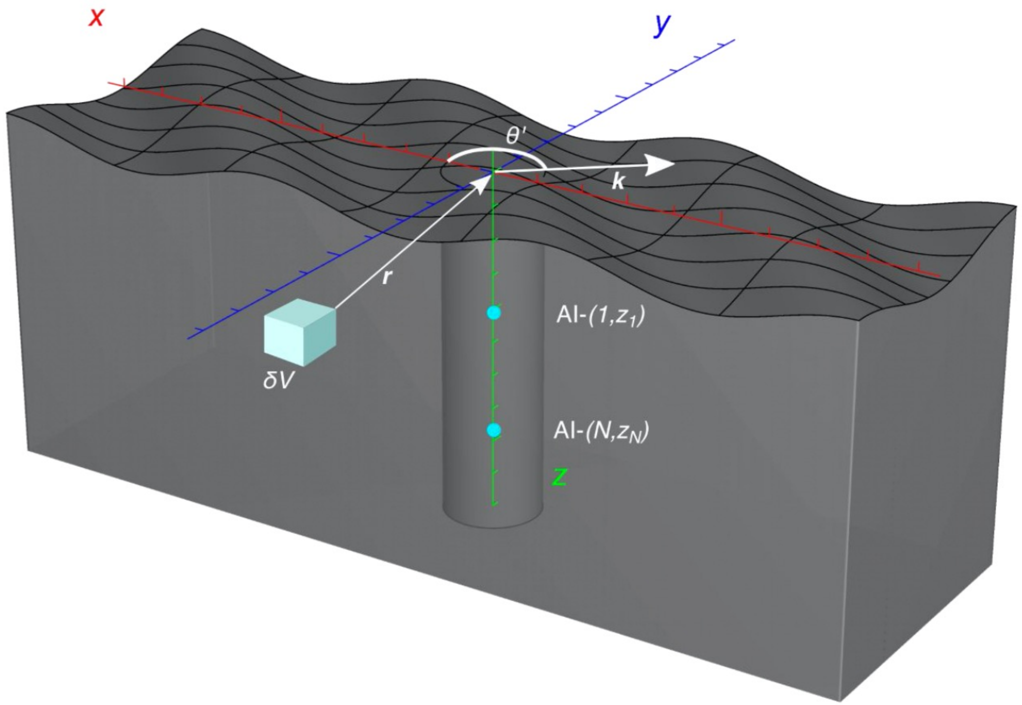
Gravity Gradient Noise

Seismic waves on the surface (Rayleigh waves) change the gravitational field experienced by the atoms and lead to a phase shift

$$\Phi_{\text{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

$$\widetilde{A}, -\widetilde{B} \propto \frac{\sin\left(\frac{\omega T}{2}\right)^2}{\omega^2}$$

We consider the simplest scenario:
Isotropic sourcing around the shaft,
single geological stratum present
(so only the fundamental Rayleigh mode)

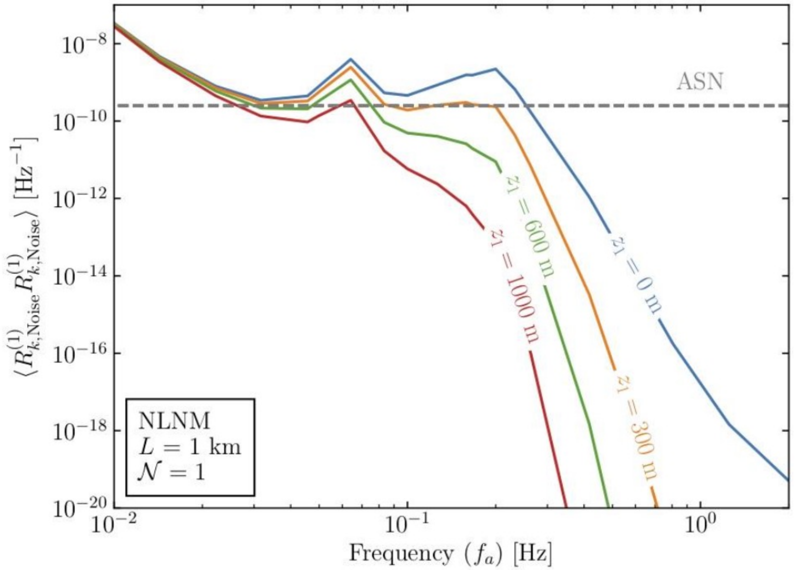


LB, V. Gibson, J. Mitchell, C. McCabe, in preparation

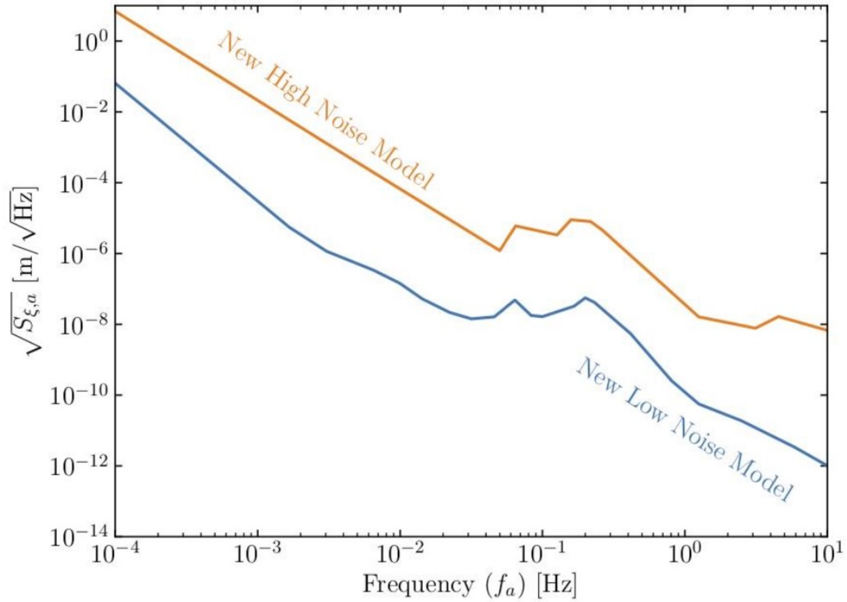
Gravity Gradient Noise

$$\Phi_{\text{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

Exponential suppression and frequency dependence



Vertical displacement (Rayleigh distributed)

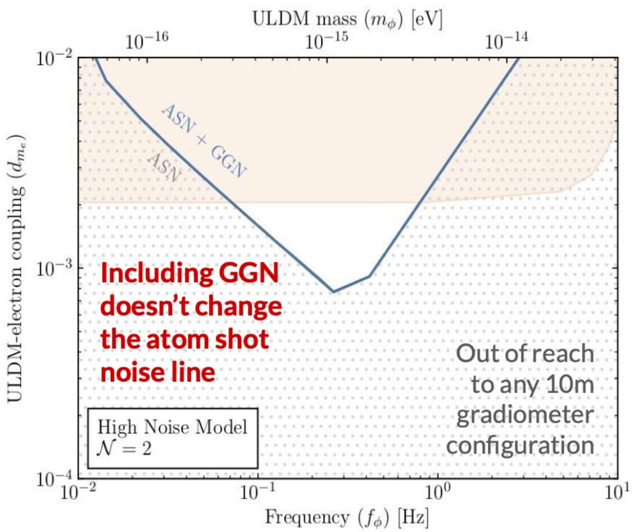


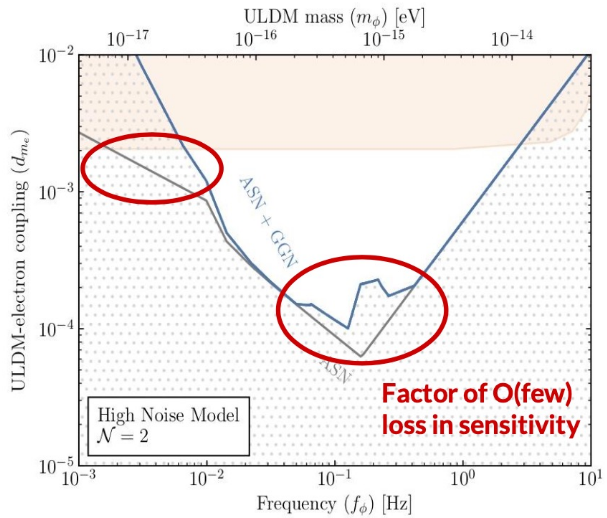
LB, V. Gibson, J. Mitchell, C. McCabe, in preparation

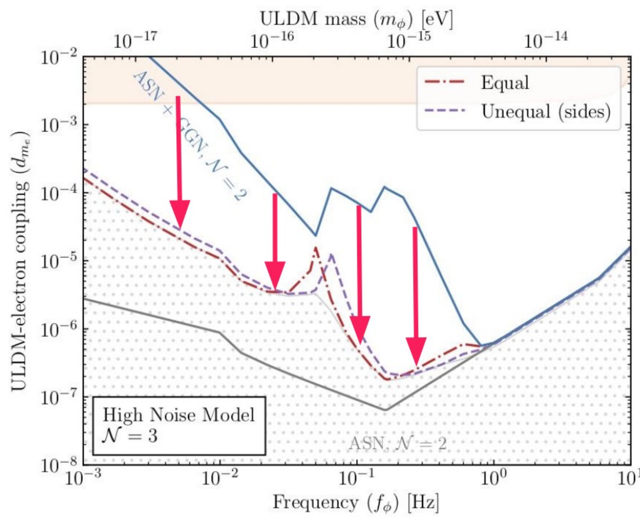
Gravity Gradient Noise

AION

Unimportant for AION-10	Not large for AION-100	Important for AION-1km







AION-100 & AION-1km: Beware of Gravity Gradient Noise (GGN)

Abou El-Neaj, …, JE et al:, arXiv:1908.00802

STE-QUEST Phase 2 Proposal

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program

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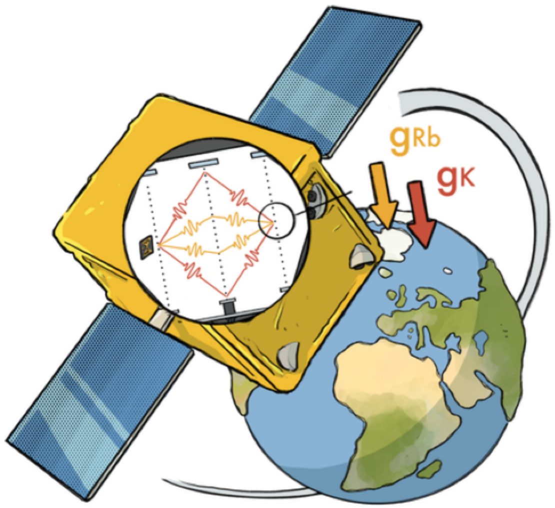
June 28, 2022



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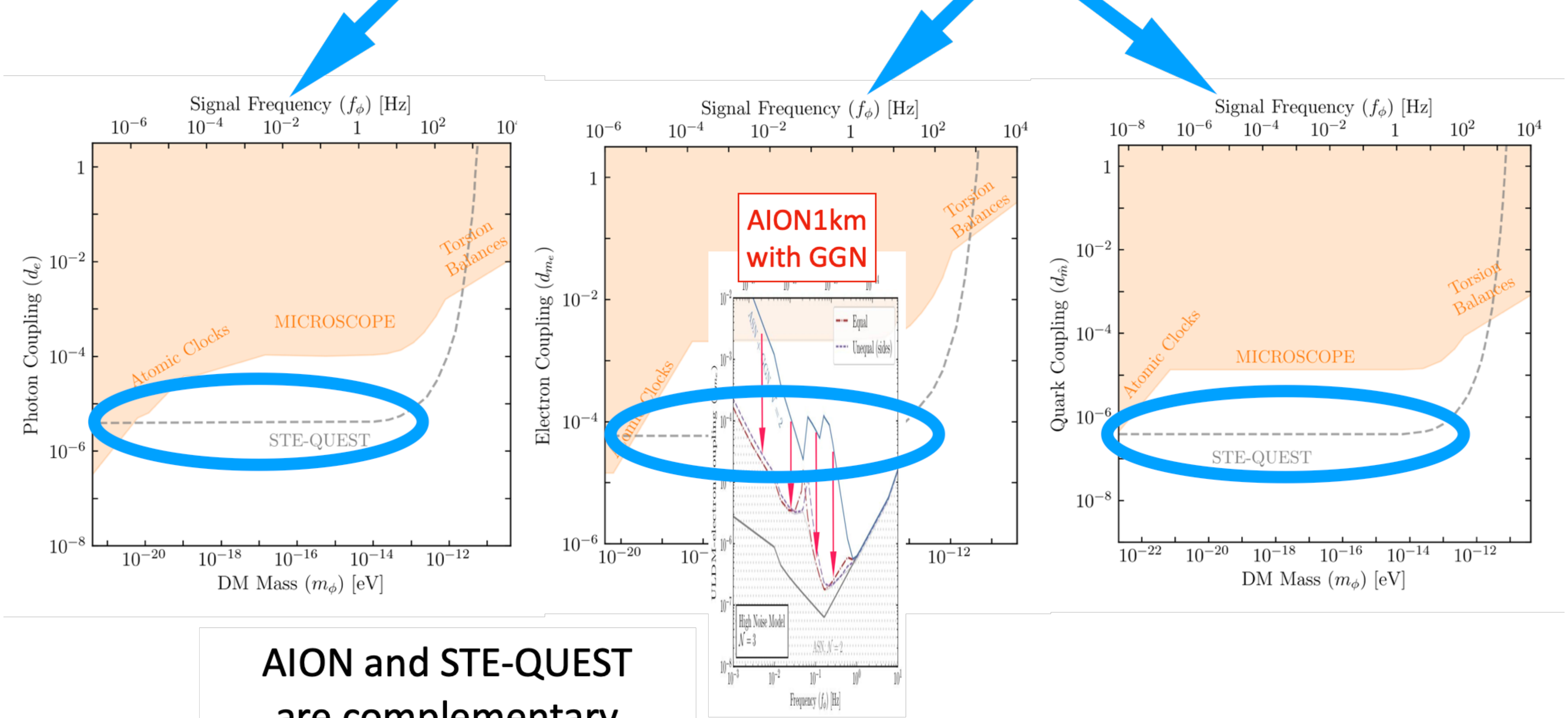
STE-QUEST Science:
Searching for Ultralight Dark Matter

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$



AION and STE-QUEST are complementary