Dark Matter Detection

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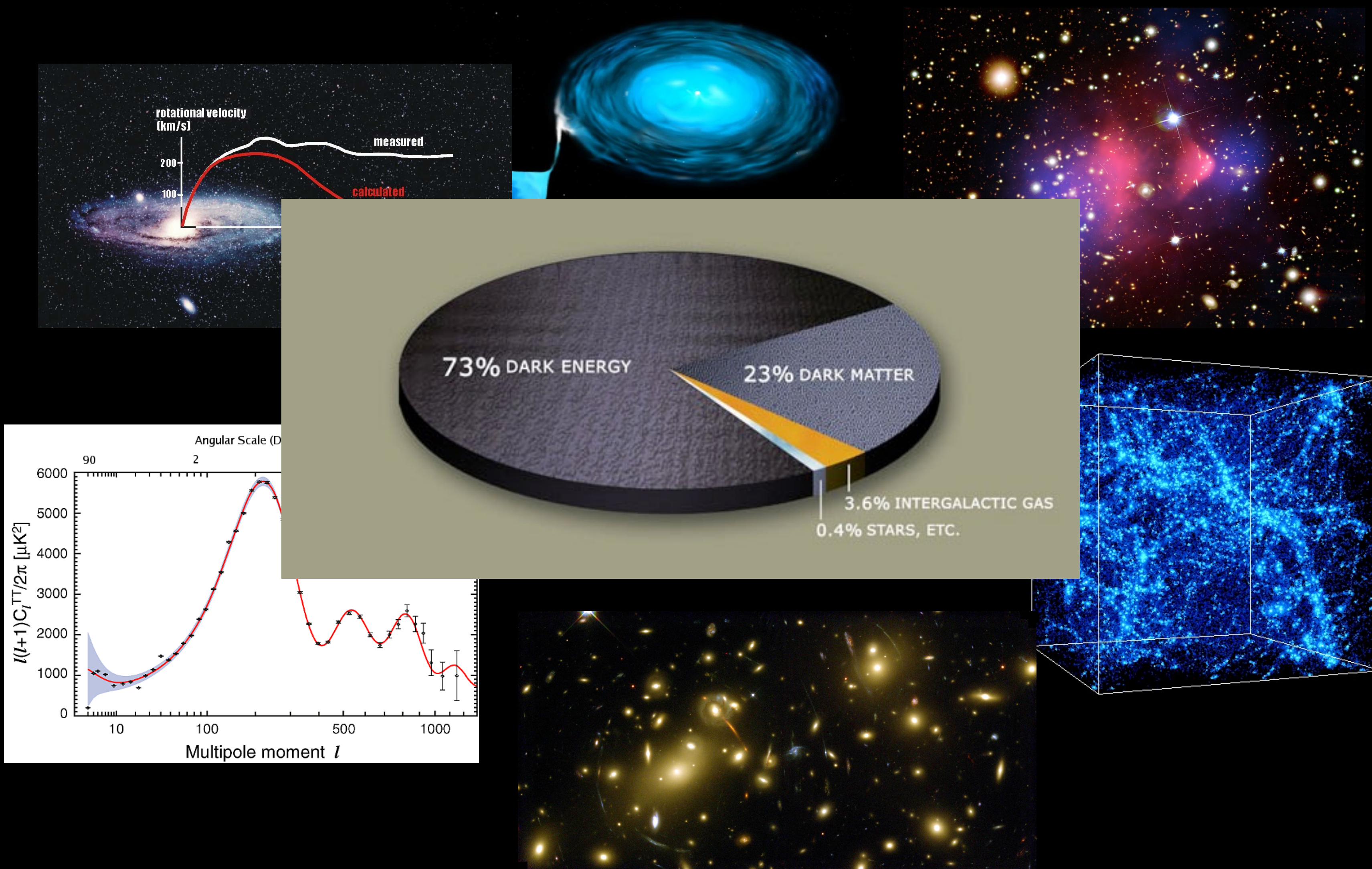
高能物理前沿讲座

2022年10月15日

Concordant universe



Searching for dark matter

- All the evidences of dark matter are from gravitational effects.

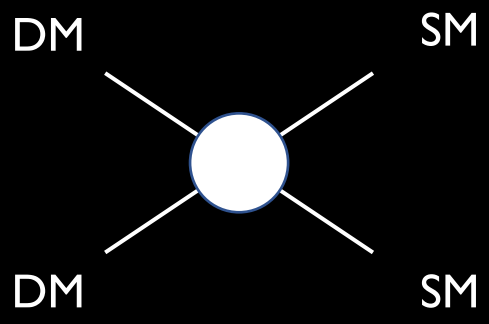
- We want to understand its particle nature:
  - Mass
  - Spin
  - Size
  - Inner structure if any
  - Interactions with Standard Model particles
  - Its self-interaction
  - …

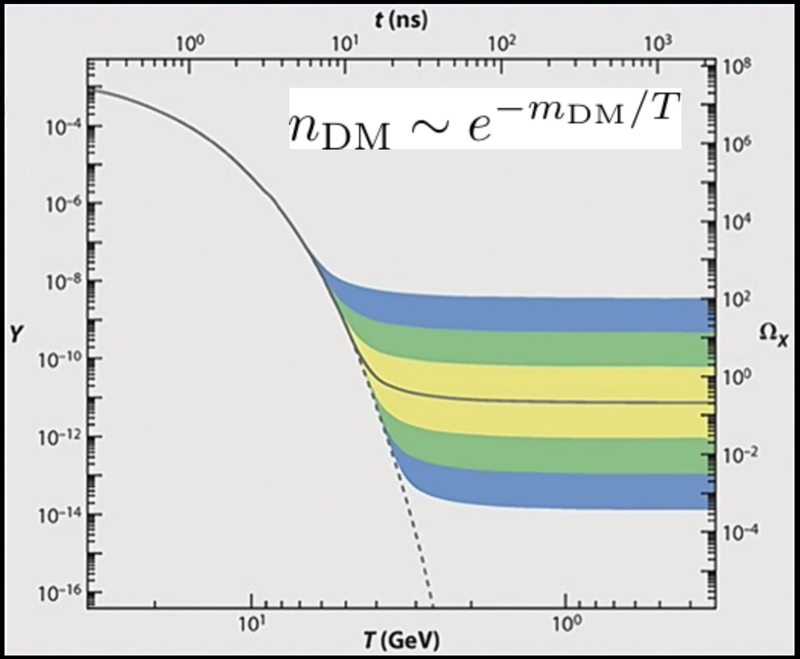
Where we start?

- We know almost nothing about dark matter except for:
  - Equation of state — Non-relativistic particles
  - Total energy density
    - 23% of the total energy density
    - About five times of the energy density of baryons
  - Its velocity around the earth
    - About 200 km/sec
  - Energy density around the earth
    - 0.4 GeV/cm^3

22.4 mol/L ~ 1Pa

The WIMP miracle





Thermal freeze out

$\Gamma_A = n_{\rm DM} < \sigma v >,$

$\Gamma_A < \mathrm{H}$

$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$$

$$\approx \frac{\alpha^2}{(200\ \mathrm{GeV})^2}$$

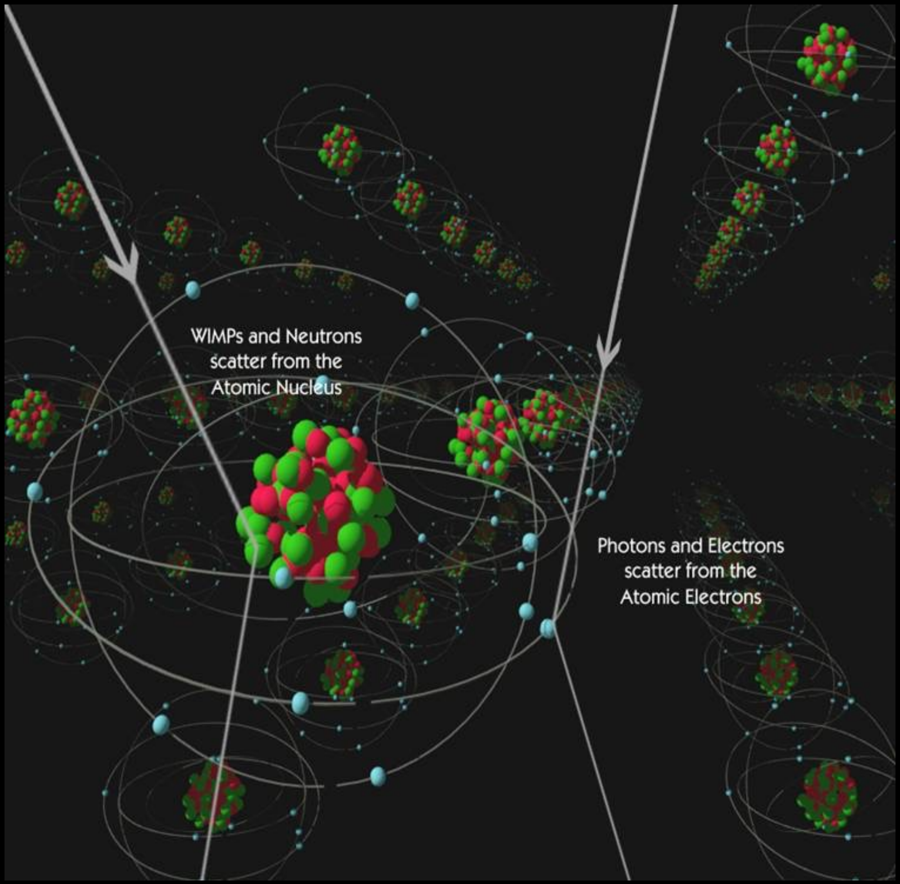
Weakly Interacting Massive Particle (WIMP)

Searching for WIMPs

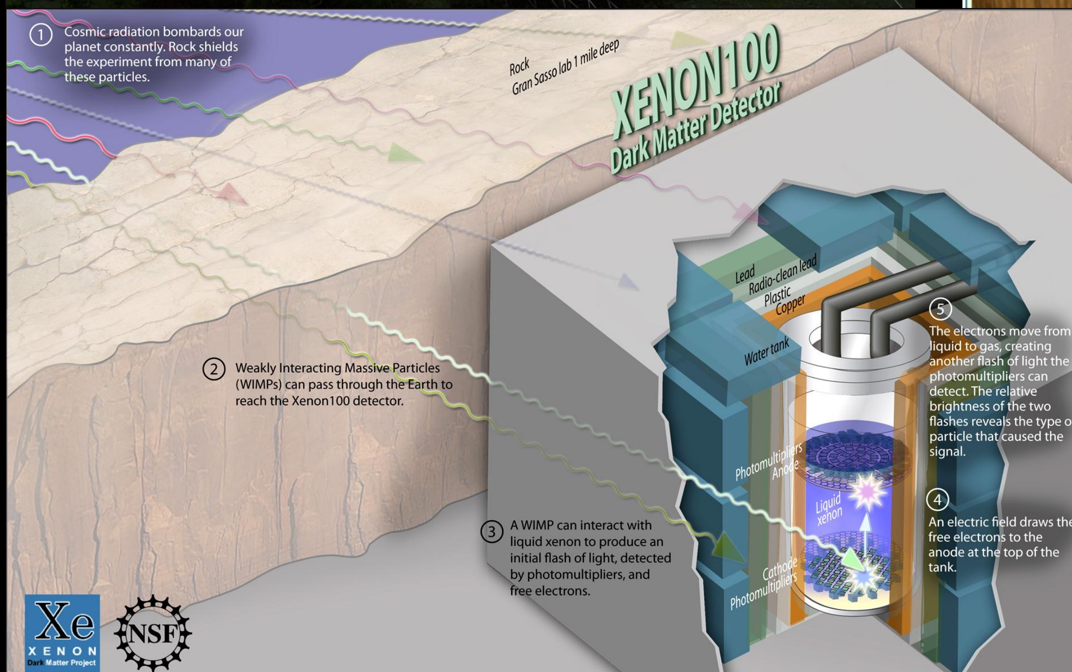
$$E_{recoil} \sim \frac{m_{\mathrm{DM}} m_T}{(m_{\mathrm{DM}} + m_T)^2} E_k$$

Proton mass ~ 1 GeV
Nucleus with *N* nucleons *N* GeV

Use heavy nuclei as target

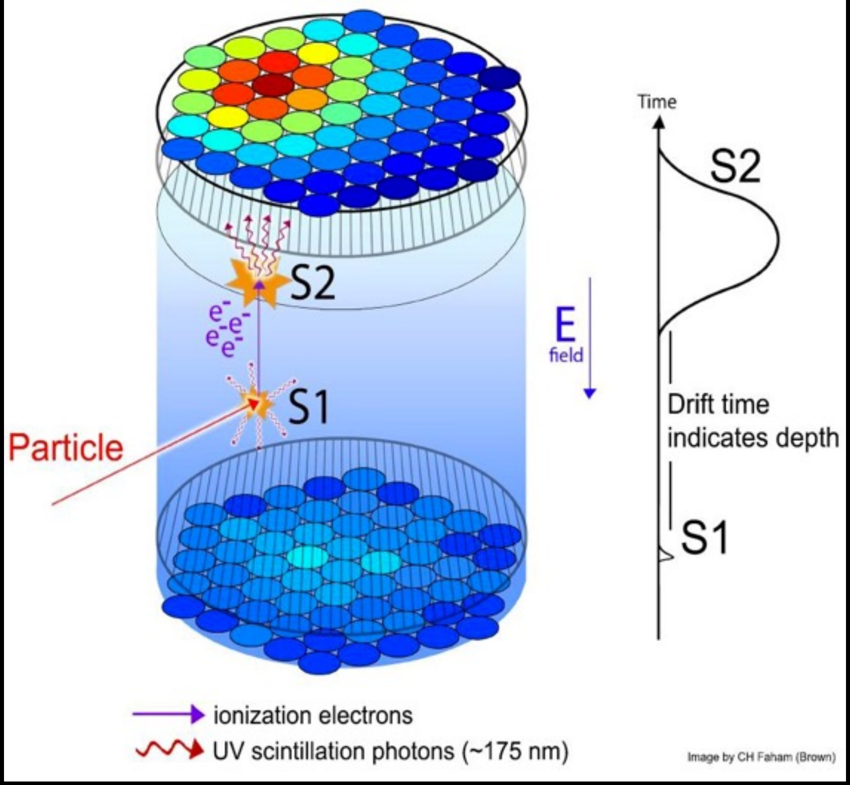


Underground labs

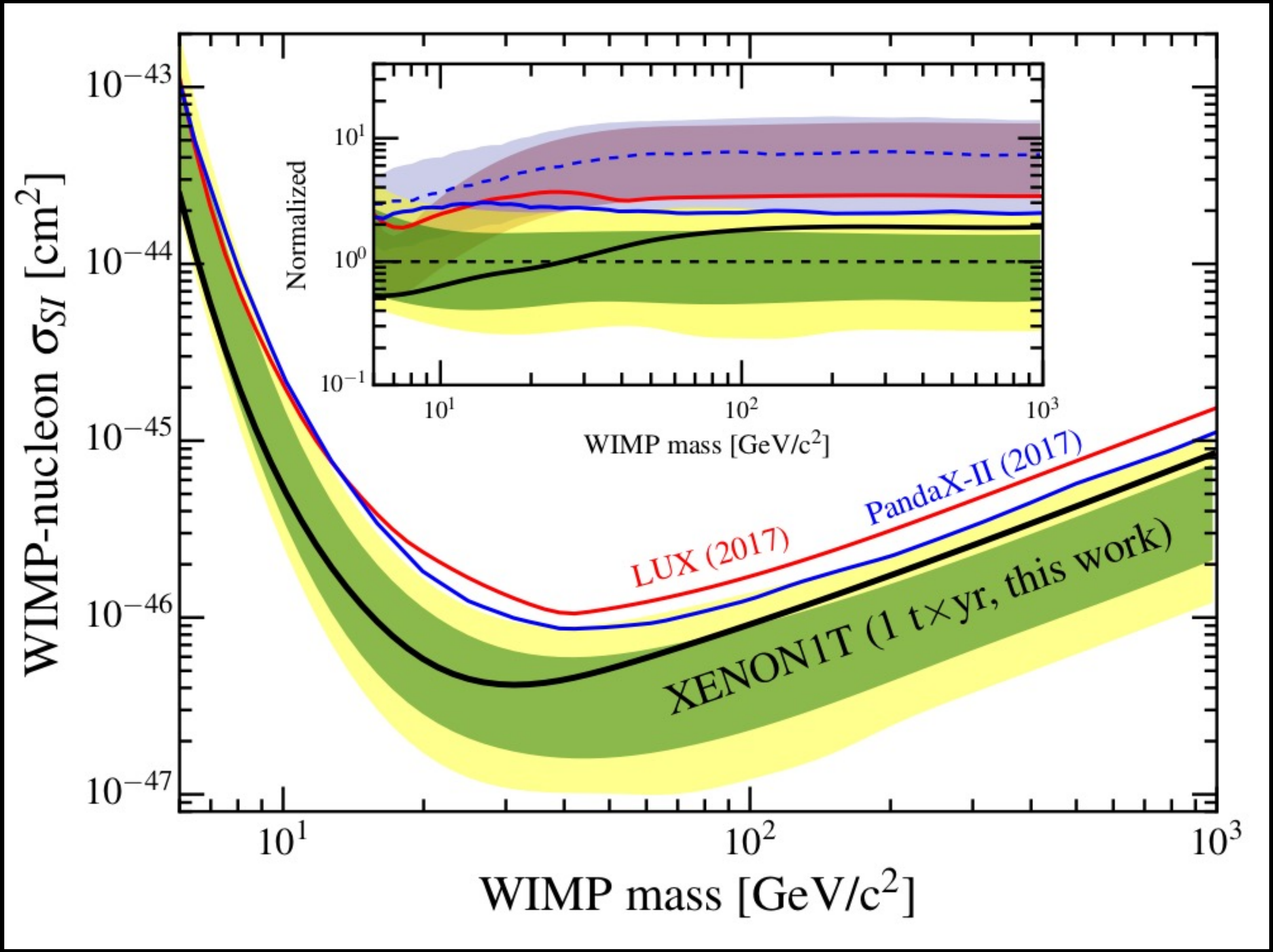


Noble gas (惰性气体) detector

- Target: xenon nucleus
- Use S1 and S2 signals to distinguish signal from background
- High threshold hold for S1 signal
- XENON, LUX, PandaX (SJTU)

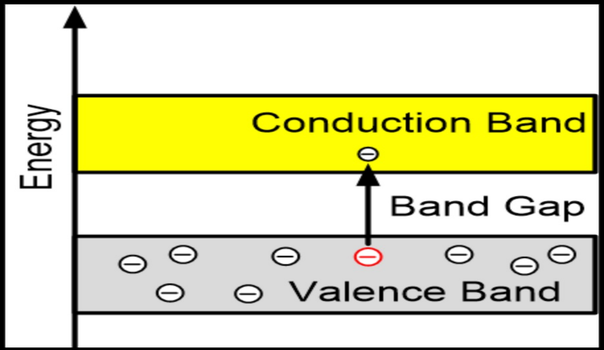


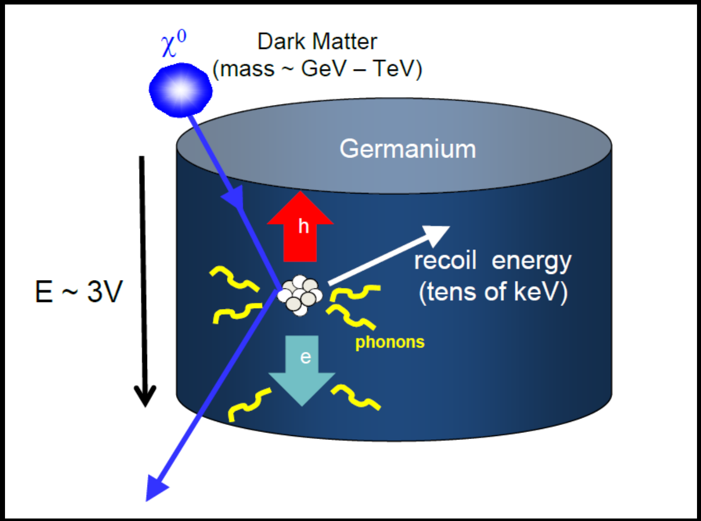
Noble gas detector



Semi-conductor detector

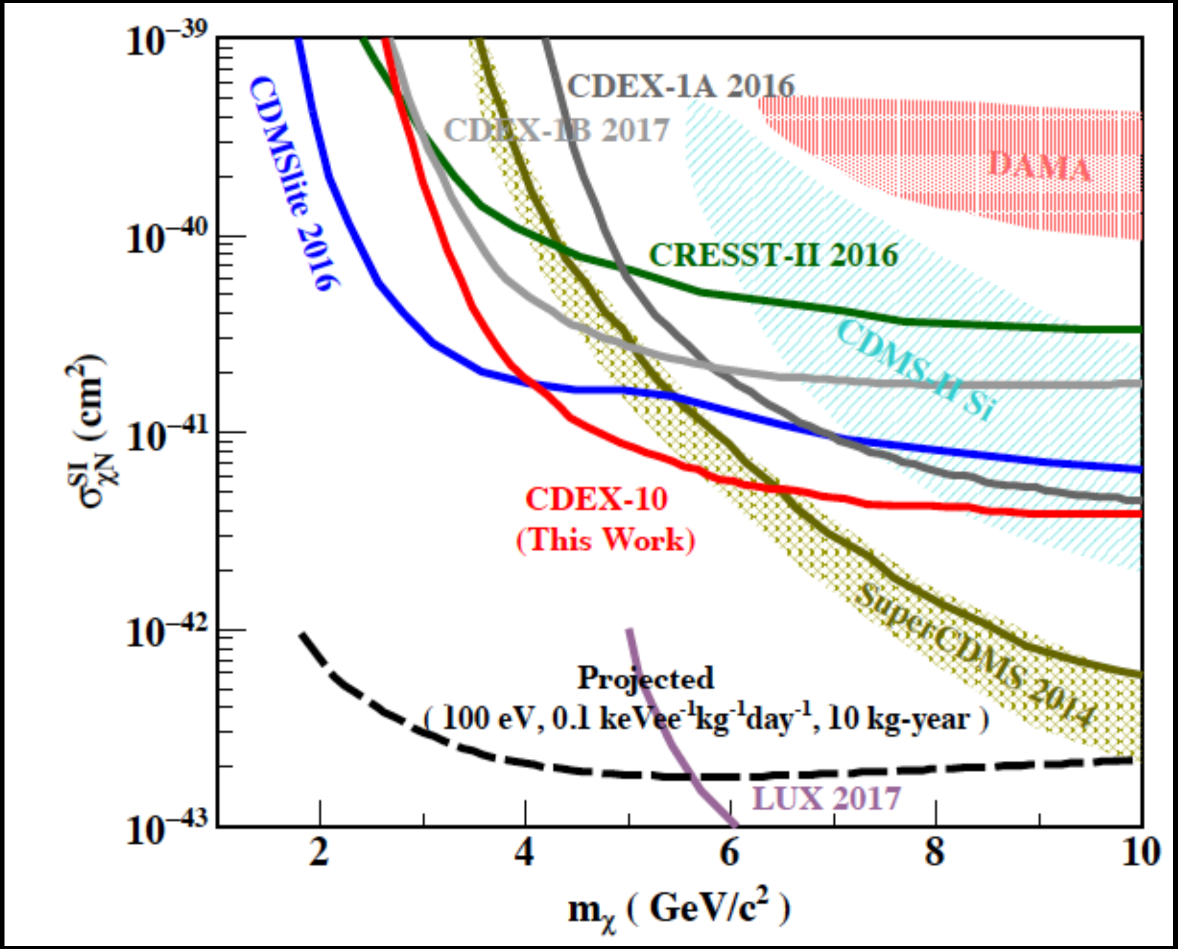
- Target: nucleus of semi-conductors (e.g. Ge)
- Use electron signal and phonon signal (low temperature)
- Low threshold hold for S1 signal
- CDMS, CDEX (Tsinghua)





Semi-conduction detector

CDEX collaboration, PRL 120 (2018) 241301



A little bit particle physics

- Effective operators
  - From relativistic operators to non-relativistic operators
  - From X-quark to X-nucleon to X-nucleus

$$\underbrace{\bar{\chi}\chi\bar{N}N \qquad \bar{\chi}\gamma_\mu\chi\bar{N}\gamma^\mu N}_{1\times 1} \qquad \underbrace{\bar{\chi}\gamma_\mu\gamma_5\chi\bar{N}\gamma^\mu\gamma_5 N}_{S_\chi \cdot S_N}$$

Spin independent

Spin dependent

A little bit particle physics

- For Spin-independent interaction:
  - $p \sim m_\chi v \sim 100\ \mathrm{MeV} \sim$ size of nucleus.
  - The DM cannot distinguish single nucleons inside the nucleus.
  - Coherent scattering. $M \propto N \rightarrow \sigma \propto N^2$
- For Spin-dependent interaction:
  - DM interacts with the spin of nucleus
  - $\sigma \propto S_N^2$

A little bit particle physics

- Momentum dependent operators

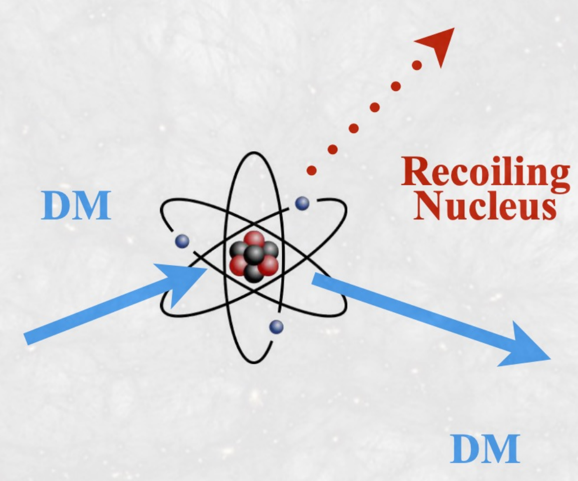
$\bar{\chi}\chi\partial_\mu\partial^\mu\bar{N}N$ $\bar{\chi}\partial_\mu\chi\bar{N}\partial^\mu N$ $\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$

q^2 $p_\chi \cdot p_N$ $\mathbf{q}\cdot\mathbf{S}_\chi\ \mathbf{q}\cdot\mathbf{S}_N$

Differential scattering rate

$$\frac{dR}{dE_{nr}} \propto N \frac{\rho_\chi}{2m_\chi m_r^2} \sigma_N \left|F^2(E_{nr})\right| \int_{v_{\min}}^{v_{esc}} \frac{f(v)}{v} d^3v$$

- N: number of targets
- ρ_χ: DM density
- m_χ: DM mass
- σ_N: interaction cross section
- $\left|F^2(E_{nr})\right|$: nuclear effects
- $\int_{v_{\min}}^{v_{esc}} \frac{f(v)}{v} d^3v$: WIMP velocity distribution

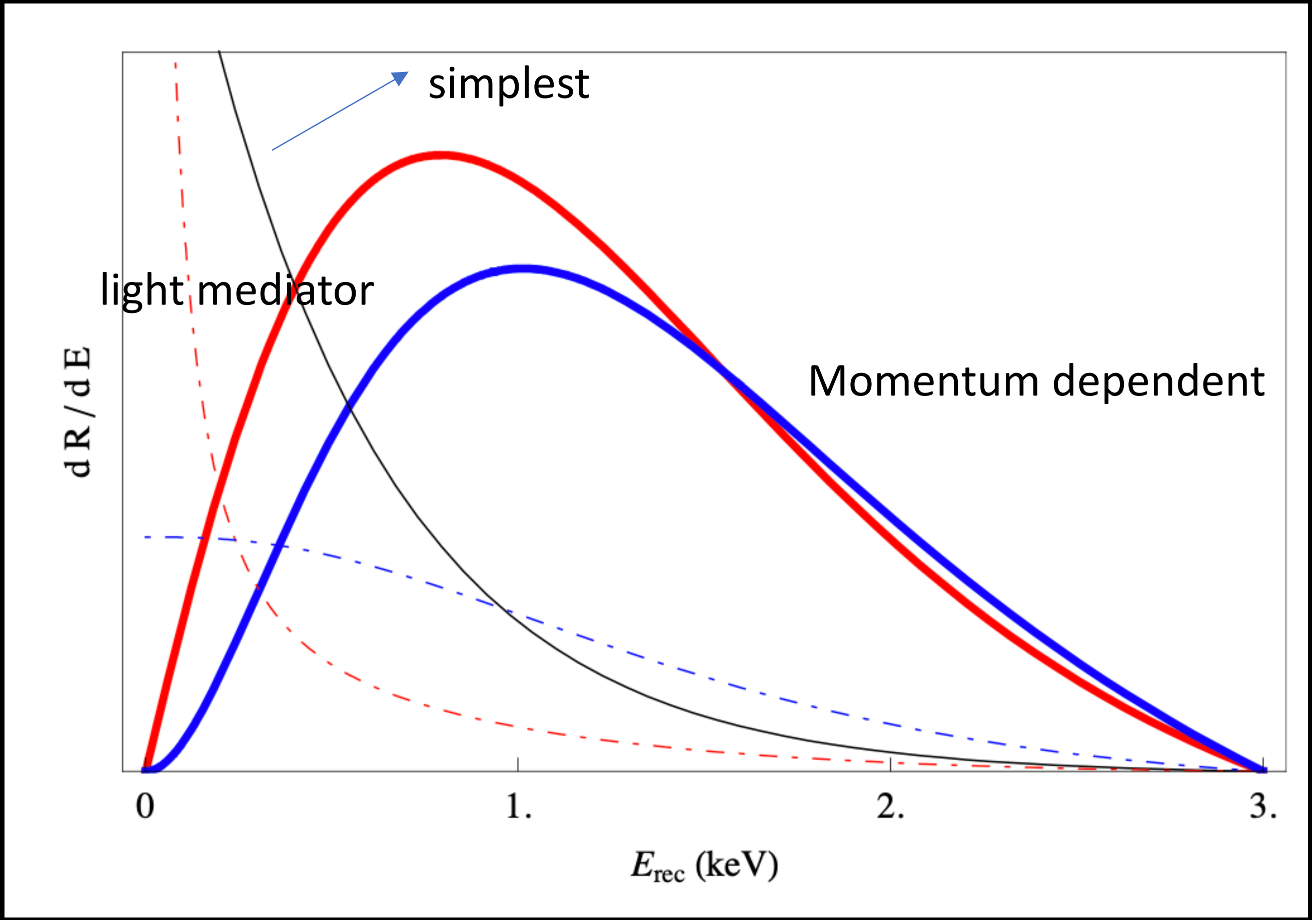


It may also depend on momentum transfer

Differential scattering rate

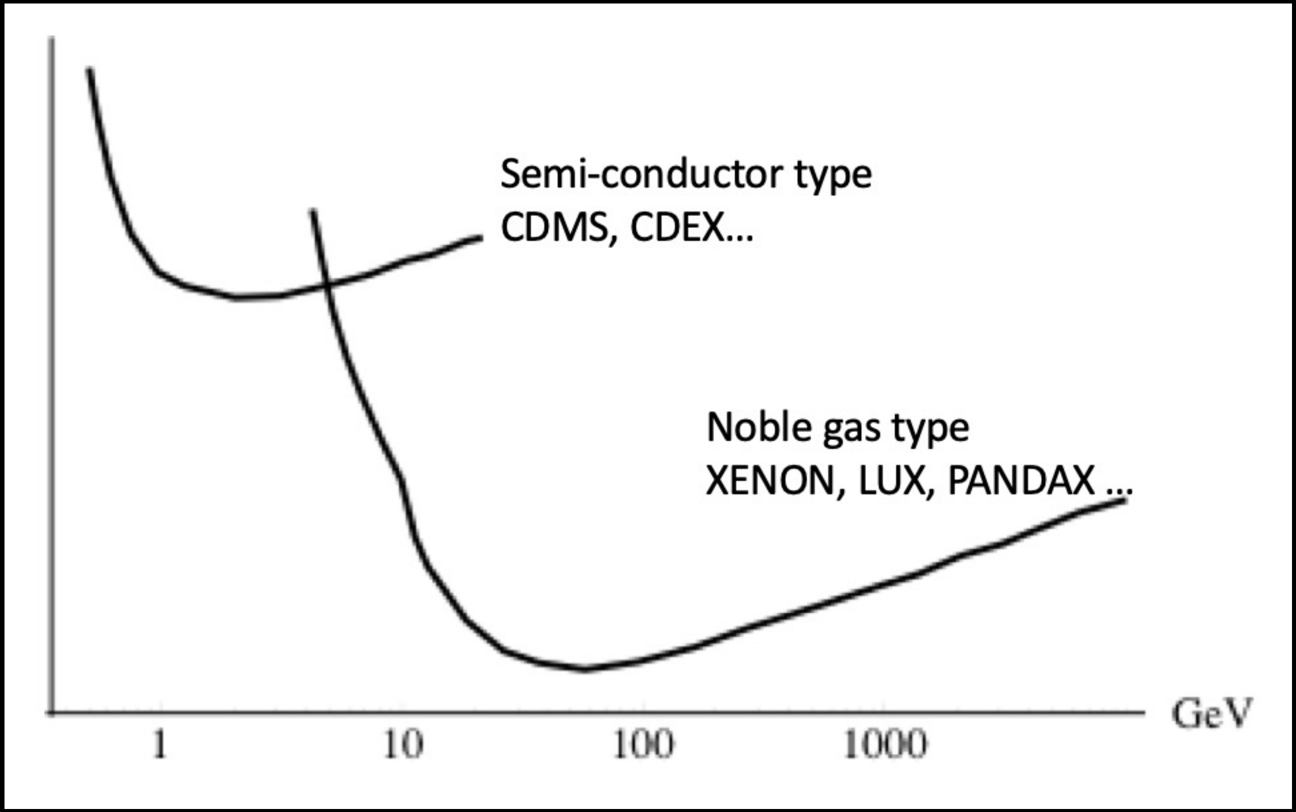
- The simplest operator $\sigma \sim const$.
- The higher dimensional operators: $\sigma \sim p^{\alpha}, \alpha \geq 2$.
- Light mediator case: momentum in the denominators. $\sigma \sim p^{\alpha}$
- The E_r dependence of dR/dE_r will also change

Differential scattering rate

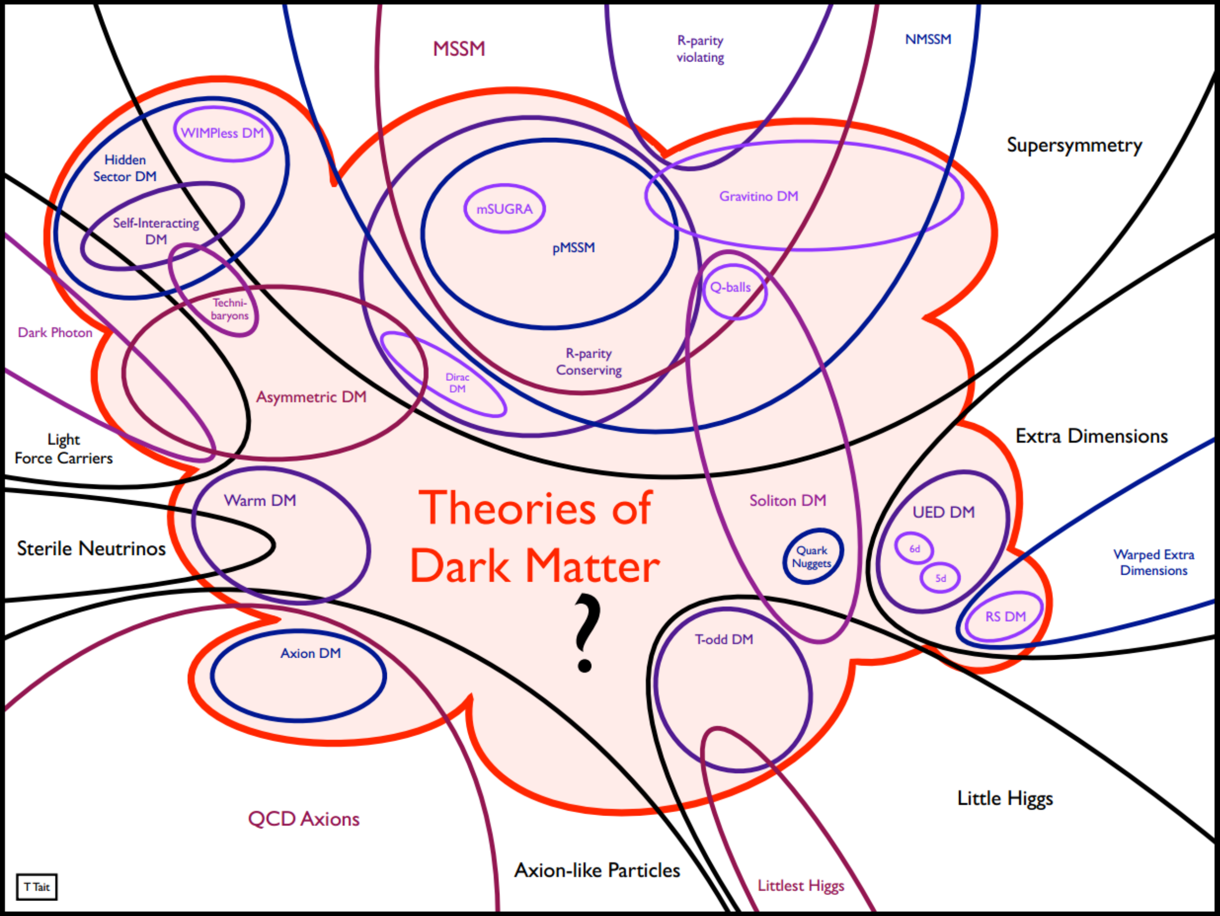


HA, S.-L. Chen, R.N.Mohapatra, S.Nussinov, Y. Zhang, 1004.3296

Searching for WIMPs

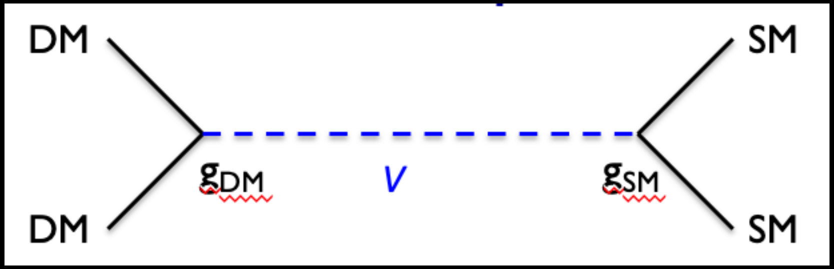


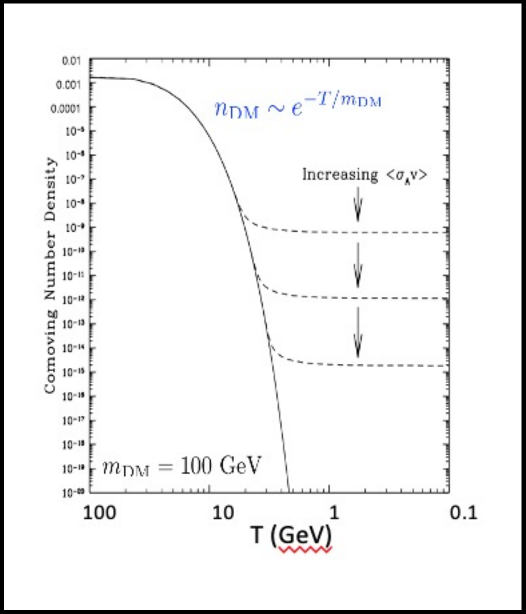
Theories of dark matter



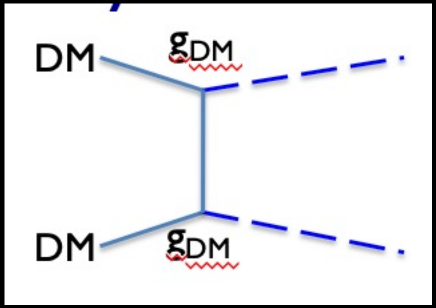
Hidden sector models

- A mediator connecting dark matter and SM



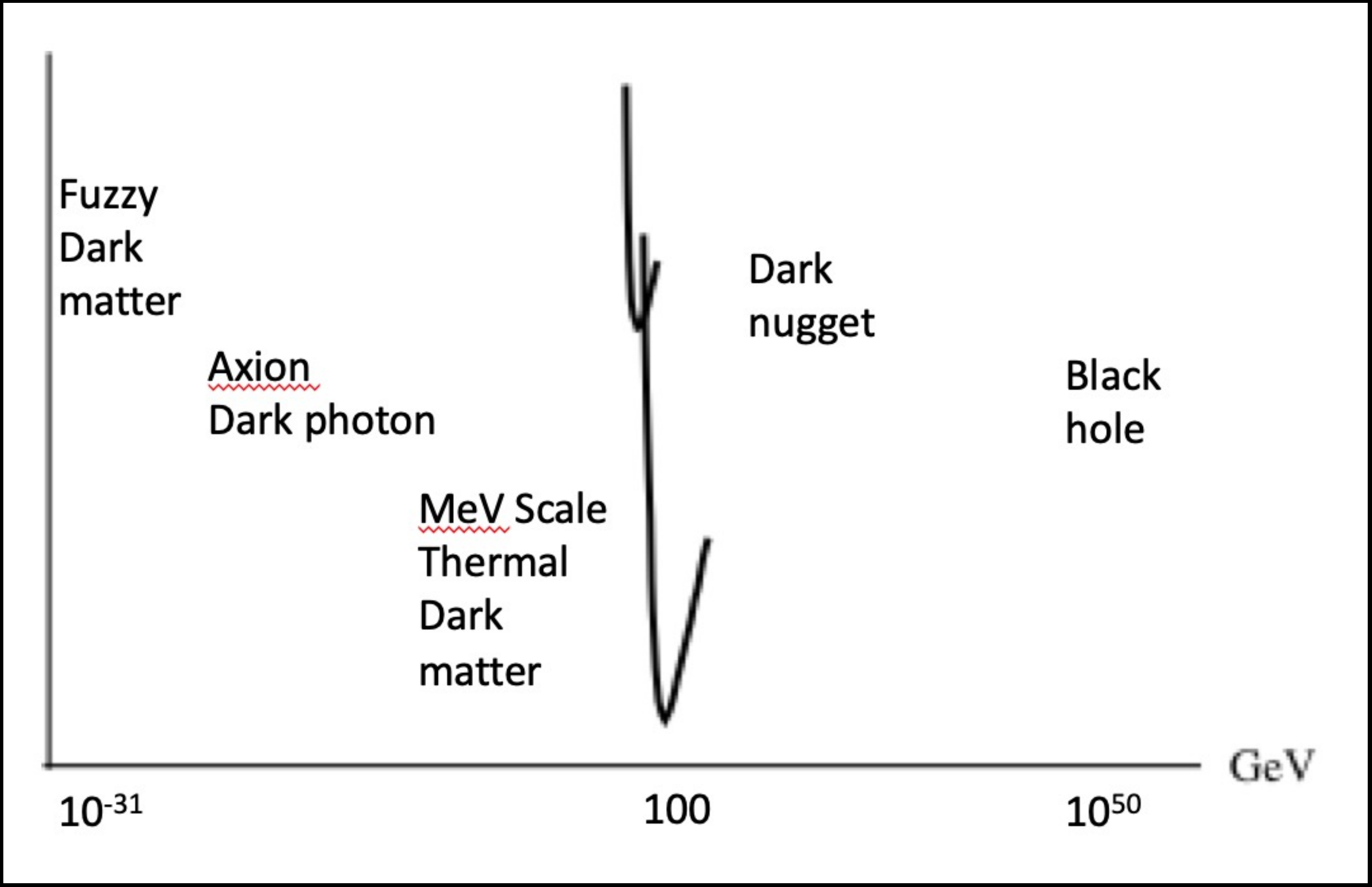


- DM annihilates to *V*



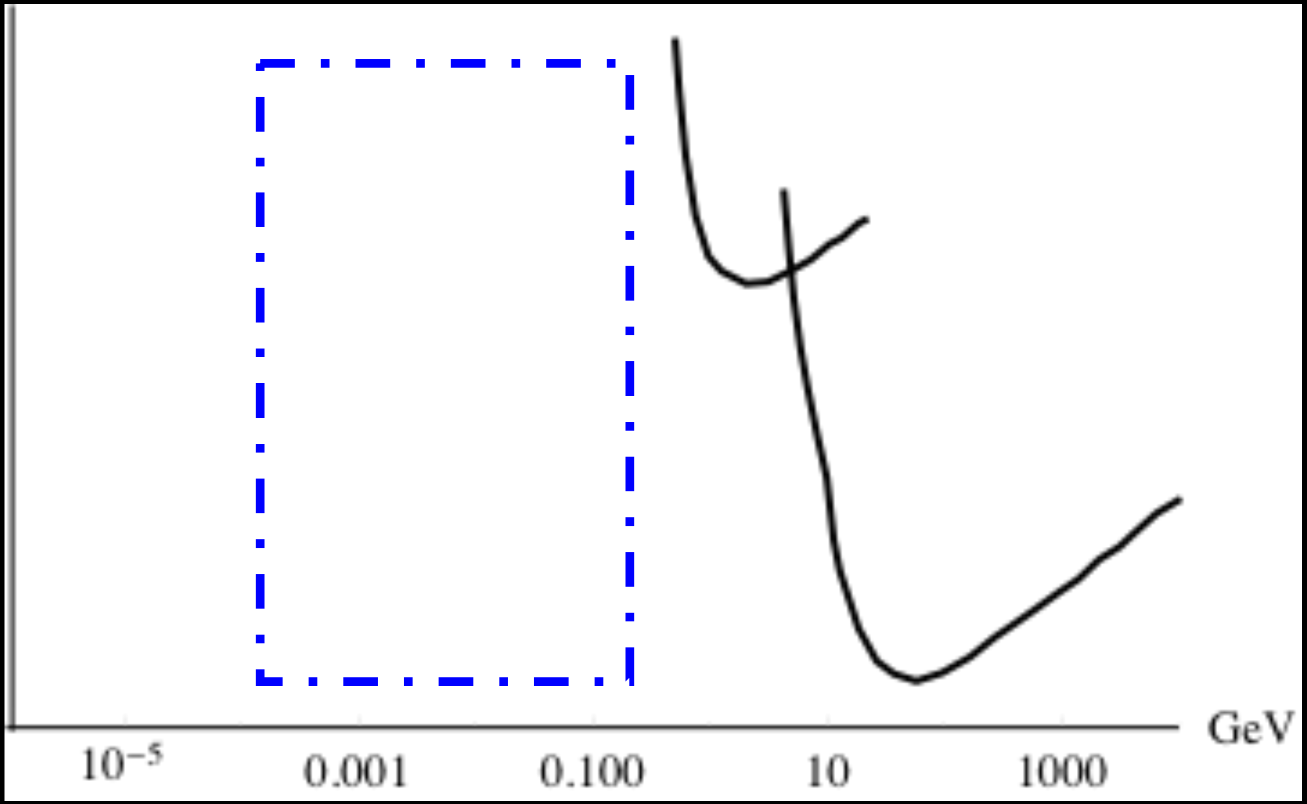
$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$$

Theories of dark matter



From GeV to MeV

- What if the DM is lighter than GeV scale?

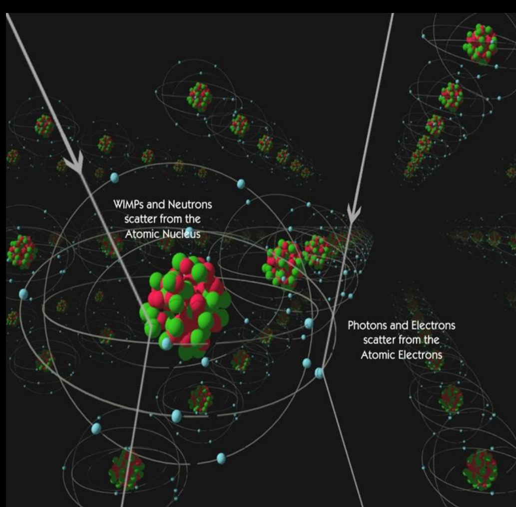


Use electron recoil for light DM

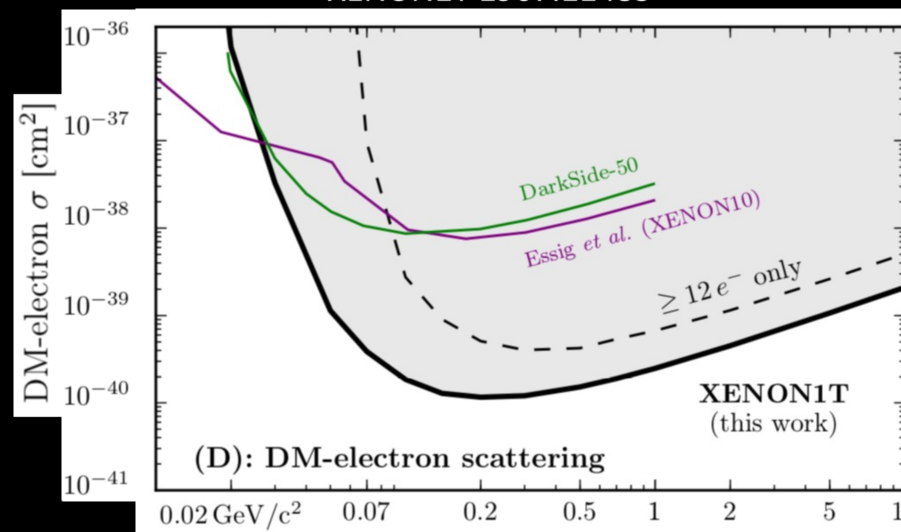
- For elastic scattering

$$E_{\rm recoil} \sim \frac{m_{\rm DM} m_T}{(m_{\rm DM}+m_T)^2} E_{\rm DM}$$

Use light targets



XENON1T 1907.11485



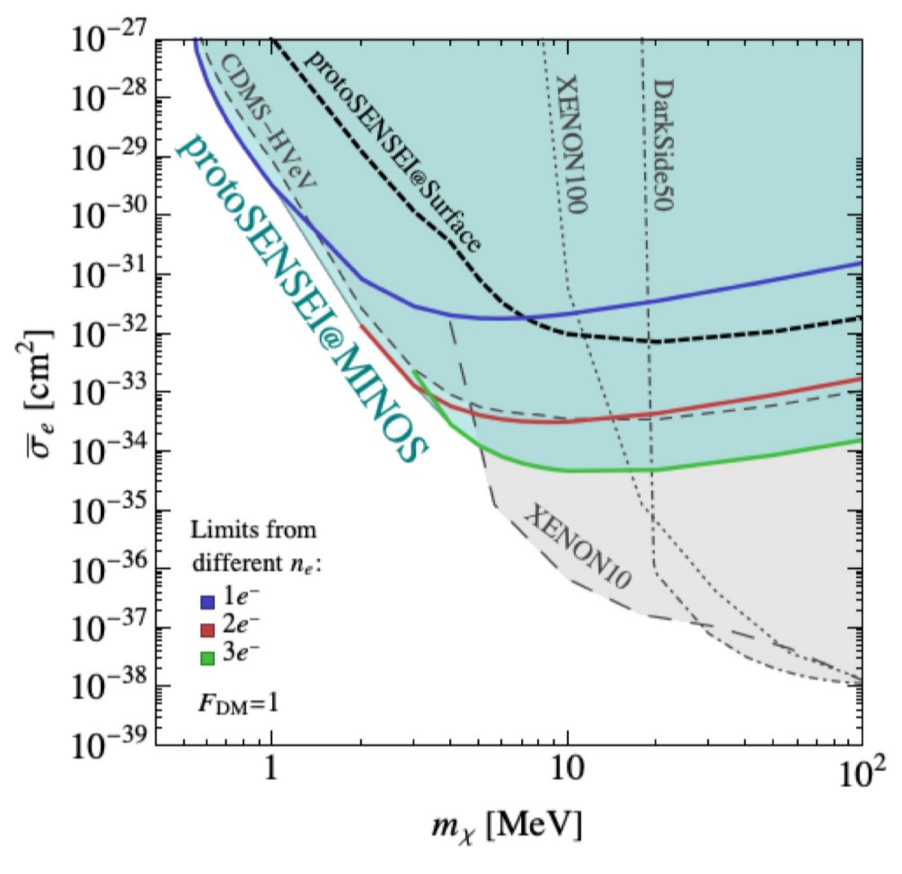
M_D > 10 MeV

Motivations

- How to search for DM if mD < 10 MeV?
  - Lower the threshold (Using semi-conductor, superconductor, or skipper CCD technology, nano tubes …)
  - Accelerate the DM particles (Sun, cosmic rays)

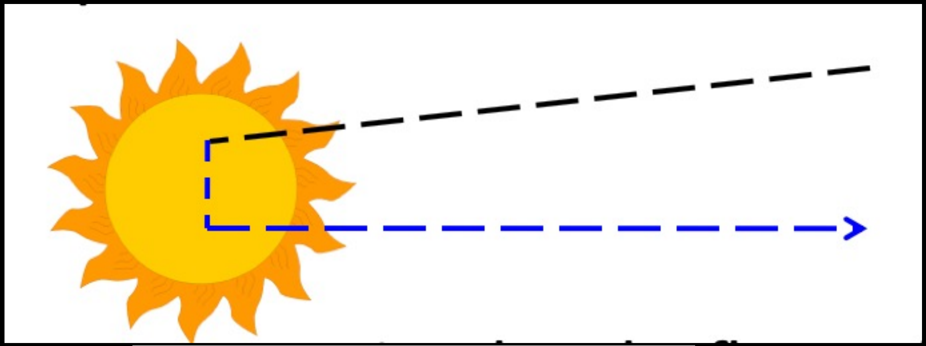
With skipper-CCD detector

SENSEI 1901.10478, 0.177 gram-days

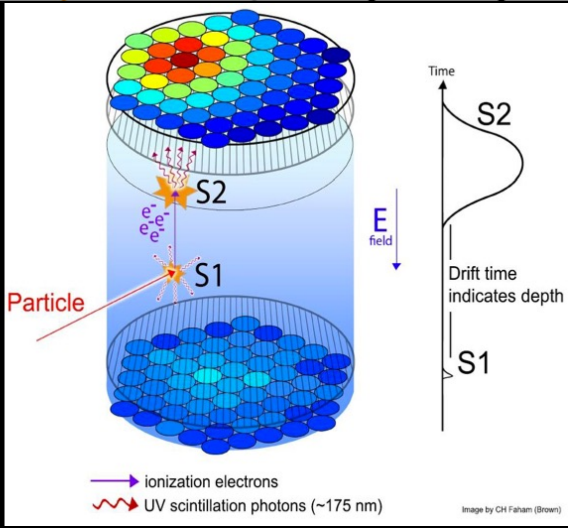


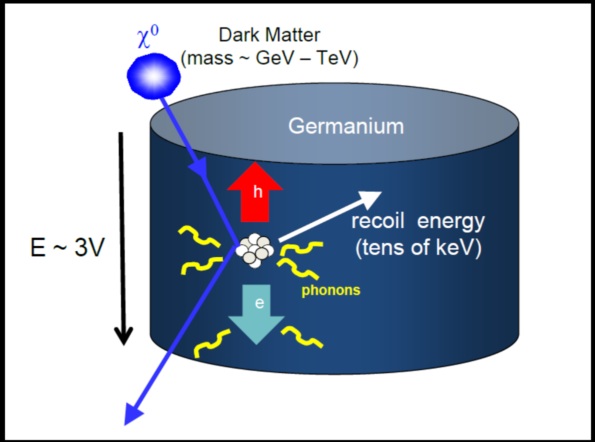
Solar accelerated DM particles

- The Sun can help us.



$T_{sun} \sim 1$ keV well above the thresholds of most experiments!





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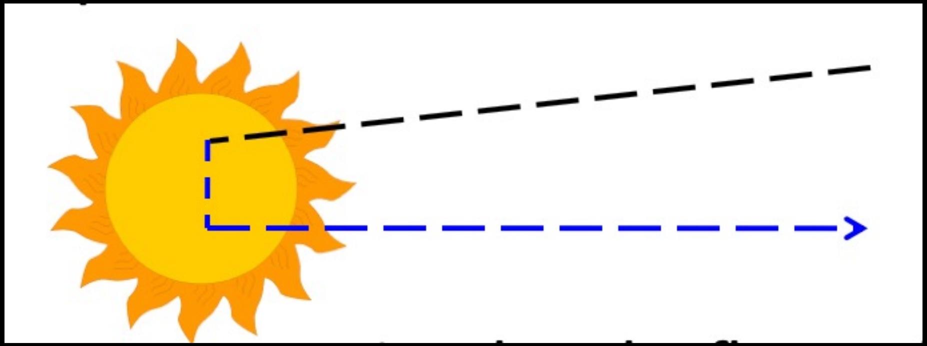


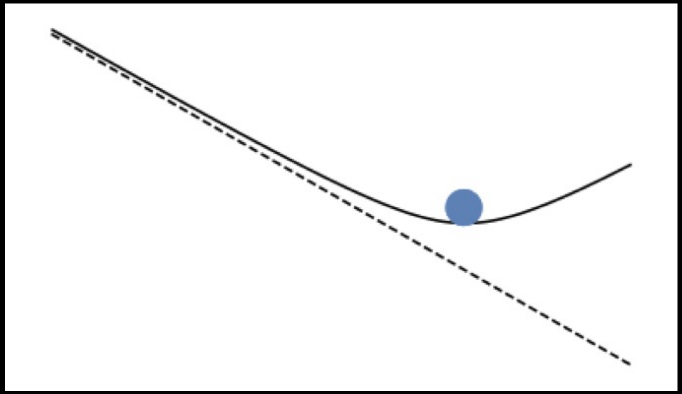
$T_{sun} \sim 1$ keV
well above the thresholds of most experiments!

- We pay the price that the flux at the earth surface is suppressed.

$$\Phi_{\mathrm{Earth}} = \Phi_{\mathrm{Sun}} \times \underbrace{\frac{\pi R_{\mathrm{Sun}}^2}{4\pi d_{\mathrm{Sun-Earth}}^2}}_{10^{-5}}$$

Solar accelerated DM particles

- Gravitational focusing effect



$$\frac{1}{2}v_{\rm DM}^2 = -\frac{G_N M_\odot}{R_\odot} + \frac{1}{2}v_{\rm DM}'^2$$

$$v_{\rm DM} R_0 = v_{\rm DM}' R_\odot$$

$$\Longrightarrow \frac{R_0^2}{R_\odot^2} = 1 + \frac{2G_N M_\odot}{R_\odot v_{\rm DM}^2}$$

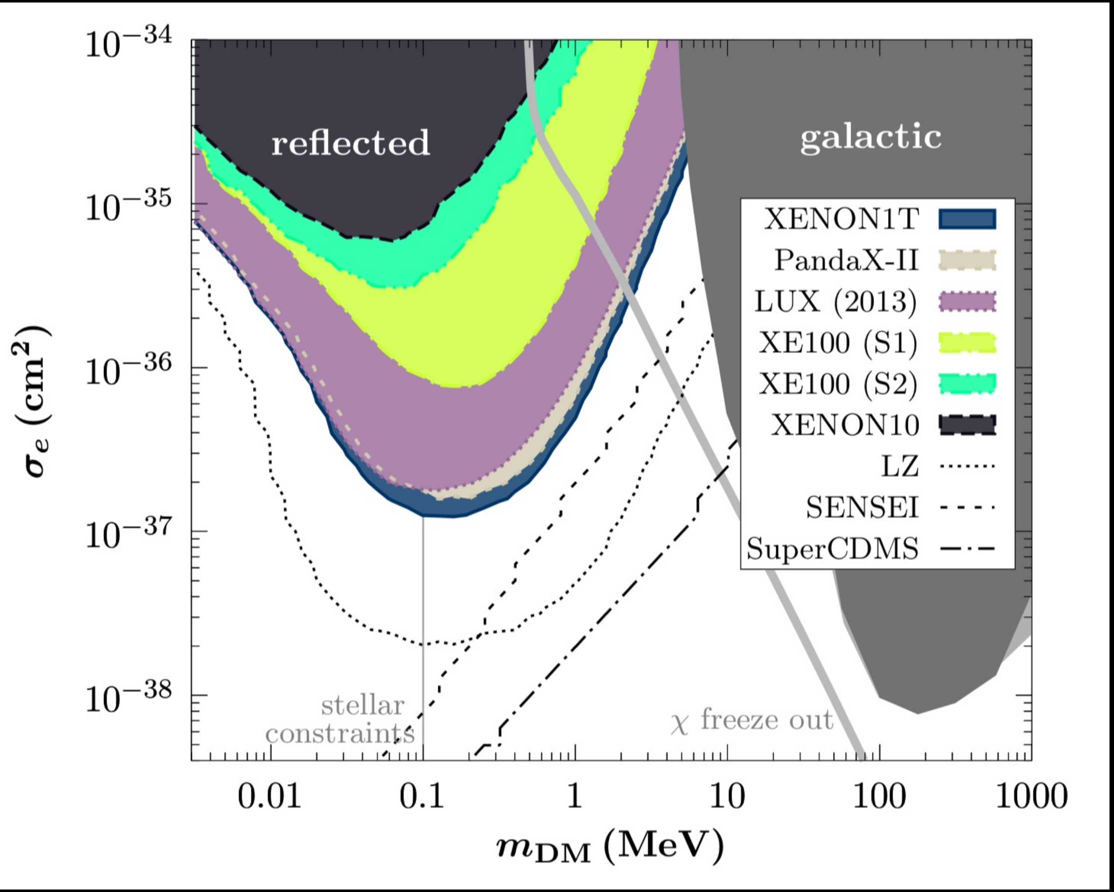
$$\frac{2G_N M_\odot}{R_\odot} = v_{\rm esc}^2 \approx (620 \text{ km/sec})^2$$

$$v_{\rm DM} \approx 220 \text{ km/sec}$$

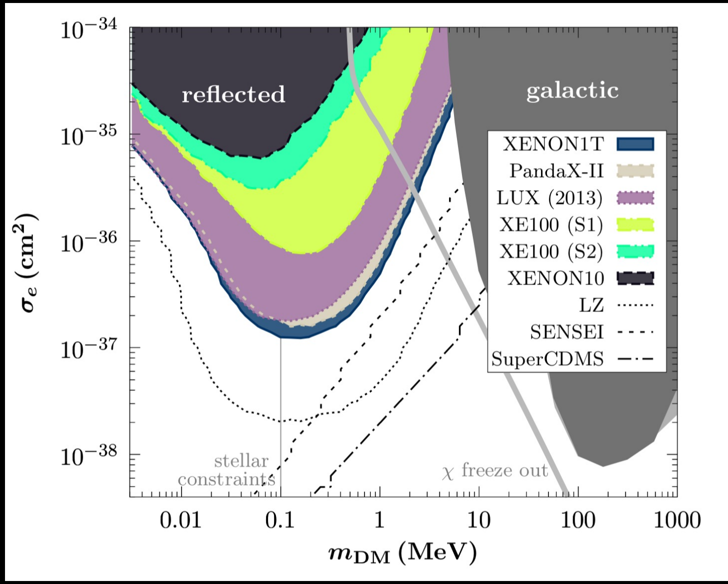
$$\Longrightarrow \frac{R_0^2}{R_\odot^2} \approx 10$$

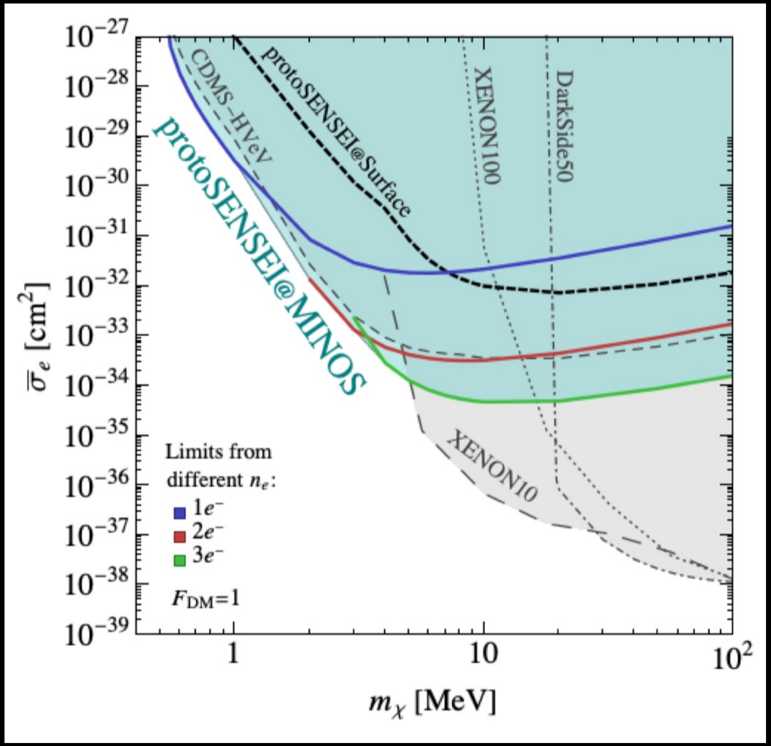
Solar accelerated DM particles

HA, M. Pospelov, J. Pradler, A. Ritz, PRL 120 (2018) 141801

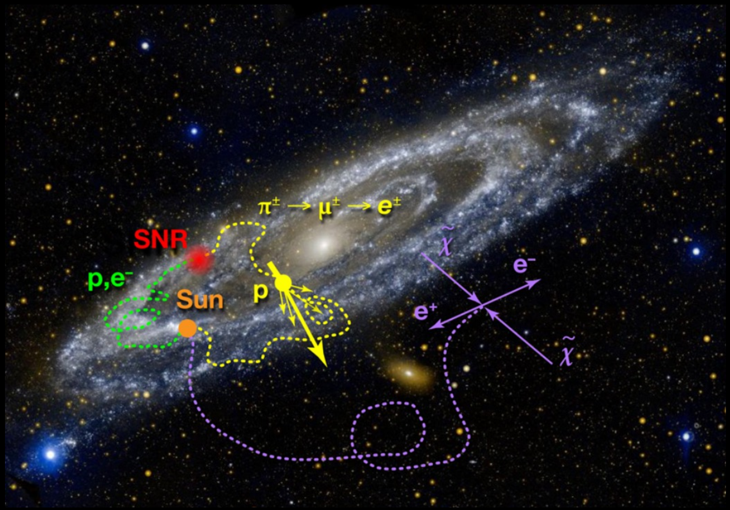


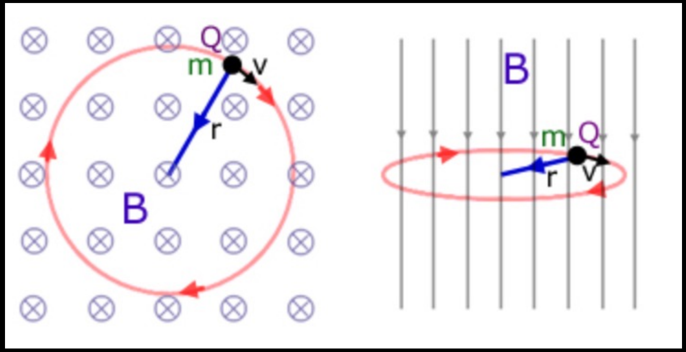
Solar accelerated DM particles

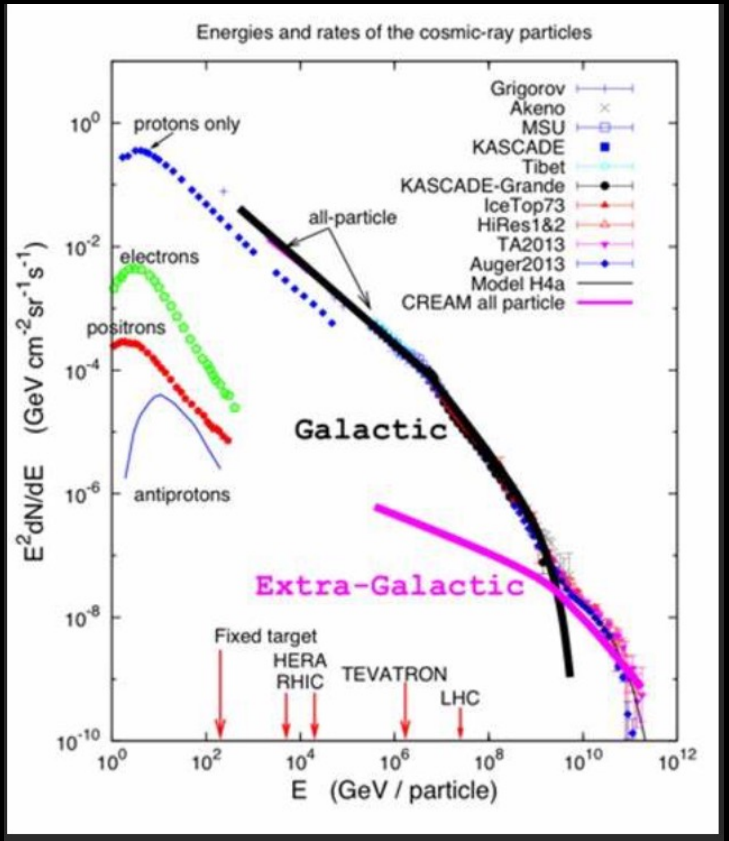




Cosmic ray accelerated DM

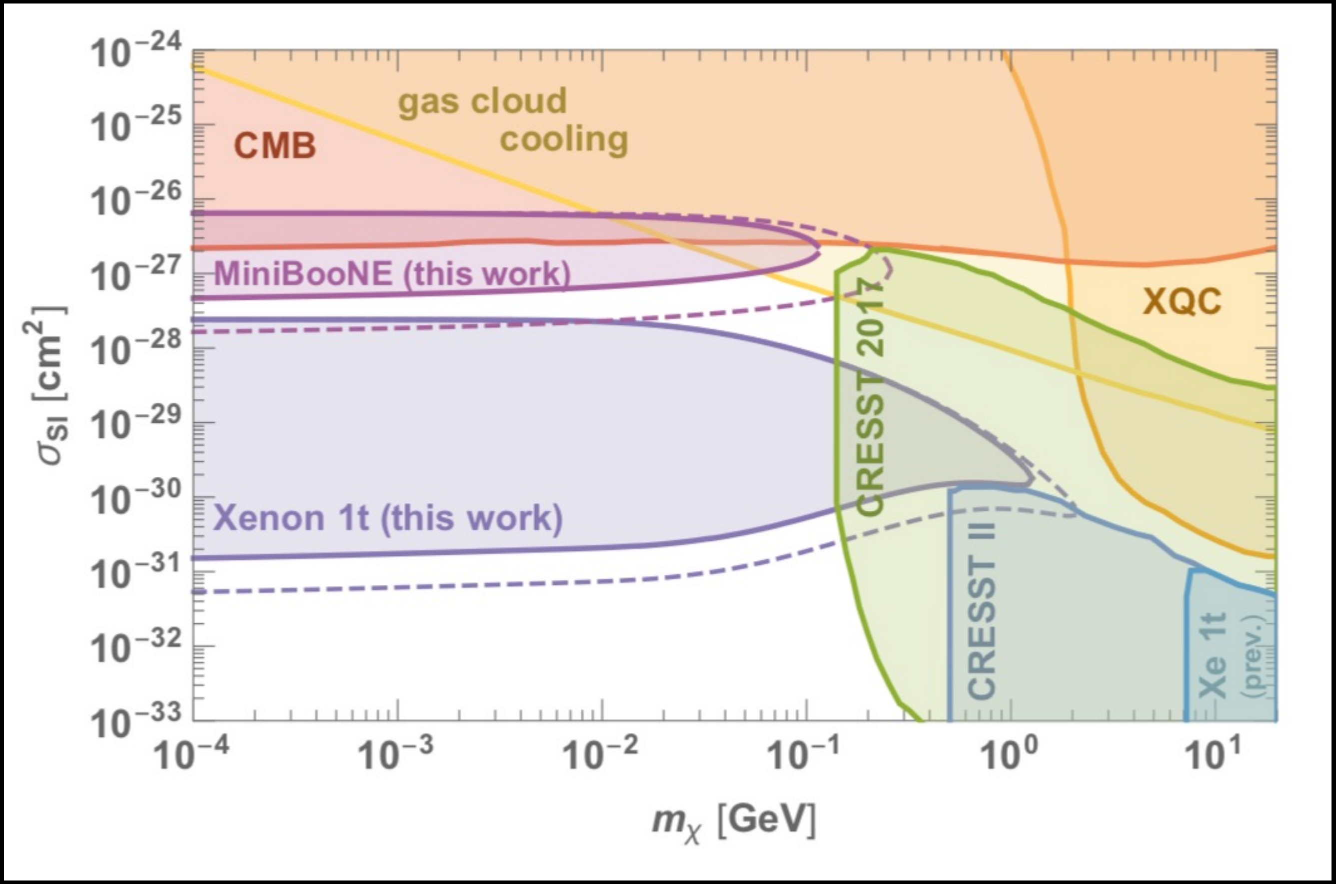




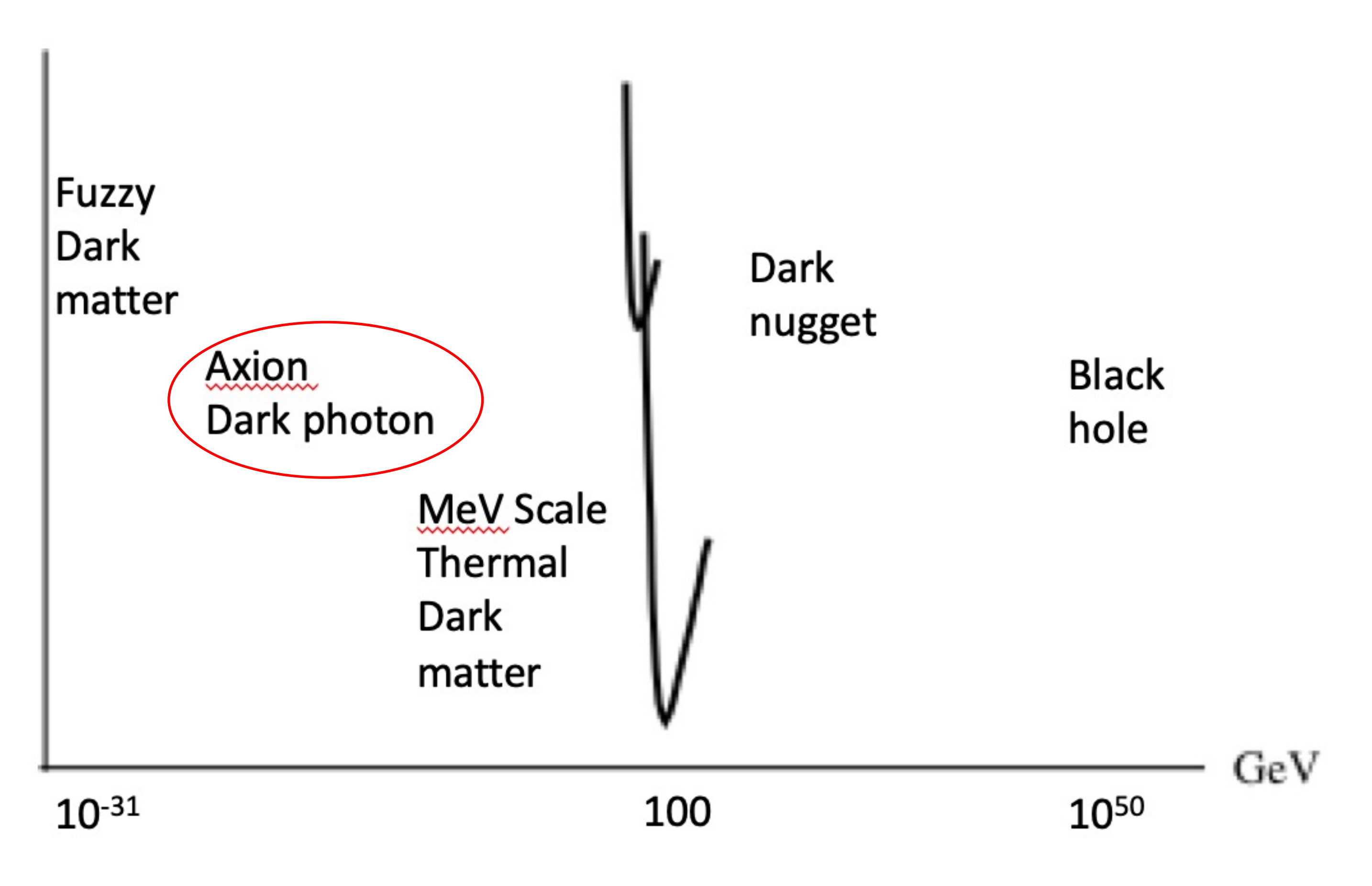


Cosmic ray accelerated DM

Bringman and Pospelov, PRL 122 (2019) 171801

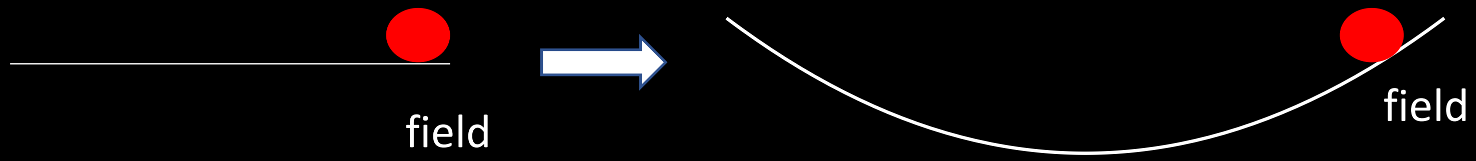


Theories of dark matter



Axion and dark photon DM

- Dark matter with mass smaller than about 200 eV must not be fermions.
- Axion, a pseudo-scalar particle
- Dark photon, a vector particle mixing with photon
- Produced in the early universe (e.g. misalignment)



What is axion?

- It is a pseudo-scalar field.
- It can interact with all the fields in the standard model.

$$g\, a\, \mathbf{E} \cdot \mathbf{B}$$

$$g\, \mathbf{E} \cdot \mathbf{d}_{\mathrm{e}}$$

↓

Oscillating electric dipole moment

$$\mathbf{d}_{\mathrm{e}} \sim a \times \mathrm{spin}$$

What is dark photon?

- It mixes with the photon field in the SM through kinetic energy.
- It is massive.
- We usually assume it has no other interactions with SM particles.

$$L_{\mathrm{EM}} = \frac{1}{2}(\mathbf{E}^2 - \mathbf{B}^2) \Longrightarrow L = \frac{1}{2}(\mathbf{E}^2 - \mathbf{B}^2) + \frac{1}{2}(\mathbf{E}'^2 - \mathbf{B}'^2) + \underbrace{\kappa(\mathbf{E}\cdot\mathbf{E}' - \mathbf{B}\cdot\mathbf{B}')}_{\text{Kinetic mixing}}$$

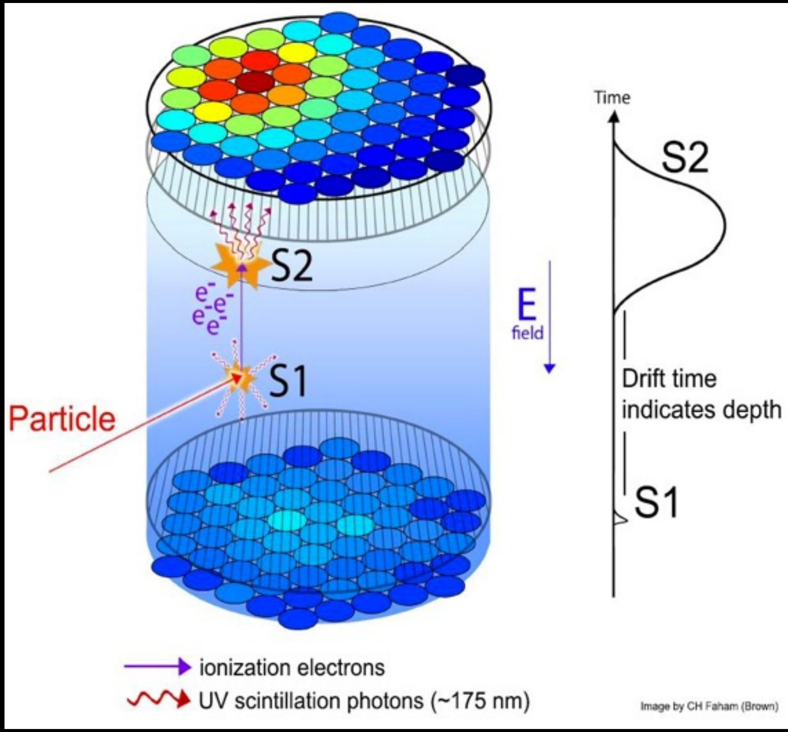
Searching for axions and dark photon with WIMP detectors

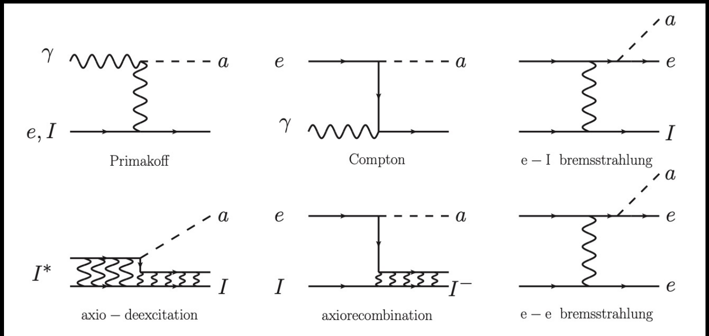
- If mass smaller than 1 keV, axions and dark photons can be produced inside the Sun, and with keV scale energy can be detected by WIMP detectors.

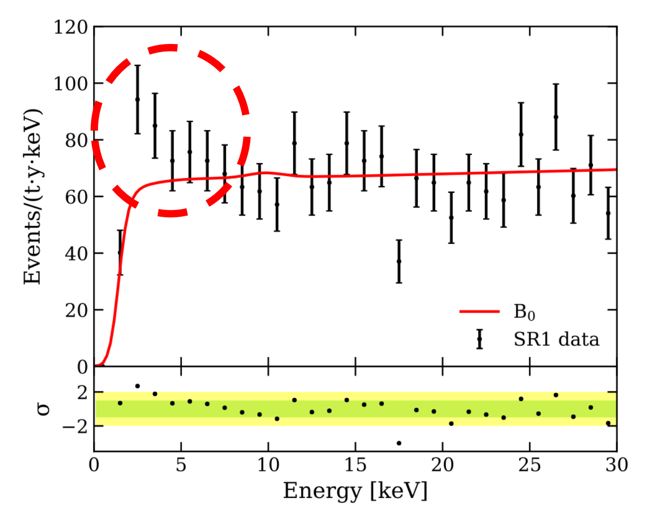
- If axions or dark photons are dark matter with mass larger than the thresholds, they can be absorbed by the detector and produce electron recoils.

Searching for axions and dark photon with WIMP detectors

- Solar axion



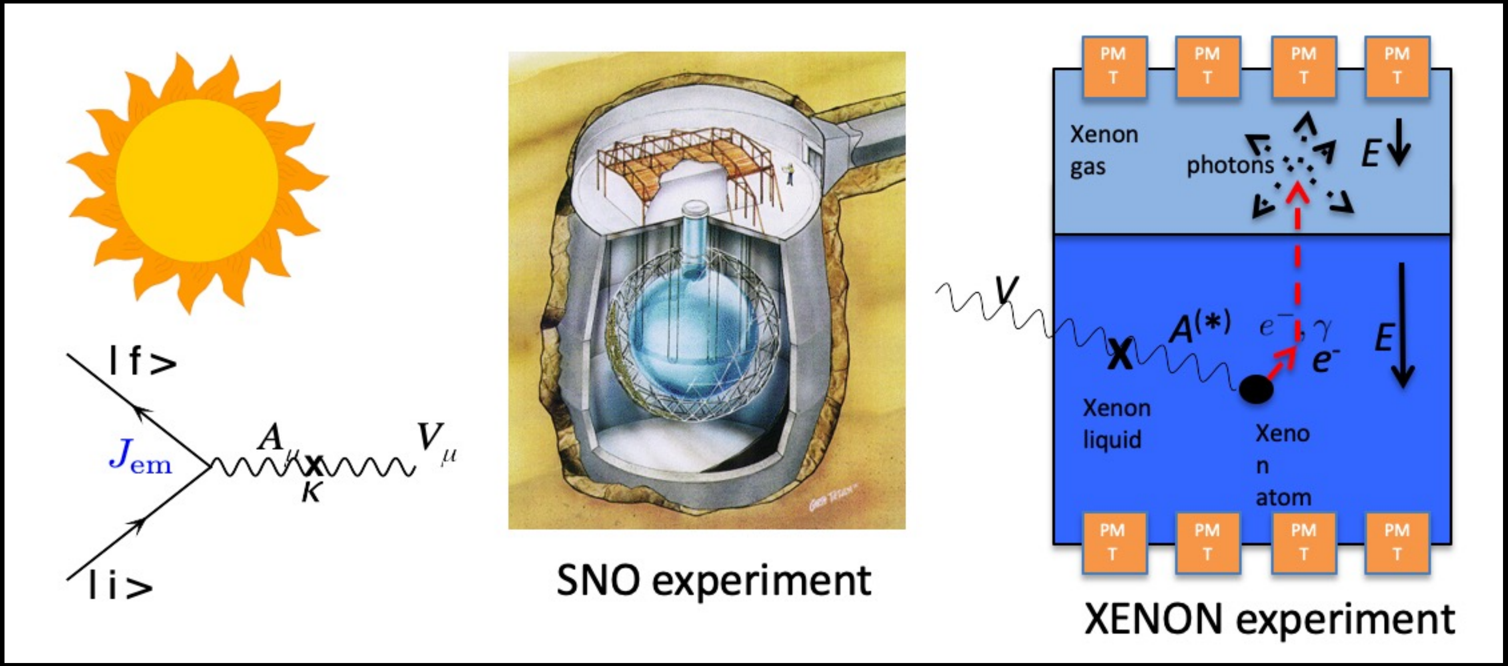




arXiv:2006.09721, XENON1T

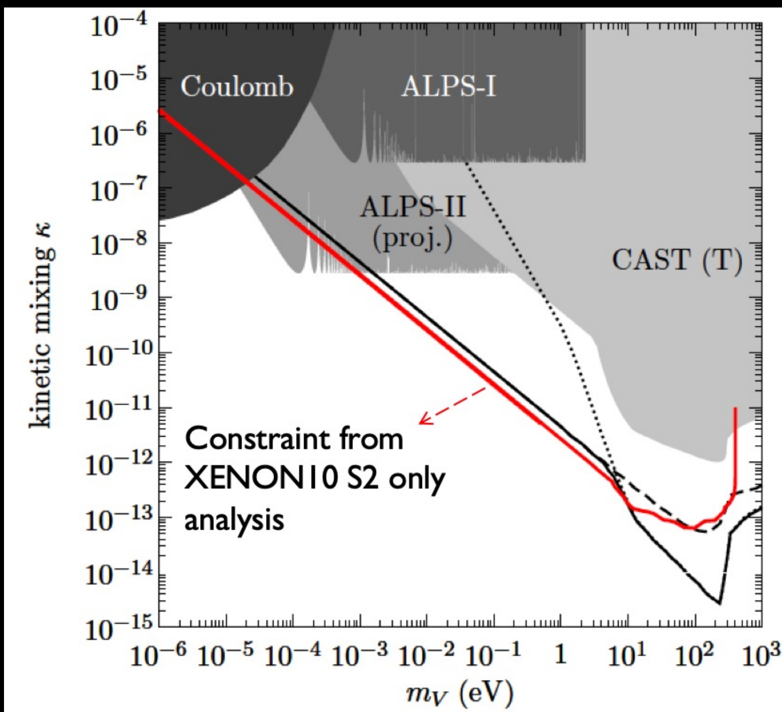
Searching for axions and dark photon with WIMP detectors

- Take dark photon as an example

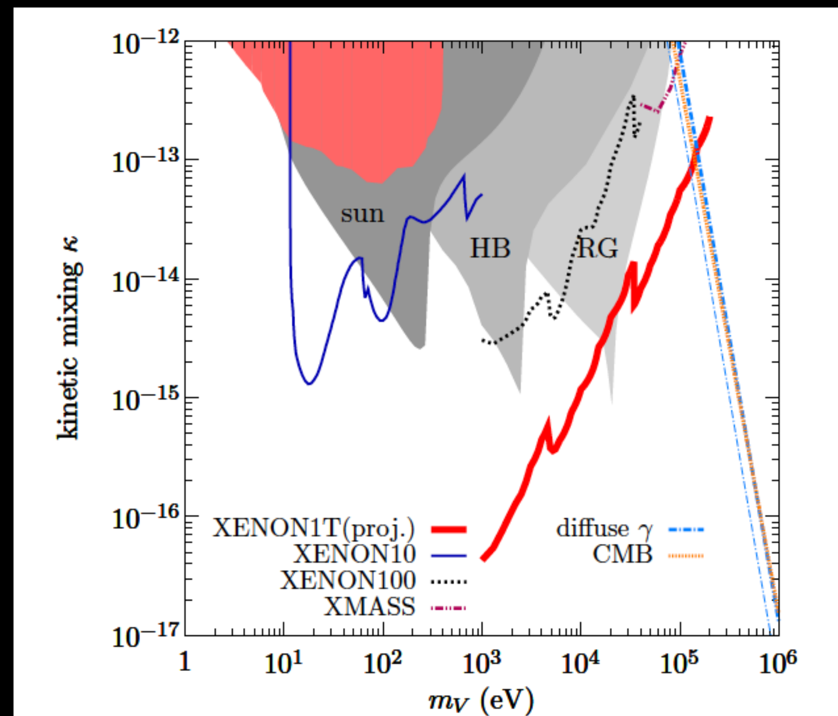


Searching for axions and dark photon with WIMP detectors

HA, Pospelov, Pradler, PLB 725 (2013) 190, PRL 111 (2013) 041302



HA, Pospelov, Pradler, Ritz, PLB 747 (2015) 331

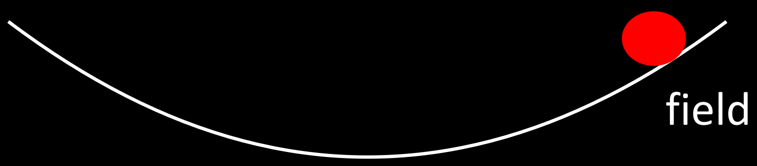


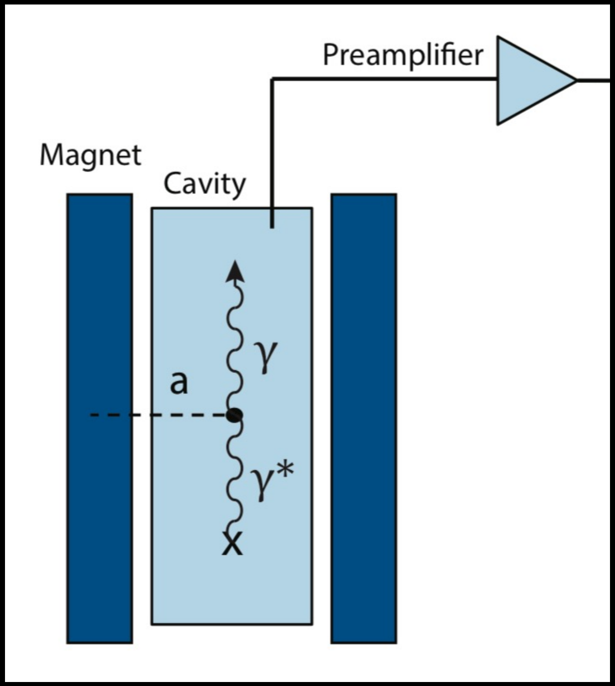
Searching for axions and dark photons with their wave-nature

- Axion coupled to electromagnetic waves

$$g\, a\, \mathbf{E} \cdot \mathbf{B}$$

Weakness: we don’t know the mass of axion …





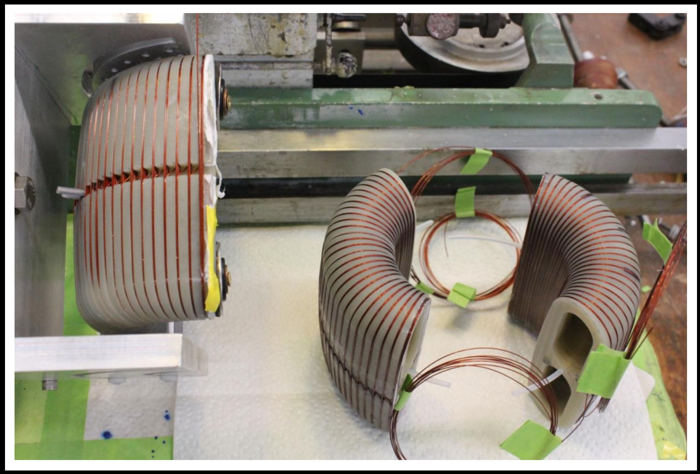
ADMX experiment

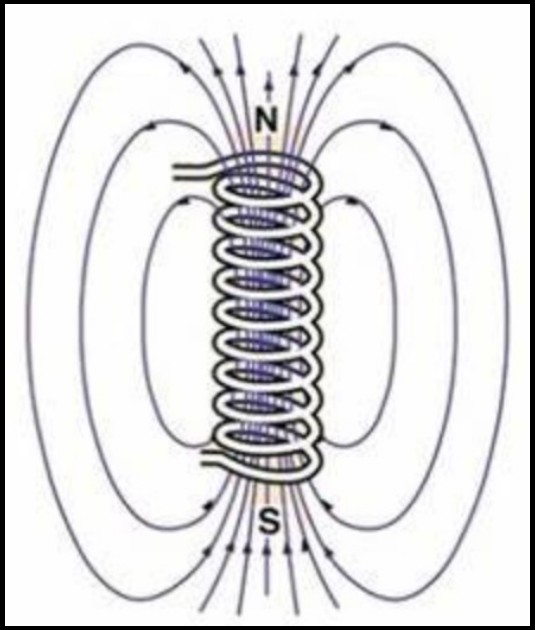
Searching for axions and dark photons with their wave-nature

- Axion induced alternative current

$$g\, a\, \mathbf{E}\cdot\mathbf{B} \longrightarrow \mathbf{J}_{\text{eff}} = g\dot{a}\,\mathbf{B}$$

ABRACADABRA





Searching for axions and dark photons with their wave-nature

- Axion induced alternative current

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ABRACADABRA

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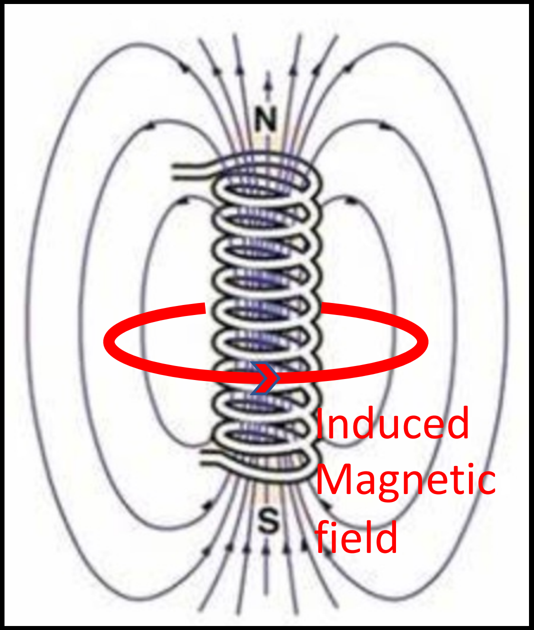
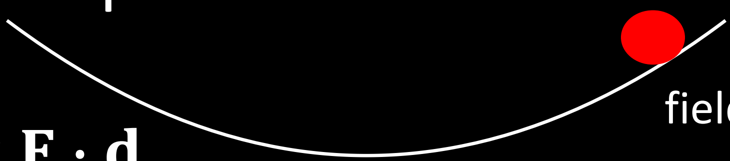
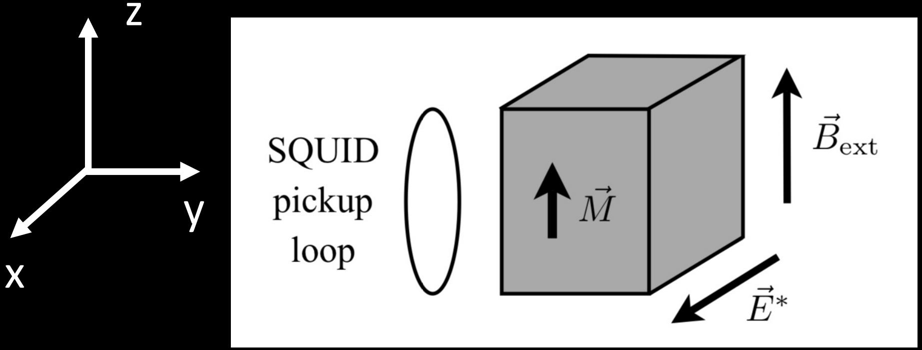


Searching for axions and dark photons with their wave-nature

- Axion induced nuclear electric dipole moment



CASPEr



$$g\,\mathbf{E}\cdot\mathbf{d}_{\rm e}$$

↓

Oscillating electric dipole moment

$$\mathbf{d}_{\rm e} \sim a \times \text{spin}$$

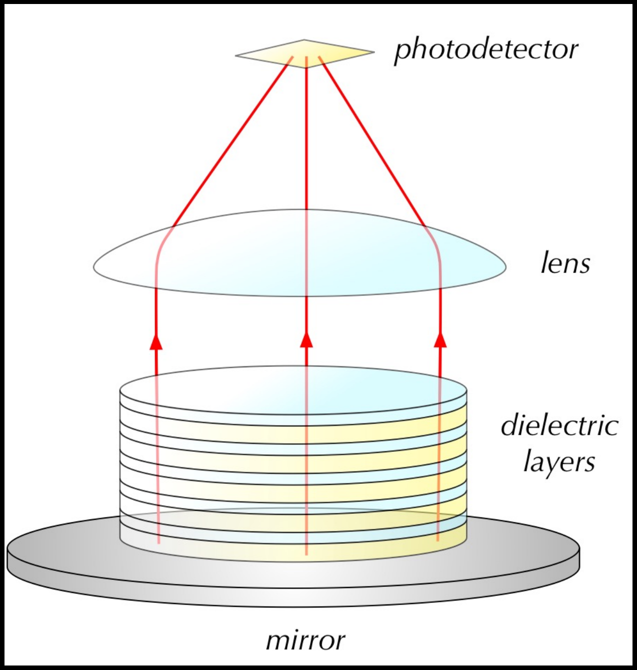
- The induced magnetic moment is resonantly enhanced if the Larmor procession of the magnetic moment and the oscillating EDM has the same frequency.

Searching for axions and dark photons with their wave-nature

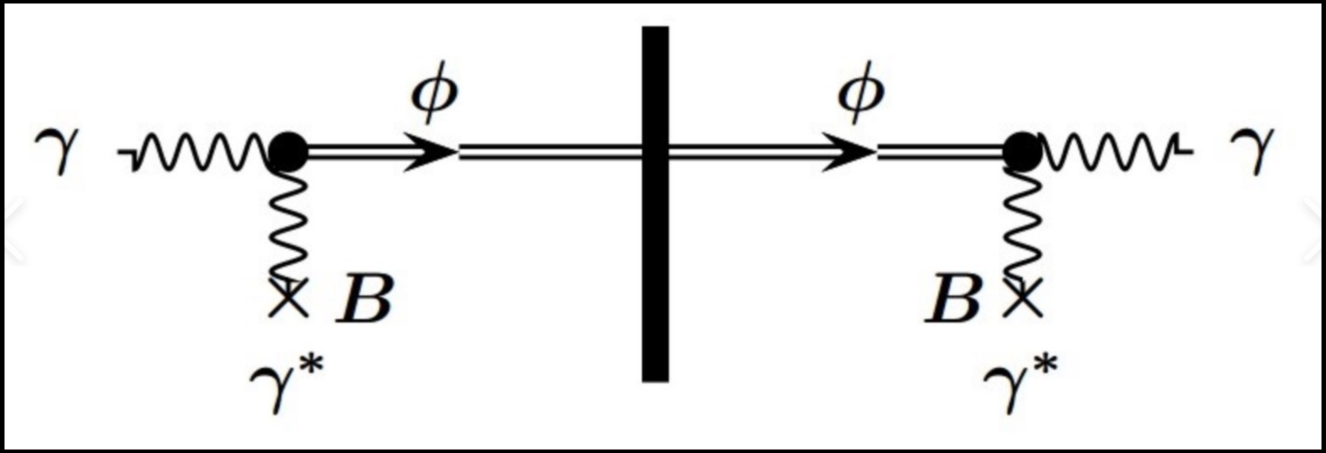
- Dark photon dark matter oscillate to on-shell photons

Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006

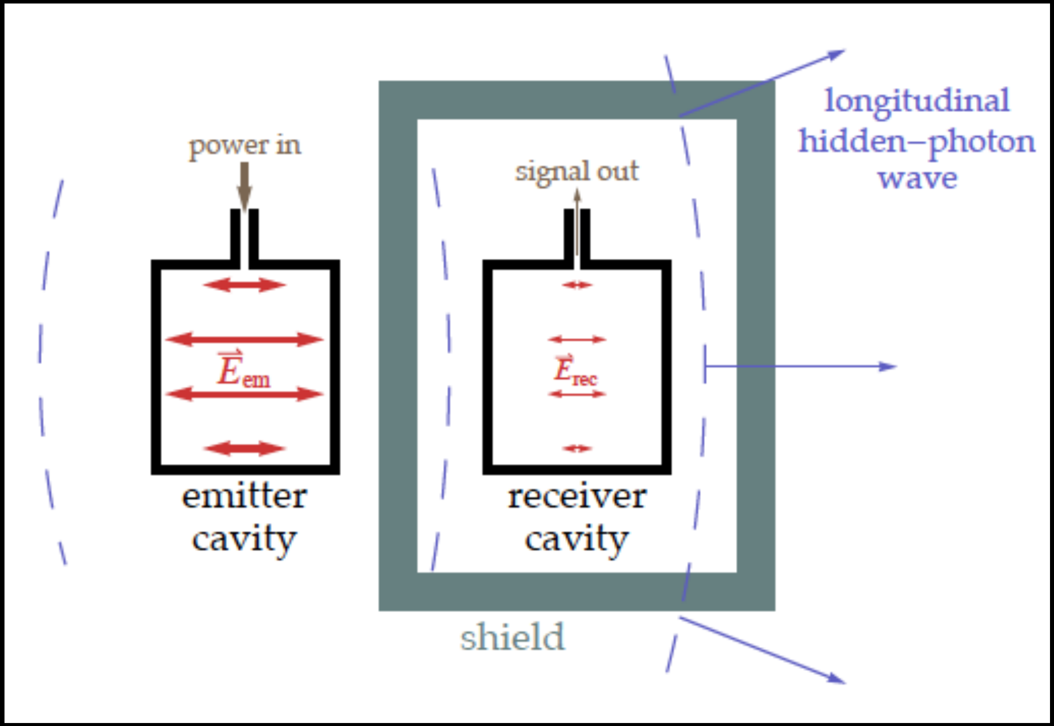
A stack of dielectric layers, with alternating indices of refraction provide a non-zero momentum for the photon to propagate.



Light shining through the wall

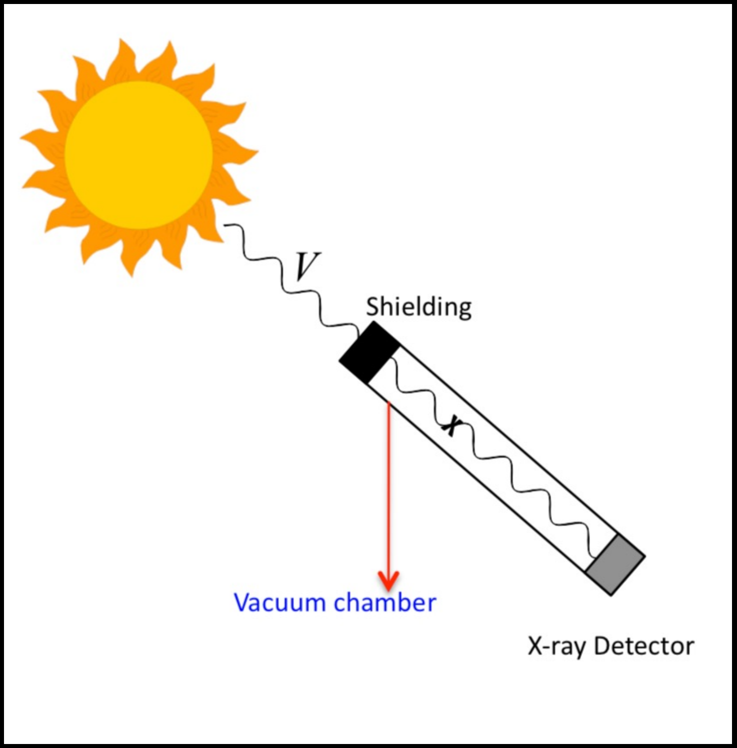


Microwave through the wall



Helioscope


LHC DIPO
OTOTYPE


V
Shielding
x
Vacuum chamber
X-ray Detector

Searching for ultralight dark matter with radio telescopes

Photon dark photon oscillation

- Dispersion relations in the vacuum

$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

  - For photon: $\omega^2 - k^2 = 0$
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - On shell dark photons cannot convert into photon in the vacuum.

Photon dark photon oscillation

- Dispersion relations in plasma

$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

  - For photon: $\omega^2 - k^2 = \omega_p^2$

$$\omega_p^2 = \frac{4\pi\alpha_{EM}n_e}{m_e}$$

  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Photons can convert into dark photon in the plasma if $\omega_p = m_{A'}$.

Photon dark photon oscillation

- Dispersion relations in plasma

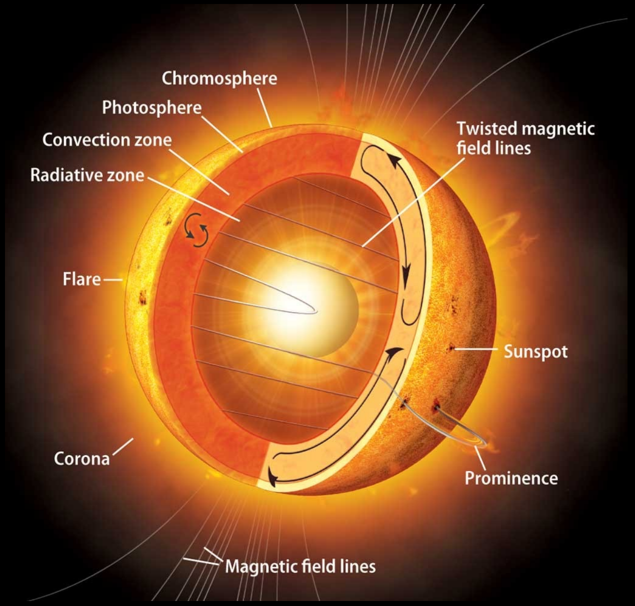
$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

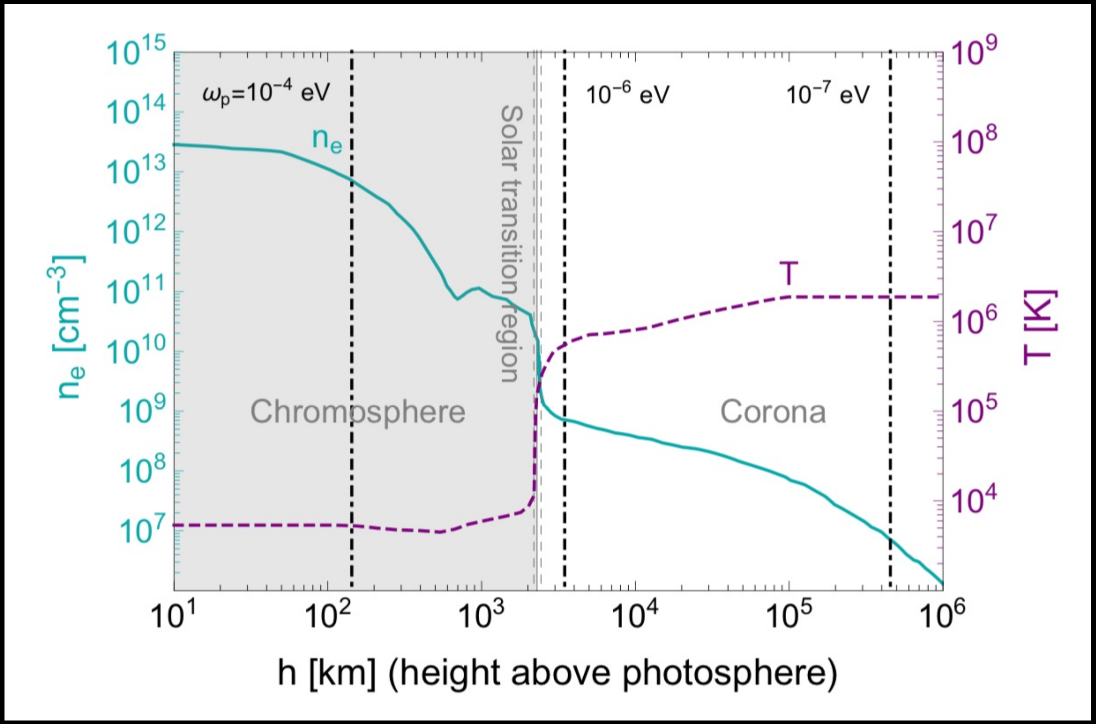
  - For photon: $\omega^2 - k^2 = \omega_p^2$

$$\omega_p^2 = \frac{4\pi\alpha_{EM}n_e}{m_e}$$

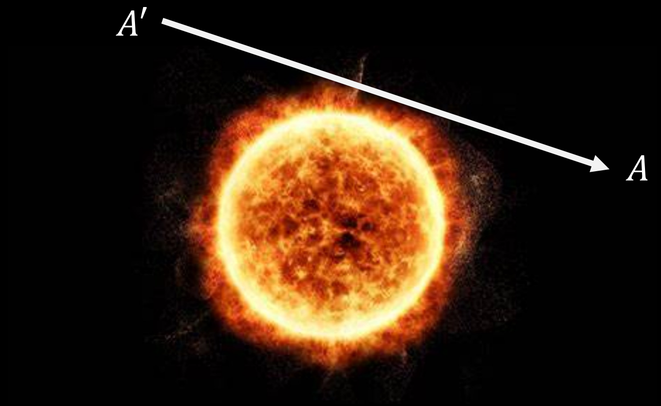
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Photons can convert into dark photon in the plasma if $\omega_p = m_{A'}$.
- The Sun's atmosphere is a vast source of plasma and may be transparent.

Solar atmosphere





Dark photon dark matter converted at the Sun's atmosphere



- Resonant conversion
  - $\omega_p = m_{A'}$
- Inside the dark matter halo
  - $v_{A'} \sim 10^{-3}$
- The frequency of the converted photon
  - $\omega \approx m_{A'}$, with the dispersion $\sim 10^{-6}$.
- The signal is a sharp peak in the solar spectrum

Calculation of the conversion rate

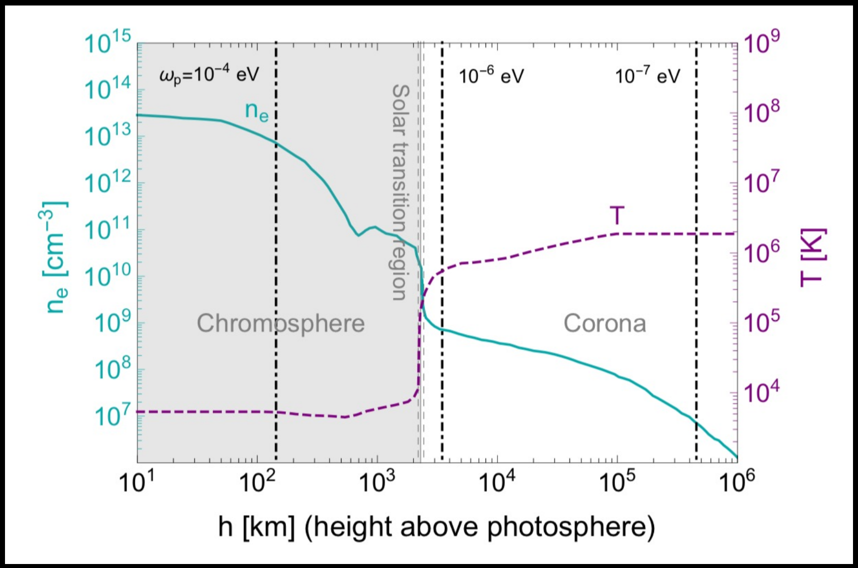
- 1 → 1 transition

$$P_{A'\to\gamma} = \frac{2}{3} \times \pi \epsilon^2 m_{A'} v_r^{-1} \left| \frac{\partial \ln \omega_p^2(r)}{\partial r} \right|^{-1}_{\omega_p(r)=m_{A'}}$$

$$S_{\rm sig} = \frac{r_c^2}{d^2} P_{A'\to\gamma} \rho_{\rm DM} v(r_c) \mathcal{B}^{-1}$$

↓

Size of the resonant region $\sim r_c$

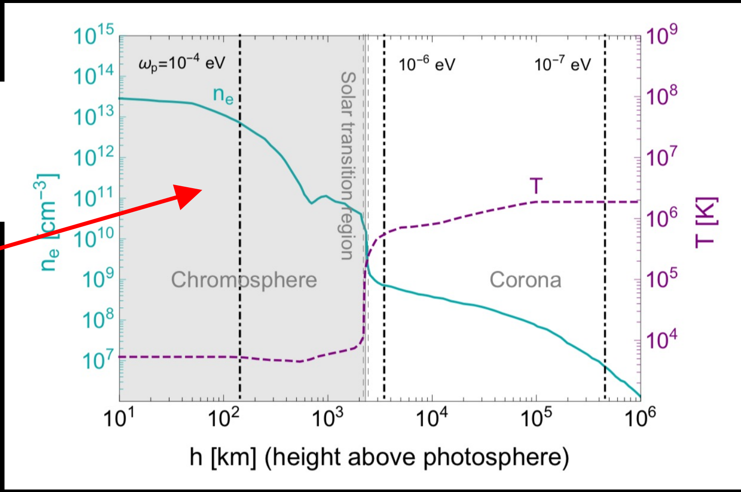


Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

$$\Gamma_{\rm inv} \approx \frac{8\pi n_e n_N \alpha^3}{3\omega^3 m_e^2}\left(\frac{2\pi m_e}{T}\right)^{1/2}\log\left(\frac{2T^2}{\omega_p^2}\right)\left(1-e^{-\omega/T}\right)$$

Photon converted in chromosphere cannot fly out.

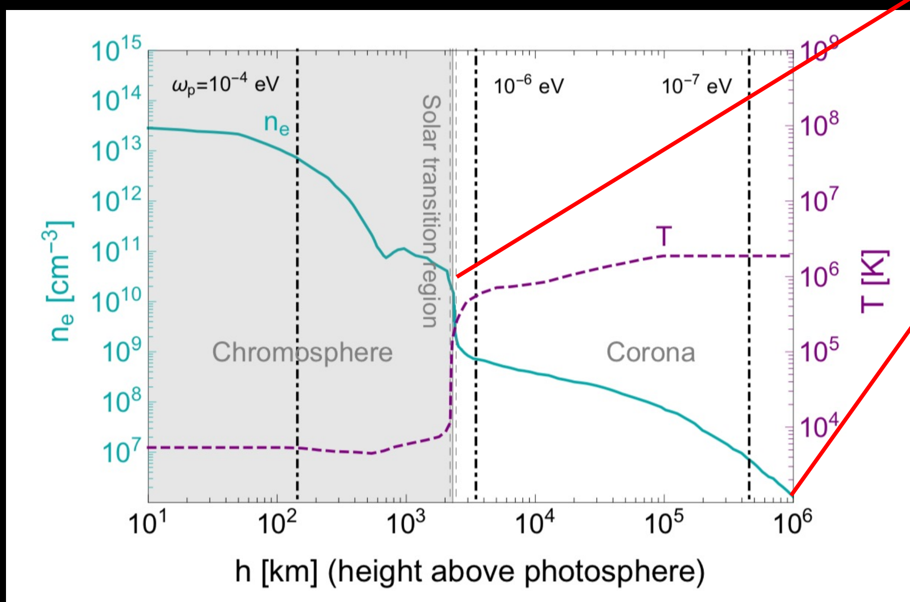


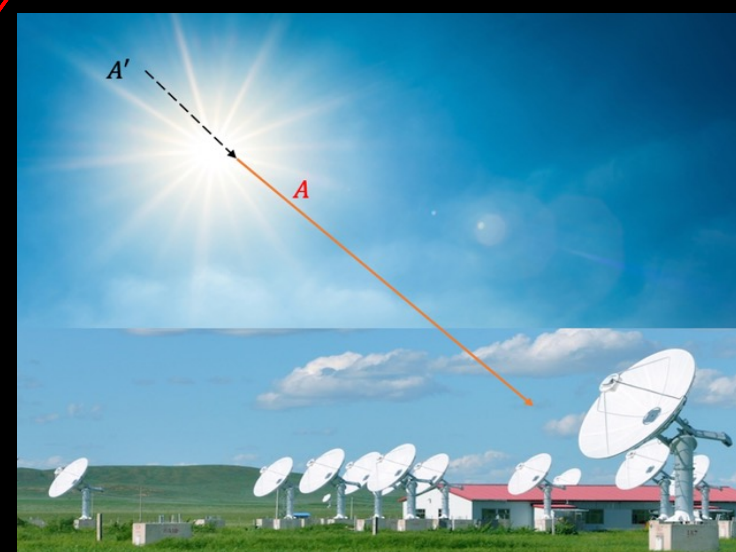
- Compton scattering
  - Compton scattering can shift the frequency of the converted photon.
- $\Gamma_{att} = \Gamma_{inv} + \Gamma_{com}$

Searching for the converted photon with radio telescopes

$f = 1\ \mathrm{GHz}$

$f = 10\ \mathrm{MHz}$





Searching for the converted photon with radio telescopes

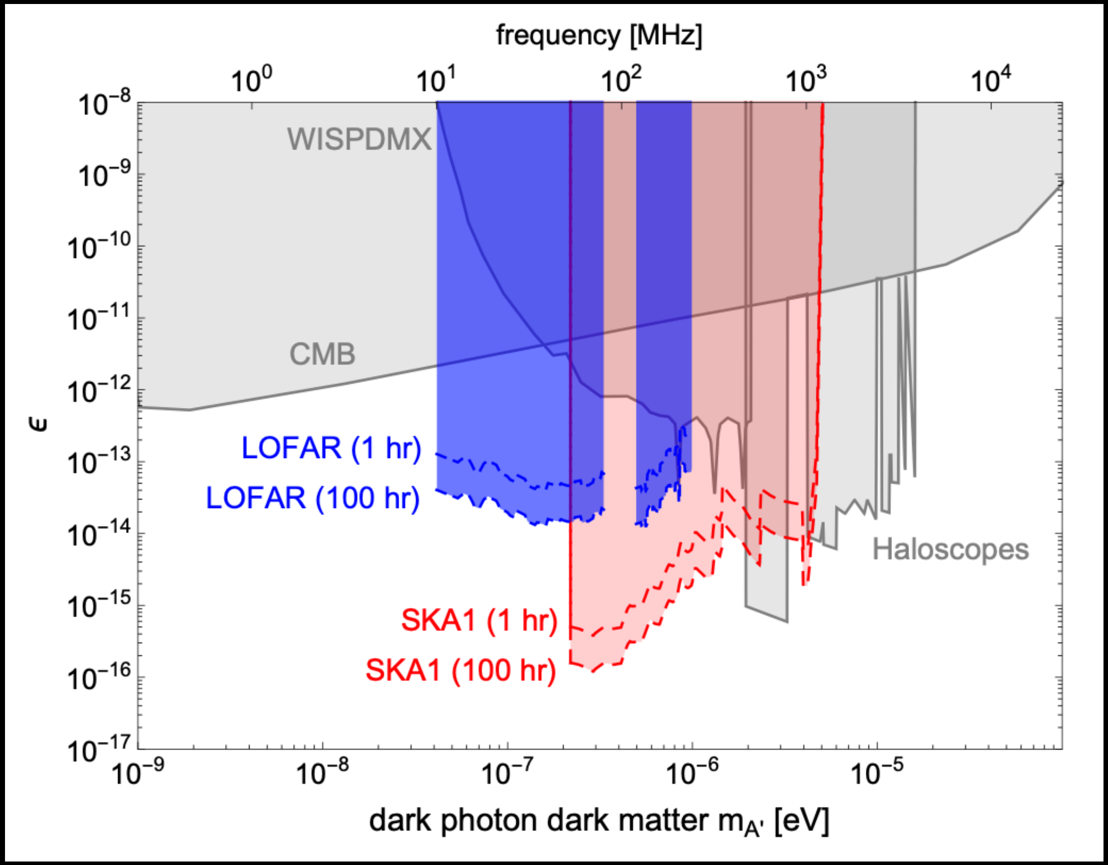
- The minimal detectable flux $S_{\rm min} = \dfrac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol} \mathcal{B} t_{\rm obs}}}$ $\quad {\rm SEFD} = 2k_B \dfrac{T_{\rm sys} + T_{\odot}^{\rm nos}}{A_{\rm eff}}$

Name	f [MHz]	$B_{\rm res}$ [kHz]	$\langle T_{\rm sys} \rangle$ [K]	$\langle A_{\rm eff} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530

West Australia

Netherland

Radiofrequency Dark Photon DM



HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

Ultralight axions dark matter

- We consider their conversion into photons

$$g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- In a constant magnetic field $B = B_0$

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + g_{a\gamma\gamma} \mathbf{B_0} a \mathbf{E}$$

Comparison with dark photon

- Dark photon

$$\mathcal{L} = \frac{1}{2}\mathbf{E}' \cdot \mathbf{E}' - \frac{1}{2}\mathbf{B}' \cdot \mathbf{B}' - \frac{1}{2}m_{A'}^2 \left(\mathbf{A}' \cdot \mathbf{A}' - A'^0 A'^0\right)$$
$$+\epsilon \left(\mathbf{E}' \cdot \mathbf{E} - \mathbf{B}' \cdot \mathbf{B}\right)$$

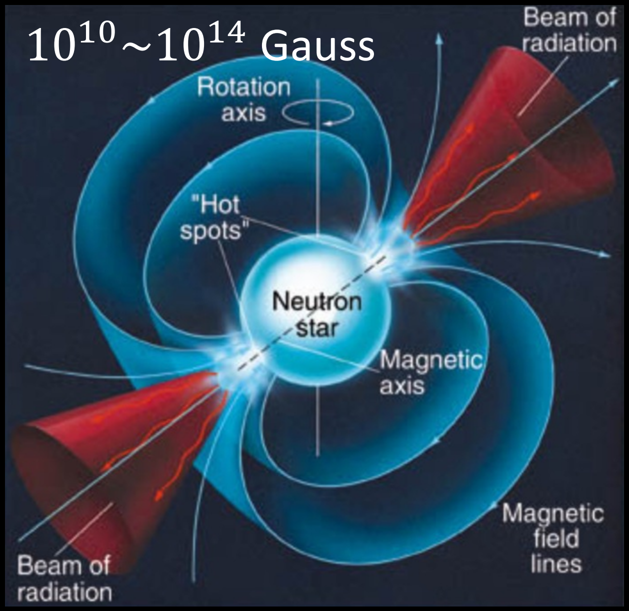
- Axion

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{B_0} a \mathbf{E}$$

- $g_{a\gamma\gamma} B_0 / m_a \leftrightarrow \epsilon$

Ultralight axions dark matter

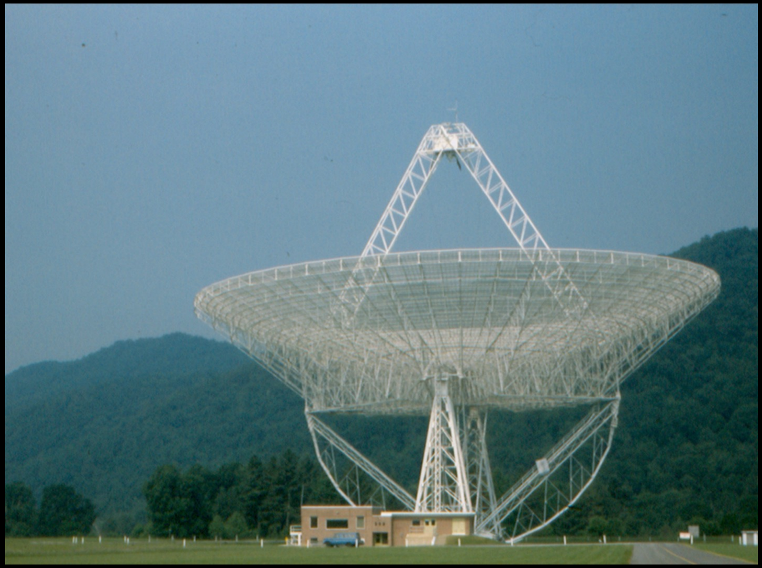
- Strong magnetic field to make the mixing larger.
- Plasma frequency equal to the axion mass.

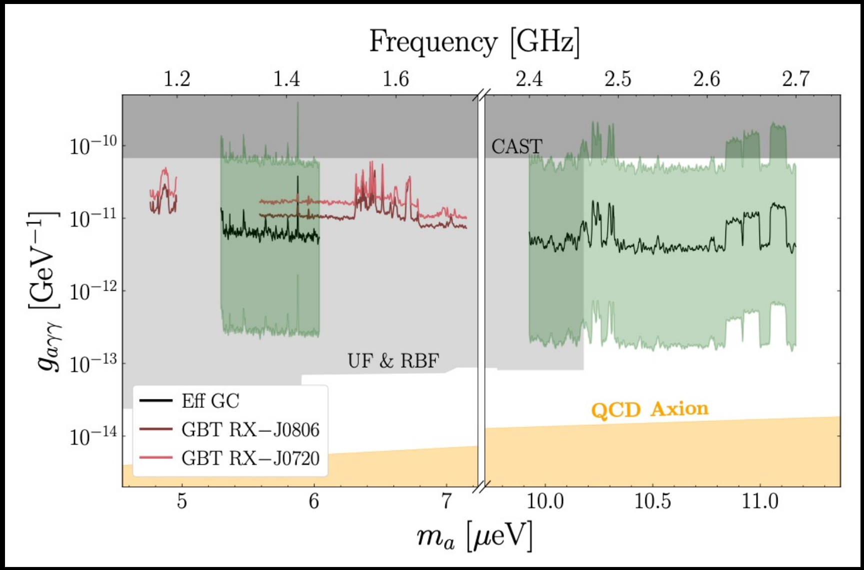


Pshirkov, Popov, 0711.1264
F.P.Huang et al. PRD 97 (2018) 123001
Hook, Kahn, Safdi, Sun, PRL 121 (2018) 241102

Result from Green Bank Telescope

100 meter diameter





Foster et al., Phys.Rev.Lett. 125 (2020) 171301

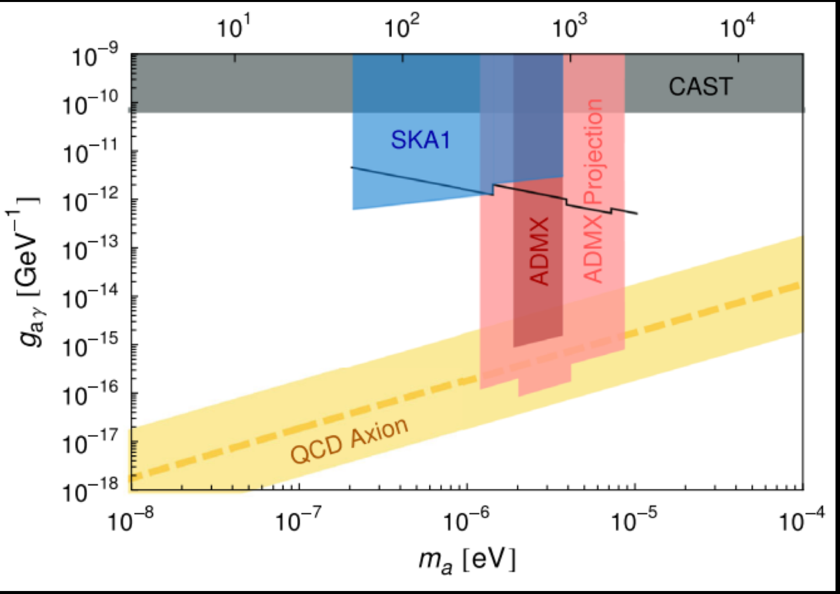
What about using white dwarves?

- Magnetic field is much smaller.
  - $B_0^{NS} \sim 10^{10} - 10^{14}$ Gauss
  - $B_0^{WD} \sim 10^7$ Gauss
- However, WDs are much larger
  - $R^{NS} \sim 10 \text{ km}$
  - $R^{WD} \sim R^{earth} \sim 10^4 \text{ km}$
- $S_{\text{sig}} \propto R^3 B_0^2$

What about white dwarves?

	Neutron Star	White Dwarf
Magnetic field	$\sim 10^{10} - 10^{14}$ Gauss	~10^7 Gauss
Radius	10 km	10^4 km

- $S_{sig} \sim R^3 B_0^2$
- The signal from white dwarves can be as strong as from neutron stars.



Wang, Bi, Yao, Yin, 2101.02585

What about using the Sun?

- Magnetic field of the Sun is tiny ($\sim$ 1 Gauss)
- But, it is much bigger!

$$R_\odot \sim 100 R^{WD} \sim 10^5 R^{NS}$$

- The Sun is much closer.

$$d_{NS} \sim d_{WD} \sim 10^7 d_\odot$$

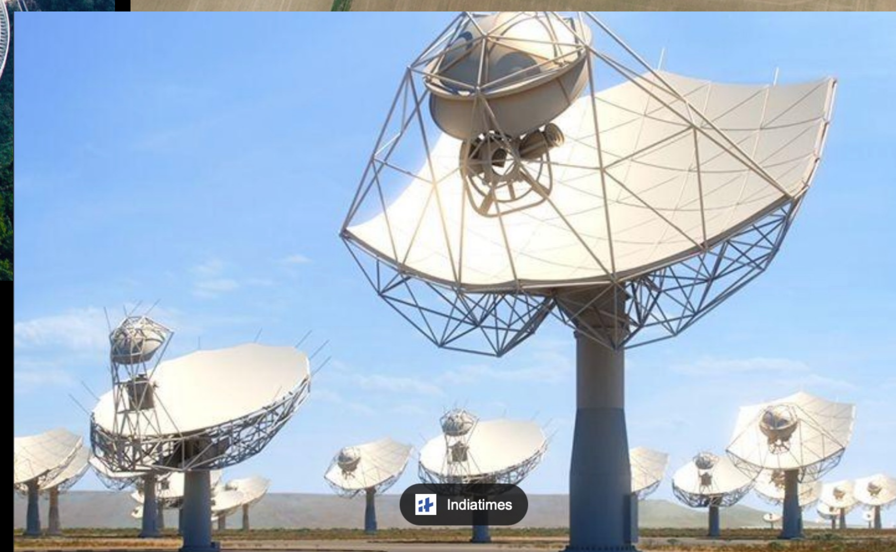
$$S_{\rm sig} \propto R^3 B_0^2 / d^2$$

- We have a vast amount of solar data.
- The signal from the Sun can be competative!

HA, F.P.Huang, J.Liu, X.Wei, in progress

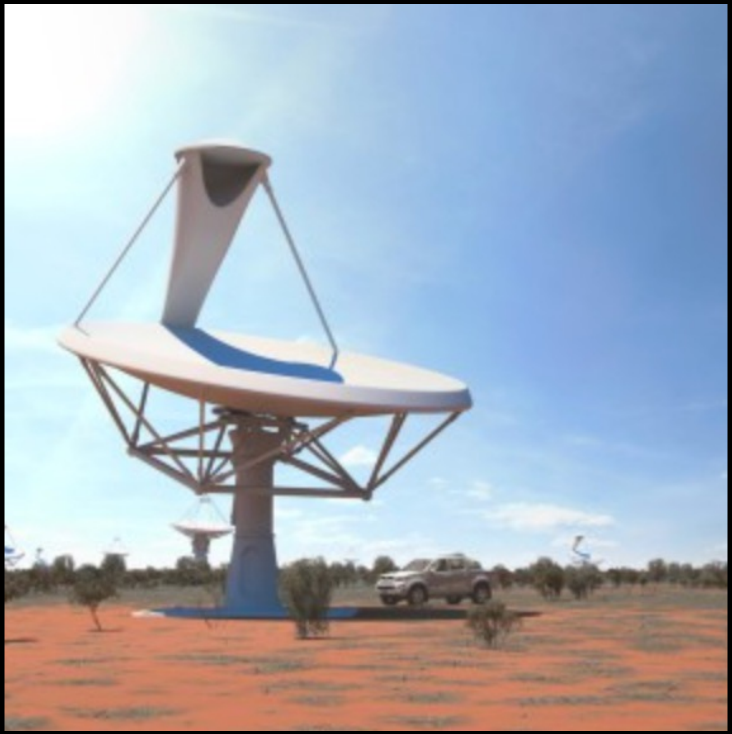
Searching for dark photon dark matter directly with radio telescopes

- Radio telescopes we have



Searching for dark photon dark matter directly with radio telescopes

- The dark photon dark matter has an interaction with the electric current, $\epsilon e A'_\mu J^\mu$ (although suppressed)

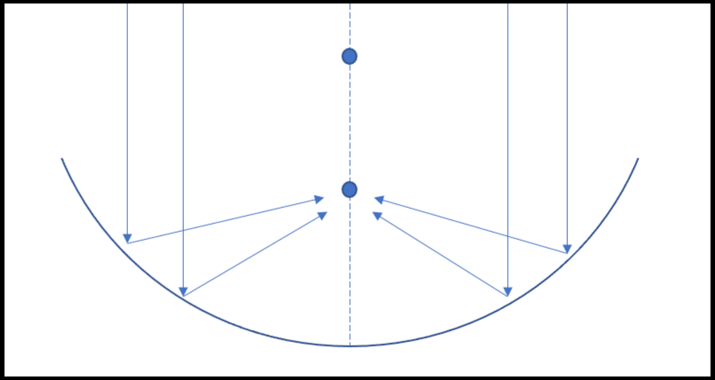


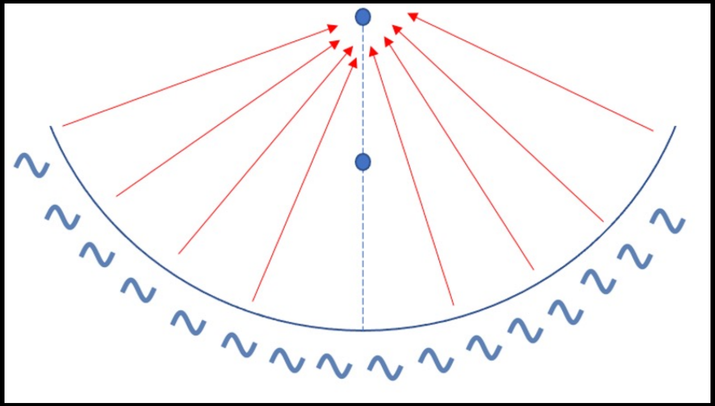
Searching for dark photon dark matter directly with radio telescopes

- For dipole antennas, the oscillation of A' induces an EM current in the antennas, and produce electronic signals.

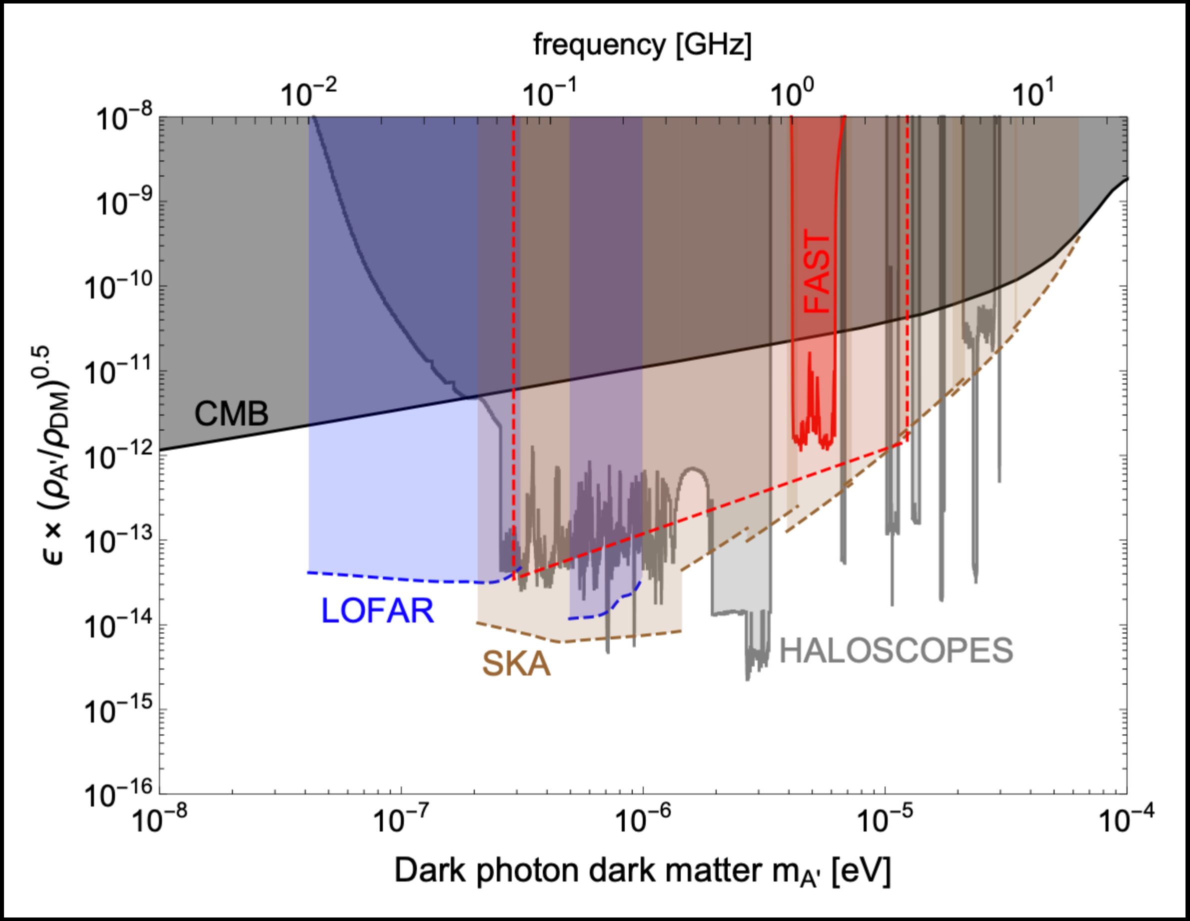
Searching for dark photon dark matter directly with radio telescopes

- For dish antennas, the oscillation of the dark photon field induces the oscillation of the electrons in the reflector plate, and produces EM waves, which can be detected by the feed.



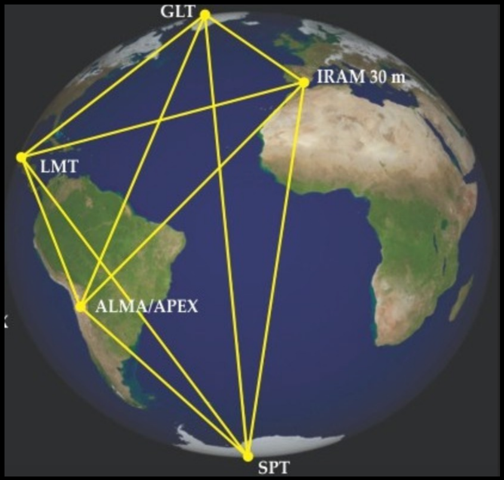


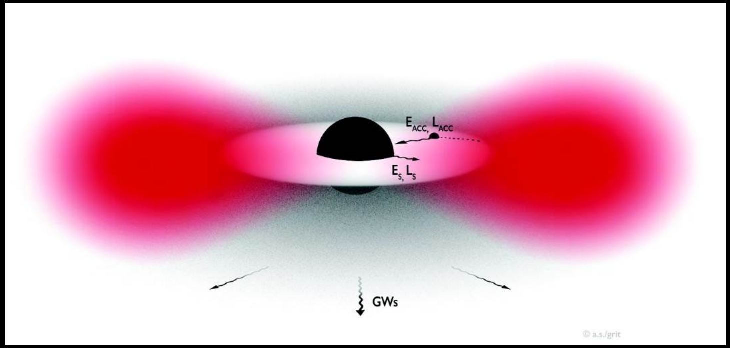
Searching for dark photon dark matter directly with radio telescopes

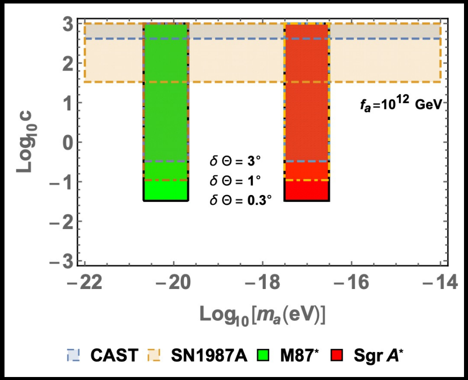


HA, S. Ge, W.-Q. Guo, X. Huang, J. Liu, Z Lu, 2207.05767

Searching for DM with Event Horizon Telescope







Y.Chen, J.Shu, X. Xue, Q. Yuan, Y. Zhao, Phys.Rev.Lett. 124 (2020) 061102

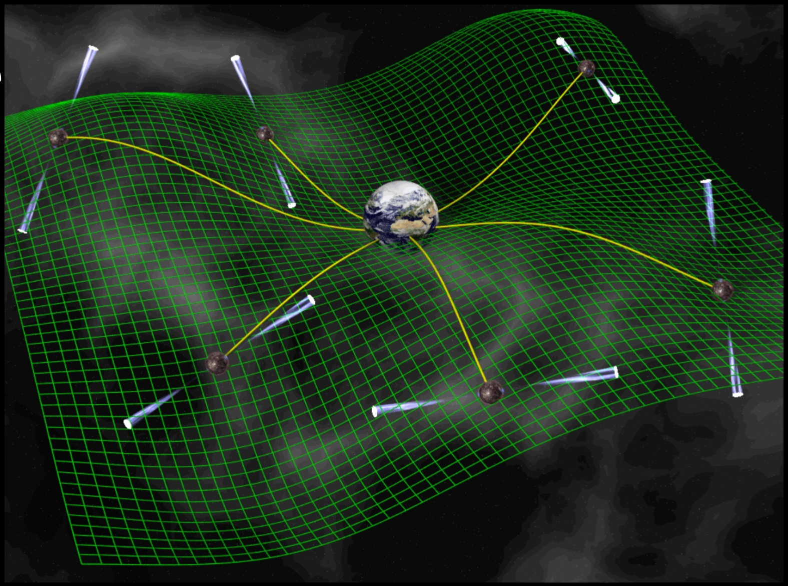
Pressure of ultralight bosonic DM

- Ideal gas $$T^\mu_\nu = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$
- For particle DM $p \ll \rho$
- For ultralight bosons $p \sim \rho \cos(2m_a t)$
- In the time scale much smaller than the mass, stars can feel a big pressure from the ultralight DM.
- The oscillation of the pressure can also induce an oscillation of the metric.

Pulsar timing array

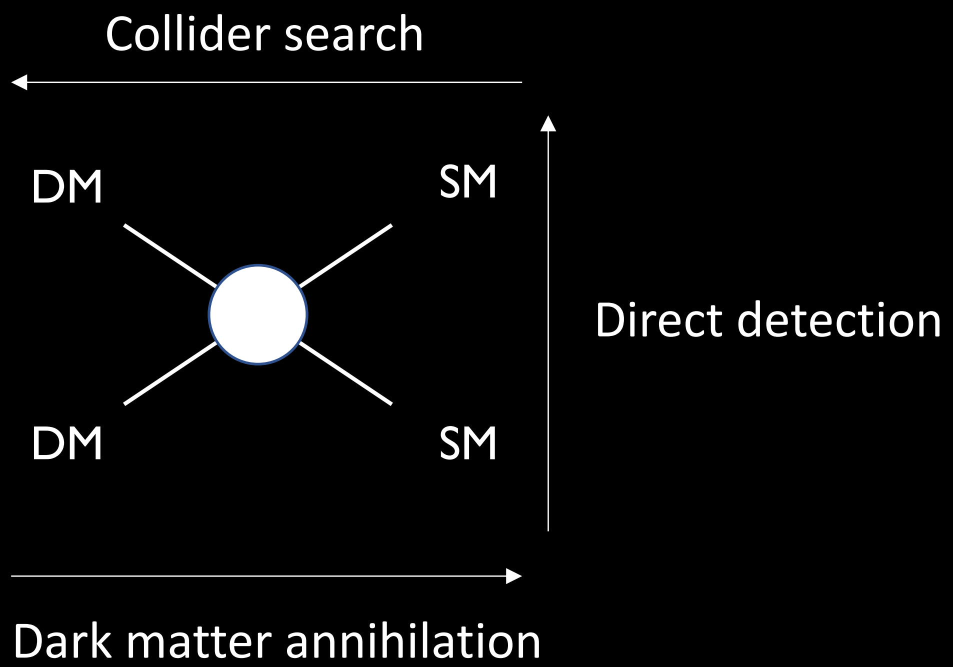
- In the case of B-L A', the pulsars are charged and oscillate following the oscillation of the A' field.

- The oscillation of the metric can change the path of the light emitted by the pulsars.

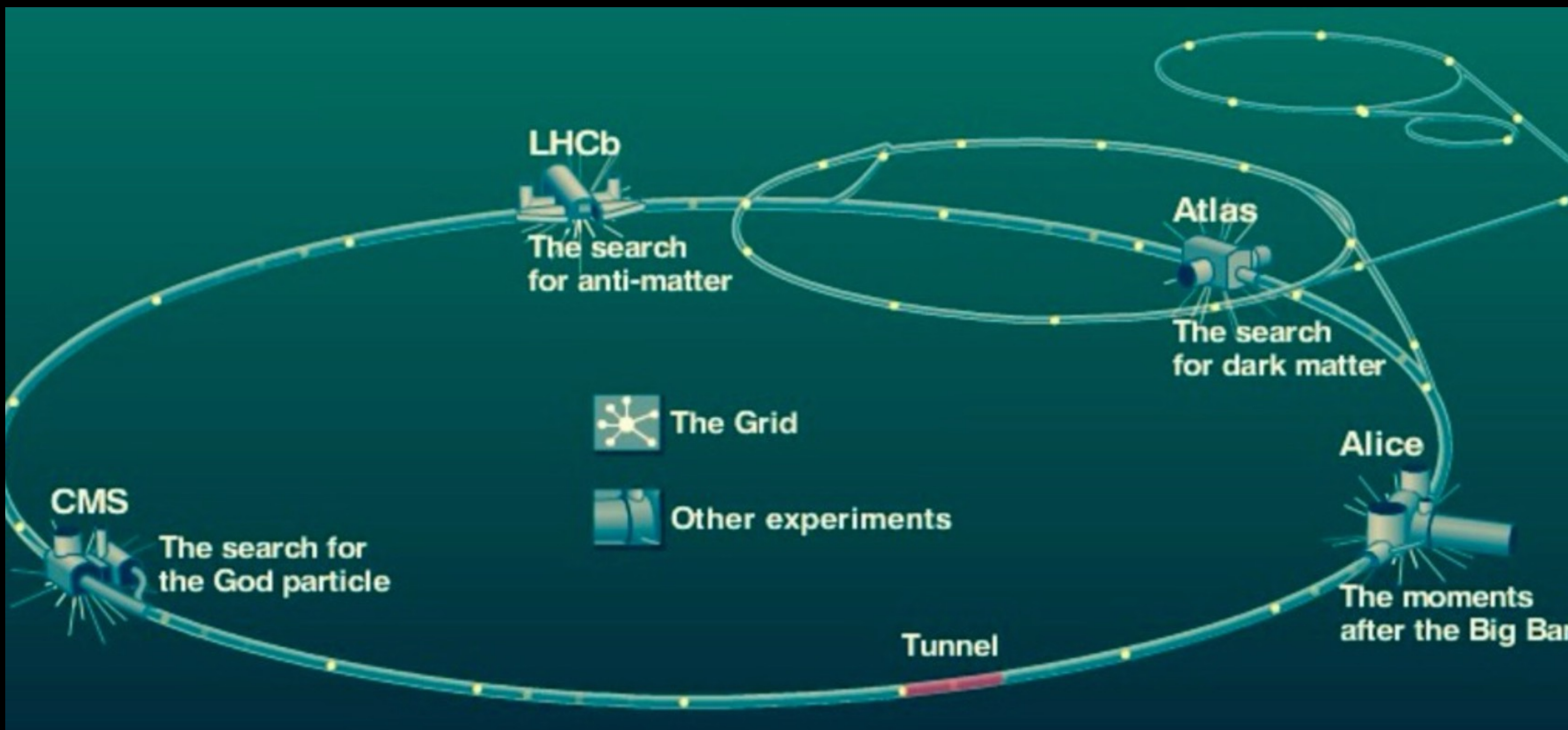


Khmelnitsky et al, JCAP 2014 (02) 019
Graham et al, Phys.Rev.D, 2016, 93 (7): 075029

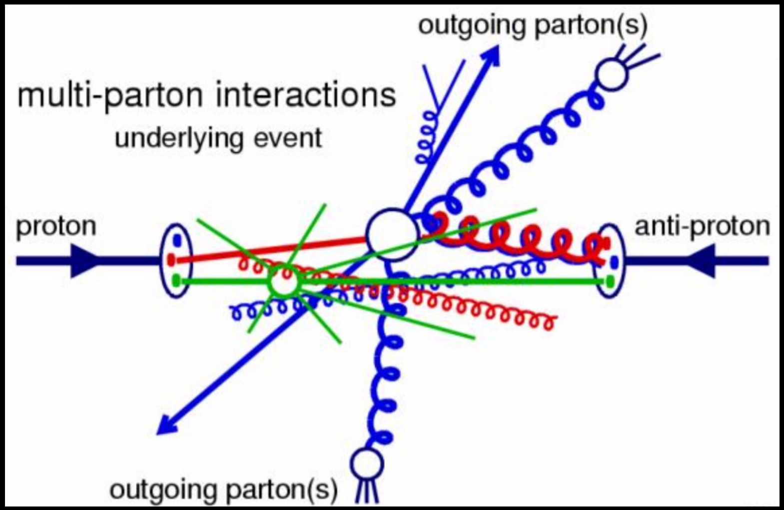
Collider searches – we produce dark matter

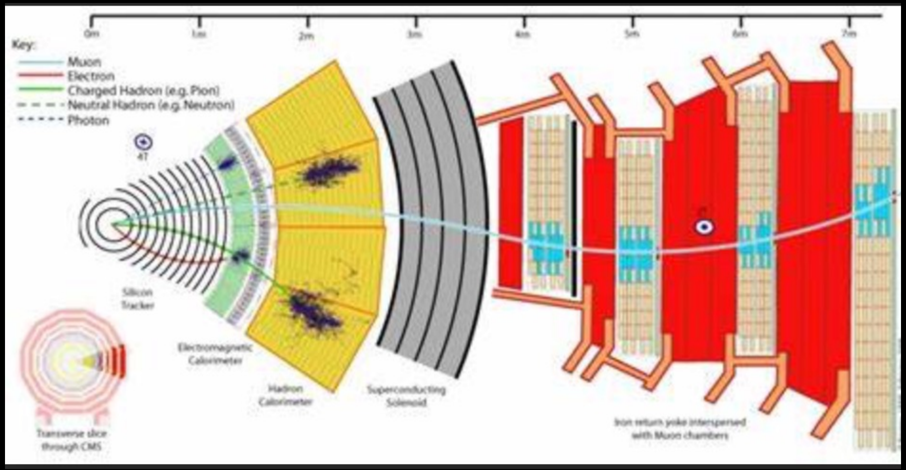


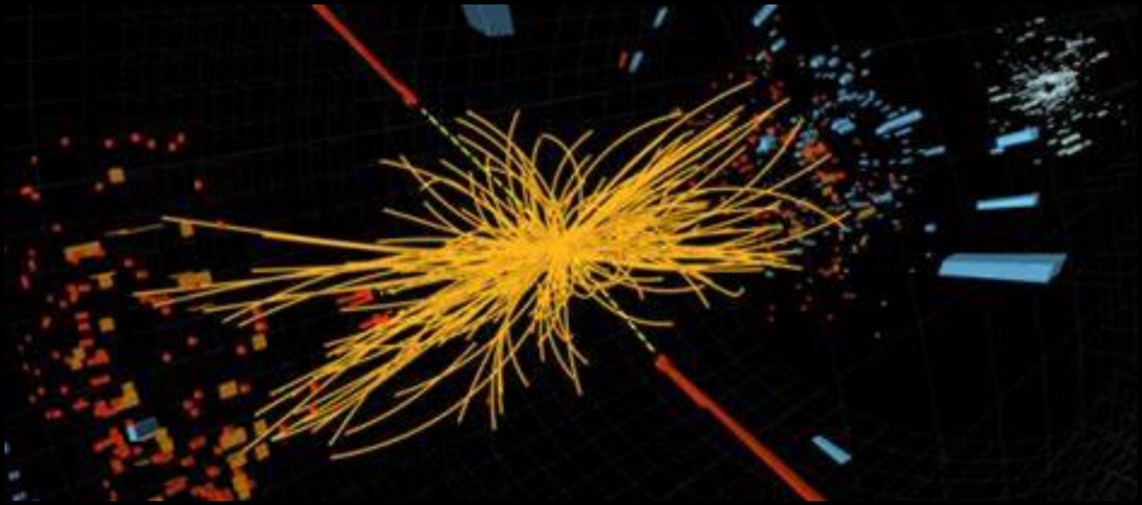
The Large Hadron Collider (LHC)



How collider works

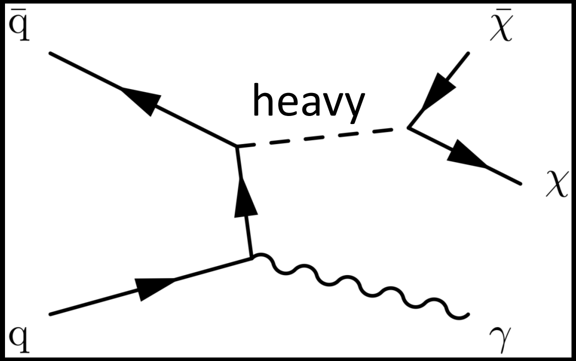


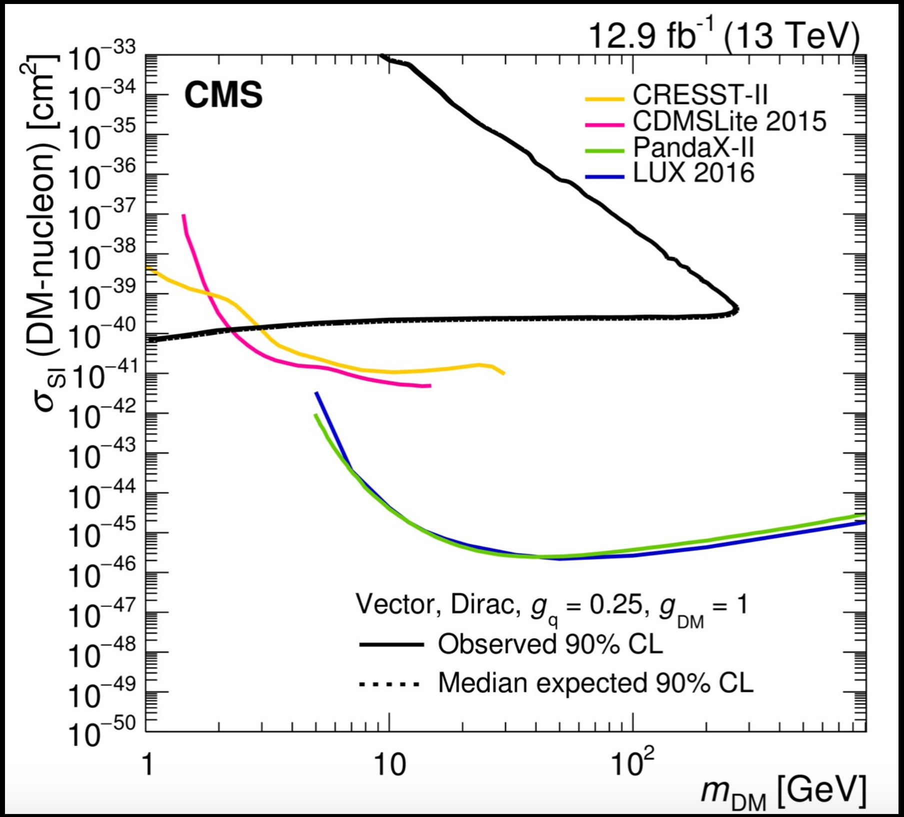




Searching for DM with LHC

- Mono-photon search

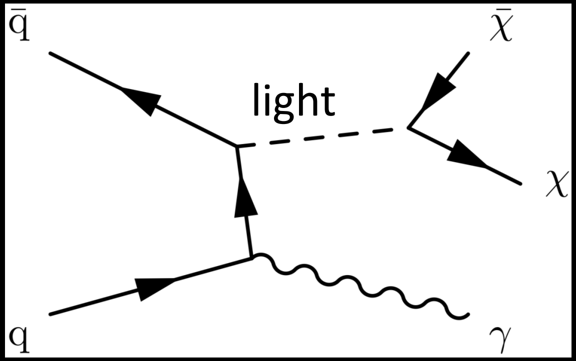


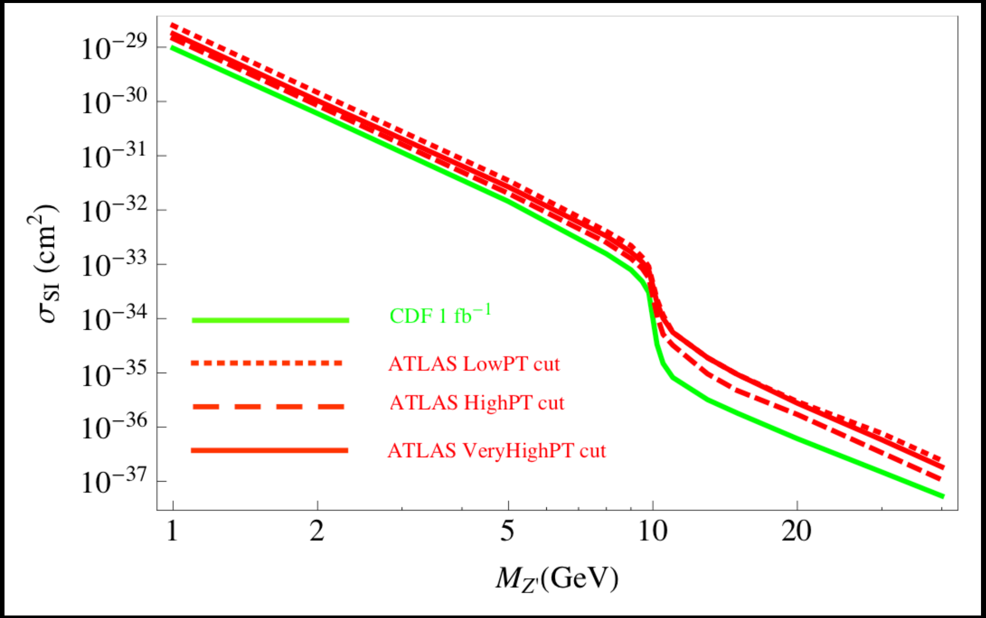


Searching for DM with LHC

- Light mediator case

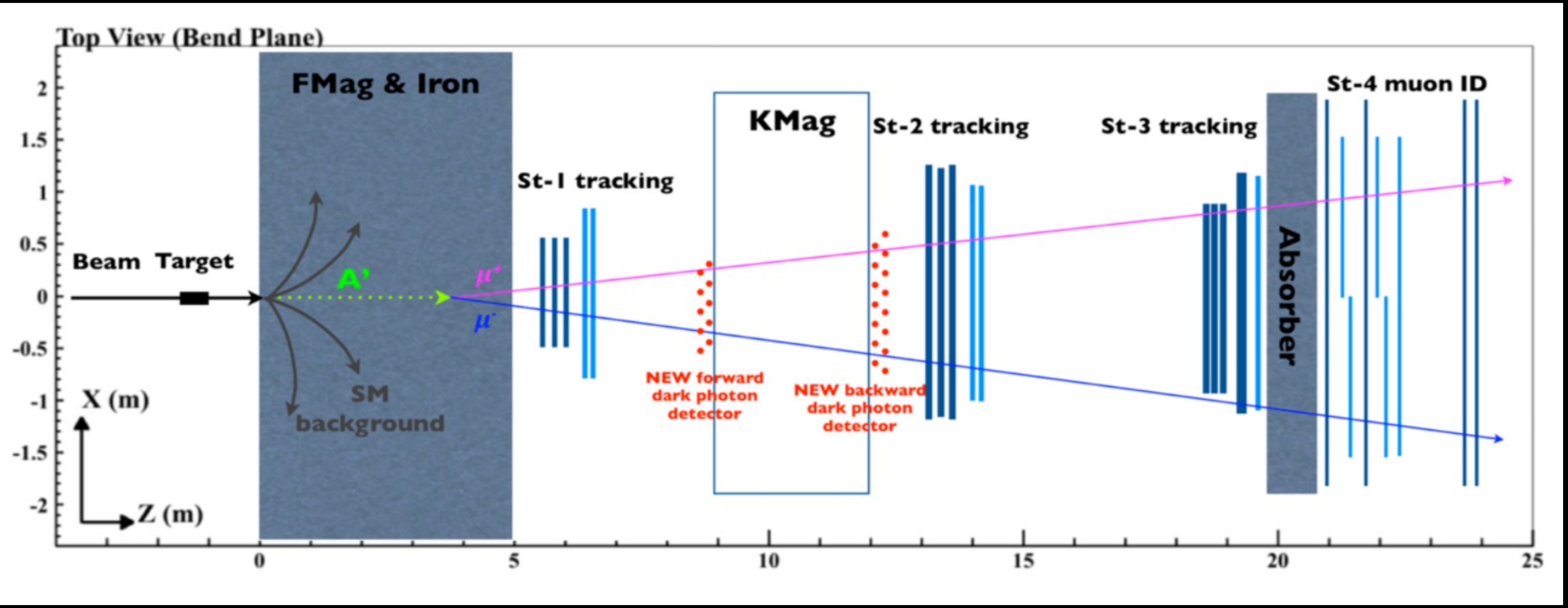
HA, X. Ji, L.-T. Wang, JHEP 1207 (2012) 182



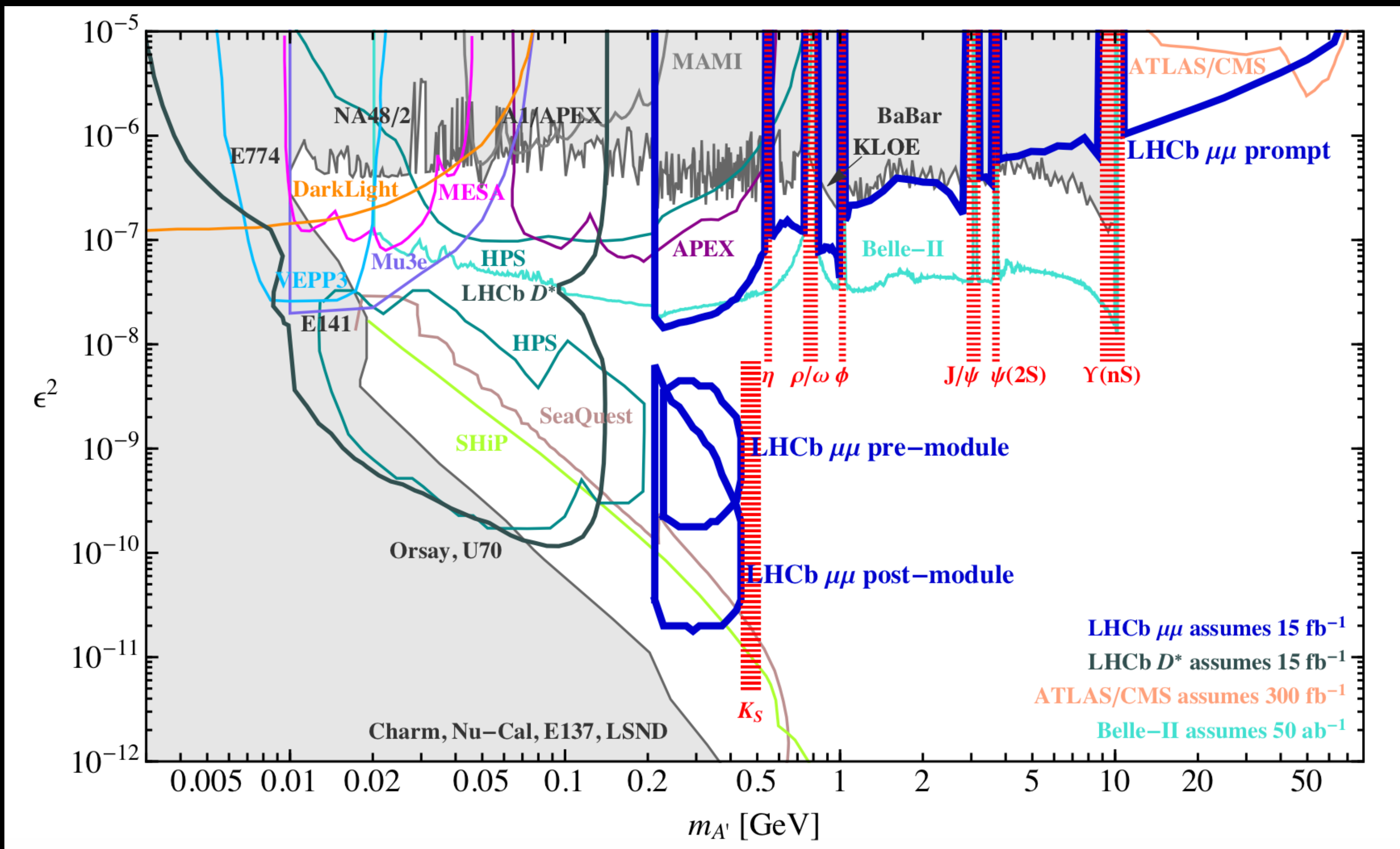


Searching for dark mediator

- Fix target experiment



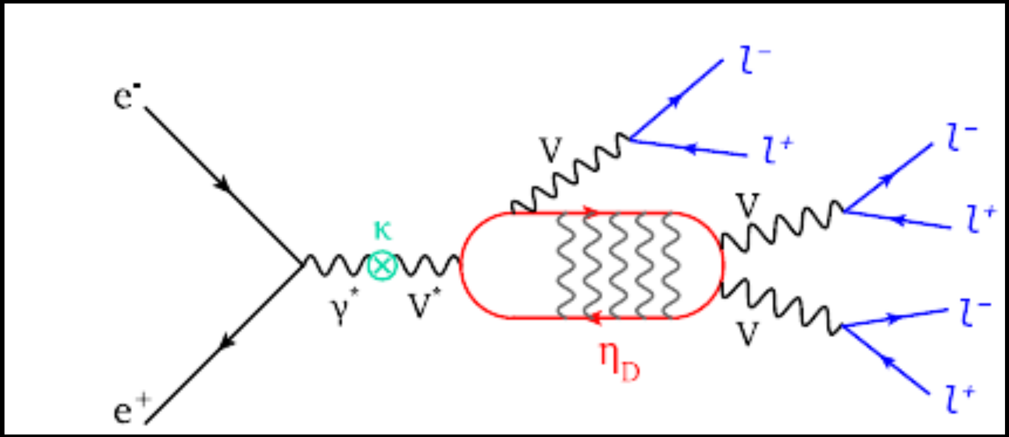
Searching for dark mediator



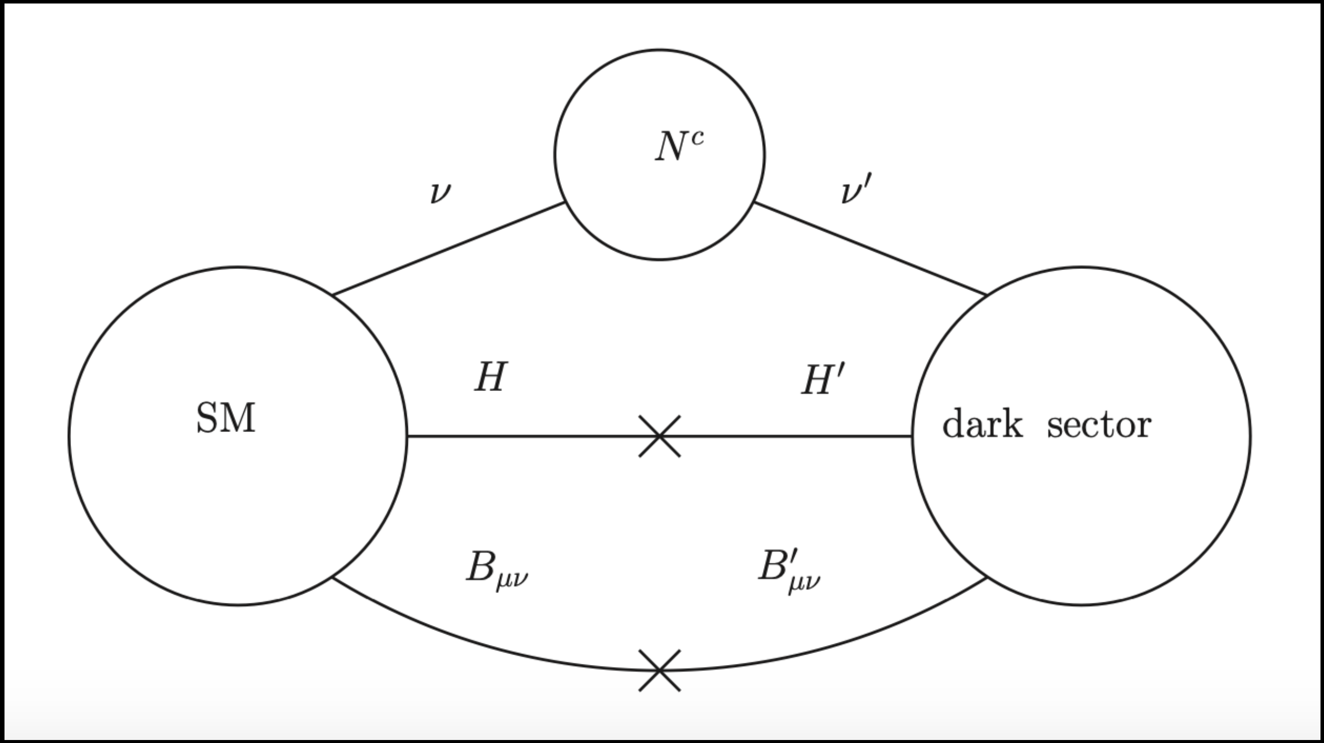
Special signal

- If DM can form bound state, there will be multiple charged leptons in the final state.
- Production rate is small, but signal is striking.

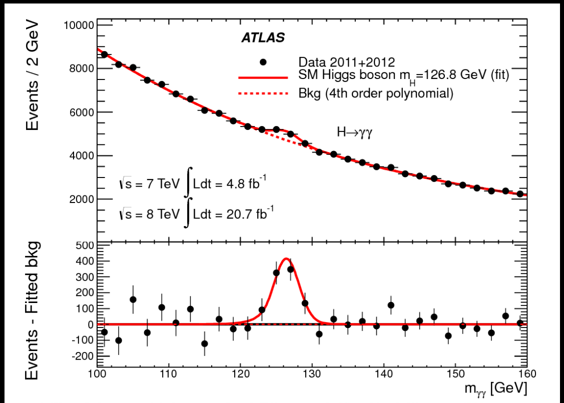
HA, Echenard, Pospelov, Zhang, PRL 116 (2016) 151801

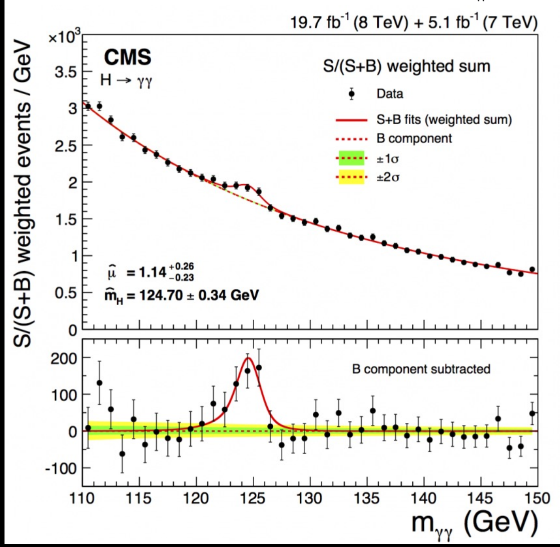


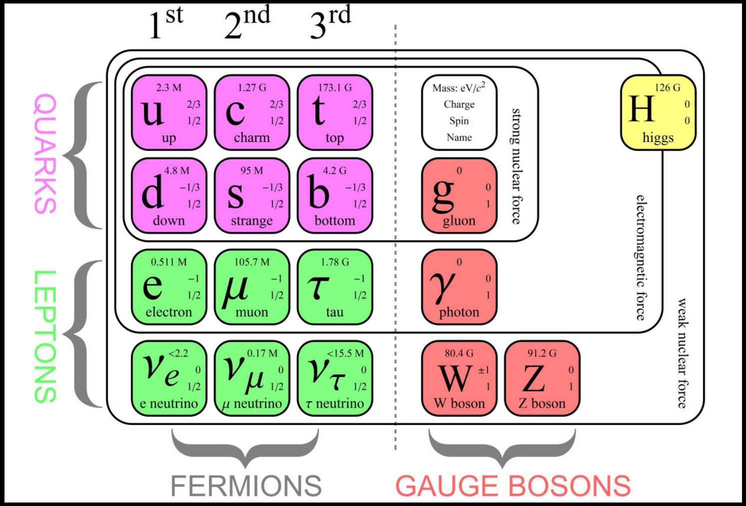
General hidden (dark) sector models



DM connected to the Higgs boson



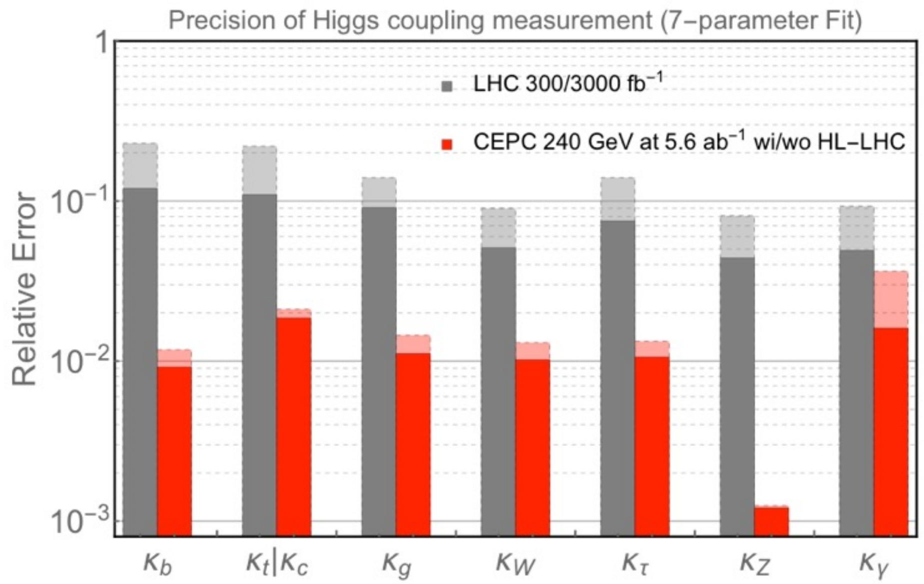


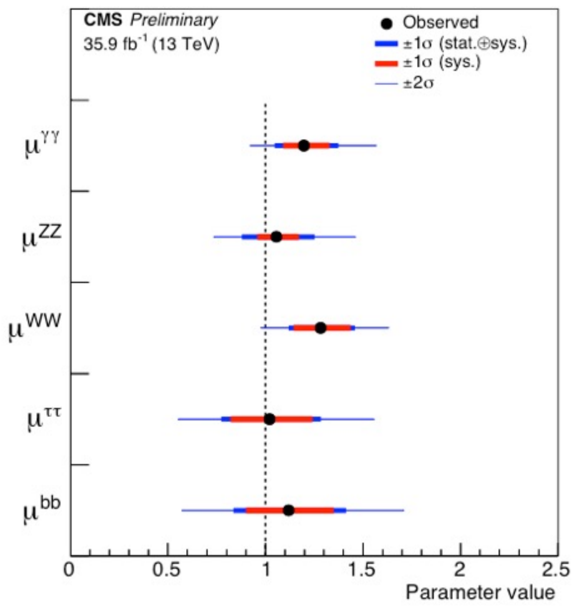


Circular electron-positron collider

Higgs invisible decay

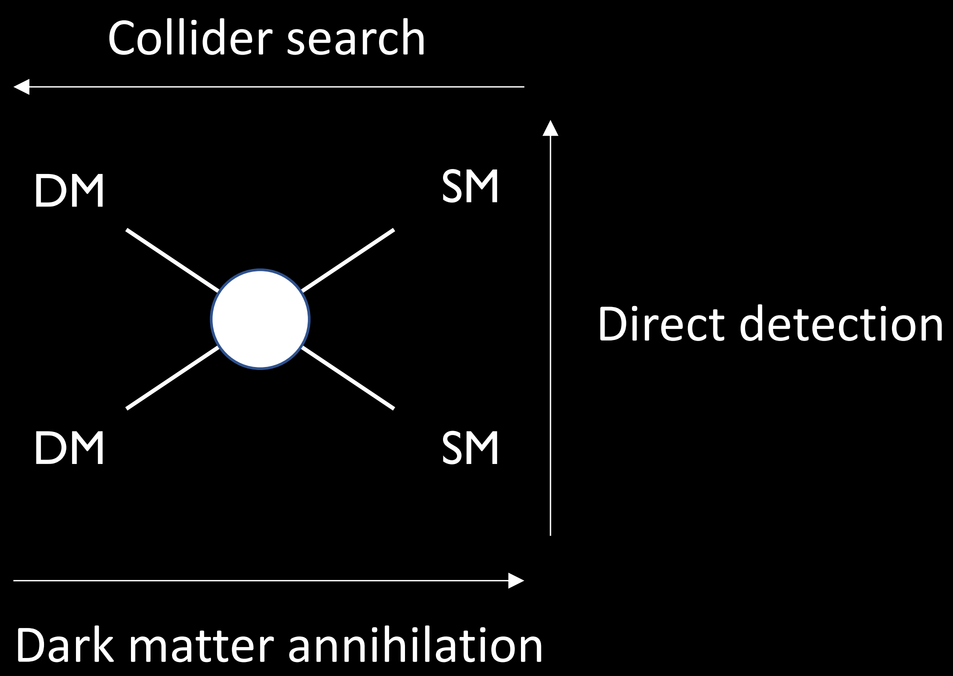
- Higgs factory





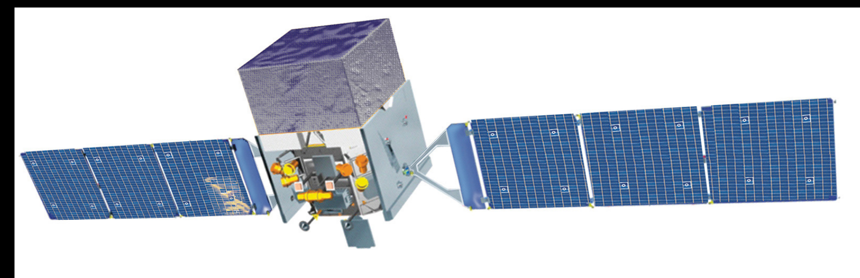
Searching for DM in cosmic rays

- Dark matter annihilates at the galactic center, generates additional cosmic rays.

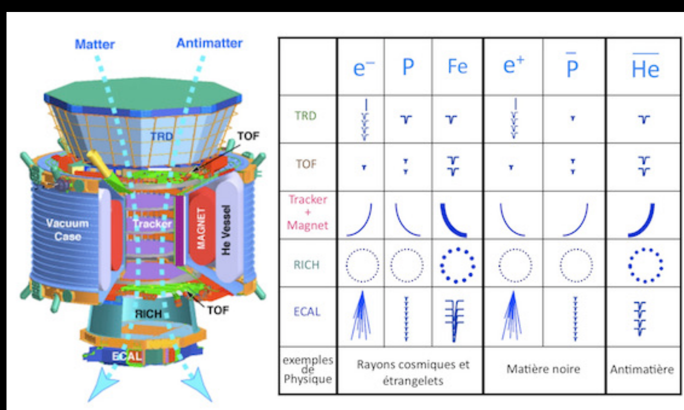


Searching for DM in cosmic rays

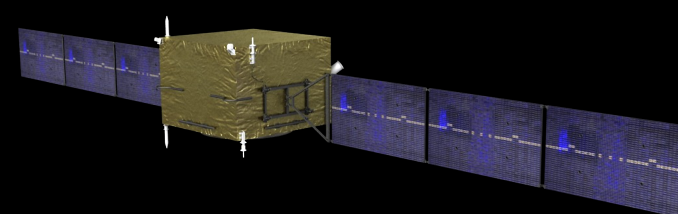
PAMELA



Fermi

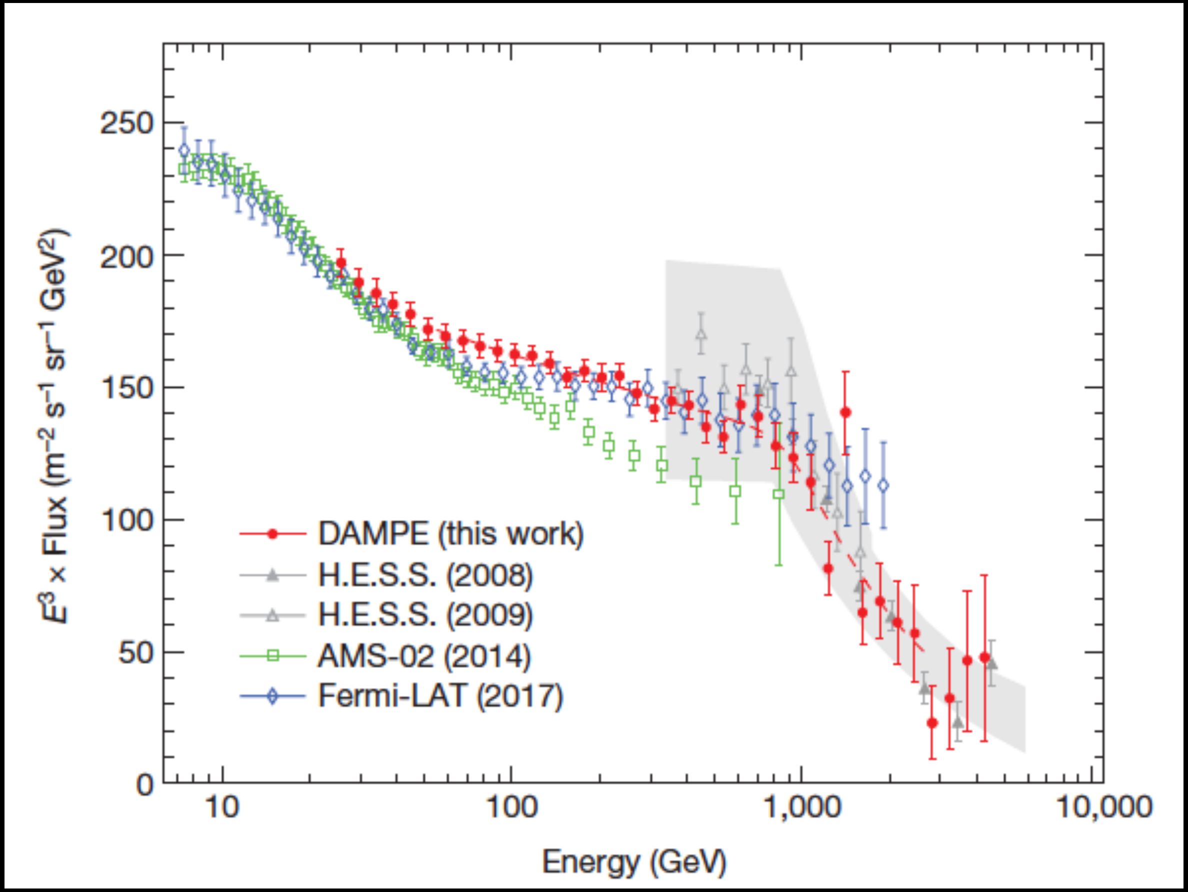


AMS02



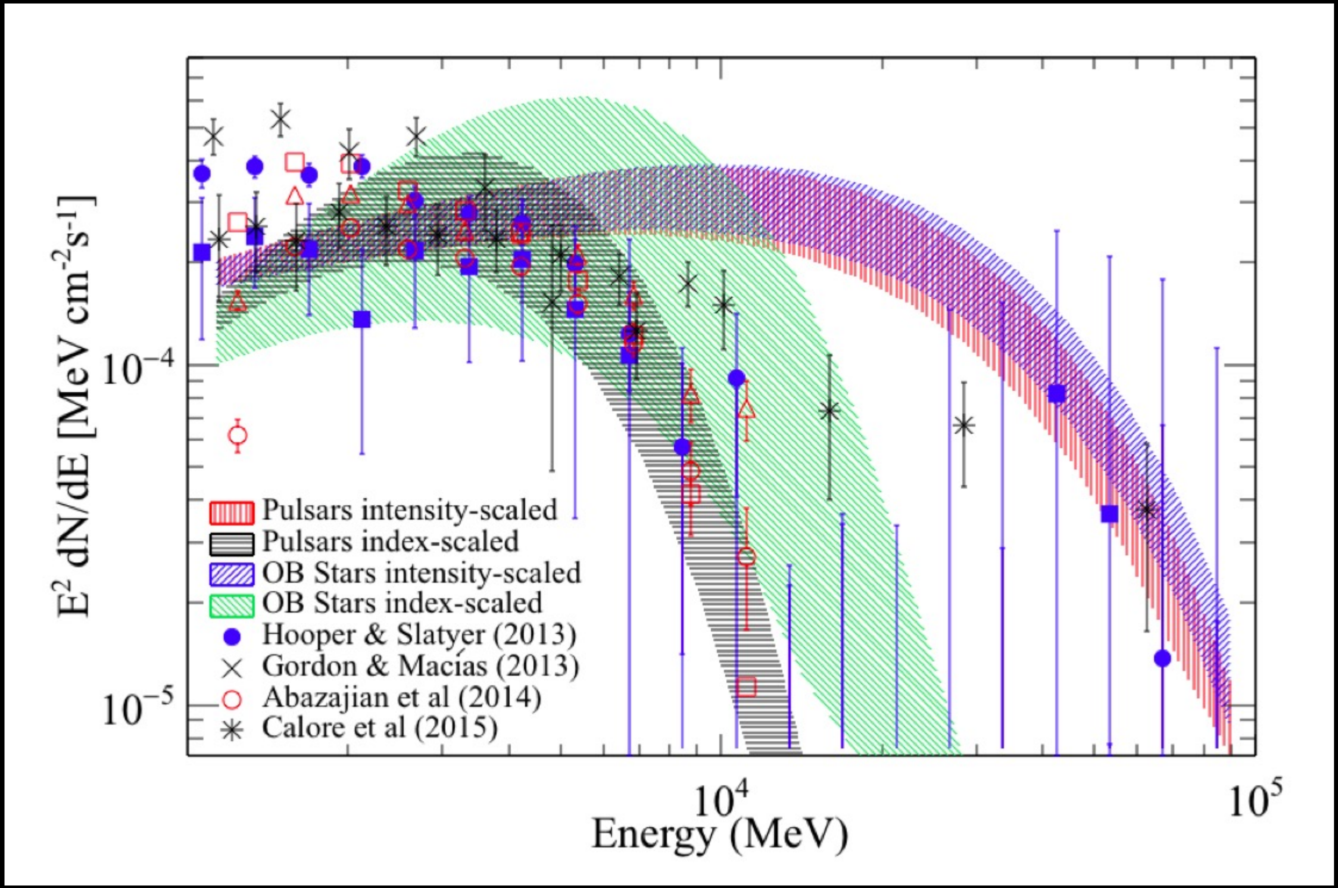
DAMPE（悟空）

Searching for DM in cosmic rays



Searching for DM in cosmic rays

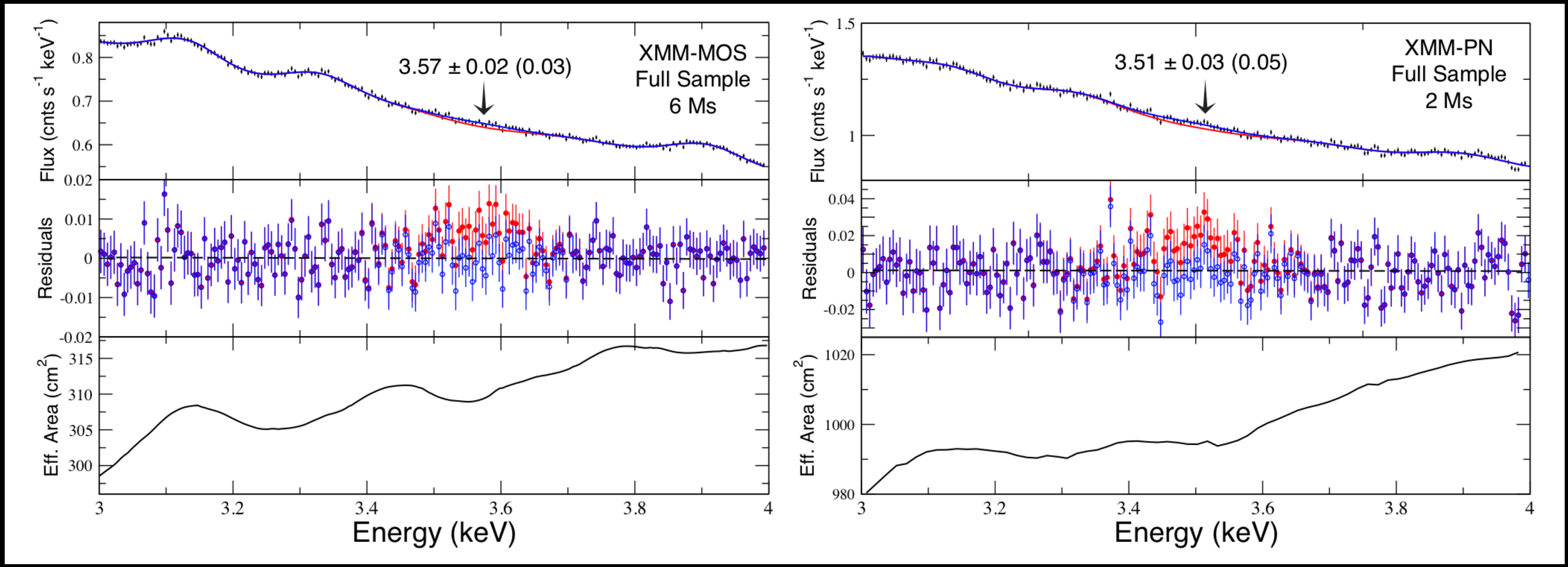
FermiLAT gamma ray spectrum



Searching for DM in cosmic rays

- With X ray telescope, a 3.5 keV access is detected

Bulbul et al, Astrophysics J. 789 (2014) 13

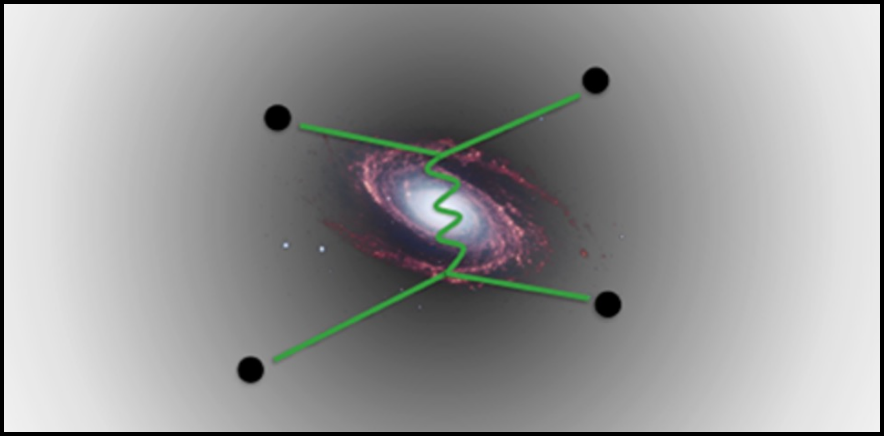


Searching for DM in cosmic rays

- We don't understand the background yet.
  - Pattern of secondary scattering
  - Astrophysics processes, such as pulsar distribution
  - Maybe some un-identified isotopes can produce X-ray signals (^{40}K).

Dark matter self interaction

- All the searches (direct, indirect, collider) depend on the connections between DM and SM sectors.
- What if the connection is superweak?



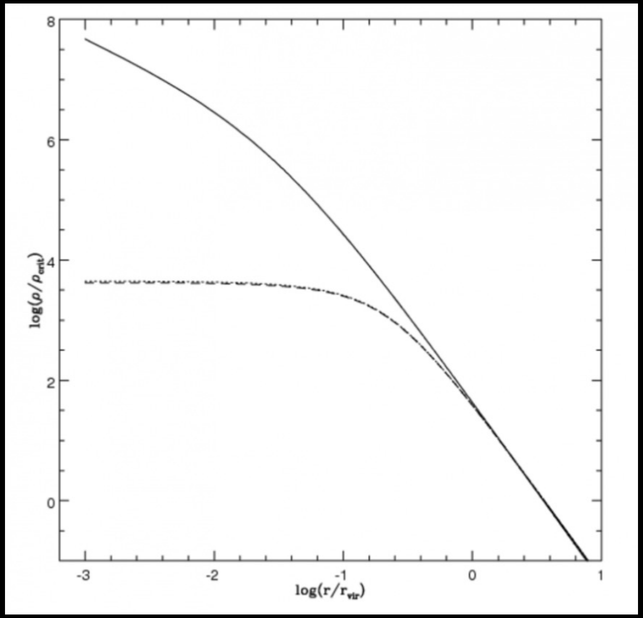
Kaplinghat, Tulin, Yu, PRL 116. 041302, 2016

Small scale structure anomaly

- Core-cusp problem
  - CDM predicts that the center of dwarf galaxies are cusp-like
  - Observation shows they are core-like
- Missing satellite problem
  - CDM predicts more satellite galaxies than we observed.
- Too big to fail problem
  - Many of the satellites are so big that there must be enough stars in it so that we can see them.

Core-Cusp problem

- Baryonic feedback
  - Supernova explosion
  - Change the potential dramatically
  - DM at the center fly away
- Dark matter self-interaction
  - Self-interaction transfers the kinetic energy from outside to inside
  - DM inside fly away with larger kinetic energy.



Galaxies with no dark matter

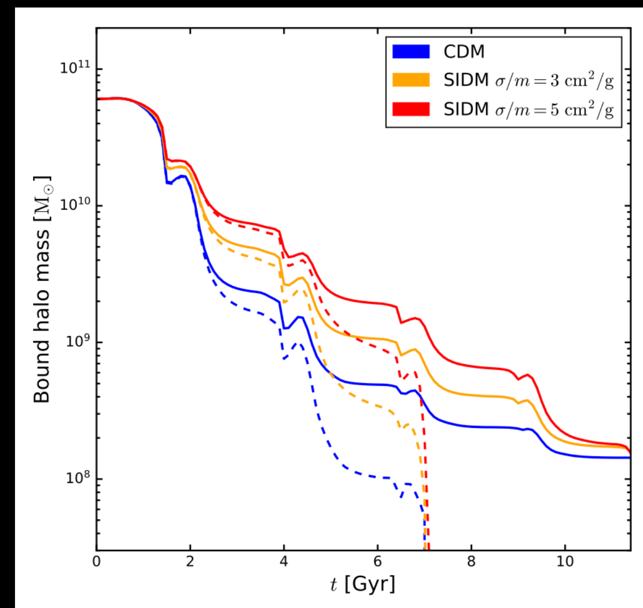
nature

Published: 29 March 2018

A galaxy lacking dark matter

Pieter van Dokkum, Shany Danieli, Yotam Cohen, Allison Merritt, Aaron J. Romanowsky, Roberto Abraham, Jean Brodie, Charlie Conroy, Deborah Lokhorst, Lamiya Mowla, Ewan O'Sullivan & Jielai Zhang

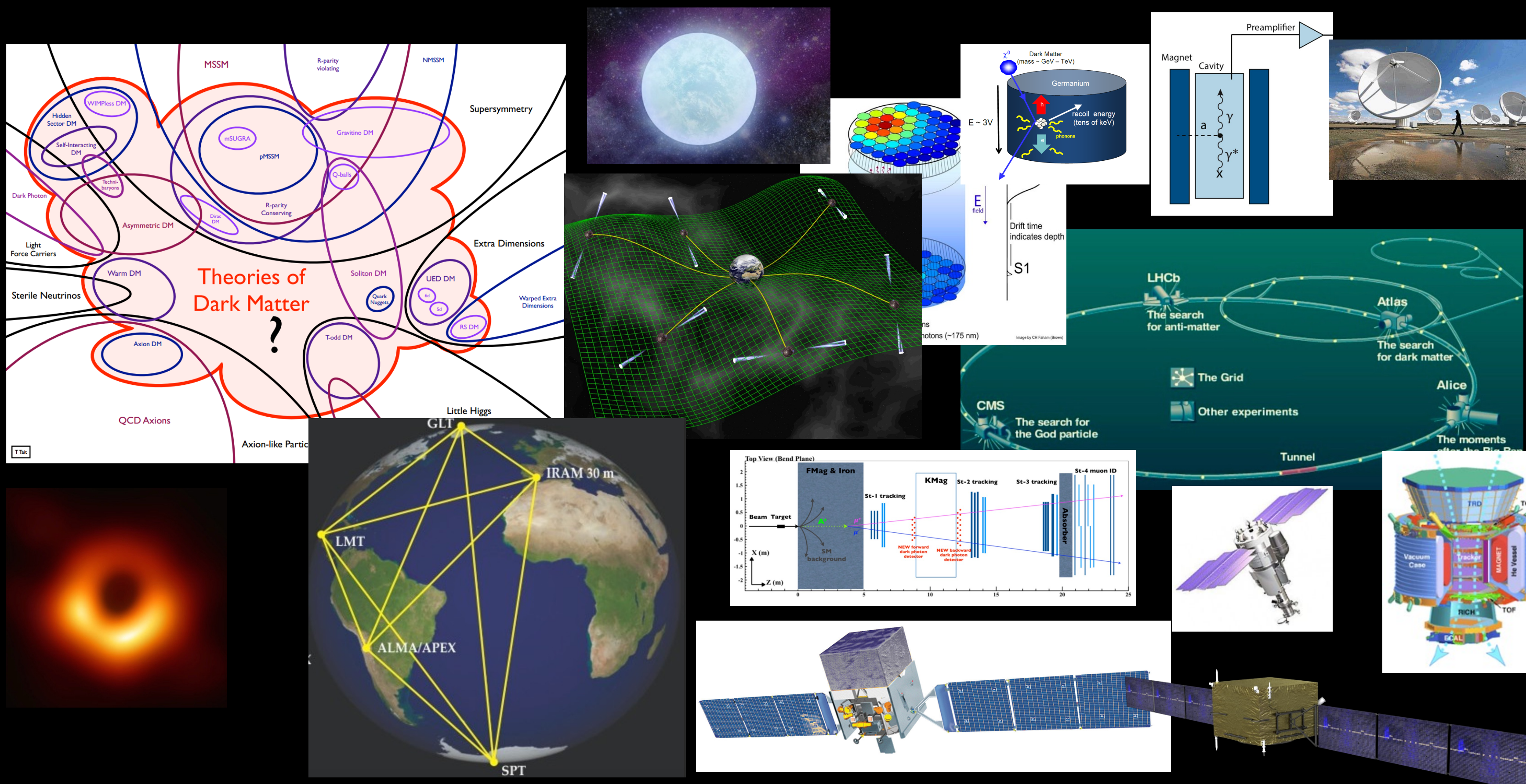
DF2



Daneng Yang, Haibo Yu, **HA**, PRL 125 (2020) 111105

Summary

We need more clever ideas to search for dark matter.




Do we know where new physics is?


We are building more and more lamp posts.