Theories and detections for light and ultralight dark matter

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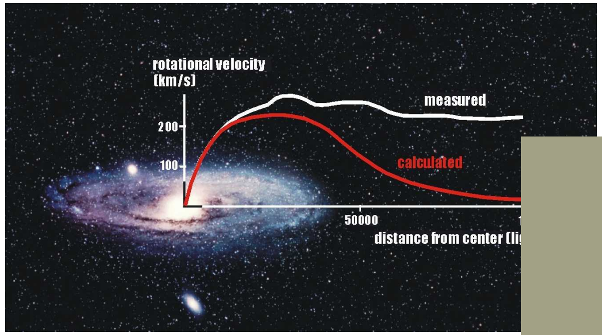
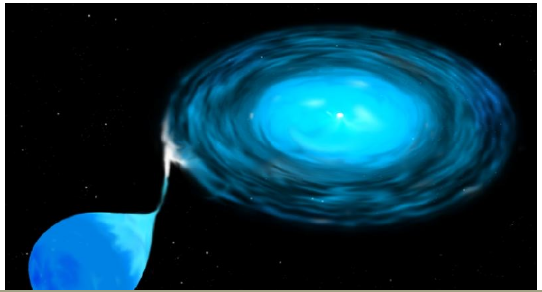
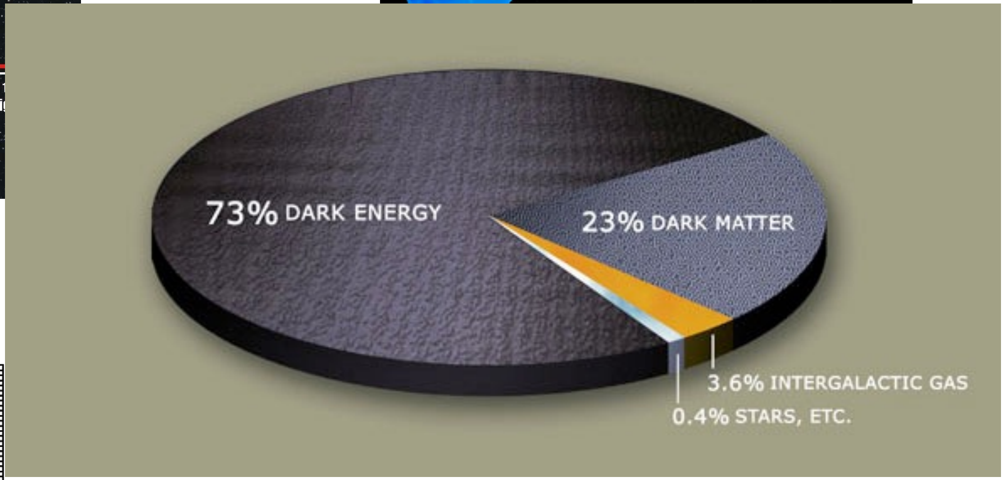
粒子物理标准模型精确检验与新物理前沿讲习活动

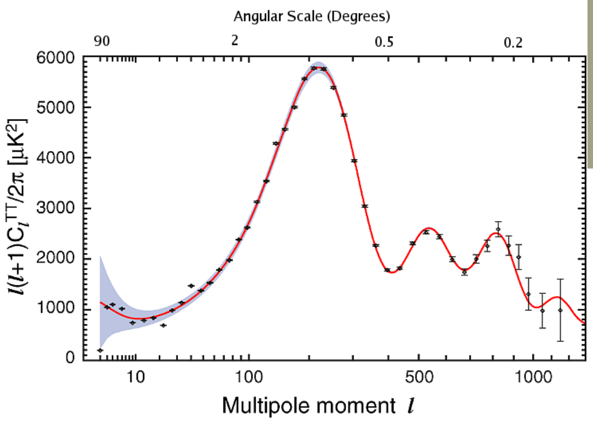
7.24–8.12，山东大学，济南

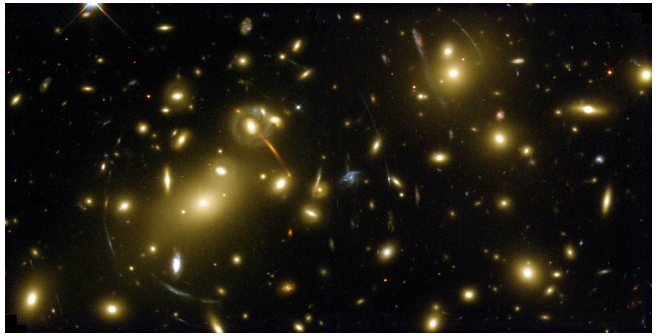
We have plenty of evidences for DM

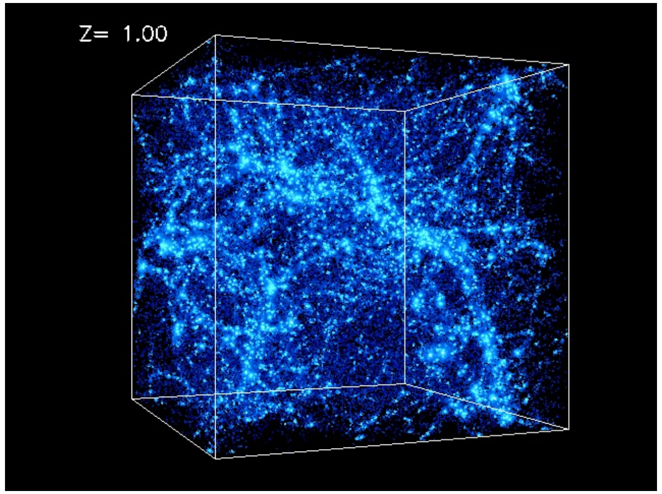












Searching for dark matter

- 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 do we start from?

- We know almost nothing about dark matter except for:
  - Stable
  - Equation of state
  - Cold enough
  - 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

Lifetime longer than the age of the Universe

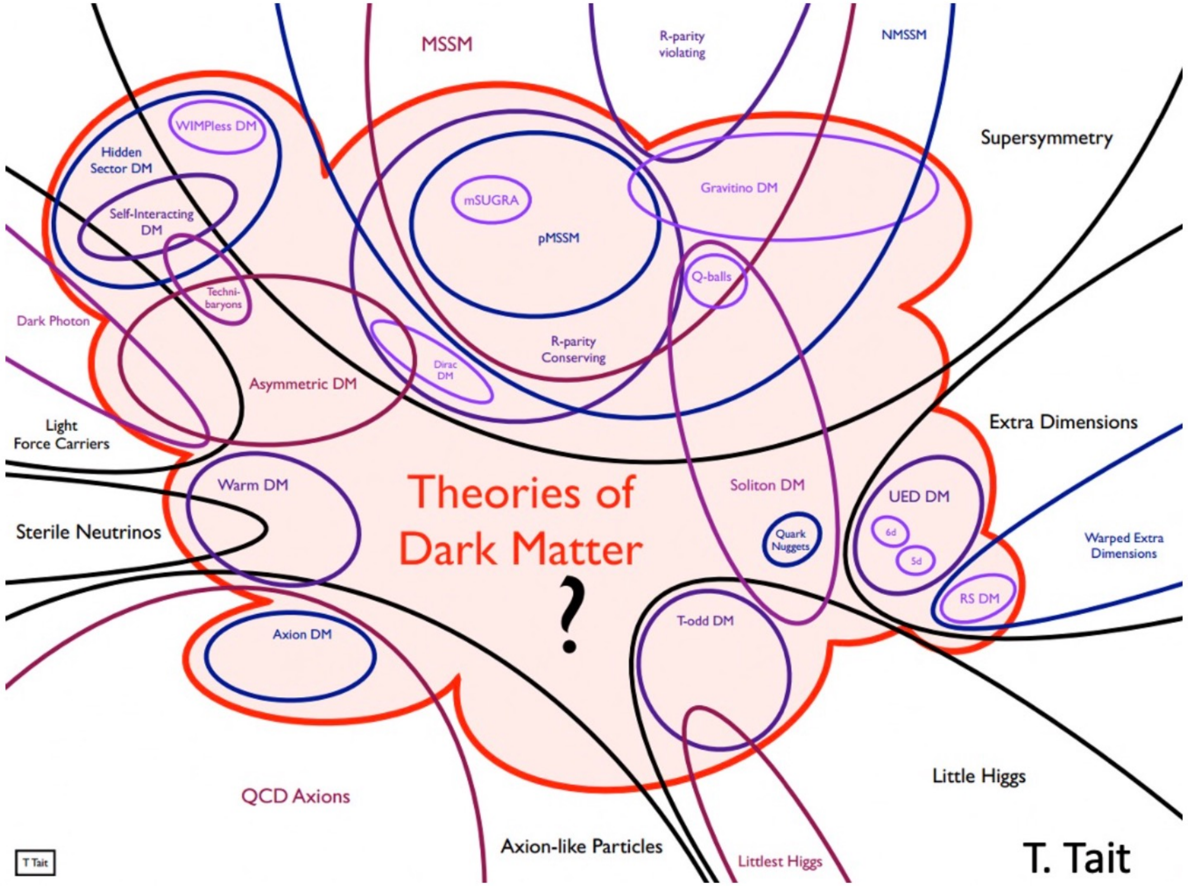
Non-relativistic particles

Or the large scale structure will be erased.

22.4 mol/L ~ 1Pa

Theories of Dark Matter

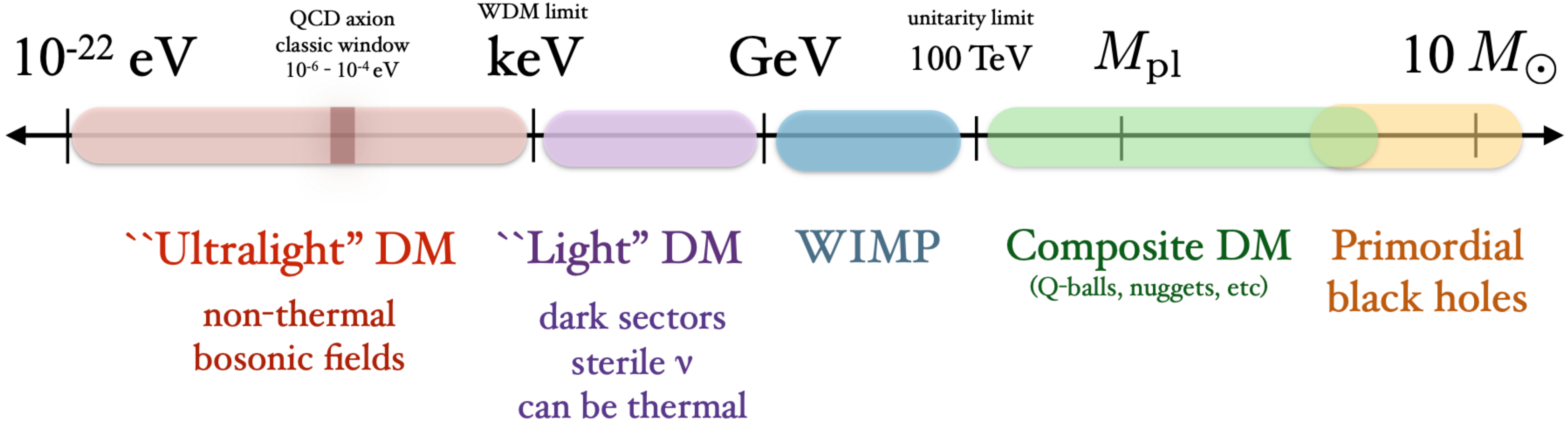
- It is very easy to build a dark matter model!
- People have already written down hundreds of DM models!
- We need to find a strategy!



Classification according to Production Mechanisms

- Freeze-out
  - WIMP, SuperWIMP, Coannihilation, Dark Sector
- Freeze-in
  - UV freeze-in, IR freeze-in
- SIMP
  - $3 \to 2, 4 \to 2$
- Asymmetric DM (DM produced like baryons)
- Ultralight Bosonic DM
- Particle production during the expansion of the Universe
- …

Classification according to DM Mass Range



T. Lin

Outline

- Dark matter production mechanisms
    - Freeze-out, Freeze-in, Asymmetric, SIMP, misalignment …
- Dark matter detetion
    - Searching for light DM
    - Searching for ultralight DM
    - Collider search for DM
    - Indirect search for DM
    - Searching for DM self interaction

Freeze-out

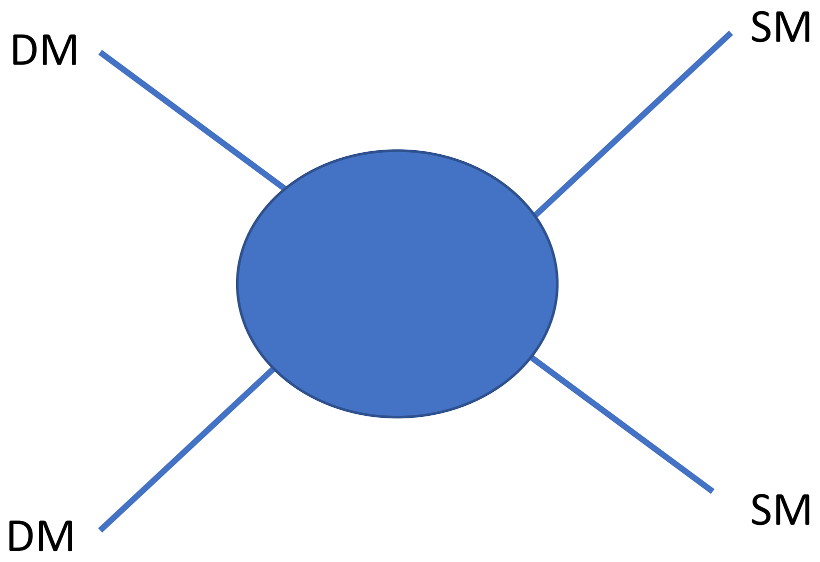
- The DM particles are in thermal equilibrium with SM particles in the early Universe.
  - Interaction.
  - The rates are important.
- The Hubble expansion rate:

$$H = \left(\frac{8\pi G\rho}{3}\right)^{1/2} \sim \frac{T^2}{M_{\rm pl}}$$

- The annihilation rate:

$$\Gamma = n_\chi \langle \sigma v \rangle$$

The rate for one DM particle to be converted into SM particle.



Freeze-out

- The annihilation stops when the DM particles cannot find an anti-particle to annihilate.

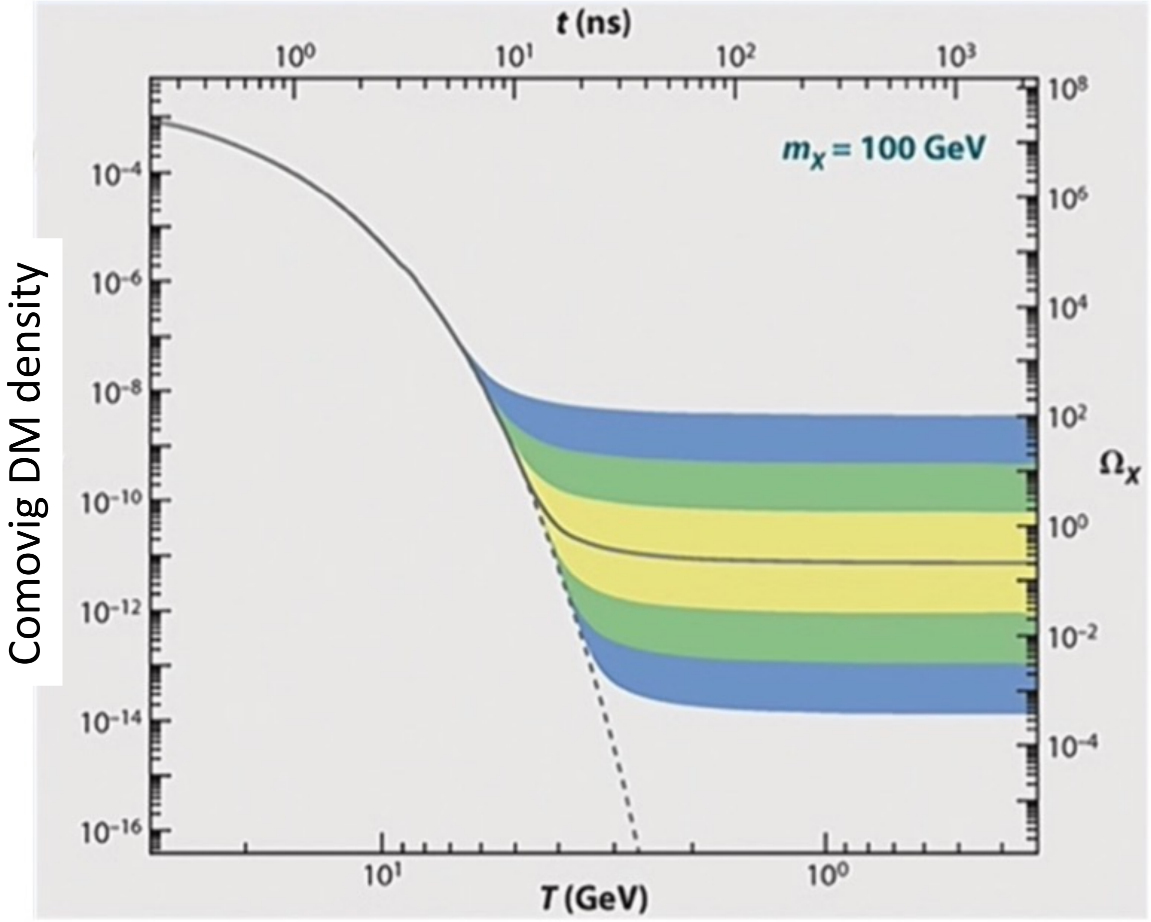
$$\Gamma < H$$

- H is a small parameter

$$H = \left(\frac{8\pi G\rho}{3}\right)^{1/2} \sim \frac{T^2}{M_{\rm pl}}$$

- Γ has to be suppressed for the condition to be satisfied.

$$\Gamma = n_\chi \langle \sigma v \rangle$$



The annihilation rate

- $\langle \sigma v \rangle \sim \alpha^p / T^2$ or α^p / m_χ^2 , α is some coupling constant, it usually does not suppressed.

- The number density $$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-E/T} \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$

  Suppressed exponentially when $m_\chi \gg T$

- For s-wave annihilation $\langle \sigma v \rangle \sim \alpha^2 / m_\chi^2$ independent of T.

The condition for freeze-out

- The condition for freeze-out is

@T_s the annihilation stops

$$\Gamma = H \quad \Longrightarrow \quad \langle \sigma v \rangle (m_\chi T_s)^{3/2} e^{-m_\chi/T_s} = \frac{T_s^2}{M_{\rm pl}}$$

$$\Longrightarrow \quad (\langle \sigma v \rangle M_{\rm pl} m_\chi) \left(\frac{m_\chi}{T_s} \right)^{1/2} e^{-m_\chi/T_s} = 1$$

$\langle \sigma v \rangle \sim \alpha^2 / m_\chi^2$

$$\Longrightarrow \quad \left(\frac{\alpha^2 M_{\rm pl}}{m_\chi} \right) \left(\frac{m_\chi}{T_s} \right)^{1/2} e^{-m_\chi/T_s} \sim 1$$

The condition for freeze-out

$$\left(\frac{\alpha^2 M_{\rm pl}}{m_\chi}\right)\left(\frac{m_\chi}{T_s}\right)^{1/2} e^{-m_\chi/T_s} \sim 1$$

Usually very large

Must be very small

$$\Longrightarrow \quad m_\chi \gg T_s$$

- It is consistent to assume DM to be non-relativistic.

Today's Universe

$$H^2 = \frac{8\pi G}{3}\rho \quad \Rightarrow \quad \frac{3H_0^2}{8\pi G} = \sum_i \rho_i \quad \text{+ curvature term}$$

Hubble parameter today (H_0)

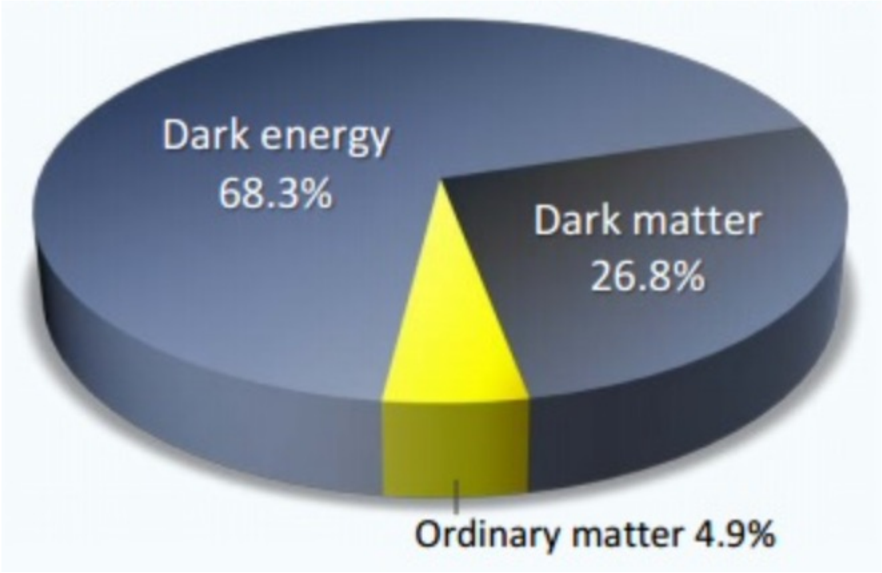
ρ_{crit} (= $\frac{3H_0^2}{8\pi G}$)

$$\Omega_i = \frac{\rho_i^{(0)}}{\rho_{\text{crit}}}$$

$\Omega_\gamma = 5.38\times10^{-5}$ $\quad$ $\Omega_b = 0.0493$

$\Omega_{DM} = 0.265$ $\quad$ $\Omega_\Lambda = 0.685$

$$\eta_b \equiv \frac{n_B}{n_\gamma} \approx 6\times10^{-10} \qquad \frac{\Omega_D}{\Omega_B} \approx 5$$



Today's energy density of DM

$$\frac{\Omega_D}{\Omega_b} \approx 5 \quad \Longrightarrow \quad \frac{n_\chi m_\chi}{\eta_b T^3 m_b} \sim 5$$

$$\Longrightarrow \quad \left(\frac{m_\chi}{m_b}\right)\left(\frac{m_\chi}{T_s}\right)^{3/2} e^{-m_\chi/T_s} \sim 10^{-9}$$

Freeze-out

- Two equations
  - From the freeze-out condition

$$(\langle \sigma v \rangle M_{\rm pl} m_\chi) \left(\frac{m_\chi}{T_s}\right)^{1/2} e^{-m_\chi/T_s} = 1$$

  - From the observation

$$\left(\frac{m_\chi}{m_b}\right) \left(\frac{m_\chi}{T_s}\right)^{3/2} e^{-m_\chi/T_s} \sim 10^{-9}$$

Freeze-out

- We look for the largest and smallest numbers.

$$\left(\frac{m_\chi}{m_b}\right)\left(\frac{m_\chi}{T_s}\right)^{3/2} e^{-m_\chi/T_s} \sim 10^{-9}$$

- Assuming m_χ is not significantly larger or smaller than m_b.

$$\Longrightarrow \quad \frac{m_\chi}{T_s} \approx \ln 10^9 \approx 20$$

The WIMP miracle

$$(\langle\sigma v\rangle M_{\rm pl} m_\chi)\left(\frac{m_\chi}{T_s}\right)^{1/2} e^{-m_\chi/T_s} = 1$$

$$\left(\frac{m_\chi}{m_b}\right)\left(\frac{m_\chi}{T_s}\right)^{3/2} e^{-m_\chi/T_s} \sim 10^{-9}$$

$$\langle\sigma v\rangle \sim 10^9 \times \frac{1}{m_b M_{\rm pl}} \times \left(\frac{m_\chi}{T_s}\right)^2$$

$$\Longrightarrow \quad \langle\sigma v\rangle \sim 10^{-8}\ {\rm GeV}^{-2} \sim 10^{-25}\ {\rm cm}^3/{\rm sec}$$

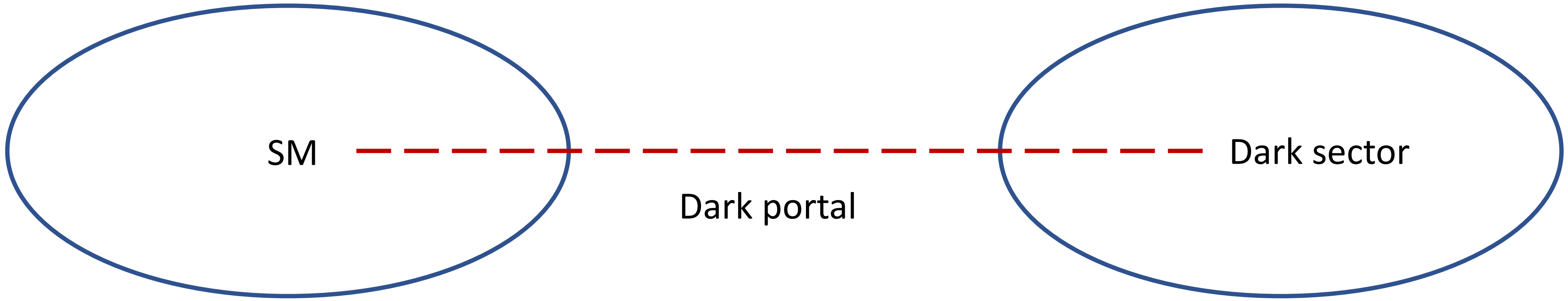
Almost independent of m_χ

$$\sim \frac{\pi\alpha_{\rm EM}^2}{(200\ {\rm GeV})^2}$$

$v_{\rm EW} = 246$ GeV, $m_H = 125$ GeV, $m_{top} = 173$ GeV, $m_W = 80.4$ GeV, $m_Z = 90.2$ GeV,

From WIMP to dark sector

- What is dark sector?



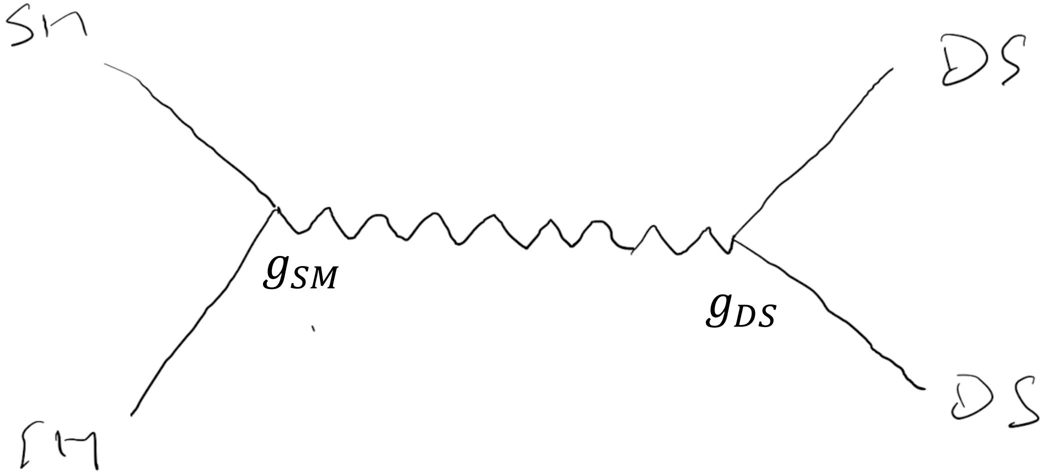
Dark Sector

- Vector dark portal

$$\sigma_{\chi N} \sim \frac{g_{SM}^2 g_{DS}^2 \mu_{N\chi}^2}{4\pi m_V^4}$$

$$\sigma_{\text{ann}} v \sim \frac{g_{DS}^4}{4\pi m_\chi^2}$$

Diagram for detection



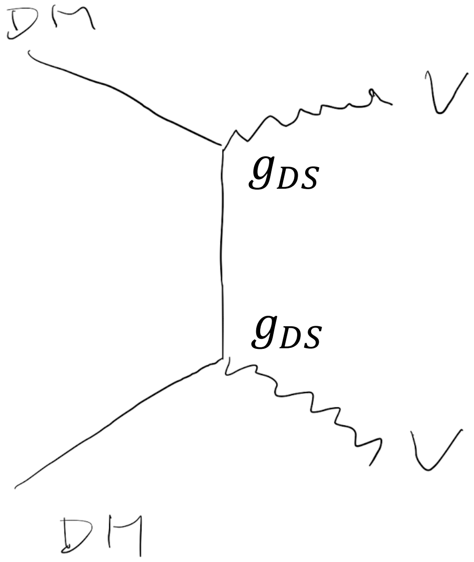


Diagram for annihilation

Dark Sector

$$\sigma_{\rm ann} v \sim \frac{g_{DS}^4}{4\pi m_\chi^2}$$

- To get the observed DM relic density

$$\langle \sigma v \rangle \sim 10^{-8}\ \mathrm{GeV} \sim 10^{-25}\ \mathrm{cm}^3/\mathrm{sec}$$

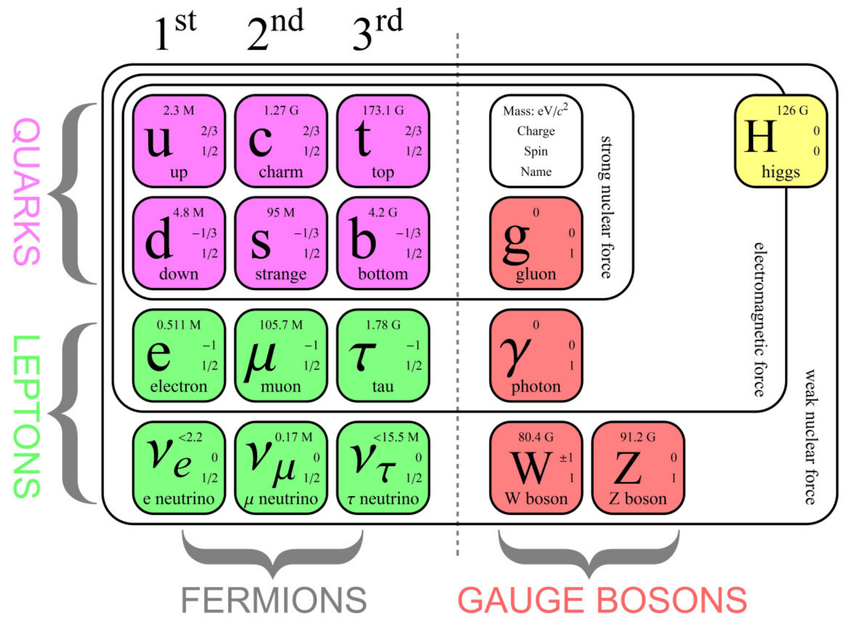
Almost independent of m_χ

- In most models, g_{DS} is free parameter, so m_χ has a large range of allowed parameter region.

- Why we need g_{SM}? The mediator should not be stable, or it will become DM. We need g_{SM} such that V can decay into SM particles.
- It is better for the decay to happen before the age of the universe is 1 sec, or the BBN will be ruined.

From WIMP to dark sector

- What are the popular portals?
- We look for operators with lowest dimensions.
- It will be easy for the operators to survive in low energy theories if the interaction is marginal.
- SM singlets with dimension < 3:



The Standard Model of Particle Physics

	SU(3)	SU(2)L	U(1)Y
Q_L	3	2	-1/6
u_R^c	3	1	2/3
d_R^c	3	1	-1/3
L	1	2	1/2
e_R^c	1	1	-1
H	1	2	1/2

The Standard Model of Particle Physics

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Relevant SM neutral Operators

- Special operators:

$|H|^2$ Dimension = 2, conserves all quantum numbers

$\bar{L}H$ Dimension = 5/2, violates lepton number

$F_{\mu\nu}$ Dimension = 2, Lorentz tensor

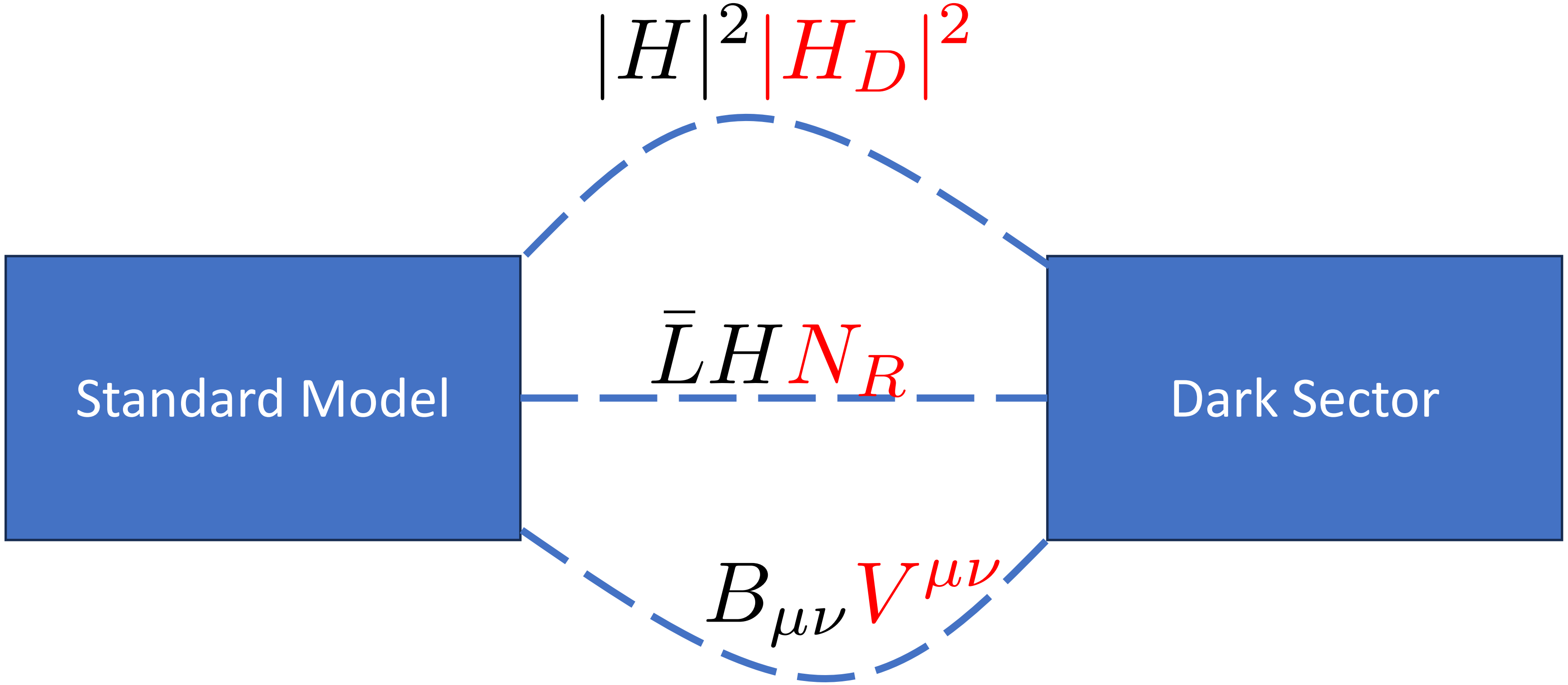
Connect to a new sector

$$|H|^2 \longrightarrow |H|^2|H_D|^2$$

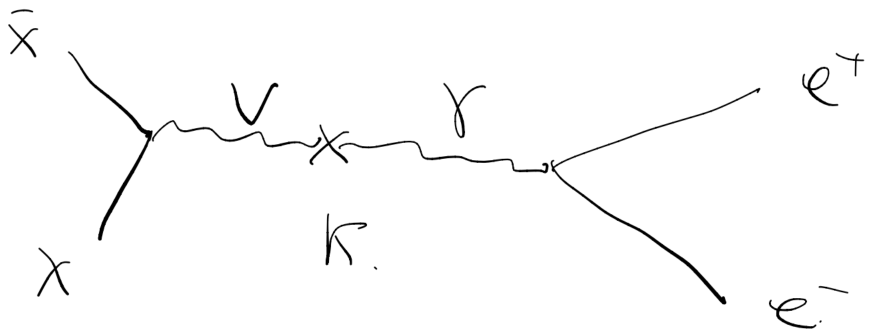
$$\bar{L}H \longrightarrow \bar{L}HN_R$$

$$B_{\mu\nu} \longrightarrow B_{\mu\nu}V^{\mu\nu}$$

Dark Portals



Kinetic mixing dark photon as the dark portal



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$$

Tiny kinetic mixing

Kinetic mixing dark photon as the dark portal

- How to diagonalize?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$$

- Redefine the photon field A_μ

$$A_\mu \to A_\mu - \kappa V_\mu$$

- After diagonalization, the dark photon couples to the EM current.

$$eA_\mu J^\mu \to eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

$$e_D V_\mu J_D^\mu \to e_D V_\mu J_D^\mu$$

→ The dark current, composed by DM

$$g_{\rm SM} = \kappa e \qquad\qquad g_{\rm DS} = e_D$$

N_R portal

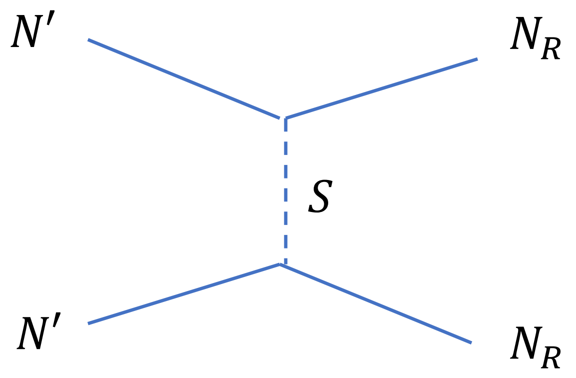
Pospelov, Ritz, Voloshin, PLB 662:53-61, 2008

$$\mathcal{L}_{\rm WIMP+mediator} = \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2}S^2 + \bar{N}' i\partial\!\!\!/ N' - \frac{m_{N'}}{2}N'^T N' + \bar{N}_R i\partial\!\!\!/ N_R - \frac{m_{N_R}}{2}N_R^T N_R - \frac{\lambda}{2}S^2 H^\dagger H - \left[Y_\nu \bar{L} H N_R - Y_{N'} S N_R^T N' + (h.c.)\right]. \quad (19)$$

Right handed neutrino

Dark matter

mediator



$N_R \rightarrow SM\ particles$

- The motivation to consider such models is to avoid direct detection constraints.

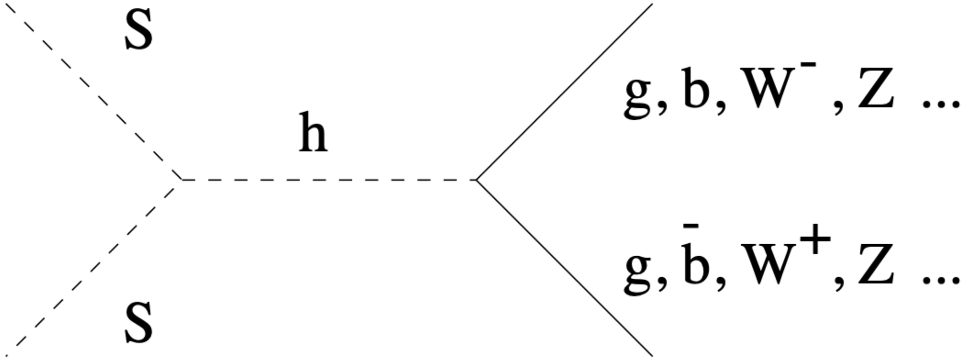
Higgs portal

Burgess and Pospelov, Nucl.Phys.B 619 (2001) 709

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S\,\partial^\mu S - \frac{m_0^2}{2}\,S^2 - \frac{\lambda_S}{4}\,S^4 - \lambda\,S^2\,H^\dagger H,$$

$$S \to -S$$

$$V = \frac{m_0^2}{2}\,S^2 + \frac{\lambda}{2}\,S^2 h^2 + \frac{\lambda_S}{4}\,S^4 + \frac{\lambda_h}{4}\left(h^2 - v_{EW}^2\right)^2.$$



Outline

- Dark matter production mechanisms
  - Freeze-out, Freeze-in, Asymmetric, SIMP, misalignment …
- Dark matter detetion
  - Searching for light DM
  - Searching for ultralight DM
  - Collider search for DM
  - Indirect search for DM
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Freeze-in

- Γ: the rate for a SM particle to be converted to DM particle.
- The Boltzmann equation of n_χ:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \Gamma n_{\rm SM}$$

$$n_{\rm SM} \sim T^3$$

Γ is a funtion of T.

- Temperature redshifts with the expansion of the universe.

$$\frac{dT}{Tdt} = -H$$

$$\longrightarrow \quad \frac{d}{dt}\left(\frac{n_\chi}{T^3}\right) = \Gamma \times \frac{n_{\rm SM}}{T^3} \sim \Gamma \quad \longrightarrow \quad \left.\frac{n_\chi}{T^3}\right|_{t_0} \sim \int_{t_{\rm RH}}^{t_0} \Gamma(t) dt$$

DM number density per entropy.

Freeze-in

- $$\frac{n_\chi}{T^3}\Big|_{t_0} \sim \int_{t_{\rm RH}}^{t_0} \Gamma(t) dt \quad \xrightarrow{\frac{dT}{Tdt} = -H} \quad \frac{n_\chi}{T^3}\Big|_{T_0} \sim \int_{T_0}^{T_{\rm RH}} \Gamma(T) \frac{dT}{HT}$$

- During radiation domination: $H \sim T^2/M_{pl}$

$$\frac{n_\chi}{T^3}\Big|_{T_0} \sim \int_{T_0}^{T_{\rm RH}} M_{\rm pl}\Gamma(T) \frac{dT}{T^3}$$

IR freeze-in vs UV freeze-in

- If the interaction is renormalizable, and dimensionless, $\Gamma \sim \alpha^n T$, by dimensional analysis.

$$\frac{n_\chi}{T^3}\Big|_{T_0} \sim \int_{T_0}^{T_{\rm RH}} \alpha^n M_{\rm pl} \frac{dT}{T^2}$$

Divergence at $T = 0$, IR dominant

- The low energy theory matters, not sensitive to high energy theory.

IR freeze-in vs UV freeze-in

- If the interaction is mediated by higher dimension operators, $\mathcal{O}_{\rm SM}\frac{1}{\Lambda^2}\mathcal{O}_\chi$

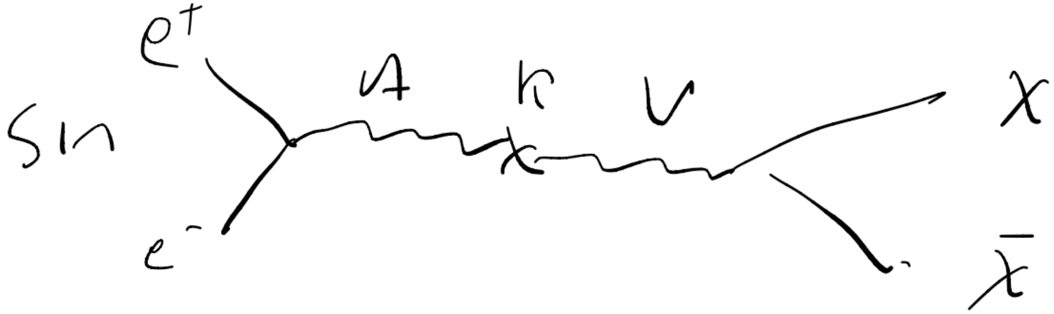
$$\Longrightarrow \quad \Gamma \sim \frac{T^5}{\Lambda^4}$$

$$\Longrightarrow \quad \frac{n_\chi}{T^3}\bigg|_{T_0} \sim \int_{T_0}^{T_{\rm RH}} \frac{M_{\rm pl}}{\Lambda^4} T^2 dT \sim \frac{M_{\rm pl} T_{\rm RH}^3}{\Lambda^4}$$

- Very sensitive to the reheating temperature.

A realistic model

- The dark photon model



$$\Gamma = \langle \sigma v \rangle n_e \sim \frac{\pi \alpha_{\mathrm{EM}} \alpha_D \kappa^2}{T^2} \times T^3 \sim \kappa^2 \alpha_{\mathrm{EM}} \alpha_D T$$

- Assuming $m_\chi > m_e, m_V$ ⟹ the integral stops at $T \sim m_\chi$.

$$\frac{n_\chi}{T^3} \sim \pi \alpha_{\mathrm{EM}} \alpha_D \kappa^2 \times \frac{M_{\mathrm{pl}}}{m_\chi}$$

A realistic model

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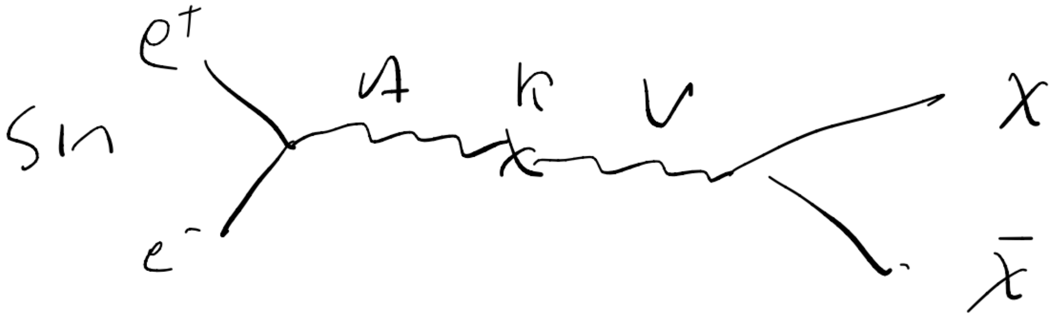

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- Assuming $m_\chi > m_e, m_V$ → the integral stops at $T \sim m_\chi$.

$$\frac{n_\chi}{T^3} \sim \pi \alpha_{\rm EM} \alpha_D \kappa^2 \times \frac{M_{\rm pl}}{m_\chi}$$

$$\frac{n_\chi m_\chi}{\eta_b T^3 m_b} \sim 5$$

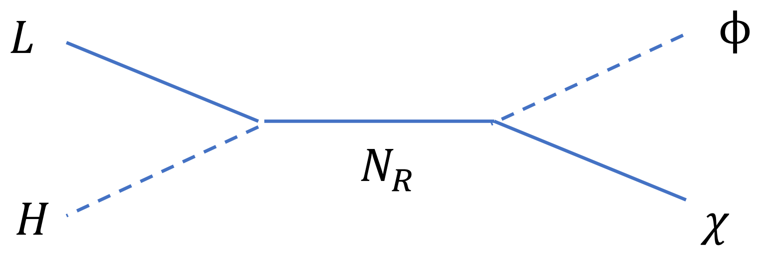
$$\pi \alpha_{\rm EM} \alpha_D \kappa^2 \sim \eta_b \times \frac{m_b}{M_{\rm pl}} \sim 10^{-28}$$

Freeze-in via N_R

$$\mathcal{L}_{\text{Seesaw}} = -Y_{\alpha\beta}\overline{L_{L\alpha}}\tilde{H}N_{R\beta} - \frac{1}{2}M_R\overline{N_R^c}N_R + h.c.\,,$$
$$\mathcal{L}_{\text{DS}} = \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + |\partial_\mu\phi| - m_\phi^2\,|\phi|^2 + V\left(\phi\right)\;,$$
$$\mathcal{L}_{\text{portal}} = y_{\text{DS}}\phi\,\overline{\chi}N_R + h.c\,,$$

	N_R	ϕ	χ (DM)
$SU(2)_L$	**1**	**1**	**1**
$U(1)_Y$	0	0	0
Z_2	+	-	-

SM thermal bath



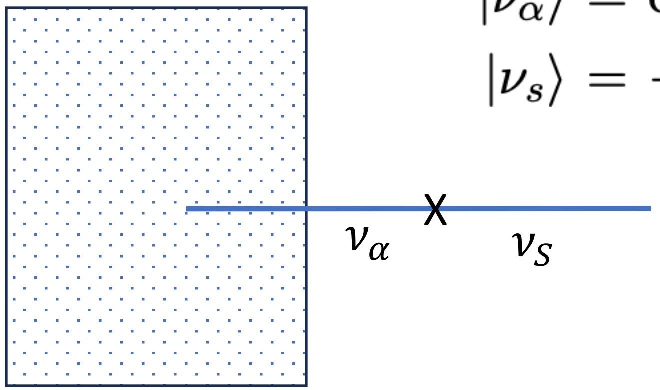
Dark sector

Sterile neutrino production

- Producing sterile neutrinos from a thermal bath

Doldelson and Widrow PRL 72 (1994), 17-20

$$|\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle,$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle,$$



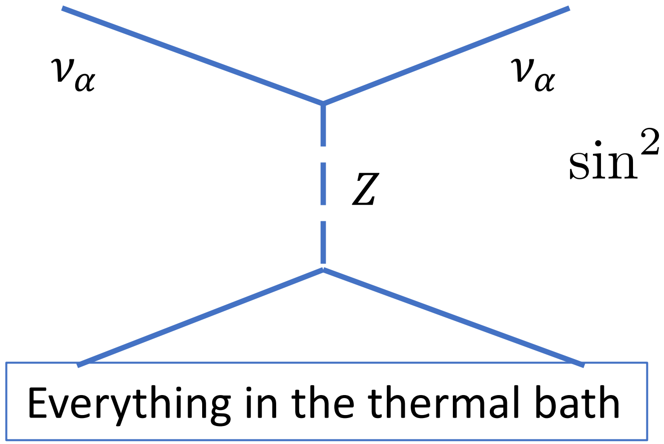
$$\Gamma_{\nu_S} \approx \frac{\sin^2(2\theta)}{4}\Gamma_{\nu_\alpha}$$

No media effect

- The active neutrinos keep scattering with the particles in the thermal bath.

Sterile neutrino production

- Media effect is important when the net interaction with Z boson is nonzero.



$$\sin^2(2\theta) \to \sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}$$

$$\Delta(p) = \frac{\Delta m^2}{2p}$$

Finite density effect

Finite temperature effect

- Resonant production when $\Delta(p) \approx V_D + V_T$.

Mikheev, Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913–917
Wolfenstein, Phys. Rev. D17 (1978) 2369–2374.
Shi and Fuller, PRL 82:2832-2835, 1999

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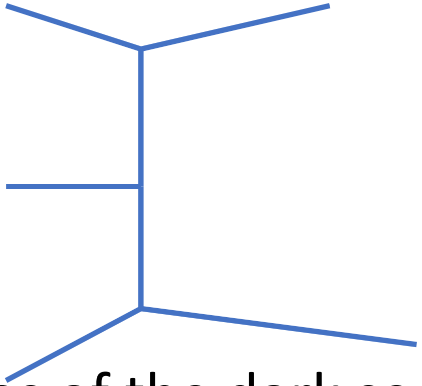
The SIMP model

- If $H < \Gamma_{3\to2}$, n_χ/T^3 decreases. If $H > \Gamma_{3\to2}$, n_χ/T^3 is conserved.
- $\Gamma_{3\to2}$ can be seen as the disappearing rate of χ.



$$\Gamma_{3\to2} \propto n_\chi^2 \longrightarrow \Gamma_{3\to2} \sim \frac{n_\chi^2 \alpha_{\rm eff}^3}{m_\chi^5}$$

- Assuming there is an interaction keeps the temperatures of the dark sector to be equal to the SM sector.

$$n_\chi \sim (m_\chi T)^{3/2} e^{-m_\chi/T} \qquad H \sim T^2/M_{\rm pl}$$

- Require at some T_F, $\Gamma_{3\to2} = H$. $\longrightarrow$

$$\left(\frac{T_F}{m_\chi}\right)^2 \alpha_{\rm eff}^3 e^{-2m_\chi/T} \sim \frac{T_F}{M_{\rm pl}}$$

The SIMP model

- $$\left(\frac{T_F}{m_\chi}\right)^2 \alpha_{\rm eff}^3 e^{-2m_\chi/T} \sim \frac{T_F}{M_{\rm pl}}$$
- The largest and smallest numbers dictate. $$\frac{m_\chi}{T_F} \sim \frac{1}{2}\ln\left(\frac{M_{\rm pl}}{T_F}\right) \sim 20$$
- The condition from the observation:

$$\frac{n_\chi m_\chi}{\eta_b T^3 m_b} \sim 5$$

$$\Longrightarrow \quad m_\chi \sim 40\ \text{MeV} \times \alpha_{\rm eff} \qquad \text{(HW)}$$

$$n_\chi \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$

A realistic model (The dark Wess-Zumino-Witten model)

- In the dark sector, An SO(6) global symmetry is spontaneously broken into SO(5) symmetry. Five goldstone particles are generated.

$$\mathcal{L}_\pi = \frac{1}{2}\partial_\mu \pi^a \partial^\mu \pi^a - 4\text{pt interactions} - \ 6\text{pt interactions} - \cdots$$

- For some topological reason ($\pi_5(SO(6)/SO(5))$=Z), there can be an additional term:

$$\mathcal{L}_{\text{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

$$\Gamma_{3\to 2} \sim n_\chi^2 \frac{N_C^2 m_\pi^5}{f_\pi^{10}}$$

It will work, when $m_\pi \sim f_\pi \sim 100$ MeV.

Symmetric vs Asymmetric

- Symmetric DM
  - $n_{DM} = n_{\overline{DM}}$ (freeze out, freeze in, SIMP …)
- Consider people living in the dark universe. What are their dark matters?
  - Most of the DM are in the form of proton.
  - A sizable portion in the form of dark atoms and dark molecules.
  - A warm DM in the form of dark electrons.
  - A small part of hot DM (SM neutrinos)
  - Dark Radiation (the CMB)

Symmetric vs Asymmetric

- Baryon-anti-baryon asymmetry
- Can it be from initial condition?
  - No, since anything before inflation are diluted.
- Can it be from random fluctuation?
  - No, since it is much larger than the random fluctuation $\sim 10^{-40}$
  - What we need is about 10^{-10}.
- There must be a mechanism to generate today's baryon-anti-baryon asymmetry

Symmetric vs Asymmetric

- Sakharov conditions for baryogenesis (JETP Lett. 5 (1967) 24)
  - Baryon number is not conserved.
  - Charge conjugation symmetry is not exact.
  - CP is not an exact symmetry.
  - Baryogenesis could have occurred during a period when the universe was not in thermal equilibrium.

Symmetric vs Asymmetric

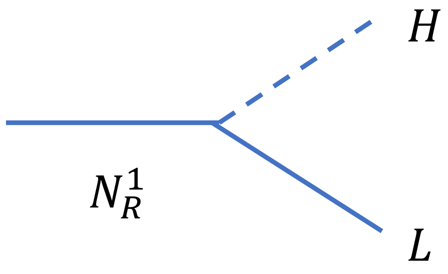
- EW baryogensis
  - Baryon number is not conserved → EW instanton breaks baryon number
  - Charge conjugation symmetry is not exact. → Weak interaction breaks C
  - CP is not an exact symmetry. → Weak interaction breaks CP
  - Baryogenesis could have occurred during a period when the universe was not in thermal equilibrium. → The universe is no tin theramal equilibrium during First order phase transition

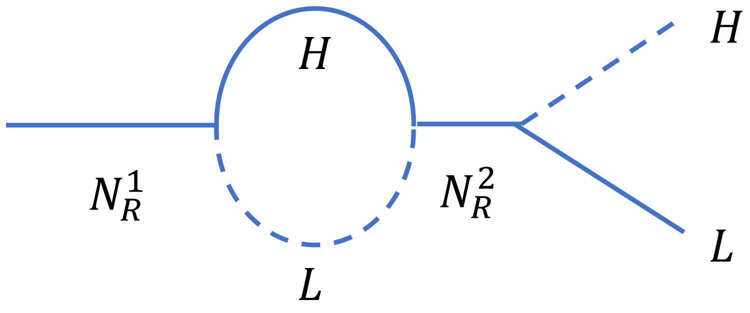
Symmetric vs Asymmetric

- Leptogenesis
  - Lepton number is not conserved → Righthanded neutrino is Majorana
  - Charge conjugation symmetry is not exact. → Yukawa interaction violates C
  - CP is not an exact symmetry. → Yukawa interaction violates CP
  - Baryogenesis could have occurred during a period when the universe was not in thermal equilibrium. → The decay of righthanded neutrtino is not in thermal equilibrium
  - Convert lepton number to baryon number

Darkogenesis (Dark baryogenesis)

- Leptogensis model
- Generate lepton number first.
  - $L \to B$ through weak sphaleron effect force $L - B = 0$.

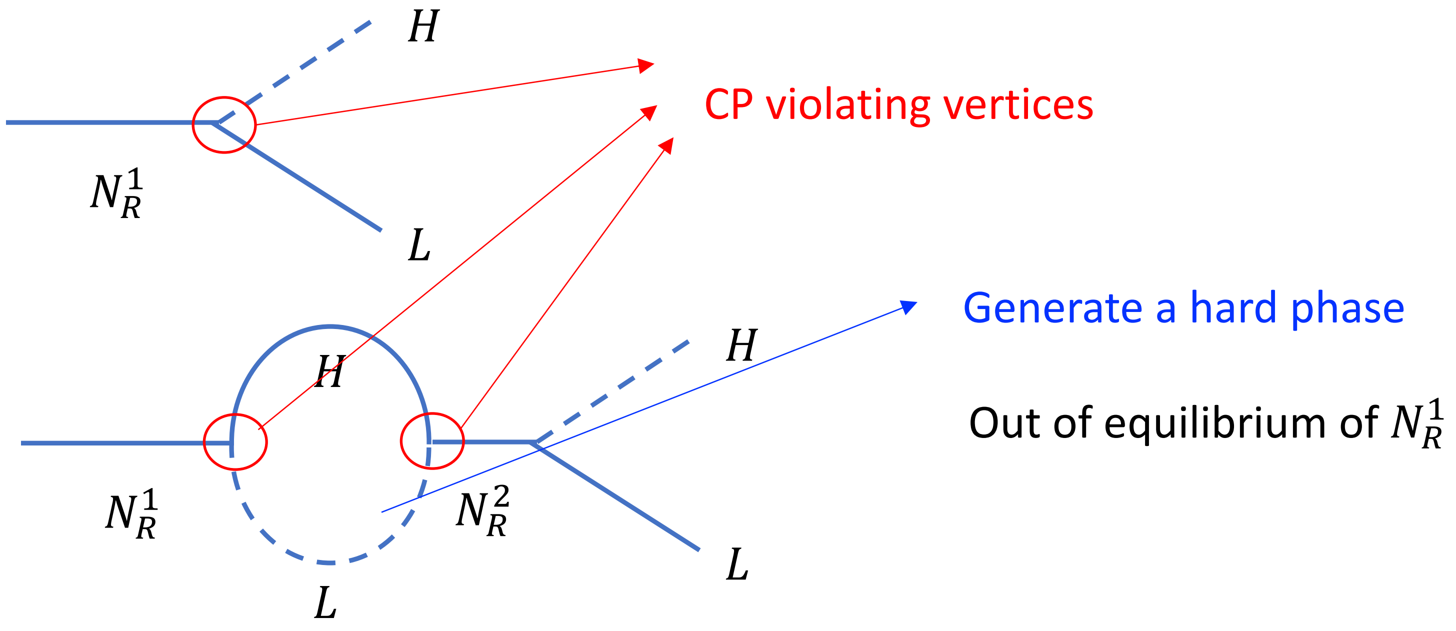




Out of equilibrium of N_R^1

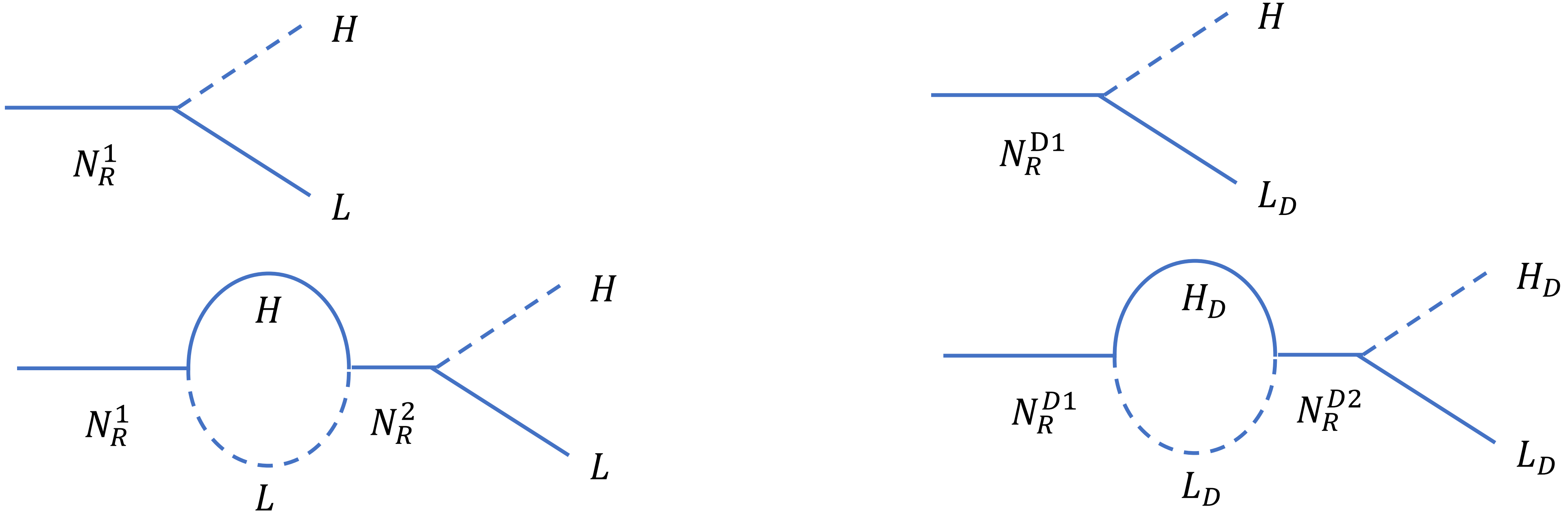
Darkogenesis (Dark baryogenesis)

- Leptogensis model
- Generate lepton number first.
  - $L \to B$ through weak sphaleron effect force $L + B = 0$.



Darkogenesis (Dark baryogenesis)

- The simplest darkogenesis model, leptogenesis in the dark sector.



Where do we start from?

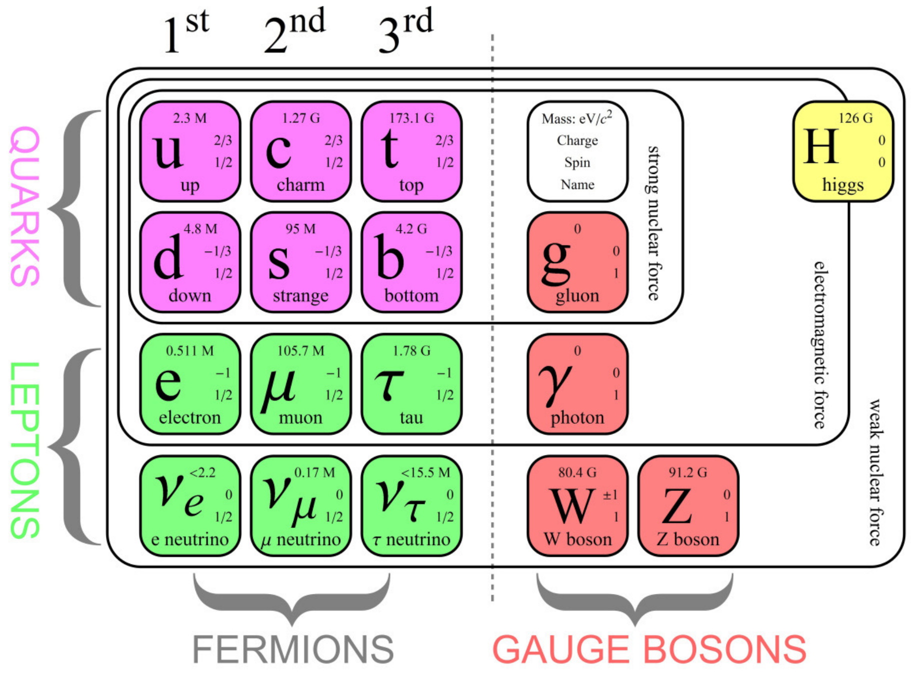
- We know almost nothing about dark matter except for:
  - Equation of state
  - Total energy density
    - 23% of the total energy density
    - About five times of the energy density of baryons
  - Its velocity around the earth
    - About 200 km/sec
  - Energy density around the earth
    - 0.4 GeV/cm^3

Darkogenesis (Dark baryogenesis)

- $\Omega_{DM} \approx 5\Omega_{\mathrm{B}}$
- Why they are so close to each other?
- Is there a reason similar to the WIMP miracle?
- In quantum theory, when something is close to each other, there is usually a approximate symmetry.
  - $m_p \approx m_n \quad \rightarrow \quad isospin\ symmetry$, slightly broken by QED and quark mass.

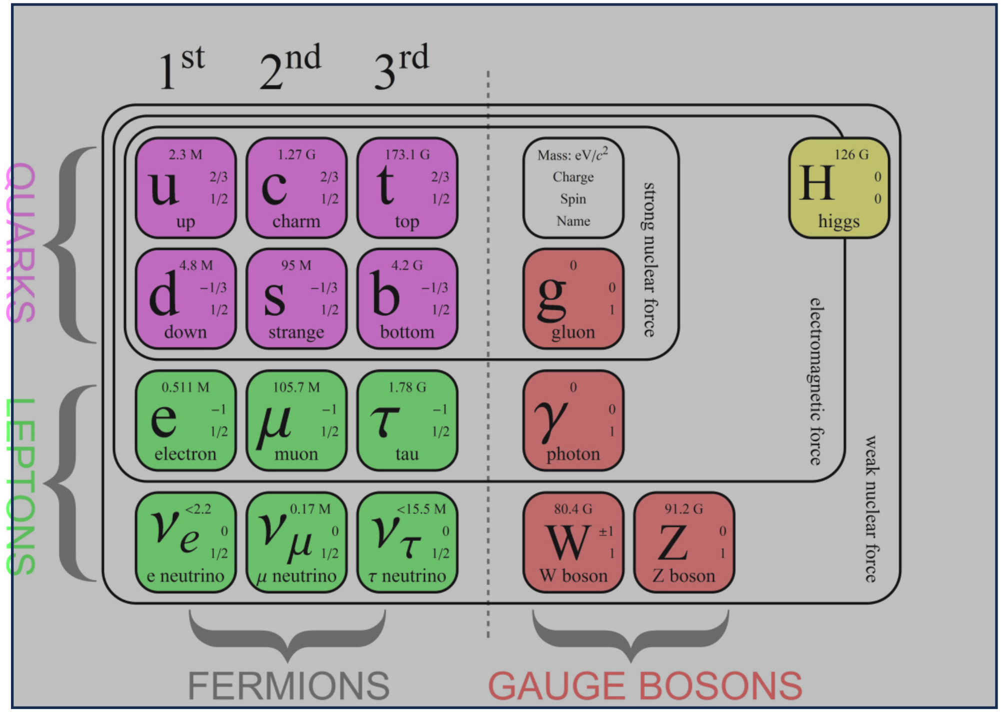
Mirror DM model

- We assume there is a mirror sector almost identical to the standard model. All the couplings are equal to



N_R portal

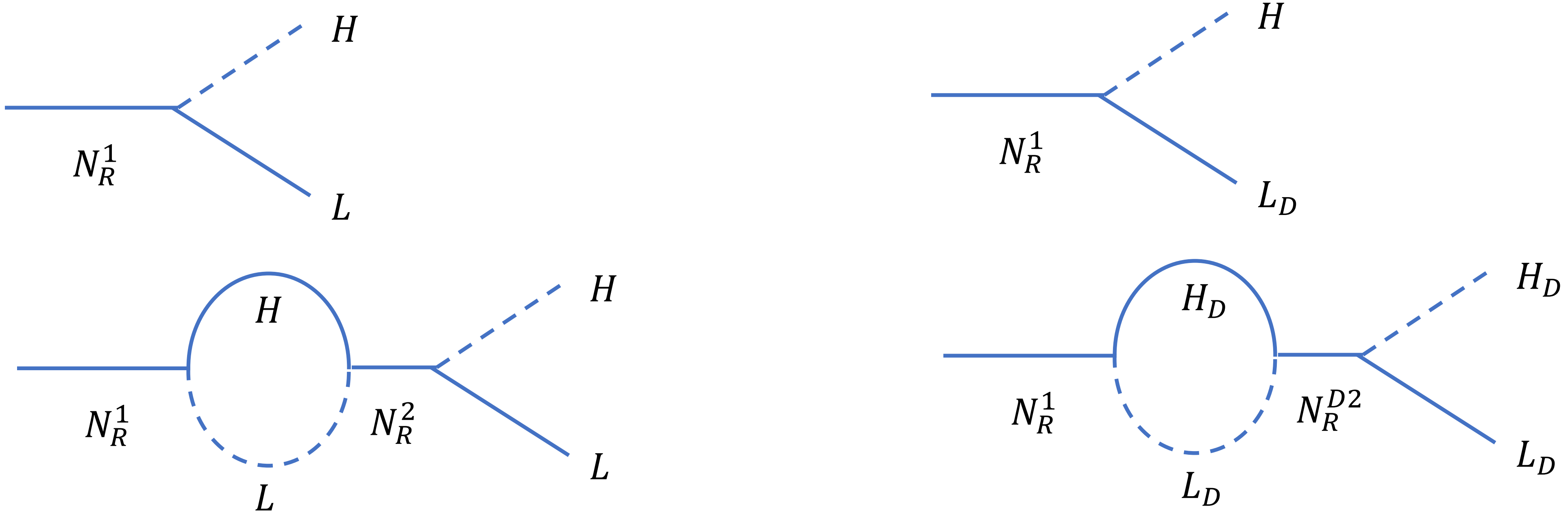
$$\bar{L} H N_R + \bar{L}_D H_D N_R$$



Mirror DM model

$$y(\bar{L}HN_R + \bar{L}_D H_D N_R)$$

Mirror symmetry ⟹ Same Yukawa in both sectors ⟹ $n_D \approx n_B$



Mirror DM model

- $n_D \approx n_B$
- We need $m_D \approx 5m_B \approx 5\ \mathrm{GeV}.$
- We can introduce a spontaneous breaking of the mirror symmetry,

$v_{EW}^D \approx 10^3\ \mathrm{TeV}$, such that baryon mass in the mirror sector is about 5 GeV.

HA, S.-L. Chen, R. N. Mohapatra, Y. Zhang, JHEP 03 (2010) 124

Symmetric vs Asymmetric

- Baryogenesis $\longrightarrow$ darkogenesis
- $\Omega_{DM} \approx 5\Omega_{\mathrm{B}}$
- Why they are so close to each other?
- Is there a reason similar to the WIMP miracle?
- In quantum theory, when something is close to each other, there is usually a approximate symmetry.
  - $m_p \approx m_n \rightarrow$ $isospin\ symmetry$, slightly broken by QED and quark mass.

Ultralight bosonic DM

- Fermionic DM cannot be ultralight because of the Pauli exclusion principle.
- Fermionic DM with mass smaller than 2 keV is excluded by the Lyman-α constraint.
- Two candidates
  - Axion and axion like particles (Pseudo scalar)
  - Dark photons (vector)

- Mass range (>10^{-21} eV, or the de Broglie wave length larger than the size of the dwarf galaxies.)

Introduction to Strong CP problem and QCD axion

Why they can be DM candidate?

- Uniformly distributed pseudo-scalar in expanding universe $a(t, \mathbf{x}) = a_0 \cos m_a t$

- RW metric: $ds^2 = dt^2 - R^2(t) d\mathbf{x}^2$

- The energy density $\rho = \frac{1}{2} m_a^2 a_0^2$

- The pressure $p = \frac{1}{2} m_a^2 a_0^2 \cos(2 m_a t)$

- $\bar{p} = 0$ for $T \gg 2\pi / m_a$.

Production of ultralight DM

- If the ultralight DMs are in thermal equilibrium with SM, they will become hot DM and be excluded by Lyman-α observations.
- They must be produced cold.
- The equation of motion of the zero mode (homogeneous part)

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

- In the early universe, $H \gg m_a$, the oscillation is over damped.

$$\dot{a}/a \sim m_a^2/H \ll m_a \ll H$$

- a can be seen as a constant field a_0.
- When $H < m_a$, a starts to oscillate with the amplitude a_0.
- The momentum will be redshifed away just like particles.

The misalignment

- Why is there a nonzero a_0?
- In the early universe, when m_a can be neglected, a enjoys a shift symmtry

$$a \to a + b_0$$

- The position of a in the field space is not necessary to be the minimum of the potential.

For dark photon dark matter

- $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$

- It may decay into neutrinos and three photons.
  - The neutrino channel is suppressed by $\kappa^2 \left(\frac{m_V}{m_Z}\right)^4$.
  - The three photon channel is suppressed by $\kappa^2 \alpha^4 m_V^8 / m_e^8$

- It is easy for the dark photon lifetime to be longer than the age of Universe.

Ultralight dark photon DM

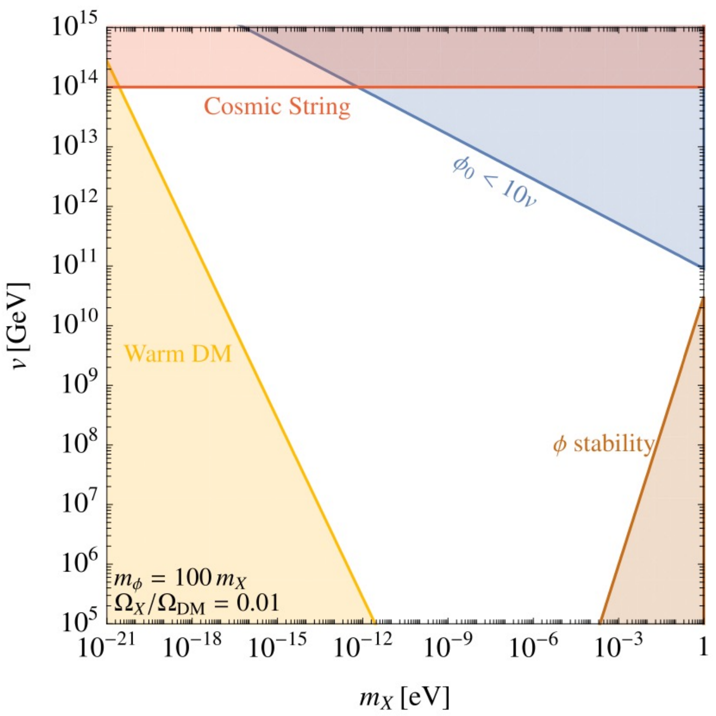
- From quantum fluctuation during inflation

  Graham, Mardon, Majendra (2015)

$$m_{A'} = 10^{-5}\ \text{eV} \times \left(\frac{10^{14}\text{GeV}}{H_I}\right)^4$$

- From parametric resonant production

  Co, Pierce, Zhang, Zhao (2018)
  Dror, Harigaya, Narayan (2018)
  Bastero-Gil, Santiago, Ubaldi, Vega-Morales (2018)
  Agrawal, Kitajima, Reece, Sekiguchi, Takahashi (2018)



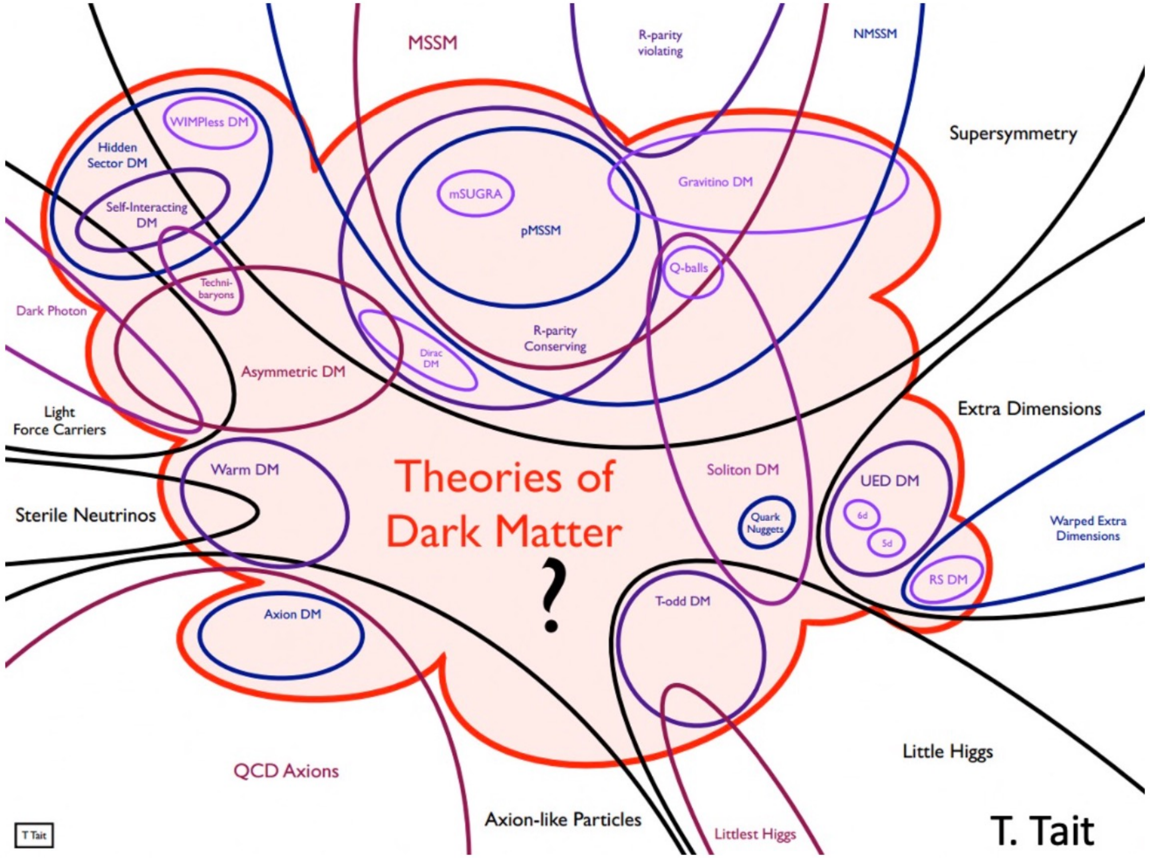
- From decay of cosmic string

  Long, Wang (2019)

- …

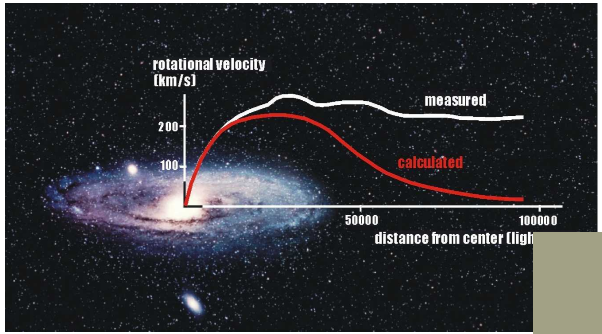
Theories of Dark Matter

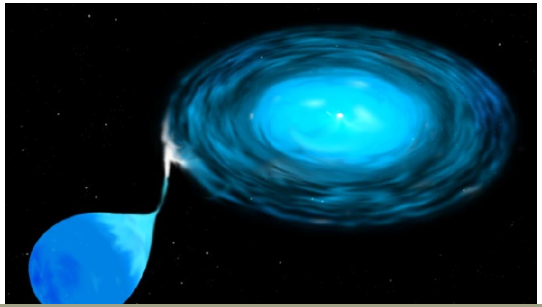
- Freeze-out
  - WIMP, SuperWIMP, Coannihilation, Dark Sector
- Freeze-in
  - UV freeze-in, IR freeze-in
- SIMP
  - $3 \to 2, 4 \to 2$
- Asymmetric DM
- Ultralight Bosonic DM
- …

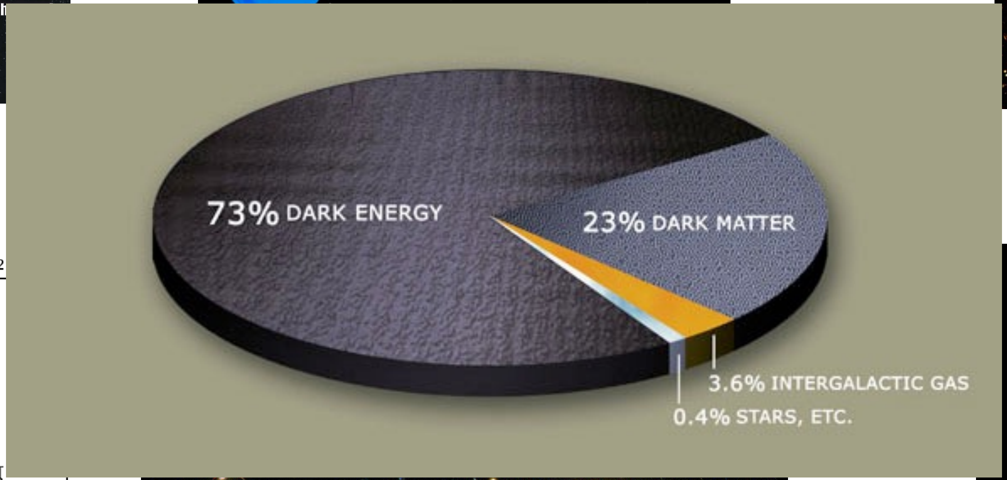


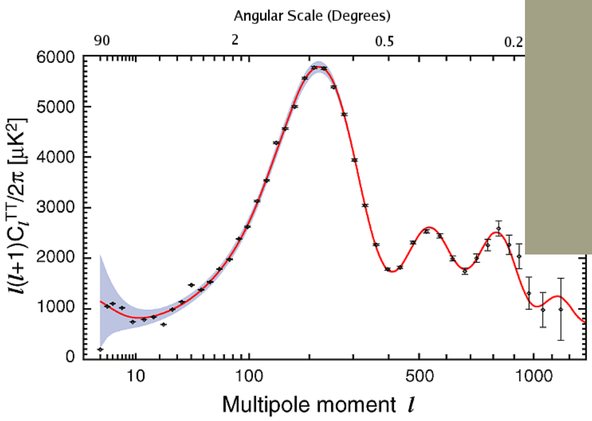
Searching for Dark Matter

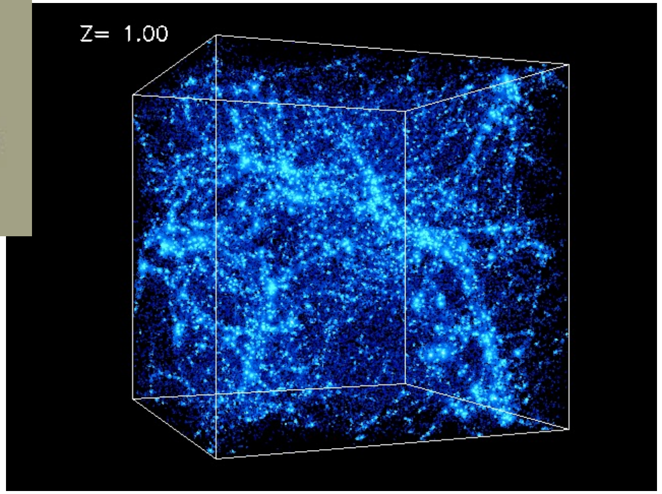
Concordant universe











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?

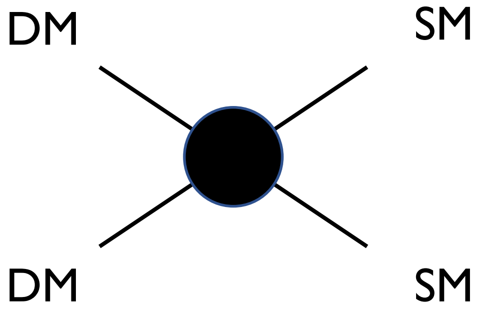
- We know almost nothing about dark matter except for:
  - Equation of state

    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

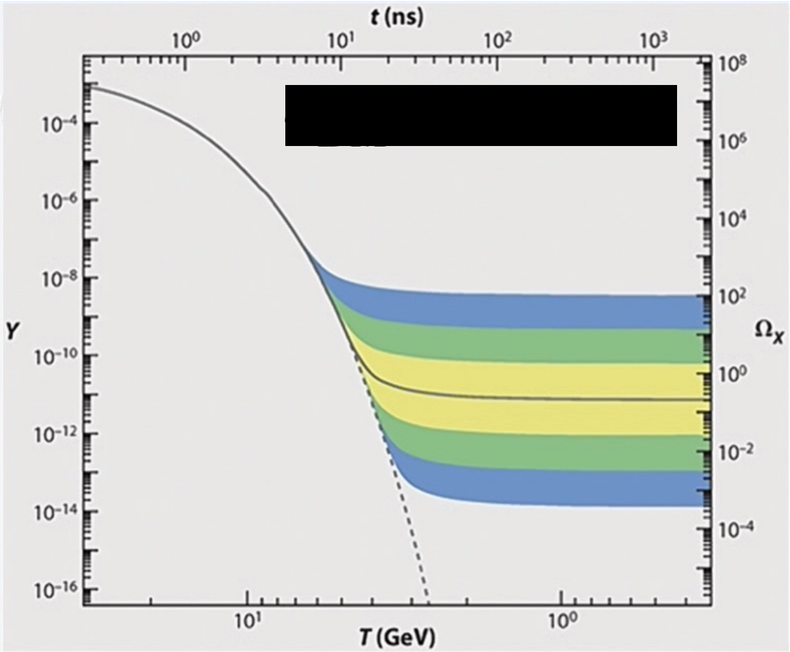
The WIMP miracle



Thermal freeze out

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

$\Gamma_A < \mathrm{H}$



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

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

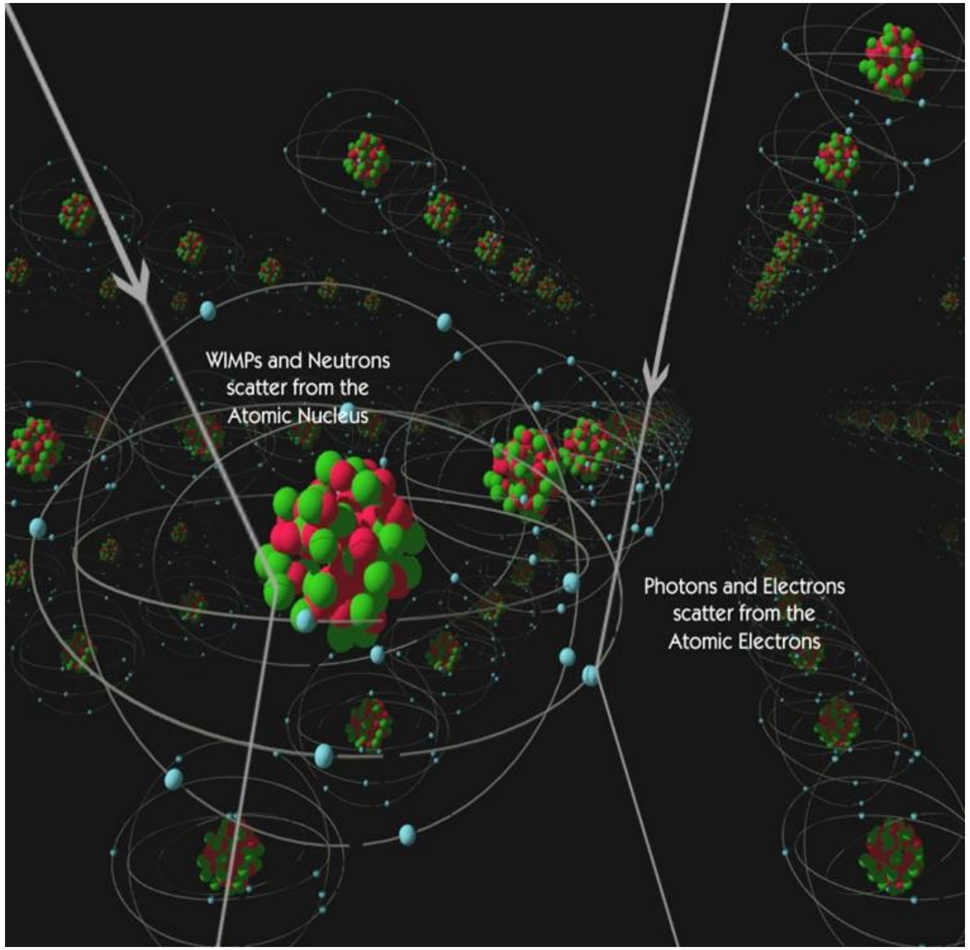
Weakly Interacting Massive Particle (WIMP)

Searching for WIMPs

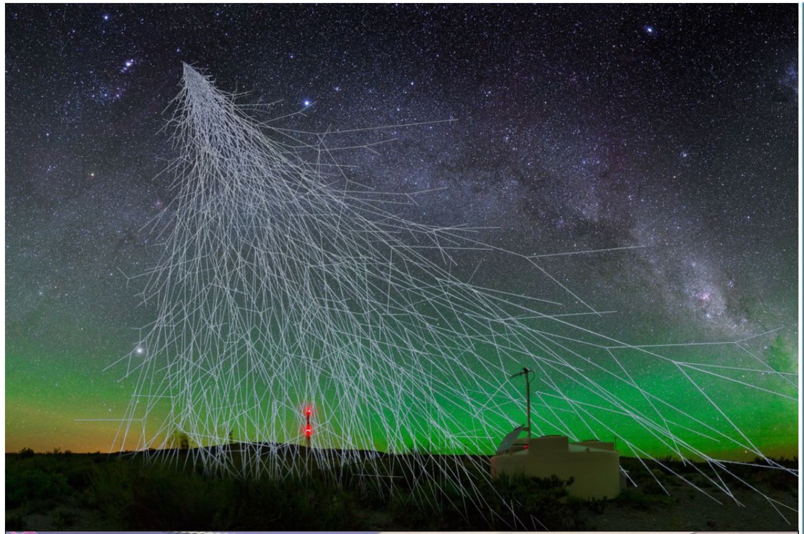
$$E_{recoil} \sim \frac{m_{\mathrm{DM}} m_T}{(m_{\mathrm{DM}} + m_T)^2} E_k$$

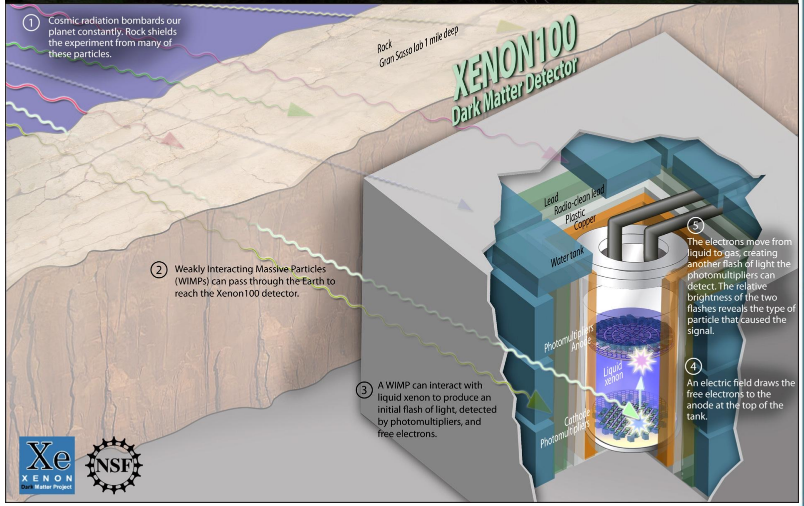
Proton mass ~ 1 GeV
Nucleus with *N* nucleons *N* GeV

Use heavy nuclei as target



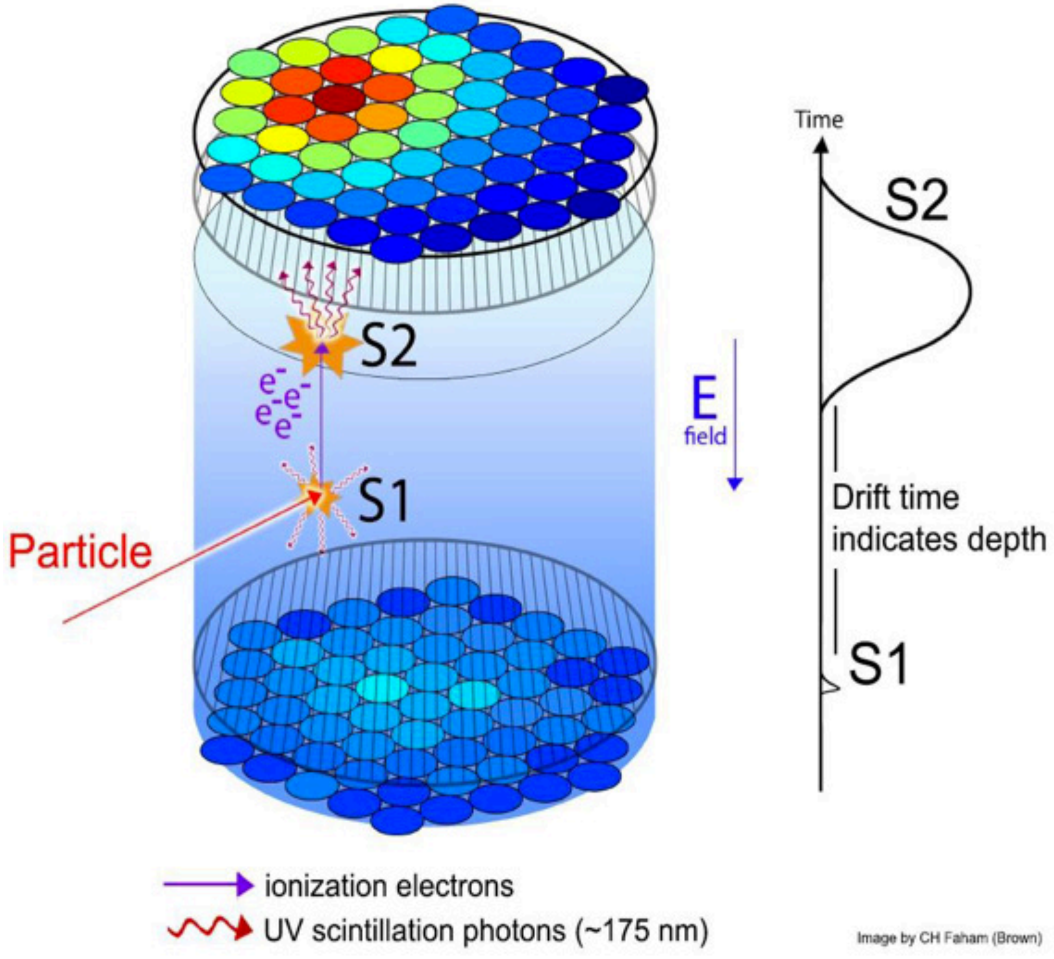
Underground labs



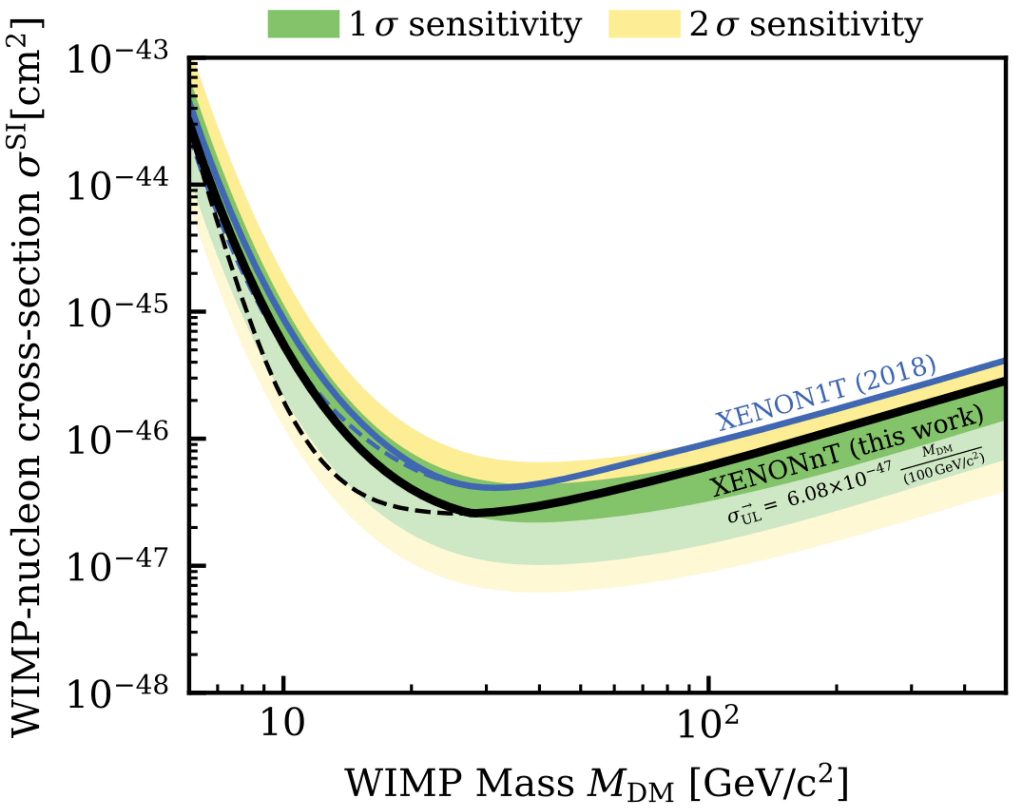


Noble gas (惰性气体) detector

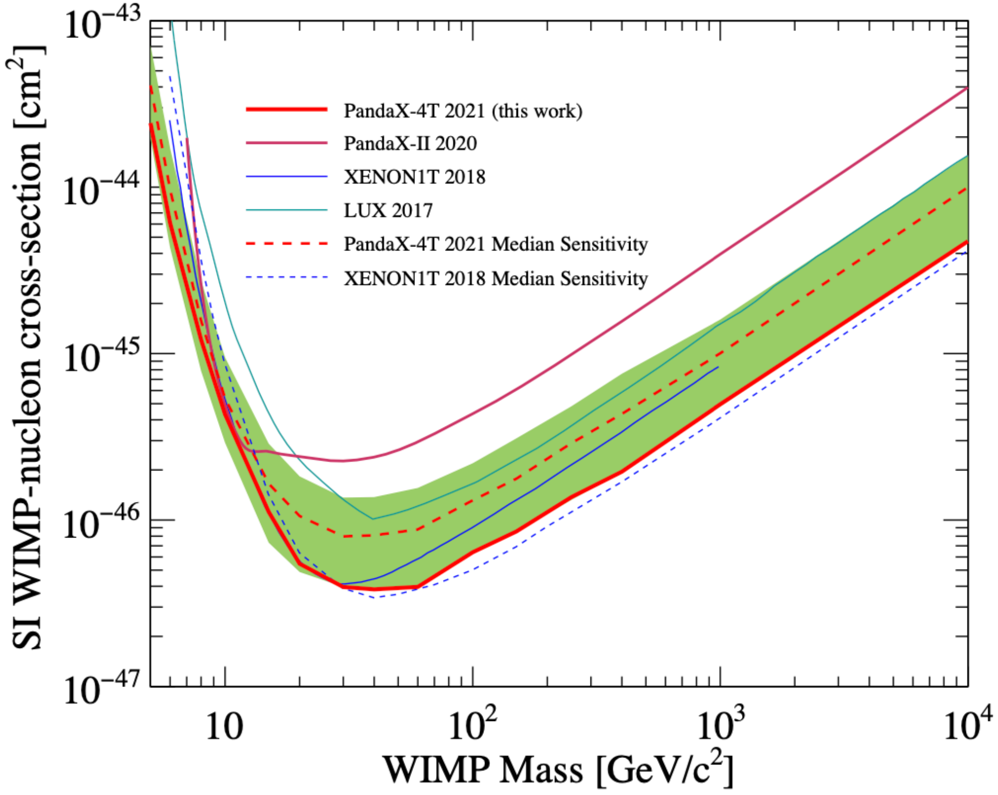
- Target: xenon nucleus
- Use S1 and S2 signals to distinguish signal from background
- High threshold hold for S1 signal
- XENON, LUX, PandaX (SJTU)



Noble gas detector



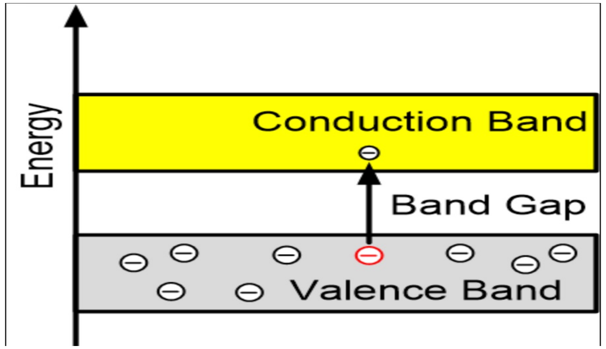
XENONnT PRL 121 (2023) 041003

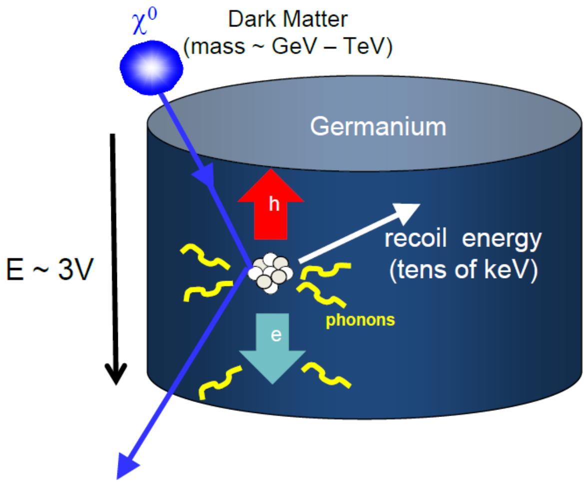


PandaX-4T PRL 127 (2021) 261802

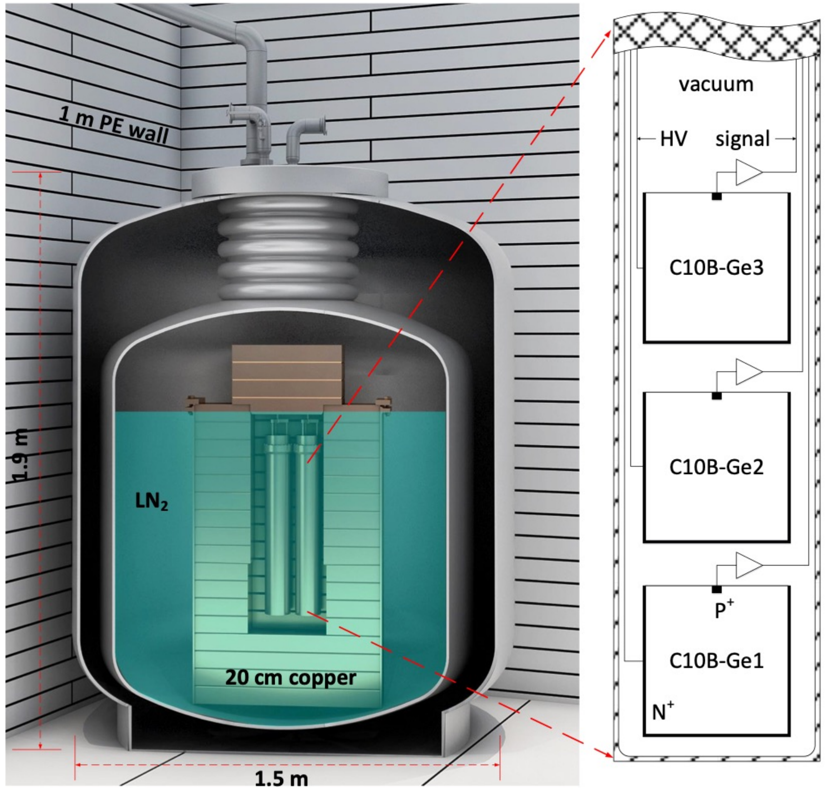
Semi-conductor detector

- 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)

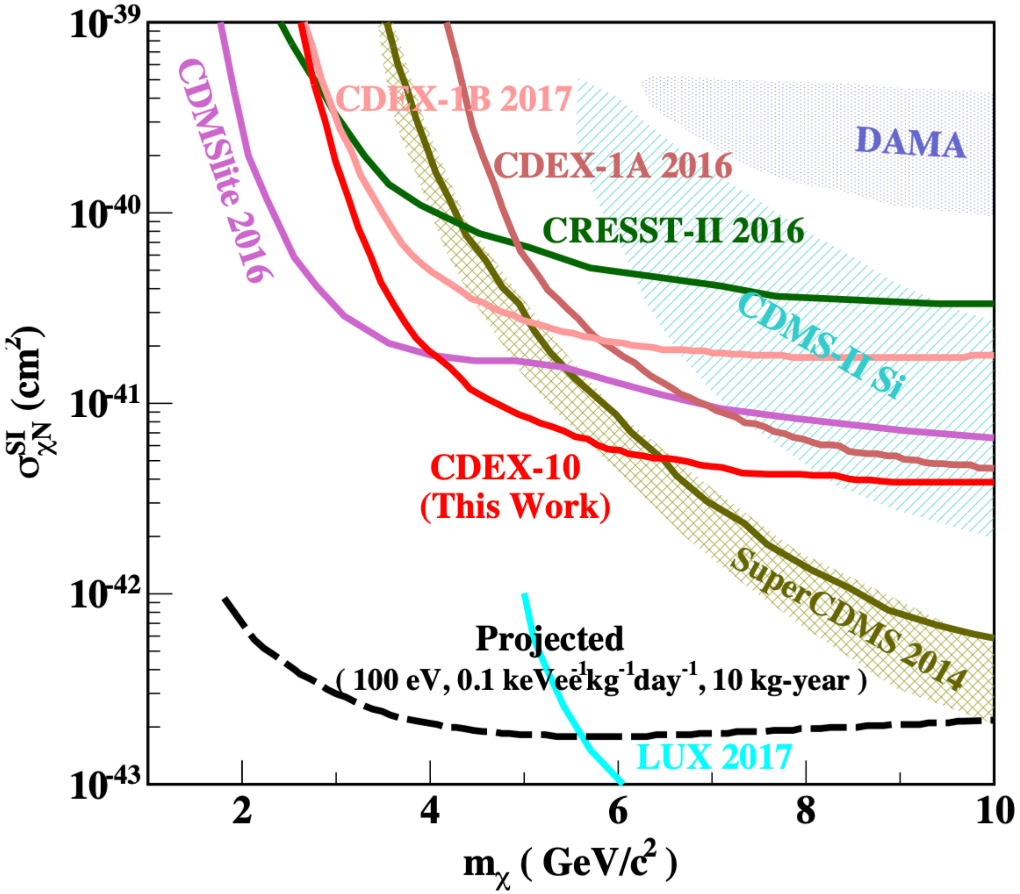




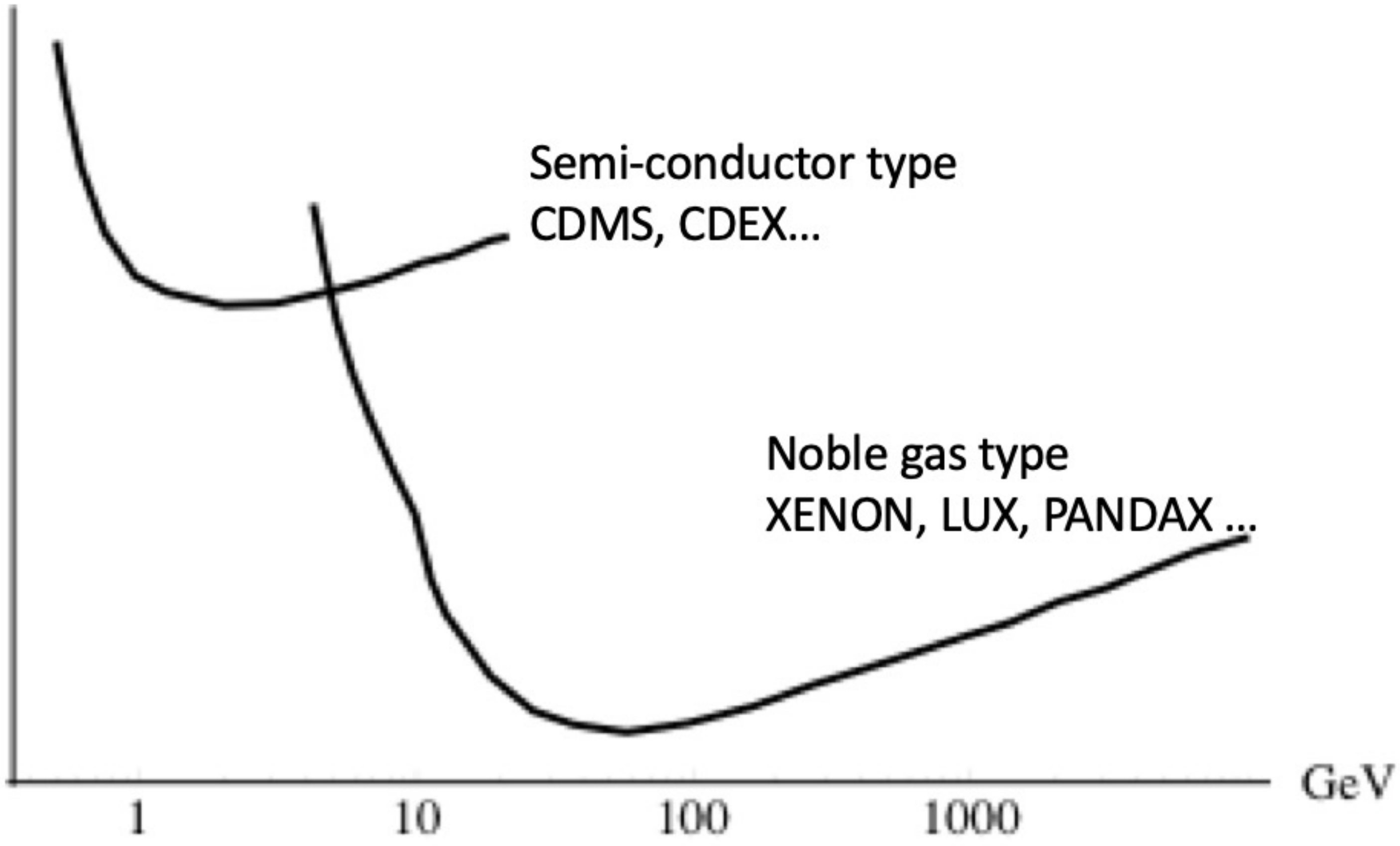
Semi-conduction detector



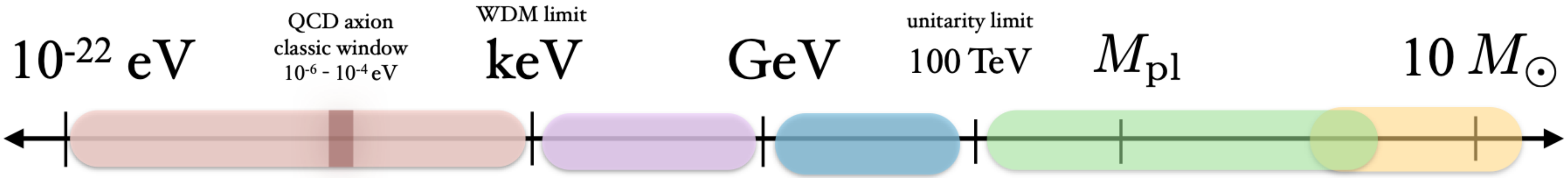
CDEX collaboration, PRL 120 (2018) 241301



Searching for WIMPs



Theories of dark matter with huge mass range

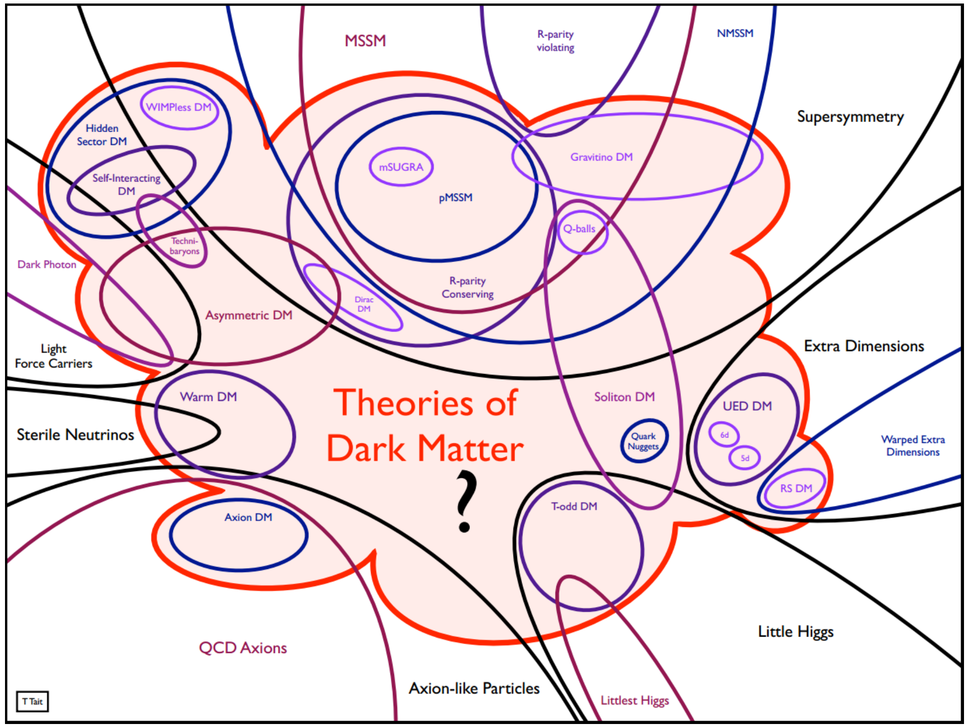


``Ultralight” DM

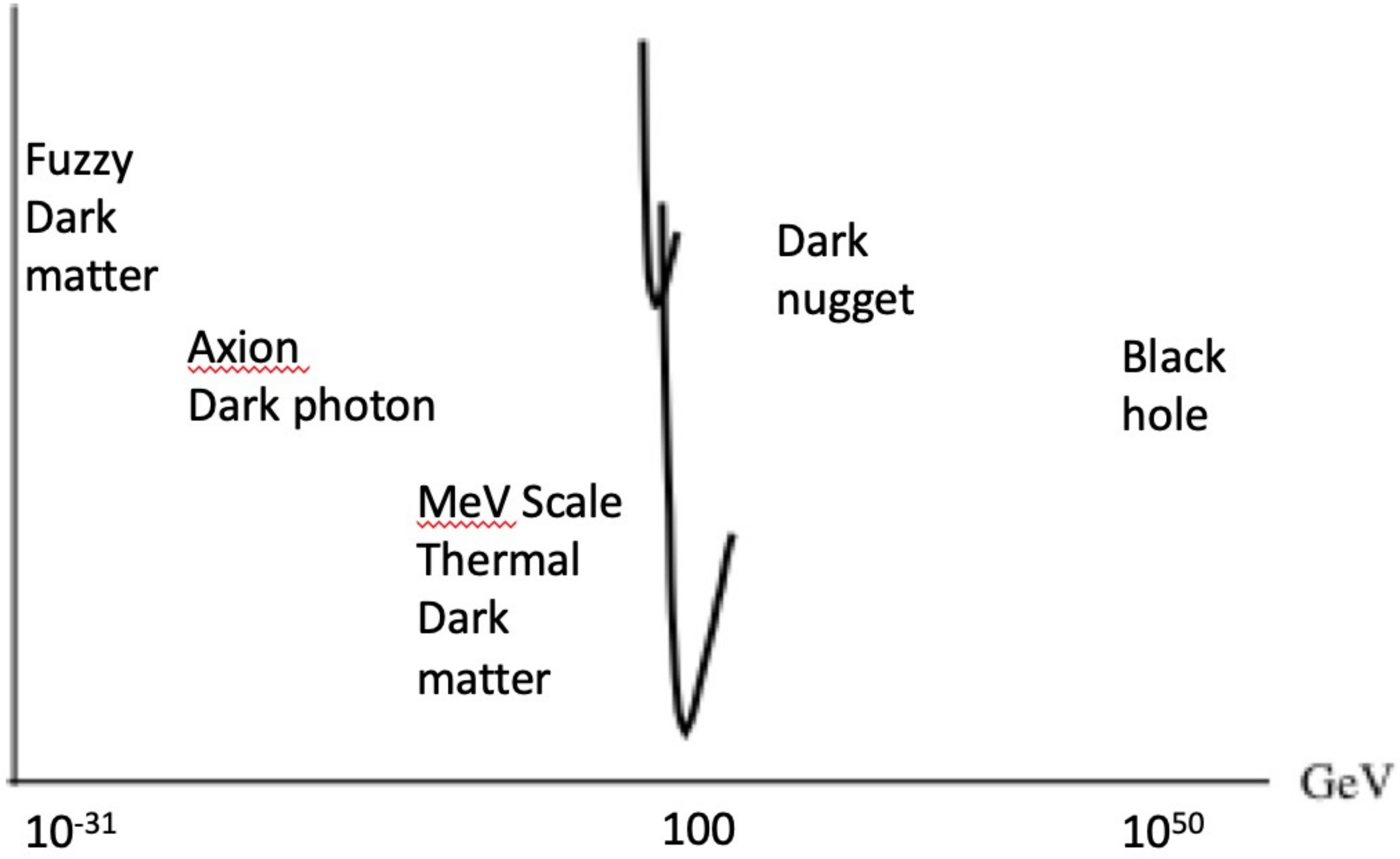
non-thermal
bosonic fields

``Light” DM

dark sectors
sterile ν
can be thermal

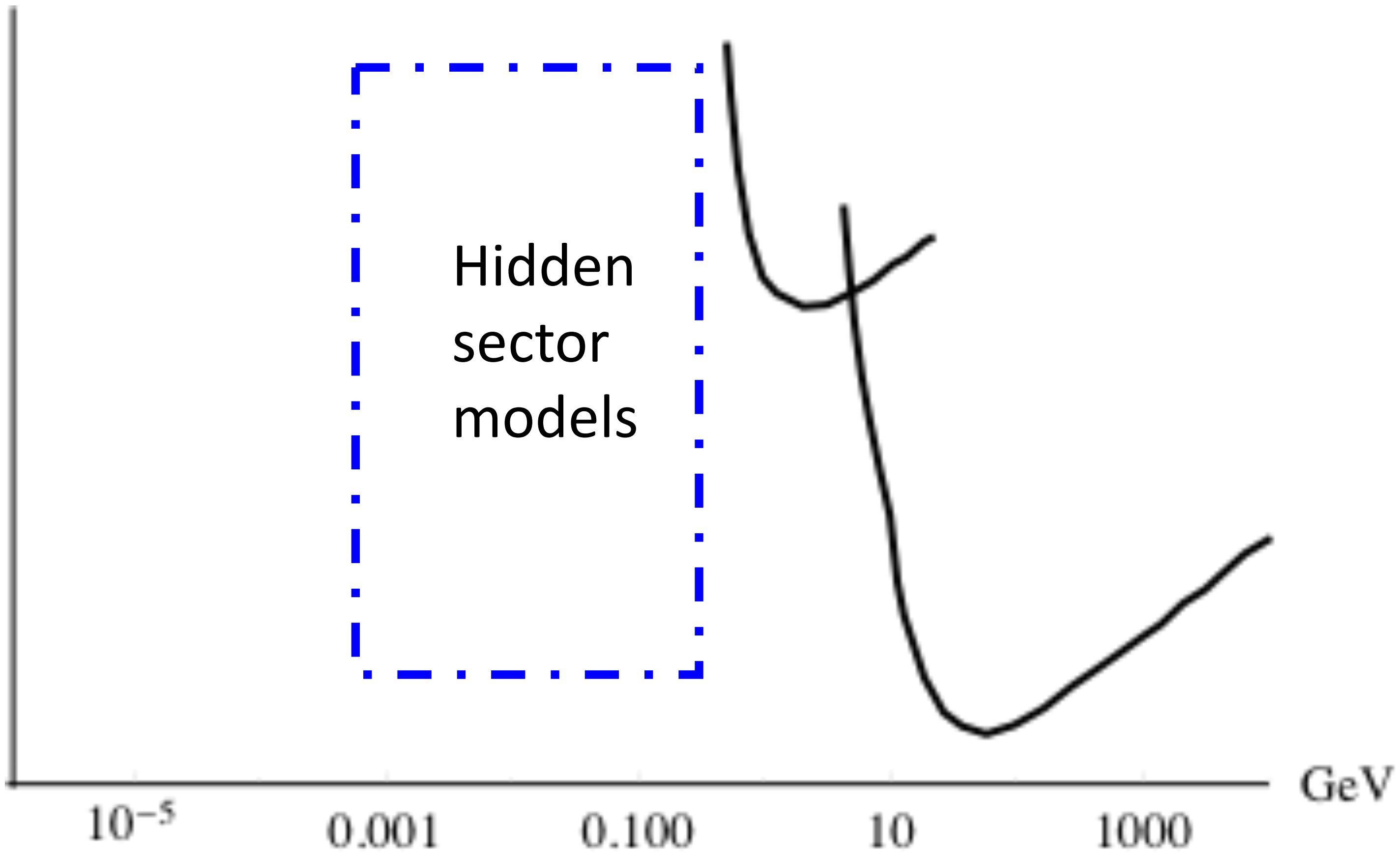


Theories of dark matter



From GeV to MeV

- What if the DM is lighter than GeV scale?

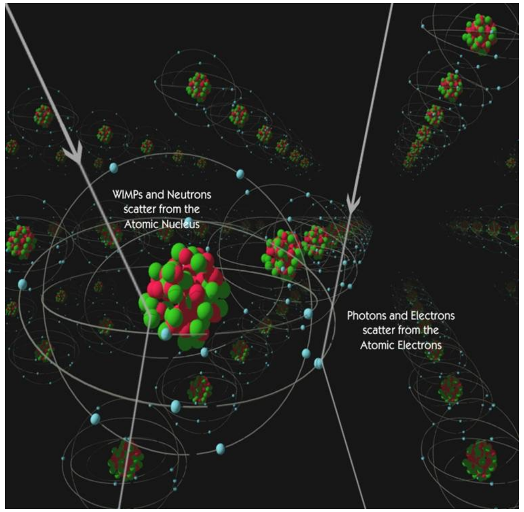


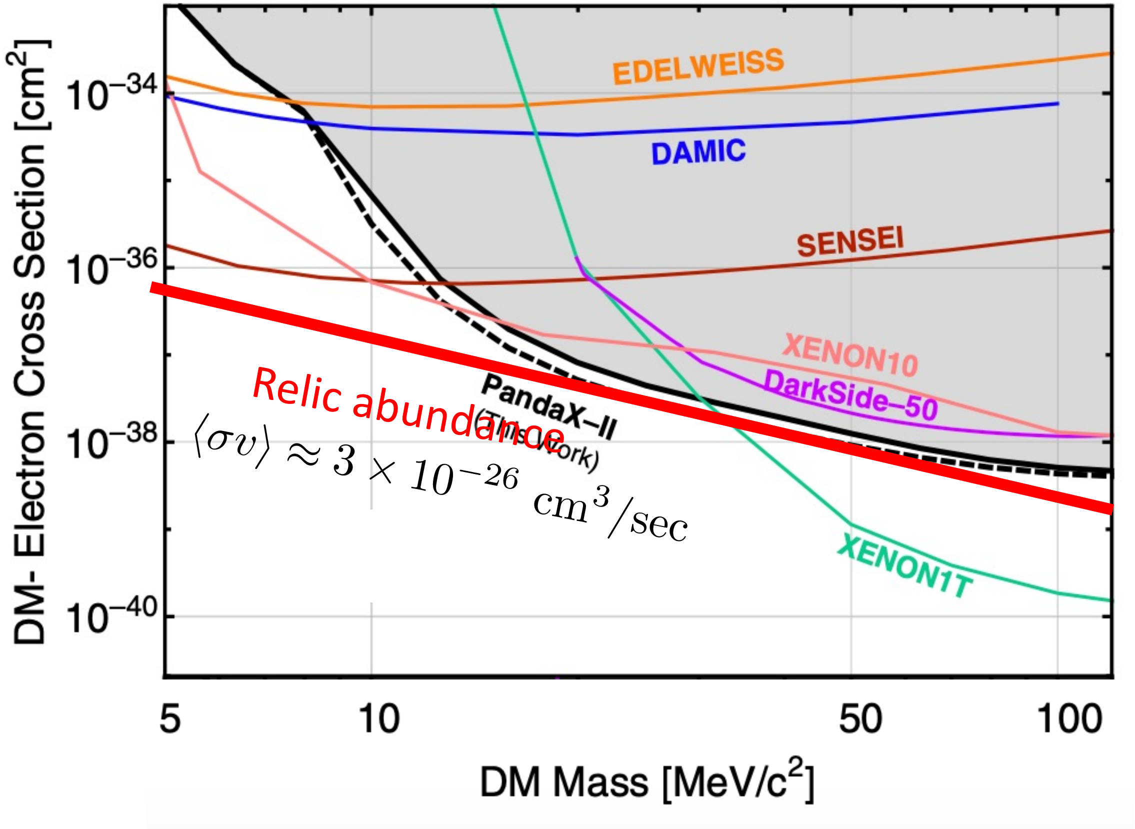
Use electron recoil for light DM

- For elastic scattering

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

Use light targets





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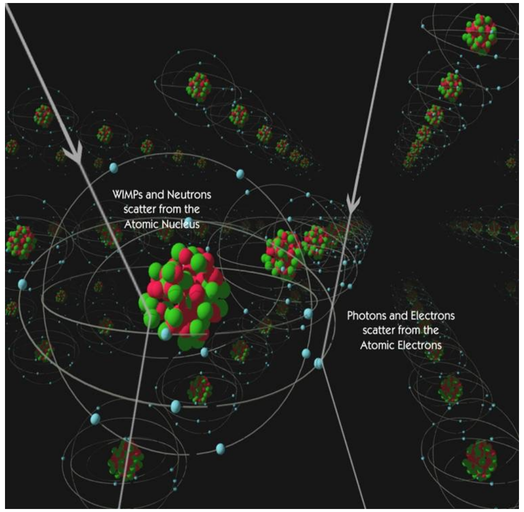
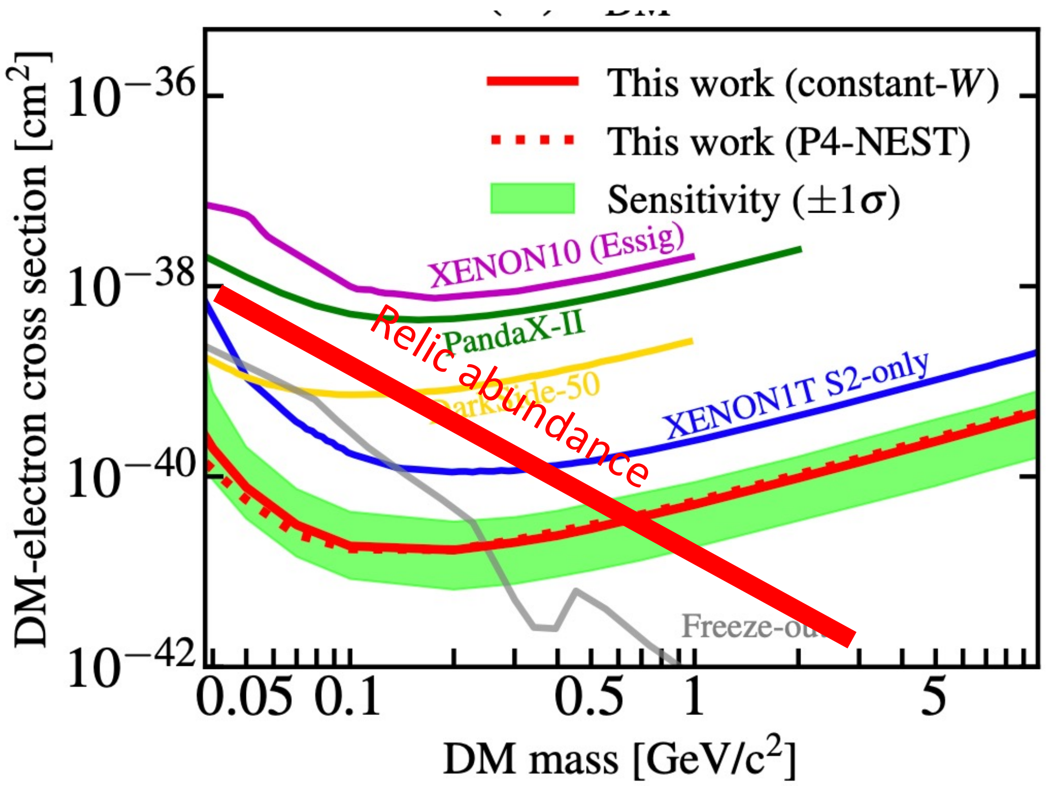




PandaX-4T, PRL 130 (2023) 261001

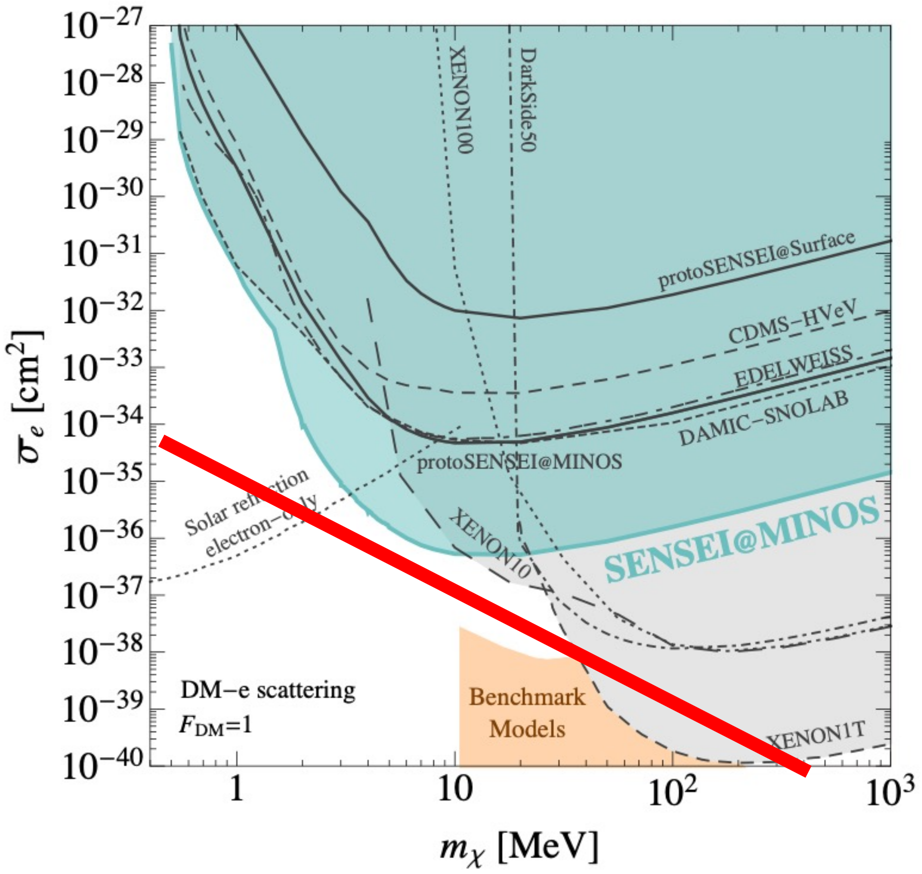
Motivations

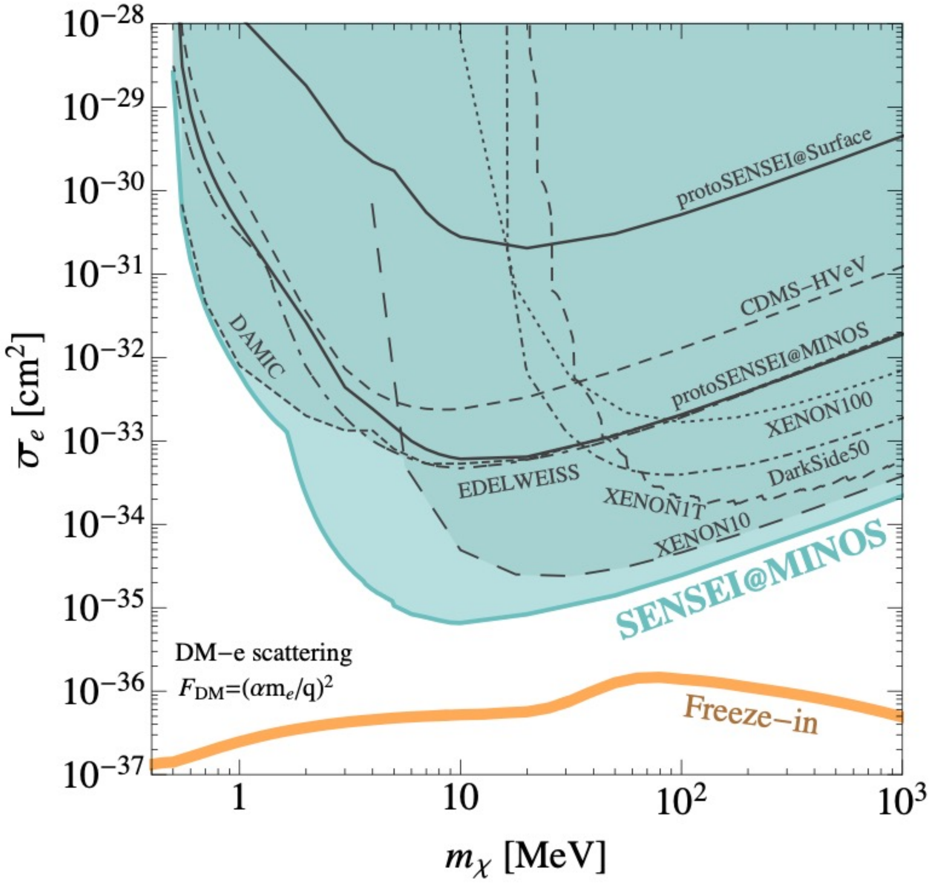
- How to search for DM if mD < 10 MeV?

  - Lower the threshold (Using semi-conductor, superconductor, or skipper CCD technology, nano tubes …)

  - Accelerate the DM particles (Sun, cosmic rays)

With skipper-CCD detector

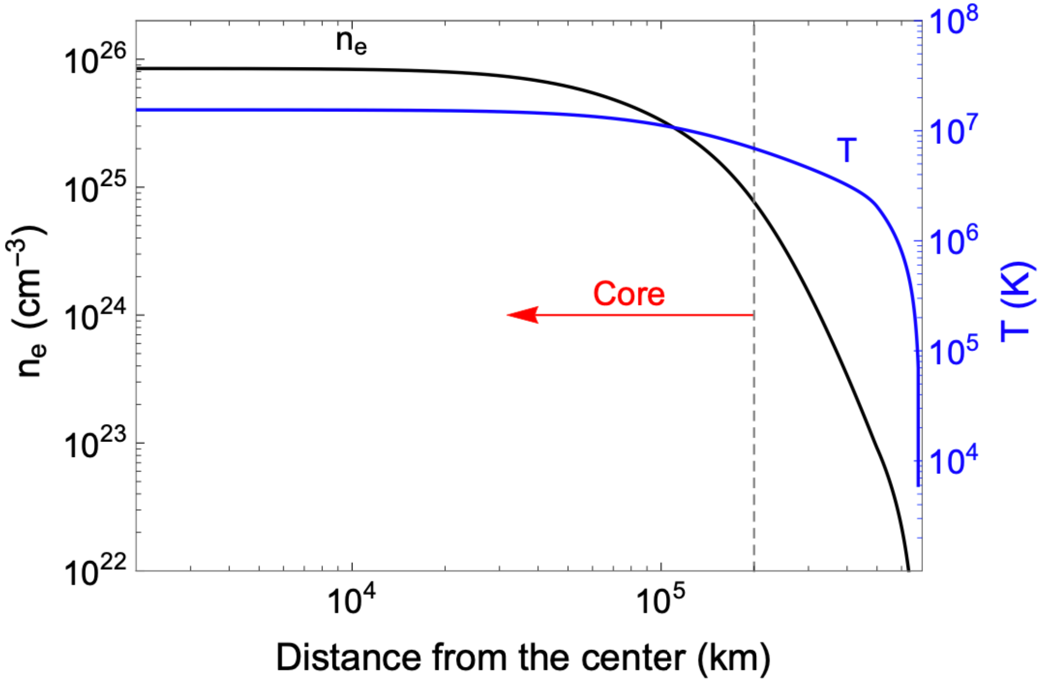


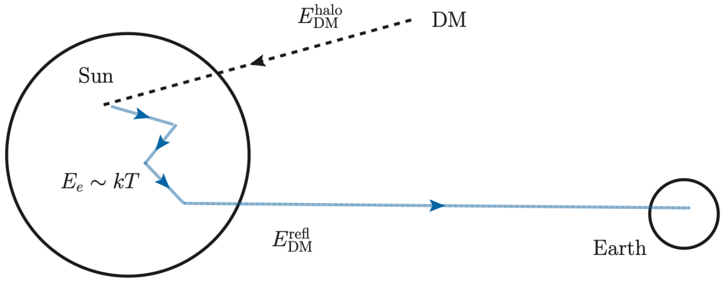


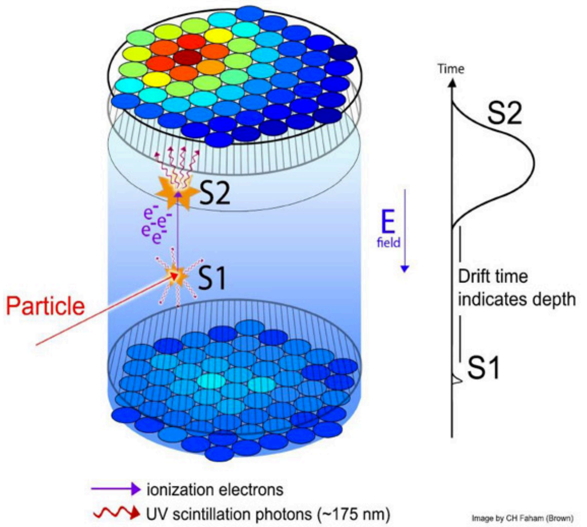
SENSEI, PRL 125 (2020) 171802

DM accelerated inside the Sun

HA, Maxim Pospelov, Josef Pradler, Phys.Rev.Lett. 120 (2018) 141801

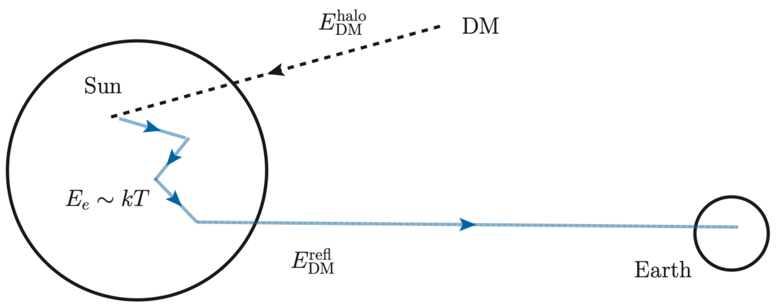






Solar accelerated DM particles

- The Sun can help us.



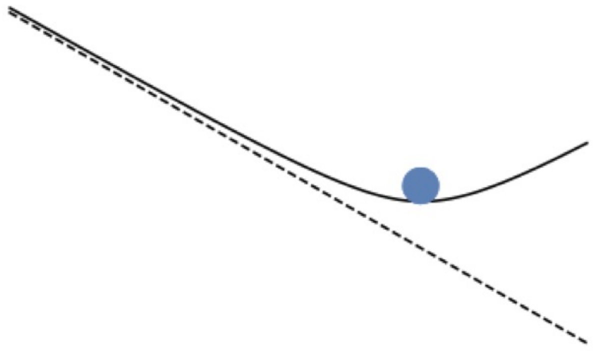
$T_{sun} \sim 1$ keV
well above the thresholds of most experiments!

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

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

Solar accelerated DM particles

- Gravitational focusing effect



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

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

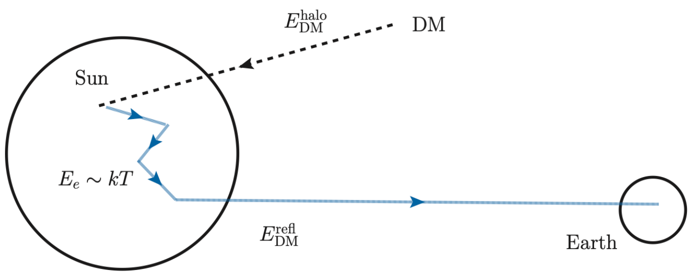
$$\Longrightarrow \frac{R_0^2}{R_\odot^2} = 1 + \frac{2G_N M_\odot}{R_\odot v_{\rm DM}^2}$$

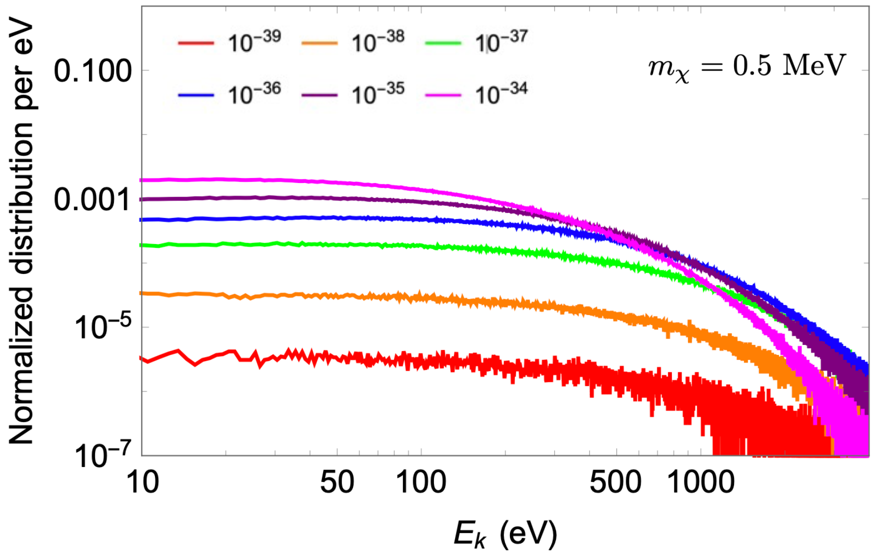
$$\frac{2G_N M_\odot}{R_\odot} = v_{\rm esc}^2 \approx (620\ {\rm km/sec})^2$$

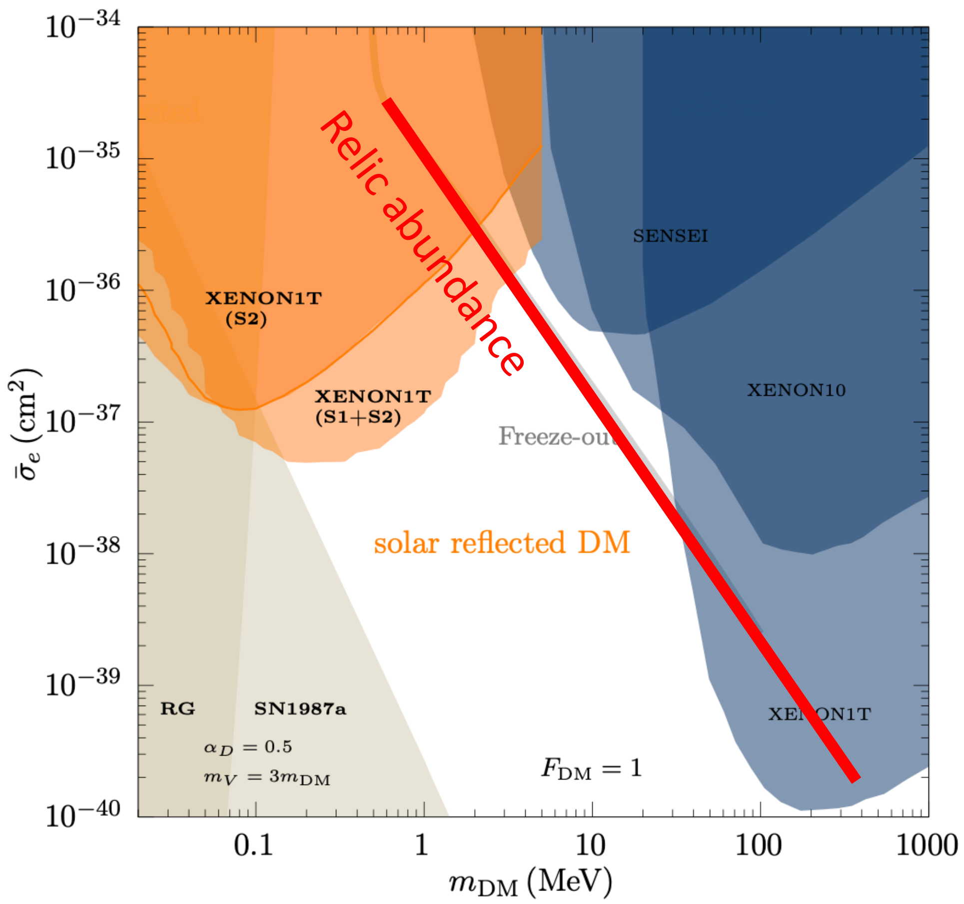
$$v_{\rm DM} \approx 220\ {\rm km/sec}$$

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

Solar Reflected DM



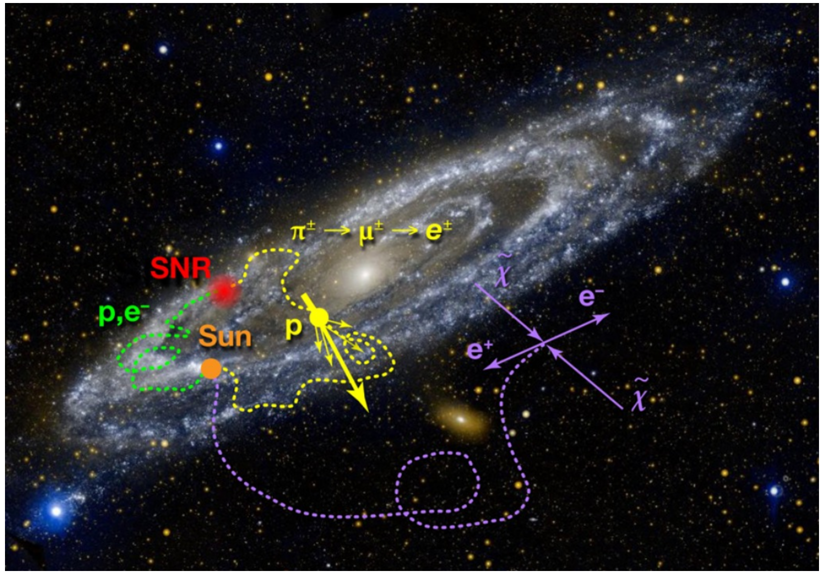


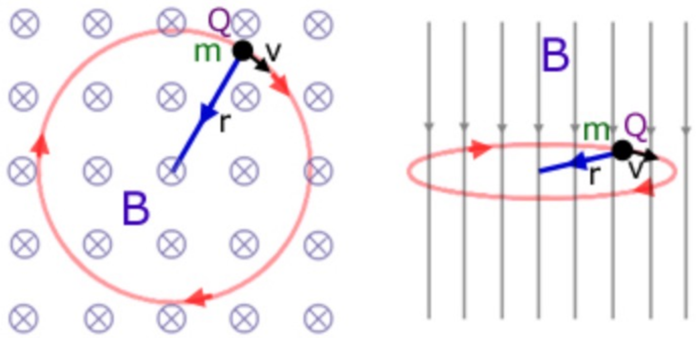


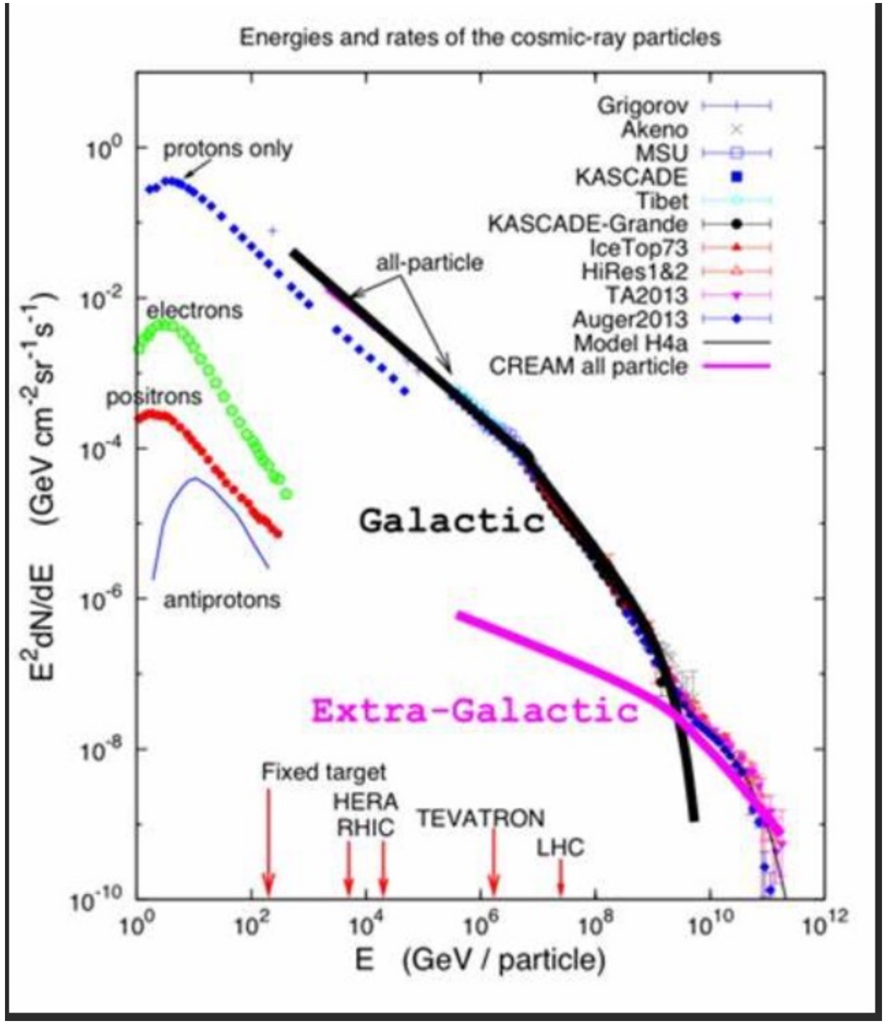
HA, Pospelov, Pradler, Ritz, PRL 120 (2018) 141801

HA, Nie, Pospelov, Pradler, Ritz, 2108.10332

Cosmic ray accelerated DM

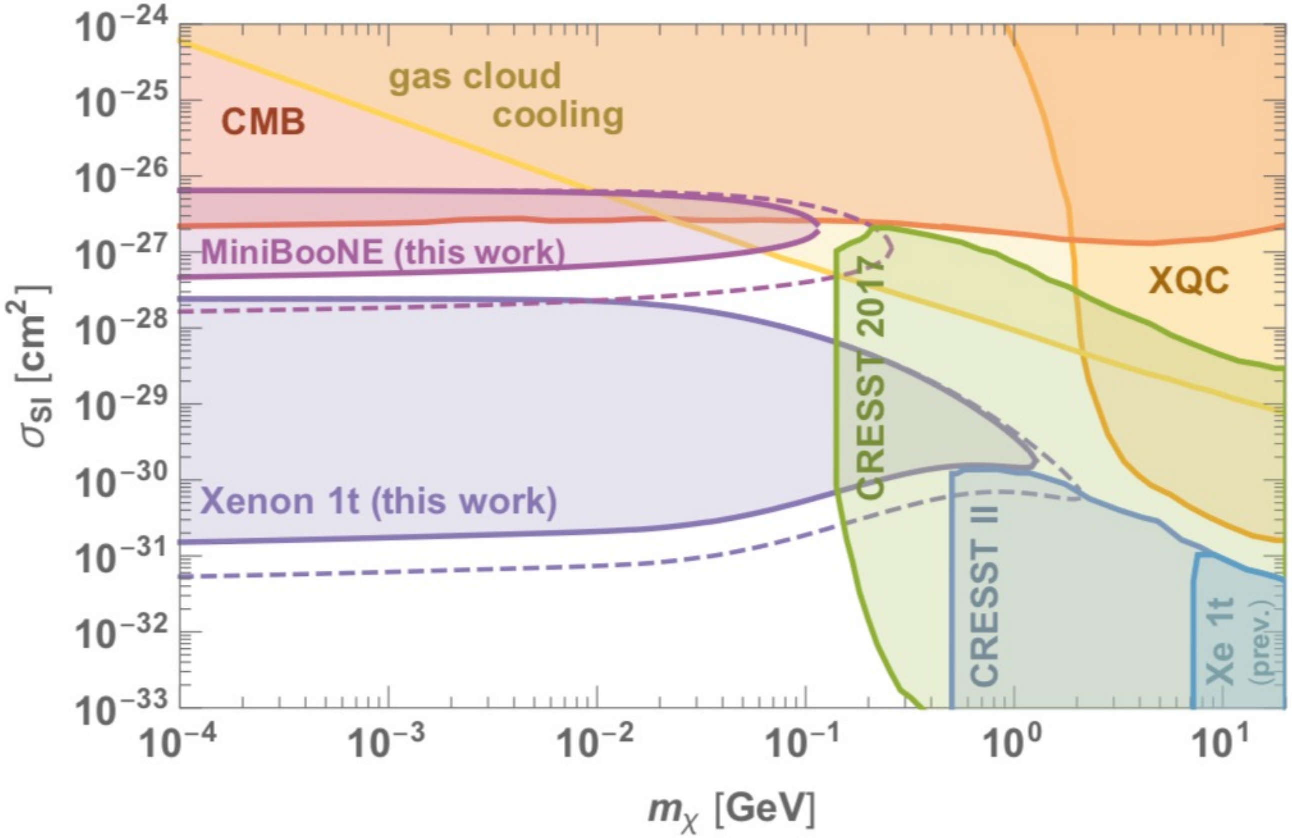




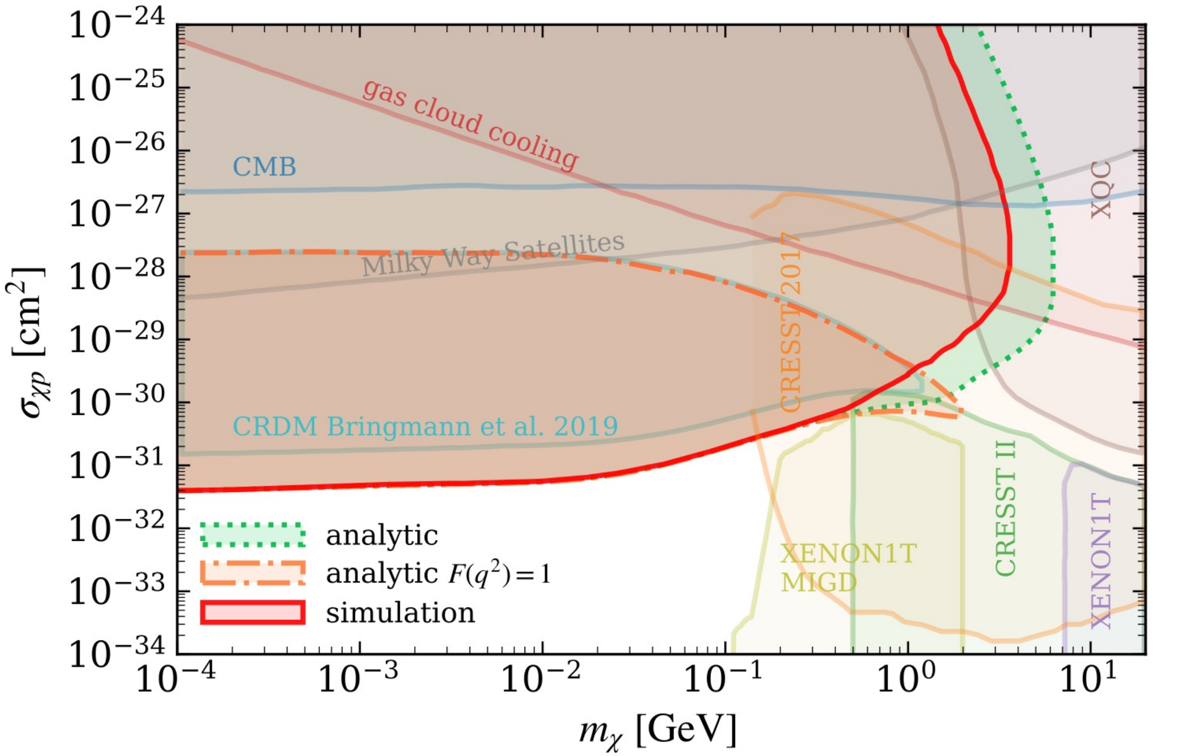


Cosmic ray accelerated DM

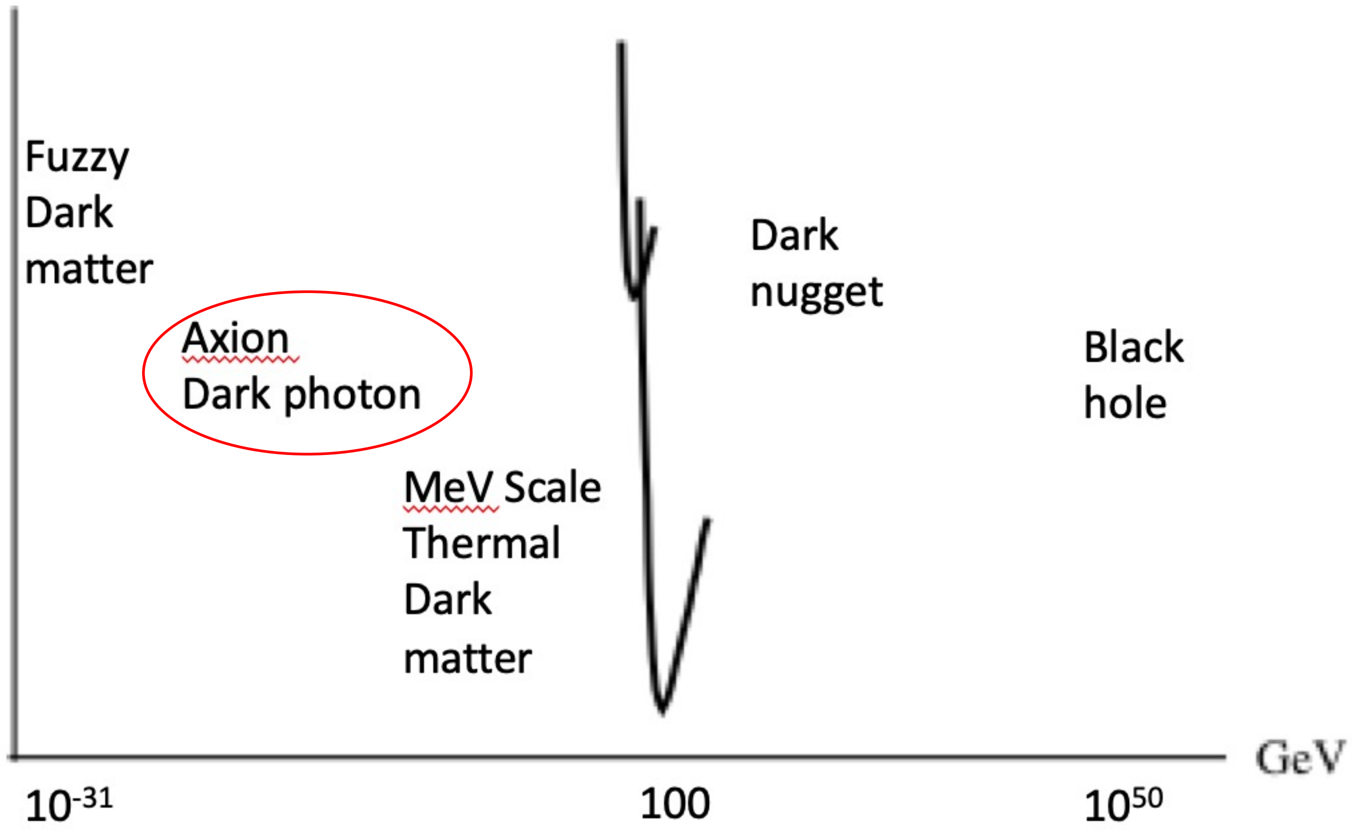
Bringman and Pospelov, PRL 122 (2019) 171801



C. Xia, Y-H Xu, Y-F Zhou, JCAP 02 (2022) 028



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)

Axion interaction with SM particles

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

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

- Primakov effect
- Axion mixing with photon
- Birefringence

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

Oscillating electric dipole moment

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

$g\ \partial_\mu a\ \bar{e}\gamma^\mu\gamma_5 e$

- Compton scattering
- Axion-electron effect

$g\ \partial_\mu a\ \bar{N}\gamma^\mu\gamma_5 N$

Axion bremstrahlung

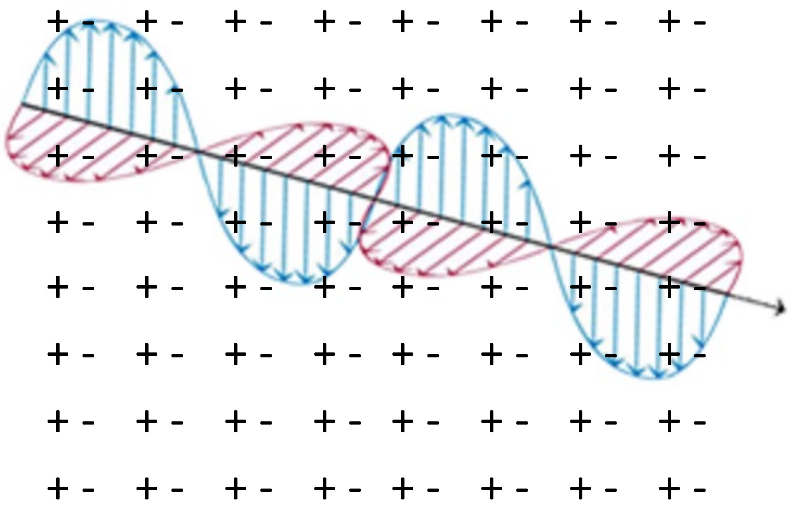
…

Photon Dark Photon Oscillation

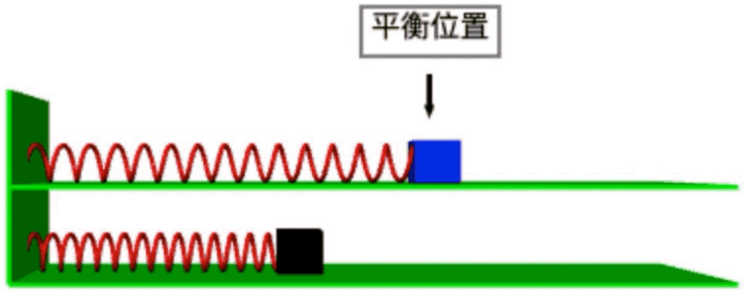
- After diagonalization:

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

- In the vacuum, V cannot be converted into A, no interaction
- In the plasma, (1) a mixing between V and A is generated. (2) a mass for A is also generated.



Photon Dark Photon Oscillation



- When $\omega_p = m_{A'}$, photon and dark photon resonantly convert into each other.

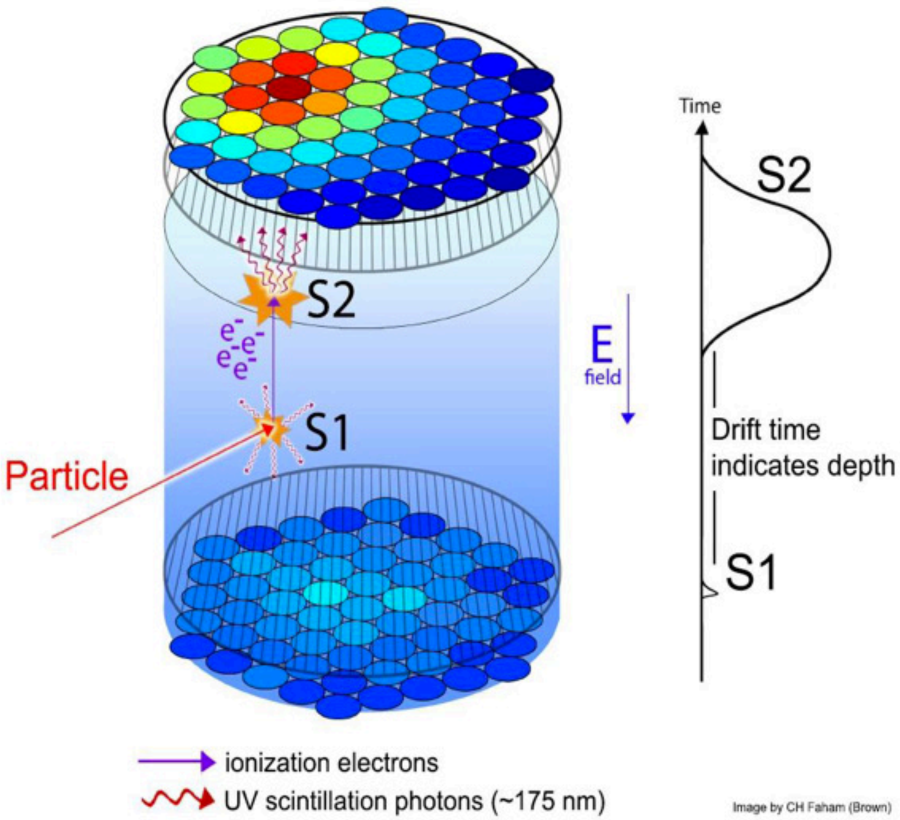
Searching for axions and dark photon with WIMP detectors

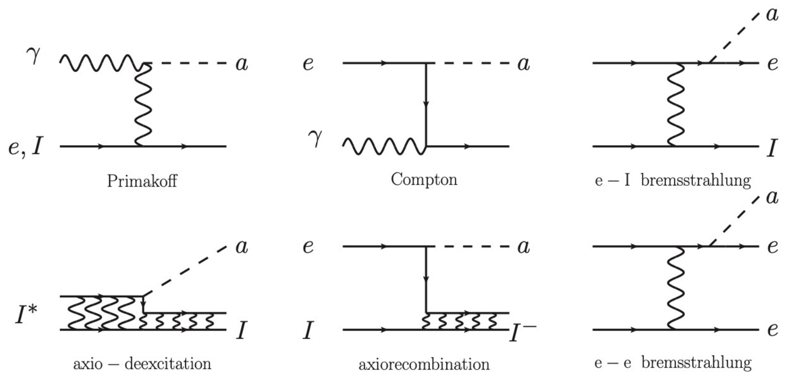
- If mass smaller than 1 keV, axions and dark photons can be produced inside the Sun, and with keV scale energy can be detected by WIMP detectors.

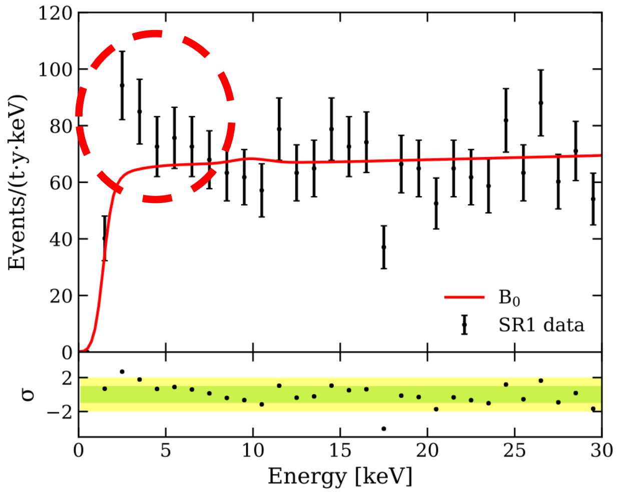
- If axions or dark photons are dark matter with mass larger than the thresholds, they can be absorbed by the detector and produce electron recoils.

Searching for axions and dark photon with WIMP detectors

- Solar axion



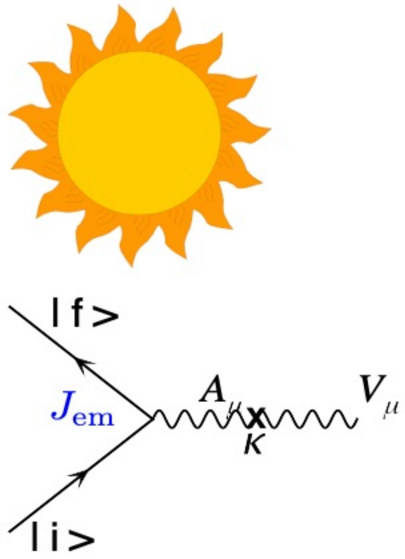


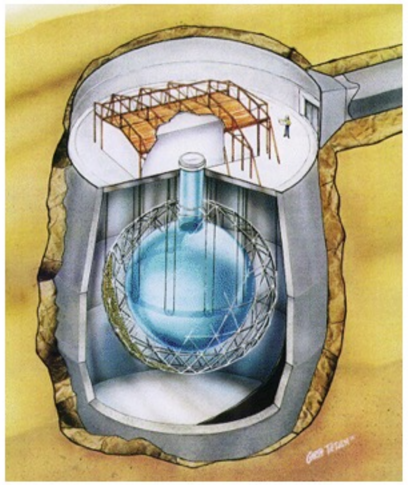


arXiv:2006.09721, XENON1T

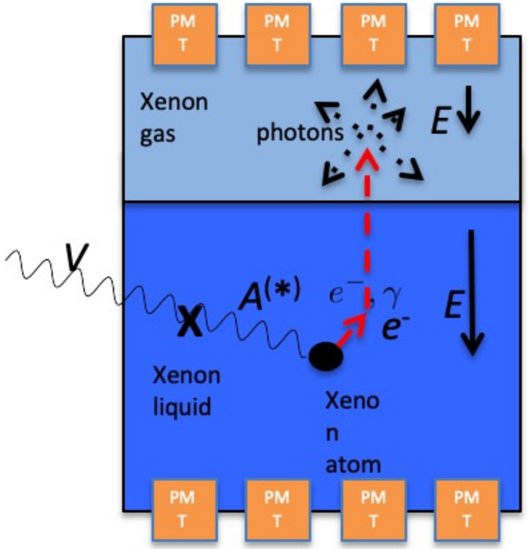
Searching for axions and dark photon with WIMP detectors

- Take dark photon as an example





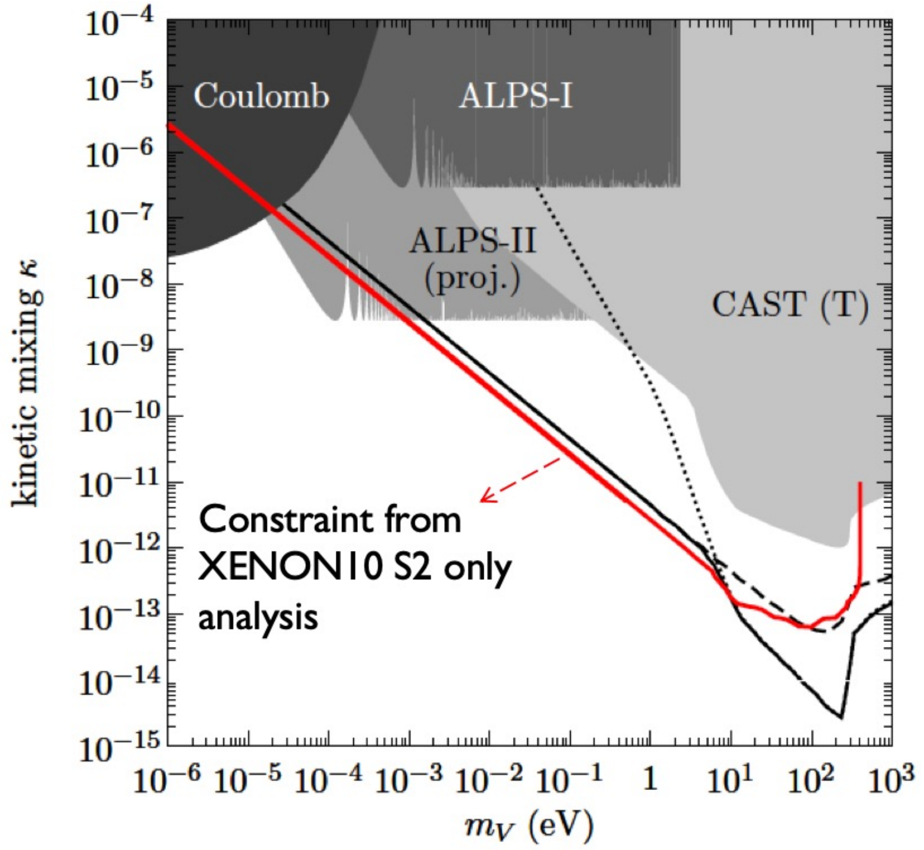
SNO experiment



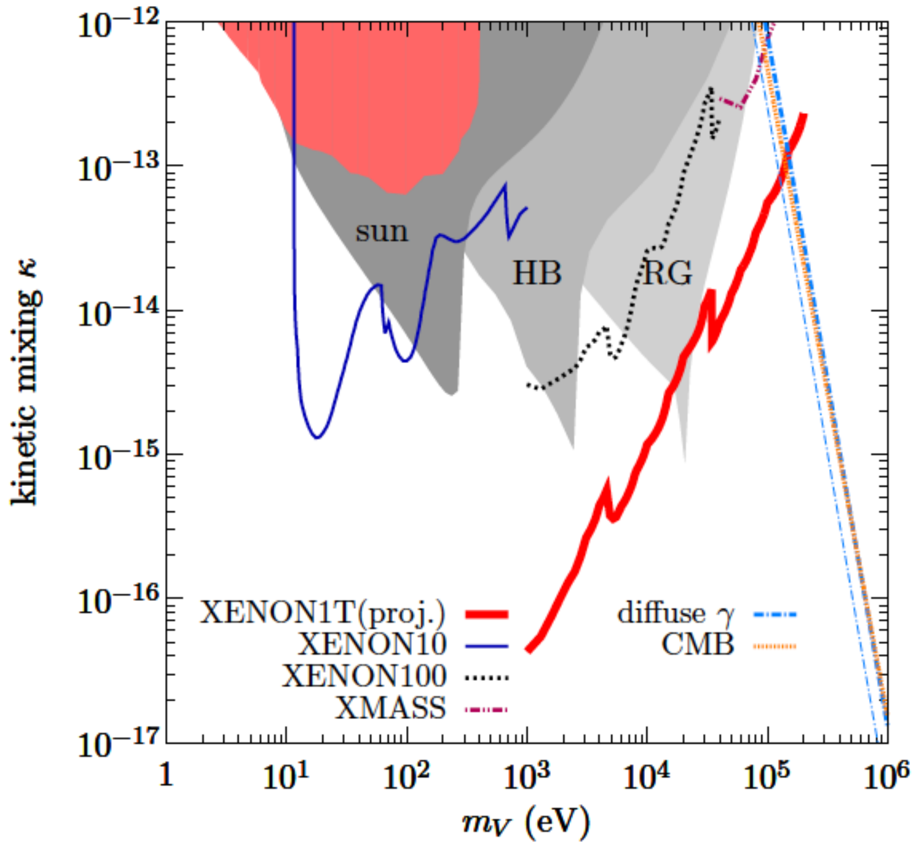
XENON experiment

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

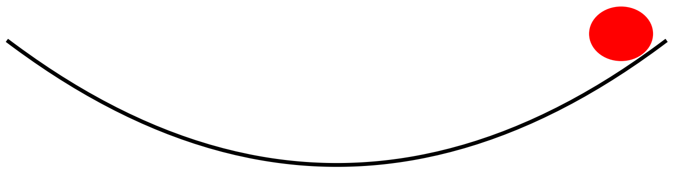


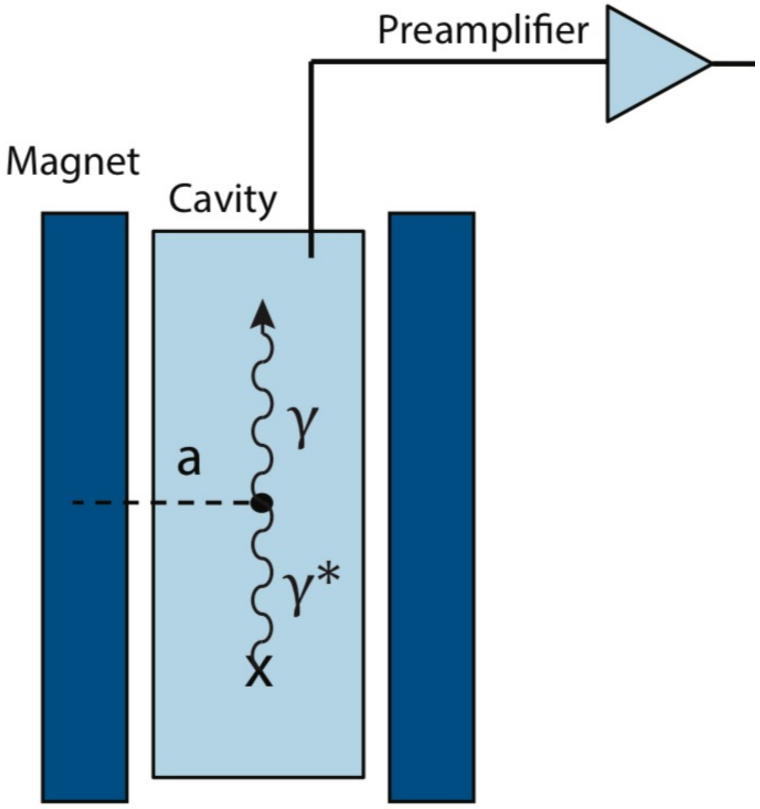
Searching for axions and dark photons with their wave-nature

- Axion coupled to electromagnetic waves

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

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

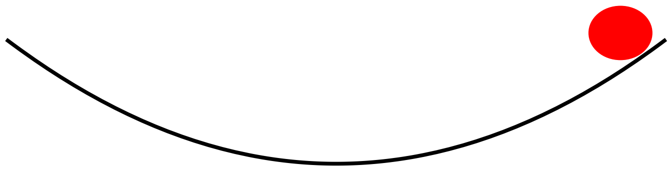




ADMX experiment

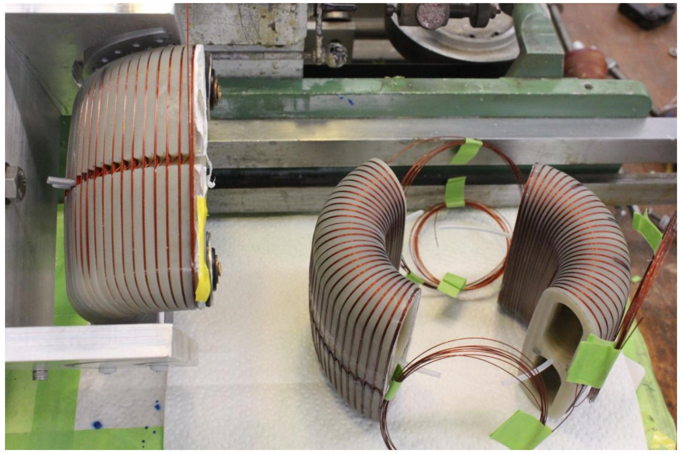
Searching for axions and dark photons with their wave-nature

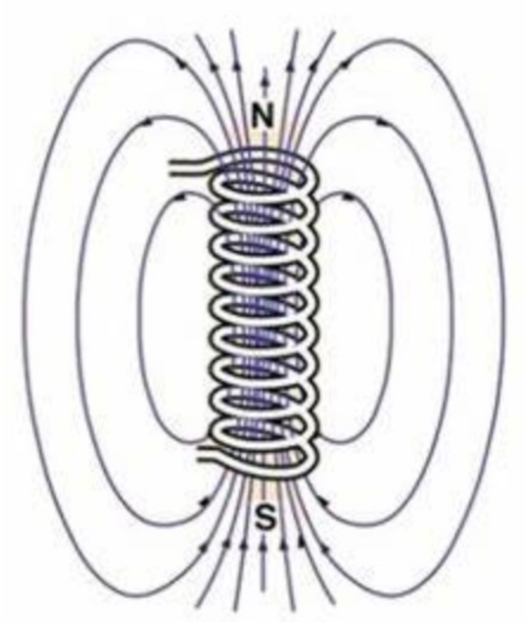
- Axion induced alternative current



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

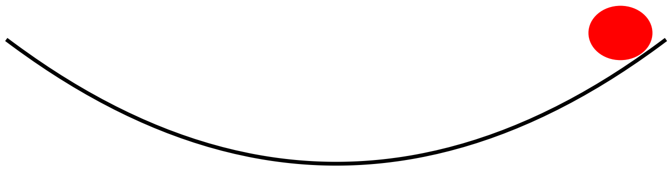
ABRACADABRA





Searching for axions and dark photons with their wave-nature

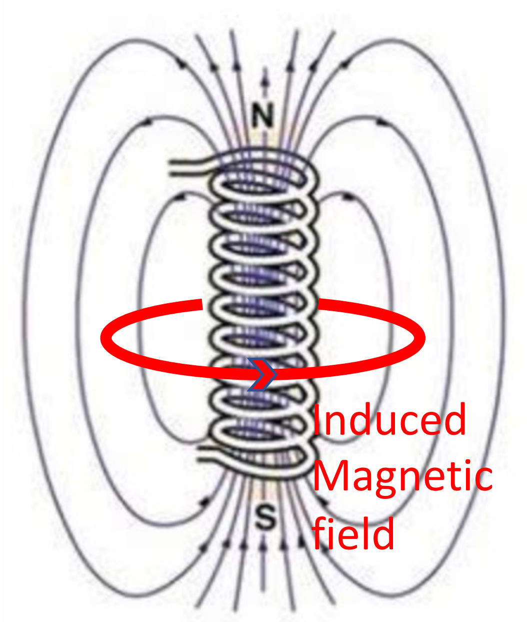
- Axion induced alternative current



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

ABRACADABRA

$$\mathbf{J}_{\rm eff} = g \dot{a}\, \mathbf{B}$$



$$\Rightarrow \quad S = \int d^4x \left(-\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\theta g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \right)$$

θ : free parameter, periodic

θ-term : total derivative.

no contribution to perturbative calculations.

– Physical consequences of θ-term.

$$F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \sim \vec{E} \cdot \vec{B}$$

$\vec{E}$ → vector, $\vec{B}$ → axial vector

pseudo scalar.

$P = -1$, $CP = -1$.

$\theta \neq 0 \Rightarrow P$, CP violation.

- Chiral anomaly:

In QCD:

$$\mathcal{L} = \sum_{q=u,d,s} \bar{q}\, i \not{D}\, q - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

$$- \sum_{q=u,d,s} m_q \bar{q} q$$

$$J_5^\mu = \sum_{q=u,d,s} \bar{q} \gamma^\mu \gamma_5 q$$

$$\partial_\mu J_5^\mu = \frac{N_f}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

$$\int [dq][d\bar{q}][dA_\mu^a]\, e^{i\int d^4x\, \mathcal{L}}$$

$$q_L \to q_L e^{i\alpha}, \quad q_R \to q_R e^{-i\alpha}$$

$$\Rightarrow \quad m\bar{q}_L q_R \to m e^{-2i\alpha} \bar{q}_L q_R$$

$$\Rightarrow \quad \theta_m \to \theta_m - 2\alpha.$$

$$\theta_m \equiv \arg(\det M_q)$$

$$[dq][d\bar{q}] \longrightarrow [dq][d\bar{q}] \exp\left\{ i \int d^4x \, \alpha \, A(x) \right\}$$

$$A(x) = -\frac{1}{16\pi^2} \varepsilon_{\mu\nu\alpha\beta} F^{a\mu\nu} F^{b\mu\nu} \, tr(t^a t^b)$$

$$= -\frac{1}{32\pi^2} \varepsilon_{\mu\nu\alpha\beta} F^{a\mu\nu} F^{a\mu\nu}$$

$$= -\frac{1}{16\pi^2} F^{a\mu\nu} \tilde{F}^{a\mu\nu}$$

$$\Rightarrow \quad \theta \longrightarrow \theta - 2\alpha$$

$$\Rightarrow \quad \theta - \theta_m \quad \text{is invariant.}$$

θ_m is trivial if $\det M_q = 0$.

Define $\theta_{tot} = \theta - \theta_m$ (physical).

θ_{tot} is a CP-violating source in SM.

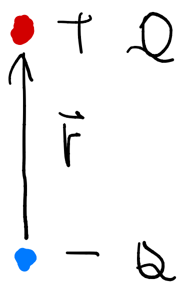
It induces CP-violating observables.

θ-term: flavor neutral.

Flavor neutral CP-violating

Observables

– Electric dipole moment



$$\vec{d}_e \equiv Q\,\vec{r}$$

In general:

$$\vec{d}_e = \int d^3\vec{x}\,\big(\delta\rho(\vec{x})\big)\,\vec{x}$$

A system with nonzero EDM should have an intrinsic vector.

For elementary particles, the only intrinsic vector is spin

$$\Rightarrow \quad \vec{d}_e \equiv d_e \frac{\vec{S}}{|S|}.$$

But: $\vec{d}_e$: $Q\vec{r}$ polar vector.

$$H = \vec{E} \cdot \vec{d}_e$$

$\vec{S}$: axial vector.

under P: $\vec{d}_e \to -\vec{d}_e$

$$\vec{S} \to \vec{S}$$

Under T: $\vec{d_e} \to \vec{d_e}$

$\vec{s} \to -\vec{s}$

$\Rightarrow$ if $d_e \neq 0 \Rightarrow \not{P}, \not{T}$.

In local QFT,

CPT theorem: CPT always conserved.

$\Rightarrow \not{T} \Rightarrow \not{CP}$.

Nonzero EDM of elementary particle

$\Rightarrow \not{P}$ and $\not{CP}$

– Neutron EDM from θ-term.

Crewther, Vecchia, Veneziano, Witten, 1979.

First rotate all the θ-angle to M_q.

$$\mathcal{H}' = m_u \bar{u} u + m_d \bar{d} d + m_s \bar{s} s$$

$$\underbrace{- i\theta_{tot} \frac{m_u m_d m_s}{m_u m_d + m_d m_s + m_s m_u} \left(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d + \bar{s}\gamma_5 s \right)}_{\delta \mathcal{L}_{CP}}$$

$$\mathcal{L}_{\pi NN} = \bar{N}\, \pi^i \sigma^i \left(i\gamma_5\, g_{\pi NN} + \bar{g}_{\pi NN} \right) N$$

CP violating

$$N = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \pi^i \sigma^i = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

pseudoscalar.

Matching:

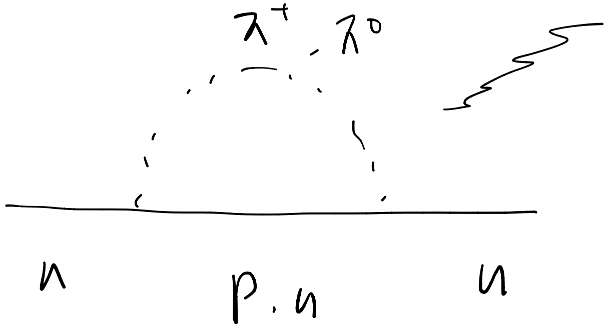
$$\bar{g}_{\pi NN} = -\frac{\theta \left(M_\Xi - M_N \right) m_u m_d}{F_\pi (m_u + m_d)(2m_s - m_u - m_d)}$$

$$\simeq 0.038\, \theta .$$

$$\vec{d}^{(N)}_e = d^{(N)}_e \frac{\vec{S}}{|S|} , \quad S = \frac{1}{2}$$

EDM operator:

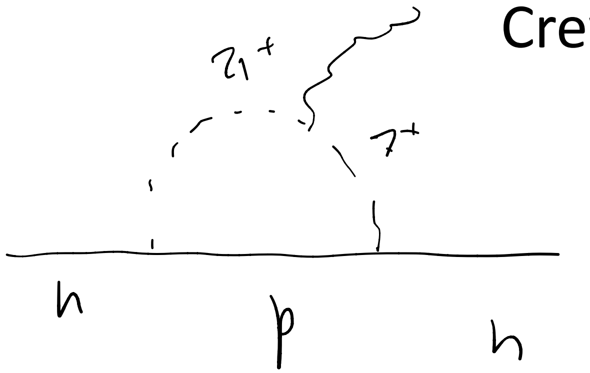
$$-\frac{1}{4} d^{(N)}_e \ \bar{n} [\gamma^\mu, \gamma^\nu] i\gamma_5 n F_{\mu\nu} .$$



Chiral loop:

Seek for chiral log enhancement.

Crewther, Vecchia, Veneziano, Witten, PLB 91 (1980) 487



$$\Rightarrow \quad d_e^{(n)} = \frac{g_{\pi NN}\bar{g}_{\pi NN}}{4\pi^2 M_N} \log\left(\frac{M_N}{m_\pi}\right)$$

$$\simeq 5.2 \times 10^{-16}\, \theta_{tot}\, (\text{cm})$$

Current constraint:

$$d_e^{(n)} < 10^{-26}\ e\,\text{cm}$$

$$\Rightarrow \quad \theta_{tot} < 10^{-10}.$$

(Strong CP problem)

How to solve the strong CP problem?

- The instanton effect in QCD gives θ a potential, up to leading order:

$$\mathcal{L} = -\frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu} + \sum_i \bar{q}_i i \not{D} q_i - m_i \bar{q}_i q_i + \frac{\theta g^2}{32\pi^2} F^{a\mu\nu} \tilde{F}^a_{\mu\nu}$$

$$V_\theta \approx \frac{\theta^2}{2} \underbrace{\lim_{q\to 0} \int d^4x e^{iq\cdot x} \left\langle T \frac{g^2}{32\pi^2} F^{a\mu\nu} F^a_{\mu\nu}(x) \frac{g^2}{32\pi^2} F^{a\mu\nu} F^a_{\mu\nu}(0) \right\rangle}$$

Nonzero due to QCD instanton effect

- θ is an angle, so the potential is periodic. $\frac{\theta^2}{2} \to 1 - \cos\theta$

Peccei-Quinn SSB

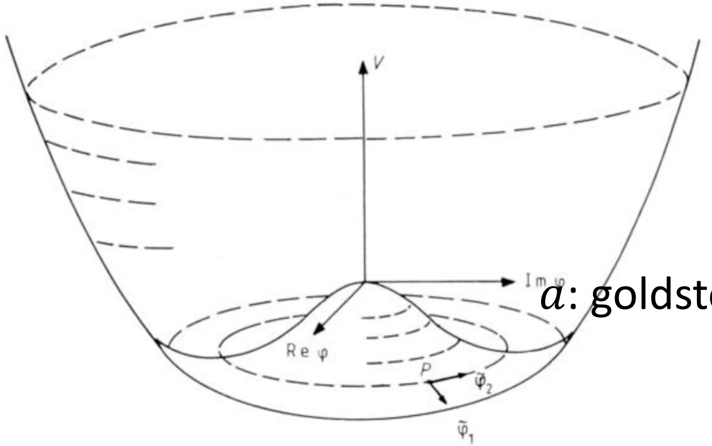
- Consider a new theory with a new quark, whose mass is from Higgs mechanism. The Yukawa interaction

$$\mathcal{L}_Y = y\bar{Q}\Phi Q$$

A new quark

Complex scalar

$$\Phi \to f\exp[ia/f]$$



a: goldstone

$$\Longrightarrow \quad m_Q = yf\exp[ia/f]$$

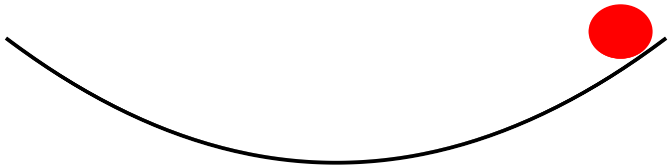
$$\Longrightarrow \quad \theta \to \theta + \frac{\alpha a}{f}$$

$$\Longrightarrow \quad V_\theta \to V\left(\theta + \frac{\alpha a}{f}\right)$$

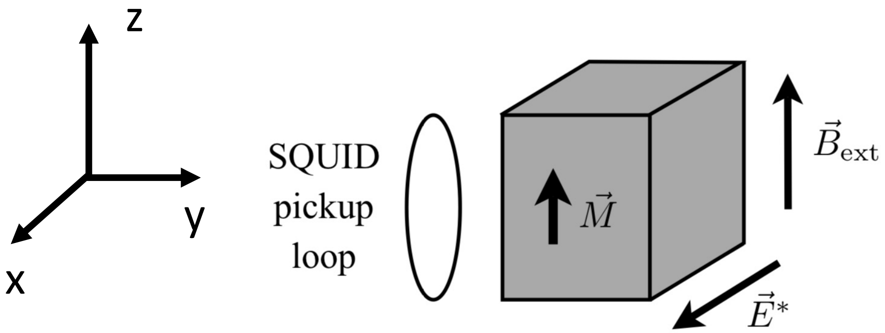
$$\Longrightarrow \quad \theta_{\rm eff} = \theta + \frac{\alpha\langle a\rangle}{f} = 0$$

Searching for axions and dark photons with their wave-nature

- Axion induced nuclear electric dipole moment



CASPEr



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

↓

Oscillating electric dipole moment

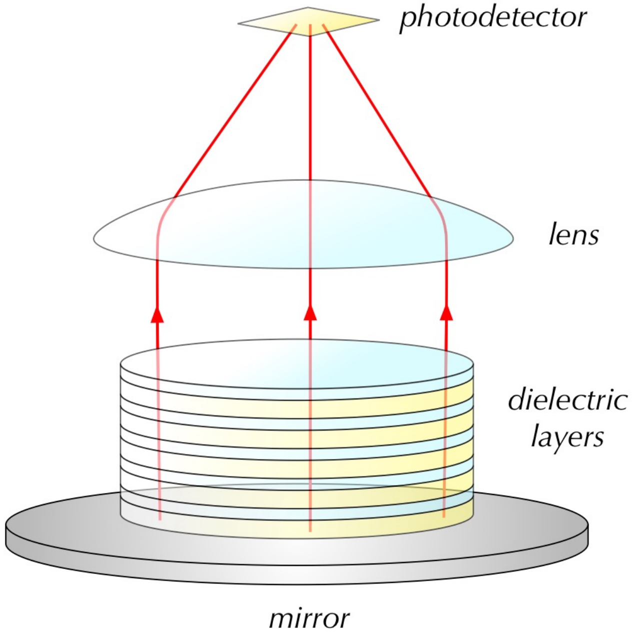
$$\mathbf{d}_{\mathrm{e}} \sim a \times \text{spin}$$

- 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

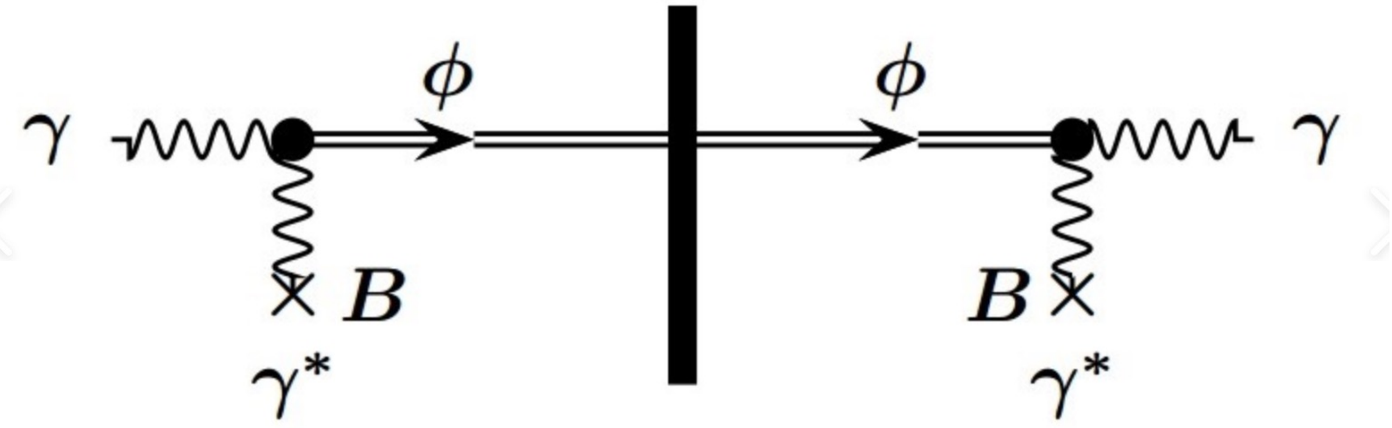
- Dark photon dark matter oscillate to on-shell photons

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

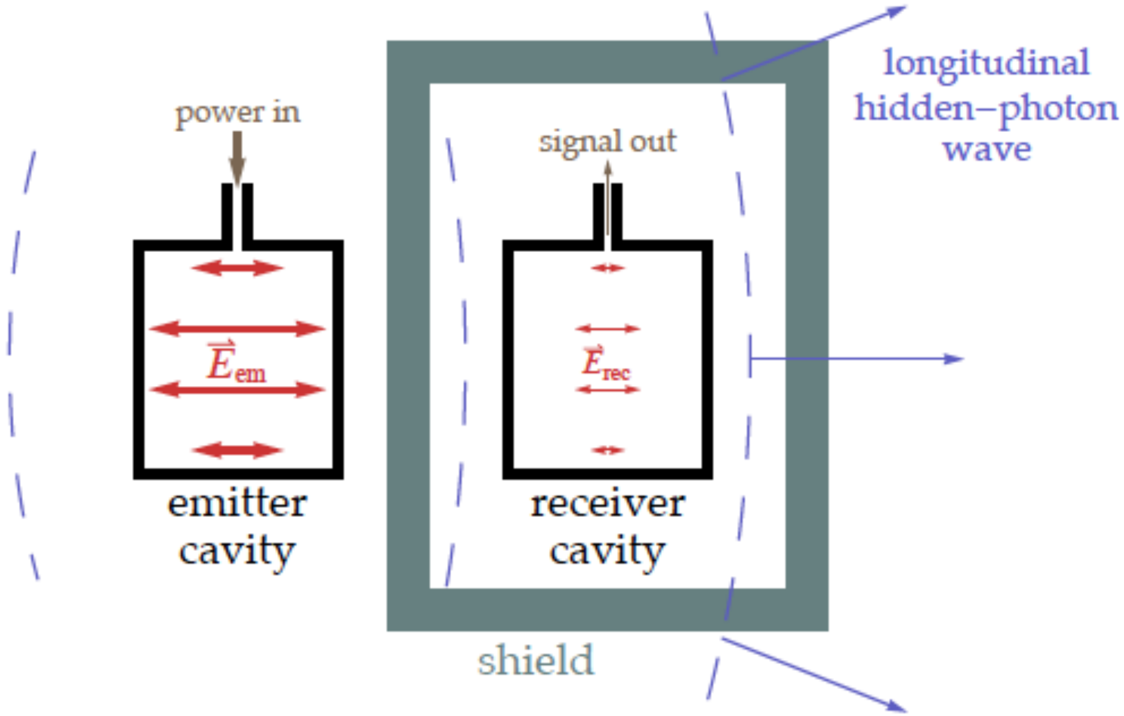


Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006

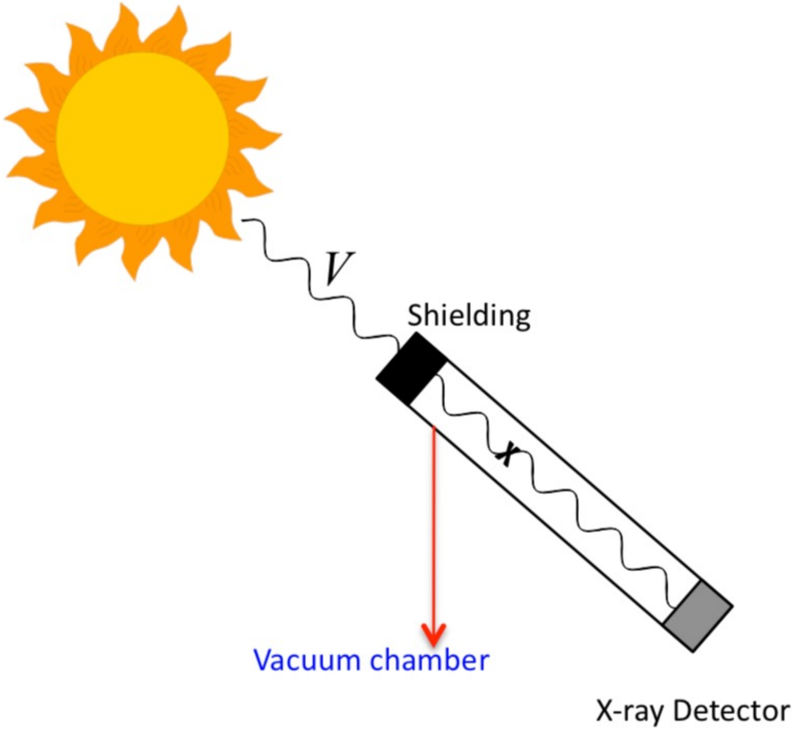
Light shining through the wall



Microwave through the wall



Helioscope



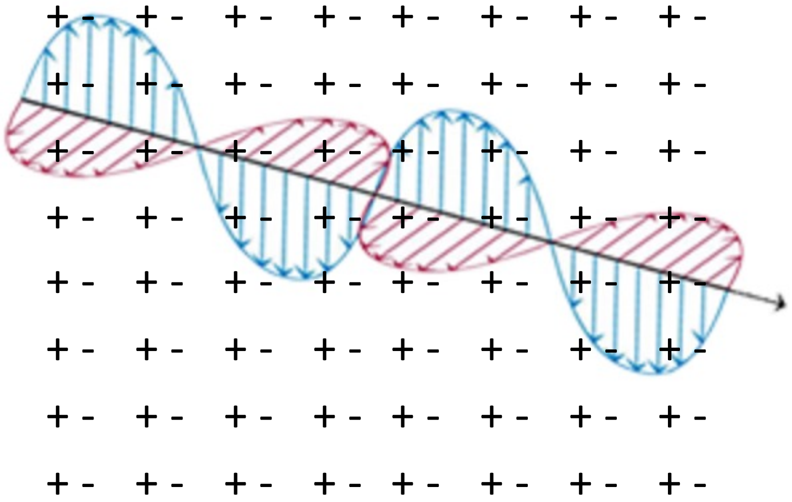
Searching for ultralight dark matter with radio telescopes

Photon Dark Photon Oscillation

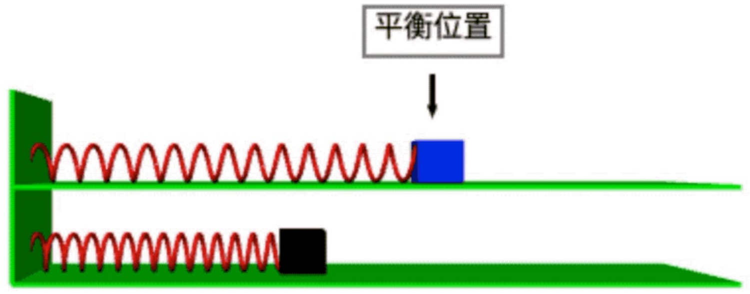
$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

V_μ and A_μ are in mass eigenstate.

- In the vacuum, V cannot be converted into A, no interaction
- In the plasma, (1) a mixing between V and A is generated. (2) a mass for A is also generated.



Photon Dark Photon Oscillation



- When $\omega_p = m_{A'}$, photon and dark photon resonantly convert into each other.

Searching for ultralight DM with radio telescopes

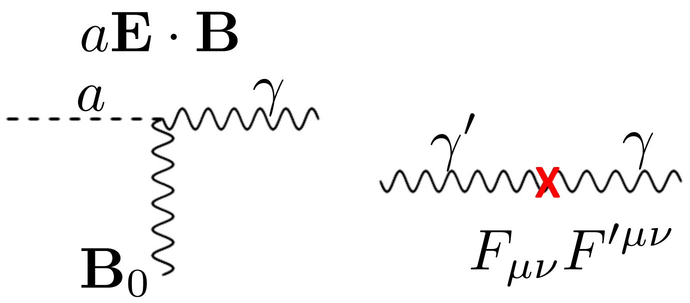
- For axion or dark photon:

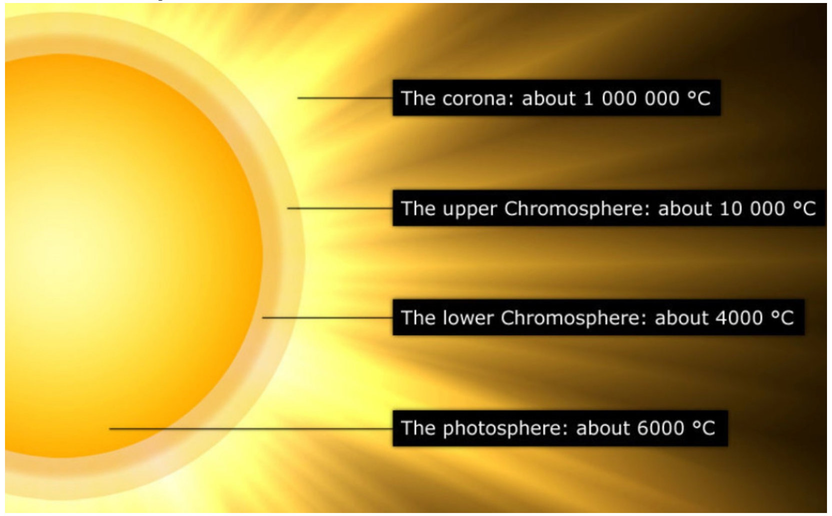
$$\omega^2 - k^2 = m^2$$

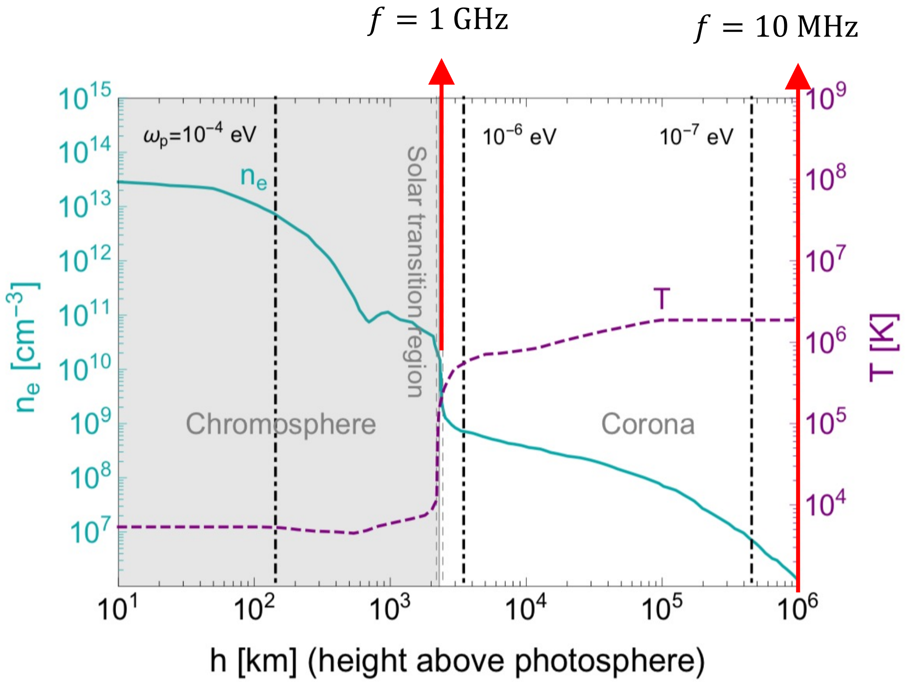
- For photon in plasma:

$$\omega^2 - k^2 = \omega_p^2$$

- For axions: plasma + magnetic field
- For dark photon: plasma

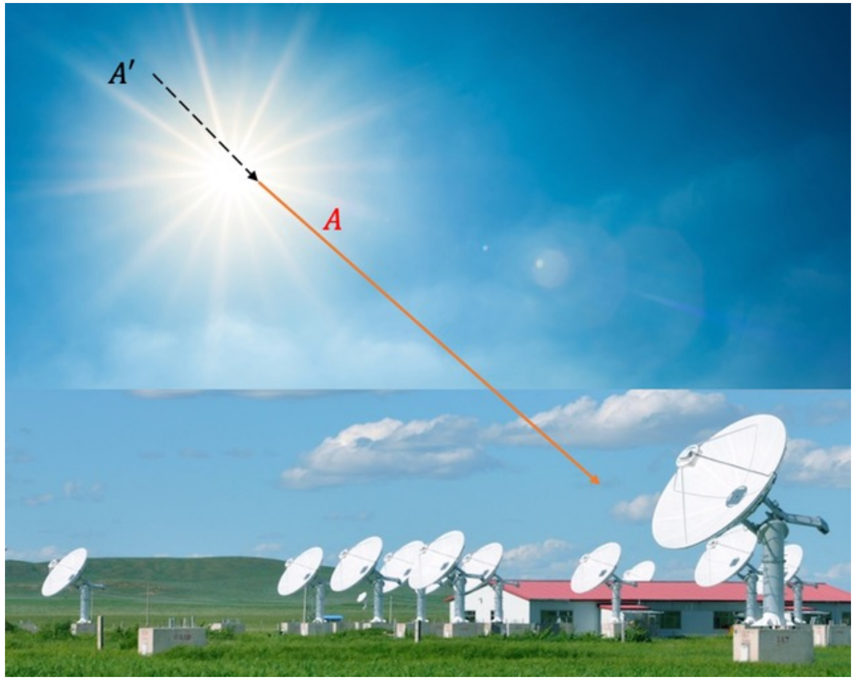






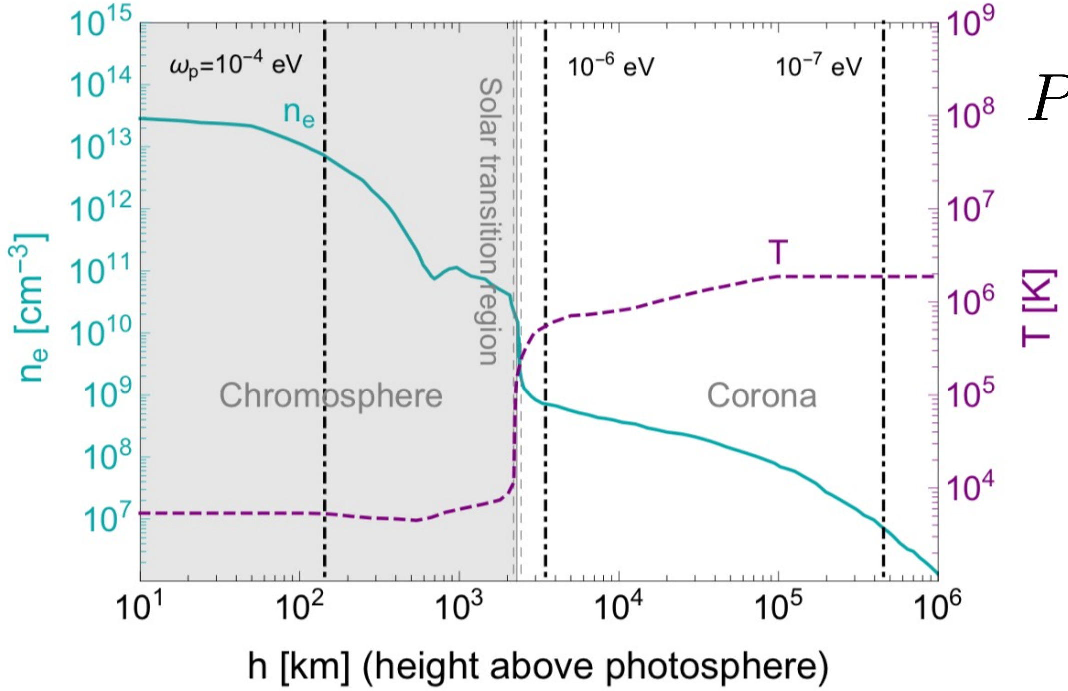
Dark photon dark matter converted at the Sun's atmosphere

- 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

- $1 \to 1$ transition



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

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

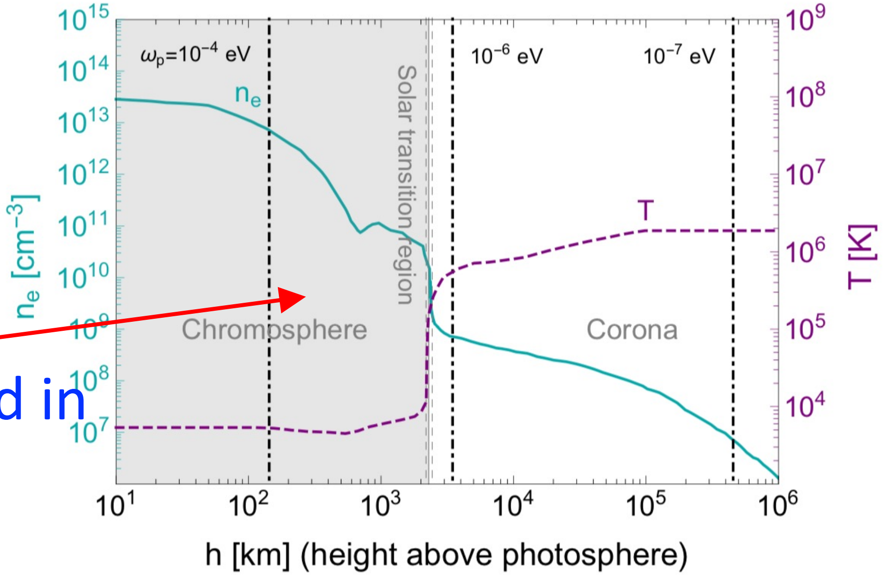
↓

Size of the resonant region $\sim r_c$

Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

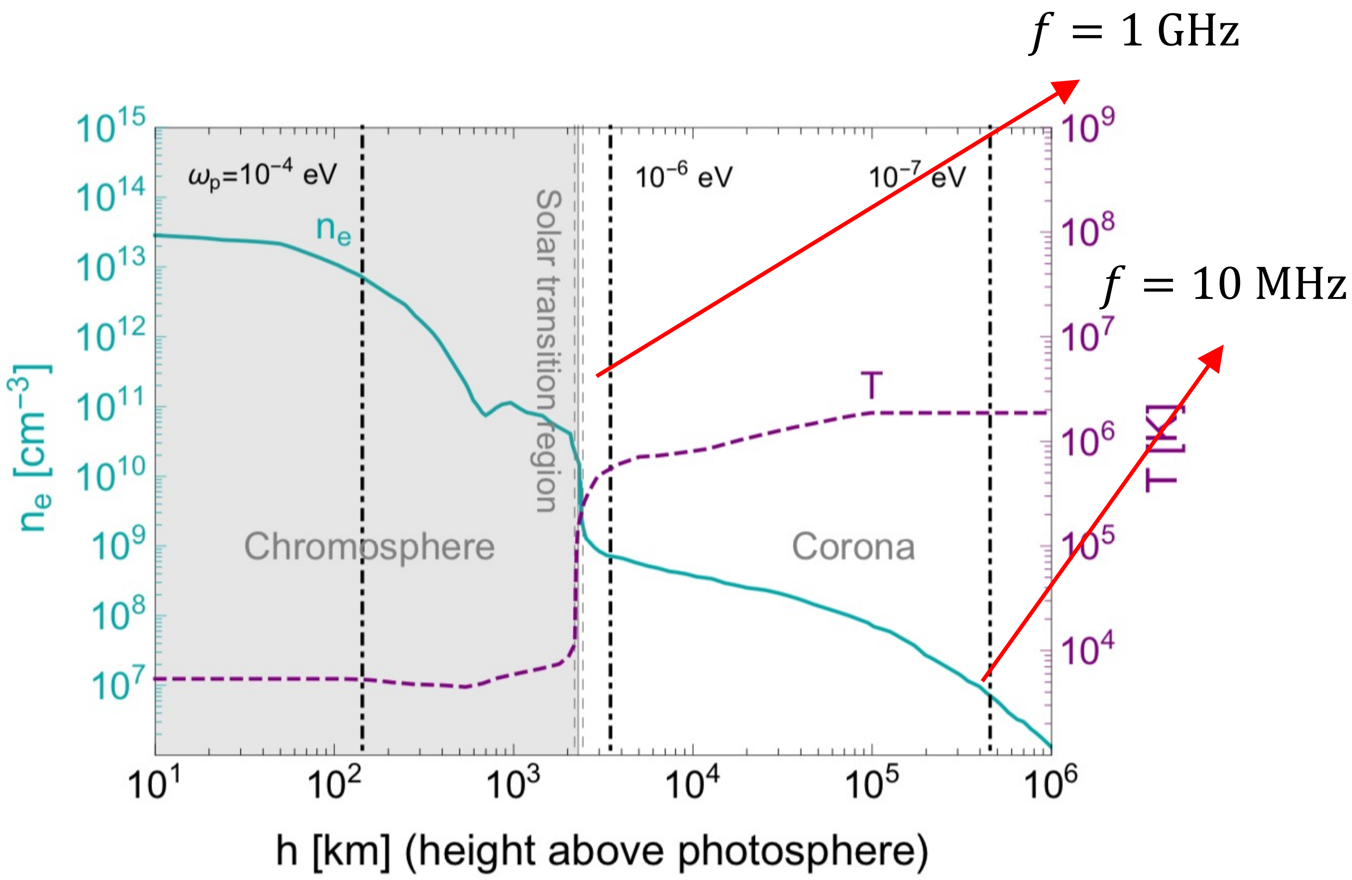
$$\Gamma_{\rm inv} \approx \frac{8\pi n_e n_N \alpha^3}{3\omega^3 m_e^2}\left(\frac{2\pi m_e}{T}\right)^{1/2} \log\left(\frac{2T^2}{\omega_p^2}\right)\left(1-e^{-\omega/T}\right)$$

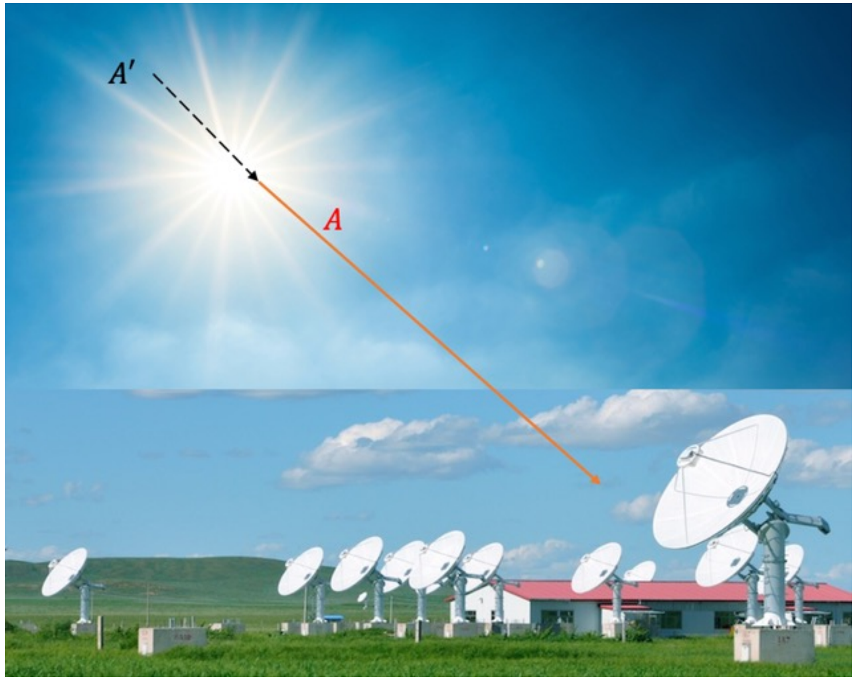


Photon converted in chromosphere cannot fly out.

- 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





Searching for the converted photon with radio telescopes

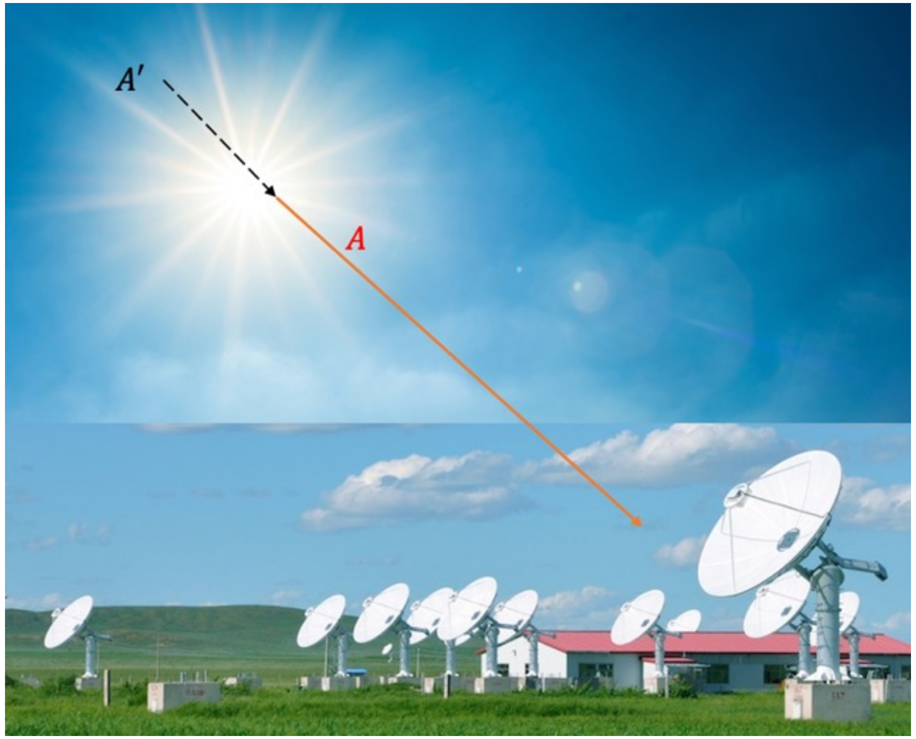
- The minimal detectable flux: $S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol} \mathcal{B} t_{\rm obs}}}$ $\quad {\rm SEFD} = 2k_B \frac{T_{\rm sys} + T_\odot}{A_{\rm eff}}$

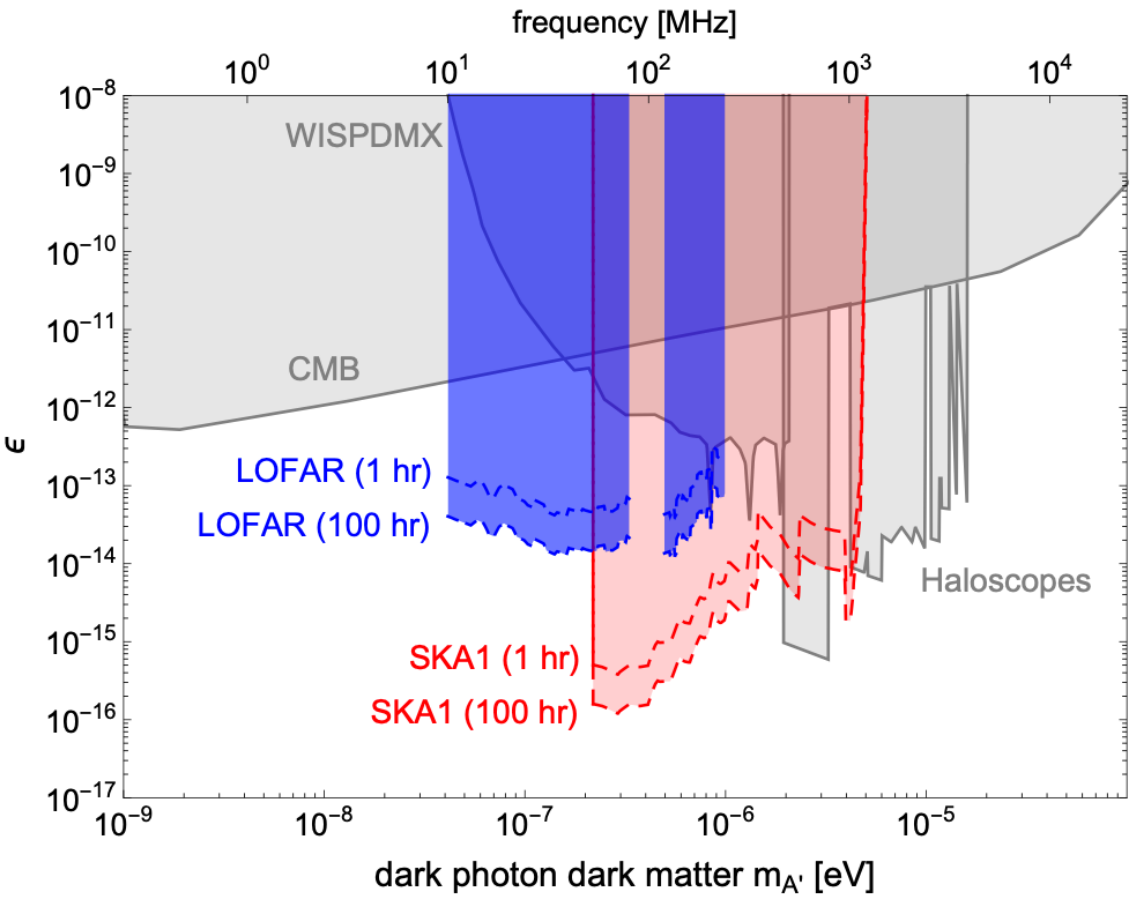
Name	f [MHz]	$B_{\rm res}$ [kHz]	$\langle T_{\rm sys} \rangle$ [K]	$\langle A_{\rm eff} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530

West Australia

Netherland

Radiofrequency Dark Photon DM

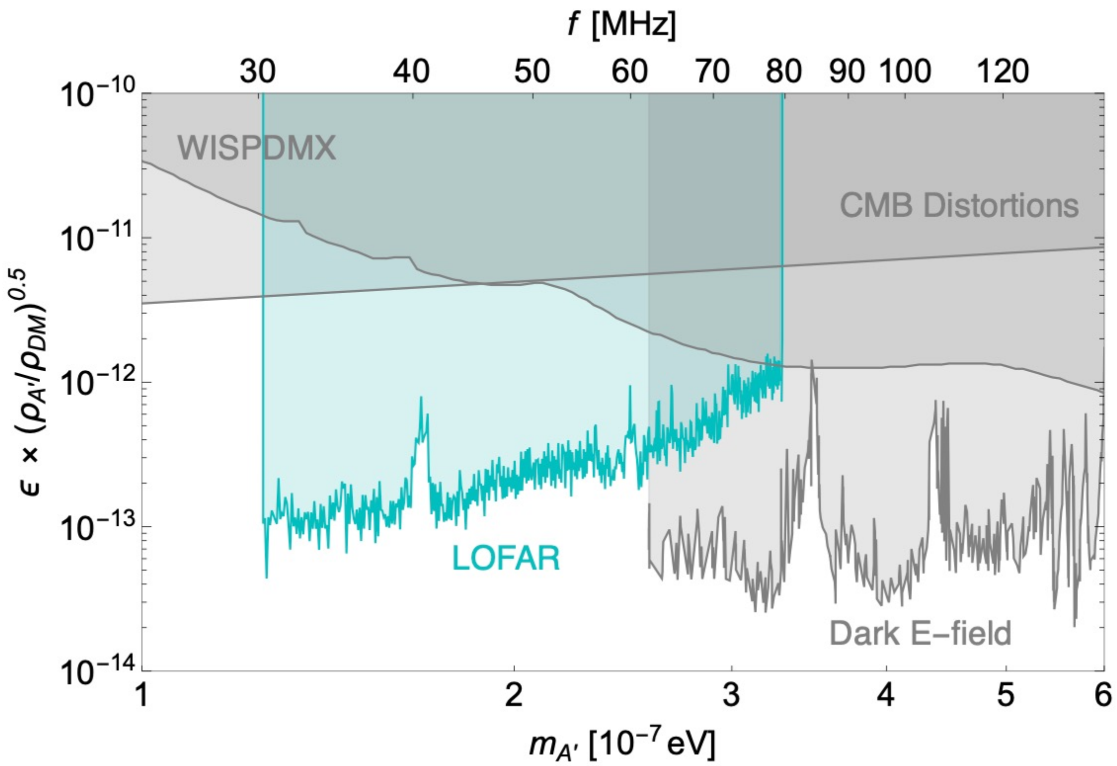




HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

Radiofrequency Dark Photon DM

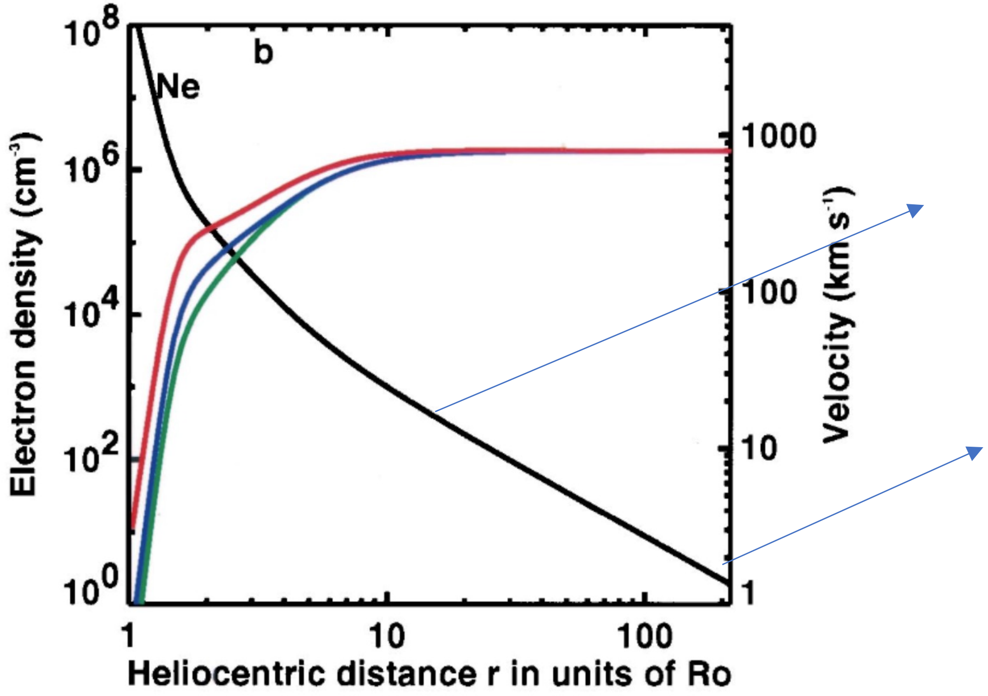
- Searching for DPDM in LOFAR data



HA, X. Chen, S. Ge, J. Liu, Y. Luo, 2301.03622

For dark photon dark matter with even smaller mass

- No terrestrial telescopes can cover $f < 10\ \mathrm{MHz}$.
- Go to outer space.
- Free electrons between Earth and Sun

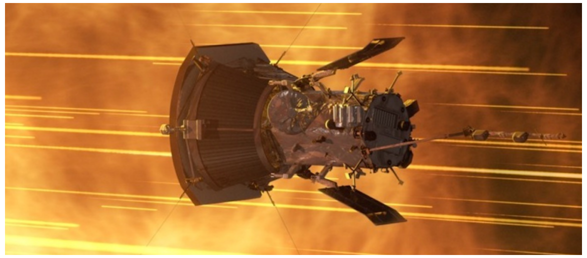


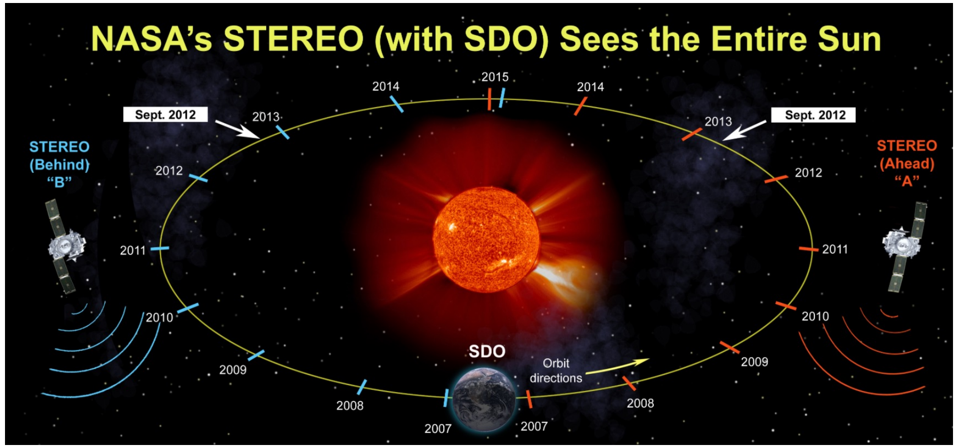
$$\frac{\omega_p}{2\pi} = 1\ \mathrm{MHz}$$

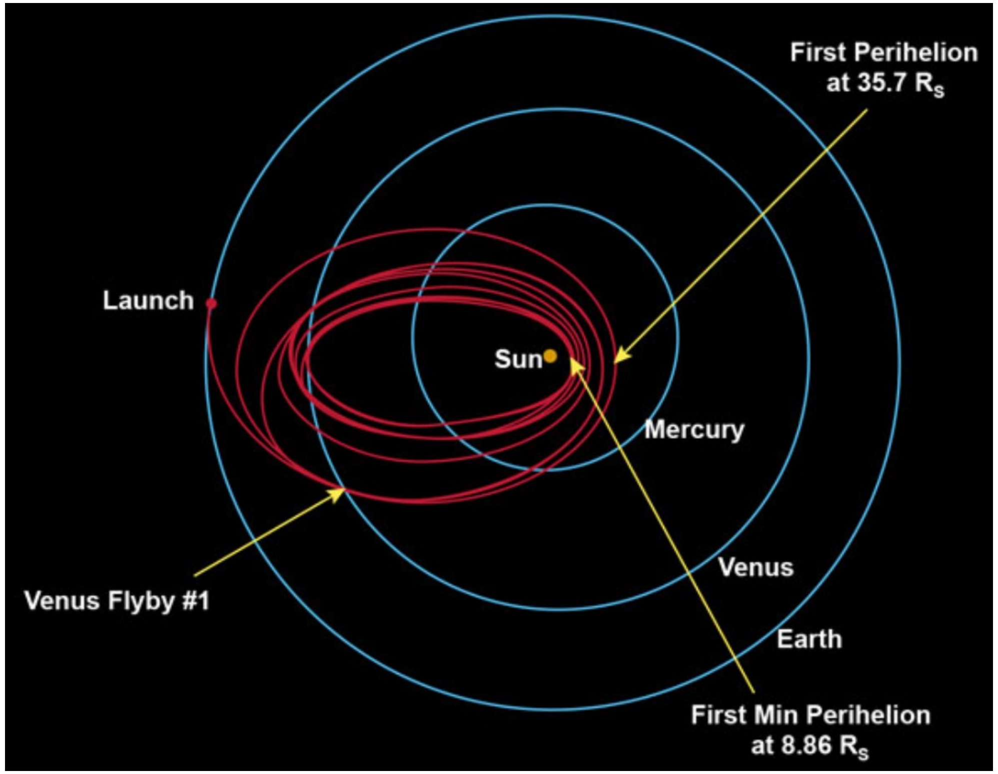
$$\frac{\omega_p}{2\pi} = 20\ \mathrm{kHz}$$

For dark photon dark matter with even smaller mass

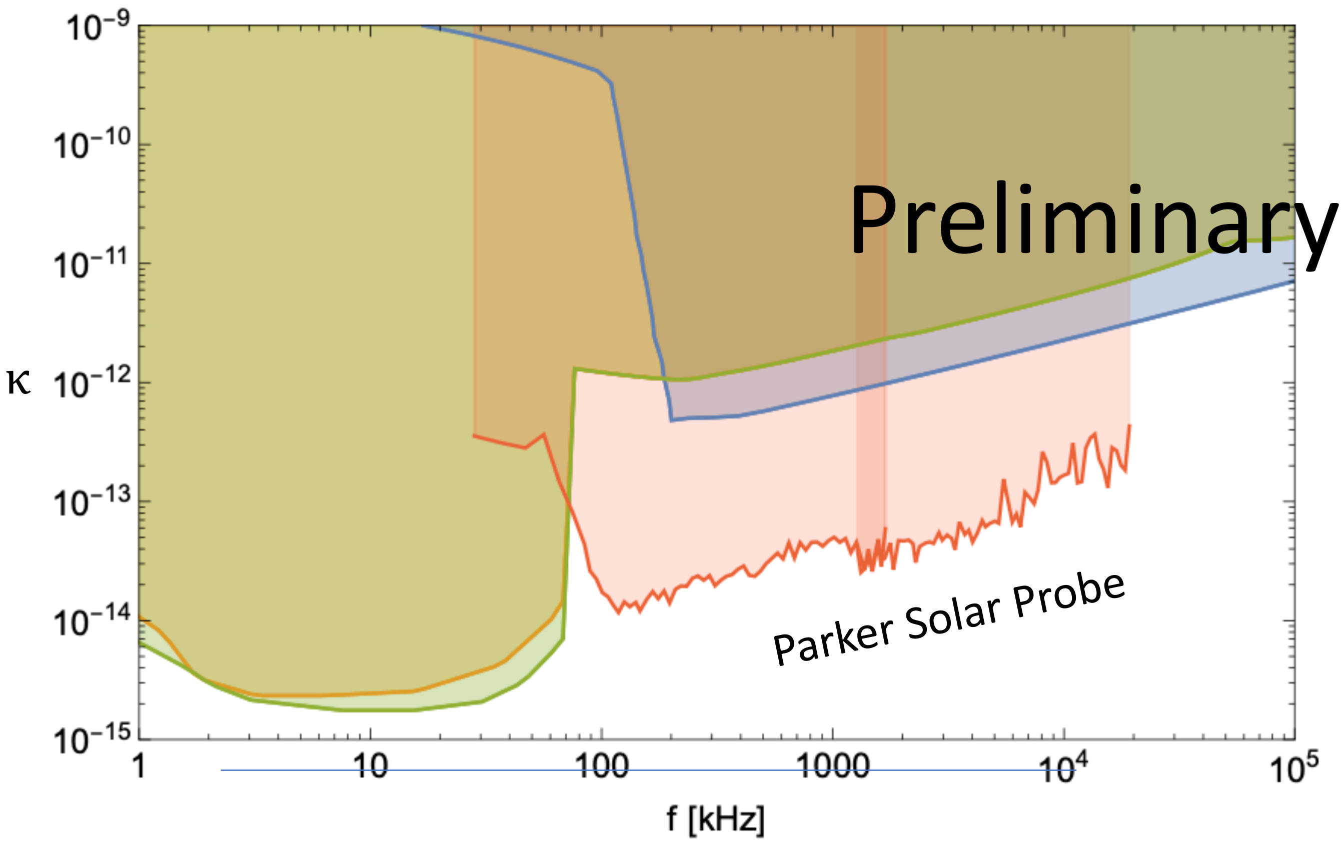
- STEREO A/B
- Parker Solar Probe







Using solar probes to search for DPDM



__HA__, Shuailiang Ge, Jia Liu and Zheming Liu, work in progress

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

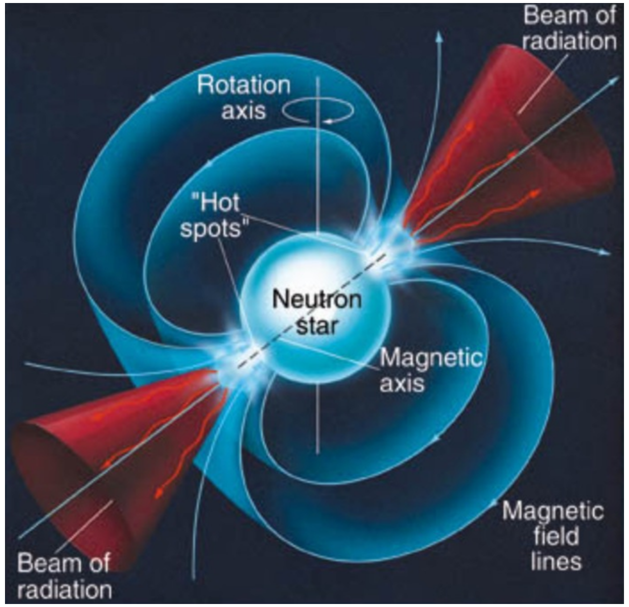
$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{B_0} a \mathbf{E}$$

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

Ultralight axions dark matter

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

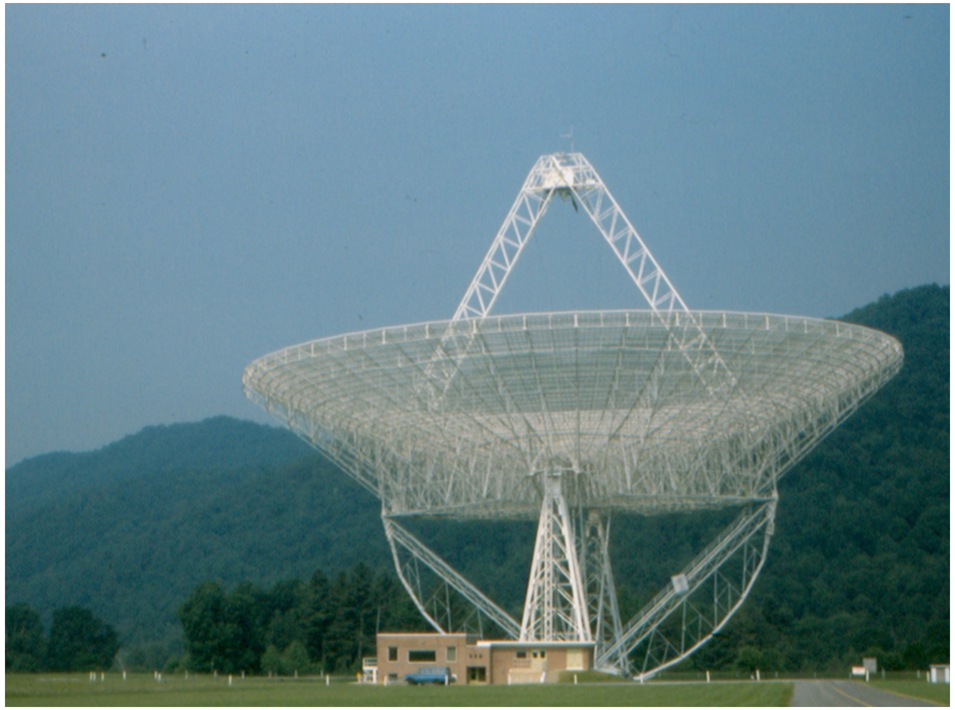
$10^{10} \sim 10^{14}$ Gauss

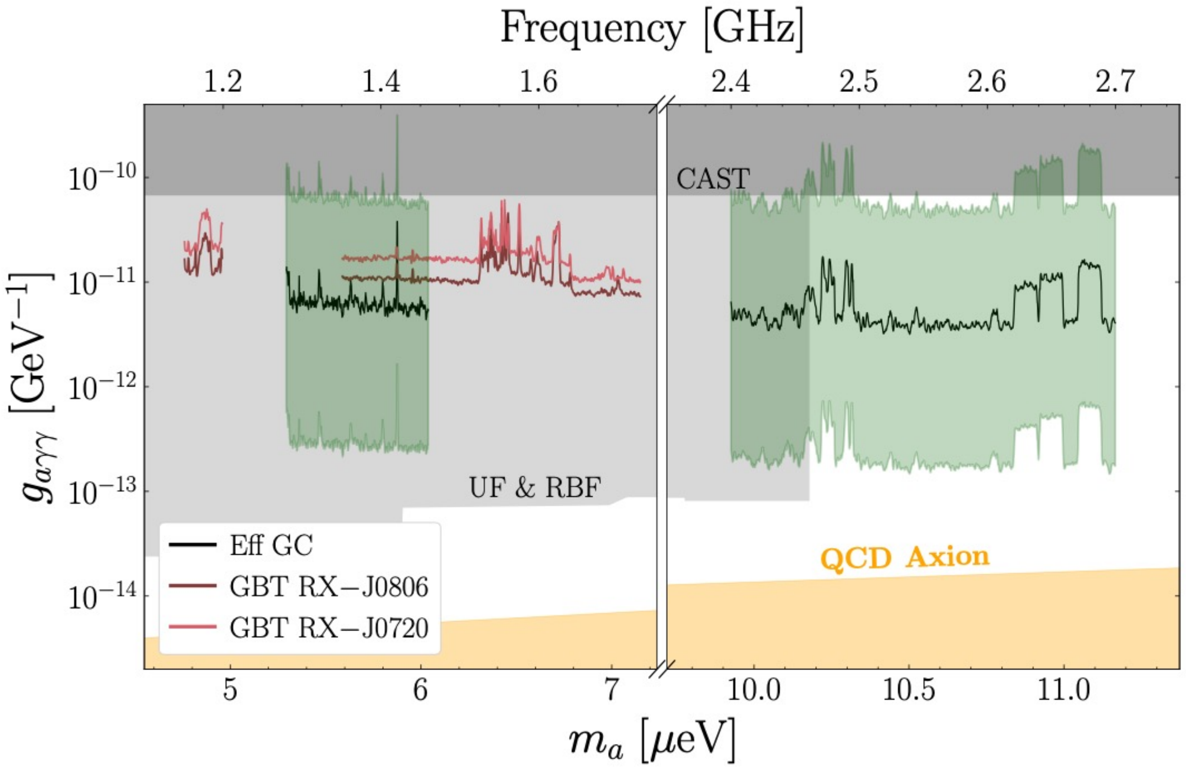


Pshirkov, Popov, 0711.1264
F.P.Huang et al. PRD 97 (2018) 123001
Hook, Kahn, Safdi, Sun, PRL 121 (2018) 241102

Result from Green Bank Telescope

100 meter diameter





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

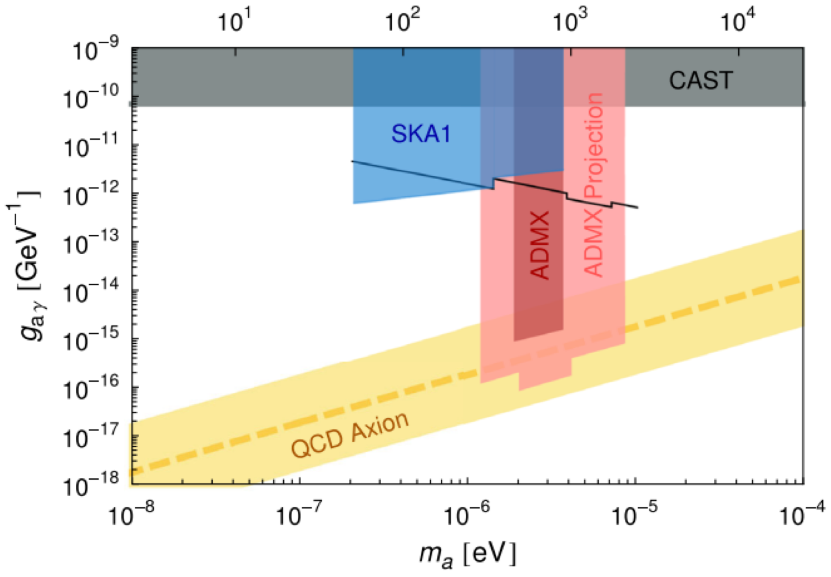
What about using white dwarves?

- 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
  - $R^{NS} \sim 10$ km
  - $R^{WD} \sim R^{earth} \sim 10^4$ 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

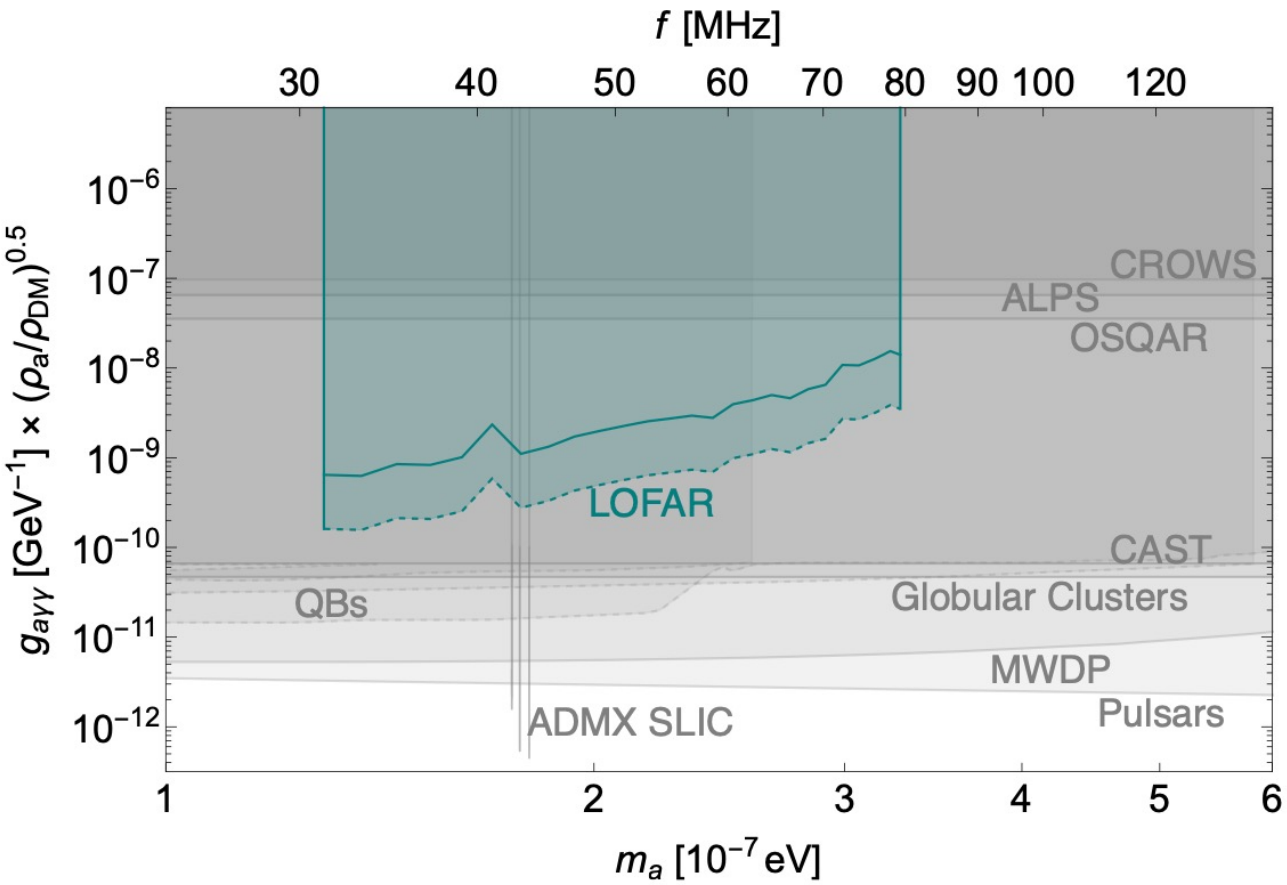
- $S_{sig} \sim R^3 B_0^2$
- The signal from white dwarves can be as strong as from neutron stars.



Wang, Bi, Yao, Yin, 2101.02585

What about using the Sun?

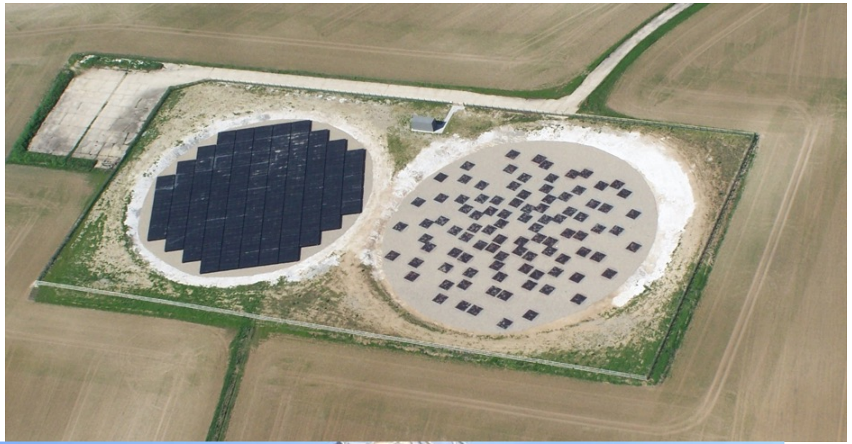
- Magnetic field of the Sun is tiny
  (~ 1 Gauss)
- But, it is much bigger!
  $R_{\odot} \sim 100 R^{WD} \sim 10^5 R^{NS}$
- The Sun is much closer.
  $d_{NS} \sim d_{WD} \sim 10^7 d_{\odot}$
  $S_{\rm sig} \propto R^3 B_0^2 / d^2$
- We have a vast amount of solar

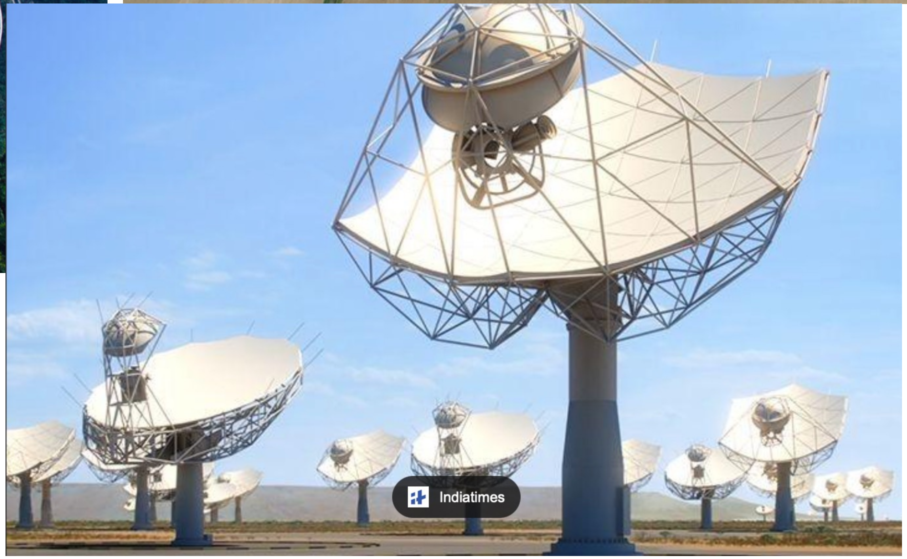


HA, X. Chen, S. Ge, J. Liu, Y. Luo, 2301.03622

Searching for dark photon dark matter directly with radio telescopes

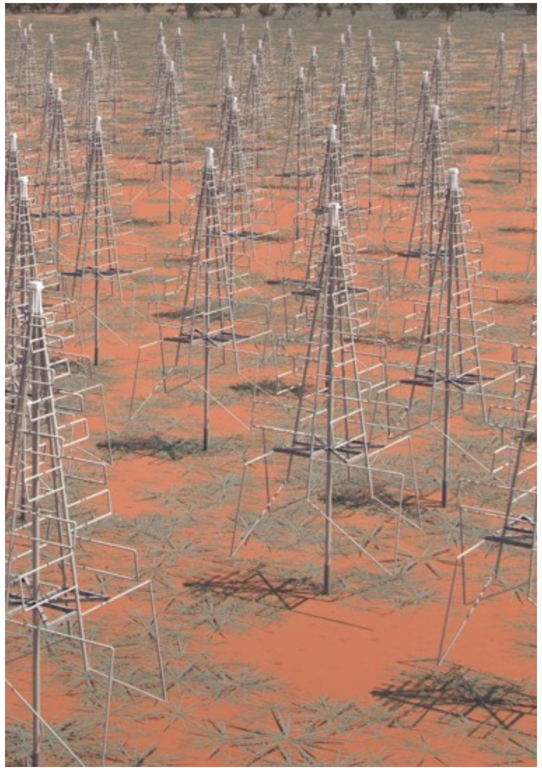
- Radio telescopes we have

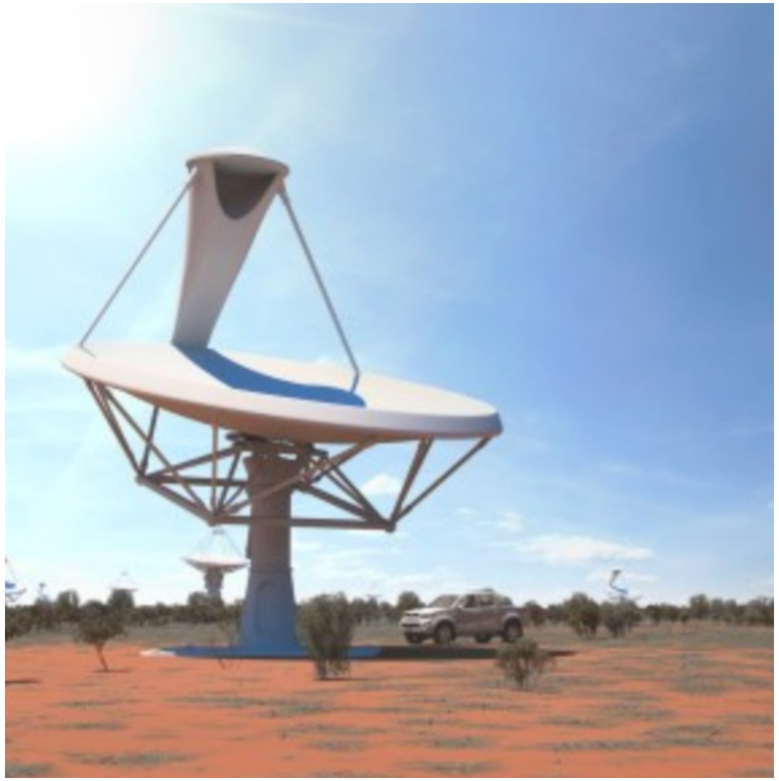




Searching for dark photon dark matter directly with radio telescopes

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

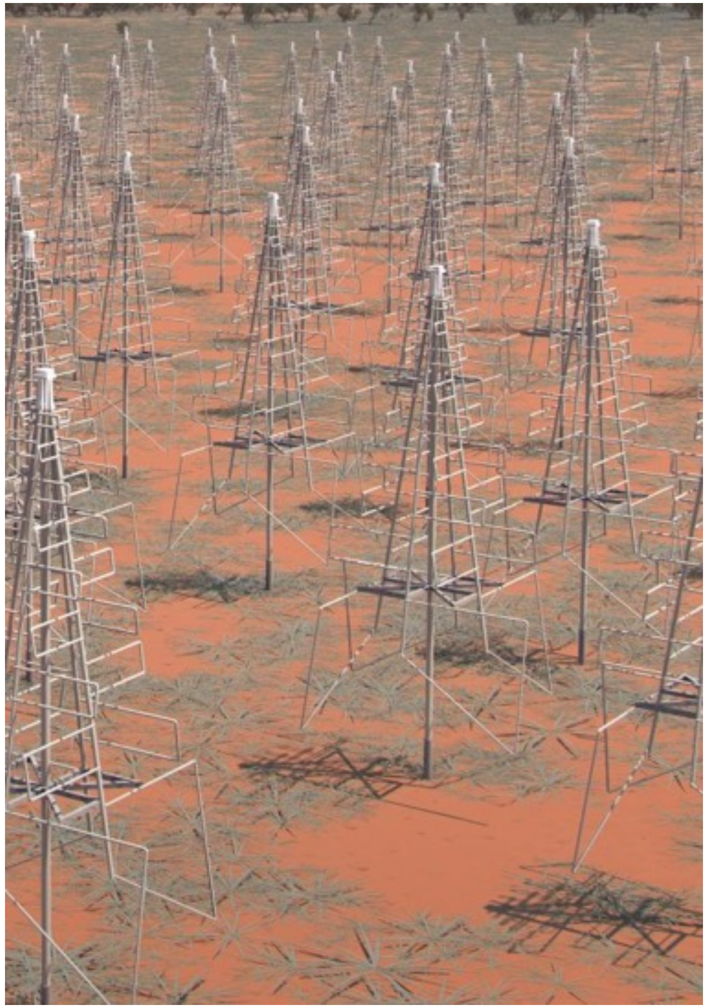




Searching for dark photon dark matter directly with radio telescopes

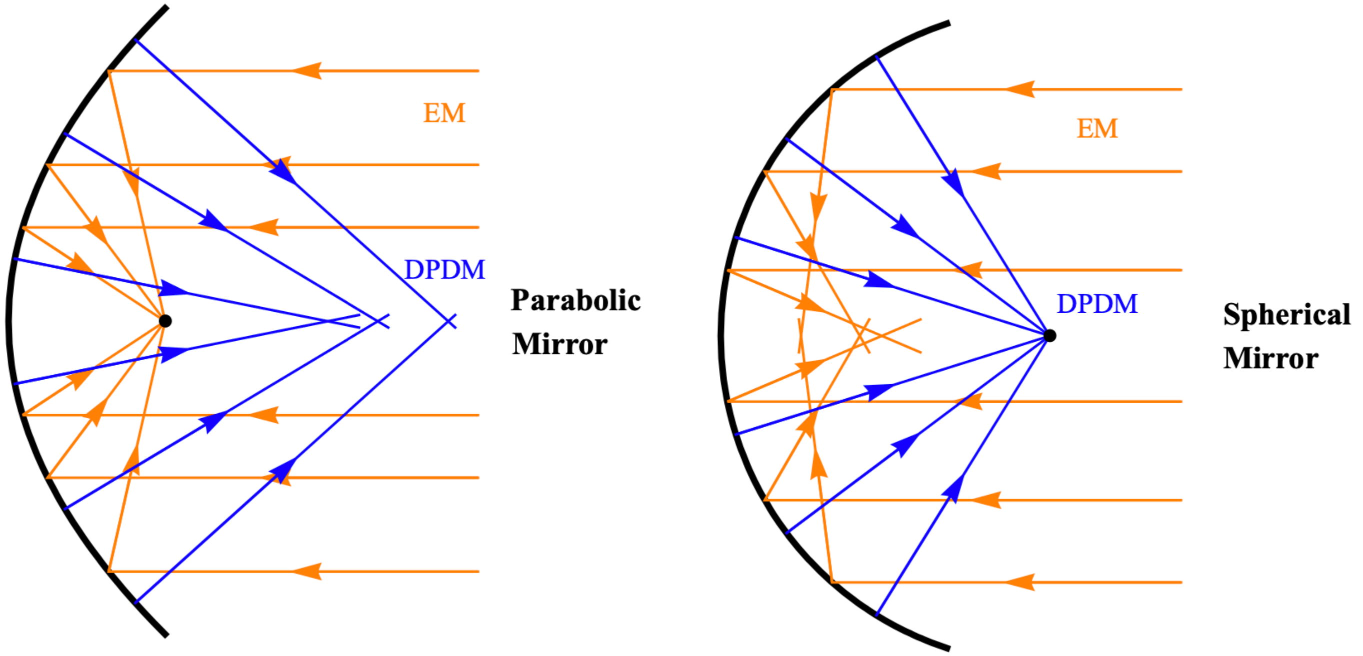
- For dipole antennas, the oscillation of A' induces an EM current in the antennas, and produce electronic signals.
- The wavelength of A', $\lambda_D \gg \lambda$

→ The units close to each other oscillate in the same phase

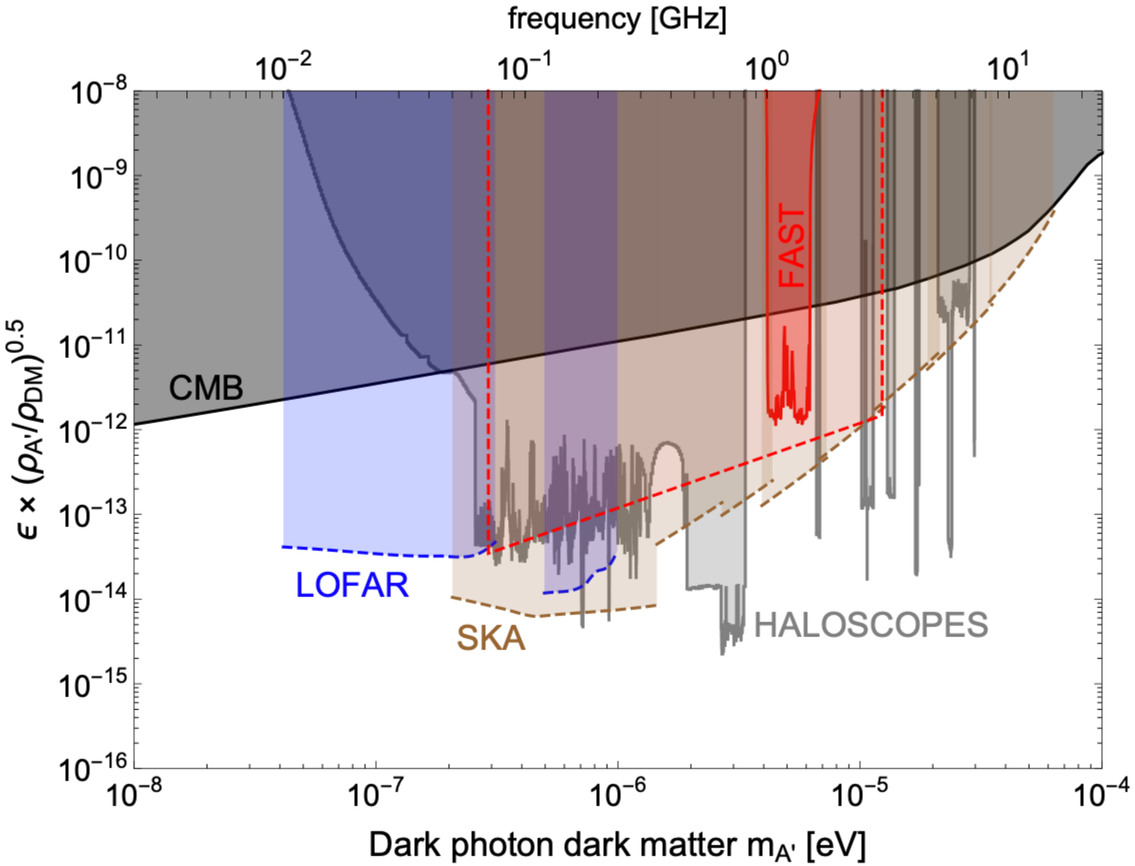


Searching for dark photon dark matter directly with radio telescopes

- 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

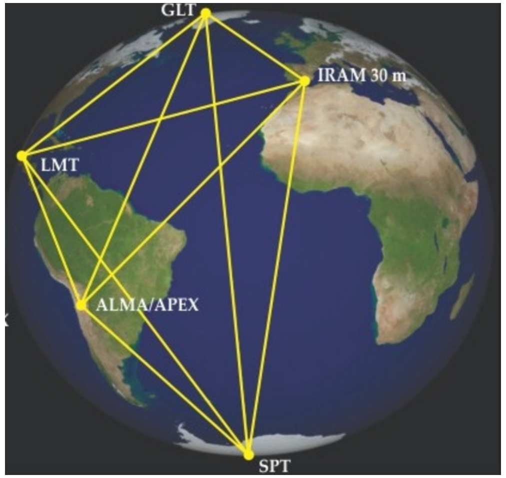


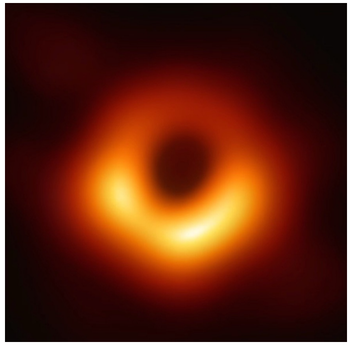
HA, S. Ge, W.-Q. Guo, X. Huang, J. Liu, Z Lu, 2207.05767, PRL 130 (2023) 181001

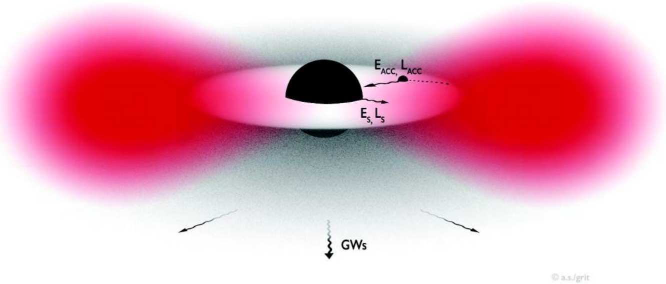
Axion induced Birefringence effect

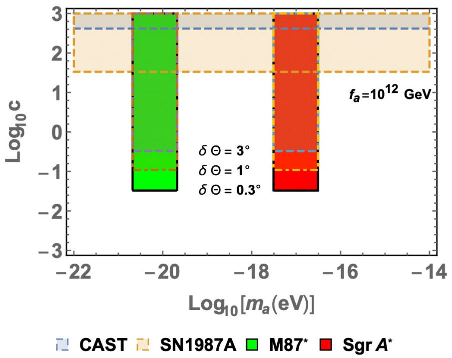
- With axion-photon interaction: $$-\partial_\mu F^{\mu\nu} + \frac{\partial_\mu a}{f}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta} = 0$$
- Using the transverse gauge: $$\nabla \dot{\mathbf{A}} = 0\ , \quad A^0 = 0$$
- For plane wave: $$\ddot{\mathbf{A}} + k^2\mathbf{A} + \frac{\dot{a}}{f}\mathbf{k} \times \mathbf{A} = 0$$
- $\mathbf{k} = k\ \hat{\mathbf{z}}, \mathbf{A} = \epsilon_x\hat{\mathbf{x}} + \epsilon_y\hat{\mathbf{y}}$: $$\dot{\epsilon}_x + \frac{\dot{a}}{f}\epsilon_y = 0 \qquad \dot{\epsilon}_y - \frac{\dot{a}}{f}\epsilon_x = 0$$
- The polarization is rotating inside the axion field.

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

$$T^{\mu}_{\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$

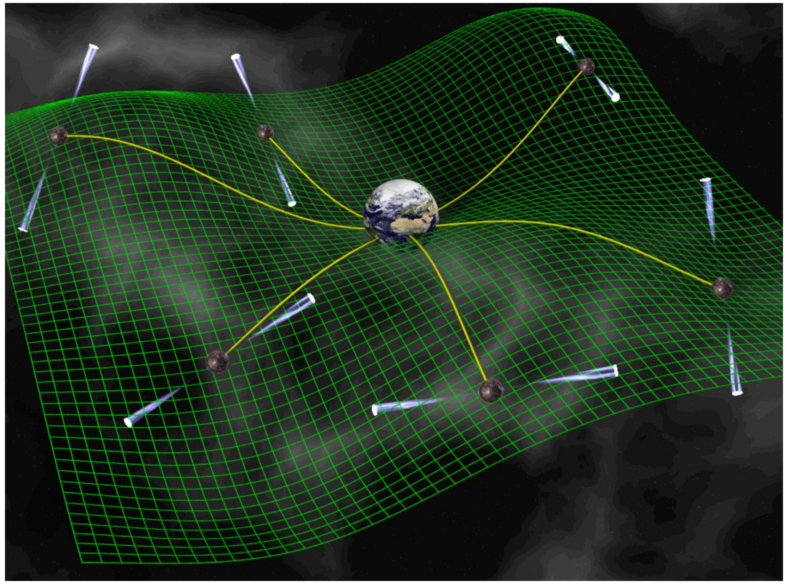
- Ideal gas
- For particle DM $\quad p \ll \rho$
- For ultralight bosons $\quad p \sim \rho \cos(2m_a t)$
- In the time scale much smaller than the mass, stars can feel a big pressure from the ultralight DM.
- The oscillation of the pressure can also induce an oscillation of the metric.

Pulsar timing array

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

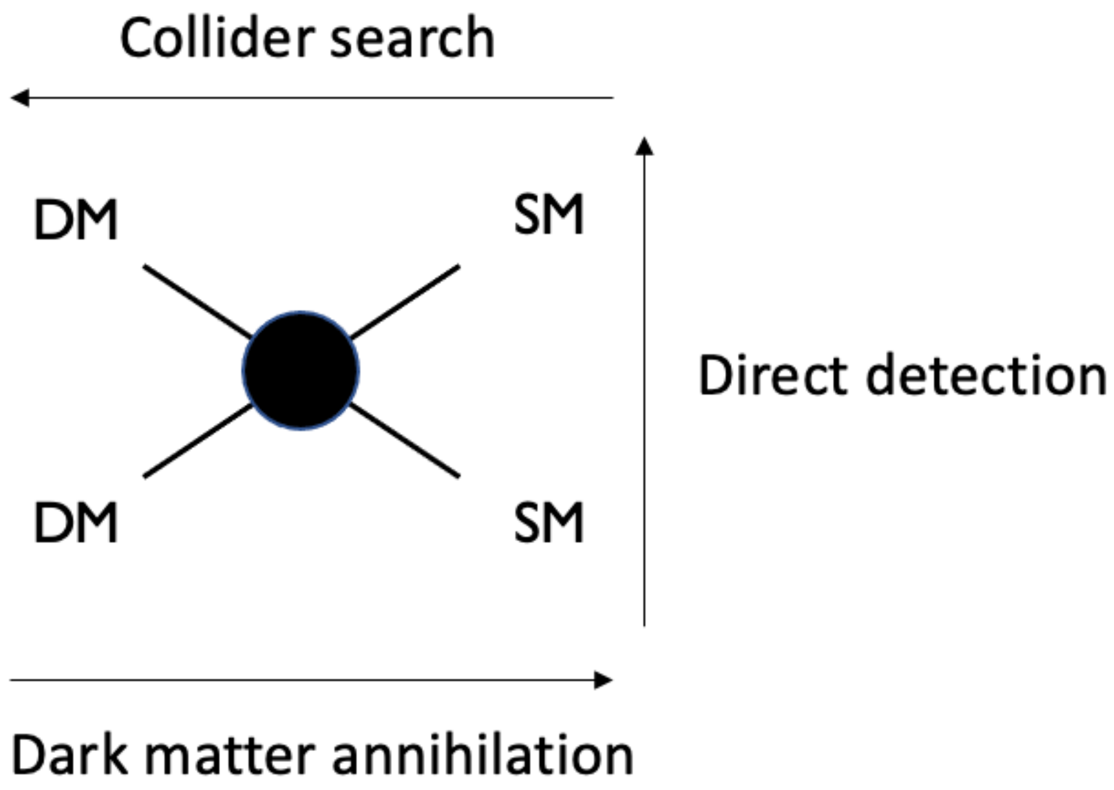
- The oscillation of the metric can change the path of the light emitted by the pulsars.

- Pulsar Polarization Arrays

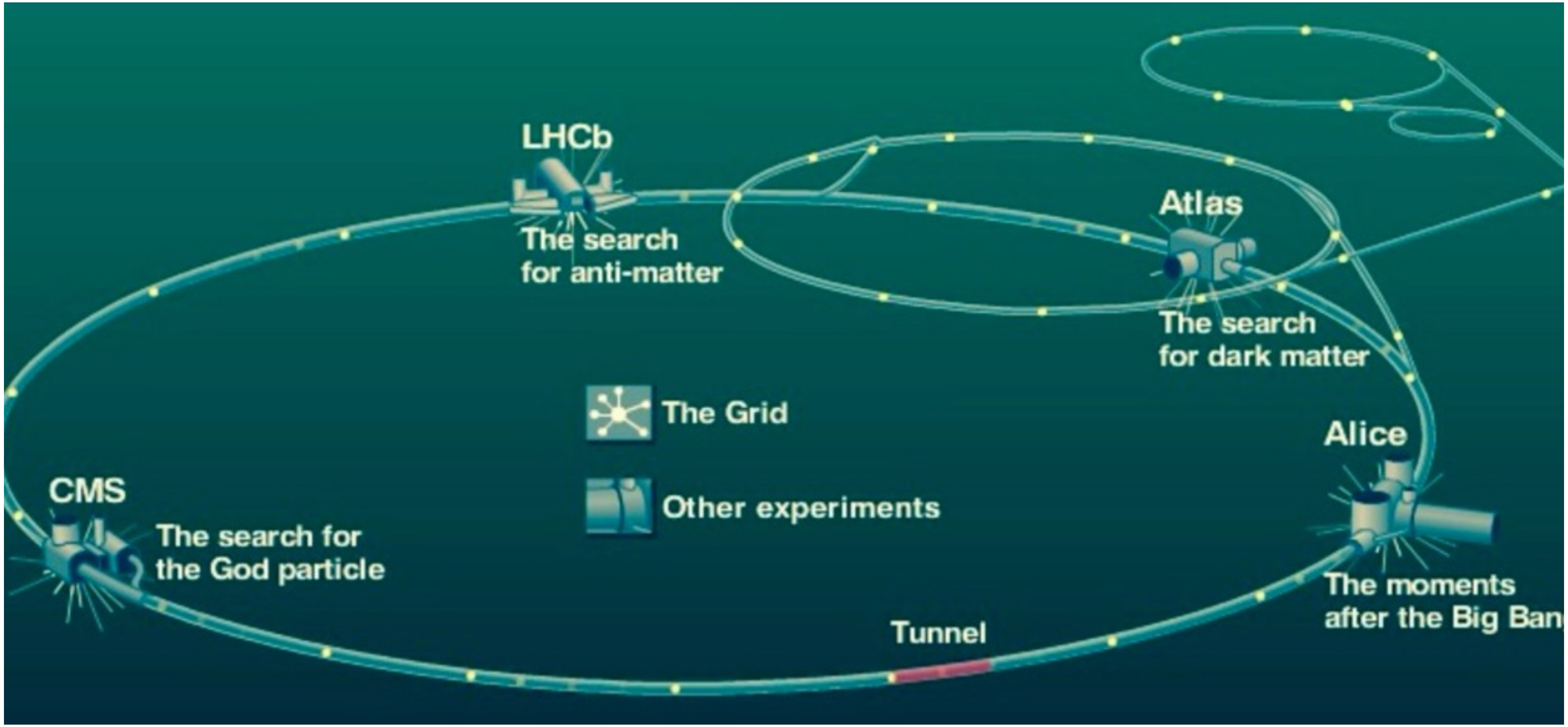


Khmelnitsky et al, JCAP 2014 (02) 019
Graham et al, Phys.Rev.D, 2016, 93 (7): 075029
Tao Liu, Xuzixiang Lou, Jing Ren, PRL 130 (2023) 121401

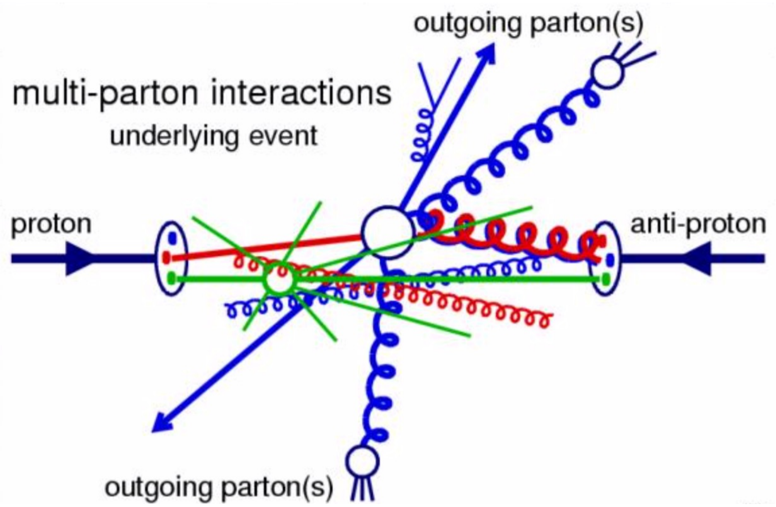
Collider searches
– we produce dark matter

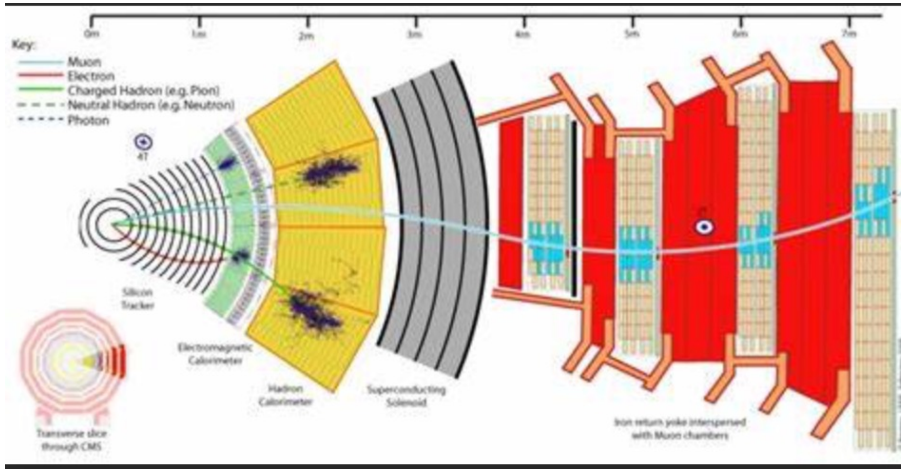


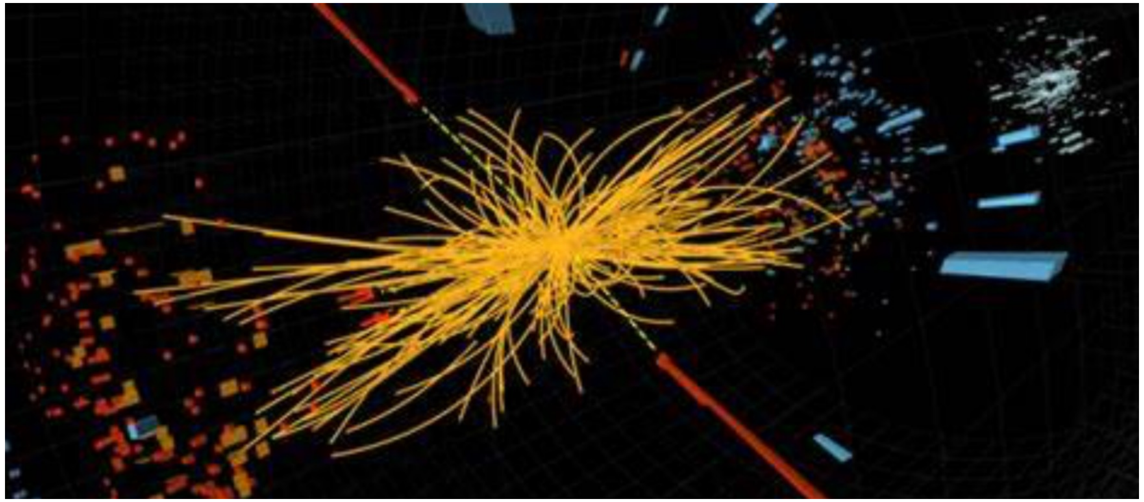
The Large Hadron Collider (LHC)



How collider works

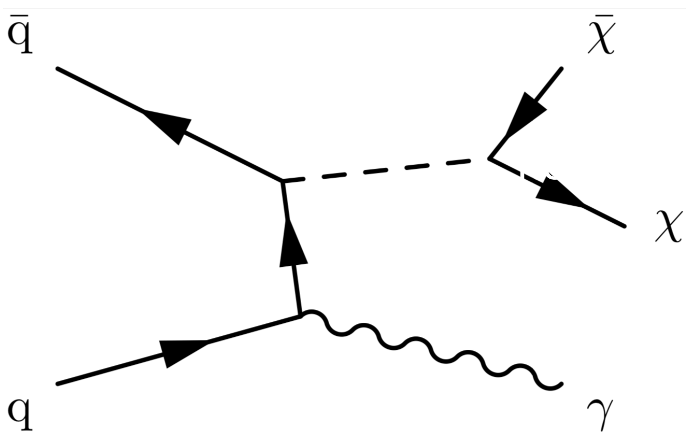


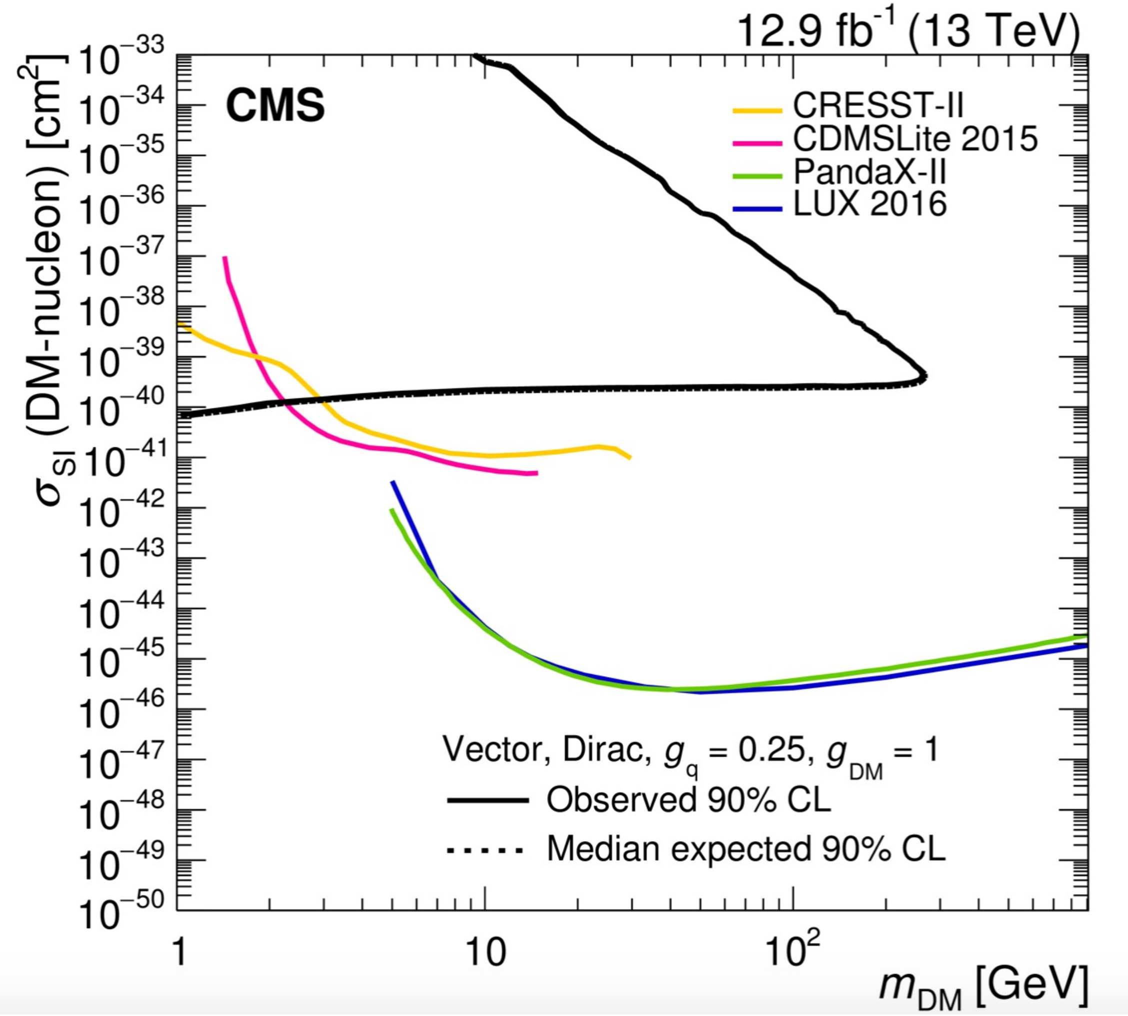




Searching for DM with LHC

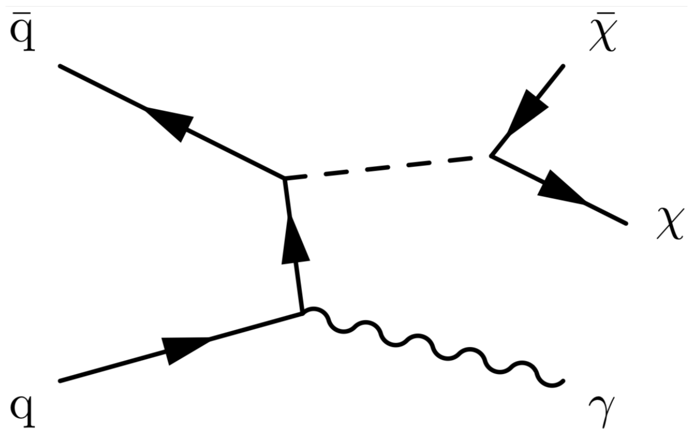
- Mono-photon search

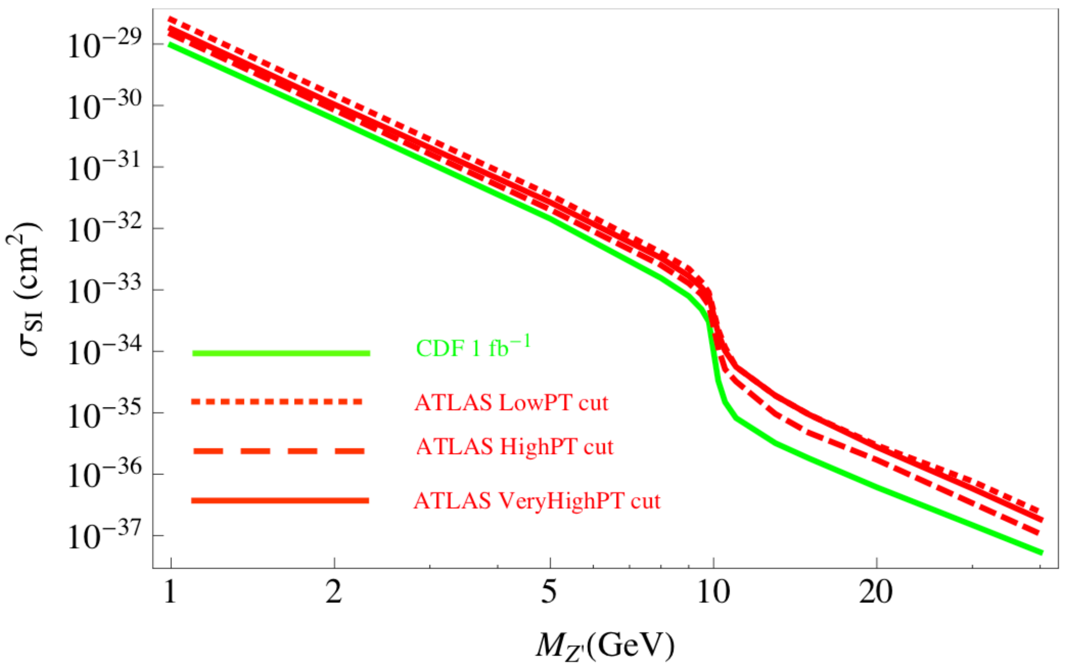




Searching for DM with LHC

- Light mediator case

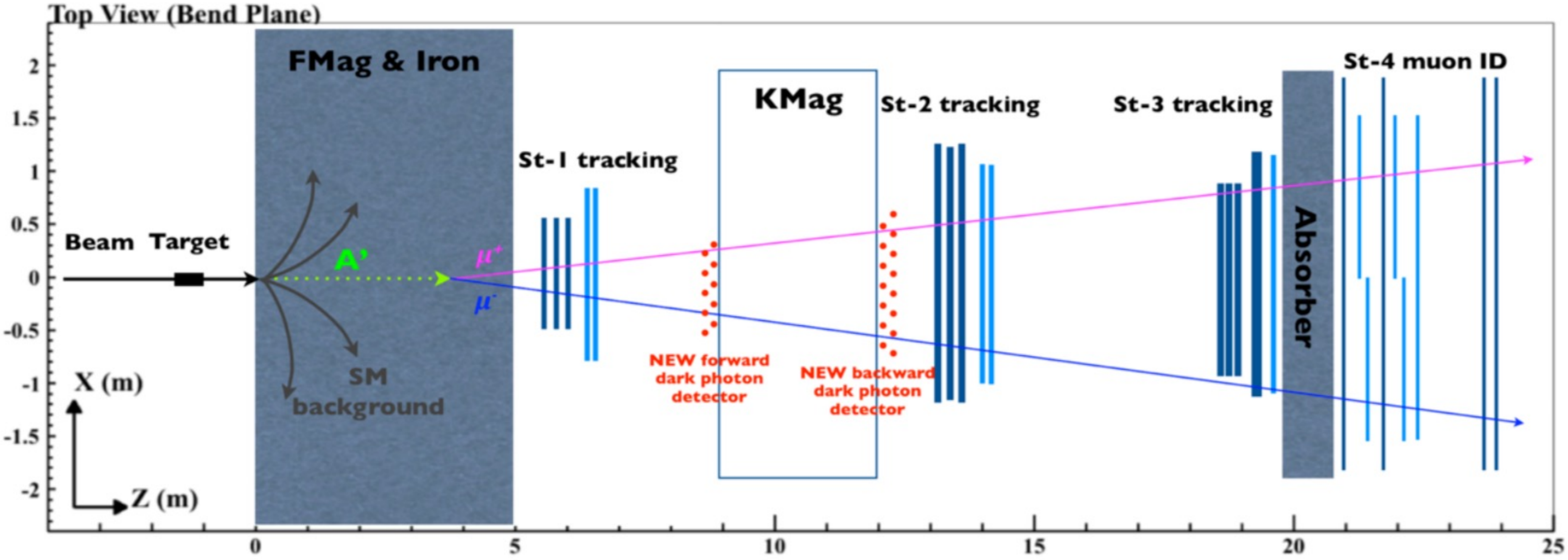




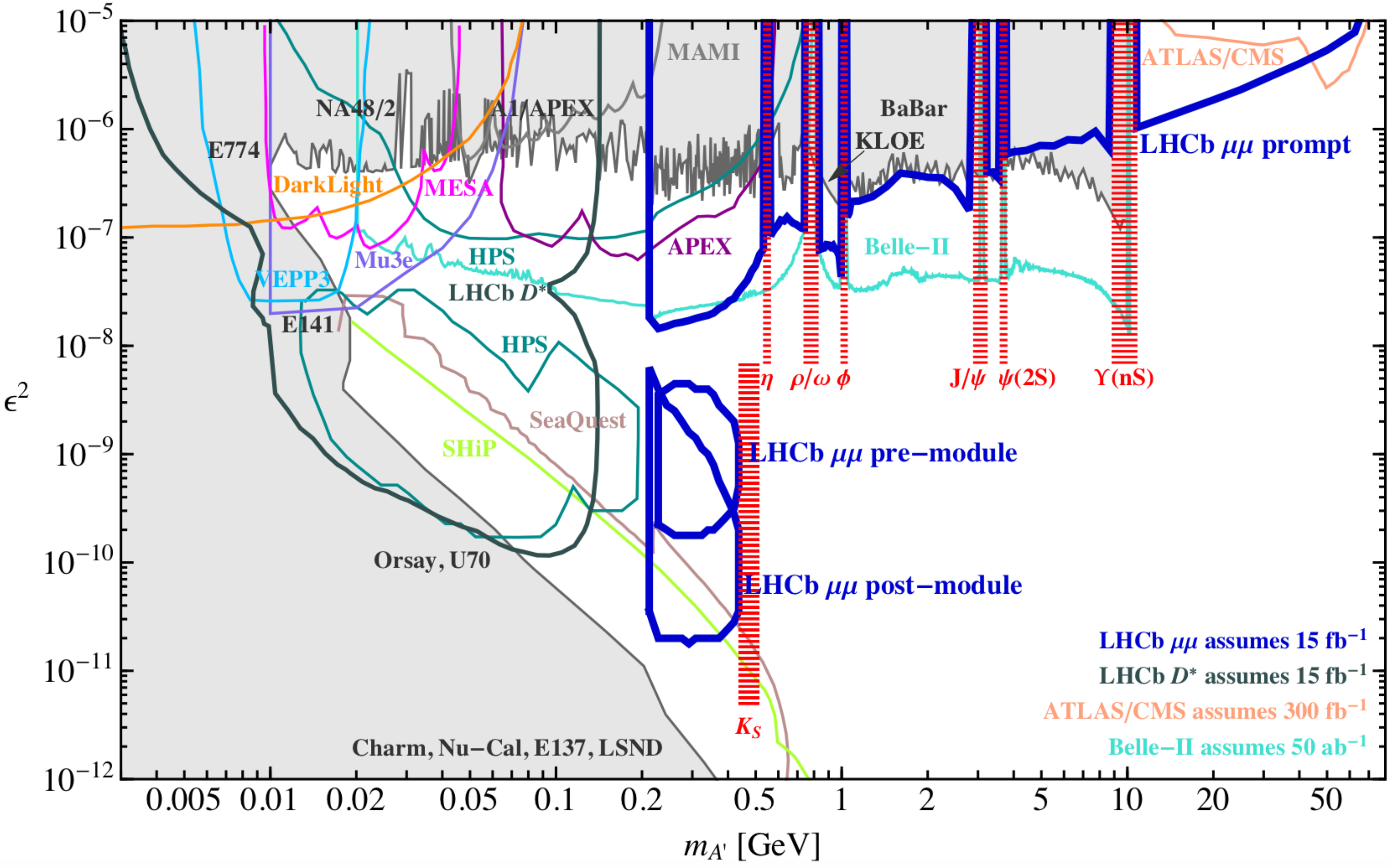
HA, X. Ji, L.-T. Wang, JHEP 1207 (2012) 182

Searching for dark mediator

- Fix target experiments

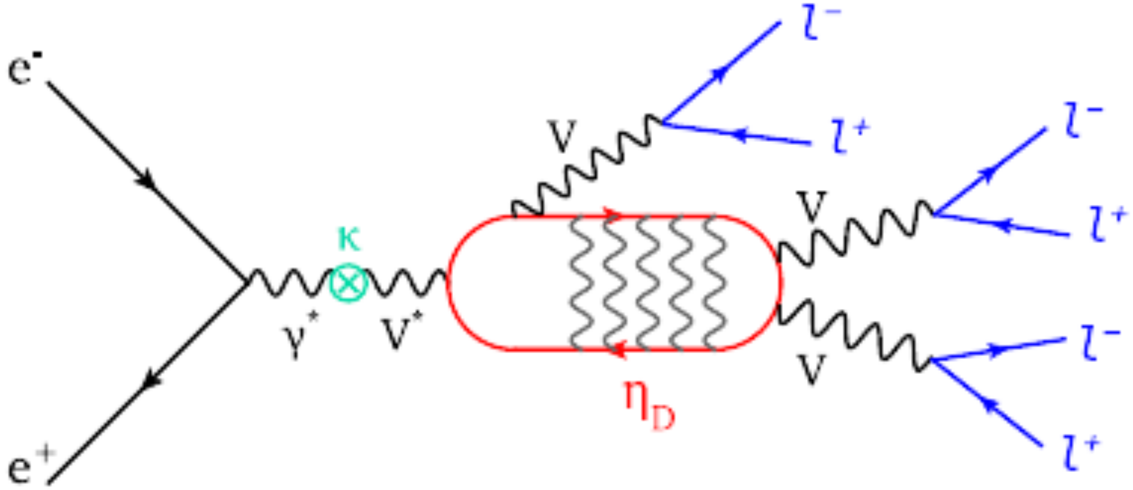


Searching for dark mediator



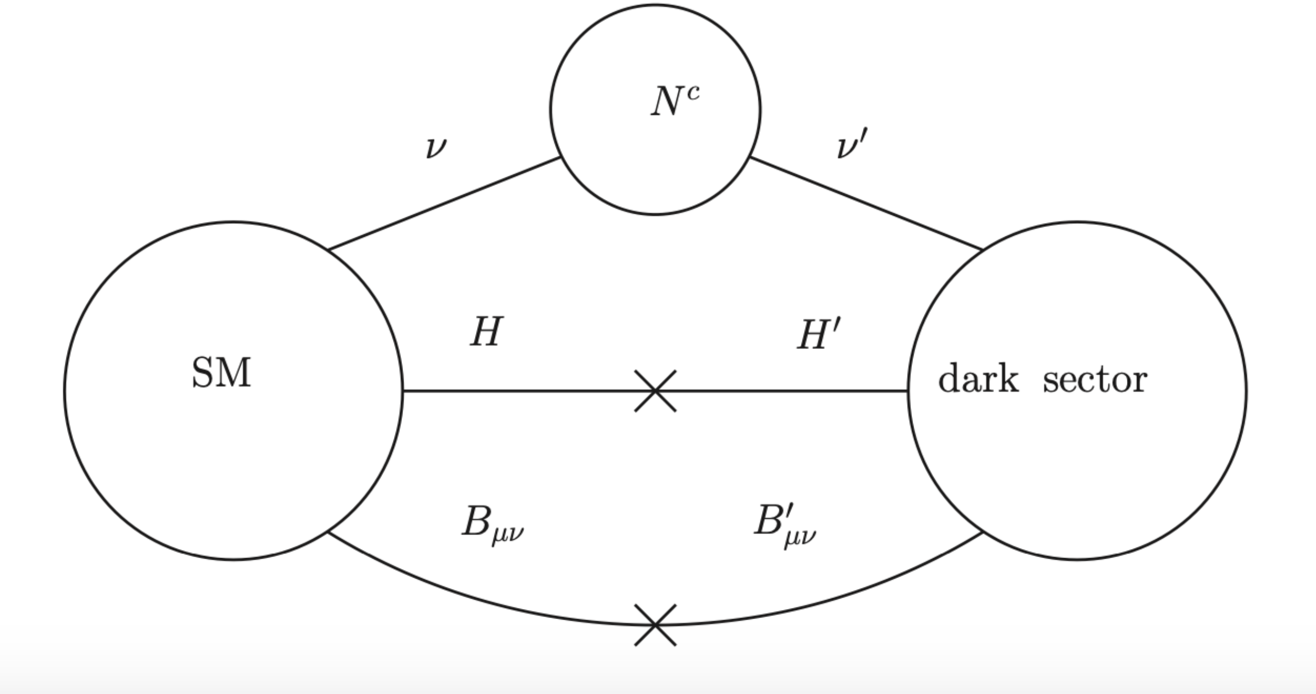
Special signal

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

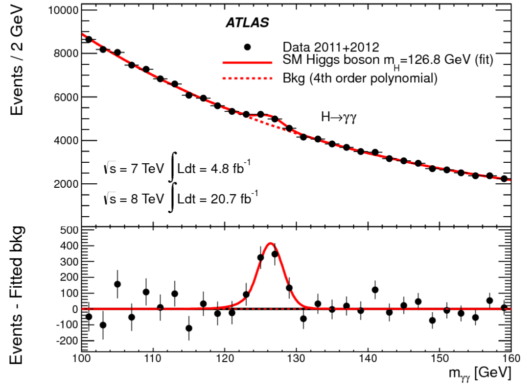


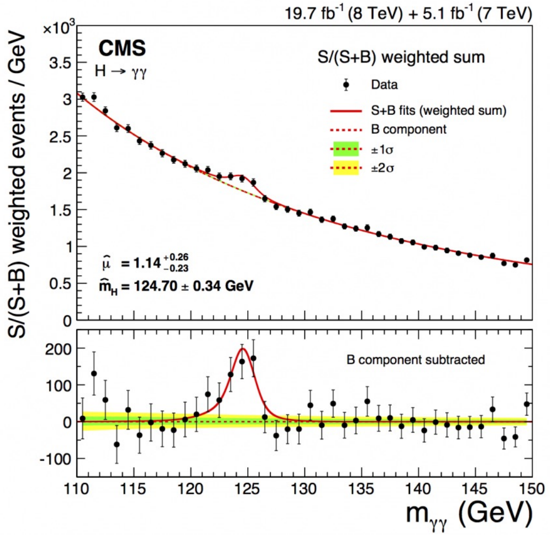
HA, Echenard, Pospelov, Zhang, PRL 116 (2016) 151801

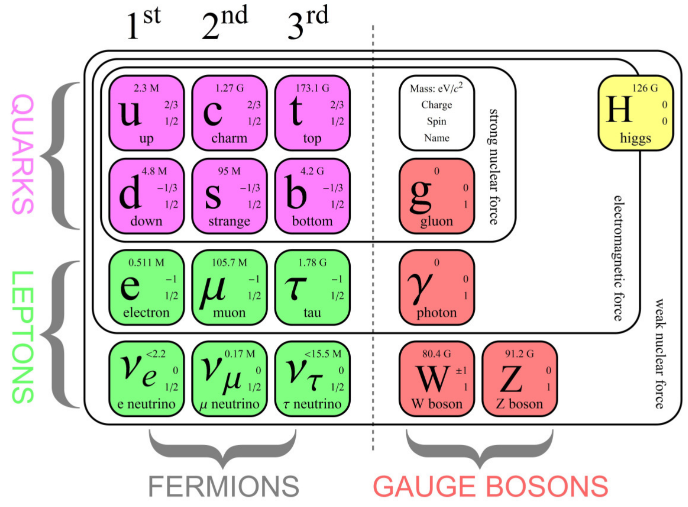
General hidden (dark) sector models



DM connected to the Higgs boson





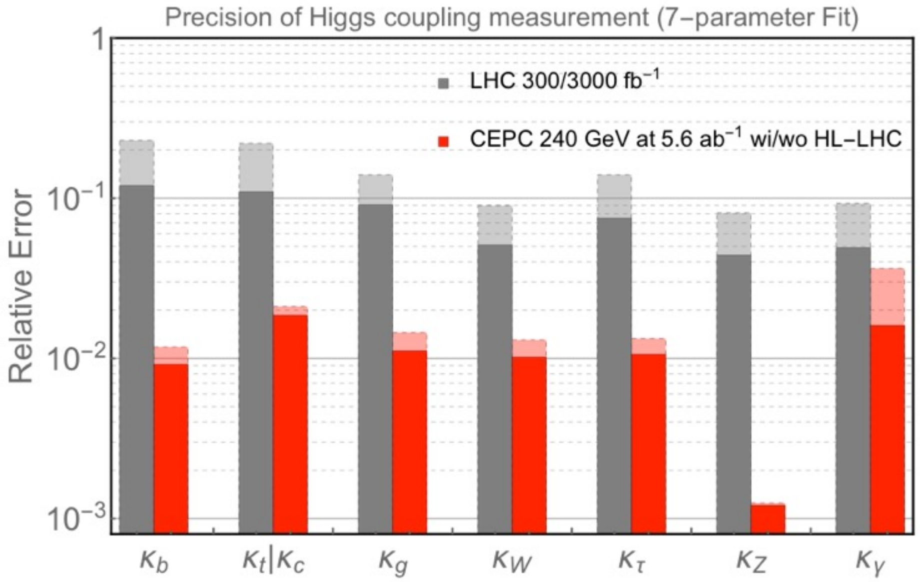


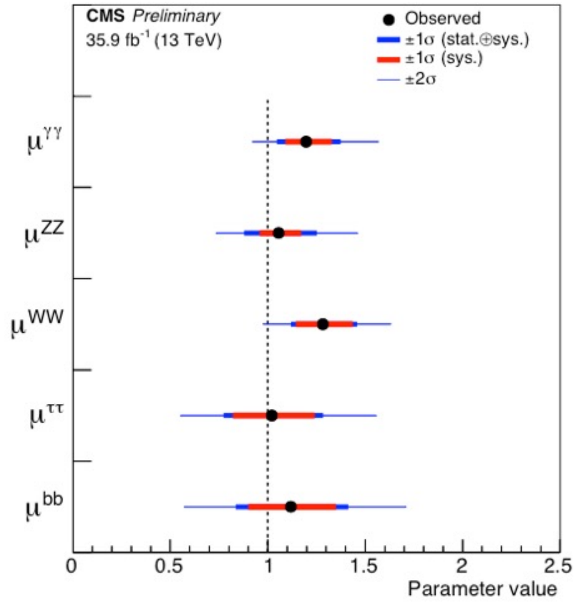
Circular electron-positron collider

proposed circular colliders

Higgs invisible decay

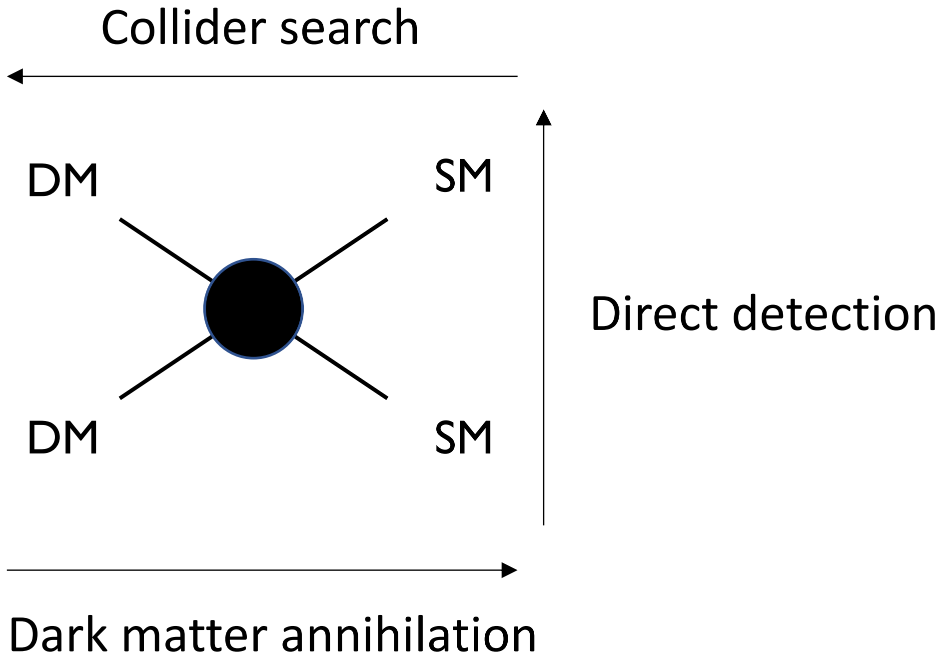
- Higgs factory





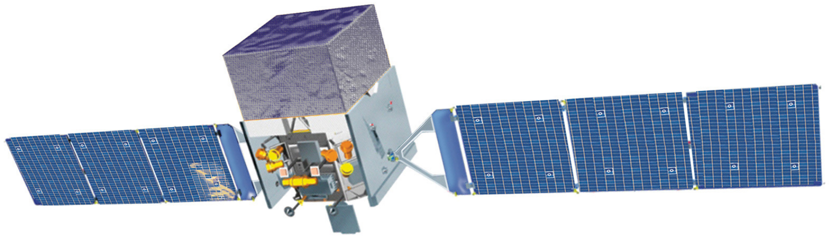
Searching for DM in cosmic rays

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

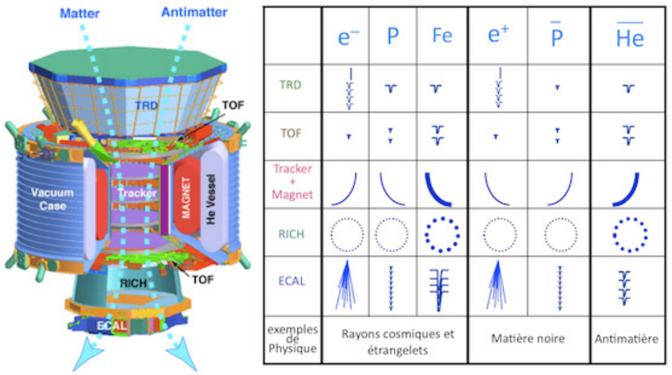


Searching for DM in cosmic rays

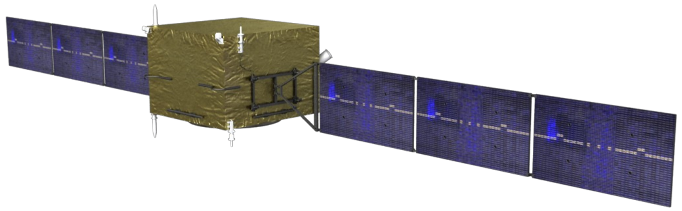
PAMELA



Fermi

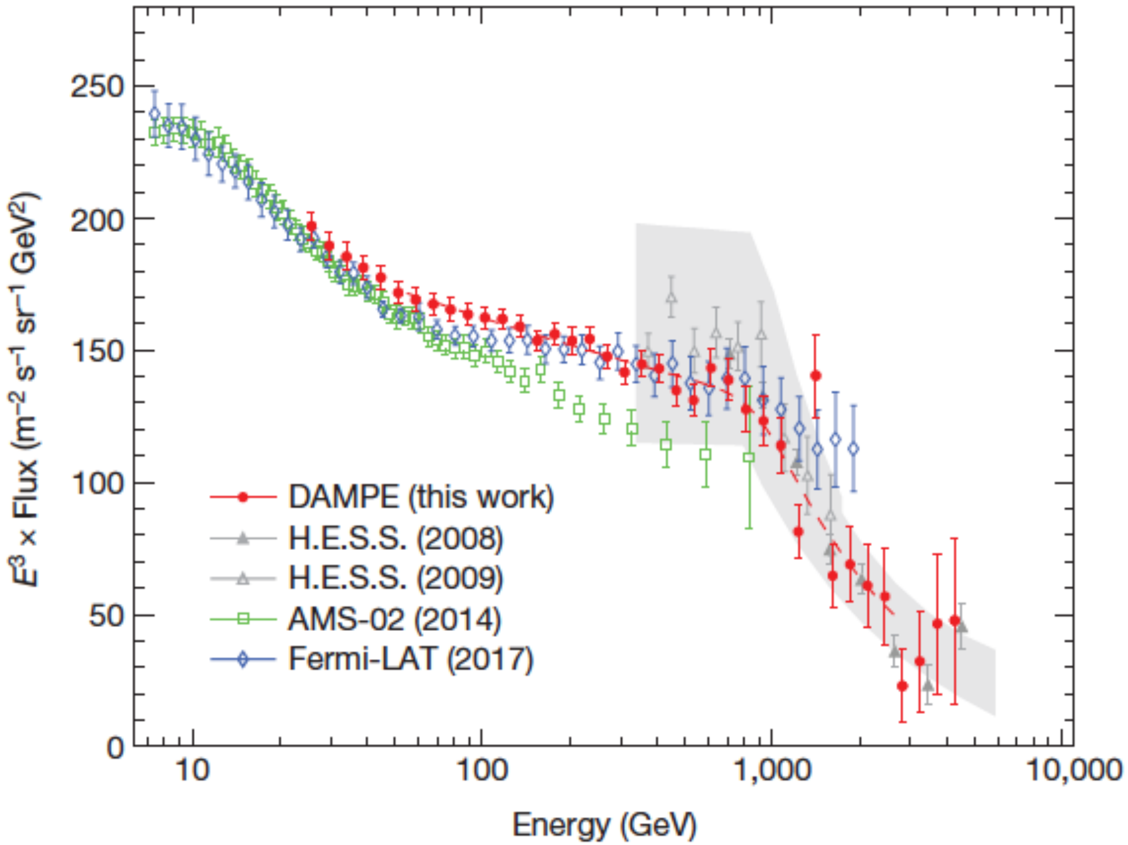


AMS02



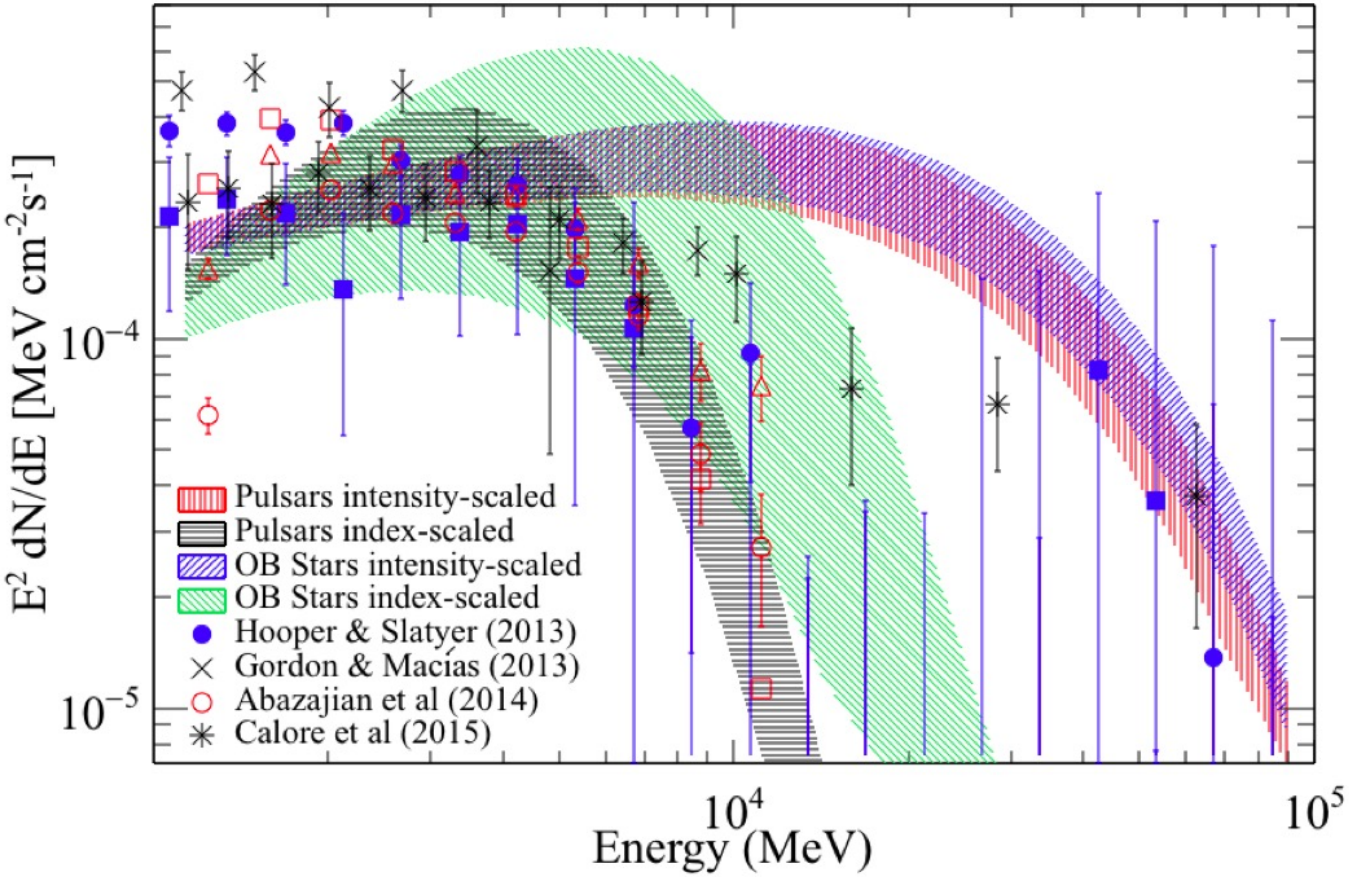
DAMPE (悟空)

Searching for DM in cosmic rays



Searching for DM in cosmic rays

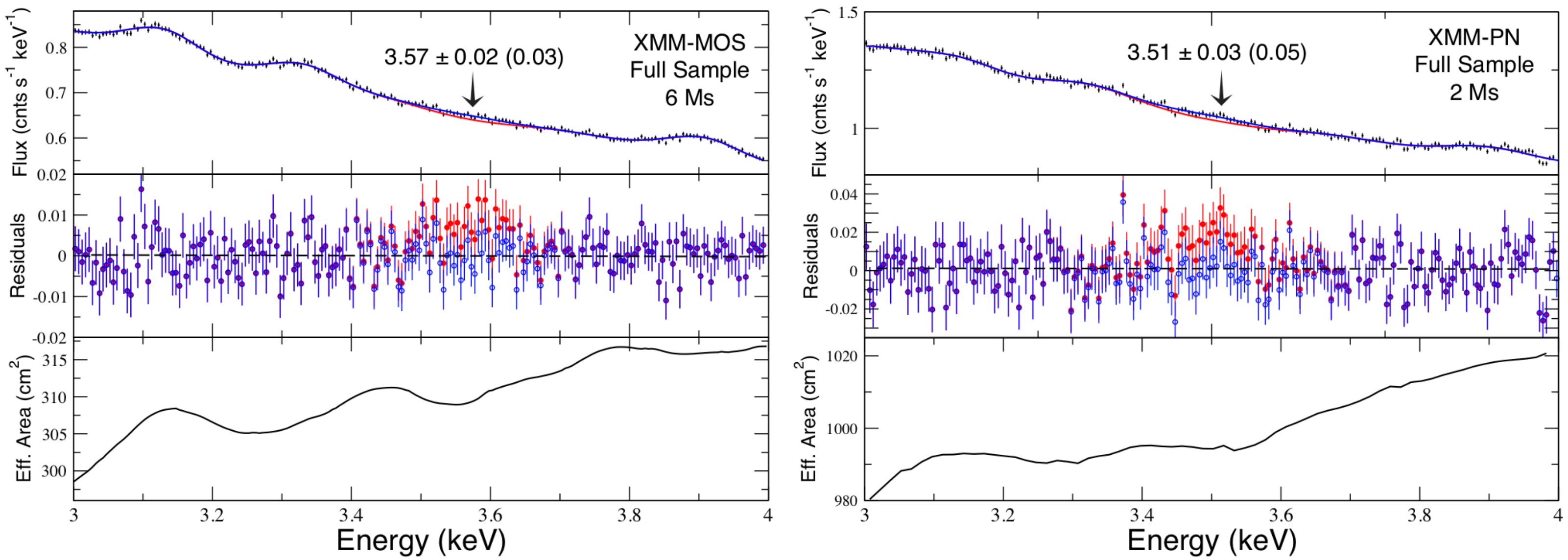
- FermiLAT gamma ray spectrum



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

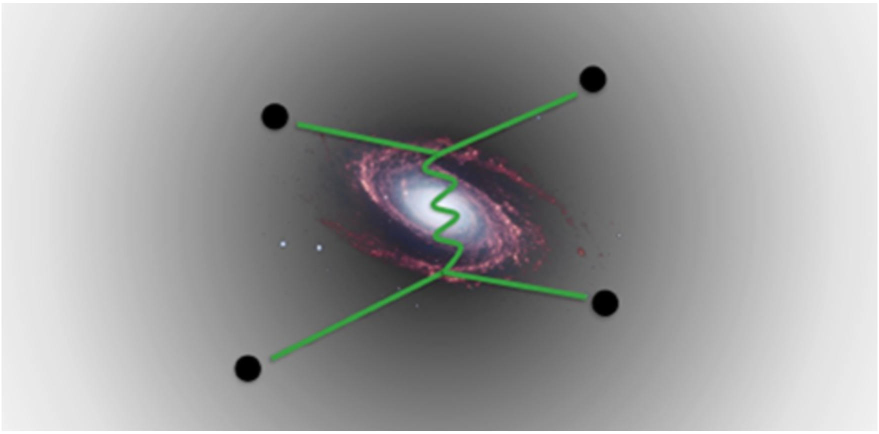


Searching for DM in cosmic rays

- 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?



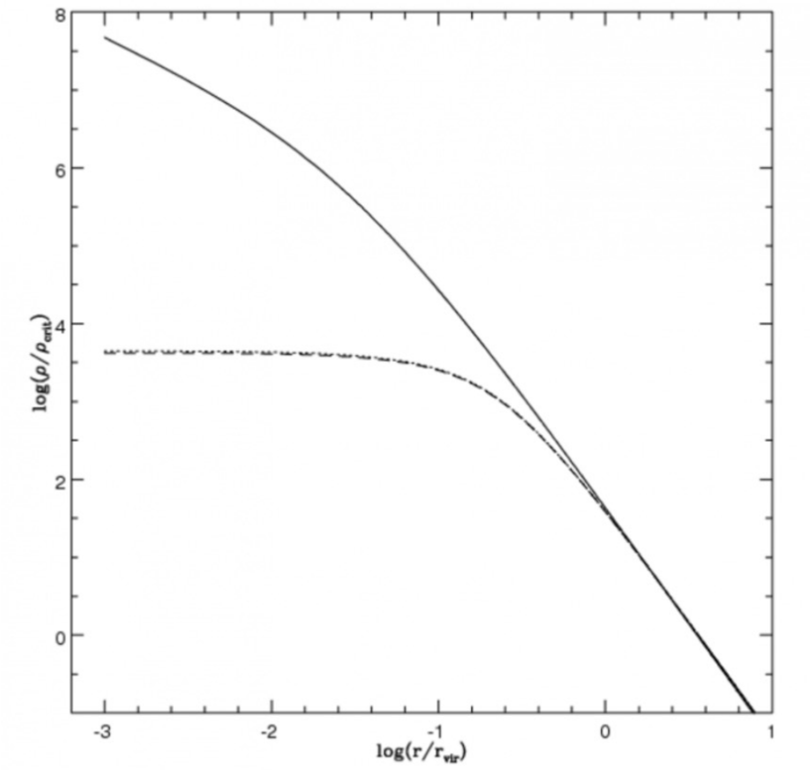
Kaplinghat, Tulin, Yu, PRL 116. 041302, 2016

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.



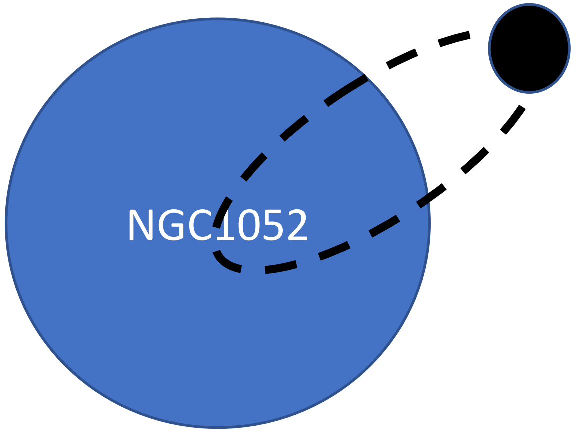
Galaxies with no dark matter

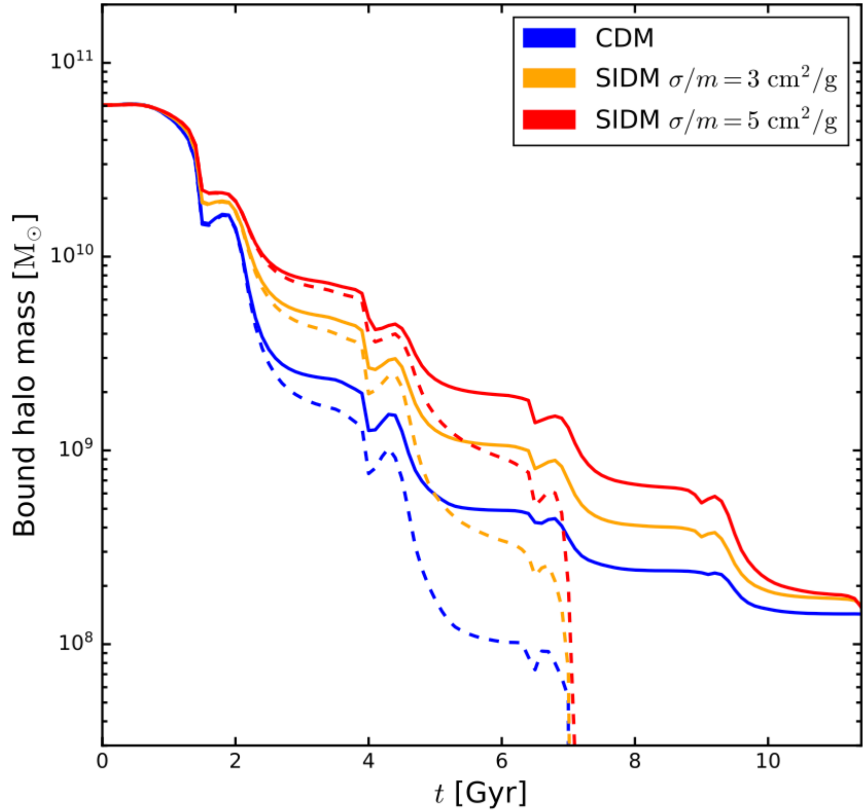
nature

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





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

Summary

We need more clever ideas to search for dark matter.