Searching for dark matter

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高能物理前沿讲座

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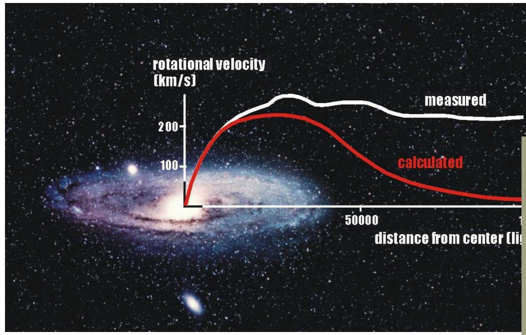
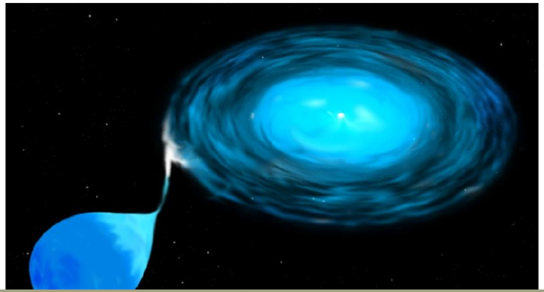
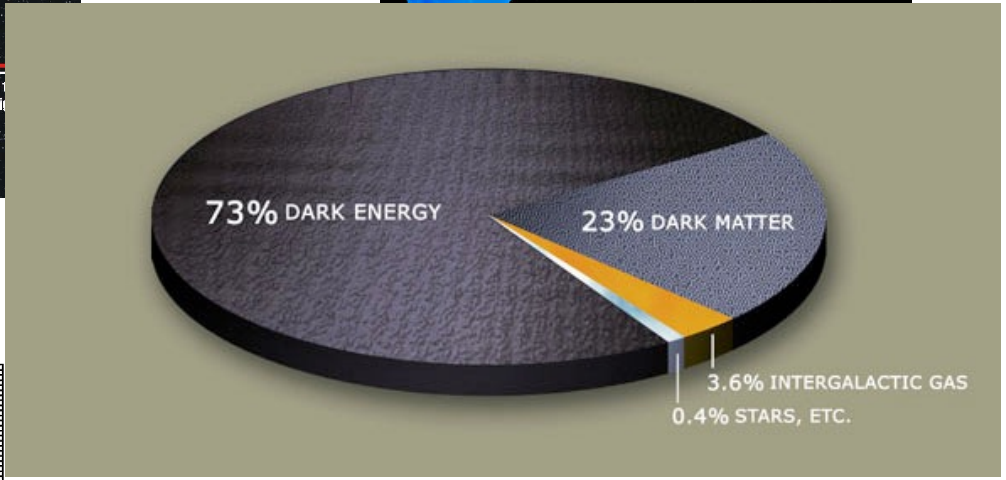
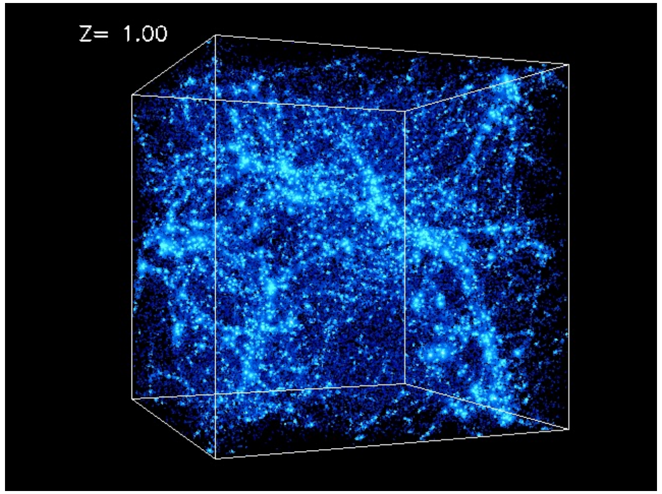
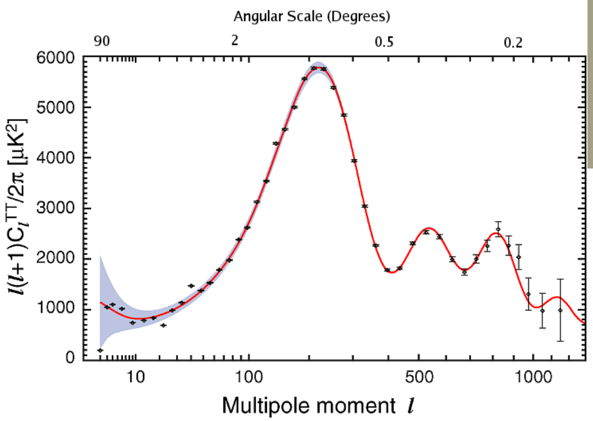
We have plenty of evidences for DM

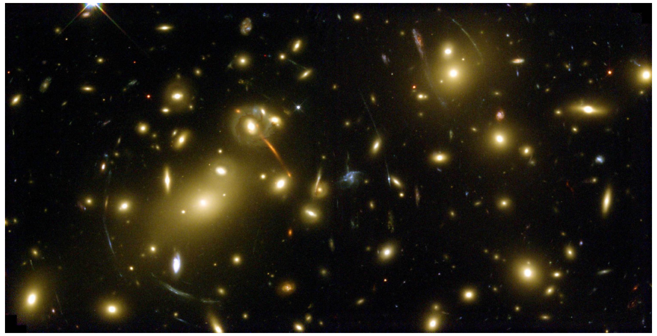












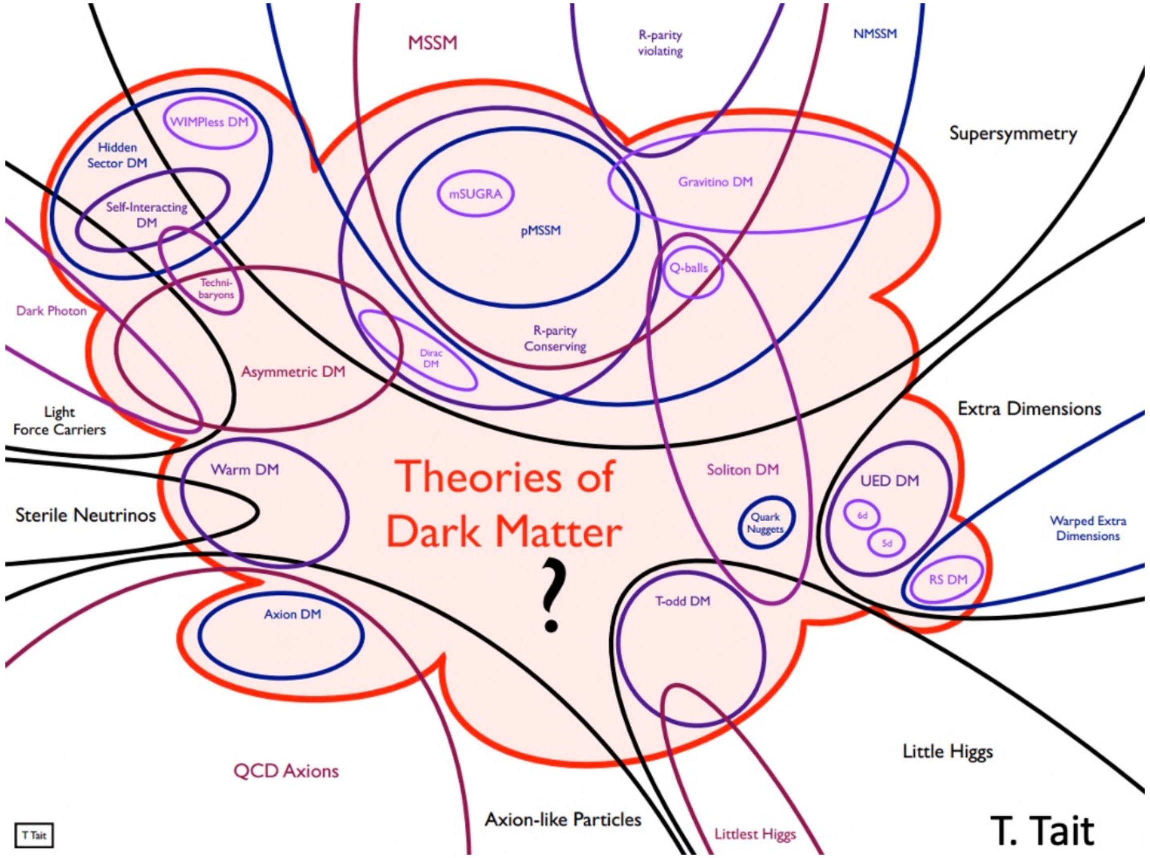
Searching for dark matter

- 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
  - …

Theories of Dark Matter

- Freeze-out
  - WIMP, SuperWIMP, Coannihilation, Dark Sector
- Freeze-in
  - UV freeze-in, IR freeze-in
- SIMP
  - $3 \rightarrow 2, 4 \rightarrow 2$
- Asymmetric DM
- Ultralight Bosonic DM
- Particle production during the expansion of the Universe



Freeze-out

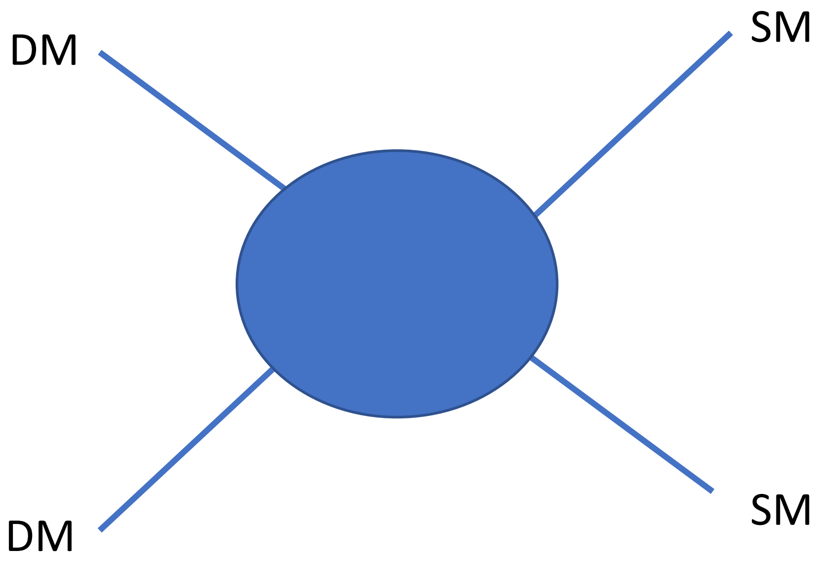
- The DM particles are in thermal equilibrium with SM particles in the early Universe.
  - Interaction.
  - The rates are important.
- The Hubble expansion rate:

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

- 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.

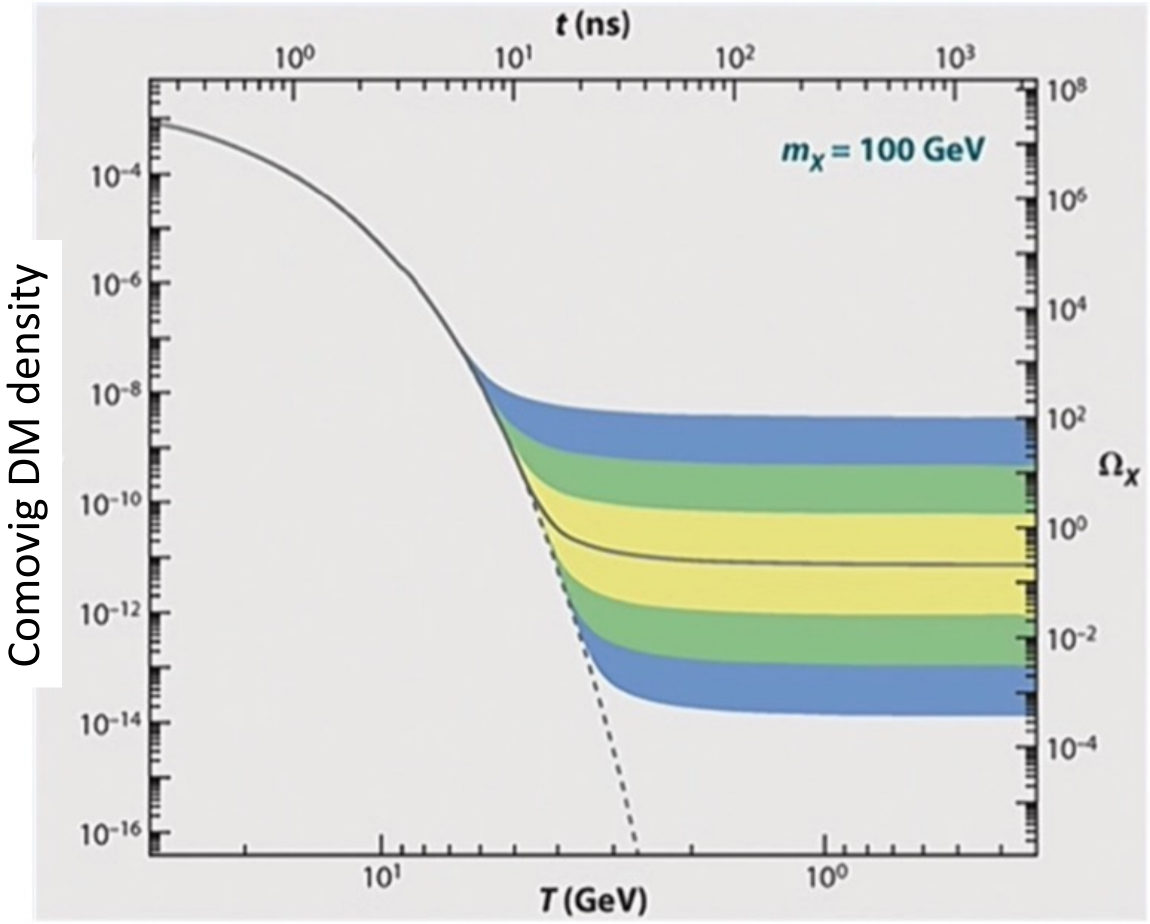
$$\Gamma < H$$

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

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

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

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

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

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

The condition for freeze-out

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

Must be very small

Usually very large

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

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

Today's Universe

Hubble parameter today

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

+ curvature term

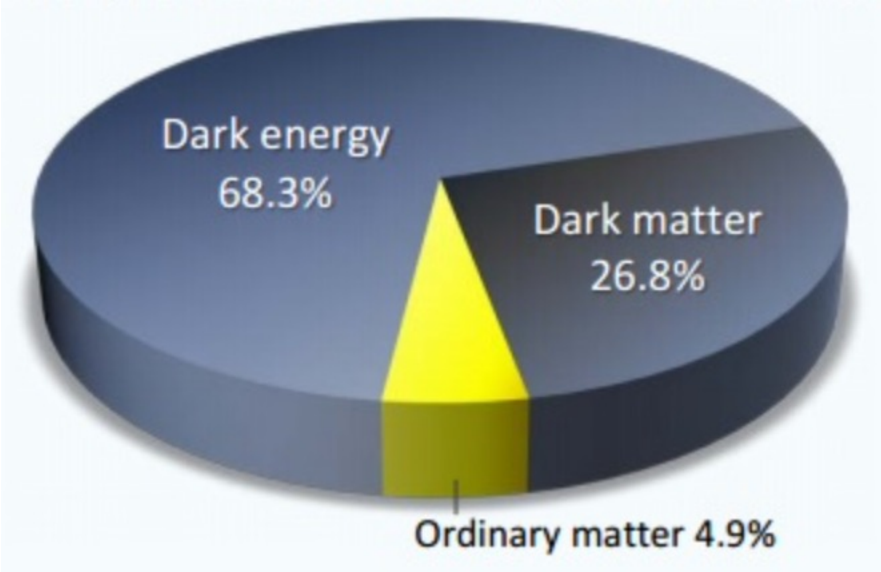
ρ_{crit}

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

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

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

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



Today’s energy density of DM

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

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

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.

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

The WIMP miracle

$$\left.\begin{array}{l} (\langle\sigma v\rangle M_{\rm pl} m_\chi)\left(\dfrac{m_\chi}{T_s}\right)^{1/2} e^{-m_\chi/T_s} = 1 \\[2ex] \left(\dfrac{m_\chi}{m_b}\right)\left(\dfrac{m_\chi}{T_s}\right)^{3/2} e^{-m_\chi/T_s} \sim 10^{-9} \end{array}\right\} \langle\sigma v\rangle \sim 10^9 \times \frac{1}{m_b M_{\rm pl}} \times \left(\frac{m_\chi}{T_s}\right)^2$$

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

Almost independent of m_χ

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

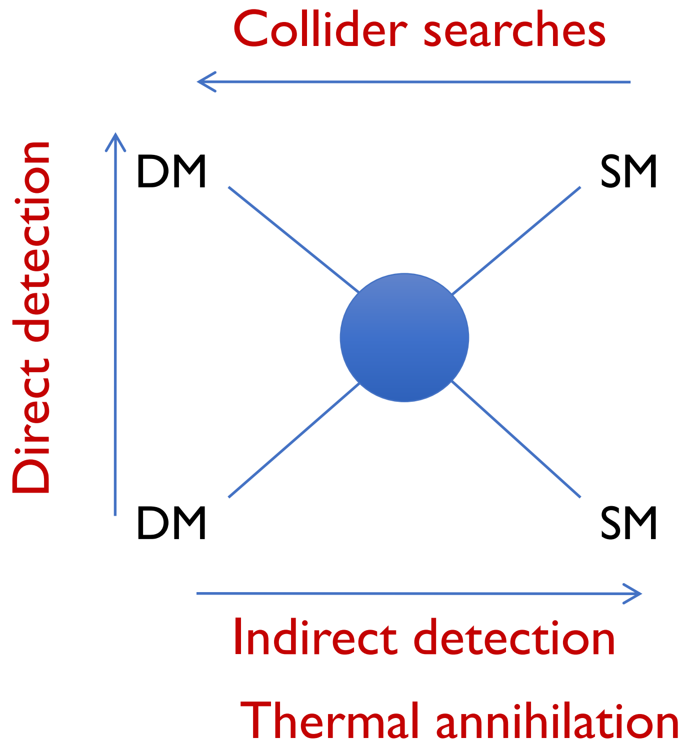
$v_{\rm EW} = 246$ GeV, $m_H = 125$ GeV, $m_{top} = 173$ GeV, $m_W = 80.4$ GeV, $m_Z = 90.2$ GeV,

The WIMP micrale

- The dark matter has to be stable. It should be protected by some symmetry.
- Stable particles in SM:
  - Photon, electron, proton, lightest neutrino
- There should be a new symmtry in the extension of the SM.
  - R-parity in SUSY
  - T-parity in little Higgs models
  - KK-parity in extra dimension models

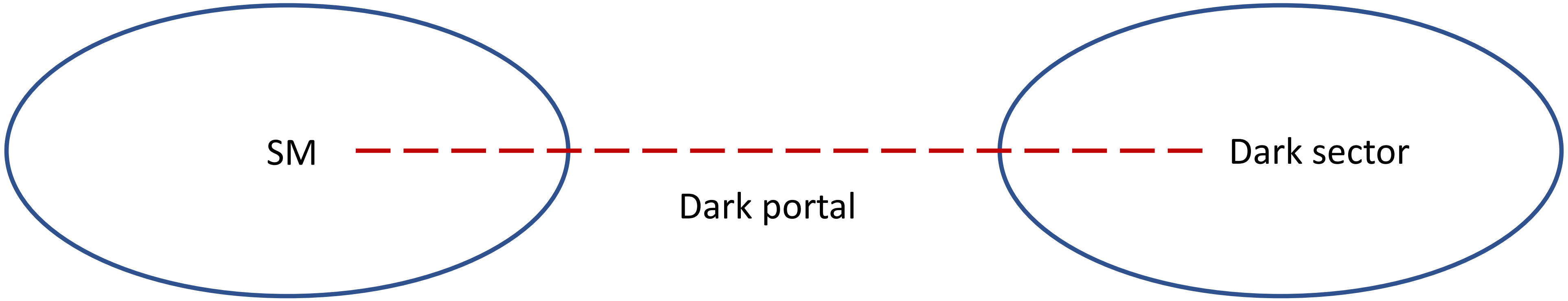
From WIMP to dark sector

- In WIMP models, the detection signals are usually strongly connected to the thermal annihilation.
- But no convincing signals have been found.
- People are forced to invent alternative scenarios.



From WIMP to dark sector

- What is the dark sector model?



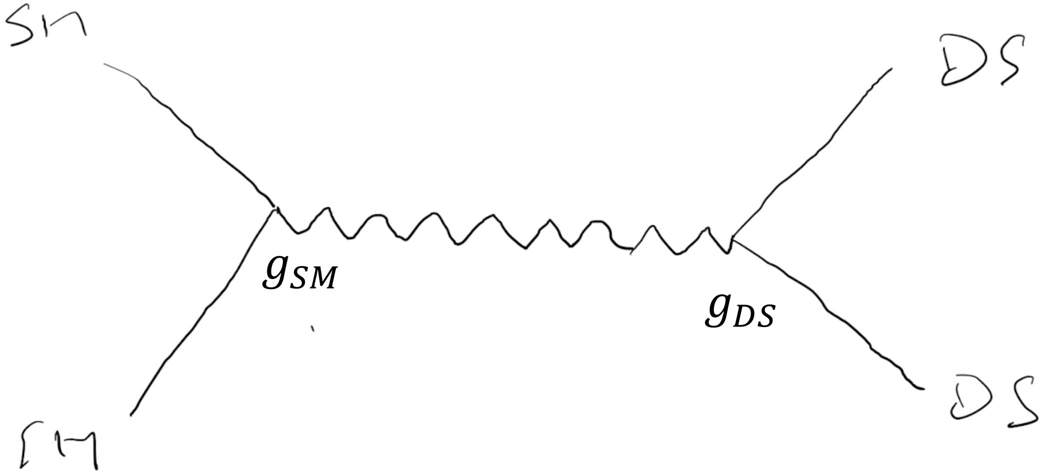
Dark Sector

- Vector dark portal

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

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

Diagram for detection



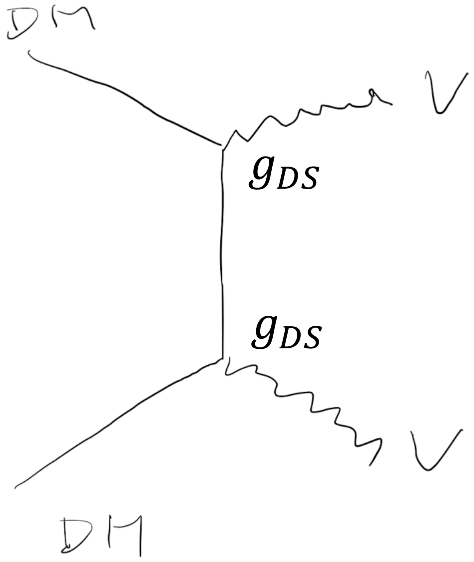


Diagram for annihilation

Dark Sector

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

- To get the observed DM relic density

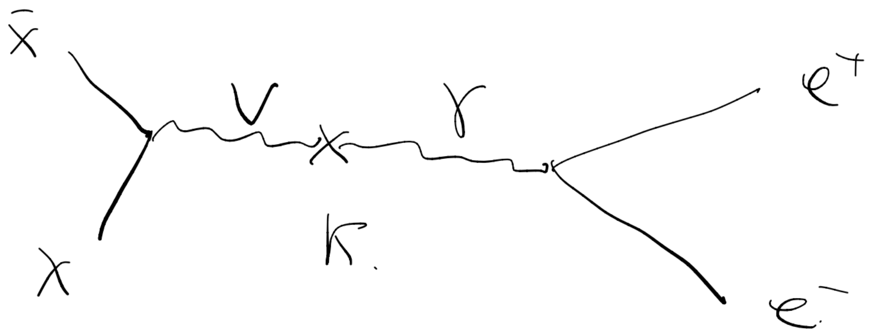
$$\langle \sigma v \rangle \sim 10^{-8}\ \mathrm{GeV} \sim 10^{-25}\ \mathrm{cm}^3/\mathrm{sec}$$

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.

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

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

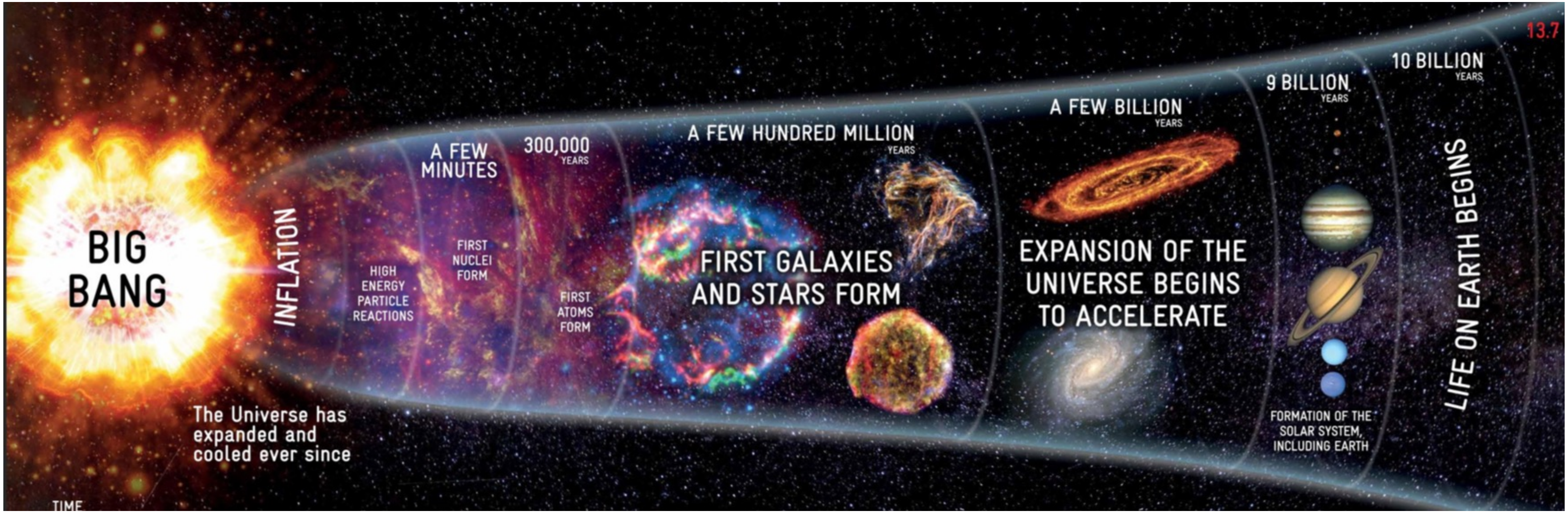
- After diagonalization, the dark photon couples to the EM current.

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

$$e_D V_\mu J_D^\mu \to e_D V_\mu J_D^\mu \longrightarrow$$ The dark current, composed by DM

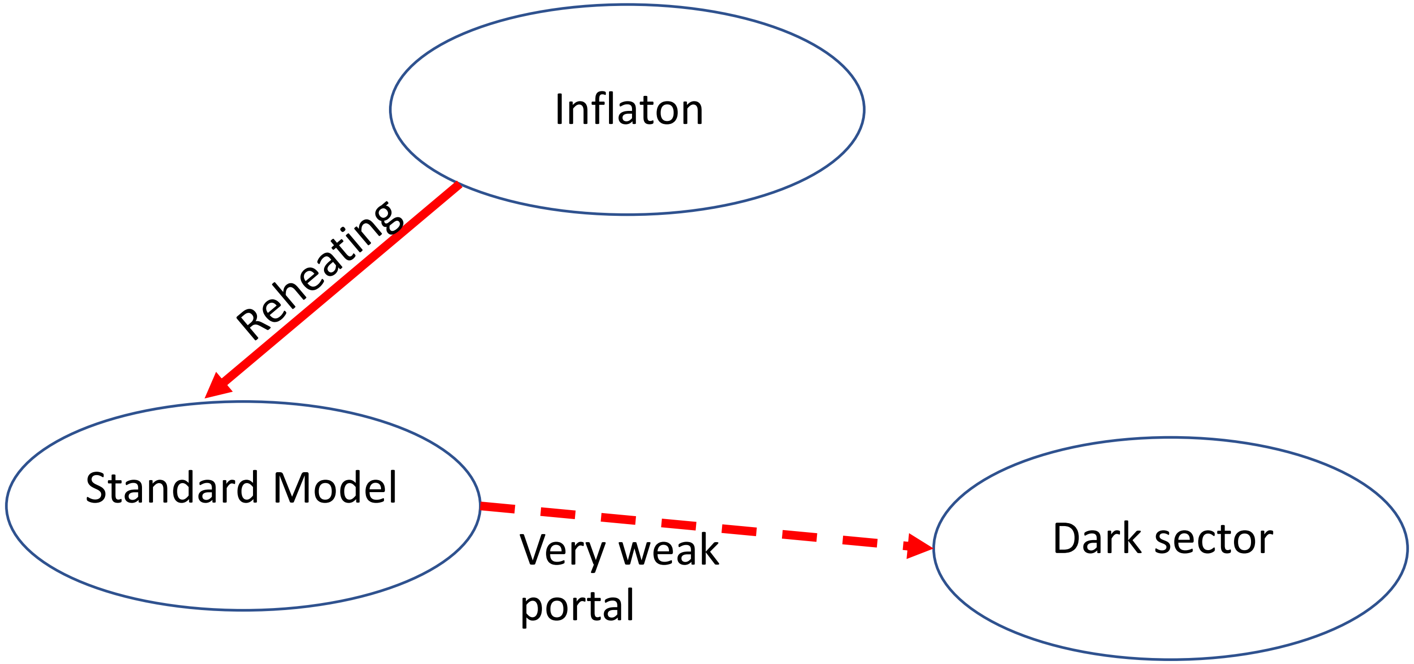
$$g_{\text{SM}} = \kappa e \qquad g_{\text{DS}} = e_D$$

Freeze-in


BIG BANG
INFLATION
HIGH ENERGY PARTICLE REACTIONS
A FEW MINUTES
FIRST NUCLEI FORM
300,000 YEARS
FIRST ATOMS FORM
A FEW HUNDRED MILLION YEARS
FIRST GALAXIES AND STARS FORM
A FEW BILLION YEARS
EXPANSION OF THE UNIVERSE BEGINS TO ACCELERATE
9 BILLION YEARS
FORMATION OF THE SOLAR SYSTEM, INCLUDING EARTH
10 BILLION YEARS
LIFE ON EARTH BEGINS
13.7
The Universe has expanded and cooled ever since
TIME

Freeze-in

- The inflaton field decays mostly to the SM sector.
- At the beginning of the thermal expansion, only SM particles in the thermal bath.
- The energy in the SM sector slowly leaked into the dark sector.



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.

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

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, $\mathcal{O}_{\rm SM}\frac{1}{\Lambda^2}\mathcal{O}_\chi$

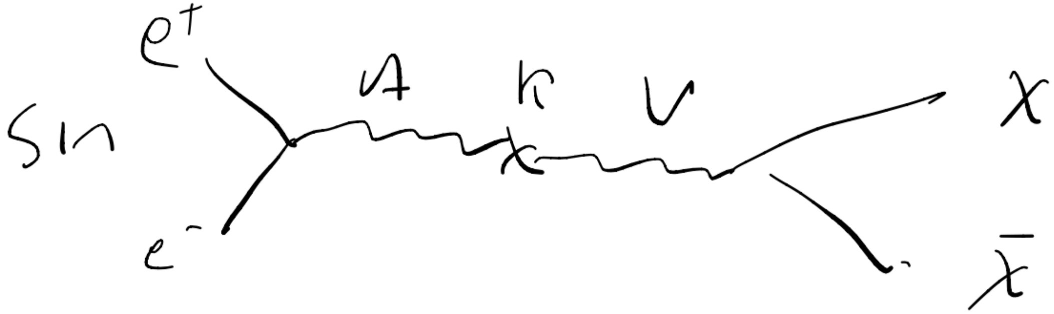
$$\Longrightarrow \quad \Gamma \sim \frac{T^5}{\Lambda^4}$$

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

- Very sensitive to the reheating temperature.

A realistic model

- The dark photon model



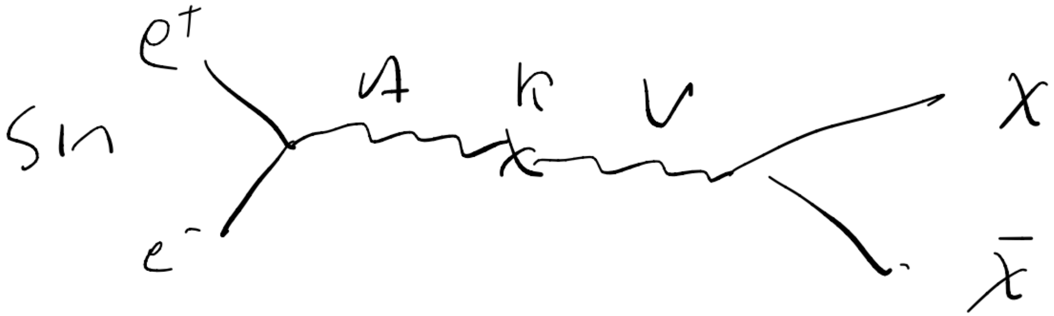
$$\Gamma = \langle \sigma v \rangle n_e \sim \frac{\pi \alpha_{\rm EM} \alpha_D \kappa^2}{T^2} \times T^3 \sim \kappa^2 \alpha_{\rm EM} \alpha_D T$$

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

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

A realistic model

- The dark photon model

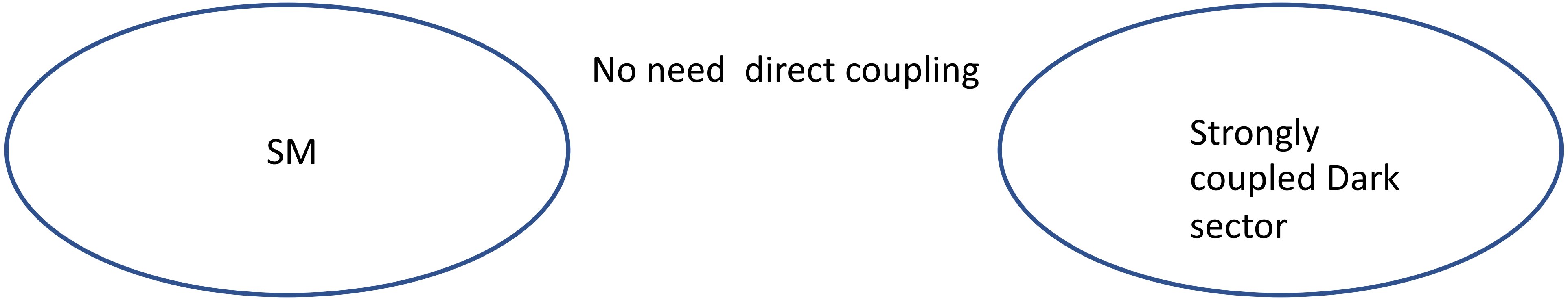


$$\Gamma = \langle \sigma v \rangle n_e \sim \frac{\pi \alpha_{\rm EM} \alpha_D \kappa^2}{T^2} \times T^3 \sim \kappa^2 \alpha_{\rm EM} \alpha_D T$$

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

$$\left.\begin{aligned} \frac{n_\chi}{T^3} &\sim \pi \alpha_{\rm EM} \alpha_D \kappa^2 \times \frac{M_{\rm pl}}{m_\chi} \\ \frac{n_\chi m_\chi}{\eta_b T^3 m_b} &\sim 5 \end{aligned}\right\} \quad \pi \alpha_{\rm EM} \alpha_D \kappa^2 \sim \eta_b \times \frac{m_b}{M_{\rm pl}} \sim 10^{-28}$$

From WIMP to SIMP



SM

No need direct coupling

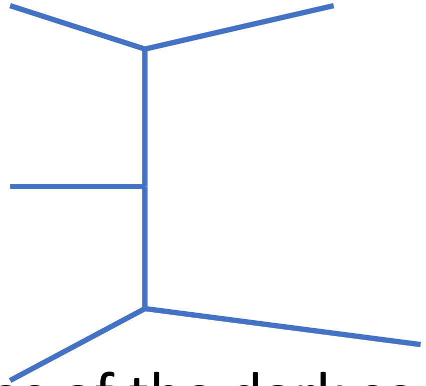
Strongly
coupled Dark
sector

$3 \rightarrow 2$ process is important

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.

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



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

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

- Require at some T_F, $\Gamma_{3\to2} = H$. $\longrightarrow$ $\left(\frac{T_F}{m_\chi}\right)^2 \alpha_{\text{eff}}^3 e^{-2m_\chi/T} \sim \frac{T_F}{M_{\text{pl}}}$

The SIMP model

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

$$\frac{n_\chi m_\chi}{\eta_b T^3 m_b} \sim 5 \quad \Longrightarrow \quad m_\chi \sim 40\ \mathrm{MeV} \times \alpha_{\mathrm{eff}}$$

(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.

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

- 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.

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.)

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)

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

- 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

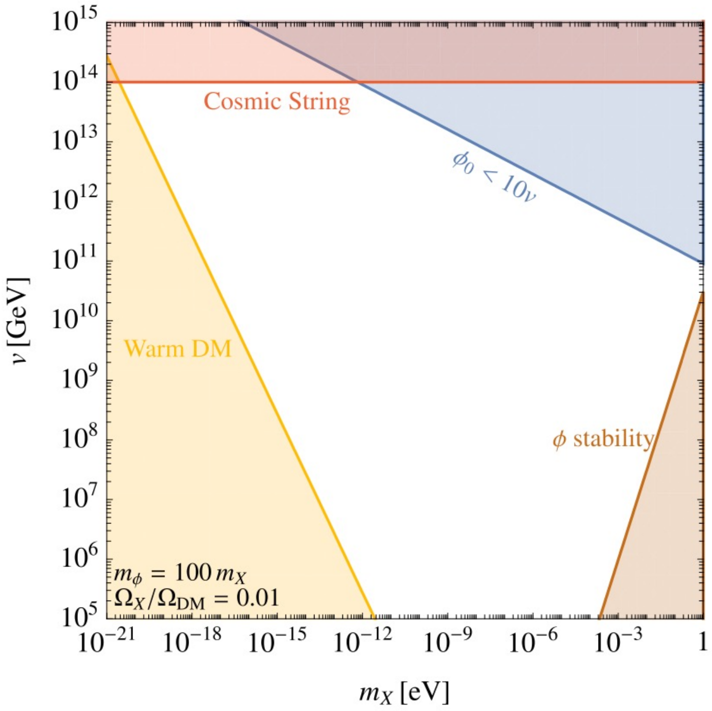
- From quantum fluctuation during inflation

  Graham, Mardon, Majendra (2015)

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

- 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)

- …

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