Theoretical aspects of dark matter physics

Kallia Petraki

Sorbonne Université, LPTHE, Paris and Nikhef, Amsterdam

Advanced Training Institute on Dark Matter
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Outline

Lecture 1

- Evidence for dark matter
- Dark matter properties
- Production mechanisms and particle candidates

Lecture 2

- Production mechanisms and particle candidates (cont)
- Interaction types: contact-type vs long-range
- Current topics

The material contained in these slides is the result of the work of many people. It is impossible to do justice to everybody's work in this limited space, and only very few references are provided. If you would like more references on a particular topic, please ask me later.

I. Evidence for dark matter

Overwhelming evidence

- Rotation curves of galaxies and of galaxy clusters cannot be explained by ordinary matter only.
- Gravitational lensing of background galaxies by clusters requires a significant dark matter component.
- 1E0657-56, aka the Bullet Cluster, shows separation of ordinary matter (gas) from dark matter.
- Cosmic microwave background radiation shows gravitational wells created by dark-matter clustering.

Dark matter in galaxy clusters

In the 1930s, Fritz Zwicky measured the velocity dispersion of galaxies in the Coma Cluster, and inferred its total mass using the Virial theorem.

Virial theorem

$$2\langle K\rangle = -\langle V\rangle$$

$$\frac{1}{2} m\, 3\sigma^2 = \frac{G M_{\mathrm{tot}}(r)\, m}{r}$$

velocity dispersion

He discovered that the luminous matter, i.e. the galaxies in the cluster, accounted for far less mass!

Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.
(16. II. 33.)

Fritz Zwicky, Helvetica Physica Acta Vol.6 p.110-127, 1933

Later on, measurements of the *X*-rays emitted by hot intra-cluster gas through bremsstrahlung, showed that the gas cannot account for the missing mass.

Galaxy clusters are DM dominated!

Rotation curves of galaxies

In 1970, Vera Rubin discovered that the rotation curves of galaxies are approximately flat.

Newtonian dynamics

$$F = \frac{GMm}{r^2} = \frac{mv^2}{r}$$

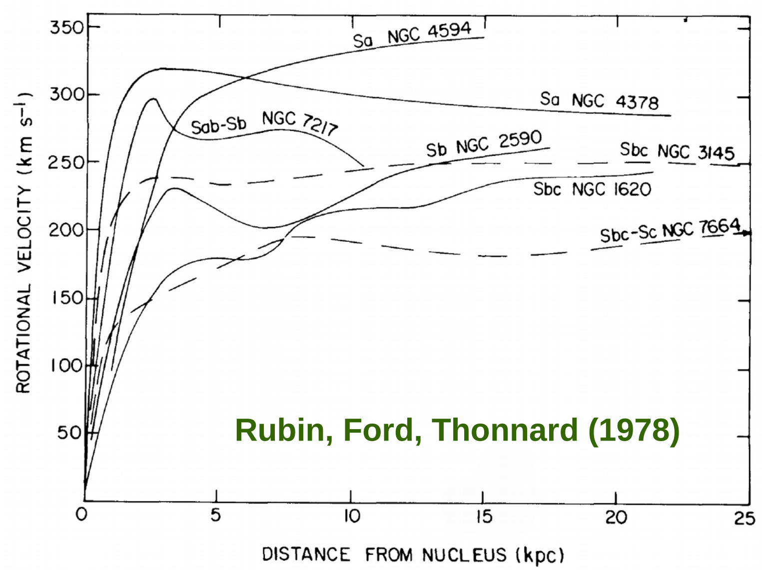
Assuming only the star density, which falls exponentially with r,

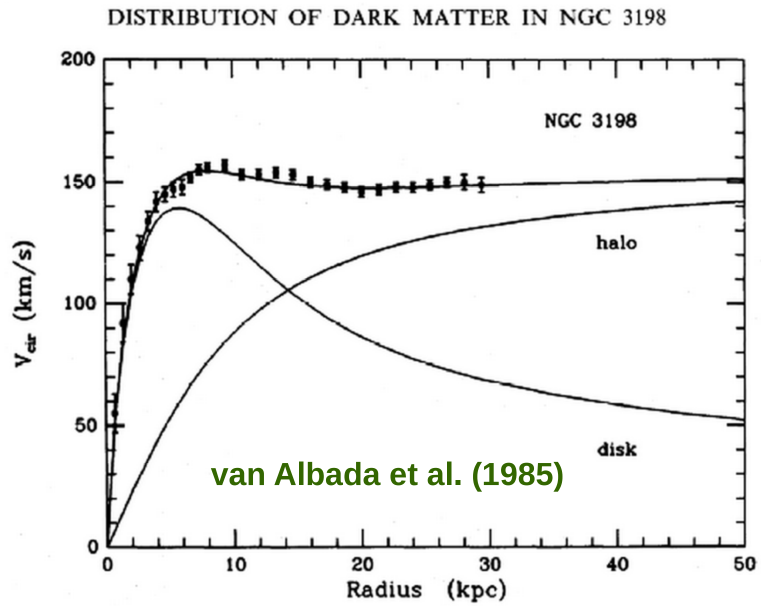
$$v \propto r^{-1/2}$$

For constant v,

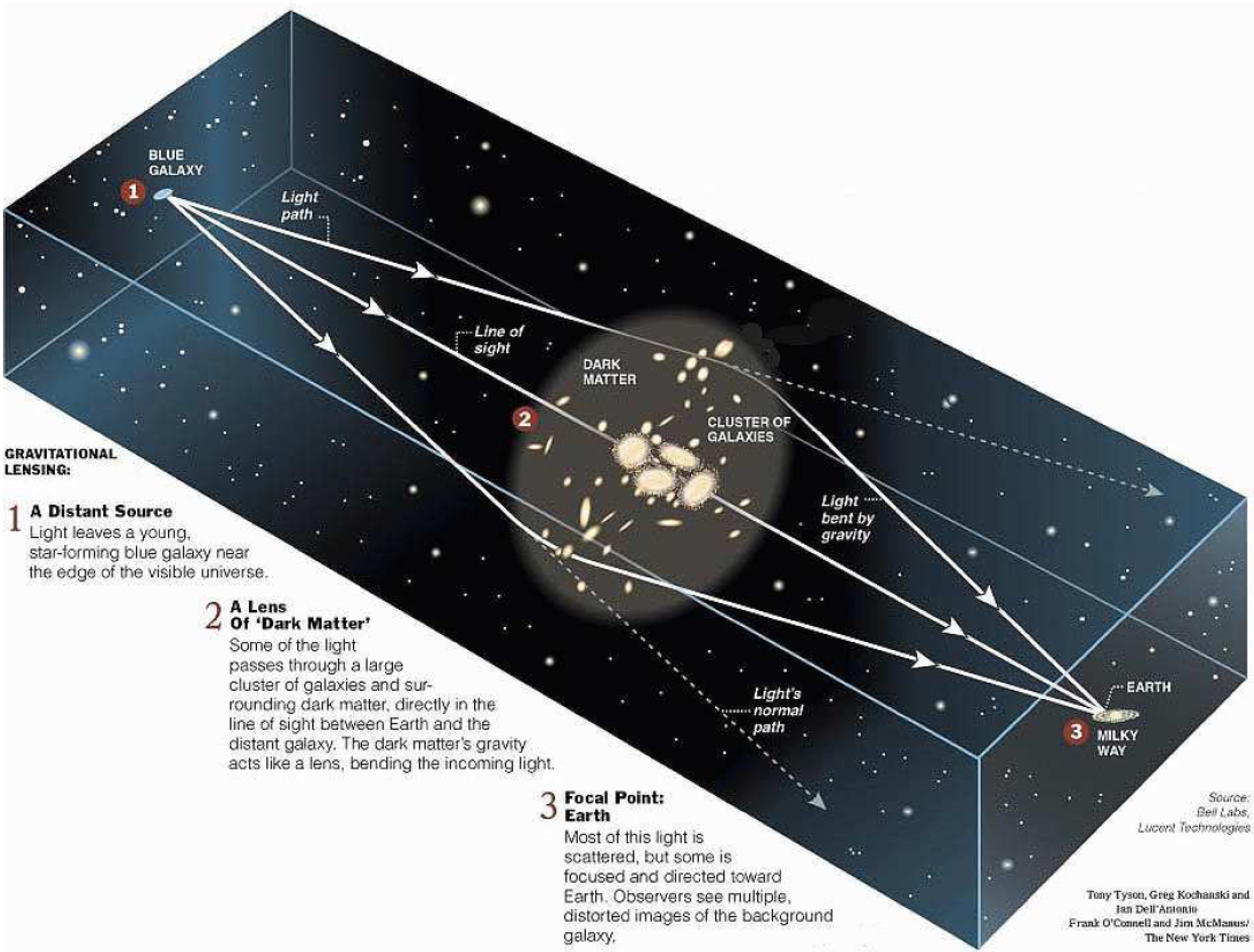
$$M(r) \propto r, \quad \rho(r) \propto r^{-2}$$
$$\Downarrow$$

Extended DM halo!

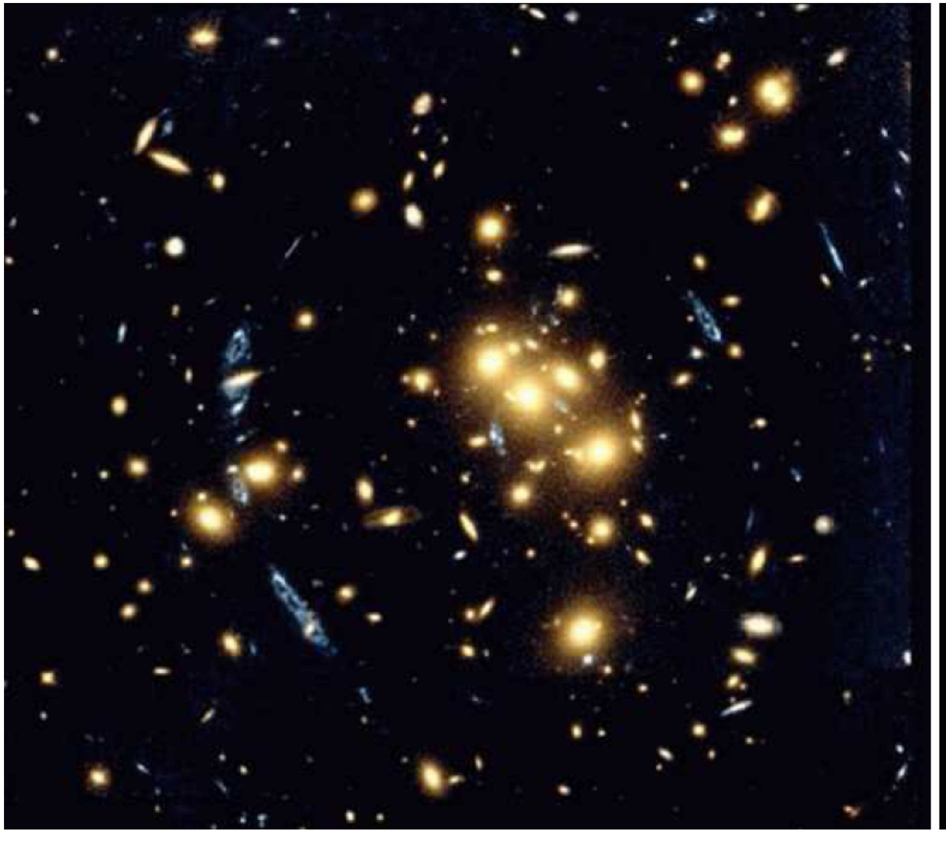


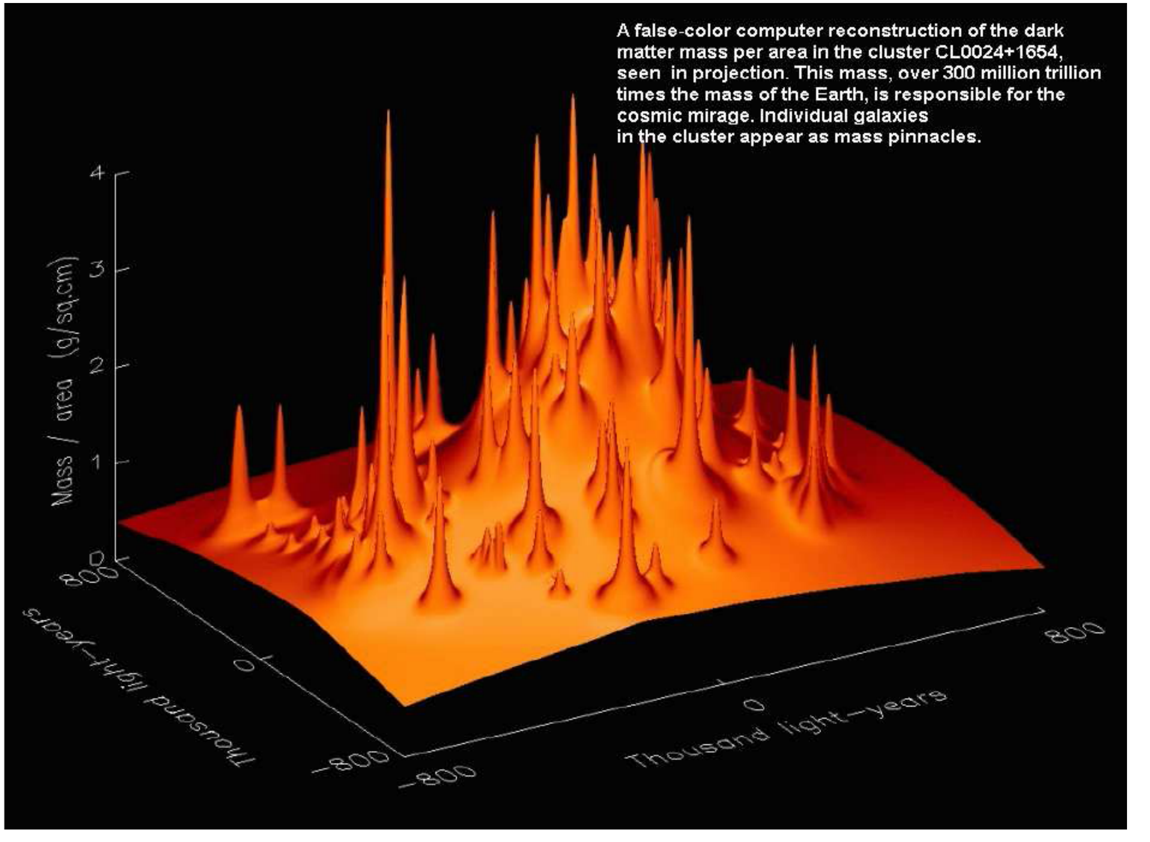


Gravitational lensing



Gravitational lensing

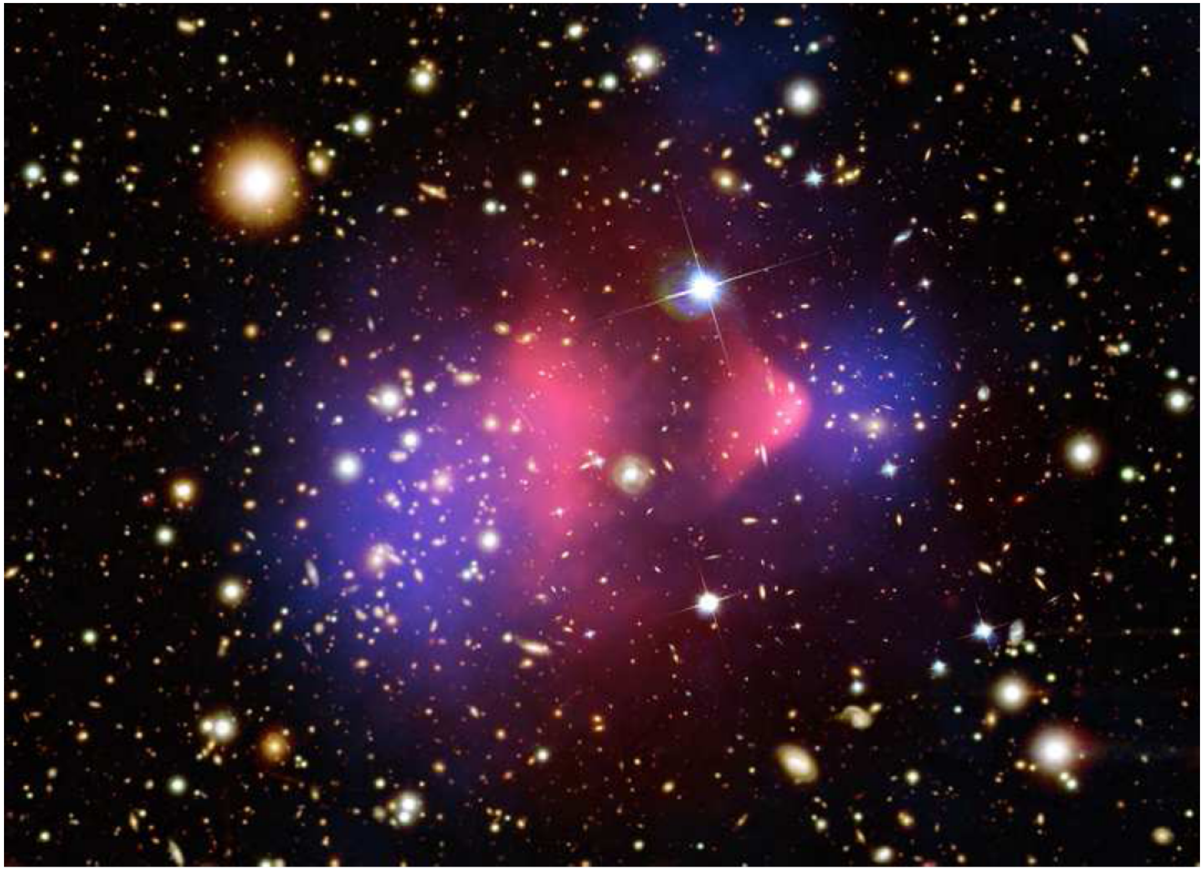




Foreground cluster CL0024+1654 produces multiple images of a blue background galaxy.

Dark matter mass reconstruction of CL0024+1654

The Bullet Cluster



Stars: optical

Gas: X-rays

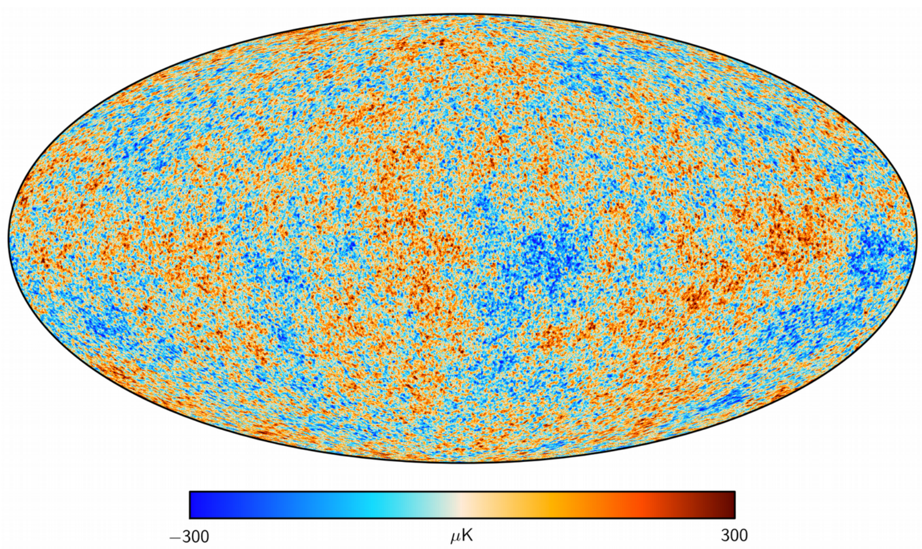
Total mass: gravitational lensing

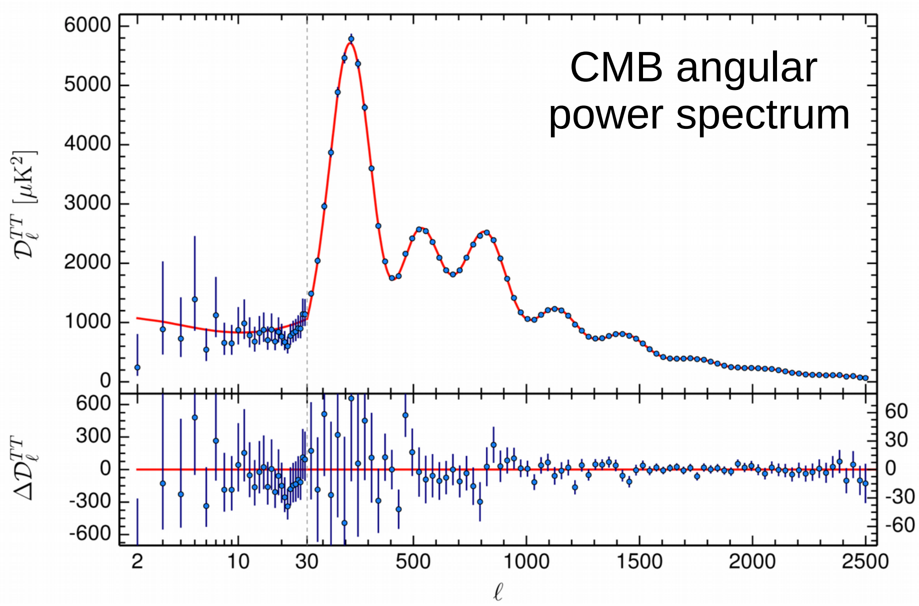
Separation of gas from the bulk of gravitating mass

- Strongly supports the DM hypothesis
- Sets upper limit on DM self-scattering, $\sigma/m_{DM} < 1.3$ barn/GeV $= 0.7\ \mathrm{cm}^2/\mathrm{g}$

Cosmic Microwave Background

CMB temperature fluctuations





Images by Planck 2015

When the universe was at temperature $T \sim \mathrm{eV}$, atoms formed and the universe became transparent to radiation.

The photon bath from that time has red-shifted into the microwave range, $T = 2.725$ K.

Temperature fluctuations measure the gravitational wells created by DM clustering!

Decompose temperature field in spherical harmonics

$$T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{T,\ell m}\, Y_{\ell m}(\hat{n})$$

$$C_\ell^{TT} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{T,\ell m} a^*_{T,\ell m}$$

The CMB angular power spectrum depends on several parameters, including Ω_B, Ω_{M}, Ω_Λ

Particle dark matter or modified gravity?

Modified Newtonian Dynamics (MOND)

In 1983, Milgrom proposed that Newtonian dynamics fails at very low accelerations.

Characteristic acceleration

$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\ s^{-2}}$$

$$a \gg a_0: \qquad a = GM/r^2$$

$$a \ll a_0: \qquad a^2/a_0 = GM/r^2$$

$$\Downarrow \quad a = v^2/r$$

$$v_\infty^4 = GM_{\mathrm{tot}}a_0^2$$

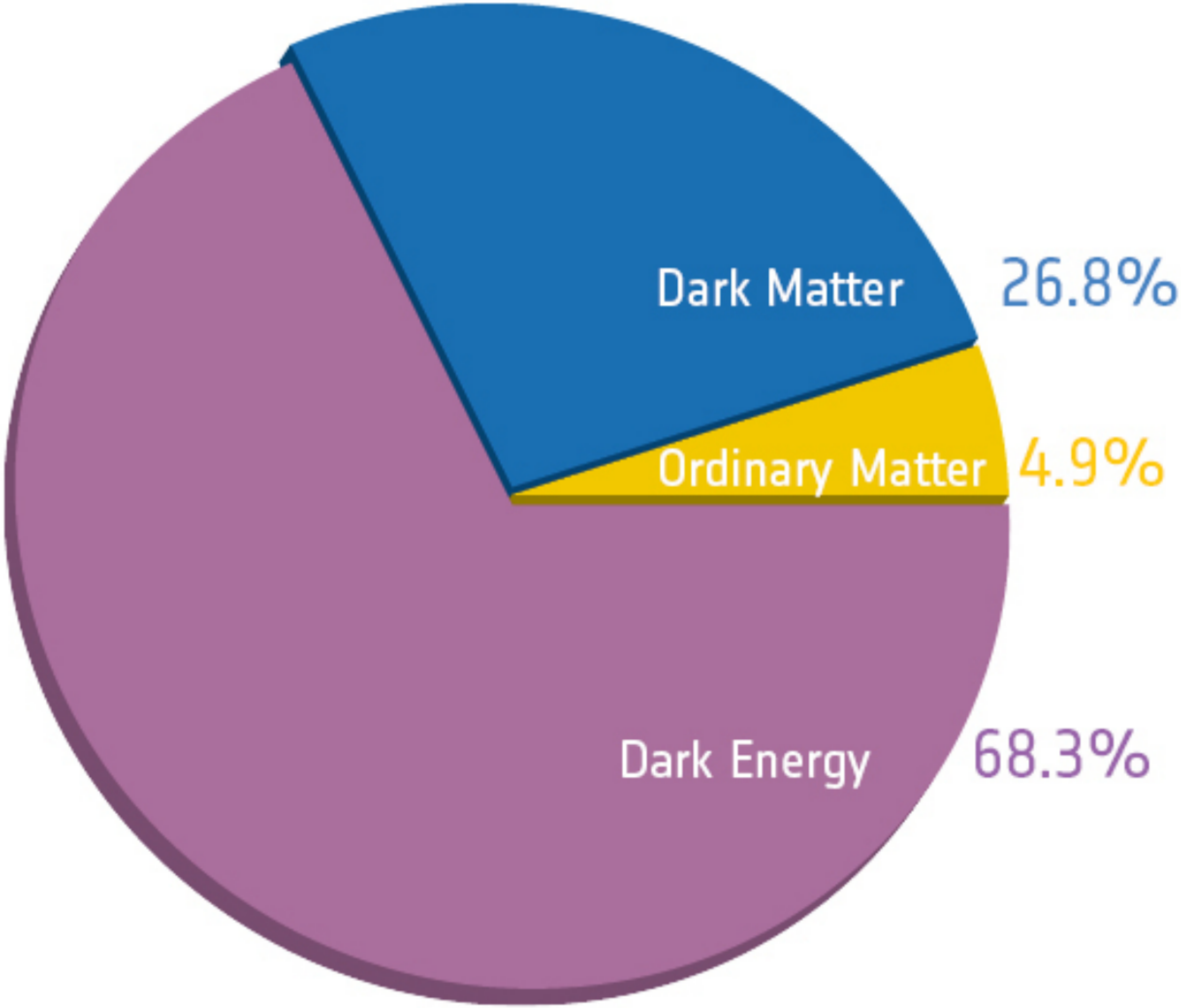
Explains flatness of rotational curves!

Very successful in galaxies.

However, MOND and relativistic generalizations

- fail at galaxy clusters;
- cannot explain the separation of the gas from the bulk of gravitating matter in the Bullet Cluster;
- cannot explain the CMB!

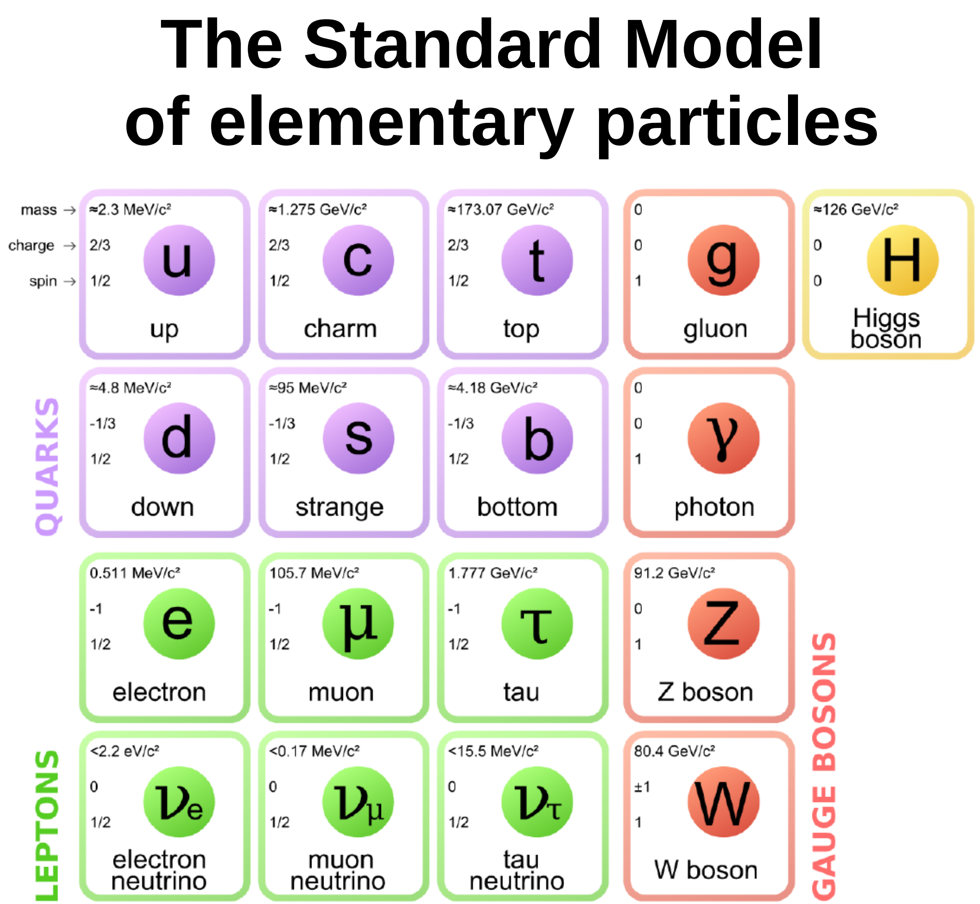
Our Universe



Planck 2015

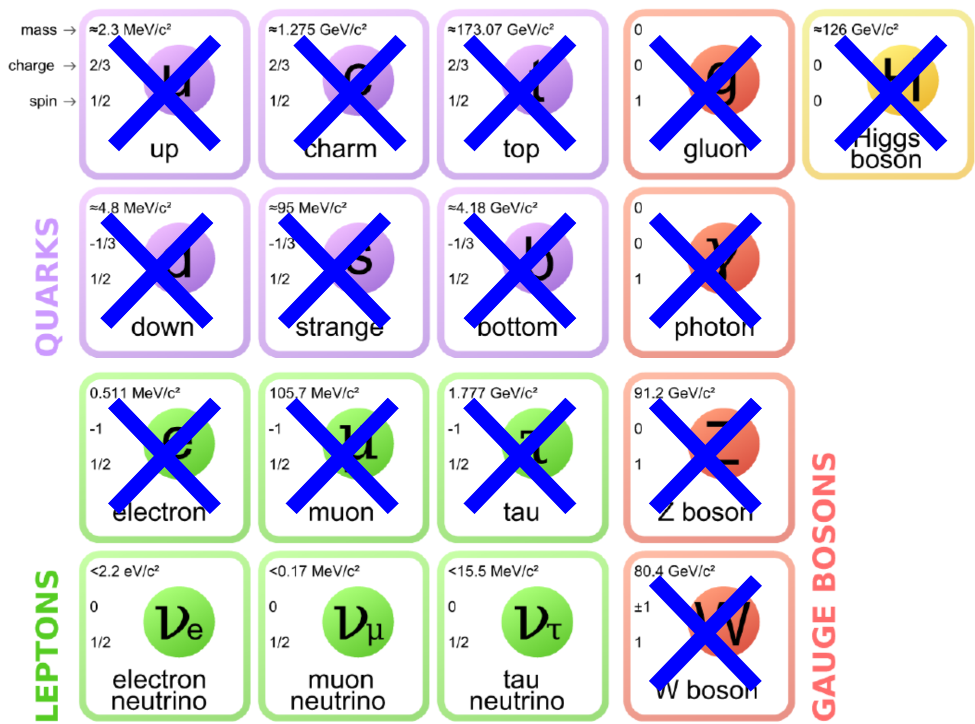
II. Dark matter properties

The knowns


The Standard Model
of elementary particles
mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

The knowns

The Standard Model of elementary particles

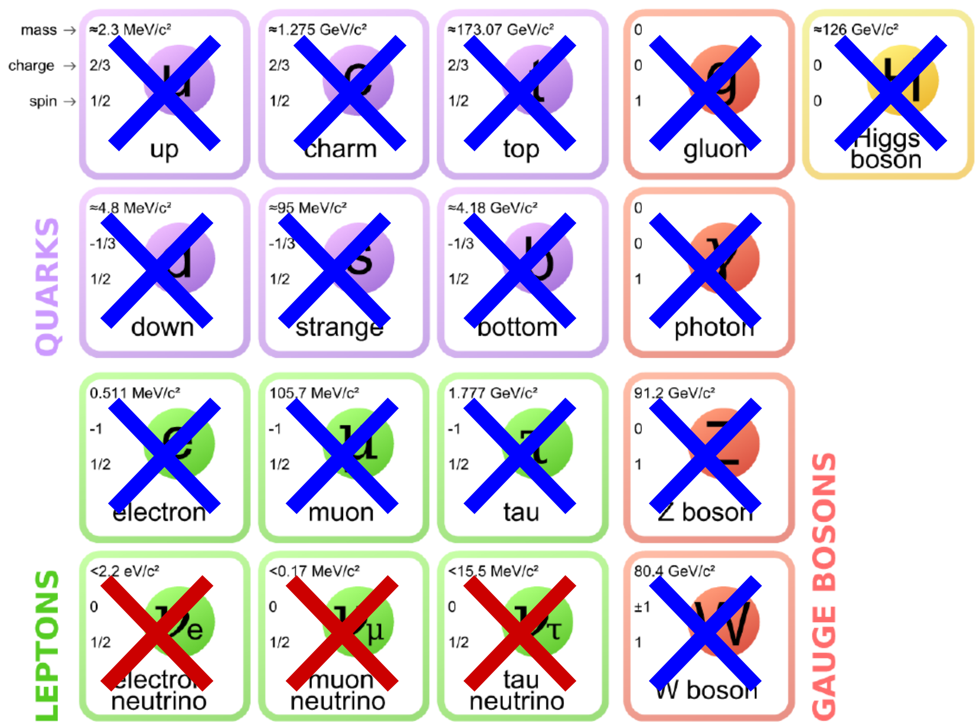


Dark Matter

- Stable or long-lived, $\tau >> t_U$
- Not electrically charged
- Non-relativistic today

The knowns

The Standard Model of elementary particles



DM: not a known particle!

Dark Matter

- Stable or long-lived, $\tau >> t_U$
- Not electrically charged
- Non-relativistic today
- **$\Omega_{DM} \simeq$ 26%** of our universe
- Large-scale gravitational clustering: **not hot**
  [hot = relativistic when gravitational clustering started]

The canonical paradigm of structure formation

Collisionless Cold Dark Matter (ΛCDM)

→ James Bullock's lecture

- **Cold DM**

  DM particles were non-relativistic when gravitational clustering started, at the time of matter-radiation equality (redshift z ~ 3400, *T* ~ eV)

- **Collisionless DM**

  (a) No significant self-scattering.
  (b) Early kinetic decoupling from the relativistic plasma.

- **Reproduces the large-scale structure (> Mpc) very well!**
- At galactic and sub-galactic scales, gravity-only simulations of collisionless ΛCDM predict too rich structure.

  Possible discrepancies with observations: "cusps vs cores", "missing satellites", "too-big-to-fail" → **too much matter in the centers of galaxies.**

Small-scale structure
Possible resolutions

- **Baryonic physics**

  Hydrodynamic simulations: modeling of star feedback. Successes and failures. Very active field.

- **Shift in the DM paradigm**

  Aim to retain success of collisionless ΛCDM at large scales, suppress structure at small scales

  – **Warm DM**

    Suppresses structure below a scale (free-streaming length).

  – **Self-interacting DM**

    Self-scatterings inside halos redistribute energy and momentum and heat up low-entropy material → overdensities get smoothed out, star-formation rate is suppressed.

Self-interacting dark matter

- Cross-section needed to affect galactic structure

$$\sigma_{\mathrm{self-scatt}}/m_{\mathrm{DM}} \sim \mathrm{barn/GeV} \sim \mathrm{cm^2/g}$$

  at dwarf-galaxy scales, v_{DM} ~ 20 km/s.

- Upper limit from Bullet Cluster is of the same order, at v_{DM} ~ 1000 km/s.

- No tension between the two, if $\sigma_{\text{self-scatt}}$ decreases with increasing v_{DM}
  $\Rightarrow$ Light mediators, long-range interactions!

III. Production mechanisms and particle candidates

Production mechanisms ↔ Candidates

thermal history

non-thermal history

Production mechanisms	Candidates
• **Freeze-out** ➢ Standard Model plasma ➢ Dark-sector plasma	• WIMPs (e.g. neutralino in SUSY, minimal DM) • Particles coupled to SM via heavy mediators (e.g. Z', Higgs portal); • Dark U(1), dark QCD
• **Asymmetry generation & freeze-out**	Mirror DM, technicolor dark QCD, dark U(1)
• **Freeze-in**	Sterile neutrino, gravitino
• **Collapse of density perturbations**	Primordial black holes → Anne Green's lecture
• **Scalar condensates** ➢ Fragmentation ➢ Misalignment	Q-balls (solitonic DM) Axions

III. Production mechanisms and particle candidates

- Non-relativistic thermal freeze-out
- Asymmetry generation & freeze-out
- Freeze-in

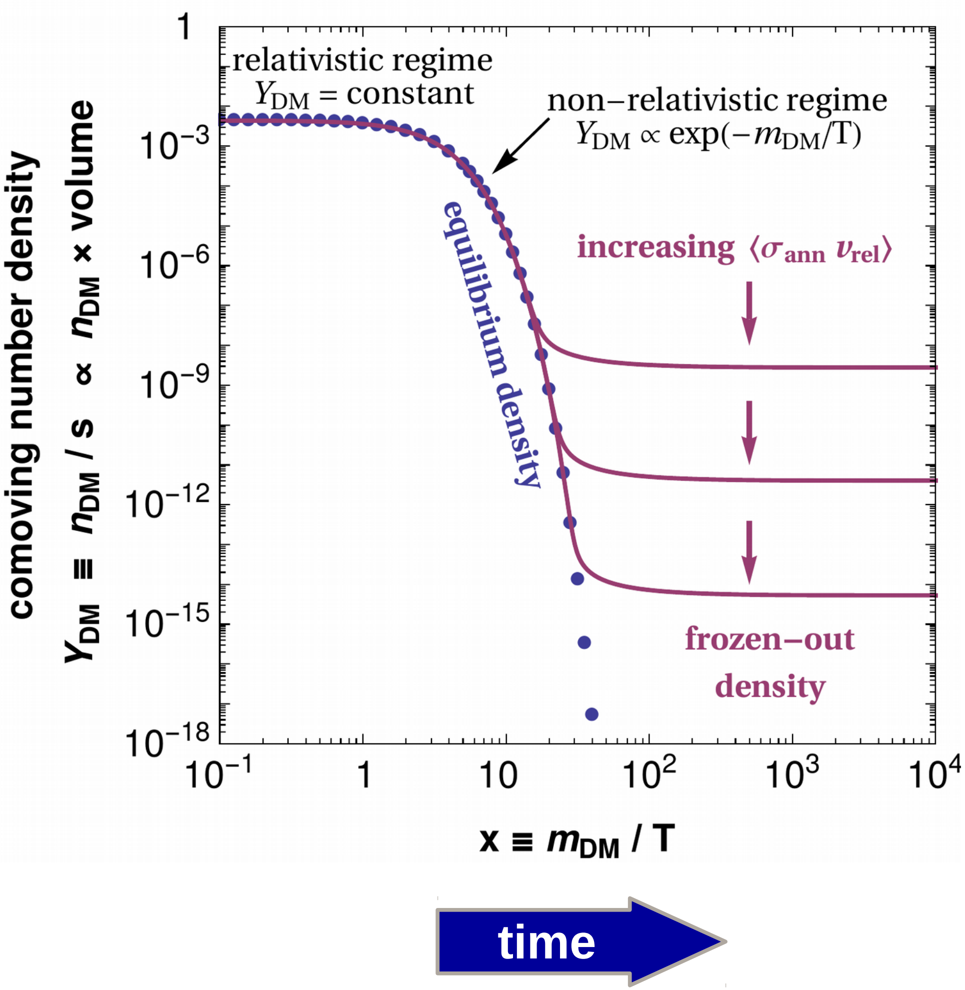
Non-relativistic thermal freeze-out

Motivation

Very generic possibility within the standard cosmological story!

Non-relativistic thermal freeze-out

How does it work?



- **At $T > m_{DM} / 3$:**
  DM is kept in chemical & kinetic equilibrium with the plasma, via
  $$X + \bar{X} \leftrightarrow f + \bar{f}$$
  $n_{DM} \sim T^3$ or Y_{DM} = const.

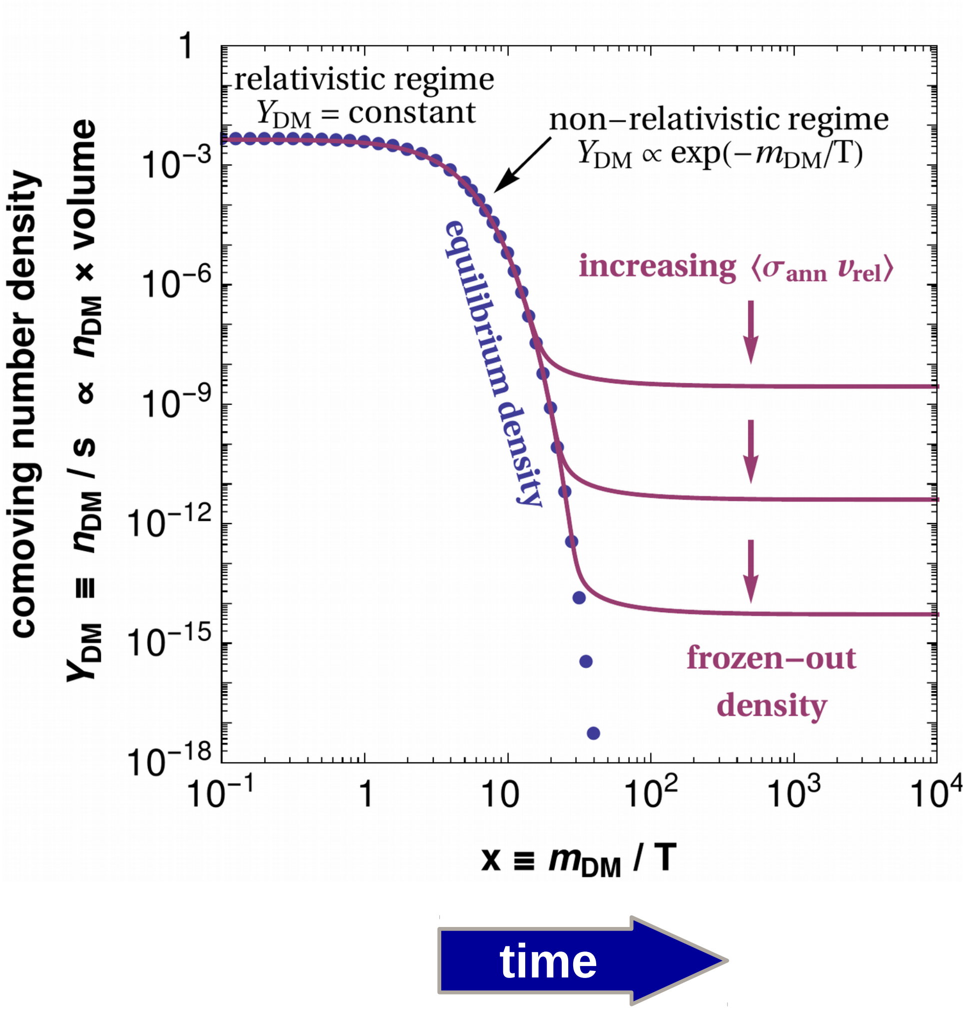
- **At $T < m_{DM} / 3$:** $Y_{DM} \propto \exp(-m_{DM} / T)$, while still in equilibrium

- **At $T < m_{DM} / 25$:** Density too small, annihilations stall ⇒ **Freeze-out!**
  $$\Omega \simeq 0.26 \times \left(\frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\sigma_{\mathrm{ann}} v_{\mathrm{rel}}} \right)$$

"canonical" annihilation cross-section

Non-relativistic thermal freeze-out

How does it work?



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- **At $T < m_{DM}/25$:** Density too small, annihilations stall **⇒ Freeze-out!**
  $$\Omega \simeq 0.26 \times \left(\frac{1pb \cdot c}{\sigma_{ann} v_{rel}}\right)$$

"canonical" annihilation cross-section

Non-relativistic thermal freeze-out

How does it work?

[Gondolo, Gelmini (1990)]

- **Boltzmann equation** (no asymmetry, $n_X = n_{\bar{X}}$)

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{\rm ann} v_{\rm rel} \rangle \left(n_X^2 - n_X^{\rm eq\,2} \right)$$

Non-relativistic thermal freeze-out

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  - Dilution due to the expansion of the universe

$$n_X \propto a^{-3} \quad \Rightarrow \quad \frac{1}{n_X}\frac{dn_X}{dt} = \frac{1}{a^{-3}}\frac{d(a^{-3})}{dt} = -\frac{3\dot{a}}{a} = -3H$$

Non-relativistic thermal freeze-out

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  - Collision term: Annihilations $X + \bar{X} \to f + \bar{f}$ $(m_f < m_X)$

$$\left.\frac{dN_X}{dt dV}\right|_{X\bar{X}\to f\bar{f}} = n_X n_{\bar{X}} \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle = n_X^2 \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle$$

Non-relativistic thermal freeze-out

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$$\left.\frac{dN_X}{dtdV}\right|_{X\bar{X}\to f\bar{f}} = n_X n_{\bar{X}} \langle \sigma_{\rm ann} v_{\rm rel} \rangle = n_X^2 \langle \sigma_{\rm ann} v_{\rm rel} \rangle$$

- Collision term: Pair creation $f + \bar{f} \to X + \bar{X}$ $\quad$ ($f,\bar{f}$ in equilibrium)

$$\left.\frac{dN_X}{dtdV}\right|_{f\bar{f}\to X\bar{X}} = \langle \sigma_{f\bar{f}\to X\bar{X}} v_{\rm rel} \rangle \left[n_f^{\rm eq} n_{\bar{f}}^{\rm eq} \right]_{E_f + E_{\bar{f}} = E_X + E_{\bar{X}}}$$

$$= n_X^{\rm eq} n_{\bar{X}}^{\rm eq} \langle \sigma_{\rm ann} v_{\rm rel} \rangle$$

using
$|\mathcal{M}|^2_{f\bar{f}\to X\bar{X}} = |\mathcal{M}|^2_{X\bar{X}\to f\bar{f}}$

Non-relativistic thermal freeze-out

How does it work?

[Gondolo, Gelmini (1990)]

Principle of detailed balance!

- **Boltzmann equation** (no asymmetry, $n_X = n_{\bar{X}}$)

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma_{\rm ann} v_{\rm rel}\rangle \left(n_X^2 - n_X^{\rm eq\,2}\right)$$

– Dilution due to the expansion of the universe

$$n_X \propto a^{-3} \quad \Rightarrow \quad \frac{1}{n_X}\frac{dn_X}{dt} = \frac{1}{a^{-3}}\frac{d(a^{-3})}{dt} = -\frac{3\dot{a}}{a} = -3H$$

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$$= n_X^{\rm eq} n_{\bar{X}}^{\rm eq} \langle\sigma_{\rm ann} v_{\rm rel}\rangle$$

using

$$|\mathcal{M}|^2_{f\bar{f}\to X\bar{X}} = |\mathcal{M}|^2_{X\bar{X}\to f\bar{f}}$$

Non-relativistic thermal freeze-out

How does it work?

[Gondolo, Gelmini (1990)]

- **Initial conditions:** Thermal distribution

$$\text{At } \; T < m_X/3: \qquad n_X^{\rm eq} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

Note: Boltzmann equation is self-correcting ⇒ It will restore n_X to the equilibrium distribution, even if it starts from non-equilibrium initial conditions, ***provided that collision terms are sufficiently large*****.**

That is, ***freeze-out has no memory*** (contrast with freeze-in later on).

Non-relativistic thermal freeze-out

How does it work?

[Gondolo, Gelmini (1990)]

- **Factor out the expansion of the universe:**

  In thermal equilibrium, the total entropy *S* is conserved.
  The entropy density $s = S/a^3$ follows

$$ds/dt = -3\,H\,s$$

$$Y_x \equiv n_x/s \;\propto\; n_x a^3$$

co-moving number density

$$\dot{n}_x + 3Hn_x = s\dot{Y}_x$$

Boltzmann equation

$$\dot{Y}_x = -s\,\langle\sigma v_{\rm rel}\rangle\,(Y_x^2 - Y_x^{\rm eq\,2})$$

The comoving density stays constant when annihilations become inefficient

freeze-out when $n_x\langle\sigma_{\rm ann}v_{\rm rel}\rangle \lesssim H$

$$\Rightarrow \Omega_x = \frac{m_x Y_x s_0}{\rho_c}\;(\times 2)$$

entropy density of the universe today

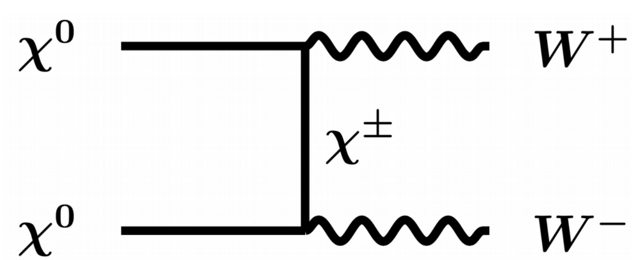
if DM non-self-conjugate

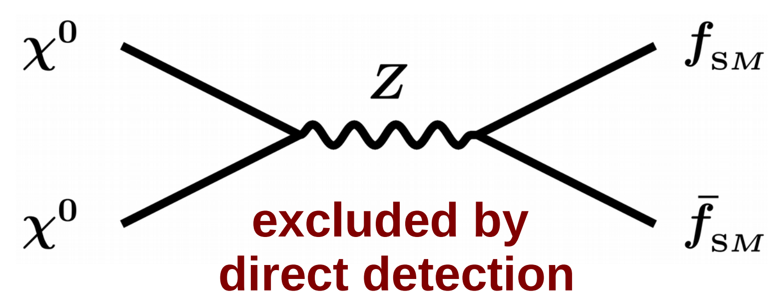
Non-relativistic thermal freeze-out

Particle candidates

- **Weakly interacting massive particles (WIMPs), coupled to the SM gauge interactions $SU(2)\times U_Y(1)$.**

  Motivated by the electroweak hierarchy problem.
  ⇒ Expect new physics at the electroweak scale.
  Caveat: Not all WIMP scenarios address the hierarchy problem.





Expected annihilation cross-section:

$$\sigma_{\mathrm{ann}} v_{\mathrm{rel}} \sim \frac{\alpha_2^2}{m_W^2} \sim \mathcal{O}(pb) \quad [\text{if } m_{\mathrm{DM}} \sim m_W]$$

WIMP miracle!

Non-relativistic thermal freeze-out
Particle candidates

- **Weakly interacting massive particles (WIMPs), coupled to the SM gauge interactions $SU(2)\times U_Y(1)$.**

Motivated by the electroweak hierarchy problem
⇒ expect new physics at the electroweak scale.
Caveat: Not all WIMP scenarios address the hierarchy problem.

Reality is typically more complicated!

Expected annihilation cross-section:

$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{\alpha_2^2}{m_W^2} \sim \mathcal{O}(pb) \quad [\text{if } m_{\rm DM} \sim m_w]$$

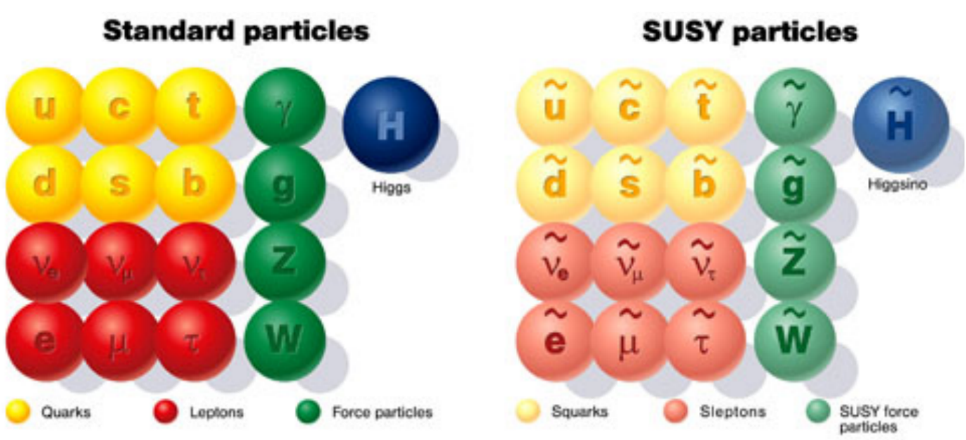
WIMP miracle!

Non-relativistic thermal freeze-out

Particle candidates

- **Weakly interacting massive particles (WIMPs), coupled to the SM gauge interactions $SU(2)\times U_Y(1)$.**

  - **Neutralino in SUSY models**



Lightest SUSY particle
stabilized by *R*-parity (not SUSY)

$$R = (-1)^{3(B-L)+2S}$$

SM particles: +1, SUSY particles: -1

The DM candidate is a linear combination of the neutral superpartners:

Bino, Wino, Higgsinos.

Plethora of annihilation channels.

Coannihilations potentially important, e.g. mass-degenerate neutralino-stop scenario.

Relic density within the MSSM parameter space varies by many orders of magnitude.

Non-relativistic thermal freeze-out

Particle candidates

- **Weakly interacting massive particles (WIMPs), coupled to the SM gauge interactions $SU(2)\times U_Y(1)$.**
  - **Inert (Higgs) doublet models**

    Stability due to Z_2 symmetry. Mass $\gtrsim$ 500 GeV from freeze-out.

  - **Minimal scenarios**

    Neutral component of a pure $SU(2)_L$ multiplet

$$\delta\mathcal{L} = \bar{X}(i\not{D} - m_x)X \quad \text{or} \quad (D_\mu X)(D^\mu X)^\dagger - m_x^2|X|^2$$

    Hypercharge determined by requiring one component to be neutral.

    For stability against renormalizable and Planck-suppressed operators, *X* has to be a spin-(1/2) 5-plet (unless other physics invoked).

    m_X~few TeV, determined by freeze-out (Sommerfeld effect important [*])

    Pure-multiplet scenarios encountered also within the MSSM (e.g. Wino).

[*] see discussion on long-range interactions

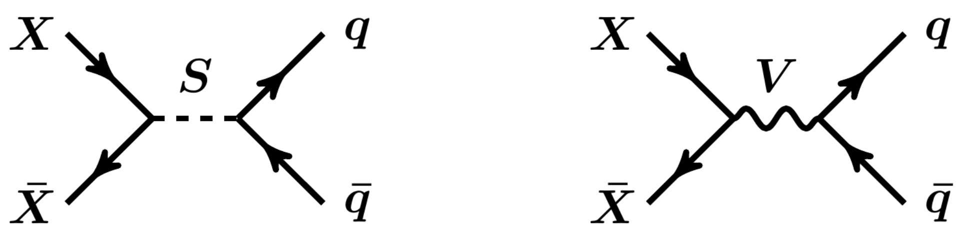
Non-relativistic thermal freeze-out
Particle candidates

- **Massive particles interacting weakly with the SM, via new (non-SM) heavy mediators.**

Such interactions are often parametrized with *effective operators*, e.g.

$$\delta\mathcal{L} \supset \overset{\text{scalar med}}{\frac{g_{XS}\,g_{qS}}{\Lambda^2_{\rm NP}}\,\bar{X}X\;\bar{q}q}, \qquad \overset{\text{vector med}}{\frac{g_{XV}\,g_{qV}}{\Lambda^2_{\rm NP}}\,\bar{X}\gamma^{\mu}X\;\bar{q}\gamma_{\mu}q}$$

scale of
new physics



Many more effective operators. Useful for placing model-independent constraints. Caveats:

- EFT does not hold at high energies → important for LHC.
- UV-complete models may contain more than one of these interactions.

→ Marcela Carena's lecture

Non-relativistic thermal freeze-out

Particle candidates

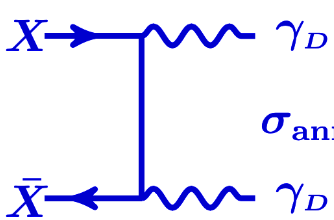
- **Thermal relics of dark sectors, annihilating into new light species**

E.g. DM charged under a dark gauged $U_{\text{D}}(1)$

$$
\begin{aligned}
\mathcal{L} &= \bar{X}(i\not{D} - m_X)X - \frac{1}{4}F_D^{\mu\nu}F_{D\,\mu\nu} + m_{\gamma_D}^2 A_D^\mu A_{D\,\mu} \\
D^\mu &= \partial^\mu + i g_D A_D^\mu \\
F_D^{\mu\nu} &= \partial^\mu A_D^\nu - \partial^\nu A_D^\mu
\end{aligned}
$$

Dark photon mass;
generated via dark Higgs or
Stueckelberg mechanisms

If $m_{\gamma_D} < m_X$



$\sigma_{\text{ann}} v_{\text{rel}} = \frac{\pi\alpha_D^2}{m^2}$

Freeze-out computation
specifies $\alpha_D = \alpha_D(m_X)$

The dark plasma may have different temperature than the SM. If in thermal contact early on, T_{SM} and T_{D} related via entropy conservation at later times

$$\frac{g_{*S}^{D}(T_D)\, T_D^3}{g_{*S}^{\text{SM}}(T_{\text{SM}})\, T_{\text{SM}}^3} = \frac{g_{*S}^{D}(T_{\text{common}})}{g_{*S}^{\text{SM}}(T_{\text{common}})}$$

More to
be said
on this!

More complex dark sectors possible!

Non-relativistic thermal freeze-out

Particle candidates – summary

- Weakly interacting massive particles (WIMPs),
  coupled to the SM gauge interactions $SU(2)\times U_Y(1)$
- Massive particles interacting weakly with & annihilating into the SM
  via non-SM mediators
- Thermal relics of dark sectors [aka secluded, hidden/dark sector DM],
  annihilating into dark radiation

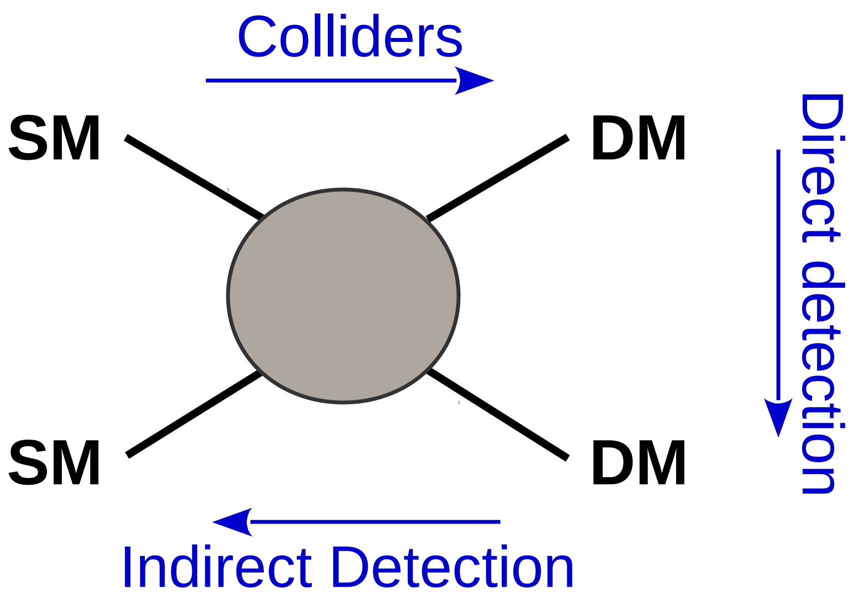
Often collectively referred to as
“WIMPs”

… but keep in mind ...

they do NOT possess the same
particle physics motivation,
and may have very different pheno!

Non-relativistic thermal freeze-out

Main detection methods



See dedicated lectures by
Matt Pyle,
Christoph Weniger,
Marcela Carena

- For secluded DM, detection requires that the dark mediators couple to the SM. In some models, cosmological considerations imply this must be so. Nevertheless, secluded models are harder to probe. Collider constraints in particular are much weaker.
- Same detection methods probe scenarios beyond WIMPs or thermal-relic DM.

III. Production mechanisms and particle candidates

- Non-relativistic thermal freeze-out
- Asymmetry generation & freeze-out
- Freeze-in

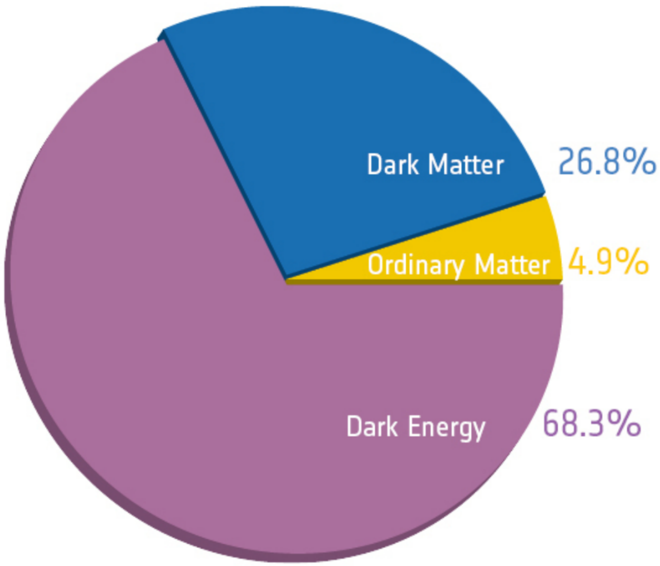
Asymmetric dark matter

Motivation

Reviews:
arXiv:1305.4939
arXiv:1308.0338

A cosmic coincidence

Why $\Omega_{DM} \sim \Omega_{SM}$?



- Unrelated mechanisms → different parameters
  → result expected to differ by orders of magnitude.
- Similarity of abundances hints towards related physics for OM and DM production.

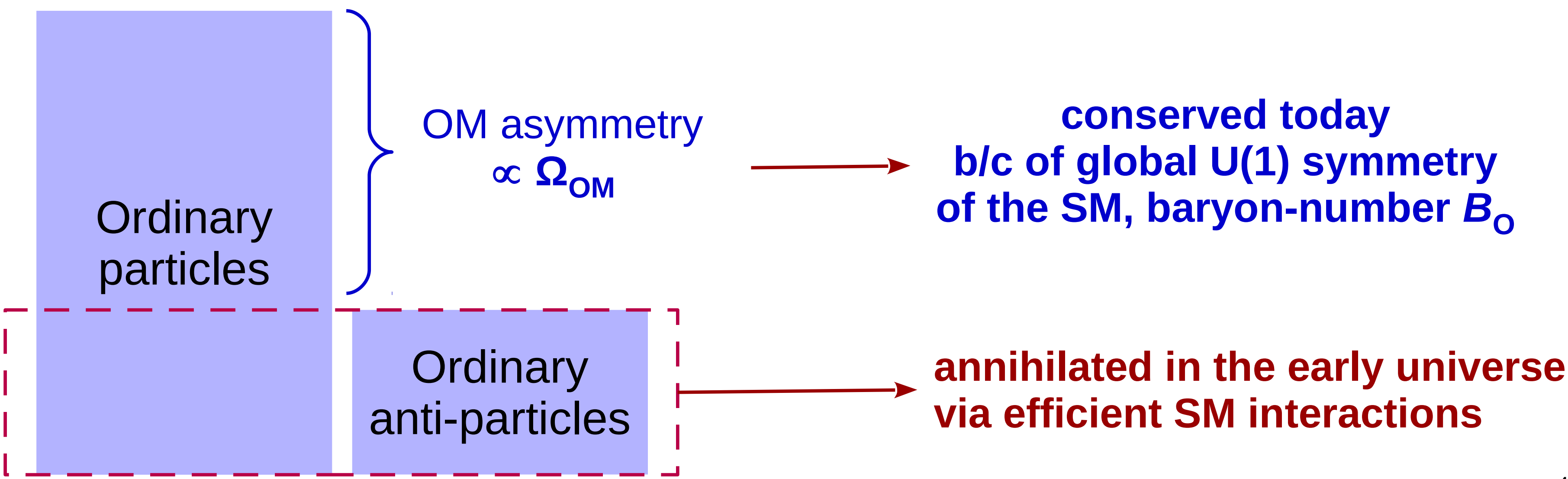
Asymmetric dark matter

Motivation

Reviews:
arXiv:1305.4939
arXiv:1308.0338

A closer look at ordinary matter

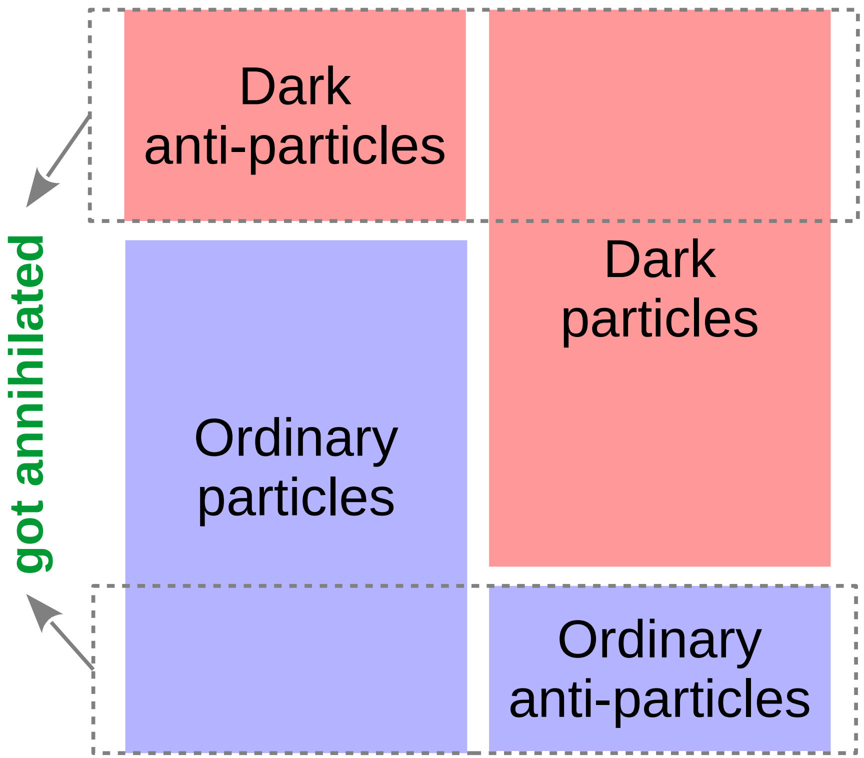
- **SM stable particles: *p, e,* γ, ν**
- ***Protons*** make up most of ordinary matter in the universe
- ***Only p, no $\bar{p}$*** present today: matter-antimatter asymmetry
  - Observational evidence: negligible antimatter in cosmic rays
  - Theoretical consistency: $p - \bar{p}$ annihilation cross-section too large



Asymmetric dark matter

The proposal

Reviews:
arXiv:1305.4939
arXiv:1308.0338

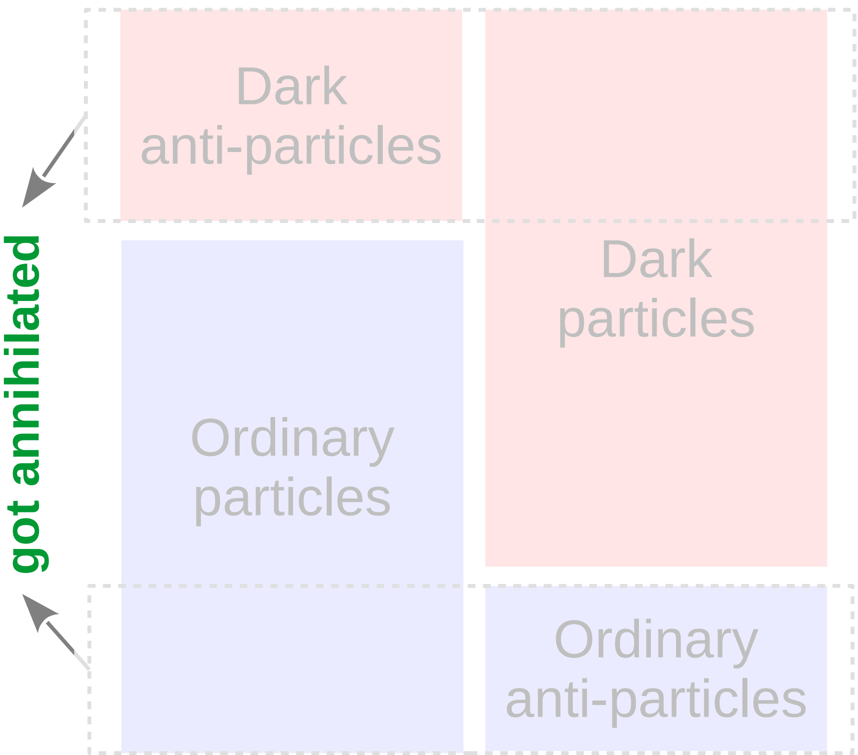


- DM relic density due to an excess of dark particles over antiparticles (asymmetry).
- Dark-ordinary asymmetries related dynamically, by processes which occurred in the early universe.
- Dark and visible asymmetries conserved separately today.

Asymmetric dark matter

The proposal

Reviews:
arXiv:1305.4939
arXiv:1308.0338



- DM relic density due to an excess of dark particles over antiparticles (asymmetry).

- Dark-ordinary asymmetries related dynamically, by processes which occurred in the early universe.

Not necessary!
ADM may be unrelated to ordinary matter

- Dark and visible asymmetries conserved separately today.

Asymmetry generation & freeze-out

Ingredients of the scenario

Reviews:
arXiv:1305.4939
arXiv:1308.0338

- **Low-energy interactions** **[operative at low temperatures]**
  - Conserved particle numbers:

    Standard Model: Ordinary Baryon number B_{SM}

    Dark sector: **Dark Baryon number B_{D} [global $U(1)$ symmetry]**
  - **Interaction that annihilates efficiently the dark antiparticles.** How strong does it have to be?

- **High-energy interactions** **[operative at high temperatures]**

B_{SM} violation + CP violation
B_{D} violation + CP violation

if correlated ⇒
related ΔB_{SM} & ΔB_{D} asymmetries

Asymmetry generation & freeze-out

Structure

Reviews:
arXiv:1305.4939
arXiv:1308.0338

energy

CONNECTOR SECTOR

particles with
G_{SM} , G_D and possibly G_{common}

Interactions which break one
linear combination of global symmetries:

conserved $B_{SM} - B_D$; broken $B_{SM} + B_D$

$\Rightarrow$ $\Delta(B_V + B_D) = 2\,\Delta B_{SM} = 2\,\Delta B_D$

STANDARD MODEL

gauge group
$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$\Rightarrow$ accidental global $\boldsymbol{B_{SM}}$
$\Rightarrow$ strong $p\bar{p}$, $n\bar{n}$ annihilation

Portal
interactions

B_{SM} & B_D
preserving

DARK SECTOR

gauge group G_D

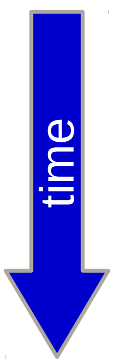
$\Rightarrow$ accidental global $\boldsymbol{B_D}$
$\Rightarrow$ efficient annihilation

Asymmetry generation & freeze-out

How does it work?

Reviews:
arXiv:1305.4939
arXiv:1308.0338

Order of events



- Asymmetry generation, typically in heavy particles carrying B_D. Possible relation with B_{SM} generation.
- B_D-violating processes become inefficient.
- Cascade of ΔB_D down to the lightest dark baryon (dark matter), via B_D-preserving decays and/or scattering processes.
- Annihilation of the symmetric component of dark matter. Has to be efficient in order to
  - not produce too much DM
  - relate ordinary and dark matter number densities

  How efficient does it have to be?

Asymmetry generation & freeze-out

How does it work?

Reviews:
arXiv:1305.4939
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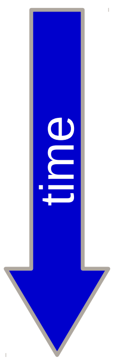
Order of events



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  - not produce too much DM
  - relate ordinary and dark matter number densities

  How efficient does it have to be?

Asymmetry generation & freeze-out

How does it work?

Conditions for asymmetry generation [Sakharov 1967]

- **Violate global $U(1)_B$ symmetry** $\Rightarrow \boldsymbol{B}_{\text{initial}} \neq \boldsymbol{B}_{\text{final}}$

- **Violate CP symmetry** (C = charge conjugation, P = space parity)

  - process S: ΔB
  - process S conjugate: $-\Delta B$

  have to happen at different rate $\Rightarrow$ need CP violation

- **Occur out of equilibrium** (arrow of time, expansion of the universe)

  - process S: ΔB
  - process S inverse: $-\Delta B$

  have to happen at different rate $\Rightarrow$ out of equilibrium

> These processes must be
> ineffective in the low-energy environment of today's universe,
> such that today ΔB = constant.

Asymmetry generation & **freeze-out**

How does it work?

Freeze-out in the presence of an asymmetry

arXiv:1103.2771
arXiv:1703.00478

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma_{\rm ann} v_{\rm rel}\rangle\left(n_X n_{\bar{X}} - n_X^{\rm eq} n_{\bar{X}}^{\rm eq}\right)$$

$$\frac{dn_{\bar{X}}}{dt} + 3Hn_{\bar{X}} = -\langle\sigma_{\rm ann} v_{\rm rel}\rangle\left(n_X n_{\bar{X}} - n_X^{\rm eq} n_{\bar{X}}^{\rm eq}\right)$$

where

$$n_X^{\rm eq} = g_X\left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-(m_X-\mu)/T} \qquad n_{\bar{X}}^{\rm eq} = g_X\left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-(m_X+\mu)/T}$$

Conserved quantity

$$\eta_X \equiv \frac{n_X - n_{\bar{X}}}{s}$$

determined during asymmetry gen

(for ordinary baryons, $\eta_B \approx 10^{-10}$)

Need to compute

$$r(t) = \frac{n_{\bar{X}}}{n_X}$$

$r = 1:$ symm DM
$r \ll 1:$ ADM

Want to find

$$r_\infty = r(t\to\infty)$$

expectation:
large $\sigma_{\rm ann} \Rightarrow r_\infty \ll 1$
small $\sigma_{\rm ann} \Rightarrow r_\infty \approx 1$

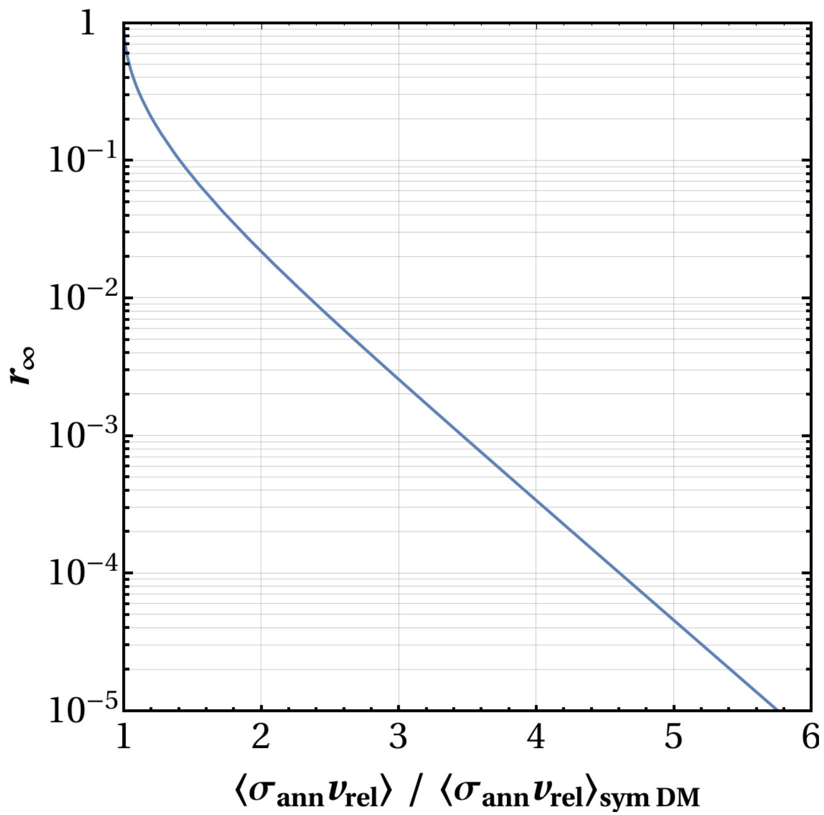
Asymmetry generation & **freeze-out**

How does it work?

arXiv:1103.2771
arXiv:1703.00478

Freeze-out in the presence of an asymmetry

$$r_\infty \approx \exp\left[-2\left(\frac{1-r_\infty}{1+r_\infty}\right)\left(\frac{\langle\sigma_{\rm ann}v_{\rm rel}\rangle}{\langle\sigma_{\rm ann}v_{\rm rel}\rangle_{\rm sym\,DM}}\right)\right]$$



We need $\sigma_{\rm ann} > \sigma_{\rm ann,\,sym}$, but not by much!

Even $\sigma_{\rm ann}/\sigma_{\rm ann,\,sym} \simeq 2$, yields $r_\infty \ll 1$.

- ◇ **Asymmetric WIMP DM possible!**
- ◇ **Lower, but no upper limit on $\sigma_{\rm ann}$.**

Asymmetric dark matter

Particle candidates

Reviews:
arXiv:1305.4939
arXiv:1308.0338

- Technicolor [Nussinov 1985; Sannino, Kouvaris et al. 2006]
- Mirror DM: dark sector = a copy of the SM with different cosmology
  [1990s: Foot, Volkas; Mohapatra et al]
- Q-balls (entirely non-thermal) [Kusenko 1998]
- WIMP ADM
- Various hidden sector models, e.g. dark U(1), dark QCD

Many papers in recent years

Asymmetric dark matter

Example: dark U(1) sector

$$G = G_{\mathrm{SM}} \times U(1)_D \times \boxed{U(1)_{B_{\mathrm{gen}}}}$$

Dark gauge force:
provides efficient DM annihilation,
and DM self-interactions

Generalized baryon number;
same as $(B\text{-}L)_{\mathrm{SM}}$ for SM particles

Asymmetric dark matter

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Asymmetry and *gauge invariance*
imply that
there must be at least **two dark species**
whose net dark electric charges
compensate each other

	gauged D	gauged B_{gen}
p_D	1	-2
e_D	-1	0

can be elementary

Asymmetric dark matter

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	gauged D	gauged B_{gen}	accidental global B_d
p_D	1	-2	2
e_D	-1	0	0

can be elementary

$$\mathcal{L} = \overbrace{\mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F_D{}^{\mu\nu} F_{D\,\mu\nu} + \bar{p}_D (i\not{D} - m_{p_d}) p_D + \bar{e}_D (i\not{D} - m_{e_d})}^{\text{accidental global } (B-L)_{\mathrm{SM}} \;\&\; B_d} e_D$$

Asymmetric dark matter

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$$+ \frac{1}{\Lambda^8} \underbrace{(\overline{u^c} d\, \overline{s^c} u\, \overline{d^c} s) \overline{e^c_D} p_D}_{} + h.c.$$

preserves $B_{\rm SM} - B_d$
violates $B_{\rm SM} + B_d$
$\downarrow$
may give rise to $\Delta B_{\rm SM} = \Delta B_d$

Asymmetric dark matter

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$$\mathcal{L} = \overbrace{\mathcal{L}_{\mathrm{SM}} - \frac{1}{4} F_D^{\mu\nu} F_{D\,\mu\nu} + \bar{p}_D (i\not{D} - m_{p_d}) p_D + \bar{e}_D (i\not{D} - m_{e_d}) e_D}^{\text{accidental global } (B-L)_{\mathrm{SM}} \,\&\, B_d} + \epsilon\, F_Y^{\mu\nu} F_{D\,\mu\nu}$$

$$+ \underbrace{\frac{1}{\Lambda^8} (\overline{u^c} d\, \overline{s^c} u\, \overline{d^c} s) \overline{e^c_D} p_D}_{} + h.c.$$

preserves $B_{\mathrm{SM}} - B_d$
violates $B_{\mathrm{SM}} + B_d$
$\downarrow$
may give rise to $\Delta B_{\mathrm{SM}} = \Delta B_d$

portal interaction:
direct/indirect detection

Asymmetric dark matter
Example: dark U(1) sector

COSMOLOGY [see e.g. arXiv:1209.5752]

Asymmetry generation	$T_{\mathrm{asym}} \gg m_{p_D}, m_{e_D}$
Freeze-out of annihilations $p_D + \bar{p}_D \to \gamma_D \gamma_D$ $e_D + \bar{e}_D \to \gamma_D \gamma_D$	$T^{\mathrm{FO}}_{p_D} \sim m_{p_D}/25$ $T^{\mathrm{FO}}_{e_D} \sim m_{e_D}/25$
Dark recombination, $p_D + e_D \to H_D + \gamma_D$	$T_{\mathrm{dark\ rec}} \sim$ binding energy $= \frac{1}{2}\left(\frac{m_{p_D} m_{e_D}}{m_{p_D} + m_{e_D}}\right) \alpha_D^2$

Residual ionization fraction

$$f_{\mathrm{ion}} \equiv \frac{n(p_D)}{n(p_D) + n(H_D)} \sim \max\left[1, \ \frac{10^{-10}}{\alpha_D^4} \left(\frac{m_{p_D} m_{e_D}}{\mathrm{GeV}^2}\right)\right]$$

Similar situation if $U(1)_D$ is mildly broken and γ_D has a small mass.

Asymmetric dark matter
Example: dark U(1) sector

PHENOMENOLOGY

- **Self-interactions inside halos**
  - Multicomponent DM: p_D, e_D, H_D ⇒ ion-ion, atom-atom & atom-ion collisions.
  - Velocity-dependent scattering cross-sections.
  - Interplay between cosmology and particle physics regulates σ_{scatt}:

    Small α_D ⇒ mostly ionized DM, $\sigma_{scatt} \propto \alpha_D^2 / v_{rel}^4$
    Large α_D ⇒ mostly atomic DM, scattering screened.

- **Direct detection,** via kinetic mixing $\delta\mathcal{L} = \epsilon F^{\mu\nu}_{Y} F_{D\,\mu\nu}$

  Similar features as DM self-scattering

Asymmetric dark matter
Example: dark U(1) sector

PHENOMENOLOGY

- **Indirect detection,** via kinetic mixing if dark photon is massive
  - Annihilations of residual symmetric component,

$$p_D + \bar{p}_D \to \gamma_D + \gamma_D$$
$$\gamma_D \to f^+_{\rm SM} f^-_{\rm SM}$$

    Rate suppressed by asymmetry, but enhanced by Sommerfeld effect [*] due to light dark photon. **[arXiv:1703.00478,1712.07489]**

  - Radiative level transitions, e.g. dark atom formation from residual ionized component (also Sommerfeld-enhanced [*])

$$p_D + e_D \to H_D + \gamma_D$$
$$\gamma_D \to f^+_{\rm SM} f^-_{\rm SM}$$

[arXiv:1303.7294; arXiv:1404.3729; arXiv:1406.2276; arXiv:1502.01755]

[*] see discussion on long-range interactions

Asymmetric dark matter

Example: dark U(1) sector

PHENOMENOLOGY

- **Indirect detection,** via kinetic mixing if dark photon is massive

The features we saw in the context of atomic DM,

- multicomponent DM
- velocity-dependent cross-sections
- radiative level transitions

are typical of asymmetric DM models coupled to light force mediators!

III. Production mechanisms and particle candidates

- Non-relativistic thermal freeze-out
- Asymmetry generation & freeze-out
- Freeze-in

Freeze-in

Motivation

- What if DM couples very weakly to all other particles?

  ⇒ Never in thermal equilibrium in the early universe

- Can it still be produced in sizable amounts?

  ⇒ DM may be produced in various scattering/decay processes, without ever reaching a density so large that its self-annihilations destroy it.

Freeze-in

How does it work?

- **Boltzmann equations**

scatterings of bath particles

$\psi + \bar{\psi} \to X + \bar{X}$

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma_{\psi\bar{\psi}\to X\bar{X}}\, v_{\rm rel} \rangle\, n_\psi^{{\rm eq}\,2} - \langle \sigma_{X\bar{X}\to\psi\bar{\psi}}\, v_{\rm rel} \rangle\, n_X^2$$
$$= \langle \sigma_{X\bar{X}\to\psi\bar{\psi}}\, v_{\rm rel} \rangle\, (n_X^{{\rm eq}\,2} - n_X^2)$$

decay of bath particles

$\psi \to X + \bar{X}$

$$\frac{dn_X}{dt} + 3Hn_X = \langle \Gamma_{\psi\to X\bar{X}} \rangle n_\psi - \langle \sigma_{X\bar{X}\to\psi} v_{\rm rel} \rangle n_X^2$$
$$= \langle \gamma_\psi^{-1} \rangle\, \Gamma^0_{\psi\to X\bar{X}} \left[n_\psi - n_\psi^{\rm eq}\, (n_X^2 / n_X^{{\rm eq}\,2}) \right]$$

Many variations, e.g. $\psi_1 + \psi_2 \to X + \psi_3 + \cdots$, $\psi_1 \to X + \psi_2$, and/or ψ_j may be out of equilibrium with the plasma (but may have a thermal history). Boltzmann equations change accordingly.

Freeze-in

How does it work?

- **Boltzmann equations**

scatterings of bath particles $\psi + \bar{\psi} \to X + \bar{X}$	$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma_{\psi\bar{\psi}\to X\bar{X}}\, v_{\rm rel}\rangle\, n_\psi^{\rm eq\,2} - \langle \sigma_{X\bar{X}\to\psi\bar{\psi}}\, v_{\rm rel}\rangle\, n_X^2$ $= \langle \sigma_{X\bar{X}\to\psi\bar{\psi}}\, v_{\rm rel}\rangle\, (n_X^{\rm eq\,2} - n_X^2)$
decay of bath particles $\psi \to X + \bar{X}$	$\frac{dn_X}{dt} + 3Hn_X = \langle \Gamma_{\psi\to X\bar{X}}\rangle n_\psi - \langle \sigma_{X\bar{X}\to\psi} v_{\rm rel}\rangle n_X^2$ $= \langle \gamma_\psi^{-1}\rangle\, \Gamma^0_{\psi\to X\bar{X}} \left[n_\psi - n_\psi^{\rm eq}\, (n_X^2/n_X^{\rm eq\,2}) \right]$

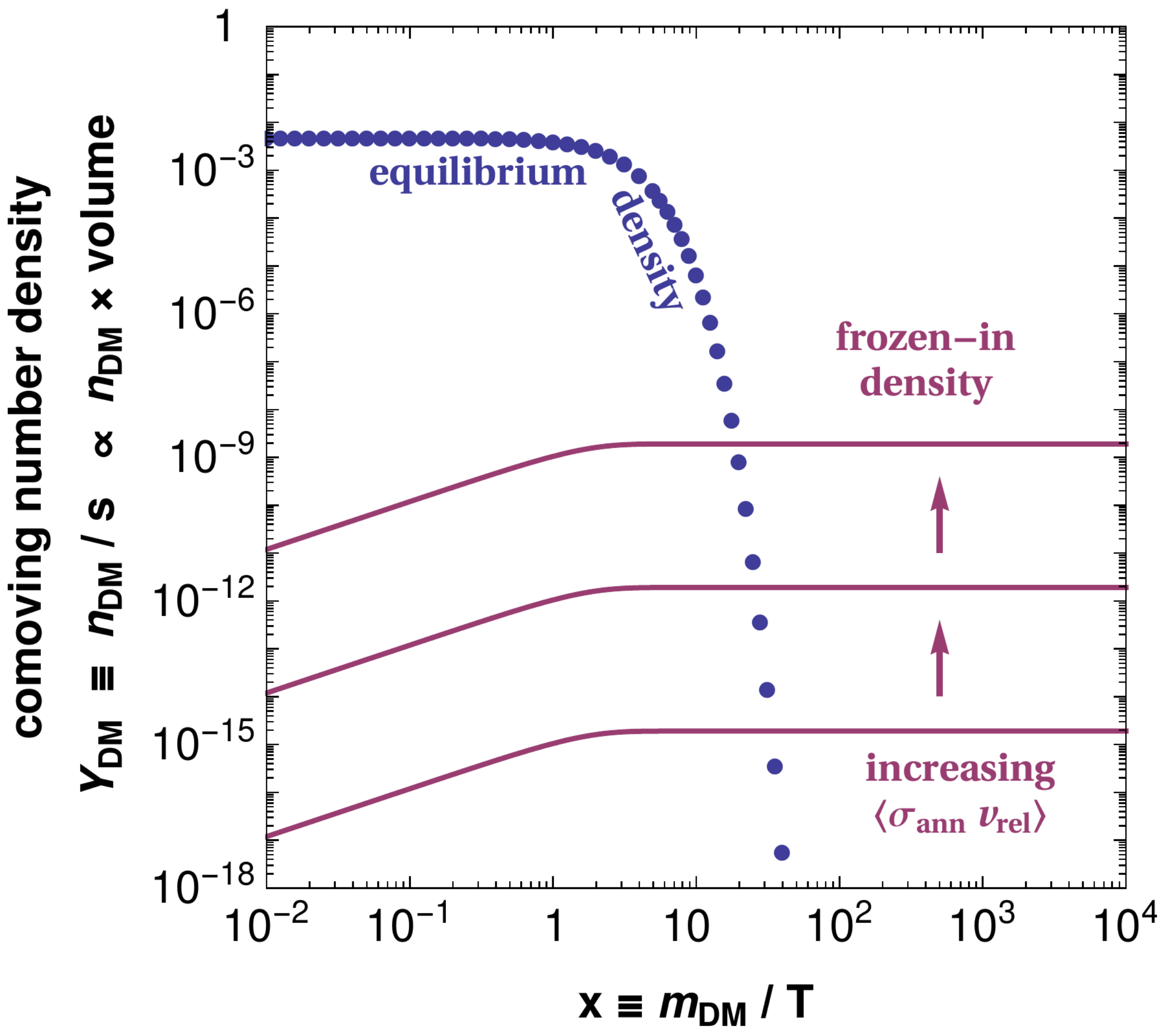
Many variations, e.g. $\psi_1 + \psi_2 \to X + \psi_3 + \cdots,\quad \psi_1 \to X + \psi_2,$ and/or ψ_j may be out of equilibrium with the plasma (but may have a thermal history). Boltzmann equations change accordingly.

- **Initial conditions**

$$n_X \ll n_X^{\rm eq} \quad \text{at high } T$$

Freeze-in

How does it work?



Relic density increases with cross-section / decay rate.

Freeze-in has memory:
Initial DM density (produced during reheating) matters!

Freeze-in

Candidates

- Sterile neutrinos with mass *M* ~ keV and mixing $\theta^2 \sim 10^{-10}$
  - Produced via oscillations from active neutrinos [arXiv:hep-ph/9303287]

$$\delta\mathcal{L} = \underbrace{-y_{\alpha a}\,\epsilon^{ij}(\bar{L}_\alpha)_i H_j N_a}_{\text{Neutrino mass mixing}} - \frac{M_a}{2}\overline{N_a^c}N_a + h.c. \;\Rightarrow$$

$$\boxed{\begin{array}{c}\textbf{mass eigenstates:}\\ m_\nu \sim y^2 v_H^2/M, \quad M_N \sim M \\ \textbf{mixing: } \theta \sim y v_H/M\end{array}}$$

Freeze-in

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mass eigenstates:

$$m_\nu \sim y^2 v_H^2/M, \quad M_N \sim M$$

$$\text{mixing: } \theta \sim y v_H/M$$

Neutrino mass mixing

  - Produced in the decays of heavy scalars **[arXiv:hep-ph/0609081]**

$$\delta\mathcal{L} = -\frac{\lambda}{2}|S|^2|H|^2 \boxed{-\frac{f_a}{2}\,S\,\overline{N_a^c}\,N_a} - y_{\alpha a}\epsilon^{ij}(\bar{L}_\alpha)_i H_j N_a$$

Coupling to the Higgs brings S in equilibrium with SM bath

Majorana mass $M_N \sim f\,\langle S\rangle$, $S \to NN$ decays produce DM.

Freeze-in

Candidates

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mass eigenstates:

$$m_\nu \sim y^2 v_H^2/M, \quad M_N \sim M$$

mixing: $\theta \sim y v_H/M$

Neutrino mass mixing

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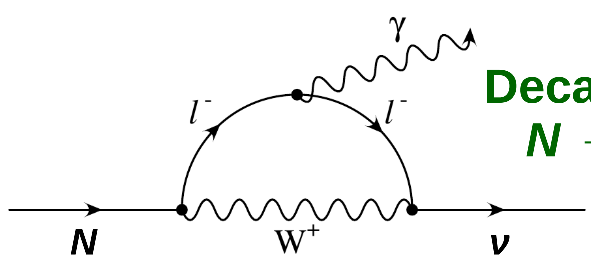
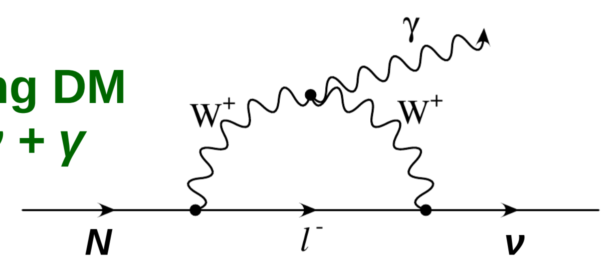


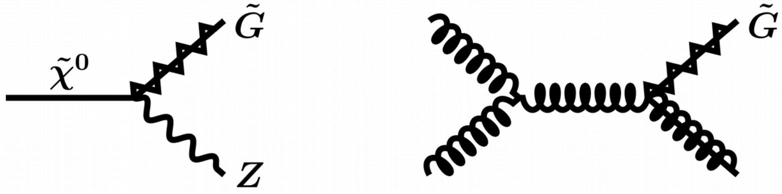
Decaying DM
N → ν + γ



Freeze-in

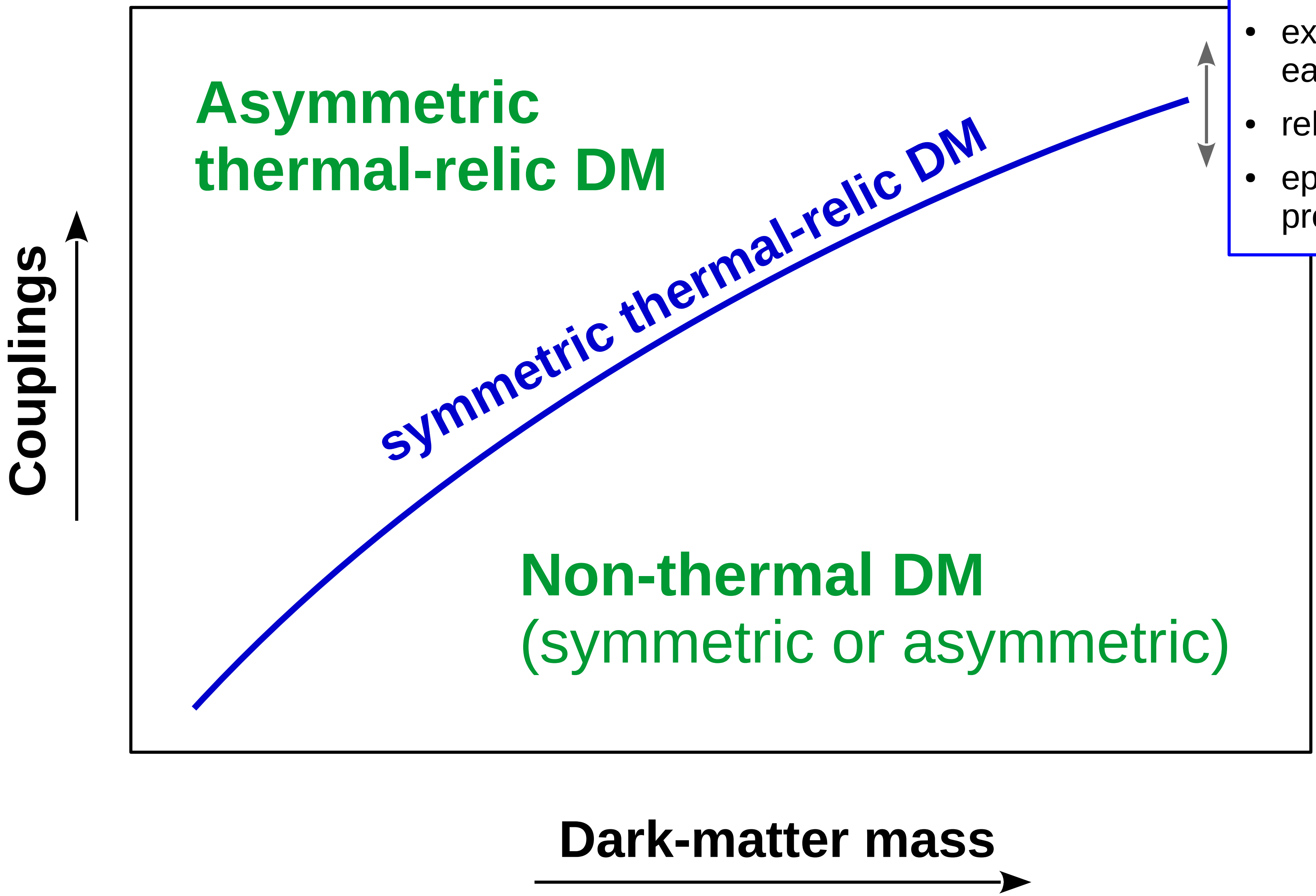
Candidates

- Gravitinos produced in scatterings and decays involving SM and SUSY particles



Stabilized by *R*-parity. Typically gravitinos are the LSP in gauge-mediated SUSY-breaking scenarios.

Phase space of a DM theory



Depends on cosmological assumptions, e.g.

- expansion rate of the early universe,
- reheating temperature,
- episodes of entropy production

IV. Interaction types

Contact-type vs *long-range* interactions

Definition

- **Contact-type interactions: $m_{DM} \lesssim m_{mediators}$**

  E.g. in the prototypical WIMP scenario, $m_{DM} \sim m_{W,Z} \sim 100$ GeV

- **Long-range interactions: $m_{DM} >> m_{mediators}$**

  How does the DM phenomenology look like?

  Non-perturbative effects: Sommerfeld enhancement and bound states

  ⇒ New radiative processes and modified rates

Light/Massless mediators
Motivation

- Self-interacting DM
- Hidden-sector models inspired by GUTs or string theory
- Models designed to explain astrophysical anomalies (e.g. Pamela positrons, IceCube PeV neutrinos)

… *but even ...*

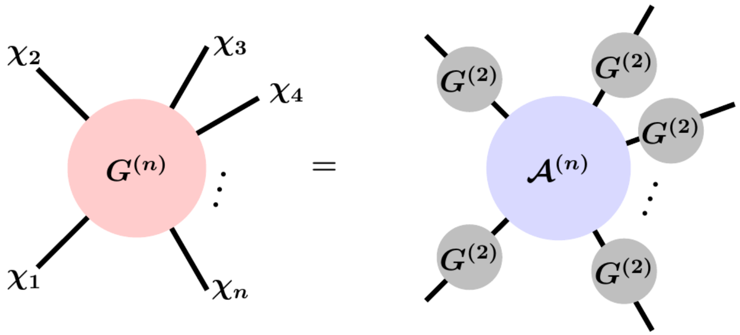
- WIMP DM with m_{DM} > TeV
- WIMP DM with m_{DM} < TeV *co*-annihilating with colored/charged partners

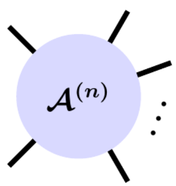
Contact-type vs *long-range* interactions

Scattering processes

Contact-type vs *long-range* interactions

Scattering processes

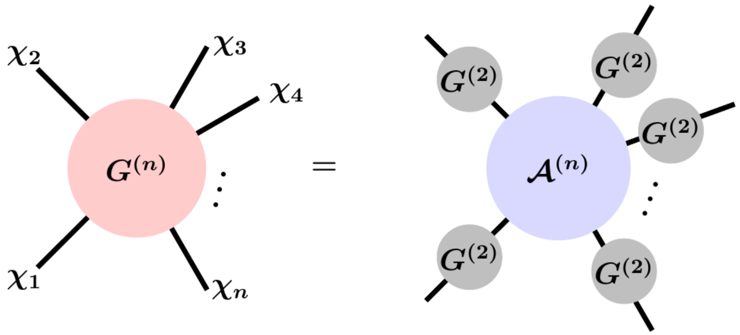


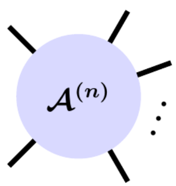
where 

includes all connected diagrams with the 1PI factors amputated.

Contact-type vs *long-range* interactions

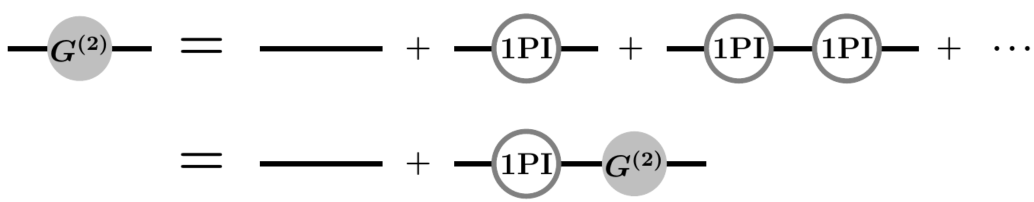
Scattering processes



where 

includes all connected diagrams with the 1PI factors amputated.

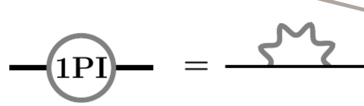
The properties of the asymptotic states are determined by resumming the self-interactions at infinity, via the Dyson-Schwinger equation



$$= \frac{iZ_j}{p_j^2 - m_j^2}$$

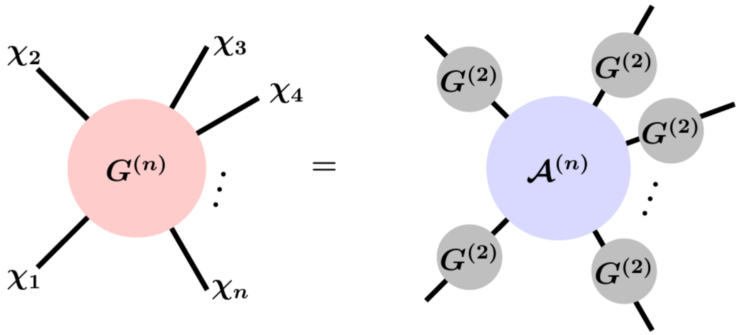
Field strength renormalization factor

Renormalized mass

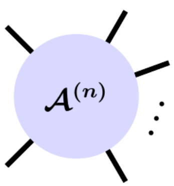
where e.g. 

Contact-type vs *long-range* interactions

Scattering processes



LSZ reduction $\Longleftrightarrow$ $\mathcal{M} = \left(\prod_{j=1}^{n} \sqrt{Z_j} \right) \mathcal{A}$

where 

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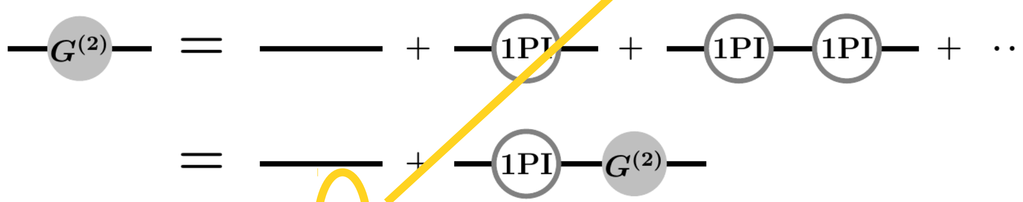
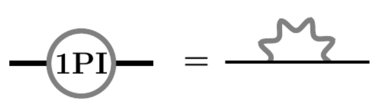


$$= \frac{iZ_j}{p_j^2 - m_j^2}$$

where e.g. 

Contact-type vs ***long-range*** **interactions**

Scattering processes

The particles interact at very large distance. We cannot define the asymptotic states by isolating the particles at infinity.

What do we do?

Contact-type vs ***long-range*** **interactions**

Scattering processes

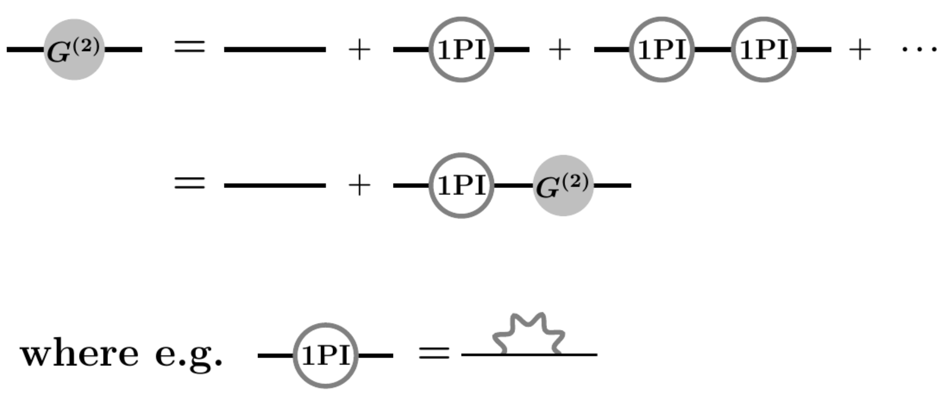
The particles interact at very large distance. We cannot define the asymptotic states by isolating the particles at infinity.

What do we do?

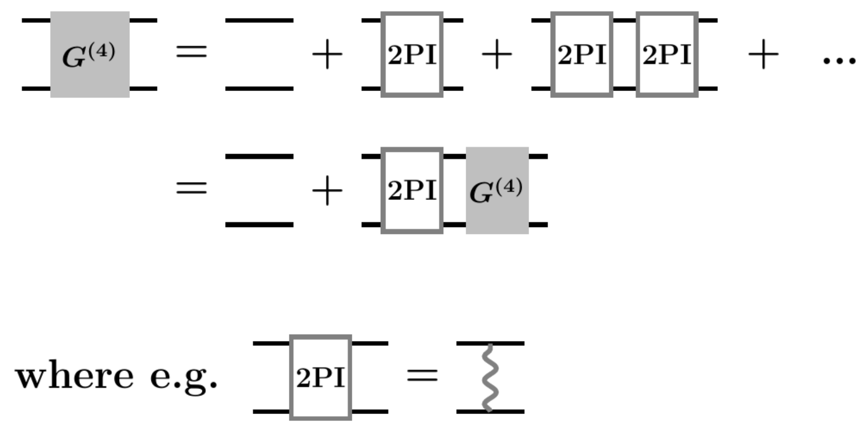
Resum 2-particle interactions at infinity!

Contact-type vs *long-range* interactions

Scattering processes



$$\mathcal{M} = \left(\prod_{j=1}^{n} \sqrt{Z_j} \right) \mathcal{A}$$



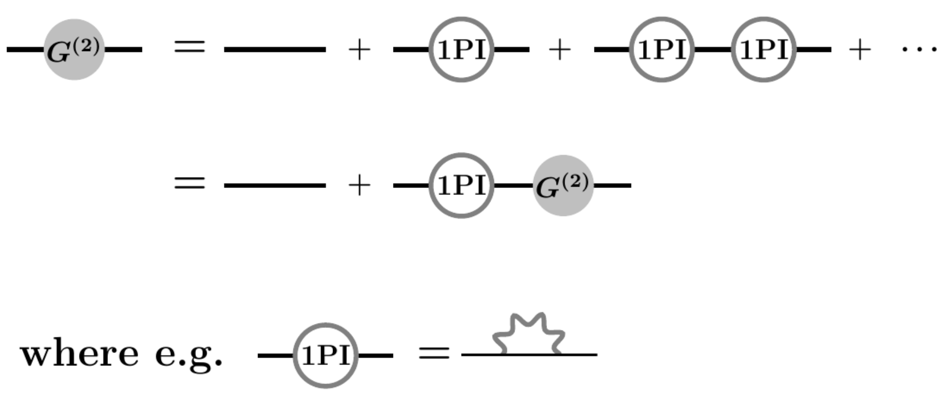
$$\mathcal{M} = \int \frac{d^3 q}{(2\pi)^3} \phi_{\vec{k}}(\vec{q}) \mathcal{A}(\vec{q})$$

field strength renormalization factors / form factors / wavefunctions

$$G^{(2)} \sim Z/\text{singularity} \quad \leftrightarrow \quad G^{(4)} \sim [\phi_{\vec{k}}]^2/\text{singularity}$$

Contact-type vs *long-range* interactions

Scattering processes



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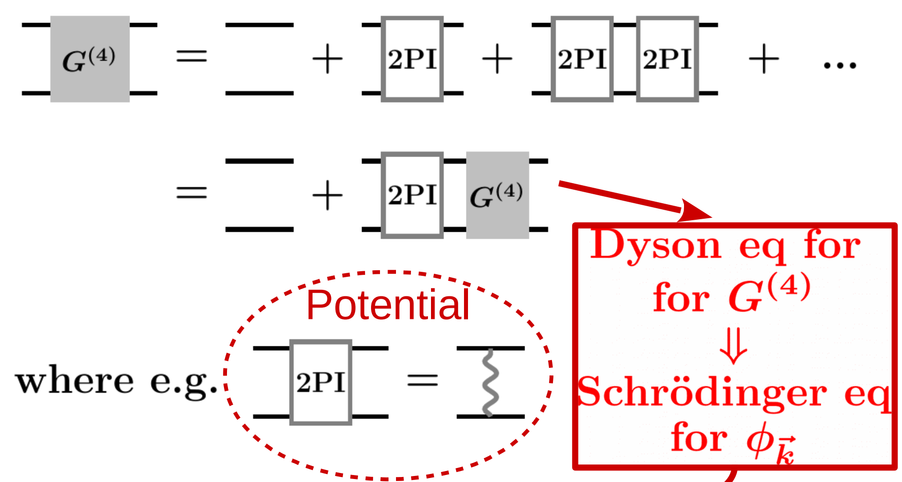
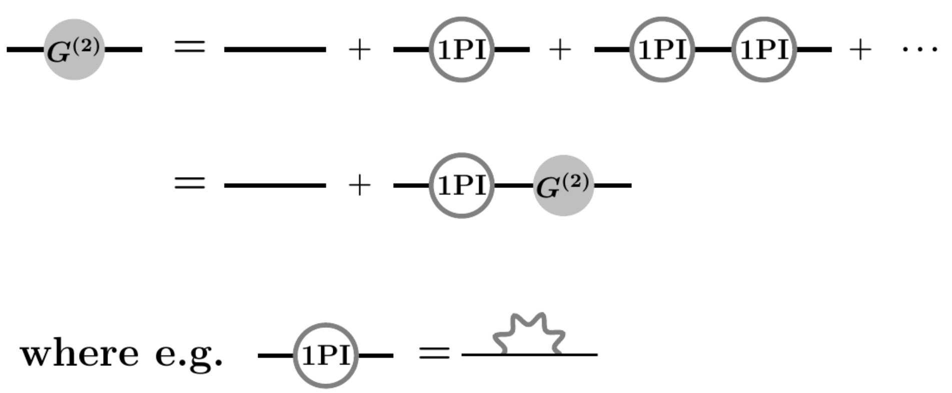


$$\mathcal{M} = \int \frac{d^3 q}{(2\pi)^3} \phi_{\vec{k}}(\vec{q}) \mathcal{A}(\vec{q})$$

Contact-type vs *long-range* interactions

Scattering processes



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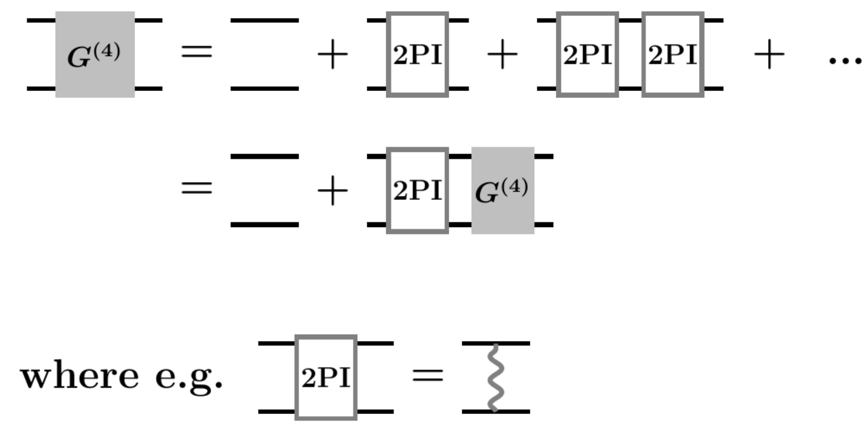


$$\mathcal{M} = \int \frac{d^3 q}{(2\pi)^3}\, \phi_{\vec{k}}(\vec{q})\, \mathcal{A}(\vec{q})$$

Expectation value of relative momentum

Relative momentum of interacting particles

No long-range force: $\phi_{\vec{k}}(\vec{q}) = \delta^3(\vec{q} - \vec{k}) \quad \overset{\text{FT}}{\Leftrightarrow} \quad \tilde{\phi}_{\vec{k}}(\vec{r}) = e^{-i\vec{k}\cdot\vec{r}}$.

In the presence of a long-range interaction: $\tilde{\phi}_{\vec{k}}(\vec{r})$ is <u>not</u> a plane wave.

Long-range interactions
Phenomenological implications

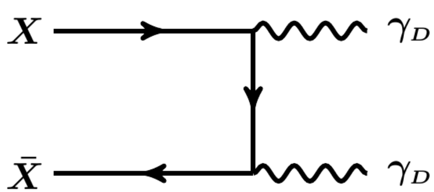
Case study: dark QED

$$
\begin{aligned}
\mathcal{L} \; &= \bar{X}(i\not{D} - m_{X})X - \frac{1}{4}F^{\mu\nu}_{D}F_{D\,\mu\nu} \\
D^{\mu} \; &= \partial^{\mu} + i g_{D} A^{\mu}_{D}; \quad \alpha_{D} \equiv g^{2}_{D}/(4\pi) \\
F^{\mu\nu}_{D} &= \partial^{\mu} A^{\nu}_{D} - \partial^{\nu} A^{\mu}_{D}
\end{aligned}
$$

Long-range interactions
Modified interaction rates

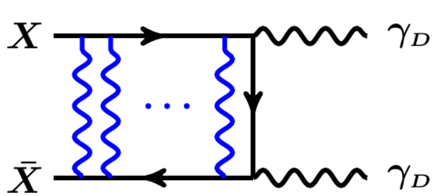
Annihilation: $X\bar{X} \to \gamma_D \gamma_D$

Standard pertubative calculation



$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \equiv \sigma_0$$

With Sommerfeld effect

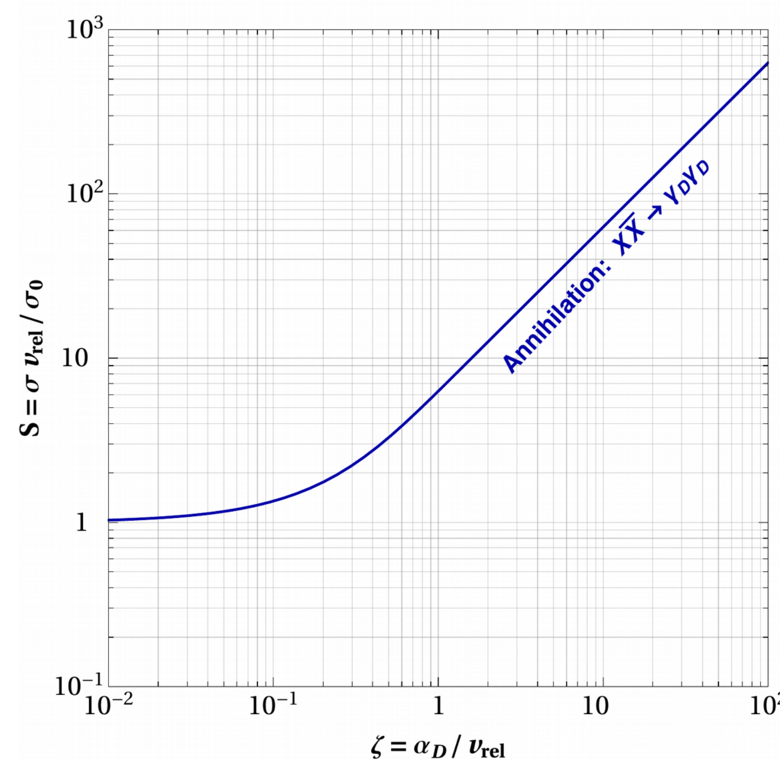


$$\sigma_{\rm ann} v_{\rm rel} = \sigma_0 \times S_{\rm ann}\left(\frac{\alpha_D}{v_{\rm rel}}\right)$$

$$S_{\rm ann}(\zeta) = |\tilde{\phi}_{\vec{k}}(\vec{r}=0)|^2 = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}}; \qquad \zeta = \alpha_D / v_{\rm rel}$$

At $\alpha_D \ll v_{\rm rel}$ $(\zeta \ll 1)$: $S_{\rm ann} \simeq 1$

At $\alpha_D \gtrsim v_{\rm rel}$ $(\zeta \gtrsim 1)$: $S_{\rm ann} \simeq 2\pi\, \alpha_D / v_{\rm rel} > 1$

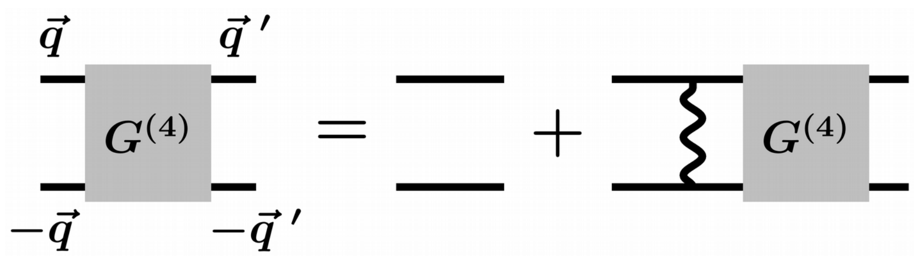


cosmo time

Long-range interactions

Scattering states and bound states

The Dyson-Schwinger equation with a Coulomb potential



where
$G^{(4)} \sim [\phi_{\vec{k}}]^2/\text{singularity}$

Solutions of the Schrödinger equation

continuous spectrum

$$\phi_{\vec{k}}(\vec{q}) \quad \overset{\text{FT}}{\Leftrightarrow} \quad \tilde{\phi}_{\vec{k}}(\vec{r})$$

$$\vec{k} = \mu \vec{v}_{\text{rel}}$$

$$E_{\vec{k}} = m_1 + m_2 + \vec{k}^2/(2\mu)$$

discrete spectrum

$$\psi_{n\ell m}(\vec{q}) \quad \overset{\text{FT}}{\Leftrightarrow} \quad \tilde{\psi}_{n\ell m}(\vec{r})$$

$$\kappa_n = \mu\alpha/n$$

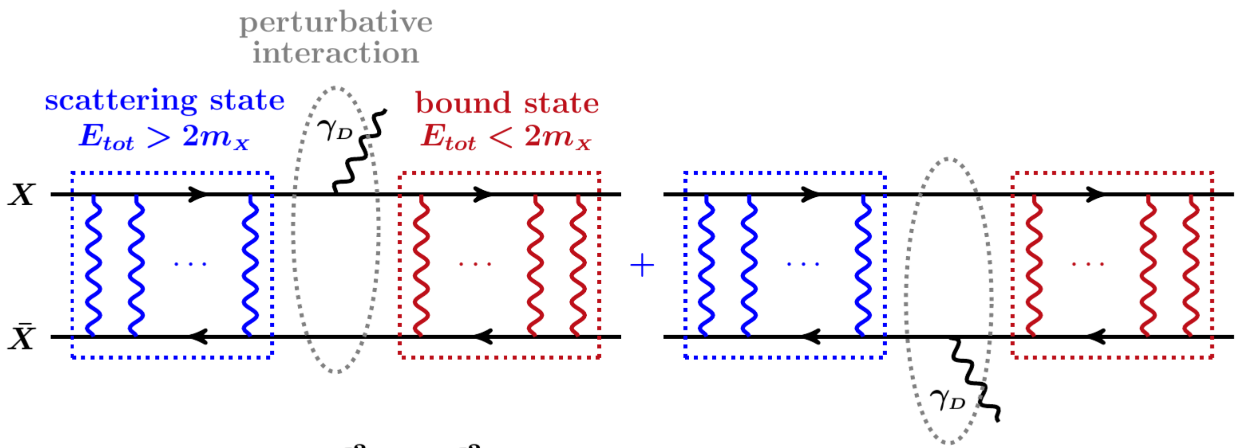
$$E_n = m_1 + m_2 - \kappa_n^2/(2\mu)$$

where $\mu \equiv m_1 m_2/(m_1 + m_2)$ is the reduced mass

Long-range interactions

More radiative processes

Bound-state formation: $X\bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$



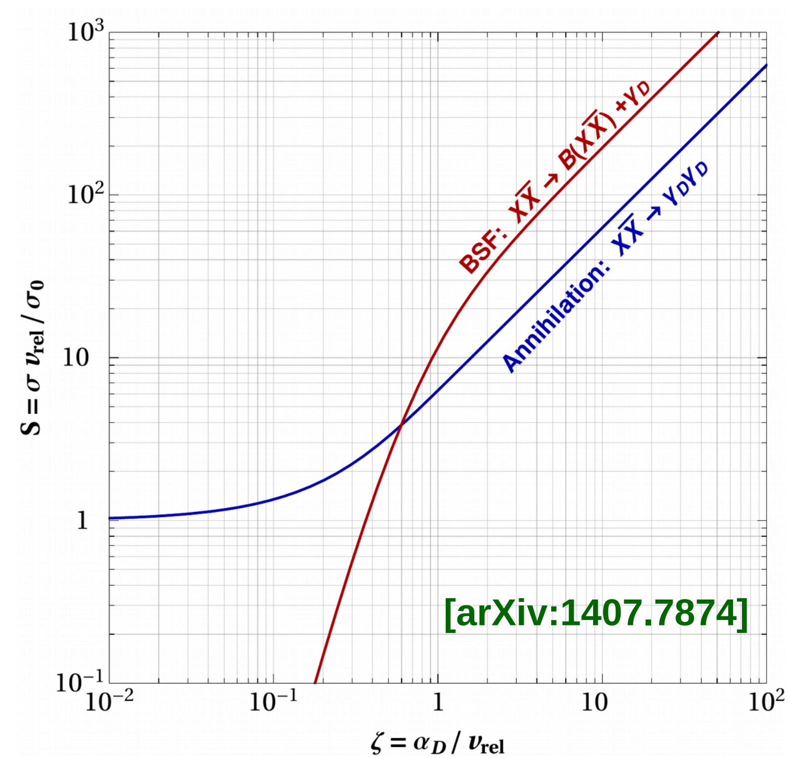
$$\mathcal{M}_{\rm BSF} = \int \frac{d^3q}{(2\pi)^3}\frac{d^3p}{(2\pi)^3}\,\phi_{\vec{k}}(\vec{q})\,\mathcal{A}(\vec{q},\vec{p})\,\psi_n^*(\vec{p})$$

$$\sigma_{\rm BSF} v_{\rm rel} = \frac{\pi\alpha_D^2}{m_X^2} \times S_{\rm BSF}(\alpha_D/v_{\rm rel})$$

$$S_{\rm BSF}(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}}\,\frac{2^9\,\zeta^4\,e^{-4\zeta\,{\rm arccot}(\zeta)}}{3(1+\zeta^2)^2}$$

At $\alpha_D \ll v_{\rm rel}$ $(\zeta \ll 1)$: $S_{\rm BSF} \simeq (2^9/3)\zeta^4 \ll 1$

At $\alpha_D \gtrsim v_{\rm rel}$ $(\zeta \gtrsim 1)$: $S_{\rm BSF} \simeq 3.13 \times (2\pi\,\alpha_D/v_{\rm rel}) > 1$



cosmo time

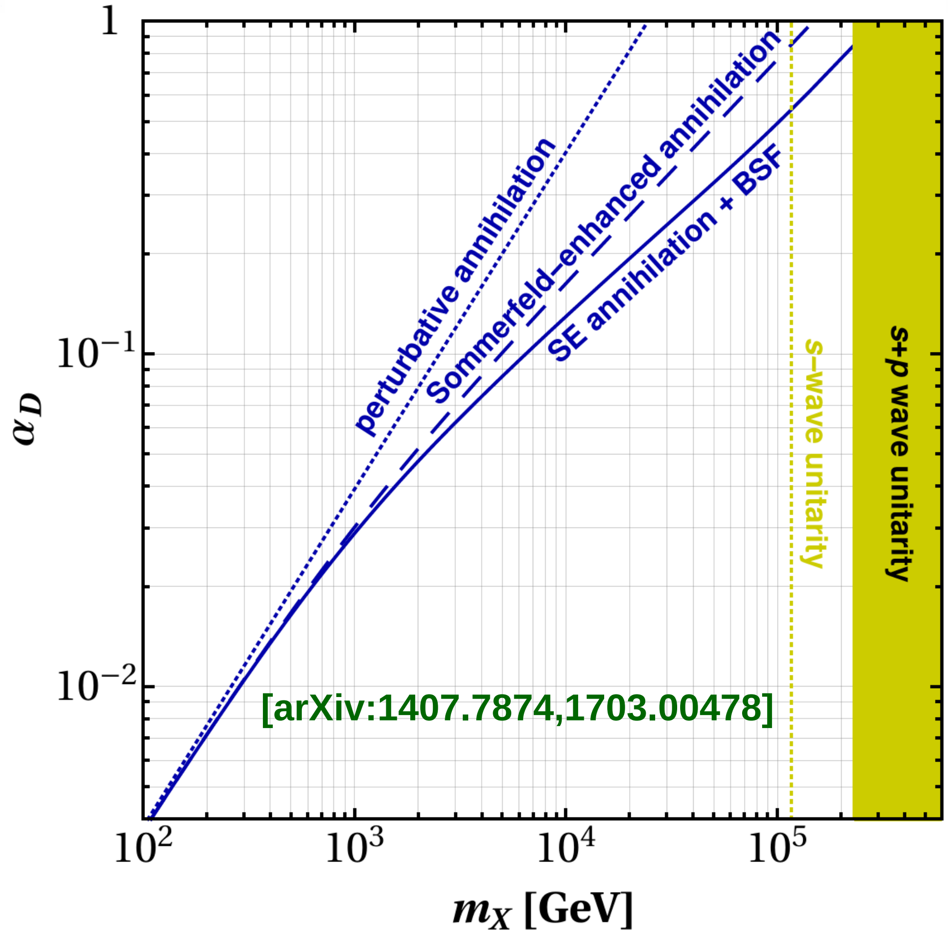
Long-range interactions

DM relic density

Direct Annihilation: $X\bar{X} \to \gamma_D\gamma_D$

Bound-state formation and decay: $X\bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$

$\mathcal{B}(X\bar{X}) \to 2\gamma_D$ or $3\gamma_D$



Long-range interactions

DM relic density

Direct Annihilation: $X\bar{X} \to \gamma_D \gamma_D$

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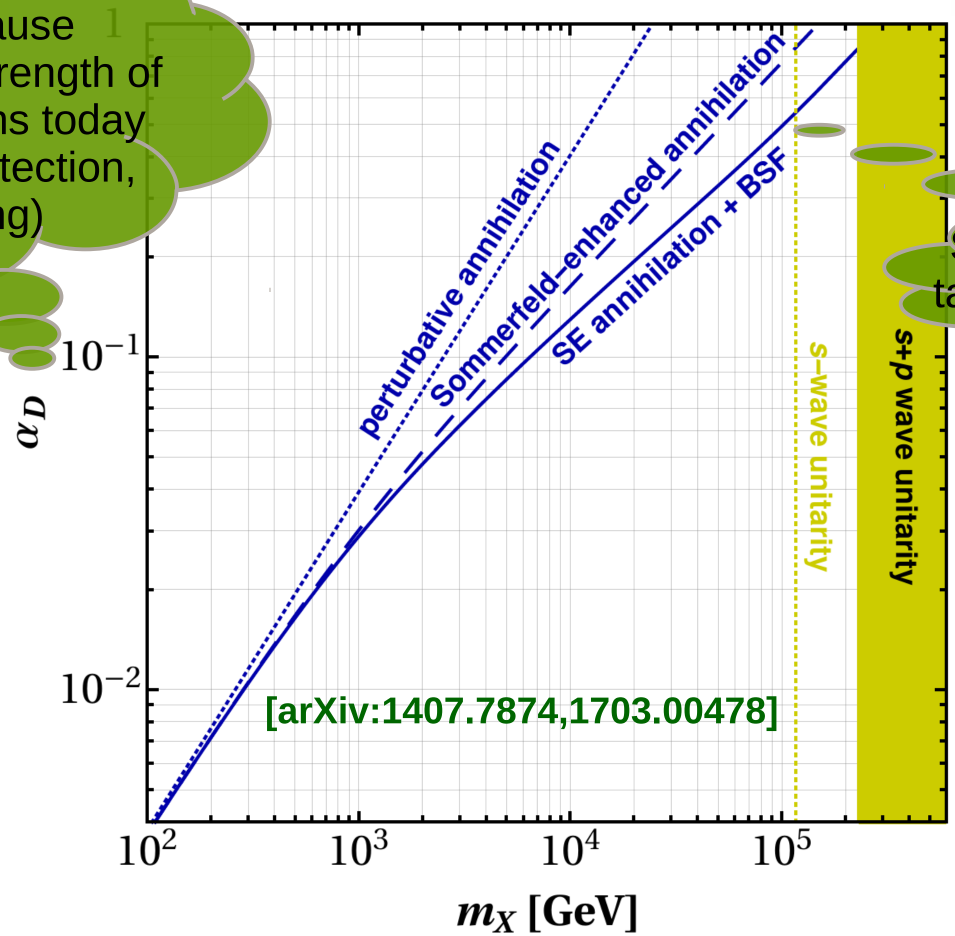
$\mathcal{B}(X\bar{X}) \to 2\gamma_D$ or $3\gamma_D$

Important because it determines the strength of the DM interactions today (direct, indirect detection, self-scattering)



Shows how the early universe tames late-time DM interactions

Long-range interactions

Massive *but still light* mediators

How light is light?

$$V(r) = -\alpha \, \frac{e^{-m_\varphi r}}{r}$$

$\mu v_{\rm rel}$: Average momentum transfer in non-relativistic scattering

$\mu\alpha, \; (\mu\alpha)^{-1}$: Bohr momentum, Bohr radius

m_φ^{-1} : Range of the potential

where $\mu \equiv m_1 m_2/(m_1+m_2)$ is the reduced mass

Wavefunctions determined by two parameters

$$\zeta \equiv \frac{\mu\alpha}{\mu v_{\rm rel}} = \frac{\alpha}{v_{\rm rel}}, \qquad d \equiv \frac{\mu\alpha}{m_\varphi}$$

Sommerfeld effect
important for $\zeta \gtrsim \mathcal{O}(1)$,
i.e. at low momentum transfer

Potential manifests as
long-range if $d \gtrsim \mathcal{O}(1)$

Bound-state levels
open up for $d \gtrsim n^2$
$(n = 1, 2, \cdots)$

Long-range interactions

Massive *but still light* mediators

WORD OF CAUTION:

The thresholds (maximum m_φ or minimum $\mu\alpha$)
for the existence of bound states
give rise to
parametric resonances in the scattering-state wavefunction
that affect the annihilation cross-section.

These resonances – often described as the
formation of bound states of zero binding energy –
do NOT account for the
formation of actual (above threshold) bound states!

How light is light?

$\mu v_{\rm rel}$: Average momentum transfer in non-relativistic scattering

$\mu\alpha,\ (\mu\alpha)^{-1}$: Bohr momentum, Bohr radius

m_φ : Range of the potential

where $\mu \equiv m_1 m_2/(m_1+m_2)$ is the reduced mass

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Potential manifests as long-range if $d \gtrsim \mathcal{O}(1)$

Bound-state levels open up for $d \gtrsim n^2$ $(n = 1, 2, \cdots)$

Long-range interactions
and good old WIMPs

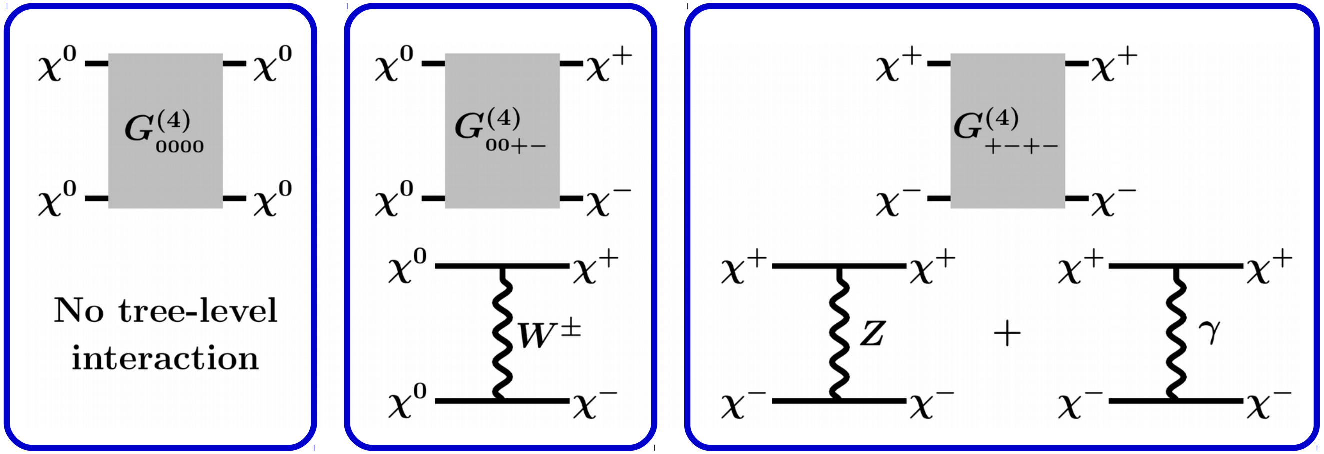
- The Weak interactions of the SM have been the prototype of contact interactions in particle physics. True for all SM particles. However

$$d_w = \frac{(m_\chi/2)\alpha_w}{m_w} \gtrsim \mathcal{O}(1) \qquad \text{for} \qquad m_\chi \gtrsim \text{TeV}$$

The Weak interactions manifest as long range!

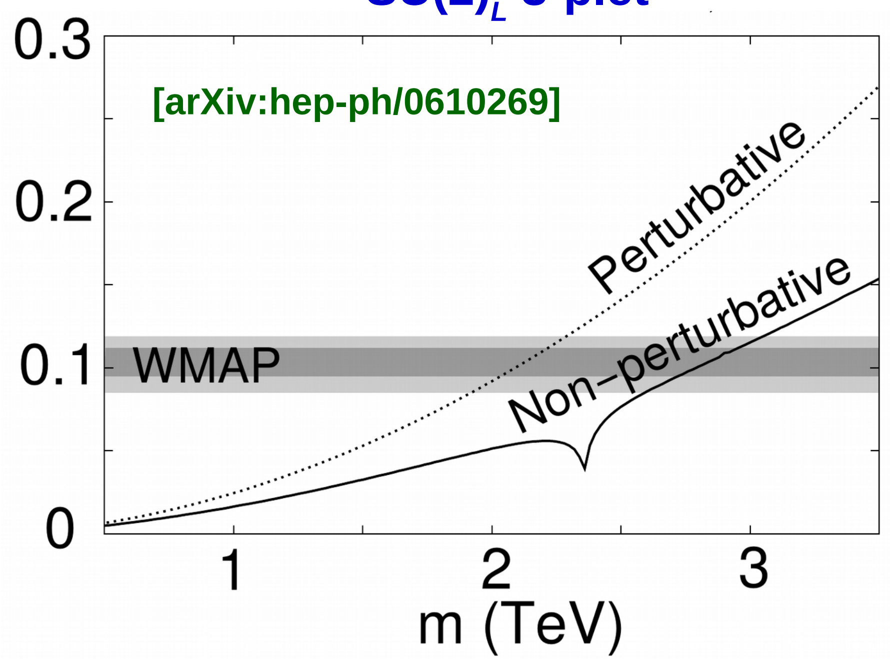
- Non-Abelian nature of WIMPs makes problem more complex.

  Consider e.g. an SU(2) triplet (Wino-like DM). During freeze-out, the neutral-charged component mass difference is less that the kinetic energy, thus:

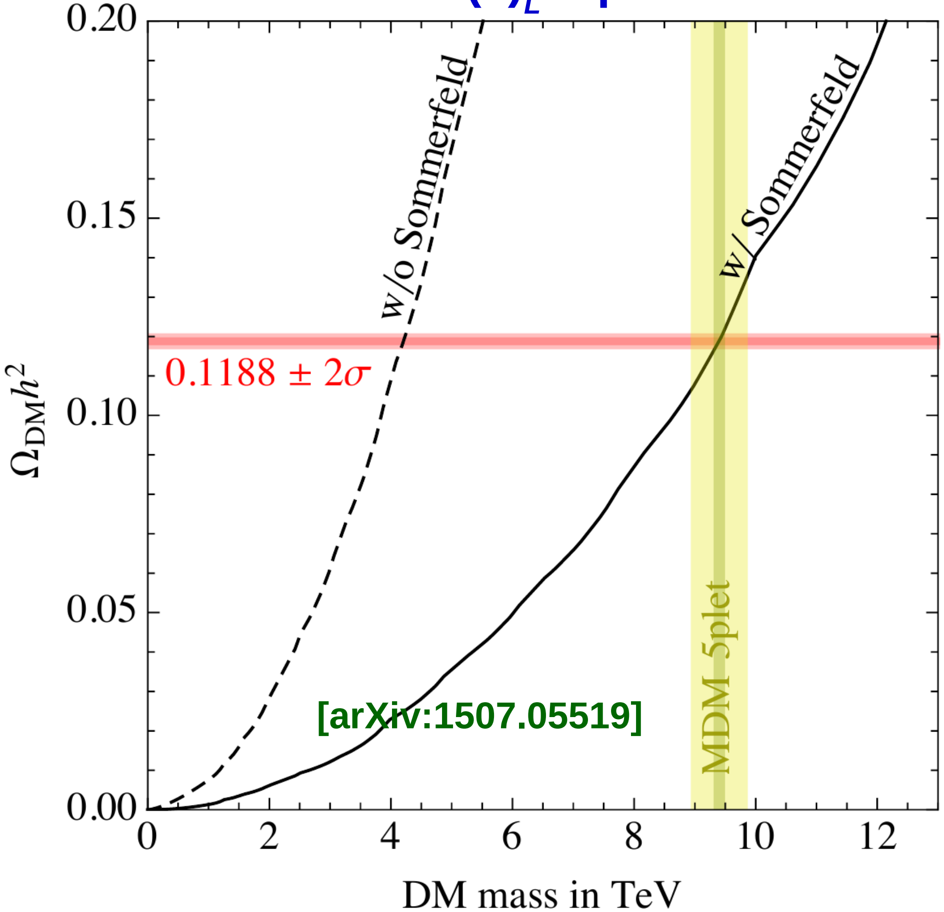


Long-range interactions
and good old WIMPs

SU(2)$_L$ 3-plet



SU(2)$_L$ 5-plet



Bound-state formation
not included

Long-range interactions

Implications for symmetric and asymmetric DM

- Relic density
  - Sommerfeld effect (SE) and BSF imply lower DM coupling to force mediators
    ⇒ affects the expected signals
- Indirect detection
  - Enhanced annihilation rates inside halos
  - Signals from radiative level transitions (BSF and other excitations/de-excitations)
  - Significant signals from asymmetric DM due to both of the above
- Direct detection
  - Velocity dependence of DM-nucleon cross-sections alters interpretation of results
  - Stable bound states (asymmetric DM) screen DM-nucleon scattering.
- Self-interactions inside galaxies
  - SE implies that σ_{scatt} decreases with v_{rel} (e.g. Rutherford scattering: $\sigma_{scatt} \sim 1/v_{rel}^4$).

    ⇒ significant effect on small scales, negligible effect on large scales

    ⇒ light mediators well-suited for self-interacting DM
  - Stable bound states (asymmetric DM) screen/curtail DM self-scattering.

V. Current topics

Very very very partial list

Current directions in dark matter research

- Galactic structure ↔ DM properties
  - Observations: Better understanding of small scales
  - Simulations: Modeling of baryonic physics and DM interactions
  - Theory: Scattering properties of self-interacting DM, input for simulations
- Light dark matter, m_{DM} < few GeV
  - Experiment: New direct-detection technologies
  - Theory: Motivation, interaction strength, benchmark models
- Heavy dark matter, m_{DM} > few TeV
  - Experiment: Indirect probes, e.g. IceCube, CTA, Hawk
  - Theory: Non-perturbative effects, radiative transitions, the role of substructure
- Metastable mediators
  - Displaced vertices at the LHC
  - Indirect signals from the sun
- Primordial black holes

Conclusion

Dark matter is an intriguing and complex problem that requires diverse expertise.

Many things to debate and calculate!