Dark Matter and the small-scale problems of structure formation

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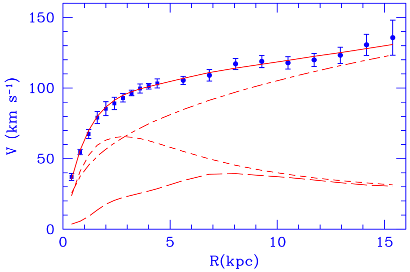
Overview

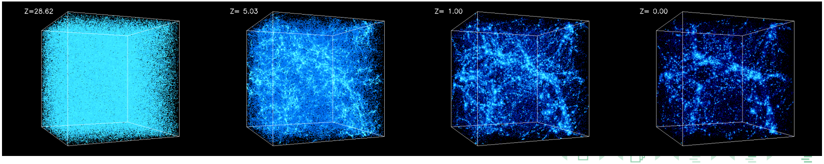
- the ΛCDM model
  - discrepancies at small scales ($\sim$ kpc)
  - possible explanations: late kinetic decoupling and self-interacting dark matter (SIDM)
- Models:
  - Dark "QED"
  - Neutrinophilic DM
  - Leptophilic DM
- Conclusion

The ΛCDM model – Summary

- $\Omega_{\Lambda\text{CDM}} h^2 \approx 0.1186$,
  $\Omega_b h^2 \approx 0.02225$.
- DM particles are
  - cold
  - collisionless
  - interact with SM mainly via gravity

  E.g. WIMPs
- hierarchical structure formation (bottom-up)





Small-scale discrepancies

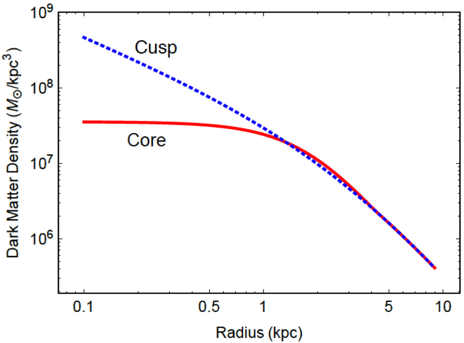
between observations and simulations

- "cusp vs core"
- "missing satellites"
- "too big to fail"

Cusp vs core

Galaxy simulations predict a cuspy DM density profile near the center (NFW)

Observations of rotational velocities predict a cored profile at small radii



hep-ph/1705.02358

Missing satellites

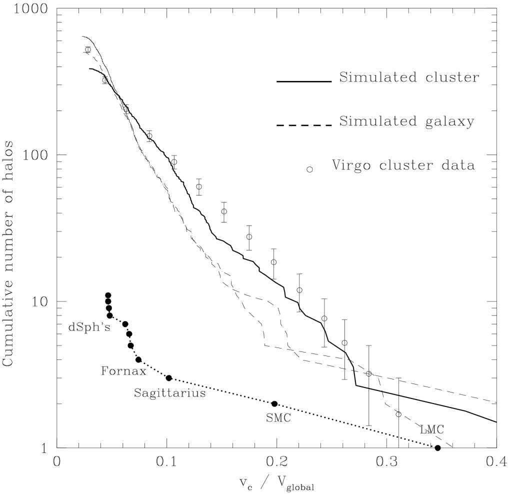
$\sim$ 100 DM subhalos expected in the Milky Way within ΛCDM model

at most 50 have been observed

same problem for the Local Group, but not for the Virgo cluster (large scale!)

maybe they are just faint satellites due to low baryonic content?

hep-ph/1705.02358



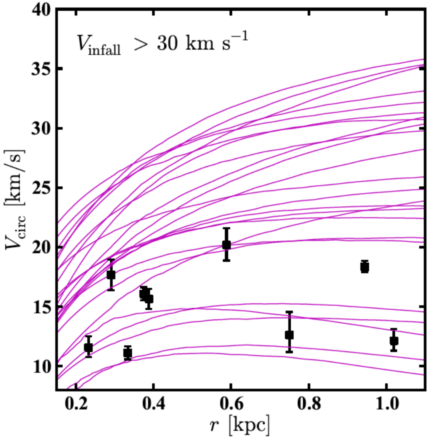
Too big to fail

The most massive dwarf spheroidal galaxies are expected to live in the most massive subhalos (the ones with the largest rotational velocities)

ΛCDM simulations, however, predict subhalos that are faster than any observed dSph galaxy.

These subhalos should be "too big to fail" to form luminous galaxies.

hep-ph/1705.02358



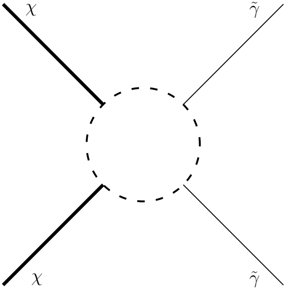
What are some possible modifications of the ΛCDM model that would explain these discrepancies?

- Late kinetic decoupling.
- Self-interacting dark matter.

Chemical and kinetic decoupling

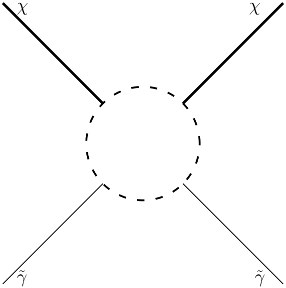
χ: DM particle, $\tilde{\gamma}$: relativistic scattering partner (thermal bath)

$\chi\chi \leftrightarrow \tilde{\gamma}\tilde{\gamma}$



chemical decoupling

$\chi\tilde{\gamma} \leftrightarrow \chi\tilde{\gamma}$



kinetic decoupling

Kinetic decoupling

Happens when the rate for elastic scattering isn't sufficient for maintaining local thermal equilibrium.

E.g. for WIMPs (ΛCDM) a simple approximation yields

$$T_{\mathrm{kd}} \approx \frac{m_\chi^{\frac{1}{4}} m_Z}{M_{\mathrm{Pl}}^{\frac{1}{4}} \left(G_F m_W^2\right)} \approx \mathcal{O}\left(10\right)\ \mathrm{MeV}\ .$$

More precise method:

$T_\chi \sim T$ at high temperatures

$T_\chi \xrightarrow{T\to 0} \left(\frac{a}{n+2}\right)^{\frac{1}{n+2}} \Gamma\left(\frac{n+1}{n+2}\right) \frac{T^2}{m_\chi}$, obtained from the Boltzmann equation, a and n are parameters which depend on the model considered

$\Rightarrow$ $T_{\rm kd}$ is defined as the temperature that matches these two asymptotic behaviours

$$\frac{T_{\rm kd}}{m_\chi} = \left(\left(\frac{a}{n+2}\right)^{\frac{1}{n+2}} \Gamma\left(\frac{n+1}{n+2}\right)\right)^{-1}$$

Bringmann, Hofmann hep-ph/0612238

Damping scales related to kinetic decoupling

- *free streaming* after kinetic decoupling from regions of high density to regions of low density, $k_{\rm fs} \propto T^{-1/2} \Rightarrow \; M_{\rm fs} \propto T^{-3/2}$

- *acoustic oscillations* of the thermal bath $\Rightarrow$ only effective until kinetic decoupling, $M_{\rm ao} \propto T^{-3} \leftarrow$ most relevant one for late kinetic decoupling

The "missing satellites" problem requires $M_d \approx 10^{10}\, M_\odot$: all substructures with mass $M < M_d$ are wiped out by acoustic damping.

This is achieved with a late kinetic decoupling,

$$M_\mathrm{d} \sim 10^{10} M_\odot \left(\frac{0.1\,\mathrm{keV}}{T_\mathrm{kd}}\right)^3 .$$

WIMPs fail, because they decouple too early,

$$M_\mathrm{d} \sim 30\, M_\oplus \left(\frac{10\,\mathrm{MeV}}{T_\mathrm{kd}}\right)^3 .$$

Note: Lyman-α constraint $M_\mathrm{d} \lesssim 10^{10}\, M_\odot$

Self-interacting dark matter

elastic $2 \to 2$ scattering $\Rightarrow$ heat from hotter outer region to colder inner region

Scattering rate:

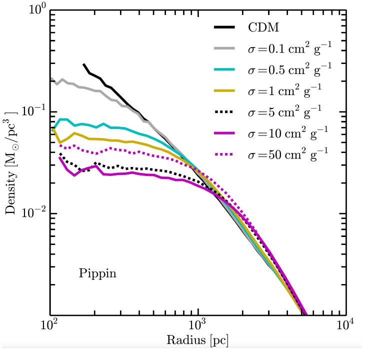
$$R_{\text{scat}} = \frac{\sigma v_{\text{rel}} \rho_{\text{dm}}}{m}$$

Consequences:
- $R_{\text{scat}} \propto \rho_{\text{dm}} \Rightarrow$ no effects on large scales

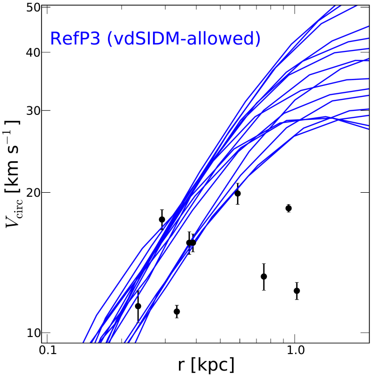
- DM is less concentrated and more spherical at the scale $1 - 10$ kpc

Velocity-dependent cross section:
- $\sigma/m \approx 0.1\,\mathrm{cm}^2/\,\mathrm{g}$ at cluster (large) scales
- $\sigma/m \approx 1\,\mathrm{cm}^2/\,\mathrm{g}$ at dwarf (small) scales is required by

"cusp vs core"



"too big to fail"



hep-ph/1705.02358

Summary:

Models featuring

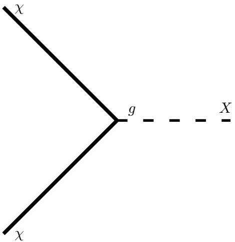
- a late kinetic decoupling, i.e. $T_{\rm kd} \sim 0.1\,{\rm kpc}$,
- and self interactions with $\sigma/m \sim 0.1 - 1{\rm cm}^2{\rm g}^{-1}$

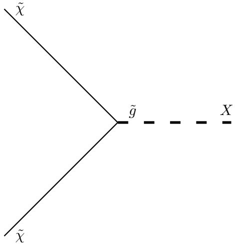
are good candidates for addressing the small-scale discrepancies.

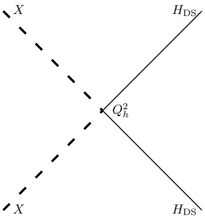
Some specific models:

- dark "QED"
- neutrinophilic DM
- leptophilic DM

A simple realization: Dark QED



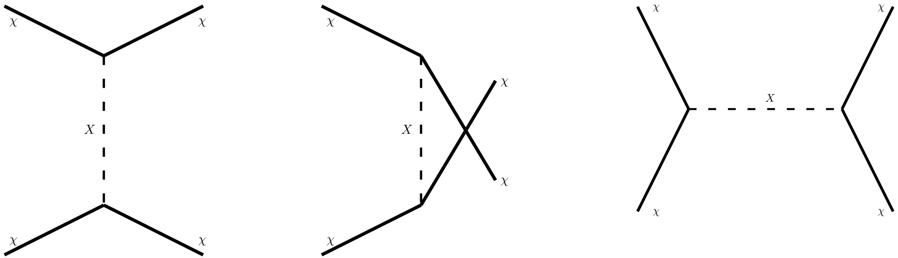




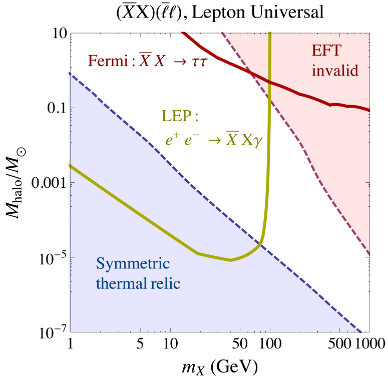
Kinetic decoupling: OB, Hofmann, Kassiteridis hep-ph/1710.09846

$$T_{\rm kd} \approx 147\,{\rm eV}\,\varepsilon|_{T_{\rm kd}}^{-1/2} \left(\frac{m_\chi}{10\,{\rm TeV}}\right)^{-\frac{1}{4}} \left(\frac{\Omega_\chi h^2}{0.12}\right)^{\frac{1}{4}} \left(\frac{m_X}{1.1\,{\rm MeV}}\right) \left(\frac{T}{T_\nu}\right)^{3/2}$$

Self interaction: $\langle \sigma_T/m_\chi \rangle_{v_{\rm therm}} \sim 0.1 - 1\,{\rm cm}^2{\rm g}^{-1}$



Relativistic scattering partner in the SM?

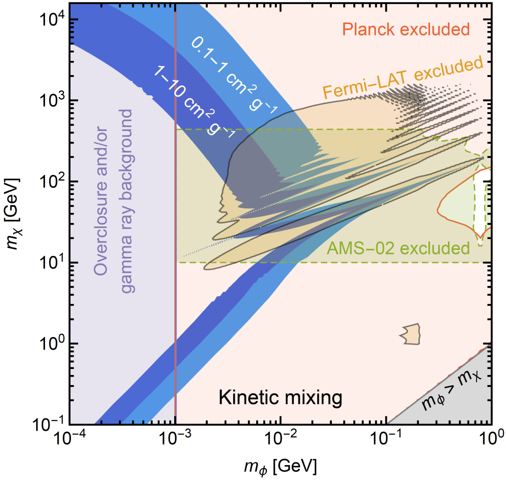


hep-ph/1305.1936

$M_d \lesssim 10^{-1}\, M_\odot$
$\Rightarrow$ charged leptons are excluded as relativistic scattering partners

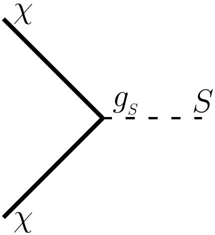
γ's are strongly constrained as relativistic scattering partners

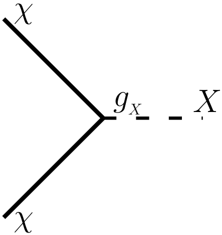
what about ν's?

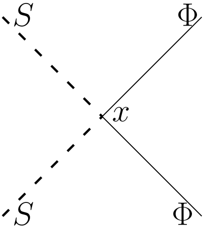


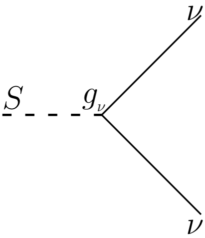
Bringmann et al. hep-ph/1612.00845

Neutrinophilic dark matter









Relic density

Relic density from the chemical decoupling from S ($\chi\chi \leftrightarrow SS$)

$$\Omega_\chi h^2 \approx 0.12 \left(\frac{\alpha}{0.1}\right)^{-2} \left(\frac{m_\chi}{\text{TeV}}\right)^2$$

Problem: α will have to be > 0.1 to solve the "missing satellites" problem
$\Rightarrow$ the $XX \leftrightarrow \chi\chi$ process determines the relic density

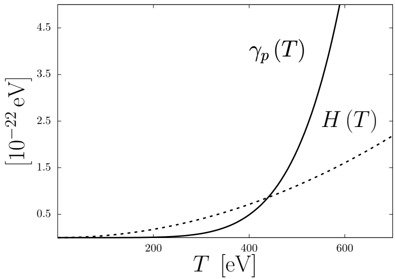
$$\Omega_\chi h^2 \approx 0.12 \left(\frac{g_X}{8 \times 10^{-11}}\right)^2 \left(\frac{114}{g_* \left(T_\text{f}\right)}\right)^{\frac{3}{2}} \times \left(\frac{m_\chi}{\text{TeV}}\right) \left(\frac{\text{PeV}}{m_X}\right)$$

OB, Hofmann, Kassiteridis hep-ph/1710.09846

Decoupling temperature

The temperature of kinetic decoupling is determined by

$$\frac{T}{m_\chi} n_\nu \sigma_{\chi\nu\to\chi\nu}\left(T_{\rm kd}\right) \sim H\left(T_{\rm kd}\right)$$



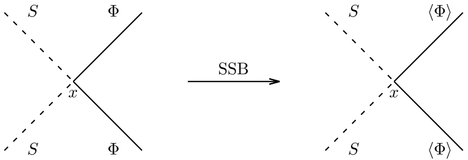
Late kinetic decoupling fixes $m_S \approx \mathcal{O}(1)$ keV.

Self-interacting dark matter

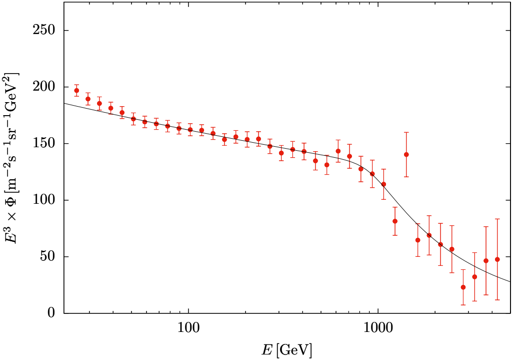
$m_S \lesssim \mathcal{O}(1)$ keV yields the wrong values of $\langle \sigma_T / m_\chi \rangle_{v_{\text{therm}}}$ for self interactions

$\Rightarrow$ change the mass of S by condensation of the scalar potential Φ after kinetic decoupling

$$m_{S,\text{obs}} = \sqrt{m_S^2 + x \langle \Phi \rangle^2 / 2}$$



DAMPE experiment



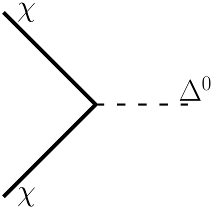
Flux of high-energy cosmic $e^{\pm}$

$\Rightarrow$ indirect detection of DM?

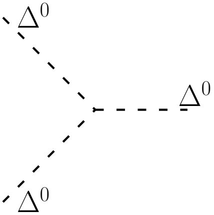
hep-ph/1711.10981

Leptophilic dark matter

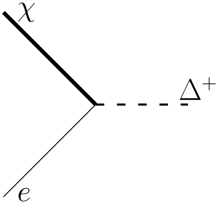
$$\boxed{\chi\,,\ \Delta^+\,,\ \Delta^0\,,\ e}$$



channel for self interaction

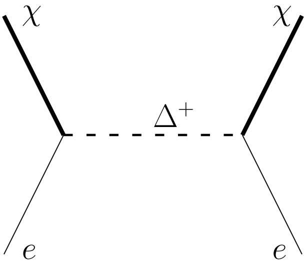


elastic scattering with Δ^0

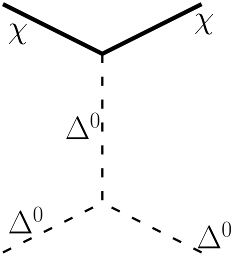


contact with the SM

Elastic scattering processes



facilitates also a decay into $e^{\pm}$

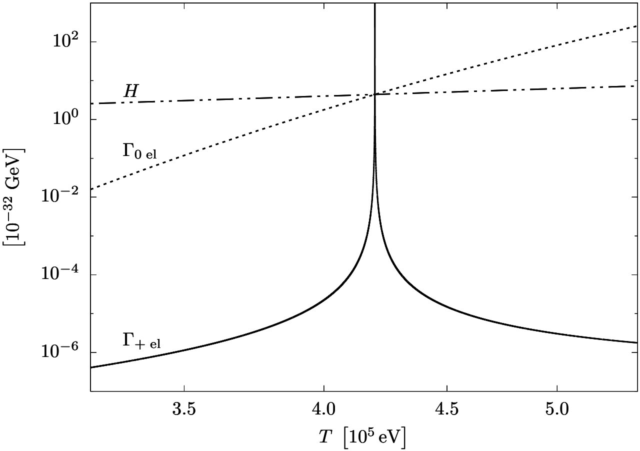


more effective at keeping χ in thermal equilibrium

Elastic scattering with Δ^+

If $(m_\chi - m_{\Delta^+})/m_\chi \ll 1 \Rightarrow$ resonant behavior for elastic scattering

$$\sigma_T^{\mp} = \frac{\pi \alpha_e^2 m^2}{4 m_\chi^4} \left[-\left(\frac{m_\chi - m_{\Delta^+}}{m_\chi} \pm \frac{m}{m_\chi} \left(1 + \frac{v^2}{2} \right) \right) + \frac{1}{2} \left(-\frac{(m_\chi - m_{\Delta^+})^2}{m_\chi^2} + \frac{m^2}{m_\chi^2} \right) \right]^{-2}$$

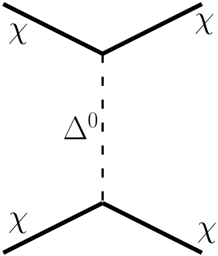


Late kinetic decopuling fixes $m_0 \sim$ keV.

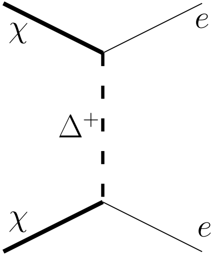
OB, Hofmann, Kassiteridis hep-ph/1812.02182

Self-interacting dark matter

$$\text{If} \quad \begin{array}{c} m_0 \sim \text{keV}, \\ \alpha_0 \sim \mathcal{O}\left(10^{-4}\right) \end{array} \quad \Rightarrow \quad \langle \sigma_T / m_\chi \rangle_{v_\text{therm}} \sim 0.1 - 1\,\text{cm}^2\text{g}^{-1}$$



$m_\chi = 1.4\,\mathrm{TeV}$	$m_0 = 7.1\,\mathrm{keV}$	$T_{\mathrm{kd}} \approx 0.42\,\mathrm{keV}$	$\langle \sigma_T/m_\chi \rangle \sim 0.1 - 1\,\mathrm{cm}^2\mathrm{g}^{-1}$



The parameters can be specifically chosen such that annihilations of the DM particles could produce the DAMPE signal.

CONCLUSION

- ΛCDM works very well at cluster scales, but there are some discrepancies with observations at the scales of dwarf galaxies
- “cusp vs core”, “missing satellites”, and “too big to fail”
- DM with a late kinetic decoupling and self interactions is able to explain these discrepancies
- easy realization if DM is completely secluded
- DM models with SM neutrinos as last scattering partners are also possible
- DAMPE results can also be accomodated in a model solving the small-scale problems

Thank you!