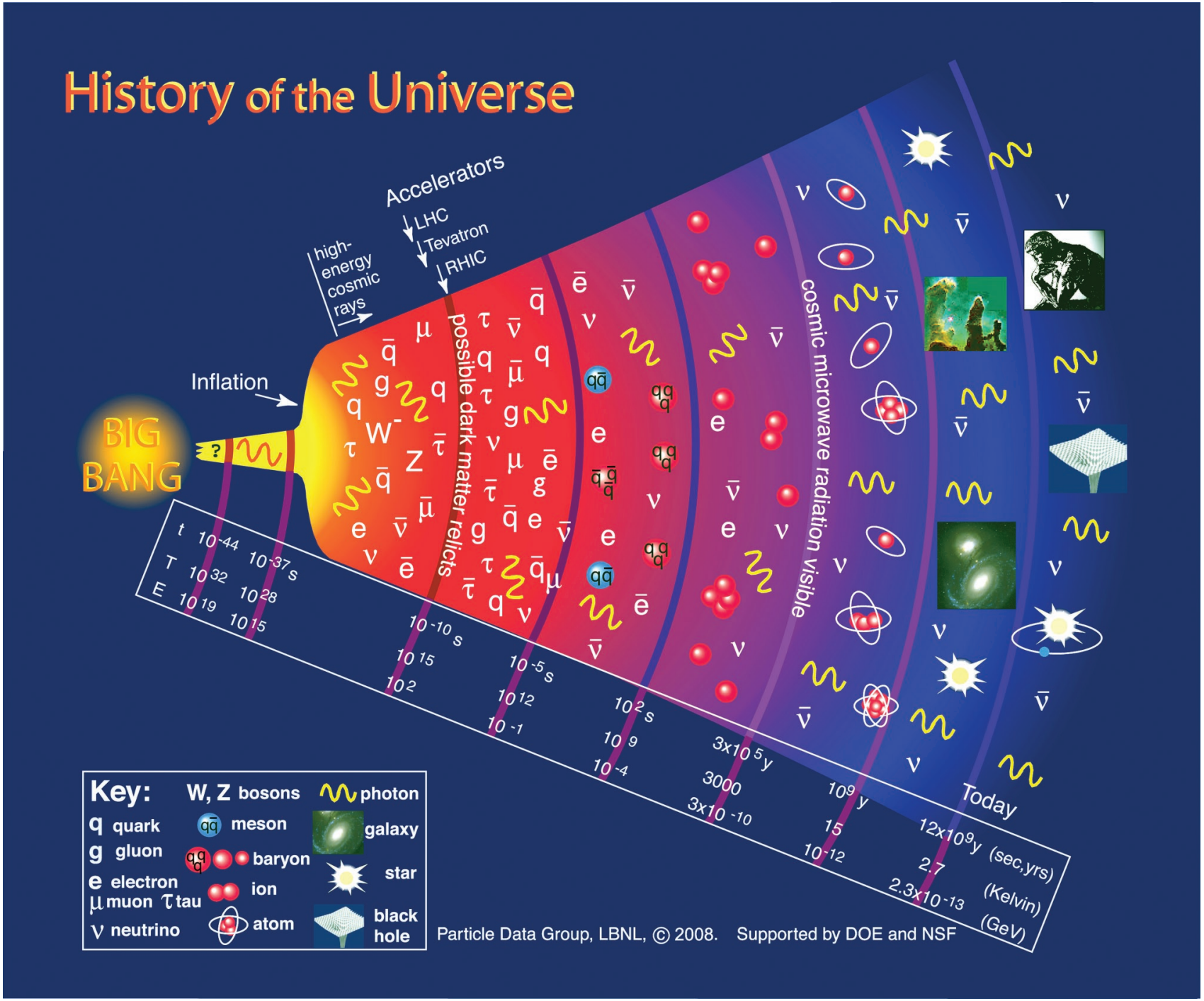
Not So Weakly Interacting Dark Matter Bonding with Sterile Neutrinos

Jörn Kersten

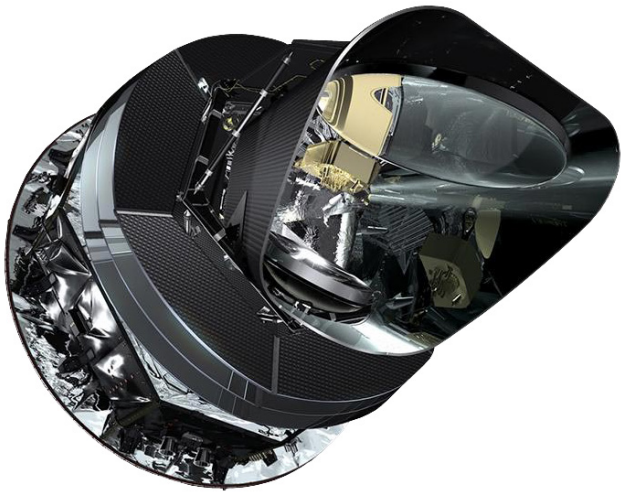
UNIVERSITY OF BERGEN

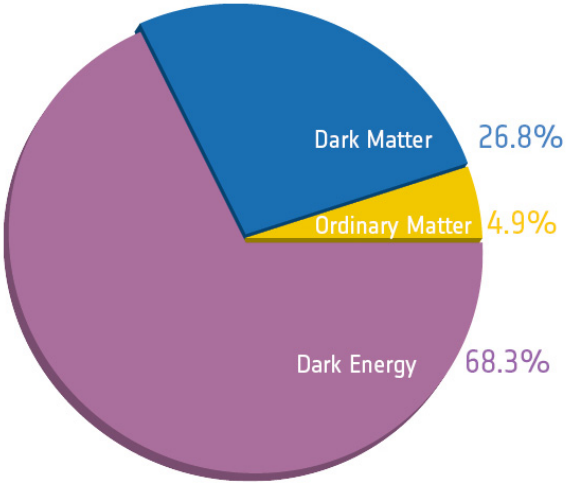
Based on Torsten Bringmann, Jasper Hasenkamp, JK, JCAP **07** (2014)
[arXiv:1312.4947]


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Outline

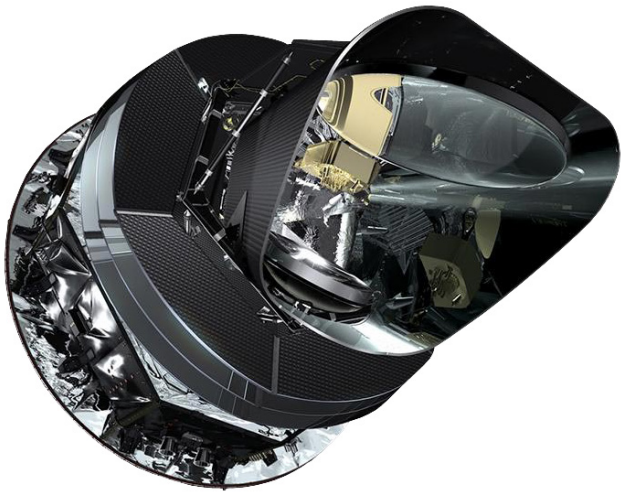
The Universe after Planck

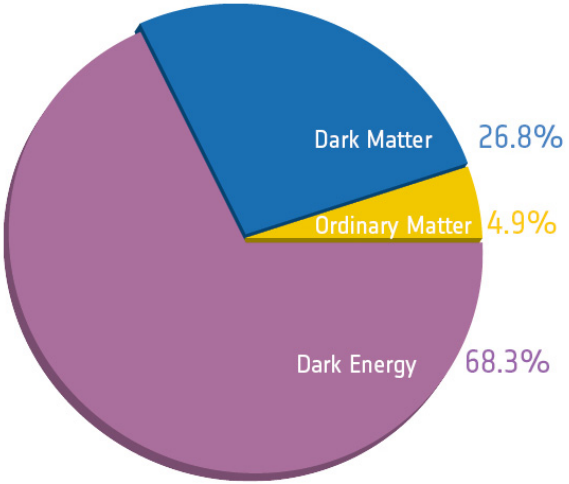




Flat ΛCDM cosmology fits data perfectly Planck, arXiv:1303.5062

The Universe after Planck





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Or does it?
Tensions in ΛCDM cosmology

Hints for Dark Radiation

- Dark radiation: relativistic particles $\neq \gamma, \nu^{\mathrm{SM}}$
- Parameterized via radiation energy density

$$\rho_{\mathrm{rad}} \equiv \left[1 + N_{\mathrm{eff}} \frac{7}{8} \left(\frac{T_\nu}{T}\right)^4\right] \rho_\gamma$$

- $T \equiv T_\gamma$
- N_{eff}: effective number of neutrino species
- Standard Model: $N_{\mathrm{eff}} = 3.046$
- Existence of dark radiation $\Leftrightarrow \Delta N_{\mathrm{eff}} \equiv N_{\mathrm{eff}} - 3.046 > 0$

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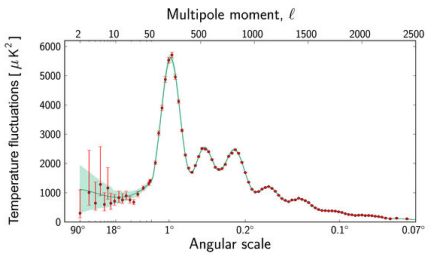
- Measurements of Cosmic Microwave Background (CMB):

$\Delta N_{\mathrm{eff}} = 1.51 \pm 0.75$ at 68% CL ACT, ApJ **739** (2011)

$\Delta N_{\mathrm{eff}} = 0.81 \pm 0.42$ at 68% CL SPT, ApJ **743** (2011)

$\Delta N_{\mathrm{eff}} = 0.31^{+0.68}_{-0.64}$ at 95% CL Planck, arXiv:1303.5076



Hints for Hot Dark Matter

- $2 \ldots 3\,\sigma$ tension: CMB ($z > 1000$) vs. local ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.3 \pm 1.2)\frac{\text{km}}{\text{s Mpc}}$ arXiv:1303.5076
  - Hubble: $H_0 = (73.8 \pm 2.4)\frac{\text{km}}{\text{s Mpc}}$ Riess et al., ApJ **730** (2011)
- Magnitude of matter density fluctuations (σ_8)

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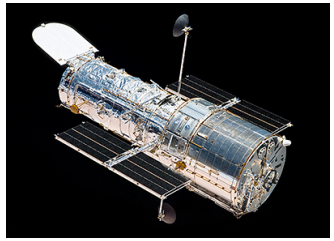
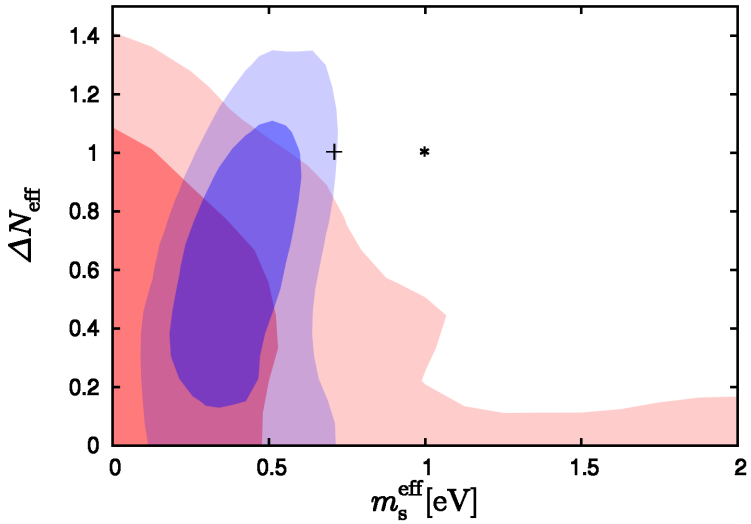


- Magnitude of matter density fluctuations (σ_8)
- Resolved by hot dark matter component $\simeq$ dark radiation
- Best fit:

$$\Delta N_{\text{eff}} = 0.61$$

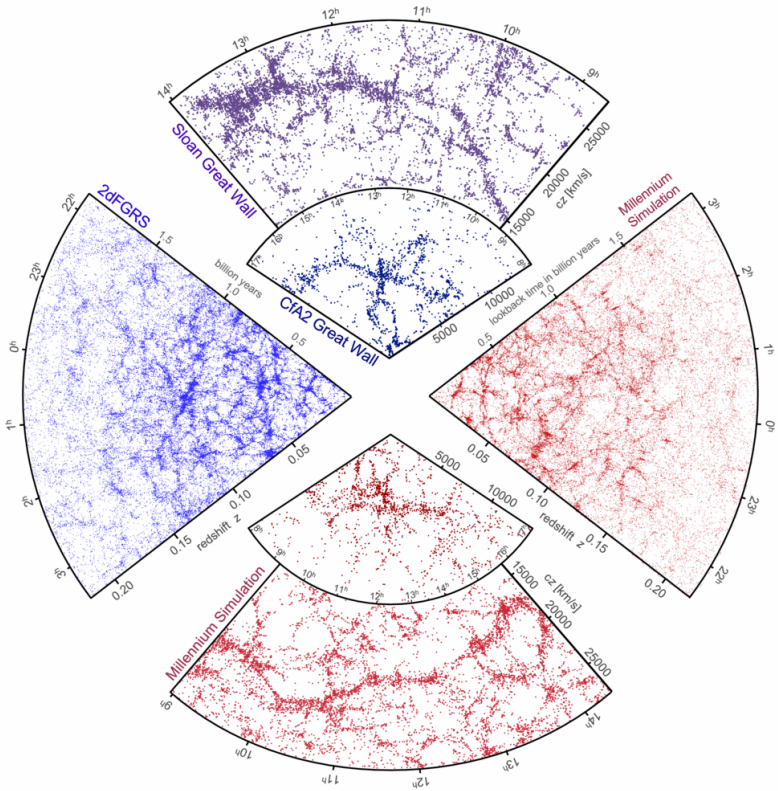
$$m_s^{\text{eff}} \equiv \left(\frac{T_s}{T_\nu}\right)^3 m_s = 0.41\ \text{eV}$$

Hamann, Hasenkamp, JCAP **10** (2013)
Wyman, Rudd, Vanderveld, Hu, PRL **112** (2014)
Battye, Moss, PRL **112** (2014)
Gariazzo, Giunti, Laveder, JHEP **11** (2013)



Small-Scale Problems of Structure Formation

Numerical simulations of structure formation with cold dark matter



Springel, Frenk, White, Nature **440** (2006)

$\rightsquigarrow$ Excellent agreement with observations

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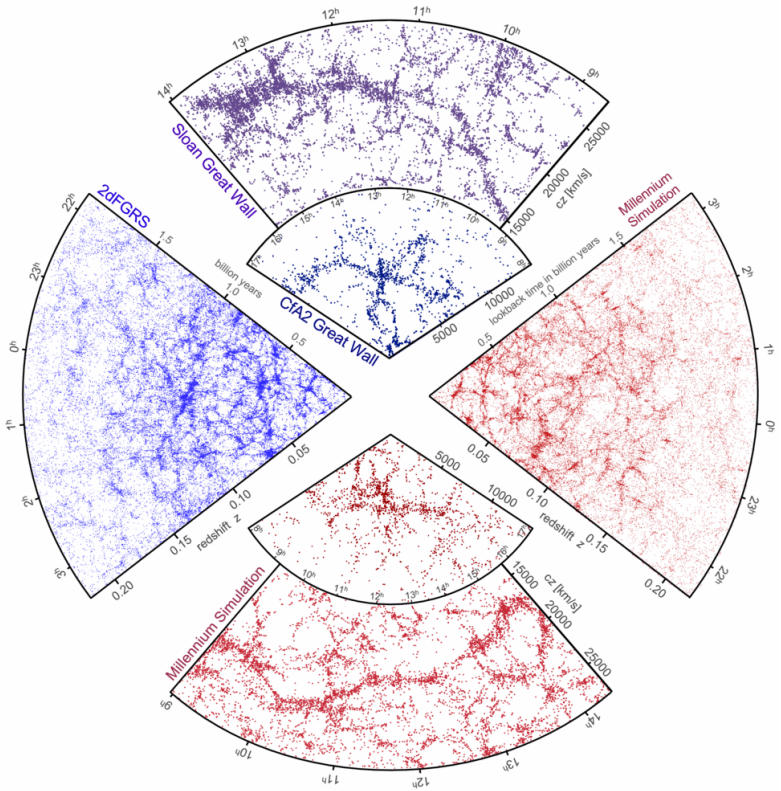
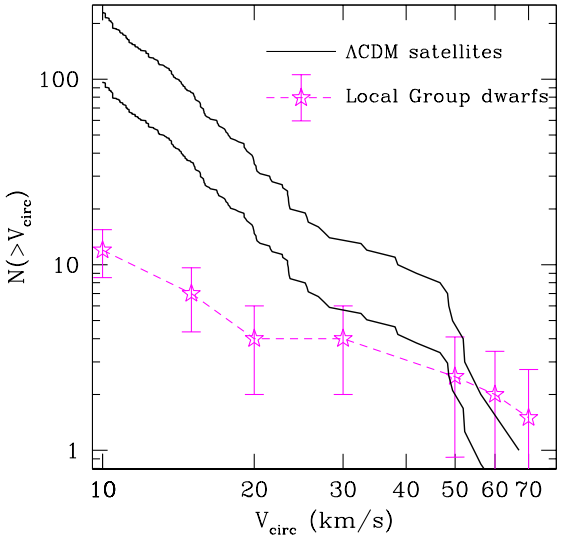


Springel, Frenk, White, Nature **440** (2006)

⇝ Excellent agreement with observations on large scales

Small-Scale Problems of Structure Formation

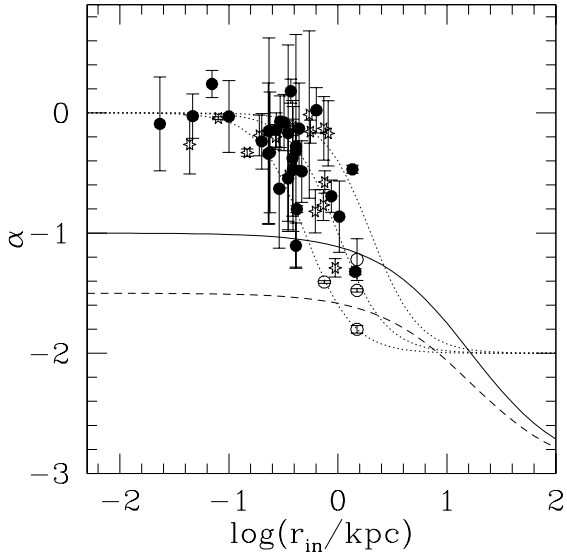
Missing satellites



Kravtsov, Adv. Astron. (2010)
Klypin et al., ApJ **522** (1999)

More galactic satellites predicted than observed

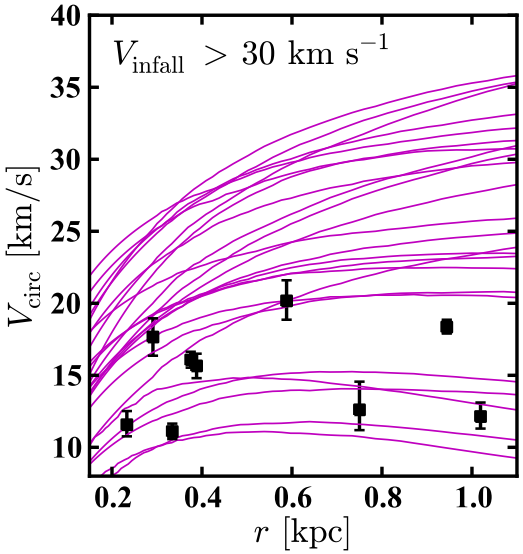
Cusp-core



De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Too big to fail

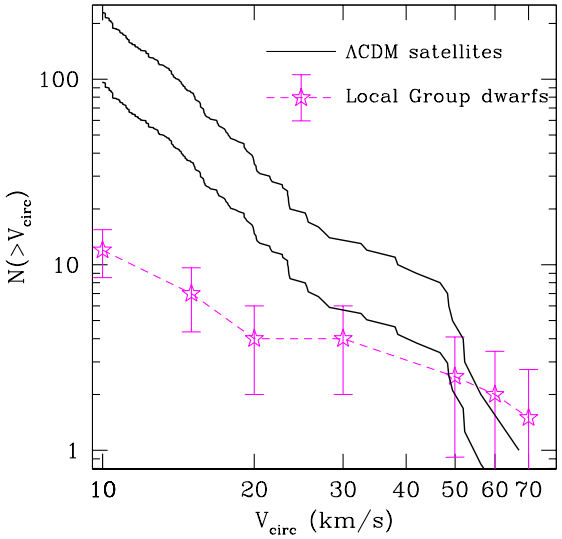


Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

Small-Scale Problems of Structure Formation

Missing satellites



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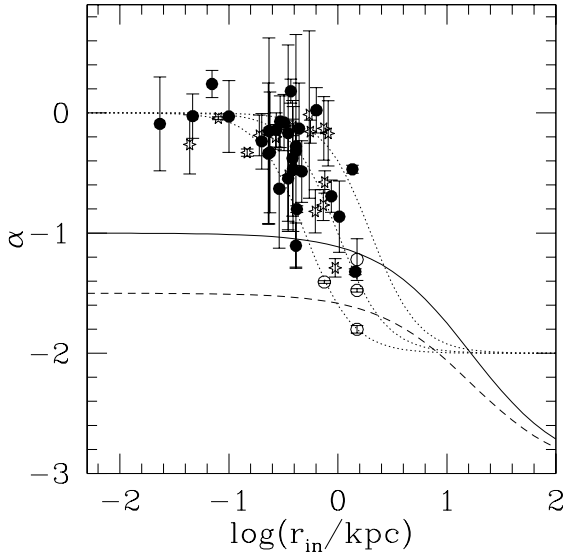

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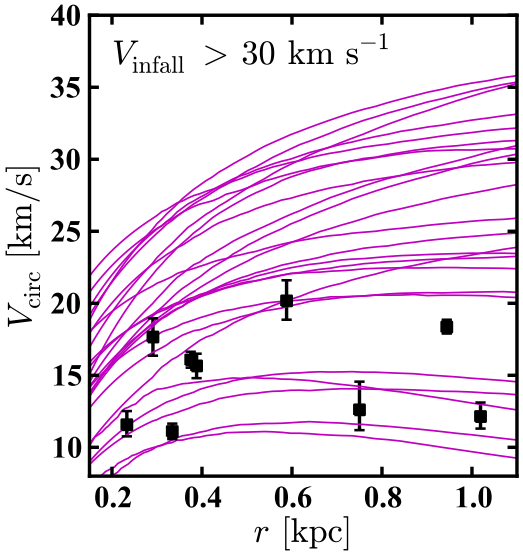

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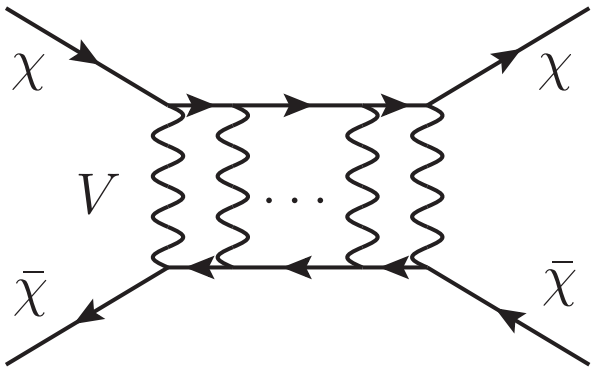
Astrophysics solutions or new particle physics?

Not-so-WIMPy Dark Matter

- Dark matter χ
  - Standard Model singlet
  - Charged under $U(1)_X$ gauge interaction
  - Mass $m_\chi \sim$ TeV
- Light gauge boson V, $m_V \sim$ MeV

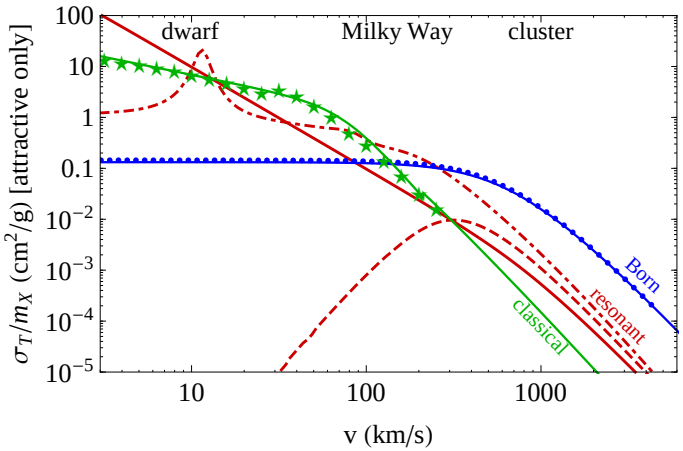
$\rightsquigarrow$ Long-range, velocity-dependent interaction
$\rightsquigarrow$ Less cuspy density profiles
$\rightsquigarrow$ Cusp-core and too big to fail solved

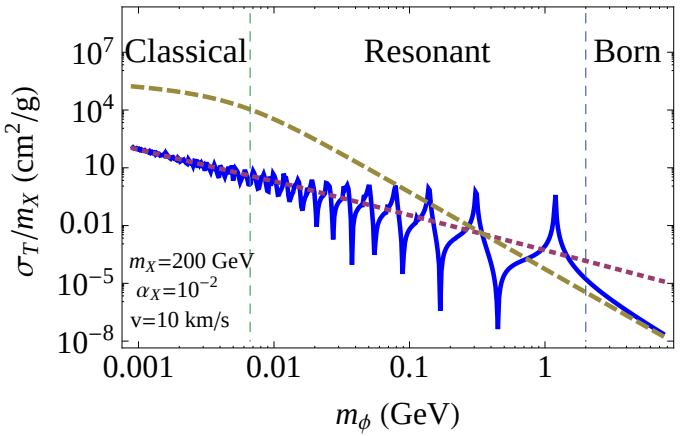


Feng, Kaplinghat, Yu, PRL **104** (2010)
Loeb, Weiner, PRL **106** (2011)
Vogelsberger, Zavala, Loeb, MNRAS **423** (2012)

Velocity-Dependent Self-Interactions

- Described by Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_V r}$
- Desired scattering cross section σ_T:
  - Large in dwarf galaxies
  - Small on larger scales to satisfy experimental limits
- Very different behavior depending on model parameters





Tulin, Yu, Zurek, PRL **110**, PRD **87** (2013)

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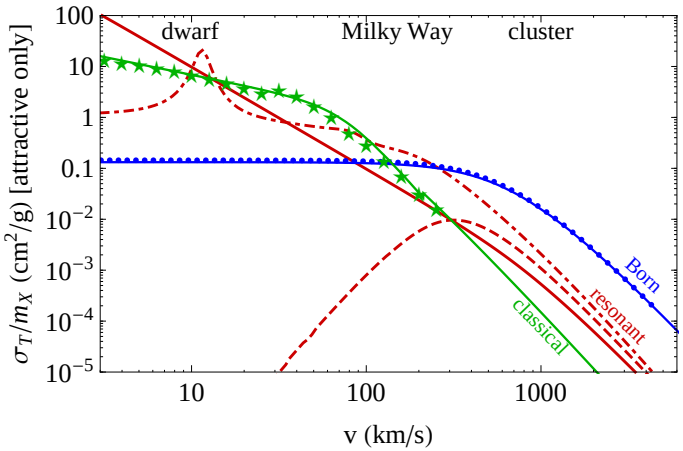
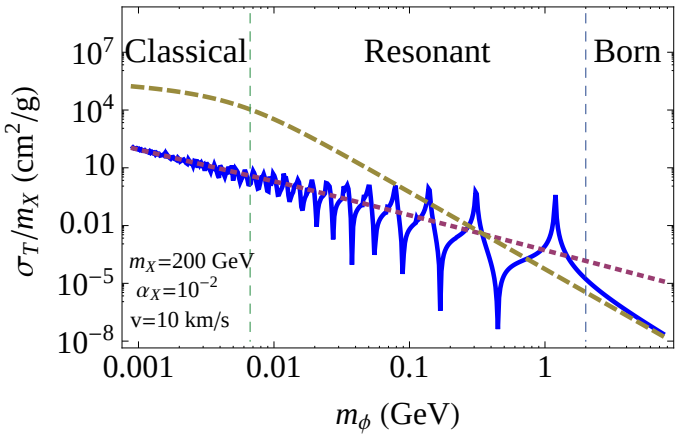




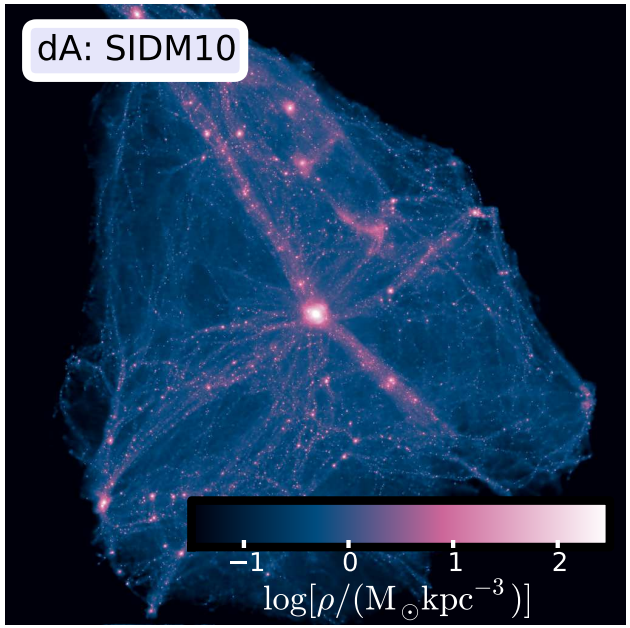
Tulin, Yu, Zurek, PRL **110**, PRD **87** (2013)

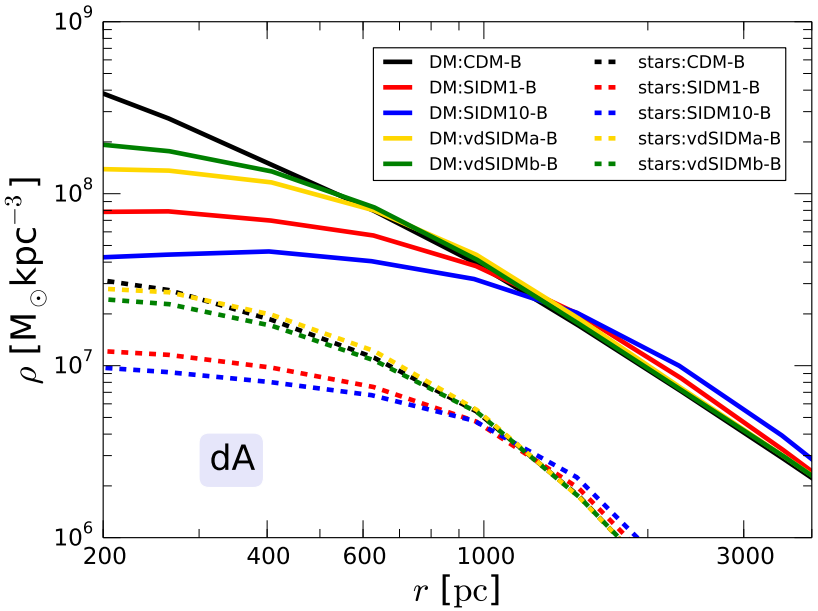
$$\text{Here: } \frac{m_\chi v}{m_V} \sim \frac{\text{TeV}}{\text{MeV}} \frac{10\,\text{km/s}}{3 \cdot 10^5\,\text{km/s}} \sim 30 \gg 1$$

$\rightsquigarrow$ classical regime $\rightsquigarrow$ analytical approximations exist

Simulating Self-Interacting Dark Matter

Simulation: formation of dwarf galaxy with dark matter + baryons



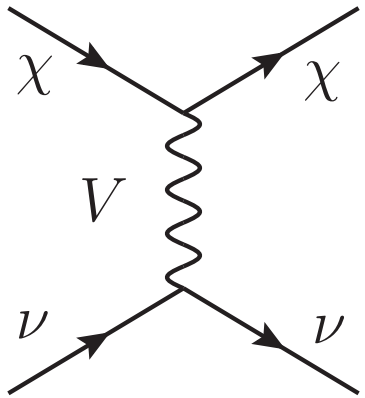


Vogelsberger, Zavala, Simpson, Jenkins, MNRAS **444** (2014)

⇝ Core, size depends on strength of self-interactions

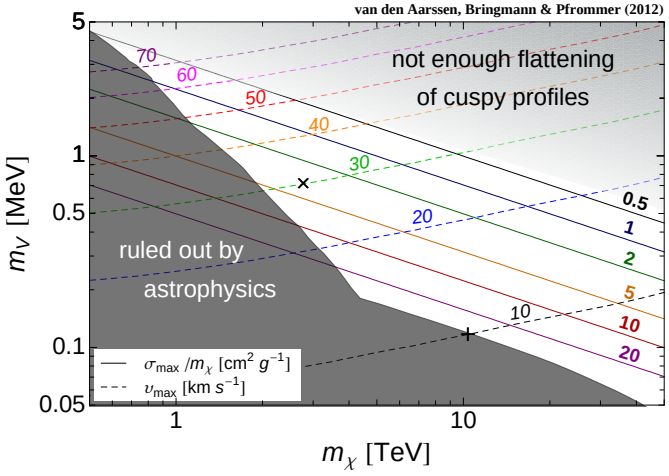
Late Kinetic Decoupling

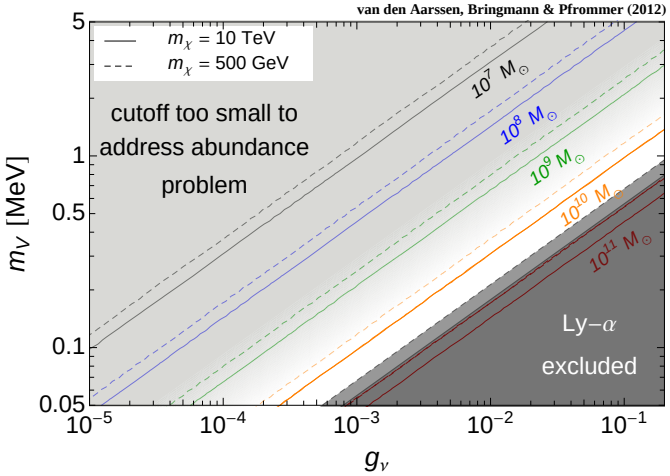
- Standard Model neutrinos coupled to V
- Dark matter scatters off neutrinos



$\rightsquigarrow$ $T_\chi = T_\nu$ until kinetic decoupling at $T \sim 100$ eV
$\rightsquigarrow$ Formation of smaller structures suppressed
$\rightsquigarrow$ Missing satellites solved

Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)





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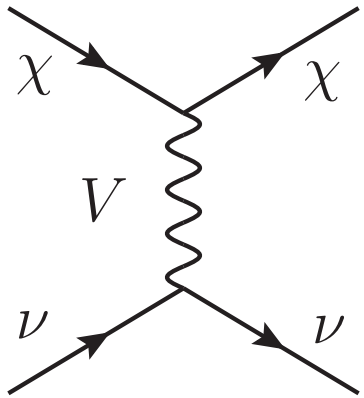

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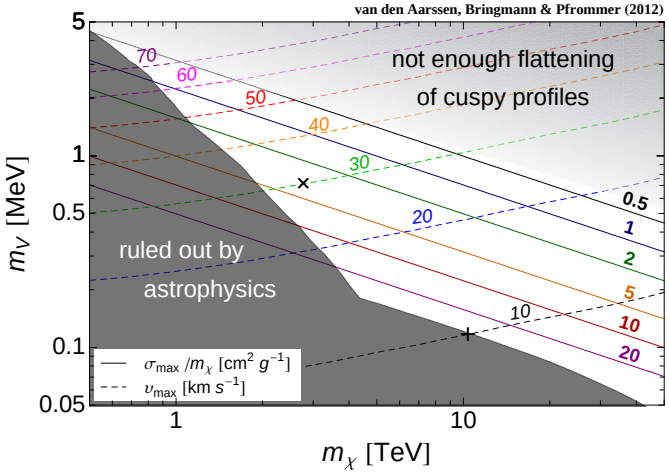
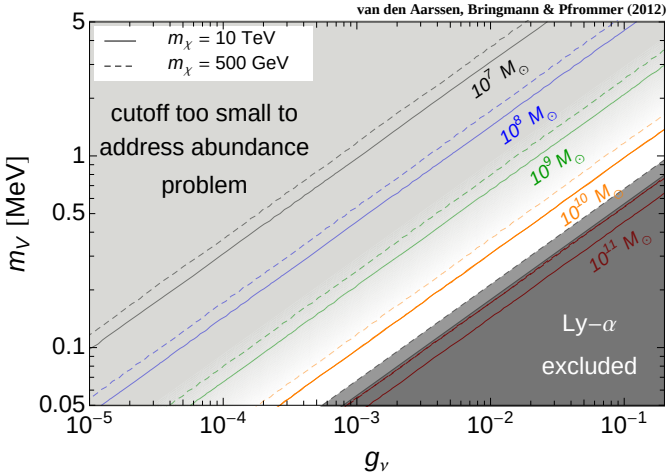
Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)

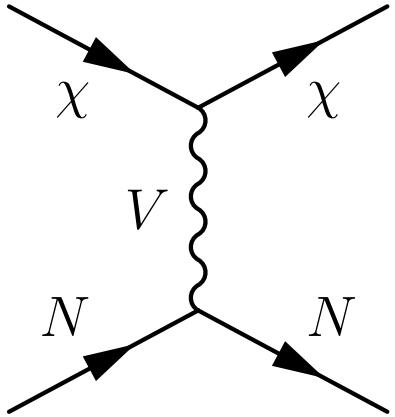
Problem: explicit breaking of $SU(2)_L$





Enter the Sterile Neutrino

- Sterile neutrino N
  - Mass $m_N \sim$ eV
  - Standard Model singlet
  - Charged under $U(1)_X$
  - Forms hot dark matter
- Dark matter scatters off sterile neutrinos



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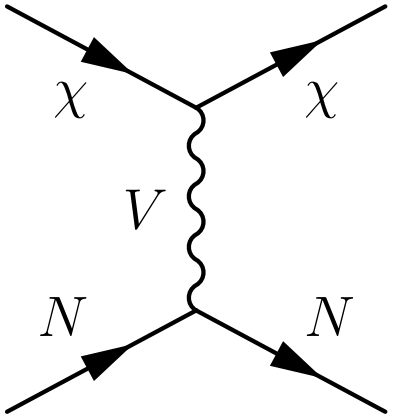

$\rightsquigarrow$ Everything solved

- All small-scale problems of structure formation
- Hot dark matter hint (CMB-local tension)
- Neutrino oscillation anomalies

Bringmann, Hasenkamp, JK, JCAP **07** (2014)

Dark Matter Production

- High temperatures: $U(1)_X$ sector thermalized via Higgs portal

$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$

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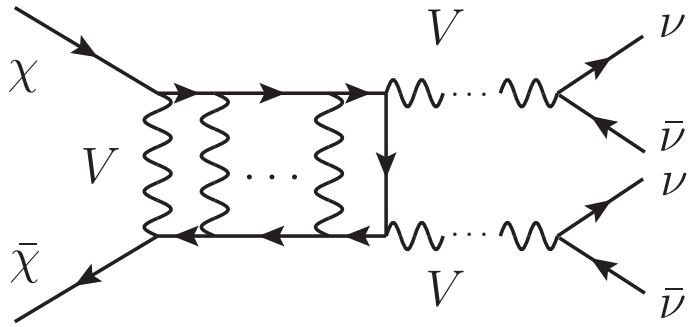
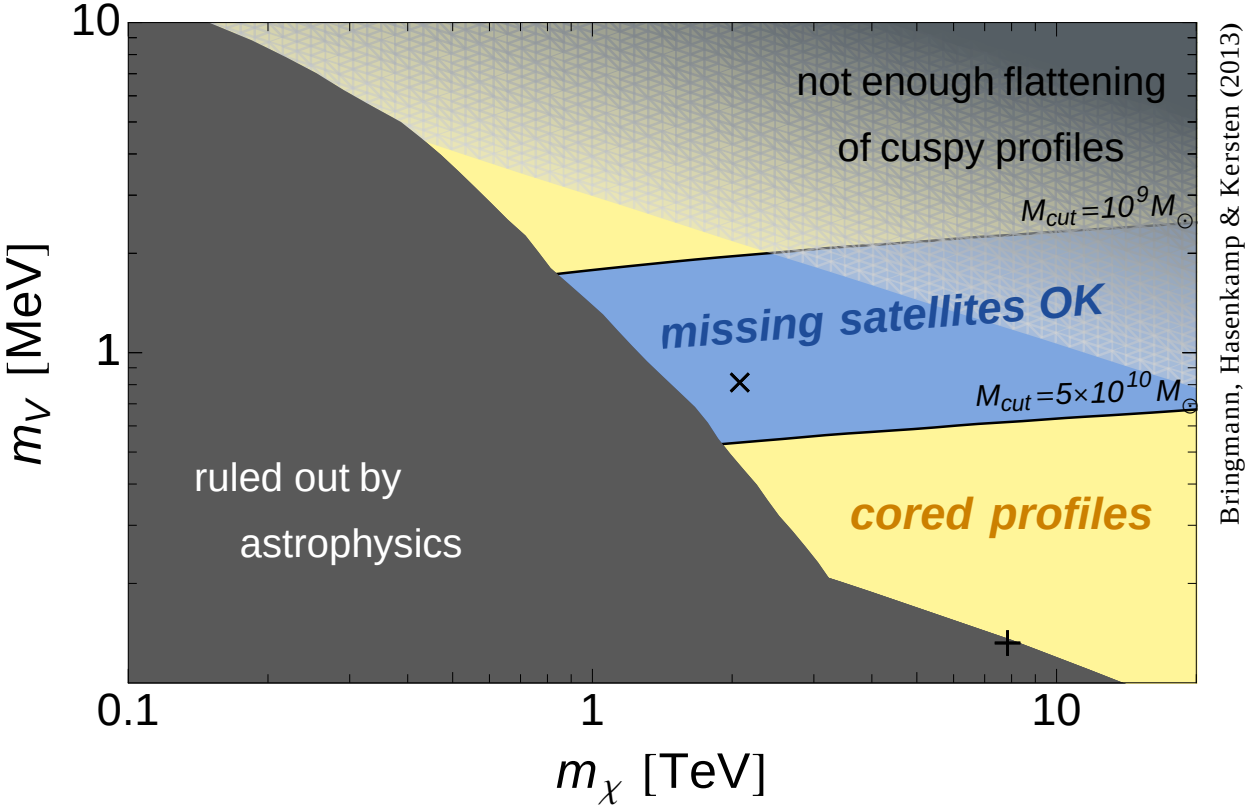
$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

$$\Omega_{\text{CDM}} h^2 \sim 0.11 \left(\frac{0.67}{g_X}\right)^4 \left(\frac{m_\chi}{\text{TeV}}\right)^2$$



Cold Dark Matter Parameter Space



- Blue band can be moved vertically by changing sterile neutrino charge and temperature
- Crosses: simulations show that too big to fail solved

Sterile Neutrino Abundance

- $T \downarrow \rightsquigarrow$ Higgs portal no longer effective
  $\rightsquigarrow U(1)_X$ sector decouples at T_x^{dpl} (depending on κ)
- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\rightsquigarrow T_N < T_\nu$ (depending on number of d.o.f. g_*)

$$\Delta N_{\text{eff}}(T) = \left(\frac{T_N}{T_\nu}\right)^4 = \left(\frac{g_{*,\nu}}{g_{*,N}}\right)^{\frac{4}{3}}\Bigg|_T \left(\frac{g_{*,N}}{g_{*,\nu}}\right)^{\frac{4}{3}}\Bigg|_{T_x^{\text{dpl}}}$$

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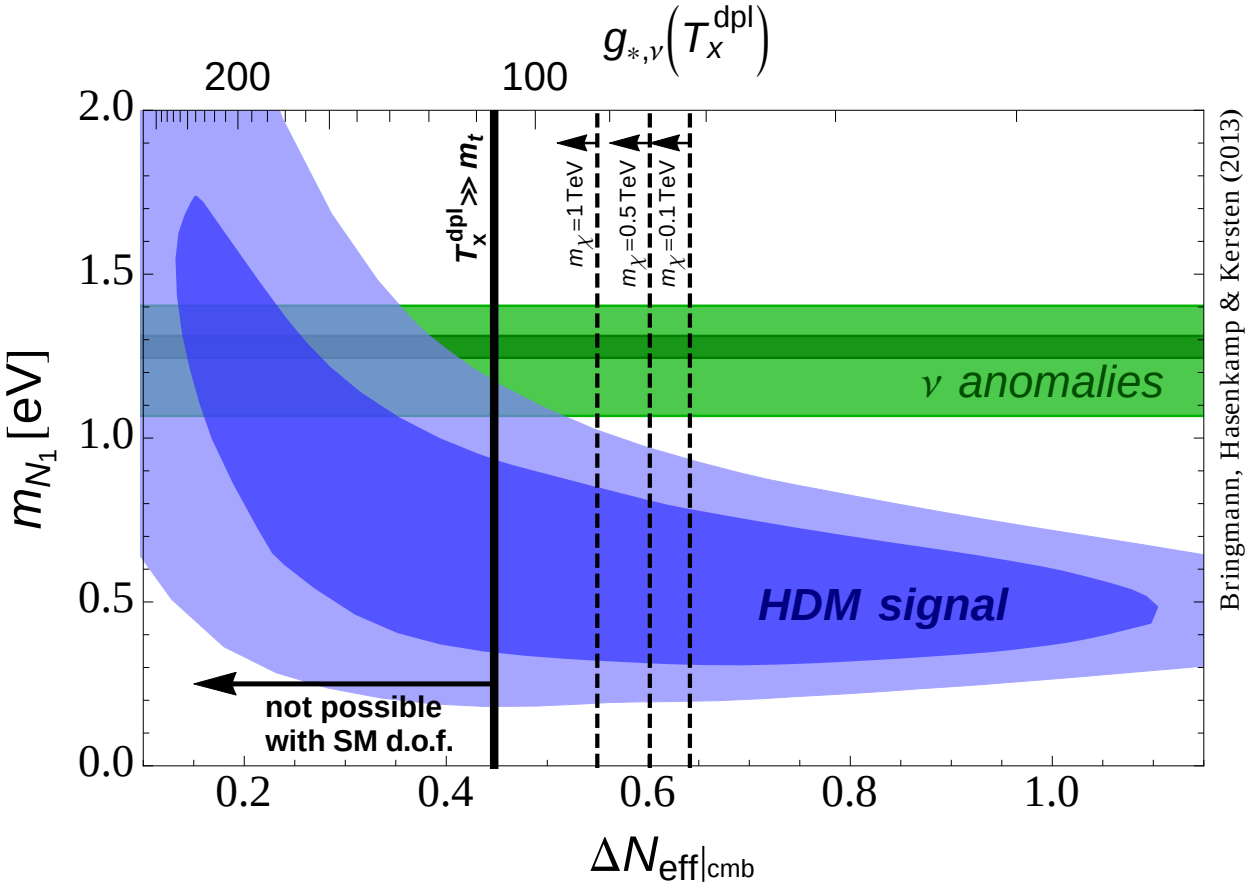
$$\Delta N_{\text{eff}}|_{\text{BBN}} < \left(\frac{58.4}{g_{*,\nu}(T_x^{\text{dpl}})}\right)^{\frac{4}{3}} \overset{!}{\lesssim} 1$$

$\rightsquigarrow$ BBN bounds satisfied for $T_x^{\text{dpl}} \gtrsim 1$ GeV
$\rightsquigarrow$ Correct order of magnitude for hot dark matter hint

Hot Dark Matter Parameter Space



$$\Delta N_{\rm eff}|_{\rm CMB} = \left(\frac{58.4}{g_{*,\nu}(T_x^{\rm dpl})}\right)^{\frac{4}{3}}$$

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow \Delta N_{\text{eff}} \simeq 1$
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV

  Hannestad, Hansen, Tram, PRL **112** (2014); Dasgupta, Kopp, PRL **112** (2014)

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- $T <$ MeV: mixing unsuppressed
- Oscillations $+$ $U(1)_X$ interactions $\rightsquigarrow$ N re-thermalize $\rightsquigarrow$ $T_N = T_\nu$
  Mirizzi, Mangano, Pisanti, Saviano, arXiv:1410.1385

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- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow \Delta N_{\rm eff} \simeq 1$
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV
  Hannestad, Hansen, Tram, PRL **112** (2014); Dasgupta, Kopp, PRL **112** (2014)
- $T <$ MeV: mixing unsuppressed
- Oscillations $+$ $U(1)_X$ interactions $\rightsquigarrow$ N re-thermalize $\rightsquigarrow$ $T_N = T_\nu$
  Mirizzi, Mangano, Pisanti, Saviano, arXiv:1410.1385

With full re-thermalization:

$$\Delta N_{\rm eff}|_{\rm CMB} \simeq \text{const.}$$

$$m_N = \frac{2\sqrt{2}}{N_{\rm eff}|_{\rm CMB}^{\;3/4}}\, m_s^{\rm eff} \simeq \frac{2\sqrt{2}}{3.6^{3/4}}\, 0.4\ \text{eV} < 1\ \text{eV}$$

$\rightsquigarrow$ Cosmology still fine but neutrino anomalies not explained

Conclusions

Particle physics solution for tensions in standard ΛCDM cosmology:

Sterile neutrinos N with mass $\lesssim$ eV + self-interacting dark matter

- $N \rightsquigarrow$ small hot DM component, oscillation anomalies solved (?)
- New interaction mediated by gauge boson with mass $\sim$ MeV
- DM-DM scatterings $\rightsquigarrow$ cusp-core, too big to fail solved
- DM-N scattering $\rightsquigarrow$ missing satellites solved

Conclusions

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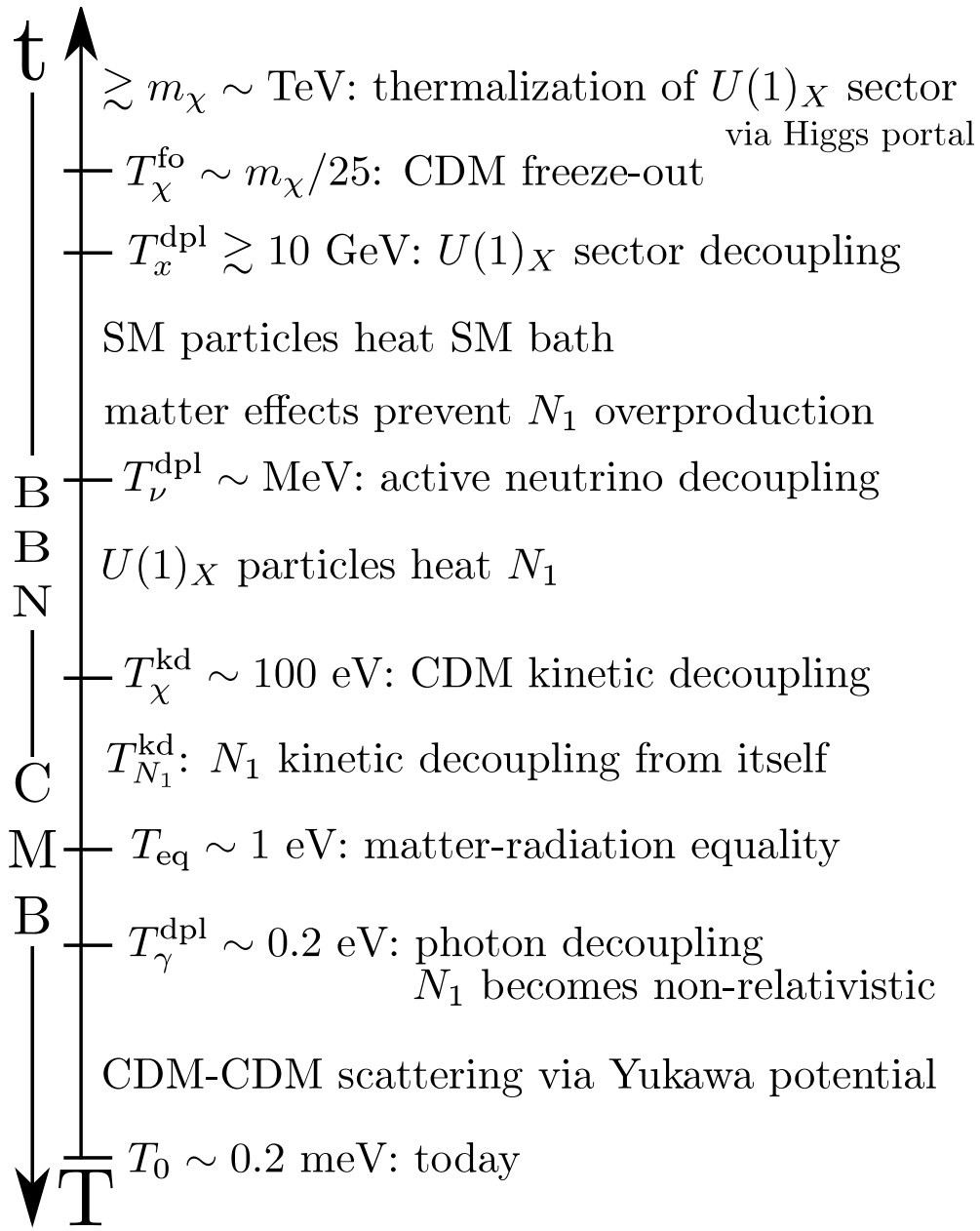
Outlook

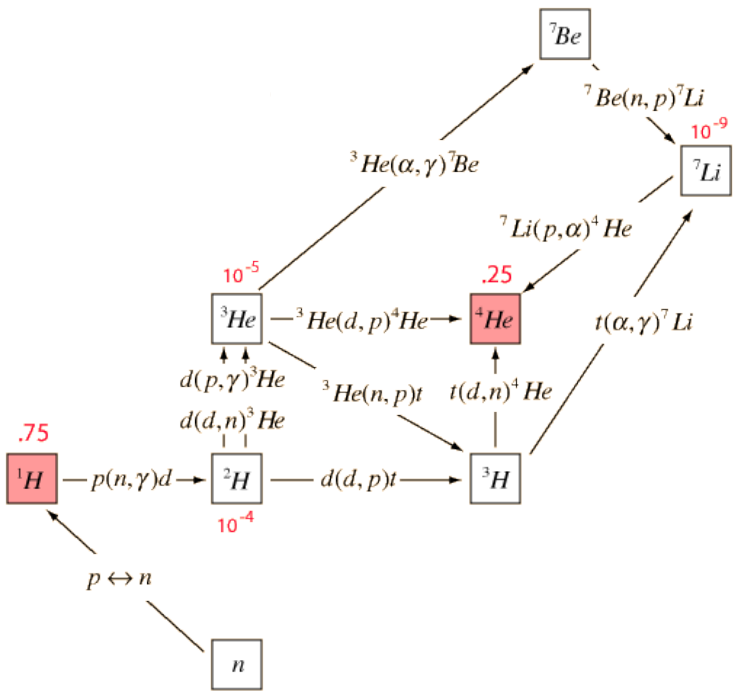
- Interaction by scalar exchange possible and favorable?
- Further options for model building
- Connection to 3.5 keV X-ray line?
- Re-thermalization
- Improved treatment of scattering in Yukawa potential

Timeline


t
$\gtrsim m_\chi \sim$ TeV: thermalization of $U(1)_X$ sector
via Higgs portal
$T_\chi^{\rm fo} \sim m_\chi/25$: CDM freeze-out
$T_x^{\rm dpl} \gtrsim 10$ GeV: $U(1)_X$ sector decoupling
SM particles heat SM bath
matter effects prevent N_1 overproduction
$T_\nu^{\rm dpl} \sim$ MeV: active neutrino decoupling
B
B
N
$U(1)_X$ particles heat N_1
$T_\chi^{\rm kd} \sim 100$ eV: CDM kinetic decoupling
$T_{N_1}^{\rm kd}$: N_1 kinetic decoupling from itself
C
M
B
$T_{\rm eq} \sim 1$ eV: matter-radiation equality
$T_\gamma^{\rm dpl} \sim 0.2$ eV: photon decoupling
N_1 becomes non-relativistic
CDM-CDM scattering via Yukawa potential
$T_0 \sim 0.2$ meV: today
T

Dark Radiation and Big Bang Nucleosynthesis

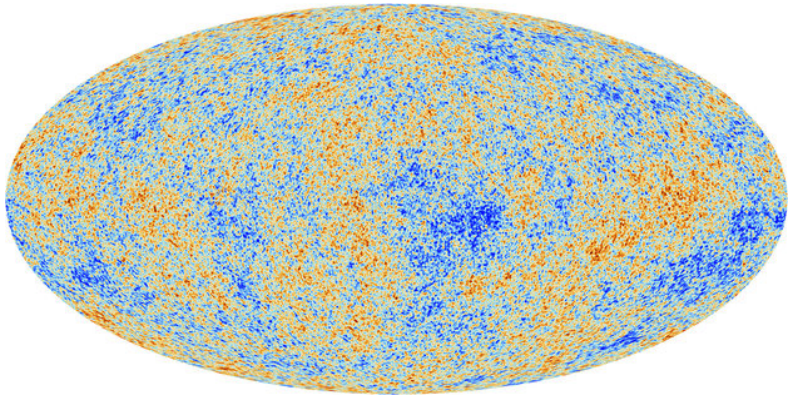
- $T \sim 1$ MeV: freeze-out of $n \leftrightarrow p$
  $\rightsquigarrow$ n/p ratio fixed
- $T \sim 0.1$ MeV: $p + n \rightarrow$ D
- Afterwards formation of ^{3}He, ^{4}He, ^{7}Li
- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ faster expansion
  $\rightsquigarrow$ more n available for D fusion
  $\rightsquigarrow$ more ^{4}He
- $N_{\text{eff}} = 3.8^{+0.8}_{-0.7}$ at 2σ CL
  Izotov, Thuan, arXiv:1001.4440
- $\Delta N_{\text{eff}} \leq 1$ at 2σ CL
  Mangano, Serpico, arXiv:1103.1261

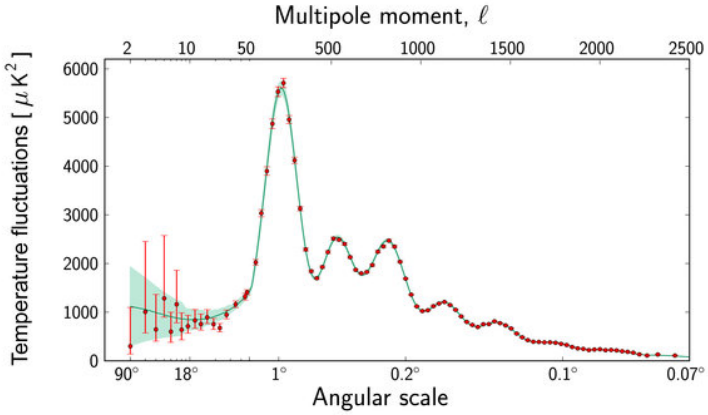


Dark Radiation Effects on the CMB

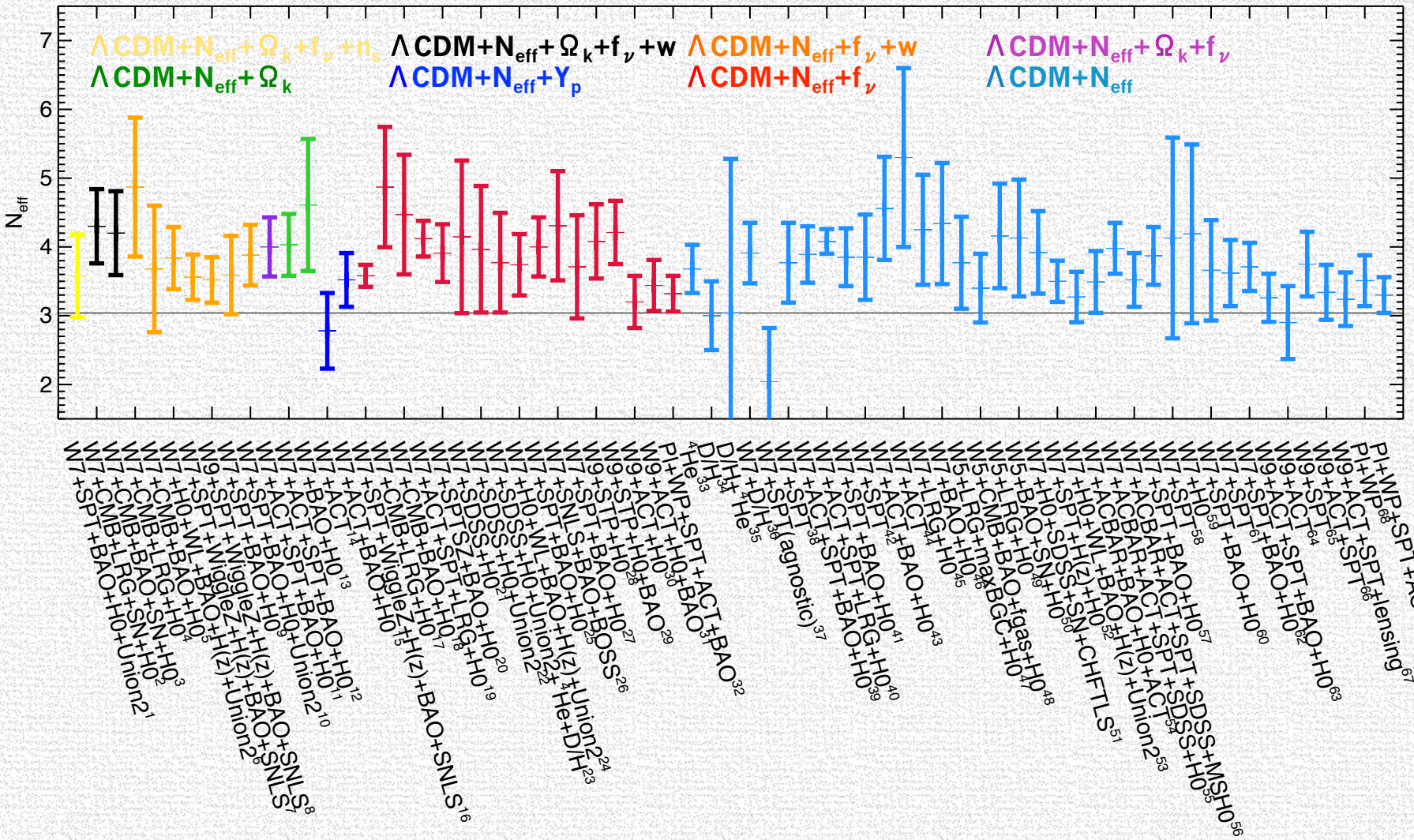
- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ later matter-radiation equality
- $1^{\text{st}}/3^{\text{rd}}$ peak ratio $\rightsquigarrow$ no change $\rightsquigarrow \rho_{\text{m}} \uparrow \rightsquigarrow t_{\text{eq}}$ unchanged
- $\rho_{\text{rad}} \uparrow \rightsquigarrow$ sound horizon $r_s \propto 1/H \downarrow$
- Peak positions $\rightsquigarrow$ no change of angular size $\theta_s = \frac{r_s}{D_A} \rightsquigarrow D_A \propto 1/H \downarrow$ (by $\rho_\Lambda \uparrow$)
- Remaining effect: increased Silk damping $\rightsquigarrow$ reduced power on small scales

Hou et al., arXiv:1104.2333





Measurements



Modified from Riemer-Sørensen et al. (2013 review) arXiv:1301.7102

Meet the Dark Side

- Dirac fermion χ (dark matter)
- Gauge boson V
- Light sterile neutrino N
- Heavier sterile neutrino N_2 with $m_{N_2} \sim 1$ MeV to cancel anomalies
- Scalar Θ breaking $U(1)_X$ with portal interaction
- Scalar ξ to enable active-sterile neutrino mixing ($v_\xi < v_\Theta$)