Joint CMB and BBN Constraints for Light Dark Sectors

Cara Giovanetti (NYU)

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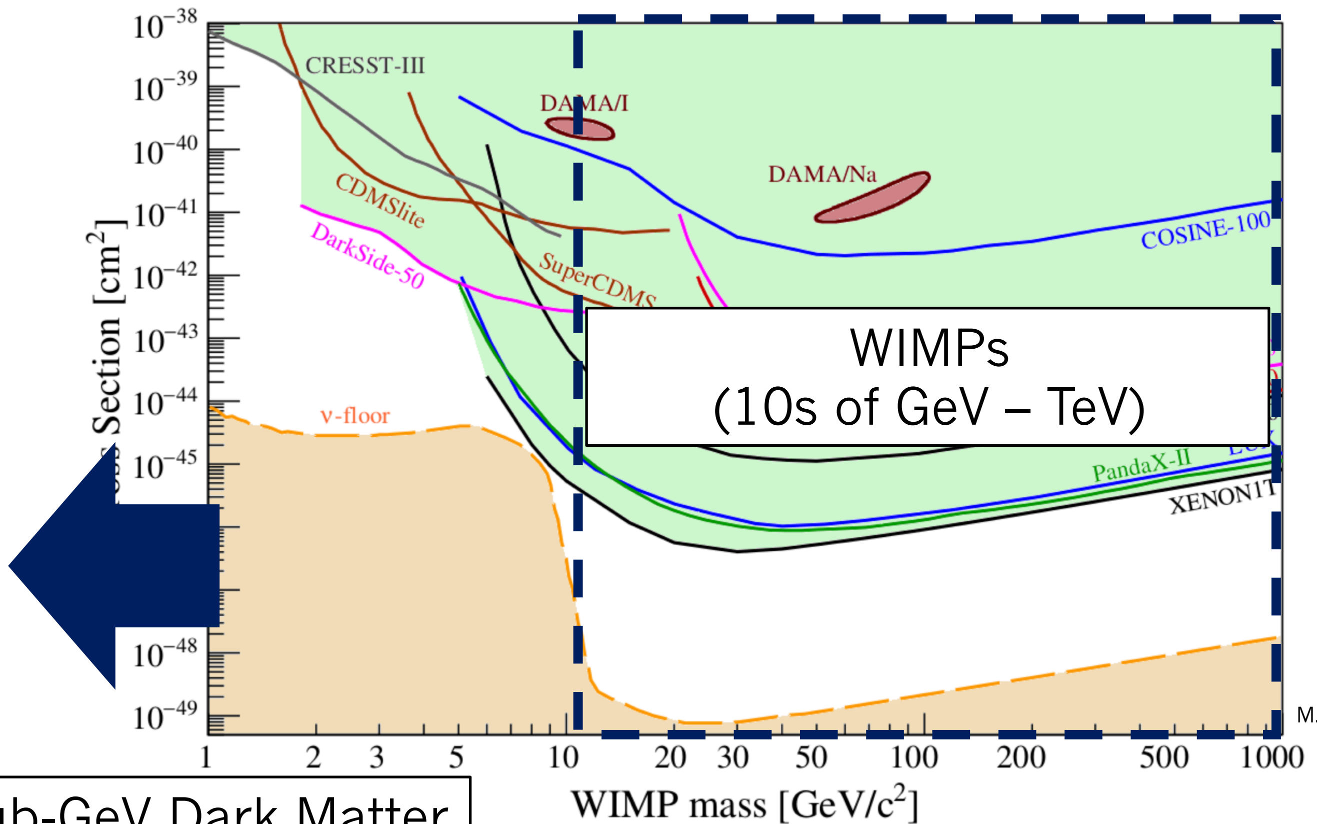
With Mariangela Lisanti, Hongwan Liu, and Joshua Ruderman

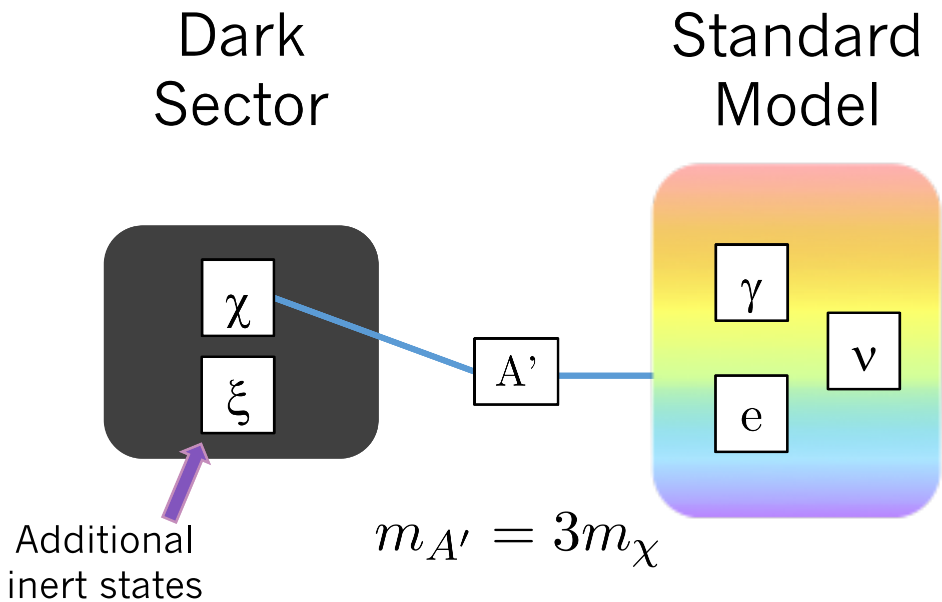
Interest in Sub-GeV Dark Matter



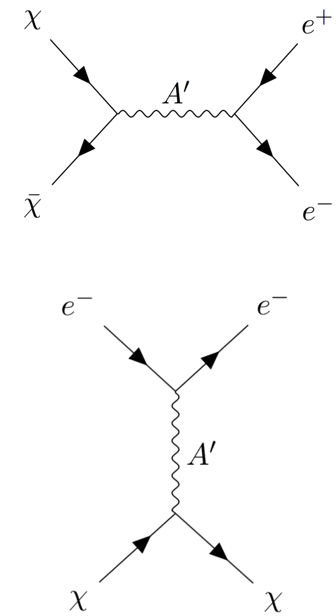
M. Schumann, 1903.03026

Sub-GeV Dark Matter
(~MeV – GeV)

Dark Photon + Dark Matter

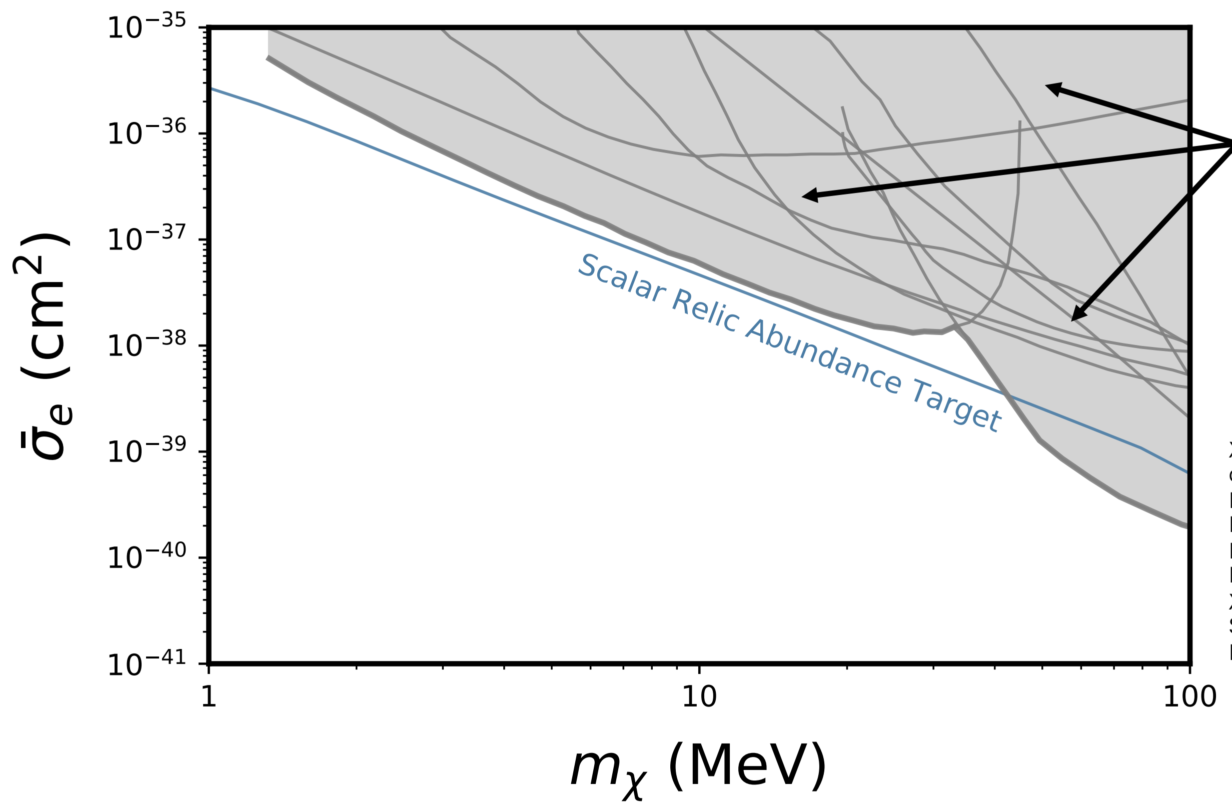


$$m_{A'} = 3m_\chi$$



Dark matter couples to Standard Model through new dark photon mediator

Current Constraints



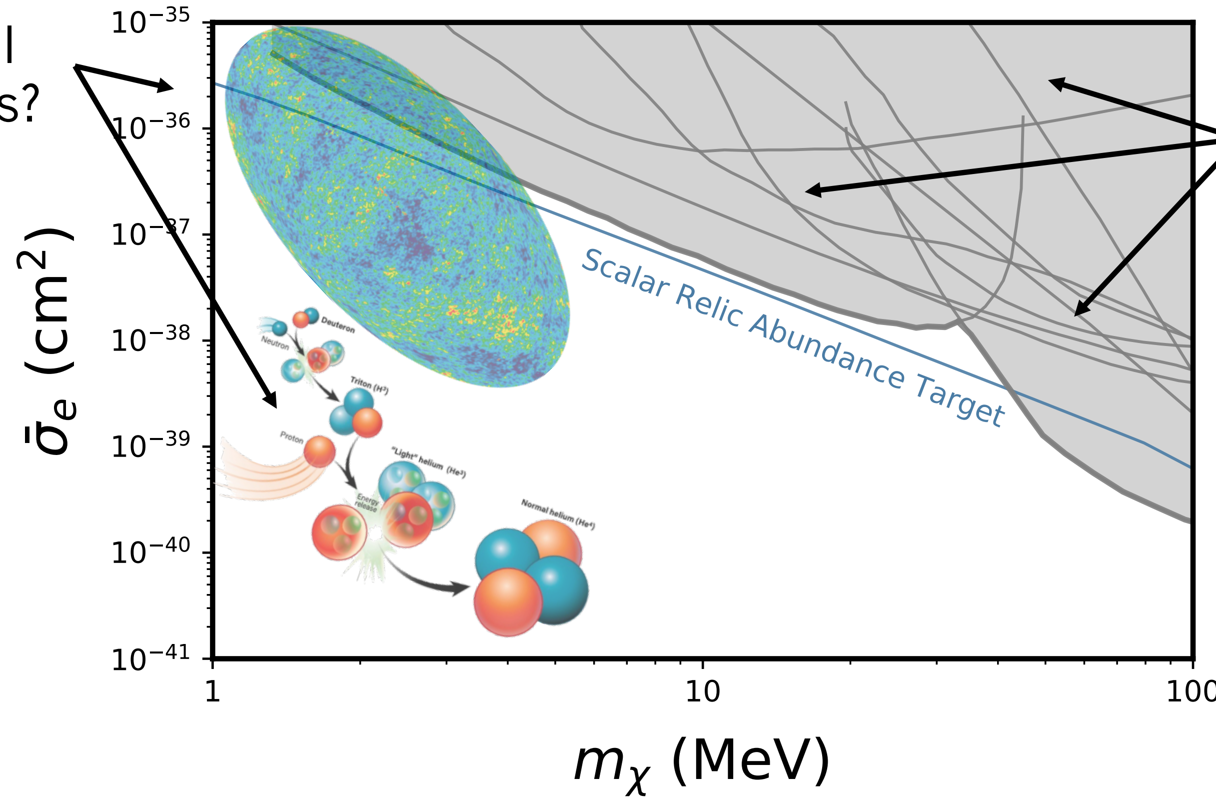
Current Constraints

Dark Photon + χ,
$m_{A'} = 3m_\chi$

XENON10 Collaboration, 1104.3088
deNiverville et al., 1107.4580
Essig et al., 1509.01598
NA64 Collaboration, 1610.02988
BaBar Collaboration, 1702.03327
Essig et al., 1703.00910
XENON Collaboration, 1907.11485
SENSEI Collaboration, 2004.11378
PandaX-II Collaboration, 2101.07479

Additional Constraints from Cosmology

Additional Constraints?



Current Constraints

Dark Photon + χ,
$m_{A'} = 3m_\chi$

Additional image credit:
NASA/WMAP 2010
Roen Kelly for Astronomy Magazine

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Additional Constraints from Cosmology

Cosmic evolution sensitive to photon temperature (T_γ) and radiation density (ρ_R)

Universe temperature

2.7 K

3,000 K

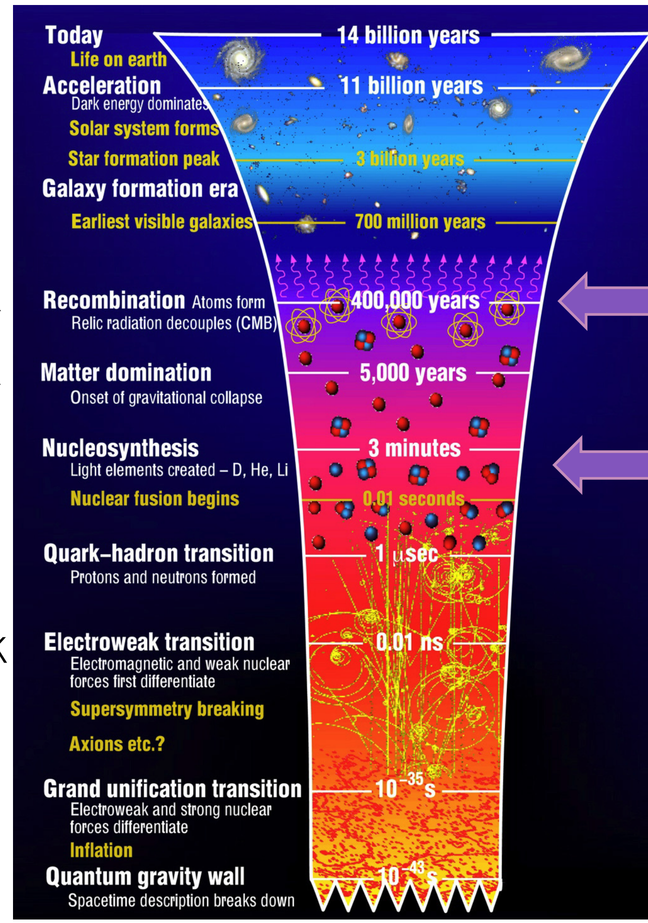
16,000 K

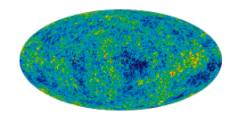
10^7 K

10^9 K

10^{10} K

$\sim 10^{16}$ K





Recombination and Cosmic Microwave Background (CMB) formation

Big Bang Nucleosynthesis (BBN)

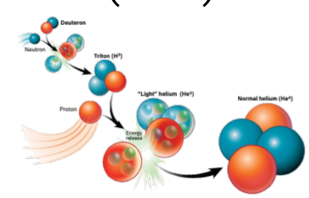


Image credit: Philip Pepper for the Stephen Hawking Centre for Theoretical Cosmology

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Additional Constraints from Cosmology

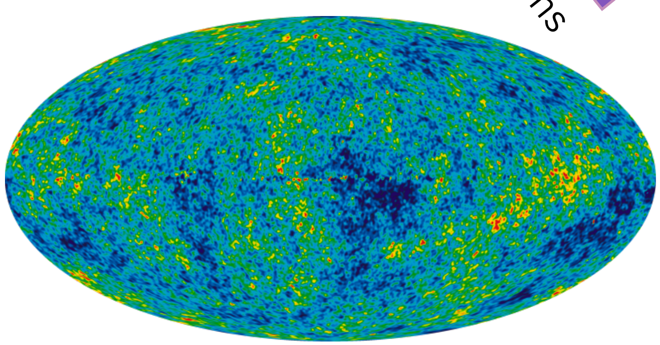
Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN) can constrain light dark matter

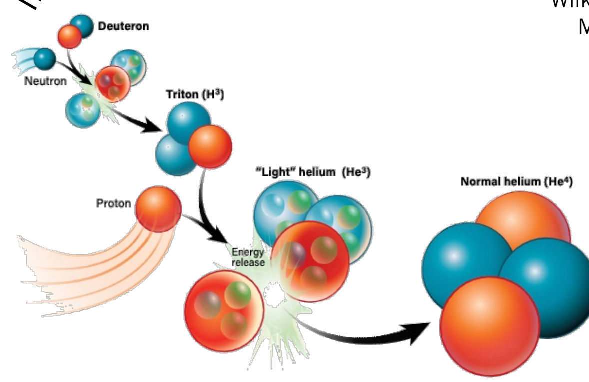
Cosmic evolution sensitive to photon temperature (T_γ) and radiation density (ρ_R)

χ changes T_γ, ρ_R

T_γ, ρ_R impacts

constrains χ





Kolb et al., Phys. Rev. D34 (1986) 2197
P. Serpico and G. Raffelt, astro-ph/0403417
Boehm et al., 1207.0497
C. M. Ho and R. J. Scherrer, 1208.4347
Boehm et al., 1303.6270
K. M. Nollet and G. Steigman, 1312.5725
K. M. Nollet and G. Steigman, 1411.6005
Wilkinson et al., 1602.01114
M. Escudero, 1812.05605
Depta et al., 1901.06944
Sabti et al., 1910.01649

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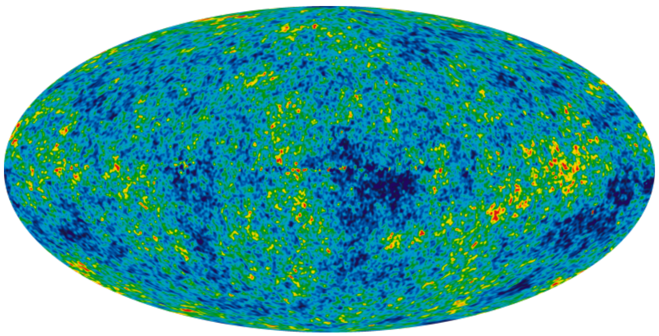
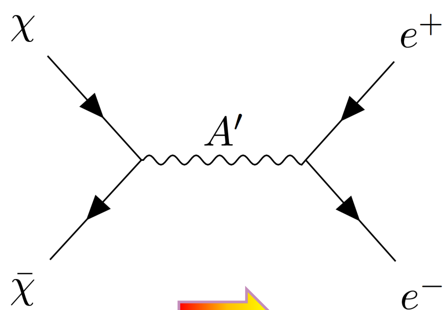
CMB Constraints



$$N_{\text{eff}} \sim \left(\frac{T_\nu}{T_\gamma}\right)^3 \left(1 + \frac{\rho_\xi}{\rho_\nu}\right)$$

N_{eff} parametrizes anomalous heating to photons and presence of additional light species



Entropy transfer from dark sector to photon sector

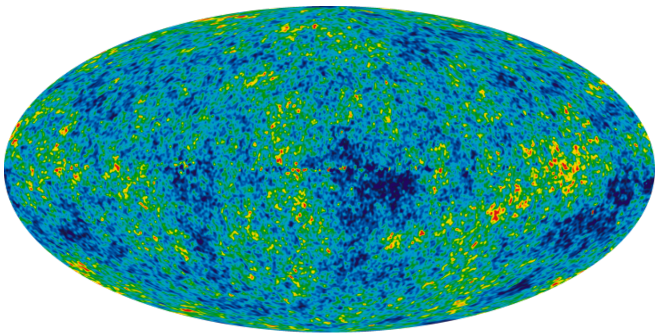
χ increases T_γ

T_ν is decreased relative to T_γ

→ N_{eff} decreases in a dark matter scenario

CMB Constraints

$$N_{\text{eff}} \sim \left(\frac{T_\nu}{T_\gamma}\right)^3 \left(1 + \frac{\rho_\xi}{\rho_\nu}\right)$$



χ increases T_γ

T_ν is decreased relative to T_γ

N_{eff} decreases in a dark matter scenario

Observation $N_{\text{eff}} = 2.92^{\pm 0.37}$

Planck Collaboration, 1807.06209

$m_\chi = 1$ MeV
$m_{A'} = 3m_\chi$

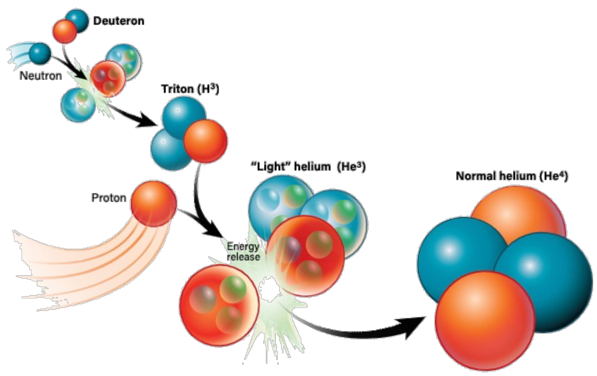
Prediction $N_{\text{eff}} = 1.46$

$N_{\text{eff}} = 2.92$

$m_\chi = 1$ MeV
$m_{A'} = 3m_\chi$
$+$ equivalent neutrinos $\boxed{\xi}$

Workaround: adding additional degrees of freedom can restore N_{eff} to its measured value

BBN Constraints



χ impacts ρ_R, T_γ

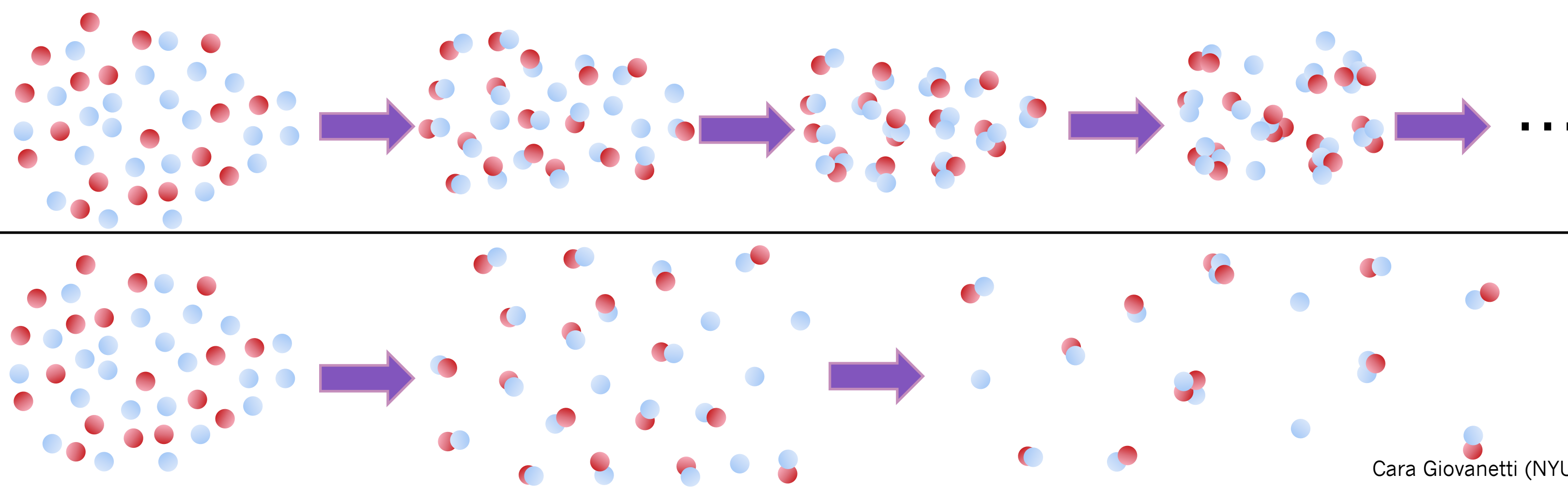
Expansion rate is proportional to ρ_R

If the expansion rate is too fast, heavy elements can't form

→ Light element abundances change in a dark matter scenario

Slow expansion

Fast expansion



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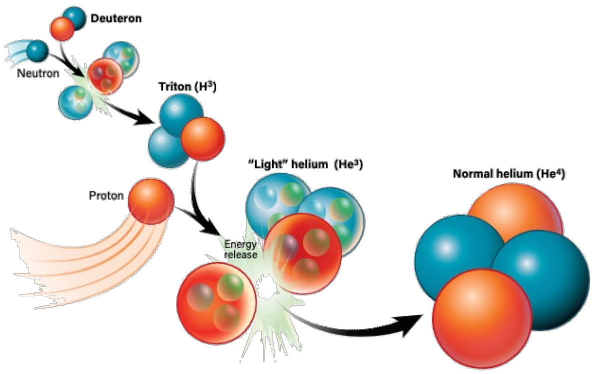
BBN Constraints

$$N_{\mathrm{eff}} \sim \left(\frac{T_\nu}{T_\gamma}\right)^3 \left(1 + \frac{\rho_\xi}{\rho_\nu}\right)$$



χ impacts ρ_R, T_γ

→ Light element abundances change in a dark matter scenario

Equivalent neutrinos increase ρ_R

→ Light element abundances are difficult to tune

Observation → $Y_P = 0.245 \pm 0.008$

(Helium-4 mass fraction)

Particle Data Group, Prog. Theor. Exp. Phys. 2020, 083C01

Prediction → $m_\chi = 1$ MeV, $m_{A'} = 3m_\chi$ ($N_{\mathrm{eff}} = 1.46$)✗: $Y_P = 0.249$ ✓

→ $m_\chi = 1$ MeV, $m_{A'} = 3m_\chi$ + equivalent neutrinos ($N_{\mathrm{eff}} = 2.92$)✓: $Y_P = 0.257$ ✗

New Constraints

Improvements upon previous work:

- Updated constraint framework to a accommodate dark sector

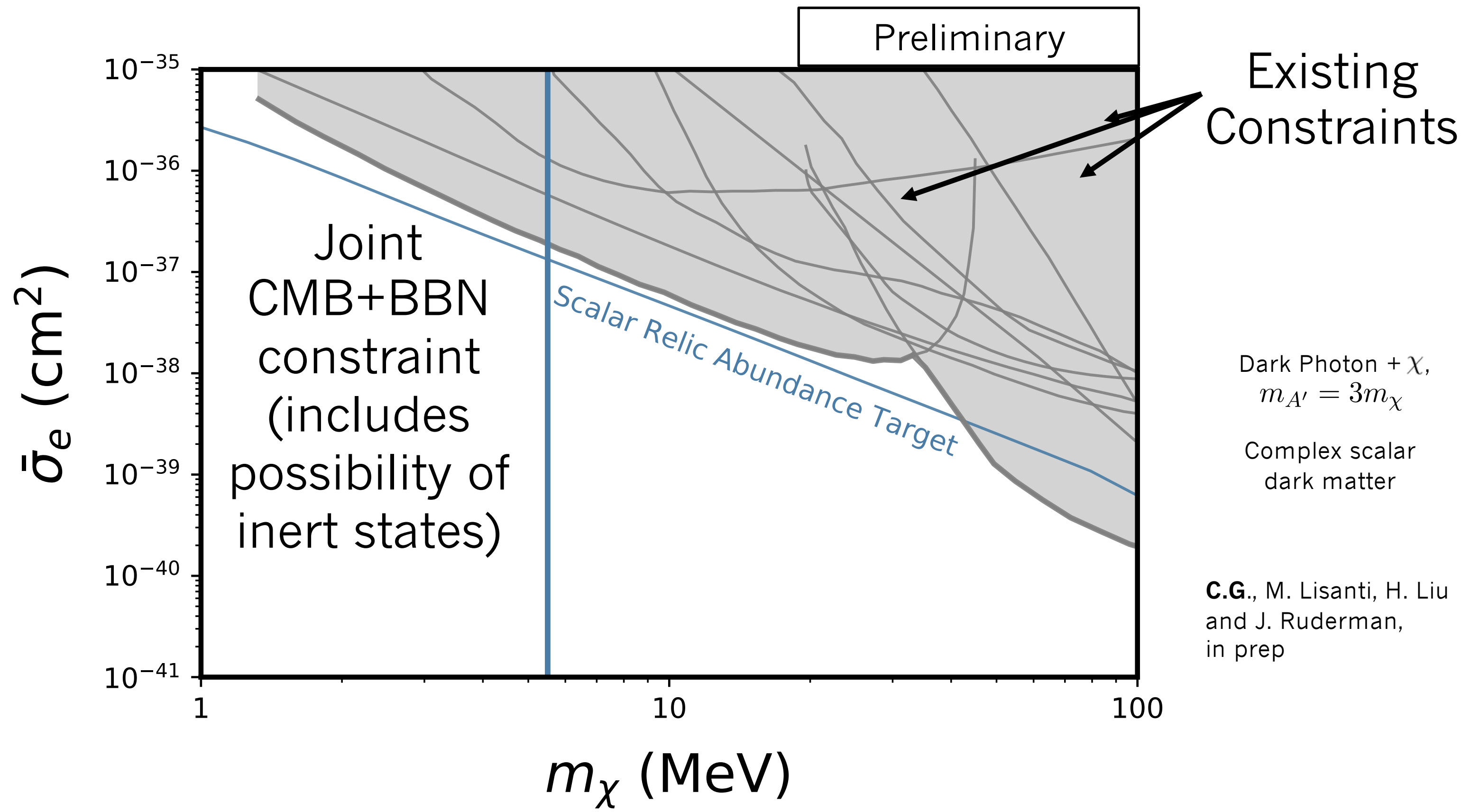
- Combined and improved upon state-of-the-art computational tools (`PRIMAT`, `nudec_BSM`) to make precise CMB and BBN predictions
  - Expanded temperature/abundance calculation routines for a dark sector
  - Included possibility of additional inert states in dark sector
  - Updated reaction network (BBN)
  - Improved treatment of neutrino decoupling

M. Escudero, 2001.04466

Pitrou et al., 1801.08023

- Implemented uncertainty calculation routines (BBN)

Results



Dark Photon + χ,
$m_{A'} = 3m_\chi$

Complex scalar dark matter

C.G., M. Lisanti, H. Liu and J. Ruderman, in prep

*Dark matter is assumed to be thermal (verified)

Summary

- CMB and BBN can constrain light dark sectors, even in the presence of additional degrees of freedom
- A hidden sector with a complex scalar χ and dark photon with $m_{A'} = 3m_\chi$ is constrained to have $m_\chi \gtrsim 5\,\mathrm{MeV}$
- Future work
    - Accommodate more exotic dark sectors
    - Address additional proposals to model build around these constraints