CDM 2023

LUMINOUS PROTON LOOPS THERMALISE LIGHT DARK MATTER

JOSHUA WOOD

PhD work under the supervision of
Assoc. Prof. Matthew Dolan and Dr. Peter Cox

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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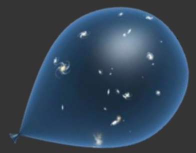
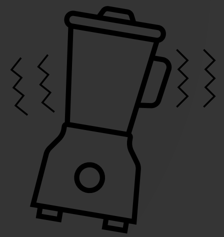
OUTLINE

- Luminous Proton Loops

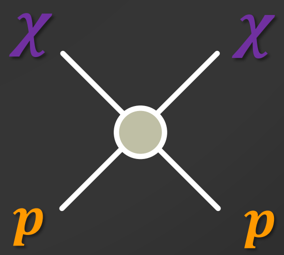
- The Early Universe



- Thermalisation of Light Dark Matter



- New Limit on DM-proton cross-section



LUMINOUS PROTON LOOPS

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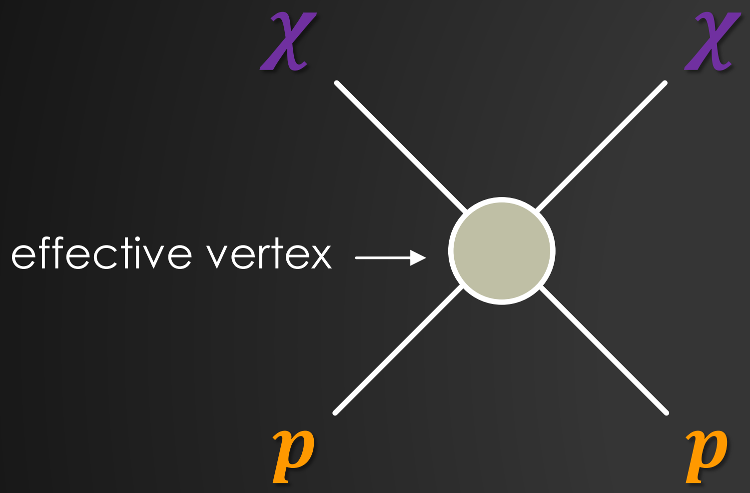
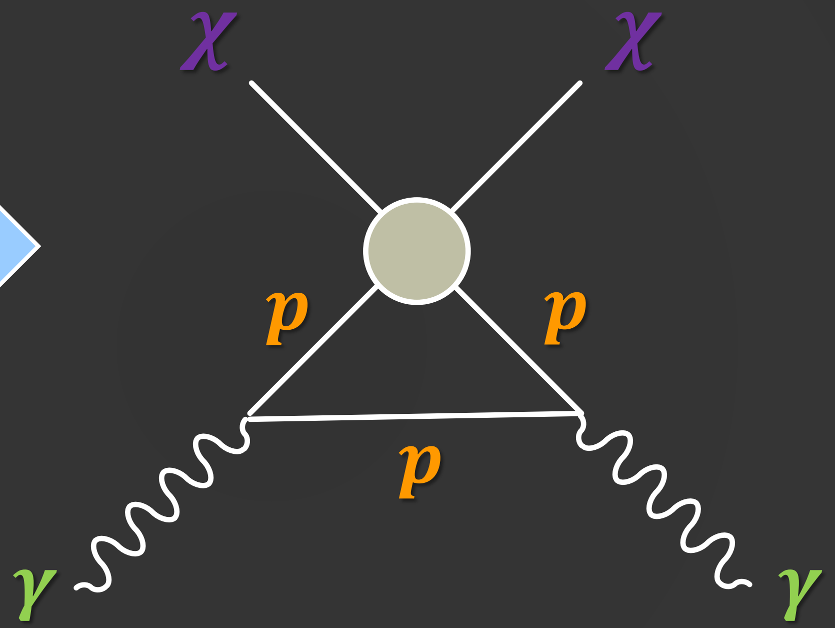
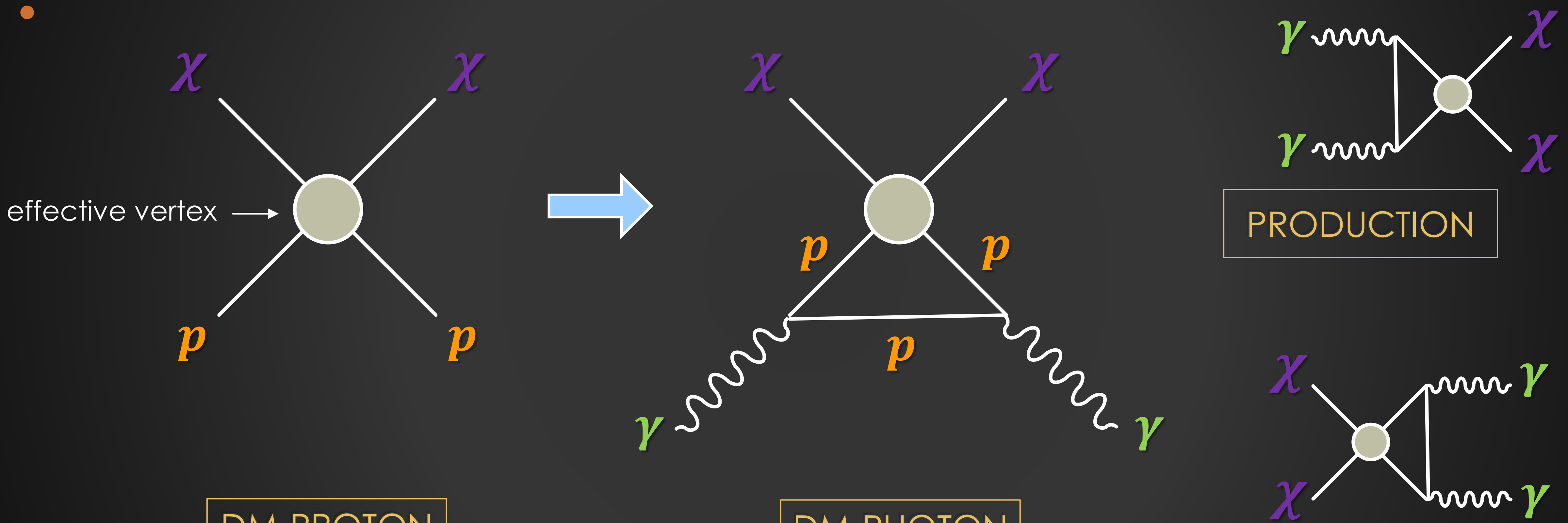




DM-PROTON SCATTERING

DM-PHOTON SCATTERING

LUMINOUS PROTON LOOPS



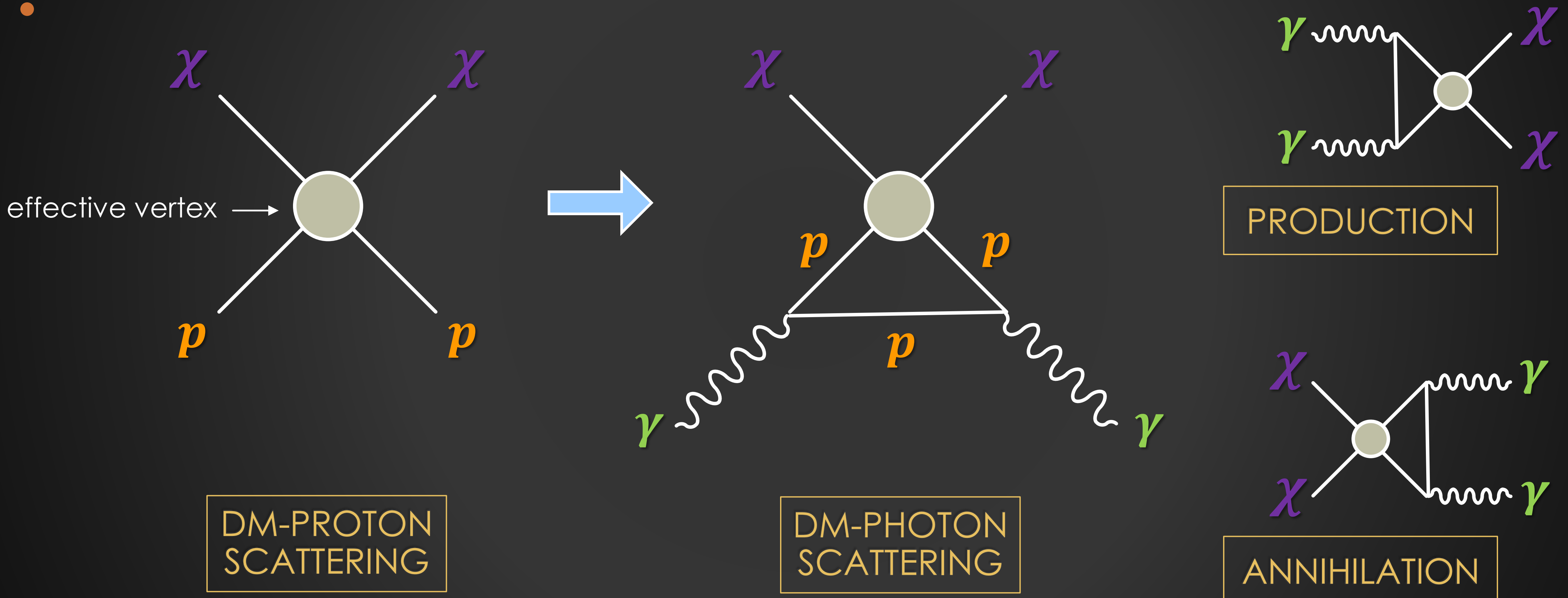
DM-PROTON SCATTERING

DM-PHOTON SCATTERING

PRODUCTION

ANNIHILATION

LUMINOUS PROTON LOOPS



Loop level suppressed, but relevant in environments with much higher density of photons compared with protons

THE EARLY UNIVERSE

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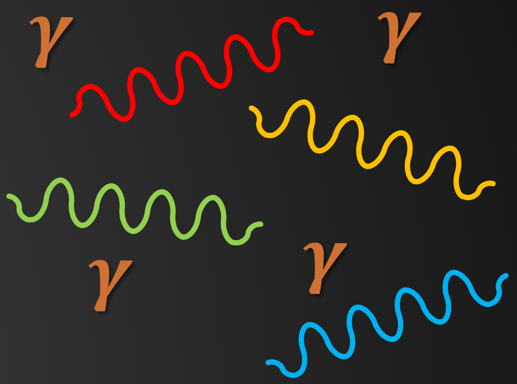
$$n_\gamma = \frac{2}{\pi^2} T^3$$



10^{-10} MeV | 10^{-9} MeV | 10^{-7} MeV | 30 keV | 1 MeV | 2 MeV

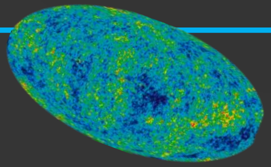
Temperature →

← time

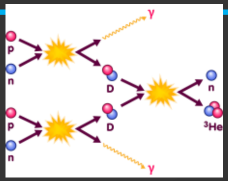
13.7×10^9 years — Present day

1×10^9 years — First Galaxies

400,000 years — CMB



10 mins — 1 sec — Big Bang Nucleosynthesis



0.1 sec — ν decoupling

ν

Inflation?

EWSB?

GUT?

?

Reheating?

Confinement?

THE EARLY UNIVERSE

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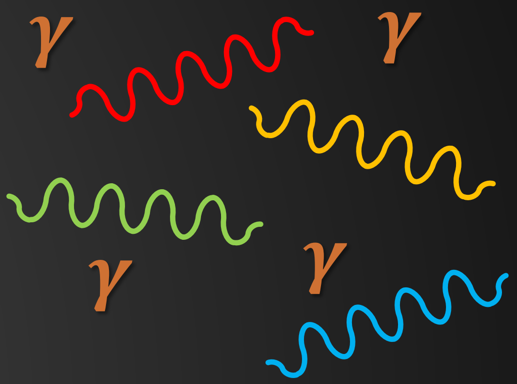

10^{-10} MeV	10^{-9} MeV	10^{-7} MeV	30 keV	1 MeV	2 MeV

Temperature →

← time

Hottest data we have

We're not sure if the universe was hotter or not

13.7×10^9 years	1×10^9 years	400,000 years	10 mins	1 sec	0.1 sec
Present day	First Galaxies	CMB	Big Bang Nucleosynthesis		ν decoupling

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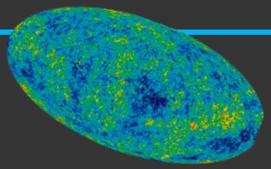

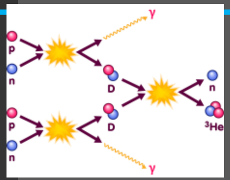

ν

?

Reheating?

Confinement?

Lots of photons, not many protons!

BBN AND ν-DECOUPLING

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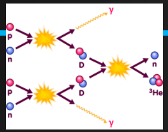
BBN | ν decoupling | ?



30 keV	1 MeV	2 MeV
10 mins	1 sec	0.1 sec

Early Universe Timeline:

- $T > 2$ MeV: Thermal bath
  $\gamma, e^-, e^+, 3\nu$ + p, n
  radiation — baryons (tiny fraction)
- $T \approx 2$ MeV: Neutrinos decouple
  weak force interactions could no longer maintain equilibrium
- keV< T <MeV: Big Bang Nucleosynthesis
  formation of nuclei – He,D,T,Li

BBN AND ν-DECOUPLING

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BBN $\qquad$ ν decoupling

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Observables:

Y_P D/H	$\Omega_b h^2$ N_{eff}
BBN (# telescopes)	CMB (Planck)

Match very well with SM + Nuclear Physics + Standard Cosmology

→ **Dark matter must have a very limited influence on this process**

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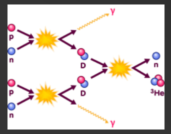
DARK MATTER DURING THE EARLY UNIVERSE

γ

χ



ν

How can dark matter affect BBN and ν-decoupling?

- Dark matter → extra degrees of freedom + extra interactions

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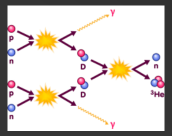
DARK MATTER DURING THE EARLY UNIVERSE

γ

χ  ν

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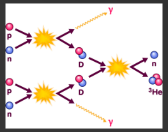
- If DM-SM interactions strong enough such that dark matter is in thermal equilibrium with the SM bath during this time:
  1. Alters Hubble expansion rate
  2. Unevenly heats photons and neutrinos
- This would alter the observables from BBN and CMB

BBN		CMB	
Y_P	D/H	$\Omega_b h^2$	N_{eff}

DARK MATTER DURING THE EARLY UNIVERSE



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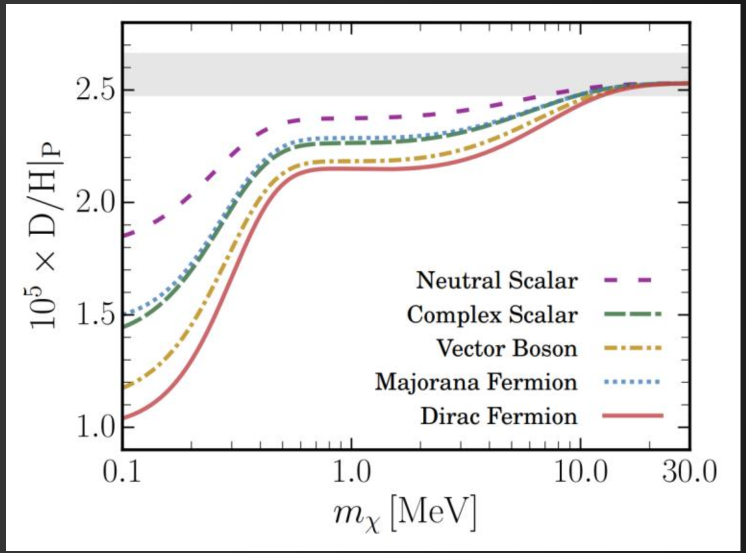

Sabti, Alvey, Escudero, Fairbairn, Blas (arXiv:1910.01649)

DARK MATTER DURING THE EARLY UNIVERSE

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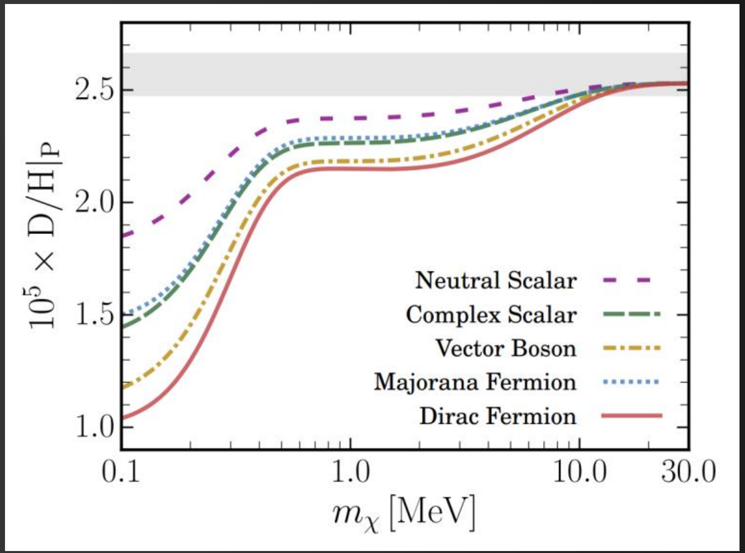

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For **heavy dark matter** with $m_\chi \gg$ MeV: 1 2 are negligible.

No worries

Become non-relativistic before ν-decoupling

DARK MATTER DURING THE EARLY UNIVERSE

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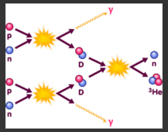

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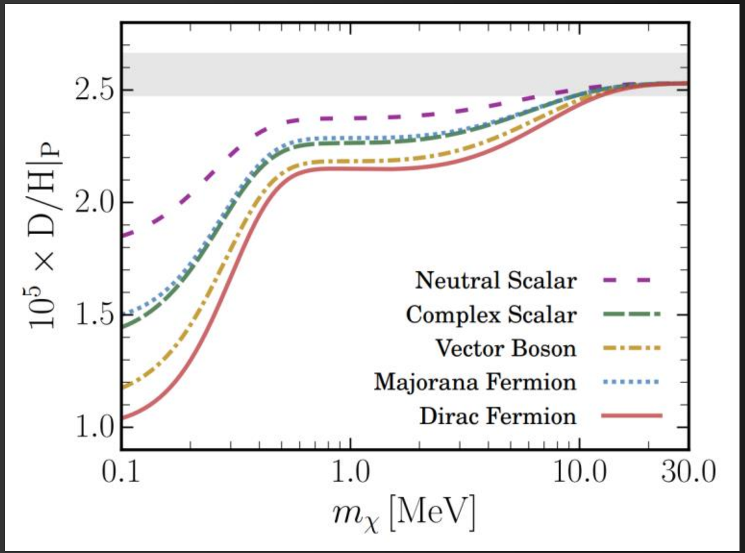

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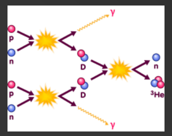
For **heavy dark matter** with $m_\chi \gg \mathrm{MeV}$: 1 2 are negligible. ✓ No worries — Become non-relativistic before ν-decoupling

For **light dark matter** with $m_\chi \lesssim 10\ \mathrm{MeV}$: 1 2 can be significant ✗ Some worries — Become non-relativistic after ν-decoupling

LUMINOUS PROTON LOOPS DURING THE EARLY UNIVERSE



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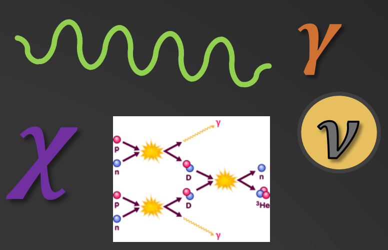
So,

Light dark matter can't be in equilibrium with the SM after ν-decoupling

"Light dark matter must be produced non-thermally"

LUMINOUS PROTON LOOPS DURING THE EARLY UNIVERSE



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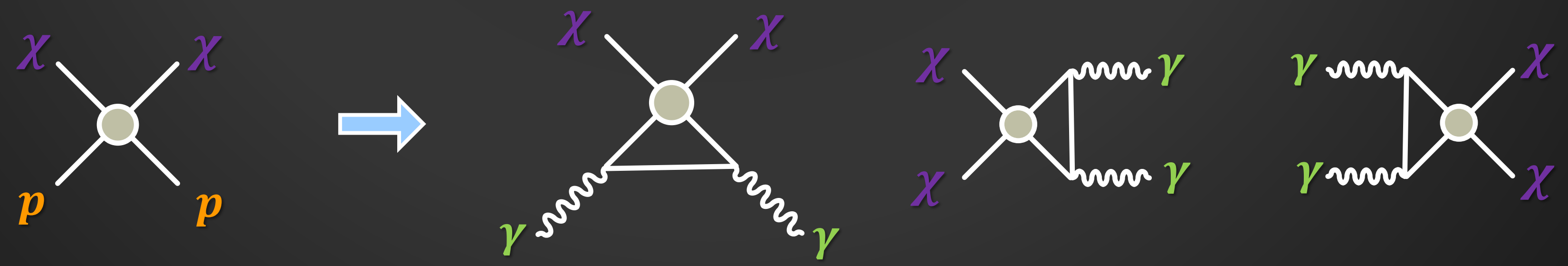
But, if DM interacts with protons,

Luminous Proton Loops can violate this!



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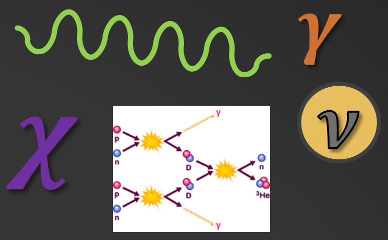

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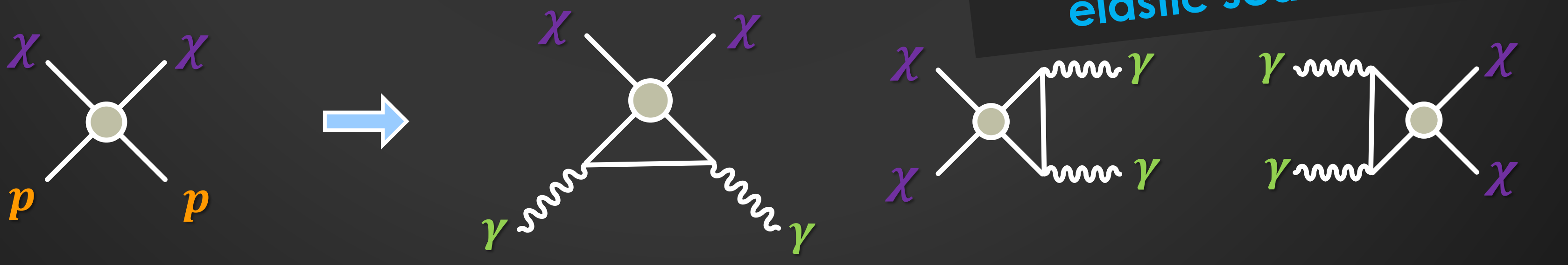
This puts a limit on the DM-proton elastic scattering cross section!



RESULTS

New limit:

$$\frac{\langle\Gamma\rangle}{H} = \frac{n_\gamma \langle \sigma_{LPL}\, v\rangle}{H} < 1$$

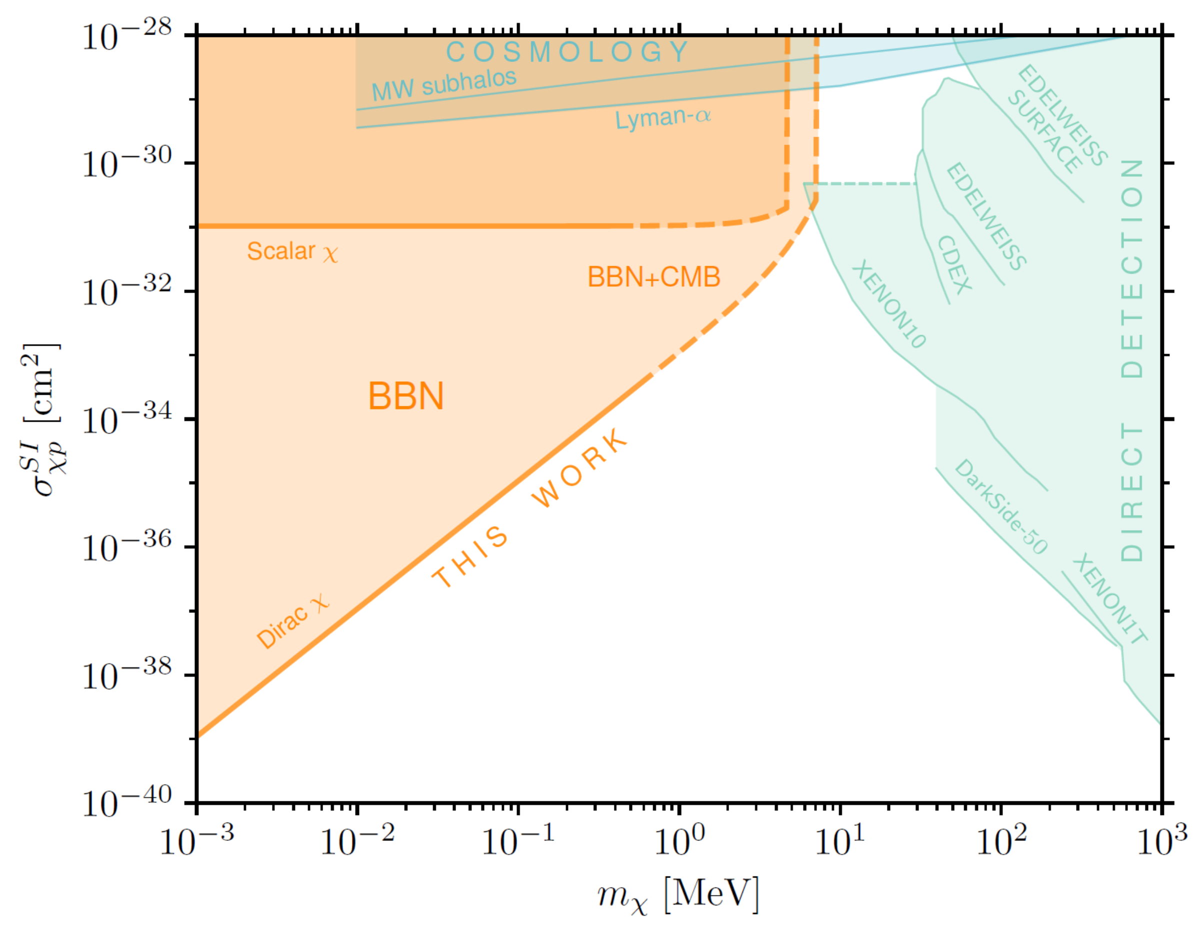
at $T = 2$ MeV

Y_P D/H	$\Omega_b h^2$ N_{eff}
BBN	CMB

BBN: $m_\chi \lesssim 0.5$ MeV

BBN+CMB: $m_\chi \lesssim 5$ MeV

must be non-thermal



Dirac: $\mathcal{O} = \frac{1}{\Lambda^2}\bar{\chi}\chi\bar{p}p$

Scalar: $\mathcal{O} = \frac{1}{\Lambda}\chi^\dagger\chi\bar{p}p$

Applies to DM-proton interactions mediated by a heavy scalar, with any fraction of $\Omega_{DM}h^2$

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ARC Centre of Excellence for Dark Matter Particle Physics
The University of Melbourne

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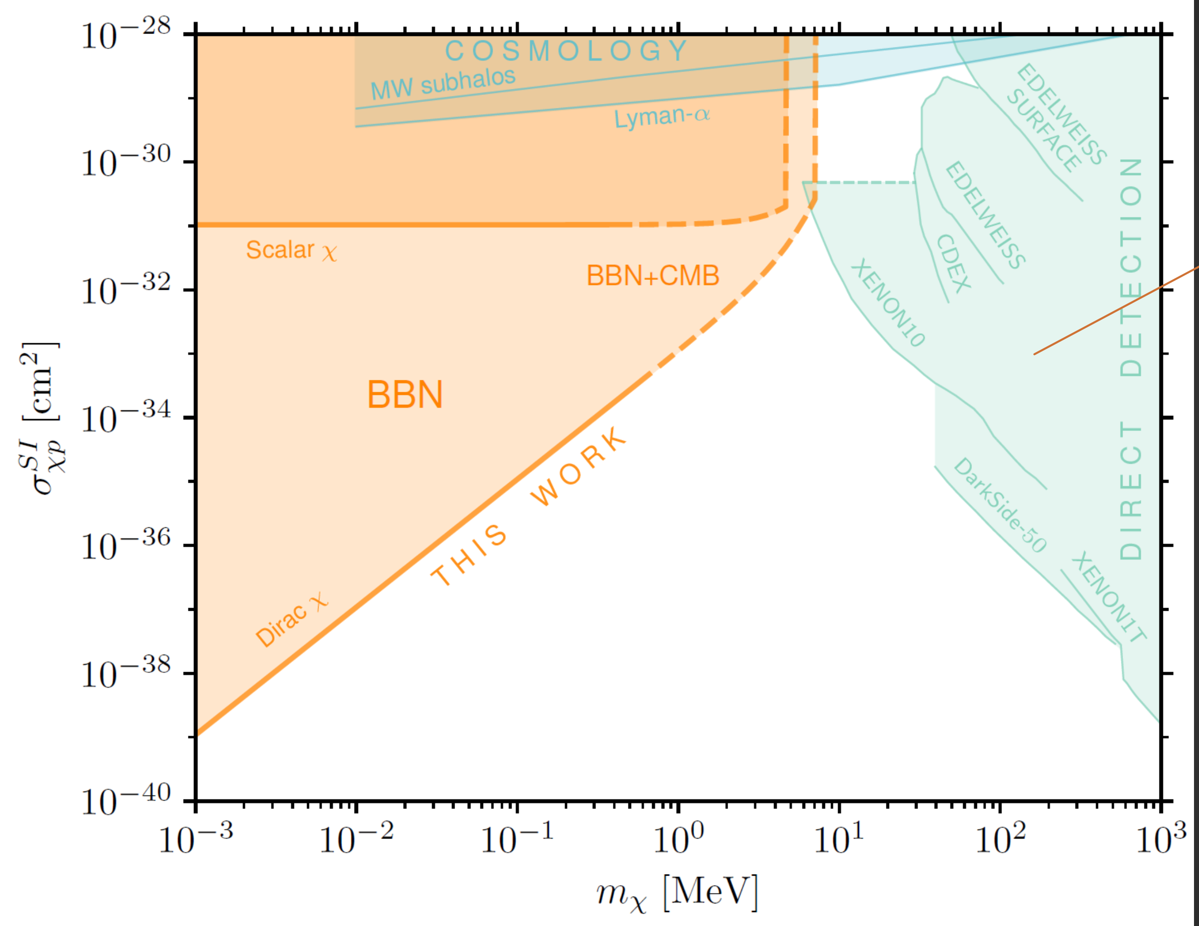

Nuclear recoils and Migdal effect

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RESULTS

DM-proton interactions supress matter power spectrum and small scale structure

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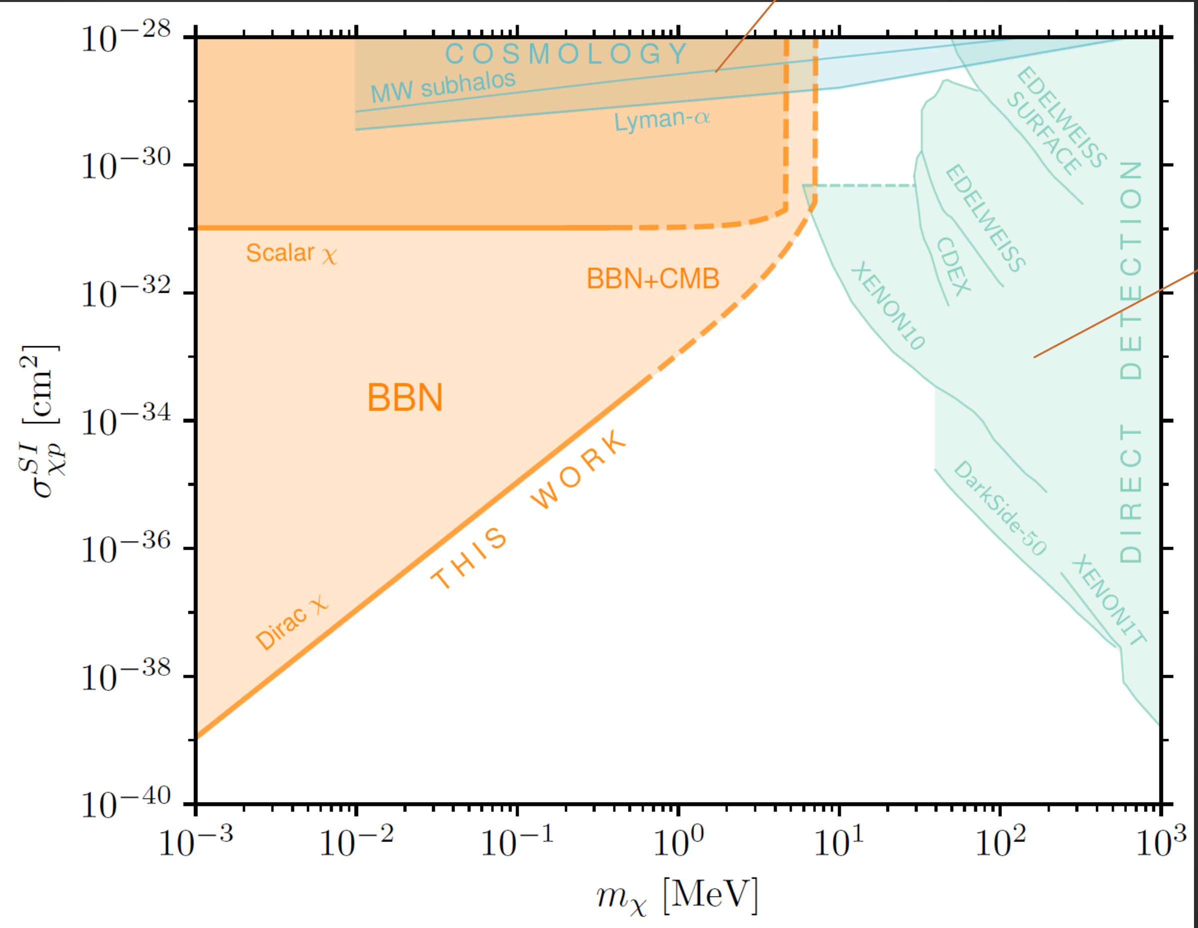

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SUMMARY

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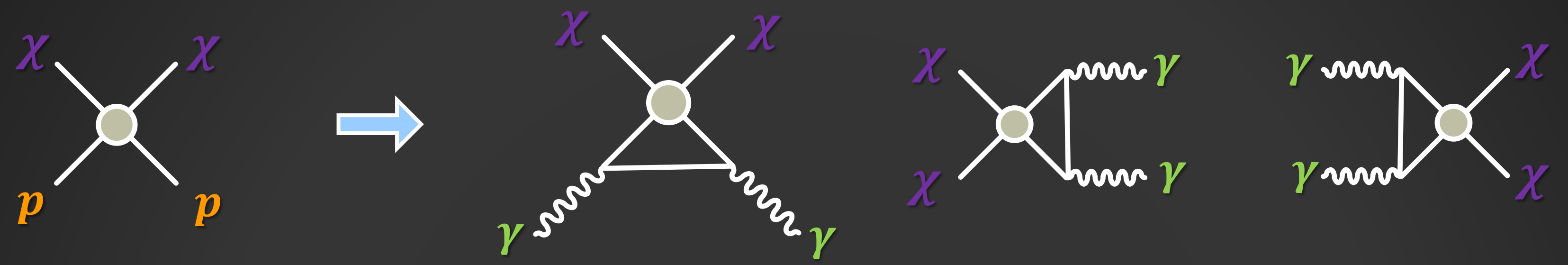

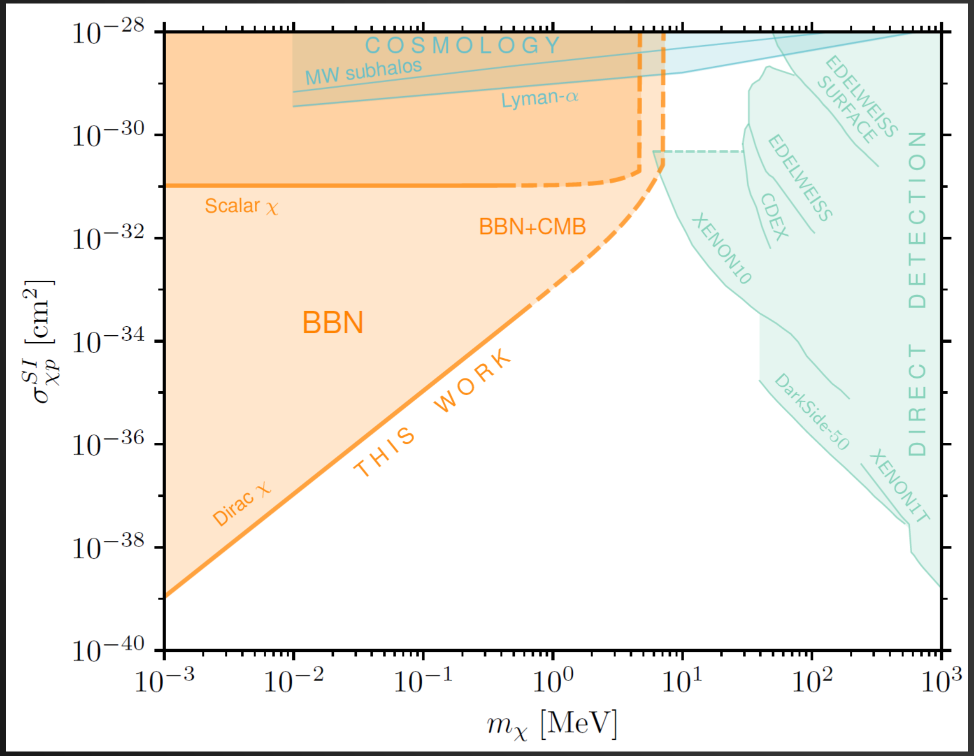

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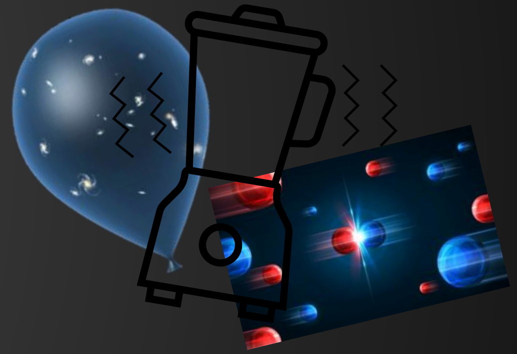

- Dirac: $\mathcal{O} = \frac{1}{\Lambda^2}\bar{\chi}\chi\bar{p}p$
- Scalar: $\mathcal{O} = \frac{1}{\Lambda}\chi^\dagger\chi\bar{p}p$

BBN		CMB	
Y_P	D/H	$\Omega_b h^2$	N_{eff}

BACKUP SLIDES

OTHER OPERATORS

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- Vector current? $\mathcal{O} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi\bar{p}\gamma_{\mu}p$

  Bound does not apply for vector mediators.

  Luminous loop vanishes due to Landau-Yang theorem.

- Light mediator?

  Bound much weaker for light scalar mediator, $m_{\phi} \ll m_{\chi}$.

  Direct detection signal enhanced.

  BUT – new light mediator also subject to BBN+CMB limits.

ϕ

EQUILIBRIUM

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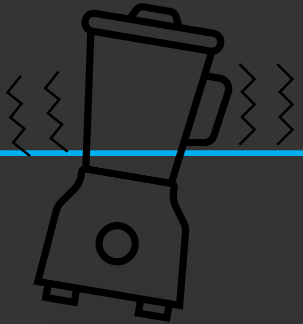
Equilibrium when

$$\frac{\langle\Gamma\rangle}{H} \gg 1$$

$\langle\Gamma\rangle$

Interaction Rate

← Faster



Slower →

H

$$H = \frac{1}{M_{Pl}}\sqrt{\frac{8\pi\rho}{3}}$$

Expansion

EQUILIBRIUM

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Interaction Rate

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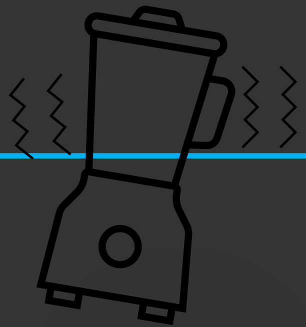

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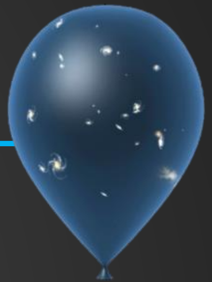
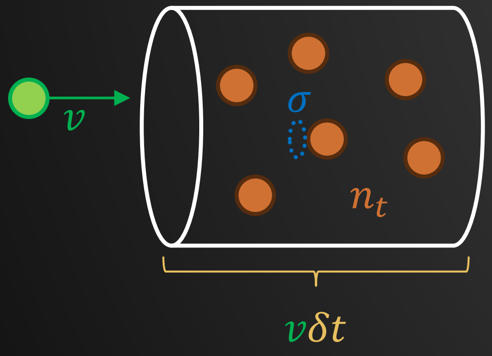


$$H = \frac{1}{M_{Pl}}\sqrt{\frac{8\pi\rho}{3}}$$

Expansion

What's the interaction rate?

$$\Gamma \delta t = n_t \times \sigma \times v\ \delta t$$



$$\therefore\ \Gamma = n_t \sigma v$$

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EQUILIBRIUM

Equilibrium when

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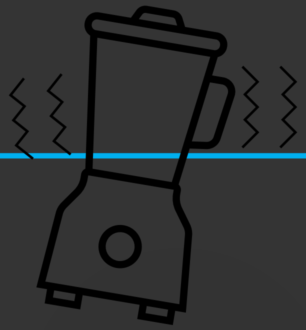
$\langle \Gamma \rangle$

Interaction Rate

← Faster



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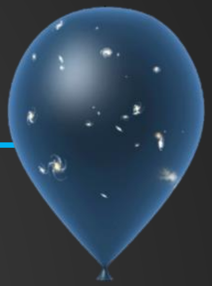

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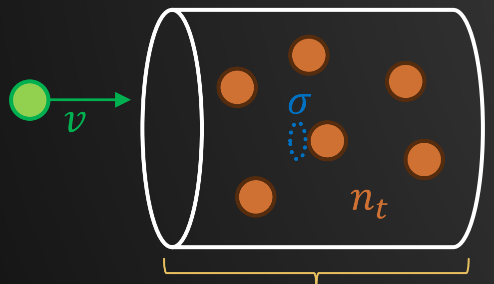

$$\therefore \Gamma = n_t \sigma v$$

But all the particles are moving?

Thermally average:

$$\langle \sigma v \rangle = \frac{1}{n_i n_t} \int \frac{d^3p_i d^3p_t}{(2\pi)^3(2\pi)^3} \sigma v\ f_i f_p$$

$$\therefore \langle \Gamma \rangle = n_t \langle \sigma v \rangle$$

EQUILIBRIUM

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Equilibrium when

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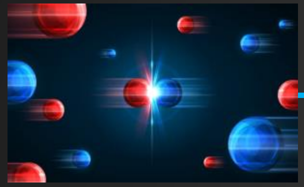
$\langle \Gamma \rangle$



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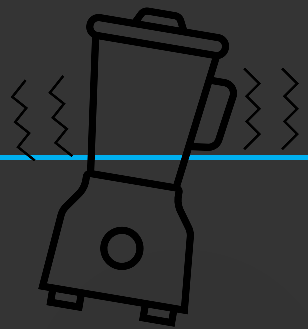
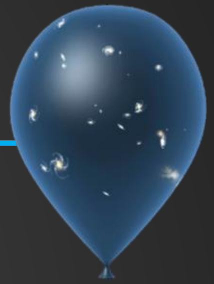


Slower →

H

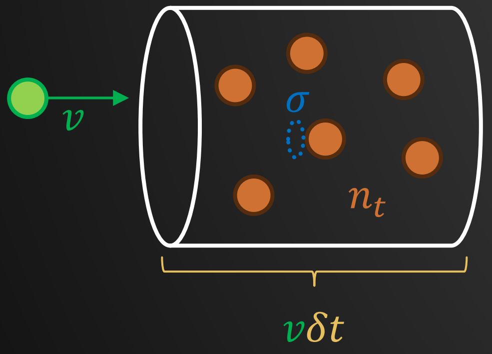


Expansion

$$H = \frac{1}{M_{Pl}}\sqrt{\frac{8\pi\rho}{3}}$$

What's the interaction rate?

$$\Gamma\delta t = n_t \times \sigma \times v\,\delta t$$



$$\therefore \Gamma = n_t \sigma v$$

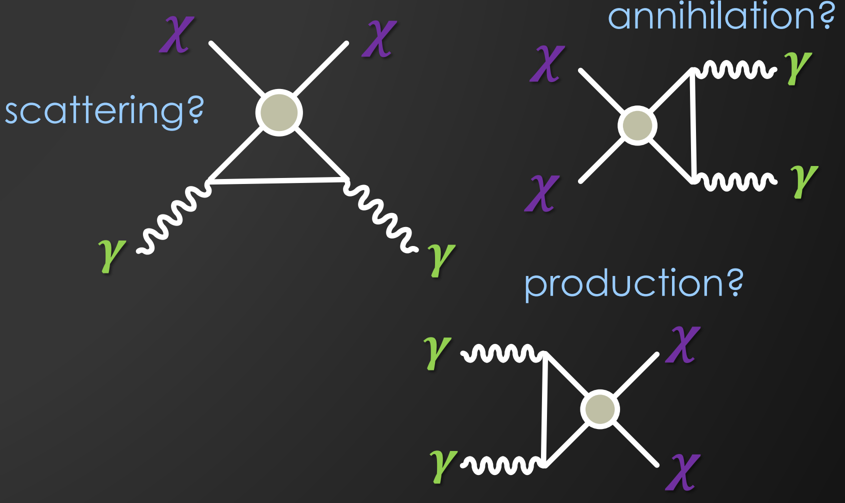
But all the particles are moving?

Thermally average:

$$\langle \sigma v \rangle = \frac{1}{n_i n_t}\int \frac{d^3p_i d^3p_t}{(2\pi)^3(2\pi)^3}\sigma v\, f_i f_p$$

$$\therefore \langle \Gamma \rangle = n_t \langle \sigma v \rangle$$

Okay, so which interaction should we think about?



EQUILIBRIUM

Joshua Wood - 2023

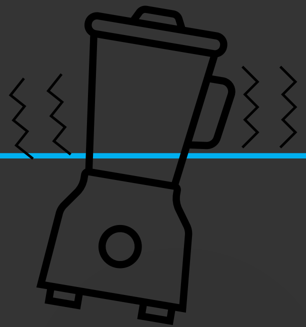
Equilibrium when

$$\frac{\langle \Gamma \rangle}{H} \gg 1$$

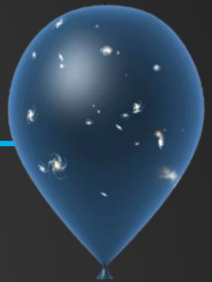
$\langle \Gamma \rangle$

Interaction Rate

Faster ← → Slower



H



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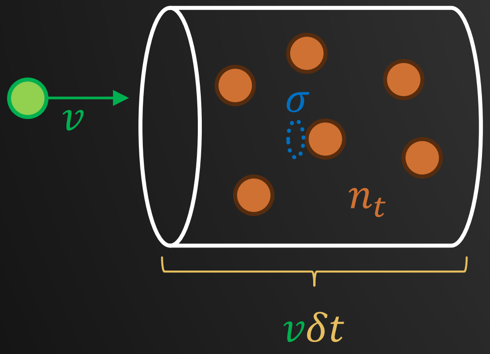

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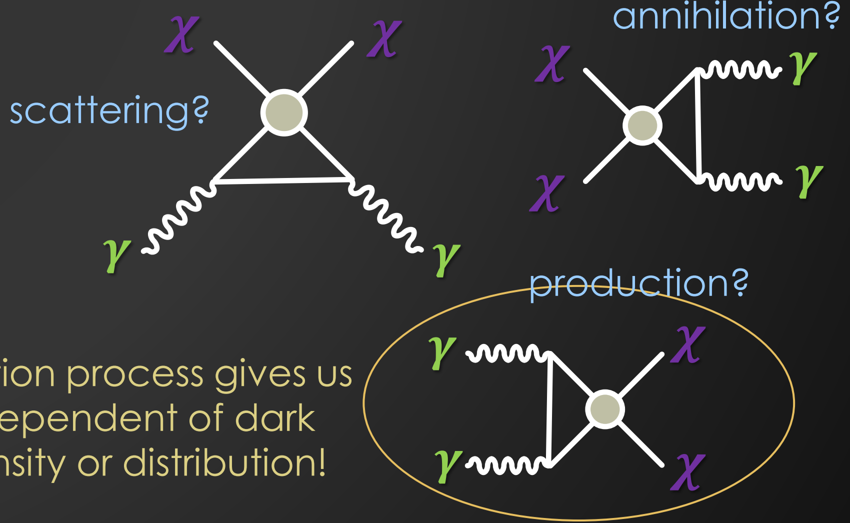


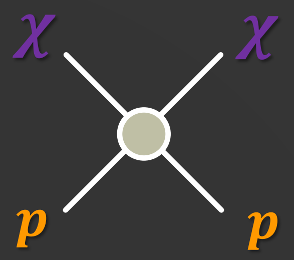
The production process gives us a rate independent of dark matter density or distribution!

CROSS-SECTIONS

Joshua Wood - 2023

Final step, calculate the cross-sections:

Effective Operator: $\mathcal{O} = \frac{1}{\Lambda^2}\bar{\chi}\chi\bar{p}p$



Fermionic dark matter with a scalar current
Will talk about other effective operators at the end!

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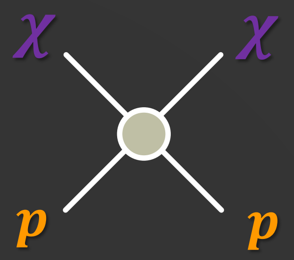

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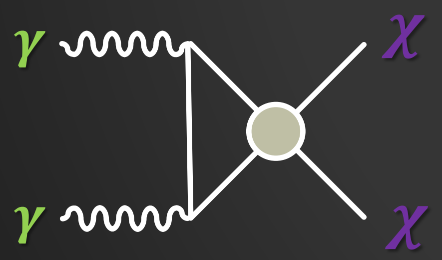

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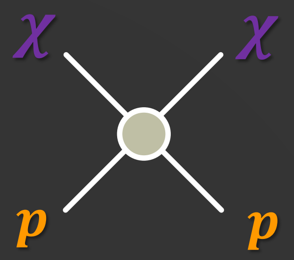

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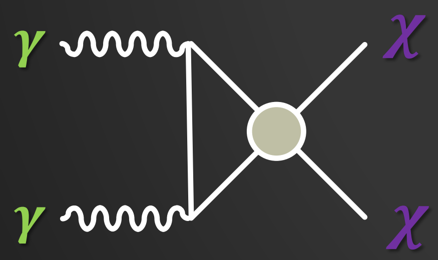
effective vertex



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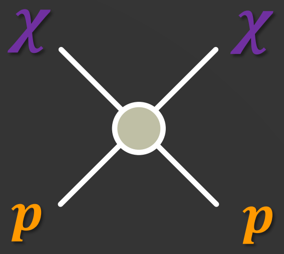

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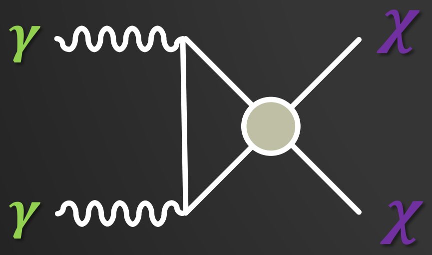
photon vertices (e^4)

effective vertex ($\frac{1}{\Lambda^4}$)



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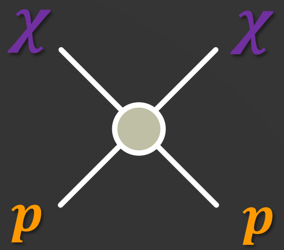

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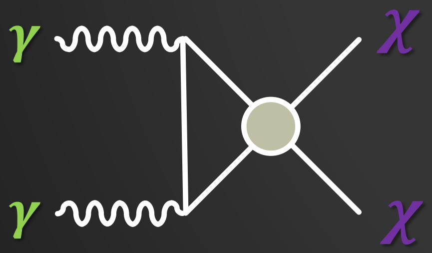
photon vertices (e^4)

effective vertex ($\frac{1}{\Lambda^4}$)

loop factor ($\frac{1}{(16\pi^2)^2}$)



CROSS-SECTIONS

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS
Joshua Wood - 2023
THE UNIVERSITY OF MELBOURNE

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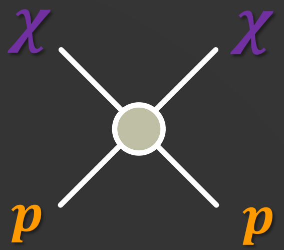

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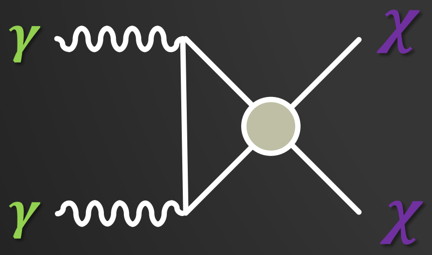
photon vertices

effective vertex

loop factor

proton triangle loop

Finite and related to $h \to \gamma\gamma$!



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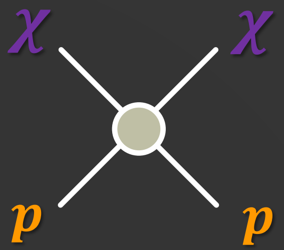

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effective vertex

photon vertices

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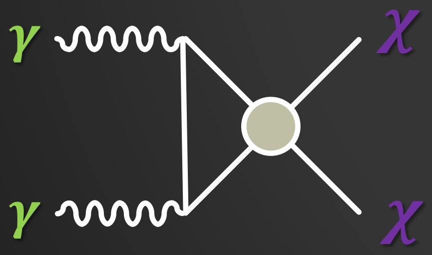
proton triangle loop

kinematics & phase space

Finite and related to $h \to \gamma\gamma$!



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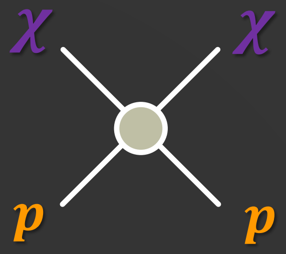

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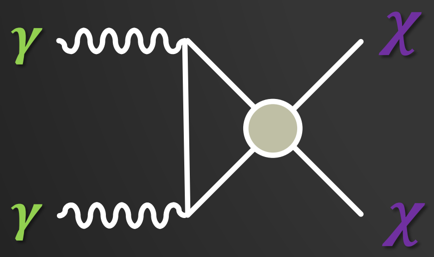
- $\frac{1}{\Lambda^4}$: effective vertex
- e^4: photon vertices
- $(16\pi^2)^2$: loop factor
- $\frac{1}{m_p^2}|F(s)|^2$: proton triangle loop — Finite and related to $h \to \gamma\gamma$!
- $\frac{1}{16\pi}\sqrt{s}\left(s - 4m_\chi^2\right)^{3/2}$: kinematics & phase space



Equilibrium Condition:
at $T = 2$ MeV

$$\frac{\langle\Gamma\rangle}{H} = \frac{n_\gamma\langle\sigma_{prod}\, v\rangle}{H} < 1$$

Equilibrium puts a limit on $\frac{1}{\Lambda^4}$ and hence, a limit on the DM-proton cross-section