REPRODUCTIVE FREEZE-IN

OF SELF-INTERACTING DARK MATTER

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NExT Institute Seminar Meeting

18th November 2020

Today

I present a new production mechanism for hidden sectors connected to the Standard Model only through gravity

➔ **Observational evidence**

➔ **Traditional mechanisms**

➔ **Gravitational Dark Matter**
The need for an alternative

➔ **Reproductive Freeze-In**
A new way

THE EVIDENCE FOR DARK MATTER

Galactic rotation curves

Motion of galaxies in clusters

Galactic gravitational lensing

CMB acoustic peaks

Universal expansion

THE EVIDENCE FOR DARK MATTER

Galactic rotation curves

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GRAVITATIONAL

Our theory of gravity could be wrong, but competing theories struggle to explain all of the evidence.

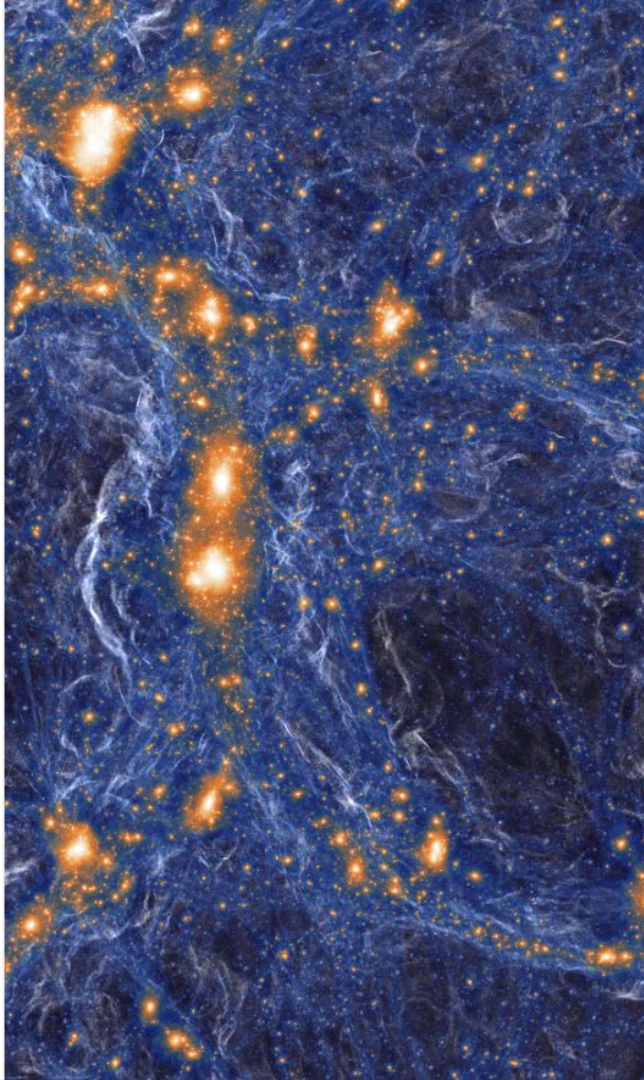
STRUCTURE FORMATION

We live in a Universe of structure (density variation). These perturbations get smeared if particles

1. Are too hot (‘**free streaming**’)
2. Interact too strongly (‘**collisional damping**’)

The SM is too hot during the era of structure formation. Simulations with CDM included match observed structure very well.

We require the scale of density damping to be **less than ~100 kpc** in comoving units.



WHAT DO WE KNOW?

The DM must be **massive** and have **gravitational interactions** with the SM.

Relic abundance $\Omega h^2 = 0.22$.

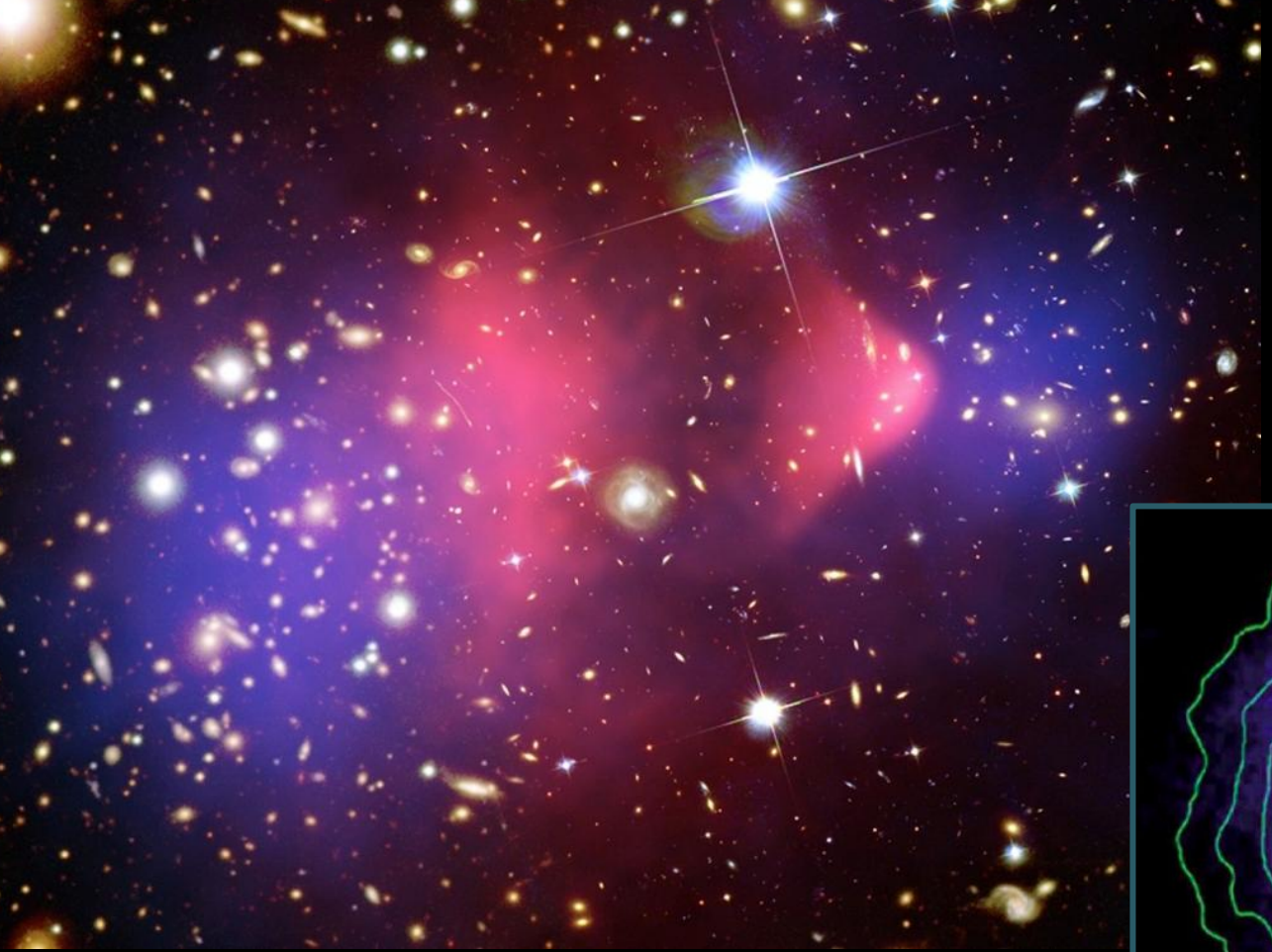
Must be **out of thermal equilibrium** (otherwise Boltzmann suppression)

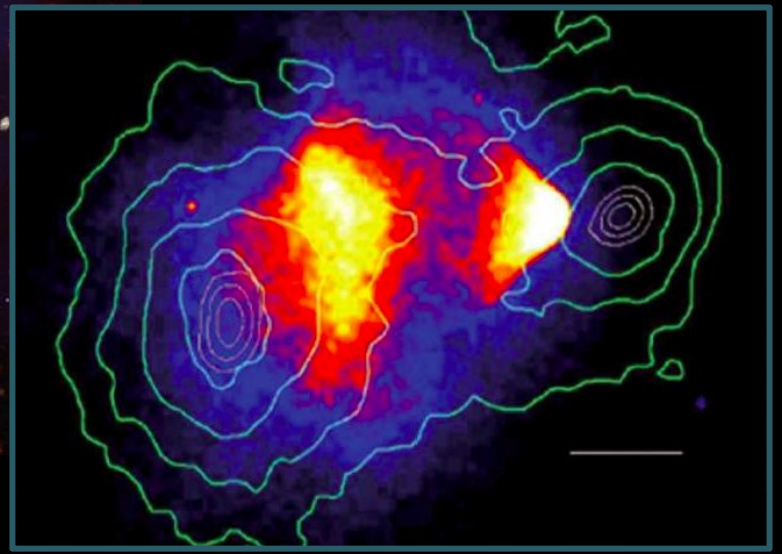
A strong upper limit on how much it can **interact with the SM** via gauge fields or portals, but no lower limit.

There is an weaker upper limit on **self interactions**.

GRAVITATIONAL LENSING:

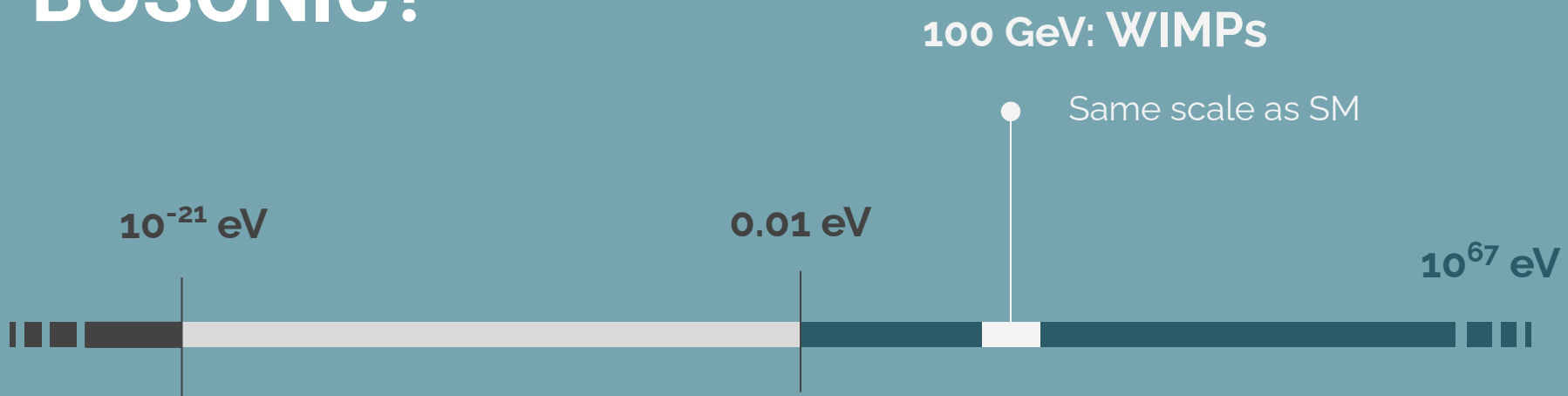
Bullet Cluster





X-Ray images from Chandra

WHAT DO WE KNOW IF DM IS BOSONIC?



De Broglie wavelength bigger than dwarf galaxies - cannot be all the DM

Well described as a coherent classical field

Axion-Like Particles, massive vector bosons

Bosonic particle dark matter

The state of the art

WIMPs

Interact with SM through non-gravitational forces about as strong as the weak force.

Produced in Freeze-Out

FIMPs

Interact feebly (very weakly) with SM through non-gravitational forces.

Produced in Freeze-In

GIMPs...?

Interact with SM only through gravity.

Produced in other ways.

Also: axions, sterile neutrinos, black holes...

The state of the art

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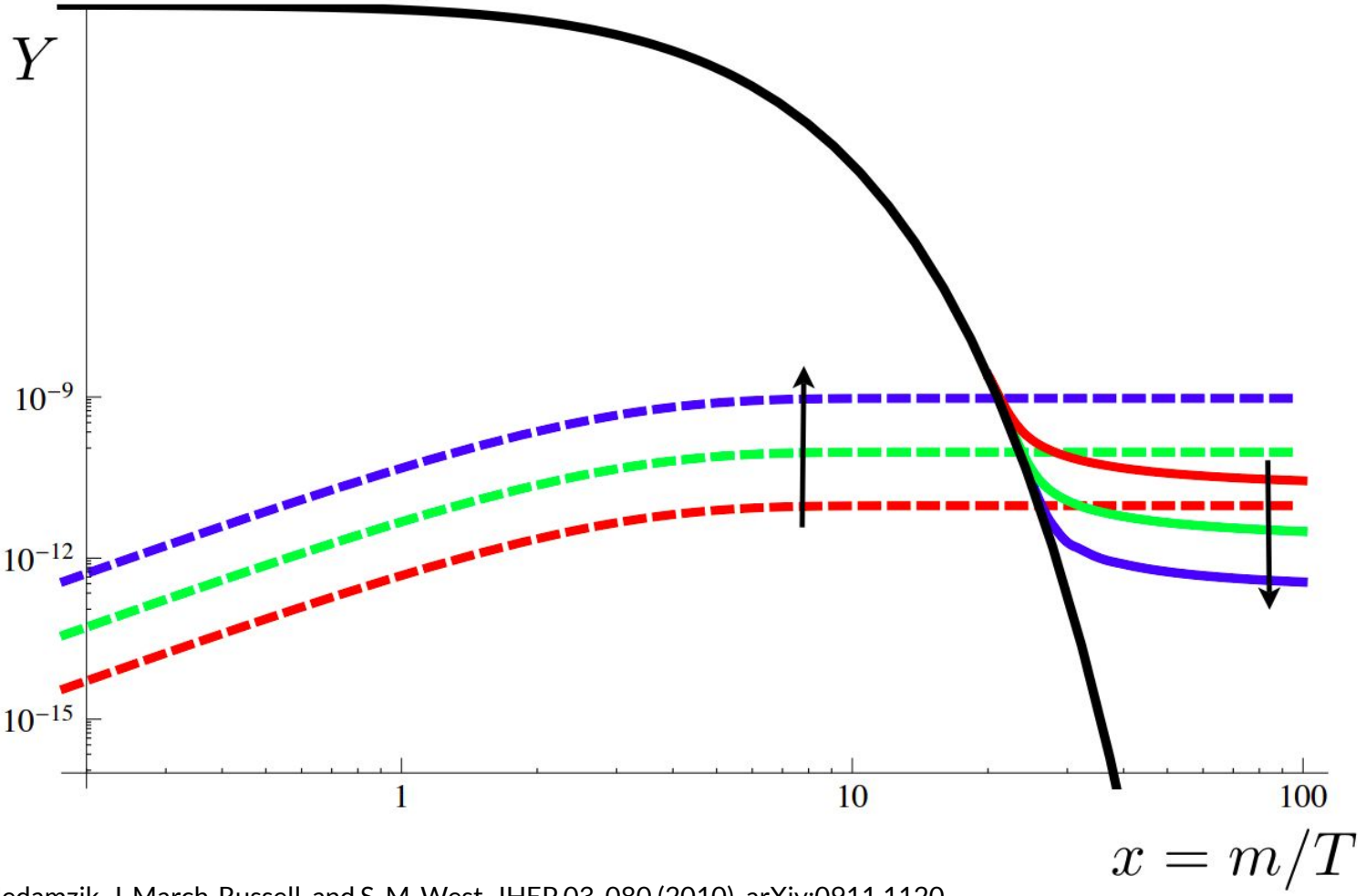
WIMPS AND FREEZE-OUT

Interaction strength ~ weak scale

Leading production mechanism is that of **freeze-out**, where DM starts in **thermal equilibrium** with the SM and with high density

1. DM goes non-relativistic - its number density per comoving volume (**yield**) goes down as it annihilates into SM particles.

2. As the Universe expands, no longer dense enough to annihilate - yield is ‘frozen out’ at a final value



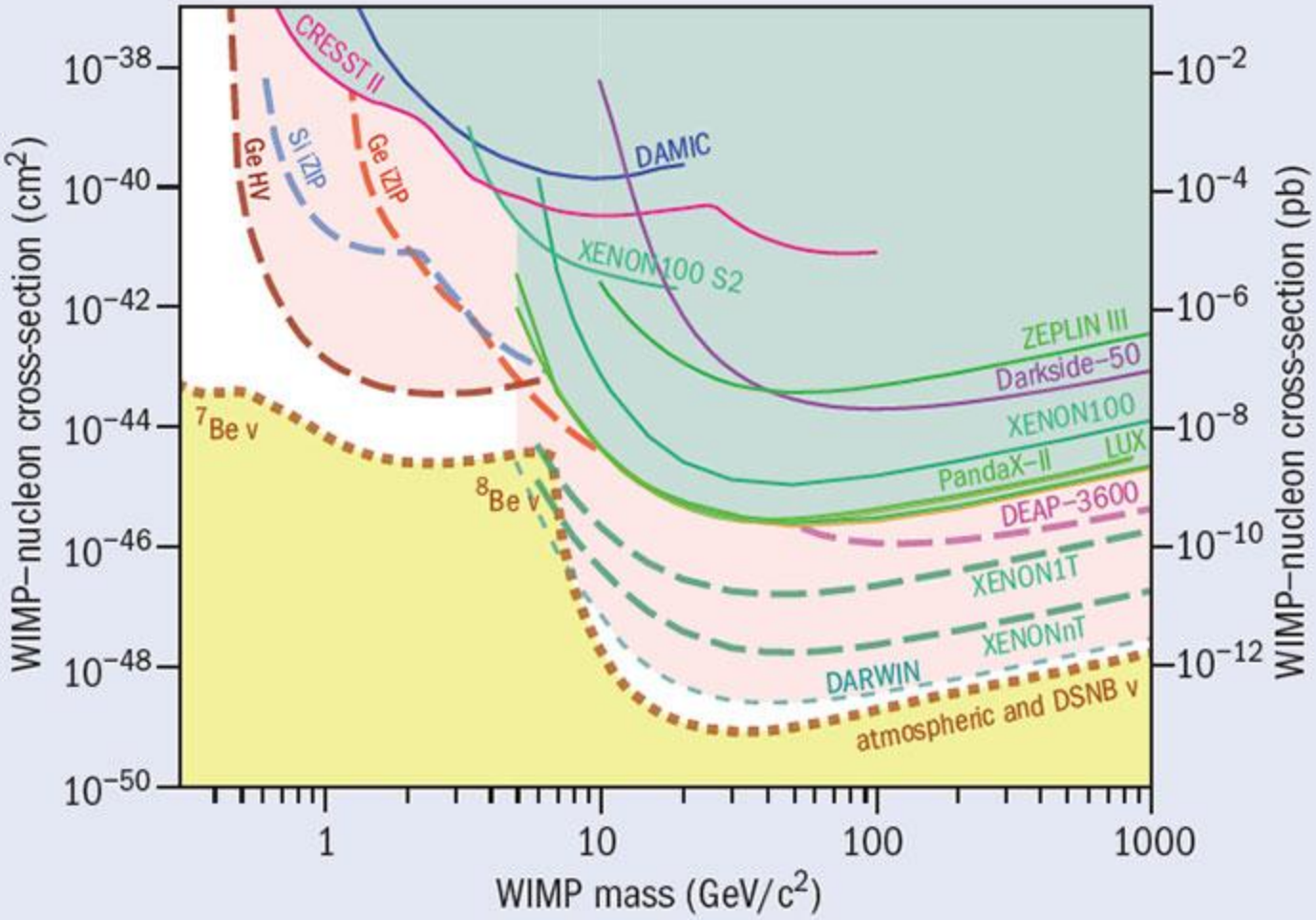
L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, JHEP 03, 080 (2010), arXiv:0911.1120

WIMP OUT

WIMPs have been very popular because of their potential observability and because of the '**WIMP miracle**' (WIMPs with weak-scale mass produce the observed amount of DM).

However, we **keep not seeing** WIMPs despite a massive international programme of experiments, and the shine is wearing off.

Effectively, the upper limit on the strength of DM-SM interactions is pushed lower and lower.

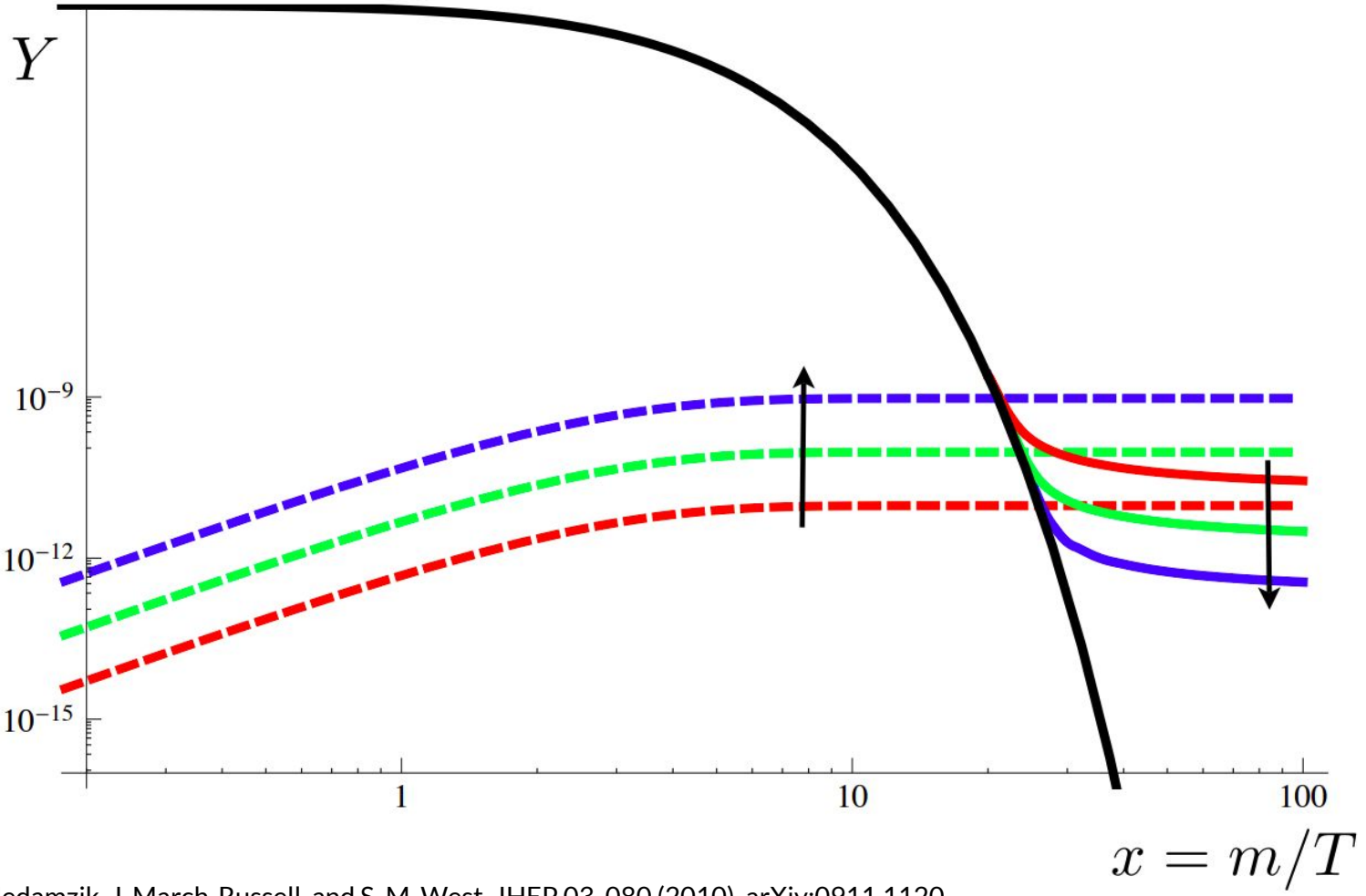

WIMP–nucleon cross-section (cm^2)
WIMP–nucleon cross-section (pb)
WIMP mass (GeV/c^2)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
1
10
100
1000
CRESST II
Ge HV
SI IZIP
Ge IZIP
DAMIC
XENON100 S2
ZEPLIN III
Darkside–50
XENON100
PandaX–II
LUX
DEAP–3600
XENON1T
XENONnT
DARWIN
^{7}Be ν
^{8}Be ν
atmospheric and DSNB ν

FIMPS AND FREEZE-IN

Feebly-Interacting - very small (but stronger than gravity) coupling to the SM via gauge or Higgs portal interactions - too small to ever be in thermodynamic equilibrium.

New mechanism of **freeze-in**:

1. DM starts with very little yield
2. Increases by production from the SM
3. Stops when SM becomes too cool



L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, JHEP 03, 080 (2010), arXiv:0911.1120

THE GRAVITY OF IT

But what if there are no gauge interactions at all?

How do you make it? Can't use freeze-in or freeze-out any more.

What happens afterwards? Depends on self-interactions.

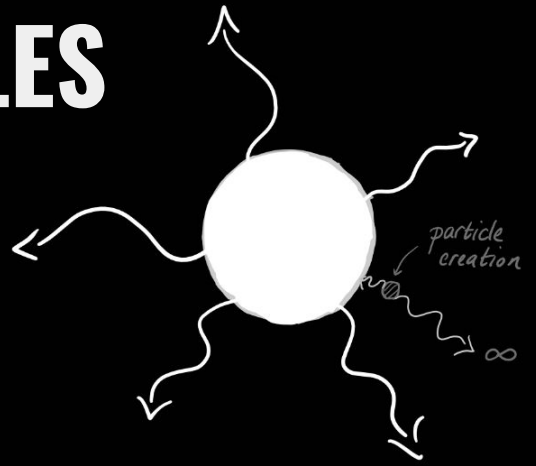
Gravitational production mechanisms e.g.

inflaton decay,

gravitational production from the SM via **gravitons**,

Hawking radiation from **Black Holes**

DARK MATTER FROM BLACK HOLES



Hawking Radiation from an early population of primordial Black Holes can provide the correct SM and DM content of the universe.

One issue - much of the DM comes out **too hot** for structure formation, and contributes too much to the relativistic degrees of freedom at Big Bang Nucleosynthesis.

Possible solution: allow DM to cool down through **self-interactions**.

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}} M}$$

O. Lennon, J. March-Russell, R. Petrossian-Byrne, **H.T**. *Black Hole Genesis of Dark Matter. JCAP* [arXiv:1712.07664]

REPRODUCTIVE FREEZE-IN

ALLOWING SELF INTERACTIONS

Consider a far-from-equilibrium, underpopulated hot sector, arising from, e.g. Hawking radiation or production from SM via graviton exchange.

Compared to equilibrium, temperature is high, number density is low (large **chemical potential** μ).

If we allow DM to **interact with itself** only, then it can relax to equilibrium by producing more states, turning kinetic into mass energy. Eventually sector will **thermalise** and the chemical potential will vanish.

How far do we get towards equilibrium, and how are observables affected?

FREEZE IT ALL ABOUT

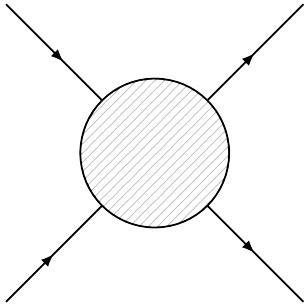
DM starts with a small number of particles and grows (like Freeze-In)

But it has no interactions with the SM, so must create its own extra states (hence **Reproductive Freeze-In**)

All depends on how the DM interacts with itself - coupling constant and the **scaling of the cross section with universal expansion**

J. March-Russell, **H.T**, S. M. West,
Reproductive Freeze-In of Self-Interacting Dark Matter
Phys.Rev.D 102 [arXiv:2007.14688]

SCENARIO

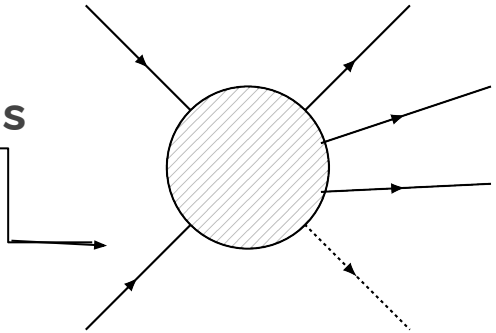


$$f(p,t) = \frac{Z(t)}{\exp[p/\tilde{T}(t)] \mp Z(t)}$$

$$Z(t) \equiv e^{-\mu/\tilde{T}}$$

Assumptions:

1. Some gravitational production mechanism populates SM & DM
2. Elastic processes fast enough for **kinetic** equilibrium - temperature T
3. Starts very hot and underpopulated - not in **chemical** equilibrium
4. No interaction with SM, but self-interactions
5. SM is hot and in full thermal equilibrium at T
6. Relevant interactions are **2-to-k inelastic collisions**



THE BOLTZMANN EQUATION

Hubble term

'collision' term

number density rate of change

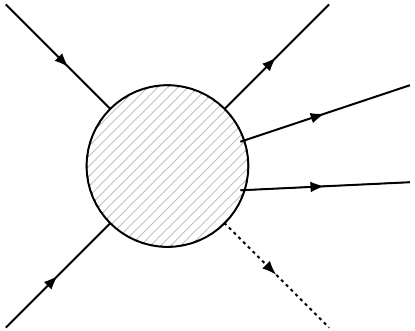
$$\dot{n}(t) + 3Hn = \frac{g}{(2\pi)^3}\int \mathrm{C}[f]\frac{d^3p}{E} \equiv c_n$$

$$c_n = g\tilde{T}^4 \sum_{k>2} (k-2)Z^2(1-Z^{(k-2)})\ \mathcal{I}_k(\tilde{T}/M)$$

$$\mathcal{I}_k(\tilde{T}/M) = A_k \left(\frac{\tilde{T}}{M}\right)^{\alpha} (1+\cdots)$$

parameterization of the cross-section

THERMALIZATION INTERRUPTED



Process converts kinetic to mass energy - temperature goes down faster than pure expansion.

Number-changing interactions become kinematically forbidden when the sector becomes non-relativistic.

Can **partially thermalise** but get stuck out of equilibrium.

We're interested in this case - what are the phenomenological consequences?

SLOW TO FAST

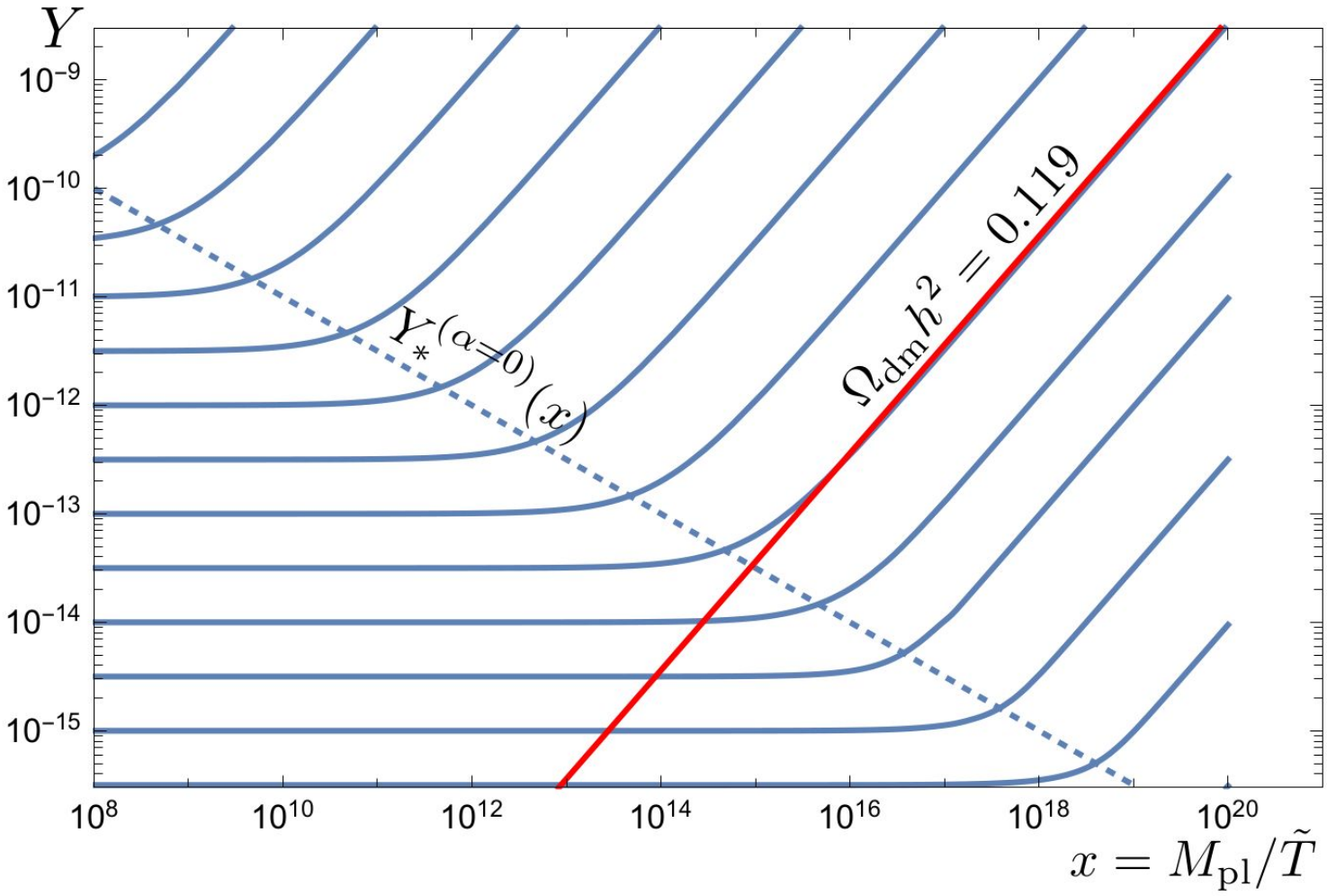
Hubble term

$$Hn \sim T^2 \widetilde{T}^3$$

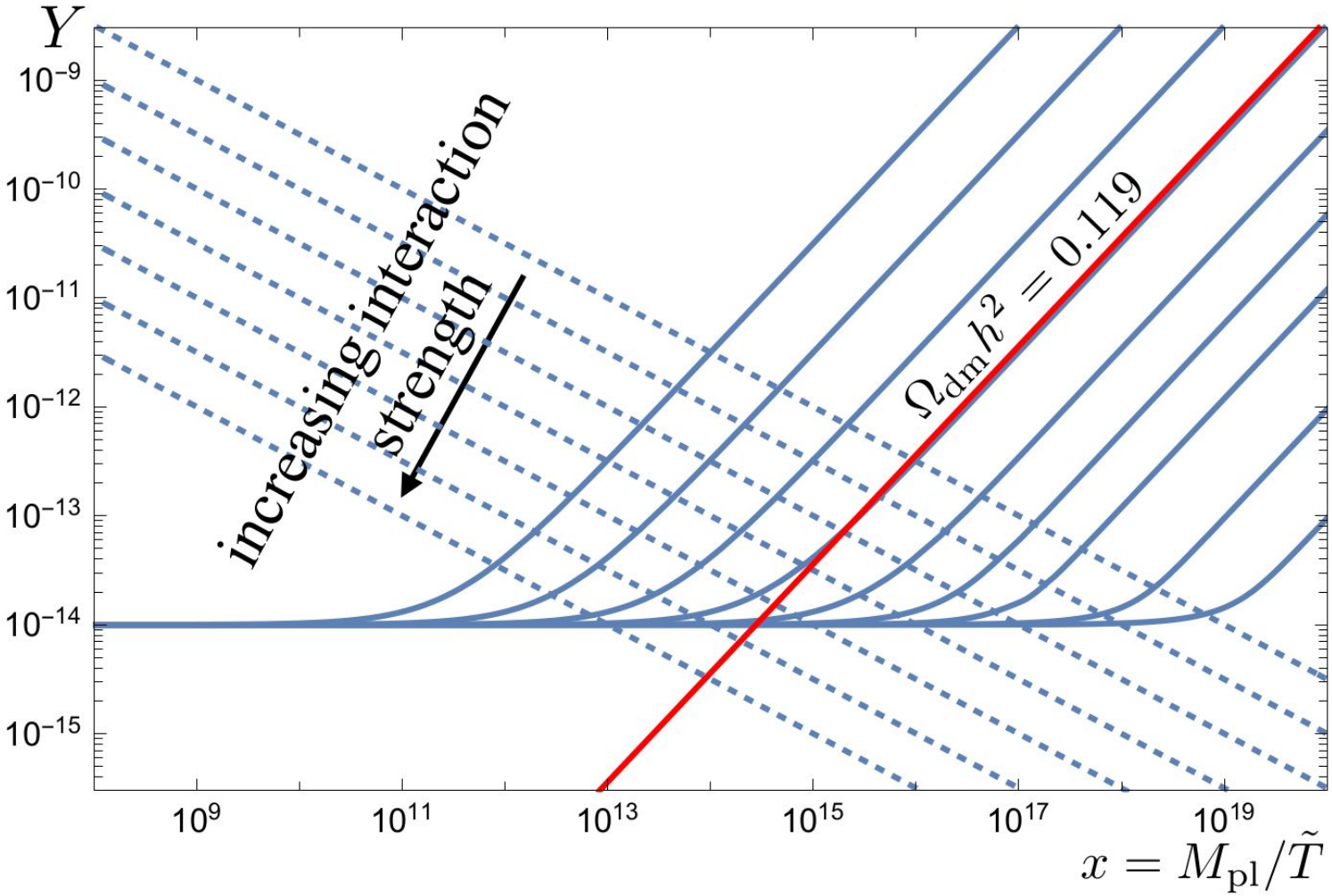
Evolution can be either **slow** or **fast** in comparison to the Hubble term.

→ $\alpha < 1$: we proceed from slow regime to fast unless we pass the mass threshold.

$\alpha = 0$


Y
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$Y_*^{(\alpha=0)}(x)$
$\Omega_{\rm dm}h^2 = 0.119$
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
$x = M_{\rm pl}/\tilde{T}$

$\alpha = 0$


Y
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
increasing interaction strength
$\Omega_{\rm dm} h^2 = 0.119$
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
$x = M_{\rm pl}/\tilde{T}$

SLOW TO FAST

Hubble term

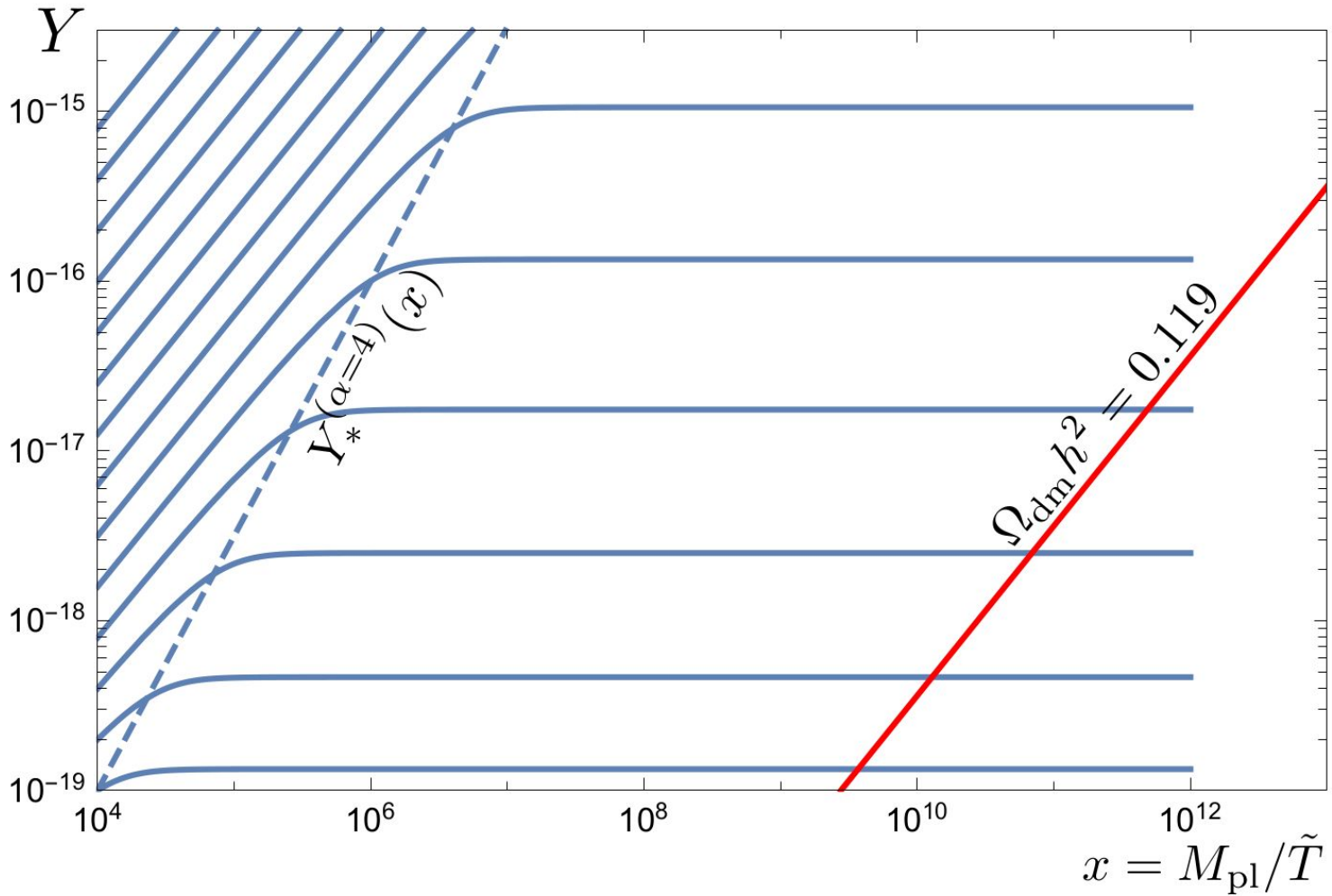
$$Hn \sim T^2 \widetilde{T}^3$$

Evolution can be either **slow** or **fast** in comparison to the Hubble term.

- **α < 1 :** we proceed from slow regime to fast unless we pass the mass threshold.

- **α > 3 :** proceed from fast to slow regime unless we pass the mass threshold

$\alpha = 4$


Y
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
$Y_*^{(\alpha=4)}(x)$
$\Omega_{\rm dm}h^2 = 0.119$
$x = M_{\rm pl}/\tilde{T}$

SLOW TO FAST

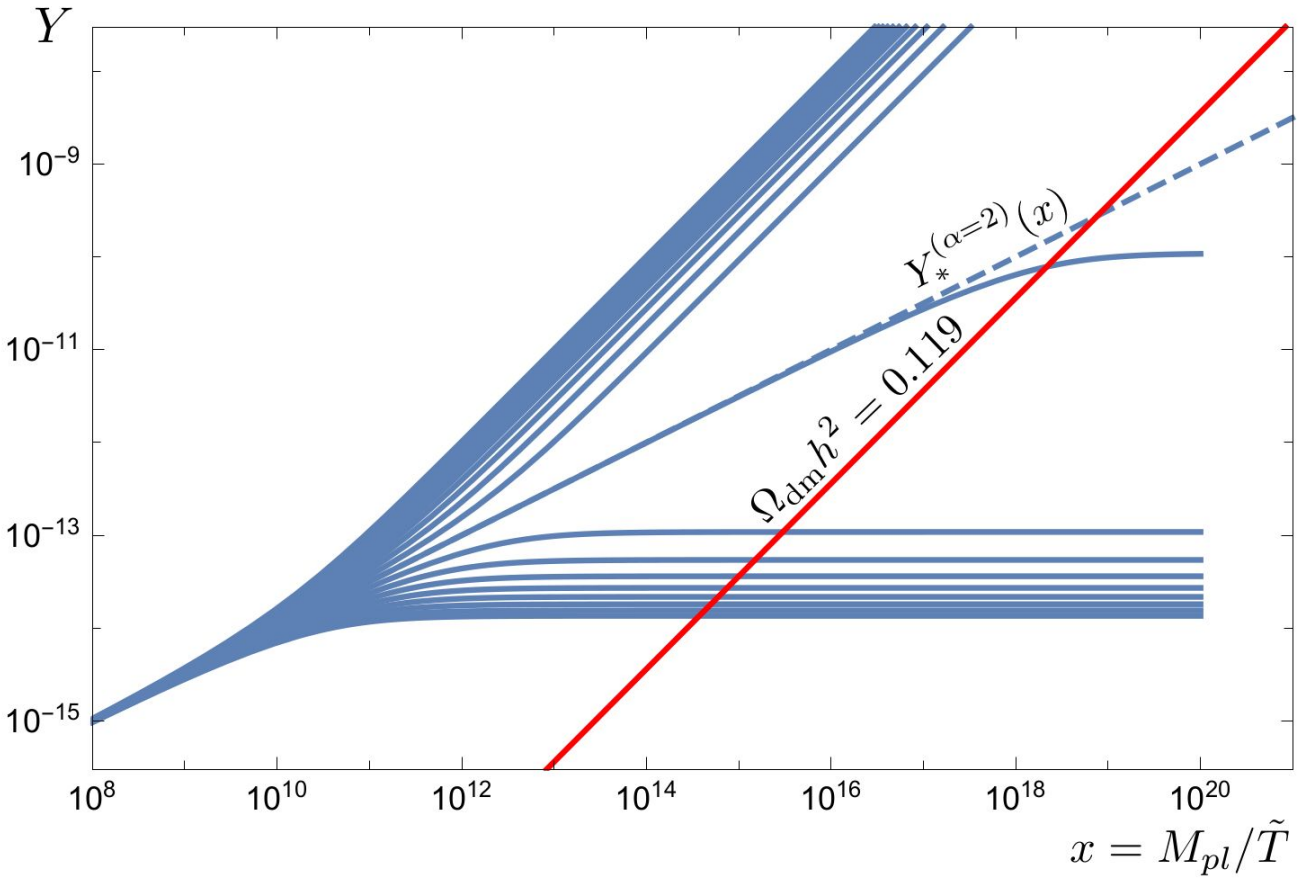
Hubble term

$$Hn \sim T^2 \widetilde{T}^3$$

Evolution can be either **slow** or **fast** in comparison to the Hubble term.

- **α < 1 :** we proceed from slow regime to fast unless we pass the mass threshold.
- **α > 3 :** proceed from fast to slow regime unless we pass the mass threshold
- **α = 2 :** evolution contained entirely within slow or fast regime (save for measure zero initial conditions)

$\alpha = 2$


Y
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
$Y_*^{(\alpha=2)}(x)$
$\Omega_{\rm dm}h^2 = 0.119$
$x = M_{pl}/\tilde{T}$

SCALAR DARK MATTER

ϕ^4 theory: $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4$

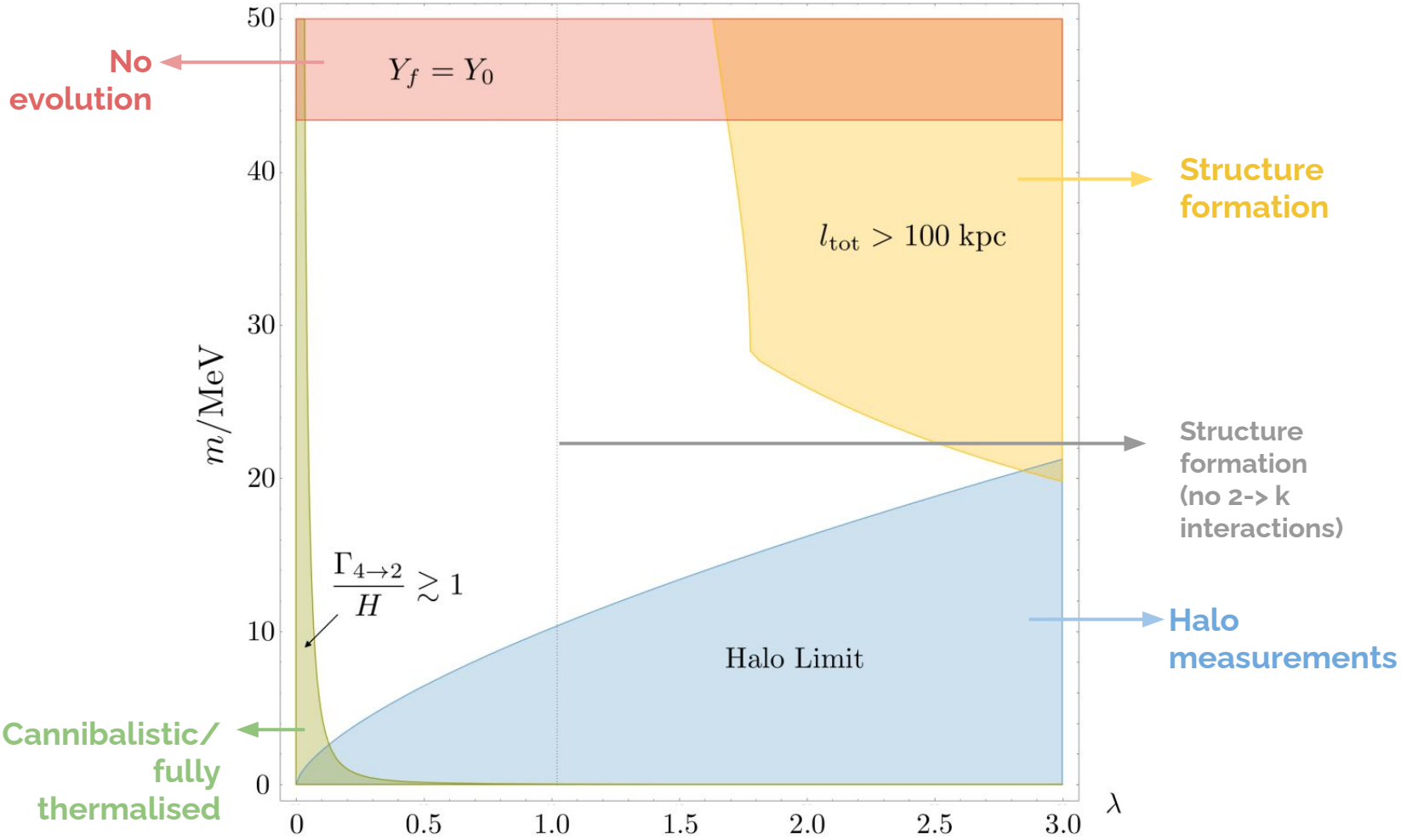
Scalar DM, α=0

Leading order number-changing is 2-to-4

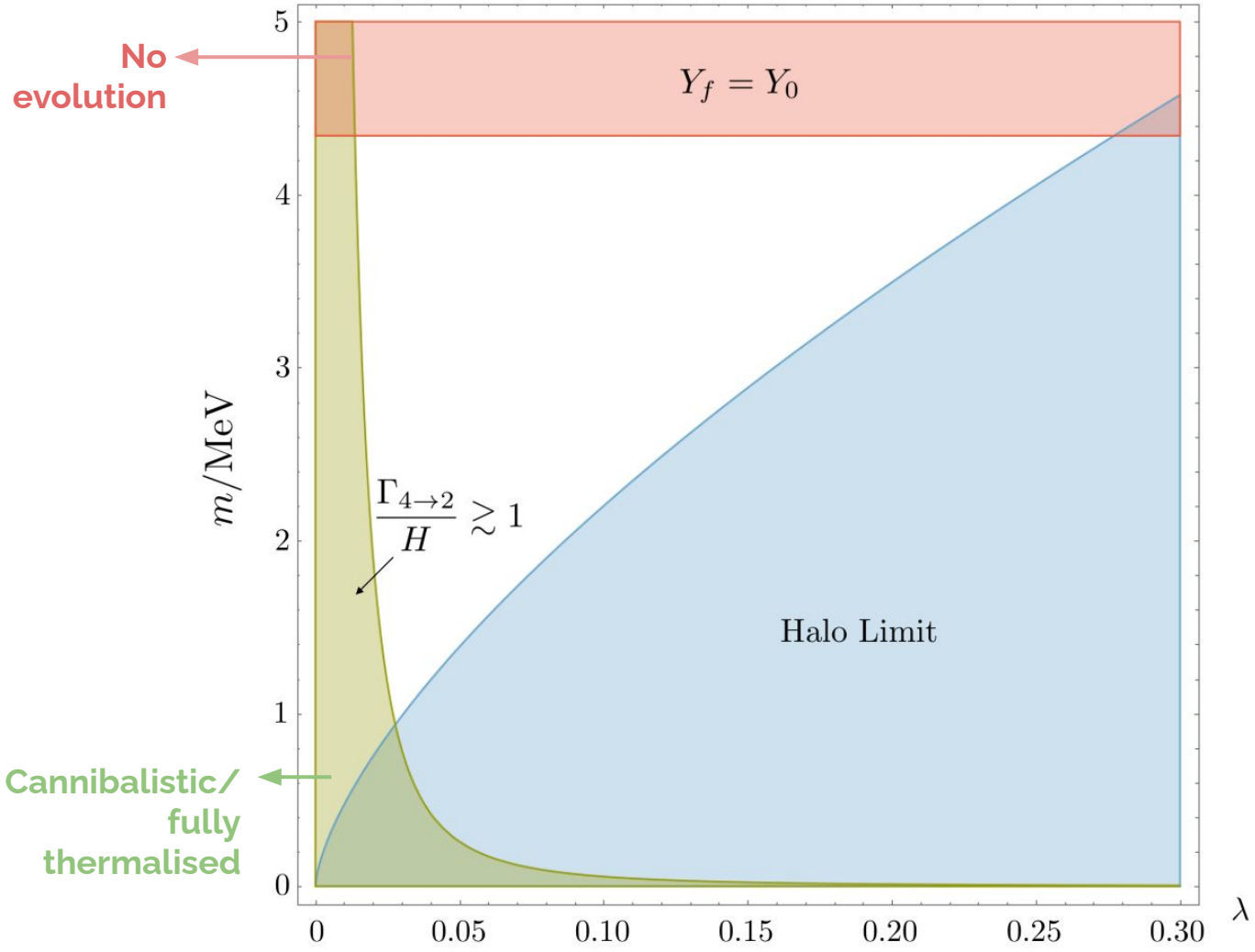
Becomes increasingly efficient vs. Hubble with universal expansion

$$c_n \approx 10^{-11}\ \lambda^4\ Z^2\ \widetilde{T}^4$$

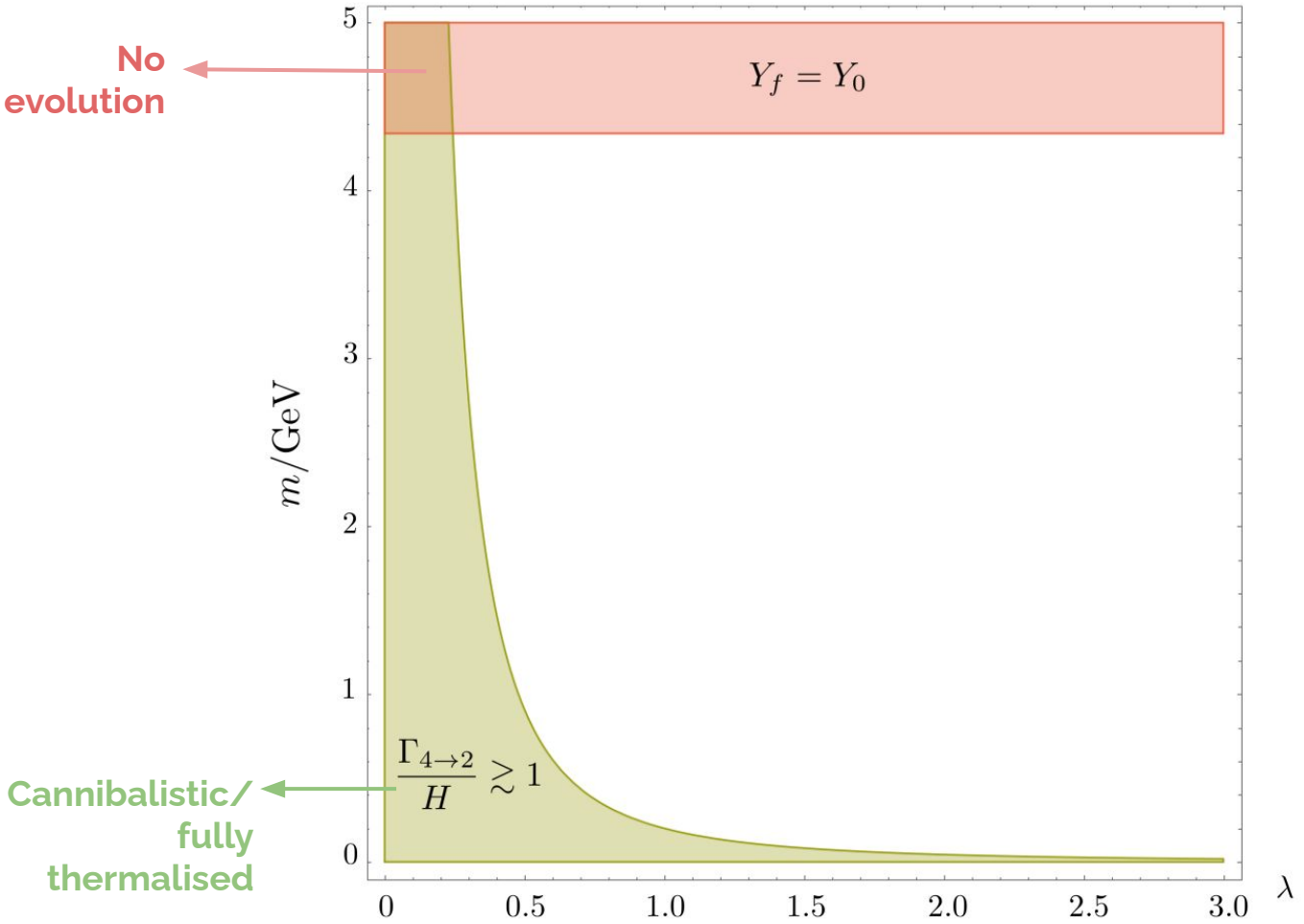
$Y_0 = 10^{-8}$


No evolution
$Y_f = Y_0$
Structure formation
$l_{\rm tot} > 100$ kpc
Structure formation (no 2-> k interactions)
$\frac{\Gamma_{4\to2}}{H} \gtrsim 1$
Halo measurements
Halo Limit
Cannibalistic/ fully thermalised
m/MeV
λ
0
10
20
30
40
50
0
0.5
1.0
1.5
2.0
2.5
3.0

$Y_0 = 10^{-7}$


No evolution
$Y_f = Y_0$
m/MeV
$\frac{\Gamma_{4\to2}}{H} \gtrsim 1$
Halo Limit
Cannibalistic/ fully thermalised
λ
0
1
2
3
4
5
0
0.05
0.10
0.15
0.20
0.25
0.30

$Y_0 = 10^{-10}$


No evolution
$Y_f = Y_0$
Cannibalistic/ fully thermalised
$\frac{\Gamma_{4\to2}}{H} \gtrsim 1$
m/GeV
λ
0
1
2
3
4
5
0
0.5
1.0
1.5
2.0
2.5
3.0

Summary

As ever-greater swaths of gauge/portal interaction parameter space are ruled out by observation, we are well motivated to **explore the alternative.**

Production mechanisms and evolution of purely-gravitationally-interacting ('secluded') sectors are qualitatively different but no less feasible.

DM must end up out-of-equilibrium, either falling out of it due to universal expansion (freeze-out) or never getting there in the first place (freeze-in and **reproductive freeze-in**).

We have shown that a wide range of parameter space exists for self-interacting secluded DM where **partial thermalisation** takes place (alleviating tensions in some production scenarios).

Many **questions** still to explore: composite dark matter, strongly coupled, other production mechanisms...

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Thank you!