

# PARTICLE DARK MATTER: NATURE & ORIGINS

Andrzej Hryczuk



## **Review Part:**

a personal selection of interesting concepts & ideas

**Results Part:** based on collaboration with

**T. Binder, T. Bringmann, M. Gustafsson, M. Laletin and S. Chatterjee**

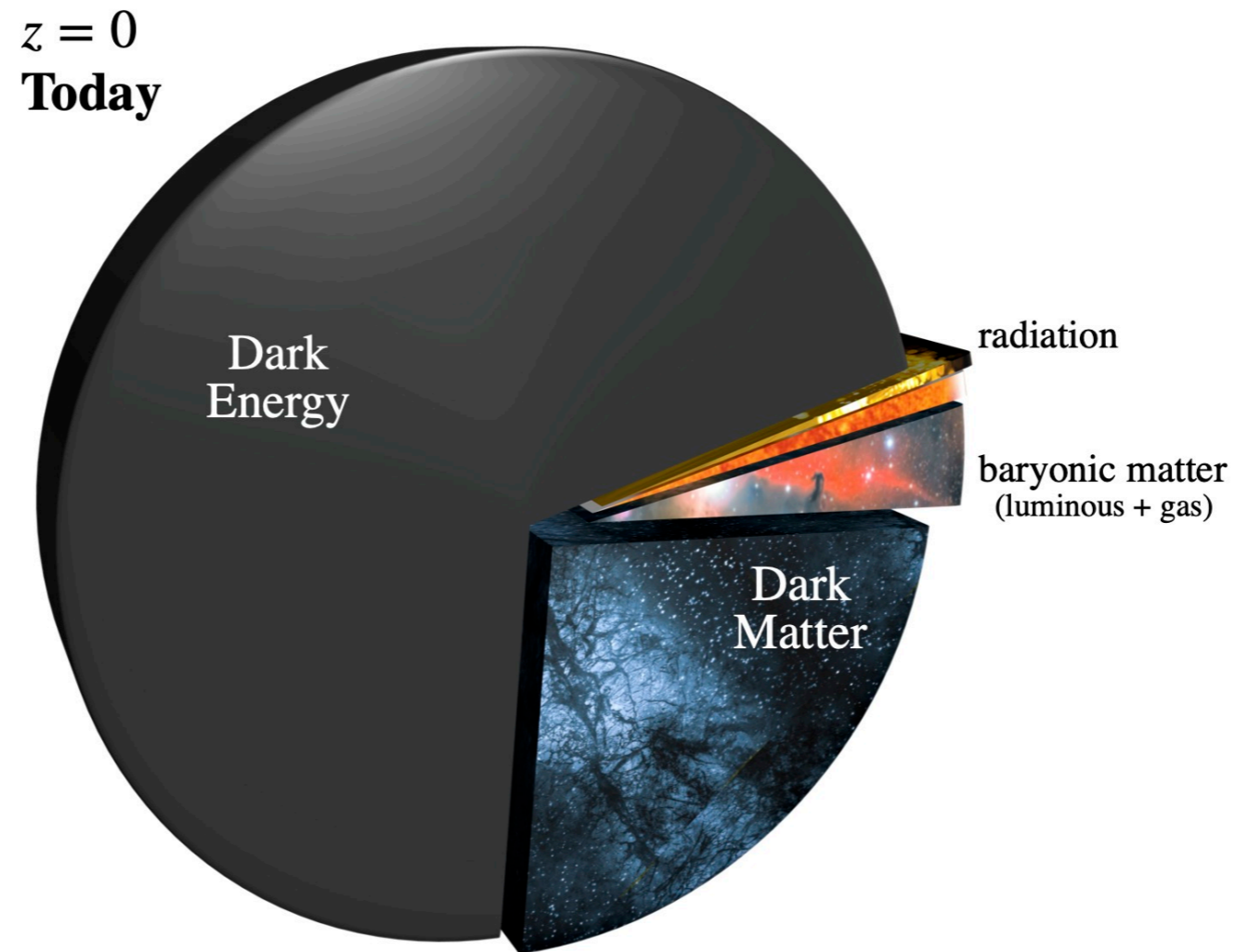
# OUTLINE

1. Particle physics perspective on Dark Matter
  - recap of **evidences & expectations**
  
2. Dark Matter status ca. AD 45<sup>2</sup>
  - observations & **theory**

---

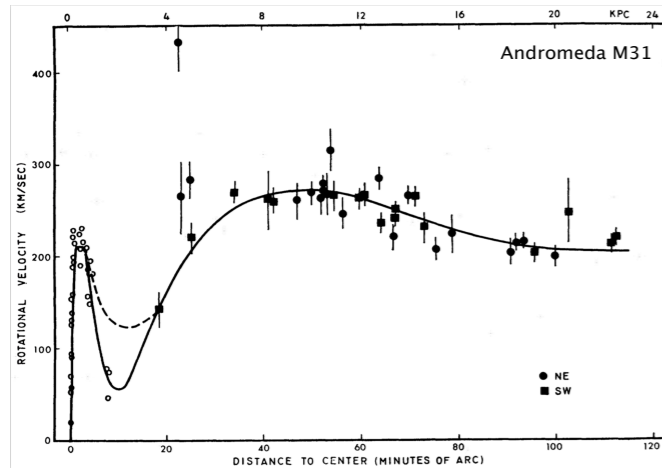
3. Advances in DM production theory
  - **departure from kinetic equilibrium**
  - **multi-component** DM scenarios

# DO WE SEE EVERYTHING THERE IS?

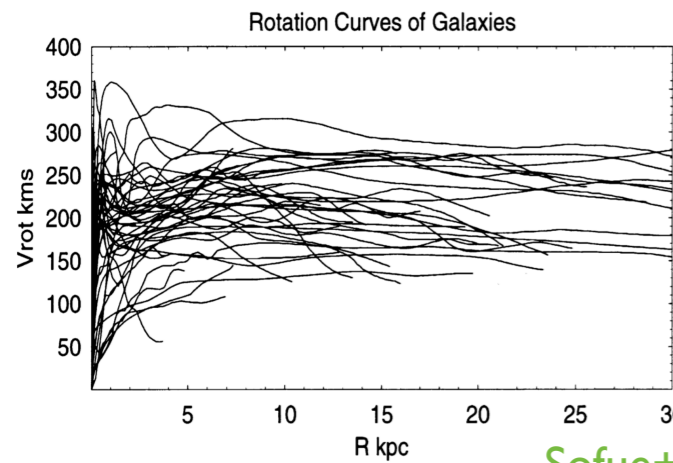
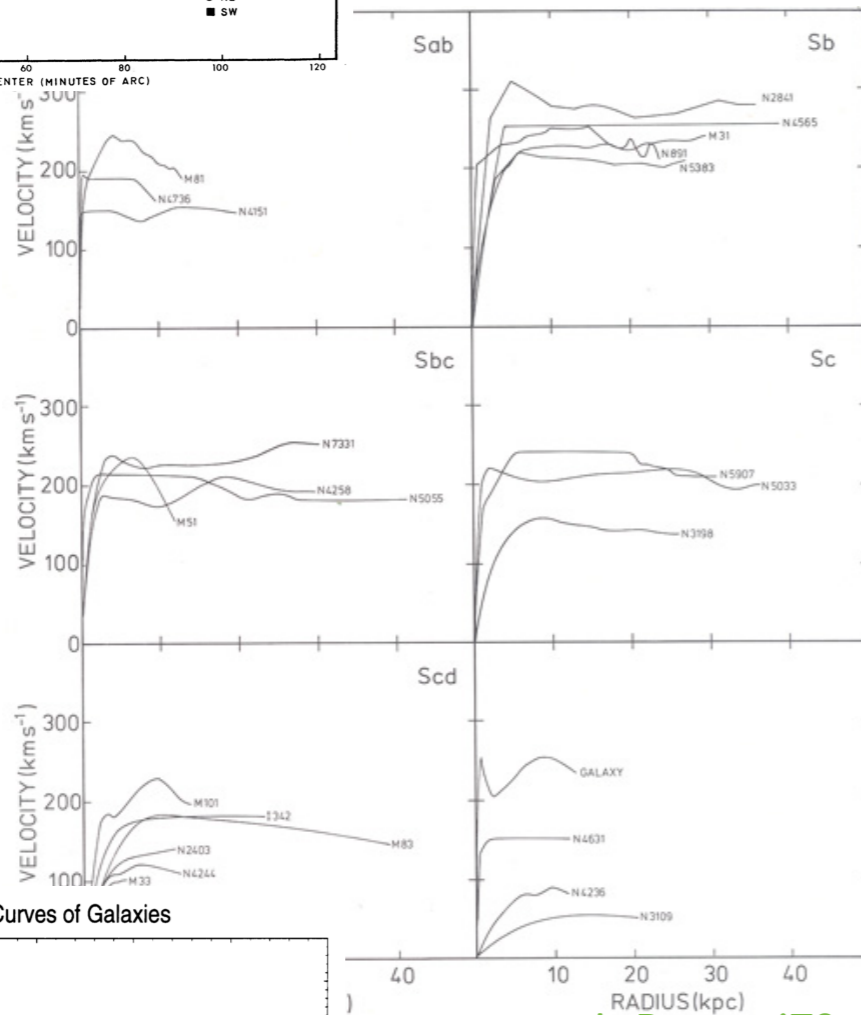


...BUT SHOULD WE REALLY EXPECT TO?

# HISTORY & EVIDENCE



Rubin+ '70



Sofue+ '99

Idea that there is some „dark matter” in the Universe has a very long history

Suggested read: Bertone & Hooper '16

But for the most part the „dark” has been understood as **a mere adjective**...

Indeed, even **the historical milestone of establishing that the rotation curves of galaxies** are close to flat at large distances, did not cement the idea that there is a „new kind of matter”

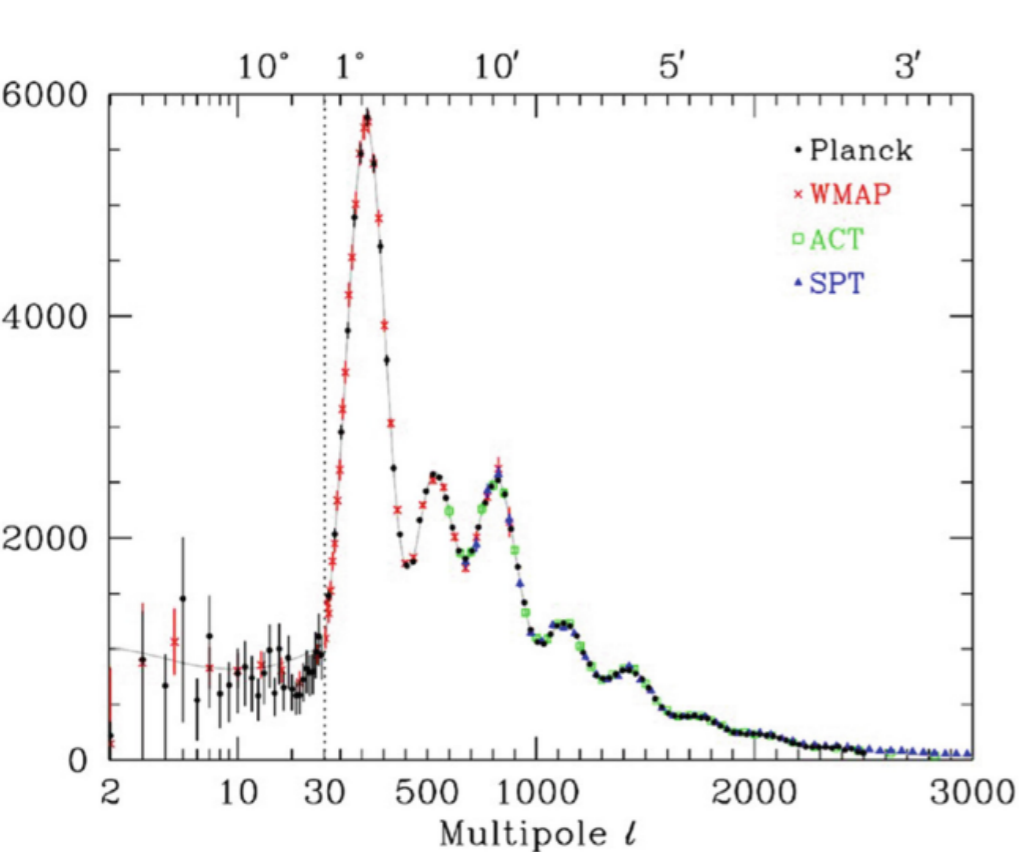
What made it to the transition to **a proper noun**?

# HISTORY & EVIDENCE

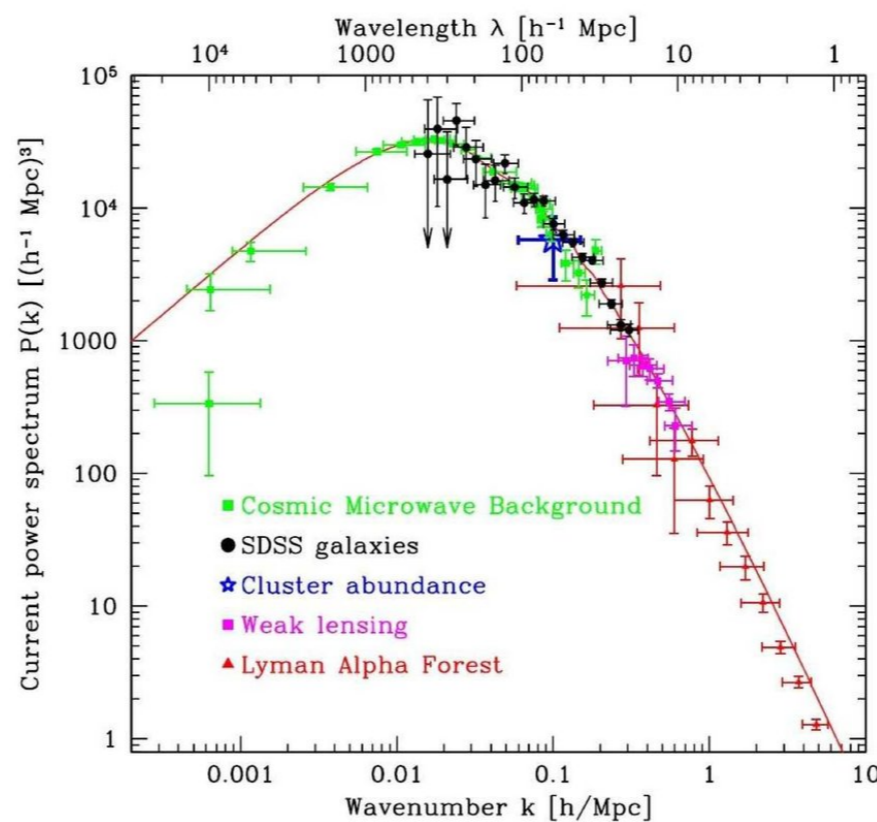
Rotation curves are commonly seen as the most direct evidence of the existence of DM

... but this frames DM as an **astrophysical „issue”** (cf. phrase like „missing mass problem”)

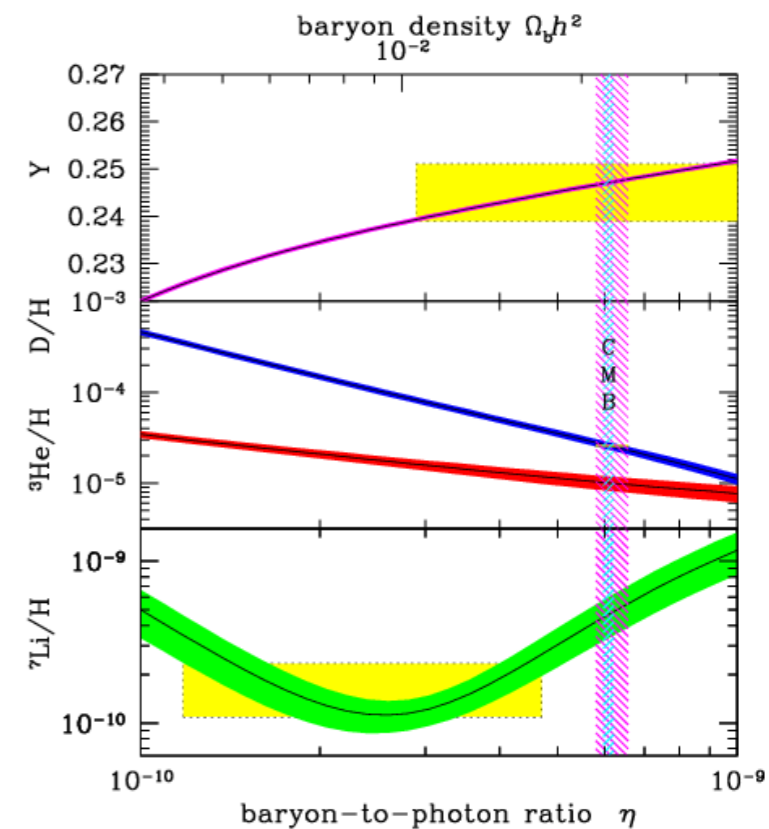
From **HEP or cosmology** perspective the most important pieces of evidence:



**CMB anisotropies**



**Matter power spectrum**



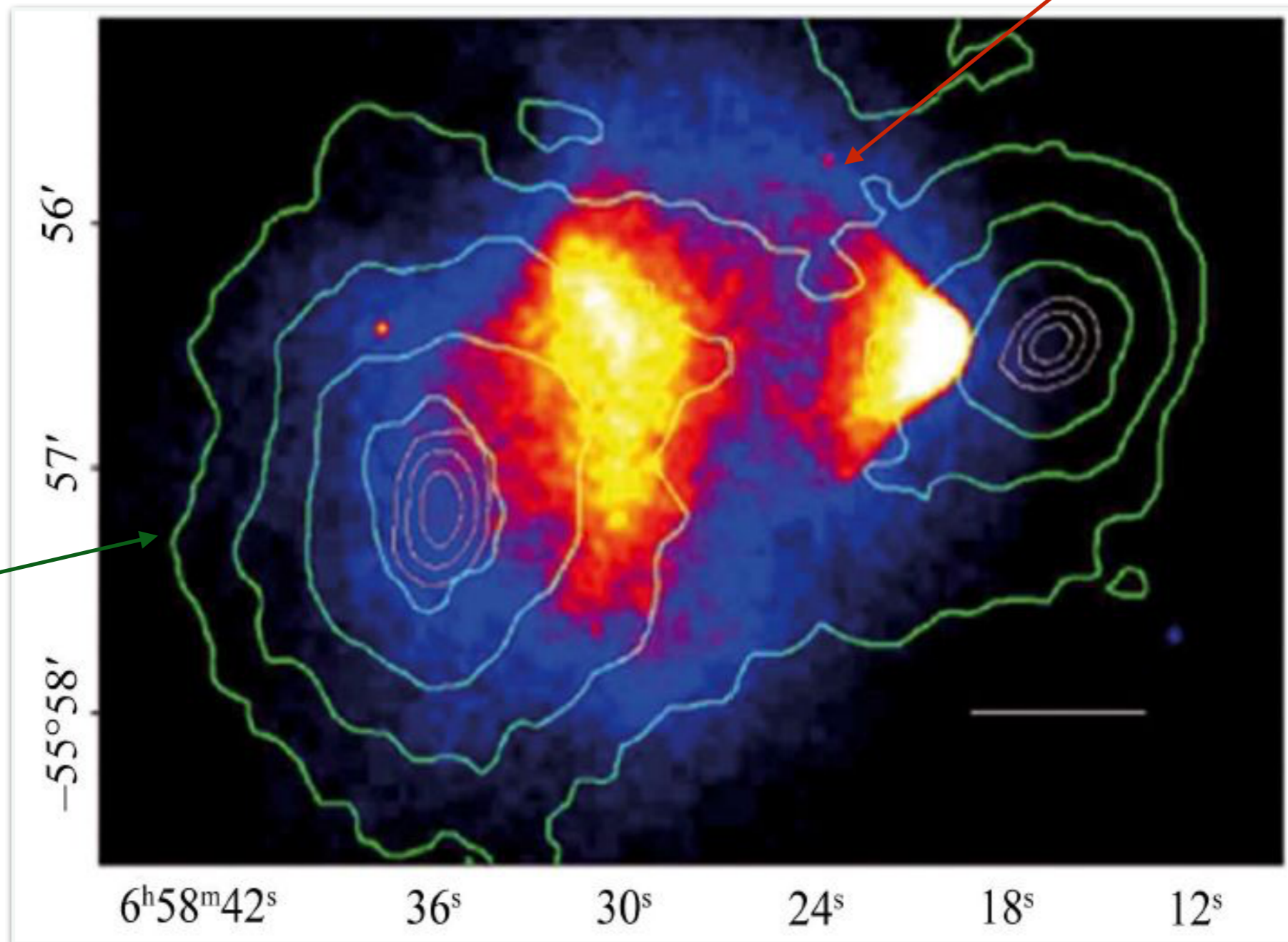
**BBN**  
(indep. measure of baryons)

# HISTORY & EVIDENCE

And then there is also of course:

hot gas from X-ray observations

mass  
distribution  
from lensing

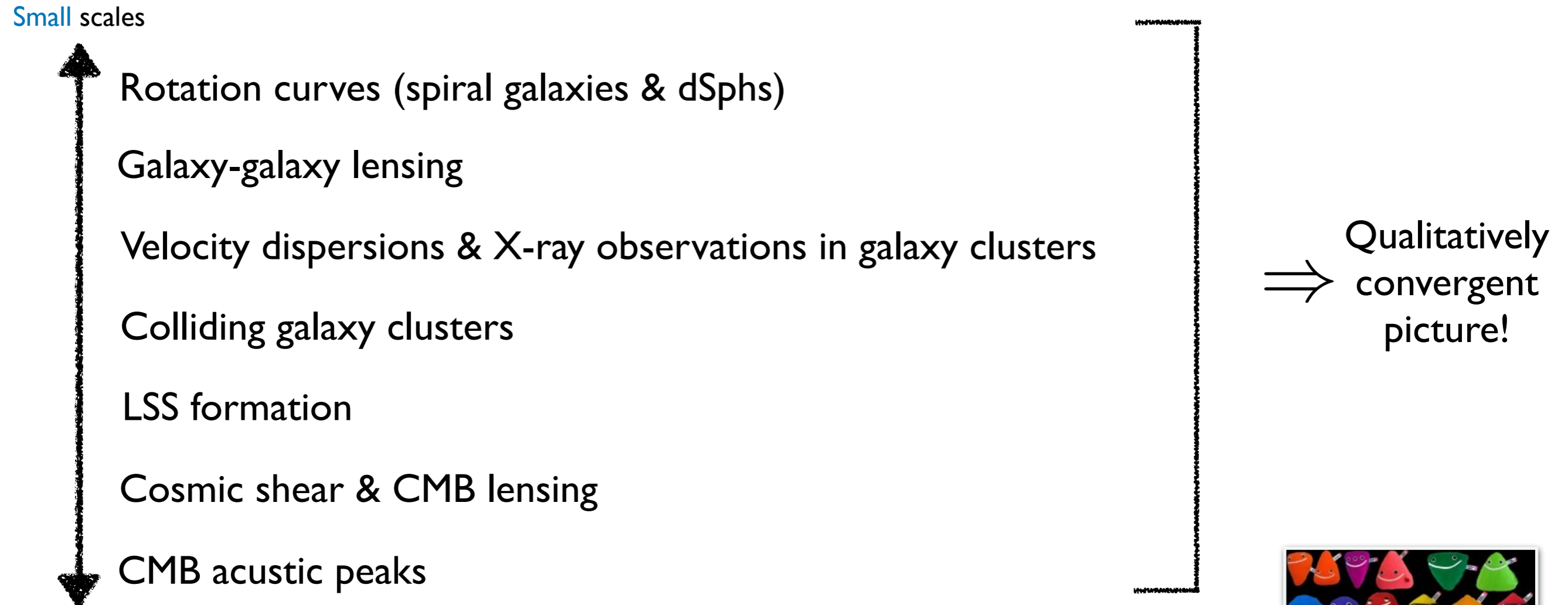


**The Bullet Cluster**  
**(and 72 similar systems →  $7\sigma$  evidence)**

Harvey+ '15

# PARTICLE DARK MATTER

There is plenty of evidence on **astrophysical** and **cosmological** length scales that **DM exists...**



Large scales

... but no direct evidence that it is a particle DM

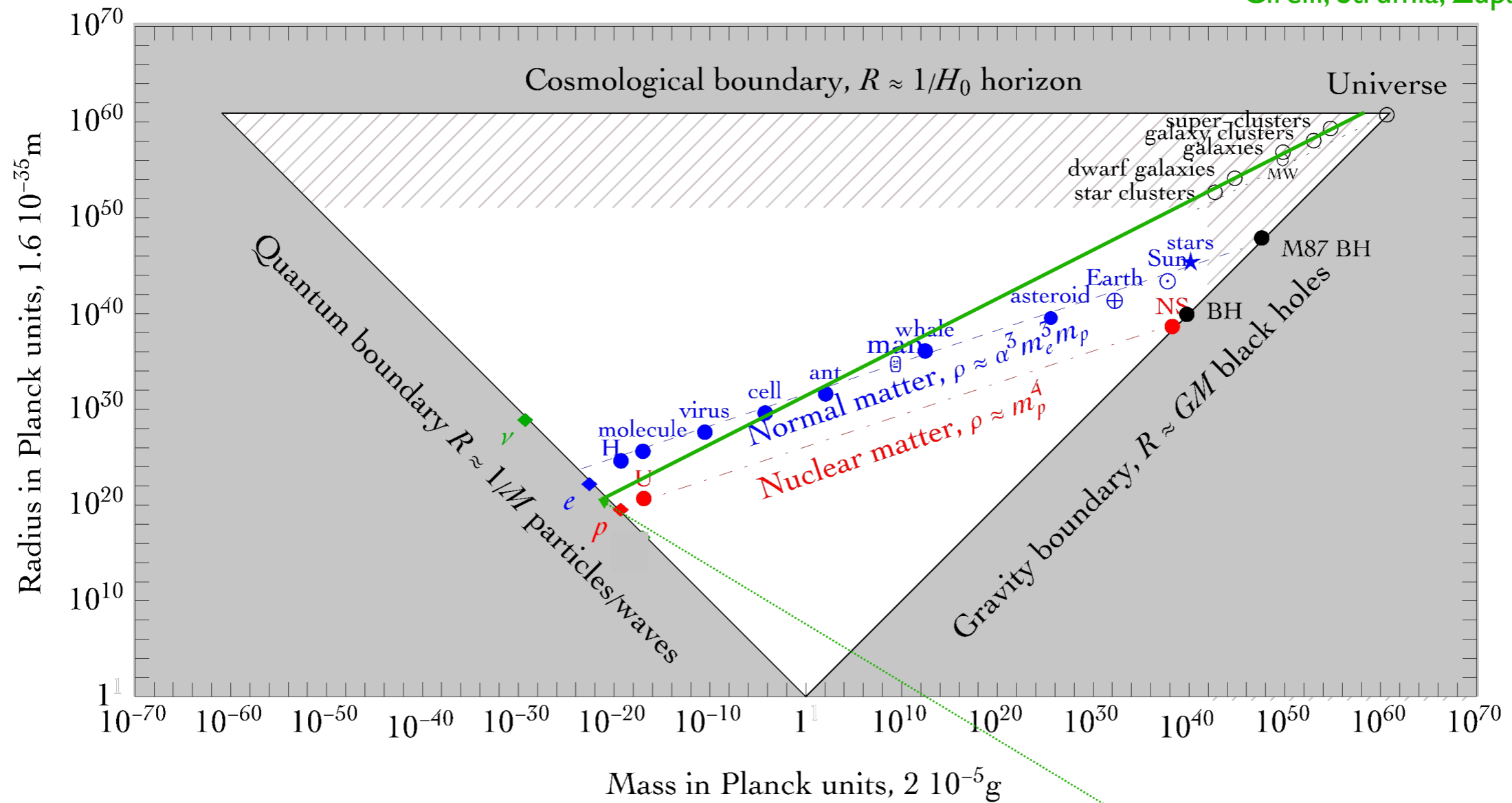


**I:**

**PARTICLE PHYSICS PERSPECTIVE**

# IF WE KNEW NOTHING ABOUT PARTICLE PHYSICS & COSMOLOGY?

Cirelli, Strumia, Zupan 2406.01705



Normal matter:  $\rho \propto M/R^3 \propto m_p / (\alpha m_e)^{-3} \propto m_p m_e^3$

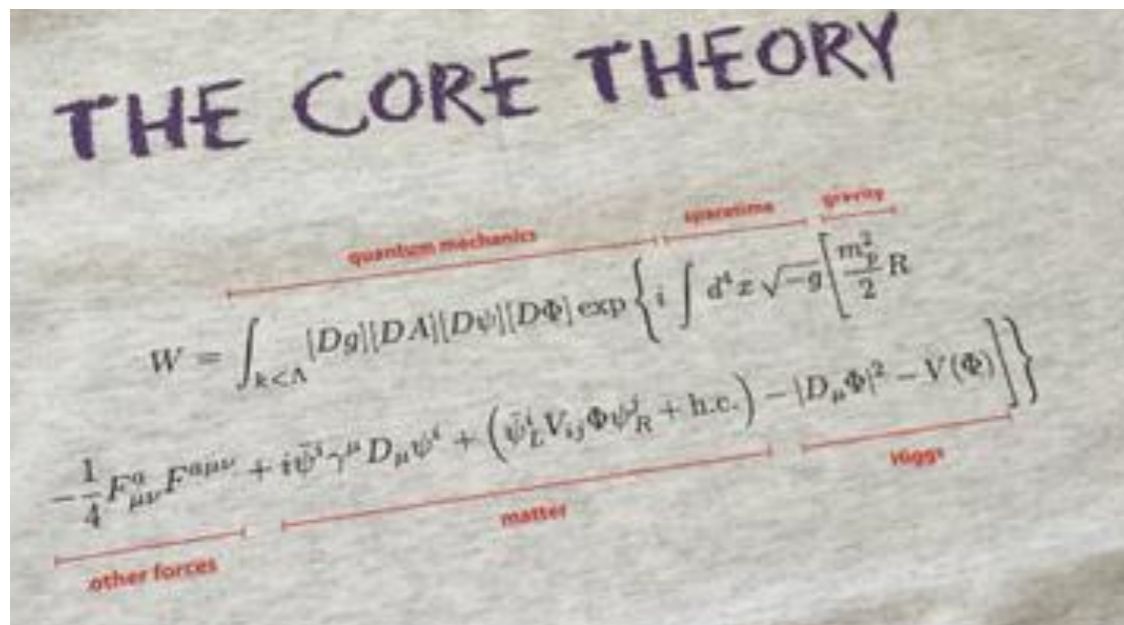
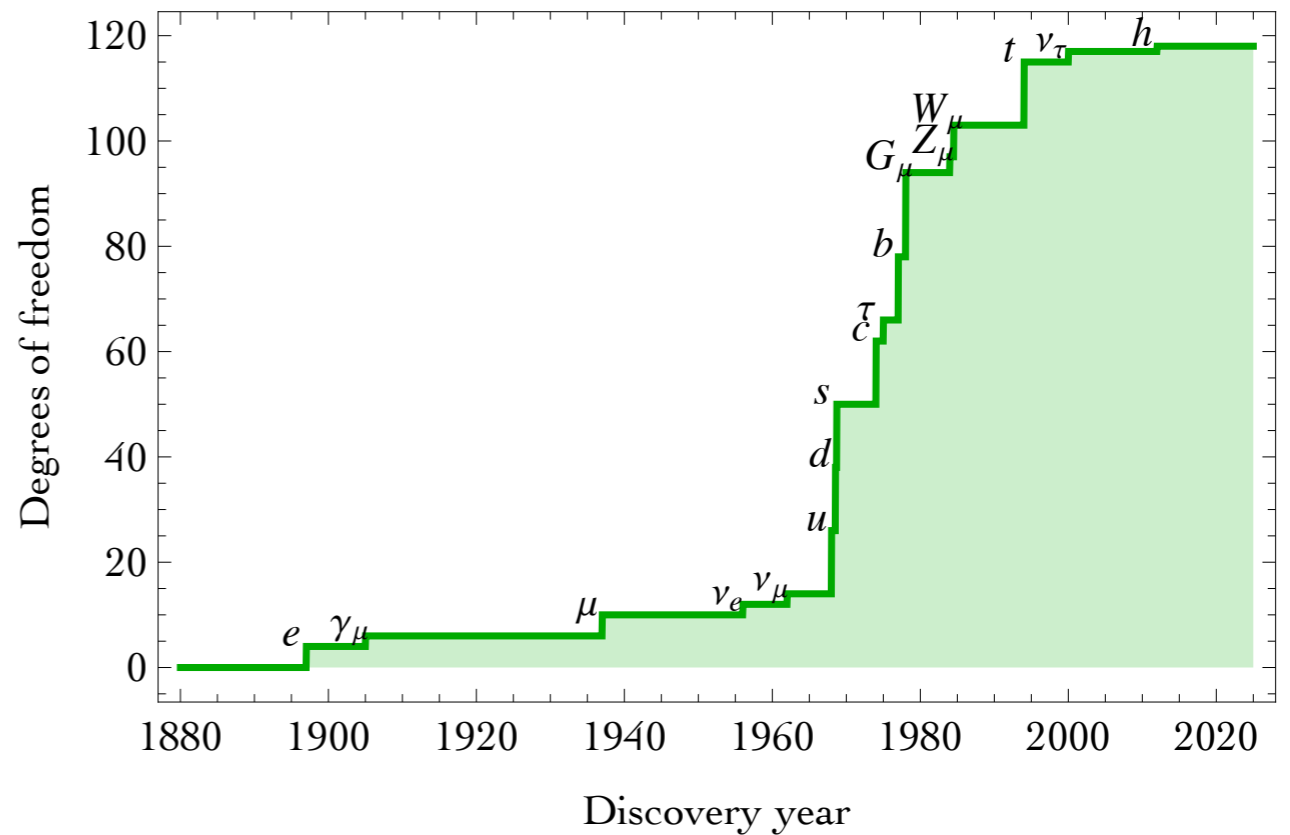
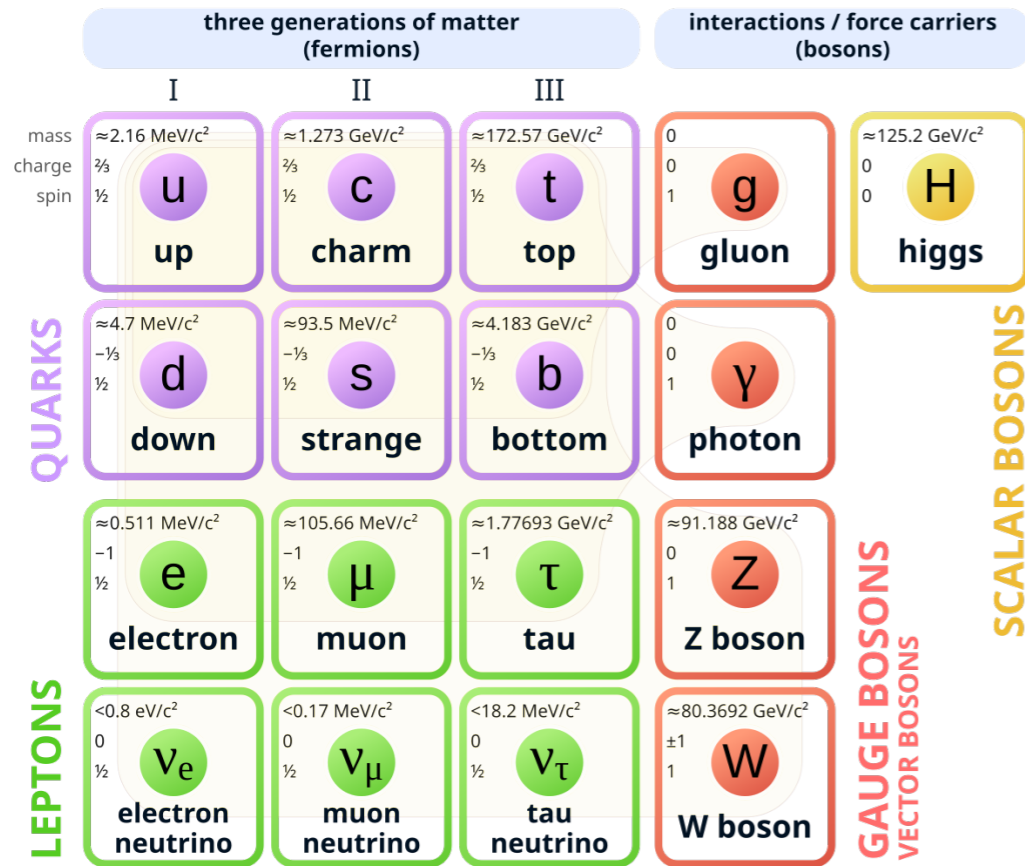
Nuclear matter:  $\rho \propto M/R^3 \propto m_p / (\alpha_s m_p)^{-3} \propto m_p^4$

Dark matter: 1 – 100 MeV ??

Both cases: expectation of a particle with mass  $\propto \rho^{1/4}$

# THE STANDARD MODEL

## Standard Model of Elementary Particles



Many more particles than needed!!!

Who ordered *all* of that?  
I. Rabi '36

# „NEW PHYSICS“

Some of the open problems of the **Standard Model**:

- Neutrino masses & oscillation anomalies
- Hierarchy problems: Higgs mass, strong CP & cosmological constant
- Unification & parameter hierarchies
- Proton decay & neutron lifetime puzzle
- $g_\mu - 2$
- ...
- Baryogenesis (matter-antimatter asymmetry)
- Dark matter
- Dark energy
- Inflation
- ...
- Quantization of gravity (or „gravitising“ QM)

# PARTICLE DARK MATTER (HIGH ENERGY PHYSICS PERSPECTIVE)

We know that the **Standard Model** (of particle physics) is **not complete**

[its extension could *in principle* be rather **minimal**... but it is far more likely that there are (many?) **new particles** we do not know yet]

it is quite possible that some of them are **a dark matter**,  
**as long as they are stable**

if so, it is natural to expect that they actually constitute **the dark matter**



particle DM is **not an anomaly**  
it is a **(generic) prediction**  
(at least on a qualitative level)

# II: STABILITY

# STABILITY or „Who wants to live forever?”

## Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$	$\approx 91.188 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
<b>LEPTONS</b>	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.3692 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

Energy-momentum  
+ EM charge +  
baryon number

Energy-momentum  
+ EM charge

Energy-momentum  
+ angular mom.

Energy-momentum  
(„Forever is our today”)

GAUGE BOSONS  
VECTOR BOSONS

SCALAR BOSONS

17(+1) (apparently)  
elementary particles



6(+1) stable

**All due to combination  
of conservation laws!**

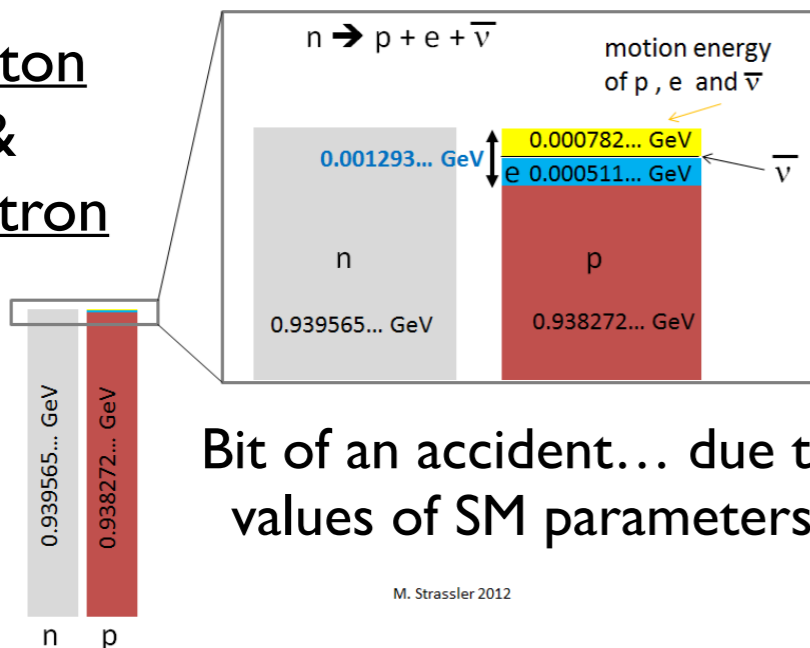
Space-time + gauge symmetry  $\Rightarrow$  stable

Space-time + global symmetry  $\Rightarrow$  meta-stable

(\*gravity tends to  
break global ones...)

„Who waits  
forever anyway?”

## Proton & Neutron



Bit of an accident... due to  
values of SM parameters

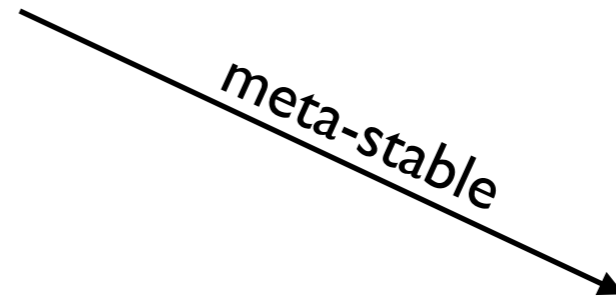
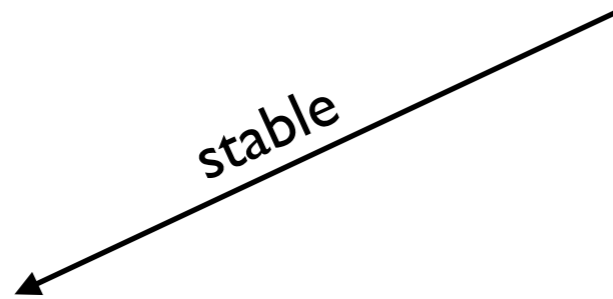
M. Strassler 2012

Nuclei:  
~3000 known  
out of which <300 stable  
(146 stable theoretically)

## Atoms:

Stability of constituents  
+ binding energy

# DARK MATTER STABILITY?



Typically by some  
**additional symmetry:**

1. **Ad hoc:** e.g.  $\mathbb{Z}_2$ ,  $\mathbb{Z}_3$ , etc.  
or global  $U(1)$
2. **Theoretically motivated**, e.g.  
 $R$ -parity in supersymmetry,  
or  $U(1)_{B-L}$
3. **Accidentally**, e.g.  
„dark baryon number”  
or fermionic 5-plet of  $SU(2)_L$

Not enough to have  
„weak” couplings or  
„small” mass differences,  
e.g. neutron lifetime is  
only  $\sim 15$  min, even though  
 $\Delta m/m_n \sim 10^{-3}$ , while for  
Higgs mixing couplings  
 $\lesssim 10^{-10}$  are needed...

but possible, e.g. sterile  
neutrinos, gravitinos... or  
PBHs

It is not hard to write a theory with stable or meta-stable states...  
but **hard to do it in a natural way** (but then also visible matter is arguably not stable naturally...)

**III:**  
**MODEL BUILDING**

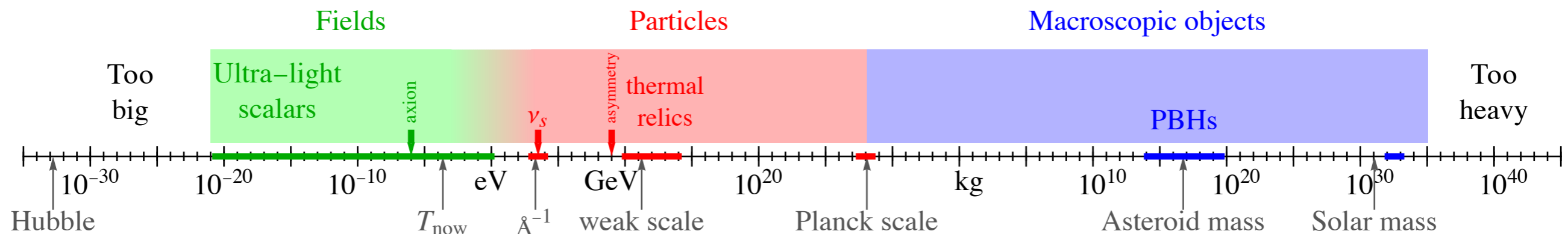
# DARK MATTER LANDSCAPE

Only one measured number — abundance:  $\Omega = 0.264 \pm 0.003$

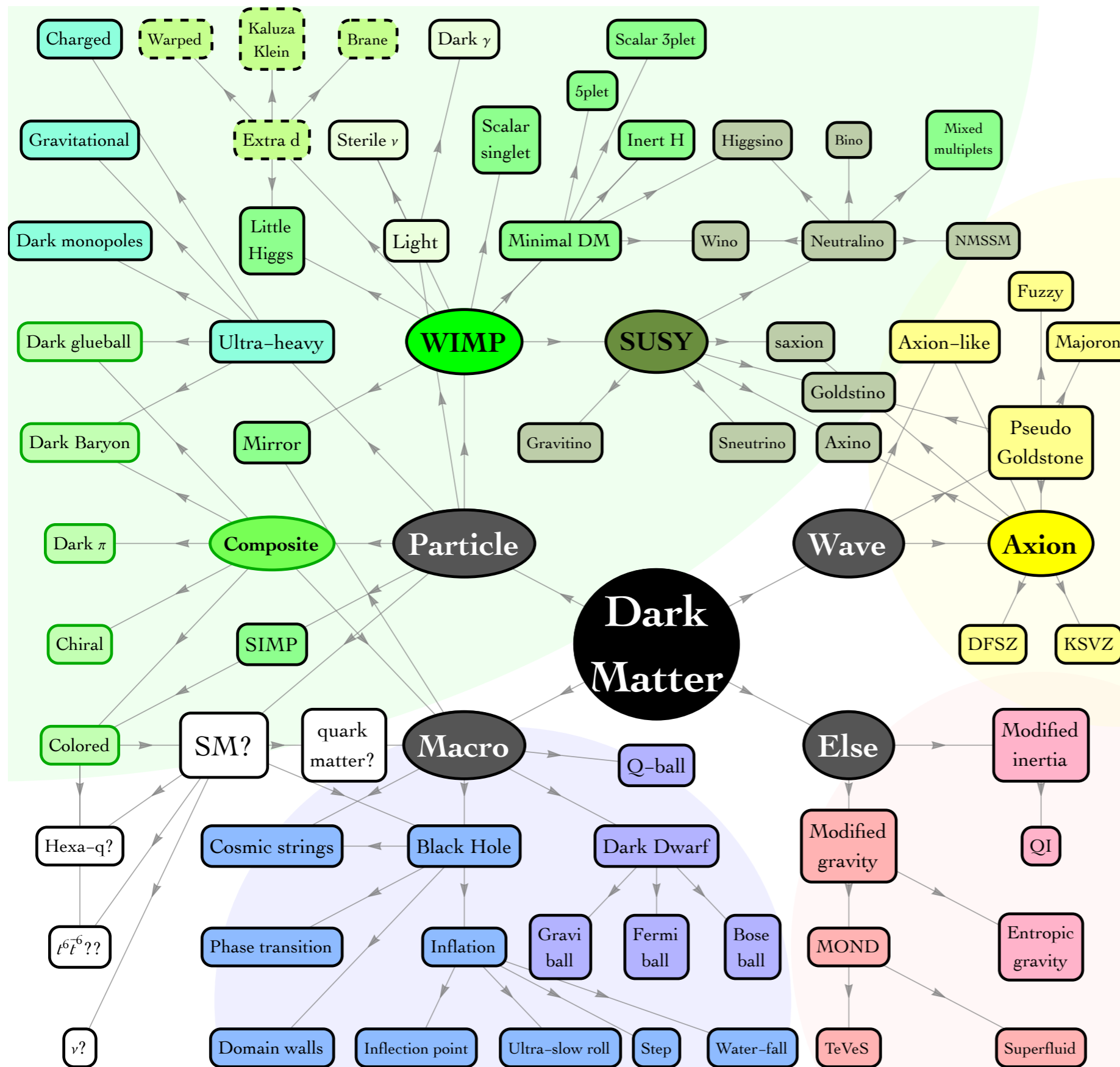
Observational requirements:

- **Dark**: not seen & dissipation-less
- **Matter**: source of grav. potential & behaves as matter in cosmological evolution
- **Cold**: non-relativistic at matter-radiation equality
- **Stable** or (at least) meta-stable
- **Adiabatic**: has the same primordial inhomogeneity as other components

The result:



# DARK MATTER LANDSCAPE



## Theoretical „requirements”:

- Embedded in a larger framework
- Motivated by other unsolved issues
- Predictive

## Theoretical wishlist:

- Minimal
- Simple/elegant
- Testable (preferably soon)

# INTERACTIONS WITH THE SM

## Gauge

$U(1)$  - milicharged

$SU(2)_L$  - minimal DM/SUSY

$SU(3)_c$  (!?)

## Portal

Interactions mediated by  
an additional particle;  
plethora of models  
(often simplified models)

## Non-renormalizable

e.g. axions, gravitinos,  
simplest sterile  $\nu$

## None (i.e. only gravitational)

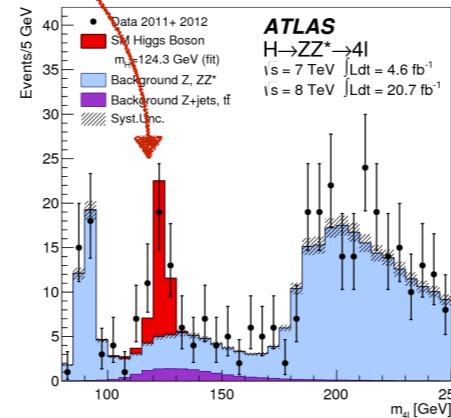
Nightmare  
(though possible)  
scenario

# NEW PHYSICS

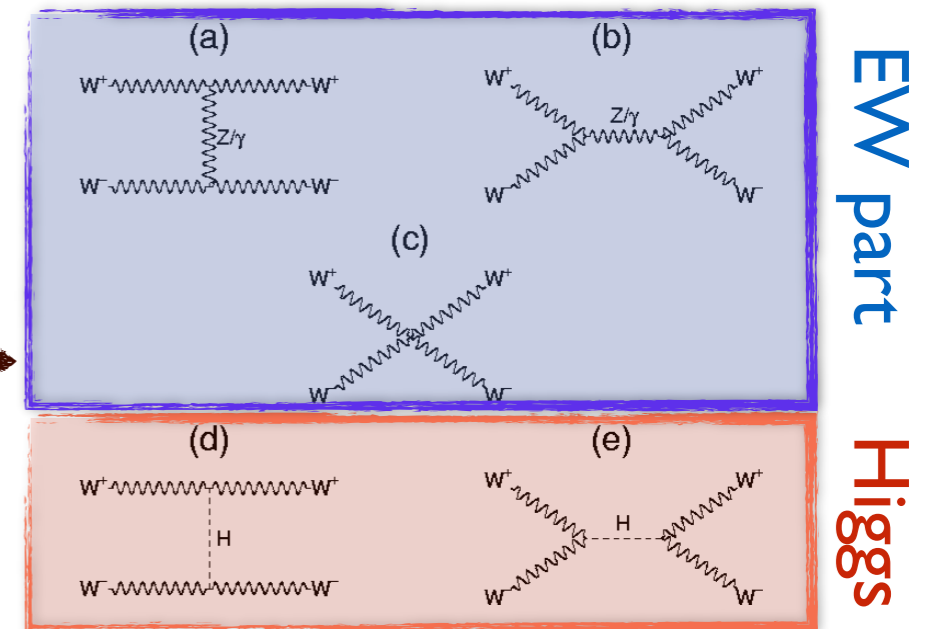
(IS ALWAYS) AROUND THE CORNER

July 2012 - the **Higgs boson**

since then:



but then we knew sth is there: *vide* so-called unitarization of the **WW** scattering cross section



Now, after the **Higgs** was found - **The Hierarchy Problem**

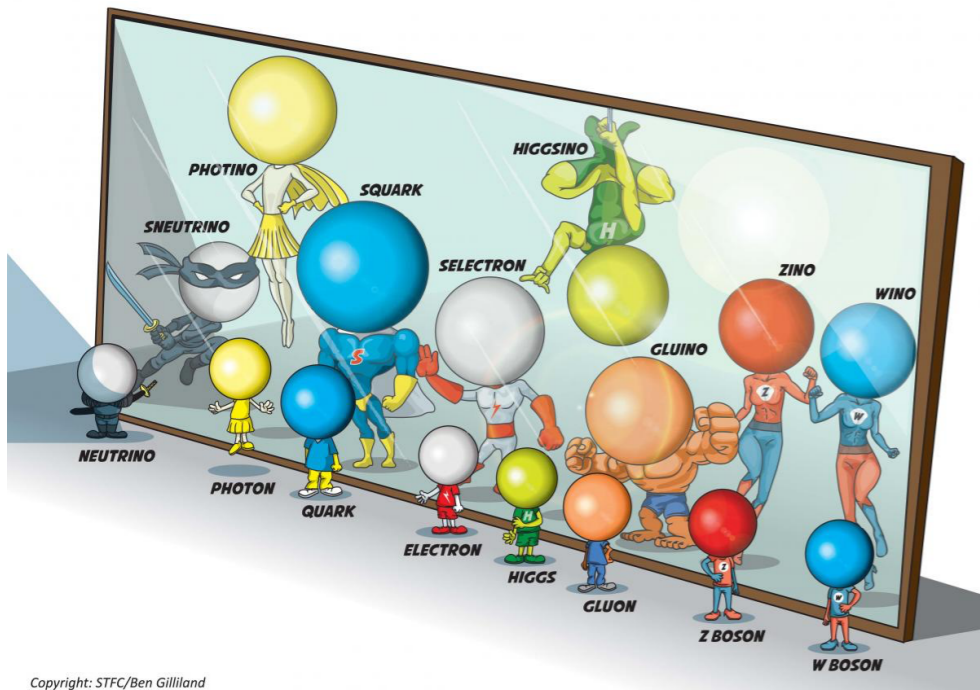
$$\Delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2} [4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2] + \mathcal{O}\left(\log \frac{\Lambda}{v}\right)$$

or in other words: why is the **Higgs boson** so light?

# SUPERSYMMETRY

(STILL) BEST MOTIVATED FRAMEWORK BEYOND SM

What people think about SUSY :



What SUSY really is:

$$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0,$$

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2(\sigma^\mu)_{\alpha\dot{\beta}} P_\mu,$$

$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0,$$

$$[Q_\alpha, M_{\mu\nu}] = -\frac{1}{2}(\sigma_{\mu\nu})_\alpha^\beta Q_\beta,$$

$$[\bar{Q}_{\dot{\alpha}}, M_{\mu\nu}] = -\frac{1}{2}(\bar{\sigma}_{\mu\nu})_{\dot{\alpha}}^{\dot{\beta}} \bar{Q}_{\dot{\beta}}.$$

$$\mathcal{L}_{SUSY} = \int d^2\theta W(\{\Phi_i\}) + \frac{1}{16g^2} \int d^2\theta \text{Tr}(W_\alpha W^\alpha) + \int d^2\theta d^2\bar{\theta} \bar{\Phi} e^{2gV} \Phi + \text{h.c.}$$

## SUSY features:

- great simplification of the theory
- Coleman-Mandula theorem
- elegant solution to Hierarchy Problem
- needed by String Theory
- coupling unification
- DM candidate for free

## SUSY bugs:

- hasn't been found yet...

(however this bug might turn out to be a feature...)

# INTERACTIONS WITH THE SM

## Gauge

$U(1)$  - milicharged

$SU(2)_L$  - minimal DM/SUSY

$SU(3)_c$  (!?)

## Portal

Interactions mediated by  
an additional particle;  
plethora of models  
(often simplified models)

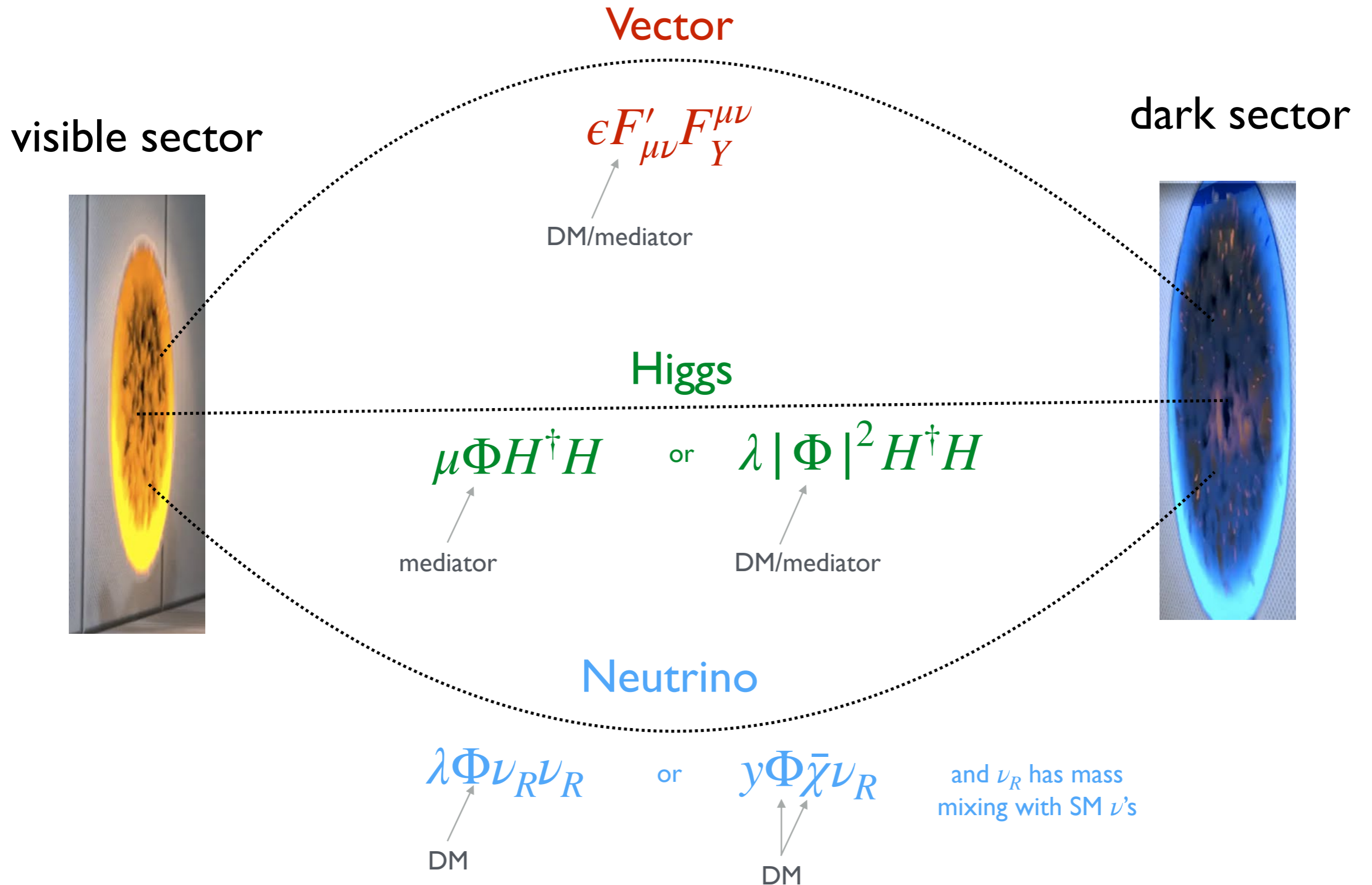
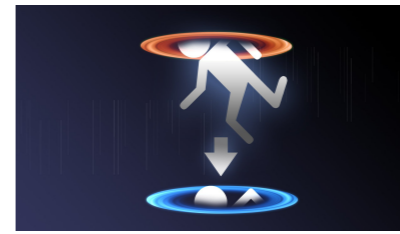
## Non-renormalizable

e.g. axions, gravitinos,  
simplest sterile  $\nu$

**None**  
(i.e. only gravitational)

Nightmare  
(though possible)  
scenario

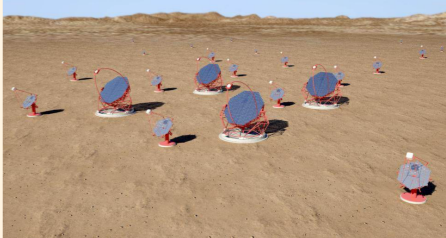
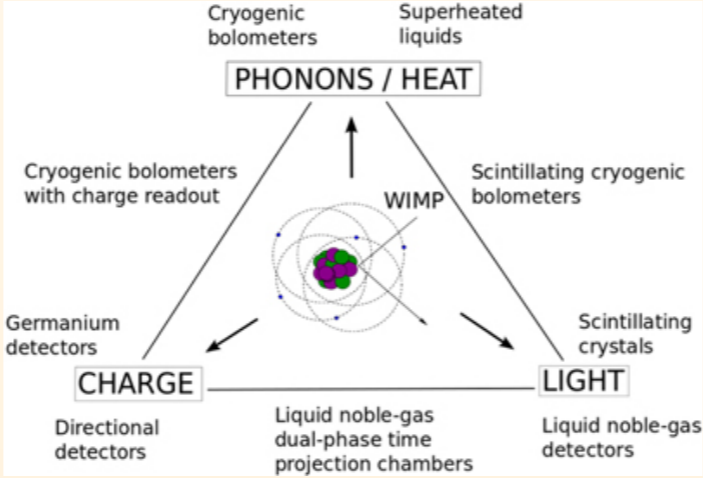
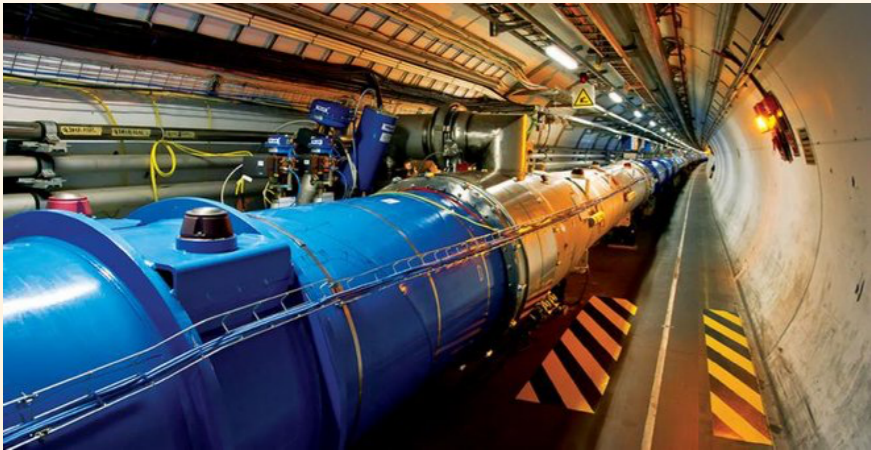
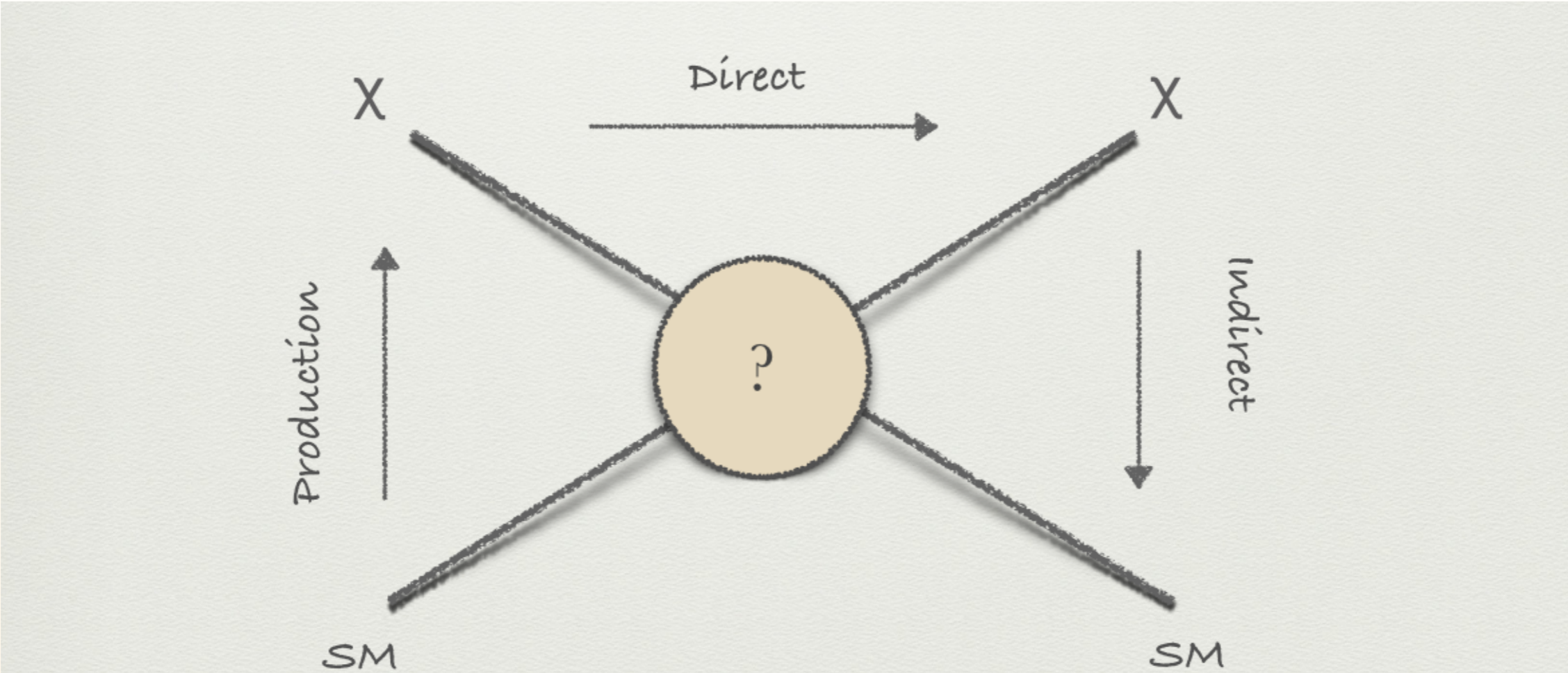
# PORTALS



\*portal mediator can also be non-renormalizable or composite (for more complex dark sector)

# IV: DETECTION

# WIMP DETECTION



# CURRENT LIMITS AND DECLINE OF THE WIMP PARADIGM

"The great tragedy of science - the slaying of a beautiful hypothesis by an ugly fact"

Aldous Huxley

On both Direct Detection and LHC front no\* signal of DM particle...

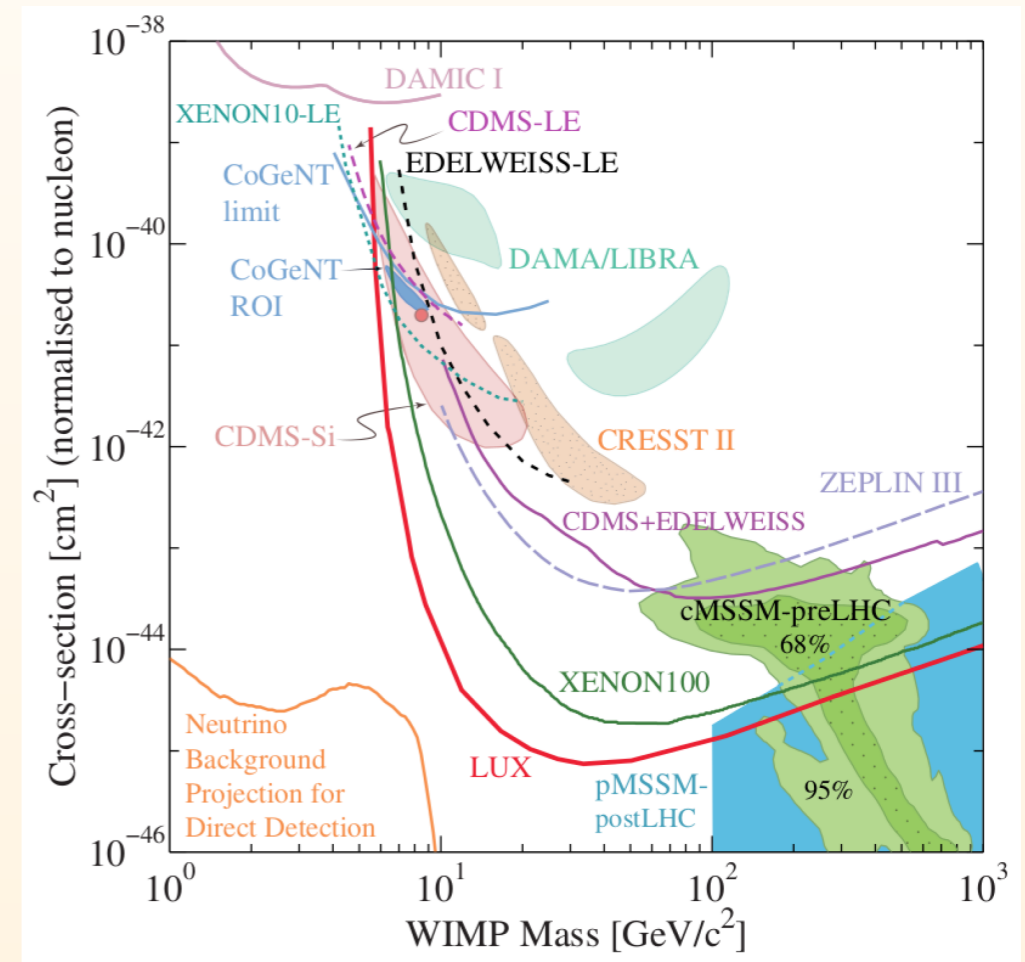
\*convincing

**ATLAS SUSY Searches\* - 95% CL Lower Limits**  
July 2024

**ATLAS Preliminary**  
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference						
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$ mono-jet	$E_T^{\text{miss}}$ 140 $E_T^{\text{miss}}$ 140	$\tilde{g}$ [1x, 8x Degen] $\tilde{q}$ [8x Degen]	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874				
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$	$E_T^{\text{miss}}$ 140	$\tilde{g}$	Forbidden 1.15-1.95	2.3	2010.14293 2010.14293			
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	$E_T^{\text{miss}}$ 140	$\tilde{g}$	2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2101.01629		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(l\bar{l})\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{\text{miss}}$ 140	$\tilde{g}$	2.2	$m(\tilde{\chi}_1^0) < 700 \text{ GeV}$	2204.13072		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 $e, \mu$	7-11 jets	$E_T^{\text{miss}}$ 140	$\tilde{g}$	1.97	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	2008.06032		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	SS $e, \mu$	6 jets	$E_T^{\text{miss}}$ 140	$\tilde{g}$	1.15	$m(\tilde{g})-m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	2307.01094		
3 <sup>rd</sup> gen. squarks direct production	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$ 6 jets	$E_T^{\text{miss}}$ 140 $E_T^{\text{miss}}$ 140	$\tilde{g}$	1.25	2.45	$m(\tilde{\chi}_1^0) < 500 \text{ GeV}$ $m(\tilde{g})-m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	2211.08028 1909.08457	
	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 $b$	$E_T^{\text{miss}}$ 140	$\tilde{b}_1$	1.255		$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 \text{ GeV}$	2101.12527 2101.12527	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0 $e, \mu$	6 $b$	$E_T^{\text{miss}}$ 140	$\tilde{b}_1$	Forbidden	0.68		$\Delta m(\tilde{\chi}_1^0, \tilde{b}_1) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_1^0, \tilde{b}_1) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1908.03122 2103.08189
	$2\tau$	2 $b$	$E_T^{\text{miss}}$ 140	$\tilde{b}_1$	Forbidden	0.13-0.85	0.23-1.35			
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	1.25			$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 $e, \mu$	3 jets/1 $b$	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	Forbidden	1.05		$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$ $m(\tilde{t}_1) = 800 \text{ GeV}$	2012.03799, 2401.13430
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\tilde{\chi}_1^0$	1-2 $\tau$	2 jets/1 $b$	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	Forbidden	1.4			
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\tilde{\chi}_1^0, \tilde{t}_1 \rightarrow \tau\tilde{G}$	0 $e, \mu$	2 $c$ mono-jet	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	0.85			$m(\tilde{t}_1, \tau)-m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow Zlh\tilde{\chi}_1^0$	1-2 $e, \mu$	1-4 $b$	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	0.067-1.18			$m(\tilde{t}_1) = 500 \text{ GeV}$	2006.05880 2006.05880
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow Zh\tilde{\chi}_1^0$	3 $e, \mu$	1 $b$	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	Forbidden	0.86		$m(\tilde{t}_1) = 360 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	2006.05880
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via WZ	Multiple $l\bar{l}$ jets $ee, \mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ 140 $E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.205	0.96		$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$ $m(\tilde{\chi}_1^0) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}, \text{wino-bino}$	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via WW	2 $e, \mu$		$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.42			$m(\tilde{\chi}_1^0) = 0, \text{wino-bino}$	1908.08215
Long-lived particles	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via Wh	Multiple $l\bar{l}$ jets	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	Forbidden	1.06		$m(\tilde{\chi}_1^0) = 70 \text{ GeV}, \text{wino-bino}$	2004.10894, 2108.07586	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $l\bar{l}\tilde{\chi}_1^0$	2 $e, \mu$		$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	1.0		$m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $l\bar{l}\tilde{\chi}_1^0$	2 $\tau$		$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.35	0.5		$m(\tilde{\chi}_1^0) = 0$	2402.00603
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu$	0 jets	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	0.26	0.7		$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1908.08215 1911.12606
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	$ee, \mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	0.55	0.94		$BR(\tilde{t}_1 \rightarrow h\tilde{\chi}_1^0) = 1$ $BR(\tilde{t}_1 \rightarrow Z\tilde{\chi}_1^0) = 1$	2401.14922 2103.11684
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$	$\geq 3 b$ 0 jets	$E_T^{\text{miss}}$ 140 $E_T^{\text{miss}}$ 140	$\tilde{H}$	0.45-0.93			$BR(\tilde{H} \rightarrow Z\tilde{\chi}_1^0) = 1$	2108.07586 2204.13072
RPV	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.21	0.66		Pure Wino Pure higgsino	2201.02472 2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\text{miss}}$ 140	$\tilde{g}$	2.05			Large $\tau$	2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{\text{miss}}$ 140	$\tilde{g}$	0.74			$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\tau(\tilde{g}) = 10 \text{ ns}$	2205.06013 2205.06013
	$\tilde{l}\tilde{l}, \tilde{l} \rightarrow l\tilde{G}$	Displ. lep		$E_T^{\text{miss}}$ 140	$\tilde{l}$	0.36	0.36		$\tau(\tilde{l}) = 0.1 \text{ ns}$ $\tau(\tilde{l}) = 10 \text{ ns}$	ATLAS-CONF-2024-011 ATLAS-CONF-2024-011 2205.06013
	$\tilde{l}\tilde{l}, \tilde{l} \rightarrow l\tilde{G}$	pixel dE/dx		$E_T^{\text{miss}}$ 140	$\tilde{l}$	0.36	0.36			
	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $l\bar{l}\tilde{\chi}_1^0$ , $\tilde{\chi}_1^0 \rightarrow Zl \rightarrow lll$	3 $e, \mu$		$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.625	1.05		Pure Wino $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	2011.10543 2103.11684
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $l\bar{l}\tilde{\chi}_1^0$ , $\tilde{\chi}_1^0 \rightarrow WWZlll\nu\nu$	4 $e, \mu$	0 jets	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.95	1.55		Large $\tau$	2401.16333	
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	$\geq 8$ jets		$E_T^{\text{miss}}$ 140	$\tilde{g}$	0.55	1.05		$m(\tilde{\chi}_1^0) = 50 \text{ GeV}, 1250 \text{ GeV}$	ATLAS-CONF-2016-003	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	$\geq 4b$		$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	Forbidden	0.95		$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-ke}$ $m(\tilde{t}_1) = 500 \text{ GeV}$	2010.01015	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	$\geq 4b$		$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	0.42	0.61			1710.07171	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{l}$	2 jets + 2 $b$		$E_T^{\text{miss}}$ 140	$\tilde{t}_1$	1.0	0.4-1.85		$BR(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\tilde{\chi}_1^0) = 100\%, \cos\theta = 1$	2406.18367 2003.11956	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{l}$	1 $\mu$	2 $b$ DV	$E_T^{\text{miss}}$ 136	$\tilde{t}_1$	1.6					
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ via $l\bar{l}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs, \tilde{\chi}_1^0 \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets	$E_T^{\text{miss}}$ 140	$\tilde{\chi}_1^0$	0.2-0.32			Pure higgsino	2106.09609	

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



...BUT this does not mean that much!

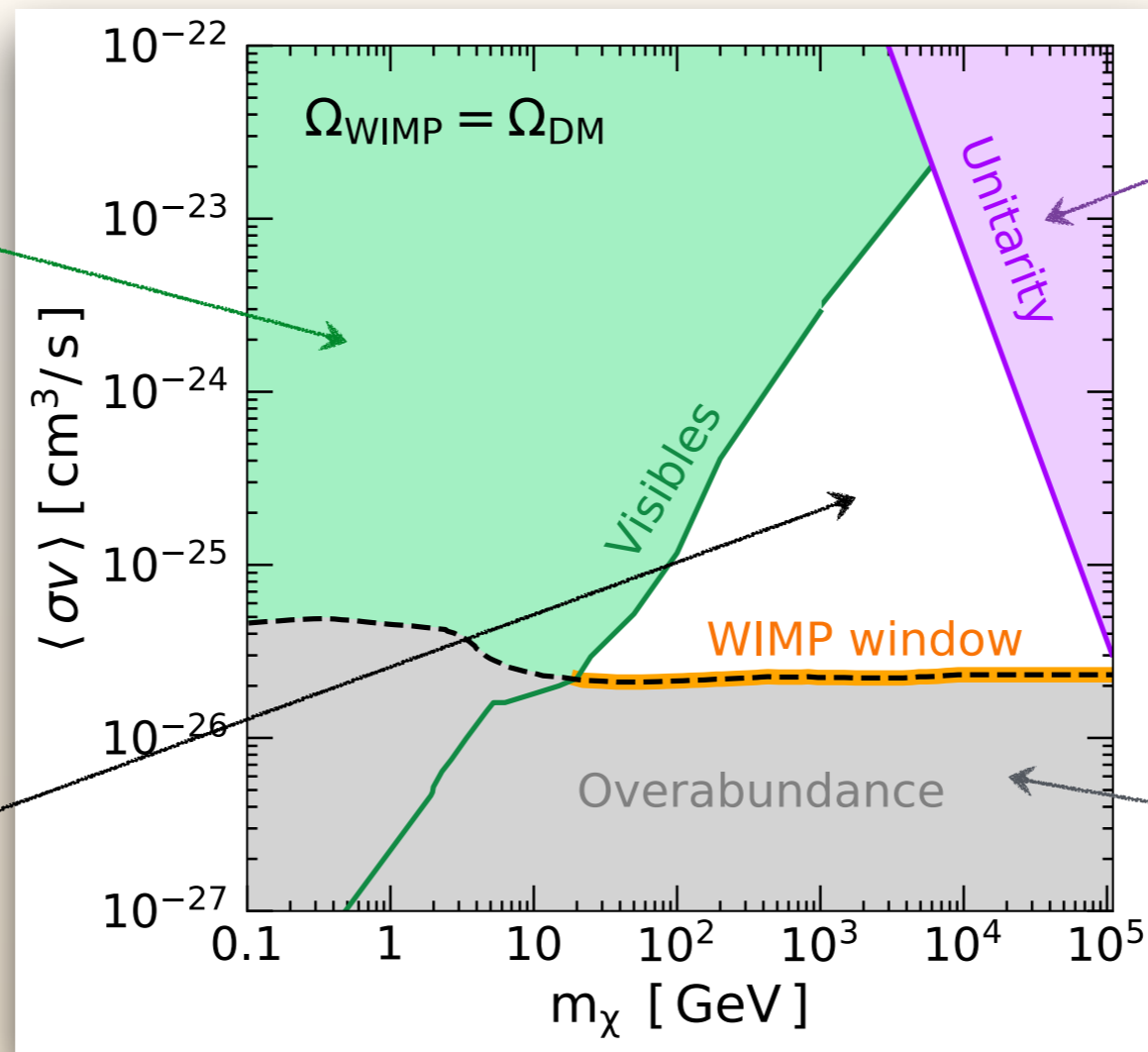
# ... BUT IN FACT WIMP NOT EVEN SLIGHTLY DEAD

Most of the (strongest) limits are based on **assumptions** motivated by theoretical prejudice (or convenience)



this can lead to a very **broad-brush conclusions**

excluded by observations



all fine!

predicted probabilities can be  $> 1$

too much dark matter

R. Leane et al; 1805.10305

# DARK MATTER CRISIS?

Personal take!

BELIEFS OF XX CENT.

„DM is **nearly certainly** WIMPs  
(or perhaps axions or sterile  $\nu$ 's)”

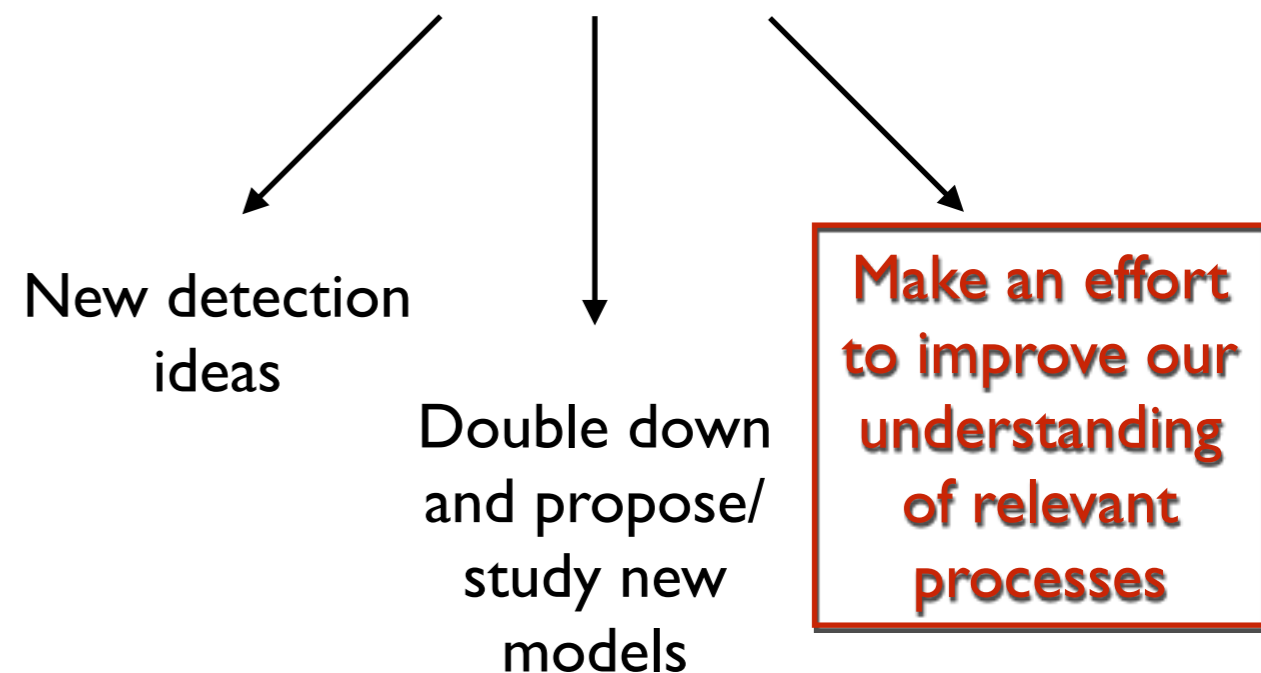
„SUSY is **just around the corner**”

⇒ Studying **BSM models**  
**and their phenomenology** in  
direct & indirect detection  
makes a lot of sense

BELIEFS OF XXI CENT.

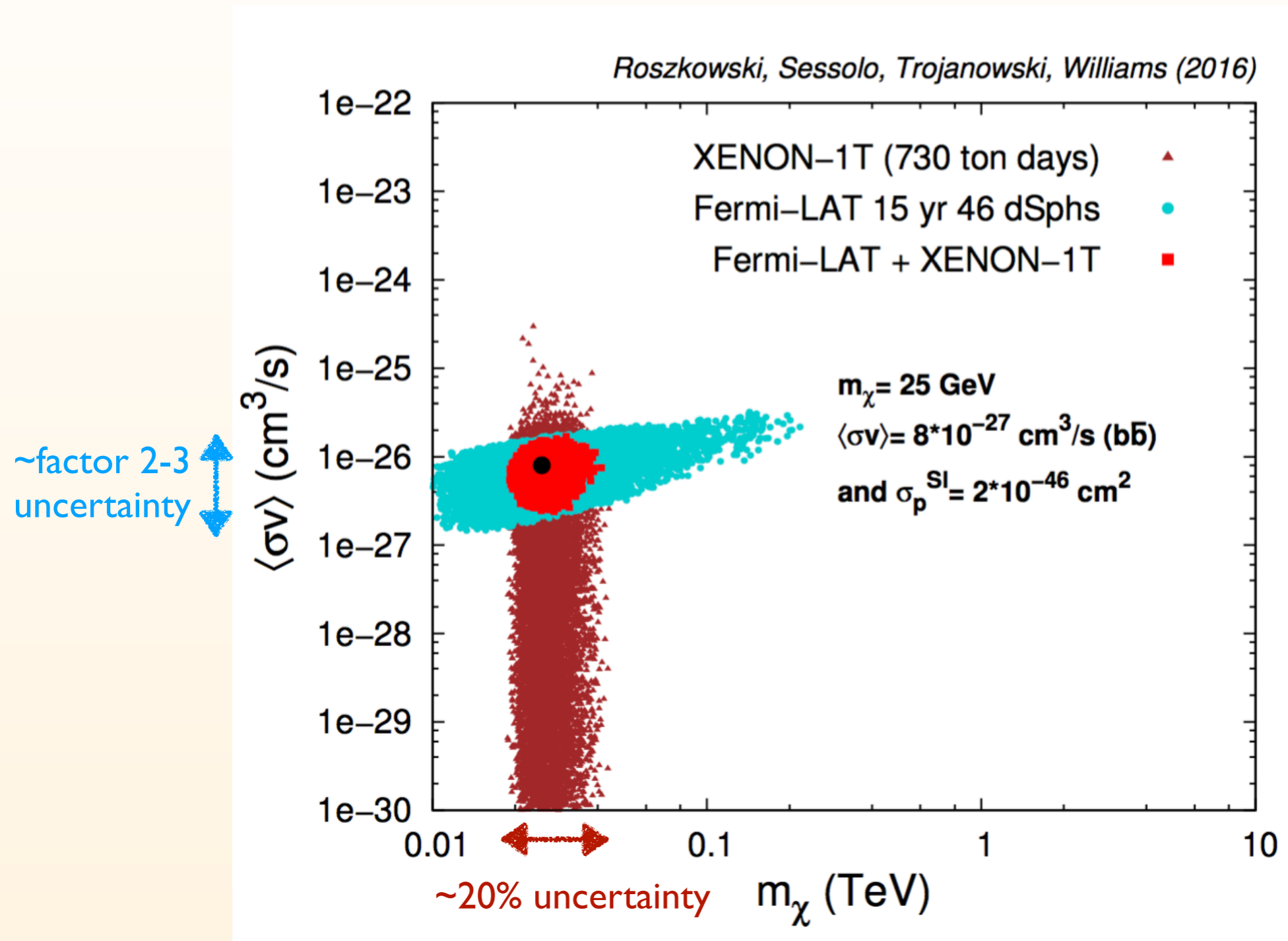
Realisation that we actually  
have no idea what DM is  
**starts to sink in**

Options:



# INFERENCE OF DM PROPERTIES?

Imagine a **clean signal** in both direct and indirect detection:

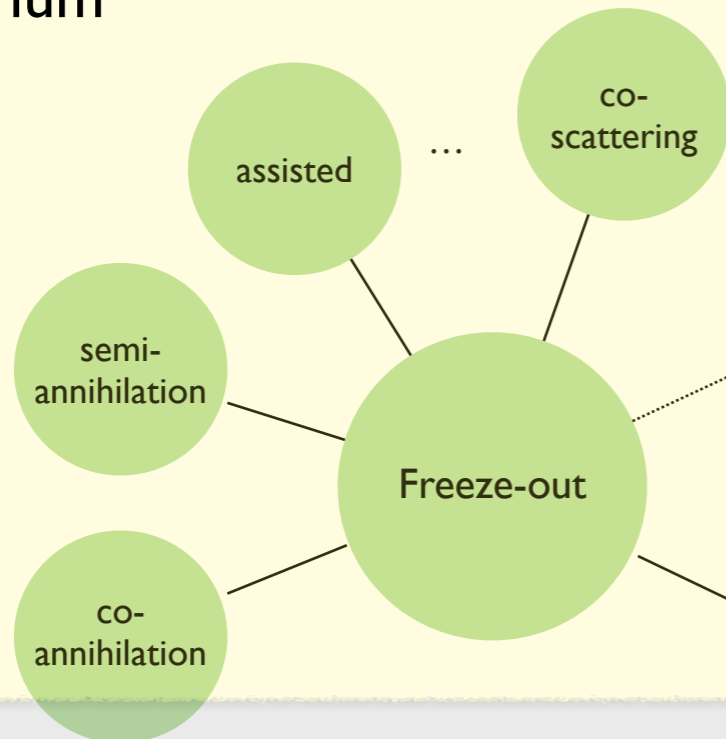


... not to mention that even this still does not say what the **true BSM physics** should be!

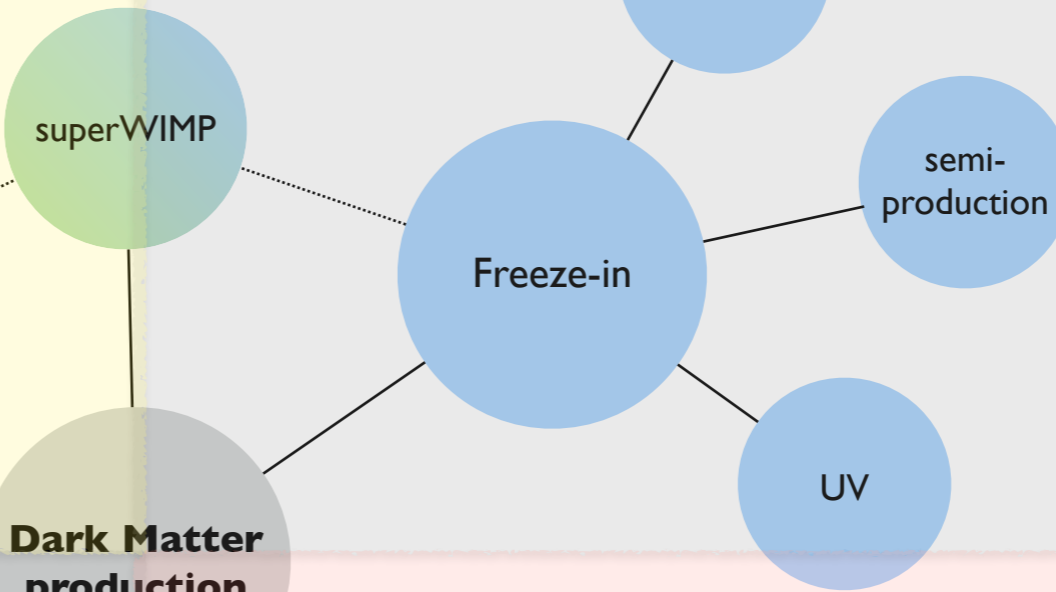
**V:**  
**PRODUCTION**

# DARK MATTER ORIGINS

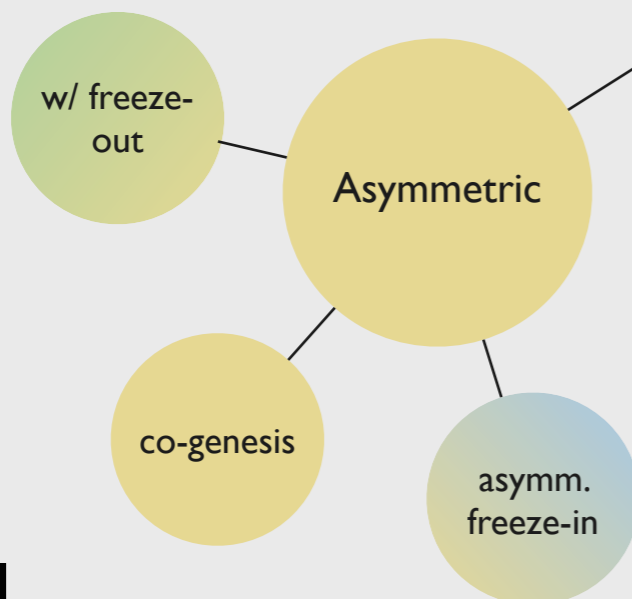
**Thermal**  
In equilibrium



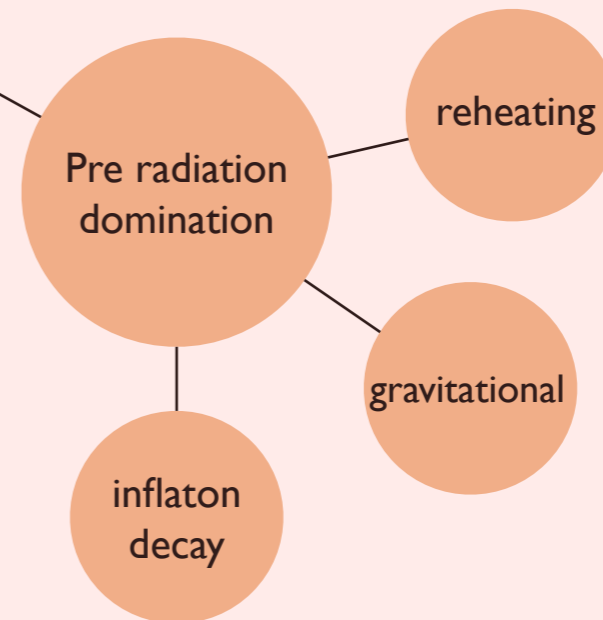
**Thermal**  
Out of equilibrium



**Dark Matter production**



Phase transitions, Misalignment, ...



**Thermal**  
Out of equilibrium

**Non-Thermal**

# MOTIVATION

## THERMAL PRODUCTION

### Theory:

#### I. Natural

Comes out **automatically** from the expansion of the Universe

Naturally leads to **cold DM**

#### II. Predictive

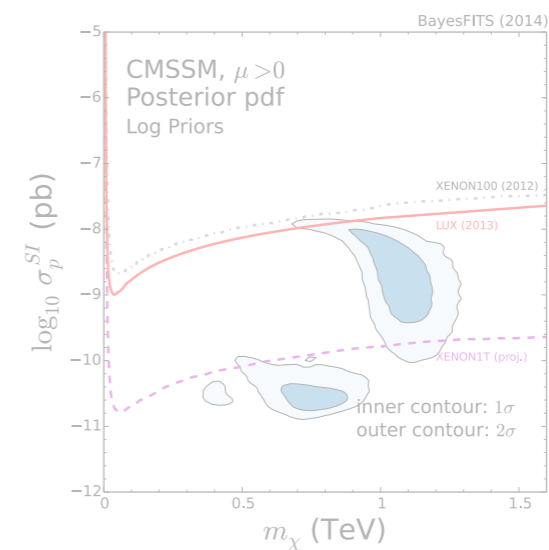
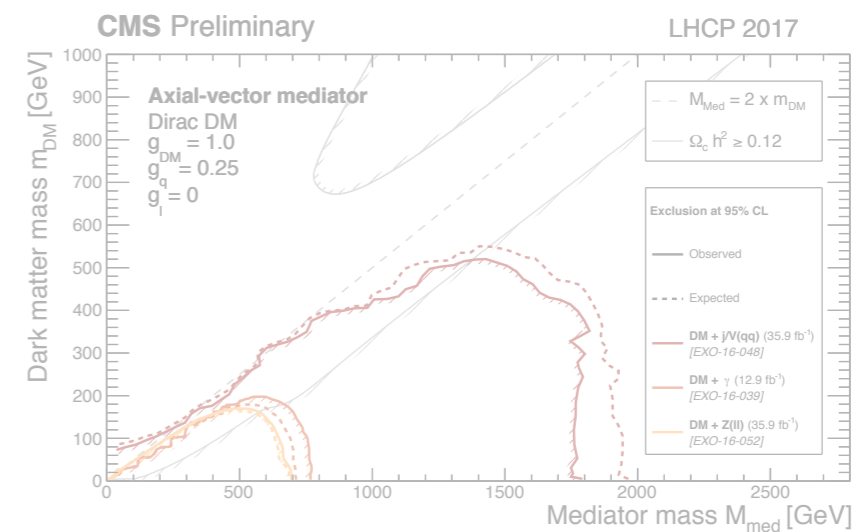
No dependence on **initial conditions**

**Fixes coupling(s)**  $\Rightarrow$  signal in DD, ID & LHC

#### III. It is not optional

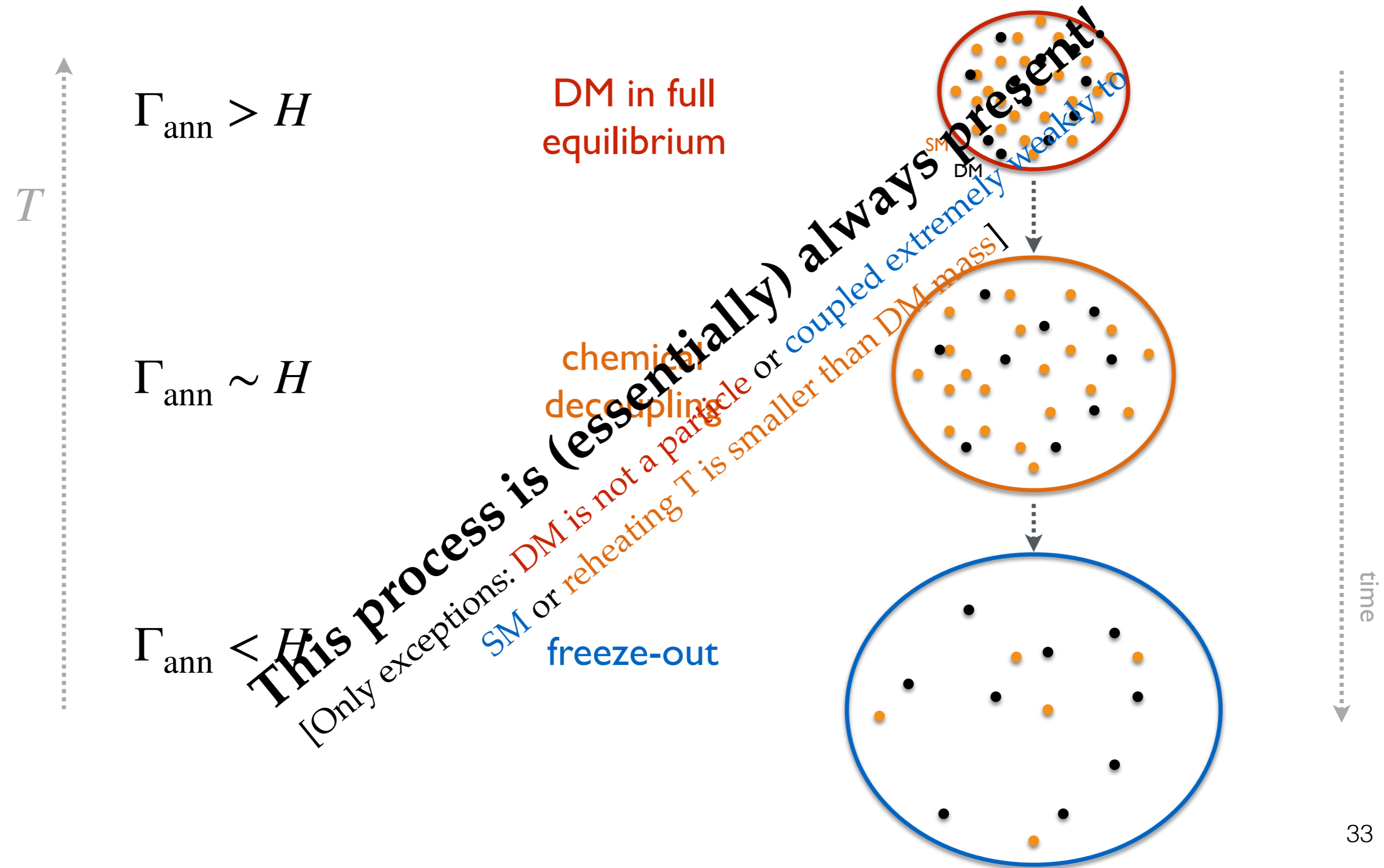
**Overabundance** constraint

To avoid it one needs **quite significant deviations** from standard cosmology



# THERMAL RELIC DENSITY

A.K.A. FREEZE-OUT



Does DM interact (somewhat) with any particle of the SM?

Yes

No (or nearly no)

At high temperature DM thermalises, has very high abundance

Is initial population (e.g. from reheating) small?

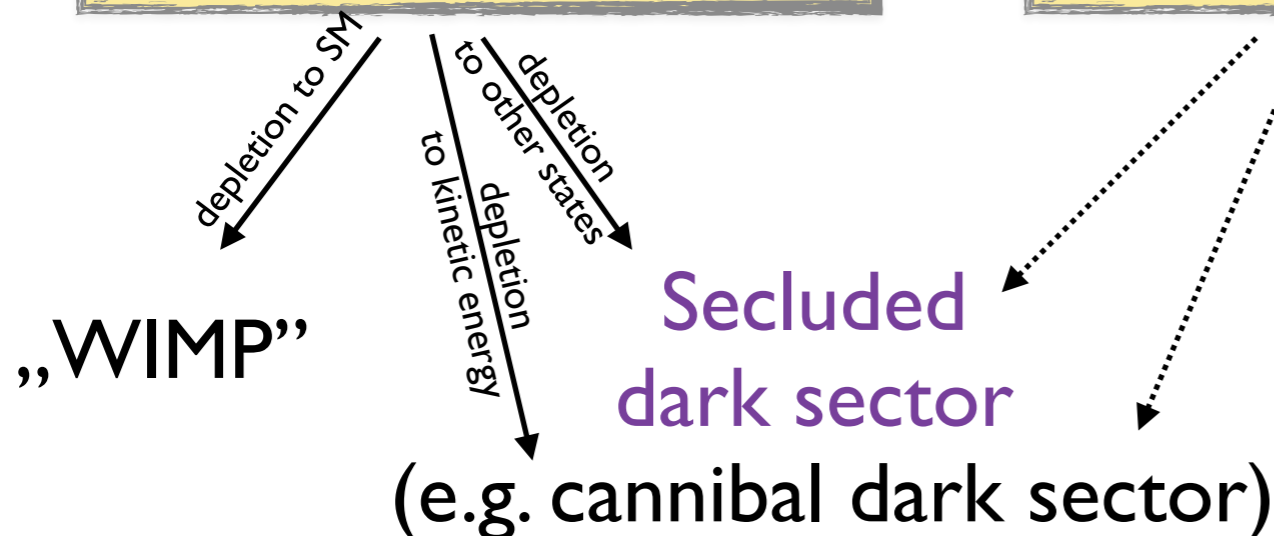
Yes

No

An **efficient depletion** is needed (freeze-out)

A **slow production** is needed (freeze-in)

„Initial condition” dependence



# WHAT IS FREEZE-IN?

Visible Sector

Dark Sector

end of inflation  
reheating

~empty

$$T \gg m_X$$

UV freeze-in

Thermal bath at  
 $T \gtrsim m_X$

production  
 $X$

Dark Sector:  
 $\chi, \dots$

expansion

IR freeze-in

$$T \sim m_X$$

Thermal bath at  
 $T \lesssim m_X$

Dark Sector:  
 $\chi, \dots$

time

Freeze-in defined like this is a (very) old idea:

this is a standard production mechanism for e.g. **sterile neutrino, gravitino, axino, ...**

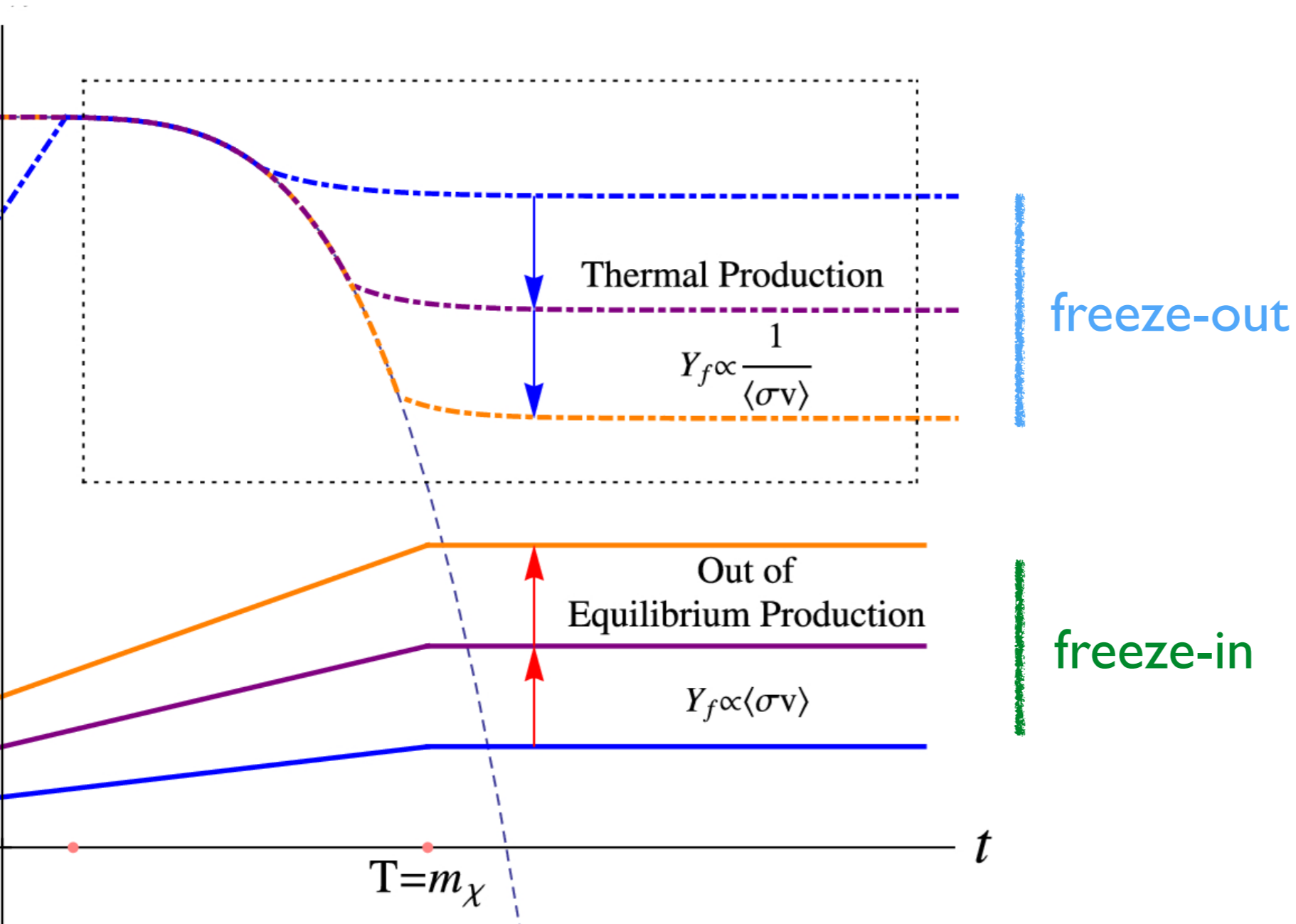
however, old works focused on what now people call **UV freeze-in**

i.e. dominated by **non-renormalizable operators** and dependent on  $T_{RH}$

**Freeze-in** = the above mechanism through renormalizable operators (**IR freeze-in**)

# FREEZE-IN vs. FREEZE-OUT

Freeze-in is in a sense the 'opposite' of freeze-out



# FREEZE-OUT vs. FREEZE-IN

## WIMPs

(Weakly Interacting Massive Particles)

DM starts in equilibrium with the SM bath

The role of the interaction with SM is to suppress DM from its huge initial population

If through annihilation typical value required

$$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/s$$

Relic abundance decreases with  $\langle\sigma v\rangle$

Requires

$$T_{\text{RH}} \gtrsim m_\chi$$

## FIMPs

(Feebly Interacting Massive Particles)

DM never in equilibrium with the SM bath

The role of the interaction with SM is to produce DM

If through annihilation typical value required

$$\langle\sigma v\rangle \lesssim 10^{-40} \text{ cm}^3/s$$

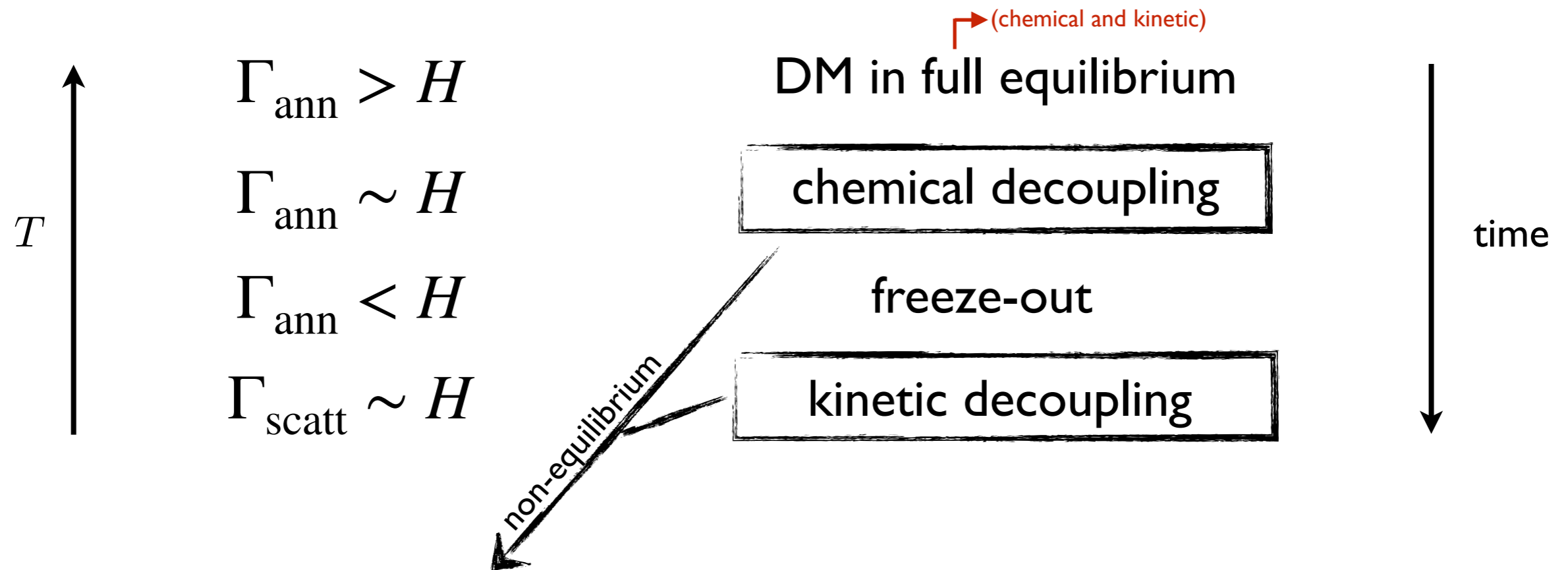
Relic abundance increases with  $\langle\sigma v\rangle$

Requires

~no initial abundance

# THERMAL FREEZE-OUT

## STANDARD SCENARIO



time evolution of  $f_\chi(p)$  in kinetic theory:

$$E (\partial_t - H \vec{p} \cdot \nabla_{\vec{p}}) f_\chi = \mathcal{C}[f_\chi]$$

# THERMAL FREEZE-OUT

## STANDARD APPROACH

Boltzmann equation for  $f_\chi(p)$ :

$$E (\partial_t - H \vec{p} \cdot \nabla_{\vec{p}}) f_\chi = \mathcal{C}[f_\chi]$$



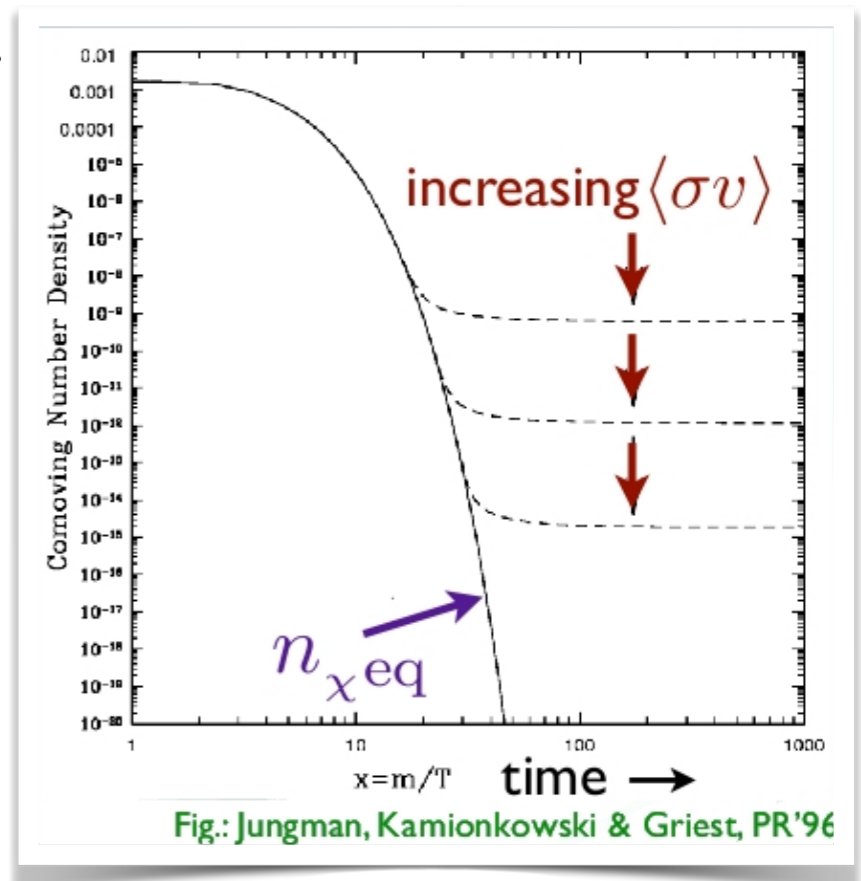
$$\frac{dn_\chi}{dt} + 3Hn_\chi = - \langle \sigma_{\chi\bar{\chi} \rightarrow ij} \sigma_{\text{rel}} \rangle^{\text{eq}} (n_\chi n_{\bar{\chi}} - n_\chi^{\text{eq}} n_{\bar{\chi}}^{\text{eq}})$$



**Critical assumption:**  
kinetic equilibrium at chemical decoupling

$$f_\chi \sim a(T) f_\chi^{\text{eq}}$$

numerical codes e.g.,  
**DarkSUSY, micrOMEGAs,**  
**MadDM, SuperISOrelic, ...**



# FREEZE-IN CALCULATION

Boltzmann equation for  $f_\chi(p)$ :

$$E (\partial_t - H\vec{p} \cdot \nabla_{\vec{p}}) f_\chi = \mathcal{C}[f_\chi]$$

with initial condition:

$$f_\chi(p, t = 0) = 0$$

The collision term:

$$\mathcal{C}[f_\chi] \sim \int d\Pi_{ij\dots\rightarrow ab} (2\pi)^4 \delta^4(\dots) |M|^2 \left[ f_i f_j \dots (1 \pm f_\chi) (1 \pm f_a) (1 \pm f_b) \dots - f_\chi f_a f_b \dots (1 \pm f_i) (1 \pm f_j) \dots \right]$$

„gain” term

(the simple one, describes production)

„loss” term

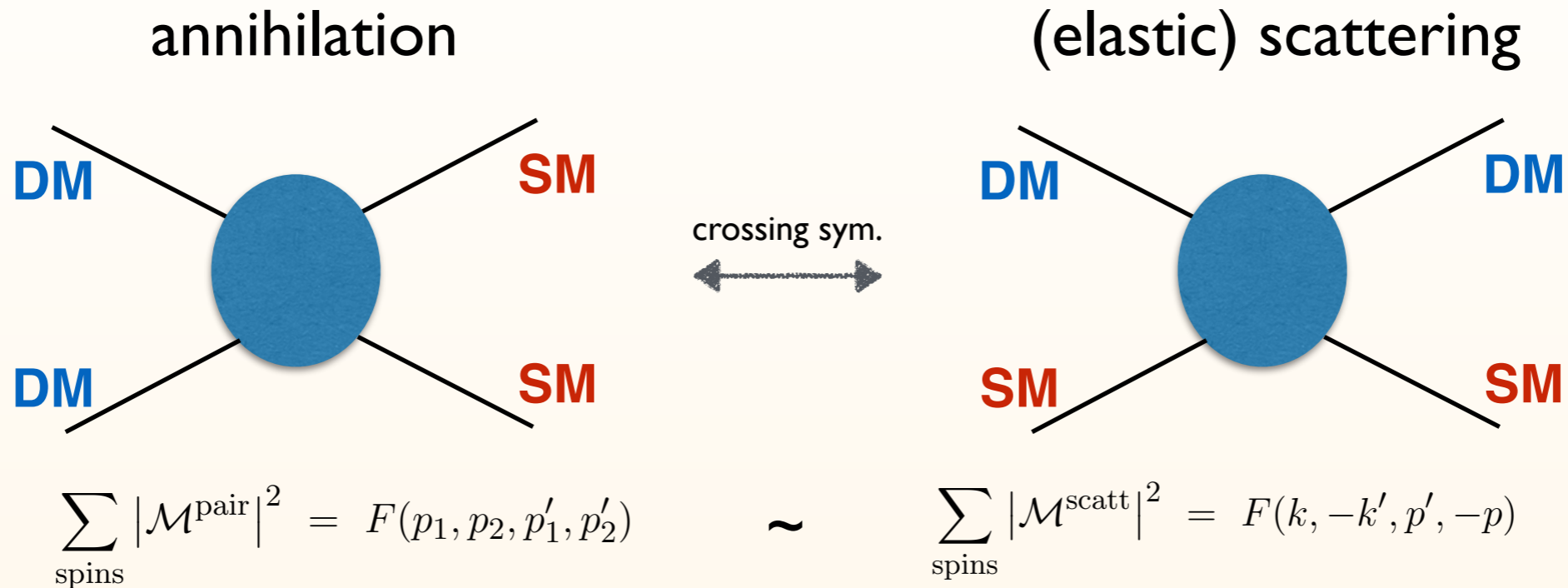
(the difficult one, usually neglected in freeze-in!)

The collision term can also contain:

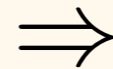
decays, annihilations, cannibalizations, ...

Note: to first approximation freeze-in production is much easier to determine than freeze-out!

# FREEZE-OUT VS. DECOUPLING



Boltzmann suppression of **DM** vs. **SM**



scatterings typically more frequent

dark matter frozen-out but typically still kinetically coupled to the plasma

$$\tau_r(T_{\text{kd}}) \equiv N_{\text{coll}}/\Gamma_{\text{el}} \sim H^{-1}(T_{\text{kd}})$$

Schmid, Schwarz, Widern '99; Green, Hofmann, Schwarz '05

Two consequences:

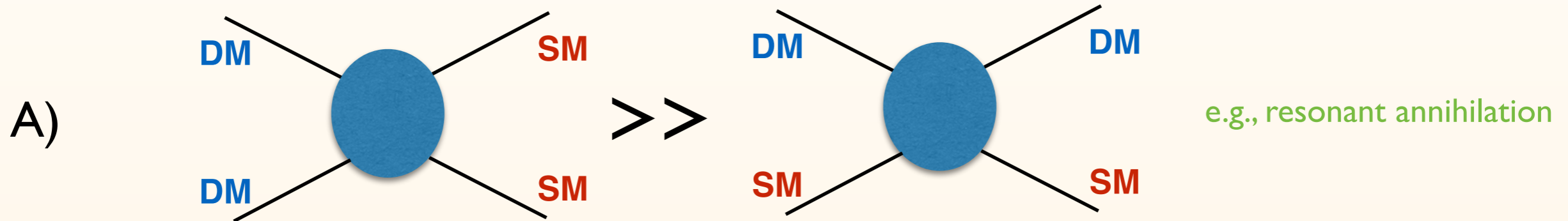
1. During freeze-out (chemical decoupling) typically:  $f_\chi \sim a(\mu) f_\chi^{\text{eq}}$
2. If kinetic decoupling much, much later: possible impact on the matter power spectrum  
i.e. kinetic decoupling can have observable consequences and affect e.g. missing satellites problem

see e.g., Bringmann, Ihle, Karsten, Valia '16

# EARLY KINETIC DECOUPLING?

A **necessary** and **sufficient** condition: scatterings weaker than annihilation  
i.e. rates around freeze-out:  $H \sim \Gamma_{\text{ann}} \gtrsim \Gamma_{\text{el}}$

Possibilities:



B) Boltzmann suppression of **SM** as strong as for **DM**  
e.g., below threshold annihilation (forbidden-like DM)

C) Scatterings and annihilation have different structure  
e.g., semi-annihilation, 3 to 2 models, ...

D) Multi-component dark sectors  
e.g., additional sources of DM from late decays, ...

# HOW TO GO BEYOND KINETIC EQUILIBRIUM?

All information is in the full BE:

both about chemical ("normalization") and kinetic ("shape") equilibrium/decoupling

$$E (\partial_t - H\vec{p} \cdot \nabla_{\vec{p}}) f_{\chi} = \mathcal{C}[f_{\chi}]$$

contains both scatterings and annihilations

Two possible approaches:

fBE

solve numerically  
for full  $f_{\chi}(p)$

have insight on the distribution  
no constraining assumptions

numerically challenging  
often an overkill

CBE

consider system of equations  
for moments of  $f_{\chi}(p)$

partially analytic/much easier numerically  
manifestly captures all of the relevant physics

finite range of validity  
no insight on the distribution

0-th moment:  $n_{\chi}$   
2-nd moment:  $T_{\chi}$   
...

# NEW TOOL!

## GOING BEYOND THE STANDARD APPROACH

- Home
- Downloads
- Contact



### Dark matter Relic Abundance beyond Kinetic Equilibrium

Authors: Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk

DRAKE is a numerical precision tool for predicting the dark matter relic abundance also in situations where the standard assumption of kinetic equilibrium during the freeze-out process may not be satisfied. The code comes with a set of three dedicated Boltzmann equation solvers that implement, respectively, the traditionally adopted equation for the dark matter number density, fluid-like equations that couple the evolution of number density and velocity dispersion, and a full numerical evolution of the phase-space distribution. The code is written in Wolfram Language and includes a Mathematica notebook example program, a template script for terminal usage with the free Wolfram Engine, as well as several concrete example models. DRAKE is a free software licensed under GPL3.

If you use DRAKE for your scientific publications, please cite

- **DRAKE: Dark matter Relic Abundance beyond Kinetic Equilibrium,** Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk, [arXiv:2103.01944]

Currently, a user guide can be found in the Appendix A of this reference. Please cite also quoted other works applying for specific cases.

**v1.0** « [Click here to download DRAKE](#)

(March 3, 2021)

<https://drake.hepforge.org>

### Applications:

DM relic density for  
any (user defined) model\*

Interplay between chemical and  
kinetic decoupling

Prediction for the DM  
phase space distribution

Late kinetic decoupling  
and impact on cosmology

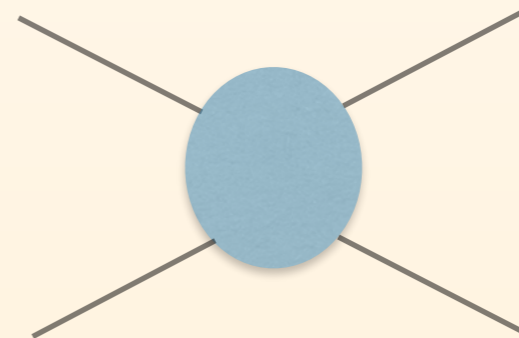
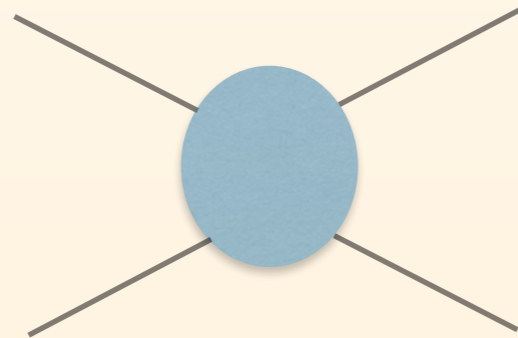
see e.g., [I202.5456](#)

...

(only) prerequisite:  
*Wolfram Language (or Mathematica)*

\*at the moment for a single DM species and w/o  
co-annihilations... but stay tuned for extensions!

**EXAMPLE A:**  
**SCALAR SINGLET DM**



# EXAMPLE A

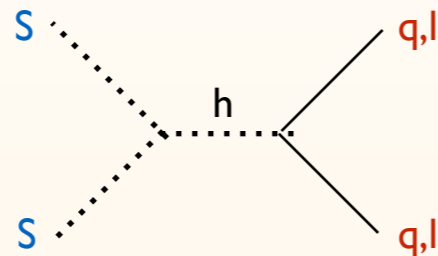
## SCALAR SINGLET DM

To the SM Lagrangian add one singlet scalar field  $S$  with interactions with the Higgs:

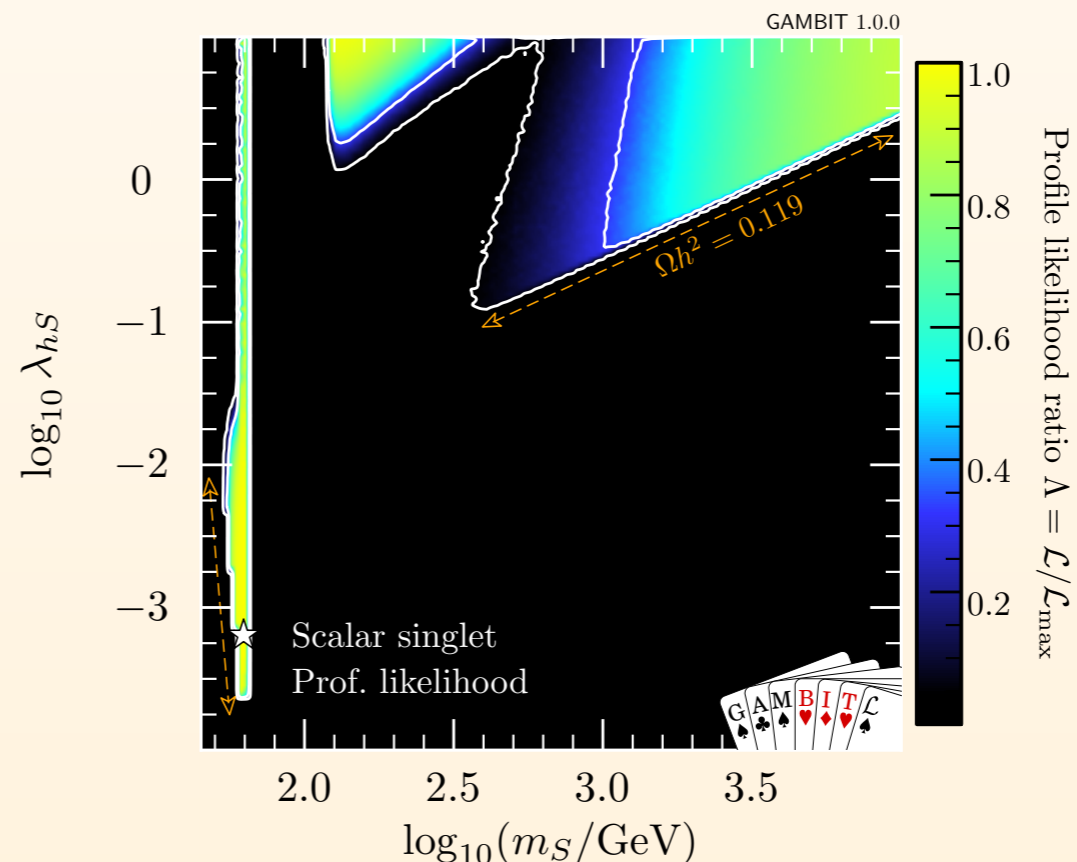
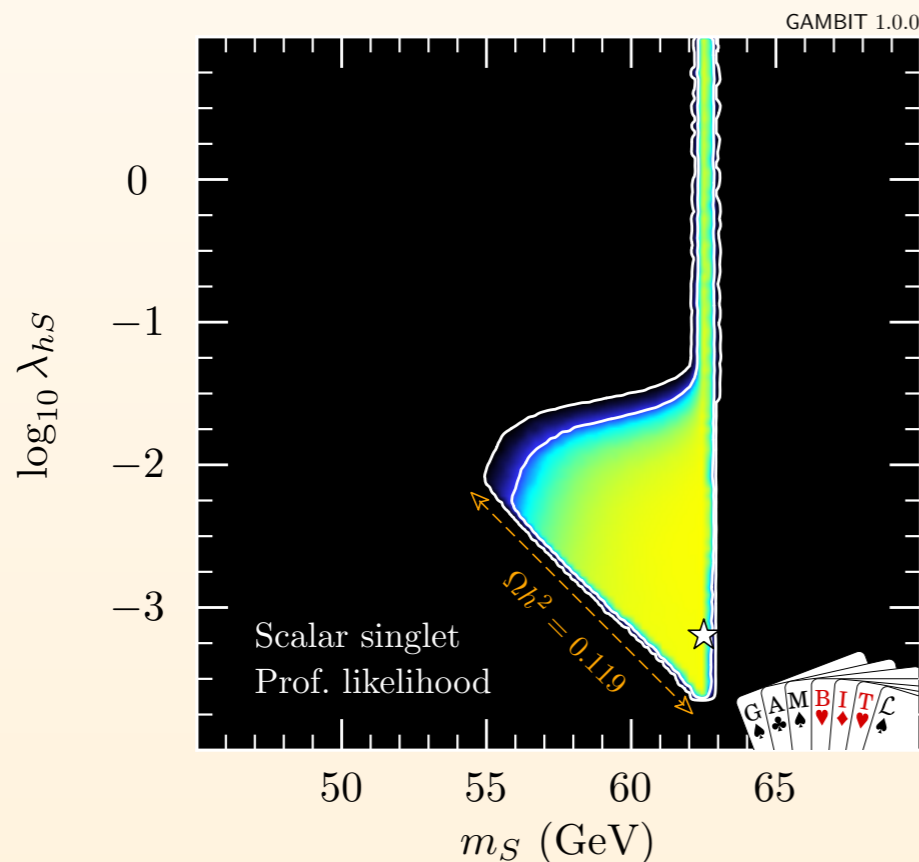
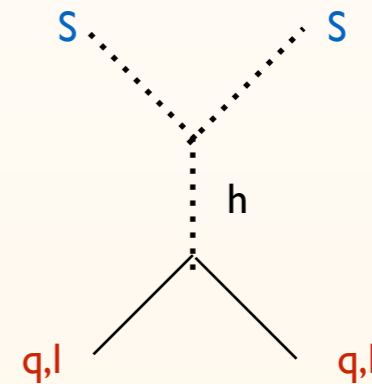
$$\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} \mu_S^2 S^2 - \frac{1}{2} \lambda_s S^2 |H|^2$$

$$m_s = \sqrt{\mu_S^2 + \frac{1}{2} \lambda_s v_0^2}$$

Annihilation  
processes:  
**resonant**



El. scattering  
processes:  
**non-resonant**

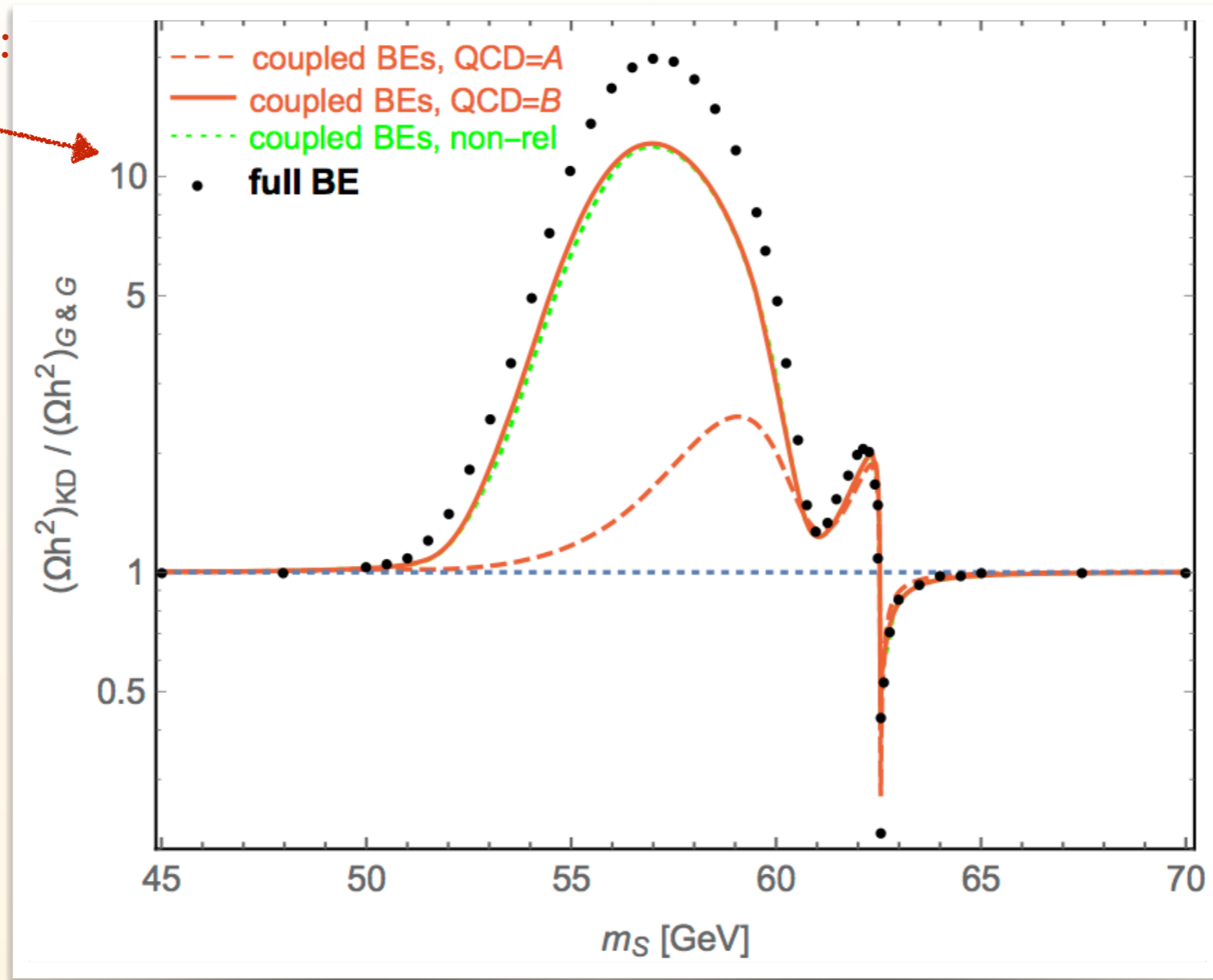


GAMBIT collaboration  
1705.07931

# RESULTS

## EFFECT ON THE $\Omega h^2$

effect on relic density:  
up to  $O(\sim 10)$



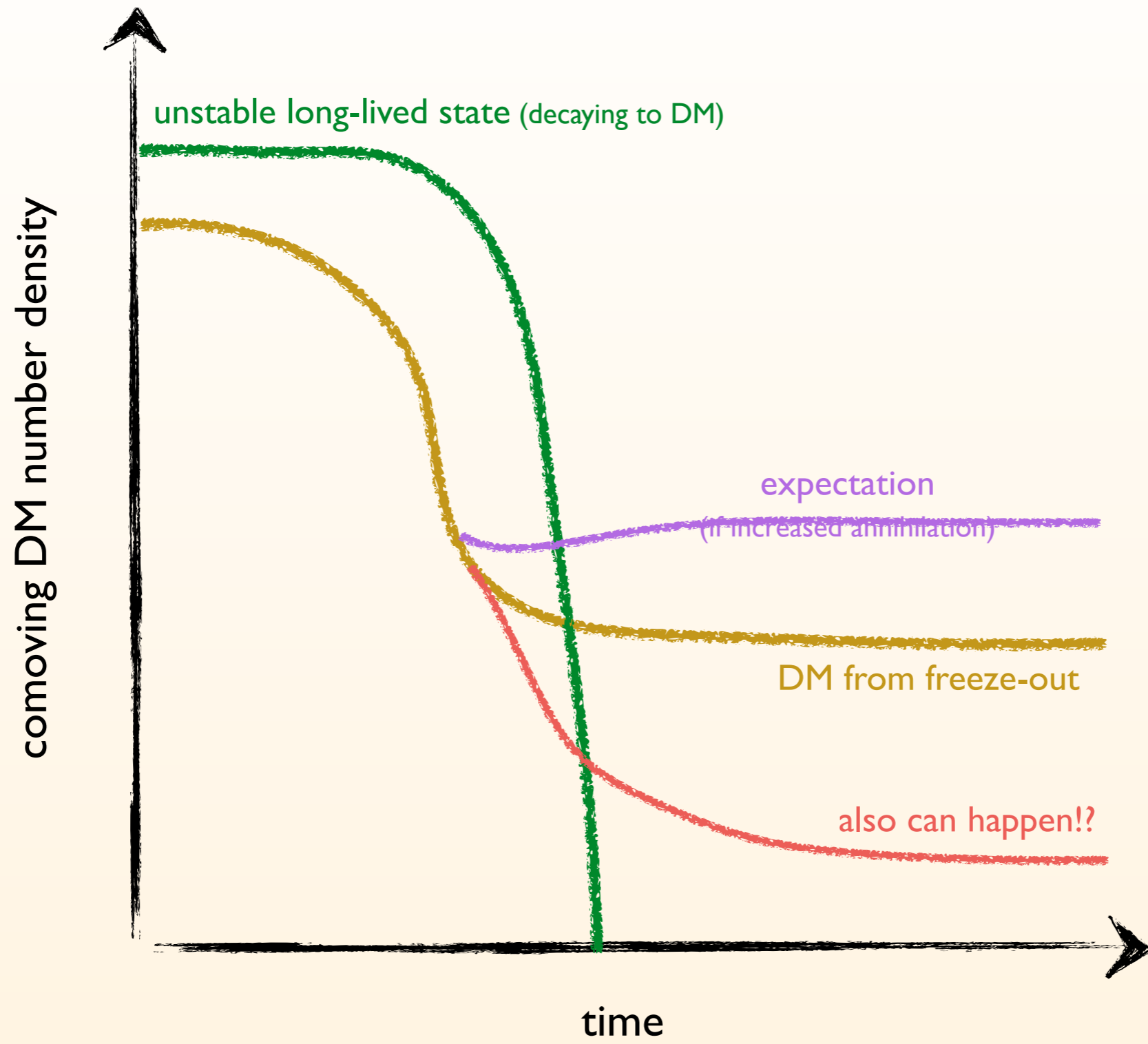
[... Freeze-out at few GeV  $\rightarrow$  what is the abundance of heavy quarks in QCD plasma?

two scenarios: QCD = A - all quarks are free and present in the plasma down to  $T_c = 154$  MeV  
 QCD = B - only light quarks contribute to scattering and only down to  $4T_c$  ...] 47

## EXAMPLE D: WHEN ADDITIONAL INFLUX OF DM ARRIVES

Sudden injection of more DM particles **distorts**  $f_\chi(p)$   
(e.g. from a decay or annihilation of other states)

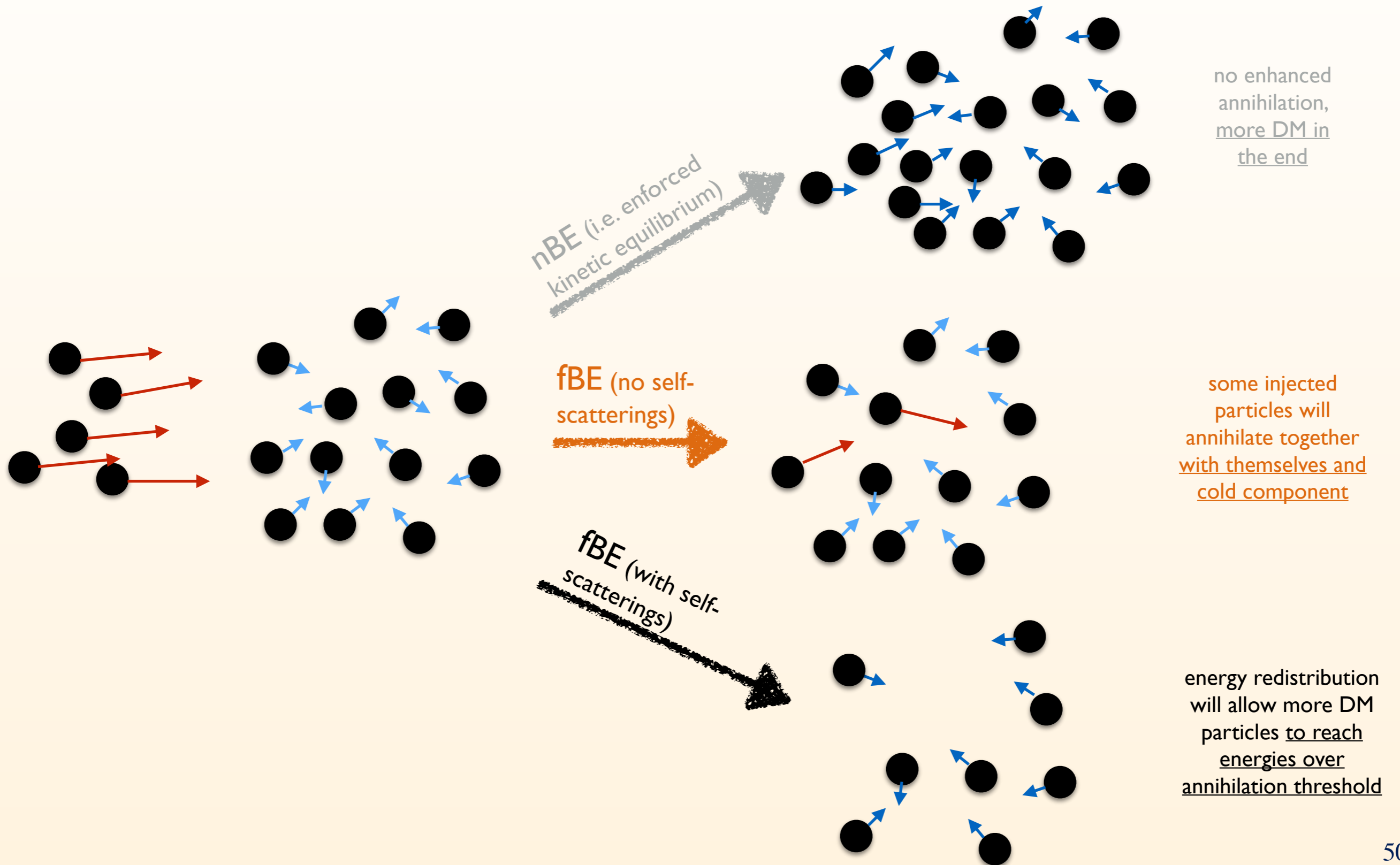
- this can **modify the annihilation rate** (if still active)
- how does the **thermalization** due to elastic scatterings happen?



1) DM produced via:
 

- 1st component from **thermal freeze-out**
- 2nd component from **a decay  $\phi \rightarrow \bar{\chi}\chi$**

2) DM annihilation has a **threshold**  
 e.g.  $\chi\bar{\chi} \rightarrow f\bar{f}$  with  $m_\chi \lesssim m_f$



# EXAMPLE EVOLUTION

1) DM produced via:

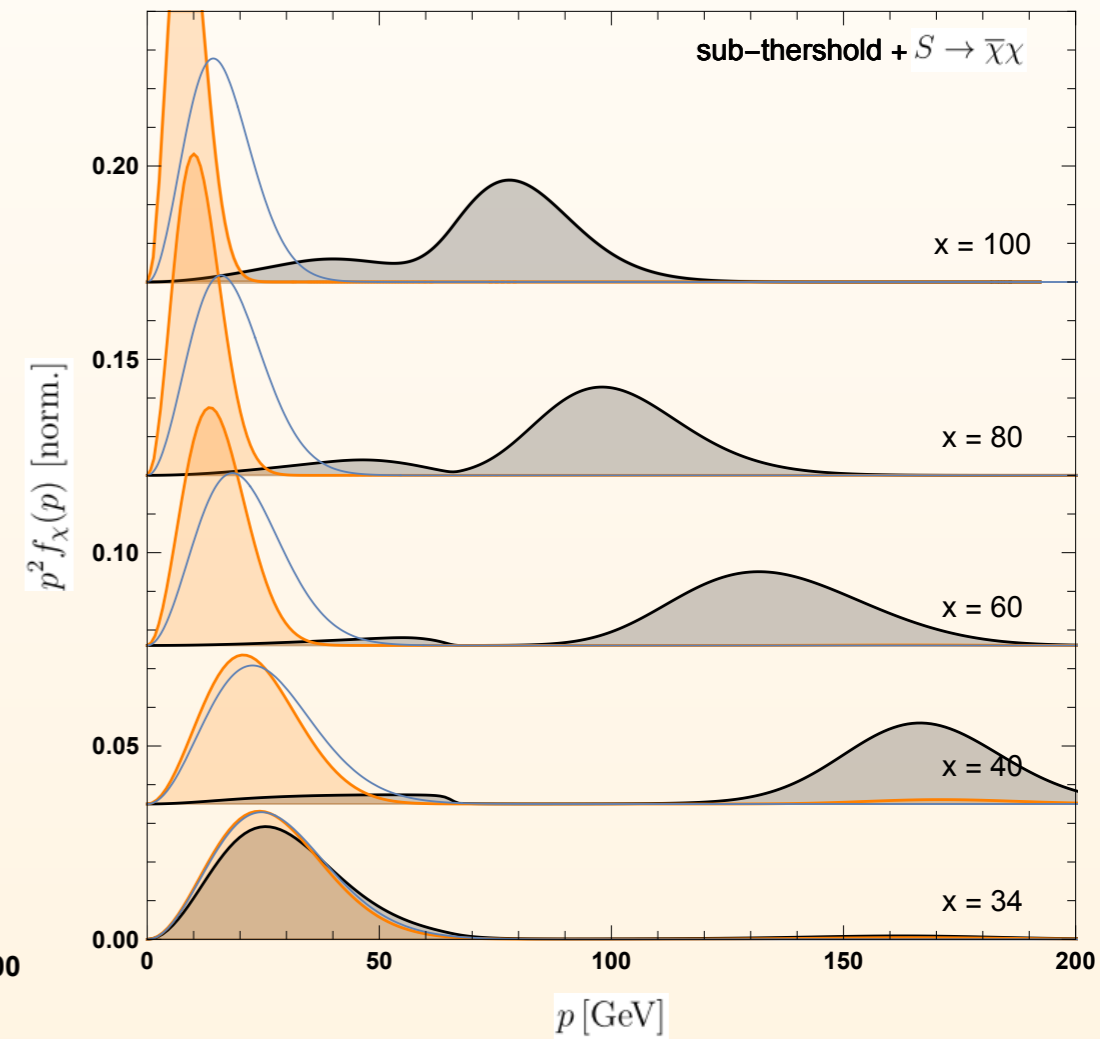
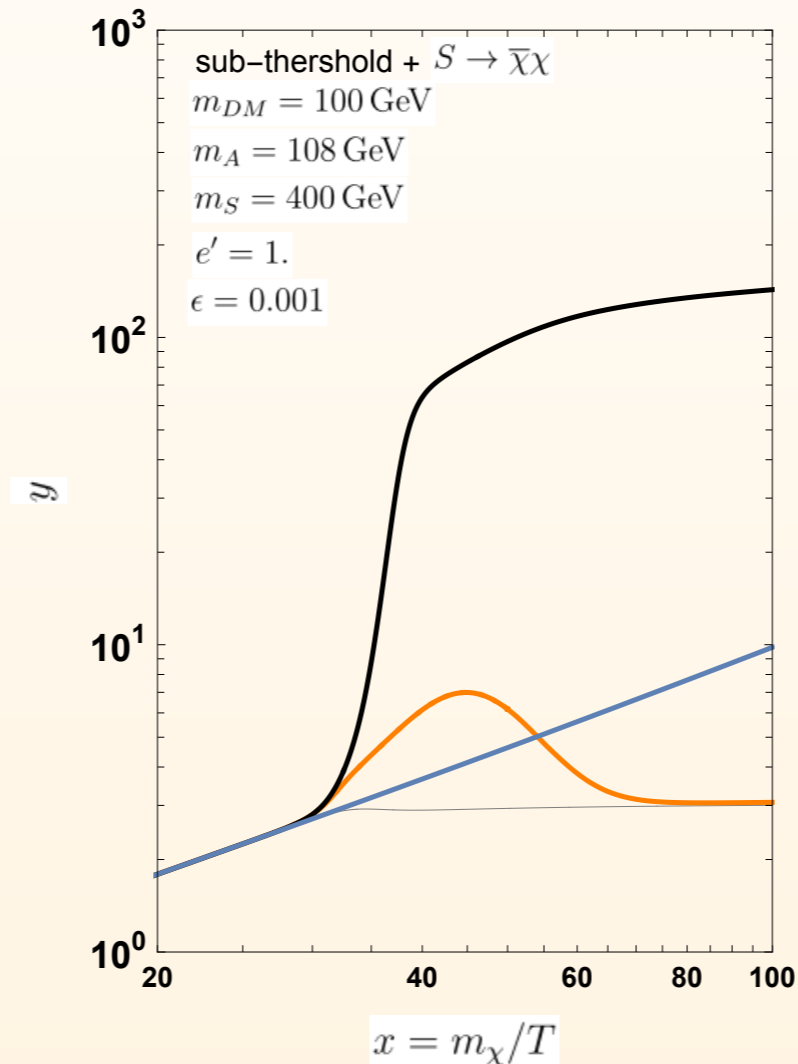
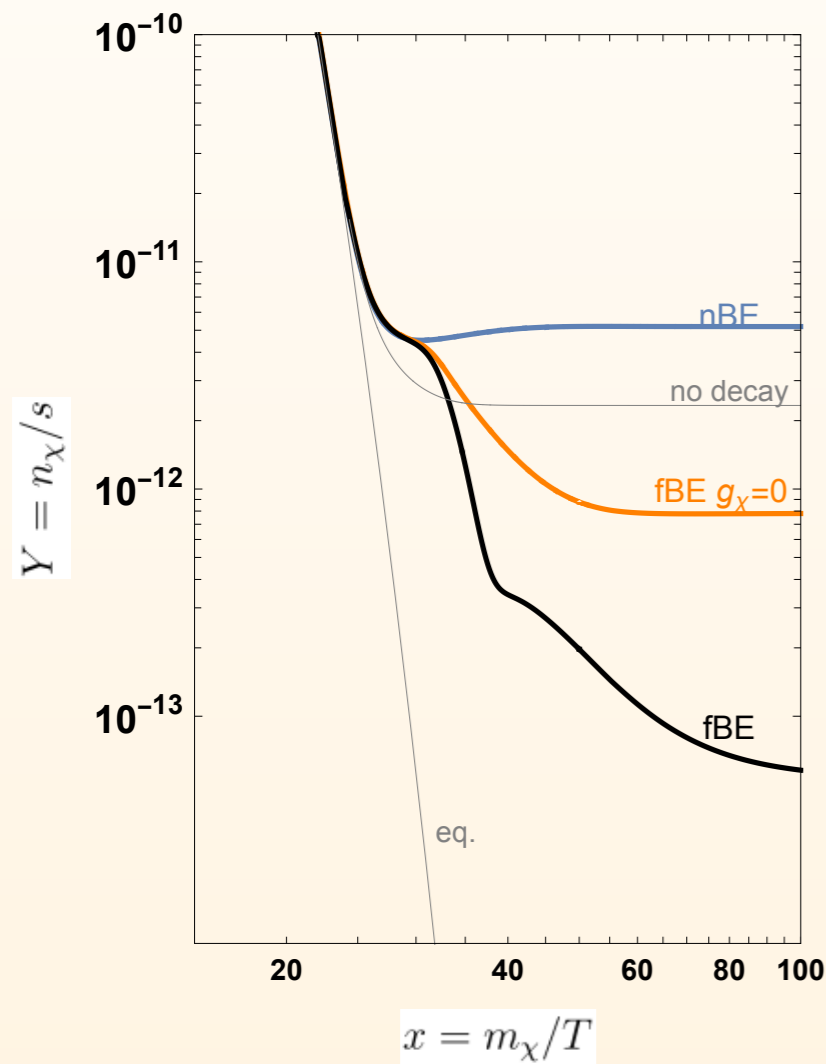
- 1st component from **thermal freeze-out**
- 2nd component from **a decay  $\phi \rightarrow \bar{\chi}\chi$**

2) DM annihilation has a **threshold**  
 e.g.  $\chi\bar{\chi} \rightarrow f\bar{f}$  with  $m_\chi \lesssim m_f$

$Y \sim$  number density

$y \sim$  temperature

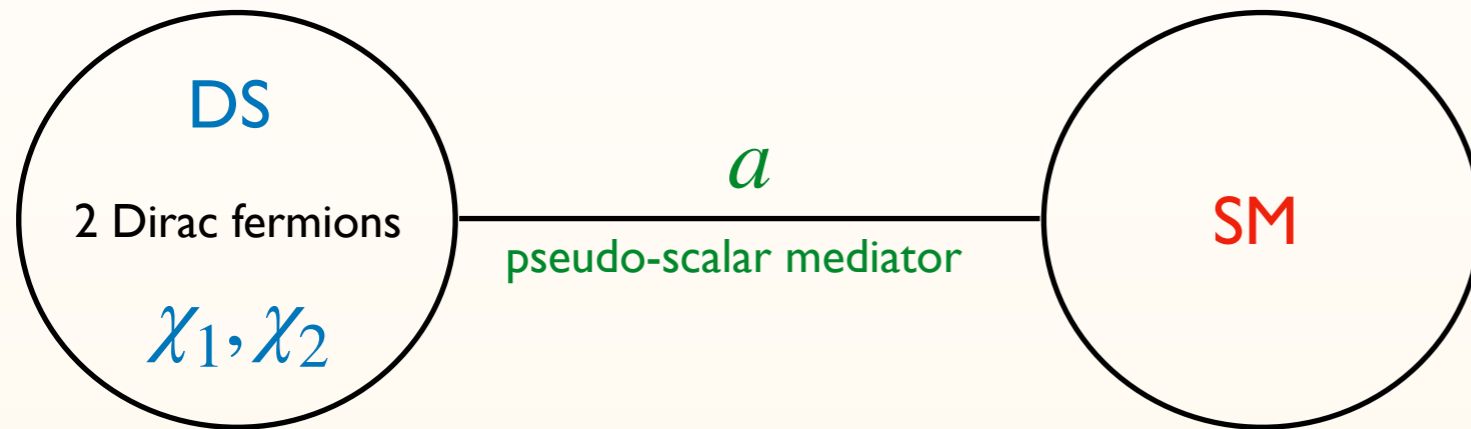
$p^2 f(p) \sim$  momentum distribution



**EXAMPLE D:**  
**EFFECT OF CONVERSION PROCESSES**

# RESULTS: THE MODEL

Let's take one of the simplest two-component DM models:



$$\mathcal{L}_{int} = - \sum_{i=1,2} i\lambda_i a \bar{\chi}_i \gamma^5 \chi_i - i\lambda_y \frac{m_f}{v} a \bar{f} \gamma^5 f$$

coupled directly to SM fermions in a MFV way

New fields:  $\chi_1, \chi_2, a$       New params:  $m_1, m_2, m_a$   
 $\lambda_1, \lambda_2, \lambda_y$

Parametrically:

$$\sigma_{11 \rightarrow SM} \sim \sigma_{1SM \rightarrow 1SM} \sim \lambda_1^2 \lambda_y^2$$

$$\sigma_{22 \rightarrow SM} \sim \sigma_{2SM \rightarrow 2SM} \sim \lambda_2^2 \lambda_y^2$$

$$\sigma_{11 \rightarrow 22} \sim \lambda_1^2 \lambda_2^2$$



Varying:

$$\lambda_1 \rightarrow \lambda_1 / c$$

$$\lambda_2 \rightarrow \lambda_2 / c$$

$$\lambda_y \rightarrow c \lambda_y$$

Keeps everything fixed,  
except conversions

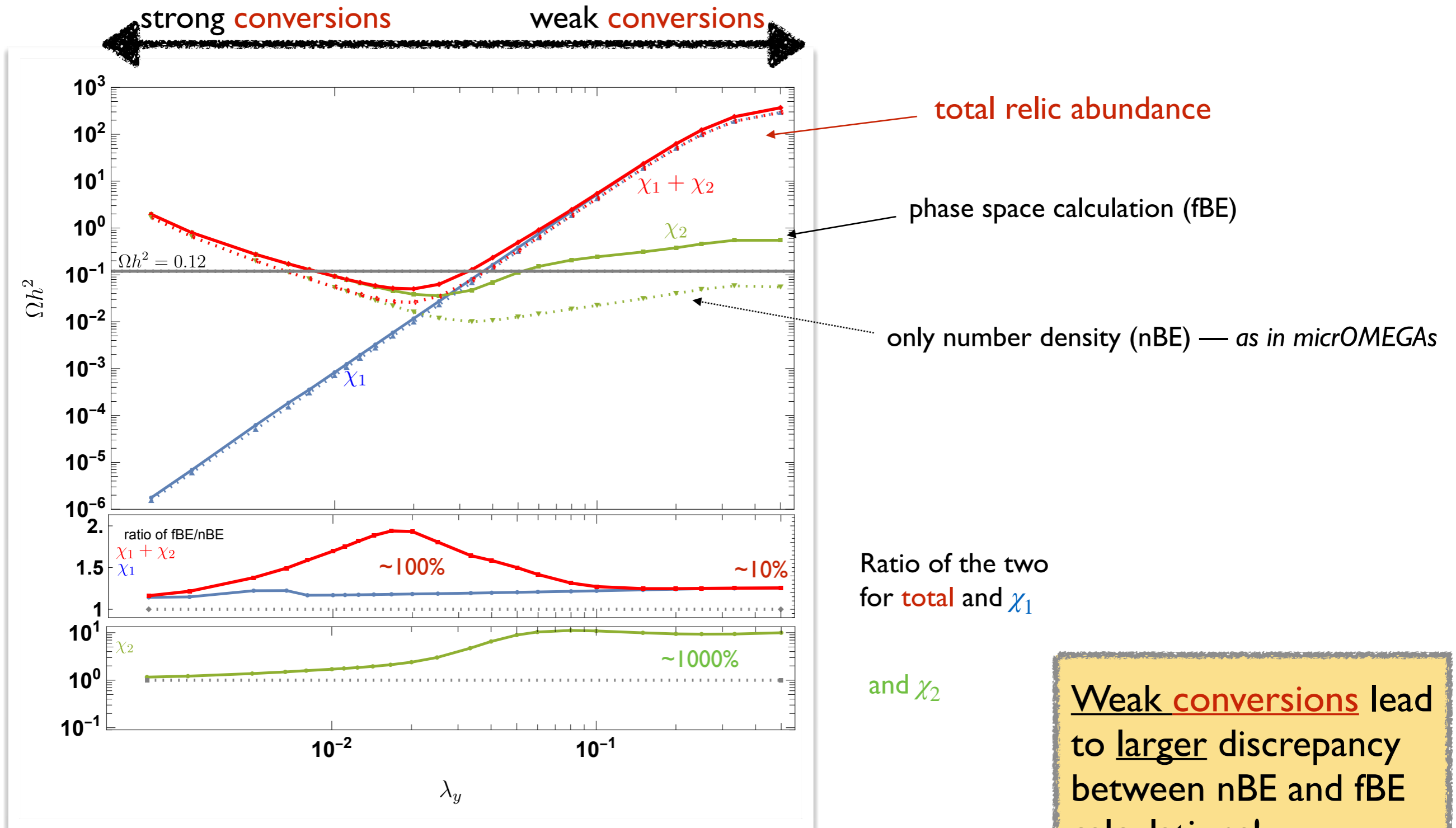
Main motivation (for models in the literature with pseudo-scalar mediator):

Evasion of the direct detection bounds... while giving strong signal in indirect detection, in particular **for explaining the Galactic Centre excess**

(see e.g. „Coy DM”)

# RESULTS: CONVERSION IMPACT

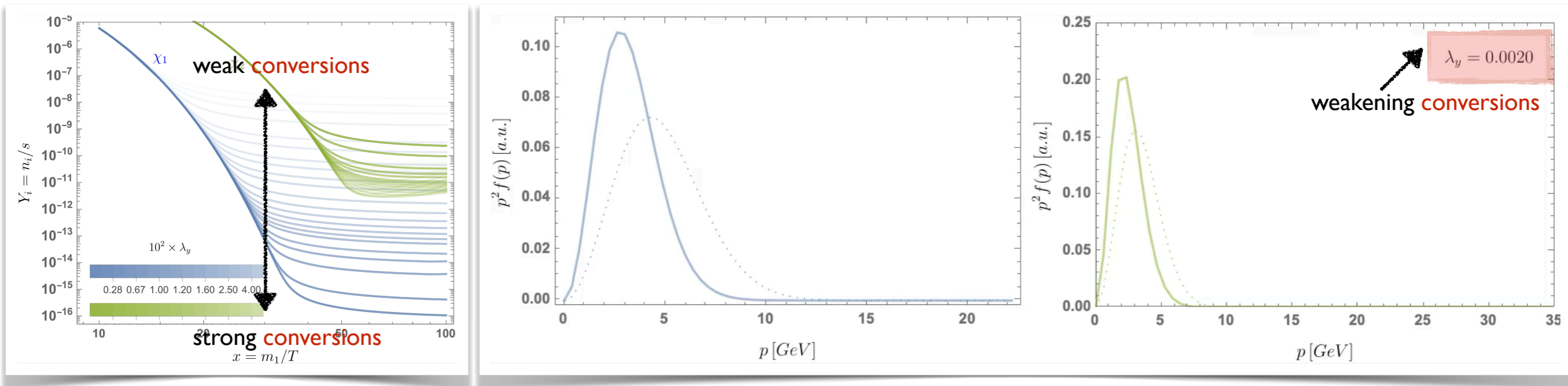
Varying:  $\lambda_1 \rightarrow \lambda_1/c$      $\lambda_2 \rightarrow \lambda_2/c$      $\lambda_y \rightarrow c \lambda_y$     Only **conversions** change!



**Weak conversions** lead to larger discrepancy between nBE and fBE calculations!

# RESULTS: CONVERSION IMPACT

weaker conversions  $\Rightarrow$  less depletion of  $\chi_1 \Rightarrow$  around  $\chi_2$  freeze-out more  $\chi_1$  in the plasma  
 $\Rightarrow$  larger distortion of thermal shape



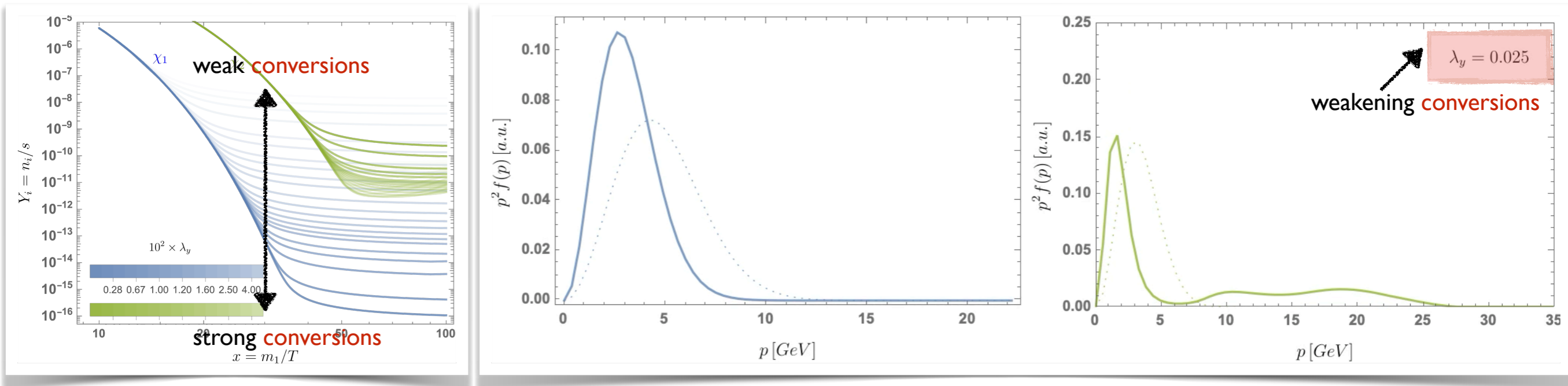
Conversions are ubiquitous in multicomponent models... but not the only processes affecting the distributions:

- decays of heavier to lighter dark sector states
- inelastic scatterings
- semi-annihilations
- cannibal ( $3 \leftrightarrow 2$ )

A.H. & Laletin 2204.07078 (see also Beauchesne & Chiang 2401.03657)  
 A.H. & Laletin 2104.05684  
 Cervantes & A.H. 2407.12104

# RESULTS: CONVERSION IMPACT

weaker conversions  $\Rightarrow$  less depletion of  $\chi_1 \Rightarrow$  around  $\chi_2$  freeze-out more  $\chi_1$  in the plasma  
 $\Rightarrow$  larger distortion of thermal shape



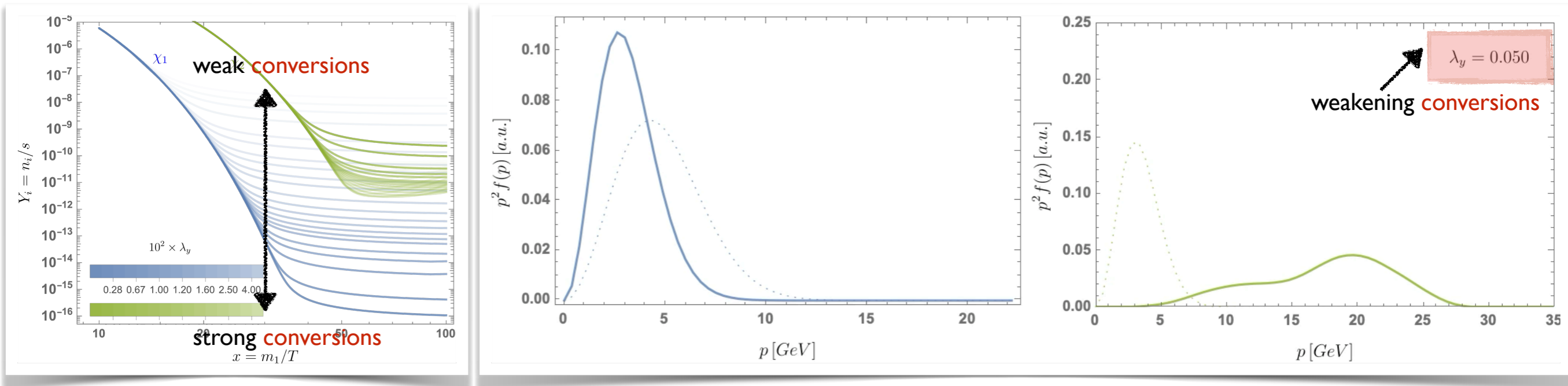
Conversions are ubiquitous in multicomponent models... but not the only processes affecting the distributions:

- decays of heavier to lighter dark sector states
- inelastic scatterings
- semi-annihilations
- cannibal ( $3 \leftrightarrow 2$ )

A.H. & Laletin 2204.07078 (see also Beuchadne & Chiang 2401.03657)  
 A.H. & Laletin 2104.05684  
 Cervantes & A.H. 2407.12104

# RESULTS: CONVERSION IMPACT

weaker conversions  $\Rightarrow$  less depletion of  $\chi_1 \Rightarrow$  around  $\chi_2$  freeze-out more  $\chi_1$  in the plasma  
 $\Rightarrow$  larger distortion of thermal shape



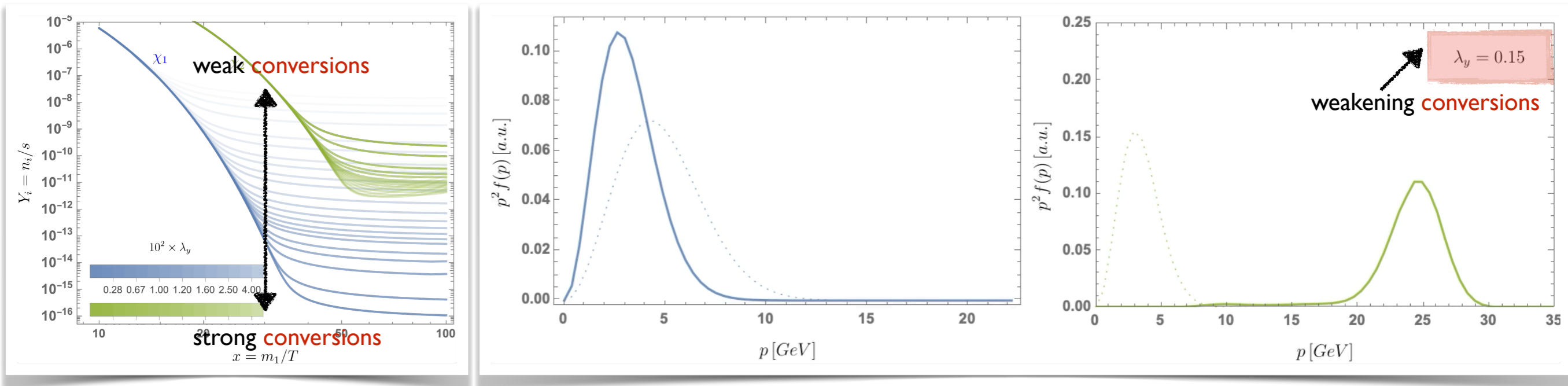
Conversions are ubiquitous in multicomponent models... but not the only processes affecting the distributions:

- decays of heavier to lighter dark sector states
- inelastic scatterings
- semi-annihilations
- cannibal ( $3 \leftrightarrow 2$ )

A.H. & Laletin 2204.07078 (see also Beuchadne & Chiang 2401.03657)  
 A.H. & Laletin 2104.05684  
 Cervantes & A.H. 2407.12104

# RESULTS: CONVERSION IMPACT

weaker conversions  $\Rightarrow$  less depletion of  $\chi_1 \Rightarrow$  around  $\chi_2$  freeze-out more  $\chi_1$  in the plasma  
 $\Rightarrow$  larger distortion of thermal shape



Conversions are ubiquitous in multicomponent models... but not the only processes affecting the distributions:

- decays of heavier to lighter dark sector states
- inelastic scatterings
- semi-annihilations
- cannibal ( $3 \leftrightarrow 2$ )

A.H. & Laletin 2204.07078 (see also Beauchesne & Chiang 2401.03657)  
 A.H. & Laletin 2104.05684  
 Cervantes & A.H. 2407.12104

# TAKEAWAY MESSAGES

**1. Dark Matter** is a **welcomed guest** in Particle Physics community; **not unexpected** (as a part of the theory) and still very much **a useful hint** for discovering BSM physics

**2. Kinetic equilibrium** is a necessary (often implicit) assumption for standard relic density calculations in all the numerical tools...

(Our new code **DRAKE**  aims at extending the current capabilities)

*“Everything should be made as simple as possible, but no simpler.”*

attributed to\* **Albert Einstein**

\*The published quote reads:

“It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience.”

„On the Method of Theoretical Physics”, The Herbert Spencer Lecture, delivered at Oxford (10 June 1933); also published in *Philosophy of Science*, Vol. 1, No. 2 (April 1934), pp. 163-169., p. 165