DARK MATTER:
ALTERNATIVE TO WIMPS

Michel H.G. Tytgat
Université Libre de Bruxelles
Belgium

Windows on the Universe, 25th Rencontres du Vietnam, Quy Nhon, August 5-11 2018

Cửa sổ đến với Vũ Trụ tiềm ẩn *

Windows on the Hidden Universe

Michel H.G. Tytgat
Université Libre de Bruxelles
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* thanks to John Hoàng

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WHY DARK MATTER?

DARK ENERGY

DARK MATTER

BARYONS

PLAN

- WIMP HISTORY IN BRIEF
- A FIMP FROM A HIDDEN SECTOR
- ABUNDANCE FROM FREEZE-IN
- DIRECT DETECTION IS TESTING FREEZE-IN
- SELF-INTERACTING DARK MATTER

The Four Basic Ways of Creating Dark Matter Through a Portal
X. Chu, Th. Hambye & M.T (2012)

Direct detection is testing Freeze-in
Th. Hambye, M.T., J. Vandecasteele & L. Vanderheyden (2018)

Solar Mass Black Holes
K. Kouvaris, P. Tinyakov & M.T. (2018)

WIMP HISTORY IN BRIEF

1. SM HAS ISSUES

hierarchy problem

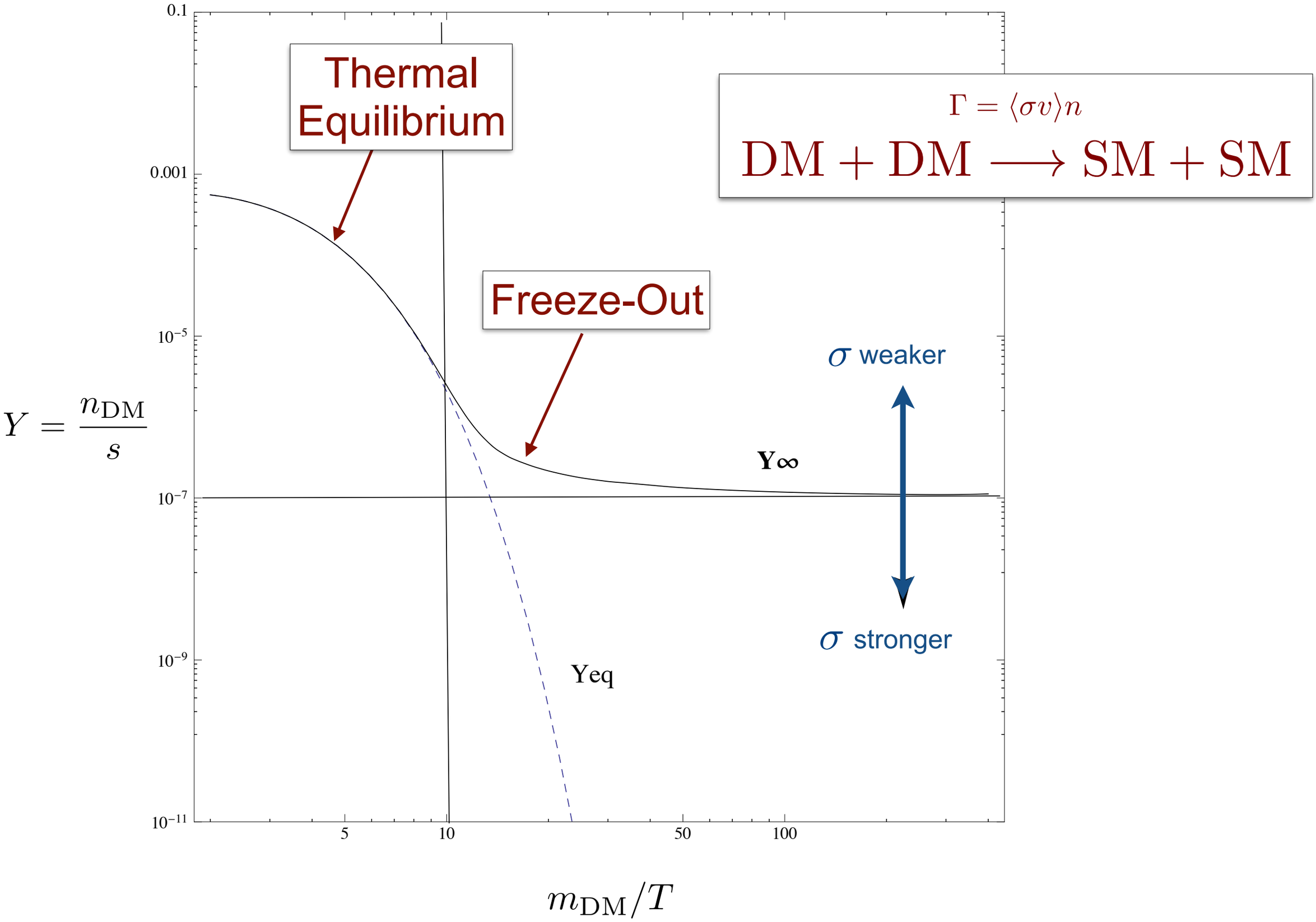
Neutralino

strong CP

Axion

see Emilian Dudas' talk

2. ABUNDANCE FROM FREEZE-OUT

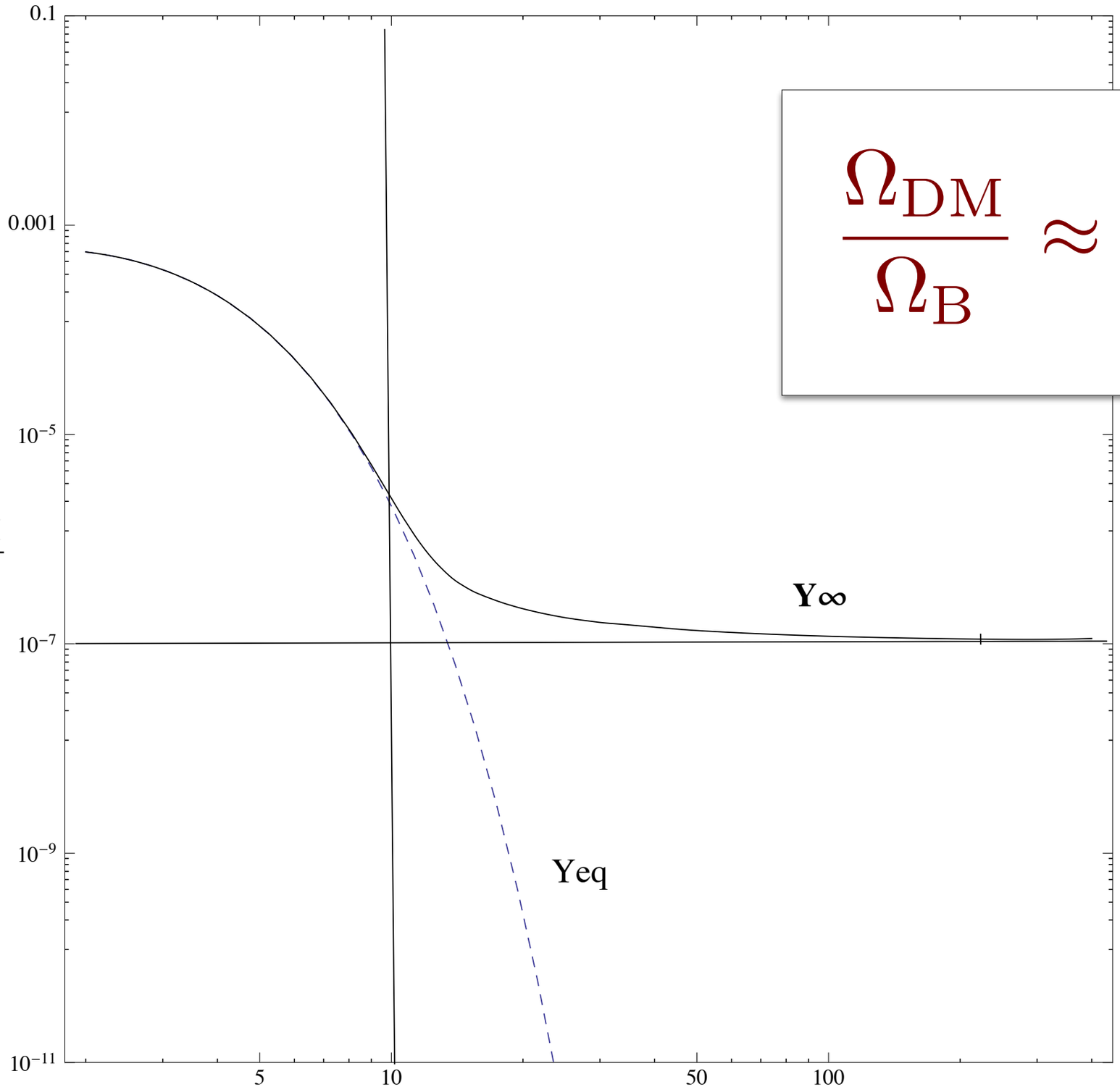


2. ABUNDANCE FROM FREEZE-OUT

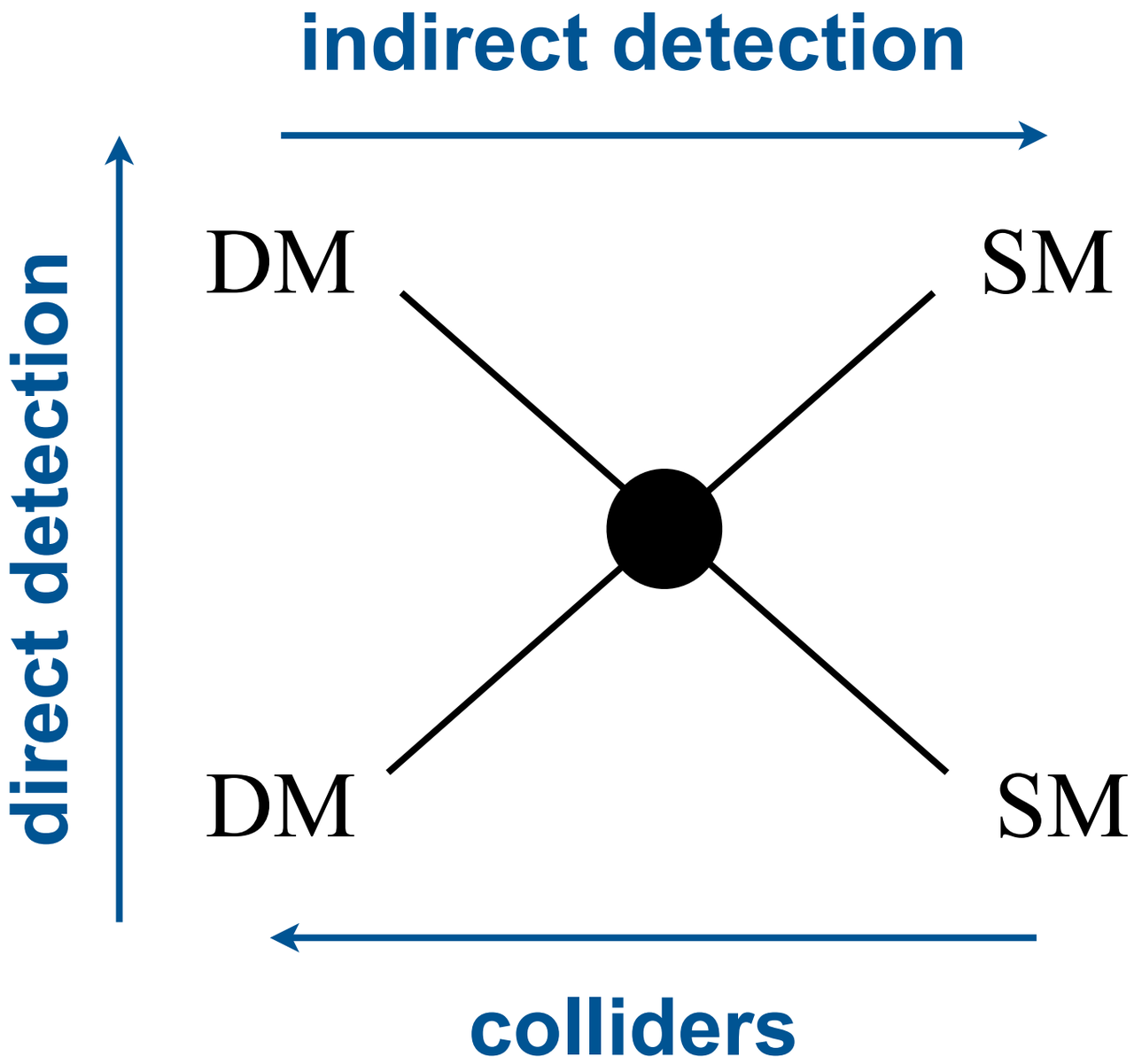
$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \approx 5 \left(\frac{\rm pb}{\langle \sigma v \rangle} \right)$$

Weak
thus WIMP

$$Y = \frac{n_{\rm DM}}{s}$$



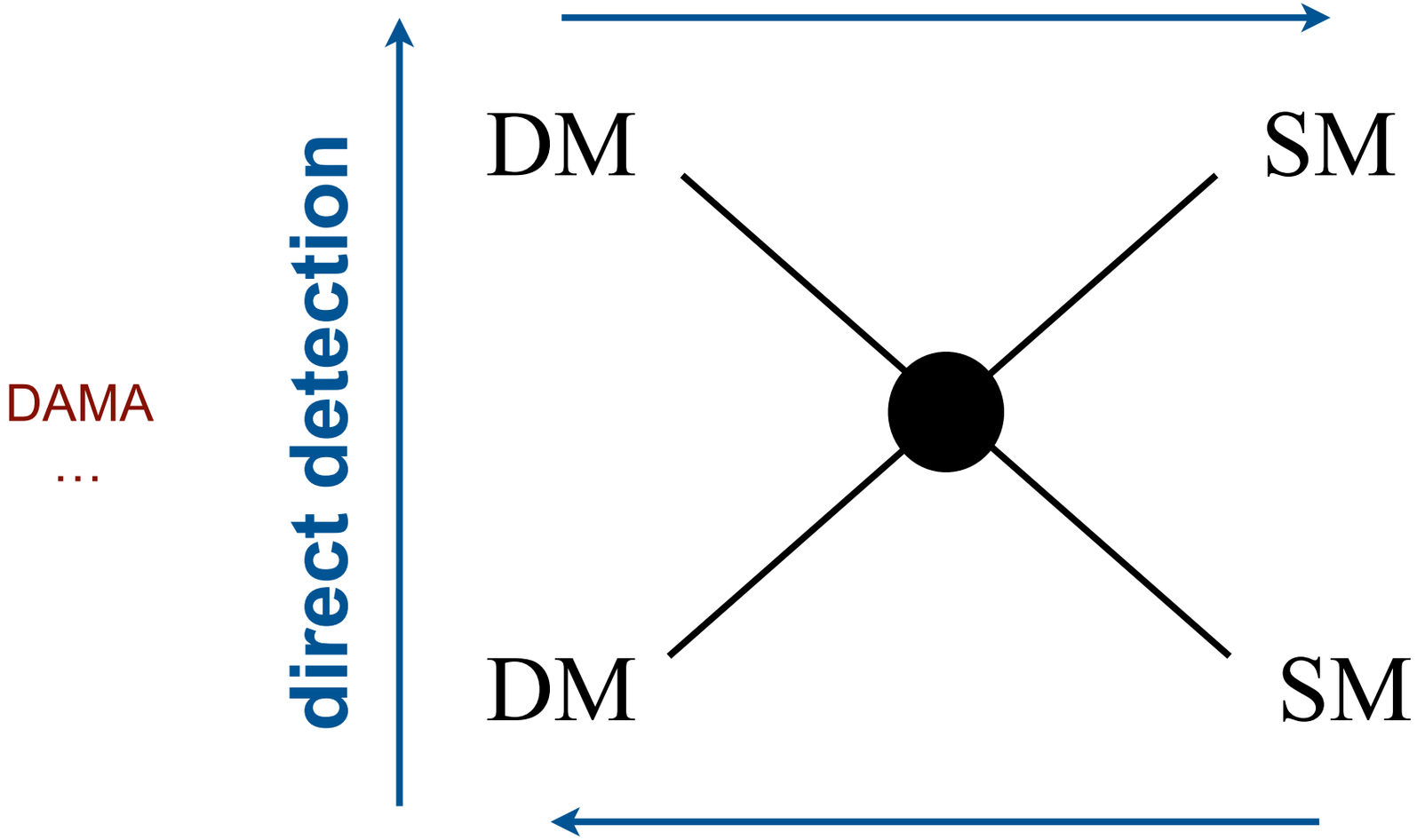
3. EXPERIMENTS



3. EXPERIMENTS

PAMELA e+/e-, FERMI (125 GeV γ-line, GC excess), …

indirect detection

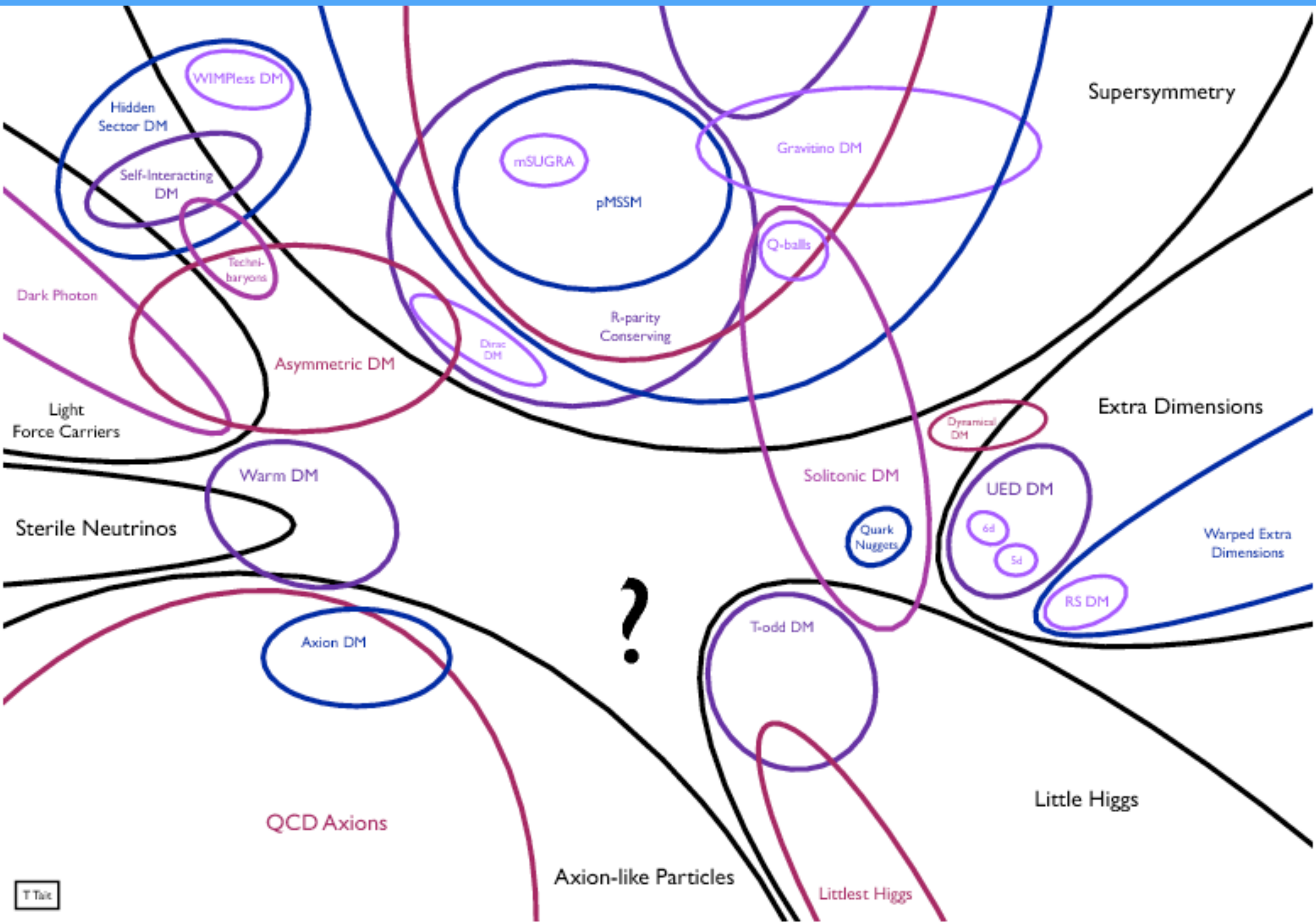


DAMA
…

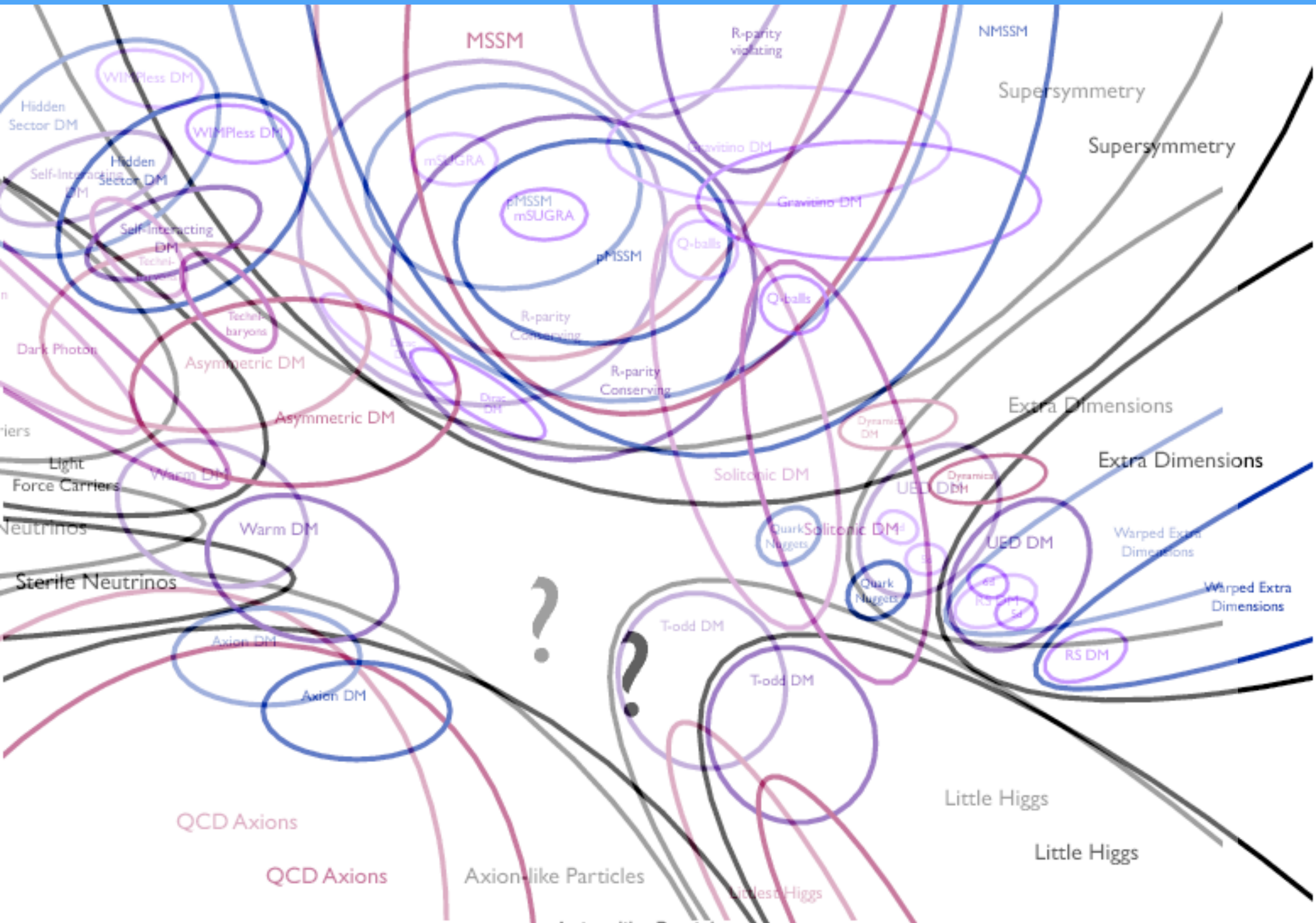
colliders

750 GeV resonance
B decay anomalies
…

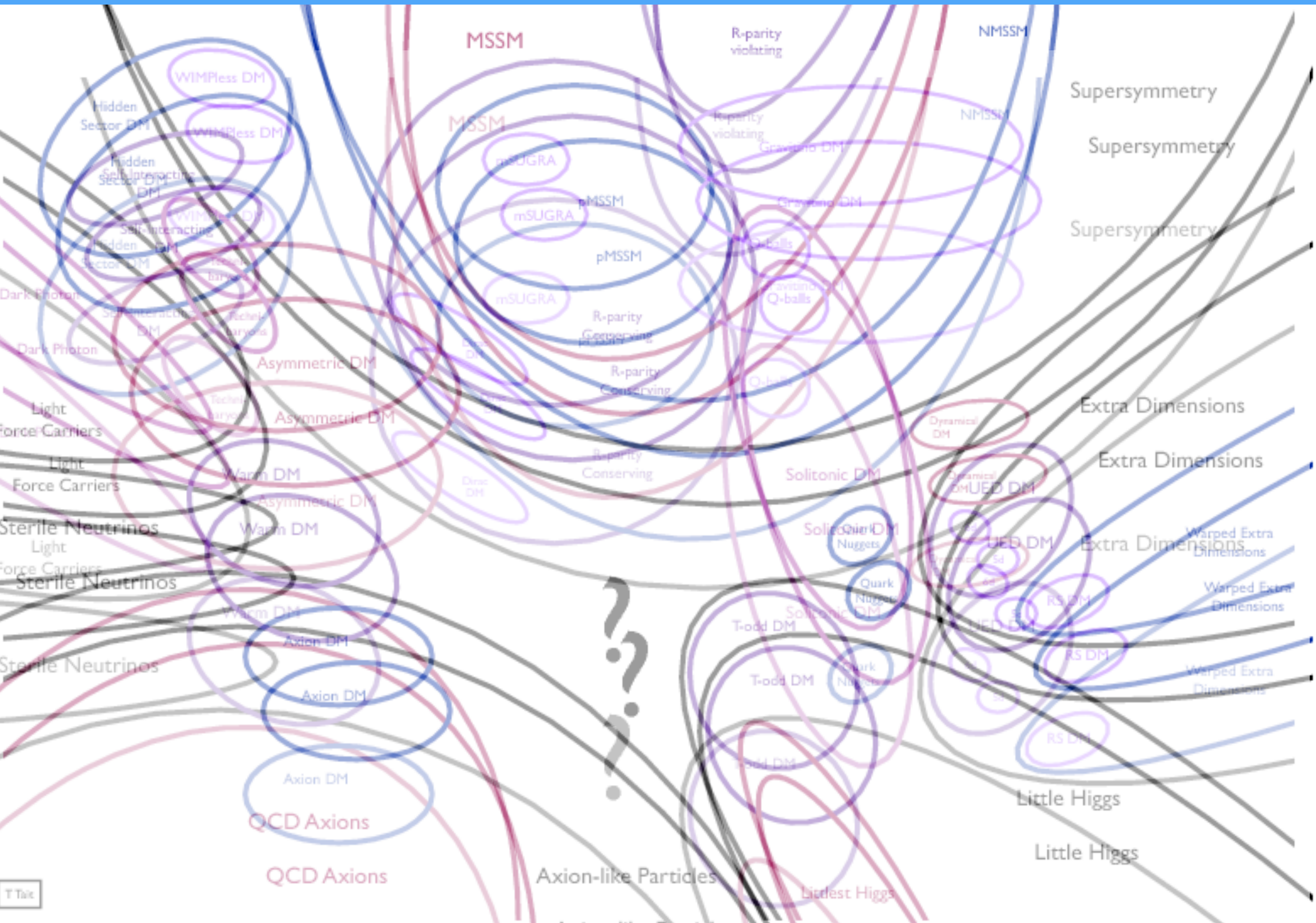
4. MODELS


WIMPless DM
Hidden Sector DM
Self-Interacting DM
Supersymmetry
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Quark Nuggets
6d
5d
Warped Extra Dimensions
Sterile Neutrinos
?
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

4. MORE MODELS

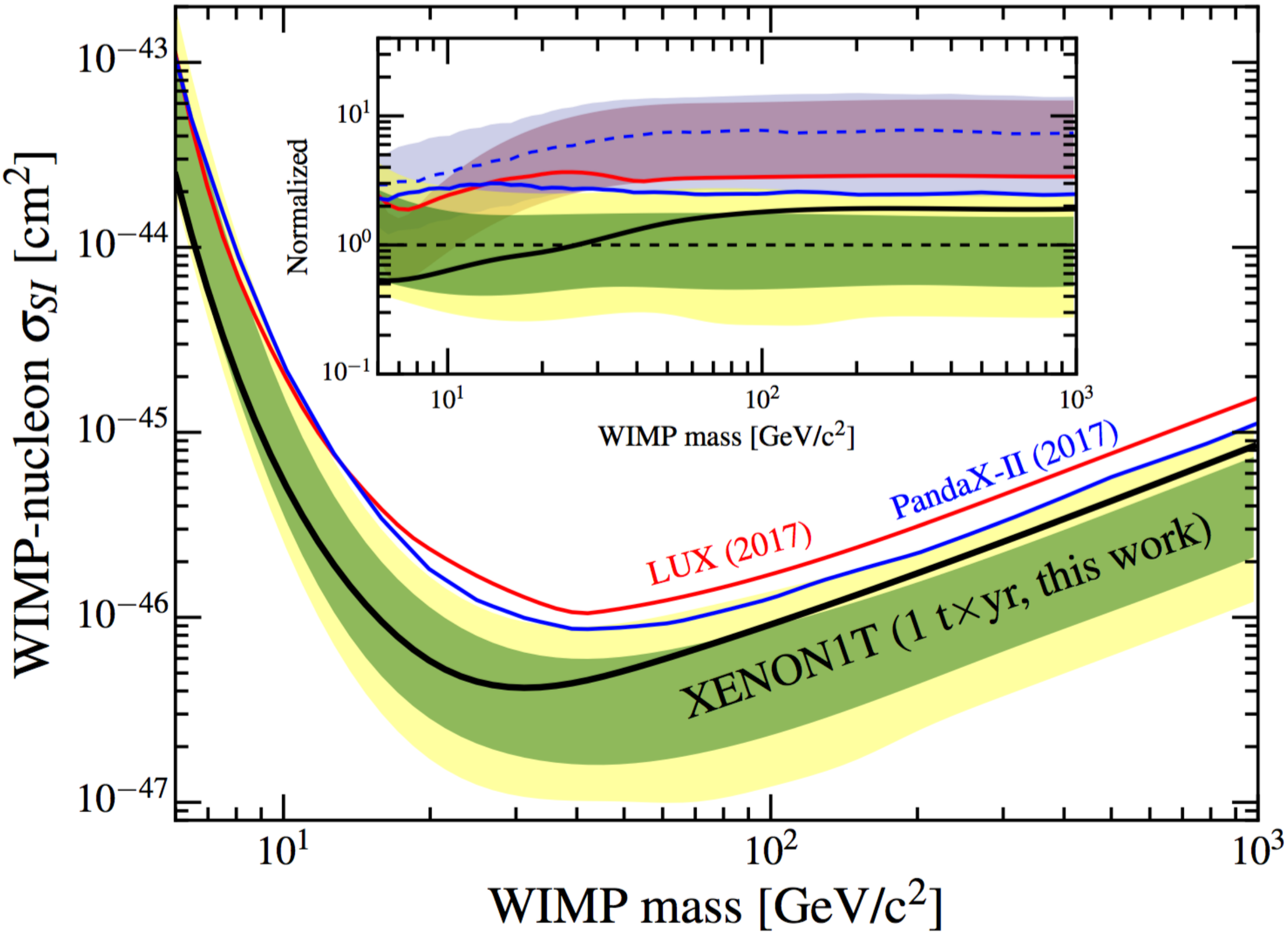


4. EVEN MORE MODELS



4. *$#@%!! MODELS

5. SO FAR NO SIGN OF A WIMP



6. THE TWILIGHT OF THE WIMPS (?)

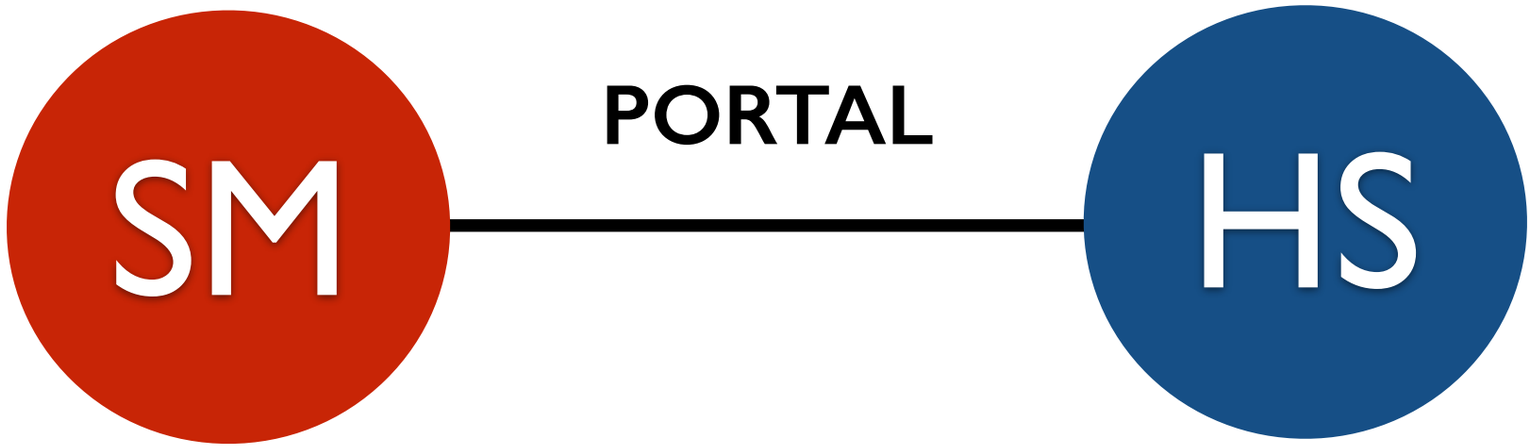
DARK MATTER FROM A HIDDEN SECTOR

ALTERNATIVE PERSPECTIVE

A HIDDEN SECTOR (HS)

SM PORTALS TO A HIDDEN SECTOR

Patt & Wilczek (2006)*



PORTAL = Cửa sổ đến với Vũ Trụ tiềm ẩn

* > 500 citations (unpublished)

NB: HS is an old story (e.g. SUSY breaking)

SM PORTALS TO A HIDDEN SECTOR

Patt & Wilczek (2006)

SM singlet operators

renormalizable interactions
(i.e. dimensionless couplings)

$\bar{L}\tilde{H}$ $\quad\Delta\mathcal{L} \supset y\,\bar{L}\tilde{H}N$ **Sterile neutrino**

Dodelson & Widrow (1994)
…

$B_{\mu\nu}$ $\quad\Delta\mathcal{L} \supset \epsilon\, B_{\mu\nu}X^{\mu\nu}$ **Kinetic mixing**

Holdom (1986)
…

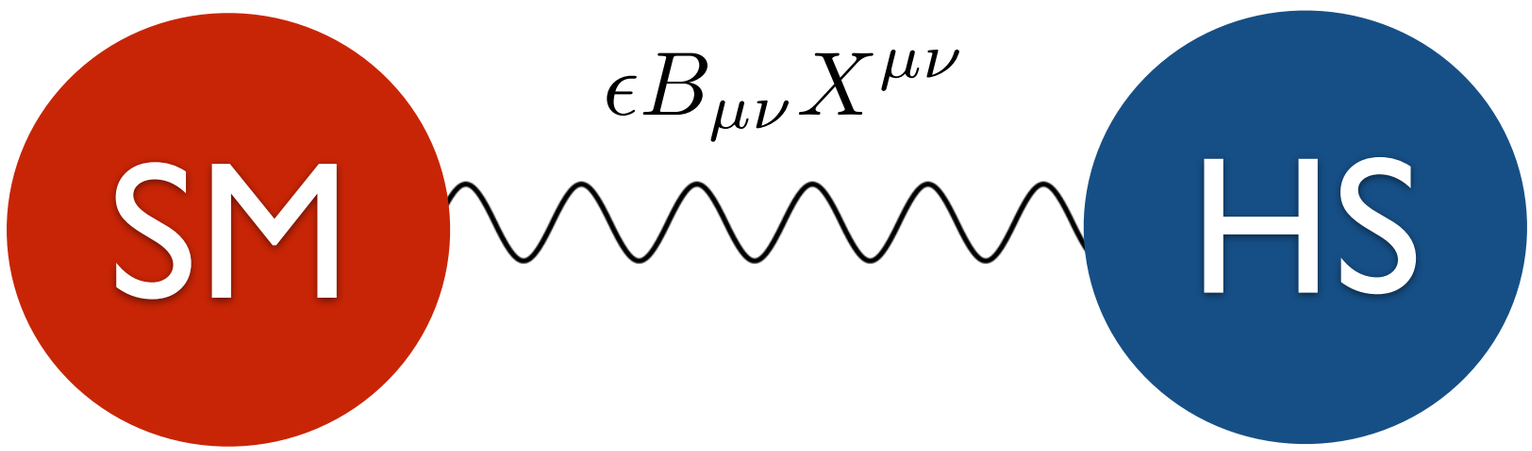
$H^\dagger H$ $\quad\Delta\mathcal{L} \supset \lambda\, S^2 H^\dagger H$ **Higgs portal**

This one is also Lorentz invariant

Linked to EWSB?

Silveira & Zee (1985)
Veltman & Ynderain (1989)
…

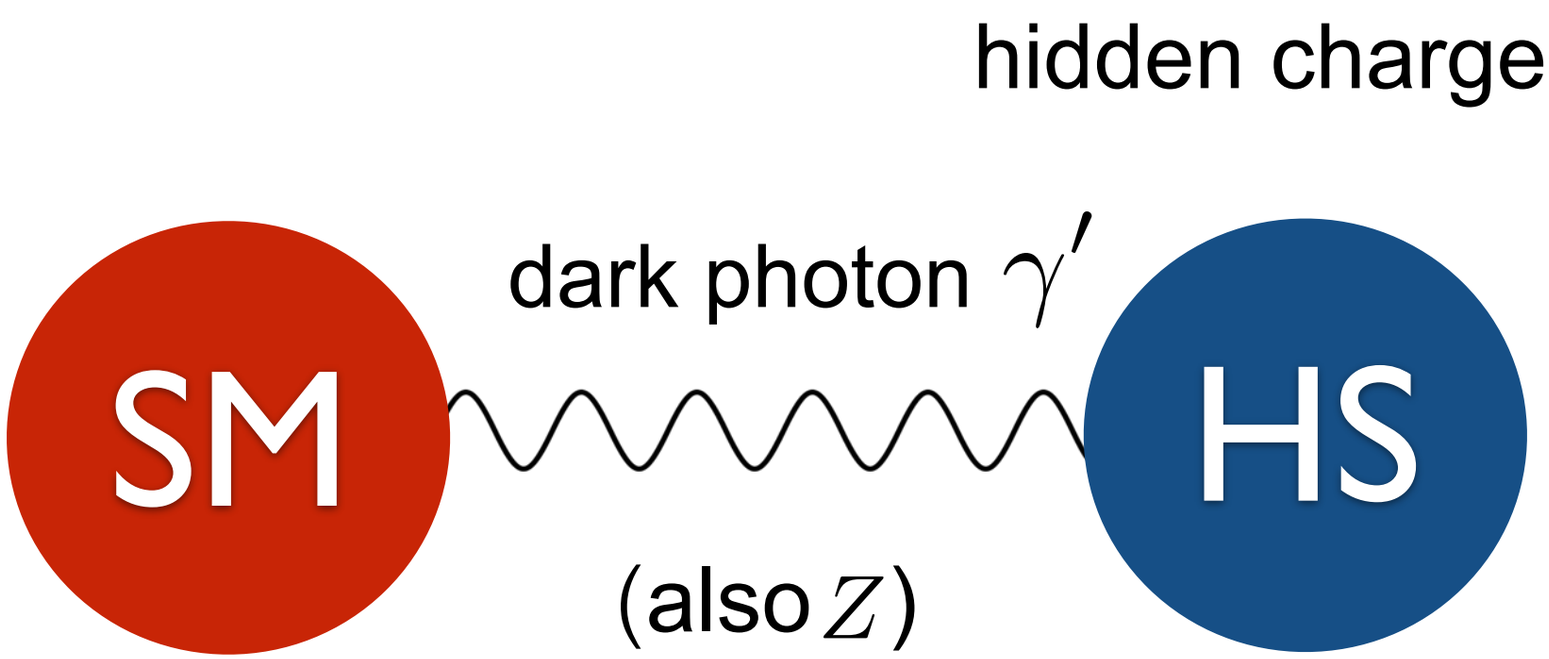
DARK MATTER THROUGH KINETIC MIXING



$$\mathcal{L} \supset i\bar{\chi}\not{D}'\chi - m_\chi \bar{\chi}\chi - \frac{1}{2} m_{\gamma'}^2 X_\mu X^\mu + \ldots$$

Feldman, Kors, Nath ’06
Pospelov, Ritz, Voloshin ’08
Chu, Hambye, M.T. ’12

DARK MATTER THROUGH KINETIC MIXING



χ has gauge interaction in HS α'

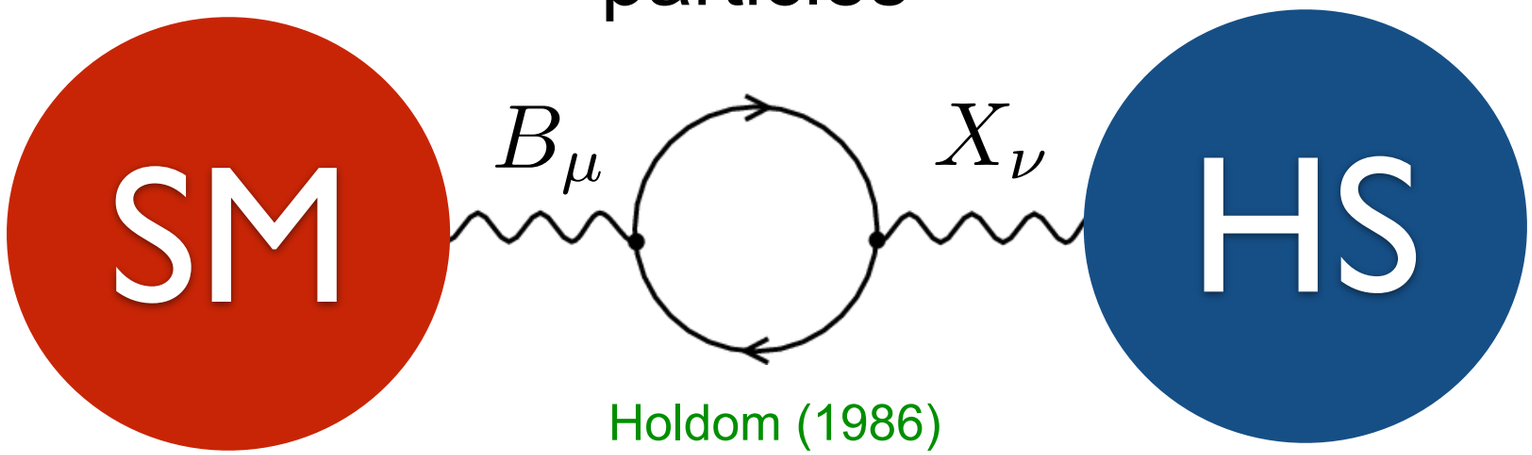
χ is stable ~ SM electron m_χ

χ suppressed coupling to SM $\kappa = \epsilon\sqrt{\alpha'/\alpha}$

4 parameters if dark photon massive $m_{\gamma'}$

FIMP THROUGH KINETIC MIXING

some
very heavy
particles



Holdom (1986)

κ is naturally tiny !

DM feebly coupled to the SM

Feebly Interacting Massive Particle
or
FIMP

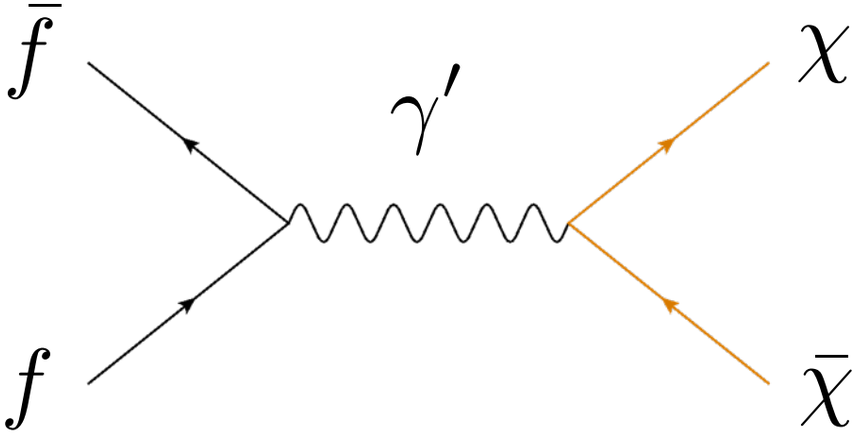
Chu, Hambye, M.T. ‘12

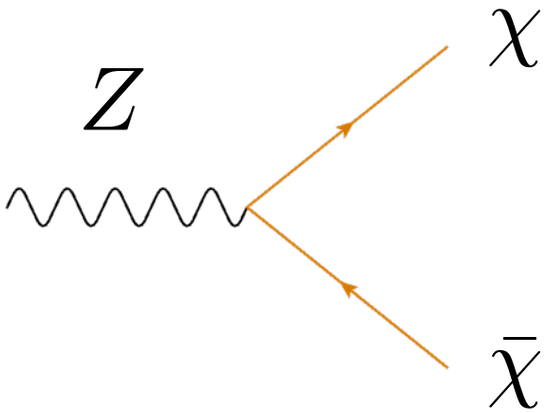
ABUNDANCE FROM FREEZE-IN

ABUNDANCE FROM FREEZE-IN

HS so feebly coupled that it never was in thermal equilibrium

FIMP abundance could have built up from slow particle creation processes



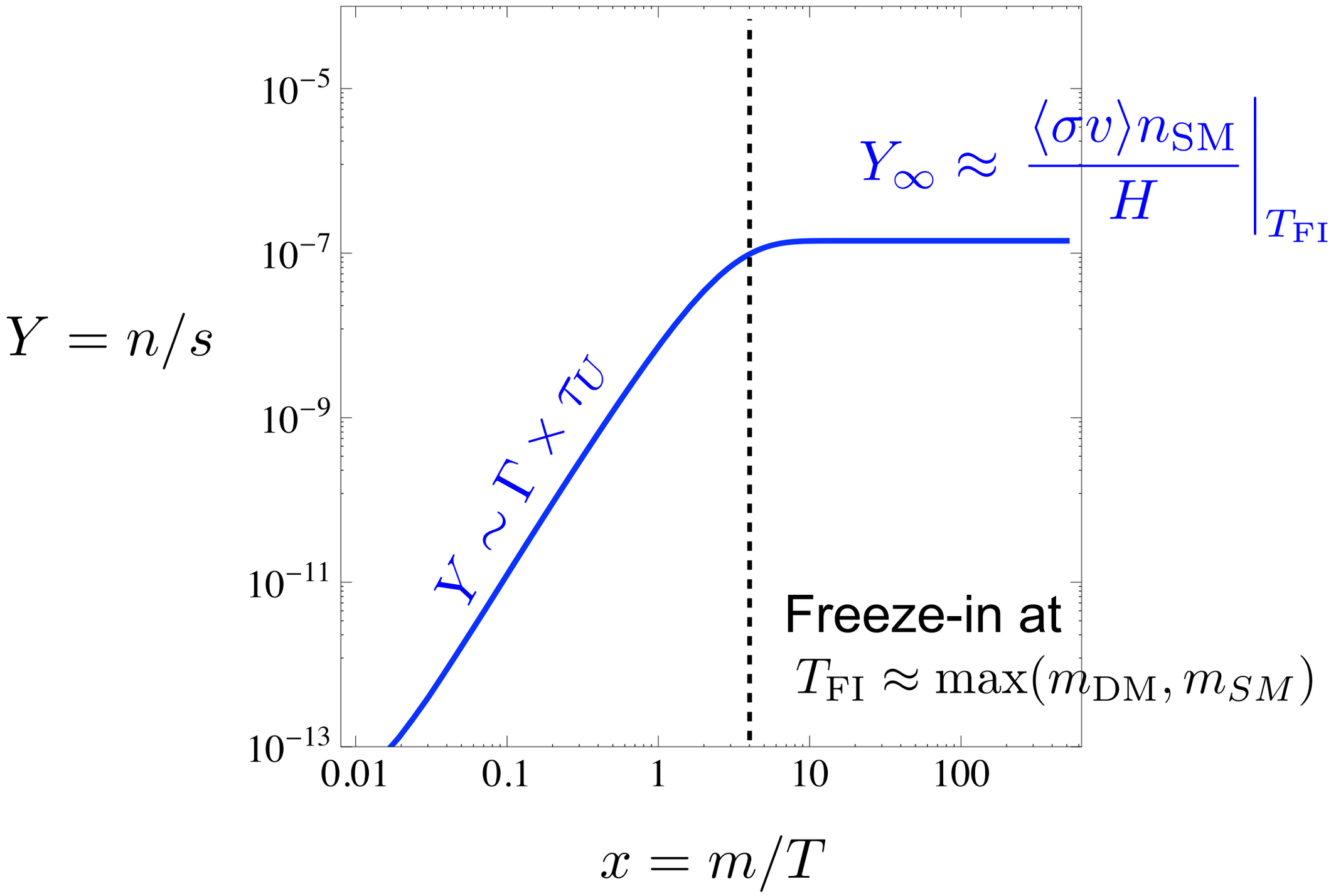


$$\propto \quad \kappa = \epsilon\sqrt{\alpha'/\alpha}$$

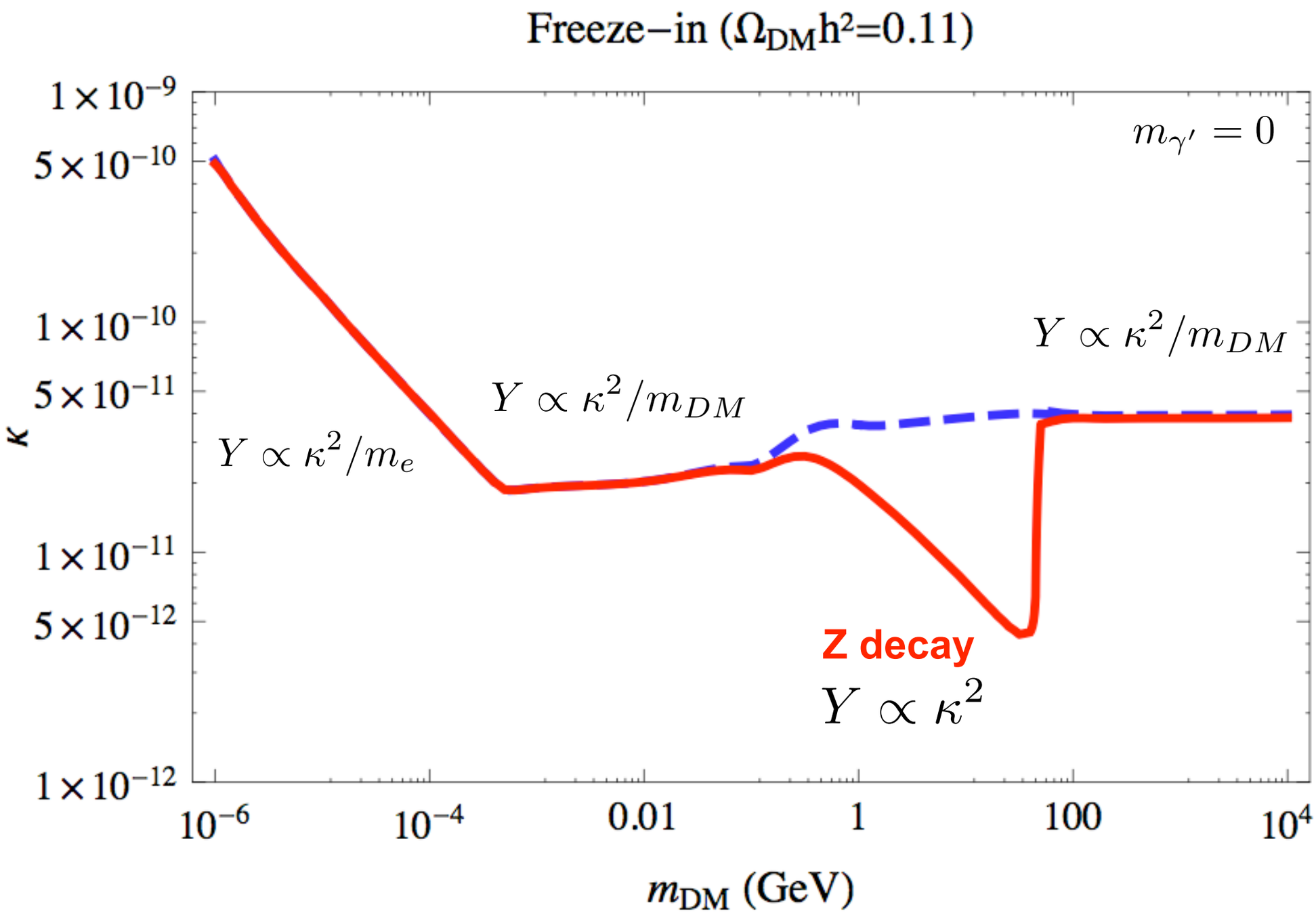
This is called FREEZE-IN

* Mc Donald ’02; Hall, Jedamzik & March-Russell ’10; Chu, Hambye, M.T. ‘12

ABUNDANCE FROM FREEZE-IN



ABUNDANCE FROM FREEZE-IN



Chu, Hambye, M.T. ‘12

ABUNDANCE FROM FREEZE-OUT

$$\mathrm{DM} + \mathrm{DM} \longrightarrow \mathrm{SM} + \mathrm{SM}$$

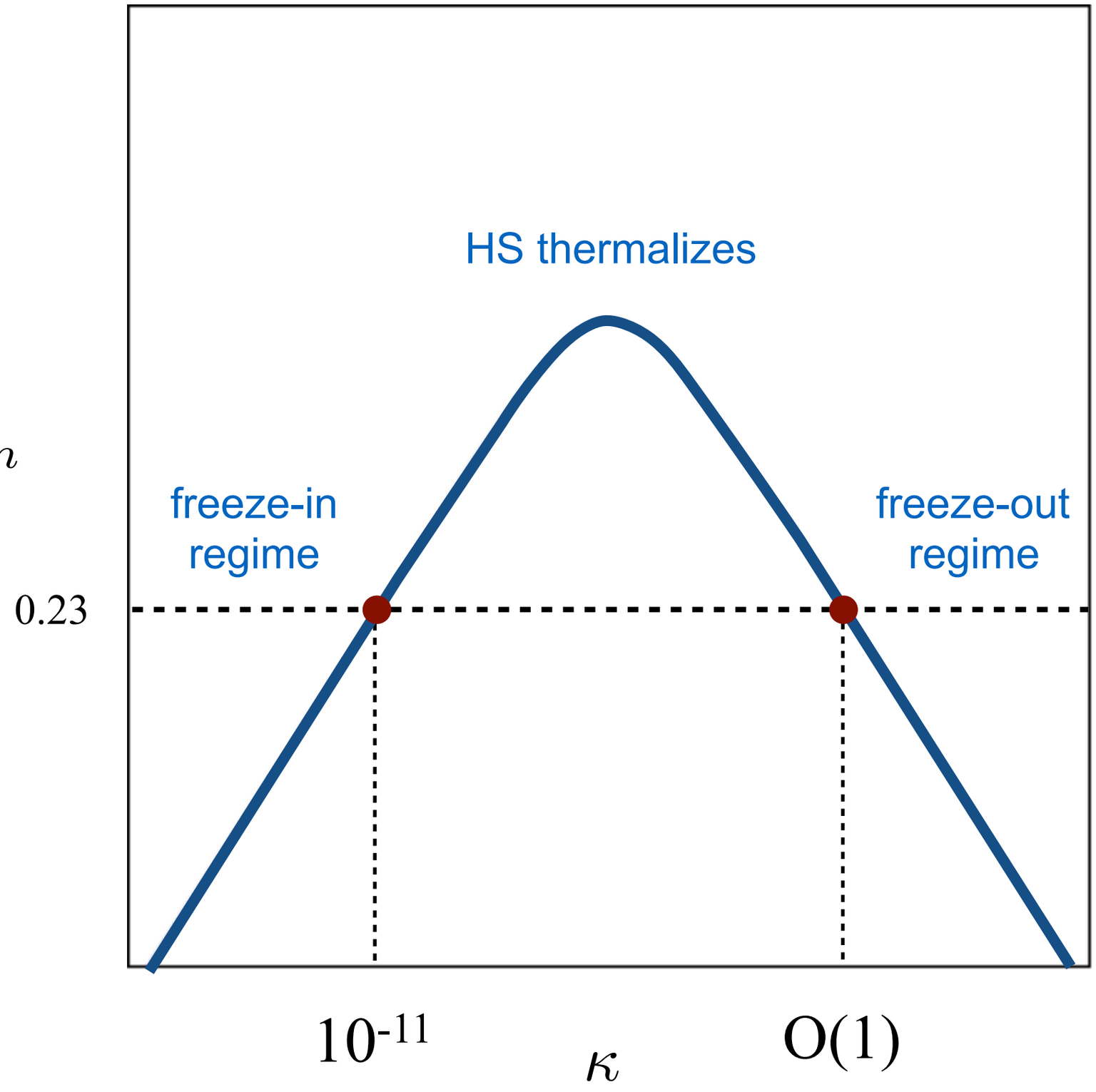
$$\Gamma = \sigma\, v\, n_{\mathrm{DM}}$$

ABUNDANCE FROM FREEZE-IN

$$\mathrm{SM} + \mathrm{SM} \longrightarrow \mathrm{DM} + \mathrm{DM}$$

$$\Gamma = \sigma\, v\, n_{\mathrm{SM}}$$

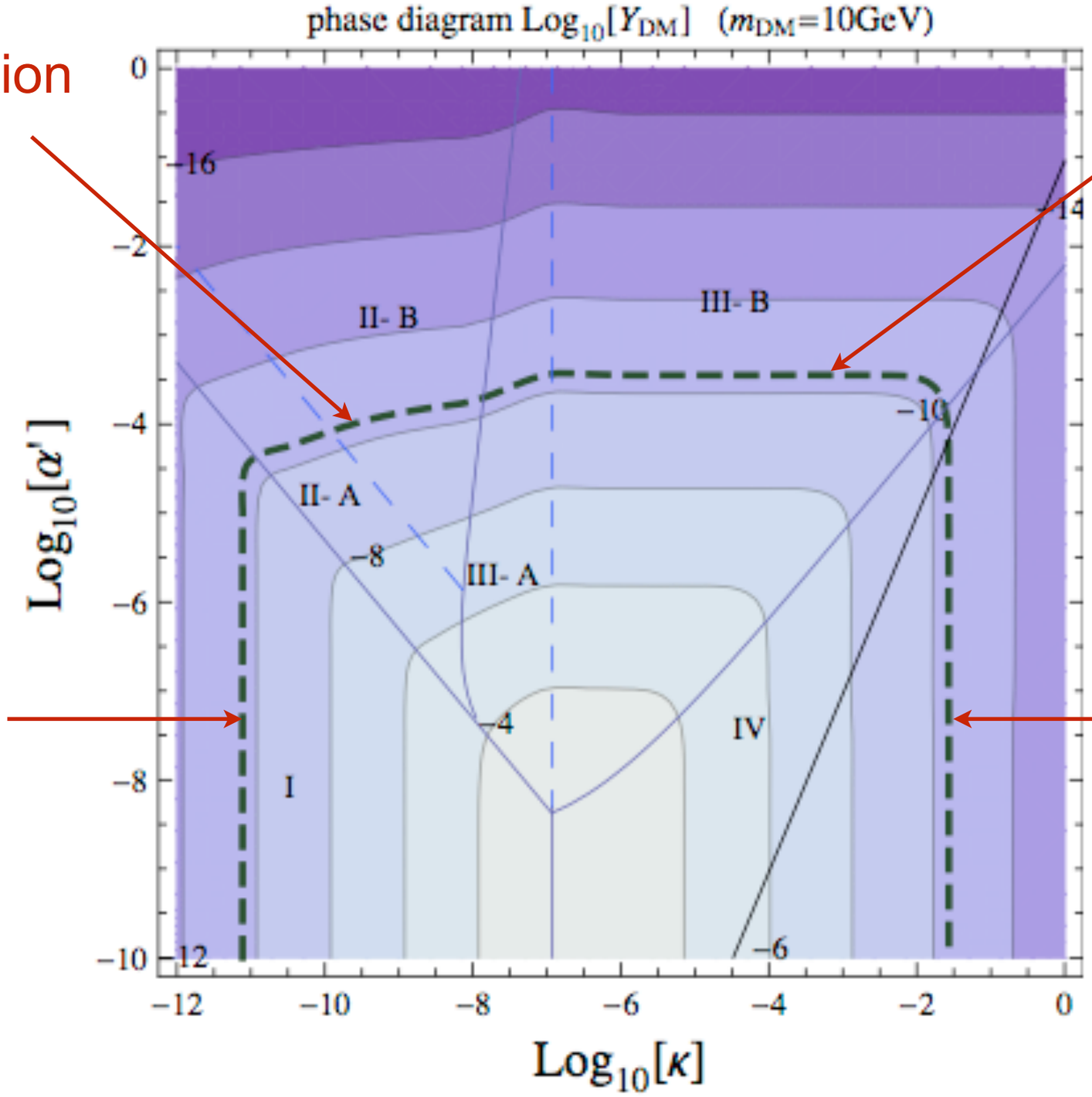
FREEZE-IN vs FREEZE-OUT



4 BASIC WAYS TO CREATE DM THROUGH A PORTAL

II : reannihilation

III : freeze-out in hidden sector (secluded DM)



I : freeze-in

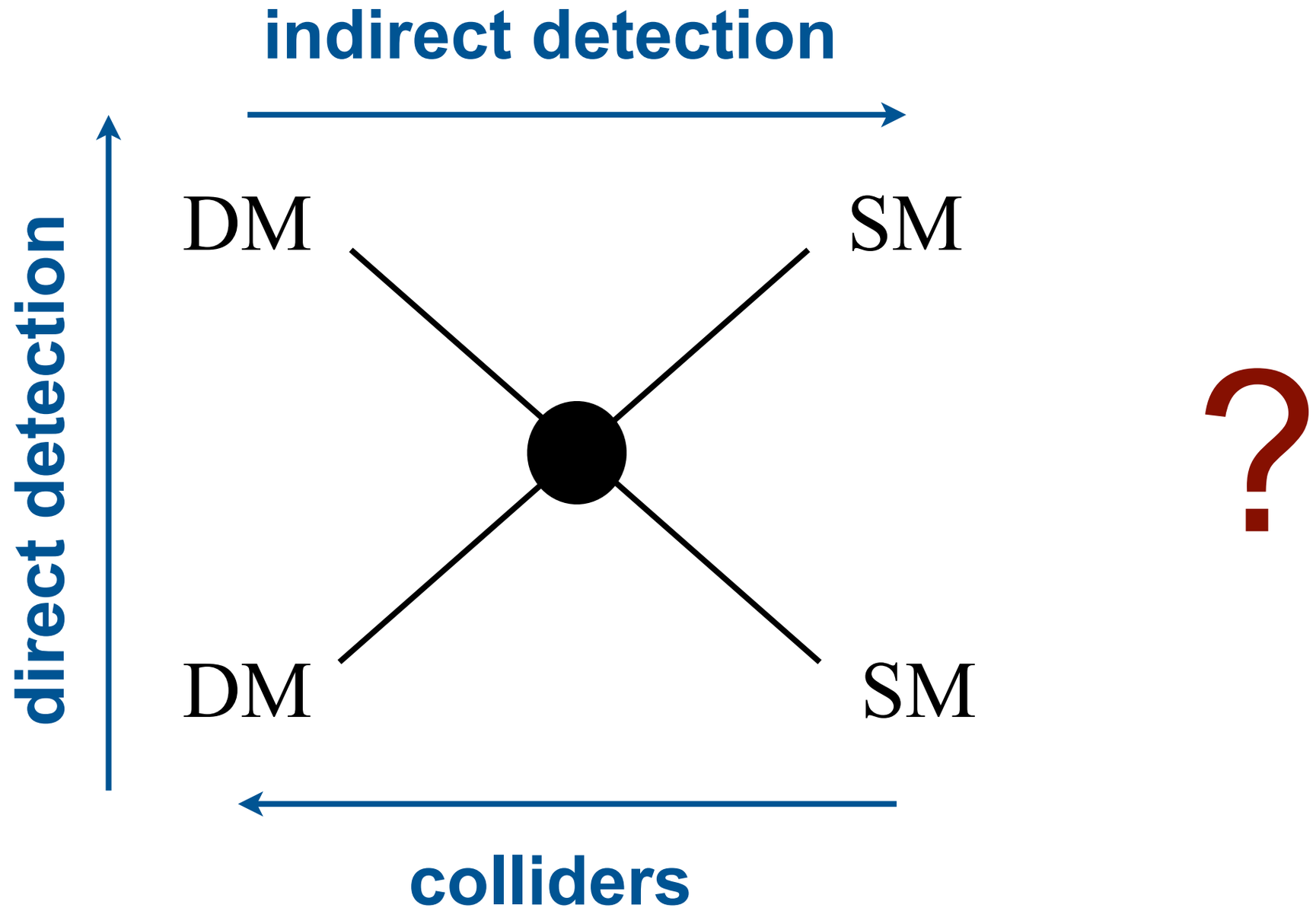
IV : usual freeze-out

Chu, Hambye, M.T. ‘12

DIRECT DETECTION IS TESTING FREEZE-IN

HOW TO TEST FREEZE-IN ?

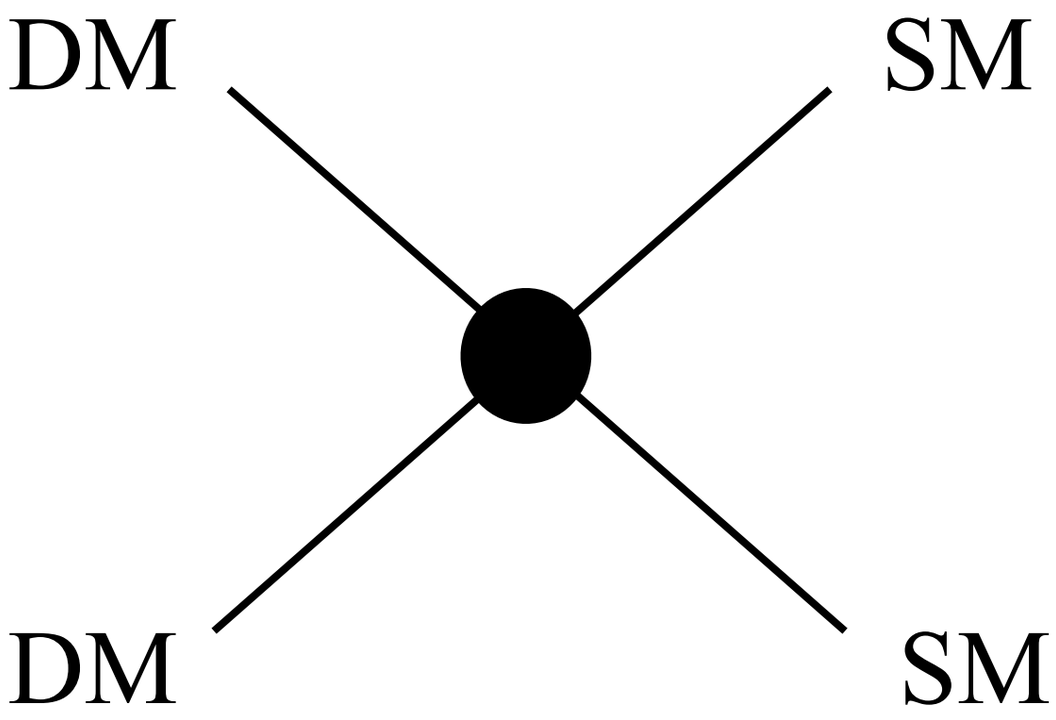
cosmic abundance $\kappa = \epsilon\sqrt{\alpha'/\alpha} = (10^{-11})$



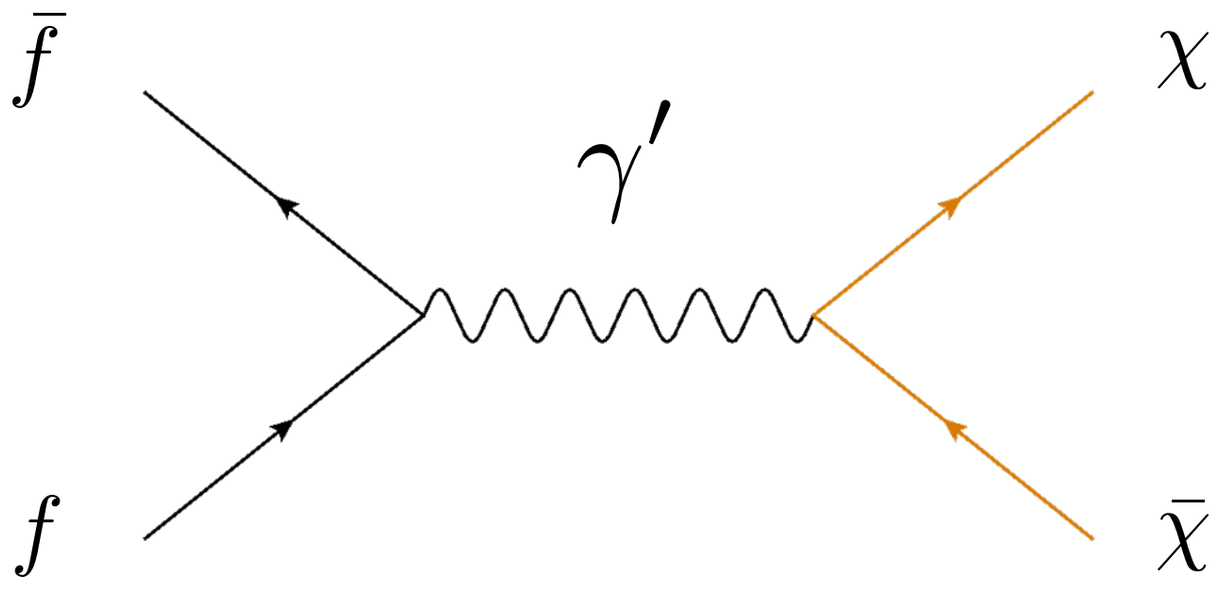
DIRECT DETECTION

cosmic abundance $\kappa = \epsilon\sqrt{\alpha'/\alpha} = (10^{-11})$

direct detection



PRODUCTION THROUGH S-CHANNEL



s-channel

determines relic abundance

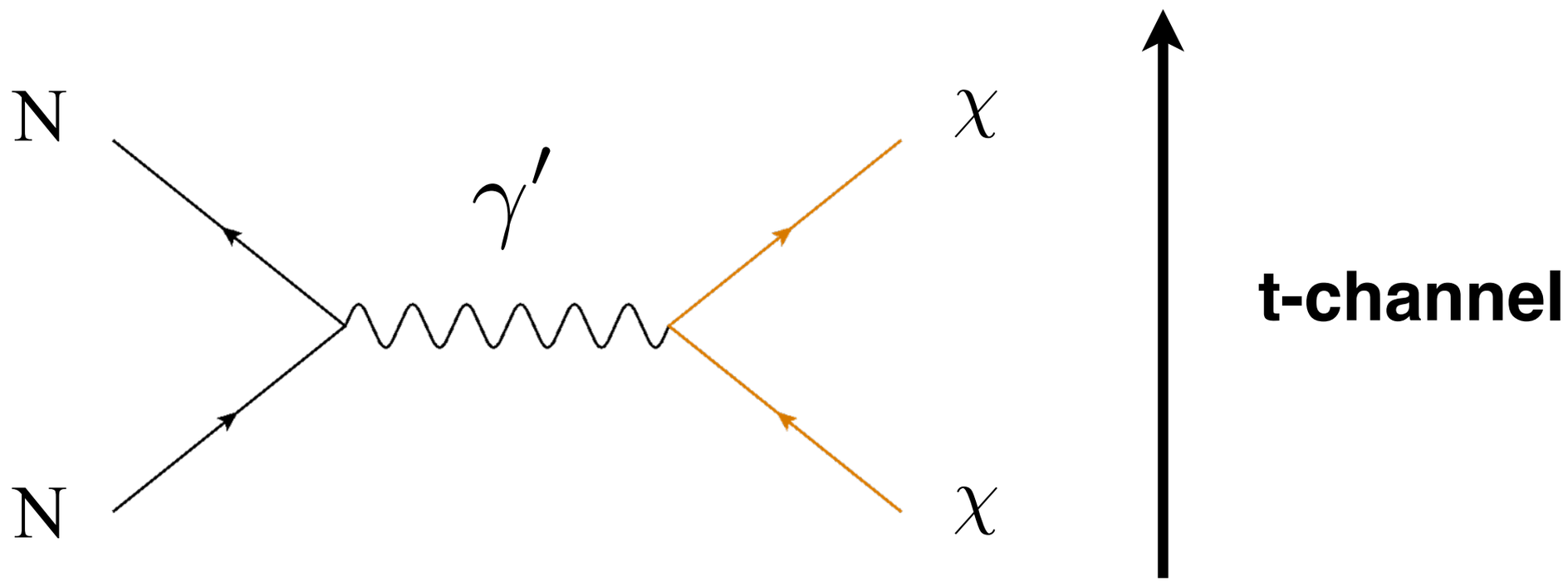
very small cross section

Rutherford (1911)

RUTHERFORD SCATTERING - DIRECT DETECTION

recoil energy

E_R



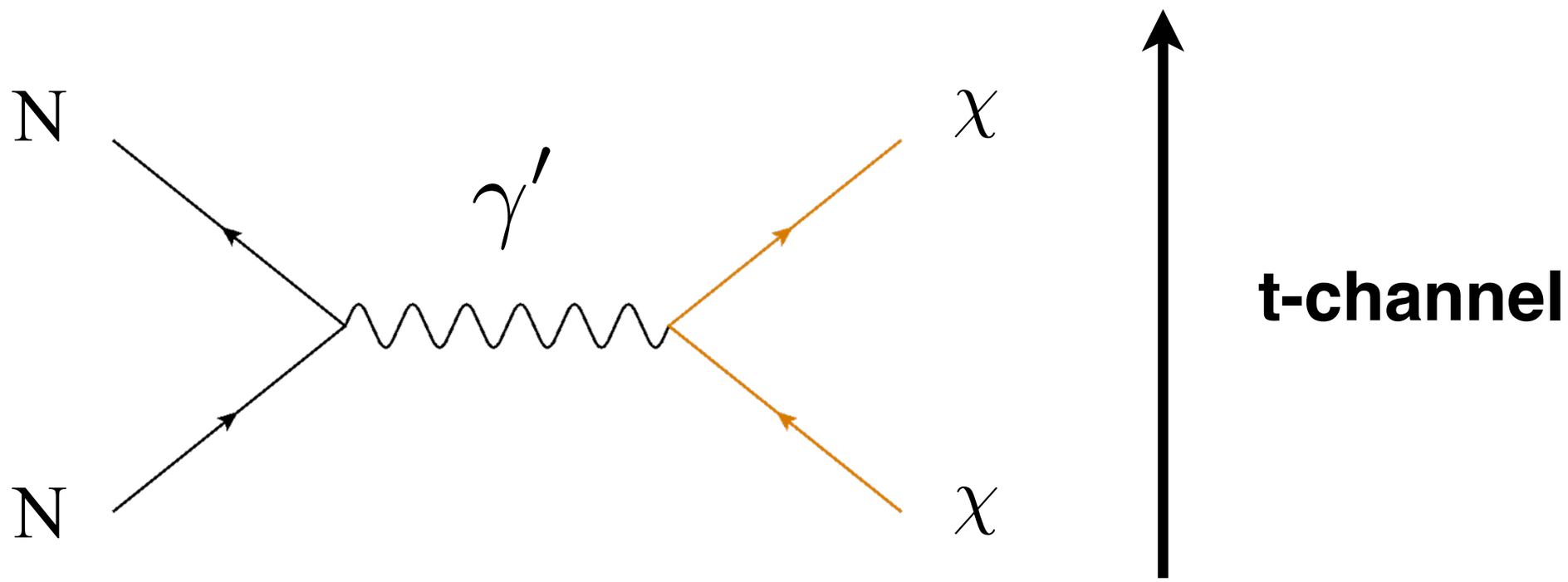
$$\frac{d\sigma}{dE_R} \propto \frac{m_N \kappa^2 \alpha^2 Z^2}{(2m_N E_R + m_{\gamma'}^2)^2}$$

RUTHERFORD SCATTERING - DIRECT DETECTION

recoil energy

E_R

in keV range

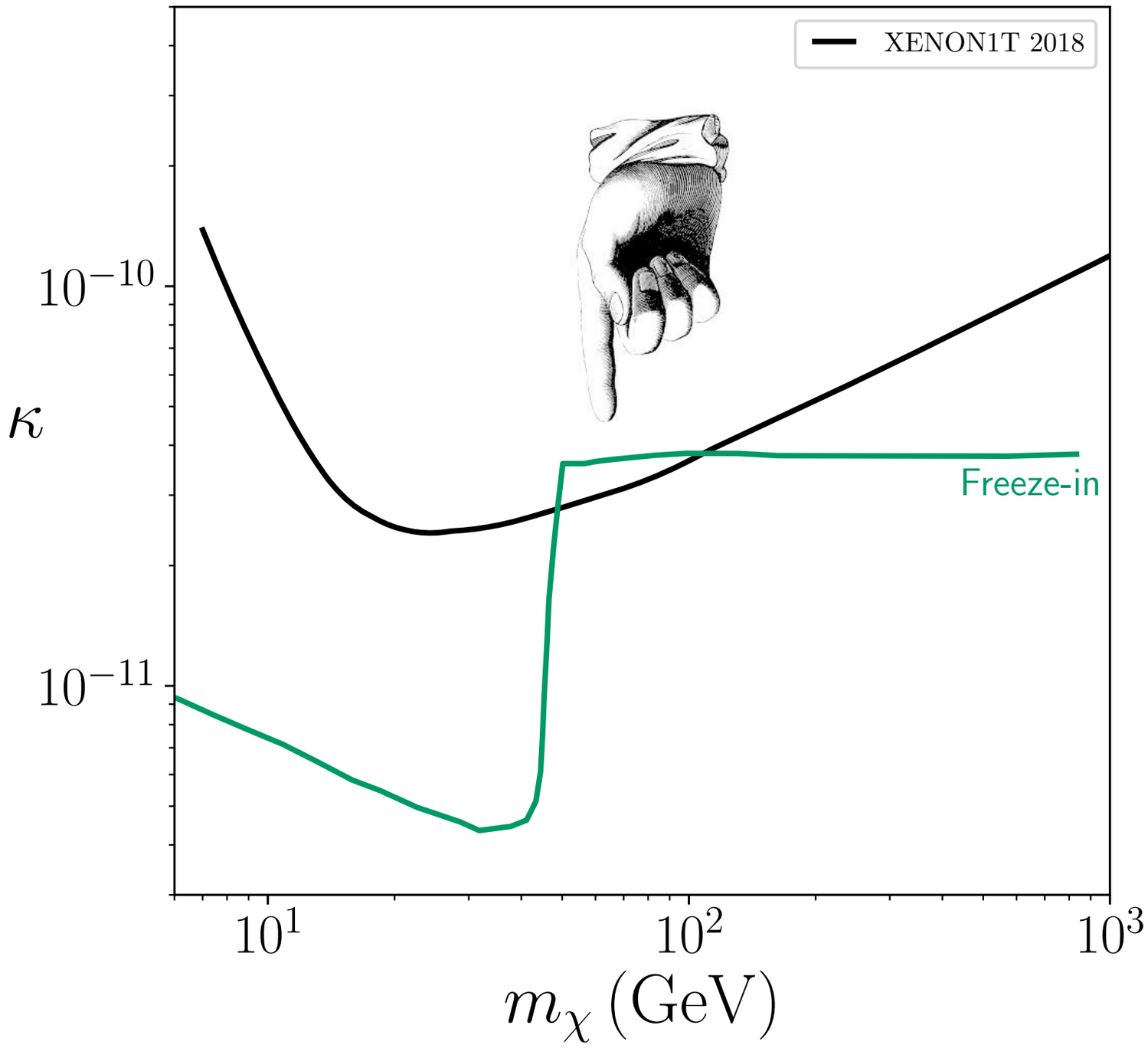


v ~ 200 km/s (halo DM)

$$\frac{d\sigma}{dE_R} \propto \frac{m_N \kappa^2 \alpha^2 Z^2}{(2 m_N E_R + m_{\gamma'}^2)^2} \sim \frac{1}{E_R^2}$$

Huge enhancement if $m_{\gamma'} \lesssim 40\ \mathrm{MeV}$

DIRECT DETECTiON IS TESTING FREEZE IN

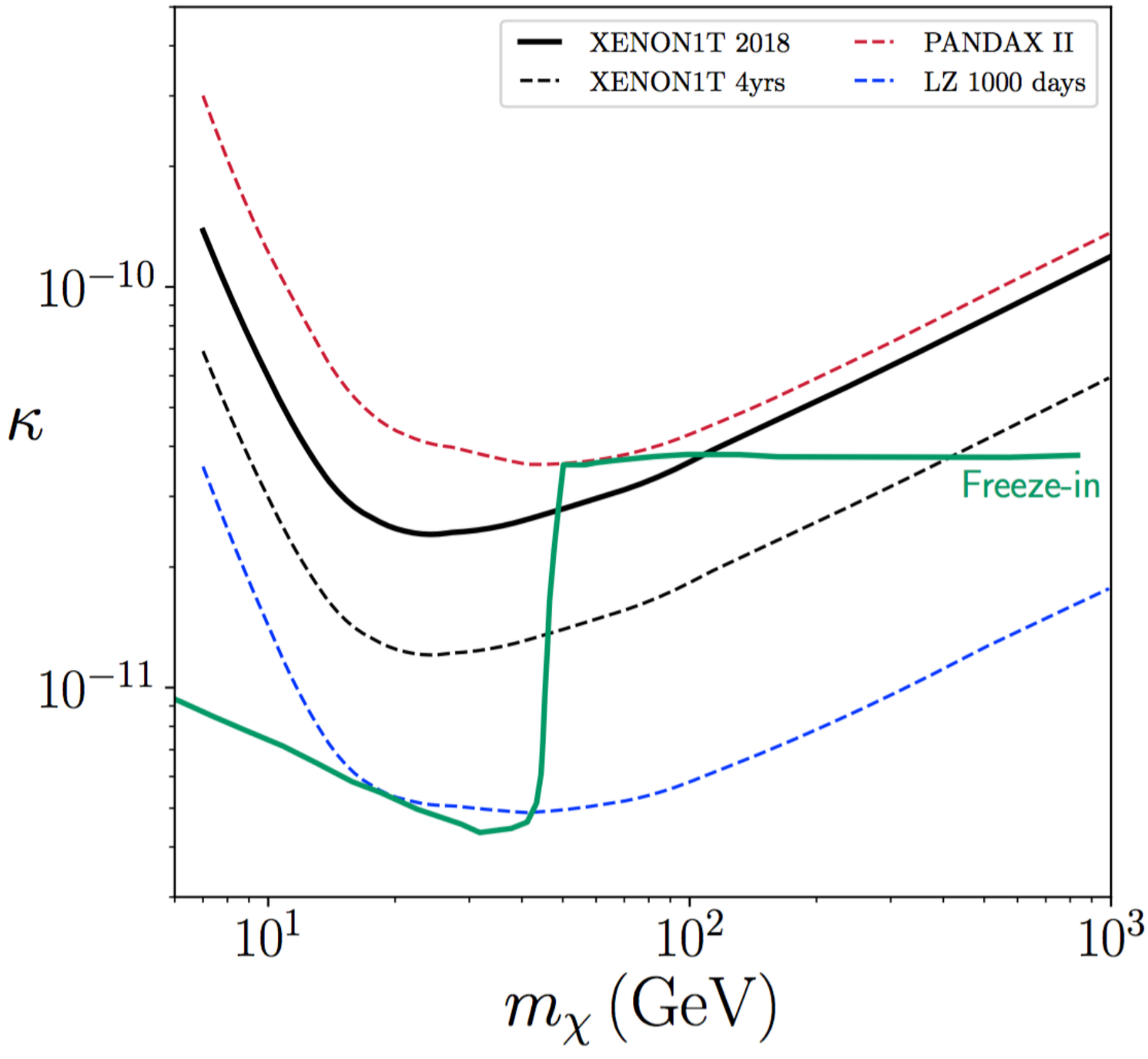


n.b.:
Not the same spectrum as a WIMP,
Must recasti the direct detection constraints

Very first direct detection test of a FI scenario !

Hambye, M.T., Vandecasteele, Vanderheyden ‘18

DIRECT DETECTiON IS TESTING FREEZE IN



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Not the same spectrum as a WIMP,
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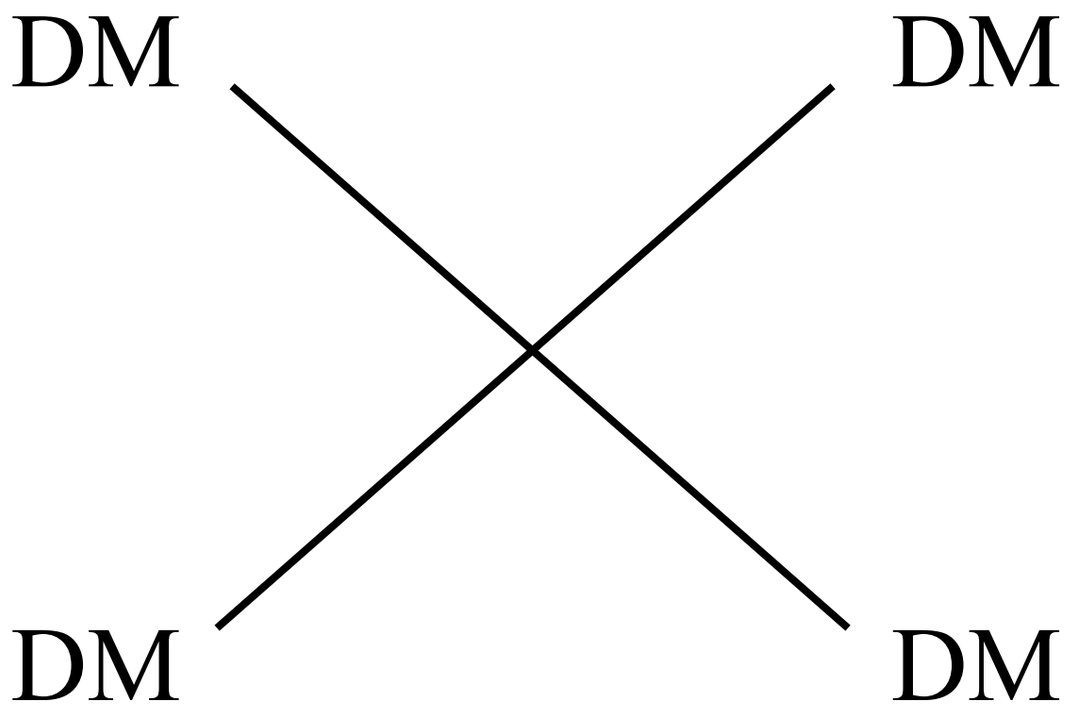
Very first direct detection test of a FI scenario !

Hambye, M.T., Vandecasteele, Vanderheyden ‘18

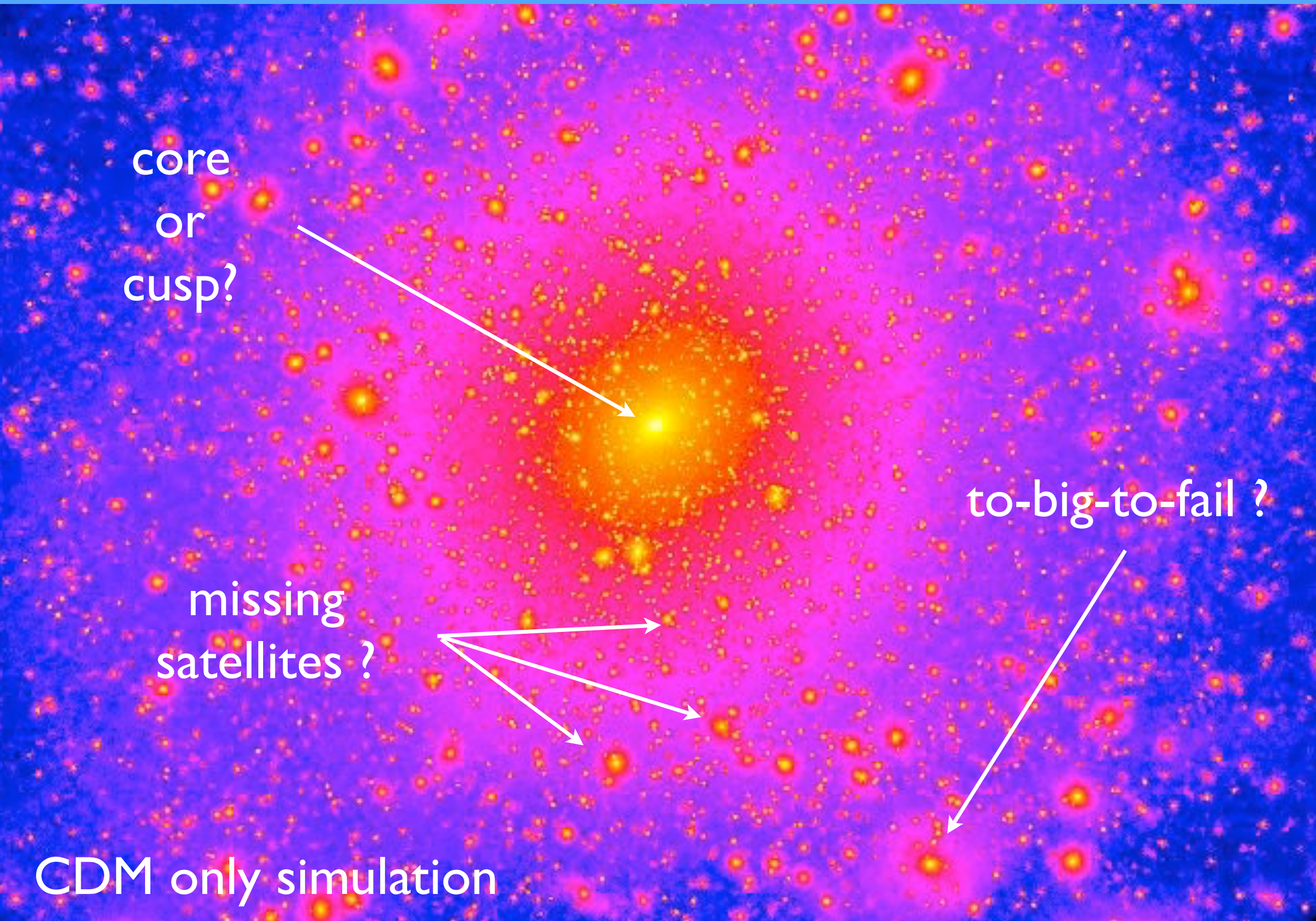
SELF-INTERACTING DARK MATTER

Self Interacting Dark Matter



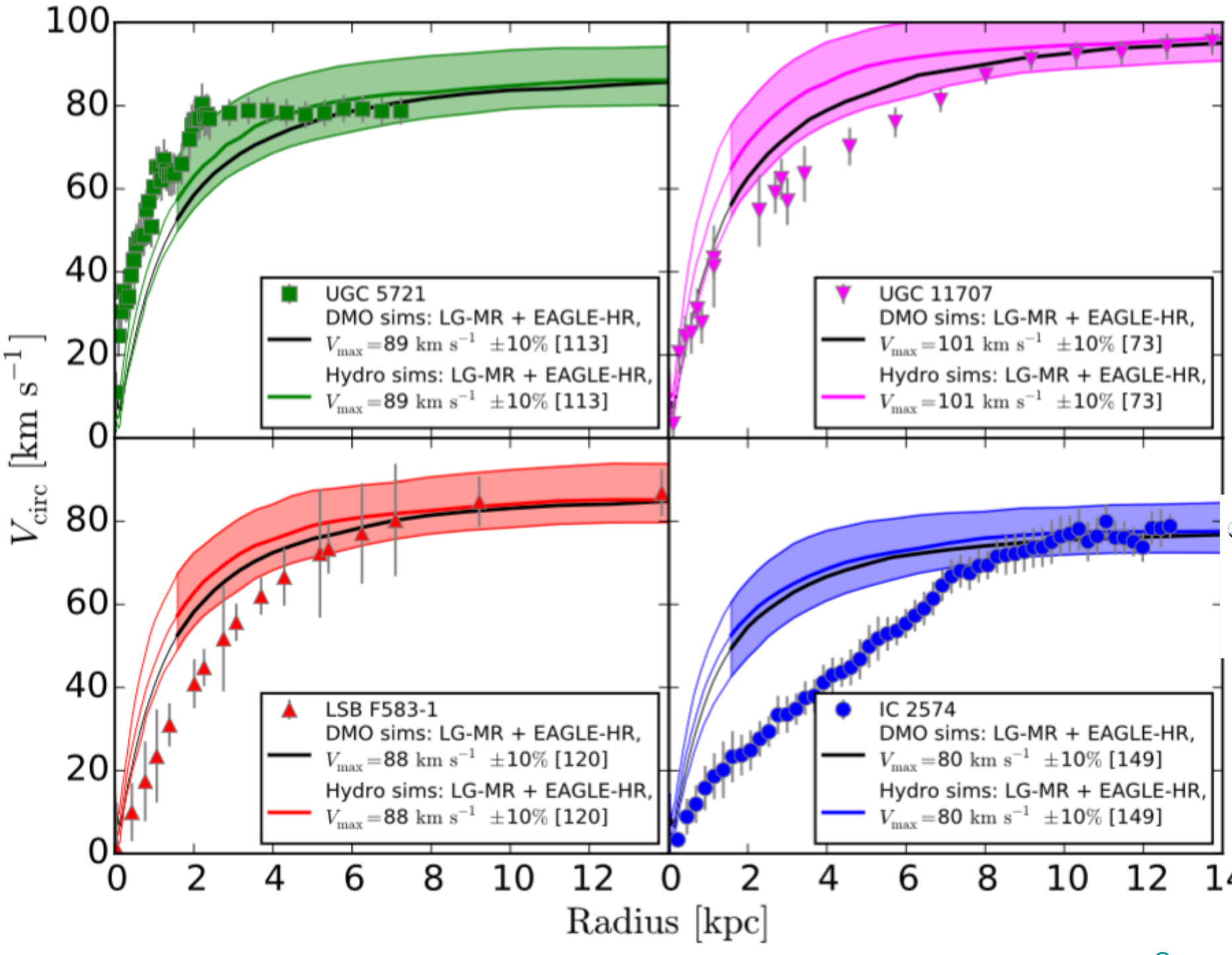
small scale structure issues (core/cusp),…

WHY SELF-INTERACTING DM ?



WHY SELF-INTERACTING DM ?

There is a **diversity problem** unexplained by CDM + BARYONS simulations (mostly dwarf galaxies)



all same V_{max}

Oman *et al*, arXiv:1504.01437

WHY SELF-INTERACTING DM ?

SIDM may alleviate the small-scale problems

core/cusp	Spergel & Steinhardt (2000),…
too-big-to-fail	Vogelsberger, Zavala & Loeb (2012),…
diversity	Hamada, Kaplinghat, Pace & Yu (2016),…

collisions ⟶ thermalized DM ⟶ core instead of cusp

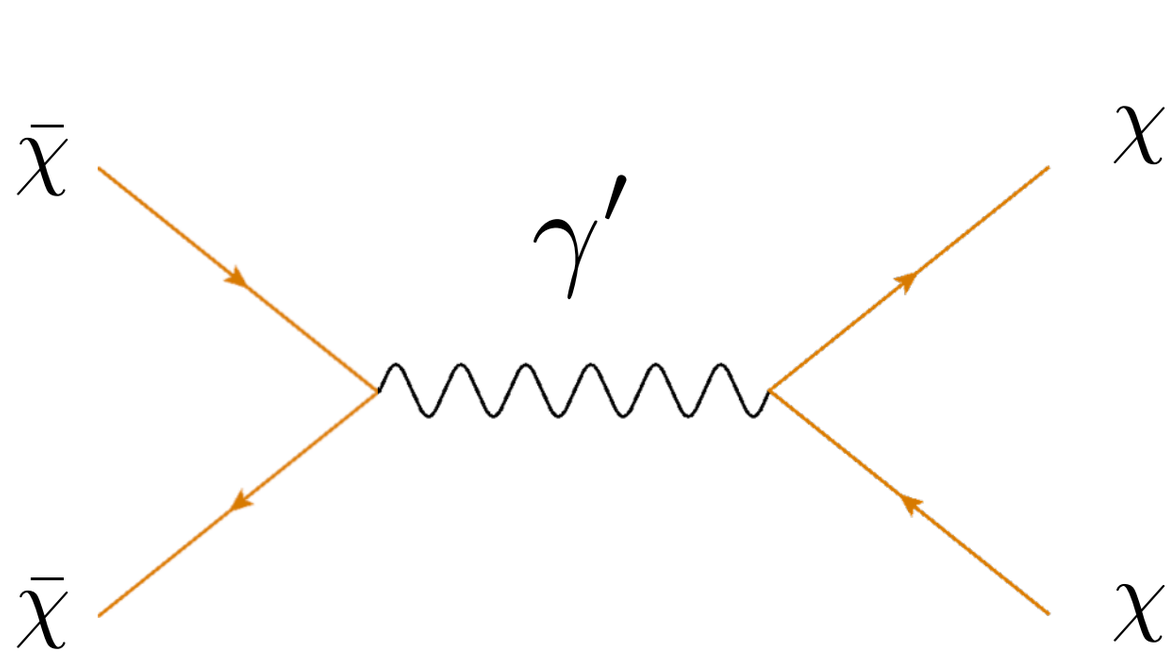
$$\frac{\sigma}{m} \sim \frac{\mathrm{cm}^2}{\mathrm{g}} \equiv \frac{\mathrm{barn}}{\mathrm{GeV}}$$

i.e. seemingly hadronic

but more generally light mediator

RUTHERFORD SCATTERING AGAIN

$v_{\rm dwarf} \sim 10$ km/s

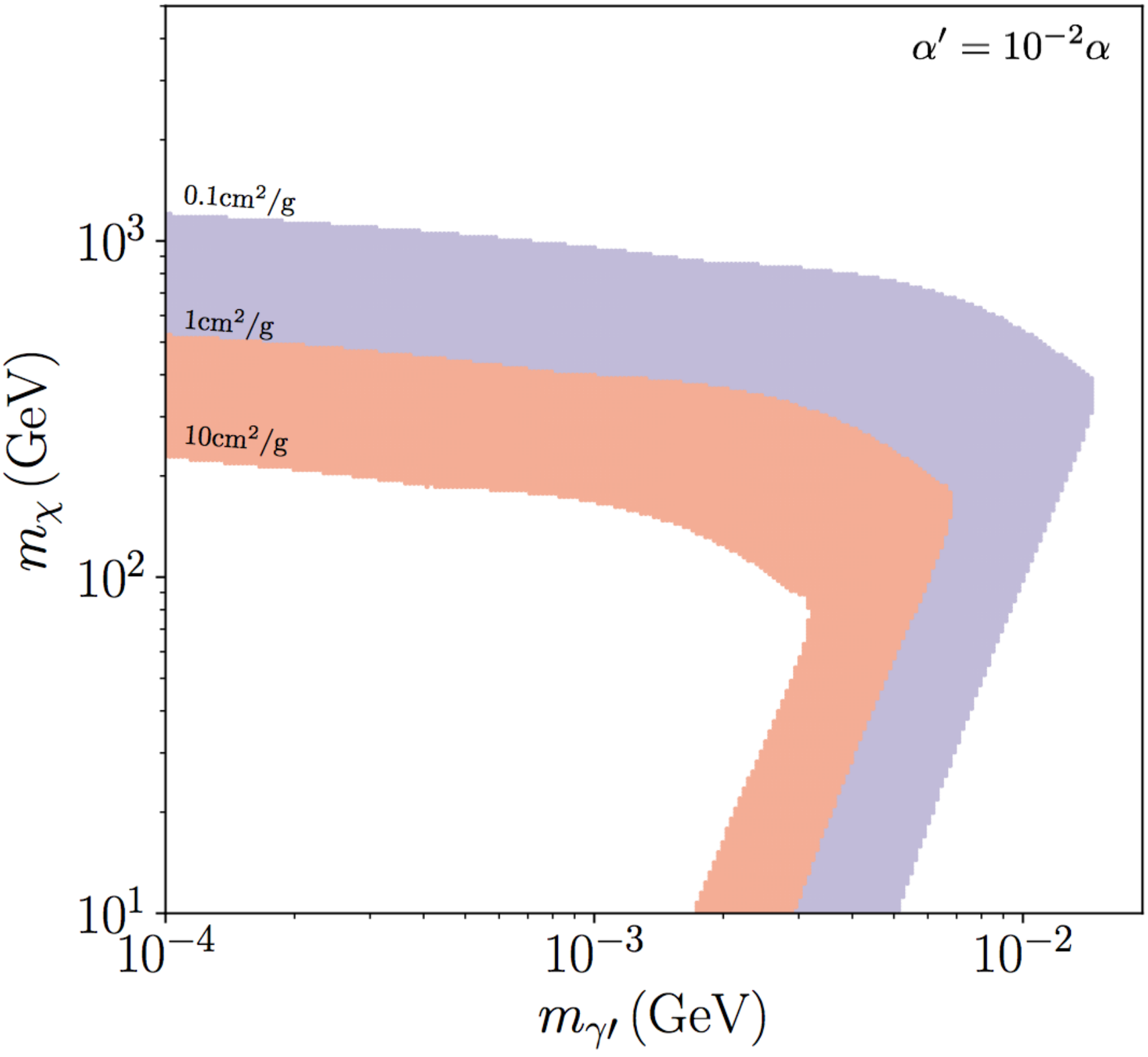


t-channel

$$\frac{d\sigma}{d\Omega} = \frac{4\alpha'^2 m_\chi^2}{(4m_\chi^2 v^2 \sin^2(\theta/2) + m_{\gamma'}^2)^2} \sim \alpha'^2 \frac{m_\chi^2}{m_{\gamma'}^4}$$

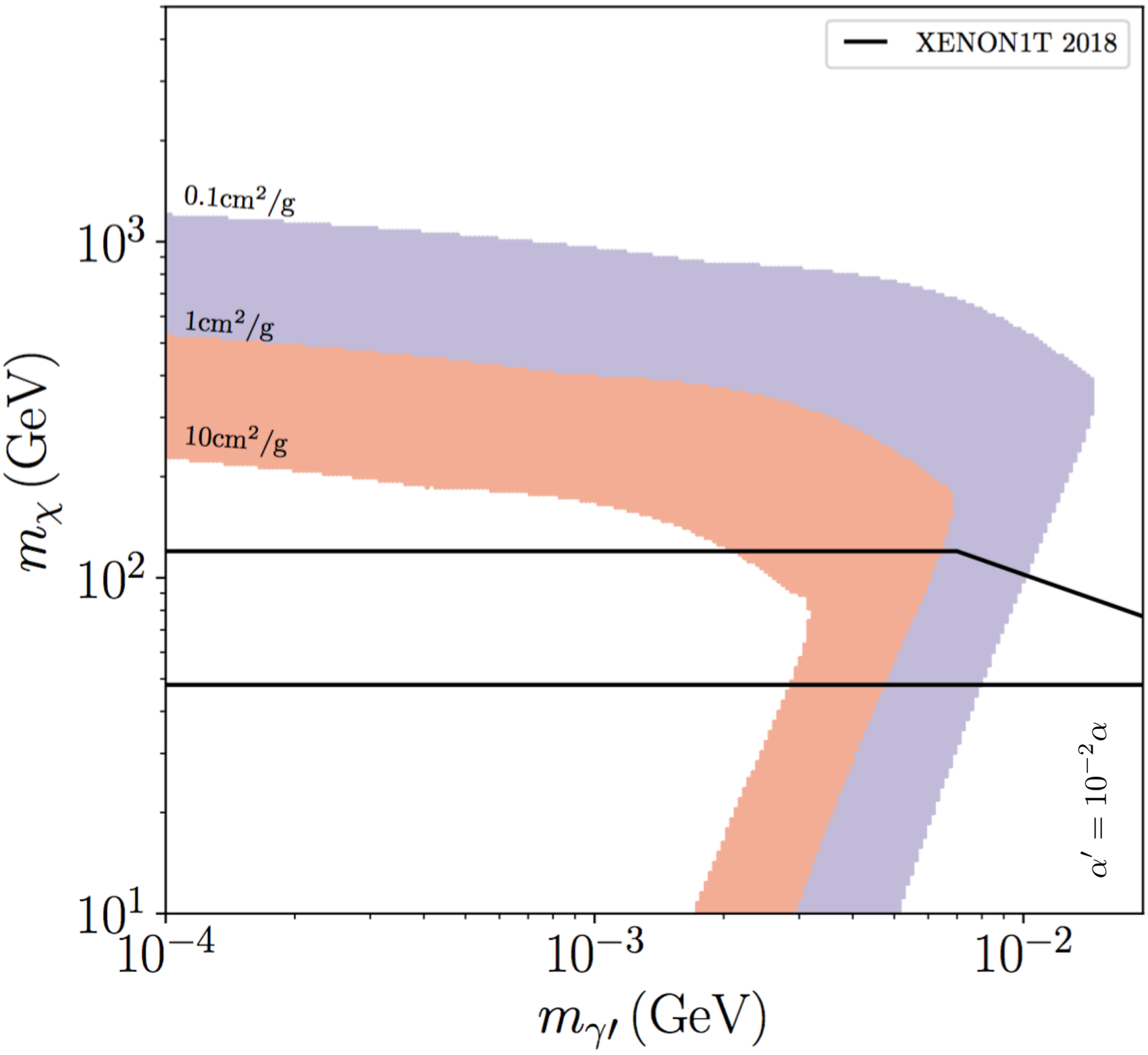
« As big as a barn » for $m_{\gamma'}$ in MeV range

SELF INTERACTING FIMP



Hambye, M.T., Vandecasteele, Vanderheyden ‘18

DIRECT DETECTION TESTS SELF-INTERACTING DM



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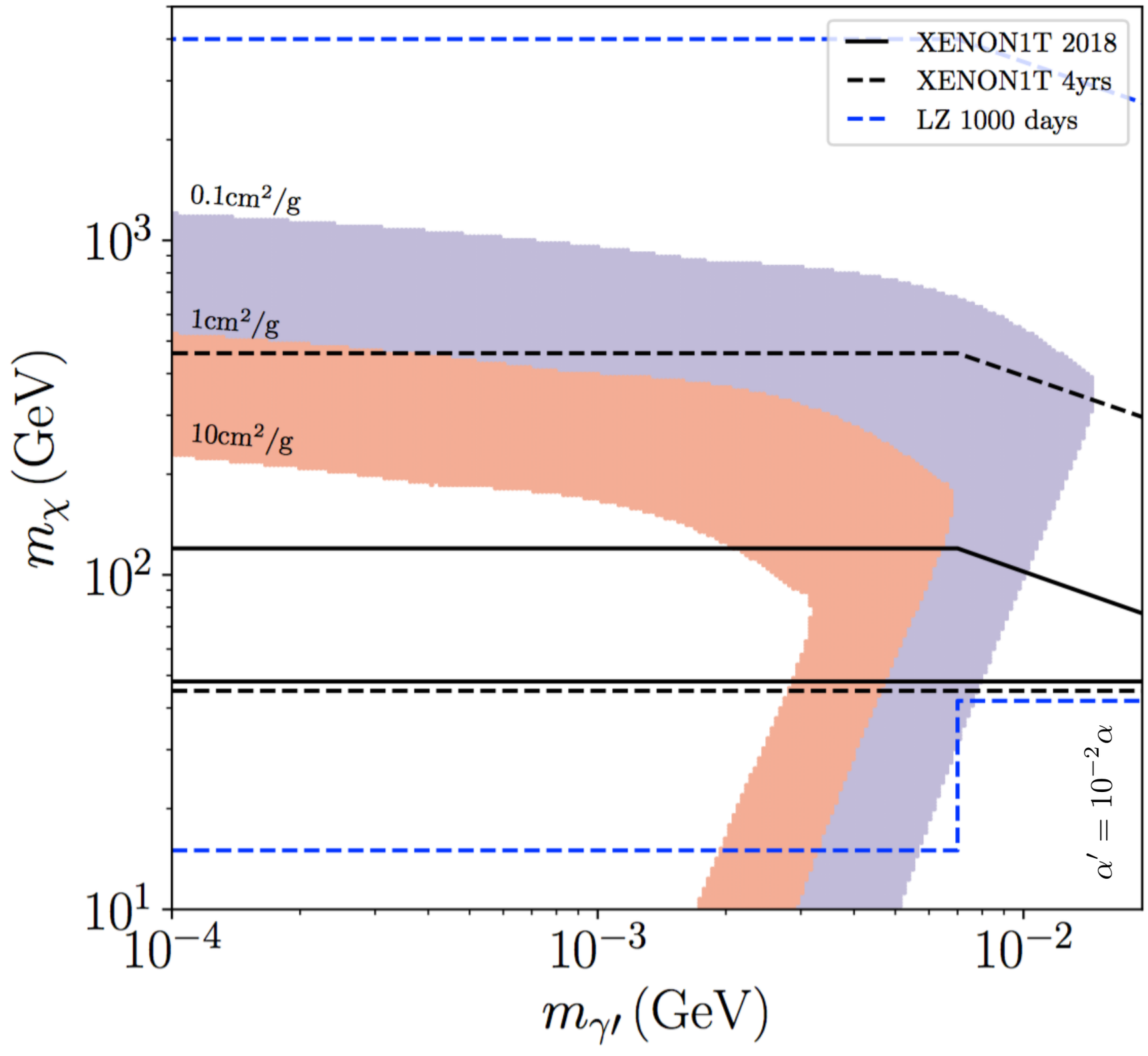
DIRECT DETECTION TESTS SELF-INTERACTING DM



Hambye, M.T., Vandecasteele, Vanderheyden ‘18

CONCLUSIONS

A **FIMP** AS AN ALTERNATIVE TO A **WIMP**

NATURAL FRAMEWORK : **HIDDEN SECTOR DM**

VERY FEEBLE INTERACTIONS

COSMIC ABUNDANCE REACHED THROUGH **FREEZE-IN**

FOR **LIGHT MEDIATOR ~ MeV** THIS PARADIGM IS BEING **TESTED BY DIRECT DETECTION** EXPERIMENTS

BY SAME TOKEN, **SELF-INTERACTING DARK MATTER**
(small scale structure issues)

CAVEAT : no clear connection to SM fundamental issues…

SIDM CAN DEVOUR NEUTRON STARS

$v_{\rm DM} \sim 200$ km/s

SIDM

Neutron Star
(not to the scale)

SIDM CAN DEVOUR NEUTRON STARS

Capture of DM by NS

Goldman & Nussinov (1989) - Kouvaris (2008)

Critical DM-n scattering cross section (neutron star)

$$\sigma_{\rm cr} = 0.45\, m_n\, R_\star/M_\star \approx 1.3\times 10^{-45}\,{\rm cm}^2$$

Maximal mass captured (normal DM environment)

$$N_{\rm acc} \approx 10^{39}({\rm TeV}/m_{\rm dm})$$

$$M_{\rm acc} \sim 10^{-15} M_\odot$$

This assumes DM does not annihilate e.g. **asymmetric DM**

SIDM CAN DEVOUR NEUTRON STARS

Assume asymmetric **fermionic** SIDM
with **attractive** self-interaction

$$V(r) = -\alpha \frac{e^{-\mu r}}{r}$$

Number of DM
to overcome
Fermi pressure

$$N_{\rm Ch} \approx \left(\frac{M_{\rm Pl}}{m_{\rm dm}}\right)^3$$

$\Rightarrow$

Number of SIDM
to overcome
Fermi pressure

$$N_{\rm Ch} \approx \left(\frac{\mu}{m_{\rm dm}\sqrt{\alpha}}\right)^3 \left(\frac{M_{\rm Pl}}{m_{\rm dm}}\right)^3$$

Small for SIDM that alleviates CDM problems!

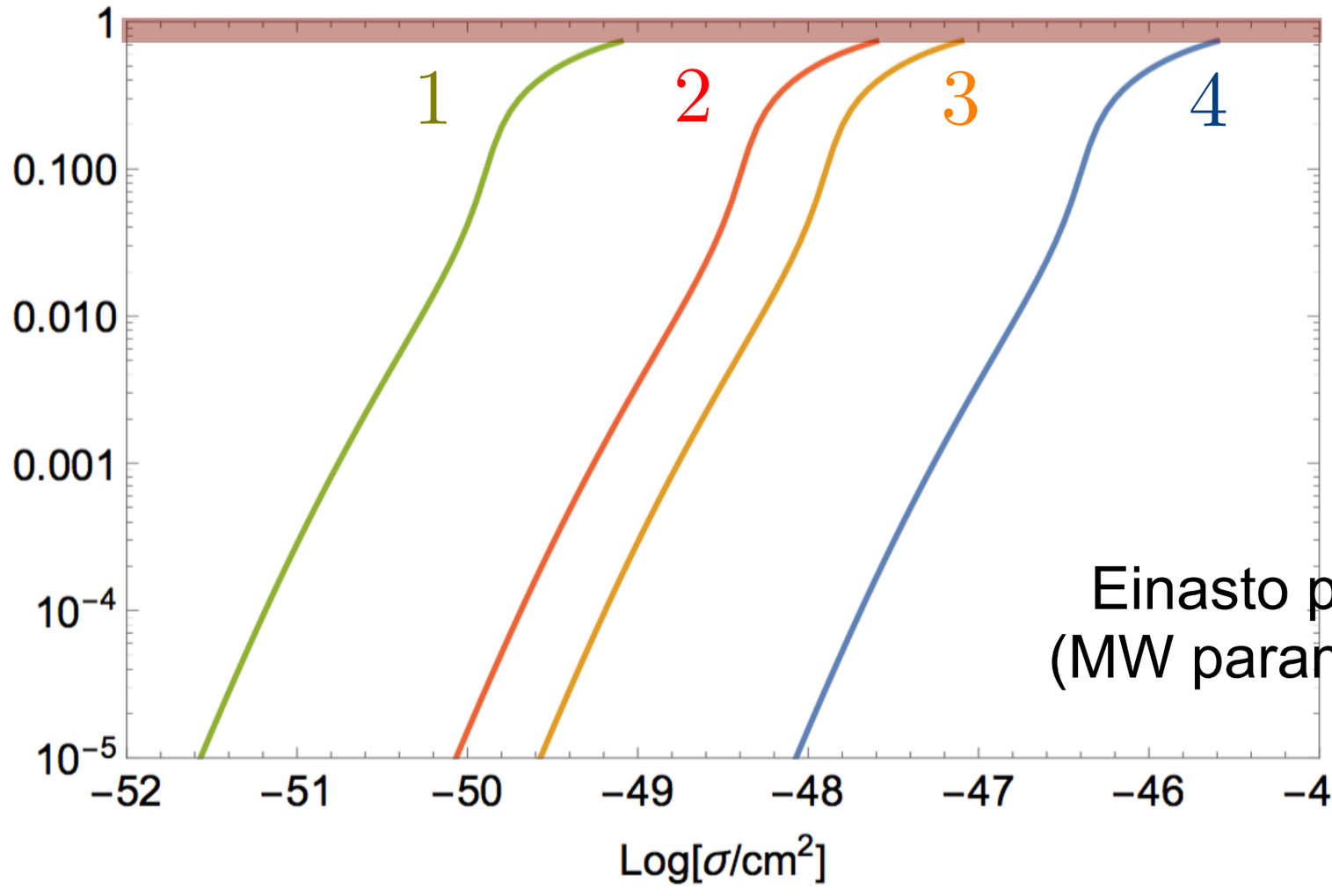
Kouvaris, Tinyakov & M.T. (2018); see also Bramante, Linden & Tsai (2017)

SIDM THAT WOULD DEVOUR NEUTRON STARS

SIDM candidates that alleviate CDM issues

#	α	μ	m	$N_{\rm cr}$	$N_{\rm Ch}$	$M_{\rm Ch}$
1	10^{-4}	1 MeV	1 TeV	$3 \cdot 10^{33}$	$6 \cdot 10^{35}$	$5 \cdot 10^{-19} M_\odot$
2	10^{-3}	10 MeV	1 TeV	$5 \cdot 10^{35}$	$2 \cdot 10^{37}$	$2 \cdot 10^{-17} M_\odot$
3	10^{-3}	1 MeV	200 GeV	$1.3 \cdot 10^{34}$	$3 \cdot 10^{38}$	$5 \cdot 10^{-17} M_\odot$
4	10^{-4}	1 MeV	200 GeV	$3.7 \cdot 10^{34}$	$8 \cdot 10^{39}$	$2 \cdot 10^{-15} M_\odot$

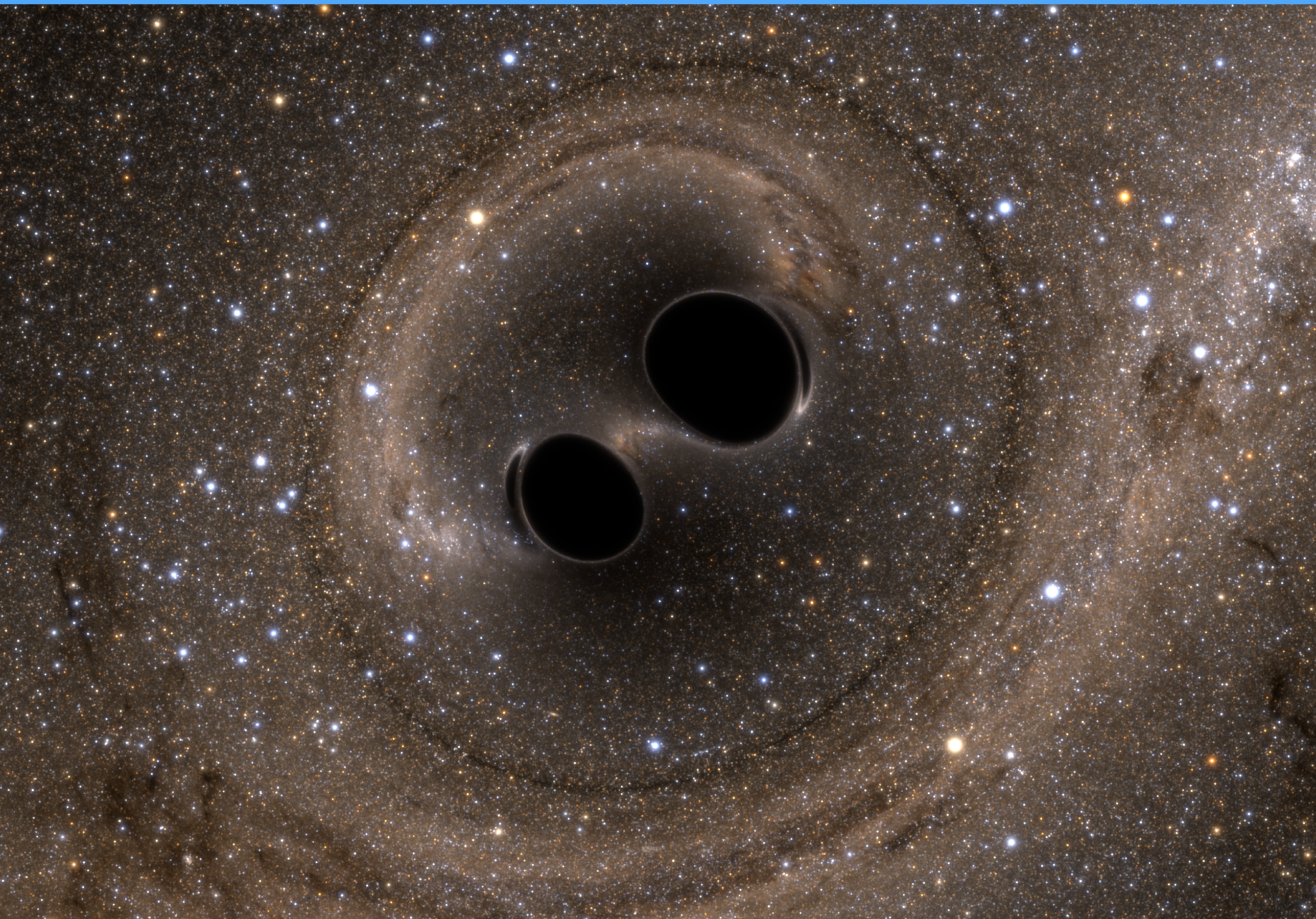
Fraction of NS transformed into BH



J2124-3358
(270 pc, 7.2 Gyr old NS)

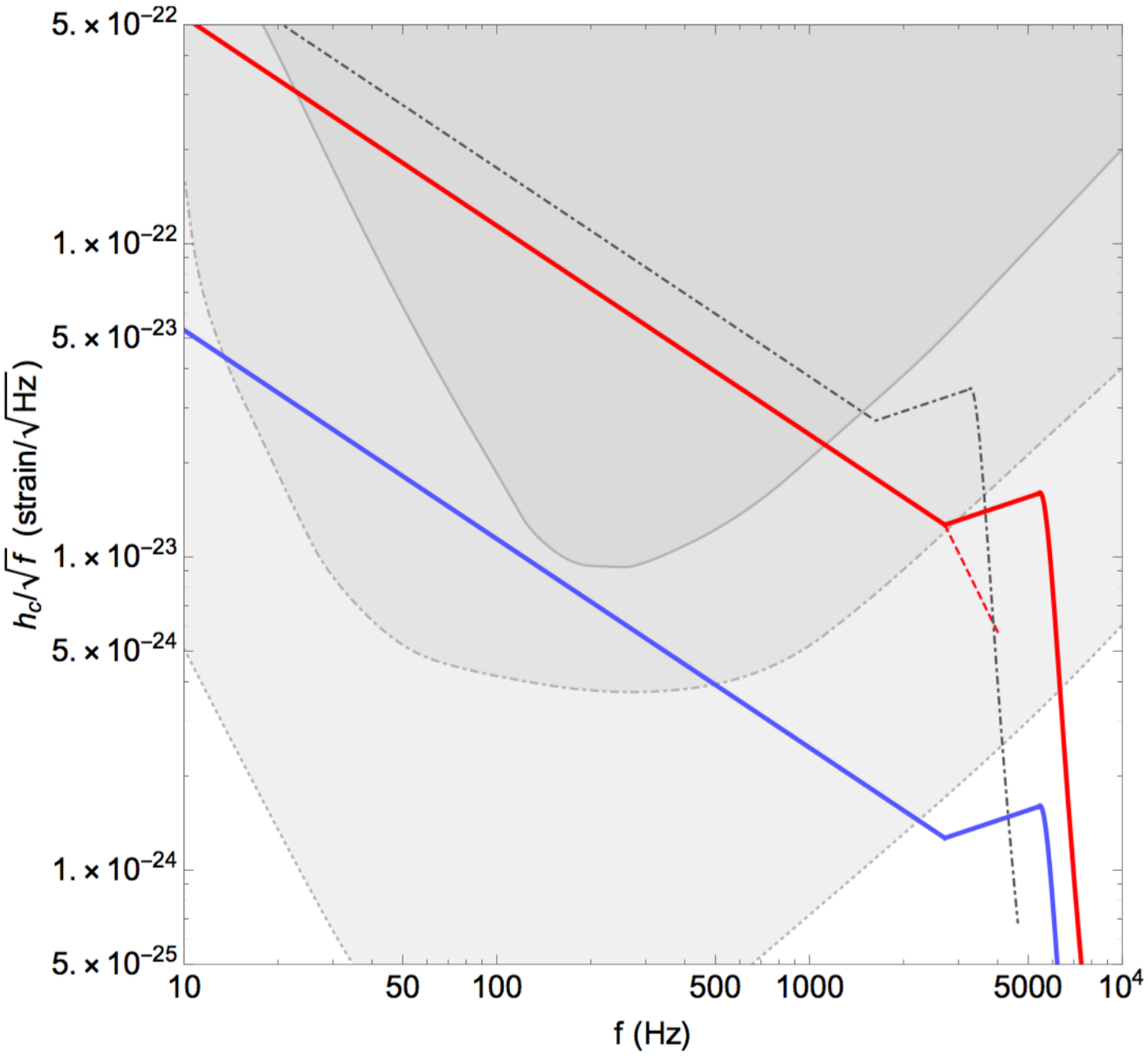
Kouvaris, Tinyakov & MT (2018)

SOLAR MASS PRIMORDIAL BLACK HOLES ?



SOLAR MASS BLACK HOLES ?

Detectors	BNS range (Mpc)	BNS detections (per year)
LIGO/Virgo	105/80	$4-80$ (2020+)
KAGRA	100	$11-180$ (2024+)
ET	$\sim 5 \cdot 10^3$ ($z \approx 2$)	$\mathcal{O}(10^3 - 10^7)$



CONCLUSIONS

A **FIMP** AS AN ALTERNATIVE TO A **WIMP**

NATURAL FRAMEWORK : **HIDDEN SECTOR DM**

VERY FEEBLE INTERACTIONS

COSMIC ABUNDANCE REACHED THROUGH **FREEZE-IN**

FOR **LIGHT MEDIATOR ~ MeV** THIS PARADIGM IS BEING **TESTED BY DIRECT DETECTION** EXPERIMENTS

BY SAME TOKEN, **SELF-INTERACTING DARK MATTER**
(small scale structure issues)

POTENTIALLY DRAMATIC CONSEQUENCES OF SIDM

CAN DESTROY NS INTO
SOLAR MASS SCALE BLACK HOLES

CONCLUSIONS

I REVIEWED **FIMP** AS AN ALTERNATIVE TO A WIMP

A **HIDDEN SECTOR** PROVIDES A NATURAL FRAMEWORK FOR A FIMP

IT IS A DM CANDIDATE WITH **VERY FEEBLE** INTERACTION

COSMIC ABUNDANCE CAN BE REACHED THROUGH **FREEZE-IN**

WHILE SEEMINGLY DIFFICULT TO TEST, **XENON1T** CURRENT DATA ARE ALREAD
TESTING SUCH SCENARIO, FOR **LIGHT MEDIATOR ~ MeV**

A **LIGHT MEDIATOR** LEADS TO STRONG **SELF-INTERACTIONS** IN THE RANGE
REQUIRED TO ALLEVIATE **SMALL SCALE ISSUES** OF CDM