TWO ASPECTS OF SIDM

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GGI, Florence, September 11th 2018

SIDM MOTIVATION

DIRECT DETECTION IS TESTING FI

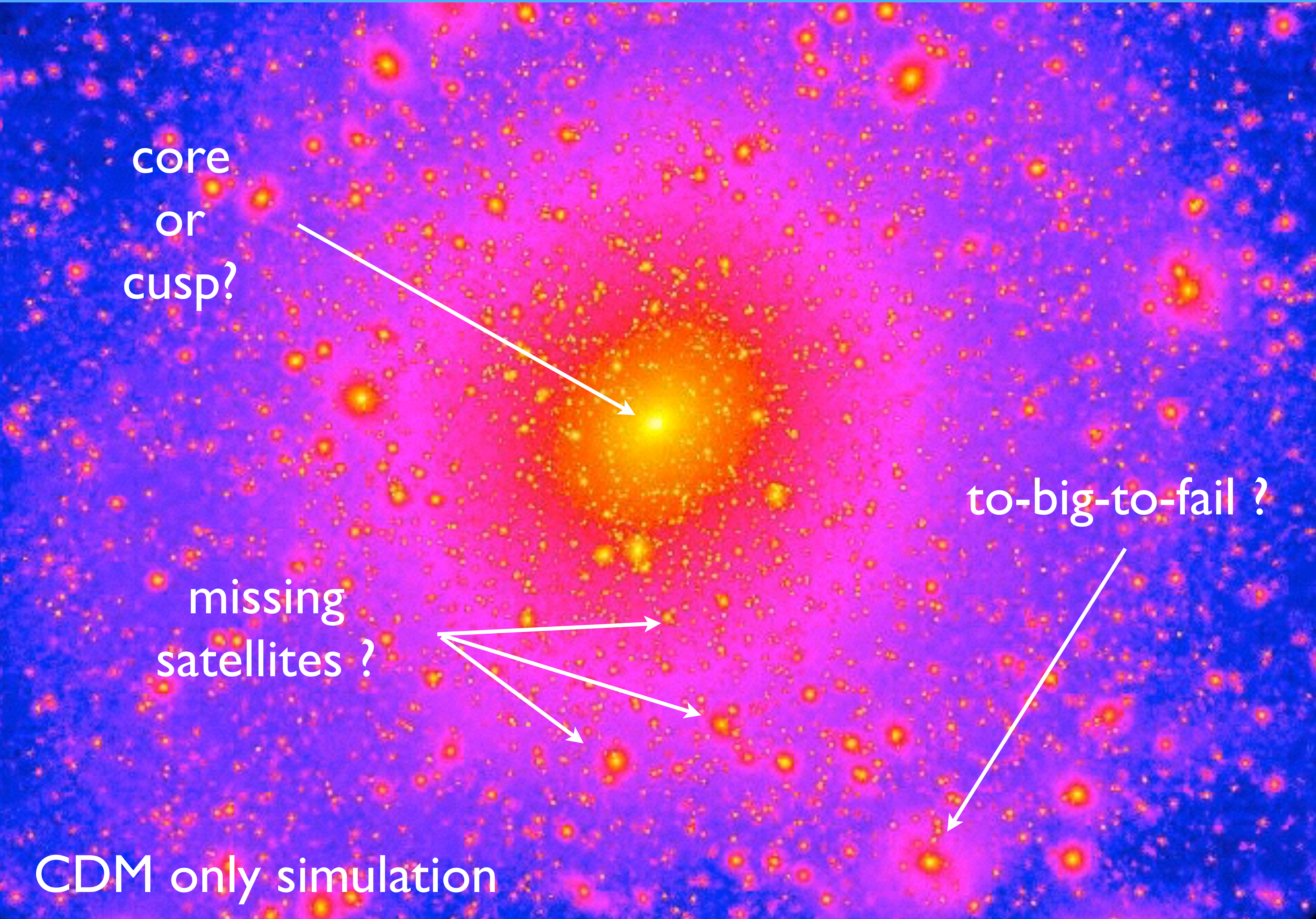
Direct detection is testing Freeze-in
Th. Hambye, M.T., J. Vandecasteele & L. Vanderheyden (2018)

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

SIDM + NS $\rightarrow$ BH

Non-primordial solar mass black holes
C. Kouvaris, P. Tinyakov, M.T. (2018)

WHY SIDM ?


core
or
cusp?
to-big-to-fail ?
missing
satellites ?
CDM only simulation

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

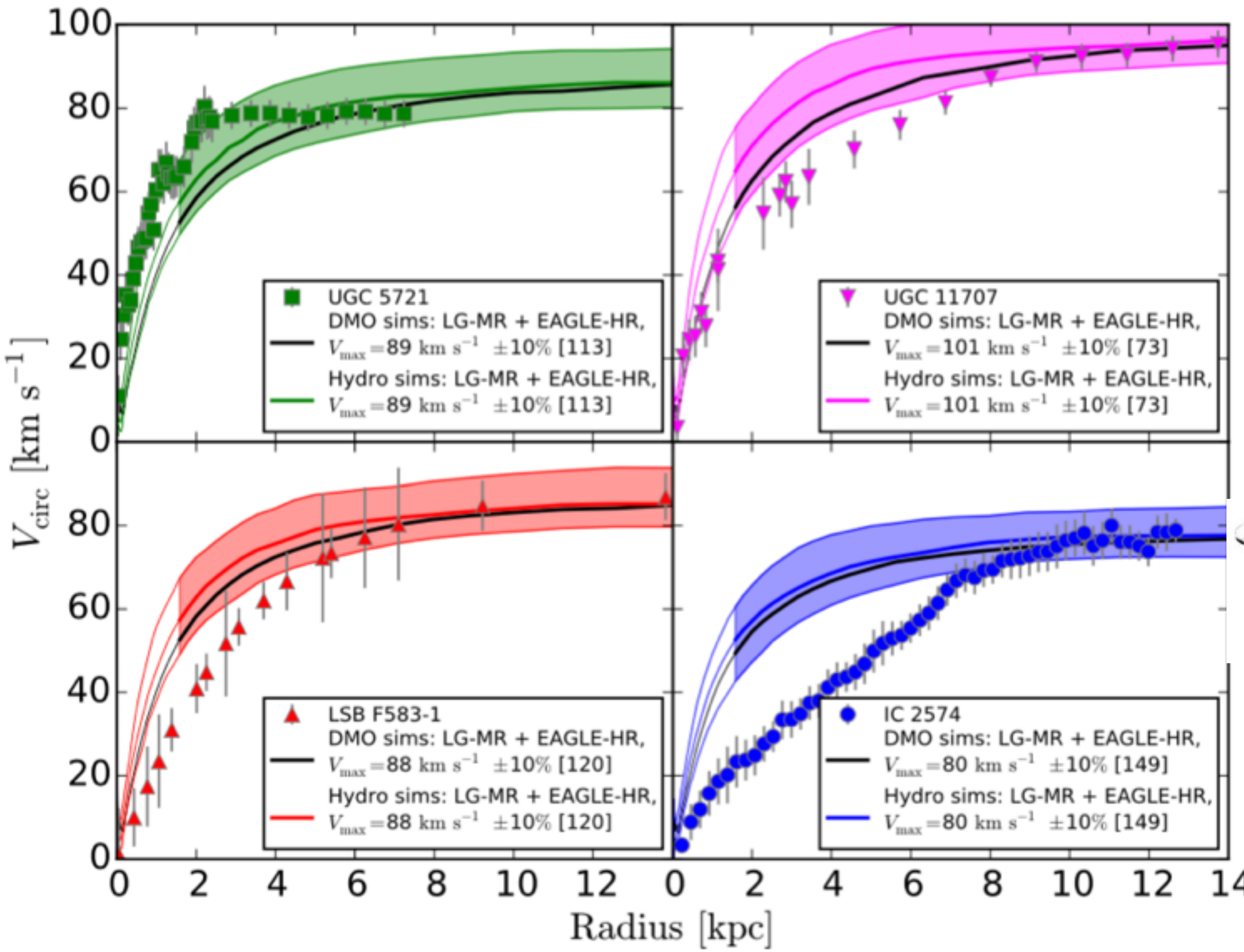
$$\frac{\sigma}{m} \sim \frac{\mathrm{cm}^2}{\mathrm{g}} \equiv \frac{\mathrm{barn}}{\mathrm{GeV}}$$

i.e. seemingly hadronic

but more generally light mediator

DIVERSITY PROBLEM

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

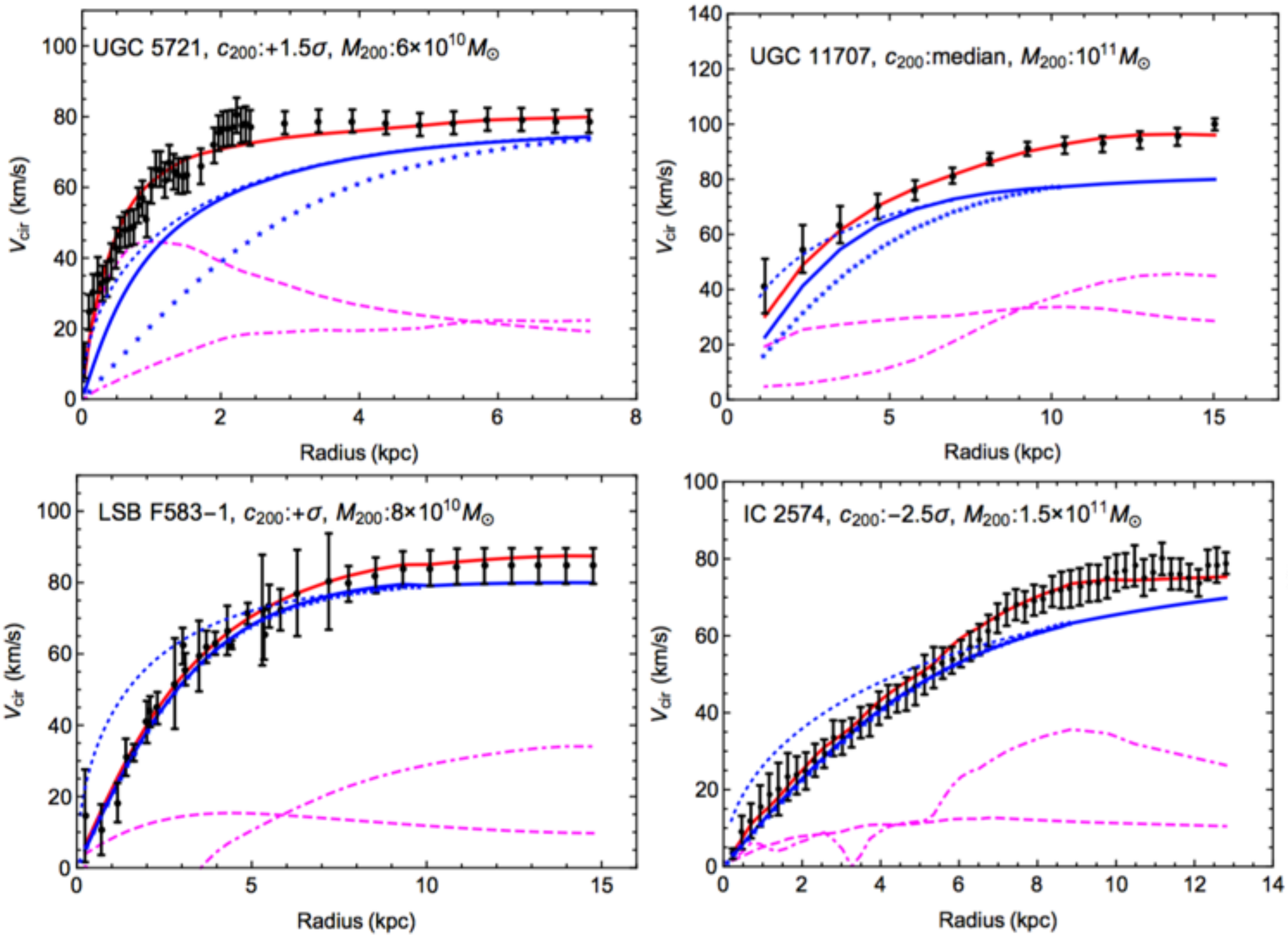


all same v_{max}

Oman *et al*, arXiv:1504.01437

DIVERSITY PROBLEM

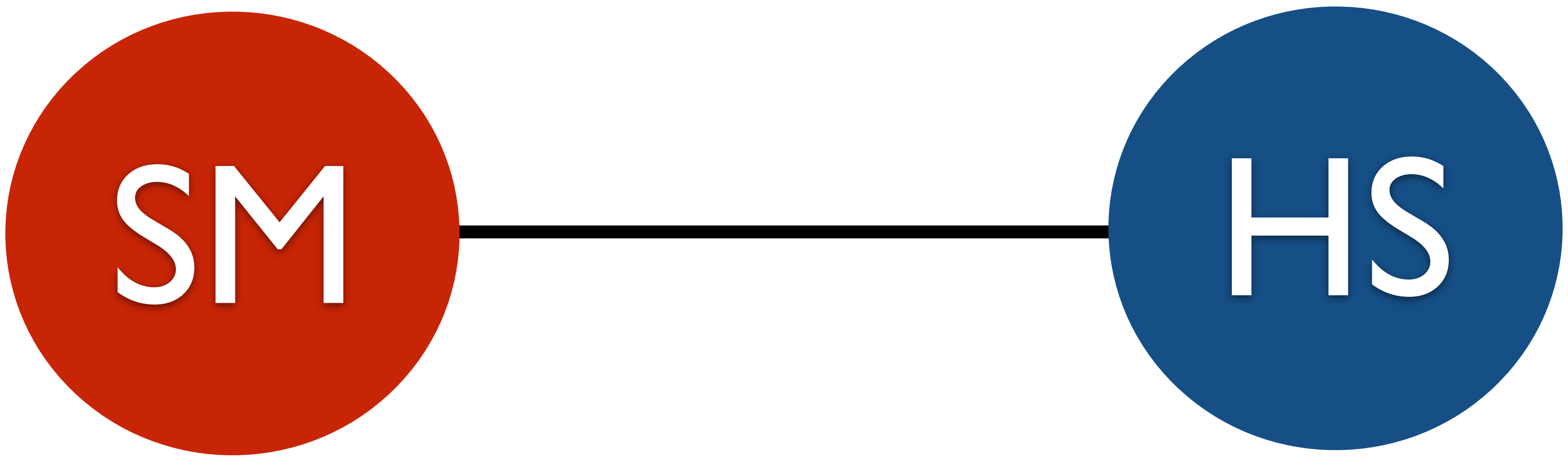
Diversity problem solved/alleviated with $\sigma/m \sim \frac{\mathrm{cm}^2}{\mathrm{g}}$



Hamada, Kaplinghat, Pace & Yu, arXiv:1611.02716

HIDDEN SECTOR

Patt & Wilczek (2006)



THE SM PORTALS

Patt & Wilczek (2006)

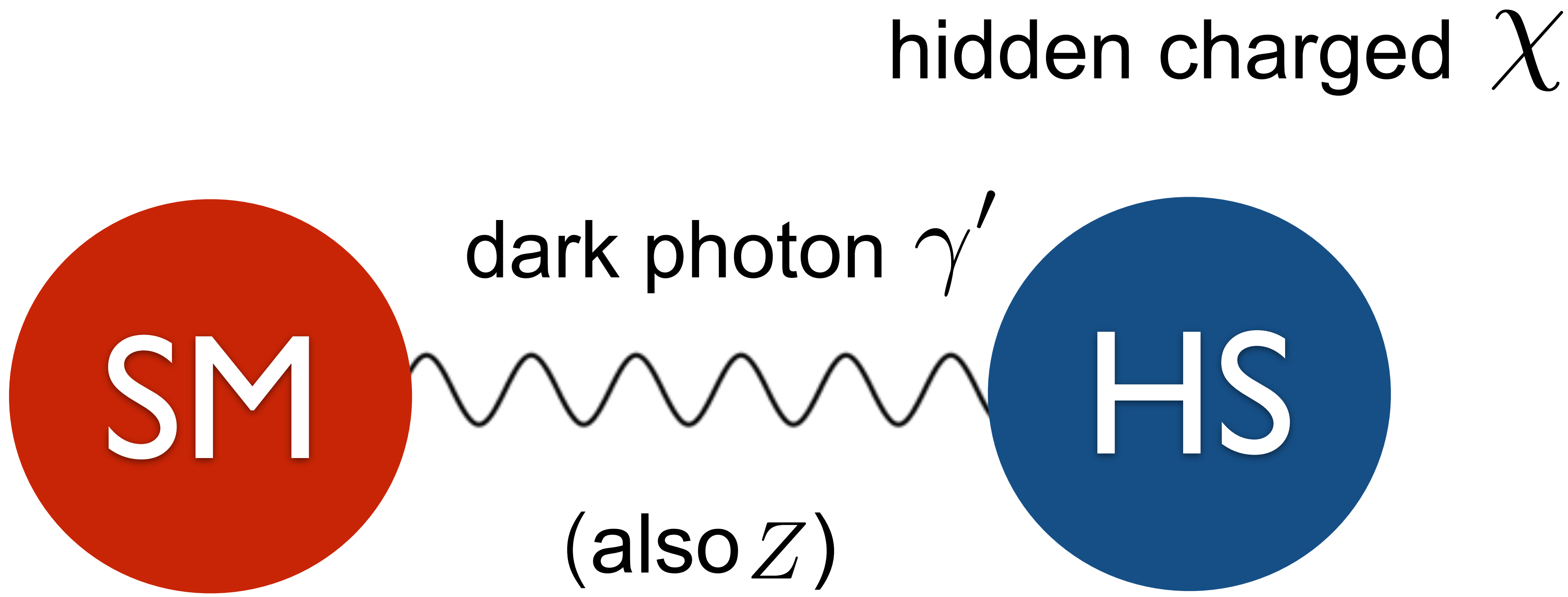
SM singlet operators	renormalizable interactions (i.e. dimensionless couplings)	
$\bar{L}\tilde{H}$	$\Delta\mathcal{L} \supset y\,\bar{L}\tilde{H}N$	**Sterile neutrino** Dodelson & Widrow (1994) …
$B_{\mu\nu}$	$\Delta\mathcal{L} \supset \epsilon\,B_{\mu\nu}X^{\mu\nu}$	**Kinetic mixing** Holdom (1986) …
$H^\dagger H$ This one is also Lorentz invariant	$\Delta\mathcal{L} \supset \lambda\,S^2 H^\dagger H$ Linked to EWSB?	**Higgs portal** Silveira & Zee (1985) Veltman & Ynderain (1989) …

PART I

DIRECT DETECTION IS TESTING FREEZE-IN

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

KINETIC MIXING



χ gauge interaction in HS α'

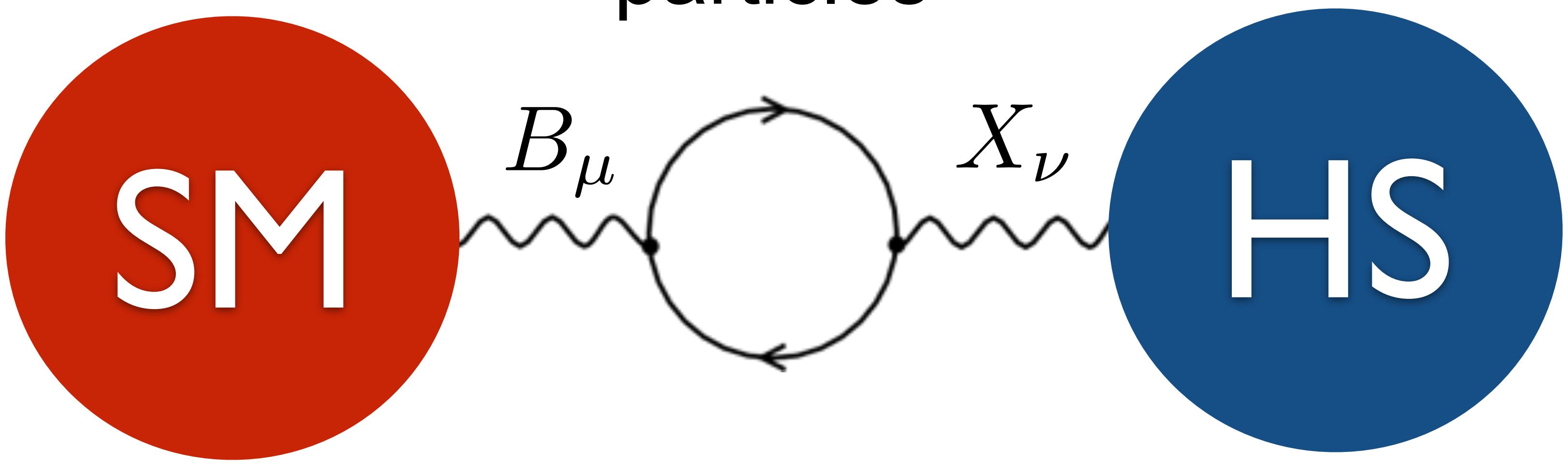
χ stable ~ SM electron m_χ

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

only 4 parameters $m_{\gamma'}$

FIMP THROUGH KINETIC MIXING

some
heavy
particles



Holdom (1986)

κ is naturally tiny !

DM feebly coupled to SM

Feebly Interacting Massive Particle

or

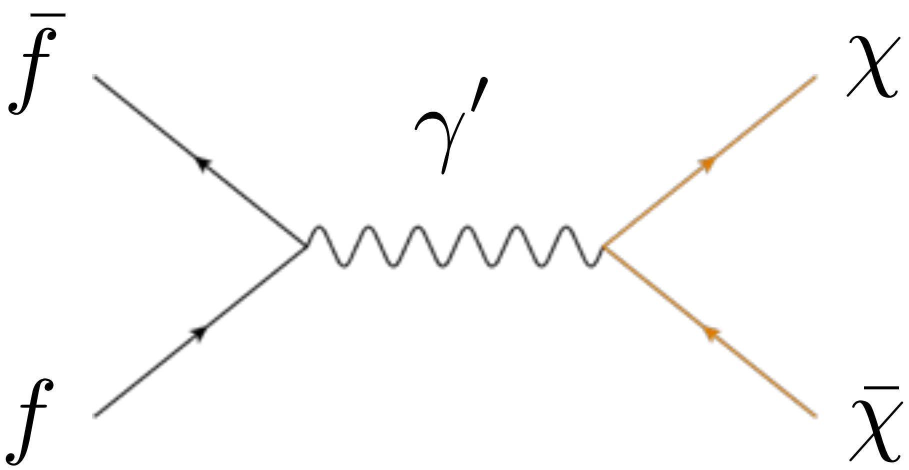
FIMP

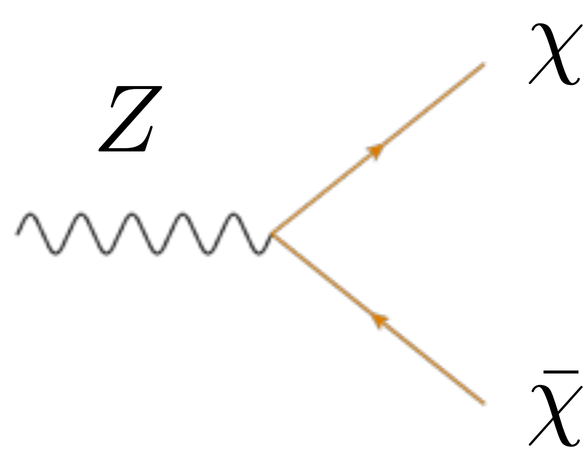
Chu, Hambye, M.T. ‘12

ABUNDANCE FROM FREEZE-IN

HS feebly coupled ~ no thermal equilibrium

abundance could built up from slow processes



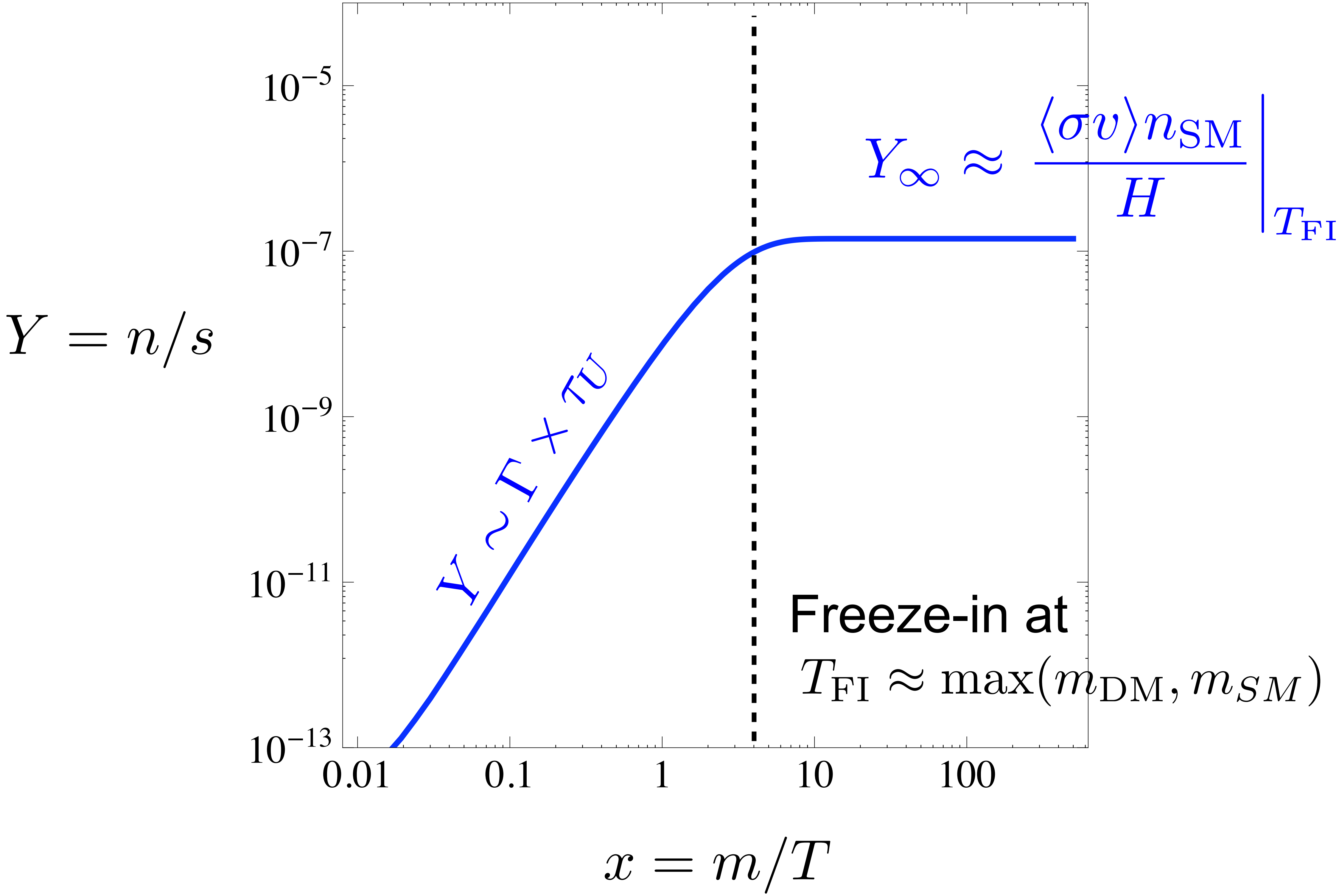


$$\propto \quad \kappa = \epsilon\sqrt{\alpha'/\alpha}$$

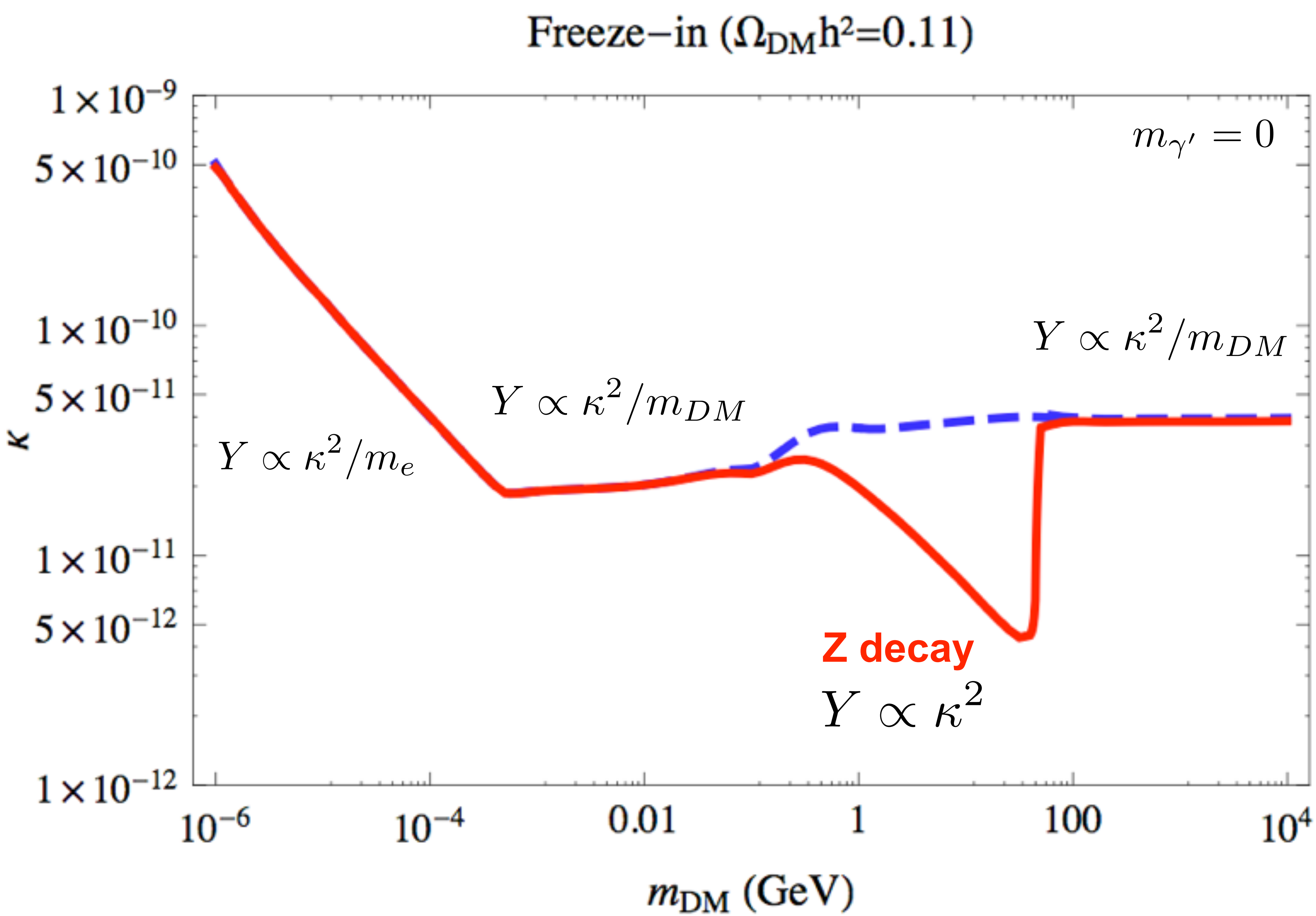
FREEZE-IN

* 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

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

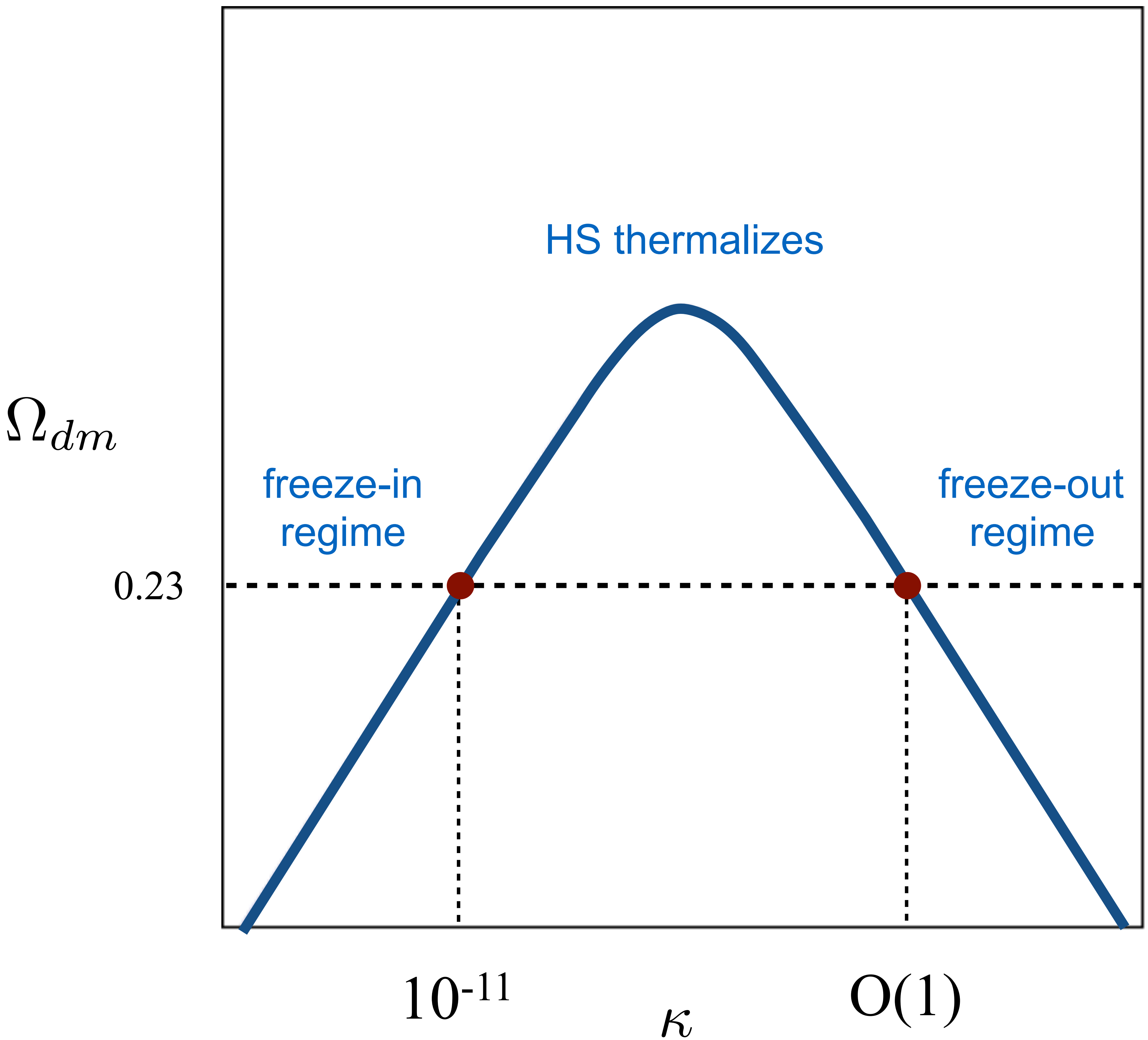
$$\Gamma = \sigma\, v\, n_{\mathrm{DM}}$$

ABUNDANCE FROM FREEZE-IN

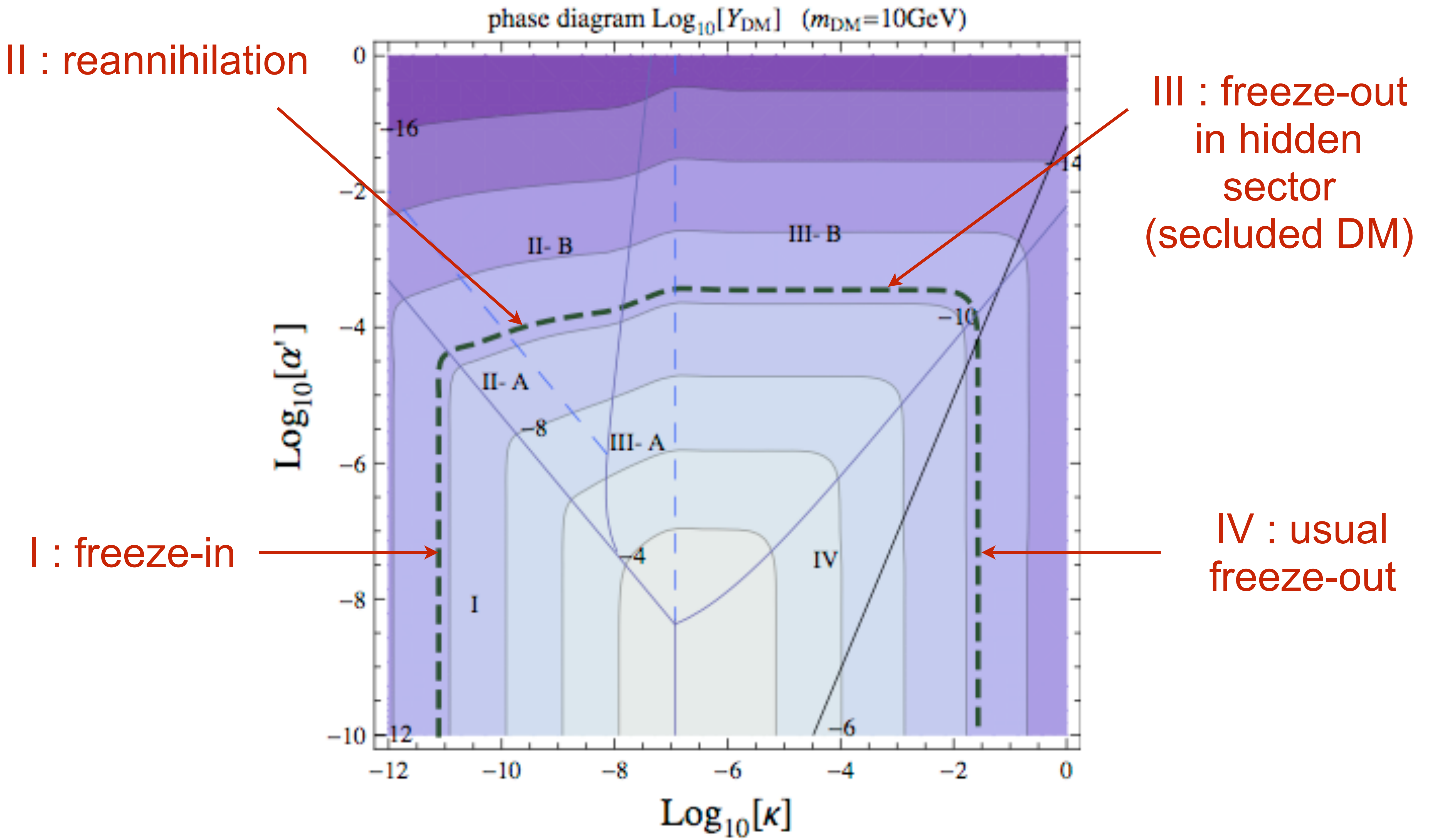
$$\mathrm{SM} + \mathrm{SM} \longrightarrow \mathrm{DM} + \mathrm{DM}$$

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

FREEZE-IN vs FREEZE-OUT



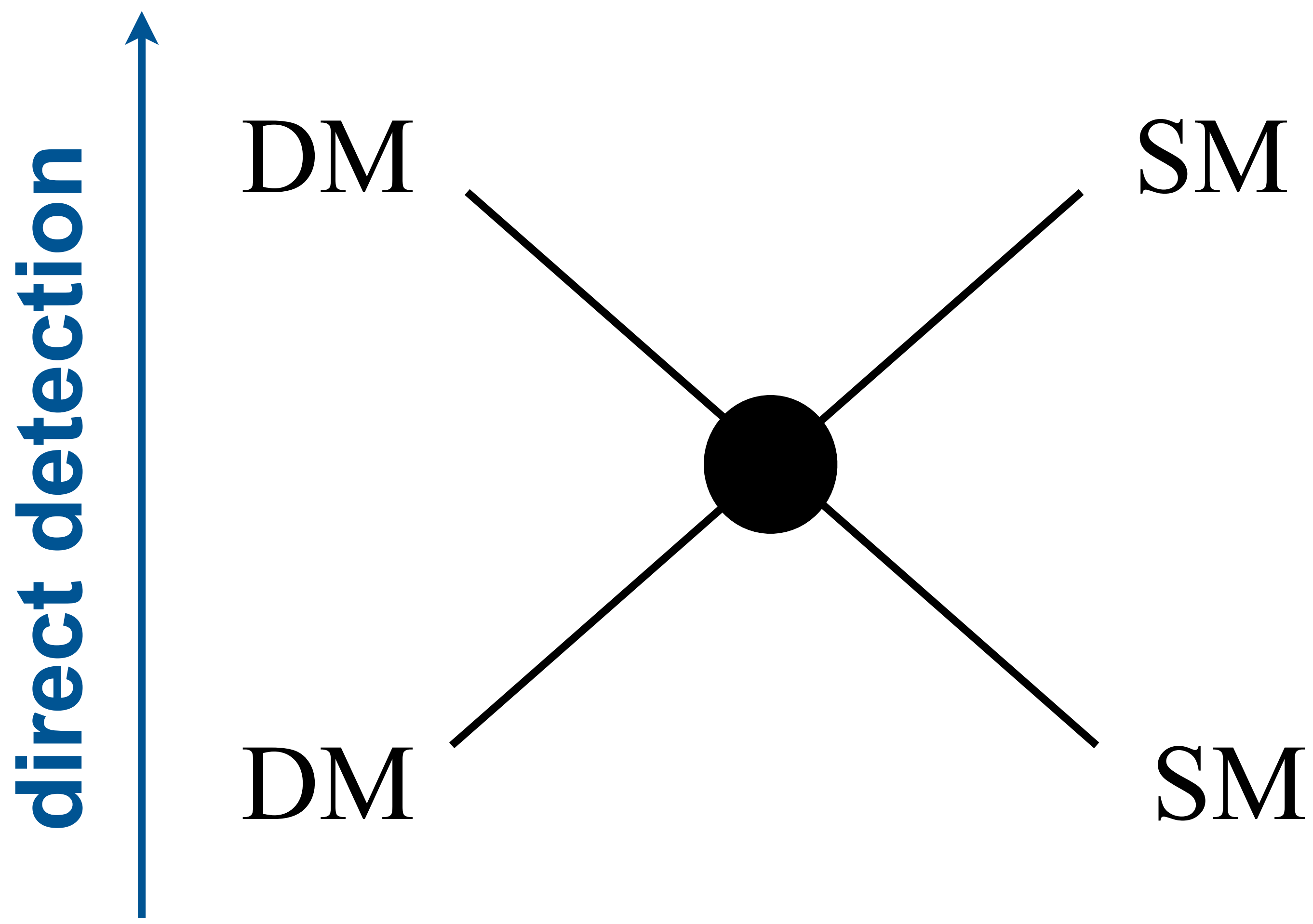
4 BASIC WAYS TO CREATE DM THROUGH A PORTAL



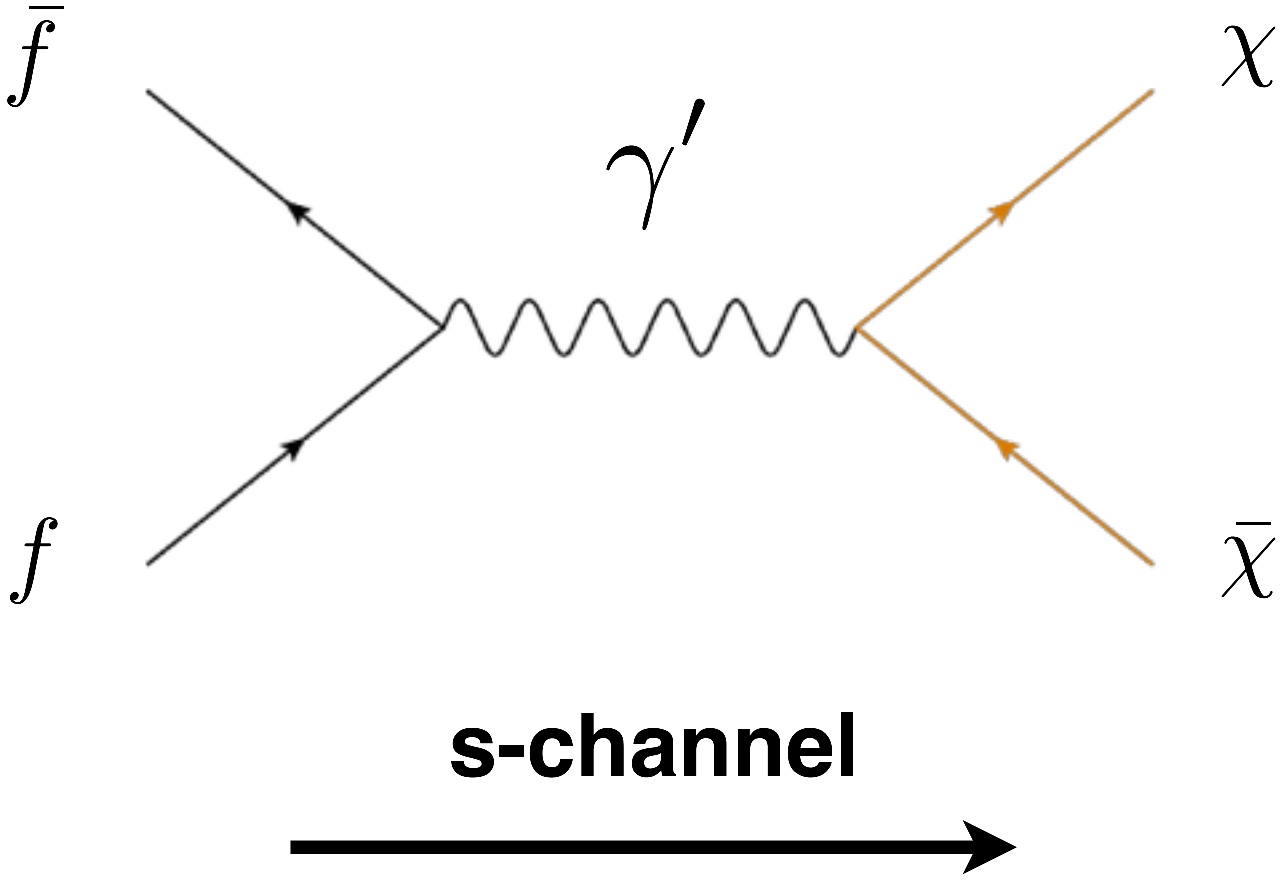
Chu, Hambye, M.T. '12

DIRECT DETECTION TEST OF FREEZE-IN

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



PRODUCTION THROUGH S-CHANNEL



determines relic abundance

very small cross section

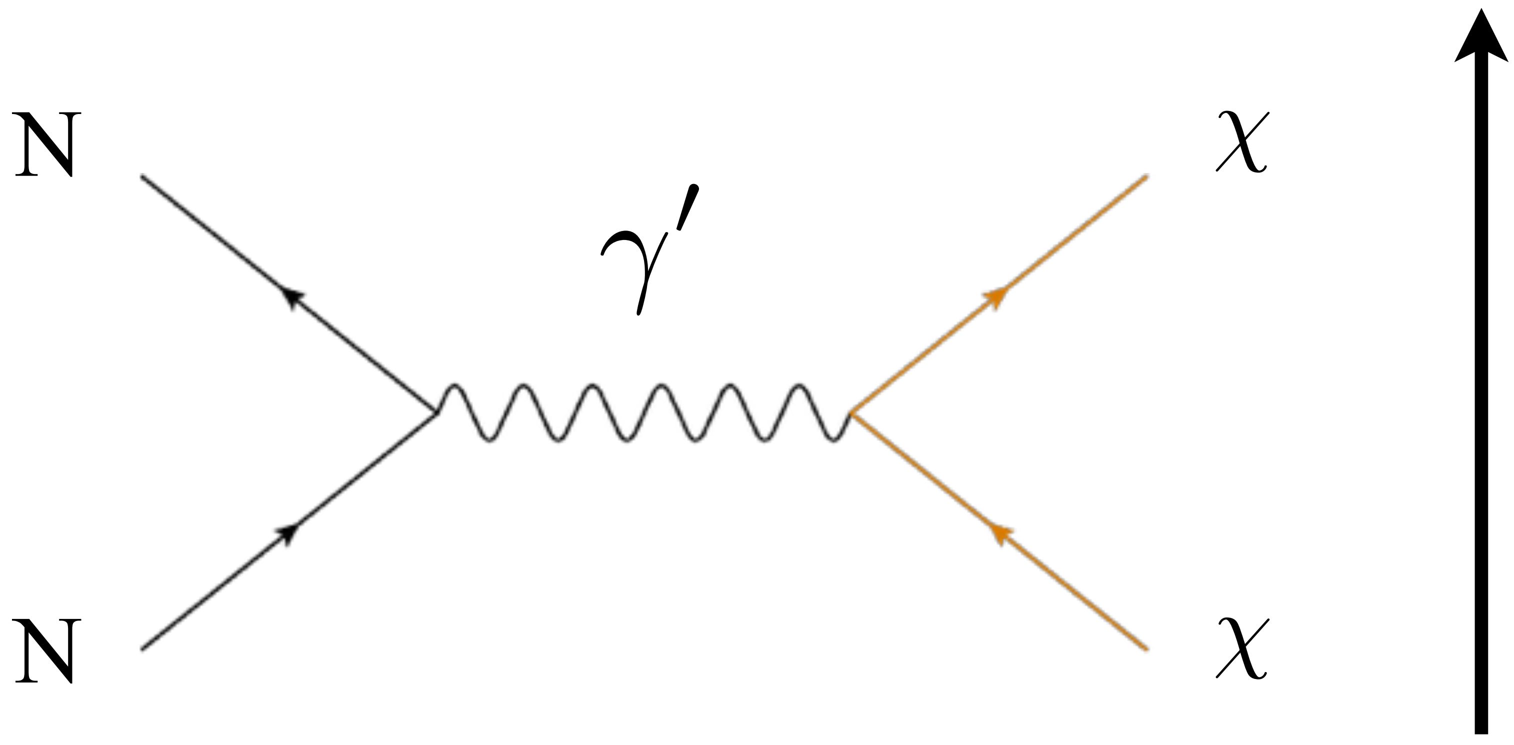
Rutherford (1911)

RUTHERFORD SCATTERING - DIRECT DETECTION

recoil energy

E_R

in keV range



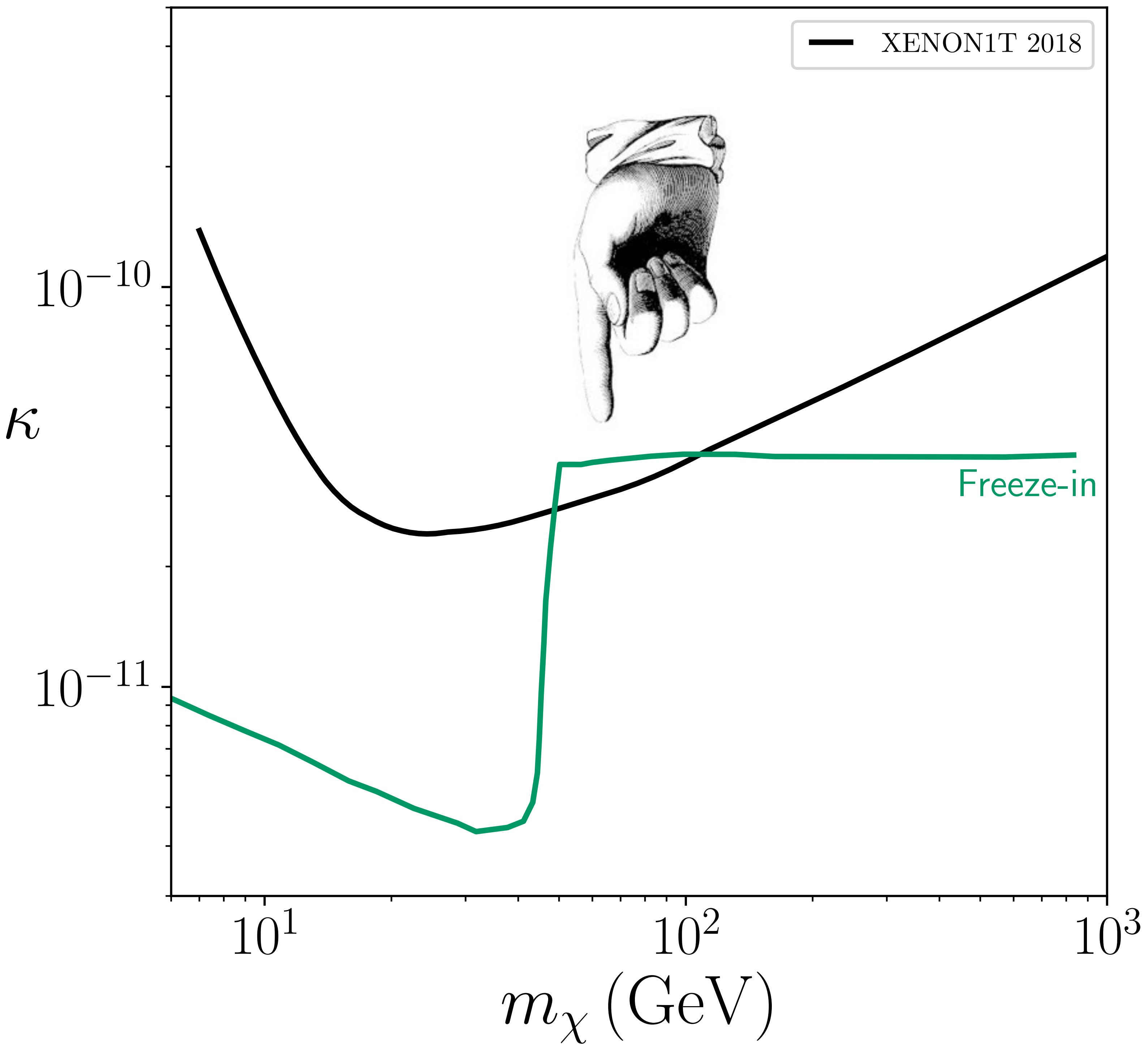
t-channel

v ~ 200 km/s (halo DM)

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

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

DIRECT DETECTiON IS TESTING FREEZE IN



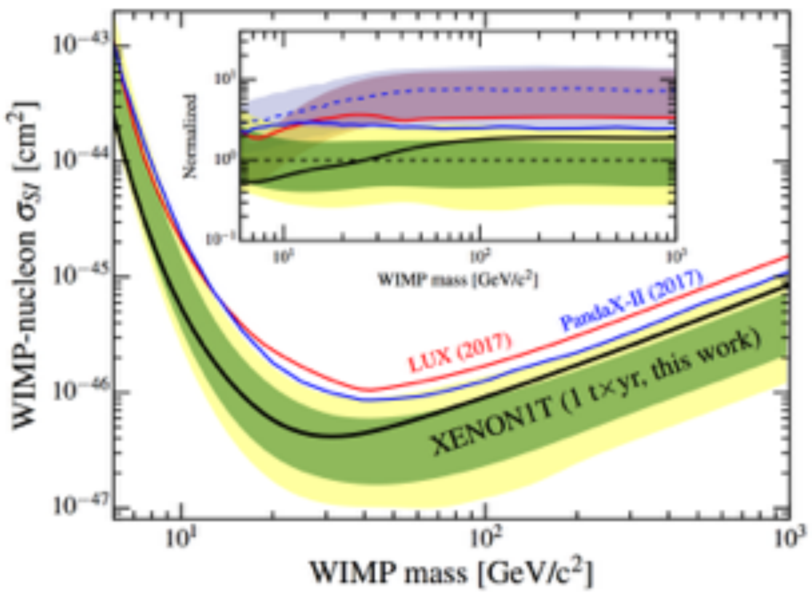
n.b.:
Not the same spectrum as a WIMP,
Must recasti the direct detection constraints

first direct detection test of a FI scenario

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

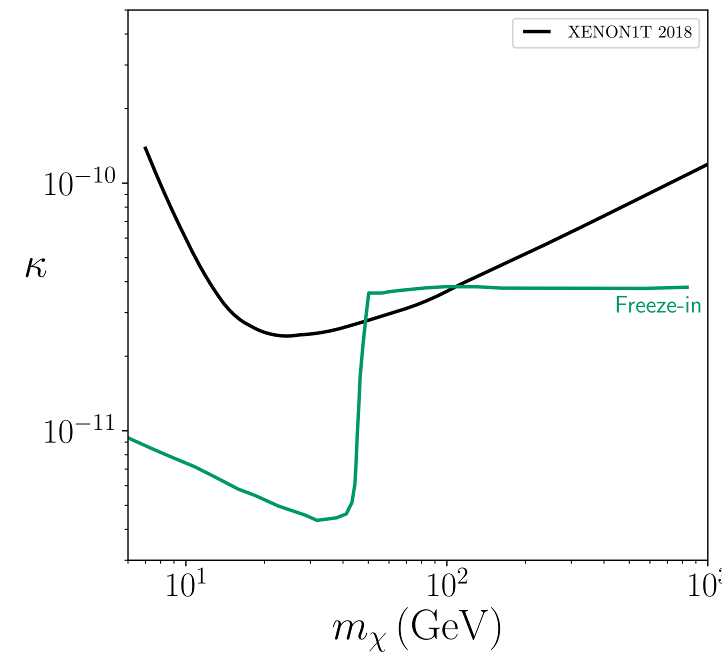
RECASTING DIRECT DETECTION LIMITS

heavy mediator

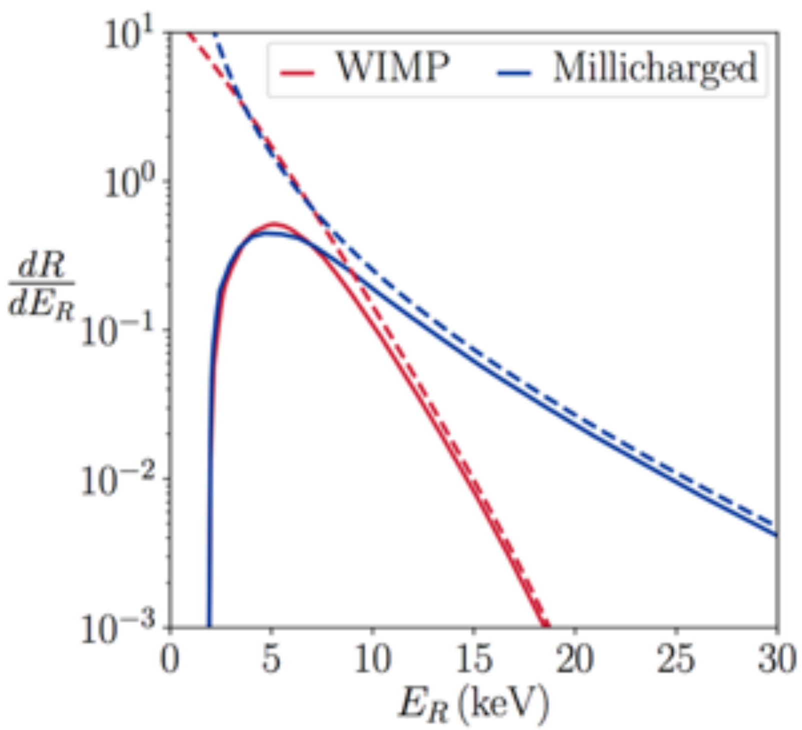


$$(m_{\rm dm}, \sigma_{{\rm dm},n})$$

light mediator



$$(m_\chi, \kappa)$$

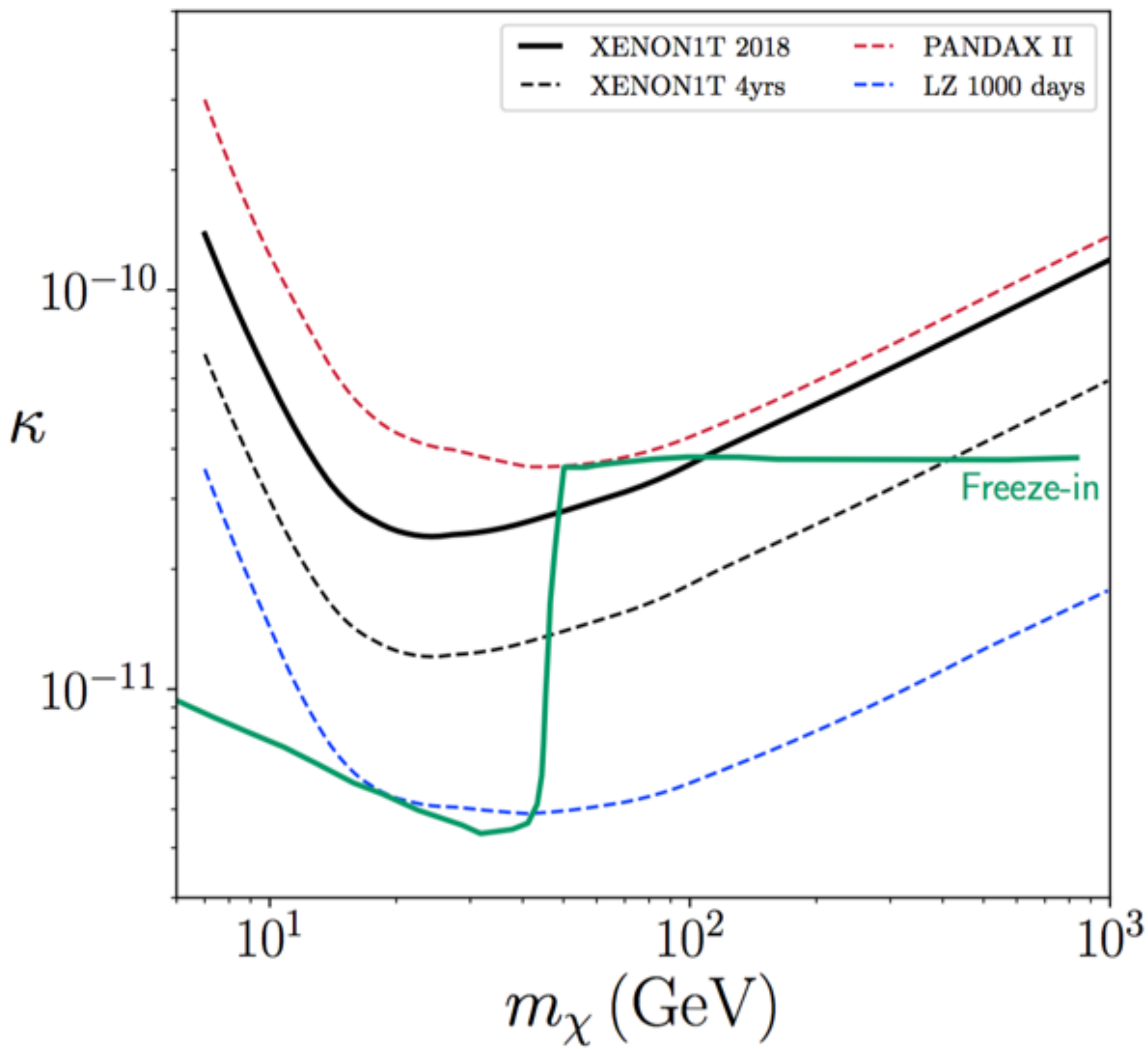


We minimized the differential rate « quadratic distance »

$$\Delta^2 = \frac{1}{R^2_{\rm exp}} \int {\rm d}E\, \epsilon(E)^2 \left(\left(\frac{{\rm d}R}{{\rm d}E} \right) - \left(\frac{{\rm d}R_\chi}{{\rm d}E} \right) \right)^2$$

XENON1T efficiency

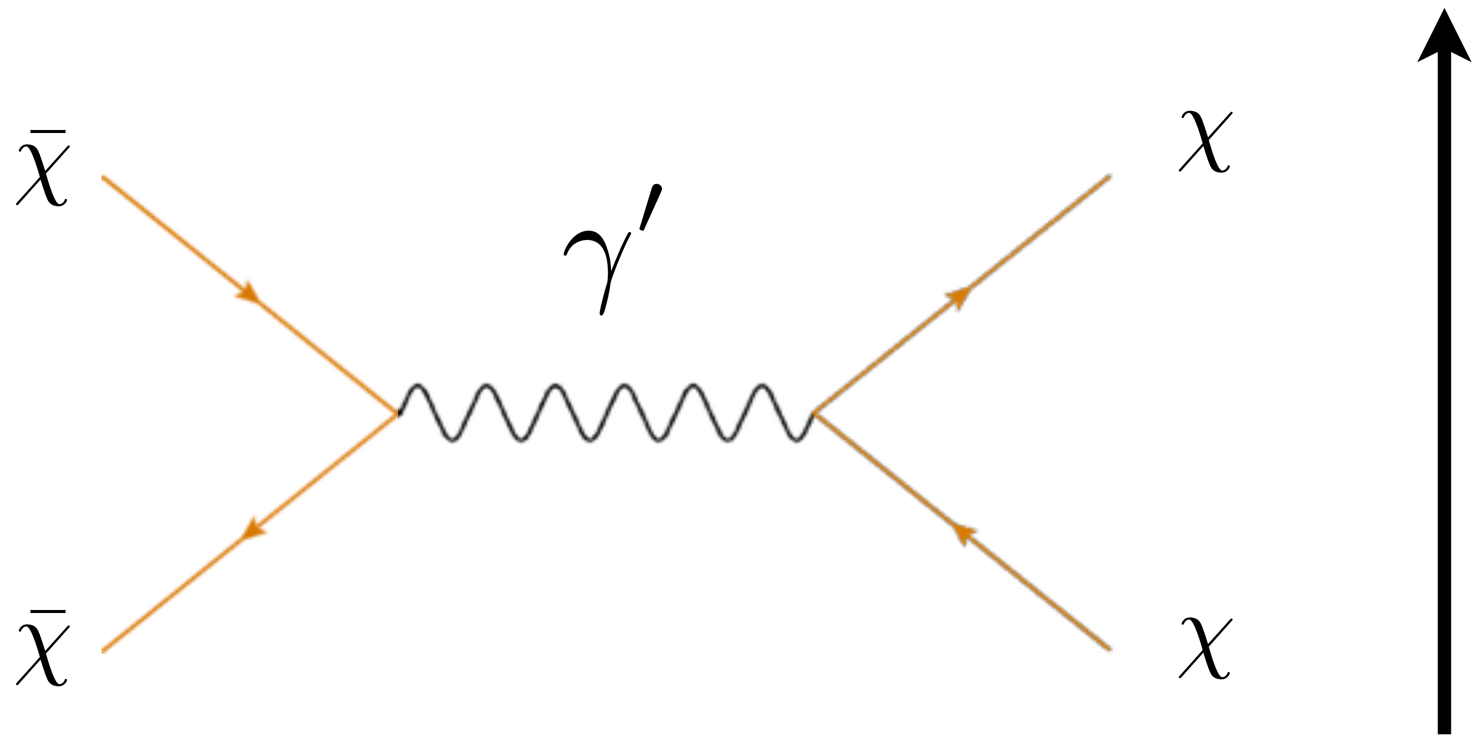
DIRECT DETECTiON IS TESTING FREEZE IN



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

SIDM : RUTHERFORD SCATTERING AGAIN

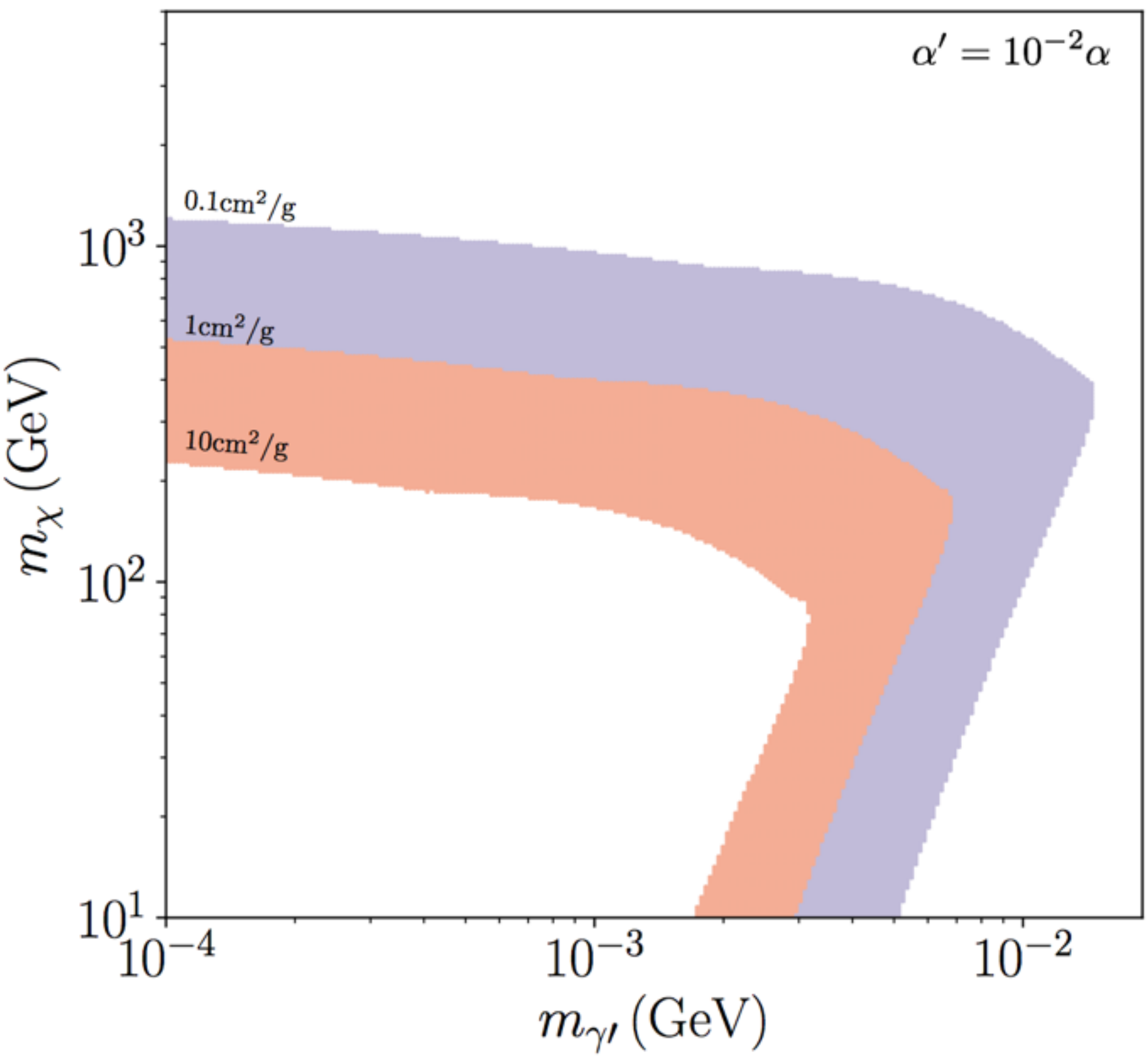
$v_{\rm dwarf} \sim 10~{\rm km/s}$



t-channel

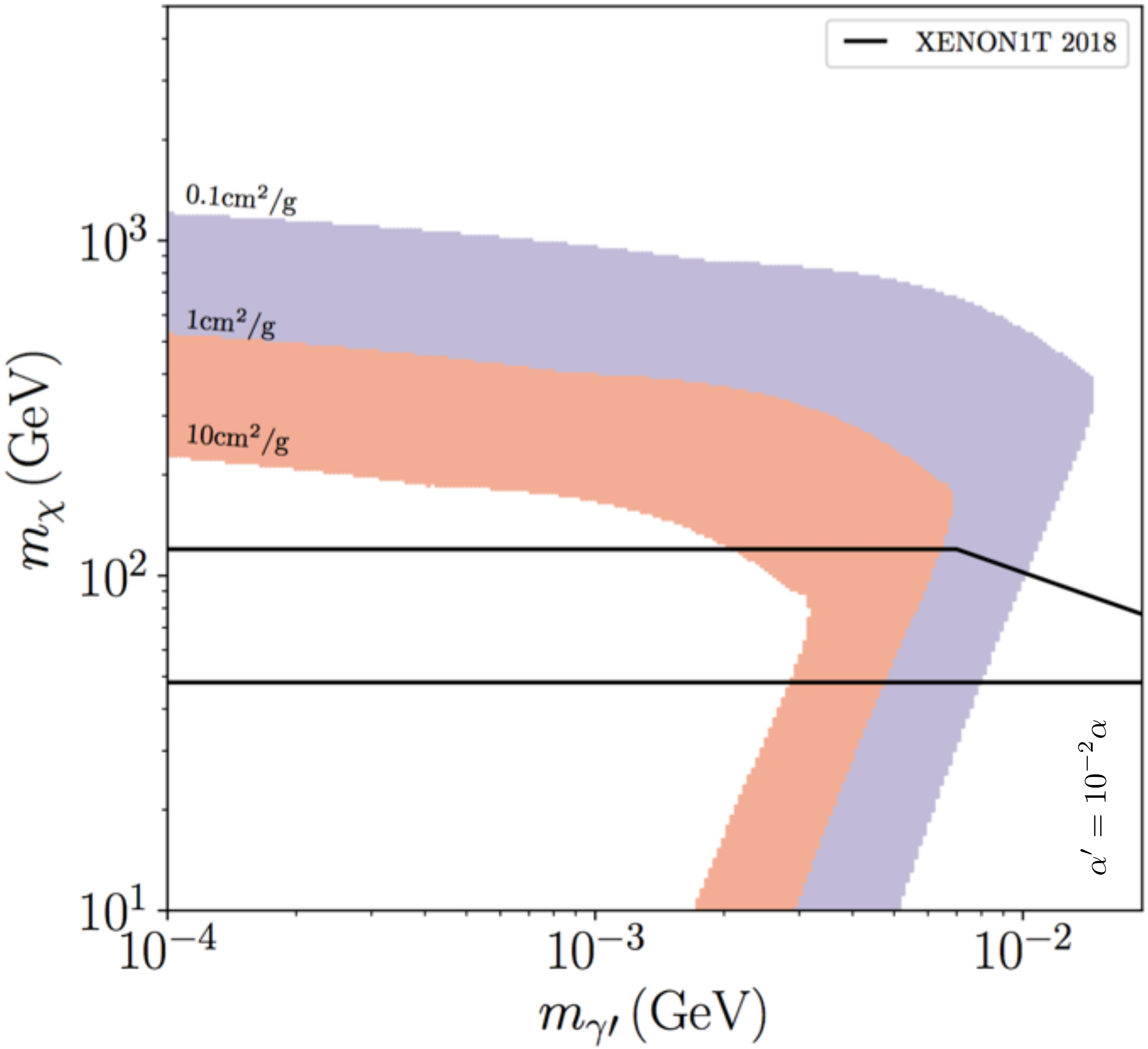
$$\frac{d\sigma}{d\Omega} = \frac{4\alpha'^2 m_\chi^2}{(4m_\chi^2 v^2 \sin^2(\theta/2) + m_{\gamma'}^2)^2} \sim \alpha'^2 \frac{m_\chi^2}{m_{\gamma'}^4}$$

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



$\alpha' = 10^{-2}\alpha$
0.1cm^2/g
1cm^2/g
10cm^2/g
m_χ (GeV)
$m_{\gamma'}$ (GeV)
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}

DIRECT DETECTION & SIDM PARAMETER SPACE



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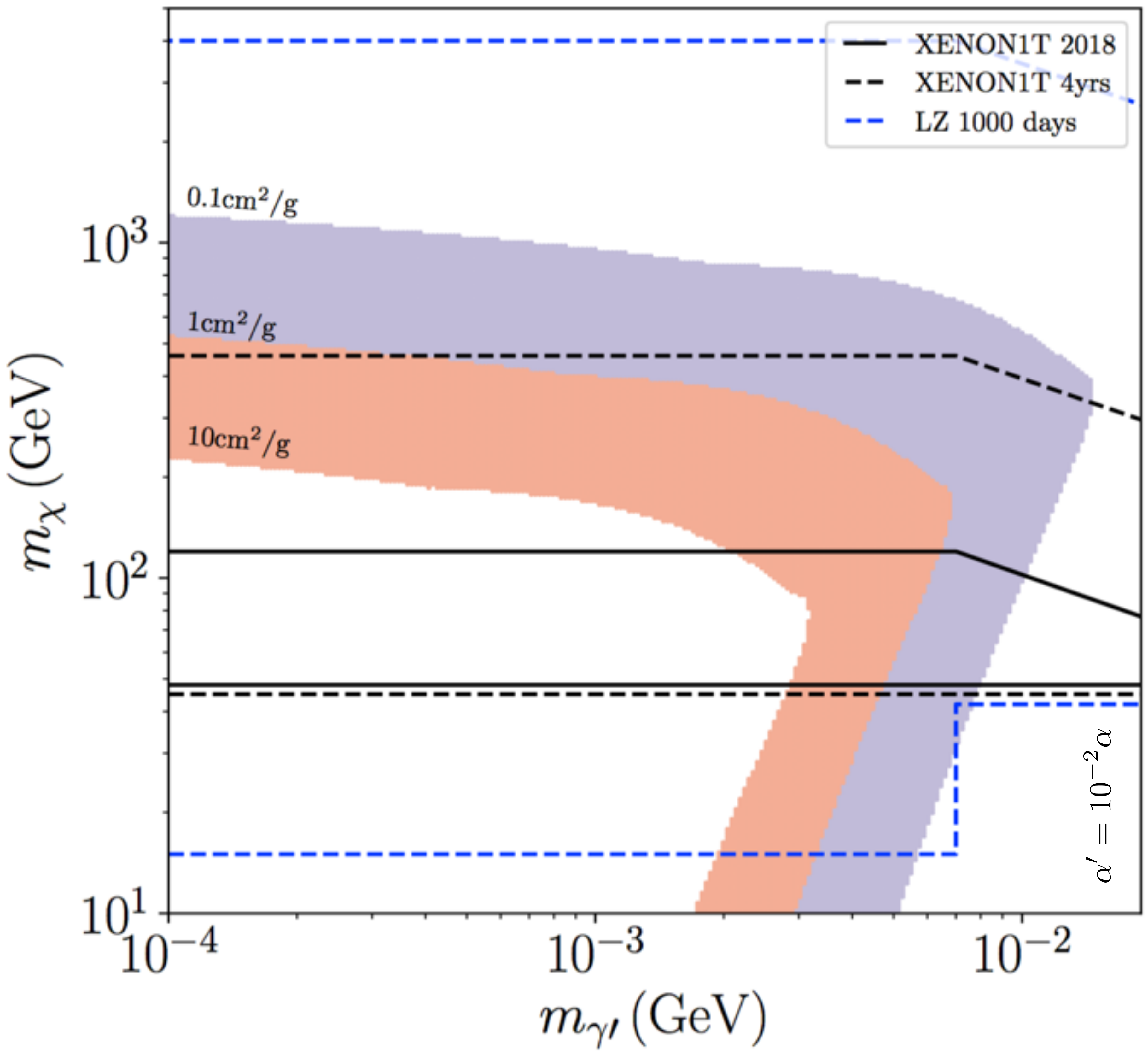
DIRECT DETECTION & SIDM PARAMETER SPACE



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

PART II

SOLAR MASS BH FROM SIDM

$m_{\mathrm{NS}} \sim m_{\odot}$

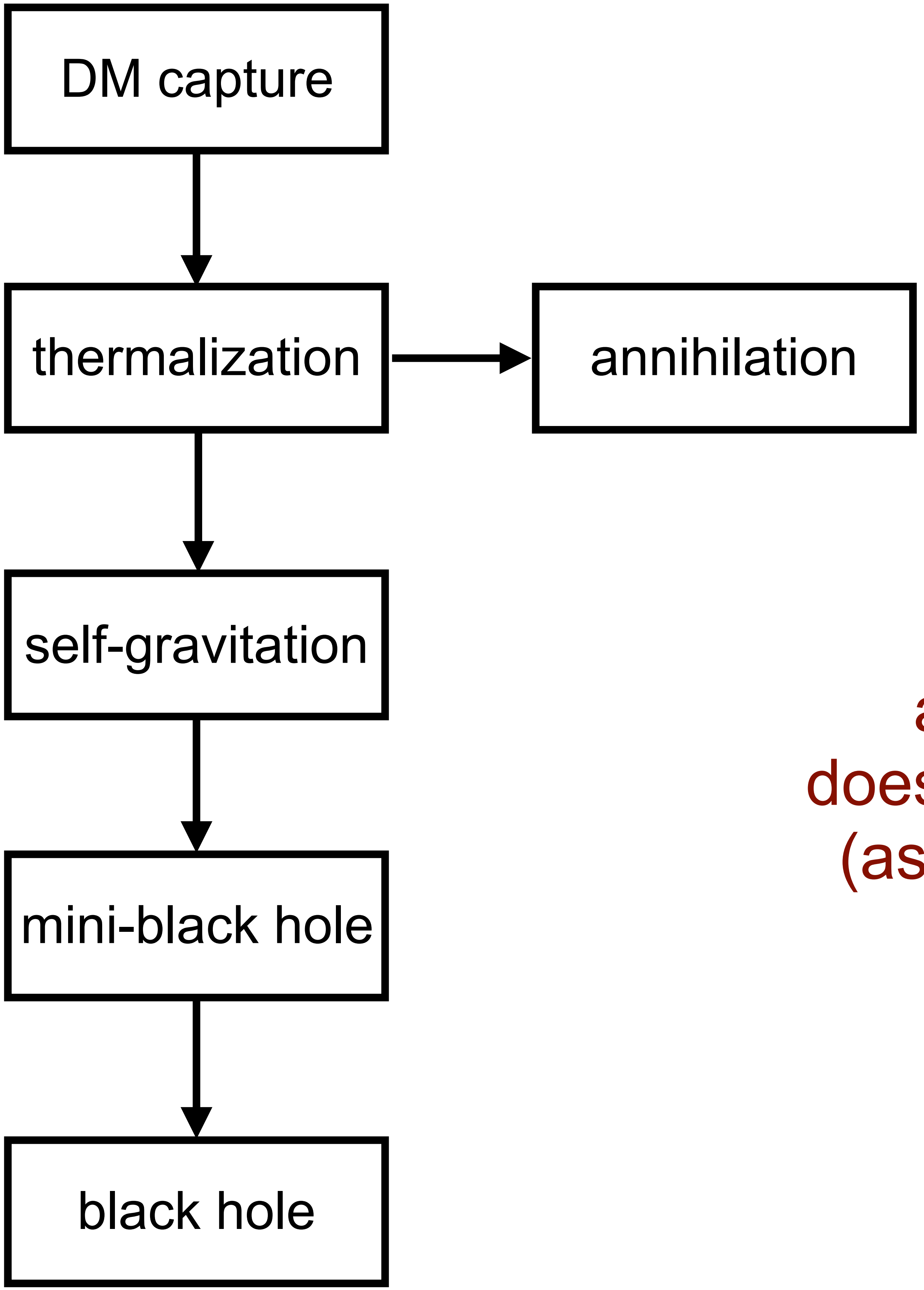
$N_B \sim 10^{57}$

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

DM
(not to the scale)

Neutron Star
(not to the scale)

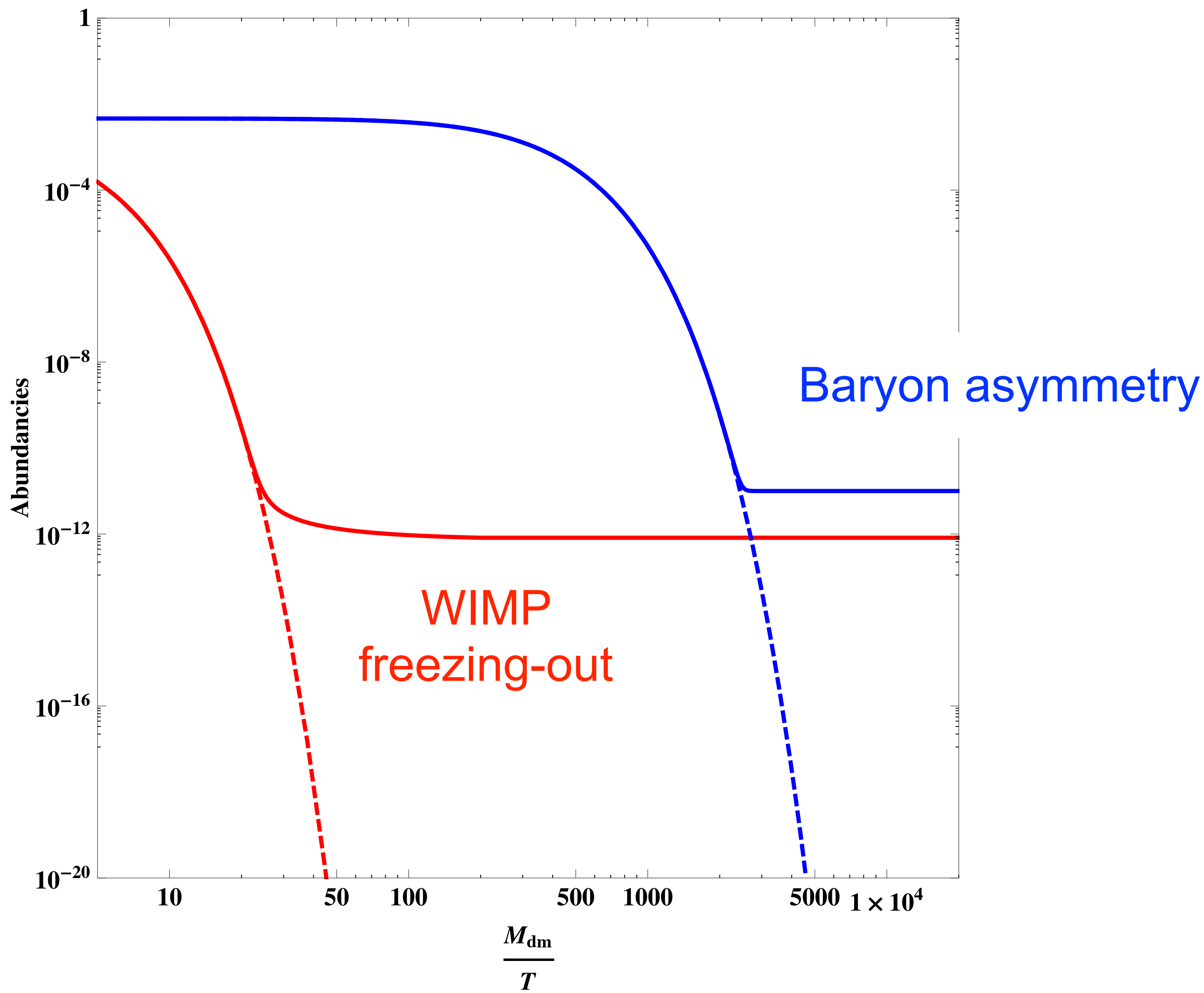
DM + NS → BH



assumes DM
does not annihilate
(asymmetric DM)

ASYMMETRIC DM

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_{DM}}{m_N}\frac{Y_{DM}}{Y_B} \approx 5 = \mathcal{O}(1)$$



CAPTURE OF DM IN NS

Capture rate

Goldman & Nussinov (1989) - Kouvaris (2008)

$$\frac{dN_{\rm acc}}{dt} = \sqrt{6\pi}\,\frac{\rho_{\rm dm}}{m_{\rm dm} v_{\rm dm}}\,\frac{R_\star R_{\rm Sch}}{1 - R_{\rm Sch}/R_\star}\,{\rm Min}\left(\frac{\sigma}{\sigma_{\rm cr}}, 1\right)$$

Critical cross section (neutron star)

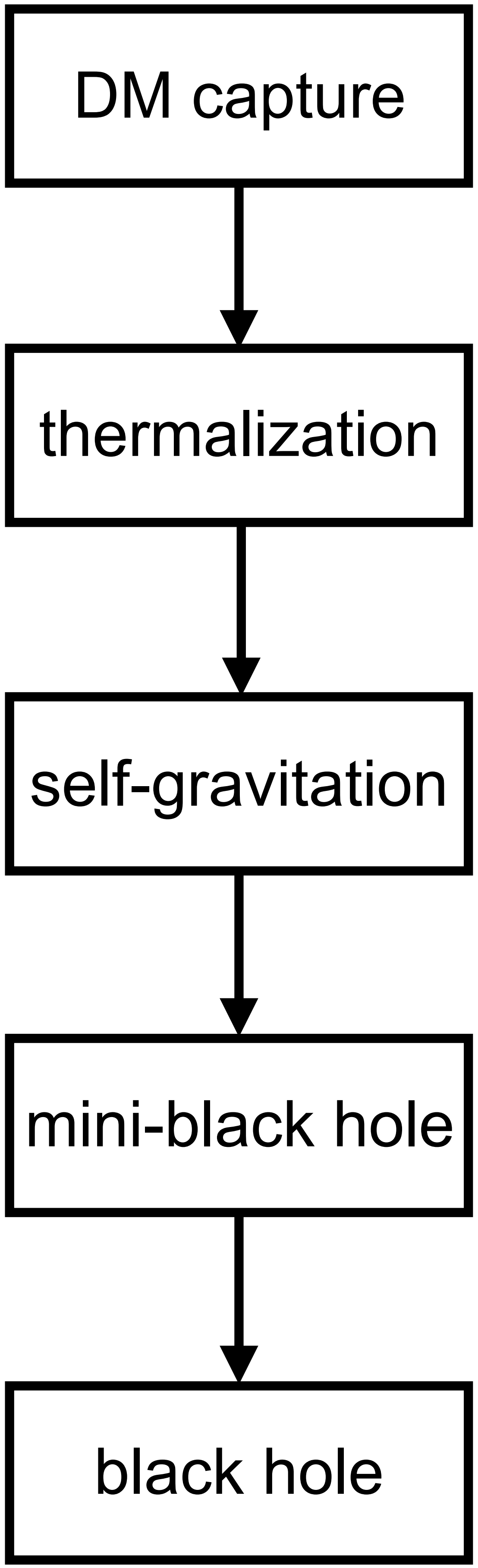
$$\sigma_{\rm cr} = 0.45\, m_n\, R_\star / M_\star \approx 1.3 \times 10^{-45}\,{\rm cm}^2$$

Maximal mass captured

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

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

DM + NS → BH



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

$$t_{th} \sim 10^2\,\mathrm{yr} \left(\frac{m_{\rm dm}}{\mathrm{TeV}}\right)^2 \left(\frac{10^{-45}\mathrm{cm}^2}{\sigma}\right)$$

Goldman & Nussinov (1989)
Kouvaris & Tinyakov (2010)

$$r_{\rm th} \approx \left(\frac{T_c}{G\rho_c m_{\rm dm}}\right)^{1/2} \sim 10\,\mathrm{cm} \left(\frac{\mathrm{TeV}}{m_{\rm dm}}\right)^{1/2} \left(\frac{T_c}{10^5\mathrm{K}}\right)^{1/2}$$

$$\frac{N_{\rm acc} m_{\rm dm}}{r_{\rm th}^3} \gtrsim \rho_c \sim 10^{39}\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \quad \longrightarrow \quad N_{\rm cr} \gtrsim 10^{38} \left(\frac{\mathrm{TeV}}{m_{\rm dm}}\right)^{5/2}$$

$$N_{\rm Ch} \gtrsim \left(\frac{M_{\rm Pl}}{m}\right)^3 \sim 5 \cdot 10^{48} \left(\frac{\mathrm{TeV}}{m_{\rm dm}}\right)^3$$

Bondi accretion

$$\frac{dM}{dt} = \frac{4\pi G^2 M^2 \rho_c}{c_s^2} - \frac{\pi^3}{15} R^2 T^4 \longrightarrow M_{\rm bh} \gtrsim 10^{-20} M_\odot$$

Hawking radiation

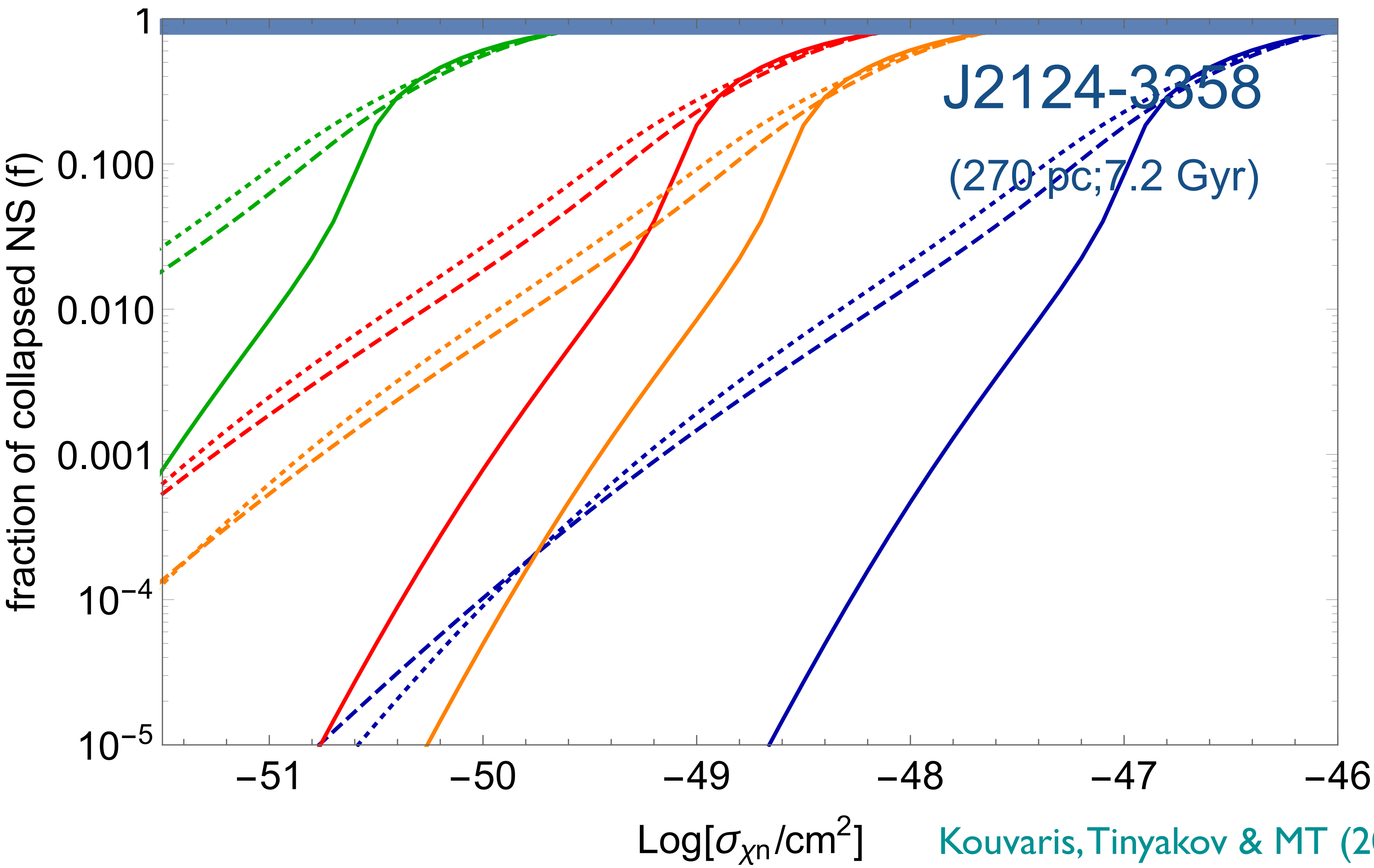
Kouvaris & Tinyakov (2013)

SIDM + NS → BH

candidates that alleviate CDM issues

#	α	$\frac{\mu}{\text{MeV}}$	$\frac{m}{\text{TeV}}$	$\frac{\sigma_{10}}{m}$	$\frac{\sigma_{100}}{m}$	N_{cr}	N_{Ch}	$\frac{M_{Ch}}{M_\odot}$
1	10^{-3}	10	1	0.1	$1.6 \cdot 10^{-3}$	$5 \cdot 10^{35}$	$2 \cdot 10^{37}$	10^{-17}
2	10^{-4}	2	0.2	4.5	$4.5 \cdot 10^{-3}$	$2 \cdot 10^{35}$	$7 \cdot 10^{40}$	10^{-14}
3	10^{-4}	1	1	0.2	$5.6 \cdot 10^{-5}$	$3 \cdot 10^{33}$	$6 \cdot 10^{35}$	10^{-18}
4	10^{-3}	3	0.2	6.4	$2.3 \cdot 10^{-1}$	$2 \cdot 10^{35}$	$7 \cdot 10^{39}$	10^{-15}

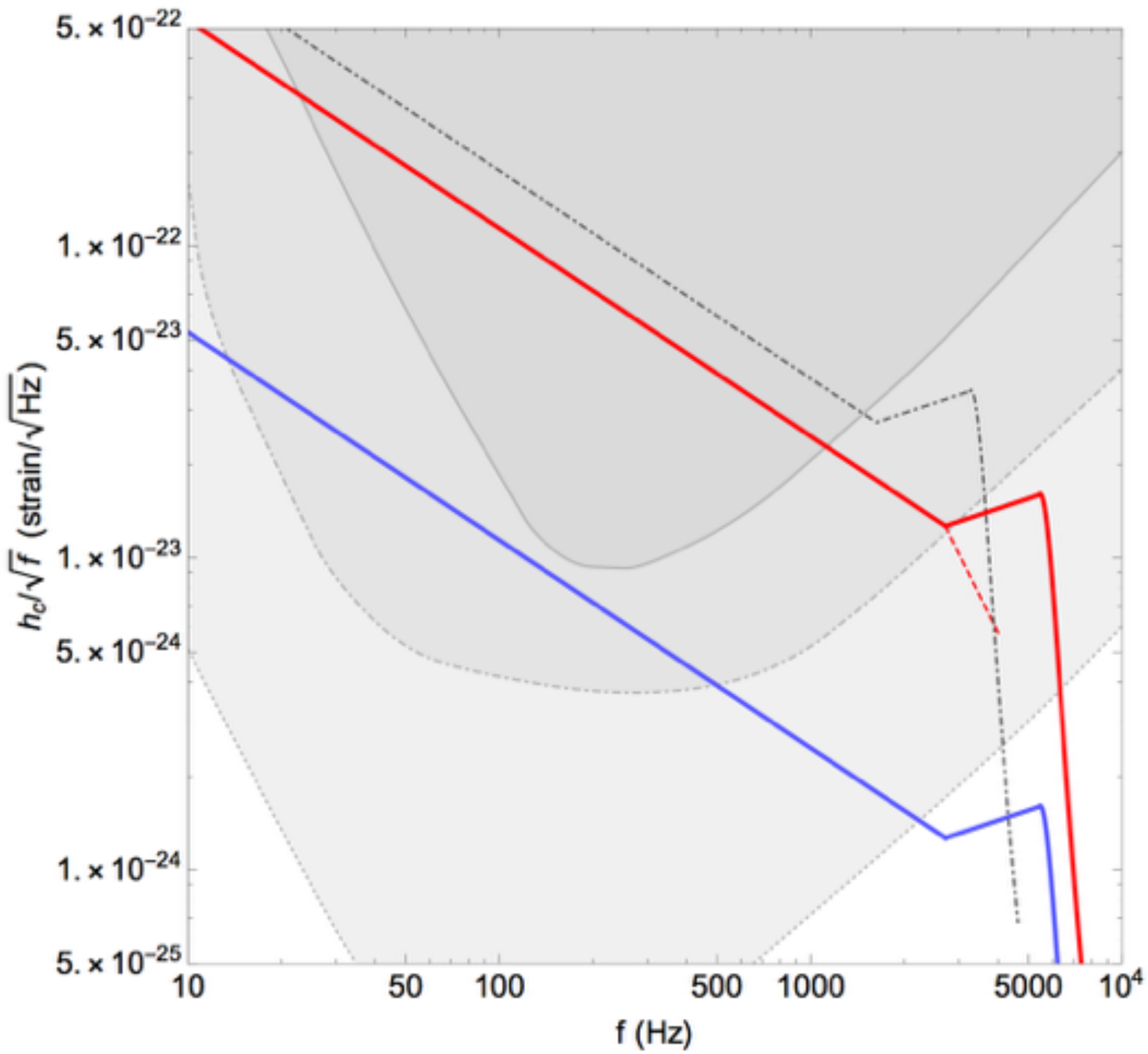
fraction of NS transformed into BH



Kouvaris, Tinyakov & MT (2018)

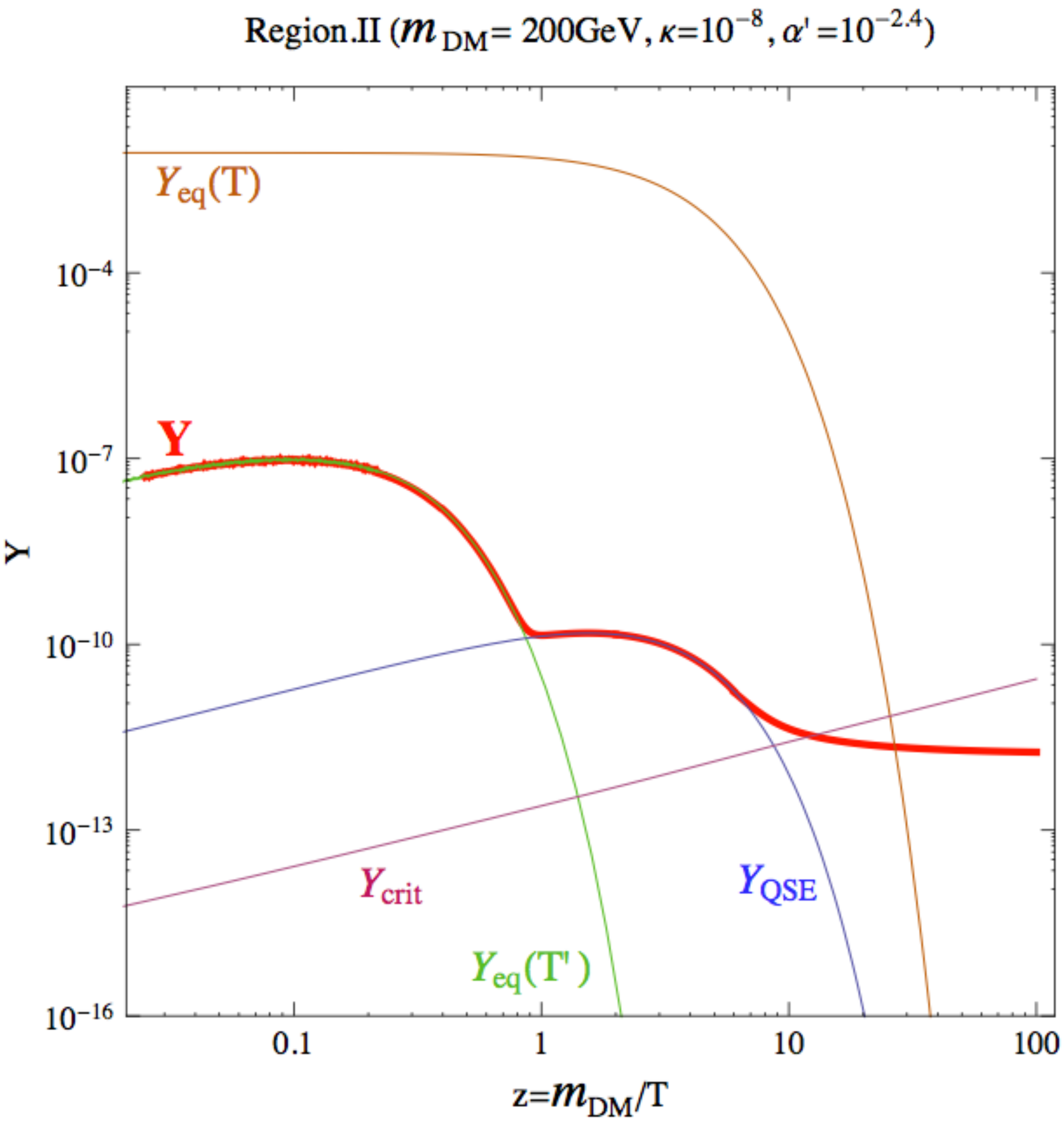
SOLAR MASS BINARY MERGERS

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

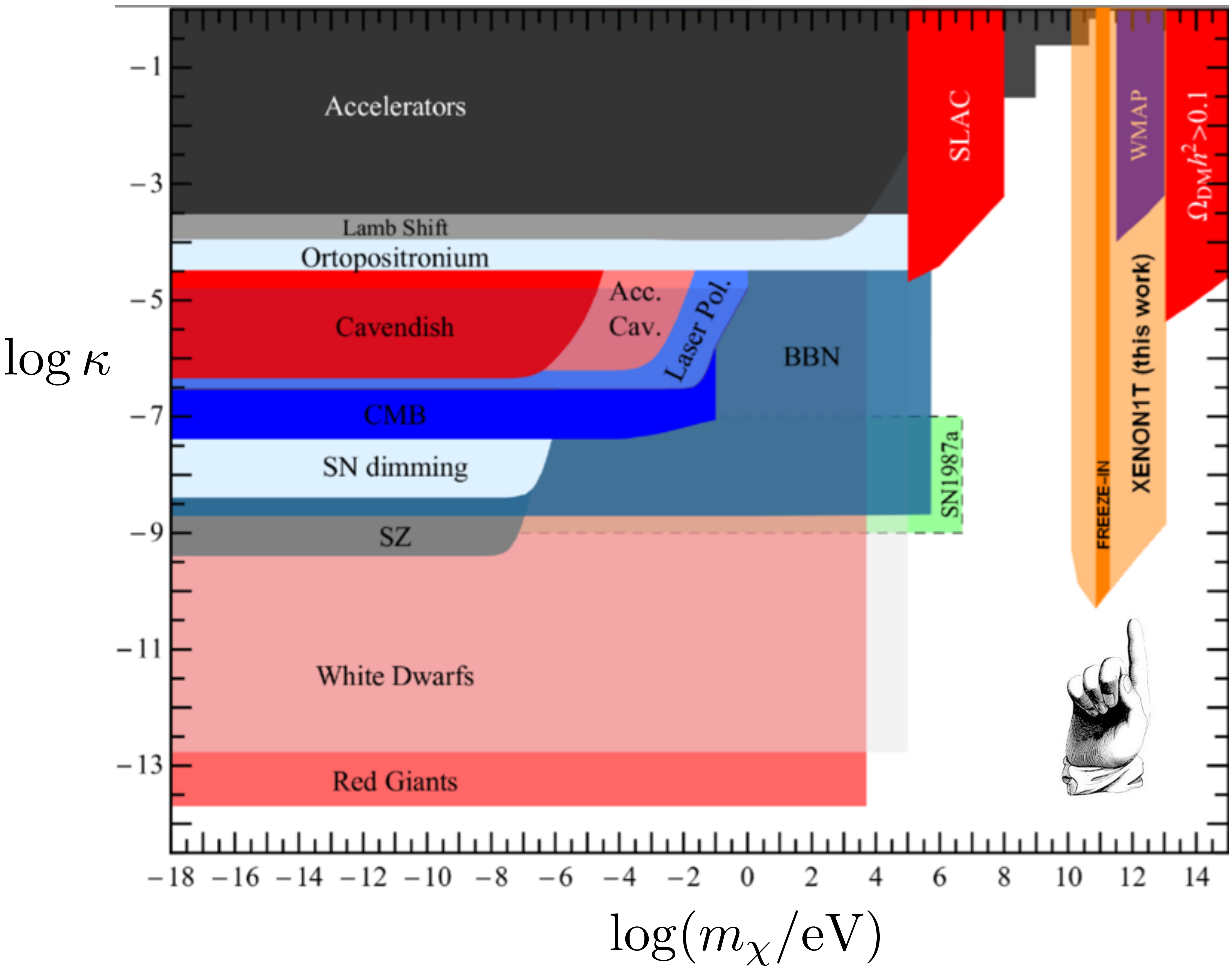


BACKUP

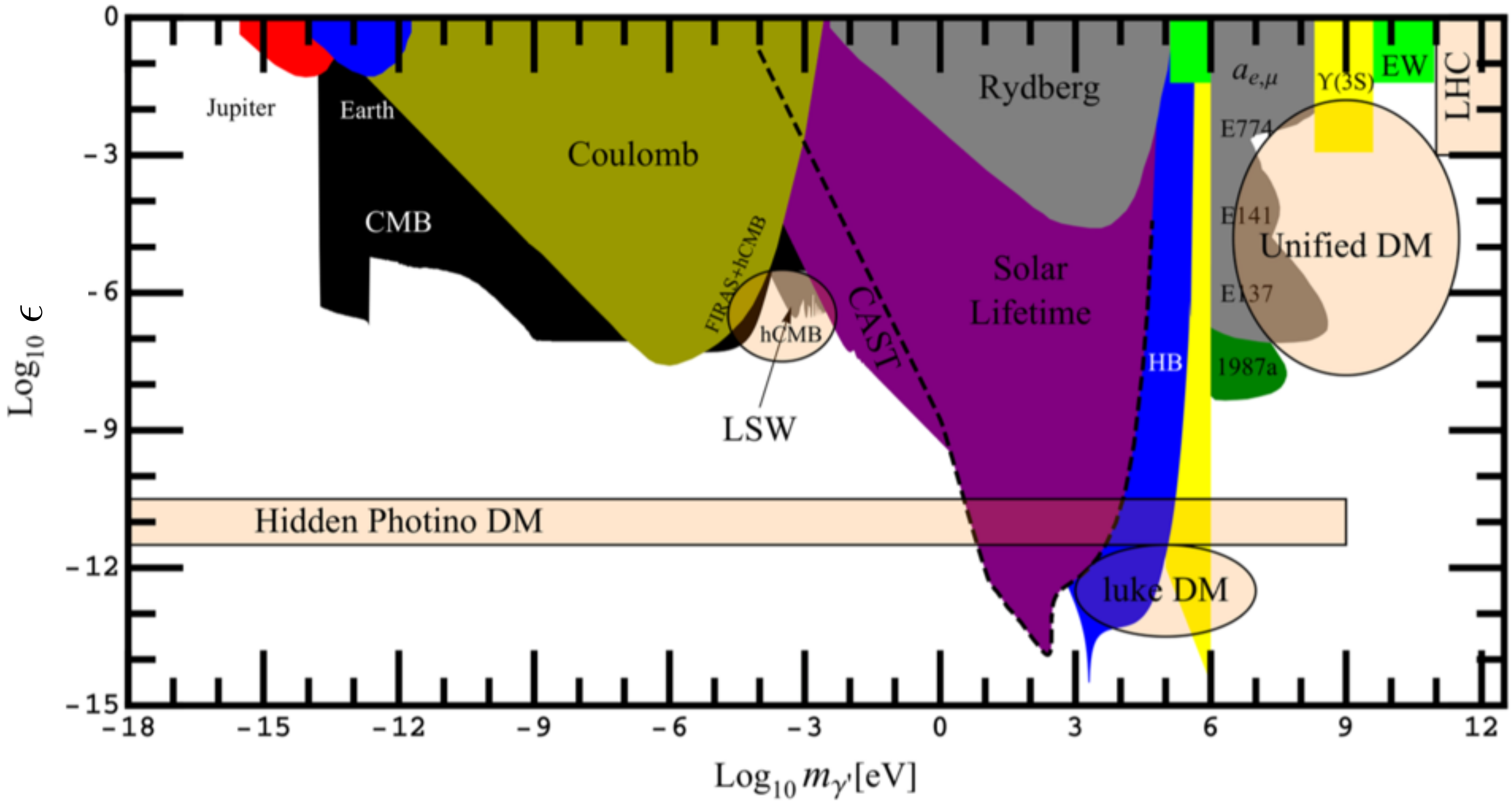
INTERMEDIATE REGIME : RECOMBINATION



CONSTRAINTS ON MILLICHARGED PARTICLES

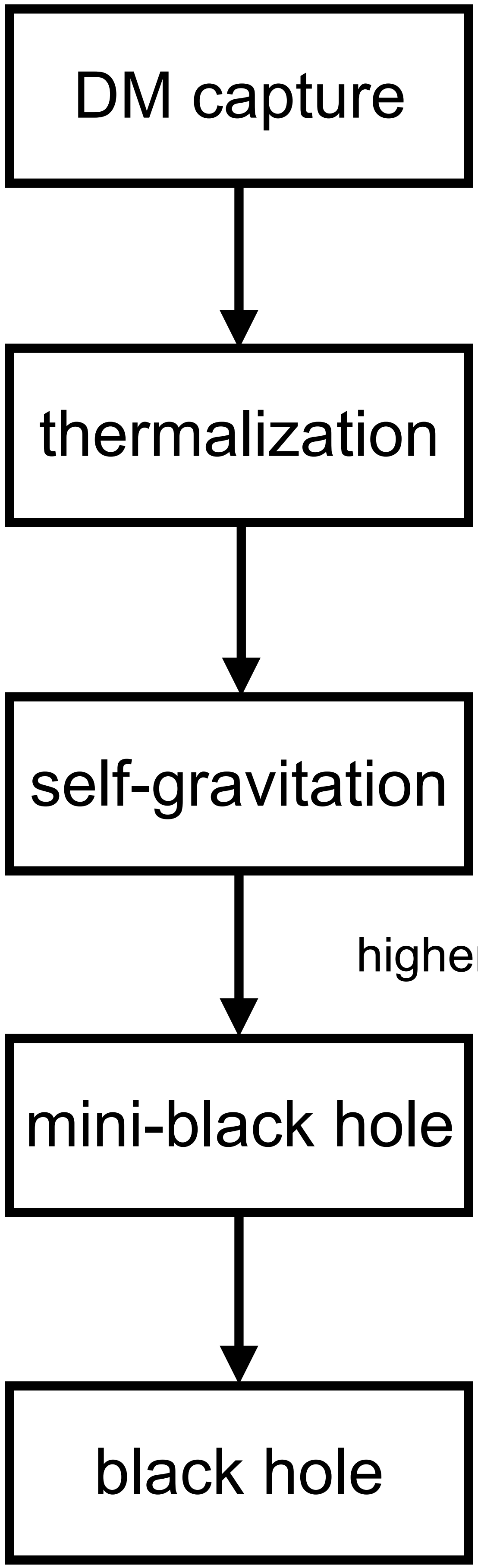


CONSTRAINTS ON DARK PHOTON



(old) compilation from Redondo & Ringwald, 2010

WIMPS THAT WOULD DEVOUR STARS



$$M_{acc} \sim 10^{39}\,\mathrm{TeV}\left(\frac{\rho_{\mathrm{dm}}}{\mathrm{GeV/cm}^3}\right)\left(\frac{t}{\mathrm{Gyr}}\right)\mathrm{Min}\left(\frac{\sigma}{\sigma_{cr}},1\right)$$

$$t_{th} \sim 10^2\,\mathrm{yr}\left(\frac{m_{\mathrm{dm}}}{\mathrm{TeV}}\right)^2\left(\frac{10^{-45}\mathrm{cm}^2}{\sigma}\right)$$

Goldman & Nussinov (1989)
Kouvaris & Tinyakov (2010)

$$r_{\mathrm{th}} \approx \left(\frac{T_c}{G\rho_c m_{\mathrm{dm}}}\right)^{1/2} \sim 10\,\mathrm{cm}\left(\frac{\mathrm{TeV}}{m_{\mathrm{dm}}}\right)^{1/2}\left(\frac{T_c}{10^5\mathrm{K}}\right)^{1/2}$$

$$\frac{N_{\mathrm{acc}} m_{\mathrm{dm}}}{r_{\mathrm{th}}^3} \gtrsim \rho_c \sim 10^{39}\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \quad\rightarrow\quad N_{\mathrm{cr}} \gtrsim 10^{38}\left(\frac{TeV}{m_{\mathrm{dm}}}\right)^{3/2}$$

higher density, higher T, further cooling, further collapse

$$\frac{GNm_{\mathrm{dm}}^2}{R} \gtrsim k_F \sim \frac{N^{1/3}}{R} \quad\rightarrow\quad N_{\mathrm{Ch}} \gtrsim \left(\frac{M_{\mathrm{Pl}}}{m}\right)^3 \sim 5\cdot 10^{48}\left(\frac{\mathrm{TeV}}{m_{\mathrm{dm}}}\right)^3$$

Overcoming Fermi pressure requires $m_{\mathrm{dm}} \gtrsim 1000\,\mathrm{TeV}$

Bramante, Linden & Tsai (2017);Kouvaris, Tinyakov & MT (2018)

PRIMORDIAL BLACK HOLES ?

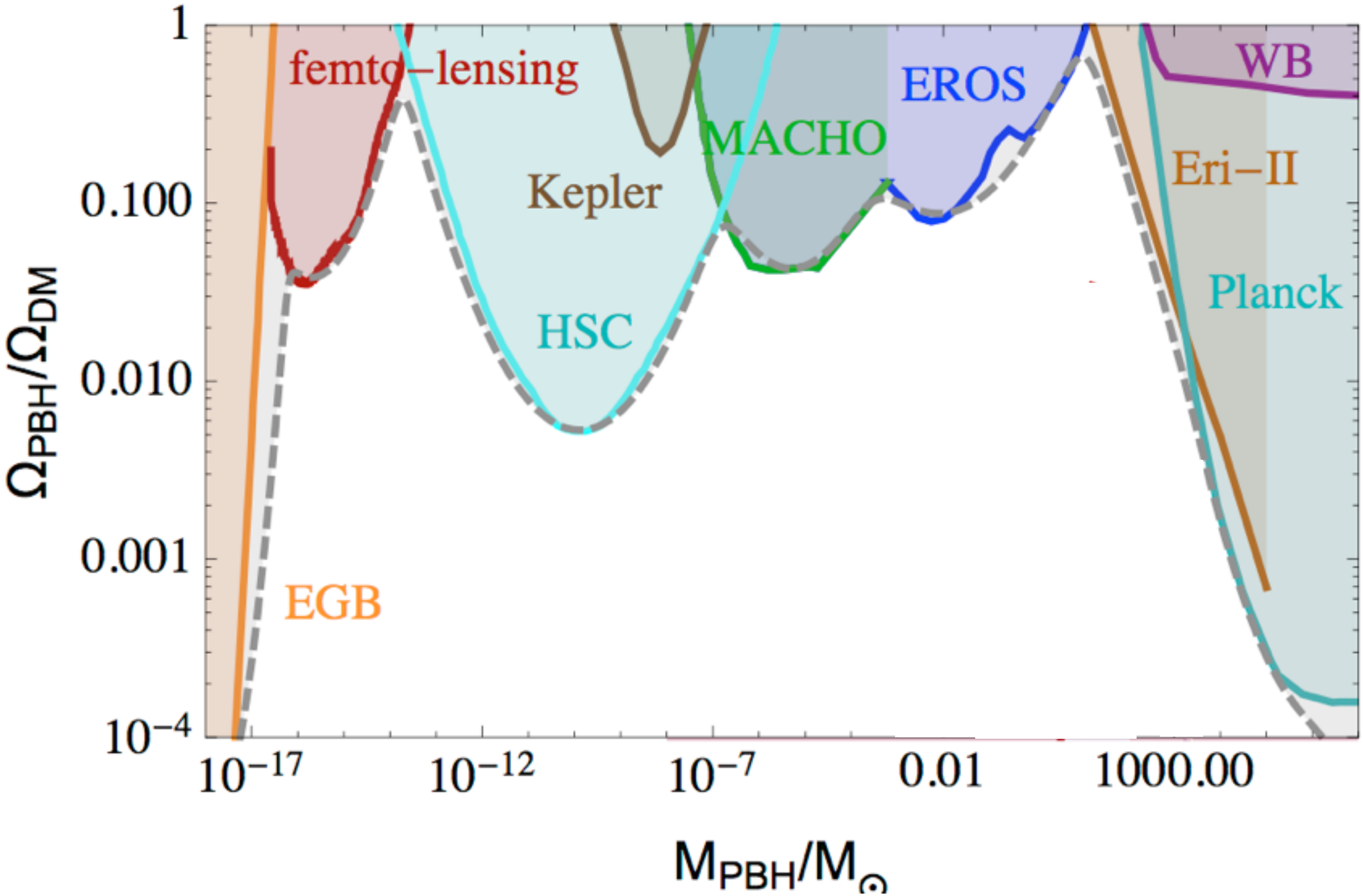


Figure from Garcia-Bellido & Clesse (2018)