New Directions for Thermal Dark Matter

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CCAPP

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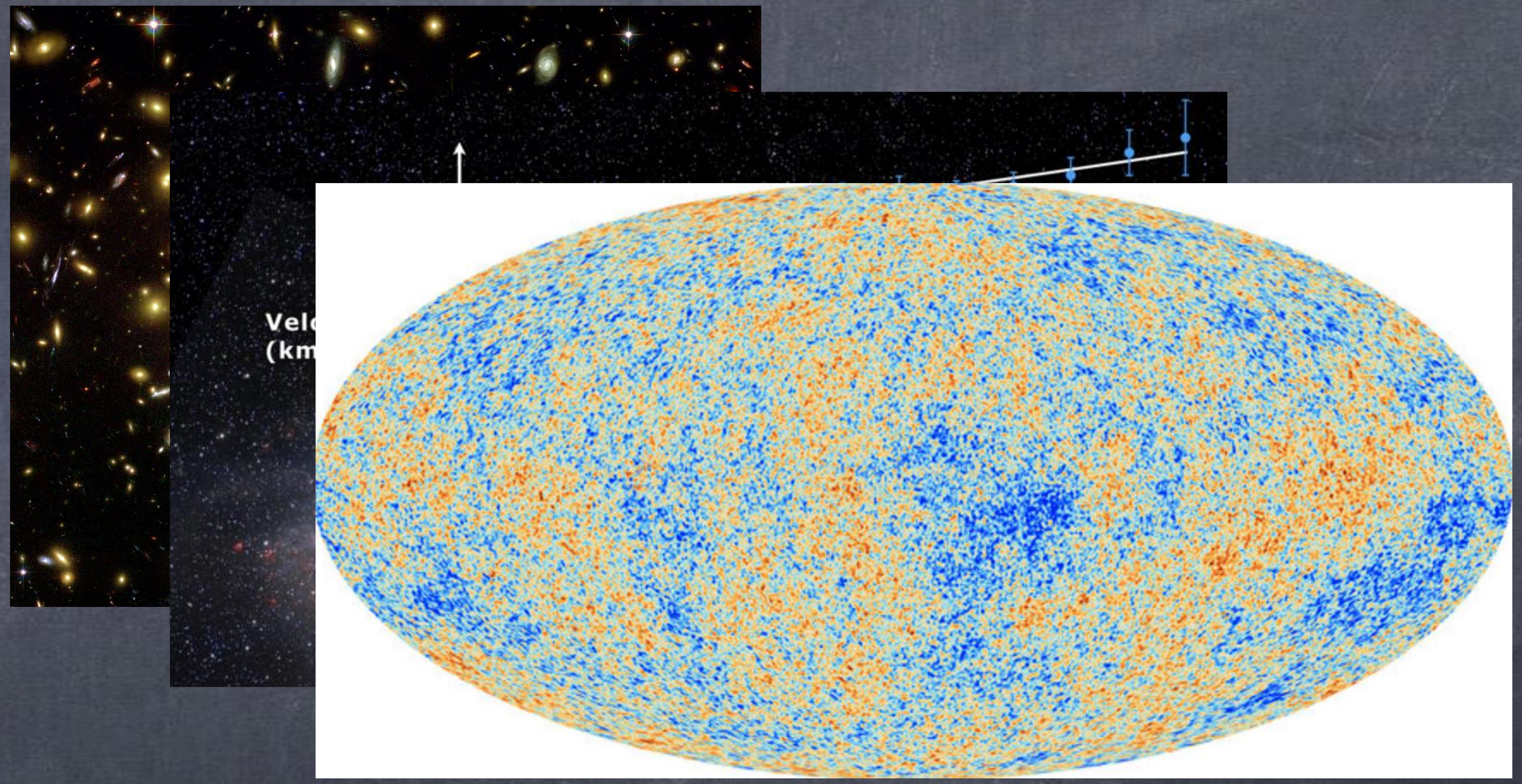
THE OHIO STATE UNIVERSITY

Dark Matter is a New Particle

Not ordinary Matter:

$$\Omega_{\rm DM} >> \Omega_{\rm Baryons}$$

(CMB) (BBN, CMB)



Not MOND:

Not light Neutrinos:

$$\Omega_\nu \approx 0.02 \left(\frac{m_\nu}{\rm eV}\right)$$

Dark Matter was made in the EU

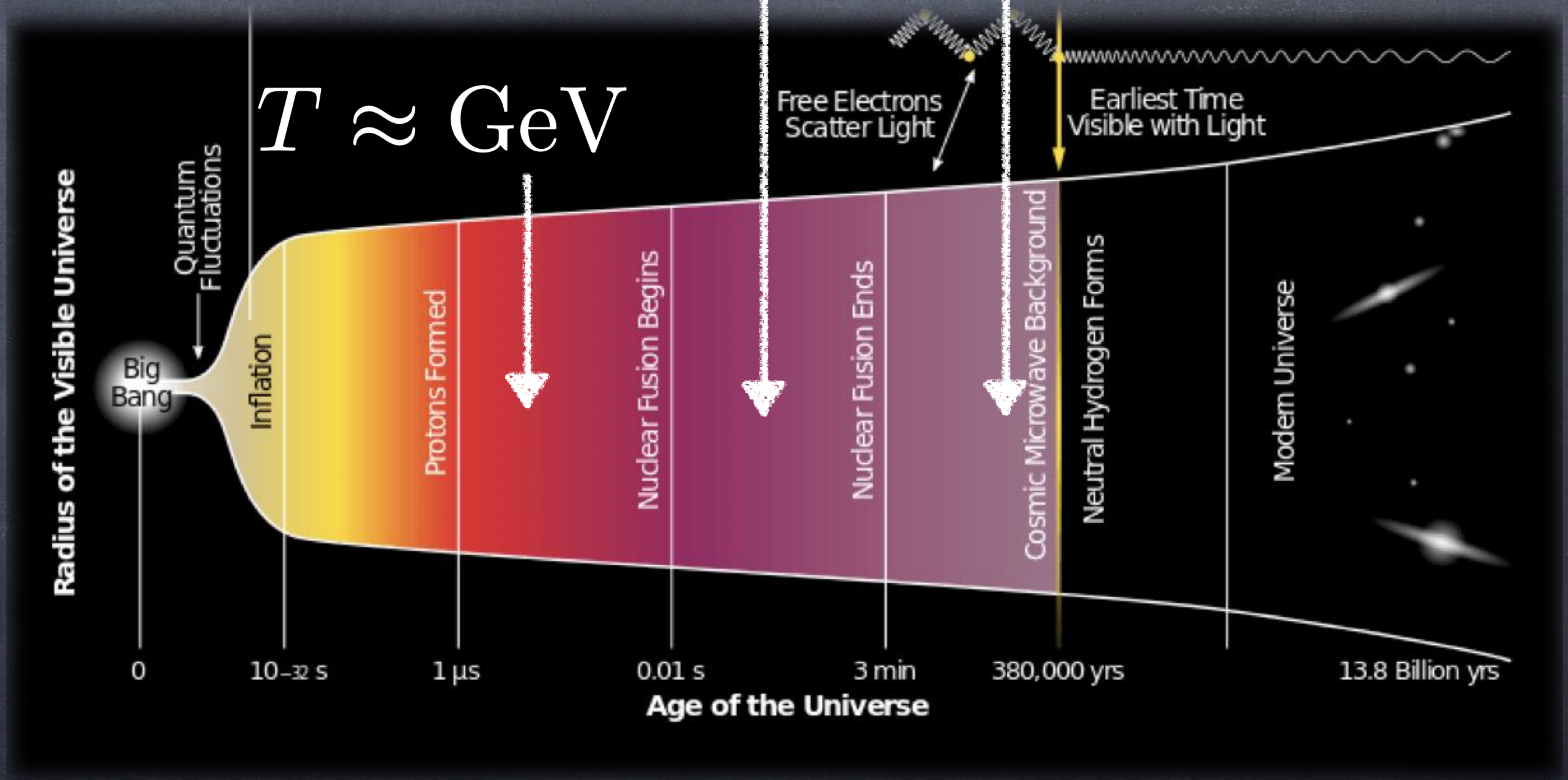
1. The EU is very hot

   T >> M

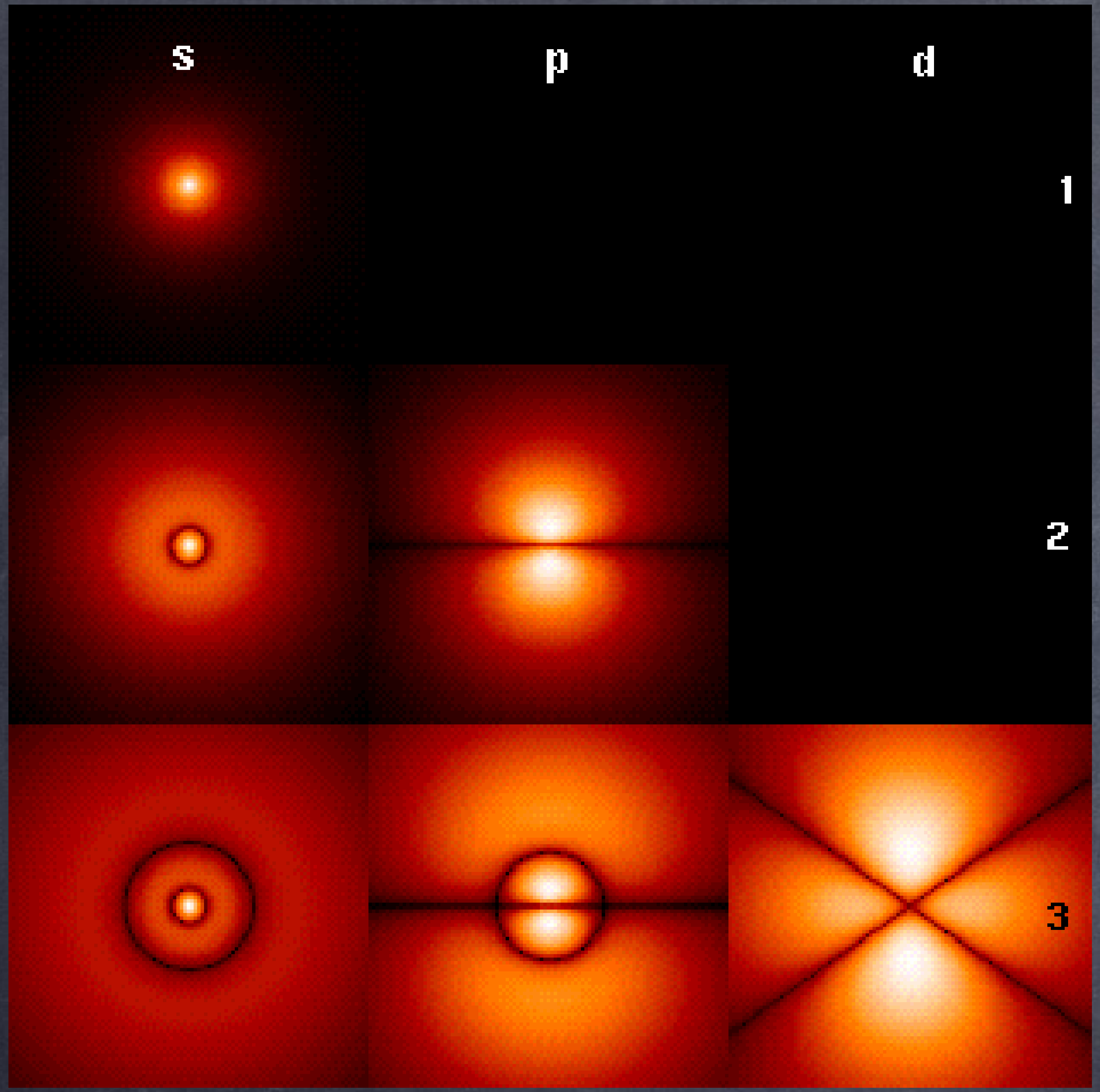
2. E = Mc^2 ensures* abundant production

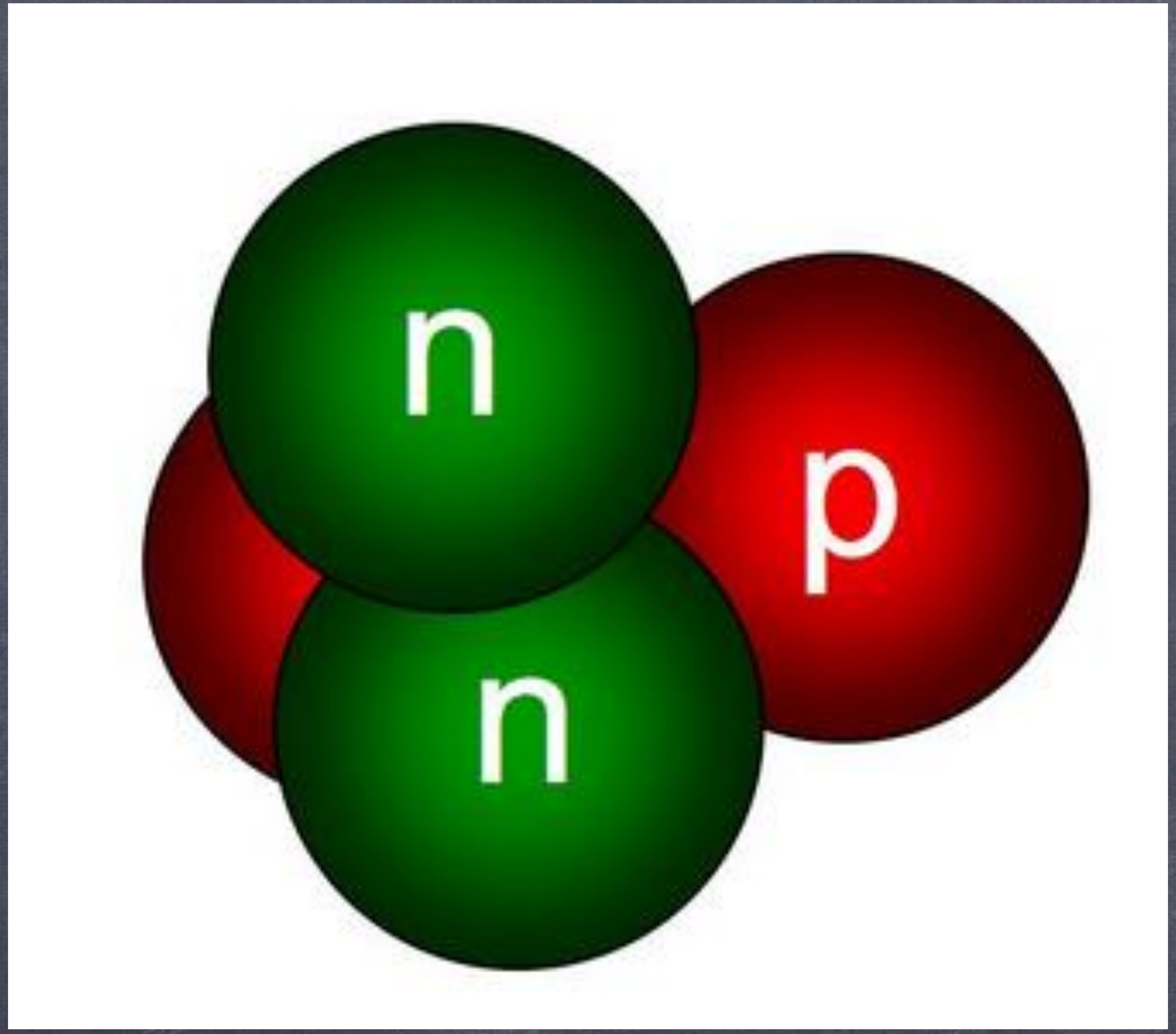
$T \approx \mathrm{MeV}$ $T \approx \mathrm{eV}$

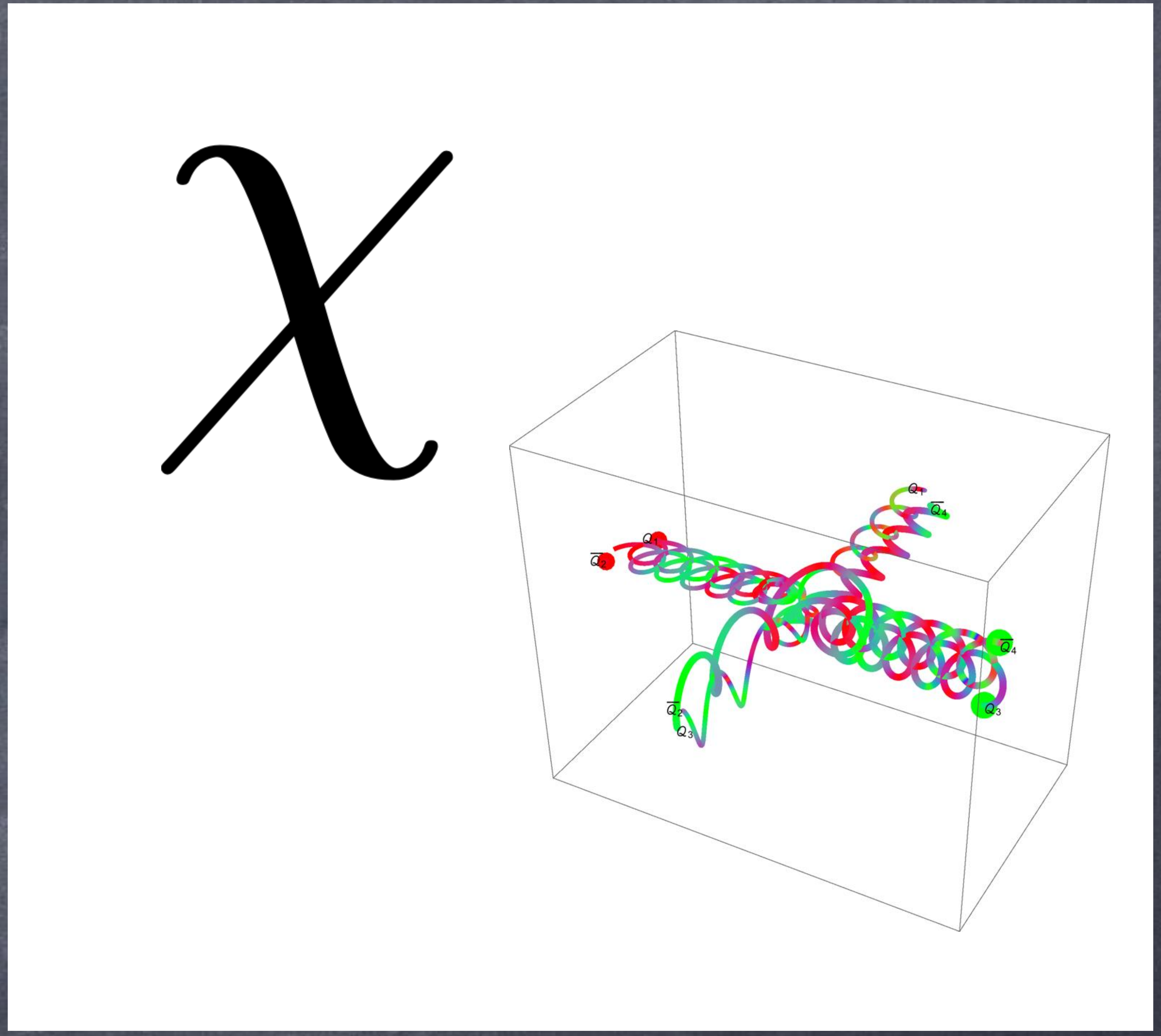
$T \approx \mathrm{GeV}$



Dark Matter probes the EU







Hydrogen Atom

Cosmic Microwave Radiation
t ≈ 300 000 years

Light Nuclei

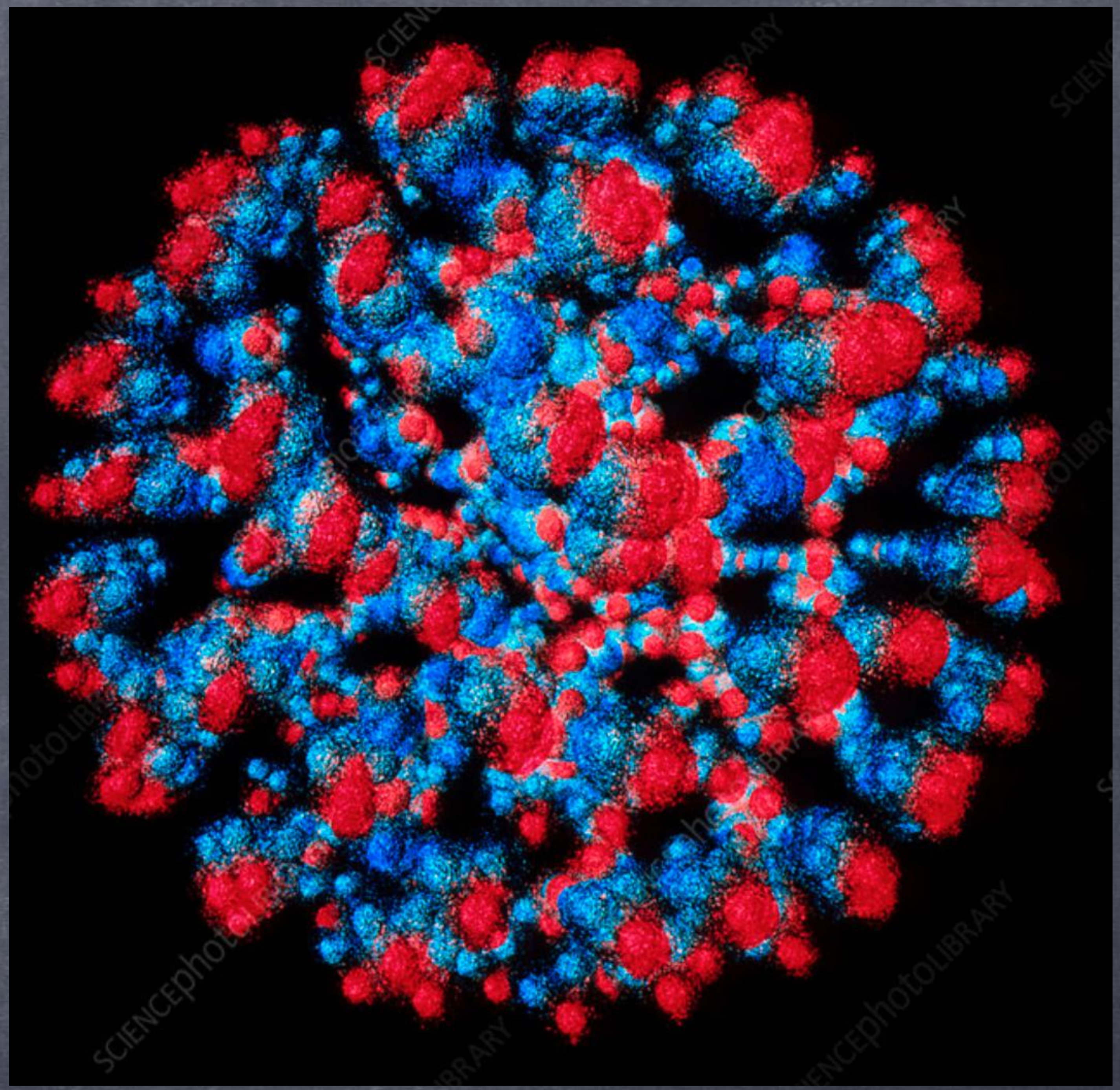
Big Bang Nucleosynthesis
H and He abundance
t ≈ 1 sec.

Dark States

DM Genesis
t < 1 sec.

Matter has structure

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

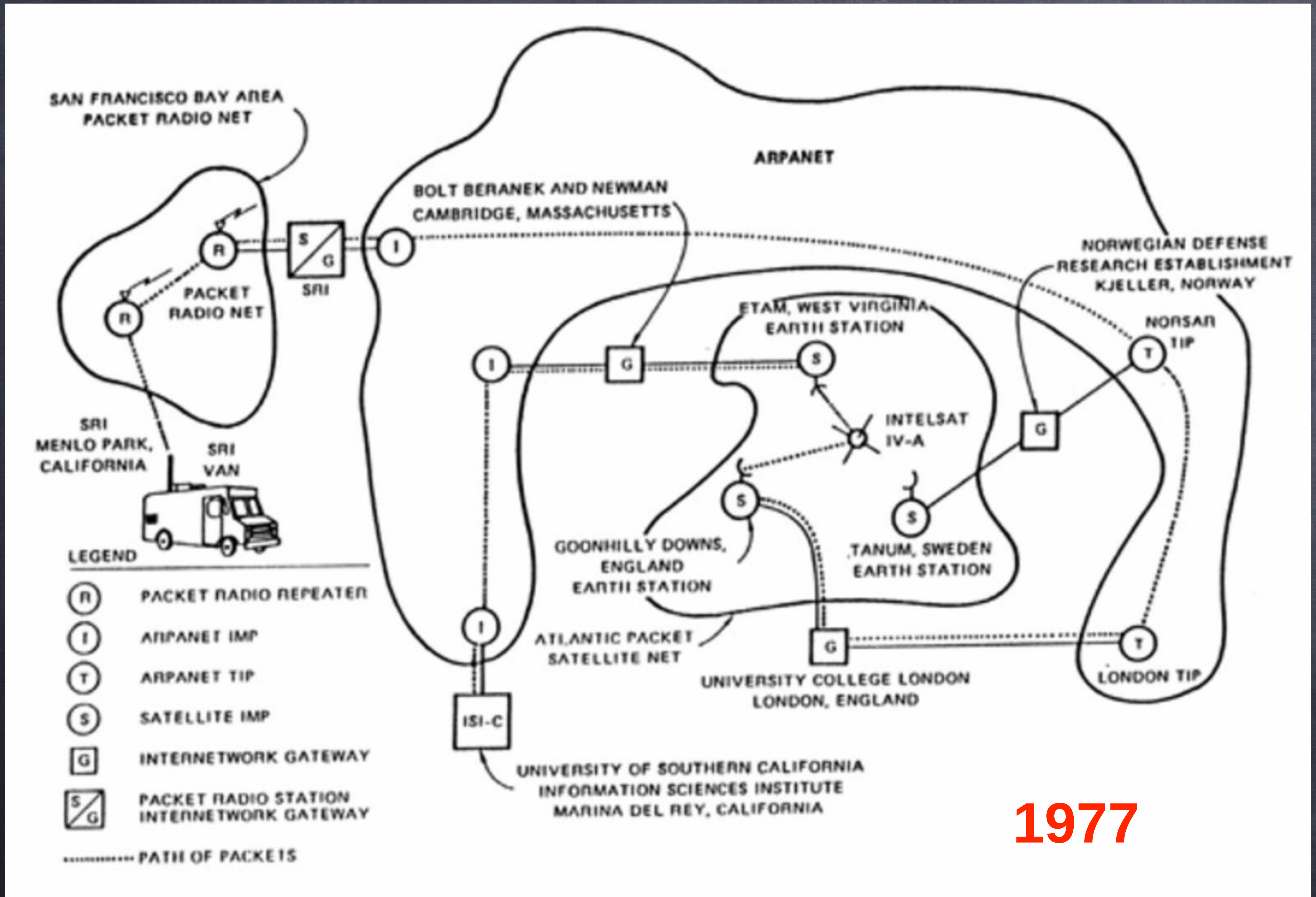


?

1 H	2 He	Z > 2 Metal

χ

Is Dark Matter complex?

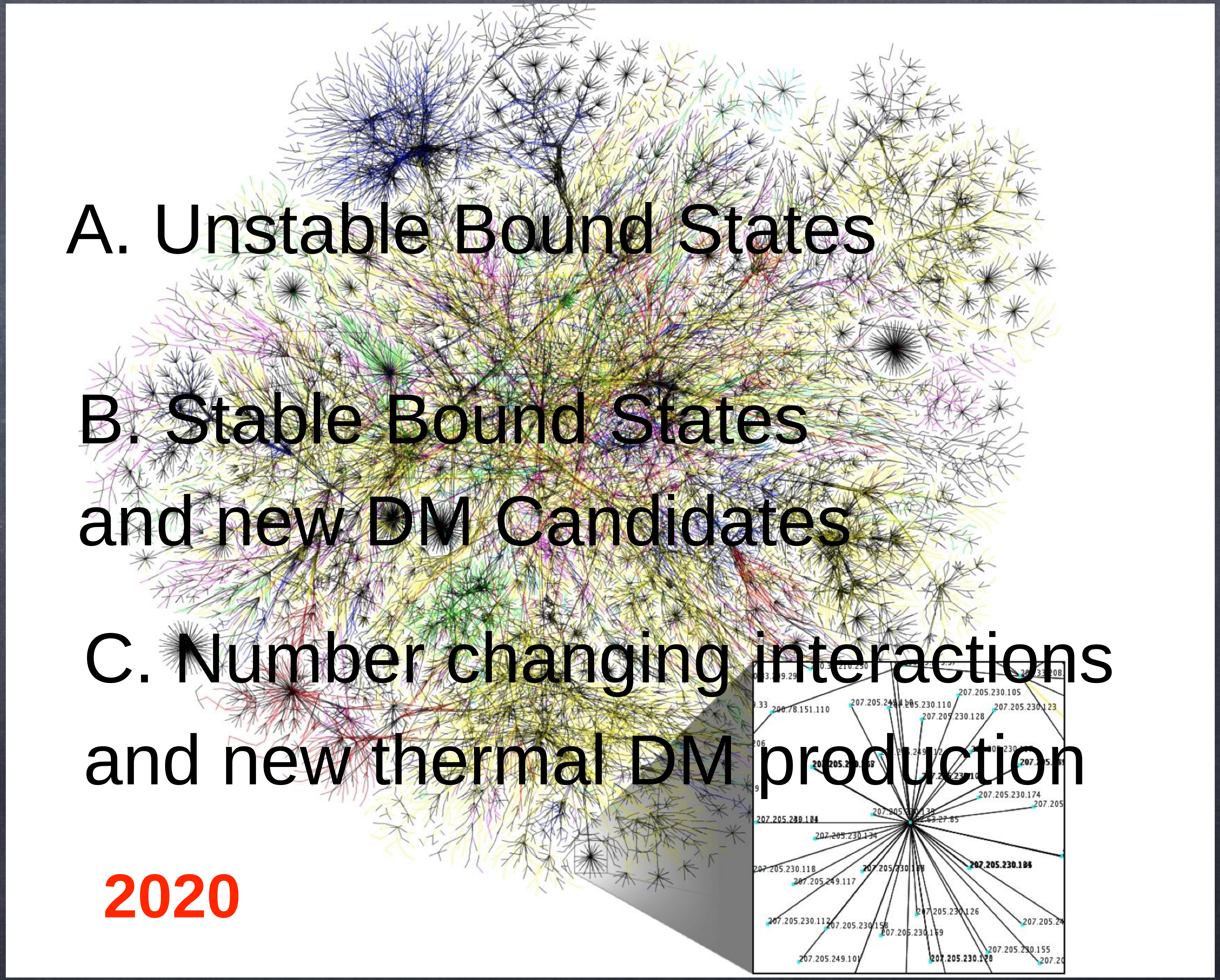


1977

A. Unstable Bound States

B. Stable Bound States
and new DM Candidates

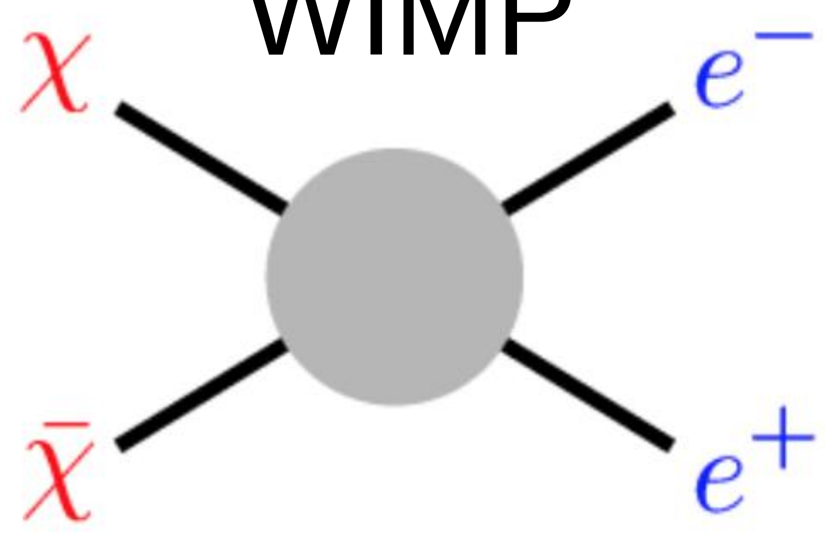
C. Number changing interactions
and new thermal DM production



2020

Freezeout in the EU

WIMP

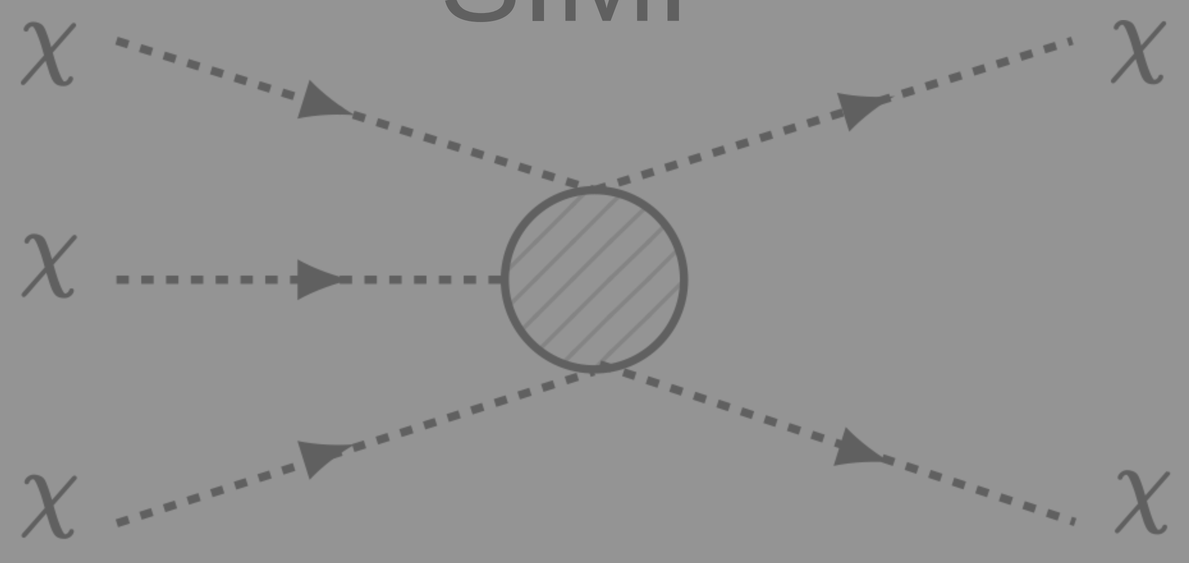


Zeldovich, Lee, Weinberg, Steigman, Turner,…

$$\Gamma_{\rm DM} = \langle \sigma v_{\rm rel.} \rangle \, n_{\rm DM} > H(T)$$

$$\Omega_{\rm DM} \, h^2 \approx \frac{0.12}{\langle \sigma v_{\rm rel.} \rangle \, [25 {\rm TeV}]^2}$$

SIMP

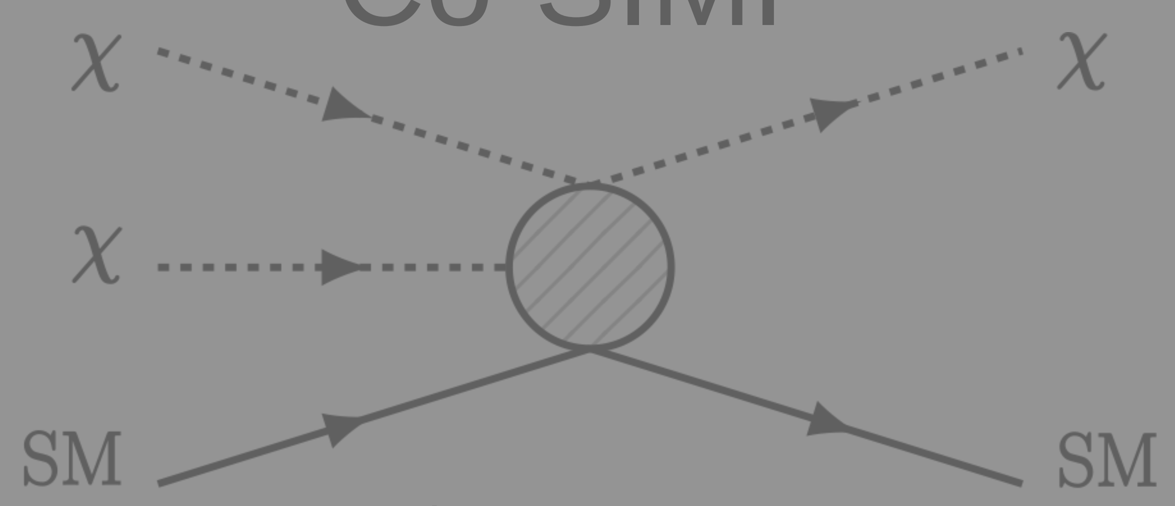


Hochberg, Kuflik, Volansky, Wacker

$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, n_{\rm DM}^2 > H(T)$$

$$\Omega_{\rm DM} \, h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}} \right) \frac{0.12}{\sqrt{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, [3 {\rm MeV}]^5}}$$

Co-SIMP

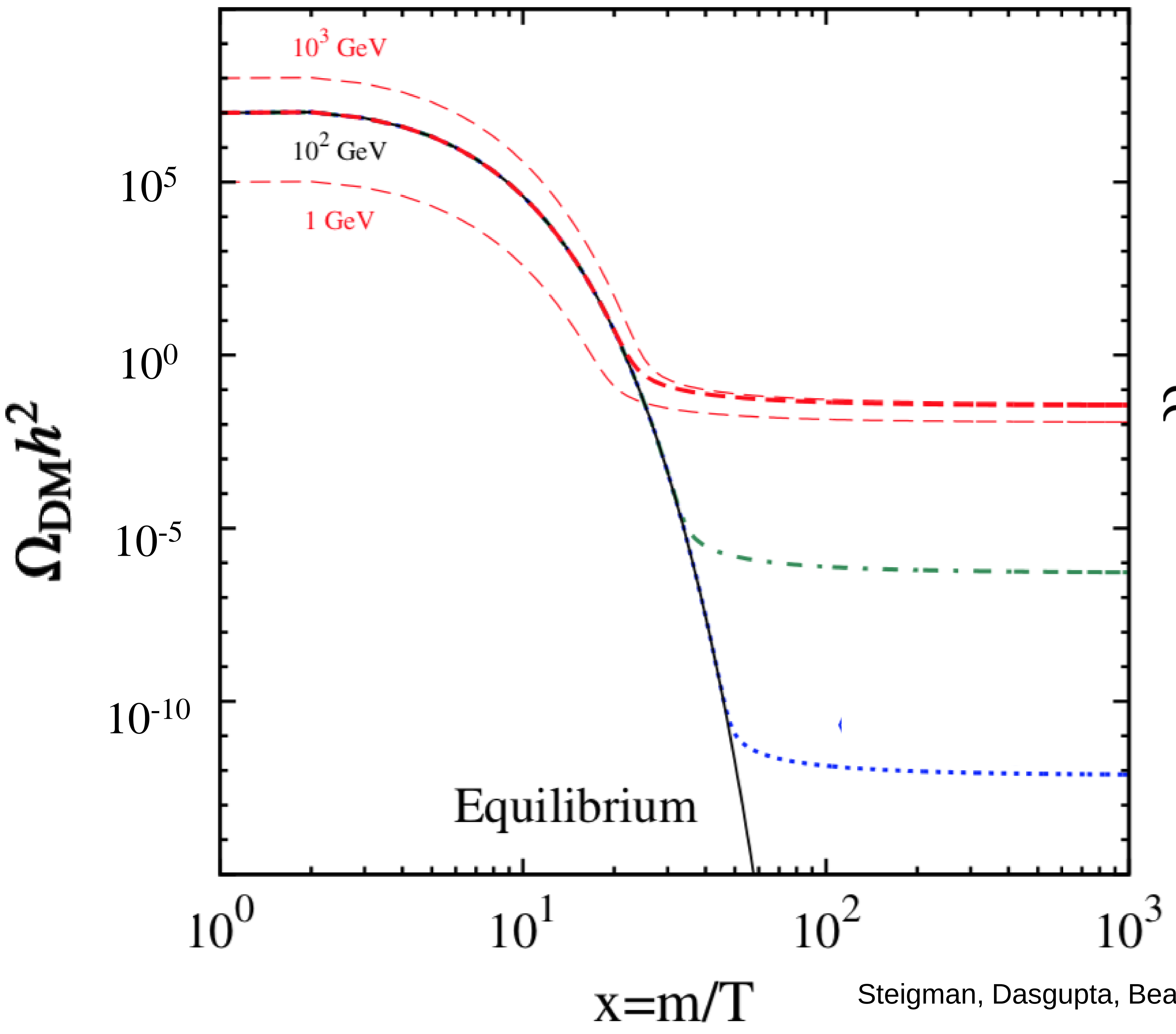


Smirnov, Beacom

$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, n_{\rm DM} n_{\rm SM} > H(T)$$

$$\Omega_{\rm DM} h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}} \right)^3 \frac{0.12}{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, [100 \ {\rm MeV}]^5}$$

WIMP Freezeout



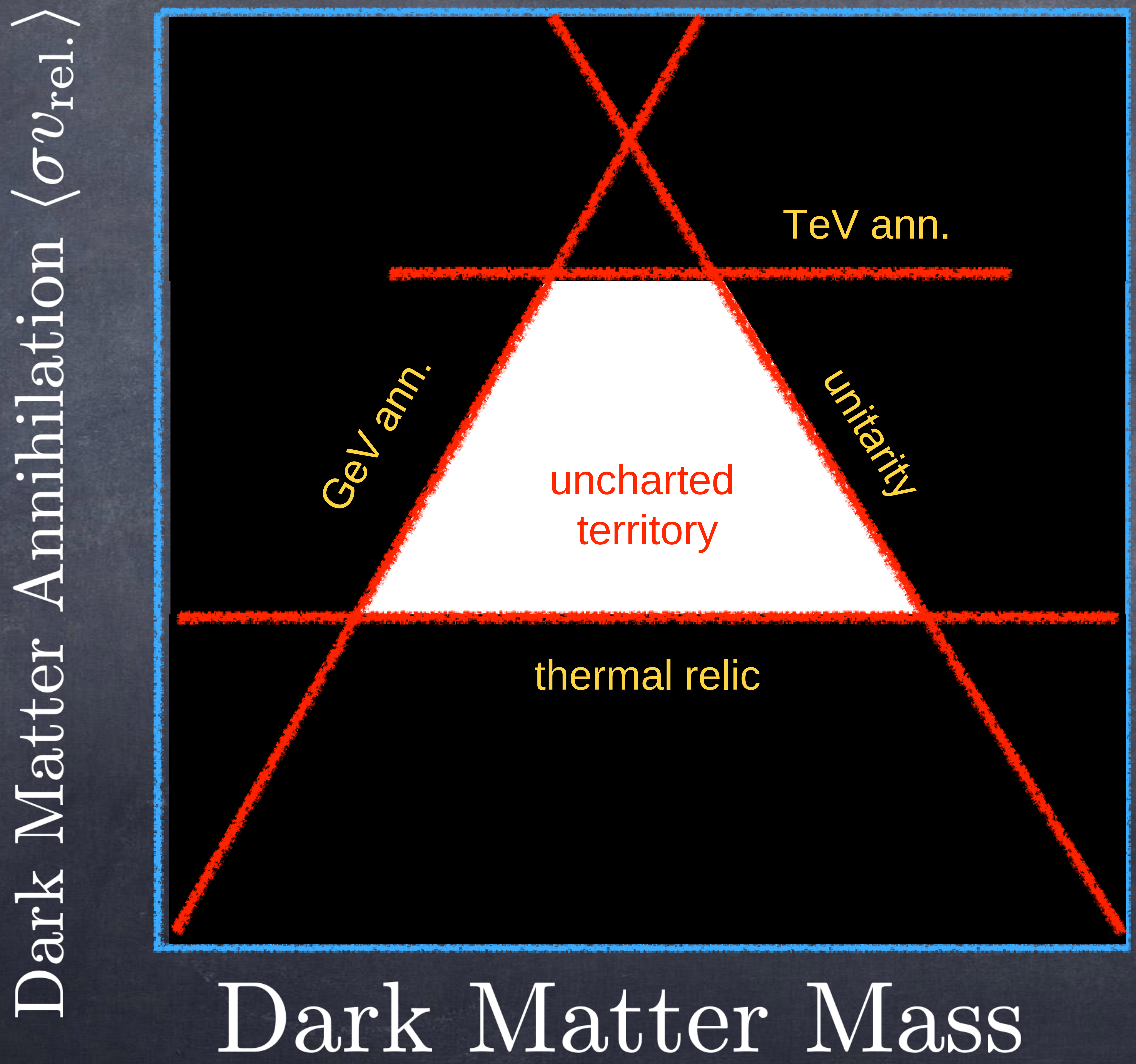
≈ 0.12

$$\Omega_{\rm DM}\, h^2 \approx \frac{0.12}{\langle \sigma v_{\rm rel.} \rangle \, [25 \mathrm{TeV}]^2}$$

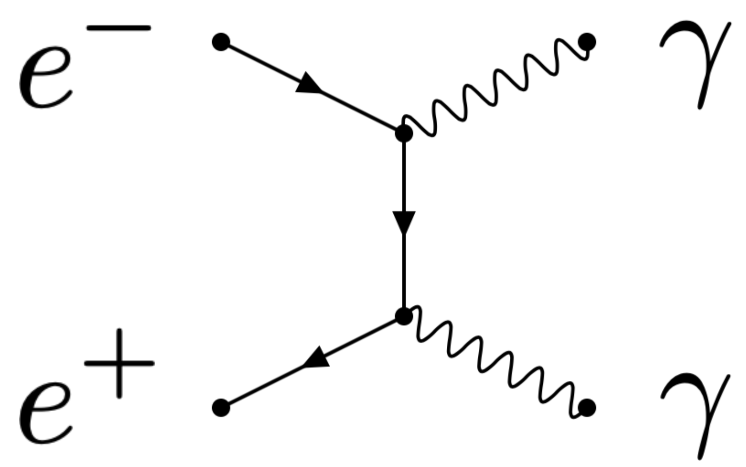
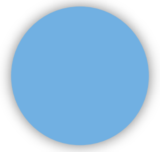
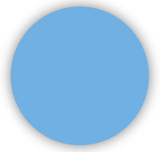
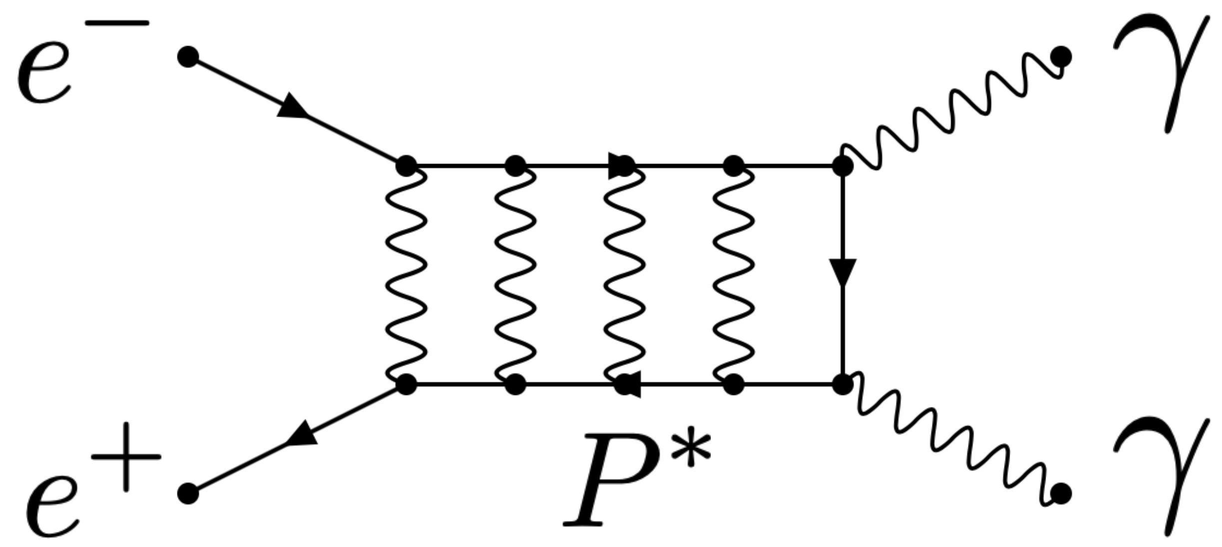
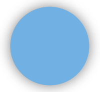
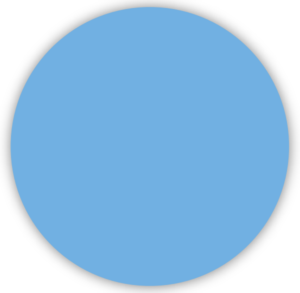
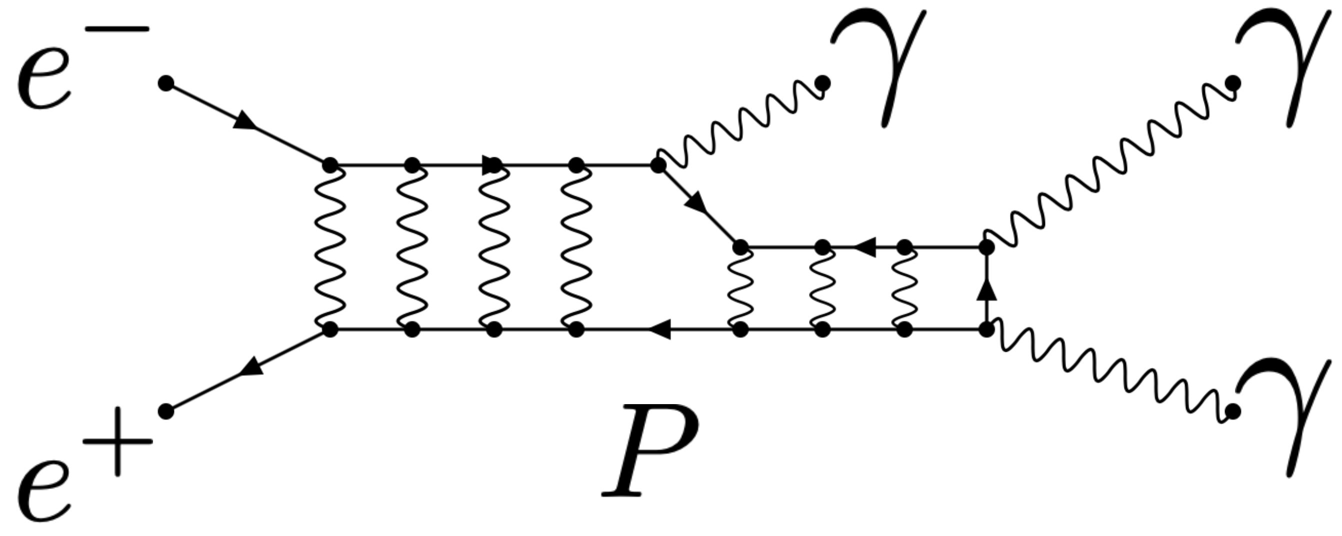
Steigman, Dasgupta, Beacom

arXiv: 1204.3622

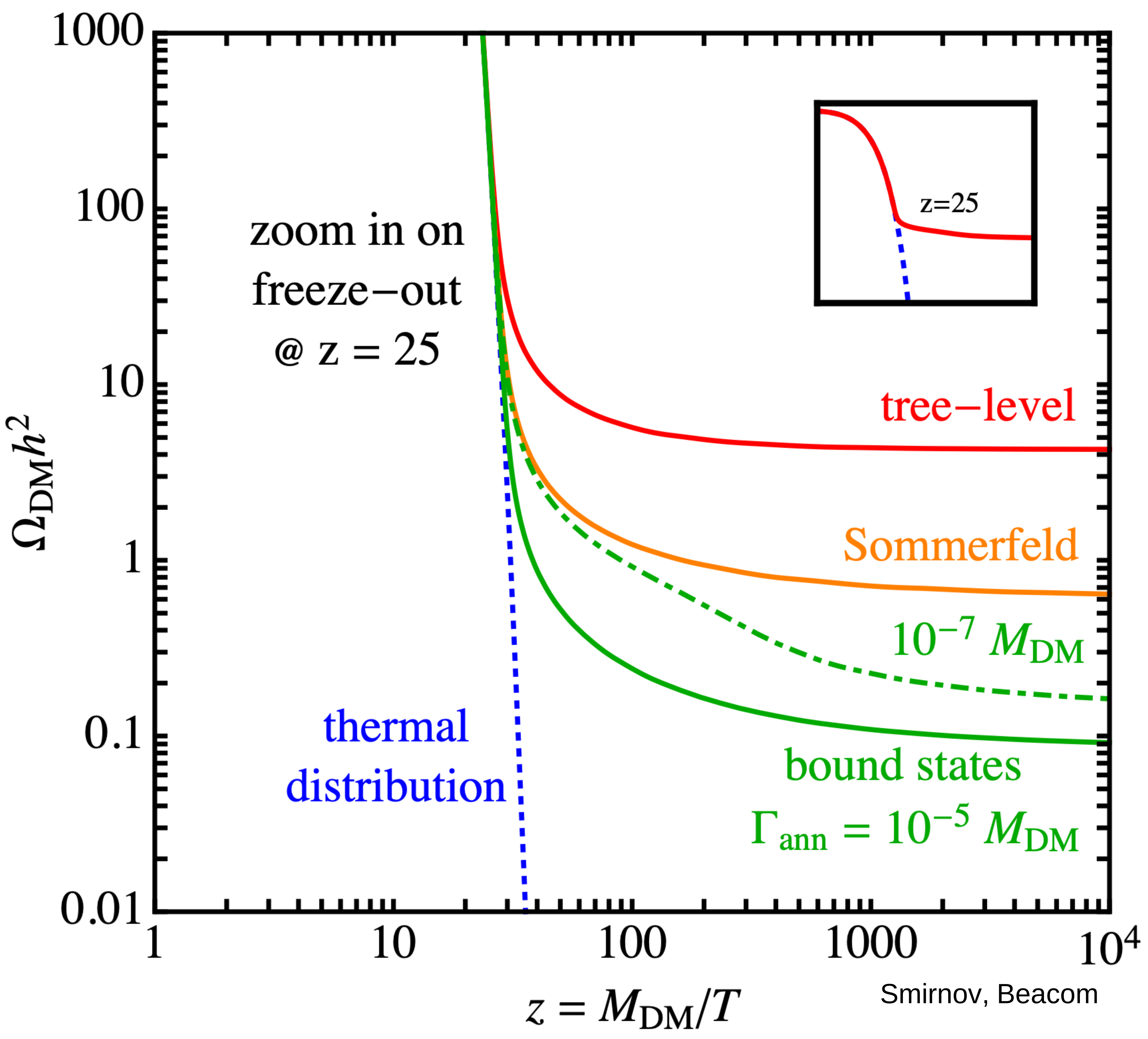
Cartoon Overview of Approach



Unstable DM Bound States

Process	Diagram	Cross-Section area	
		large velocity	small velocity
$e^+ e^- \to \gamma\gamma$			
$e^+ e^- \to P^* \to \gamma\gamma$			
$e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$	 Assuming Parapositronium (J=0)		

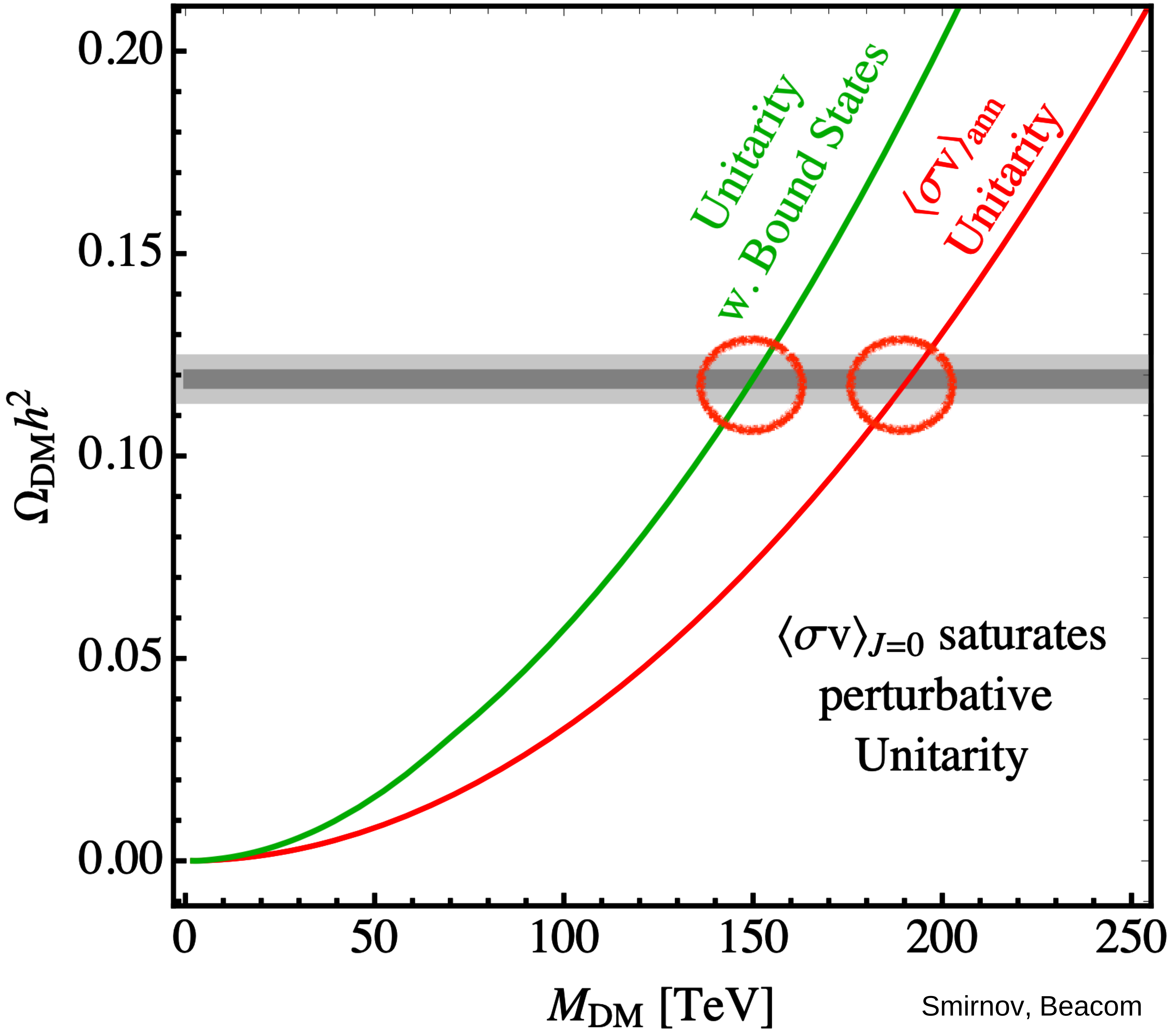
Effect on the Freezeout



Smirnov, Beacom

arXiv: 1904.11503

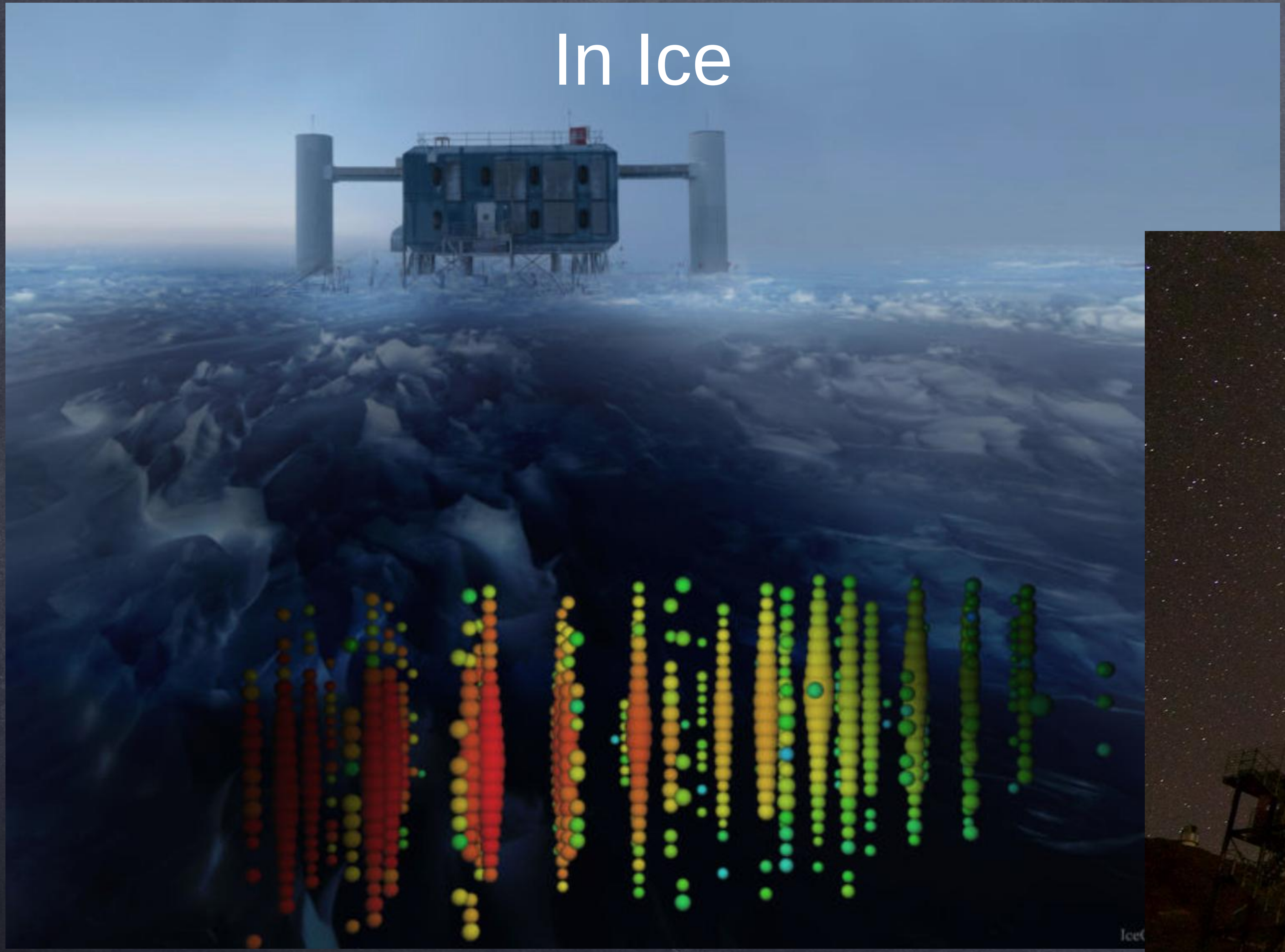
Maximal WIMP Mass

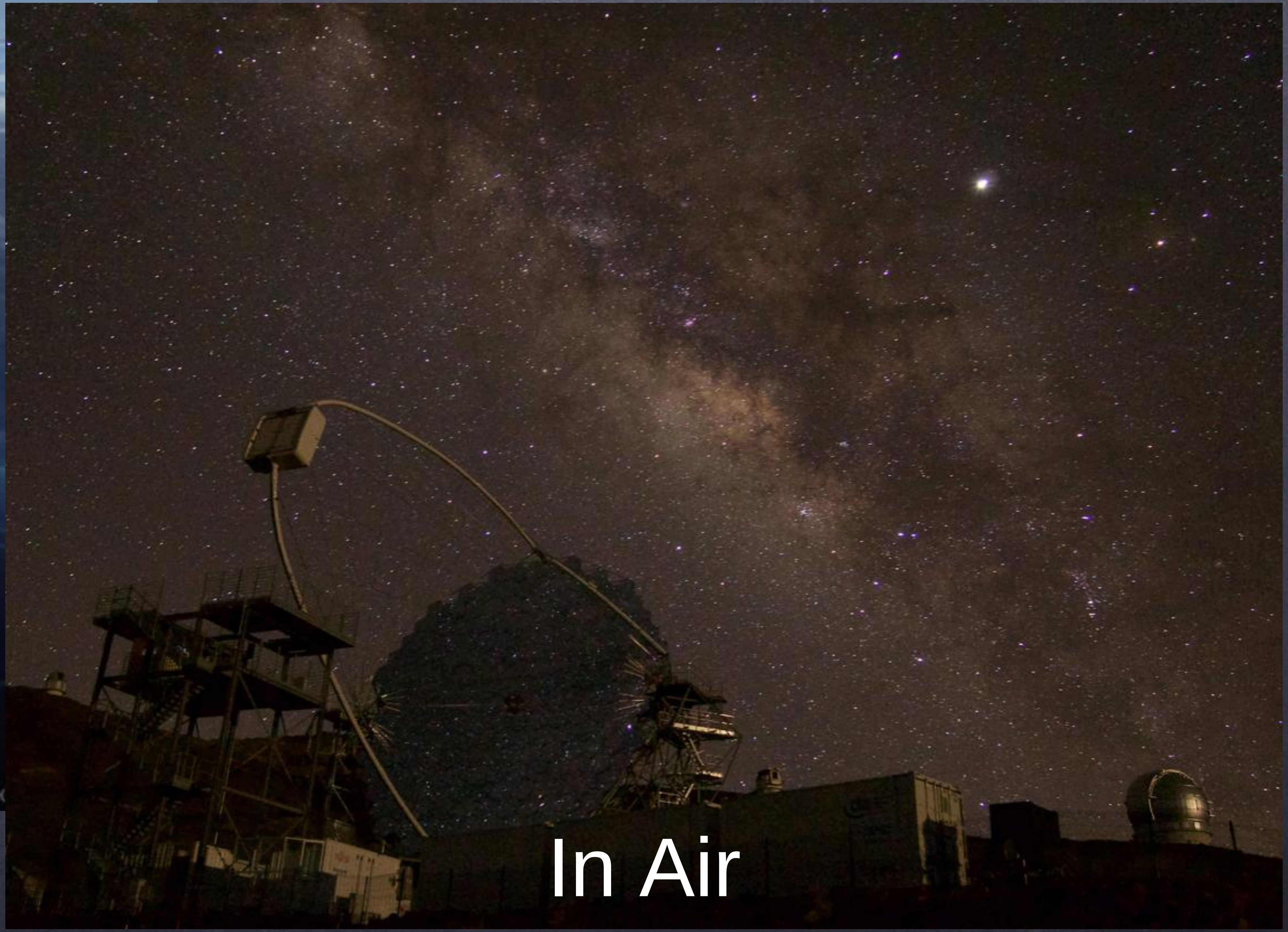


Smirnov, Beacom

arXiv: 1904.11503

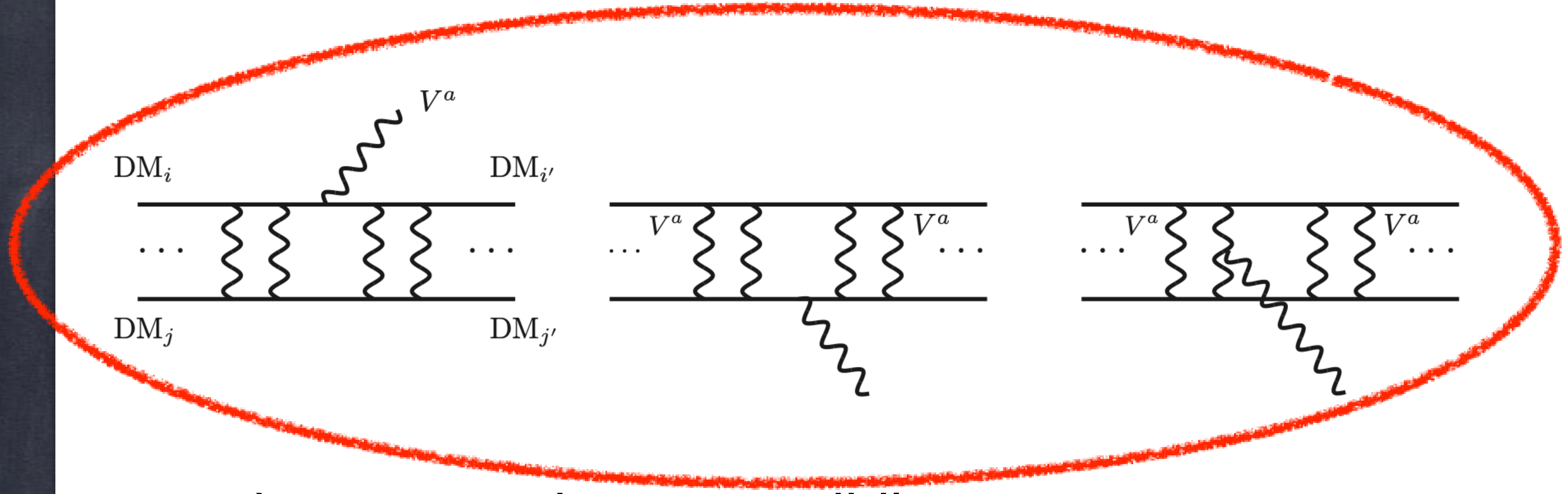
Cherenkov Detectors



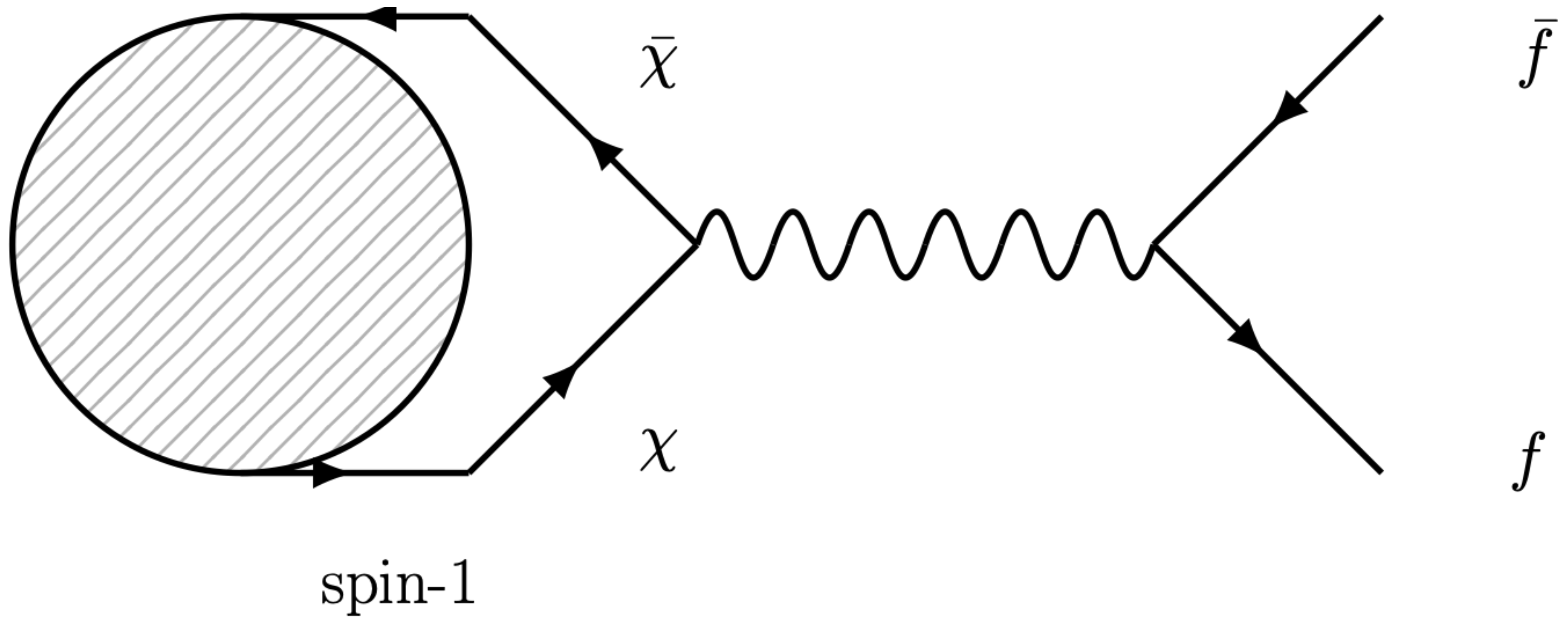


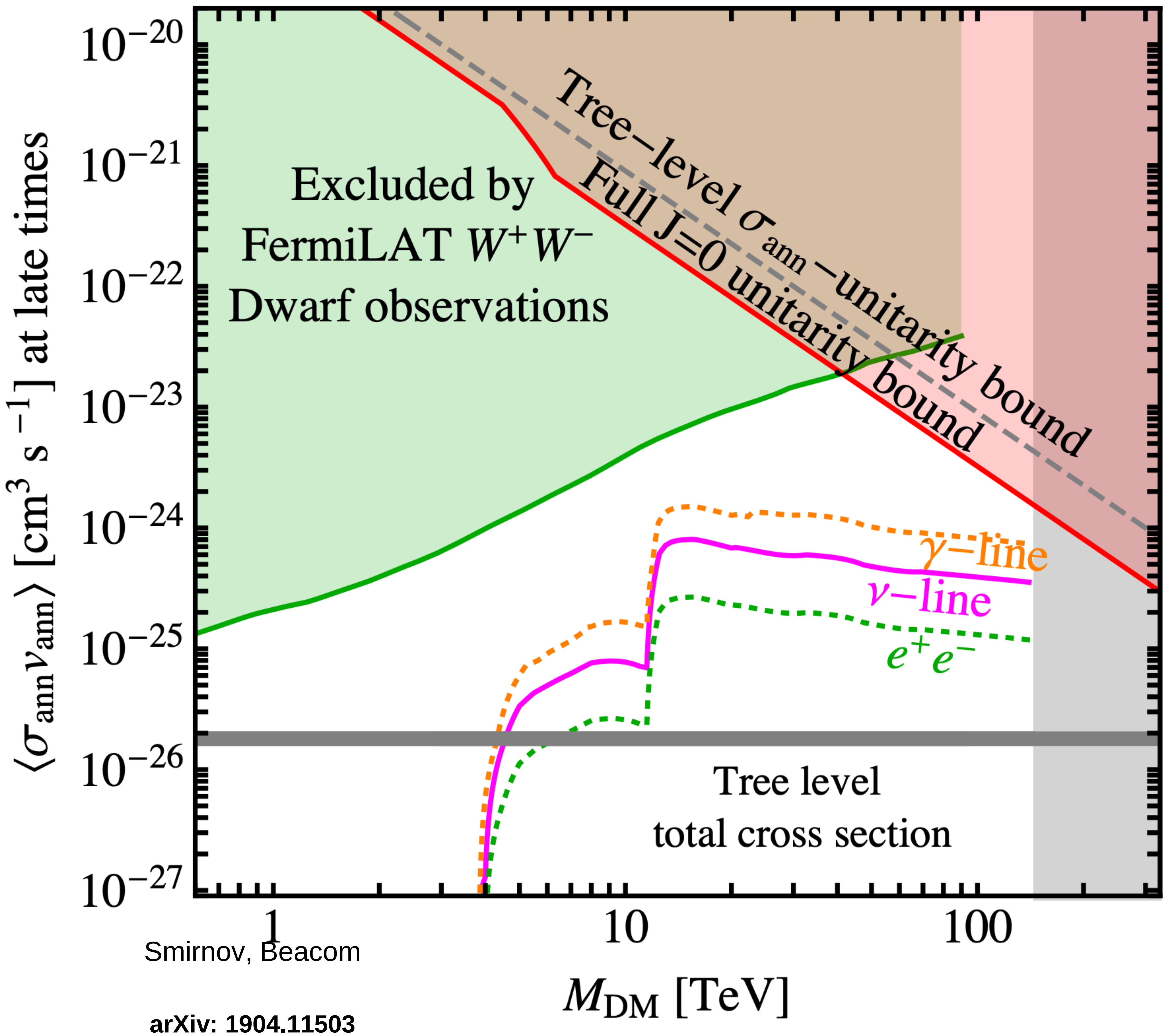
New DM Signals

A) DM Bound State forms:



B) DM Bound State annihilates:

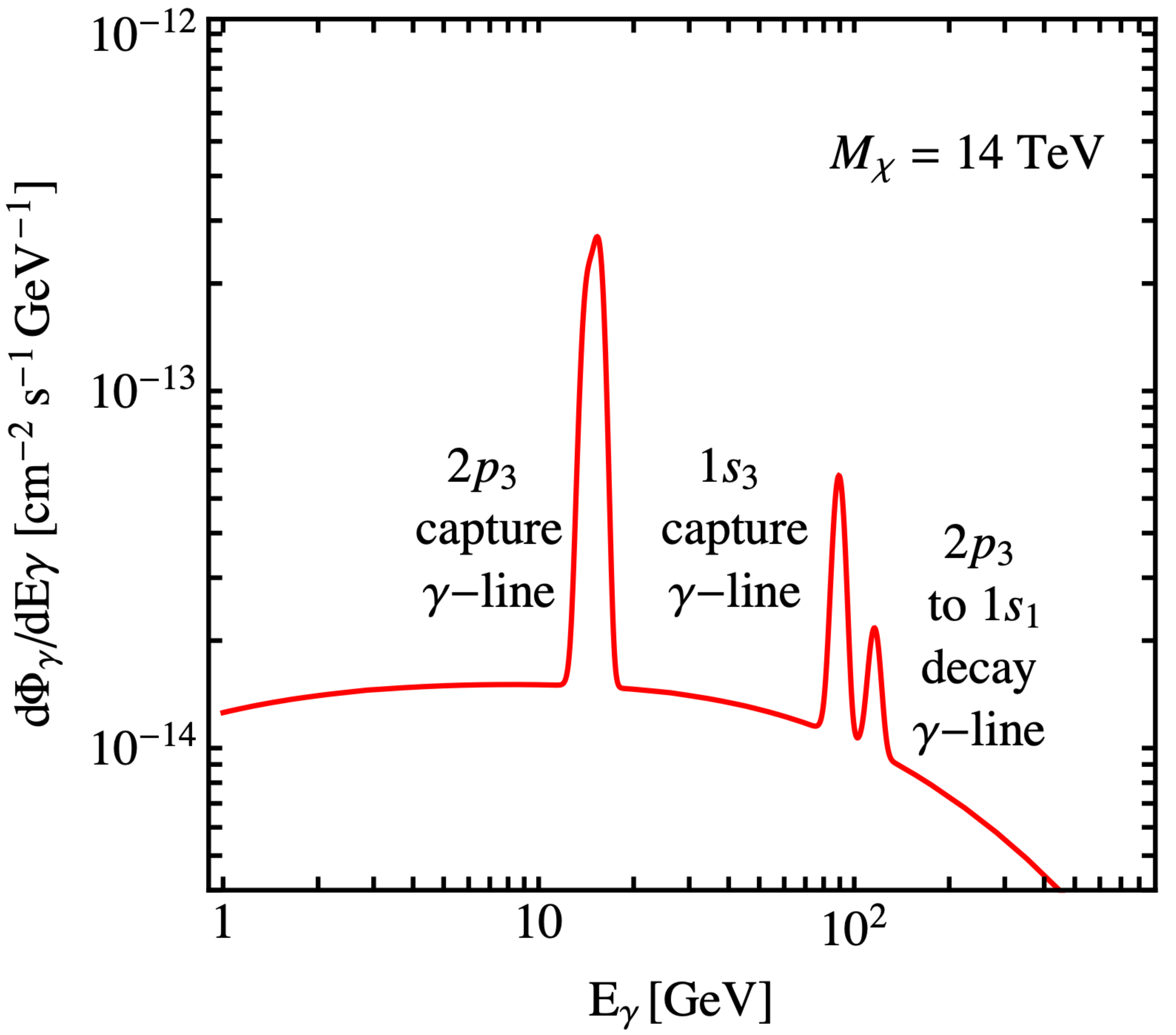


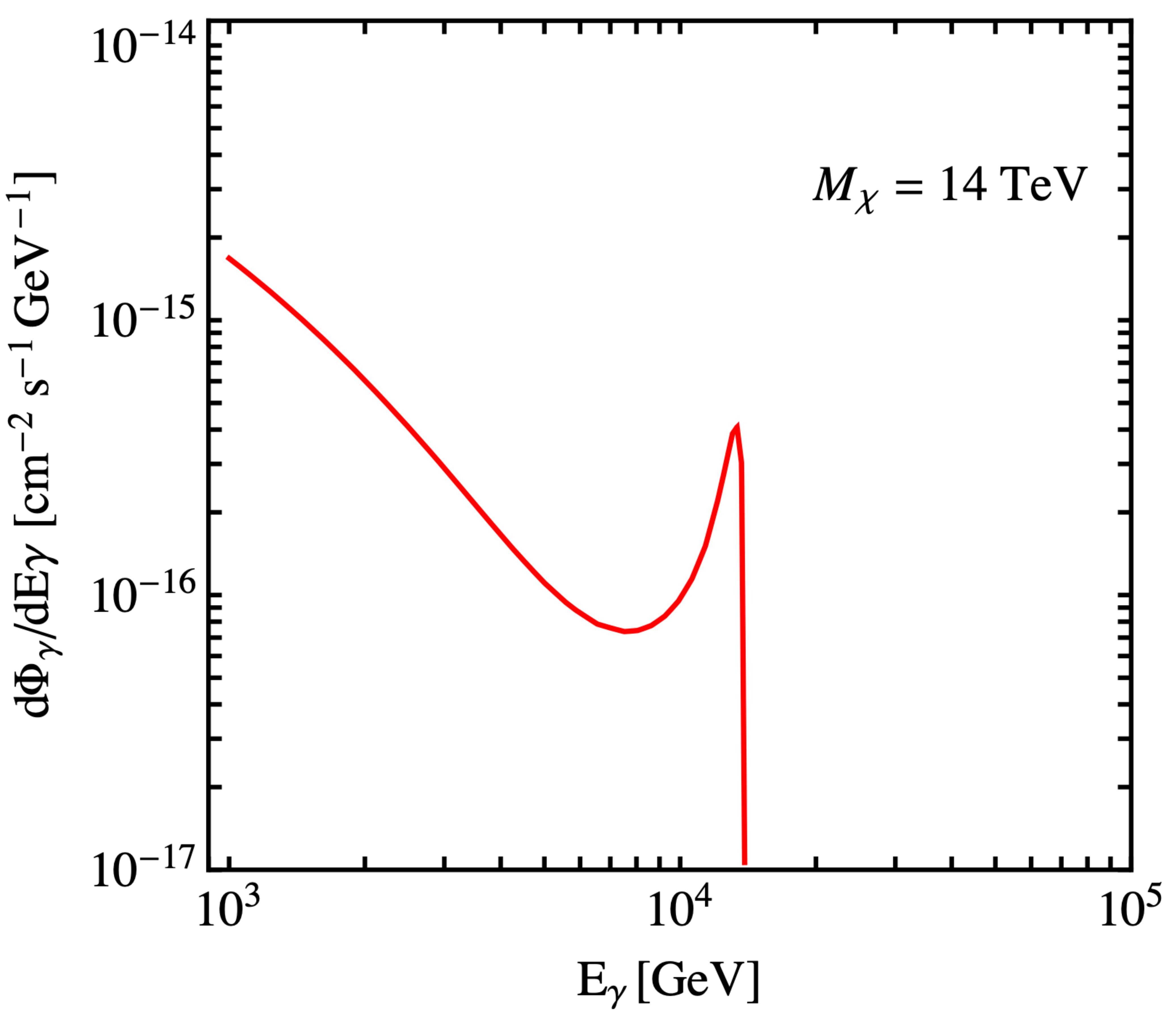


Smirnov, Beacom

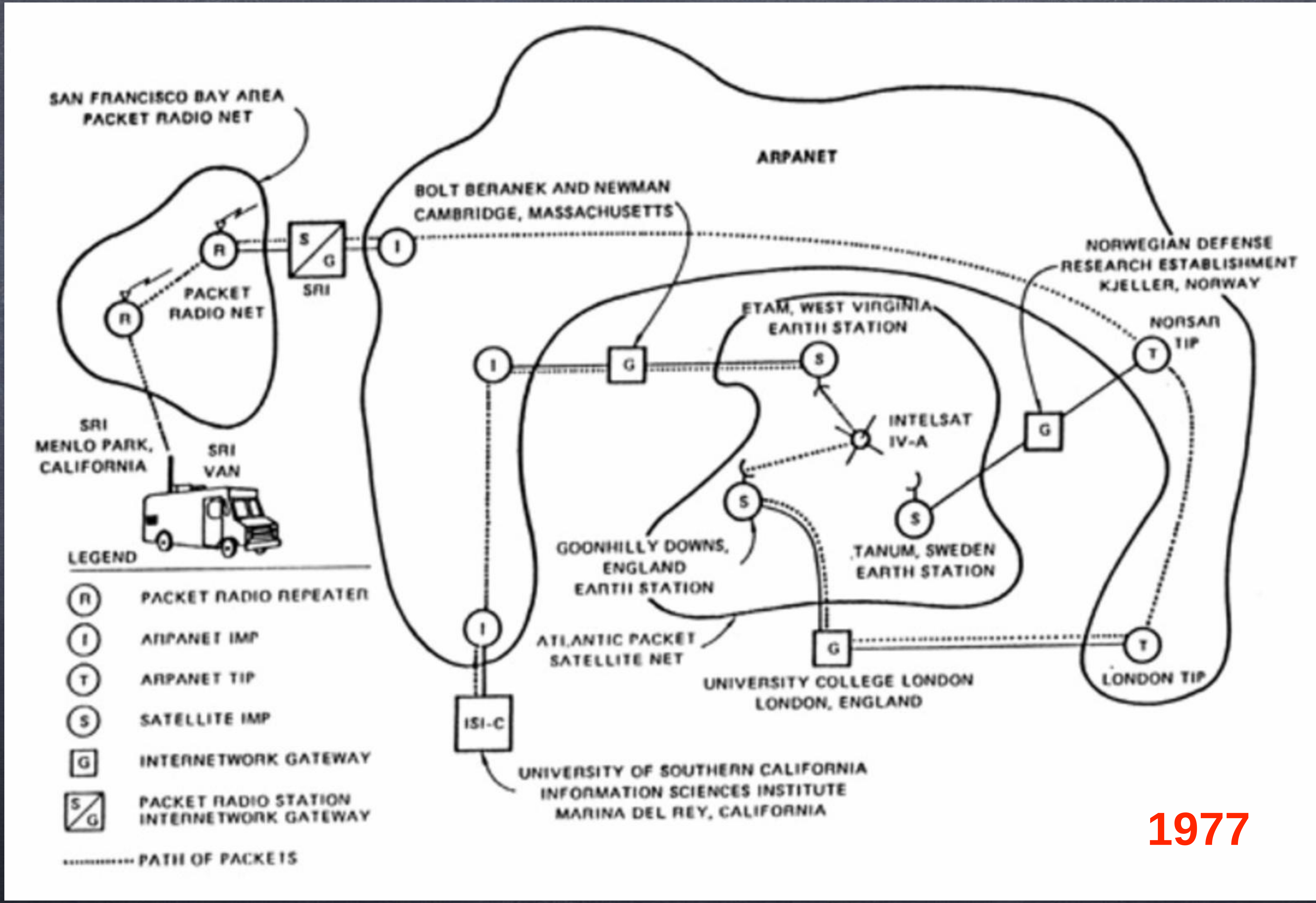
arXiv: 1904.11503

Example: DM Spectroscopy (SU(2) 5-plet)





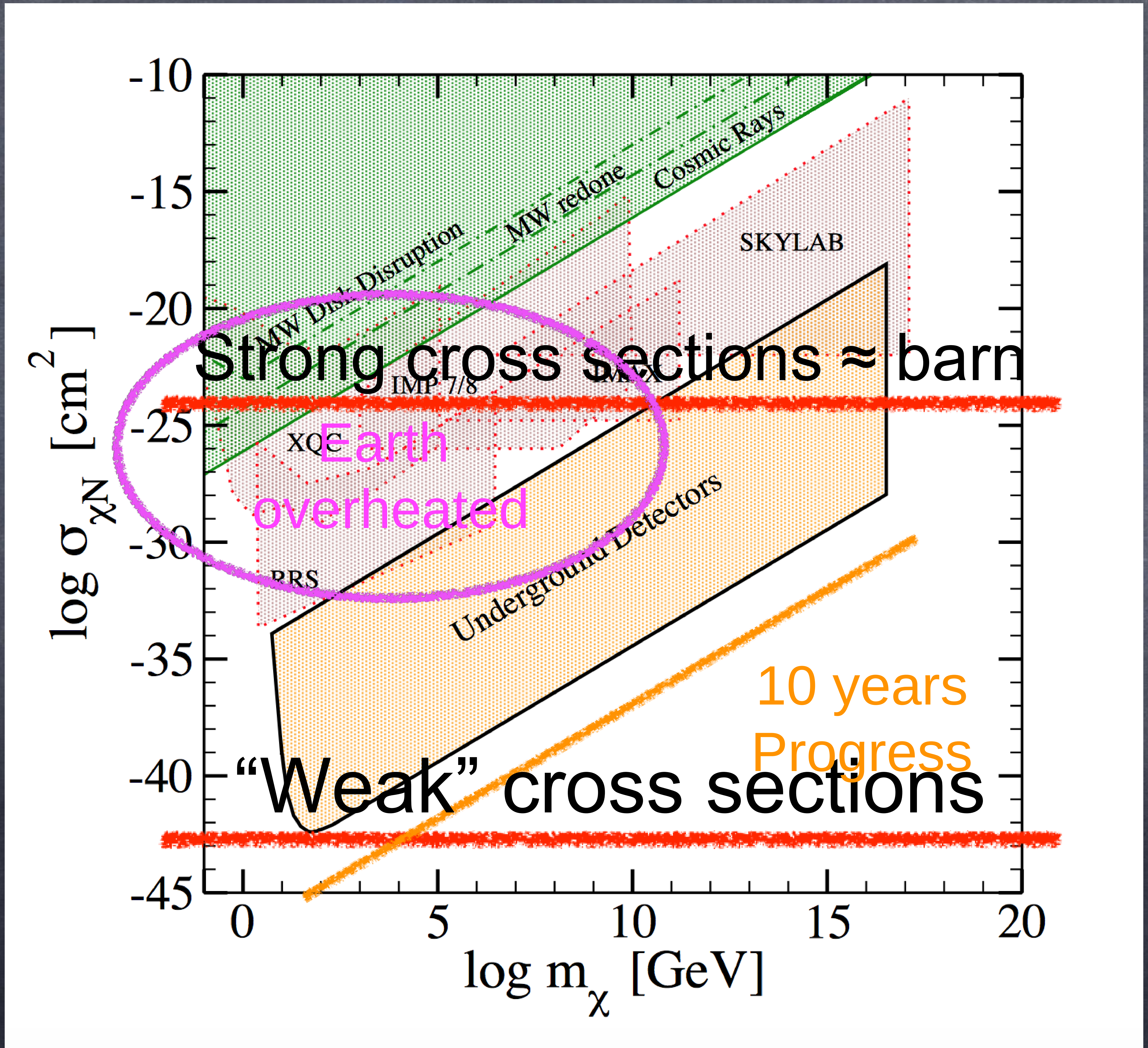
Beyond WIMPs



1977

QCD Charged DM ?

The allowed Parameter Space



J. Beacom et al. 2007

Color-Charged Dark Matter Model

$$(SU(3)_c, SU(2)_L, U(1)_Y)$$

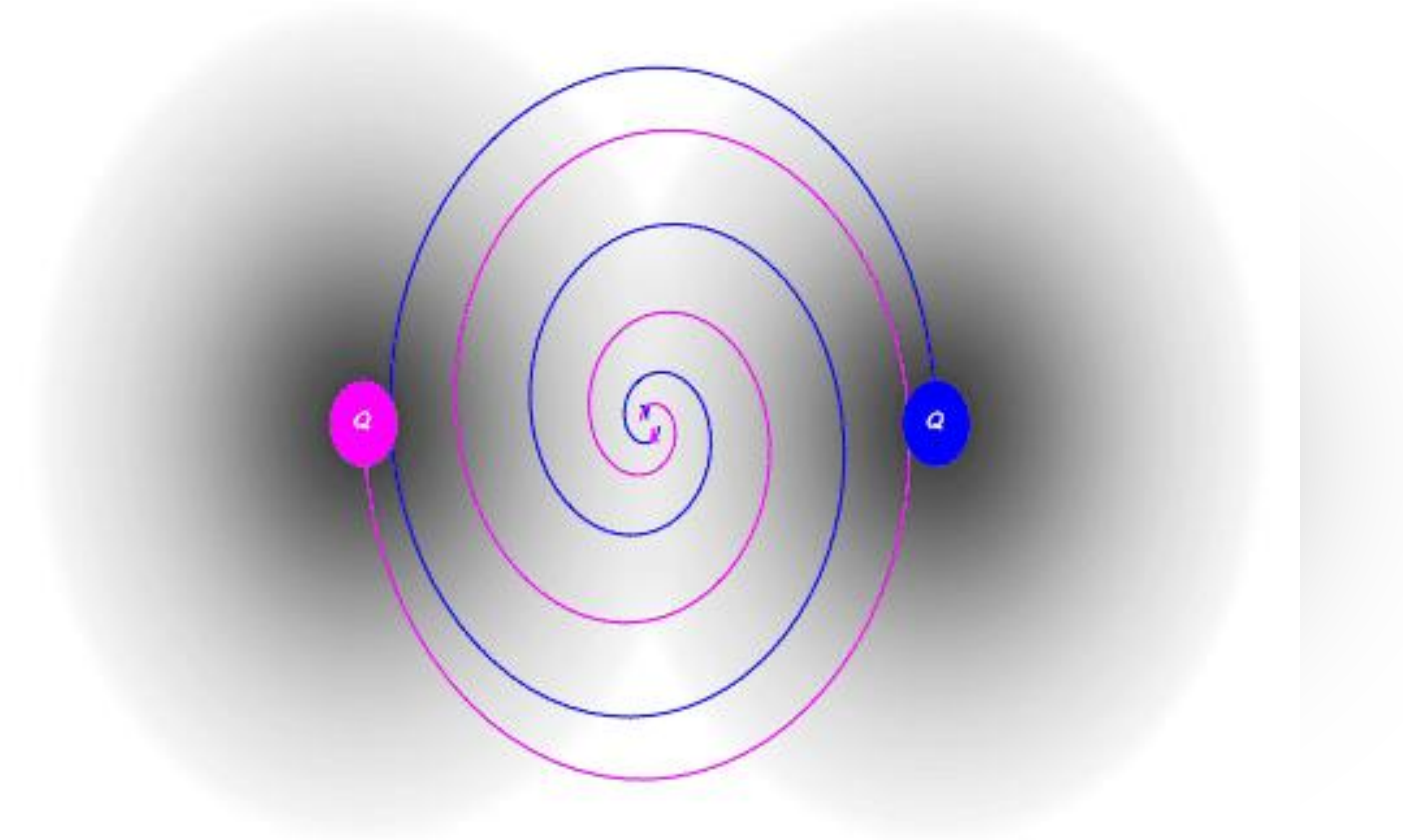
$$Q = (3, 1, 0)$$

$$Qqq \qquad e = 4/3 \text{ or } e = -2/3 \text{ or } e = -1/3$$

$$Q = (3, N, Y)$$

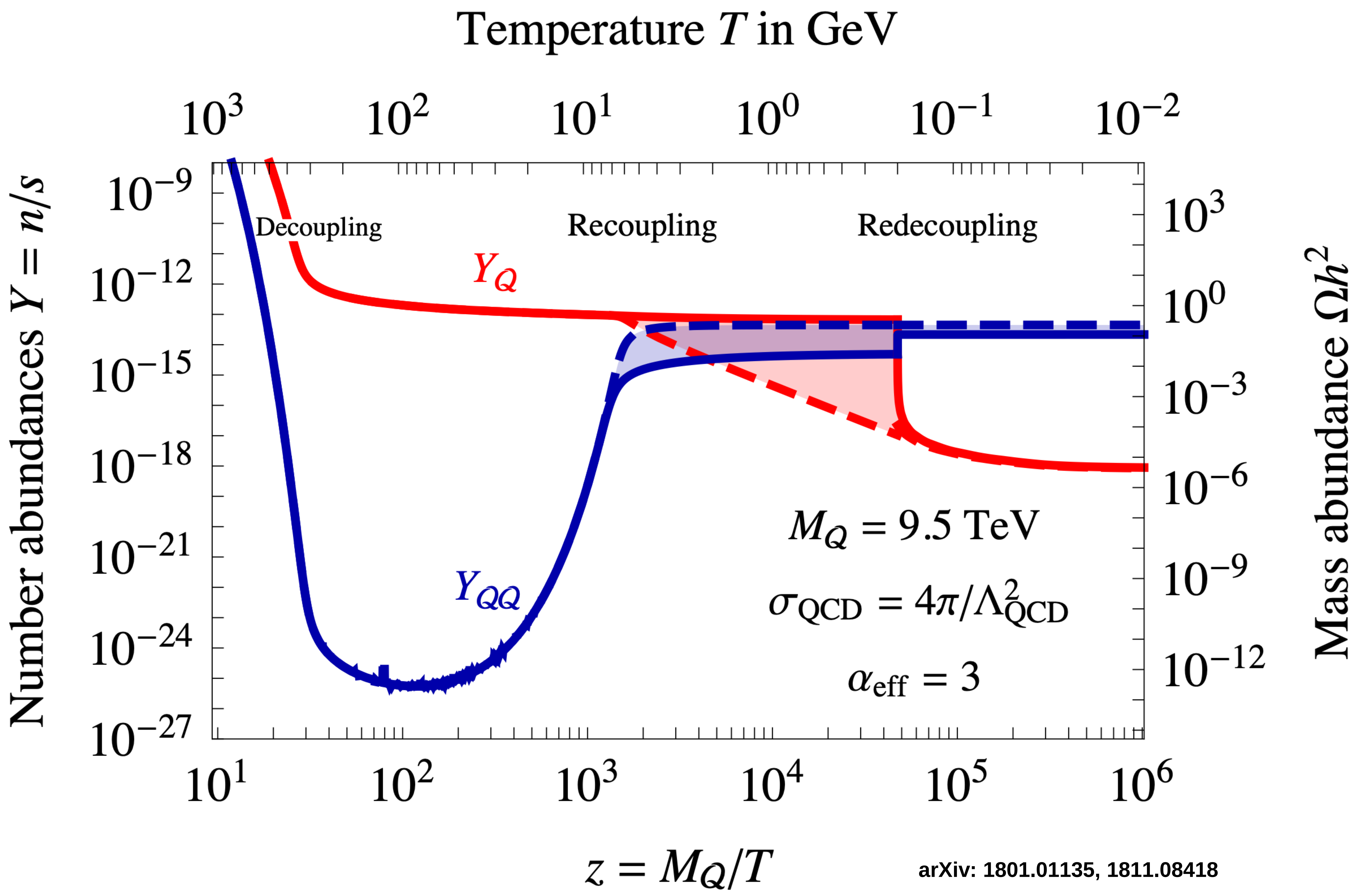
$$Q = (8, 1, 0) \qquad Q\,g$$

Idea: Chromocatalysis



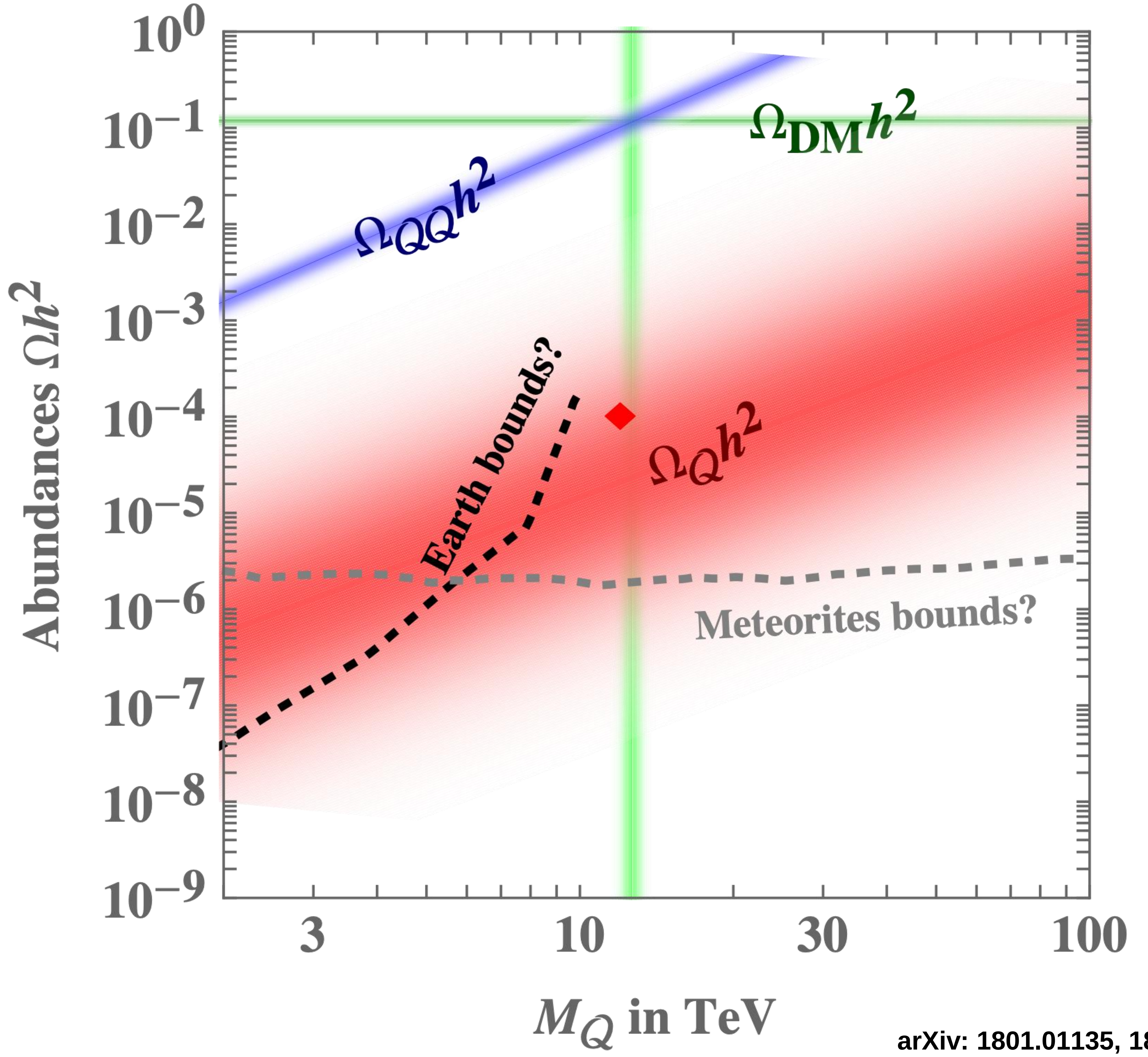
Bindi
DN

Chromo-catalysis in Cosmology



arXiv: 1801.01135, 1811.08418

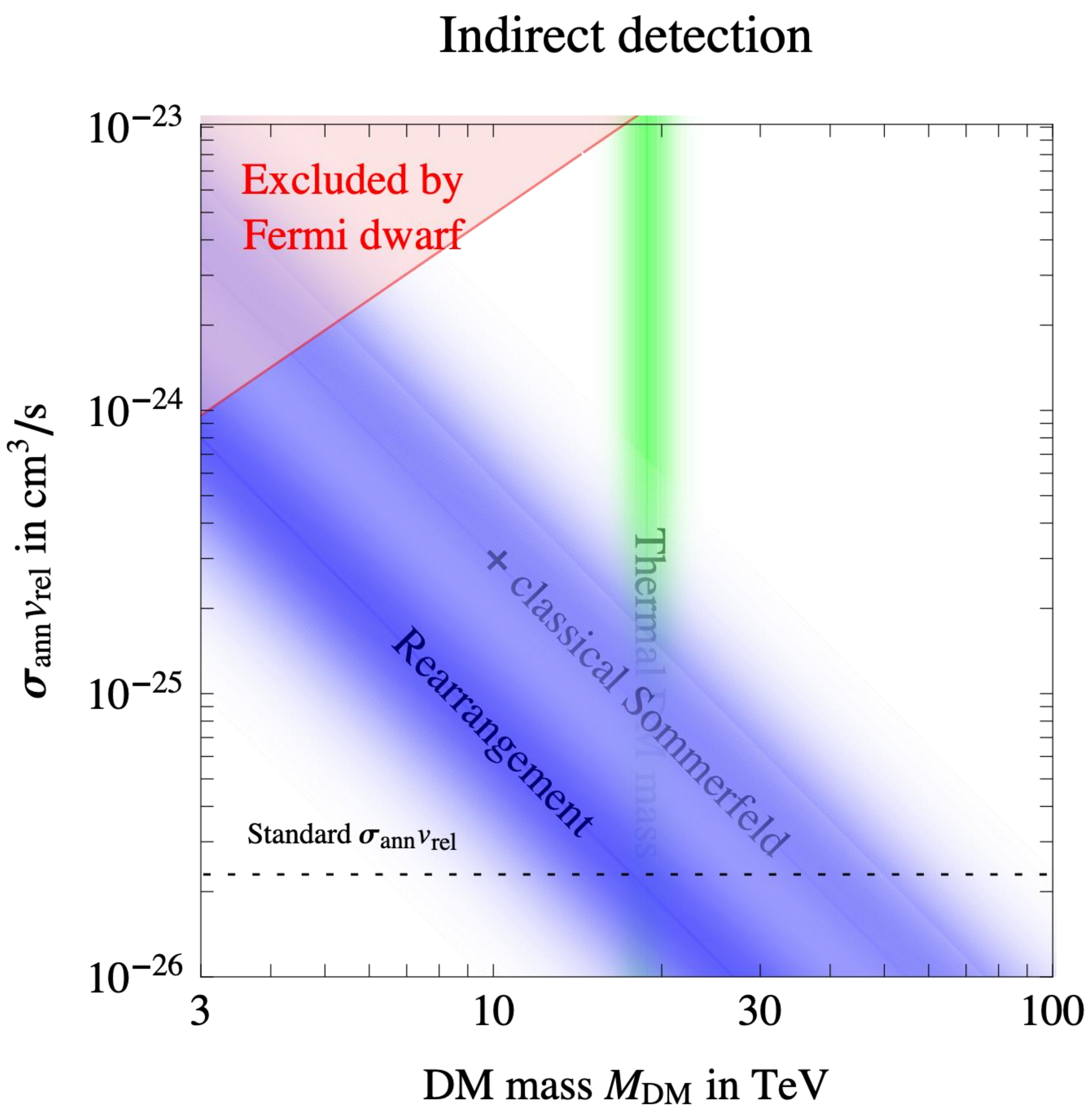
Abundances Today

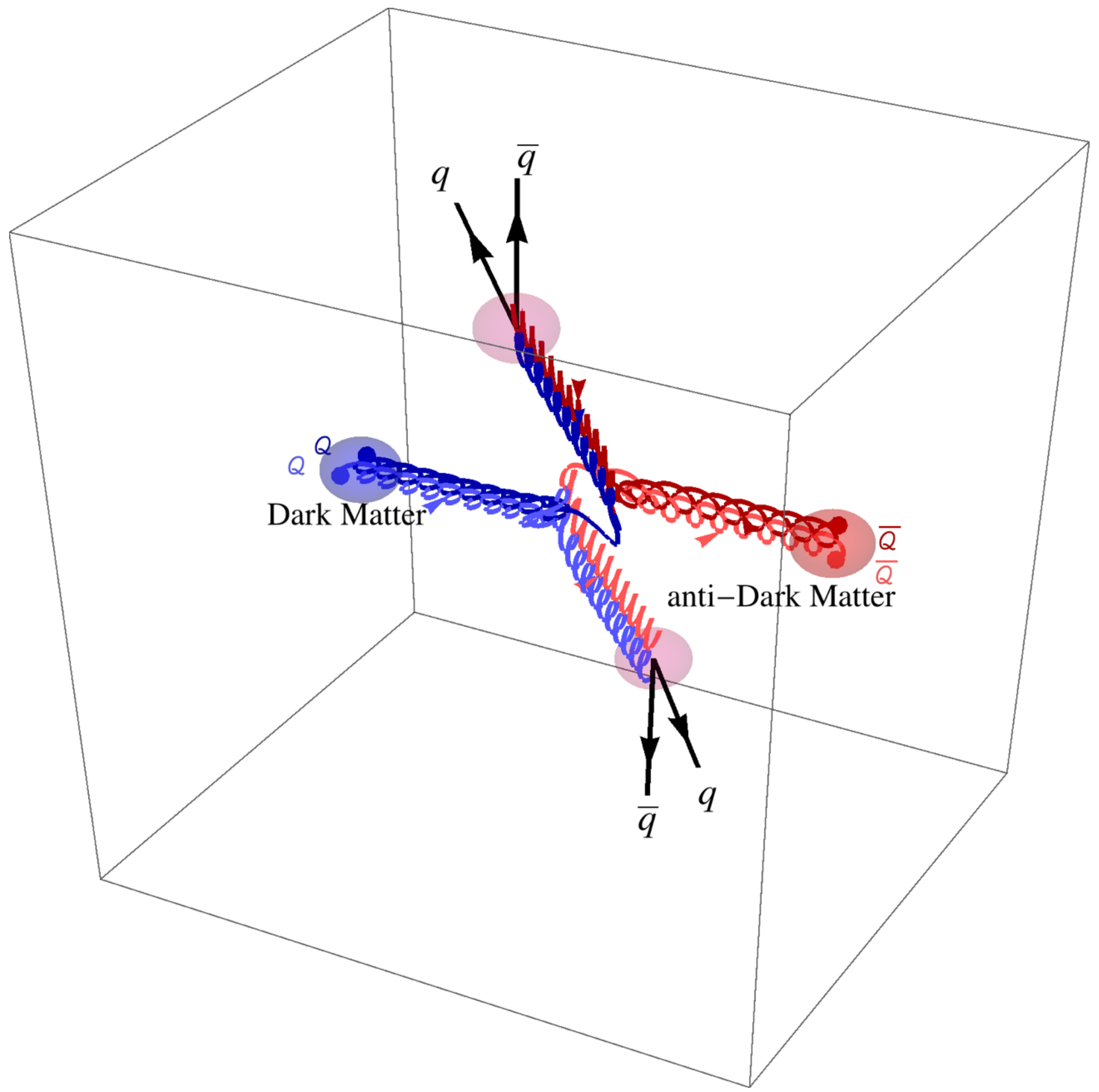


arXiv: 1801.01135, 1811.08418

Direct Dectection & Chromopolarizability

Rearrangement Annihilation





arXiv: 1801.01135

Mining Dark Matter

Element Studied	$N_{\rm SIMP}/N_N$ at $M_{\rm SIMP} = 10\,{\rm TeV}$ Bound	Expectation?	Formation Mechanism
He space	–	10^{-10}	BBN
Be Earth	$7\,10^{-9}$ [26]	No	BBN
Oxygen water	$3\,10^{-14}$ [26]	No	accumulation
Enriched petro-C^{14}	10^{-16} [26]	10^{-16}?	accumulation
Iron Earth	10^{-12} [31]	10^{-16}?	accumulation
Meteorites	$4\,10^{-14}$ [32]	10^{-15}?	capture

Table 2: *Experimental bounds on the density of Strongly Interacting Massive Particles with non-exotic electric charges, compared to the expected abundance of our hybrid, roughly estimated assuming that it binds in nuclei (otherwise they sink).*

[6]The SIMP thermonuclear energy content Mc^2 could be artificially released through $Q\bar{Q}$ annihilations, and is about 10^4 times larger than the world fossil energy reserve, 10^{23} J.

Nuclear Searches

A. “Stuck” isomers can be de-excited by the hybrids

B. Life-time measurements or near by detectors search for the signal

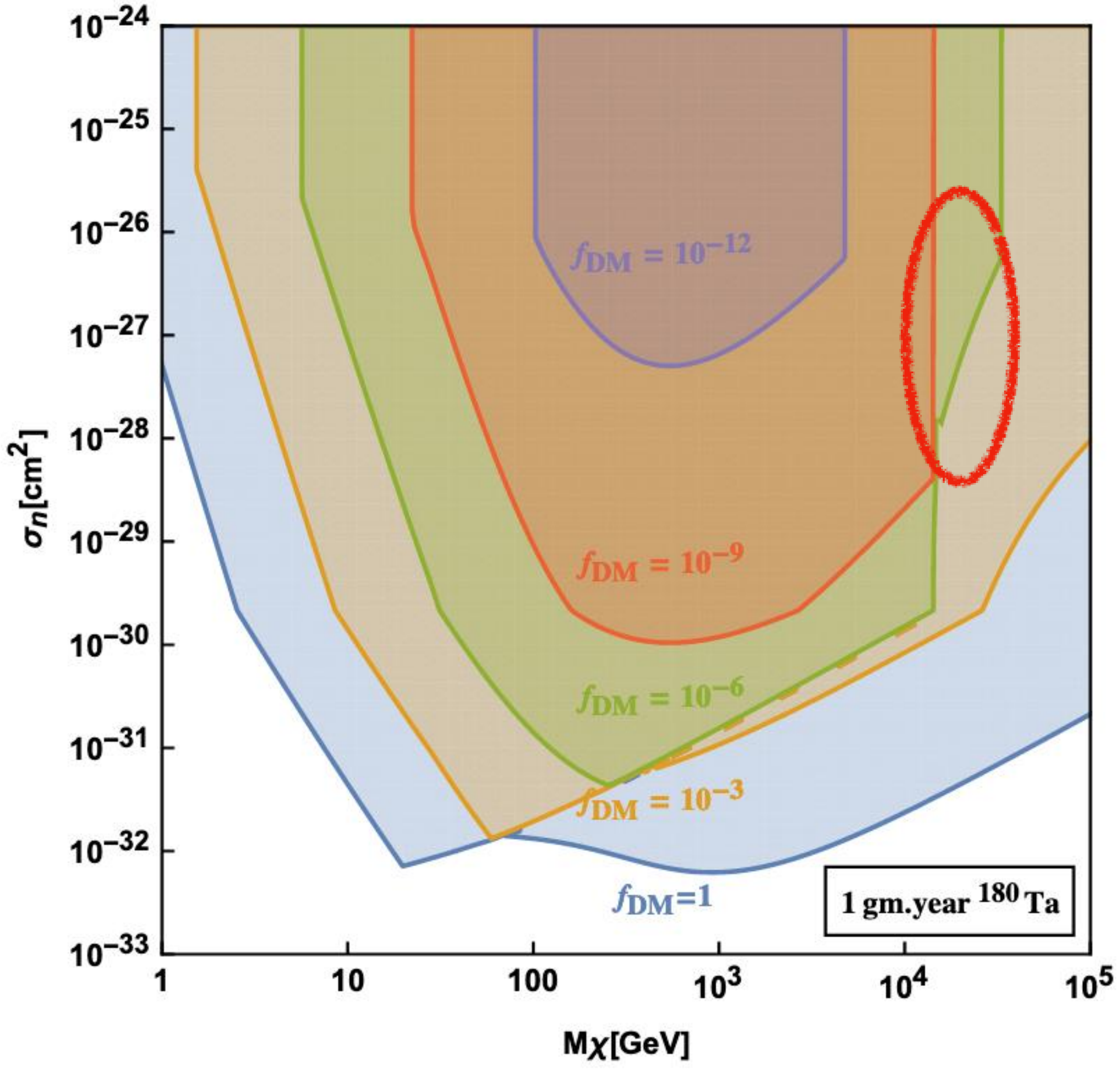
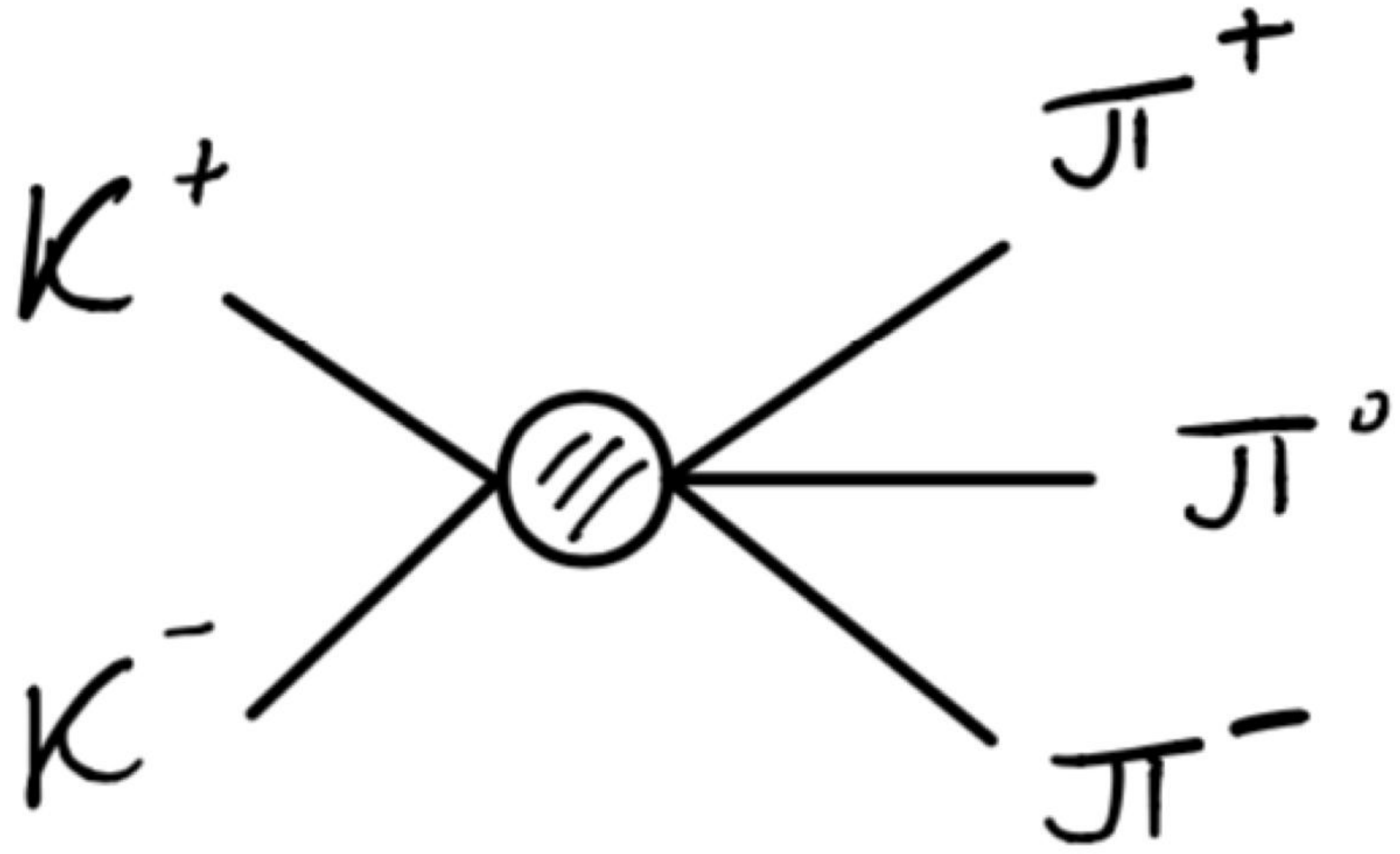


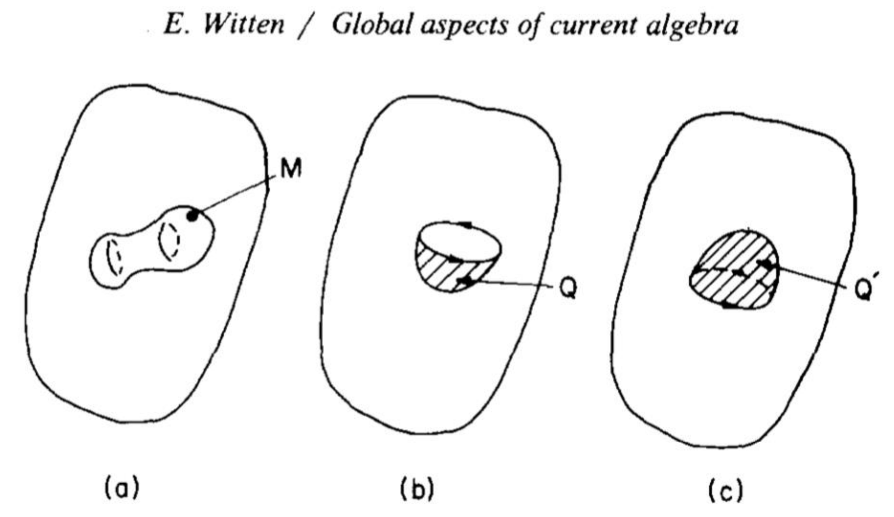
FIG. 3. Projections for limits on per-nucleon cross-section for DM that interacts strongly with nuclei that correspond to 1 gram year exposure for ^{180m}Ta

arXiv: 1907.00011, M. Pospelov, S. Rajendran, and H. Ramani

Number Changing Interactions

Inspiration: QCD at low Energies





$$\mathcal{L} \supset \frac{N_c}{240\pi^2 f_\pi^5} \int d^4x \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr}\left[A\partial_\mu A \partial_\nu A \partial_\alpha A \partial_\beta A\right] ,$$

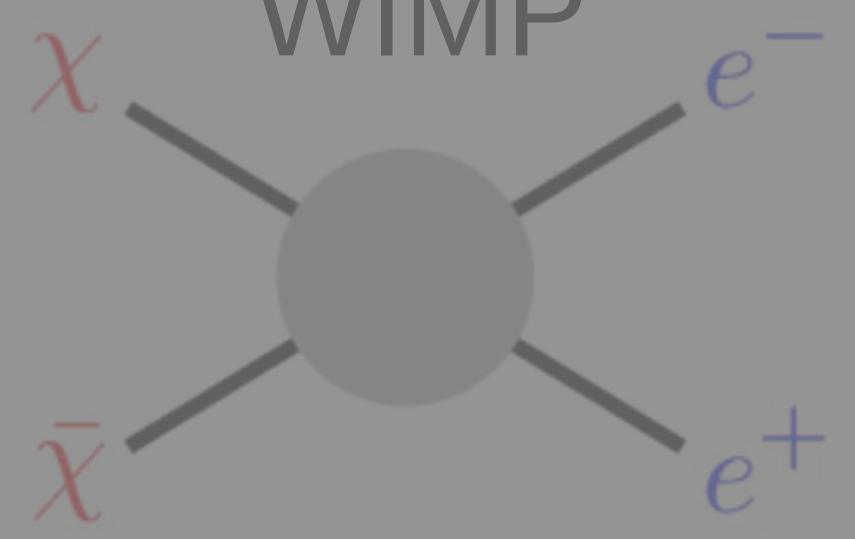
with $4\pi f_\pi \approx \Lambda_D$ and $A = \sum_a \lambda_a \pi^a$

$$\langle \sigma_{32} v_{\rm rel}^2 \rangle = \frac{5\sqrt{5}}{2^{11}\pi^5 f_\pi^5 z_\pi^2} \left(\frac{m_\pi}{f_\pi}\right)^5 \frac{N_c^2}{N_\pi^3} \underbrace{\frac{1}{5!}\sum T^2_{\{ijklm\}}}_{=t^2}$$

E. Witten (1983)

Freezeout in the EU

WIMP

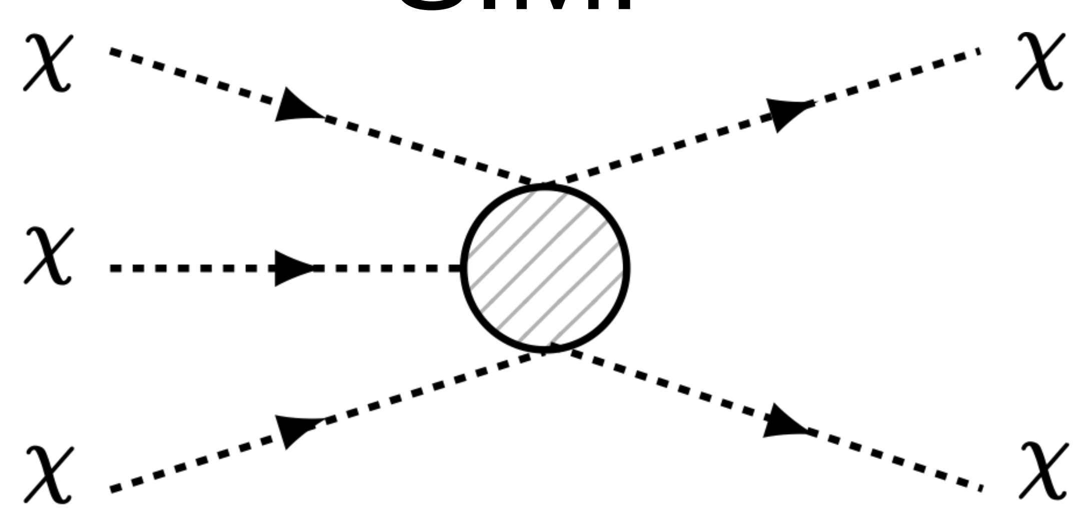


Zeldovich, Lee, Weinberg, Steigman, Turner,…

$$\Gamma_{\rm DM} = \langle \sigma v_{\rm rel.} \rangle \, n_{\rm DM} > H(T)$$

$$\Omega_{\rm DM}\, h^2 \approx \frac{0.12}{\langle \sigma v_{\rm rel.} \rangle \, [25 \rm TeV]^2}$$

SIMP

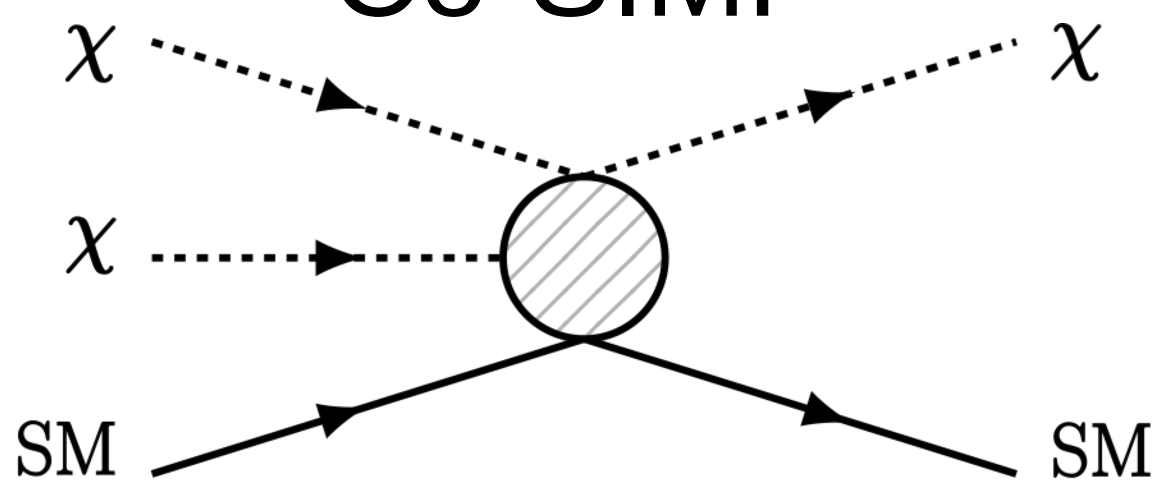


Hochberg, Kuflik, Volansky, Wacker

$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, n_{\rm DM}^2 > H(T)$$

$$\Omega_{\rm DM}\, h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}}\right) \frac{0.12}{\sqrt{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, [3 \rm MeV]^5}}$$

Co-SIMP



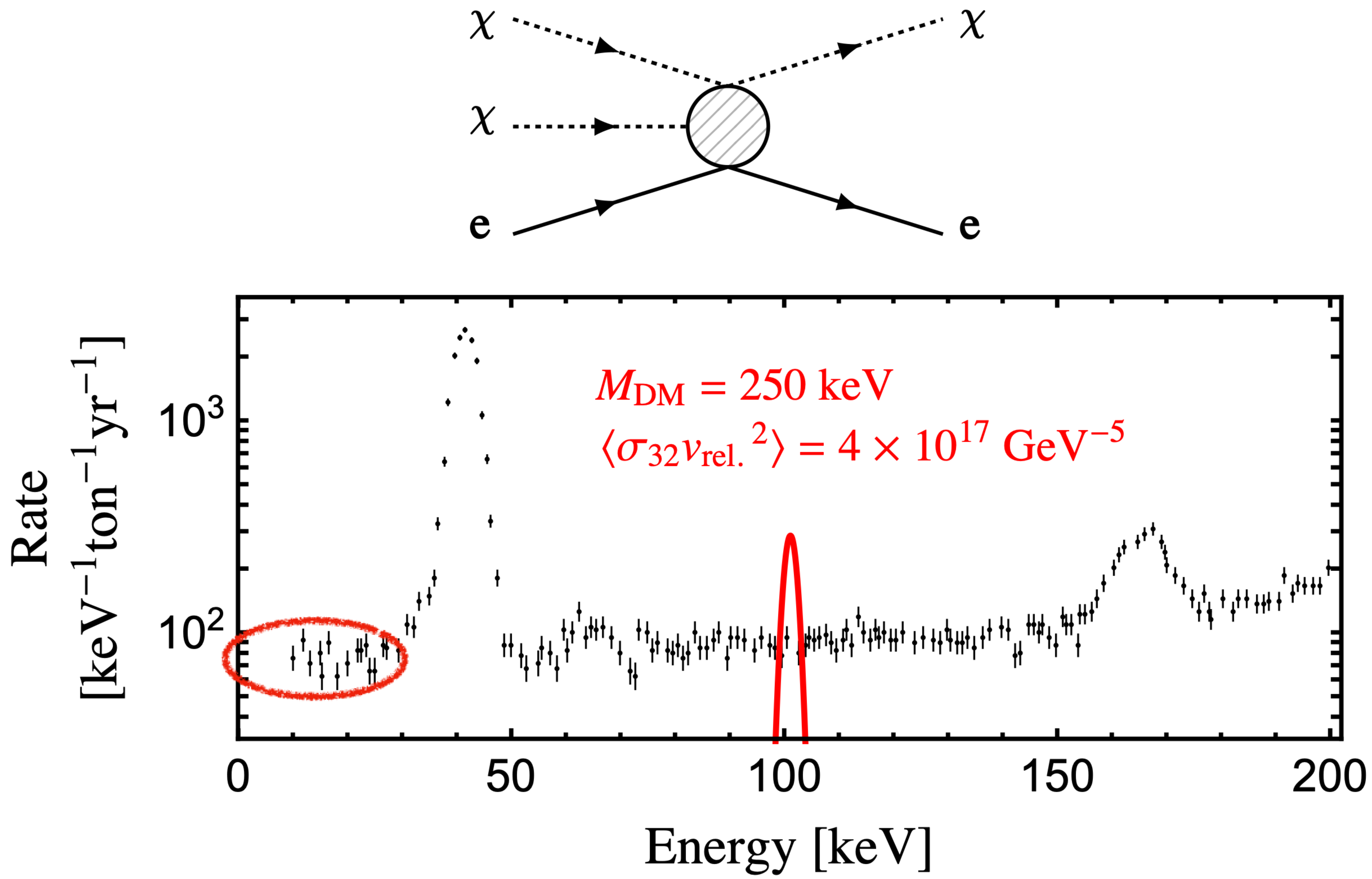
Smirnov, Beacom

$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, n_{\rm DM} n_{\rm SM} > H(T)$$

$$\Omega_{\rm DM} h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}}\right)^3 \frac{0.12}{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, [100 \ \rm MeV]^5}$$

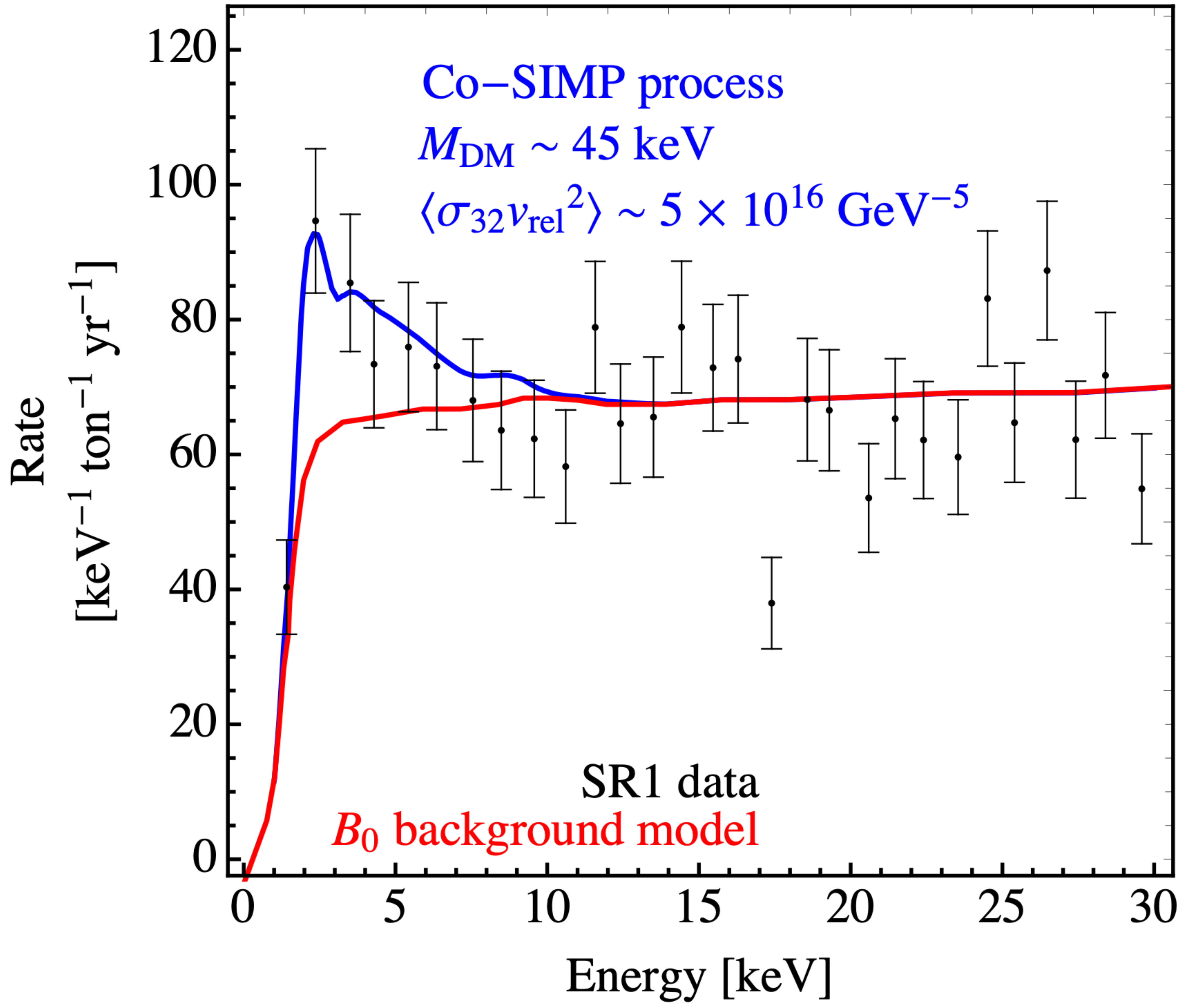
Electrophilic Co-SIMP

Monoenergetic Recoil



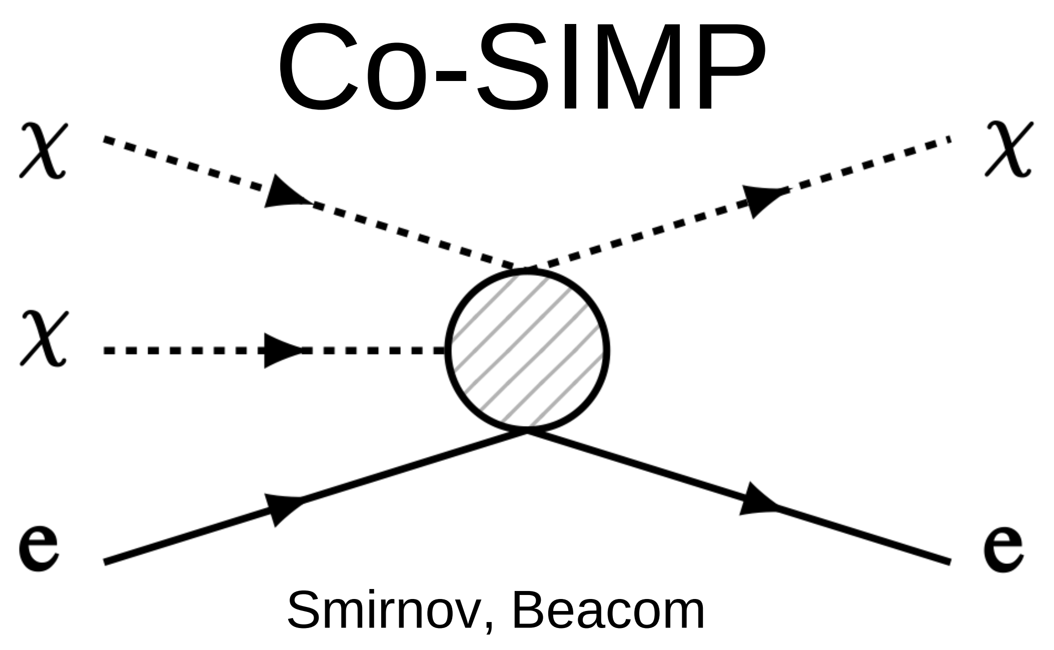
arXiv: 2002.04038; J. Smirnov, J. Beacom

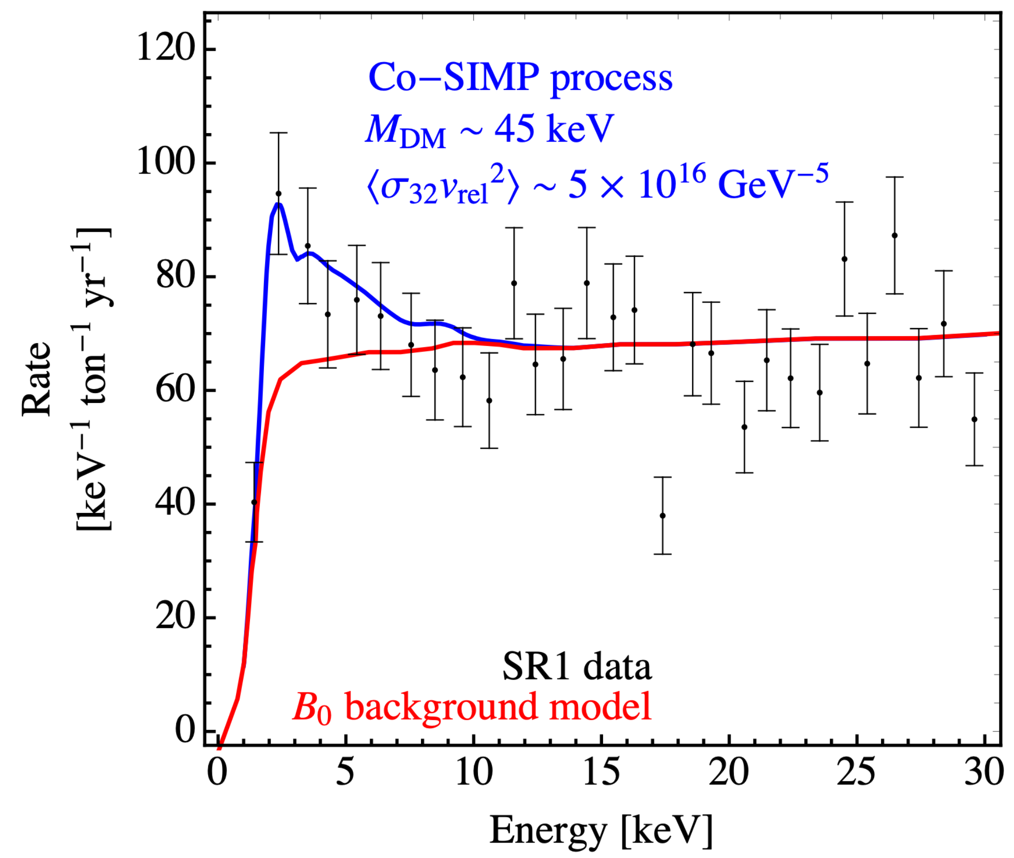
XENON1T Signal



v2 on arXiv today: arXiv: 2002.04038v2; J. Smirnov, J. Beacom

Look right here effect





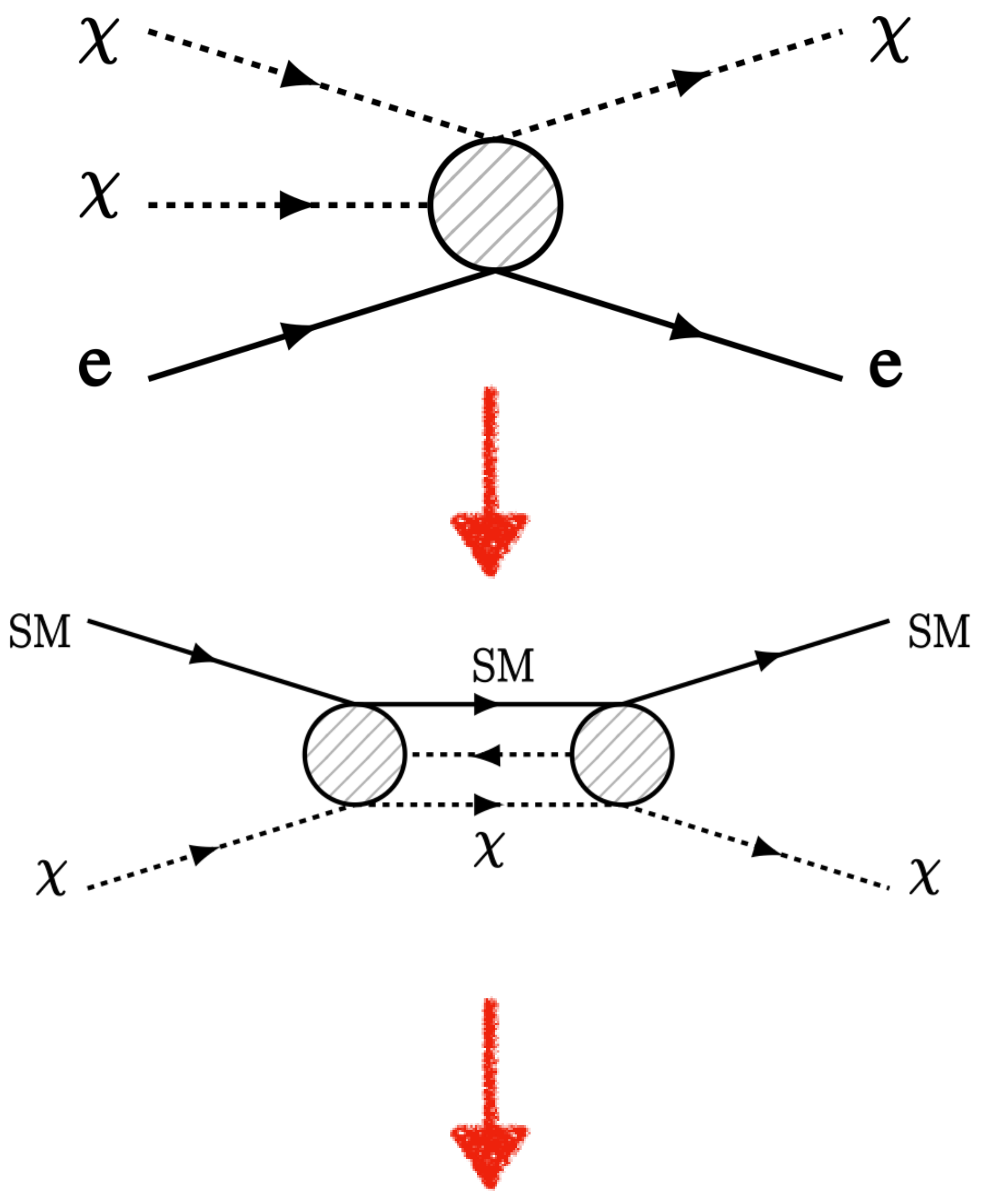
Given XENON1T mass and exposure:

$$+50 \text{ events} \Rightarrow M_{\rm DM} \approx 30 - 50 \text{ keV}$$

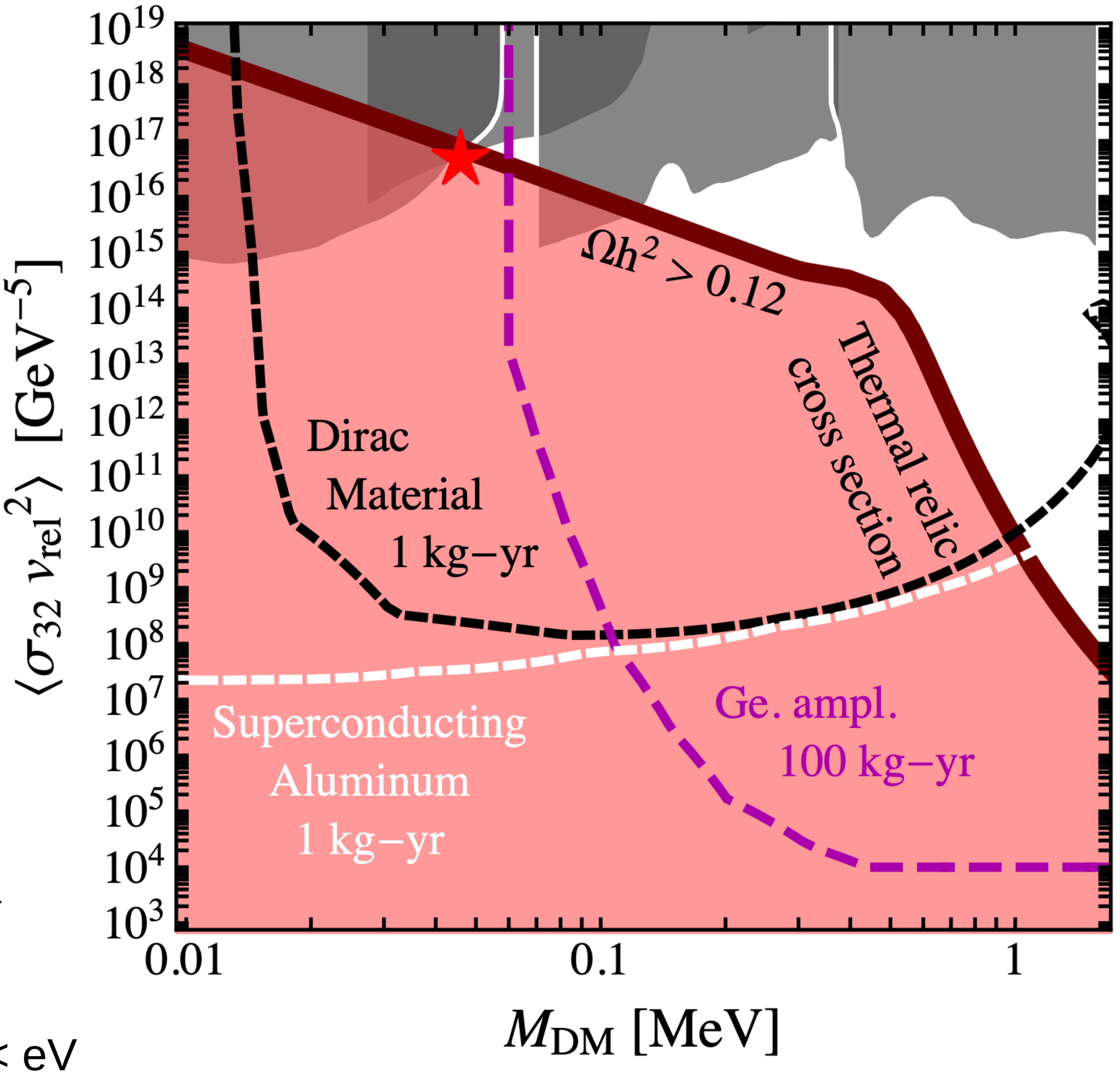
$$\Rightarrow E_R \approx 2 - 6 \text{ keV}$$

Implications

Scattering off Electrons



$$\sigma_{\chi e} \sim 10^{-37} \mathrm{cm}^2 \qquad E_R \approx v_{\mathrm{rel}}^2 \frac{\mu^2}{M_{\mathrm{SM}}}$$



Detectors with lower energy thresholds < eV

arXiv: 2002.04038; J. Smirnov, J. Beacom

Consequences

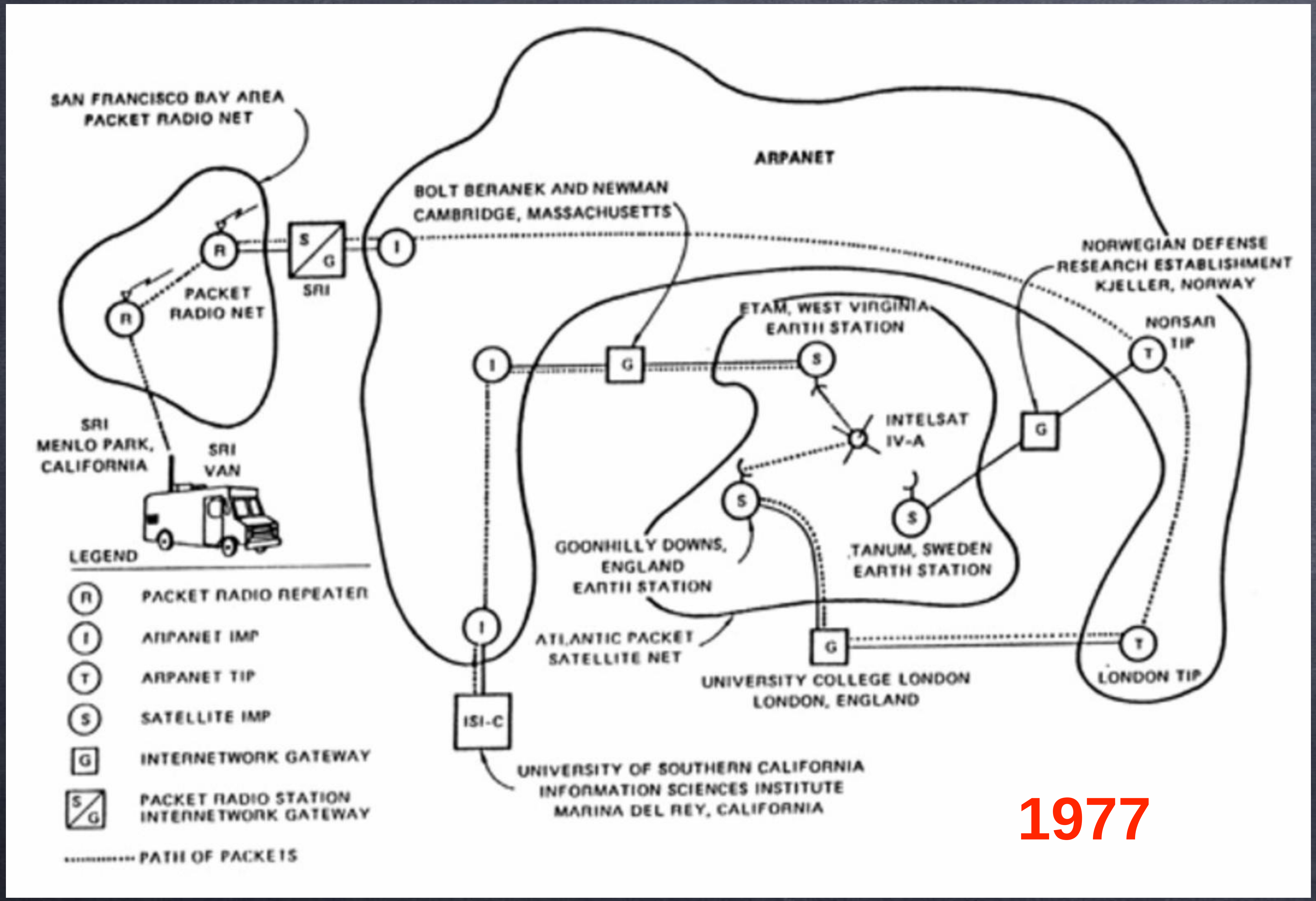
A. New target for low energy recoils at 30 - 50 keV

B. Modified Signal shape in Argon due to atomic structure

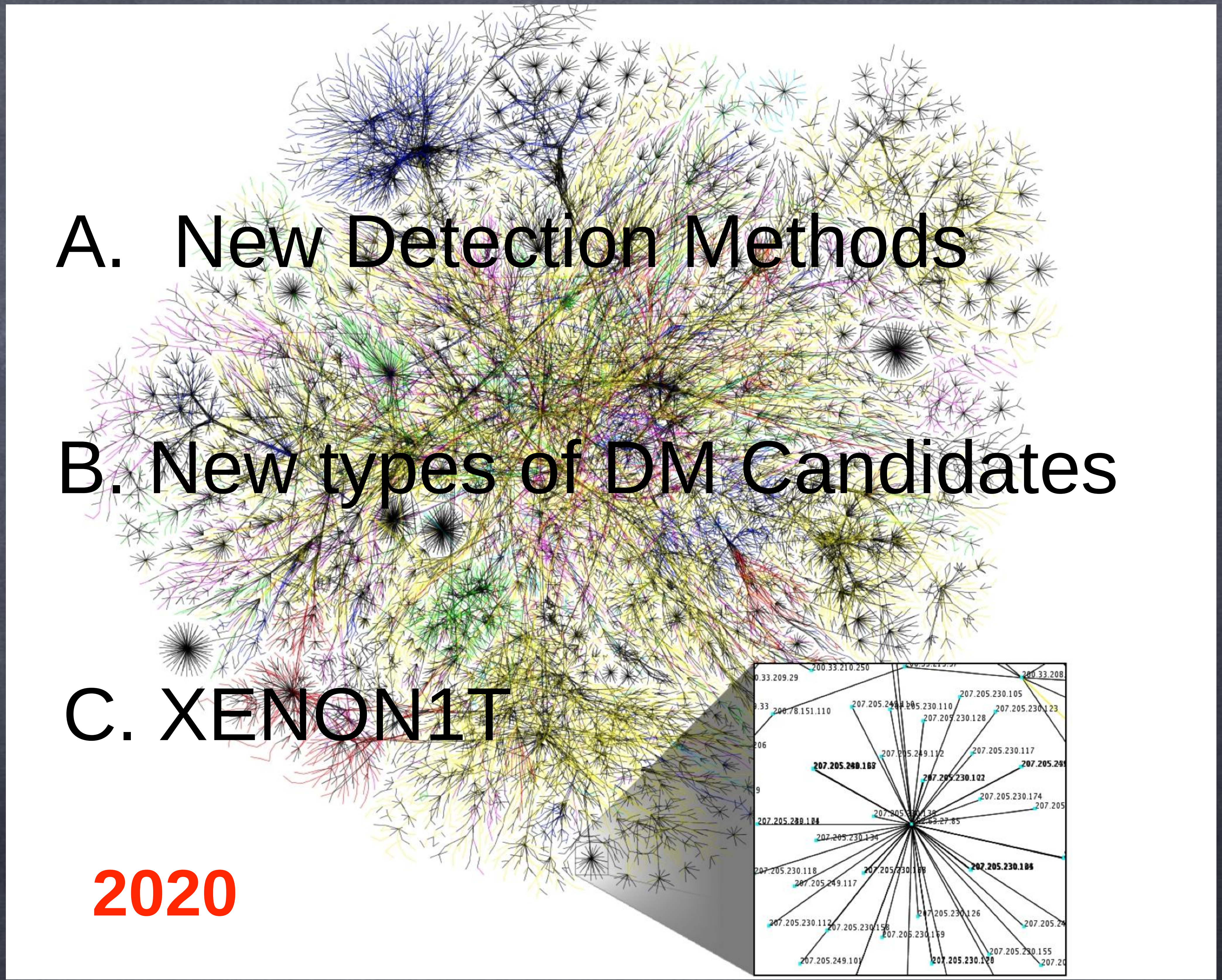
C. Richer light sector possible: UV completion needed to check consistency with BBN

D. New collider signatures expected (UV models)

New Directions for Thermal Dark Matter



1977



A. New Detection Methods

B. New types of DM Candidates

C. XENON1T

2020

Thanks!

Questions for UV completions

A. Emerging

Showers?Hadronic and

Electromagnetic

B. Opacity of materials

C. Loop coefficients

-> Work in progress with: Bei

Zhou and John Beacom