Dark Matter Bound States

Juri Smirnov

Research Fellow: Stockholm University

Stockholm University

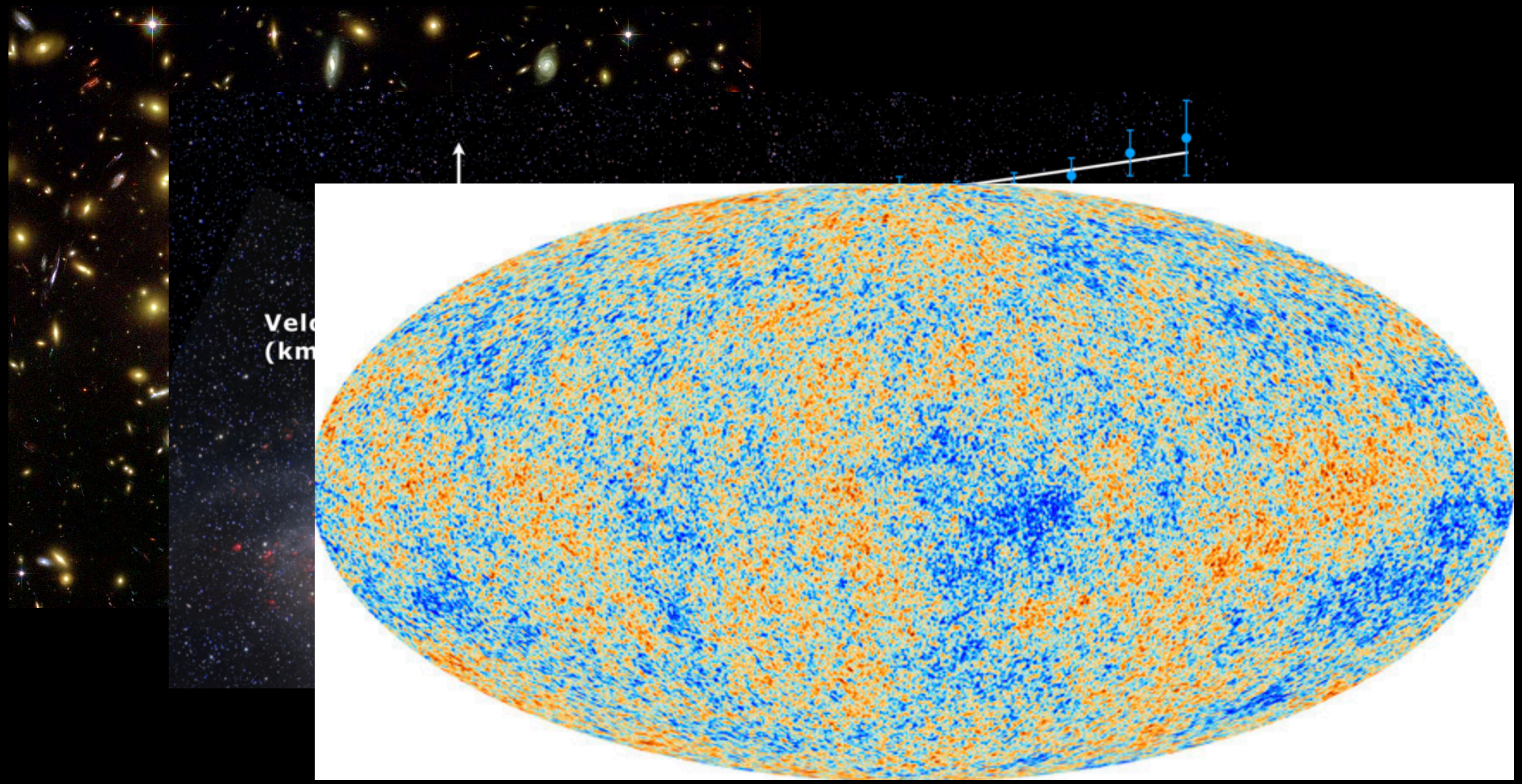
CERN BSM Forum Seminar
Wien: 19/07/22

Many thanks to my collaborators: John Beacom (OSU), Tracy Slatyer, Pouya Asadi, Greg Ridgeway (MIT), Eric Kuflik, Eric D. Kramer (Hebrew U.), Rebecca Leane (SLAC)

Dark Matter is a New Particle

Not ordinary Matter: $\Omega_{\rm DM} >> \Omega_{\rm Baryons}$

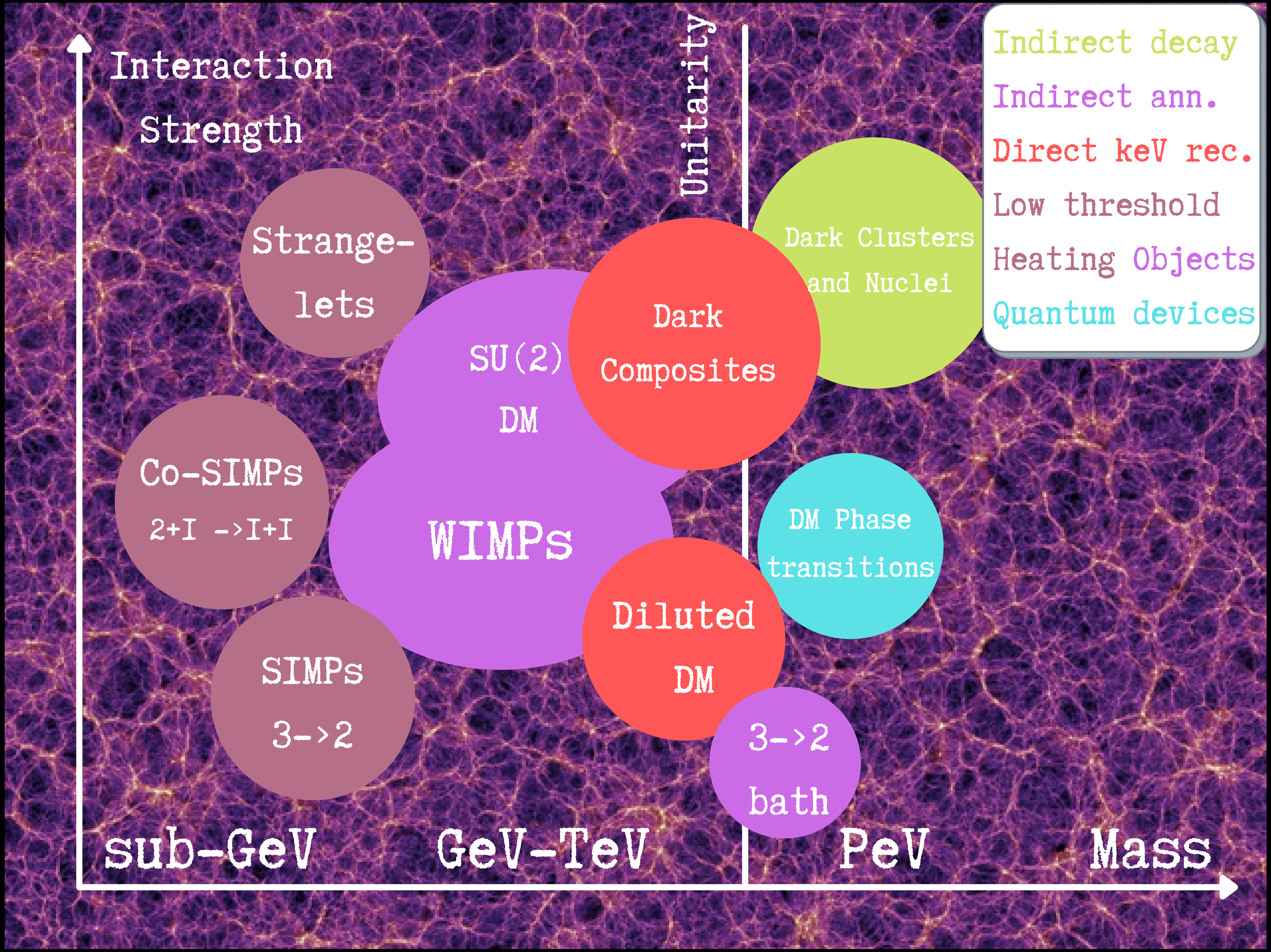
(CMB) (BBN, CMB)



Not MOND:

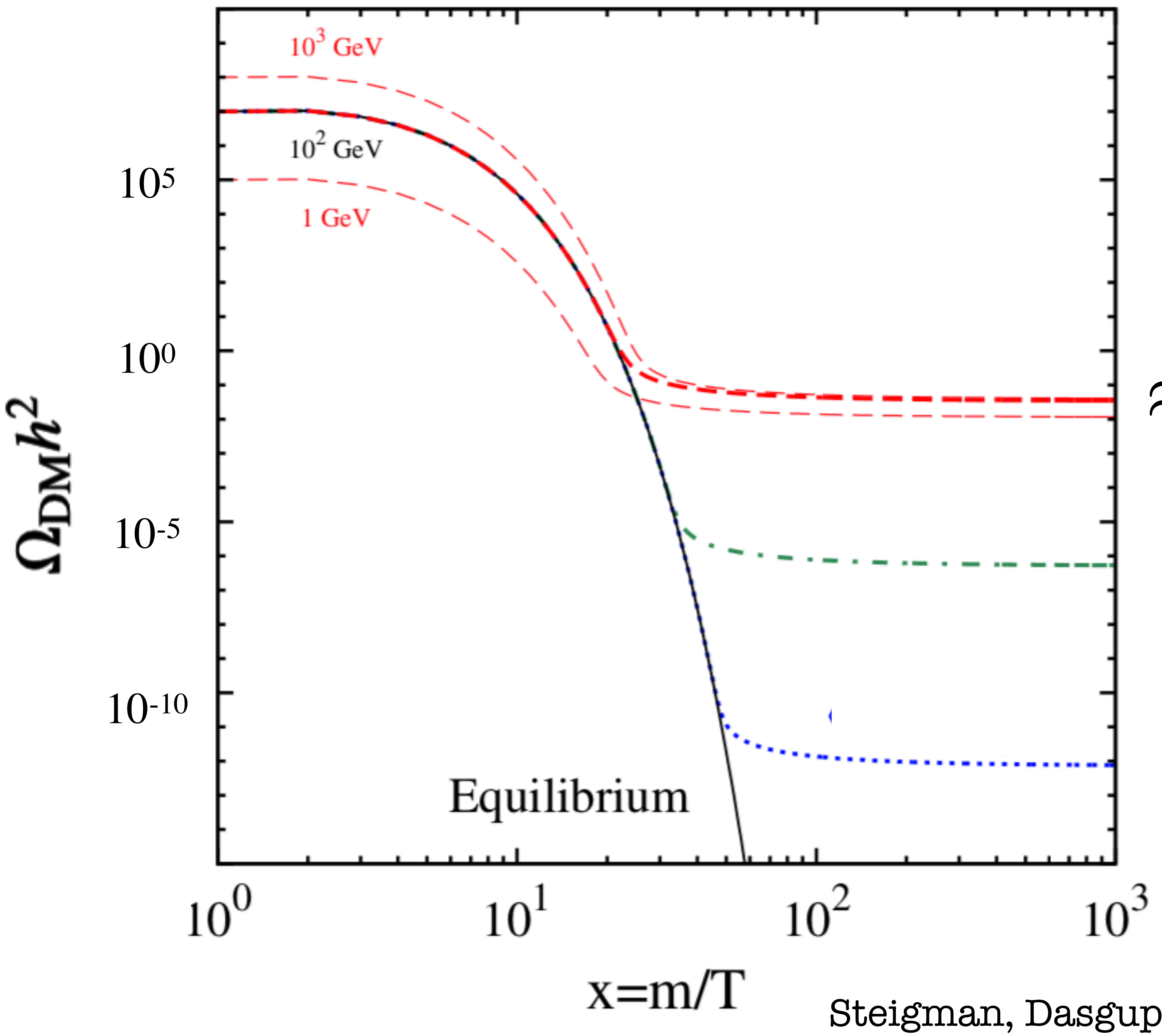
Not light Neutrinos: $\Omega_\nu \approx 0.02 \left(\frac{m_\nu}{\rm eV}\right)$

Thermal Model Space



Freeze-out and Un-stable Bound States

WIMP Freezeout

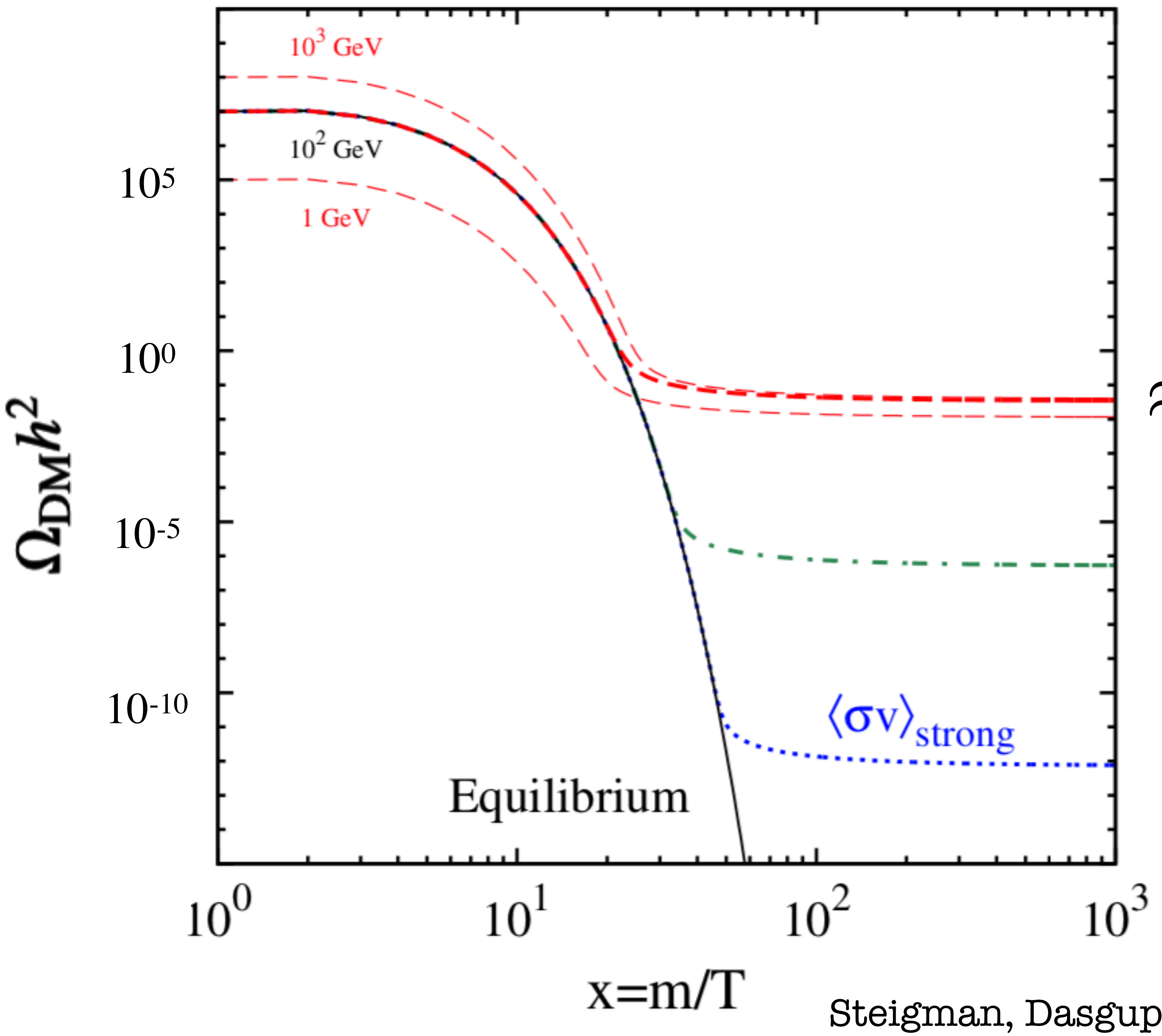


≈ 0.12

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

Steigman, Dasgupta, Beacom: 1204.3622

WIMP Freezeout

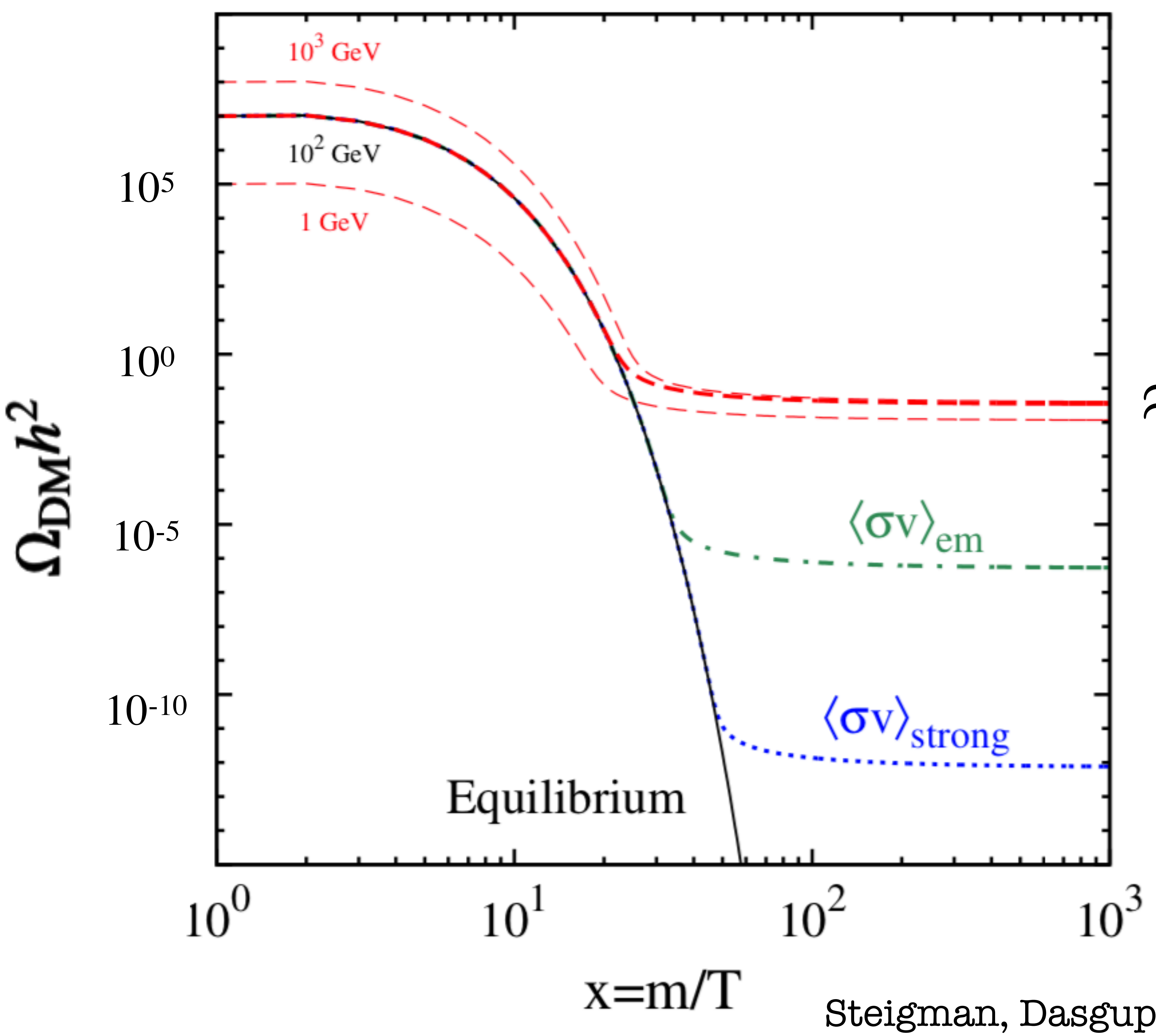


≈ 0.12

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

Steigman, Dasgupta, Beacom: 1204.3622

WIMP Freezeout

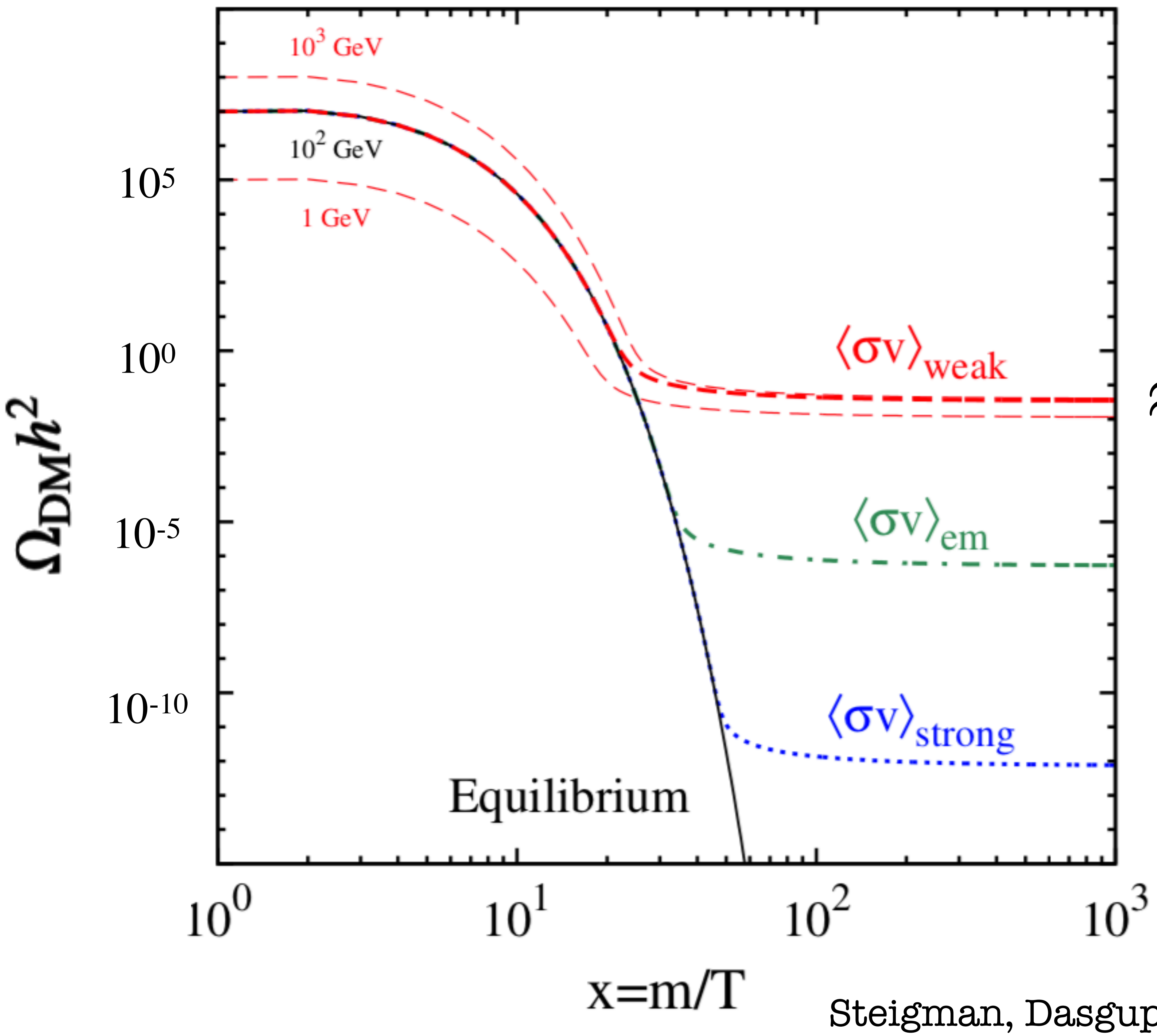


≈ 0.12

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

Steigman, Dasgupta, Beacom: 1204.3622

WIMP Freezeout



≈ 0.12

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

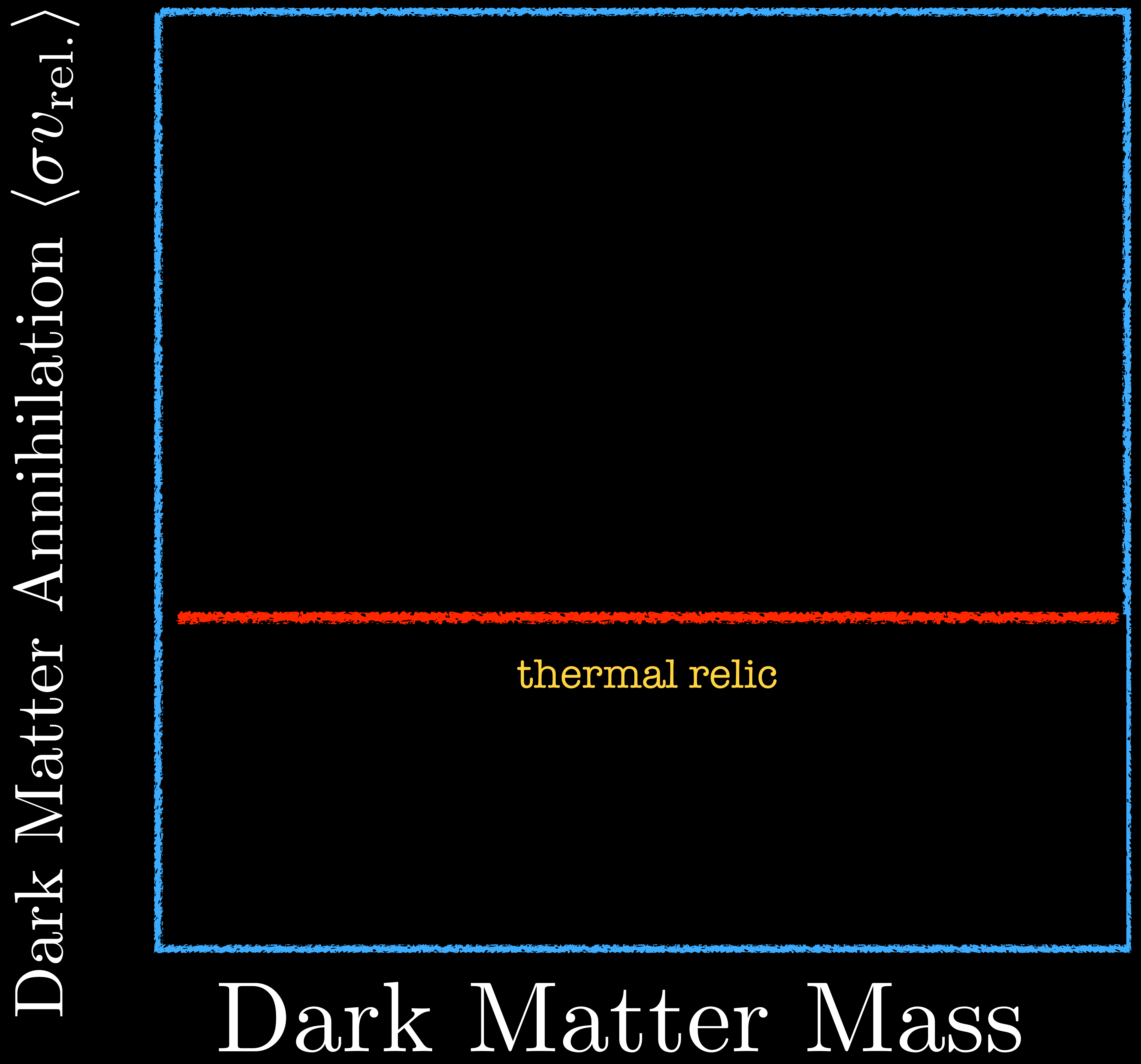
Steigman, Dasgupta, Beacom: 1204.3622

Cartoon Overview of Approach

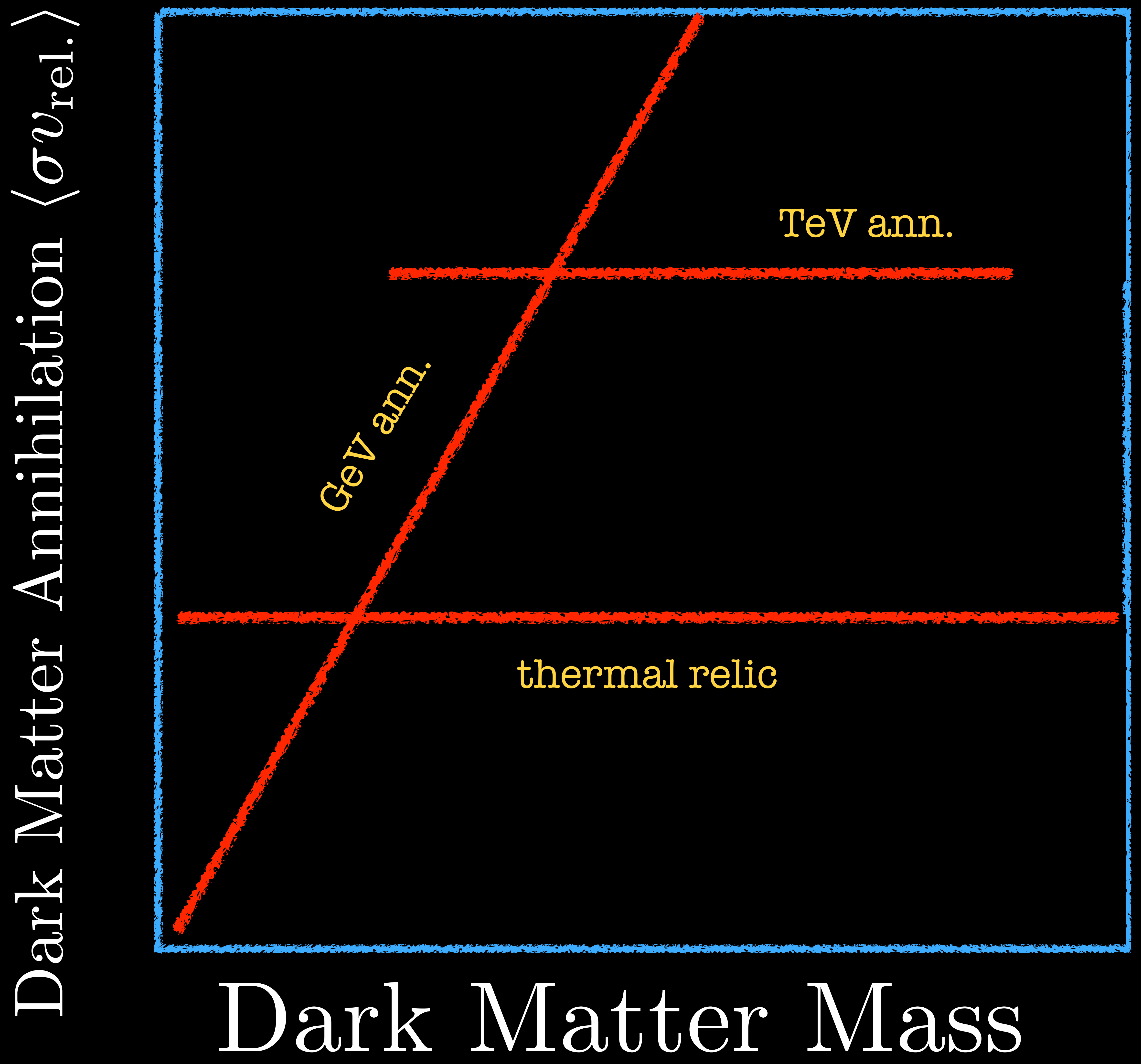
Dark Matter Annihilation $\langle \sigma v_{\rm rel.} \rangle$

Dark Matter Mass

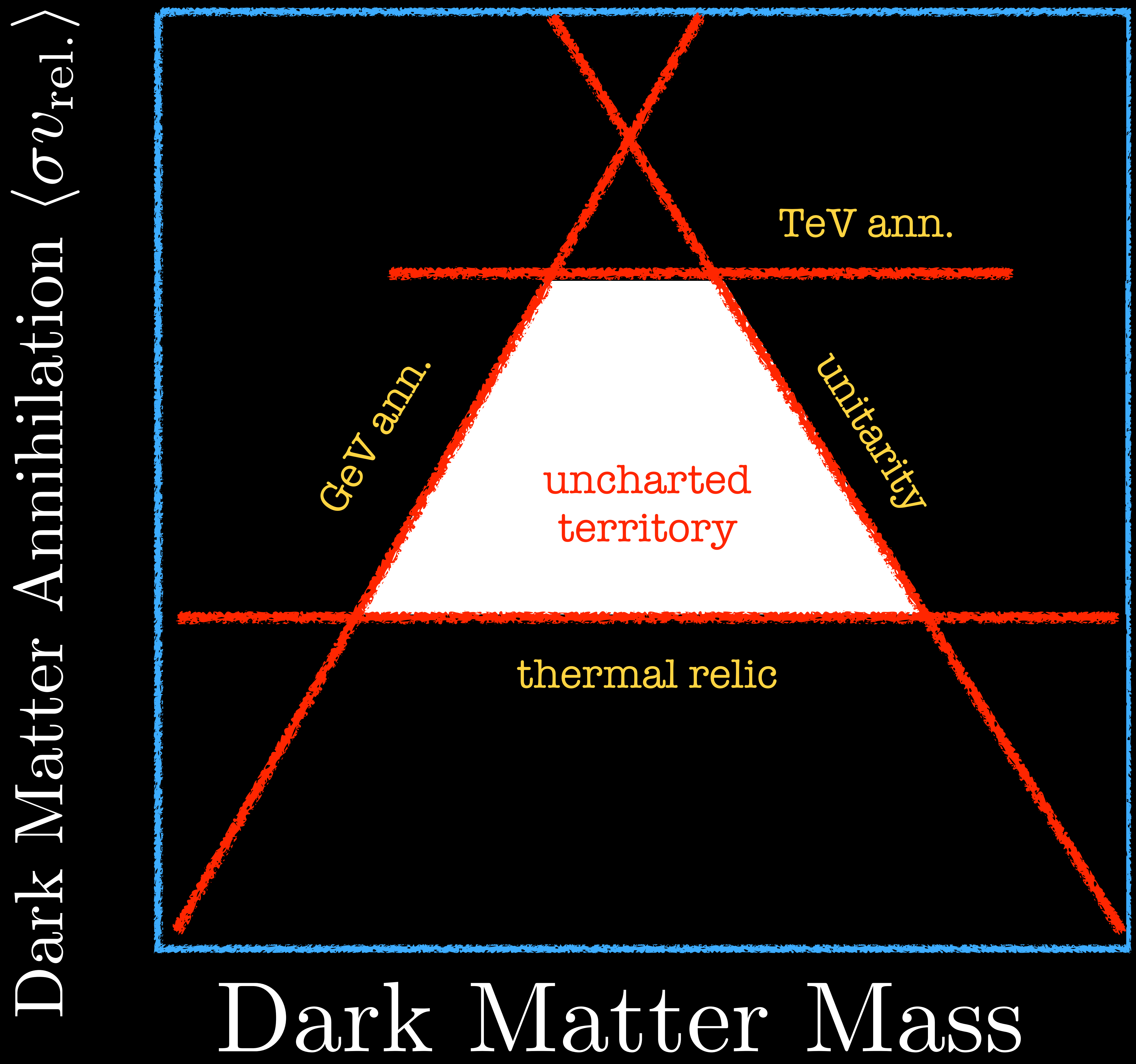
Cartoon Overview of Approach

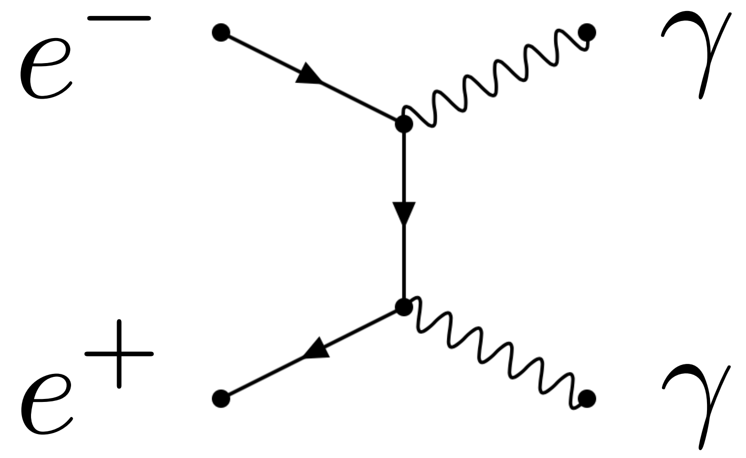
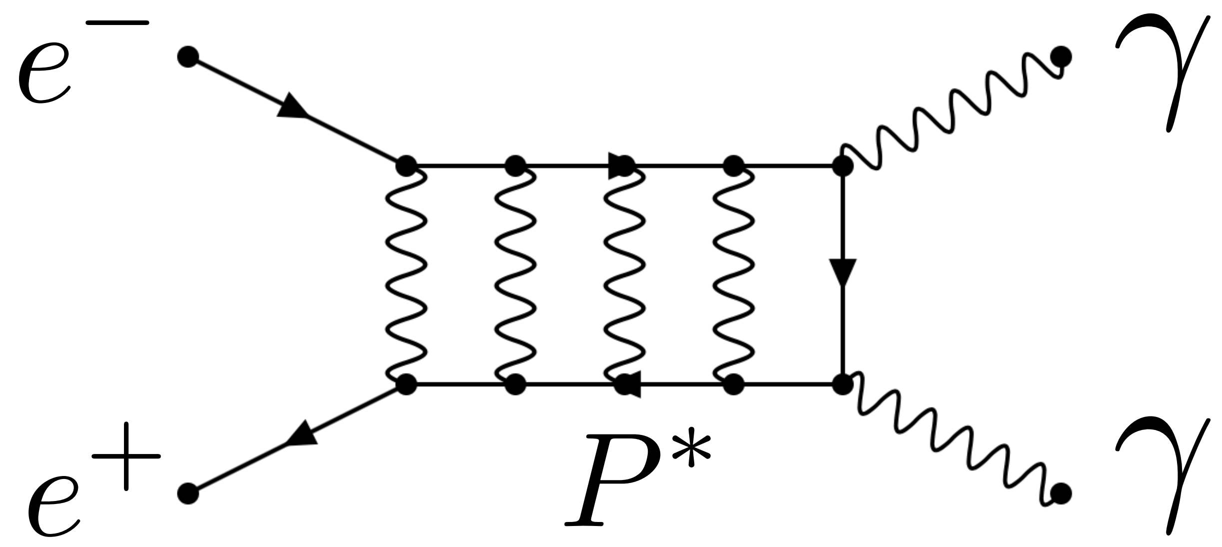
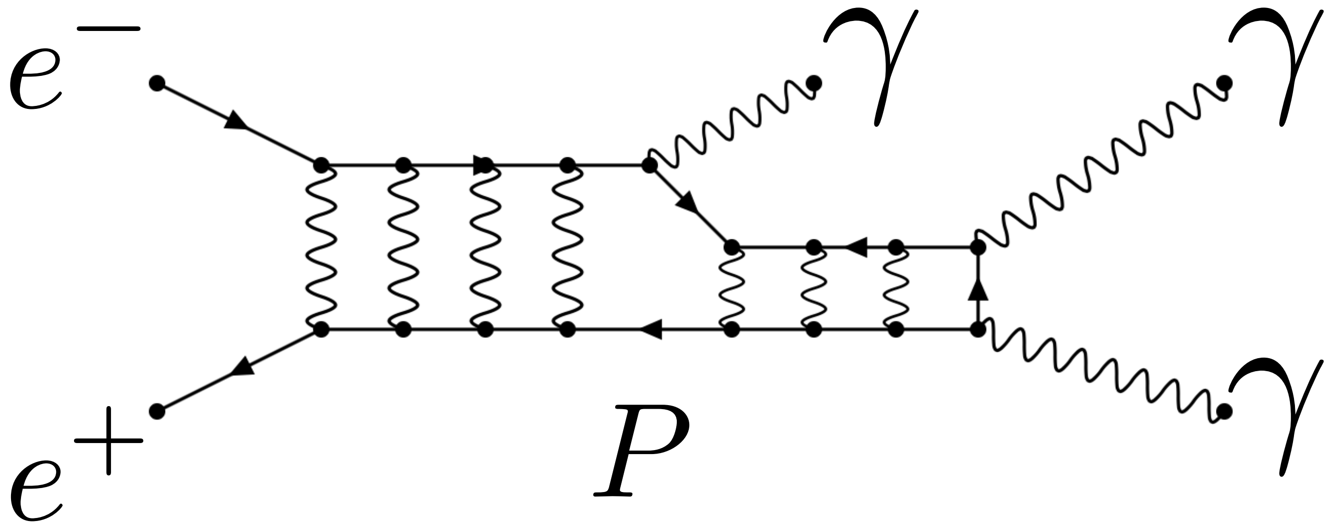


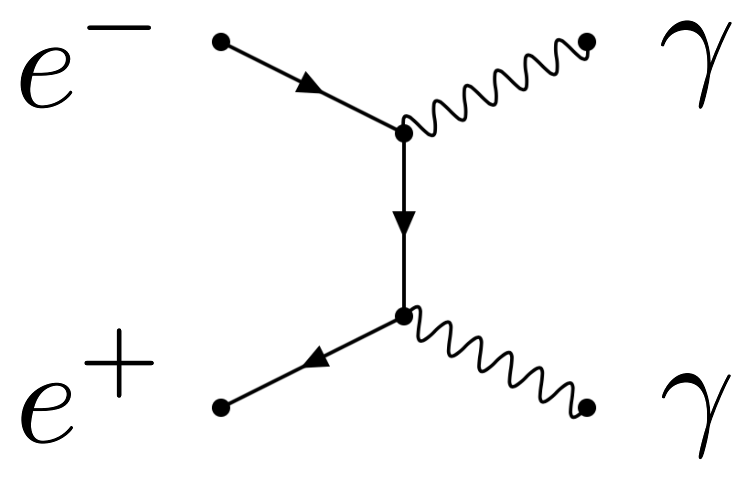
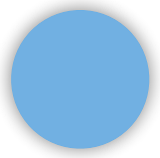
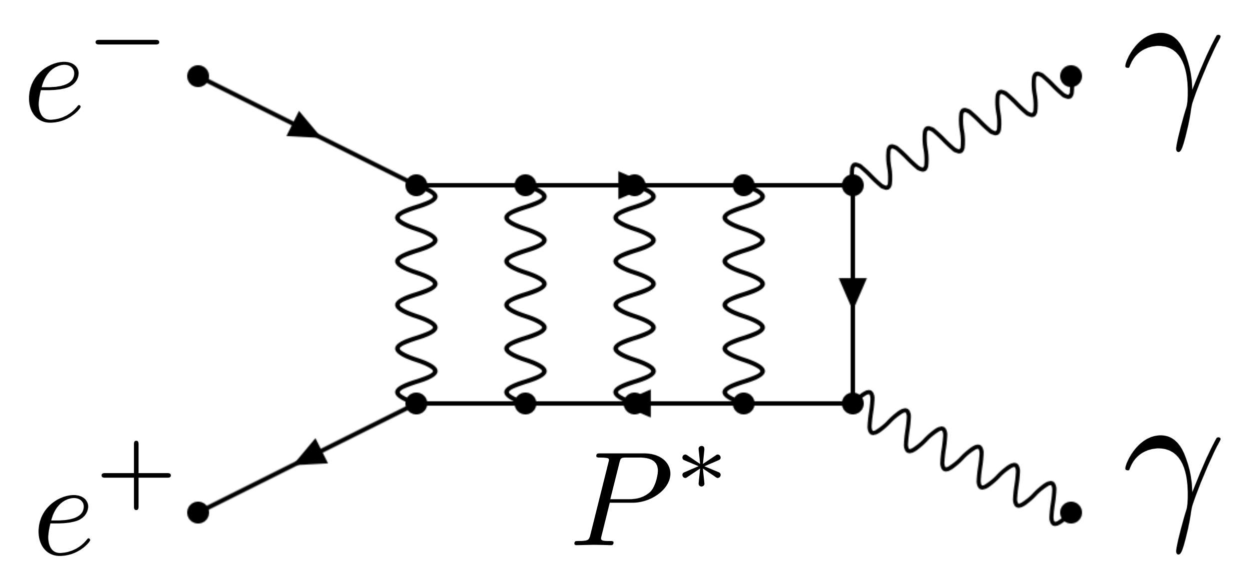
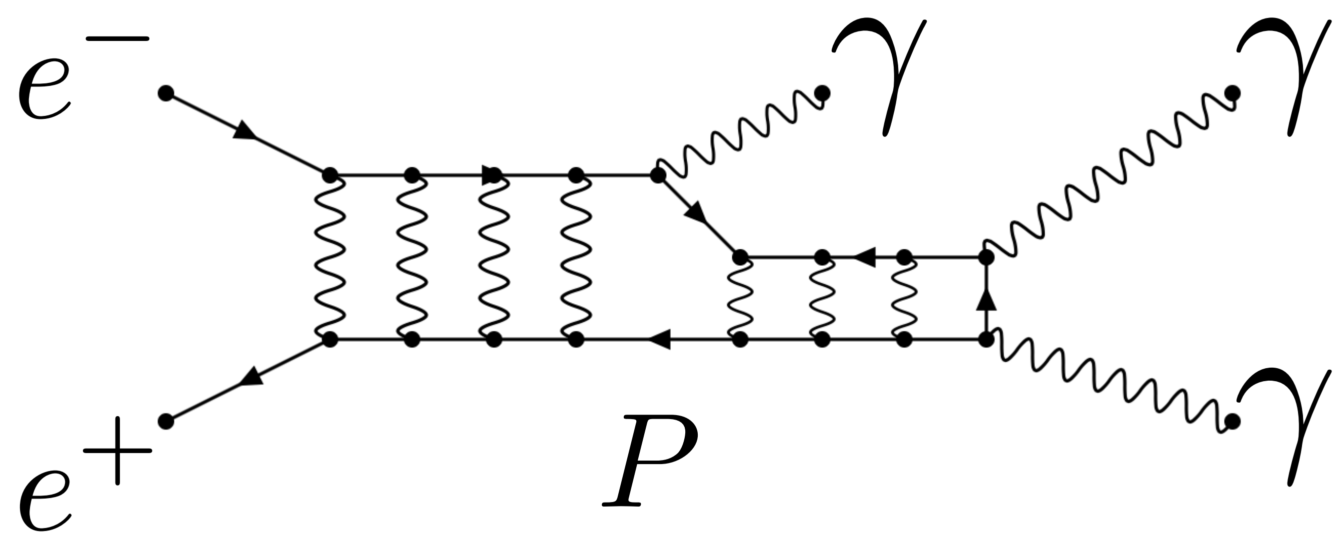
Cartoon Overview of Approach

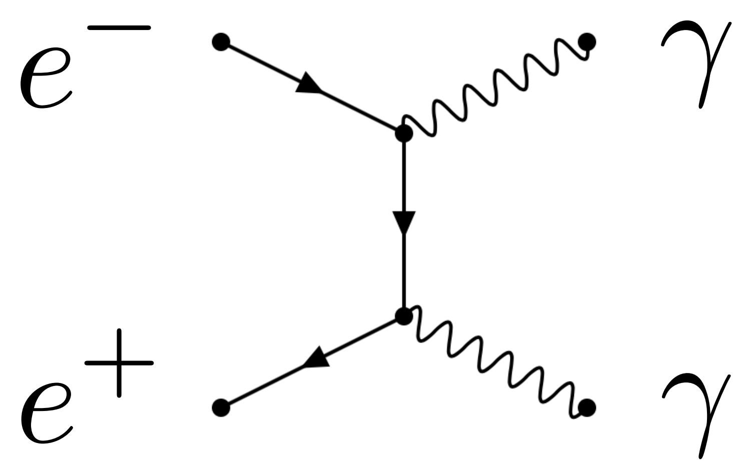
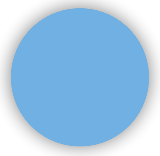
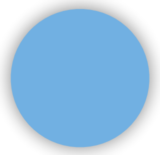
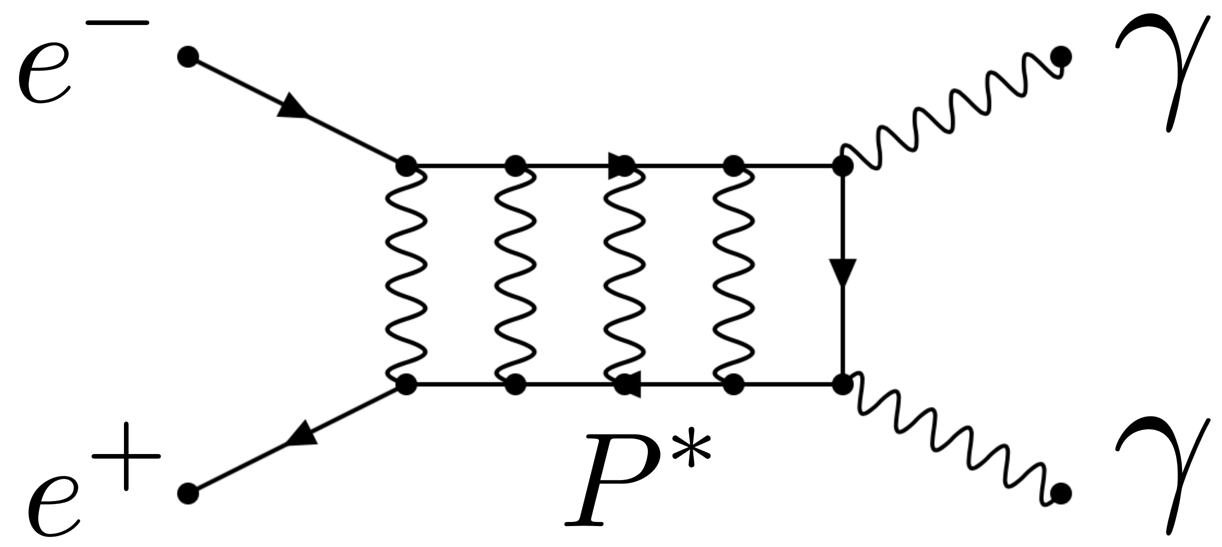
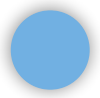
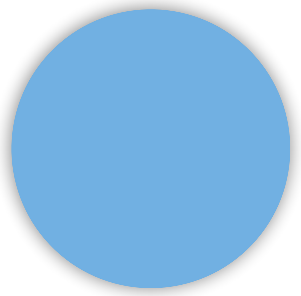
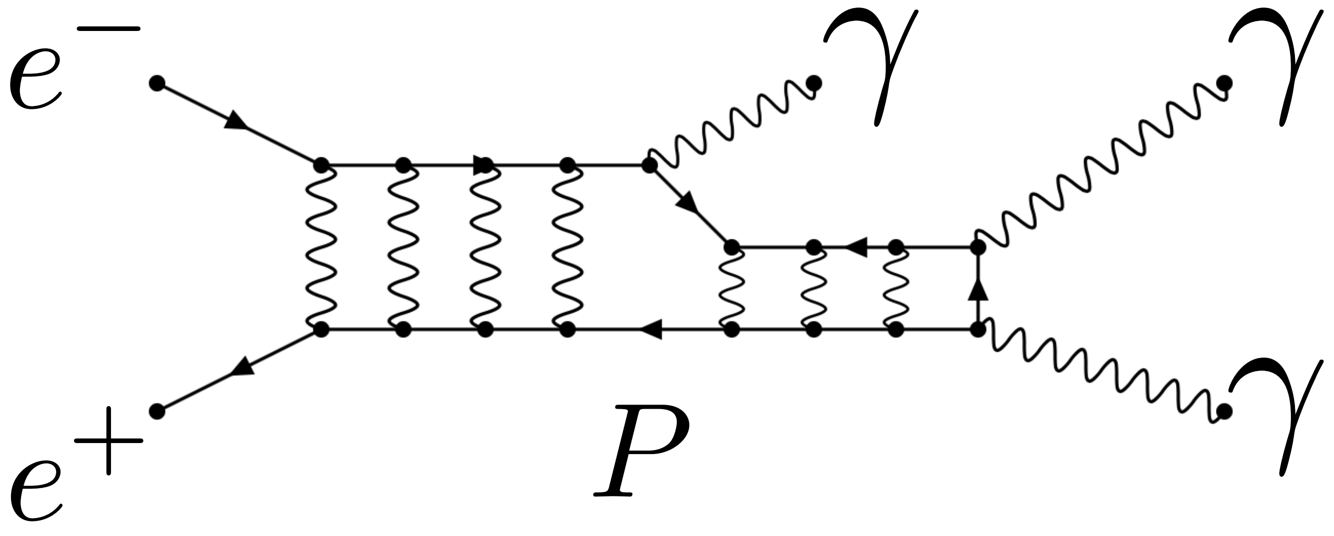


Cartoon Overview of Approach

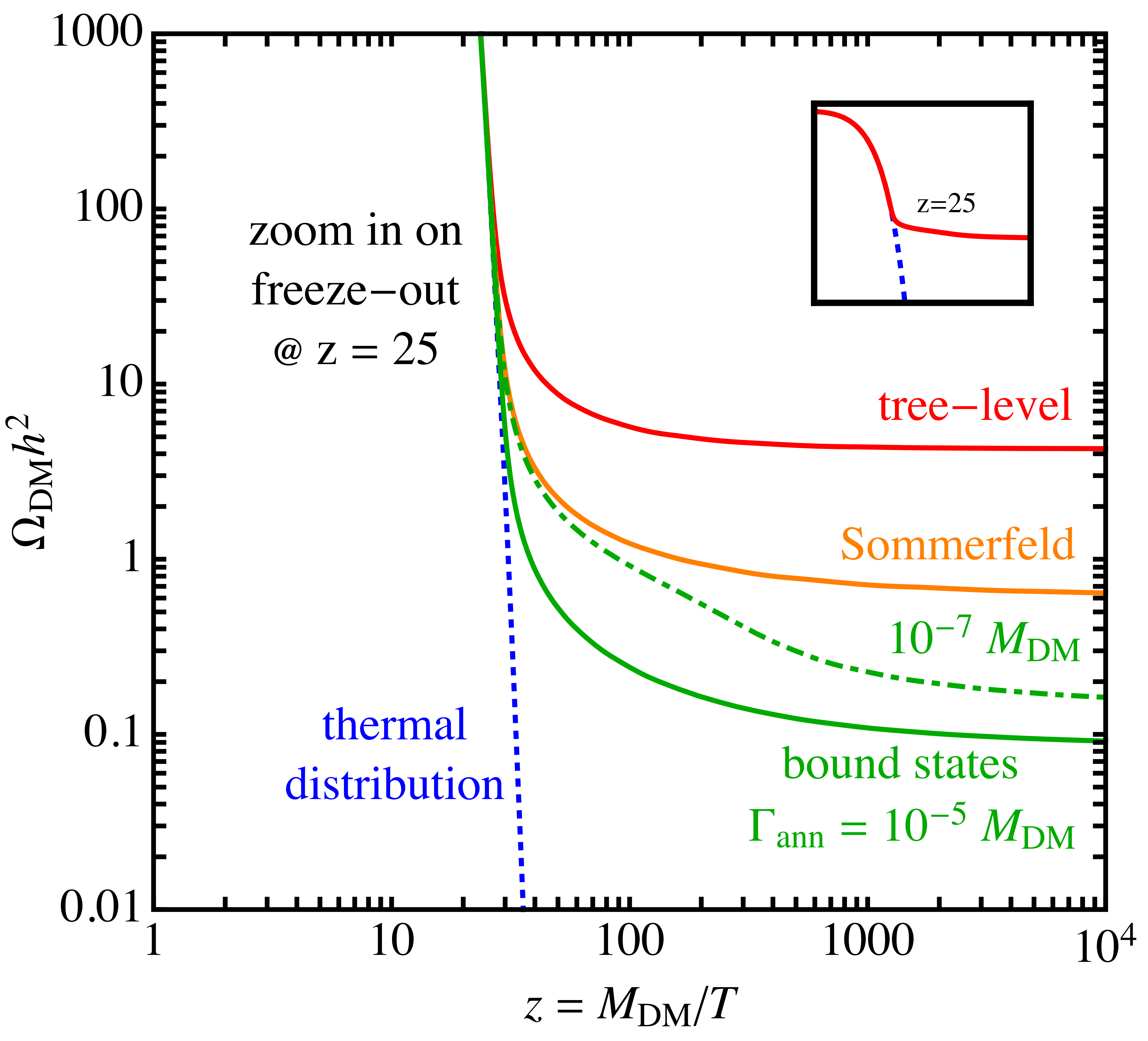


Process	Diagram	Cross-Section area	
$e^+ e^- \to \gamma\gamma$			
$e^+ e^- \to P^* \to \gamma\gamma$			
$e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$	 Assuming Parapositronium (J=0)		

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

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



B. v. Harling, K. Petraki,
1407.7874

P. Asadi et al.
1610.07617

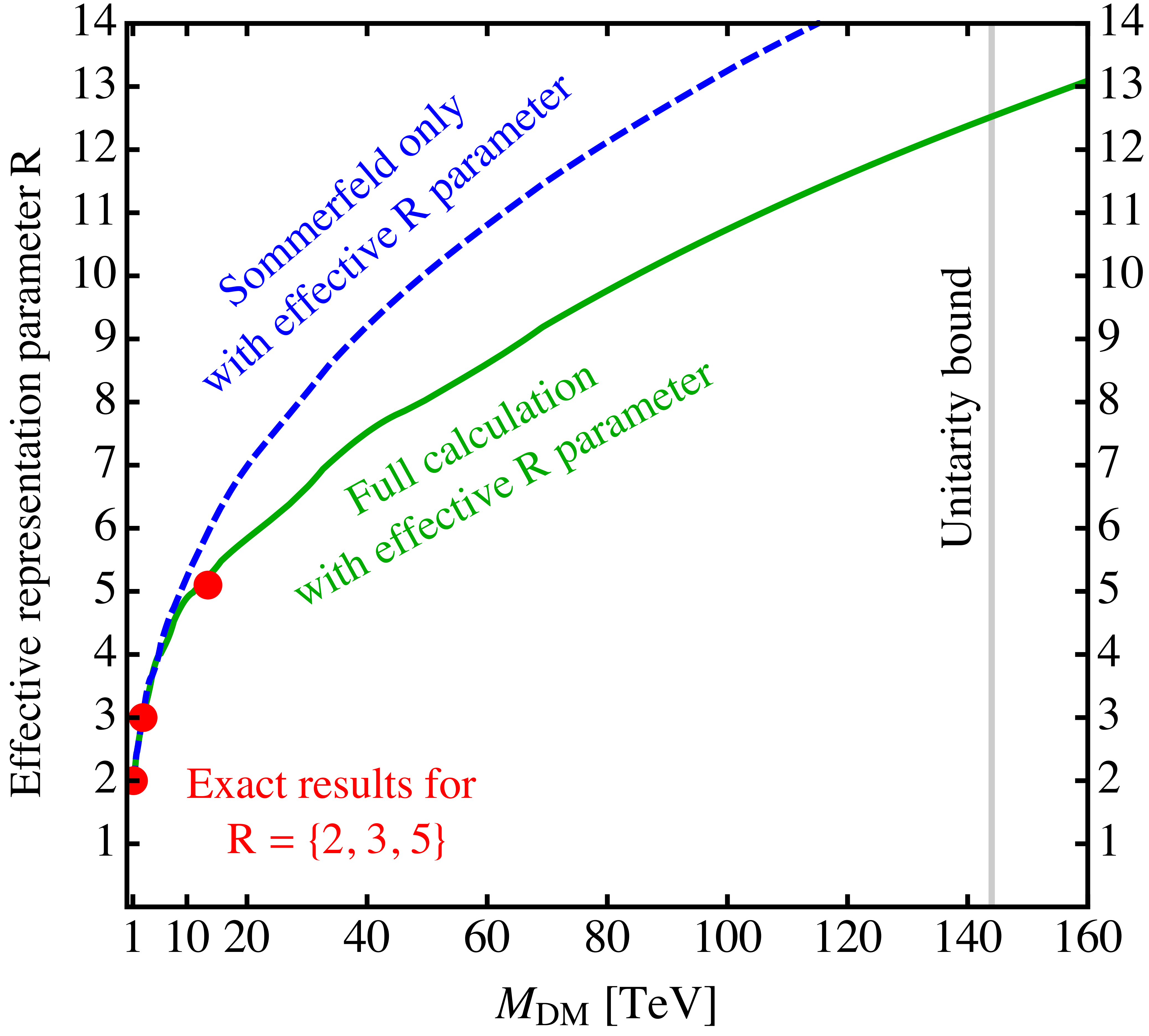
Mitridate et al.
1702.01141

J. Hartz, K. Petraki
1805.01200

J. Smirnov, J. F. Beacom
1904.11503

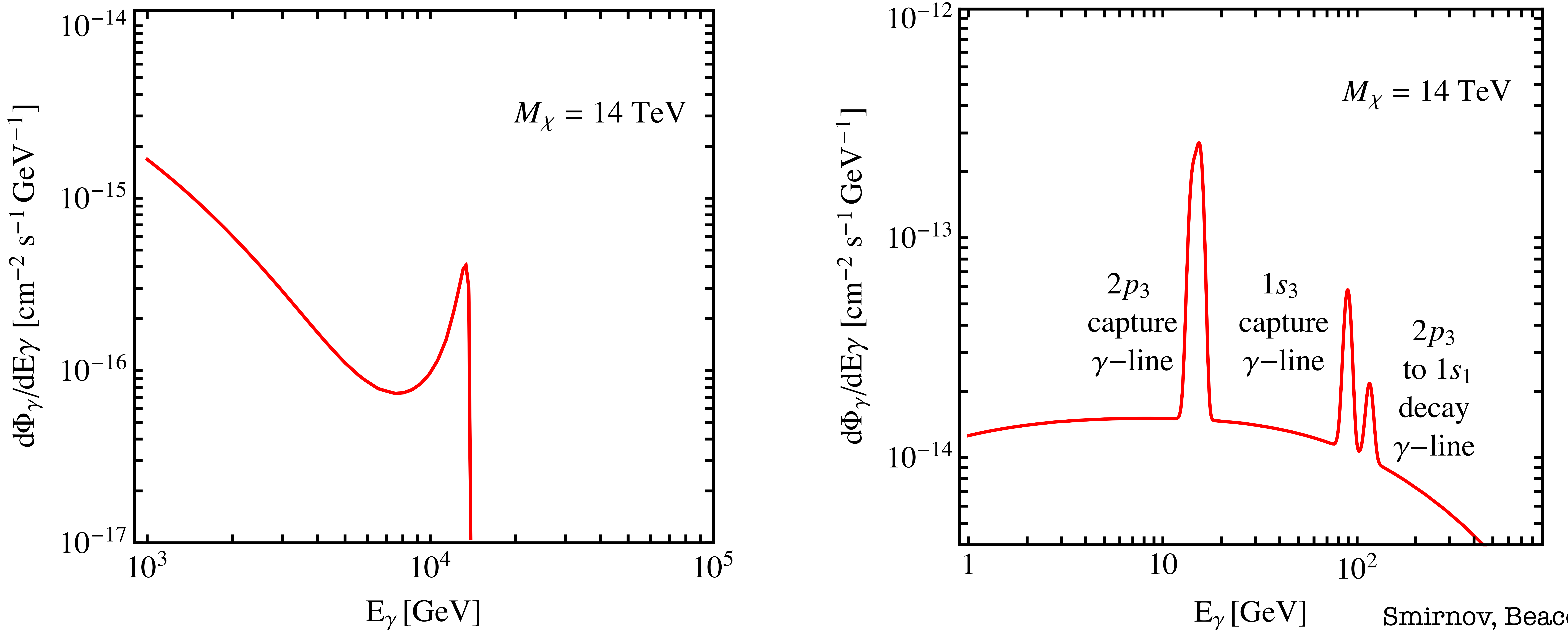
S. Bottaro et al.
2107.09688

Electroweak Dark Matter



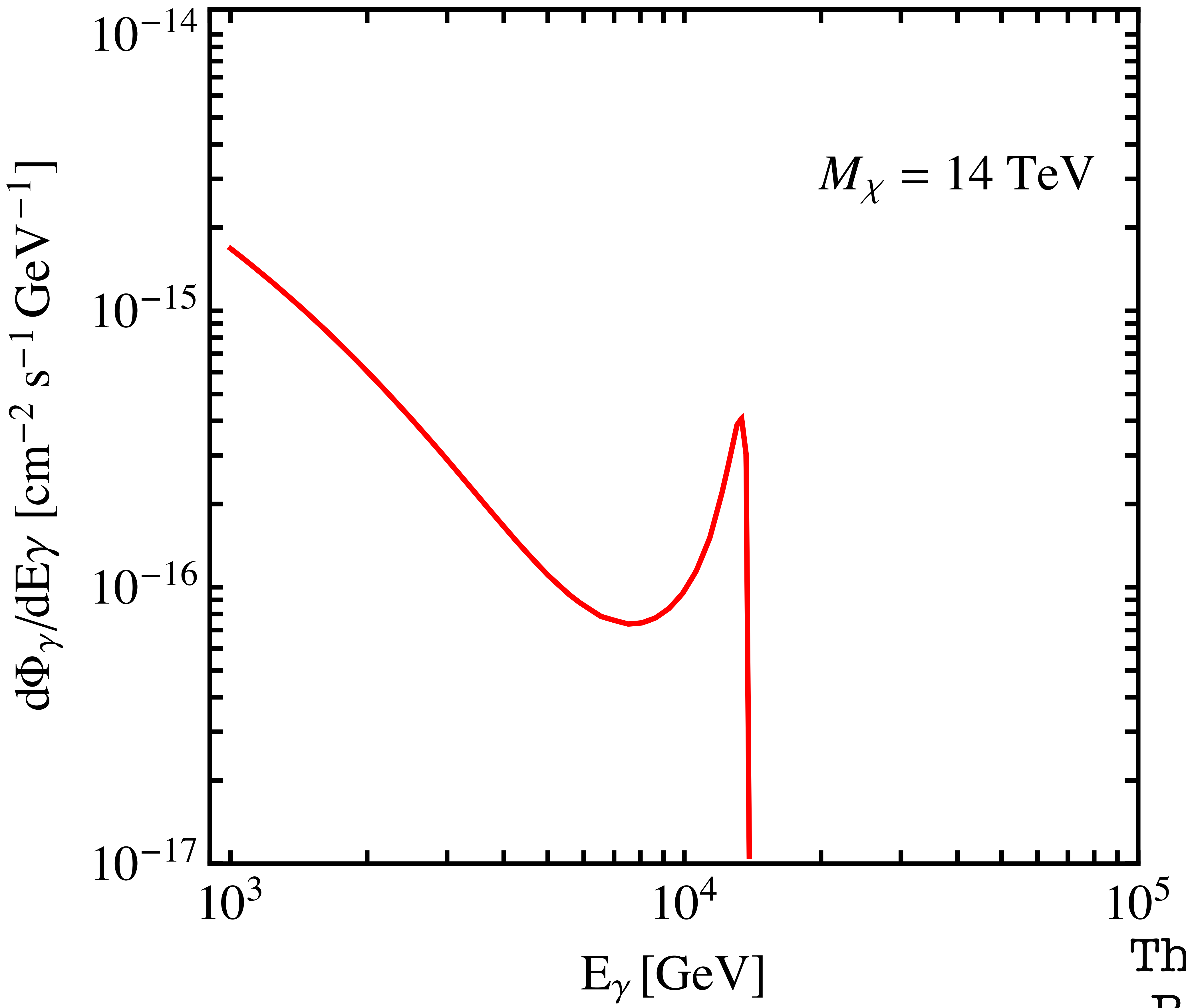
Smirnov, Beacom:
1904.11503

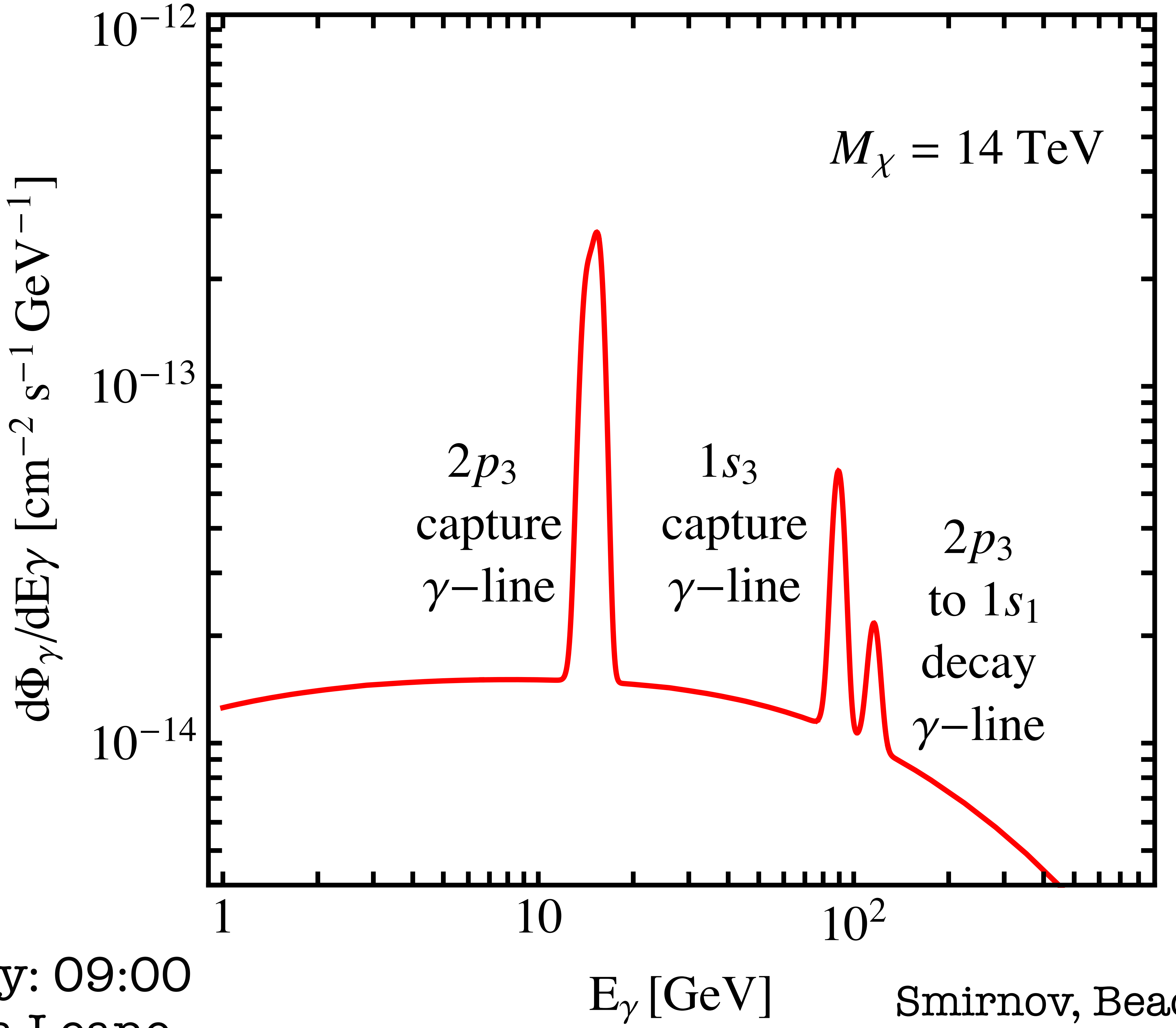
Example: DM Spectroscopy (SU(2) 5-plet)



Smirnov, Beacom: 1904.11503

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

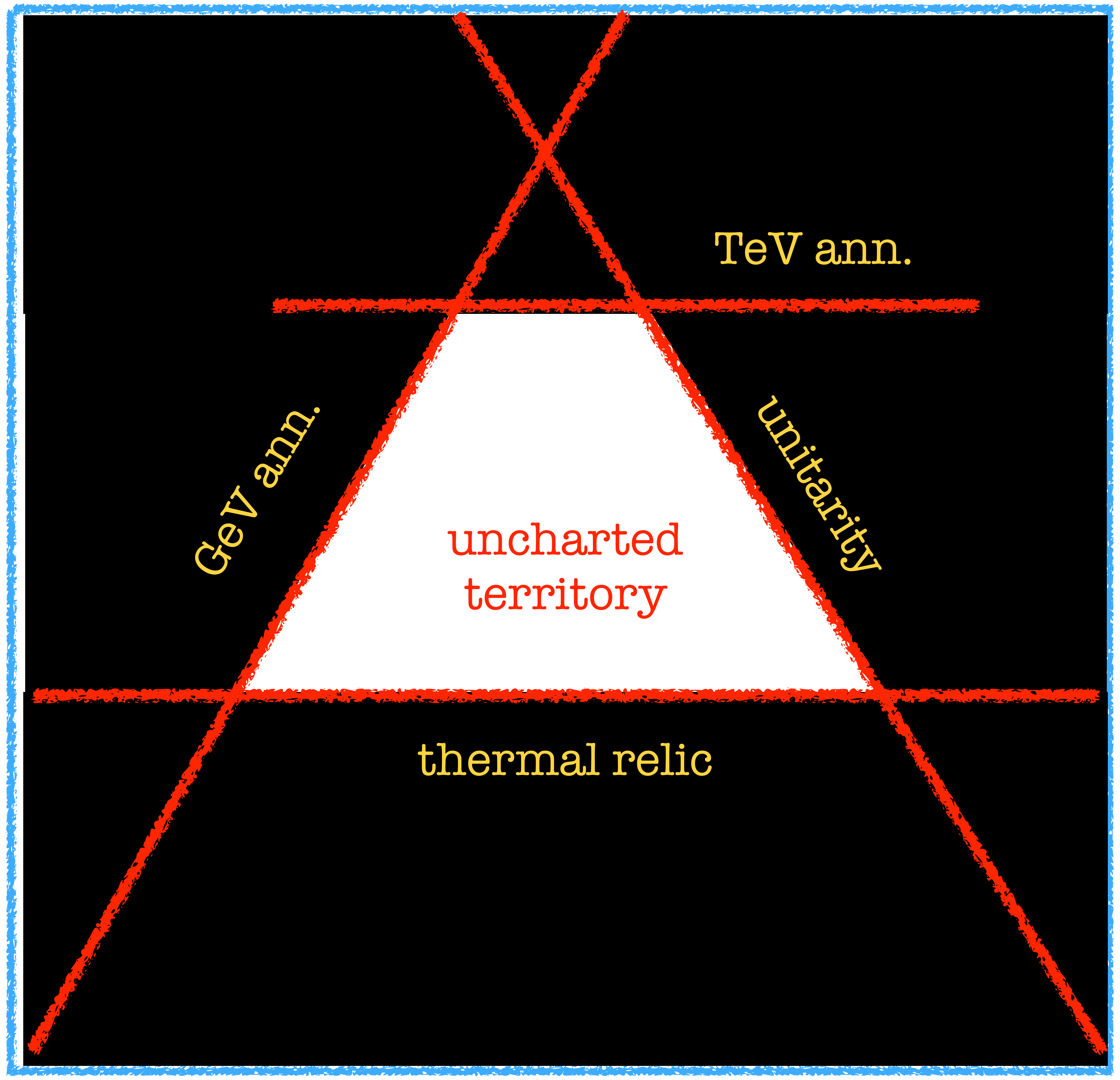


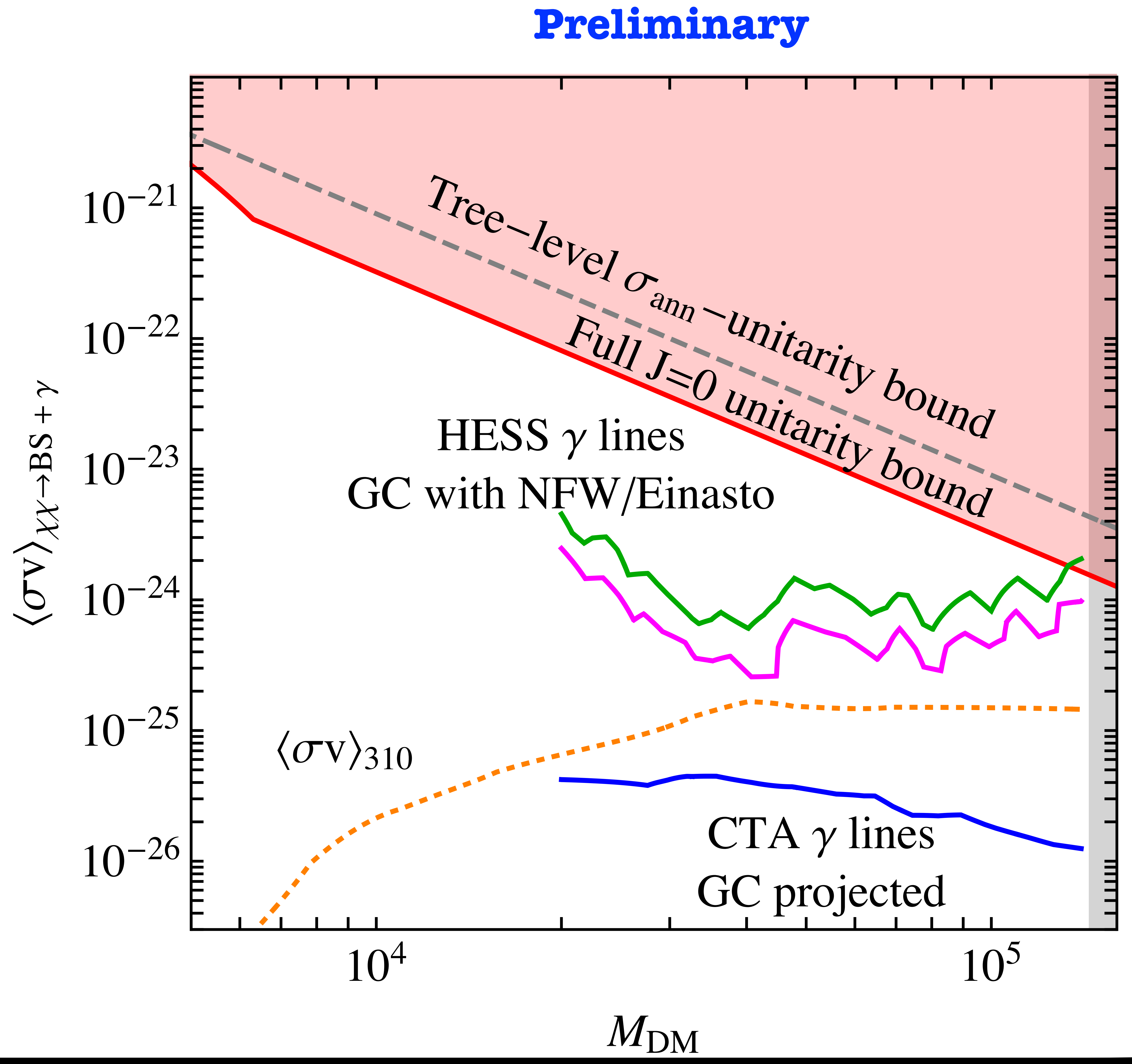


Thursday: 09:00
Rebecca Leane

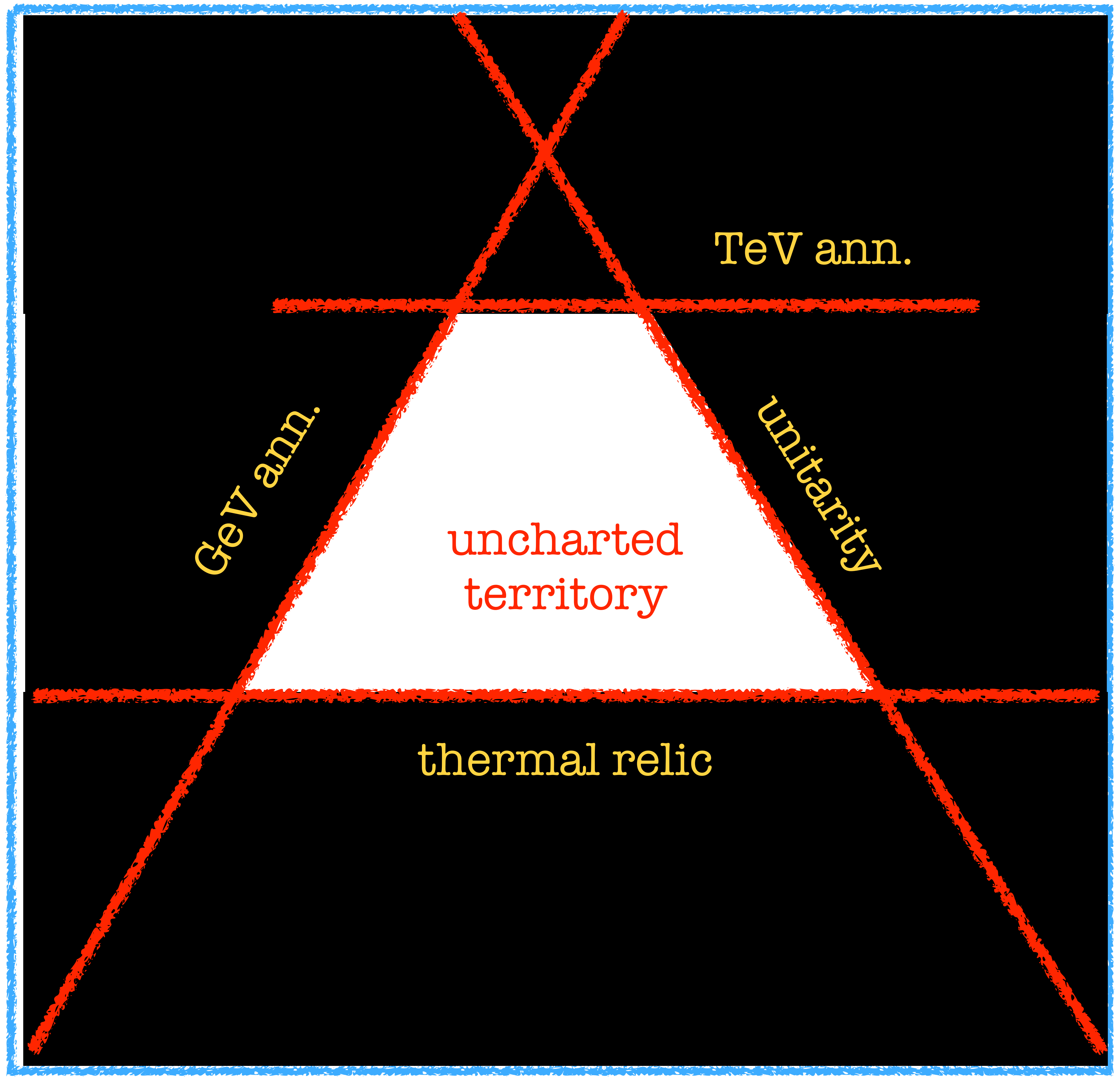
Smirnov, Beacom: 1904.11503

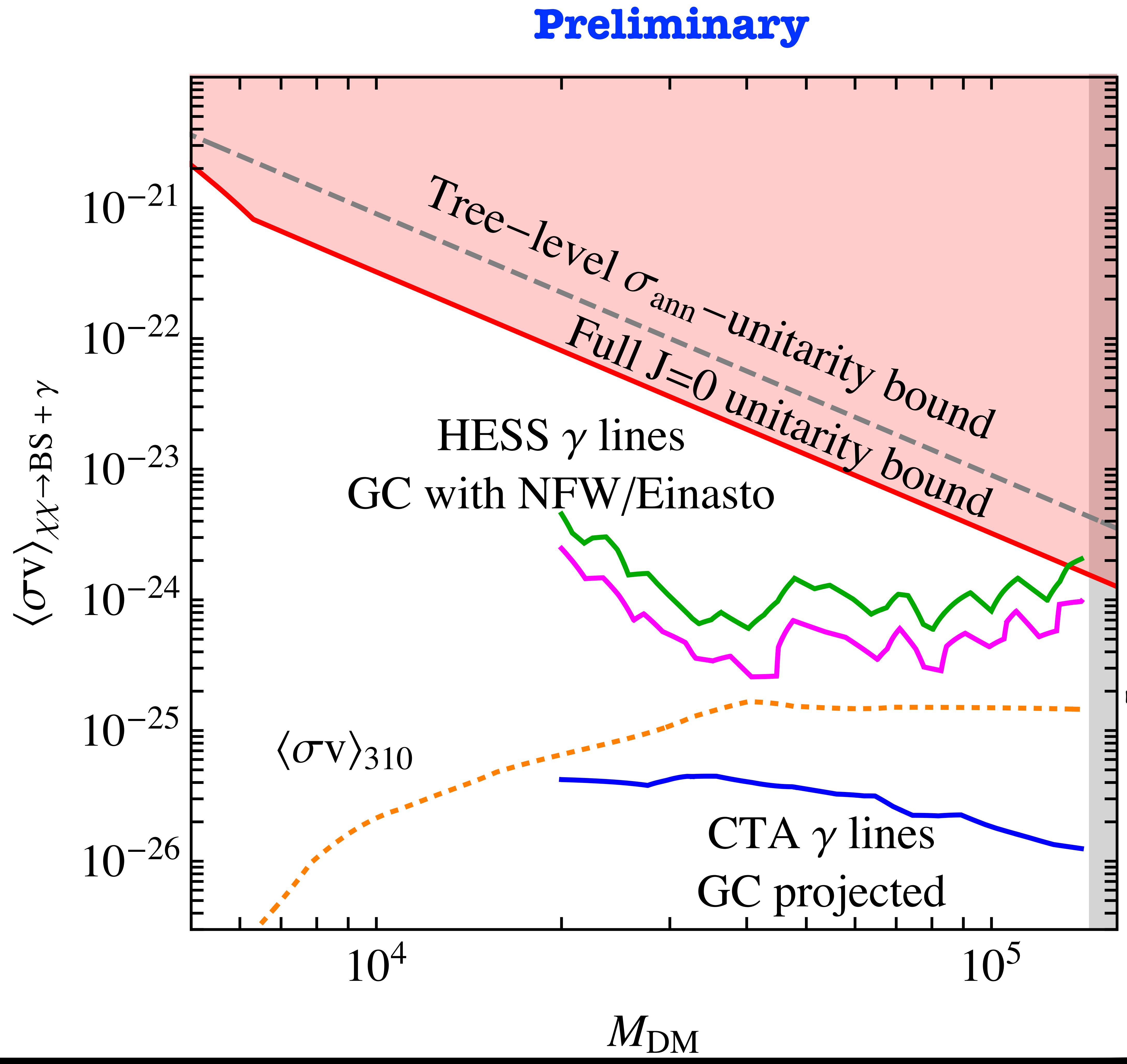
Example: Sensitivity to Heavy Dark Matter





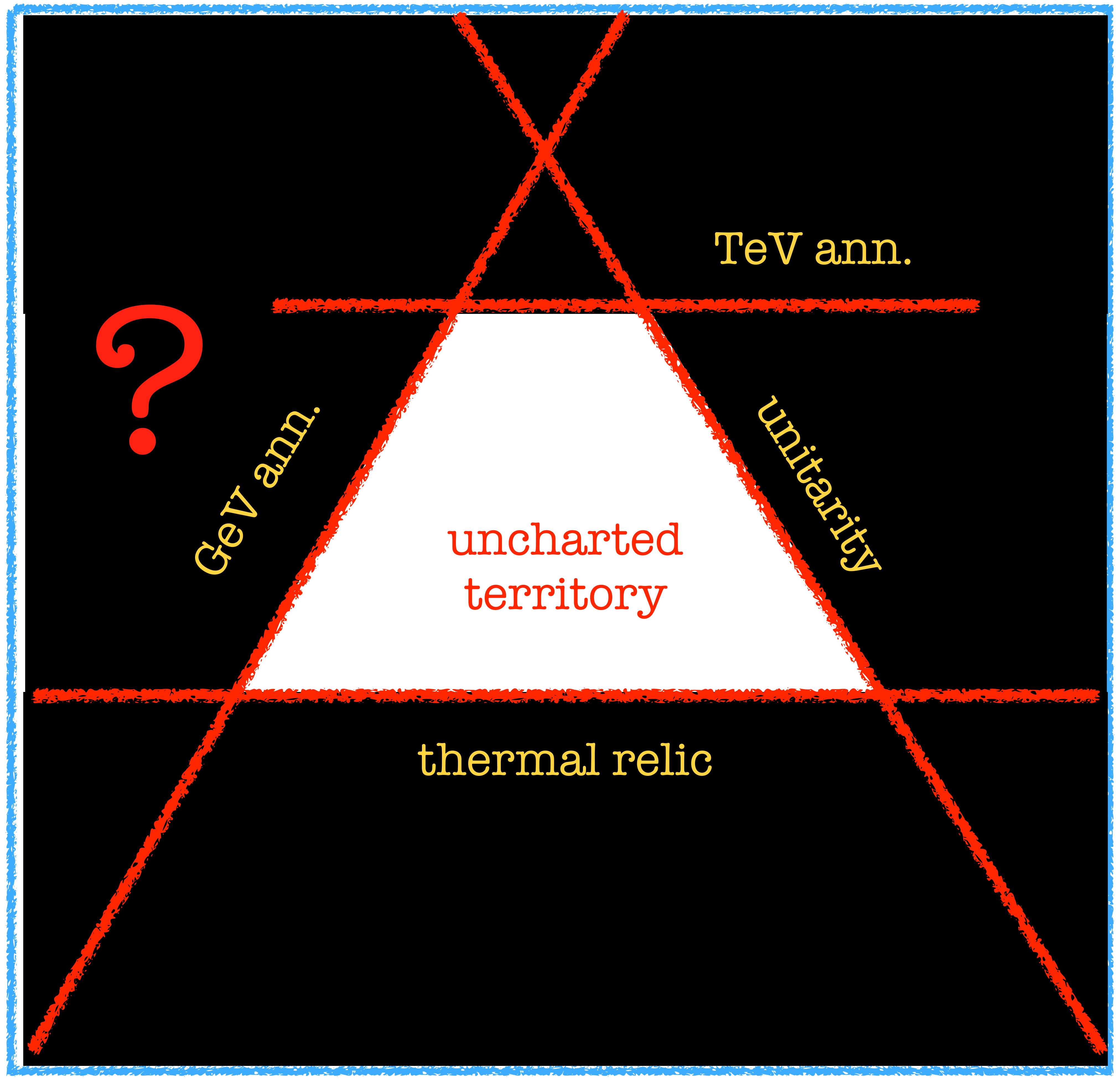
Example: Sensitivity to Heavy Dark Matter



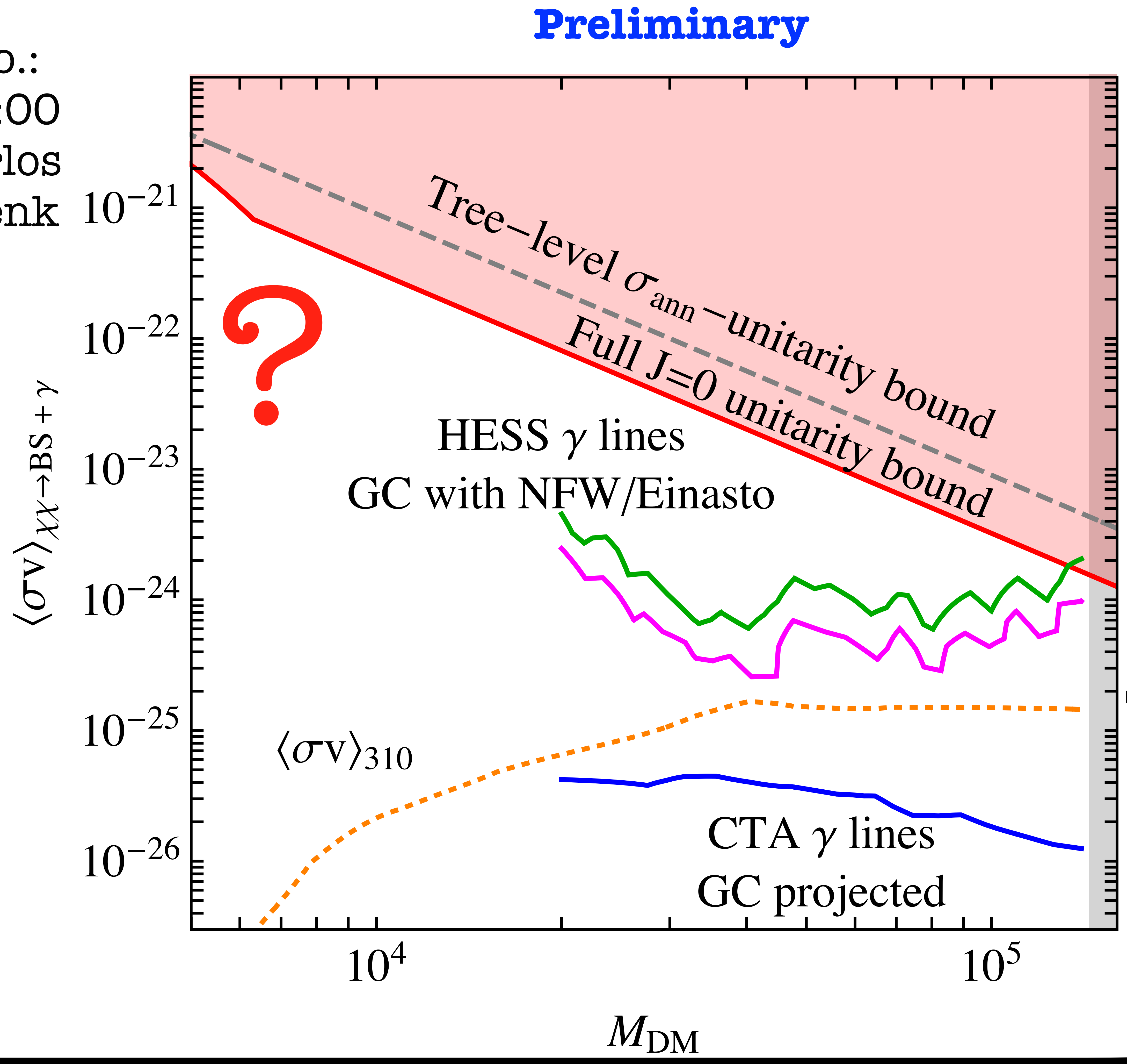


Thursd.: 15:00 Judith Perez-Romero

Example: Sensitivity to Heavy Dark Matter



Mo.: 10:00 Carlos Frenk



Thursd.: 15:00 Judith Perez-Romero

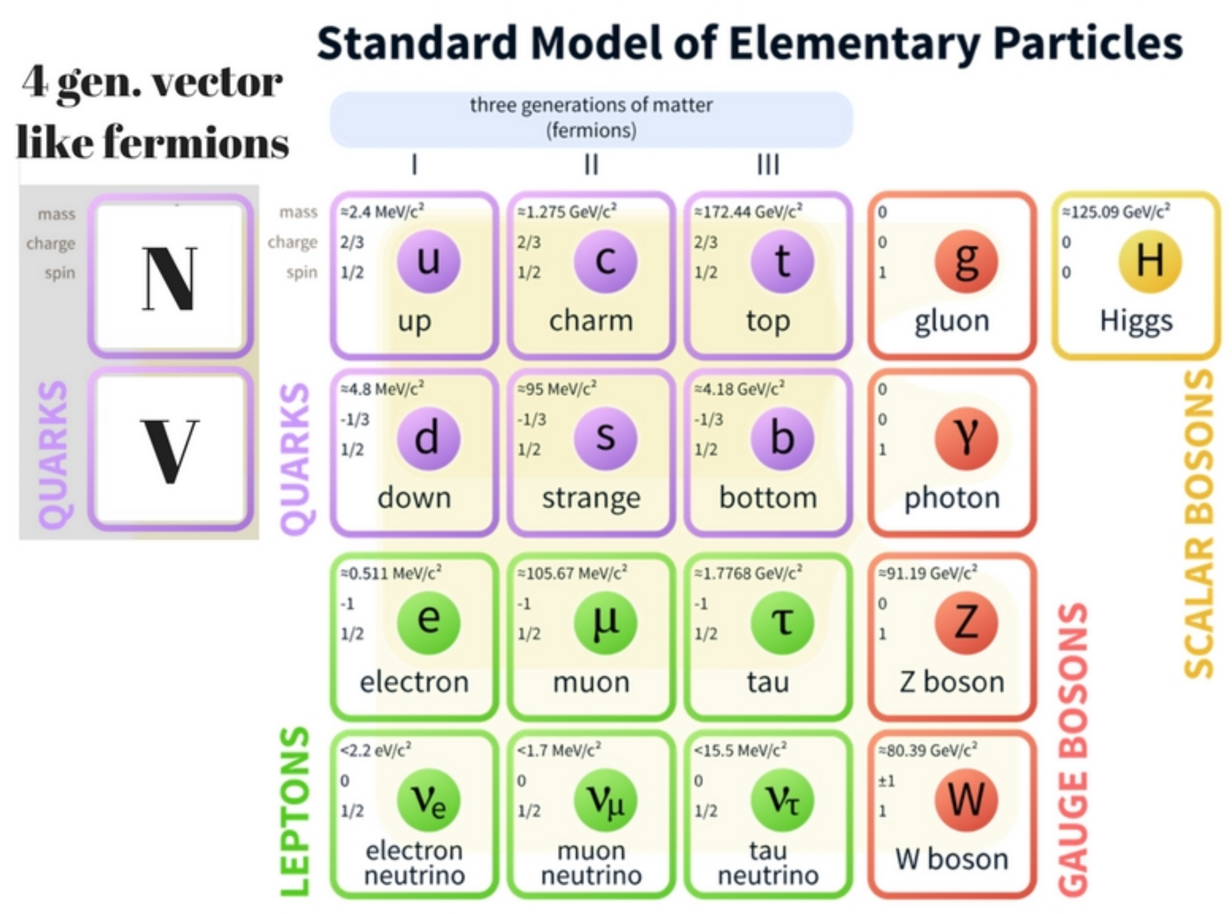
Phase Transitions and Stable Bound States

Beyond QCD

Dark Matter stability

$$SU(N)_{\rm DC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SU(N)_{\rm DC} \times SU(3)_c \times U(1)_{\rm em}$$



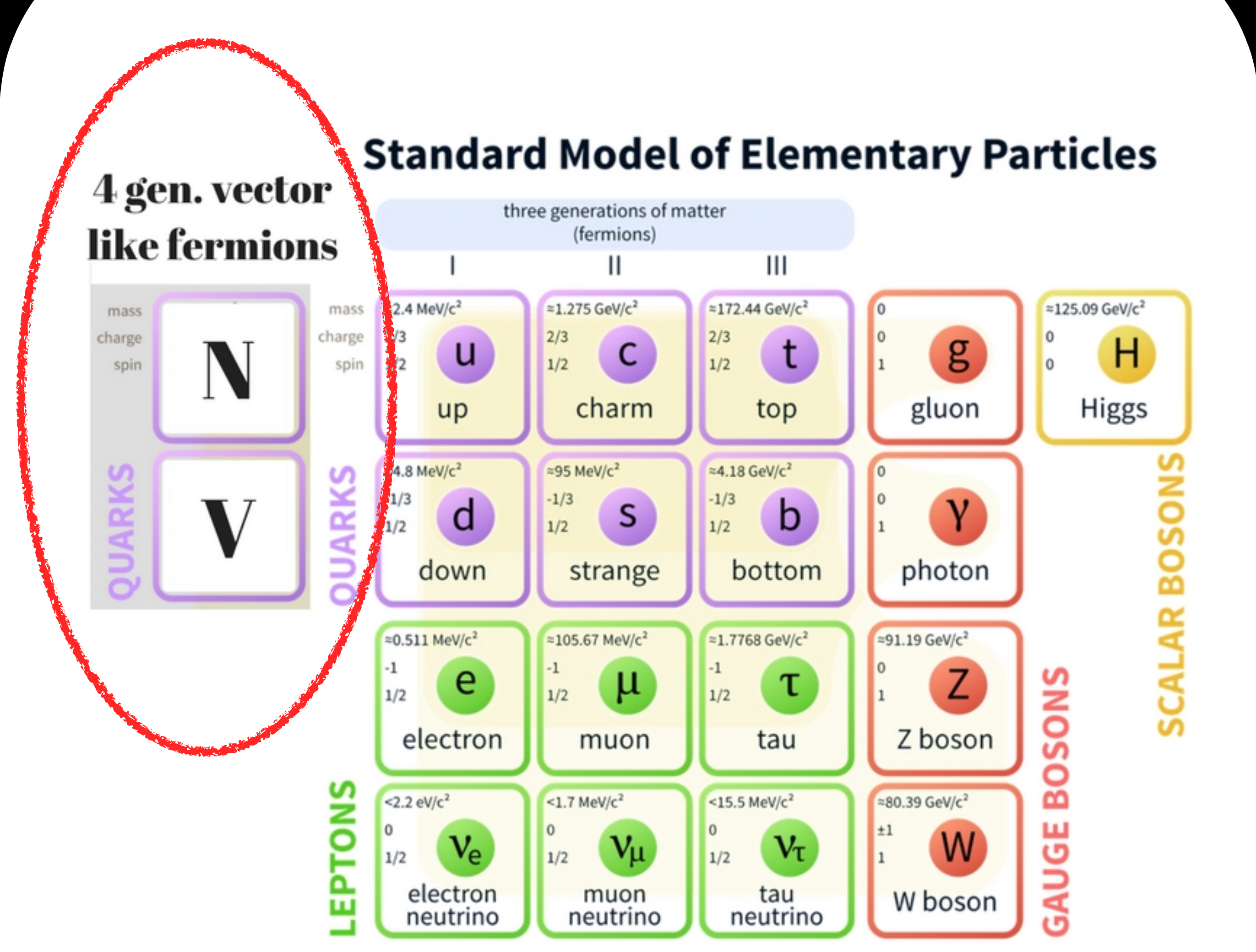
1503.08749

Dark Matter stability

$$SU(N)_{\rm DC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SU(N)_{\rm DC} \times SU(3)_c \times U(1)_{\rm em}$$

New Baryon Number → DM candidate

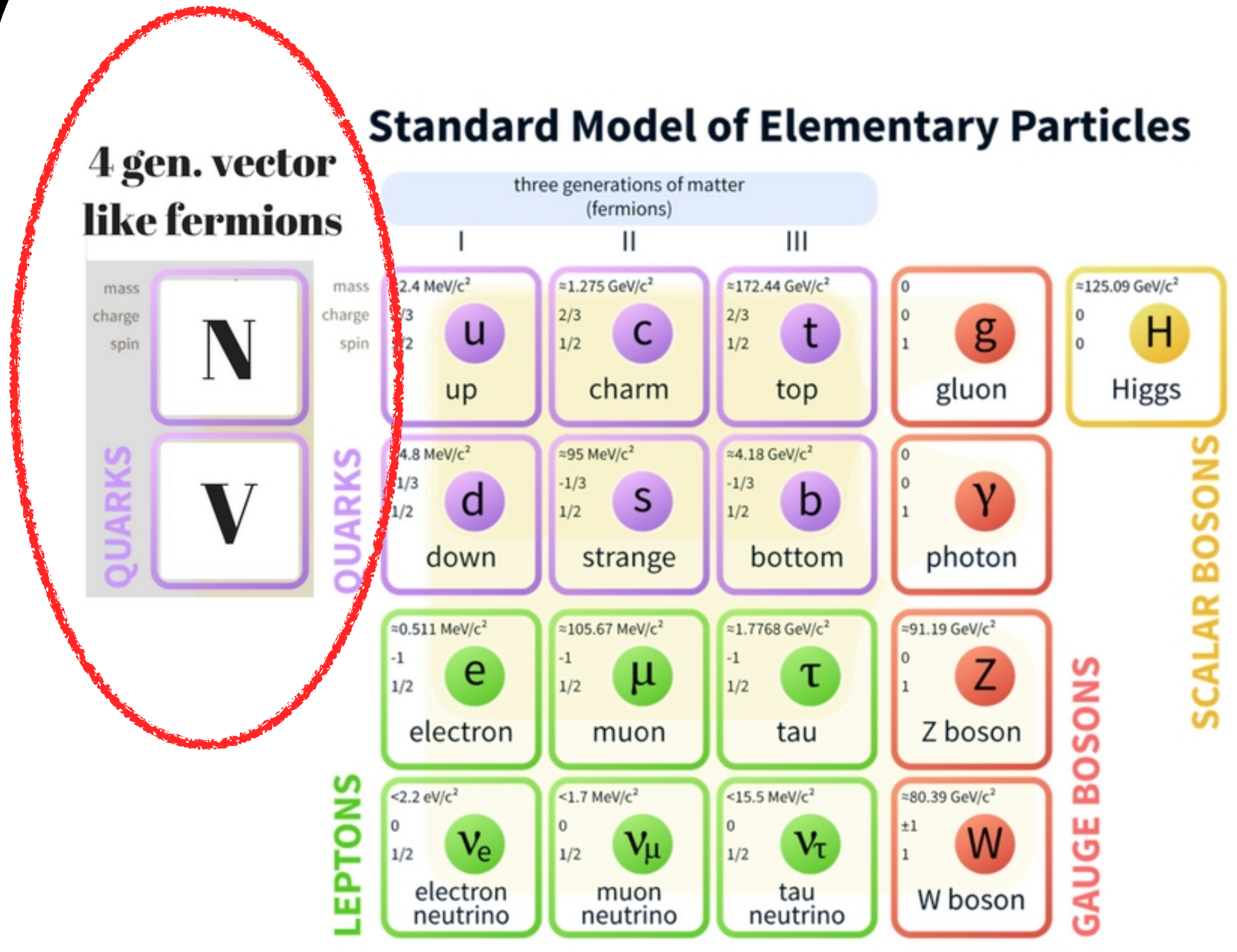


1503.08749

Dark Matter stability

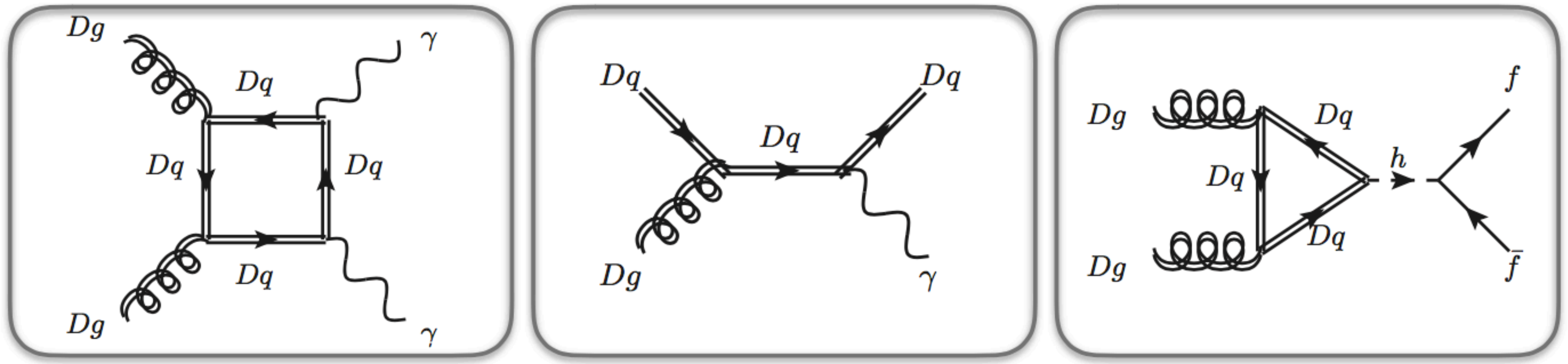
$$SU(N)_{\rm DC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$SU(N)_{\rm DC} \times SU(3)_c \times U(1)_{\rm em}$$



New Baryon Number → DM candidate

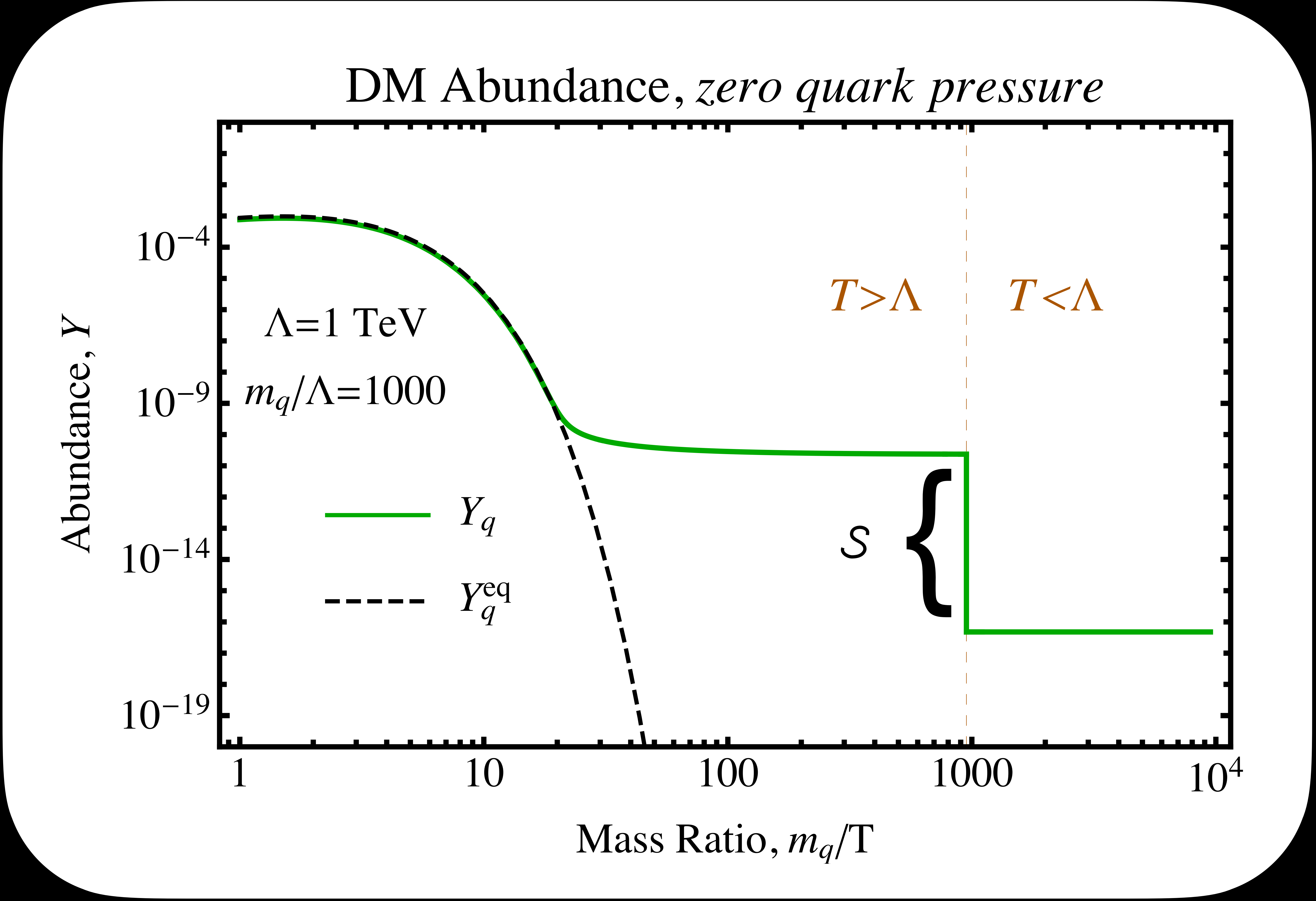
Thermal contact with the SM sector



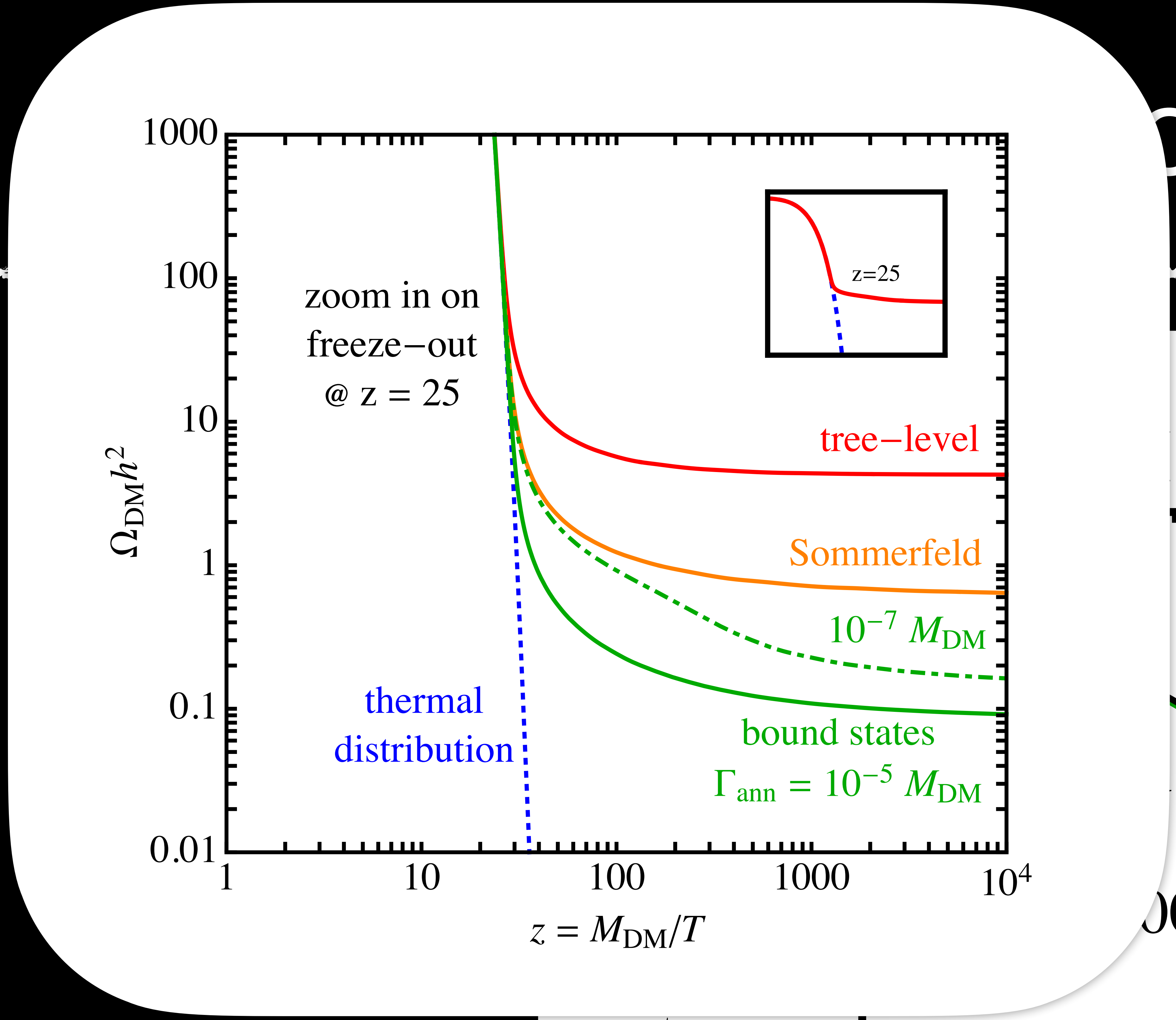
1503.08749

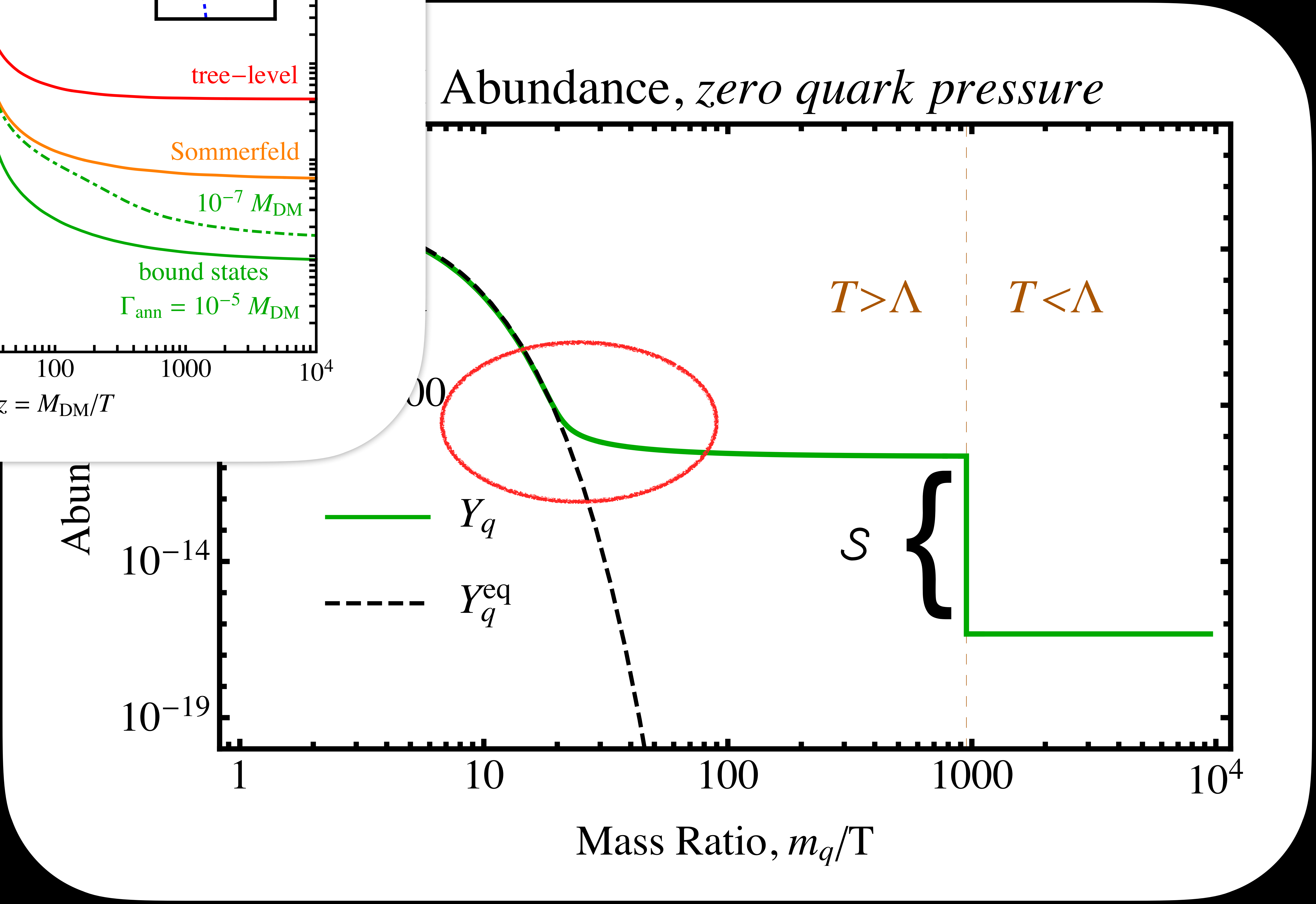
The Relic Abundance

Freeze-out & Confinement

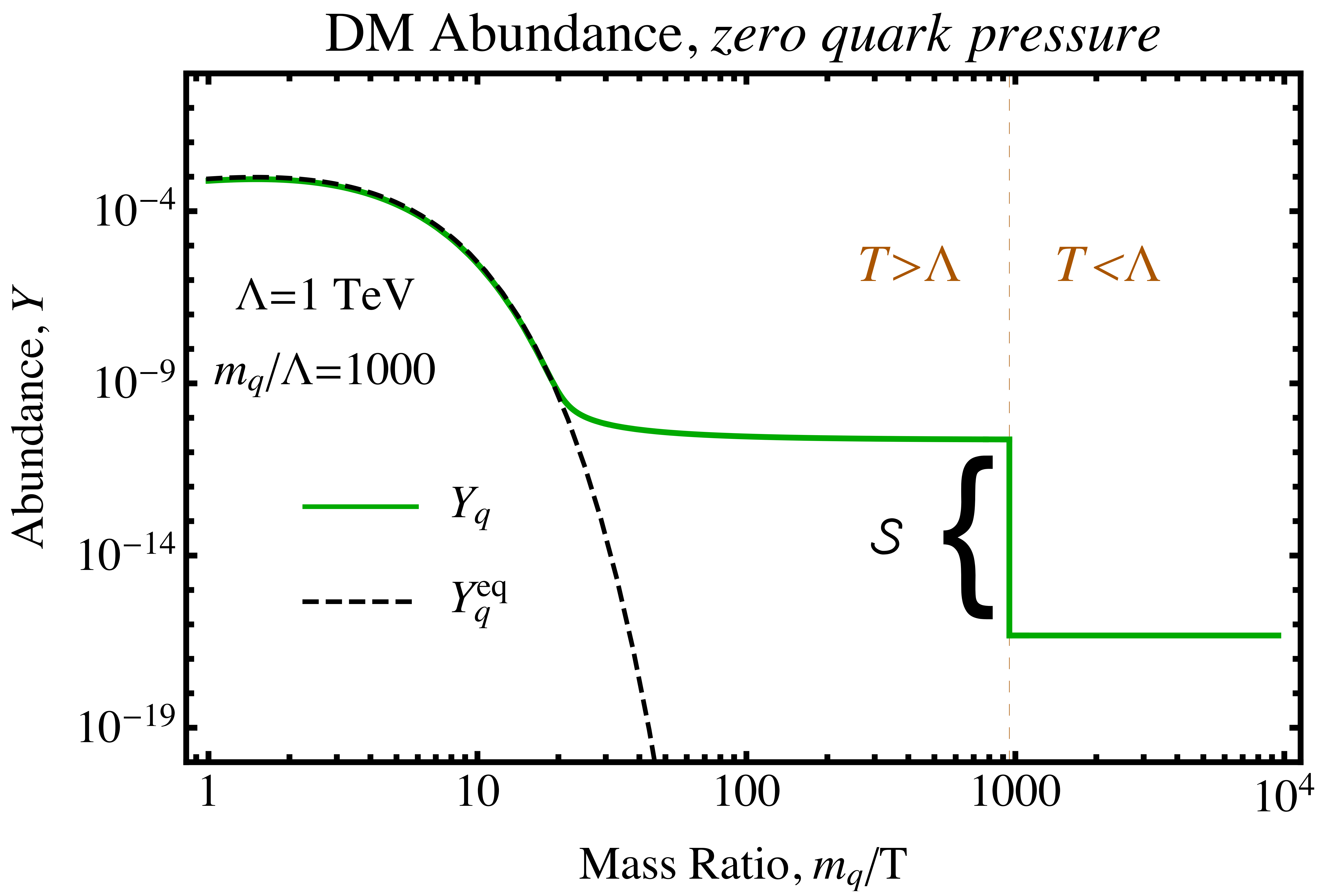


out & Confinement

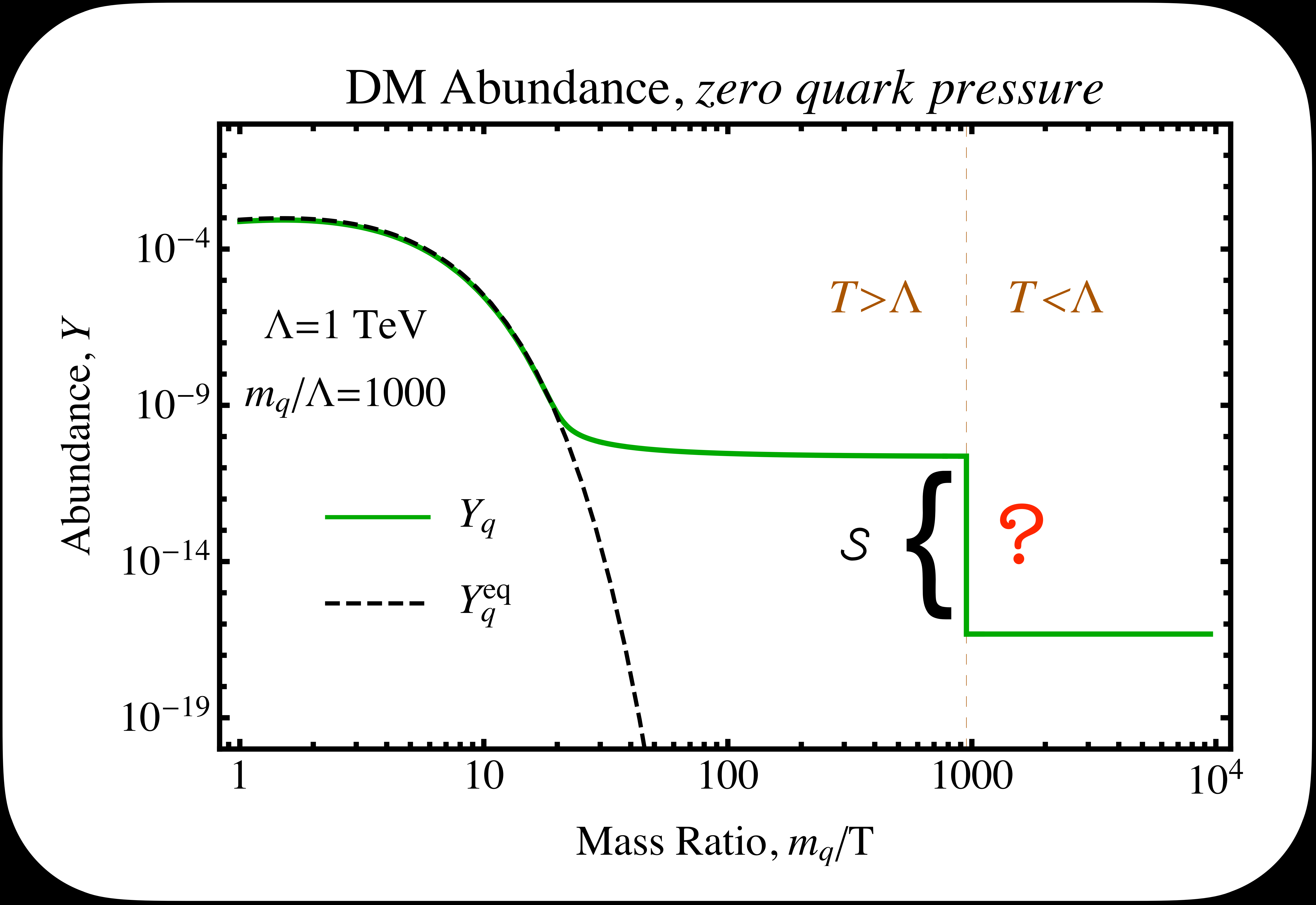




Freeze-out & Confinement



Freeze-out & Confinement



First Idea: Geometrical Confinement

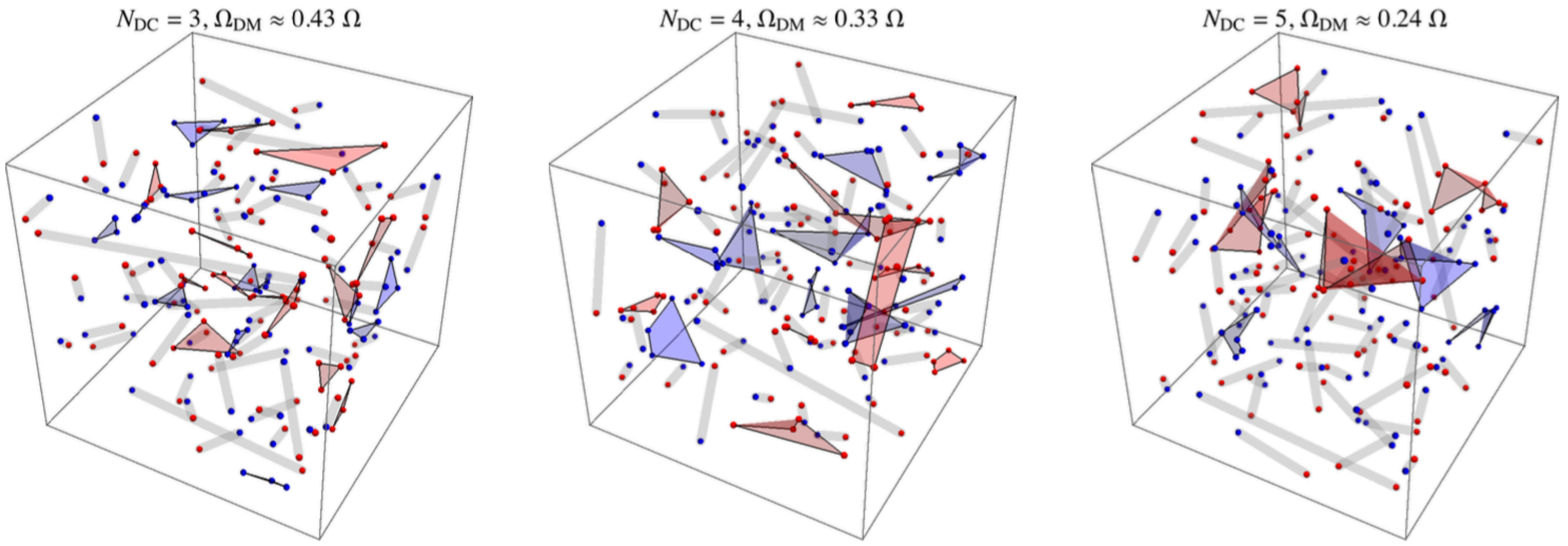
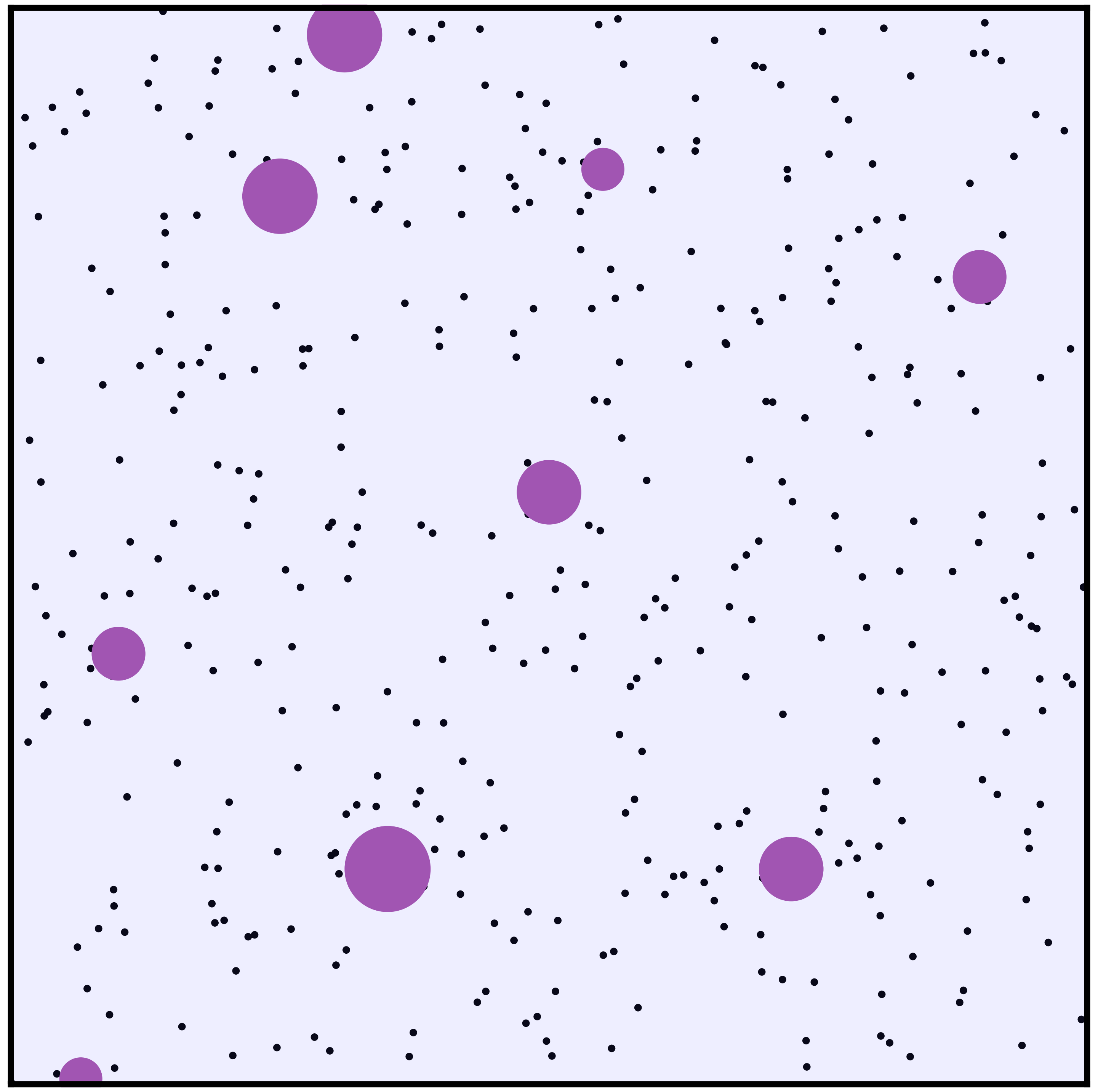
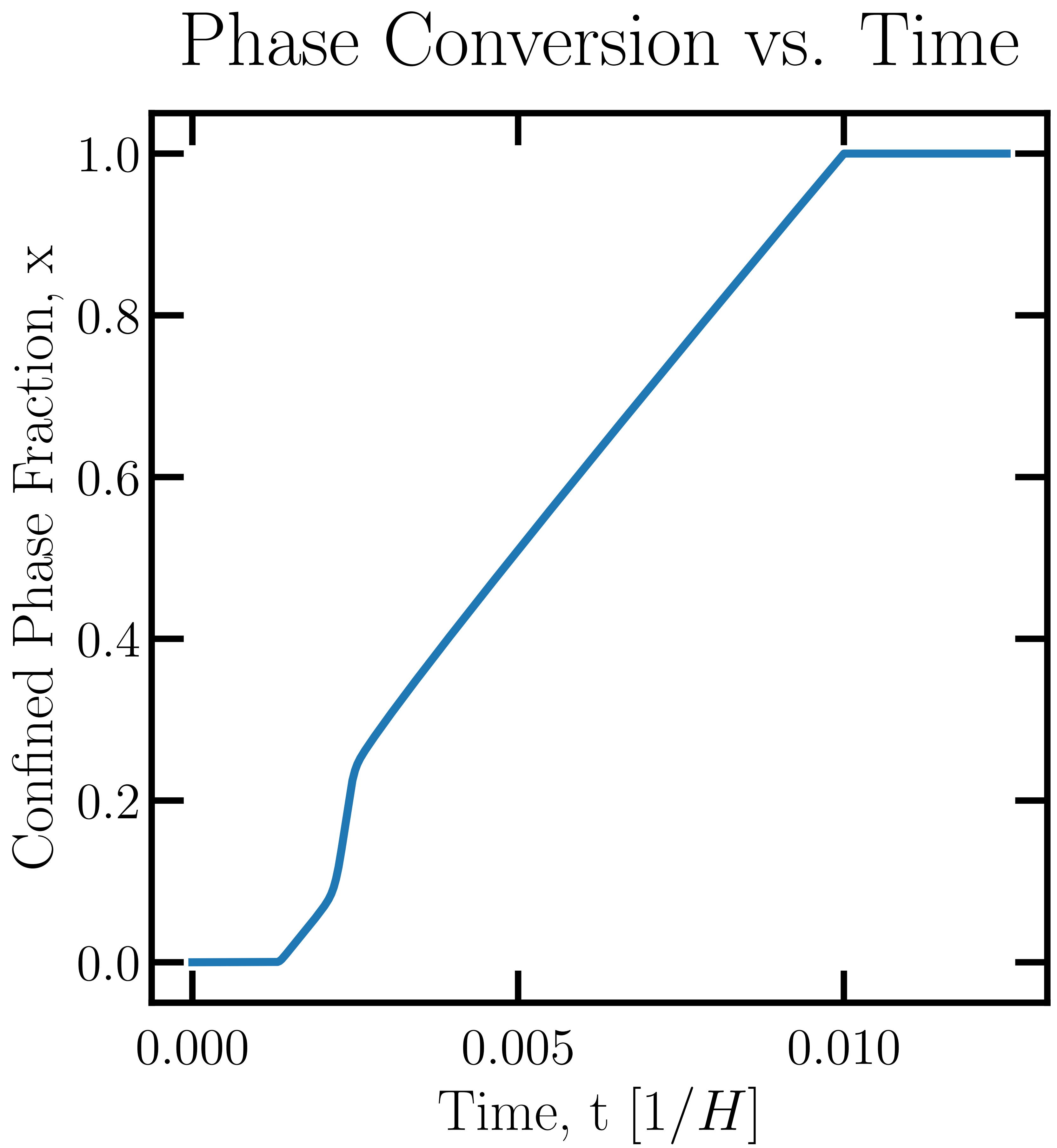


Figure 5: *Examples of dark condensation for* $N_{DC} = 3$ *(left),* 4 *(middle) and* 5 *(right). Dark quarks* $\mathcal{Q}$ *(anti-quarks* $\bar{\mathcal{Q}}$*) are denoted as red (blue) dots, placed at random positions. We assume that each DM particle combines with its dark nearest neighbour, forming either unstable* $\mathcal{Q}\bar{\mathcal{Q}}$ *dark mesons (gray lines) or stable* $\mathcal{Q}^{N_{DC}}$ *dark baryons (red regions) and* $\bar{\mathcal{Q}}^{N_{DC}}$ *dark anti-baryons (blue regions).*

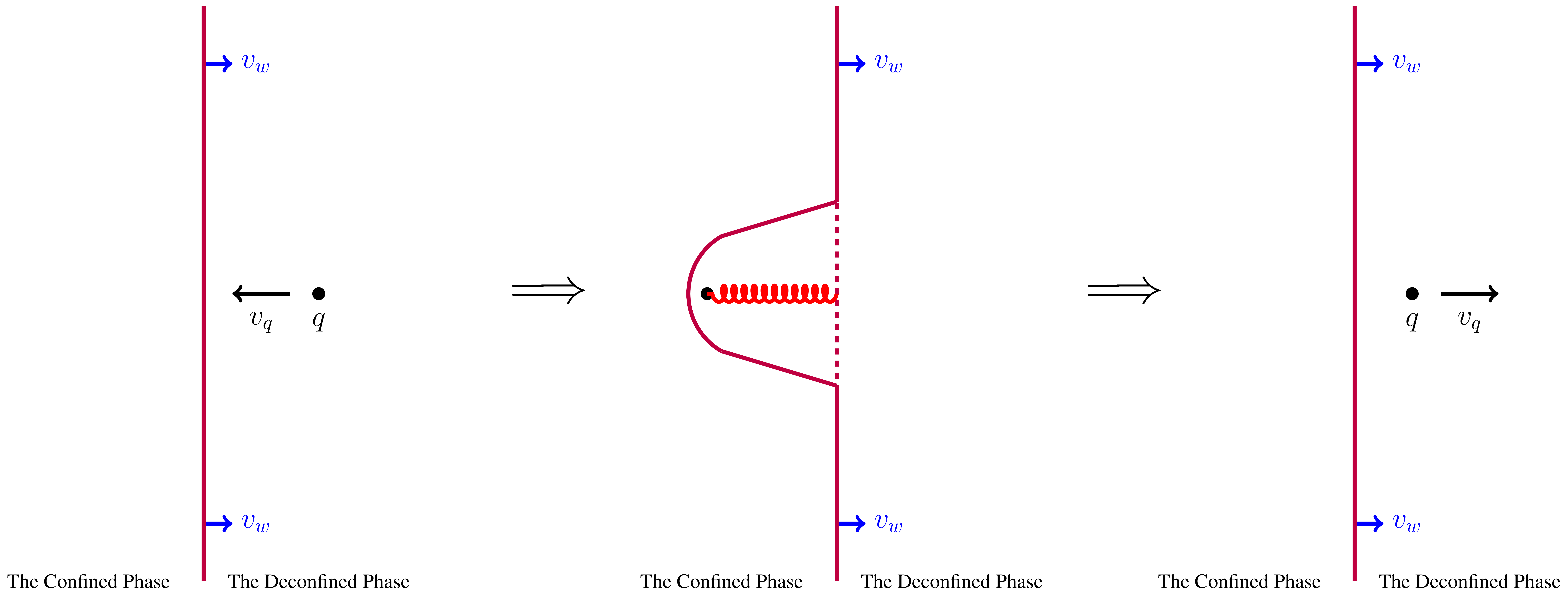
Dark Matter as a weakly coupled Dark Baryon
A. Mitridate et al. : 1707.05380

Second Thought: Details of 1. Oder PT

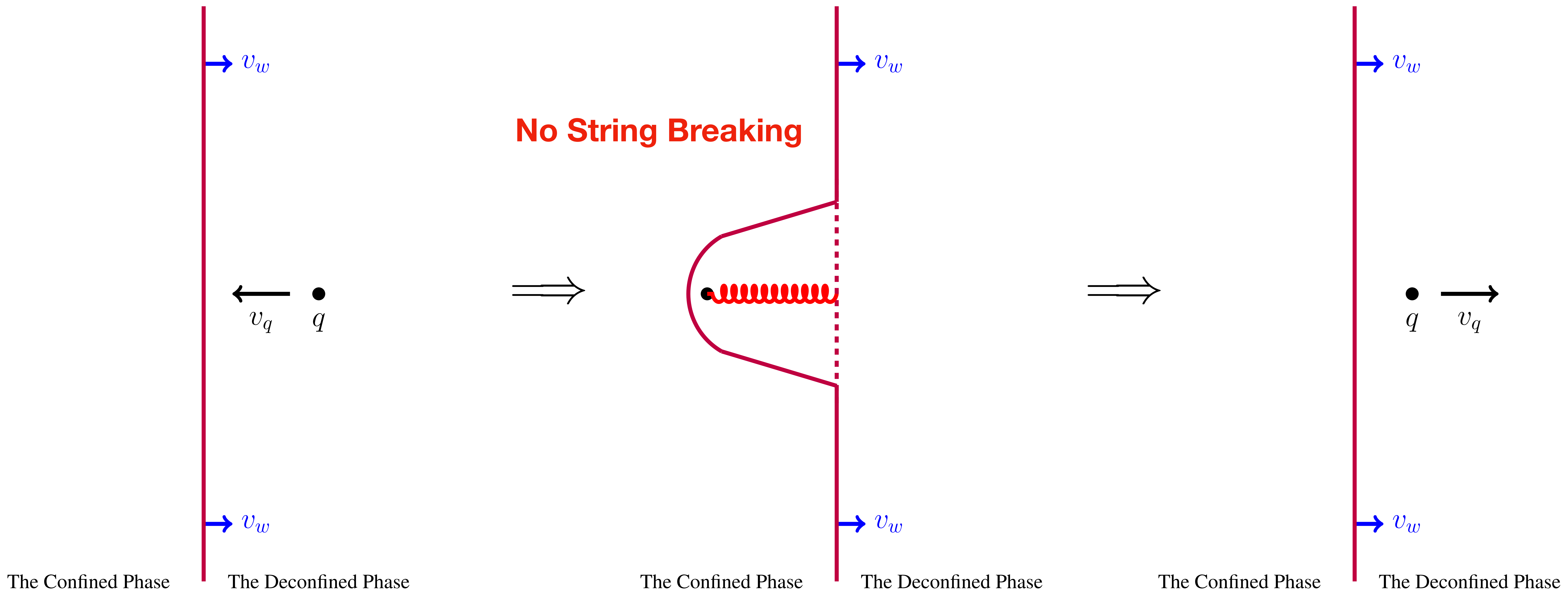




Compression by the Bubble Wall



Compression by the Bubble Wall



Dynamical Confinement

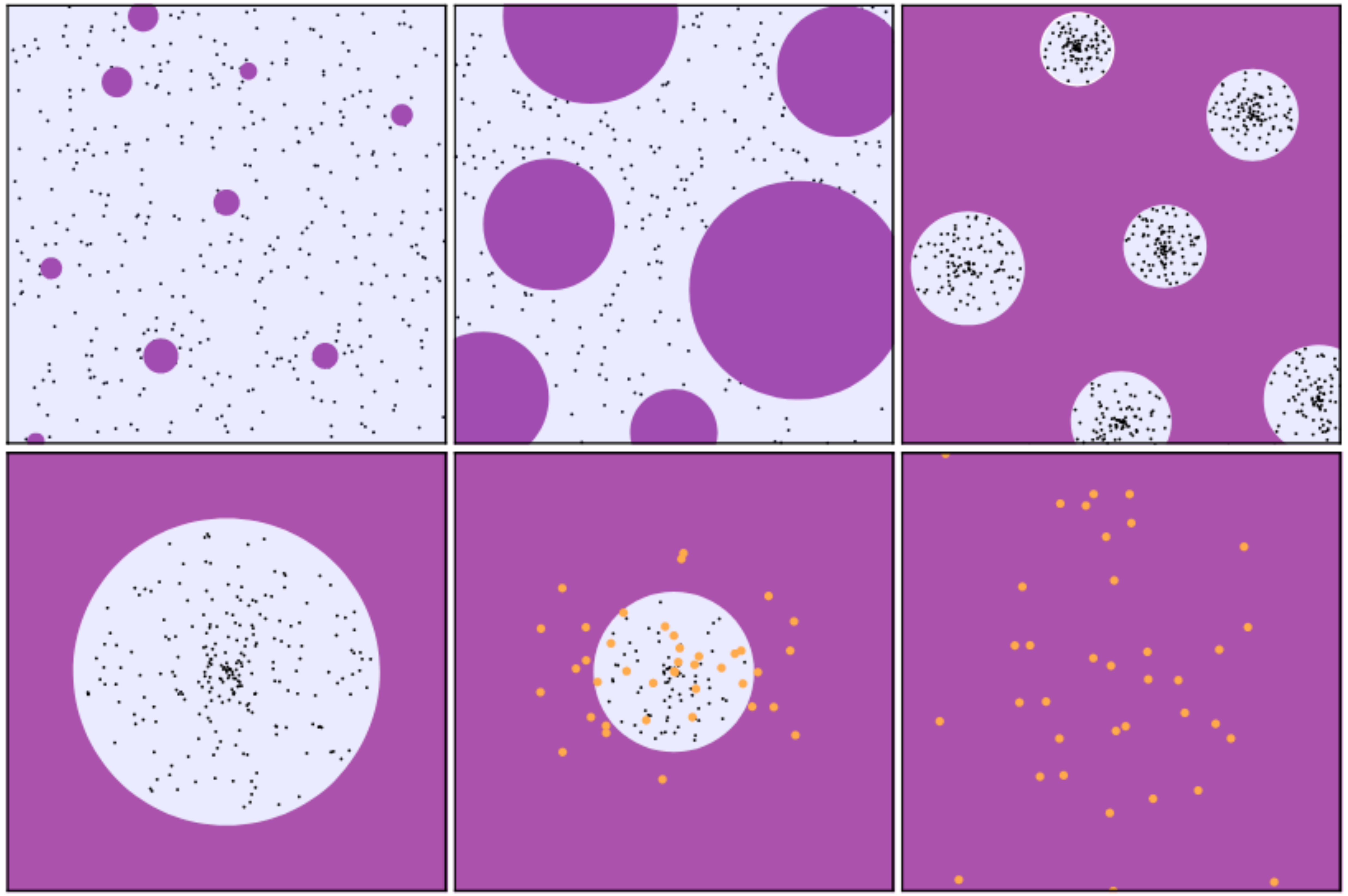
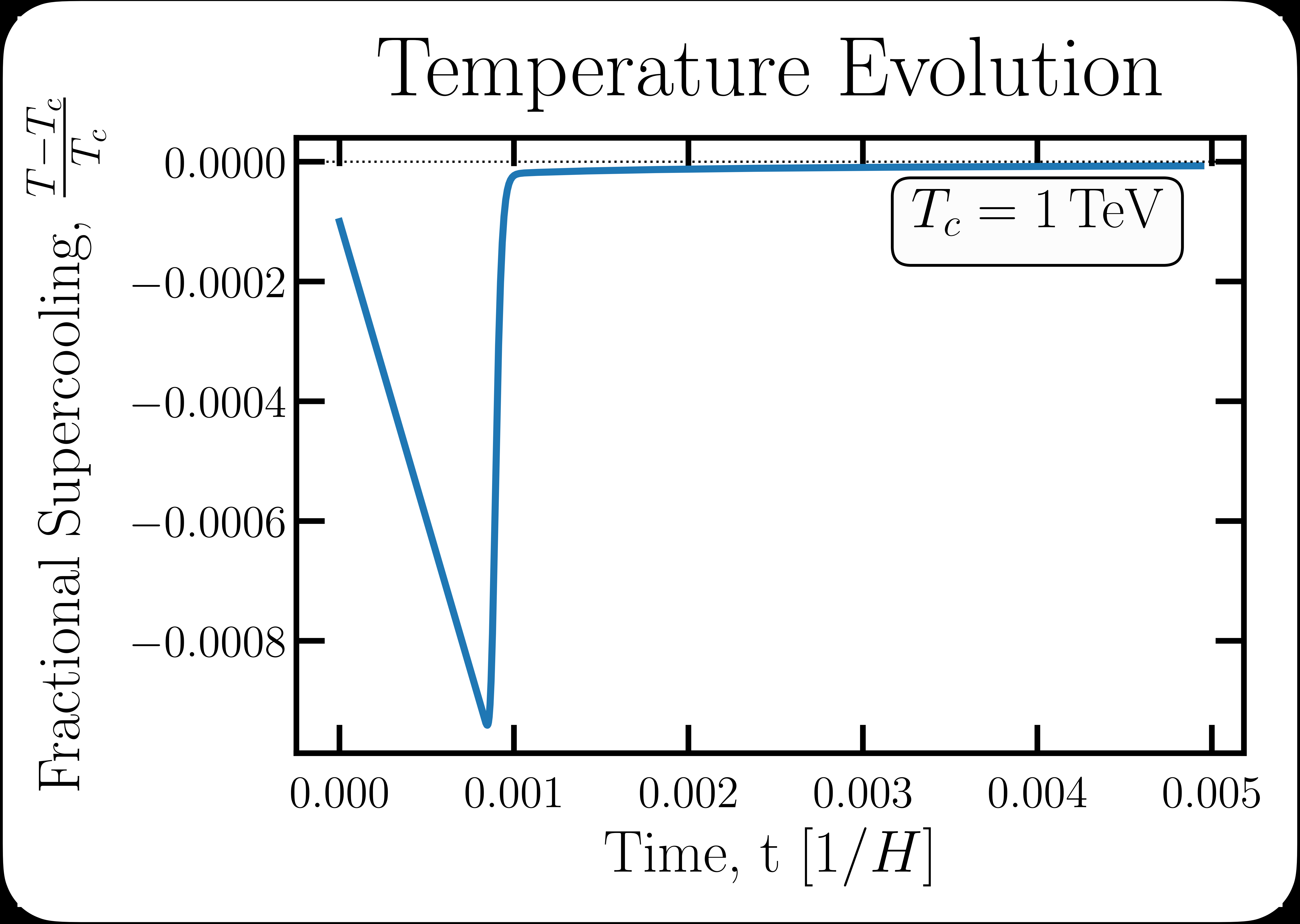


Figure: Pouya Asadi

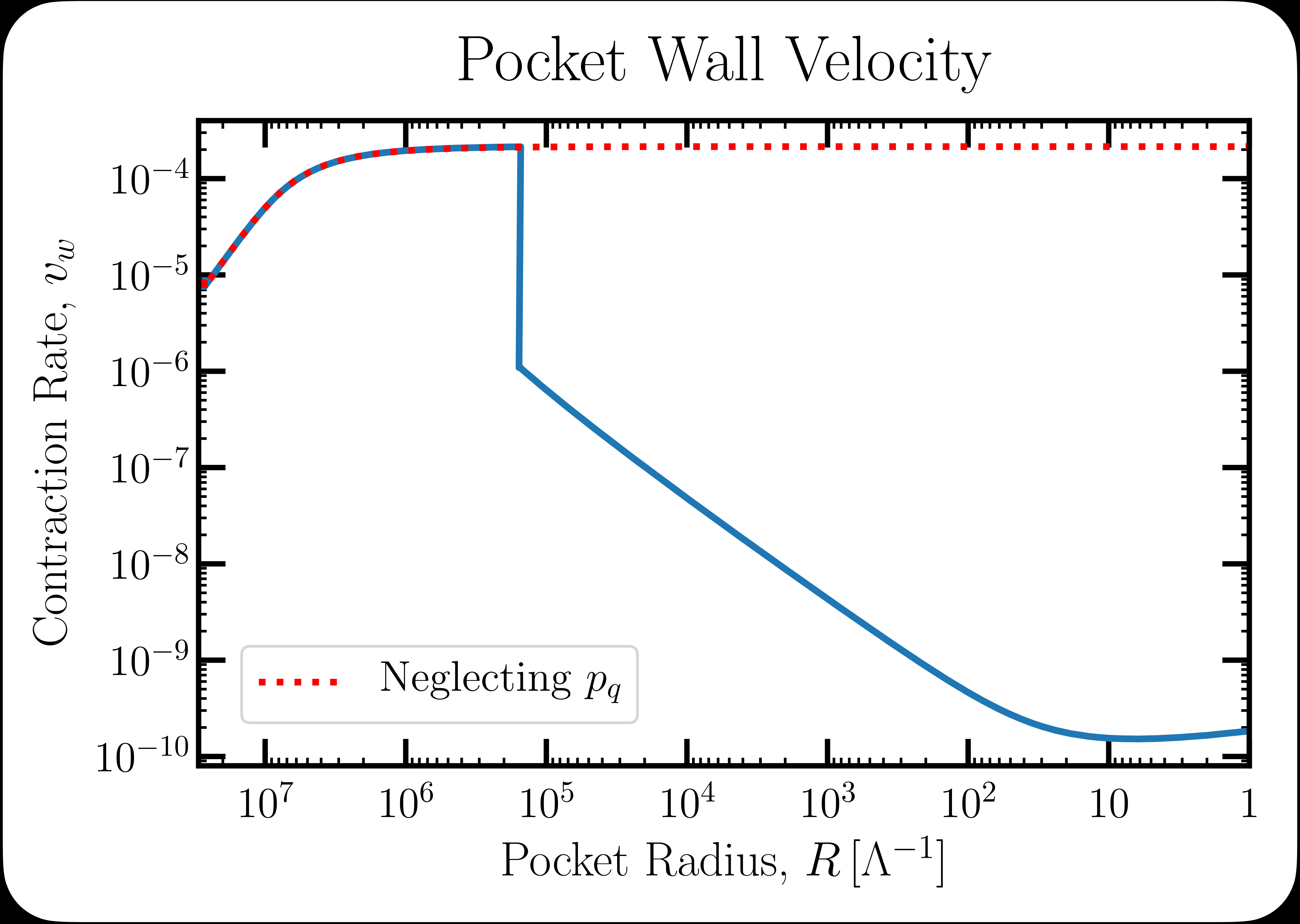
2103.09822: Pouya Asadi, Greg Ridgway (MIT), Eric D. Kraemer, Eric Kuflik (Hebrew University), Tracy Slatyer (MIT), **JS**

Dynamics of the Phase Transition I



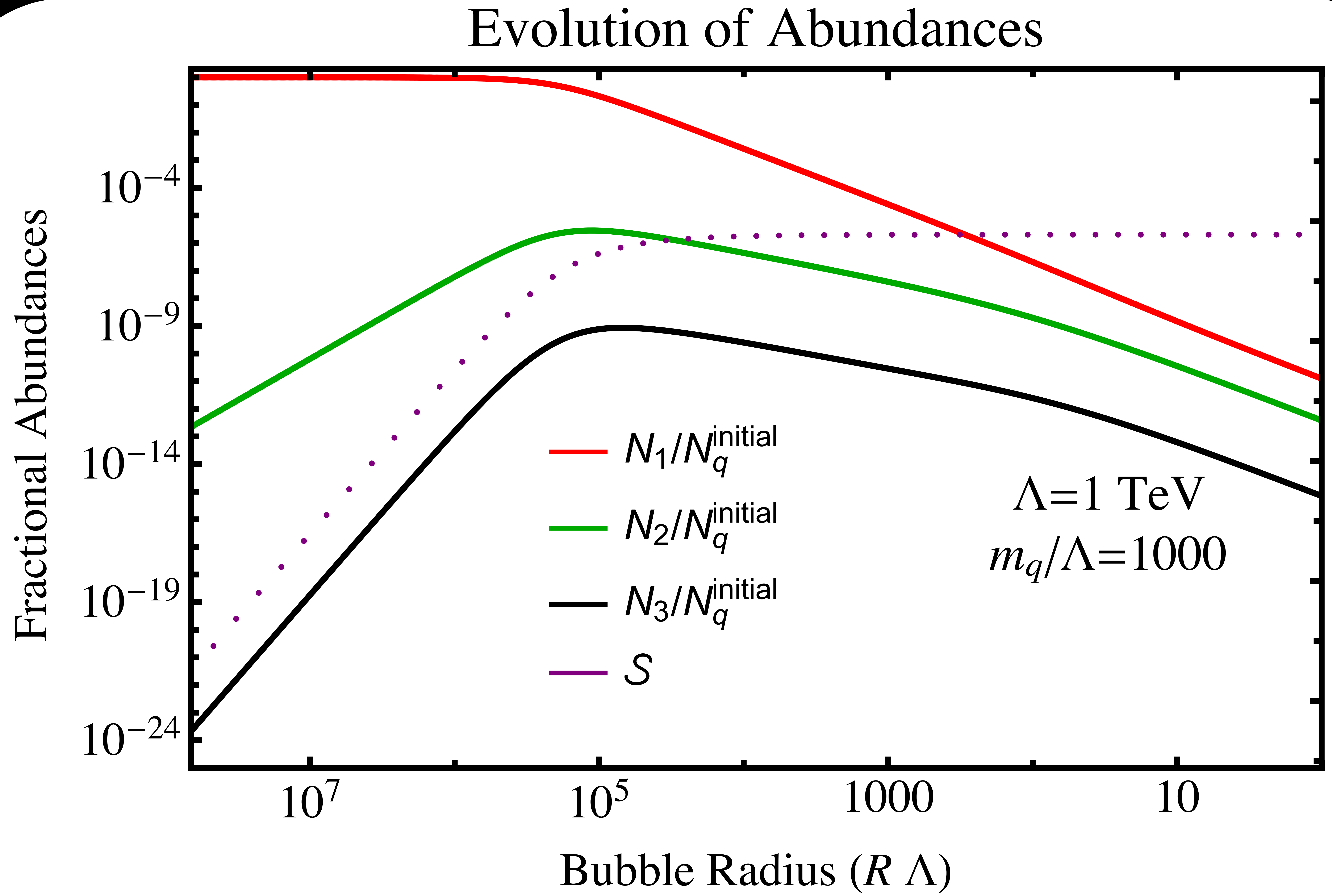
2103.09822

Dynamics of the Phase Transition II

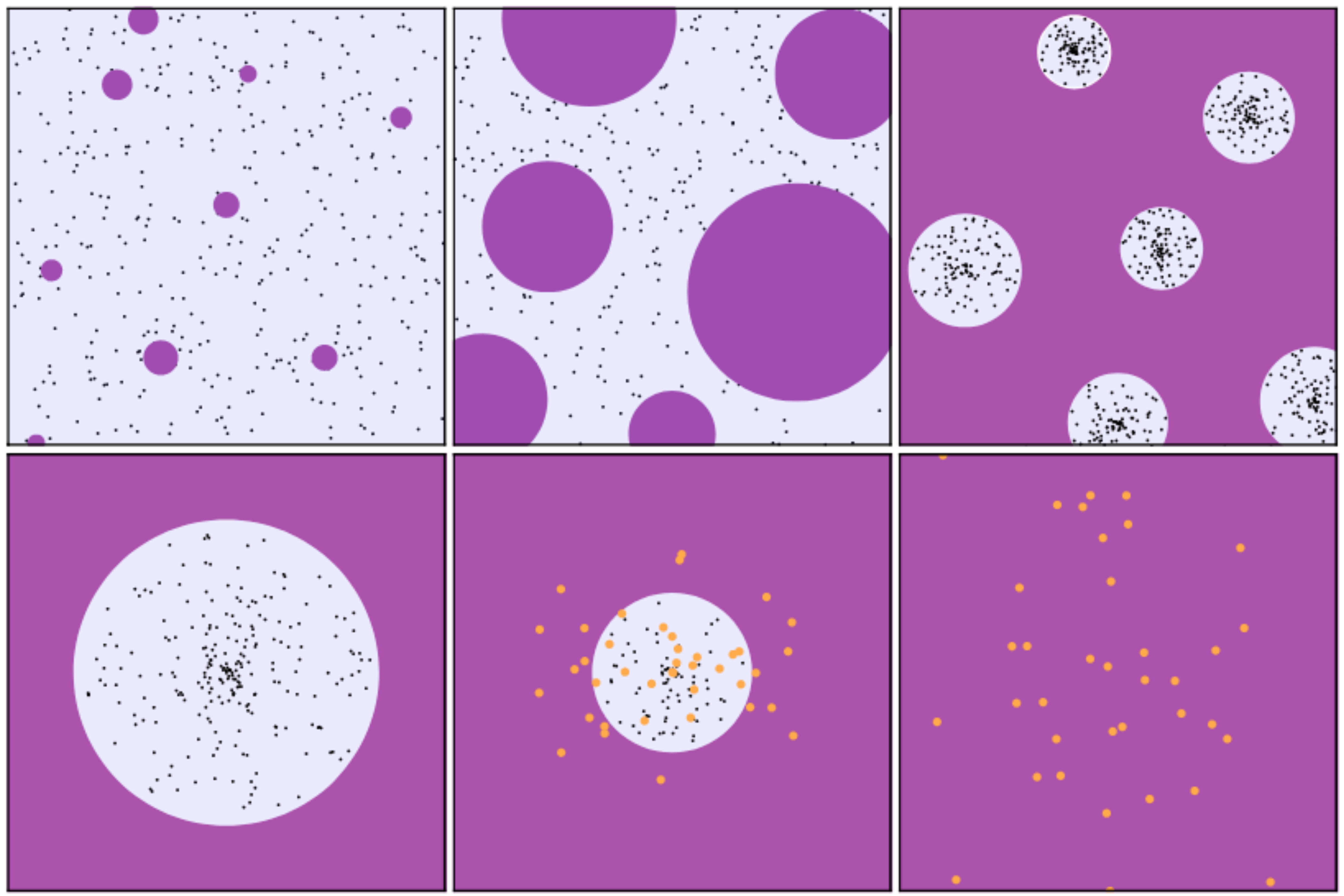


2103.09822

Local Boltzmann Evolution

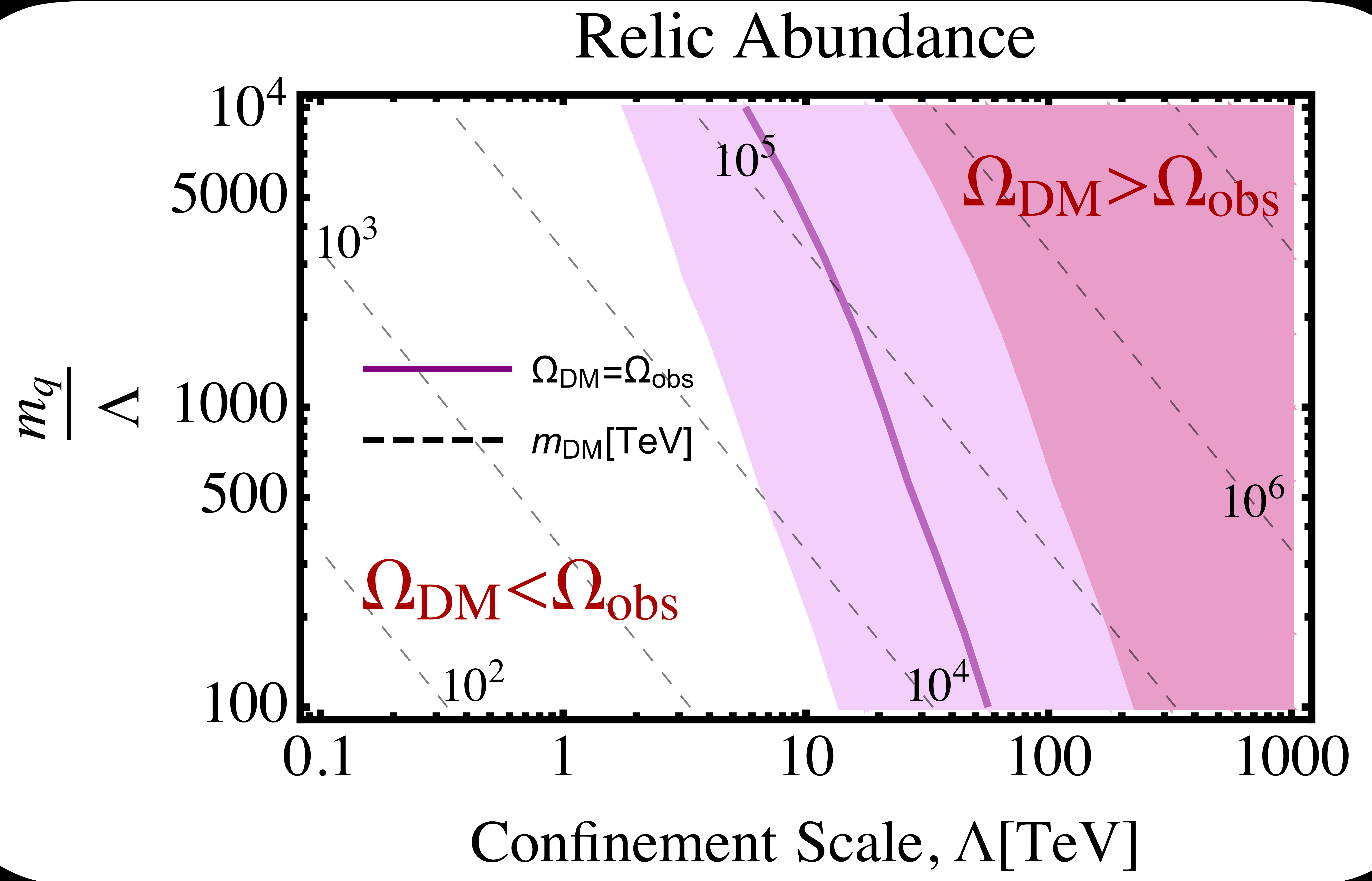


Minimal Abundance and Asymmetry



$$S_{\rm AS} = \frac{\sqrt{N_0}}{N_0} = \frac{1}{\sqrt{N_0}}$$

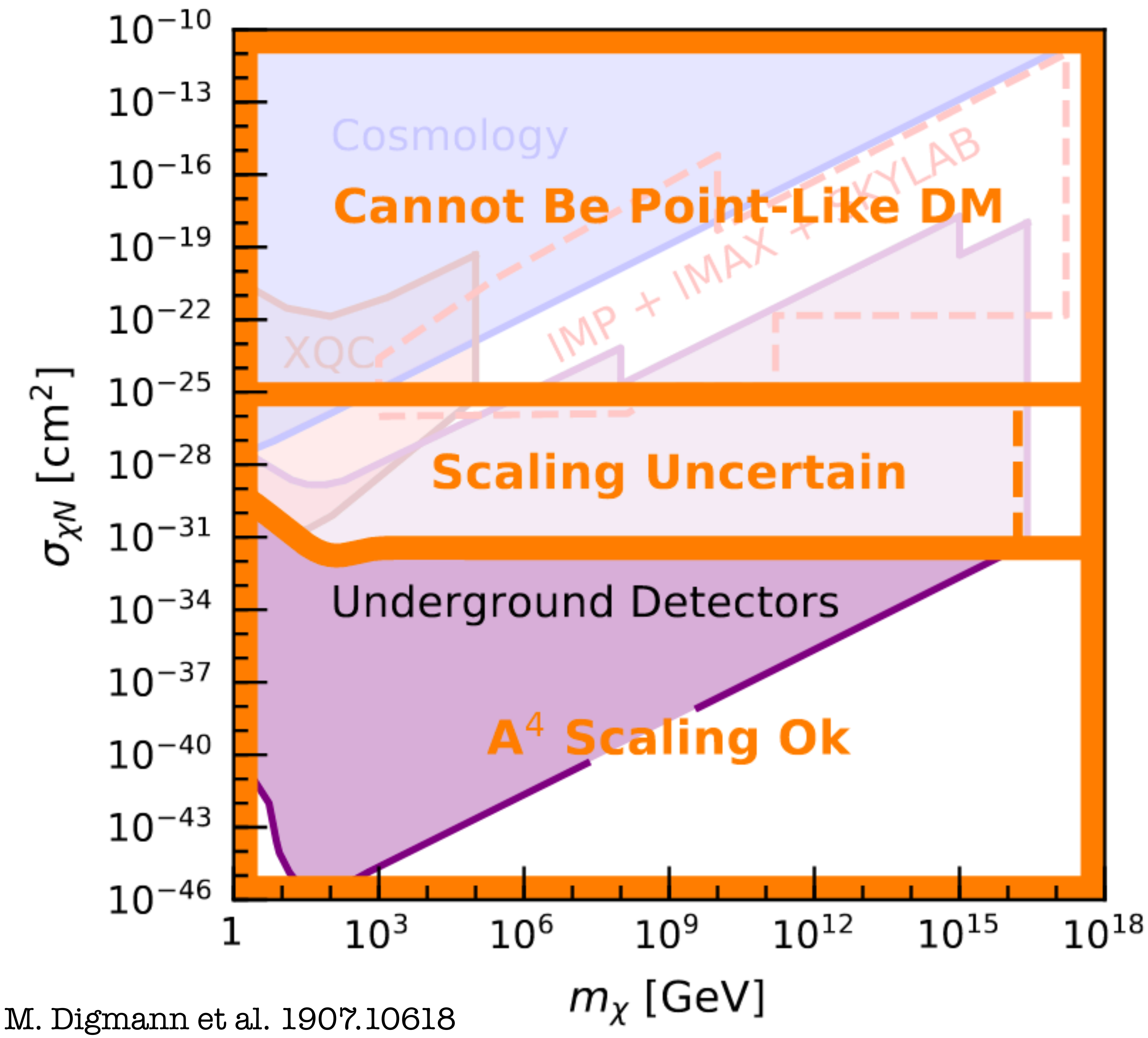
Result for Relic Abundance



2103.09822

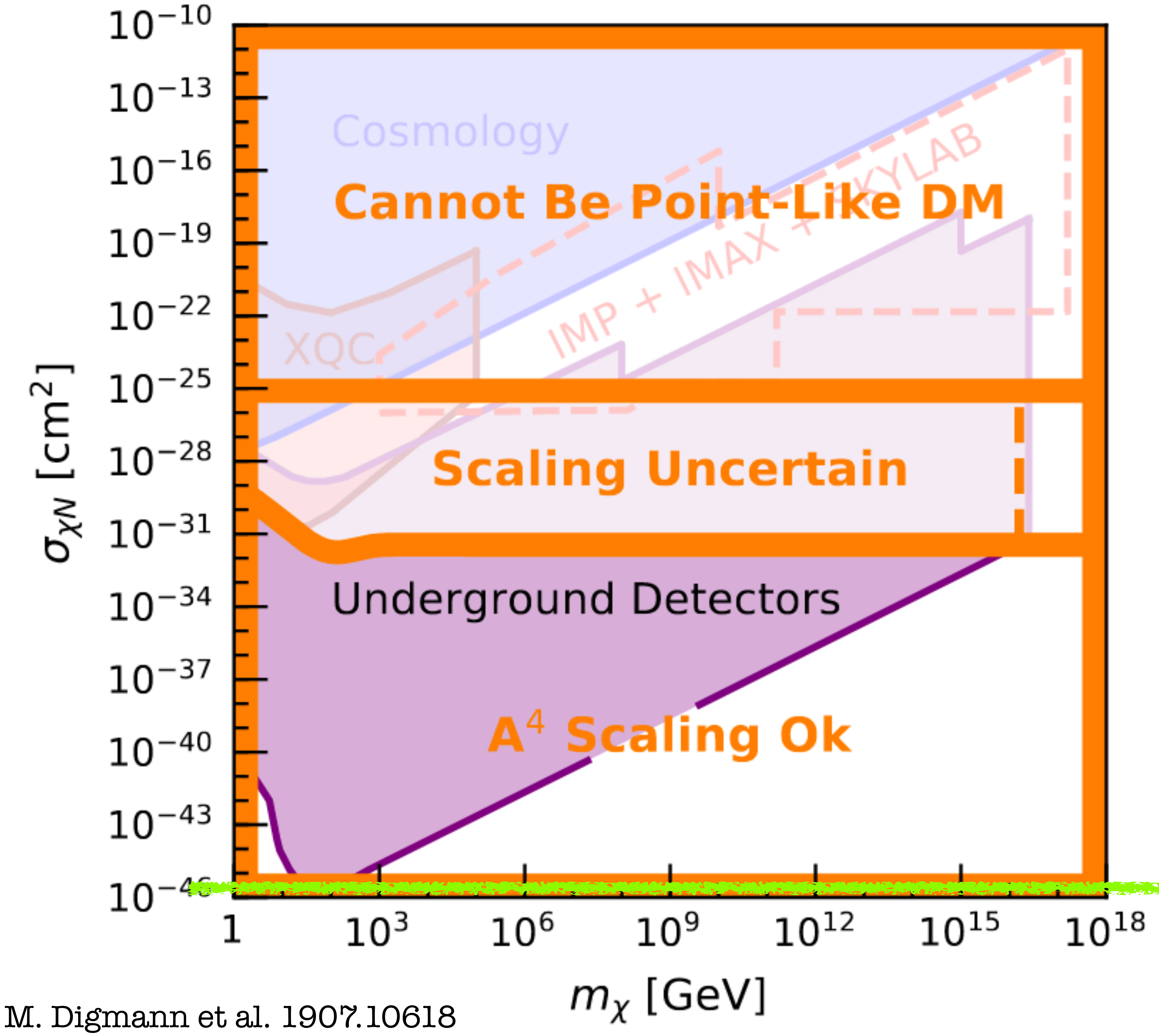
Weakly or Rarely?

Generic Feature: Residual Interactions



M. Digmann et al. 1907.10618

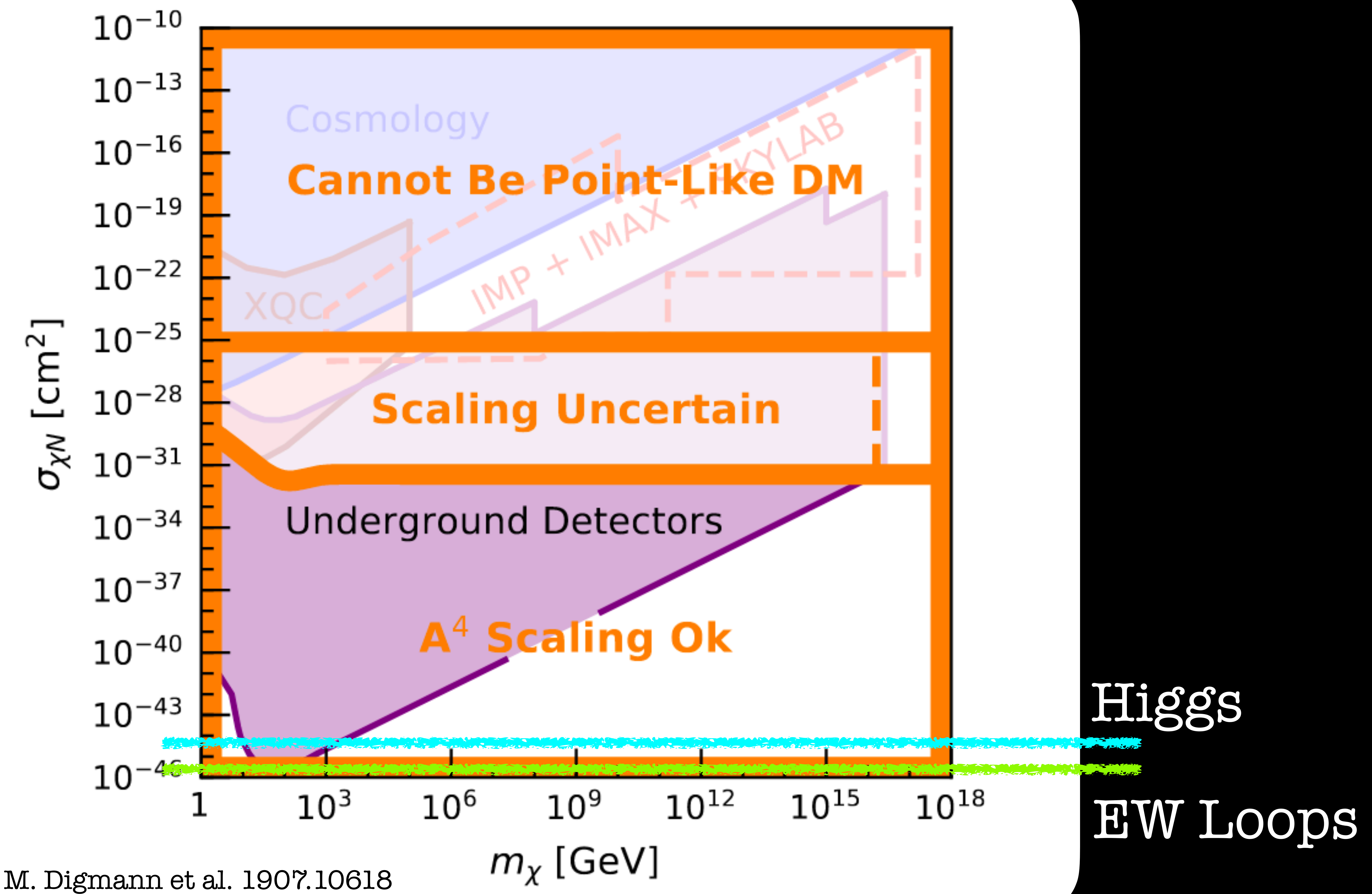
Generic Feature: Residual Interactions



M. Digmann et al. 1907.10618

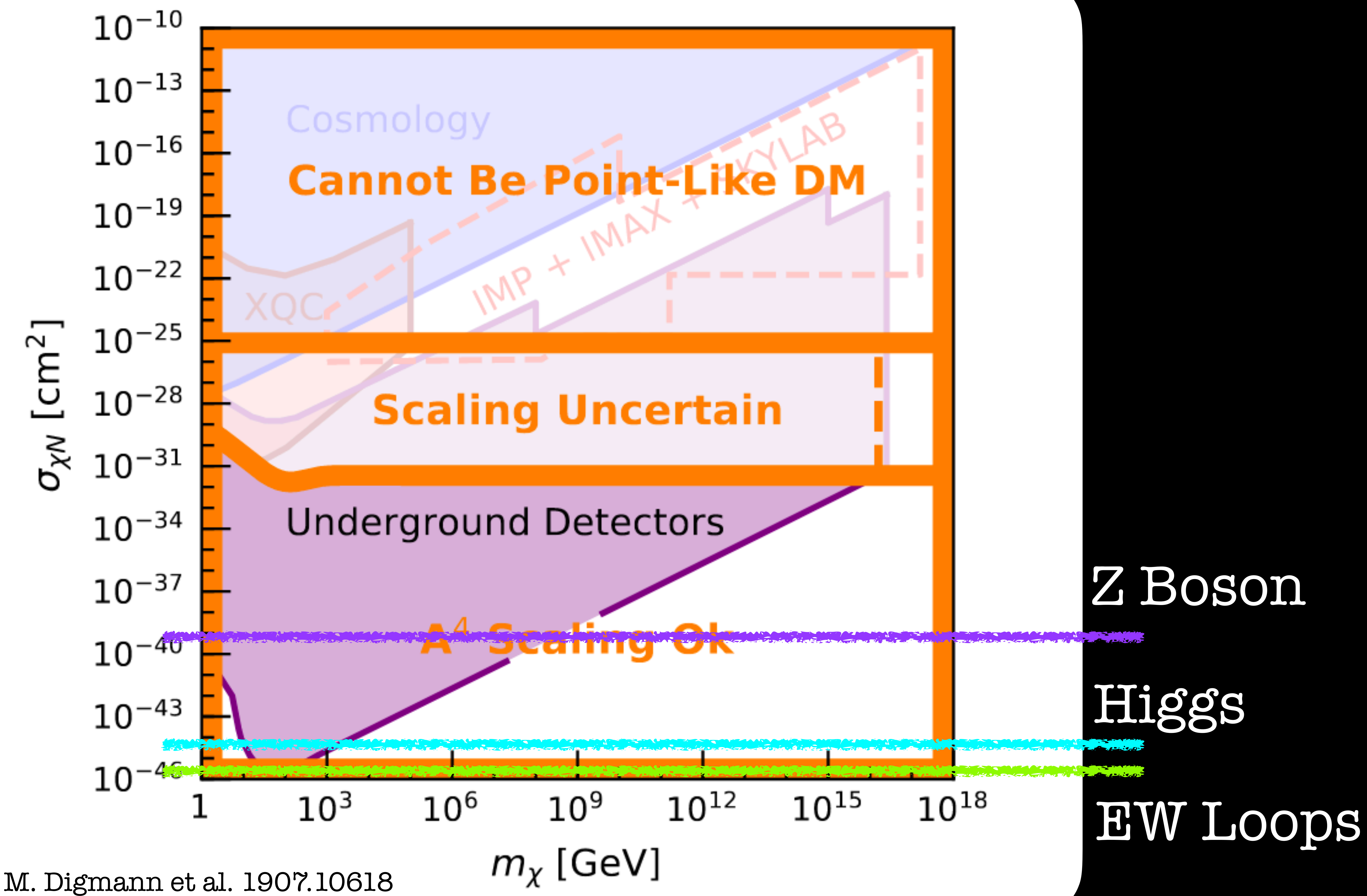
EW Loops

Generic Feature: Residual Interactions



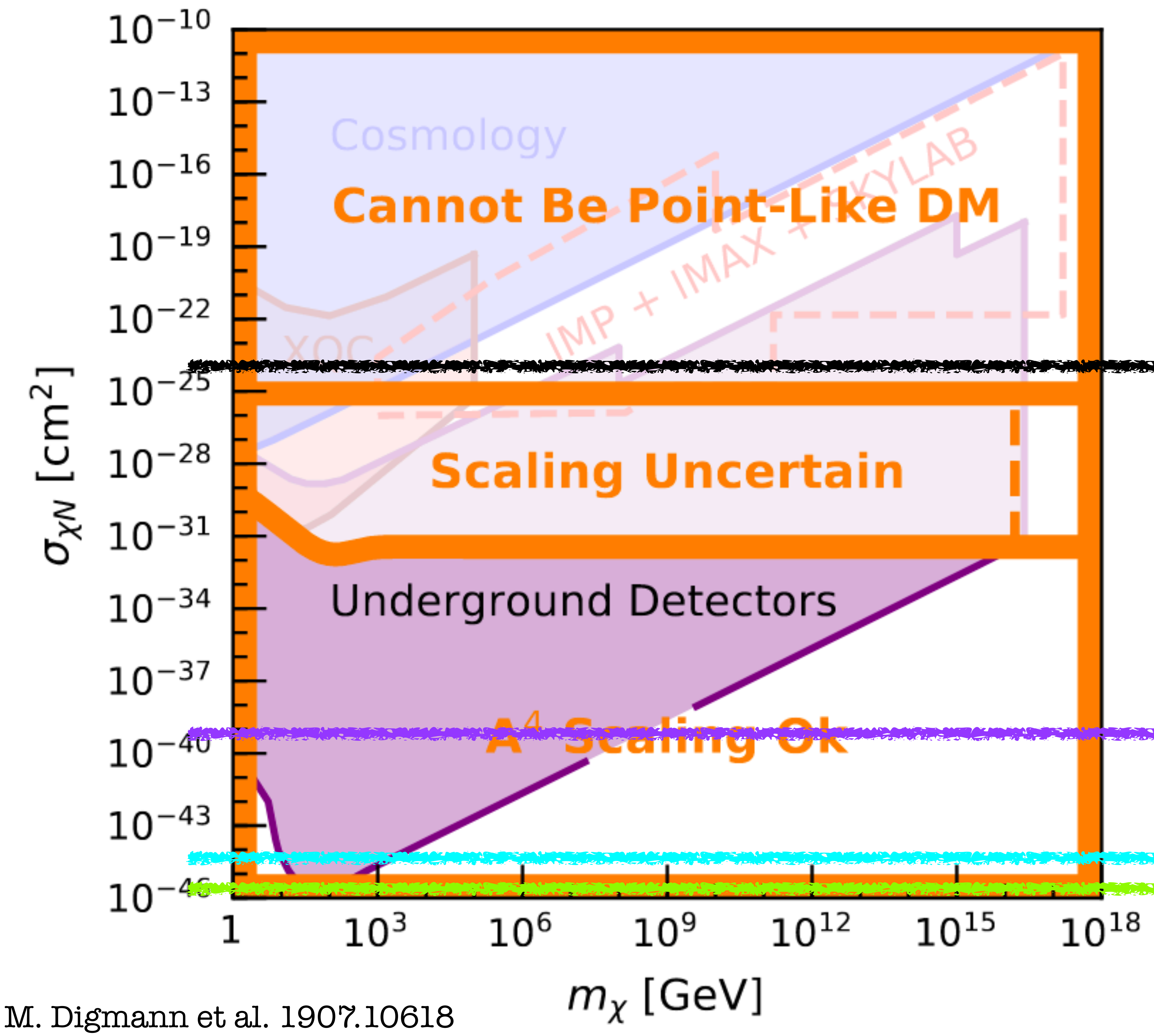
M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



Nuclear

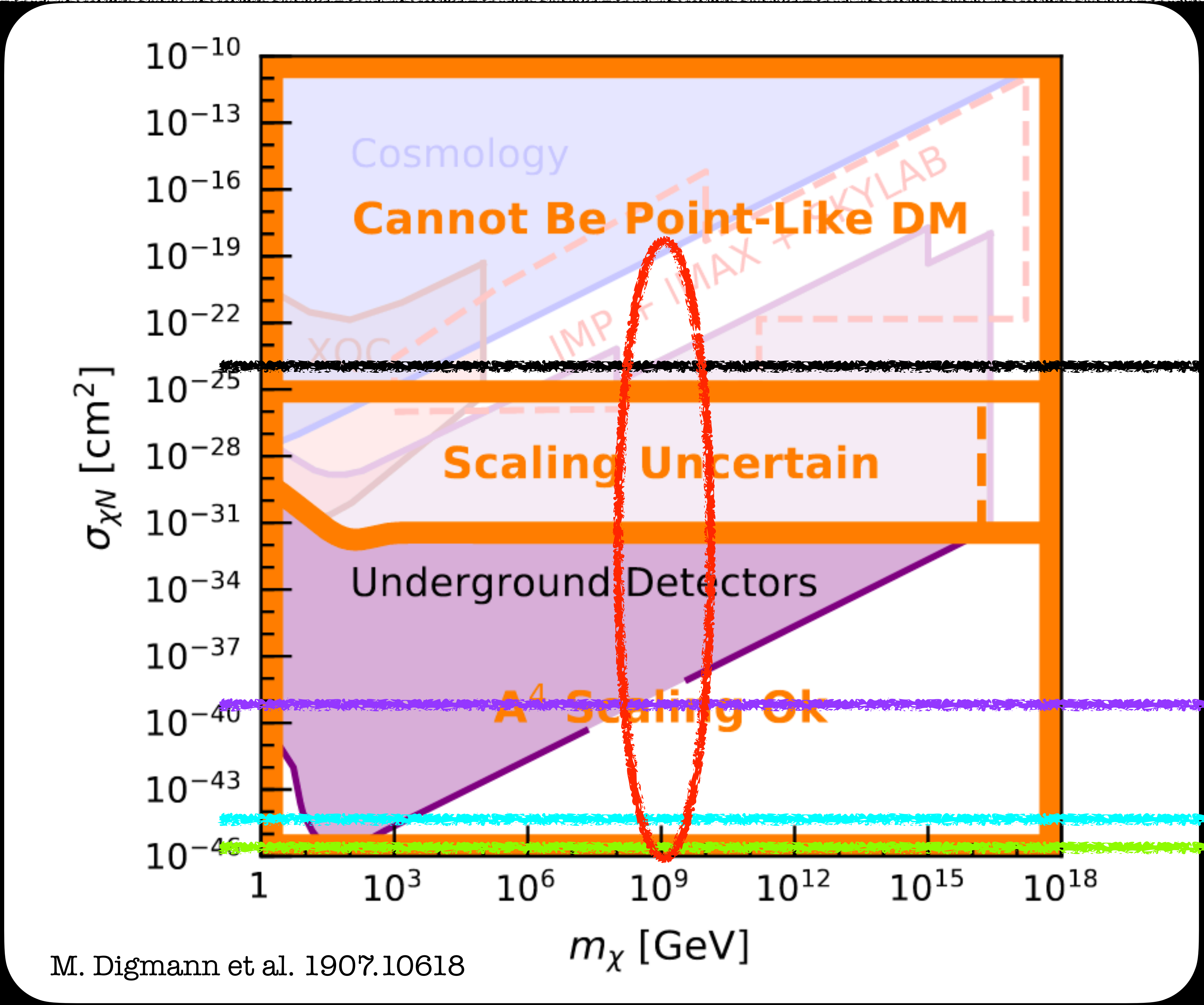
Z Boson

Higgs

EW Loops

M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



QCD Interactions: 1801.01135, 1811.08418

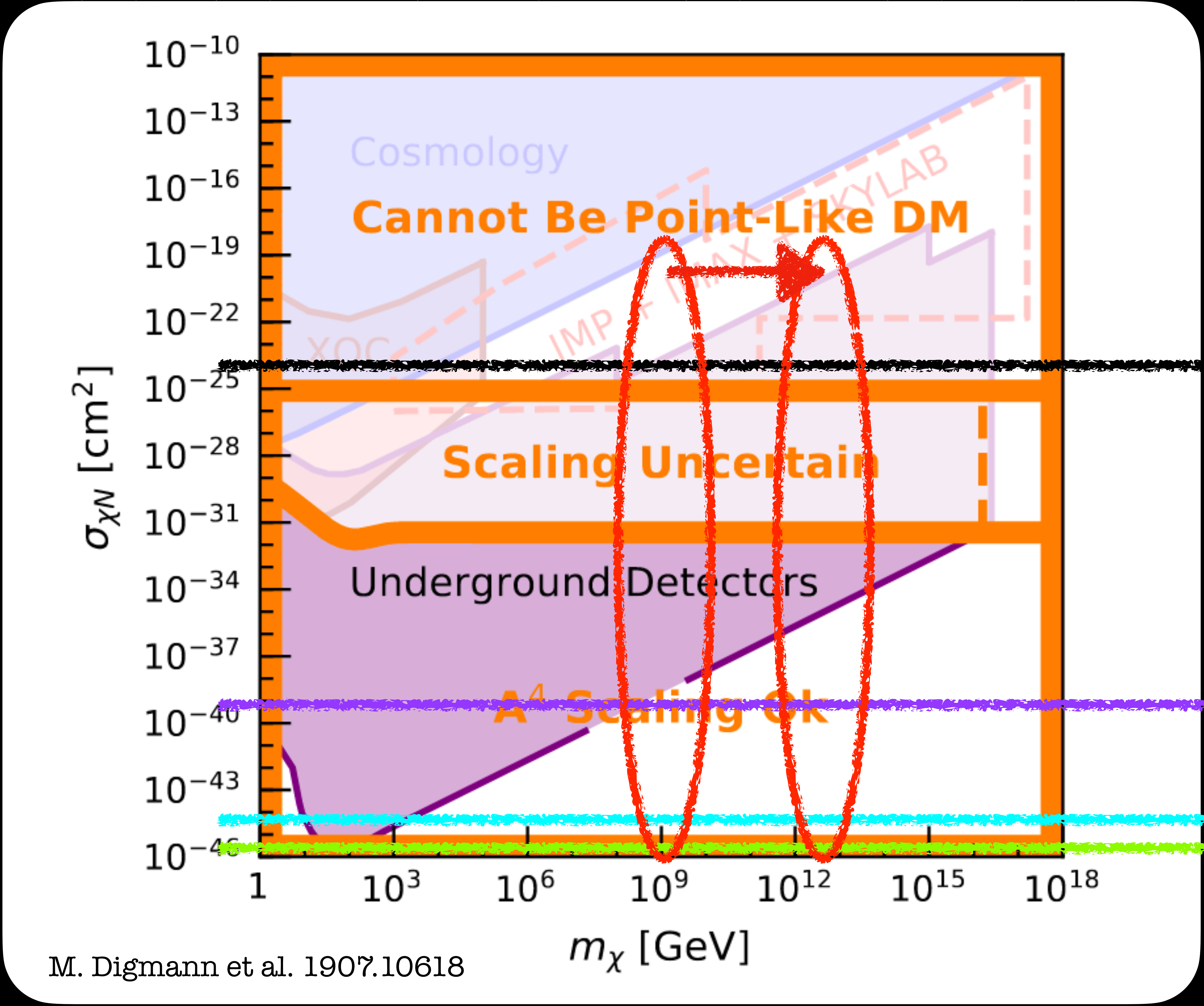
Nuclear

Z Boson

Higgs

EW Loops

Generic Feature: Residual Interactions



QCD Interactions:
1801.01135,
1811.08418

Nuclear

Dilution Effects:
2203.15813

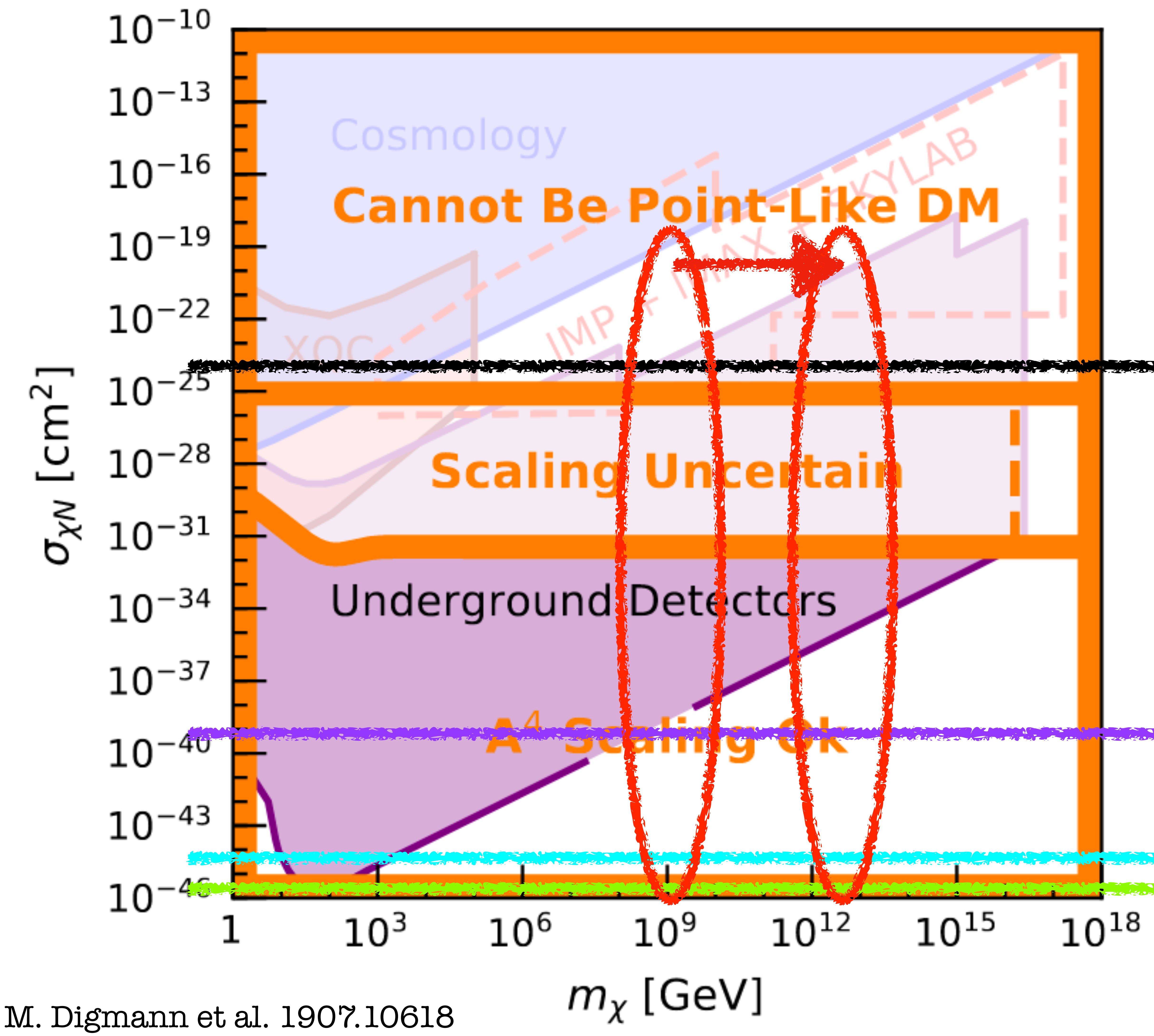
Z Boson

Higgs

EW Loops

Generic Feature: Residual Interactions

Tuesday: 15:50
Carlos Blanco
Mesoscale



M. Digmann et al. 1907.10618

QCD Interactions:
1801.01135,
1811.08418

Nuclear

Dilution Effects:
2203.15813

Z Boson

Higgs

EW Loops

New Search Directions

New Search Directions

New Search Directions

Coincidence Detection:

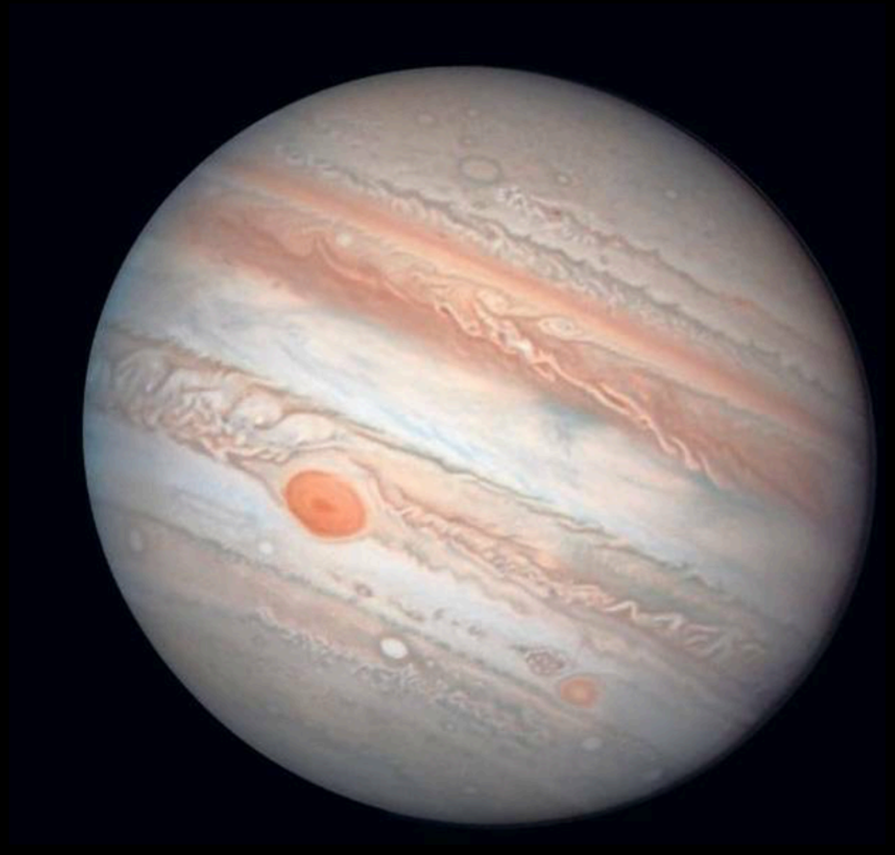
2008.10646,
2203.02309

New Search Directions

Coincidence Detection:

2008.10646,
2203.02309

DM heating Signals:



2010.00015

New Search Directions

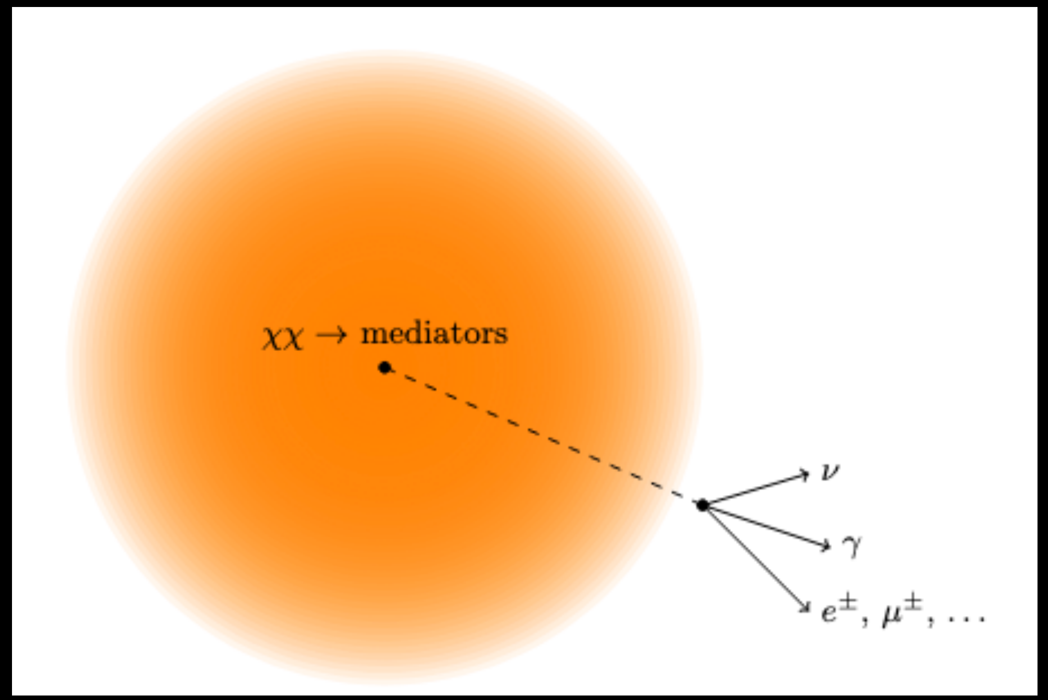
Coincidence Detection:

2008.10646,
2203.02309

DM heating Signals:

2010.00015

DM Long-Lived Mediators:



1808.05624

New Search Directions

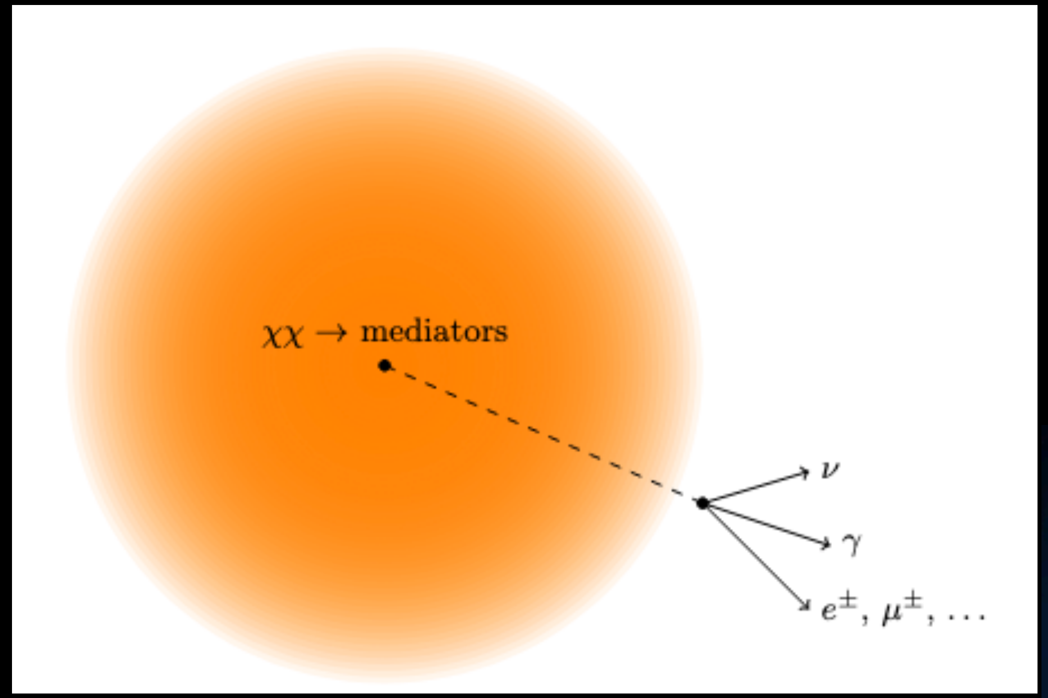
Coincidence Detection:

2008.10646,
2203.02309

DM heating Signals:

2010.00015

DM Long-Lived Mediators:



1808.05624

White Dwarf Ignition:

1805.07381
+ In preparation

Thanks!

QCD Example

Color-Charged Dark Matter Model

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

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

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

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

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

Color-Charged Dark Matter Model

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

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

Qqq $\quad e = 4/3$ or $e = -2/3$ or $e = -1/3$

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

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

Color-Charged Dark Matter Model

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

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

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

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

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

Color-Charged Dark Matter Model

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

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

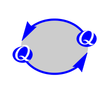
Qqq $\quad e = 4/3$ or $e = -2/3$ or $e = -1/3$

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

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

Idea: Chromocatalysis

The Q^2

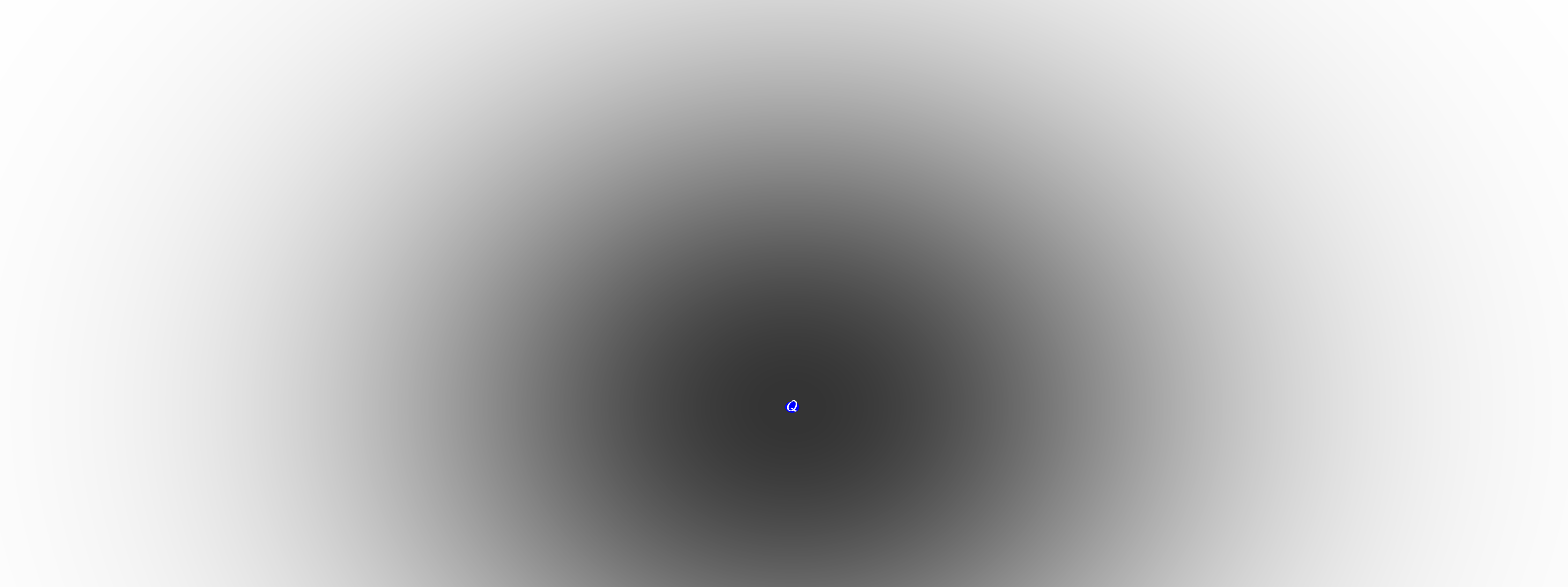


$$\text{Size} \approx \frac{1}{\alpha_3\, M_Q}$$

Binding Eenergy $\approx \alpha_3^2 M_Q$

DM candidate

Hybrids Q g



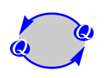
$$\text{Size} \approx \frac{1}{\Lambda_{\text{QCD}}}$$

Binding Energy $\approx \Lambda_{\text{QCD}}$

Dangerous

Idea: Chromocatalysis

The Q^2



$$\text{Size} \approx \frac{1}{\alpha_3 \, M_Q}$$

Binding Eenergy $\approx \alpha_3^2$

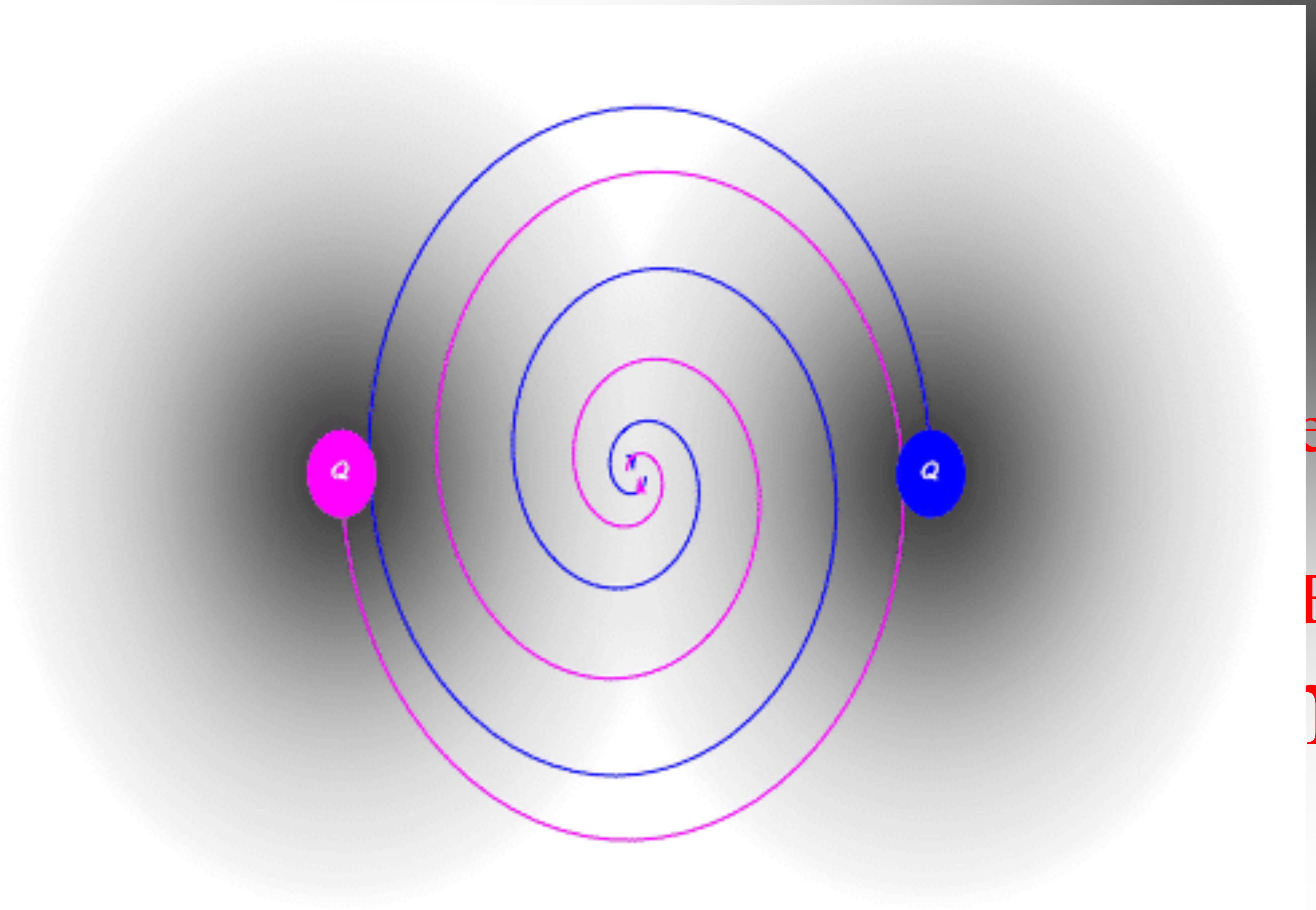
DM candida

Hybrids Q g

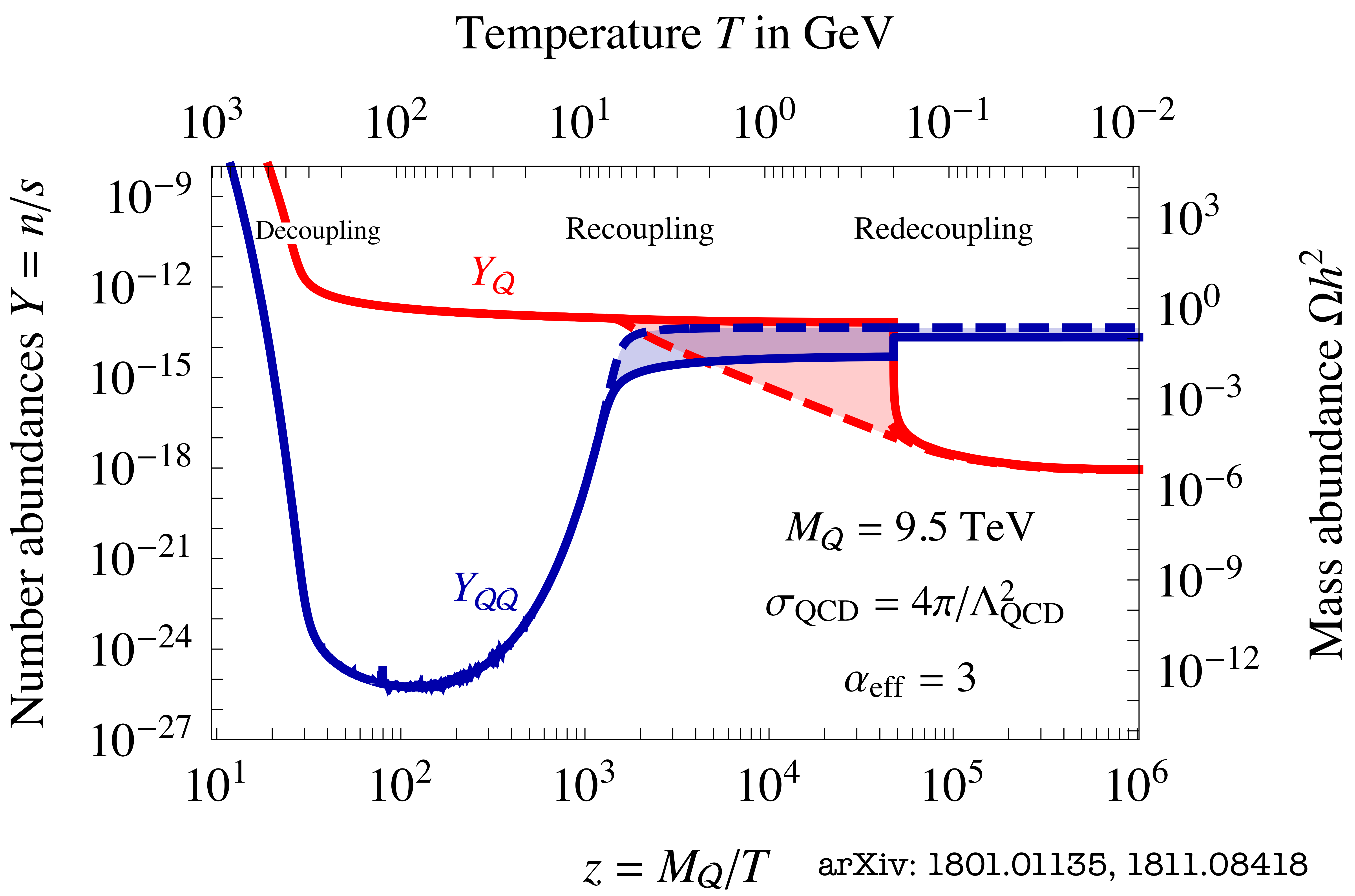
$$\text{e} \approx \frac{1}{\Lambda_{\text{QCD}}}$$

Energy $\approx \Lambda_{\text{QCD}}$

ngerous

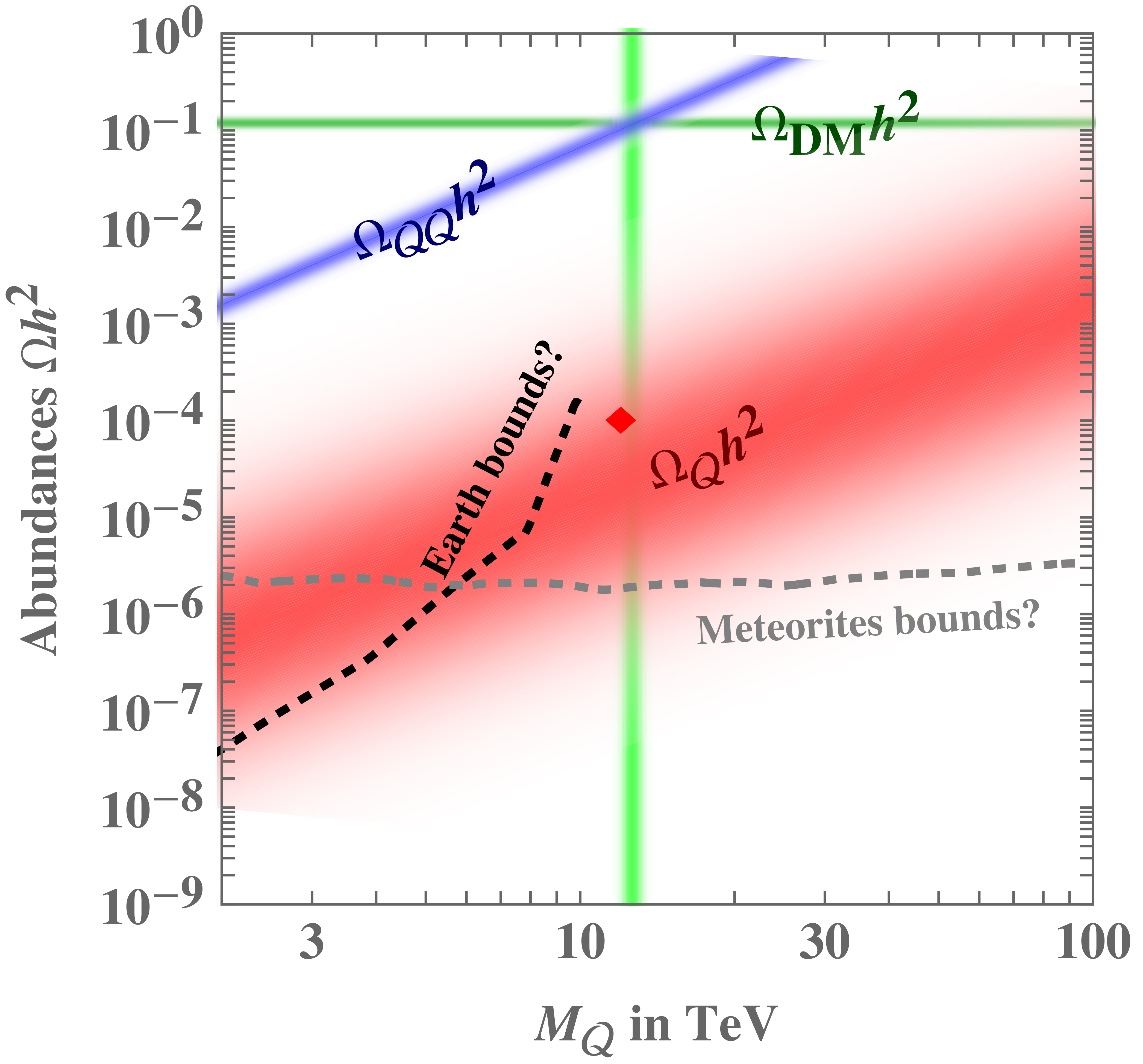


Chromo-catalysis in Cosmology



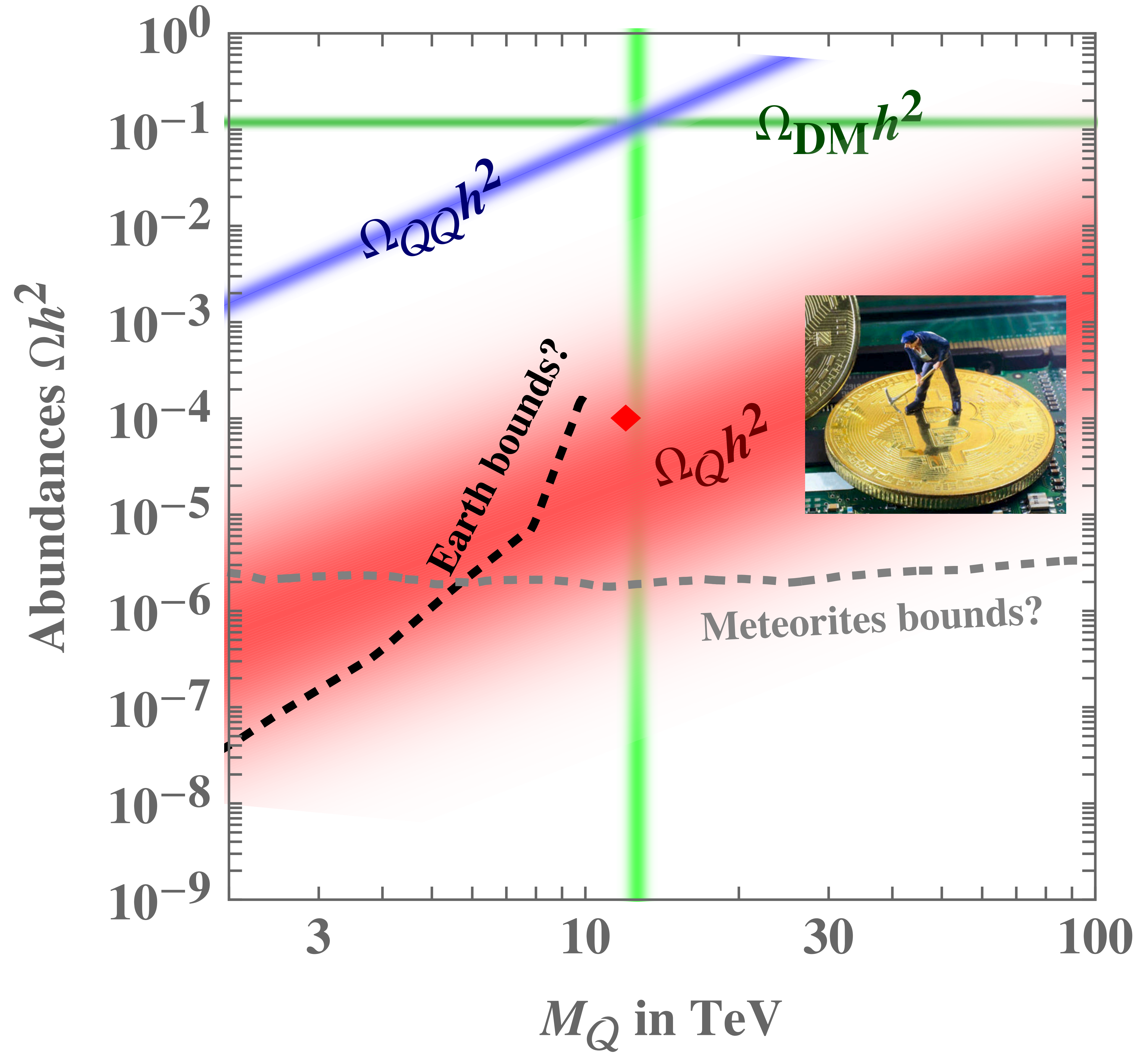
arXiv: 1801.01135, 1811.08418

Abundances Today



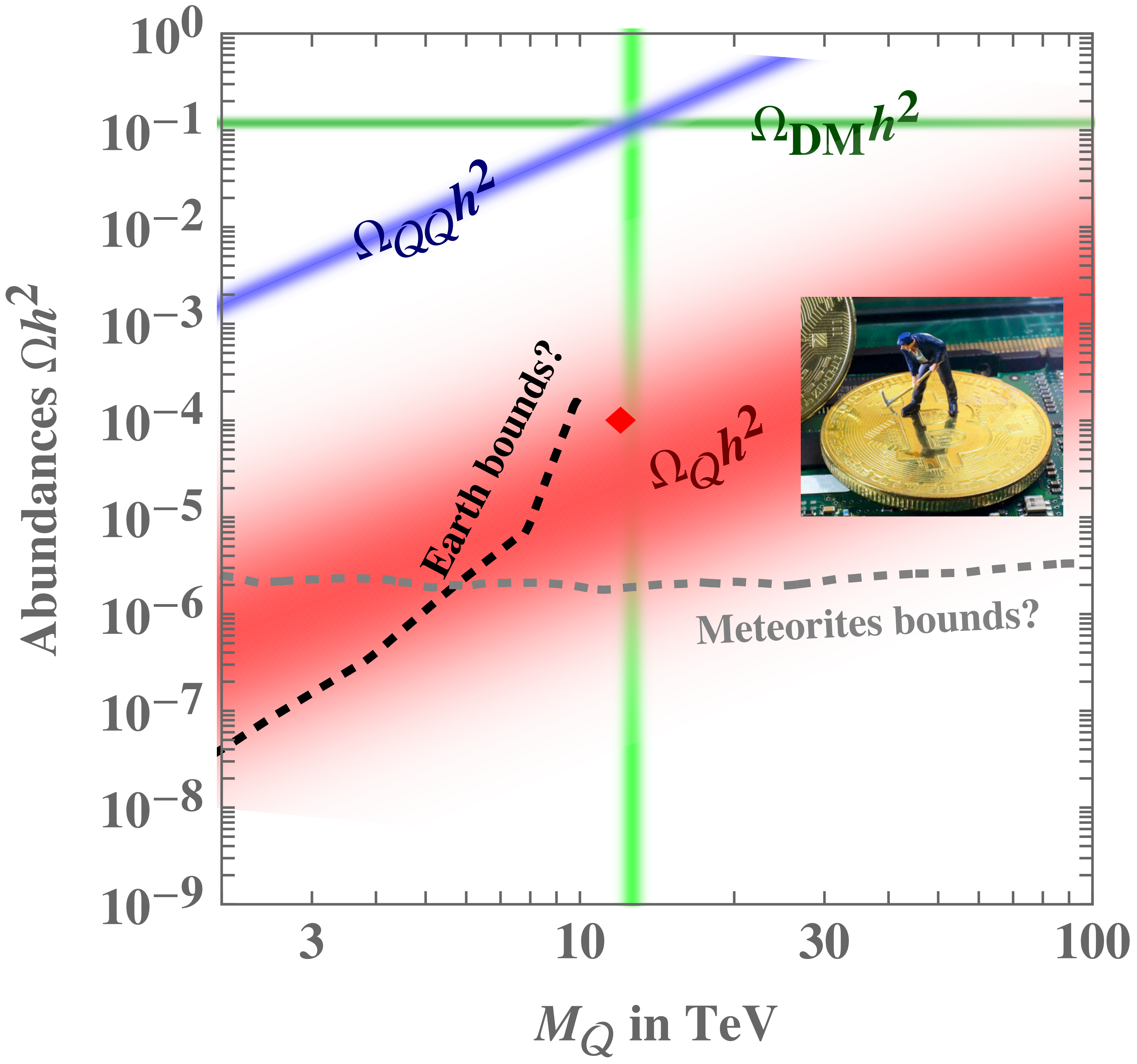
1801.01135, 1811.08418

Abundances Today



1801.01135, 1811.08418

Abundances Today



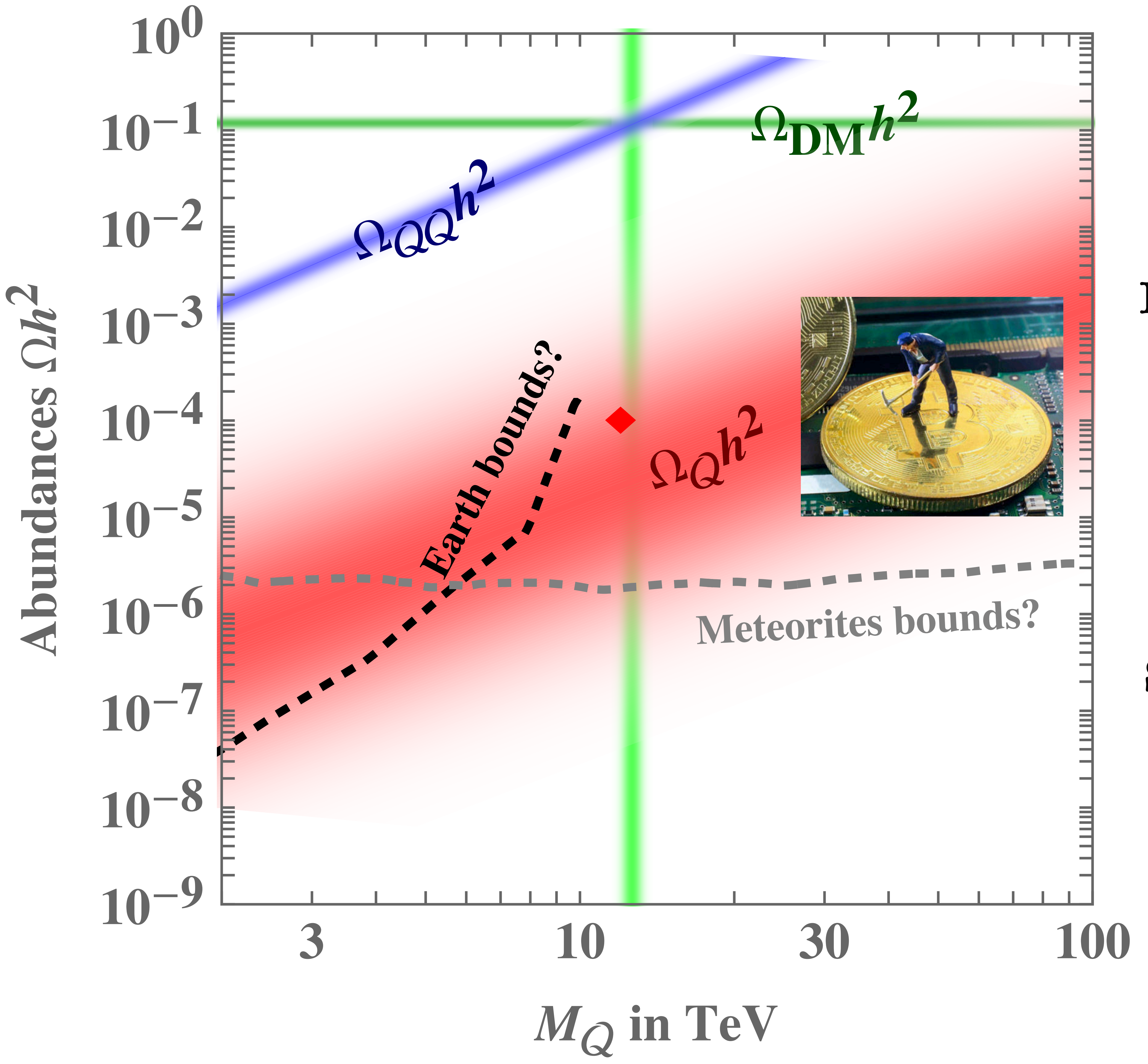
Mo: 09:00
Maxim
Pospelov

Poster:
Palio-
detectors
Sebastian
Baum

1801.01135, 1811.08418

Abundances Today

Open Question:
Nuclear Binding
of Isospin = 0 ?



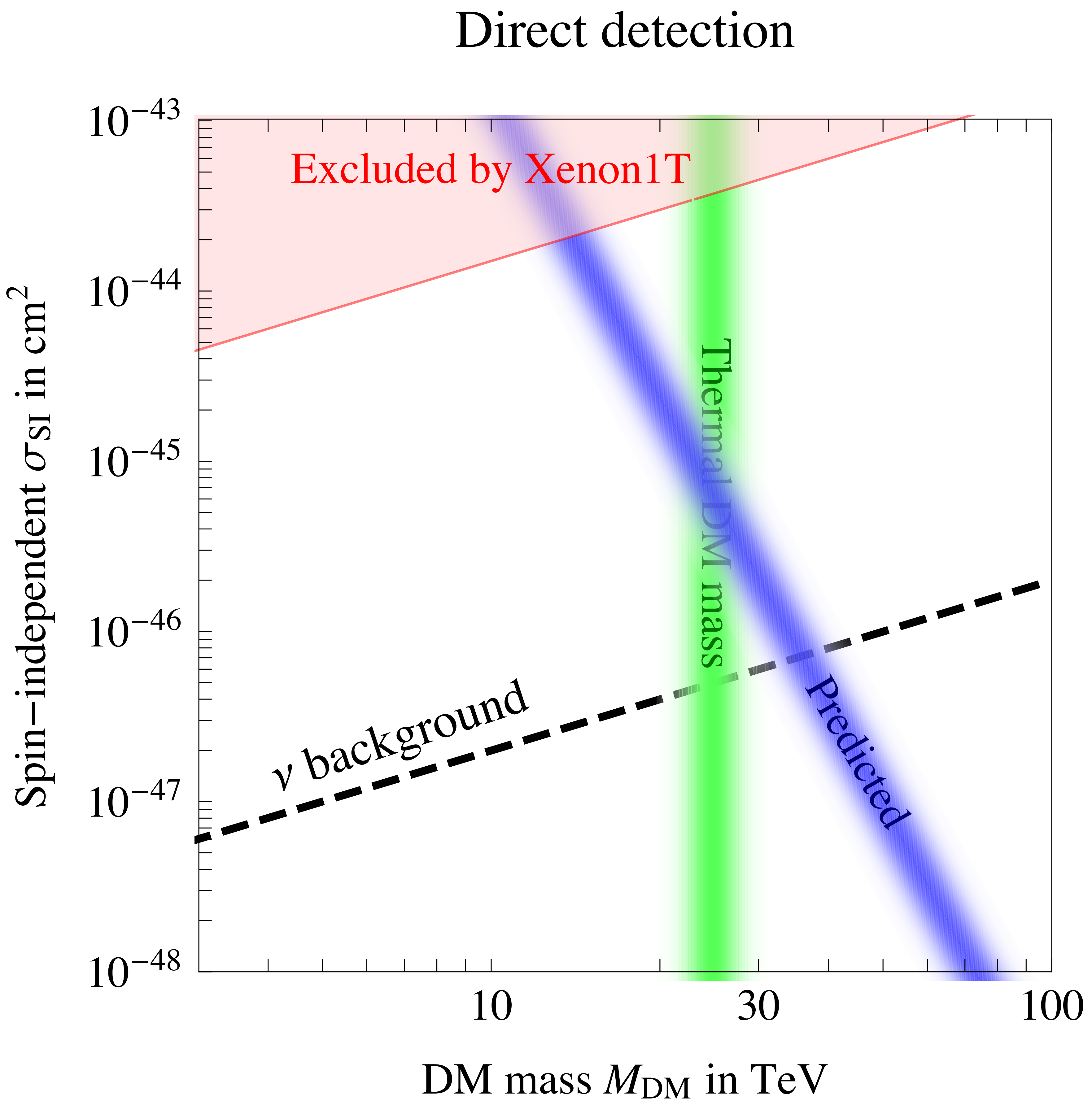
Mo: 09:00
Maxim
Pospelov

Poster:
Palio-
detectors
Sebastian
Baum

1801.01135, 1811.08418

Direct Dectection & Chromopolarizability

Direct Dectection & Chromopolarizability



arXiv: 1801.01135

$$\mathcal{L}_{\rm eff} = C_S^g \mathcal{O}_S^g + C_{T_2}^g \mathcal{O}_{T_2}^g = M_{\rm DM}\bar{B}B[c_E \vec{E}^{a2} + c_B \vec{B}^{a2}]$$

$$C_{T_2}^g(M_Z) = -M_{\rm DM} c_E, \qquad C_S^g(M_Z) = \frac{C_{T_2}^g(M_Z)}{4}\frac{\pi}{\alpha_3}$$

$$\frac{f_N}{m_N} = -12 C_S^g(M_Z) f_g - \frac{3}{4} C_{T_2}^g(M_Z) g(2, M_Z)$$

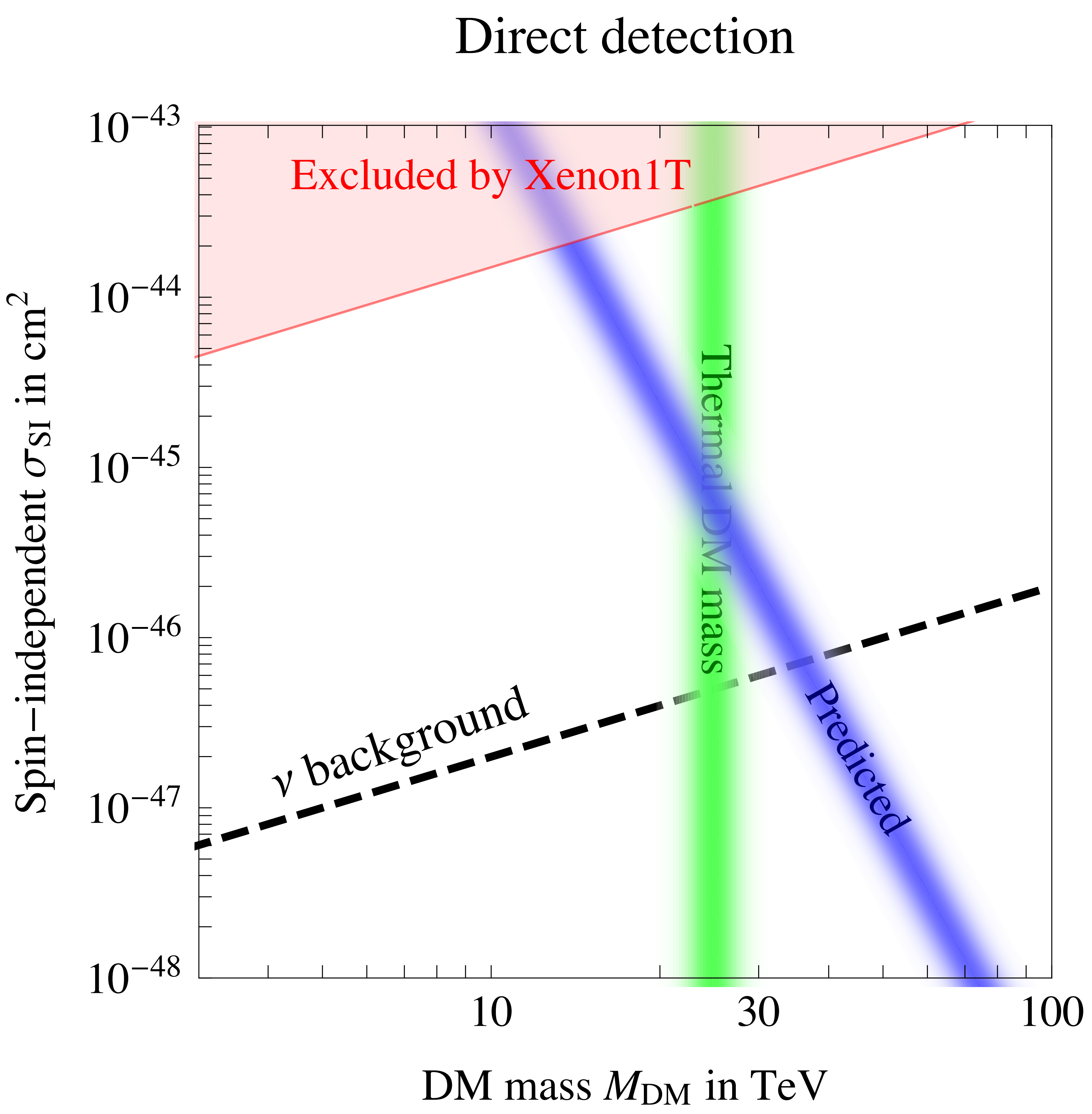
$$\sigma_{\rm SI} = \frac{f_N^2}{4\pi}\frac{m_N^2}{M_{\rm DM}^2}$$

$$\approx 2.3\ 10^{-45}\,{\rm cm}^2 \times \left(\frac{20TeV}{M_{\rm DM}}\right)^6 \left(\frac{0.1}{\alpha_3}\right)^8 \left(\frac{c_E}{1.5\pi a^3}\right)^2 .$$

$$c_E = \frac{8\pi\alpha_3}{3}\frac{C}{N_c^2 - 1}\langle B|\vec{r}\frac{1}{H_8 - E_{10}}\vec{r}|B\rangle$$

$$c_E|_{\rm DM} = (0.36 + 1.17)\pi a^3$$

Direct Dectection & Chromopolarizability



arXiv: 1801.01135

$$\mathcal{L}_{\rm eff} = C_S^g \mathcal{O}_S^g + C_{T_2}^g \mathcal{O}_{T_2}^g = M_{\rm DM} \bar{B} B [c_E \vec{E}^{a2} + c_B \vec{B}^{a2}]$$

$$C_{T_2}^g(M_Z) = -M_{\rm DM} c_E, \qquad C_S^g(M_Z) = \frac{C_{T_2}^g(M_Z)}{4} \frac{\pi}{\alpha_3}$$

$$\frac{f_N}{m_N} = -12 C_S^g(M_Z) f_g - \frac{3}{4} C_{T_2}^g(M_Z) g(2, M_Z)$$

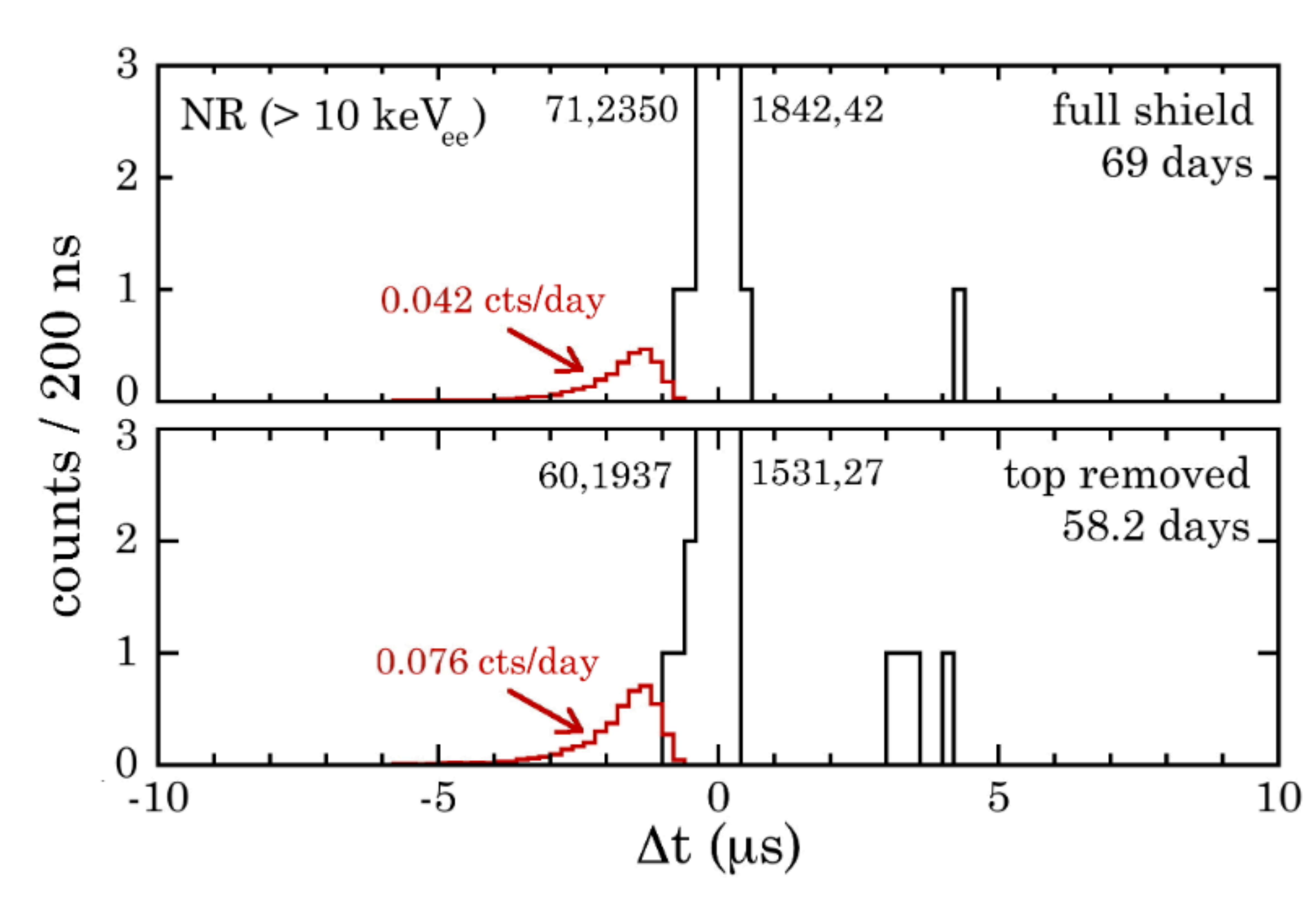
$$\sigma_{\rm SI} = \frac{f_N^2}{4\pi} \frac{m_N^2}{M_{\rm DM}^2}$$

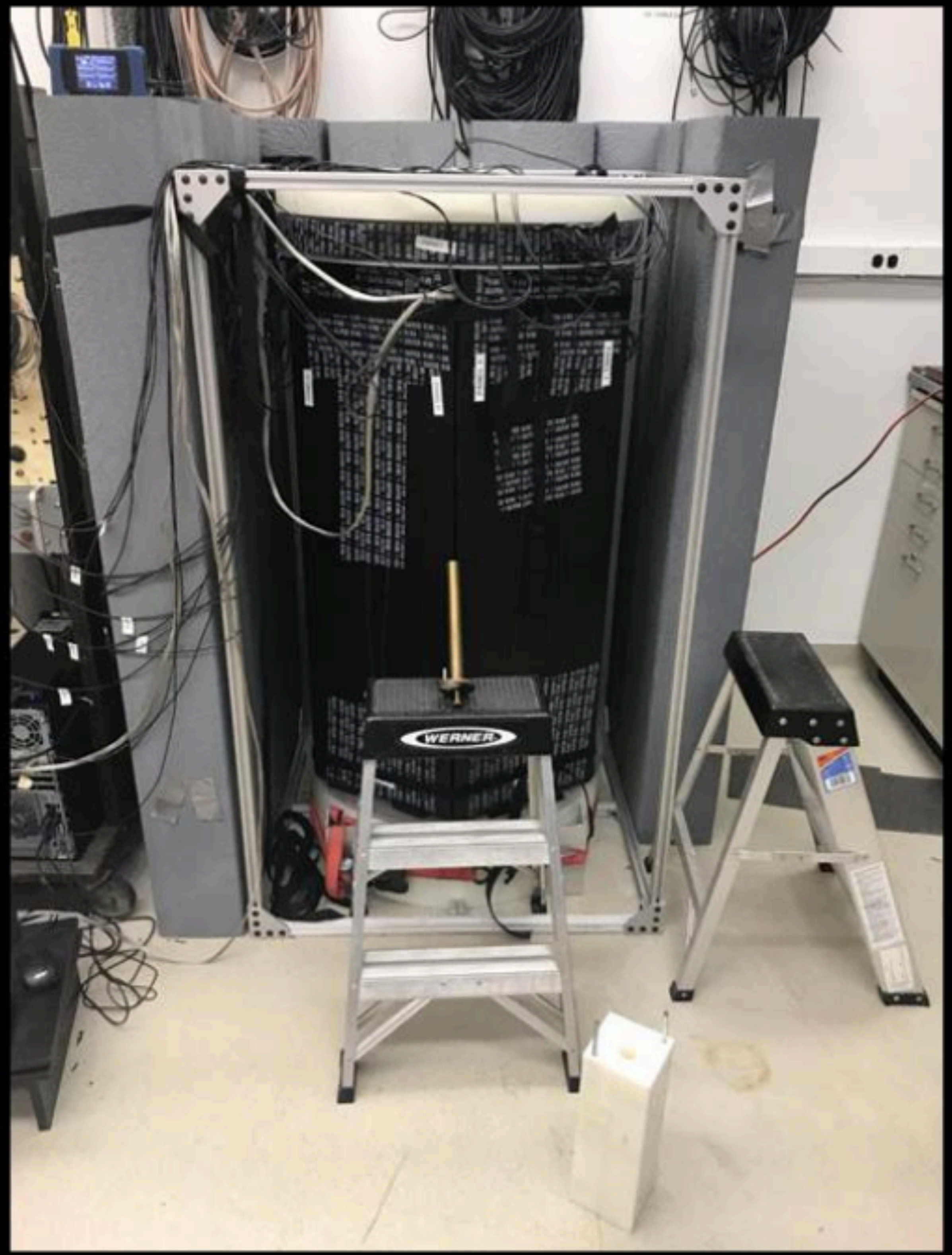
$$\approx 2.3\ 10^{-45}\,{\rm cm}^2 \times \left(\frac{20 TeV}{M_{\rm DM}}\right)^6 \left(\frac{0.1}{\alpha_3}\right)^8 \left(\frac{c_E}{1.5\pi a^3}\right)^2.$$

$$c_E = \frac{8\pi\alpha_3}{3} \frac{C}{N_c^2 - 1} \langle B | \vec{r} \frac{1}{H_8 - E_{10}} \vec{r} | B \rangle$$

$$c_E|_{\rm DM} = (0.36 + 1.17)\pi a^3$$

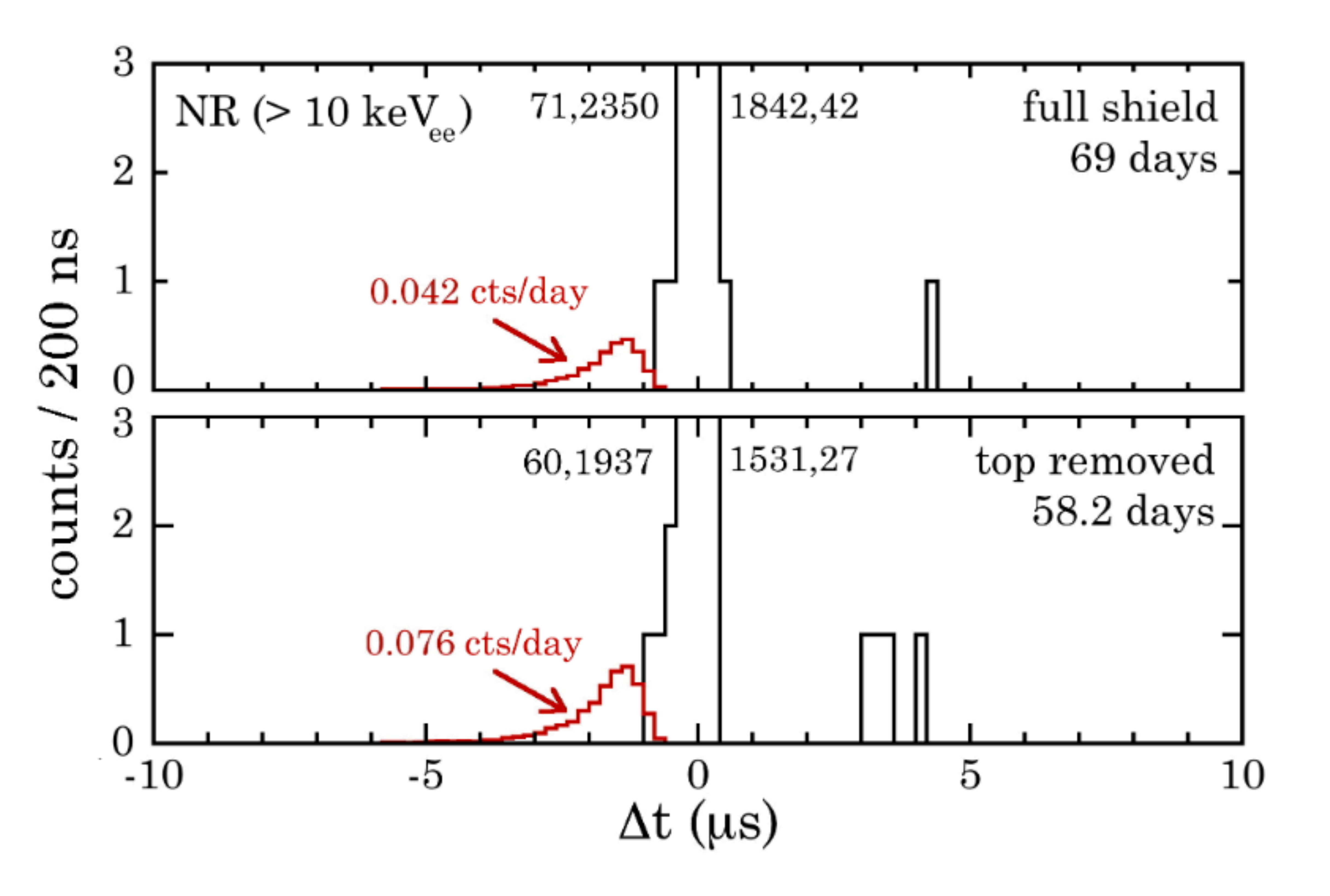
Large Scattering Cross Sections

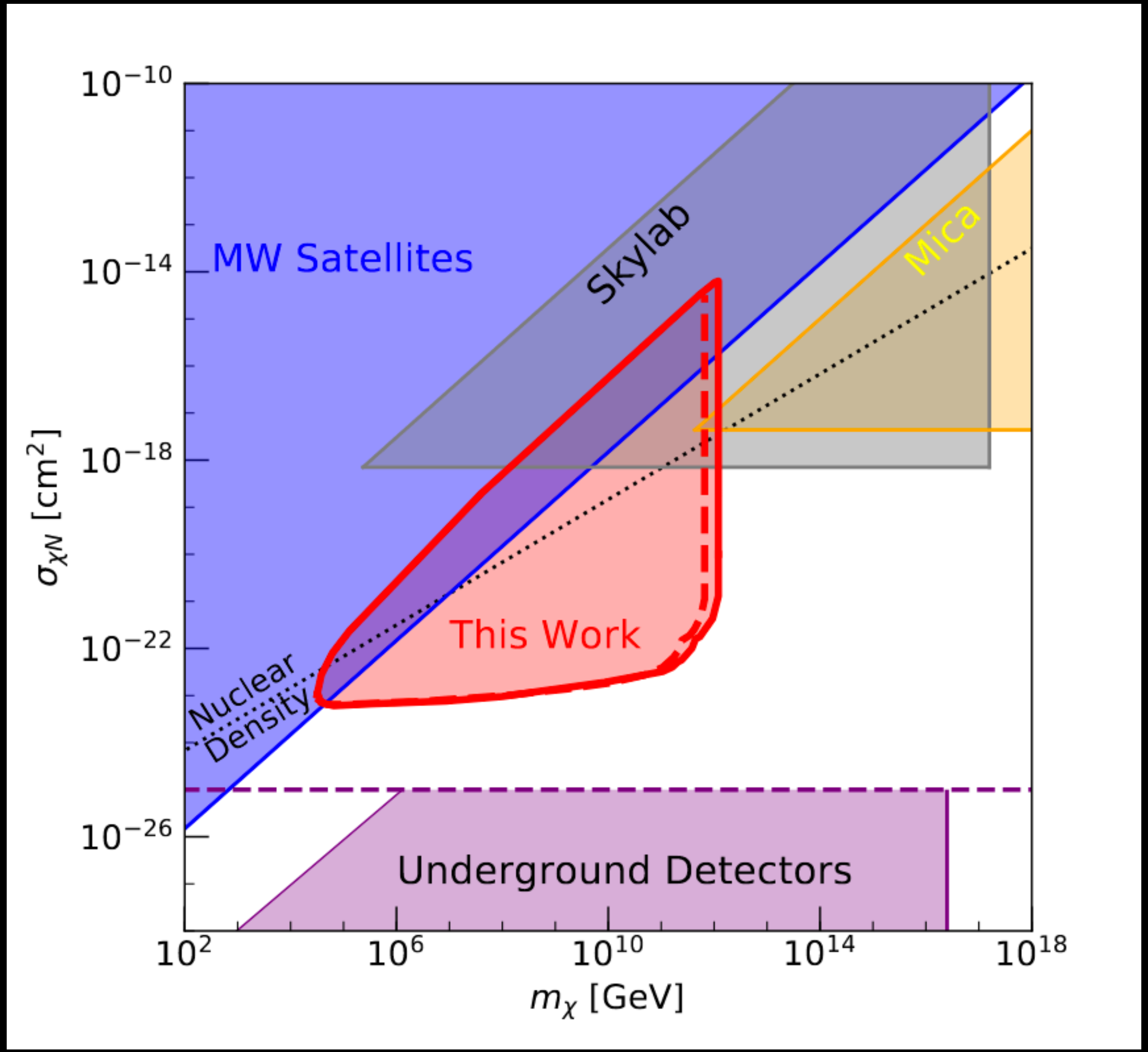




2008.10646: C. Cappiello, J.I. Collar, J. F. Beacom

Large Scattering Cross Sections

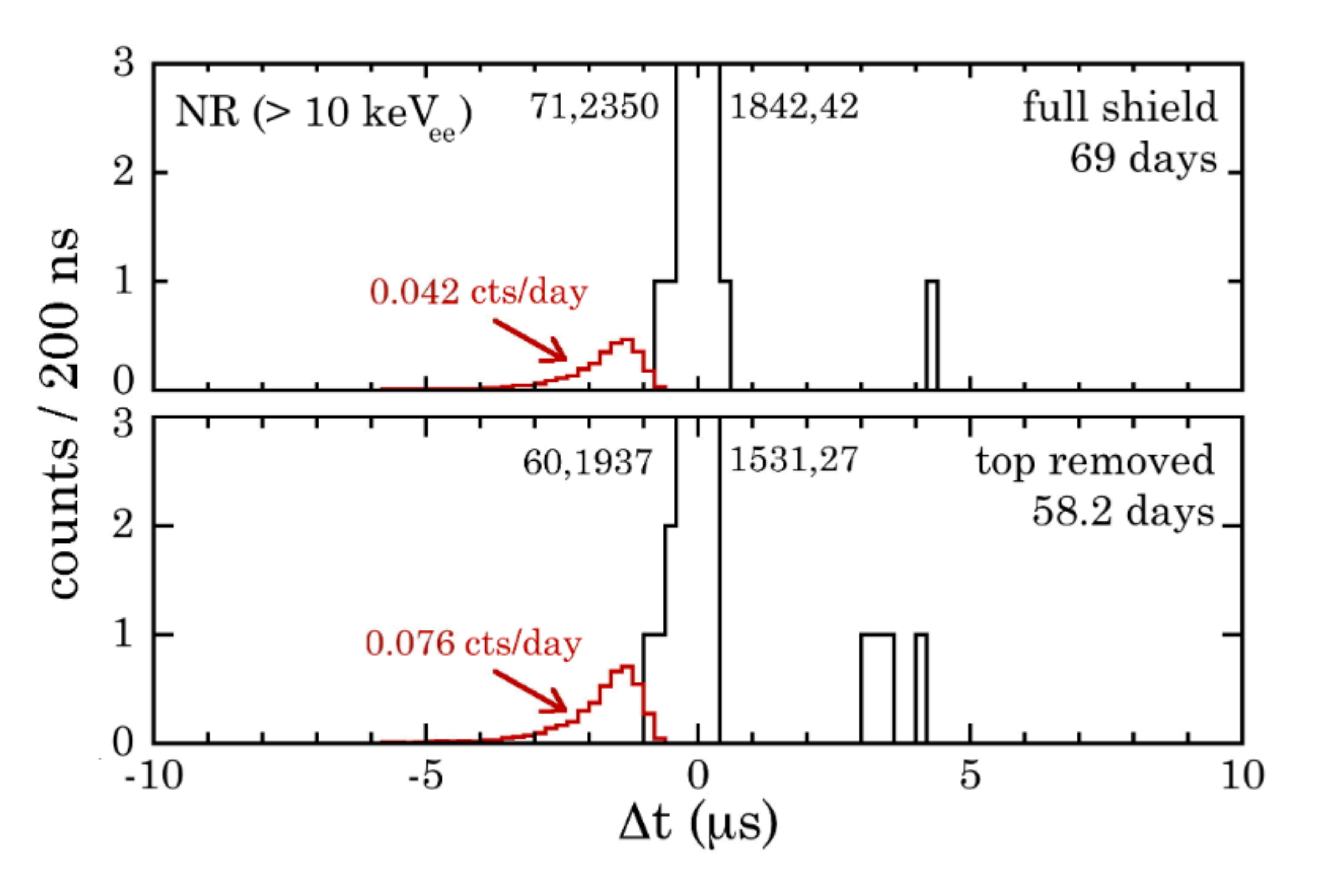


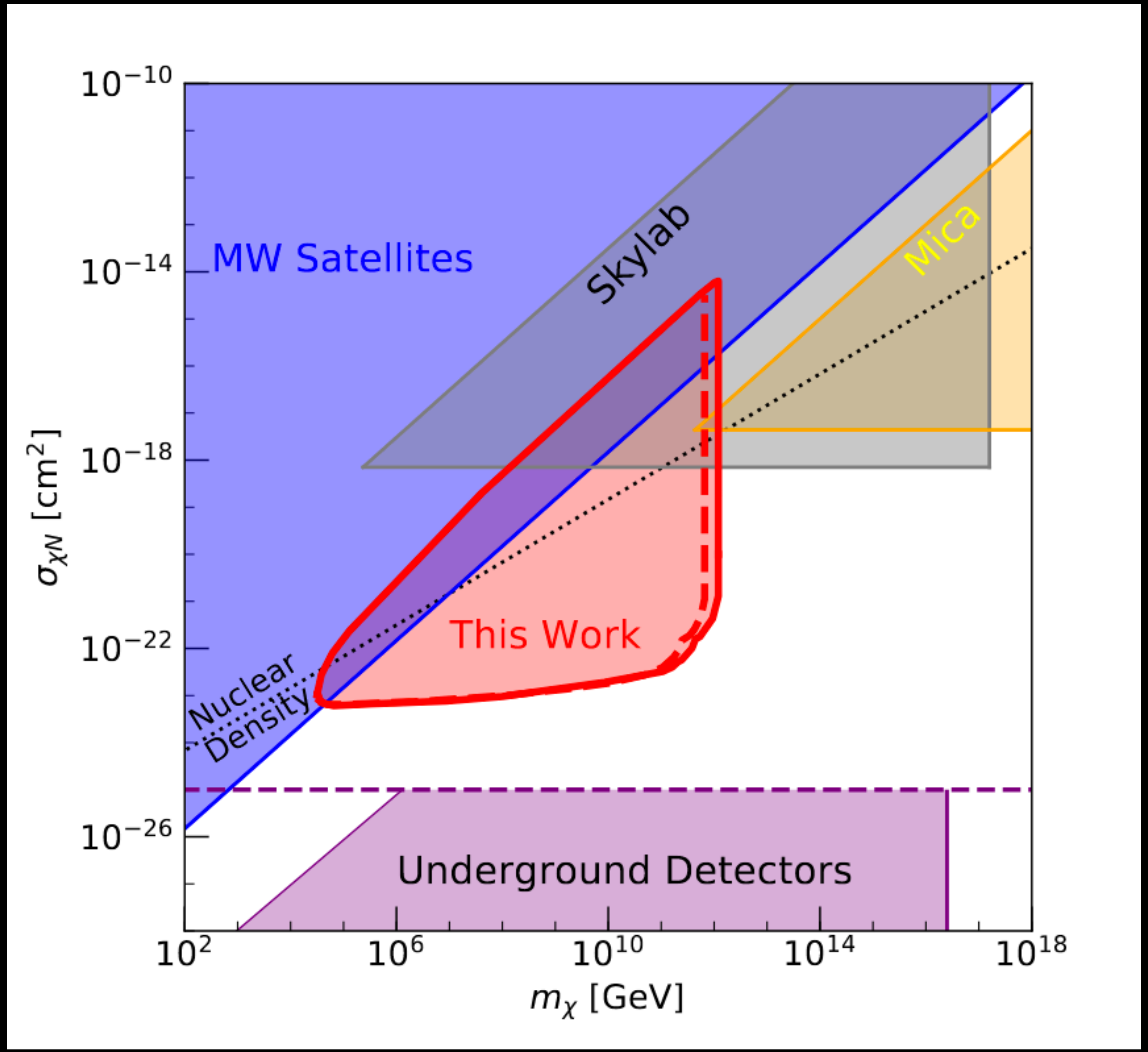


2008.10646: C. Cappiello, J.I. Collar, J. F. Beacom

Large Scattering Cross Sections

See also: A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
https://arxiv.org/pdf/2203.02309.pdf

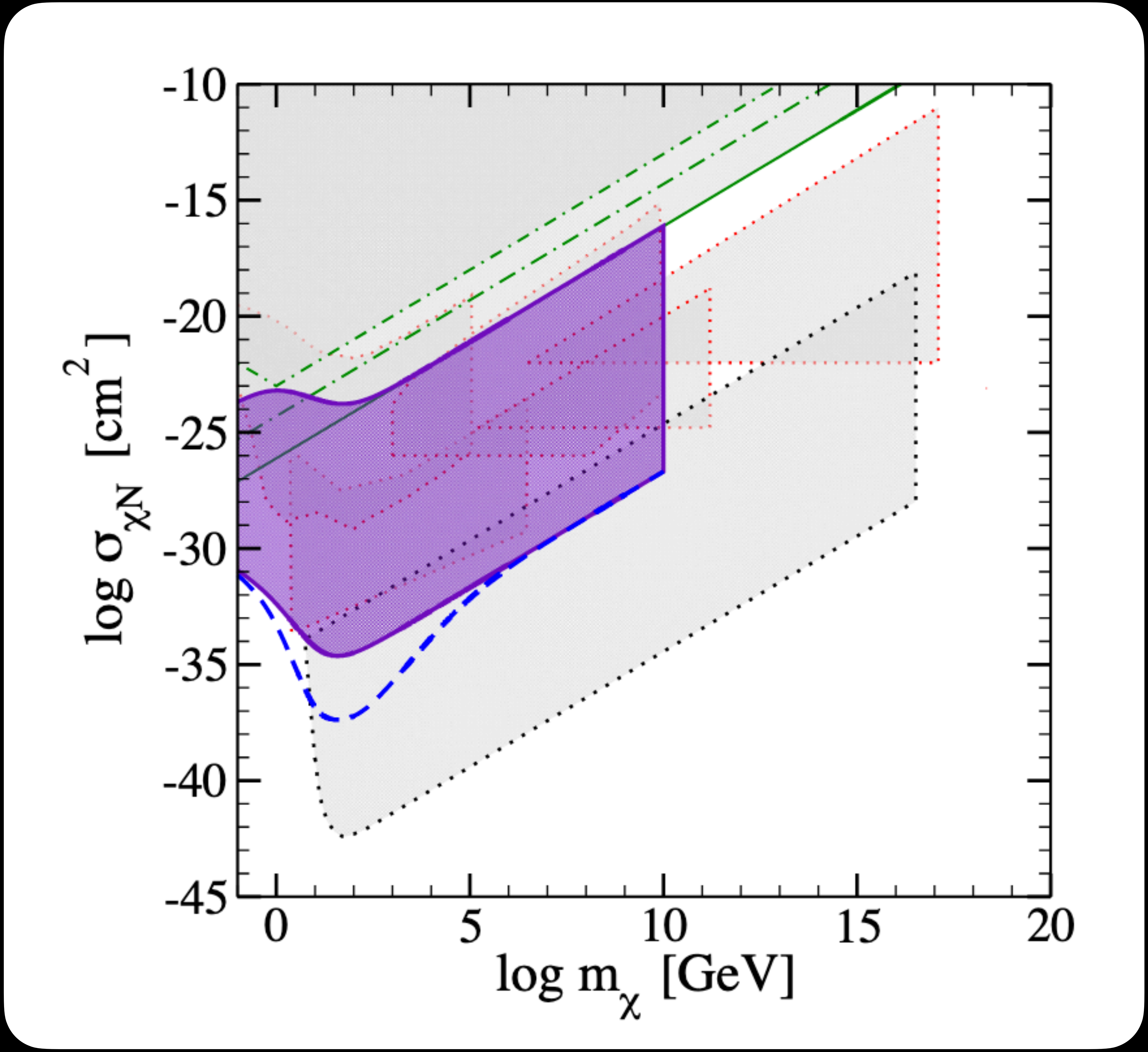




2008.10646: C. Cappiello, J.I. Collar, J. F. Beacom

Accumulation/Annihilation

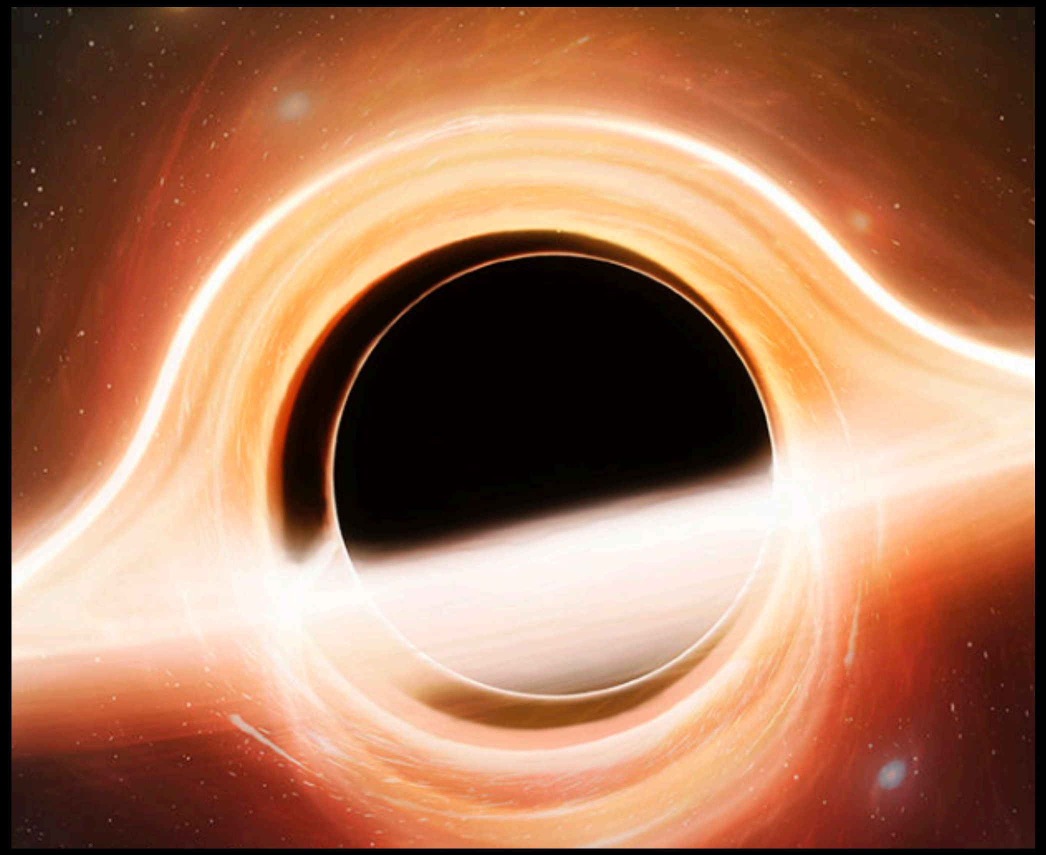
The Earth Heat Flow



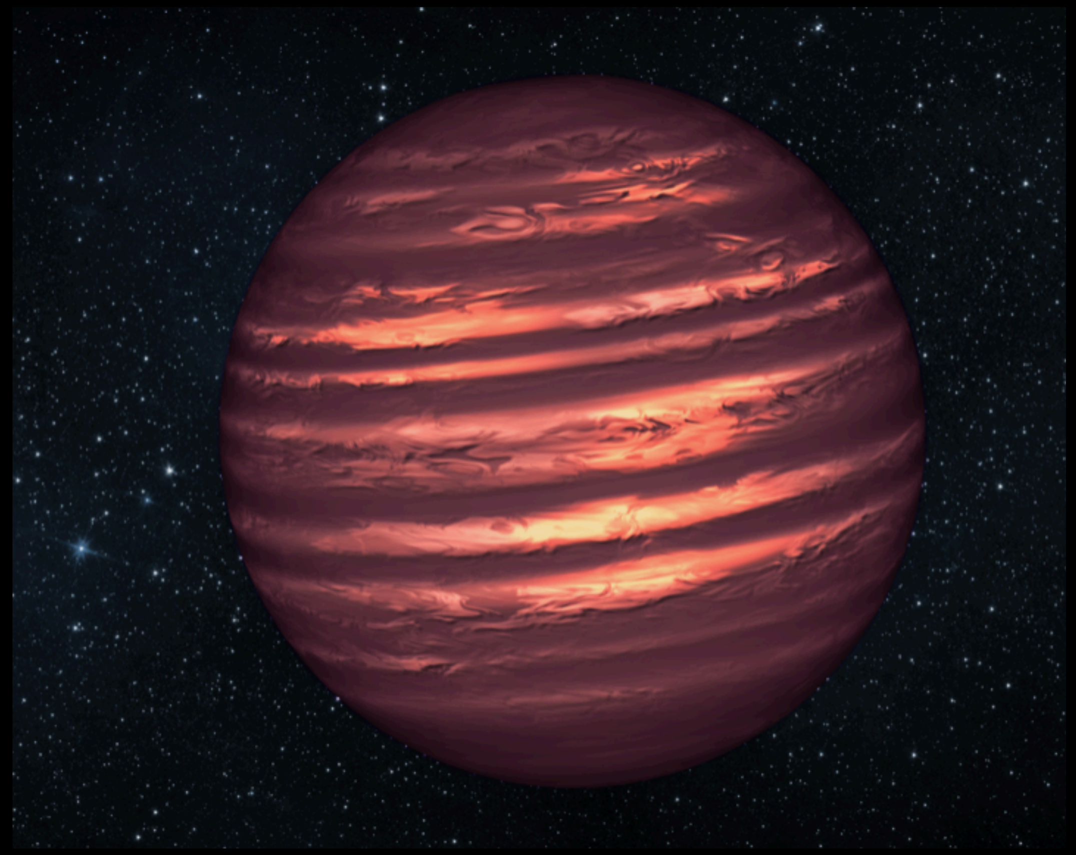
$\tau_{GB} < 0.01$ s

J. Beacom et al. 2007

Stuff in Space



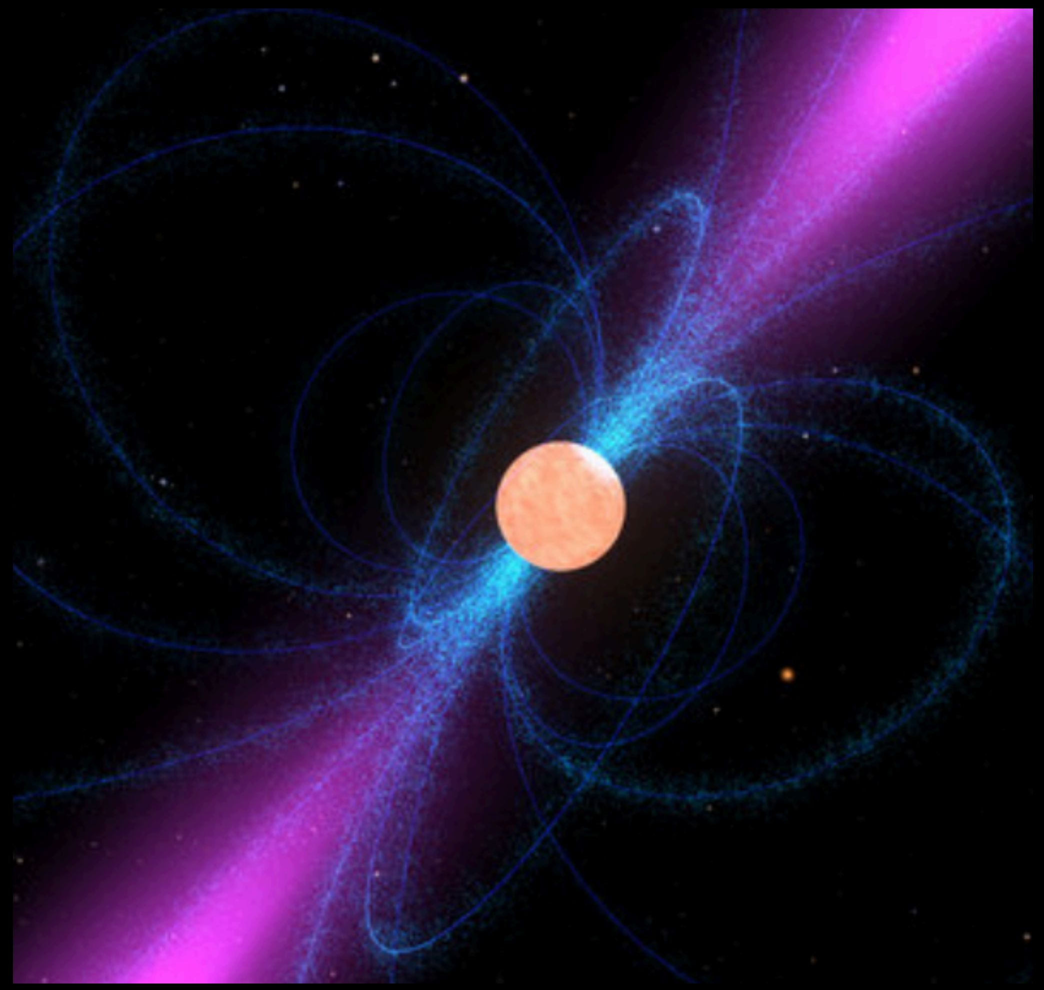
M > few M_{Sol}



M = 10^{-1} - 10^{-2} M_{Sol}

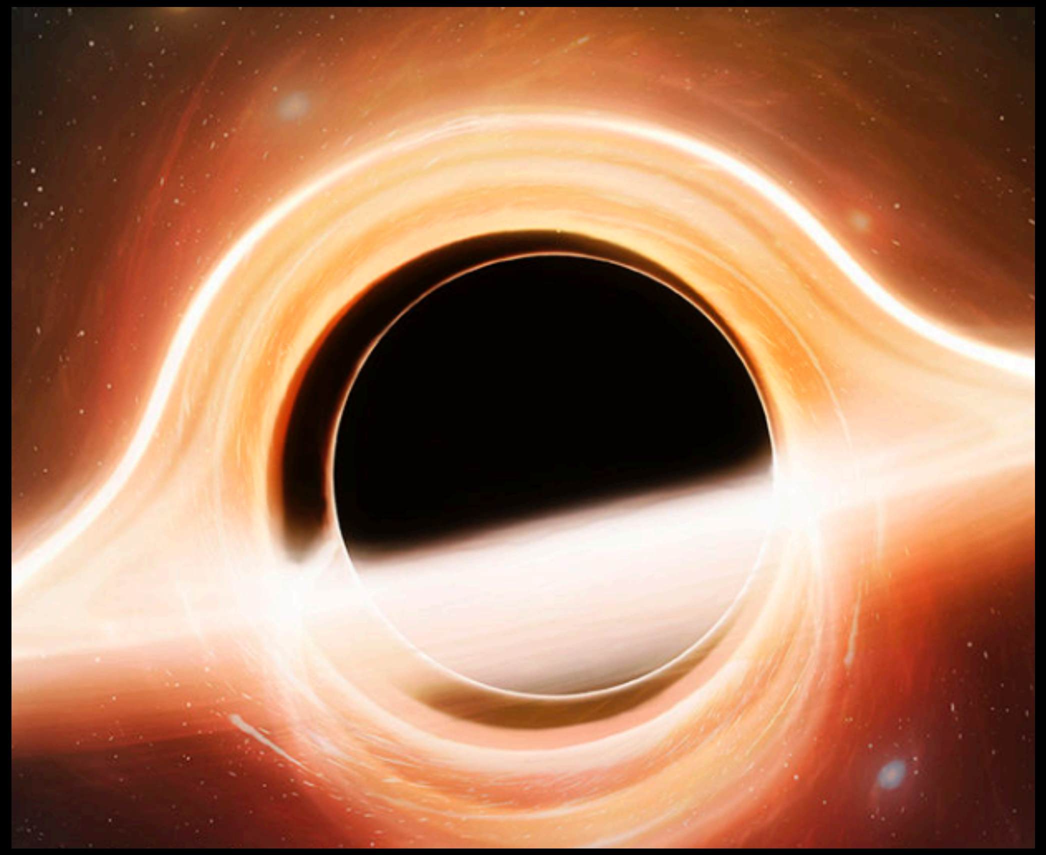
M = 10^{-3} M_{Sol}

M = M_{Sol}

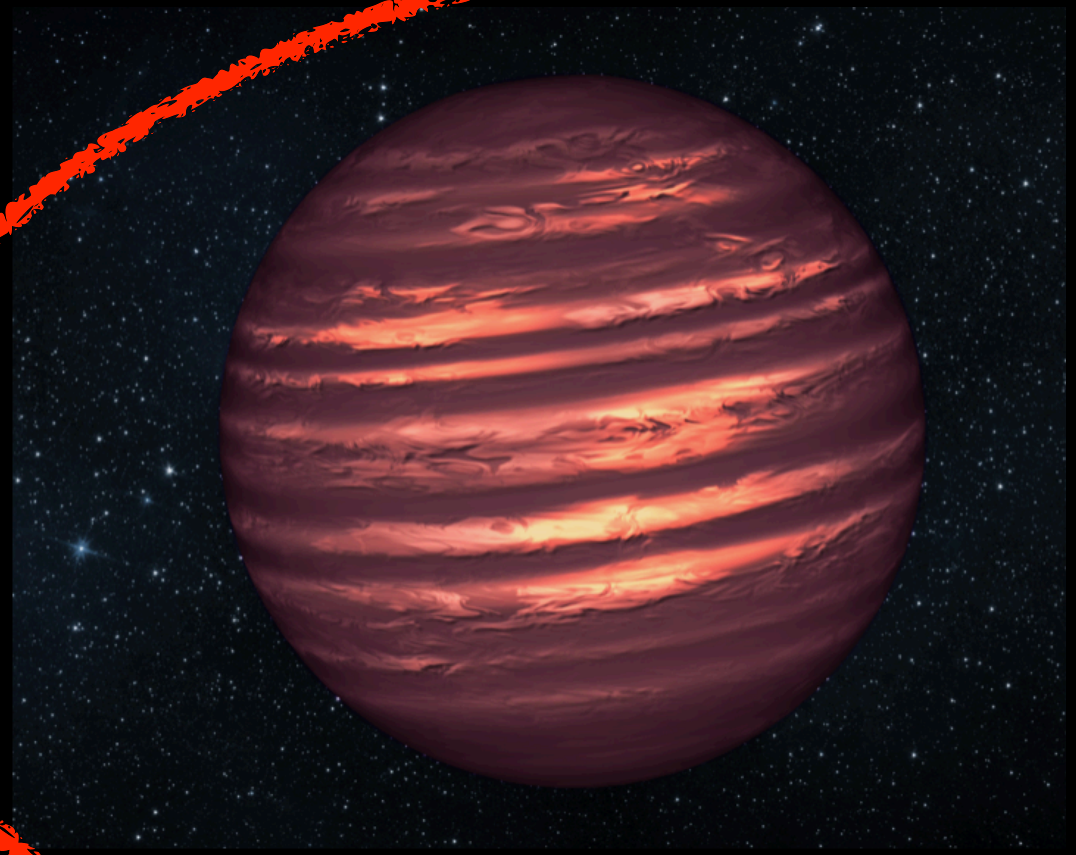


M = 1.4 M_{Sol}

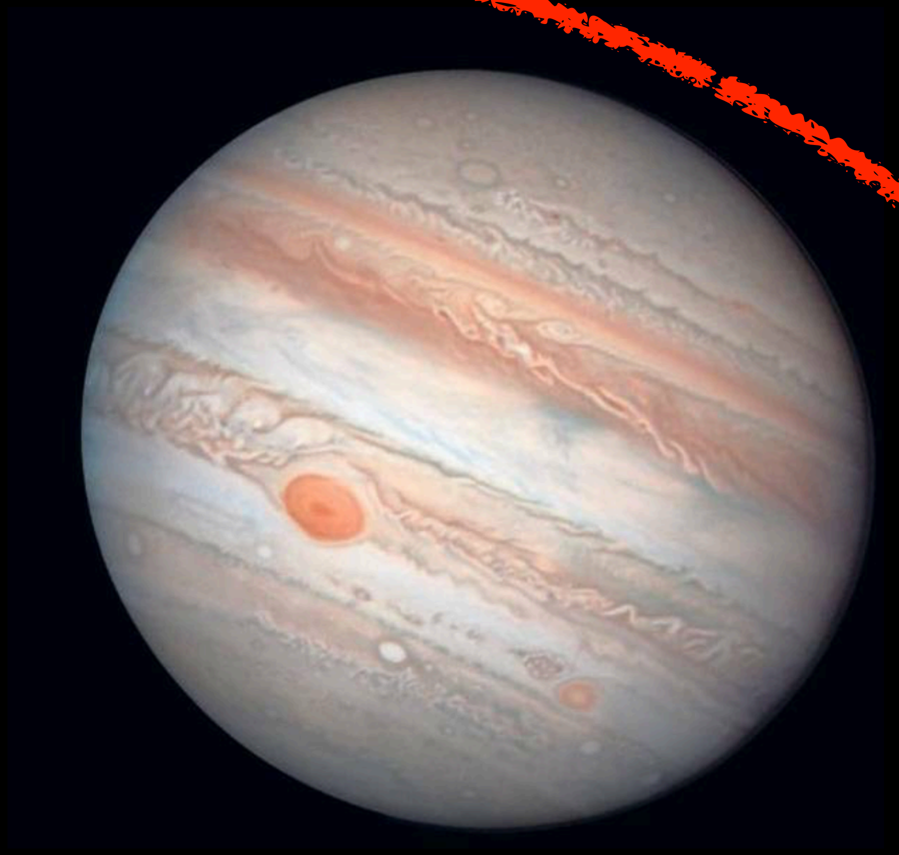
Stuff in Space



M > few M_{Sol}



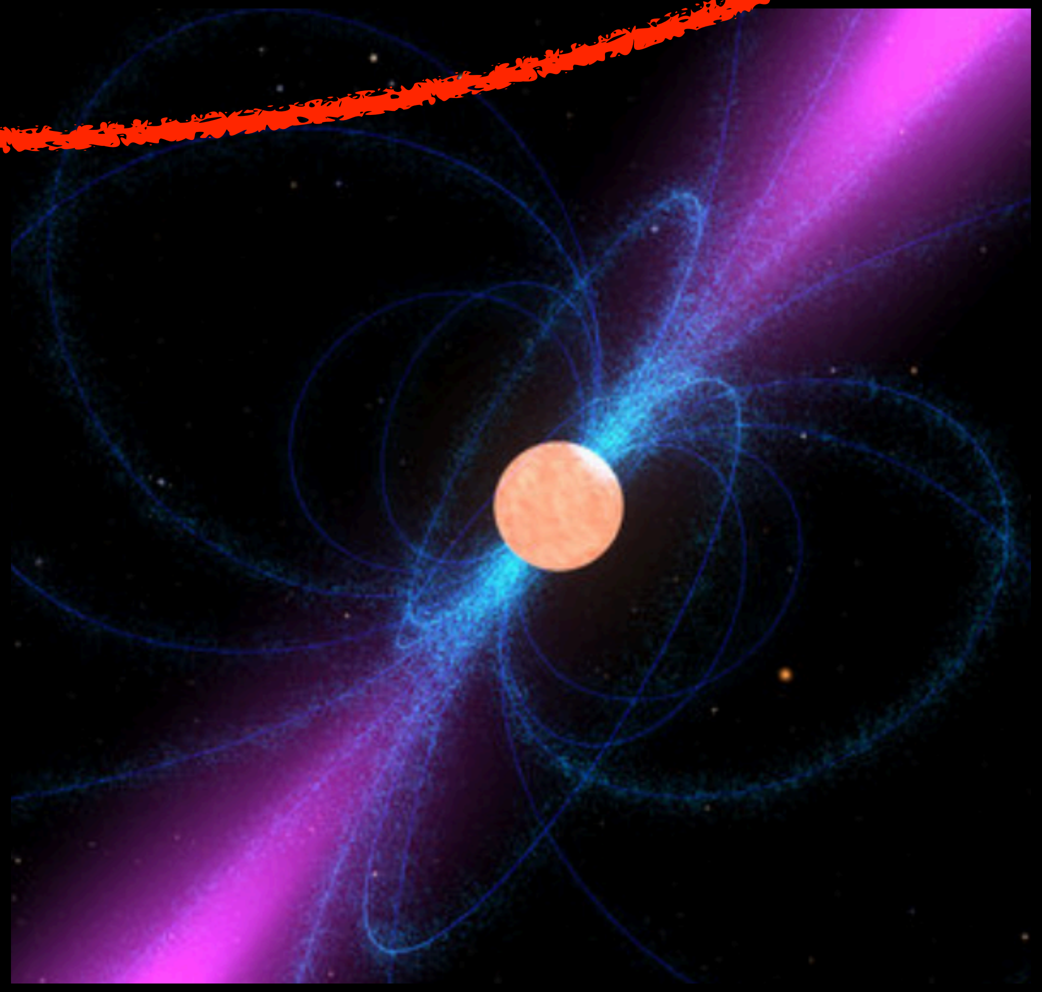
$M = 10^{-1} - 10^{-2}\ M_{Sol}$



$M = 10^{-3}\ M_{Sol}$

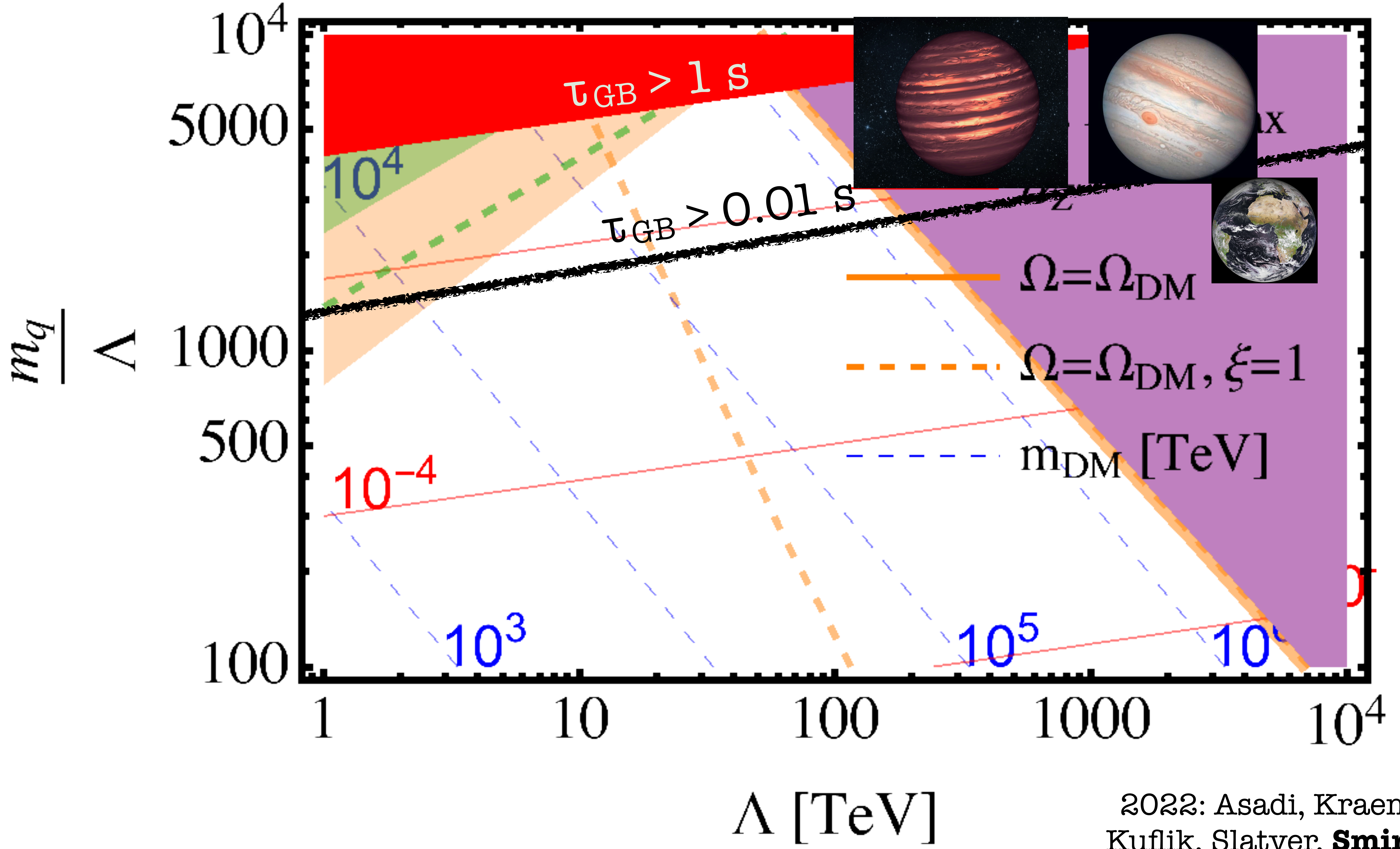
$M = M_{Sol}$

$\tau_{GB} < 0.2$ s



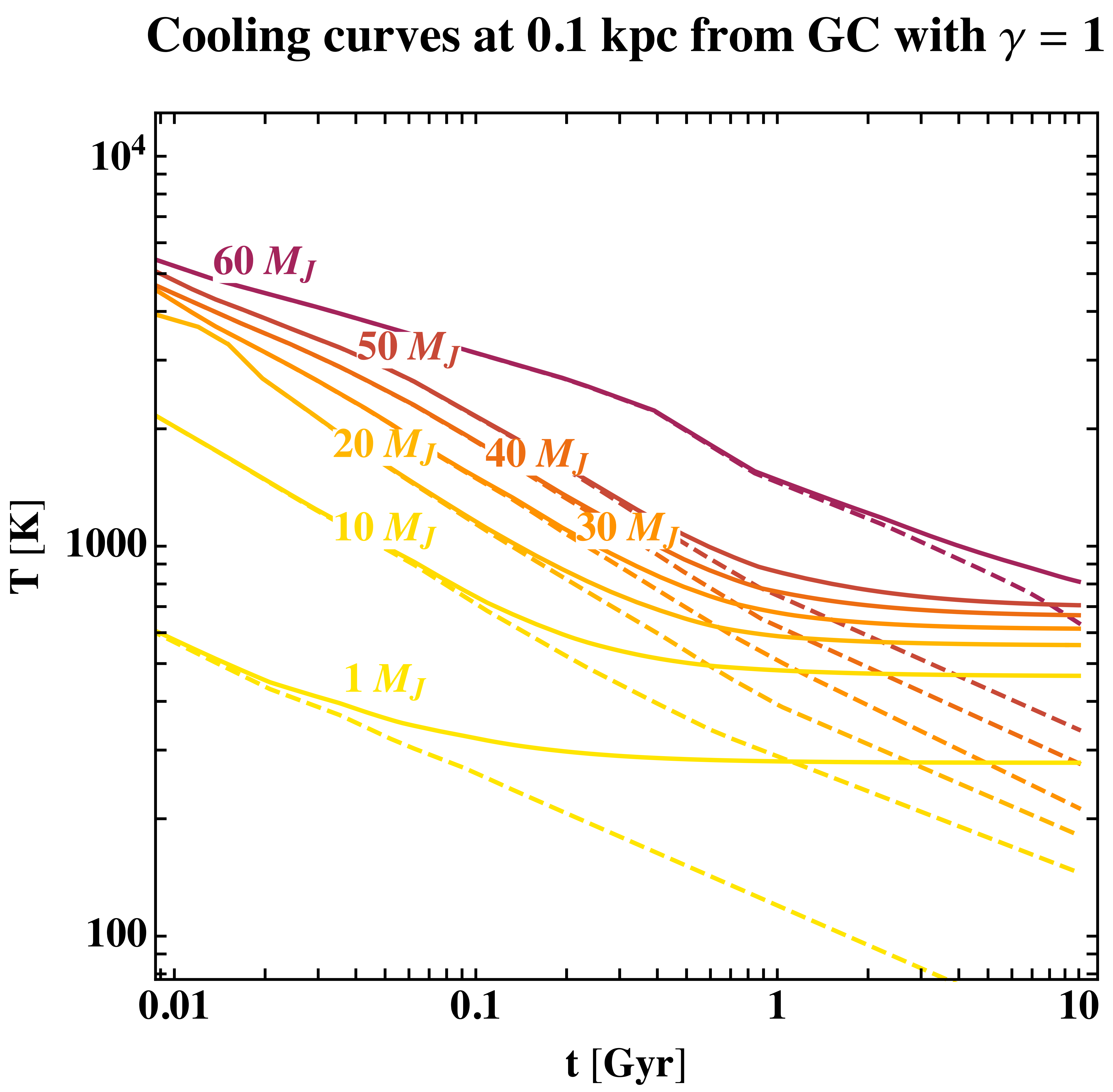
$M = 1.4\ M_{Sol}$

Glueball Lifetimes



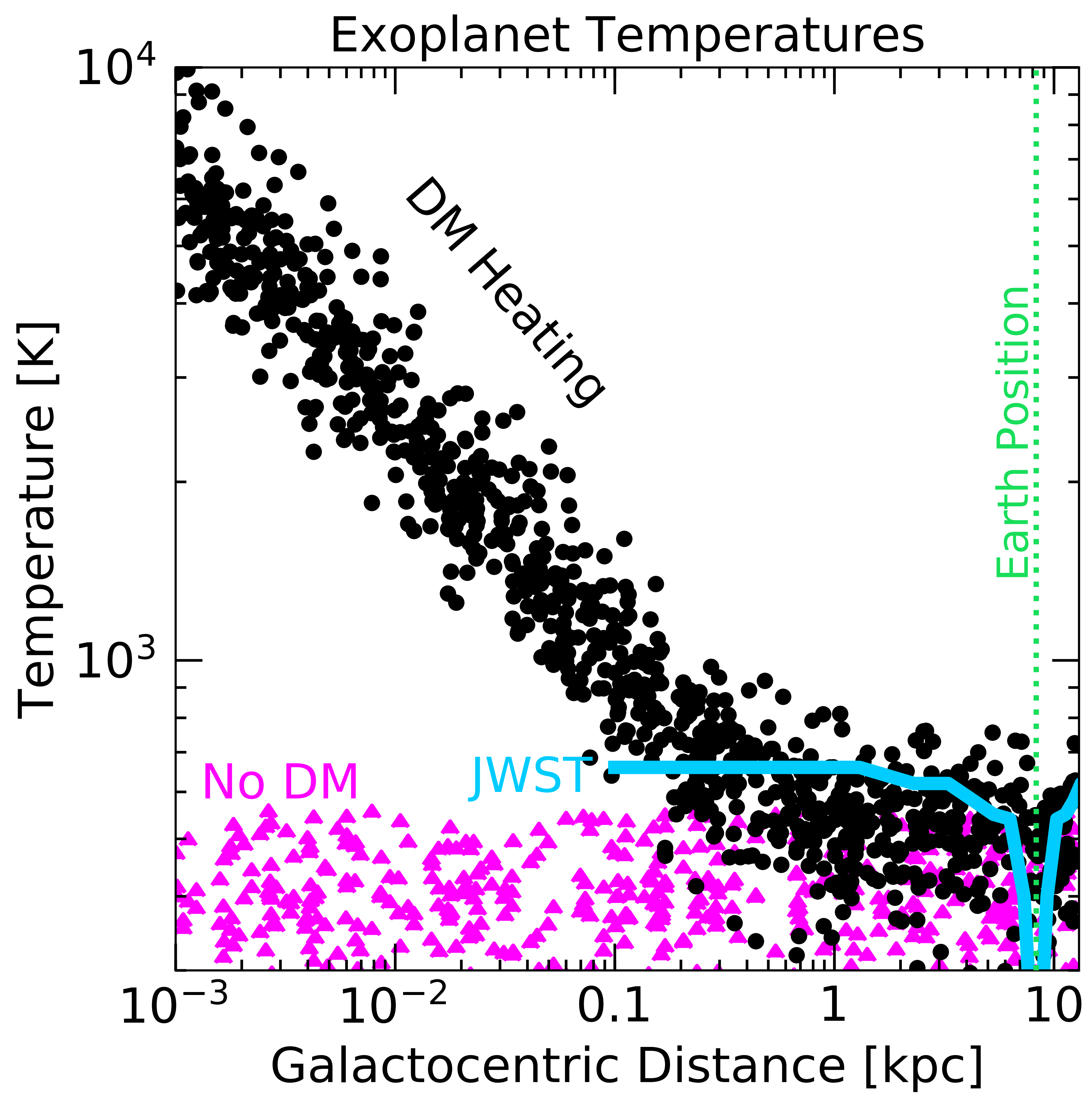
2022: Asadi, Kraemer, Kuflik, Slatyer, **Smirnov**

Temperature Evolution



Work in progress: M. Benito (NICPB), R. K. Leane (Stanford), **J. Smirnov**

What can we expect?



arXiv: 2010.00015; R. K. Leane (Stanford), **J. Smirnov**