Beyond WIMPs

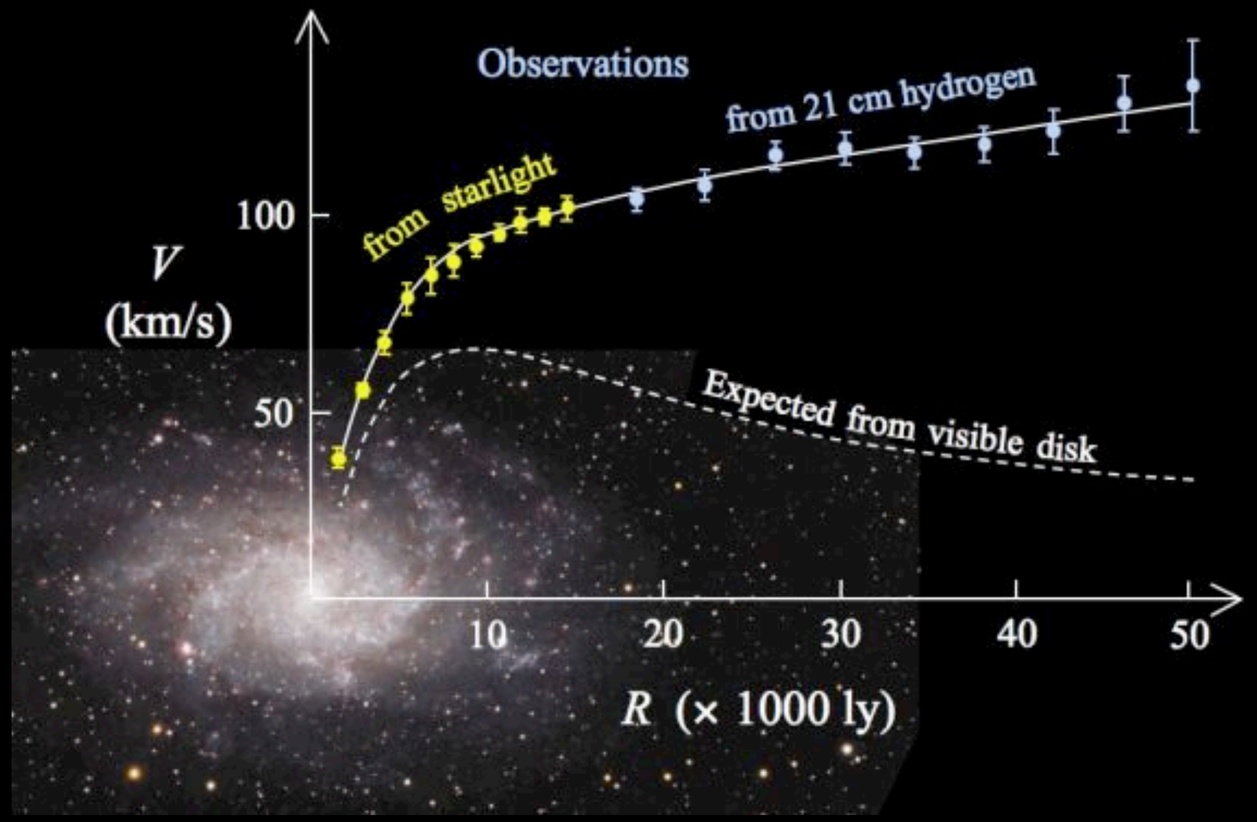
Juri Smirnov, Lecturer @ University of Liverpool

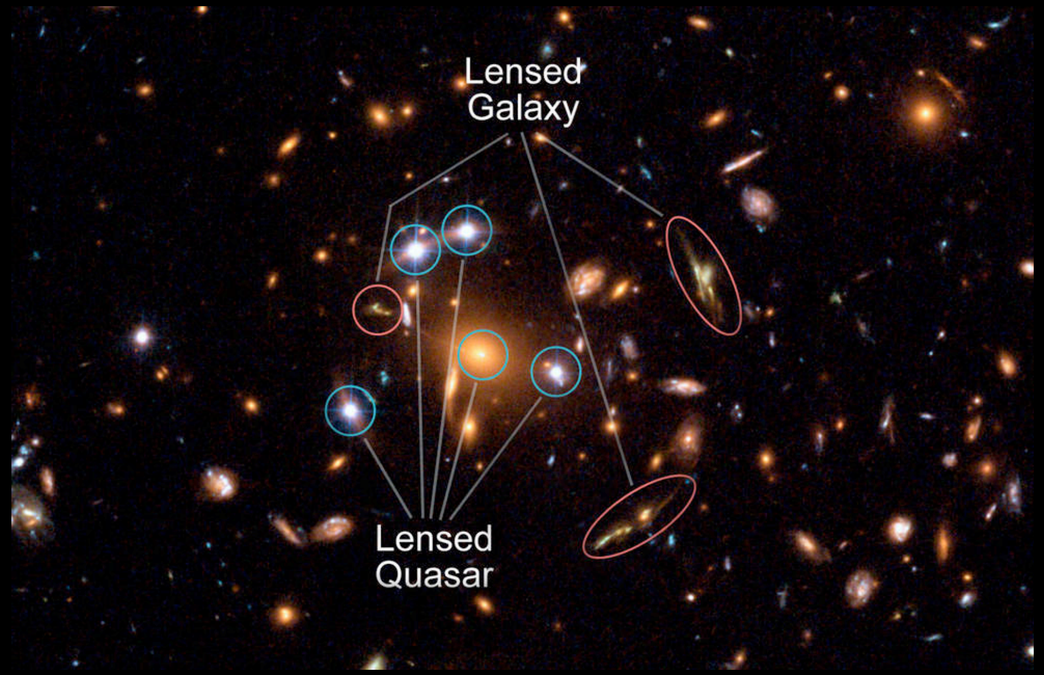
Asymptotic Safety meets Particle Physics and Friends
Hamburg: 21/12/23

Many thanks to my collaborators: Manuel Reichert (U. Sussex), Carlos Blanco (Princeton U.), Tracy R. Slatyer (MIT), Eric Kufik (U. Jerusalem), Pouya Asadi (MIT), John F. Beacom (CCAPP)

Observational Evidence

Evidence in Different Systems





Don’t Mess wit the Force

Observed:

$$R_c \sim M^{1/3}$$

Expected from a matter system of given density

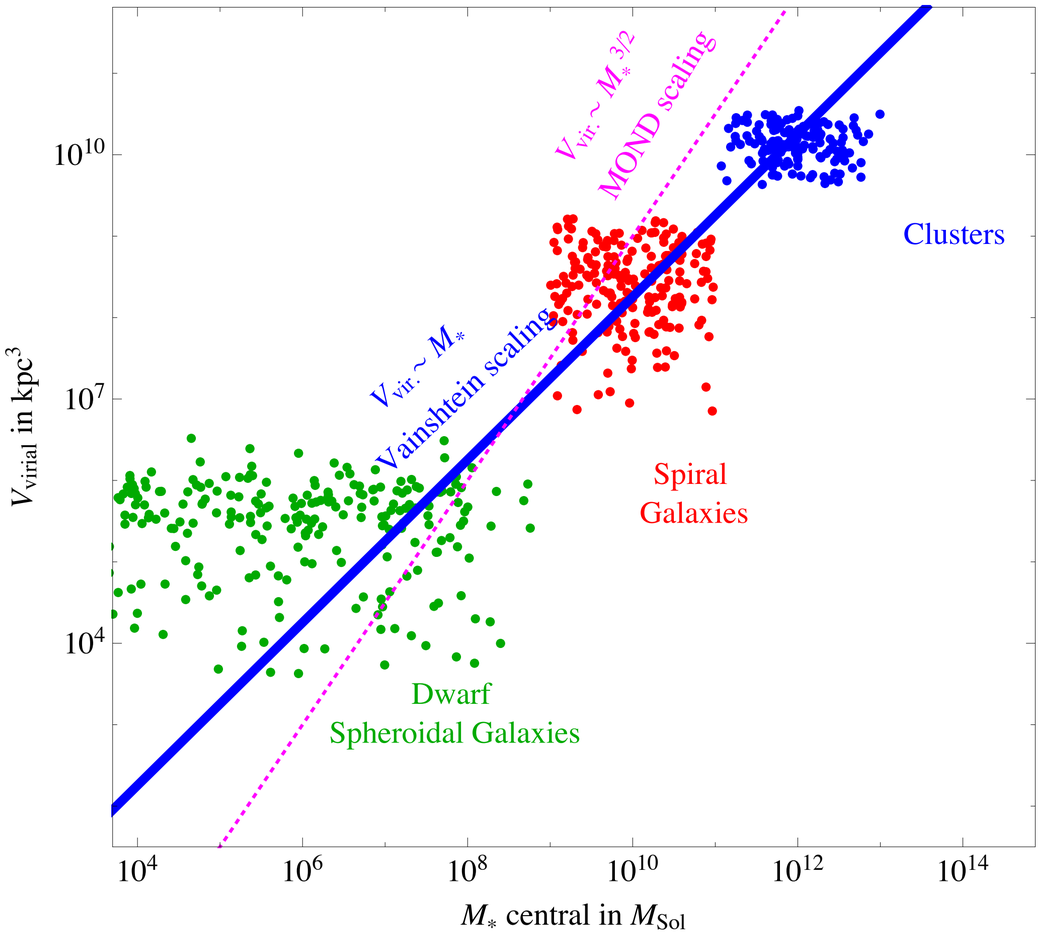
Modified Newtonian Dynamics (MOND):

$$a_c = \text{constant} \sim M/R_c^2$$

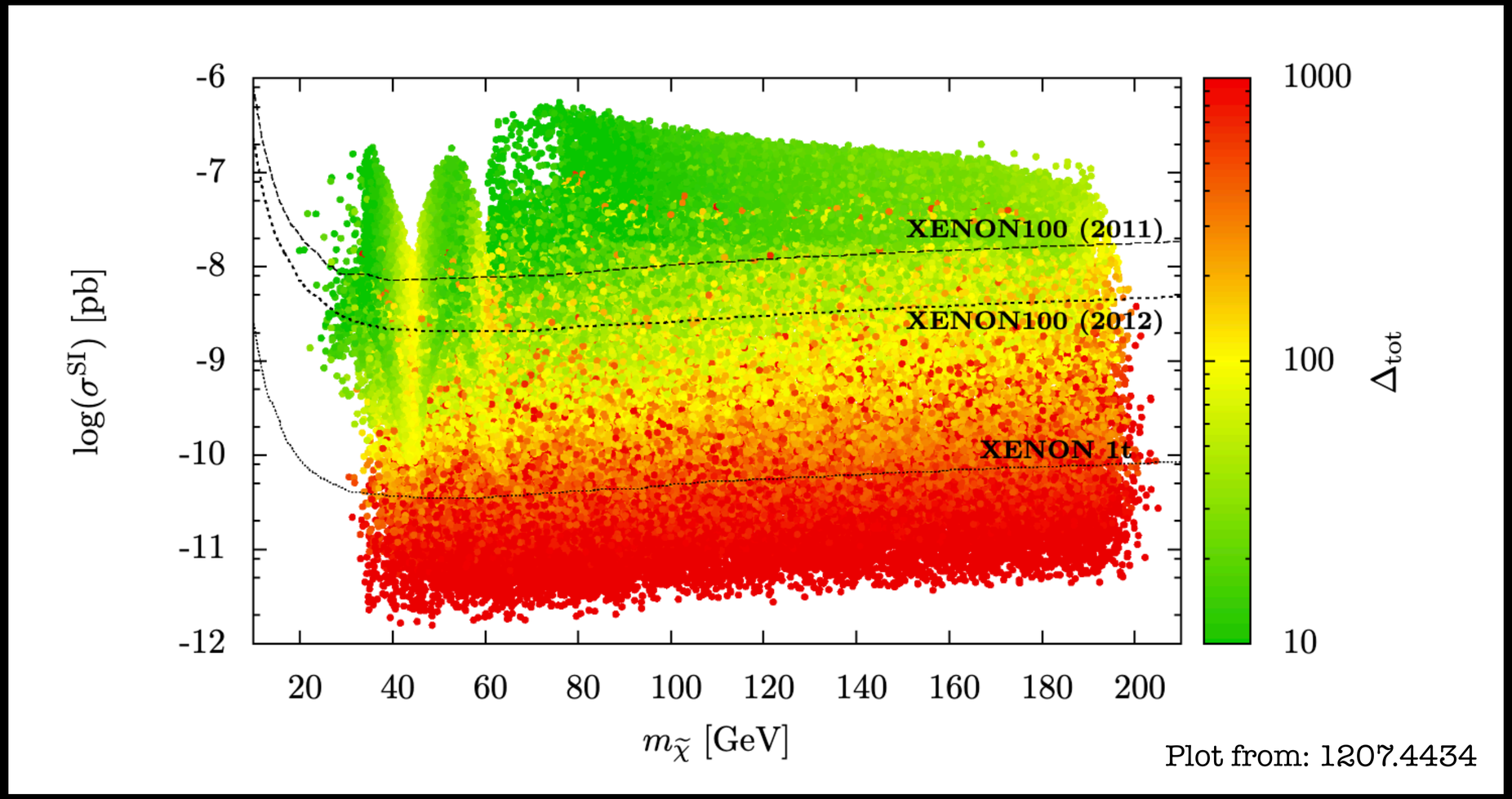
Implies:

$$R_c \sim M^{1/2}$$

Difficult to reconcile across systems.

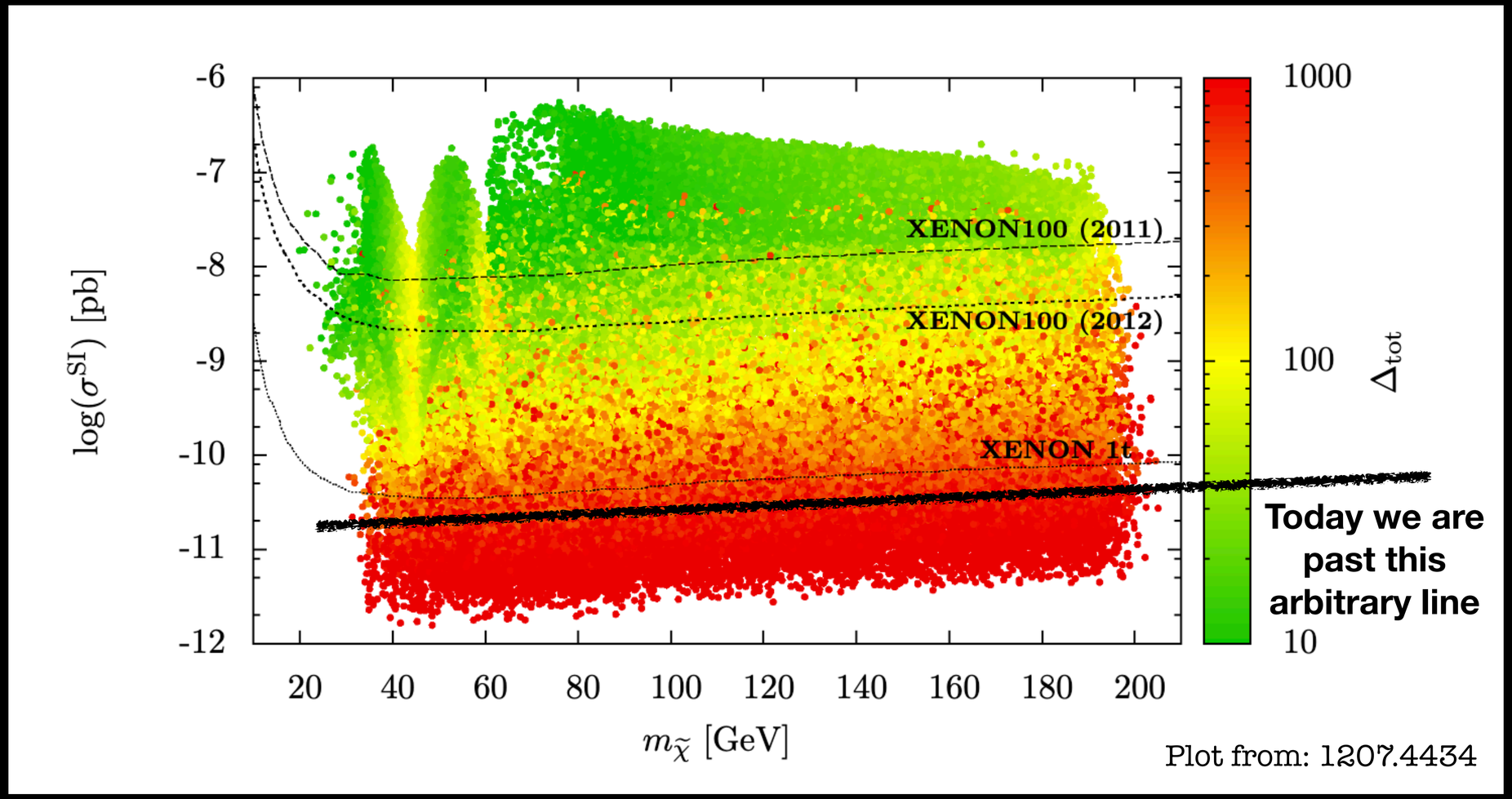


In Search of Lost Naturalness



Plot from: 1207.4434

In Search of Lost Naturalness



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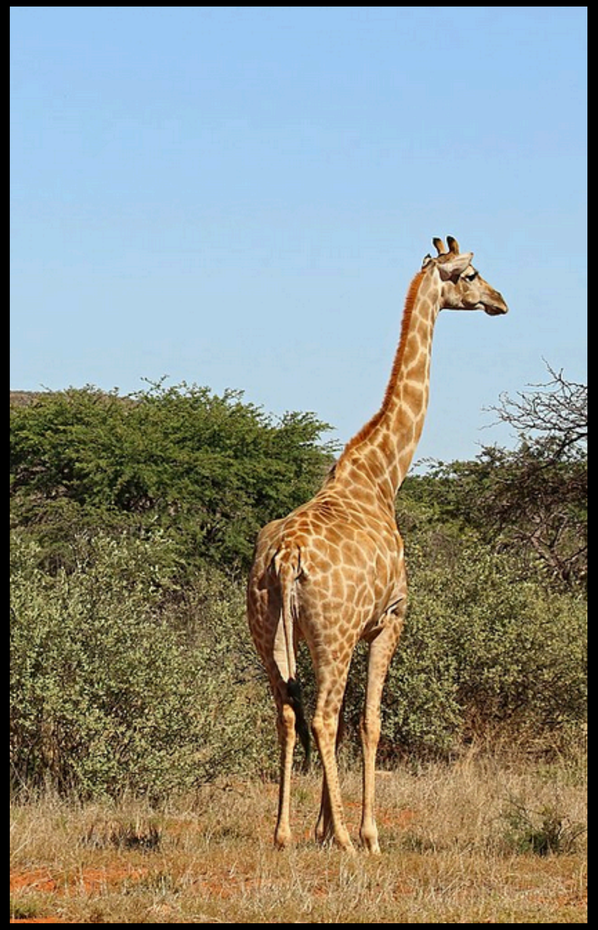
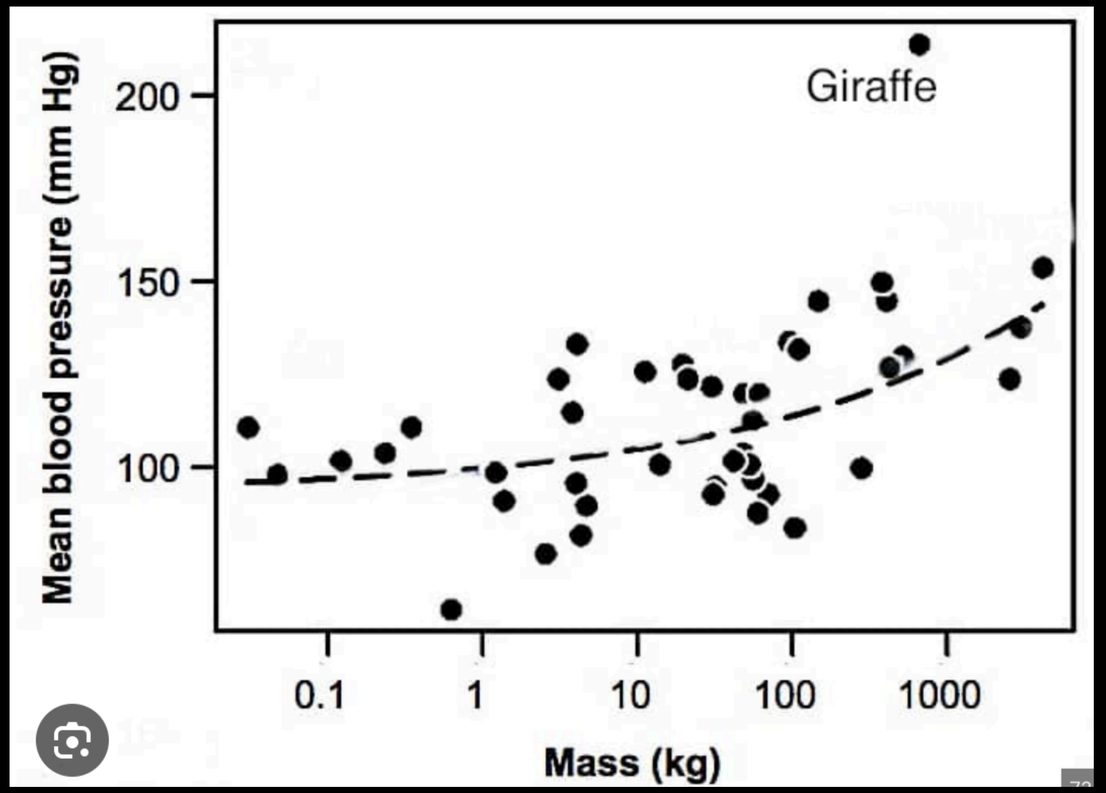
Naturalness and Spherical Cows





Naturalness and Spherical Cows

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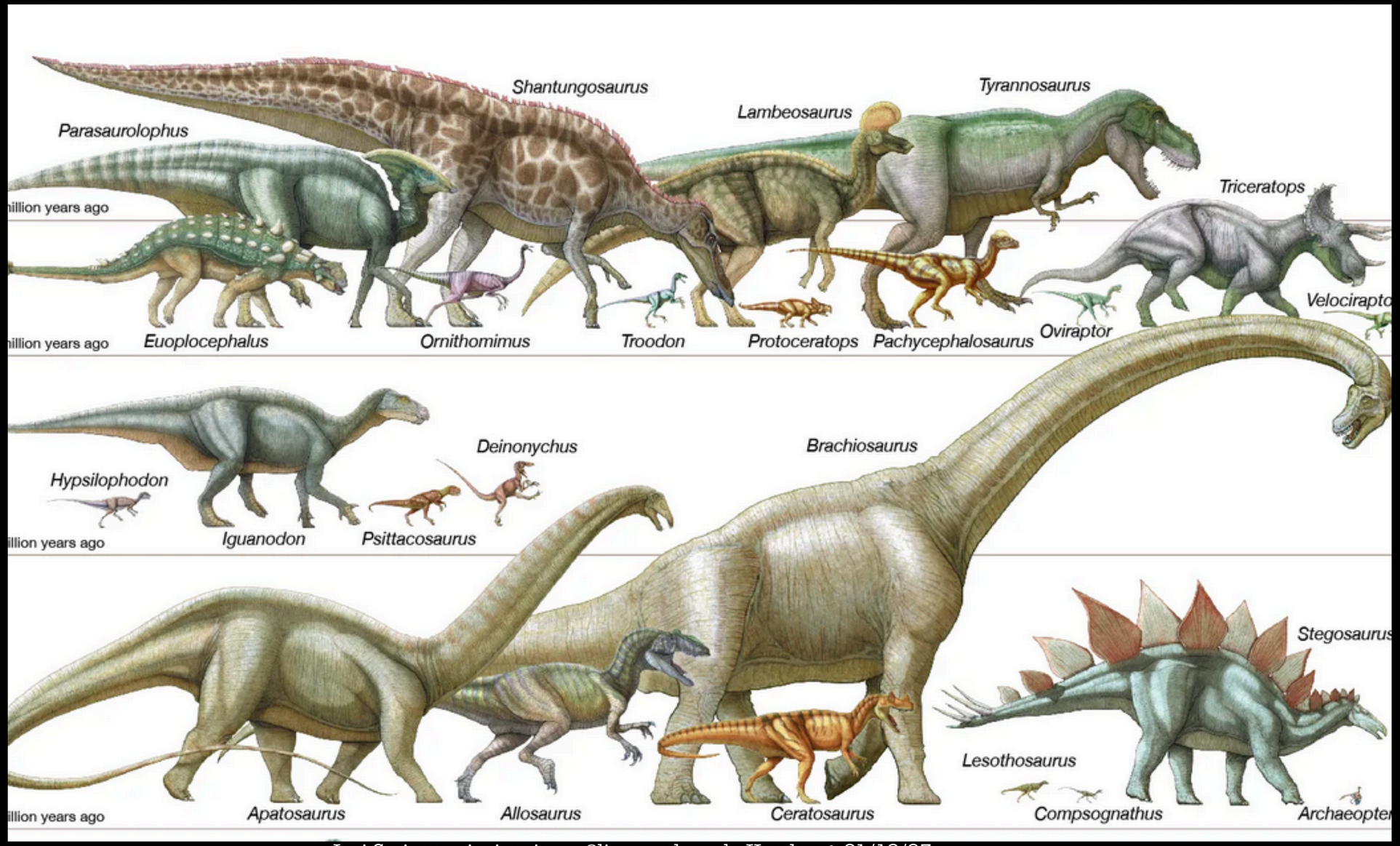
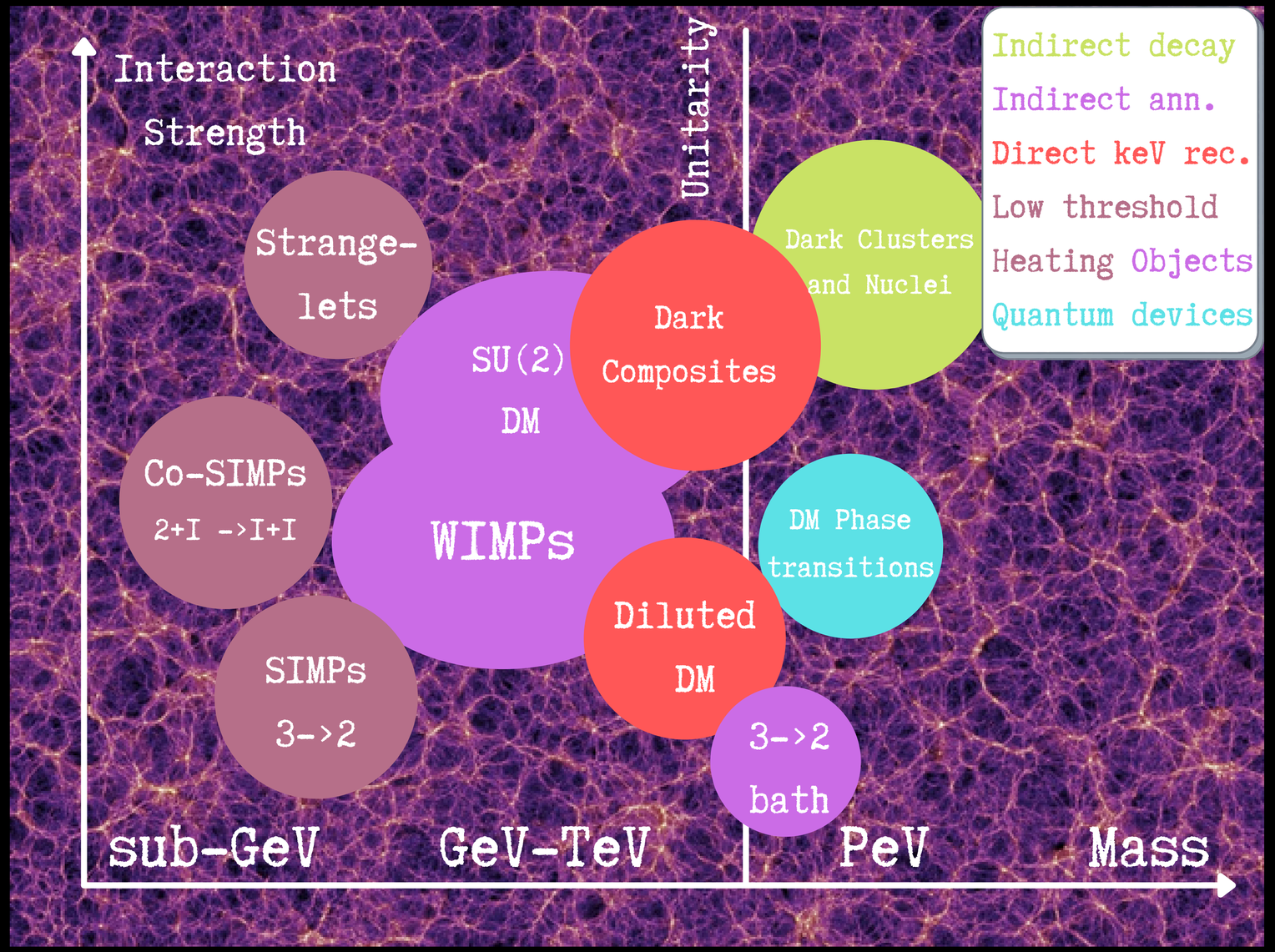
Naturalness and Spherical Cows



Dark Matter Scenario Space



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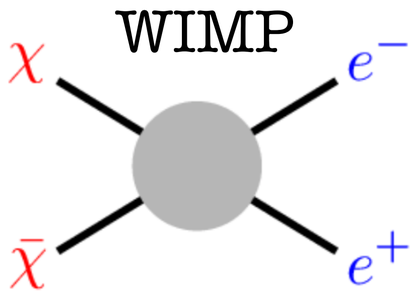
Thermal Production

Types of Freezeout



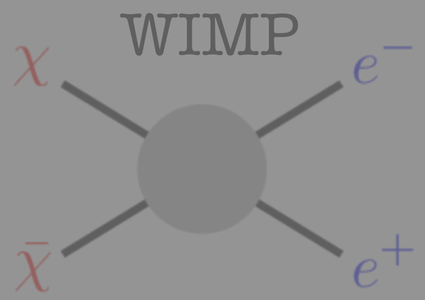
Zeldovich, Lee, Weinberg, Steigman, Turner,...

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

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

Types of Freezeout

WIMP



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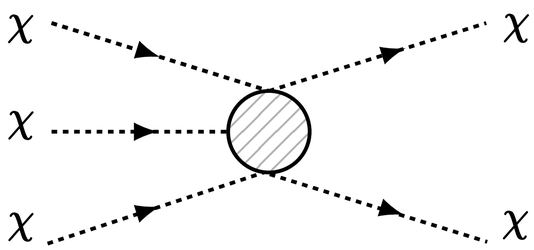
SIMP



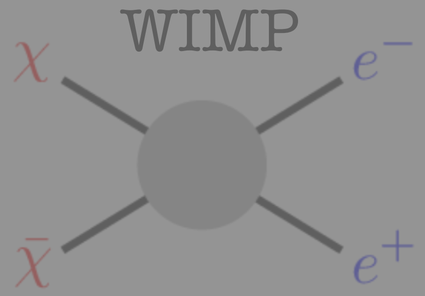
Hochberg, Kuflik, Volansky, Wacker

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

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

Types of Freezeout

WIMP



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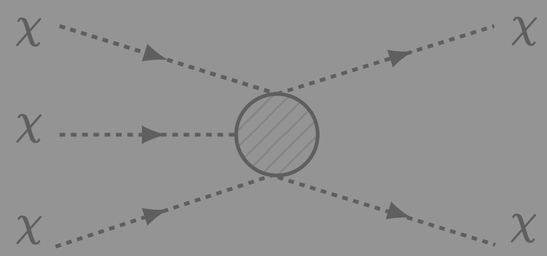

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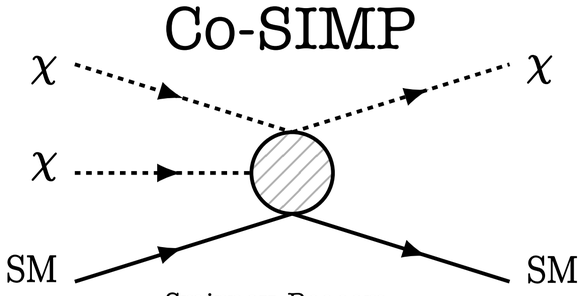
Co-SIMP



Smirnov, Beacom

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

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

WIMPs all the Way

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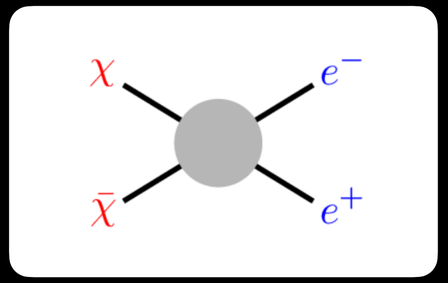
Cartoon of Target Space



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

Dark Matter Mass

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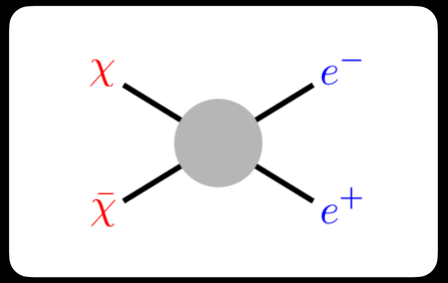
Cartoon of Target Space



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

thermal relic

Dark Matter Mass

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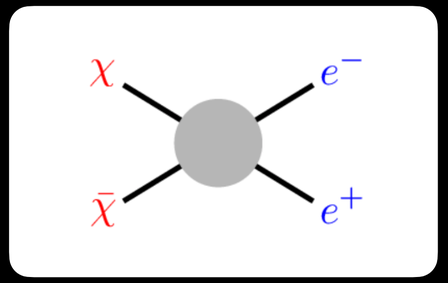
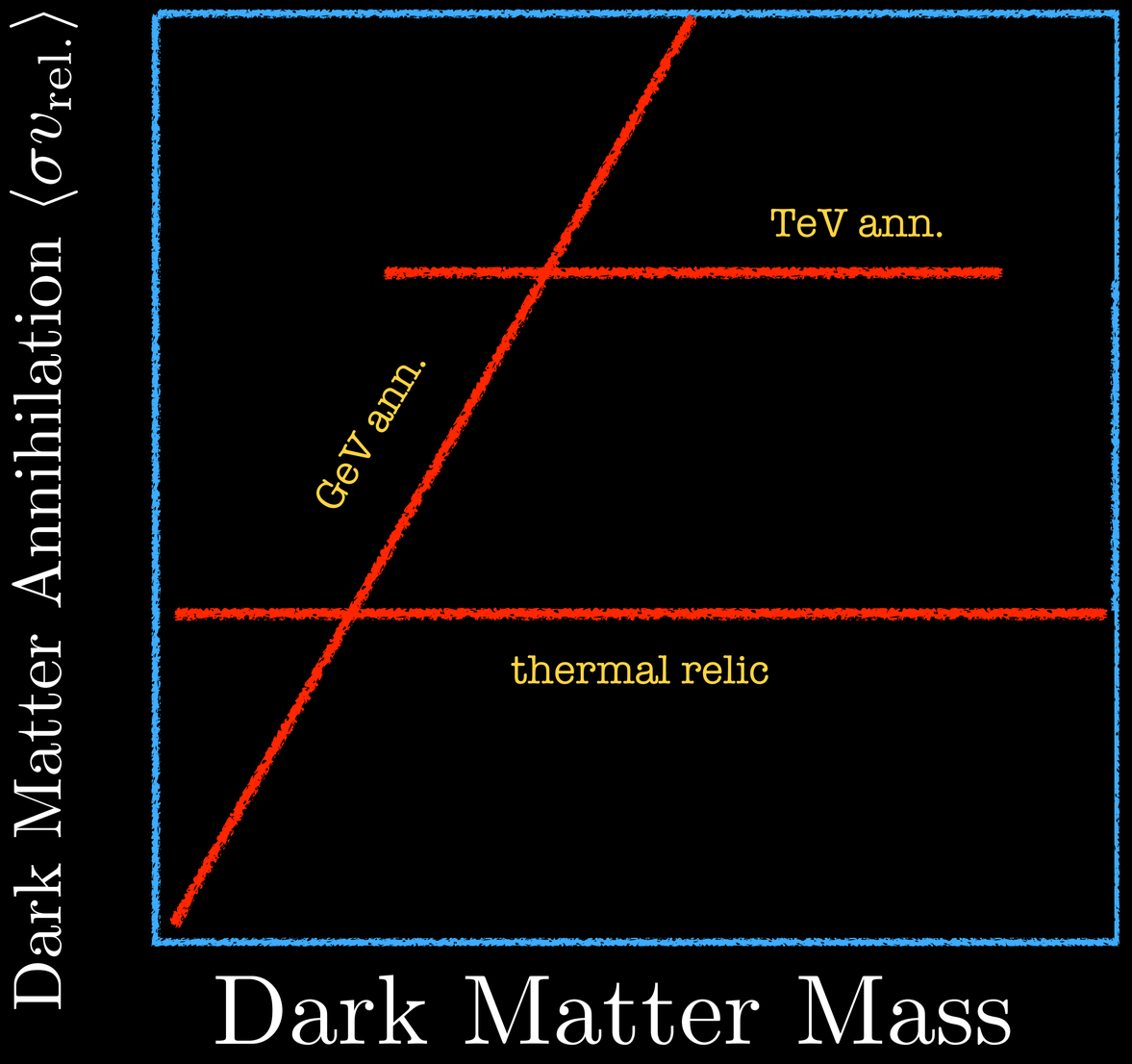
Cartoon of Target Space





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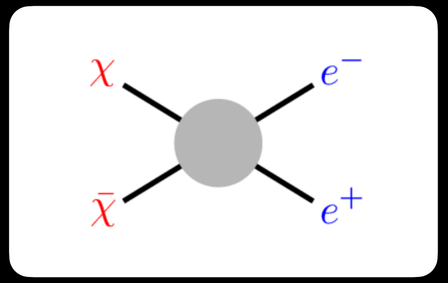
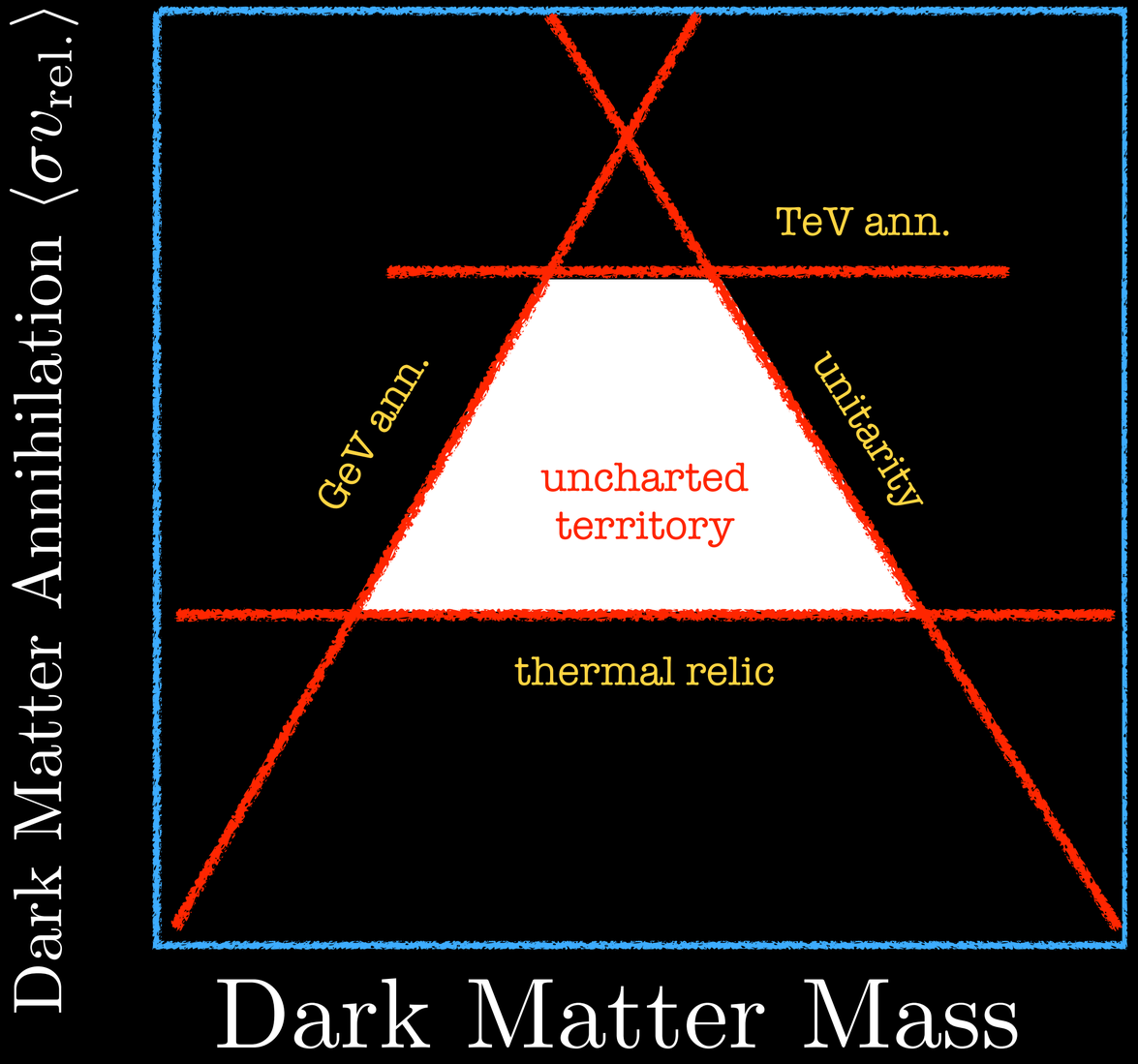
Cartoon of Target Space





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Truly Weak Interactions

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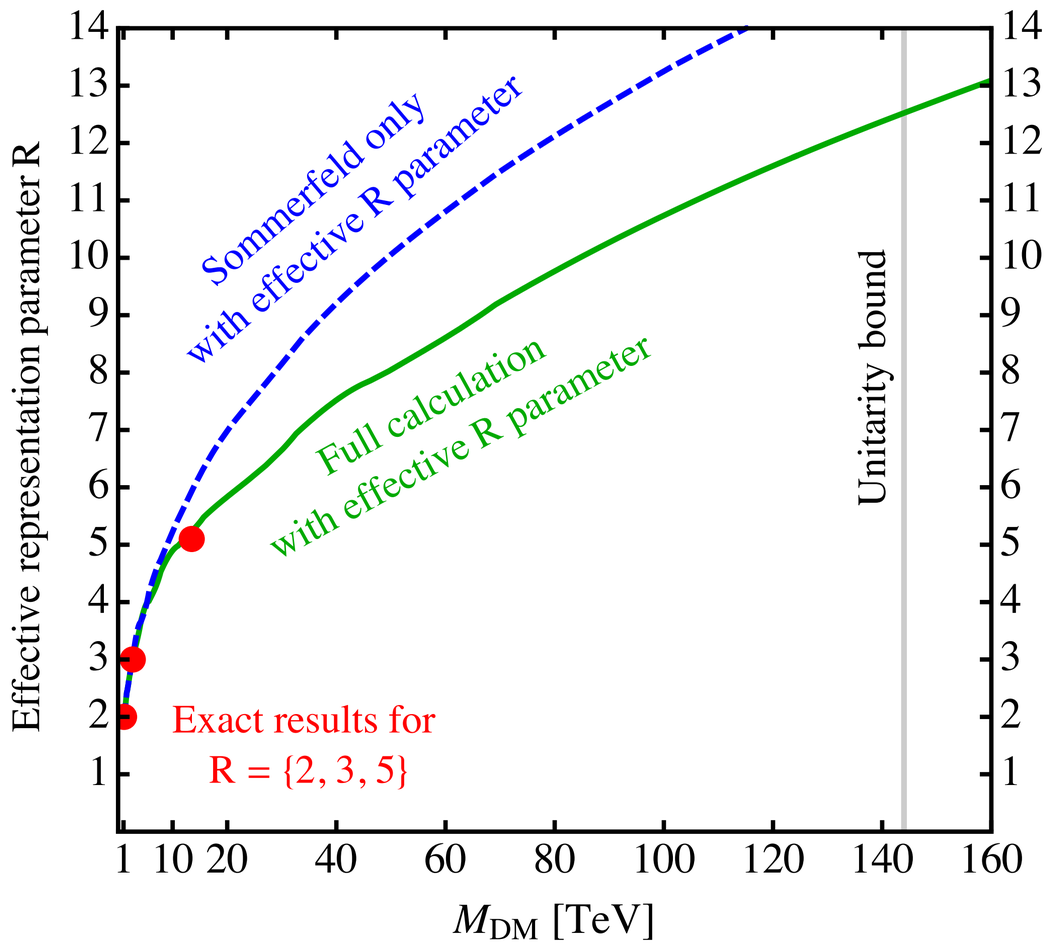
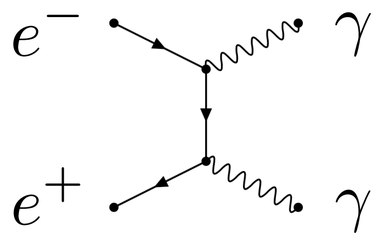
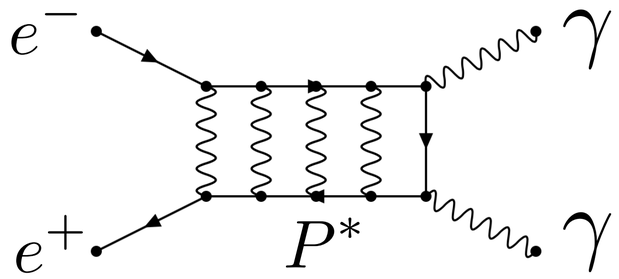
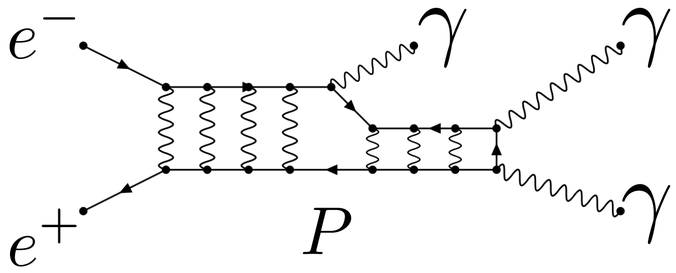
Electroweak Dark Matter

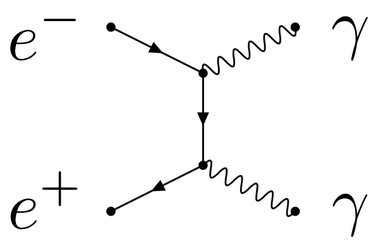
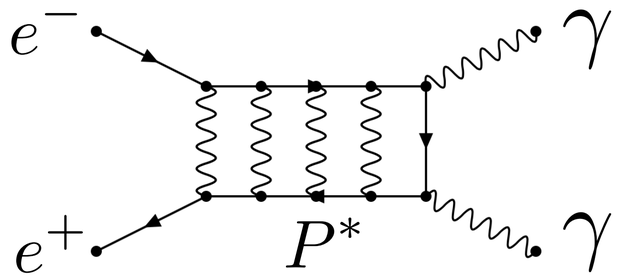
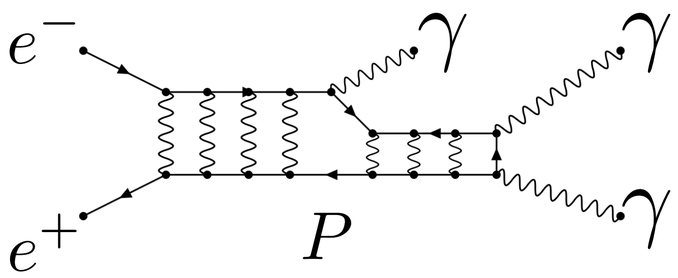


J. Smirnov, J. F. Beacom:
1904.11503

Process	Diagram	Cross-Section area
$e^+ e^- \to \gamma\gamma$		
$e^+ e^- \to P^* \to \gamma\gamma$		
$e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$		

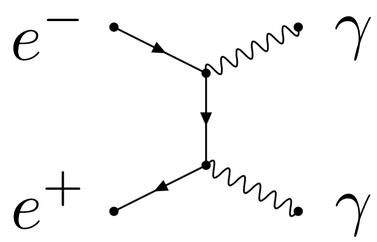
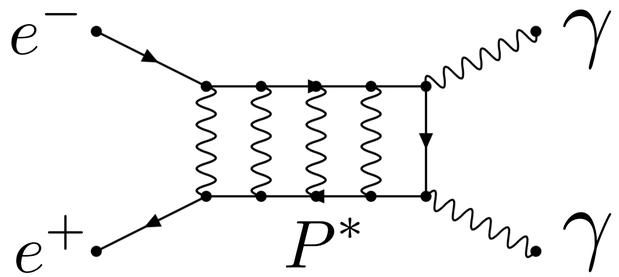
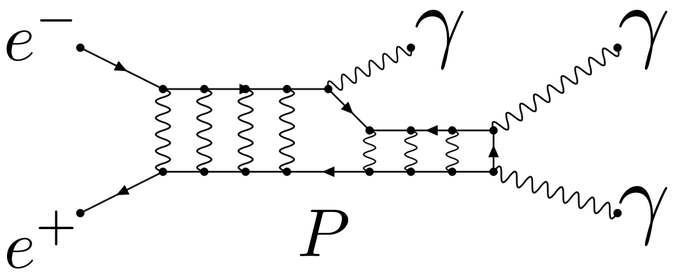
J. Smirnov: 2212.14361

Assuming Parapositronium (J=0)

Process	Diagram	Cross-Section area
$e^+ e^- \to \gamma\gamma$		large velocity
$e^+ e^- \to P^* \to \gamma\gamma$		
$e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$		

J. Smirnov: 2212.14361

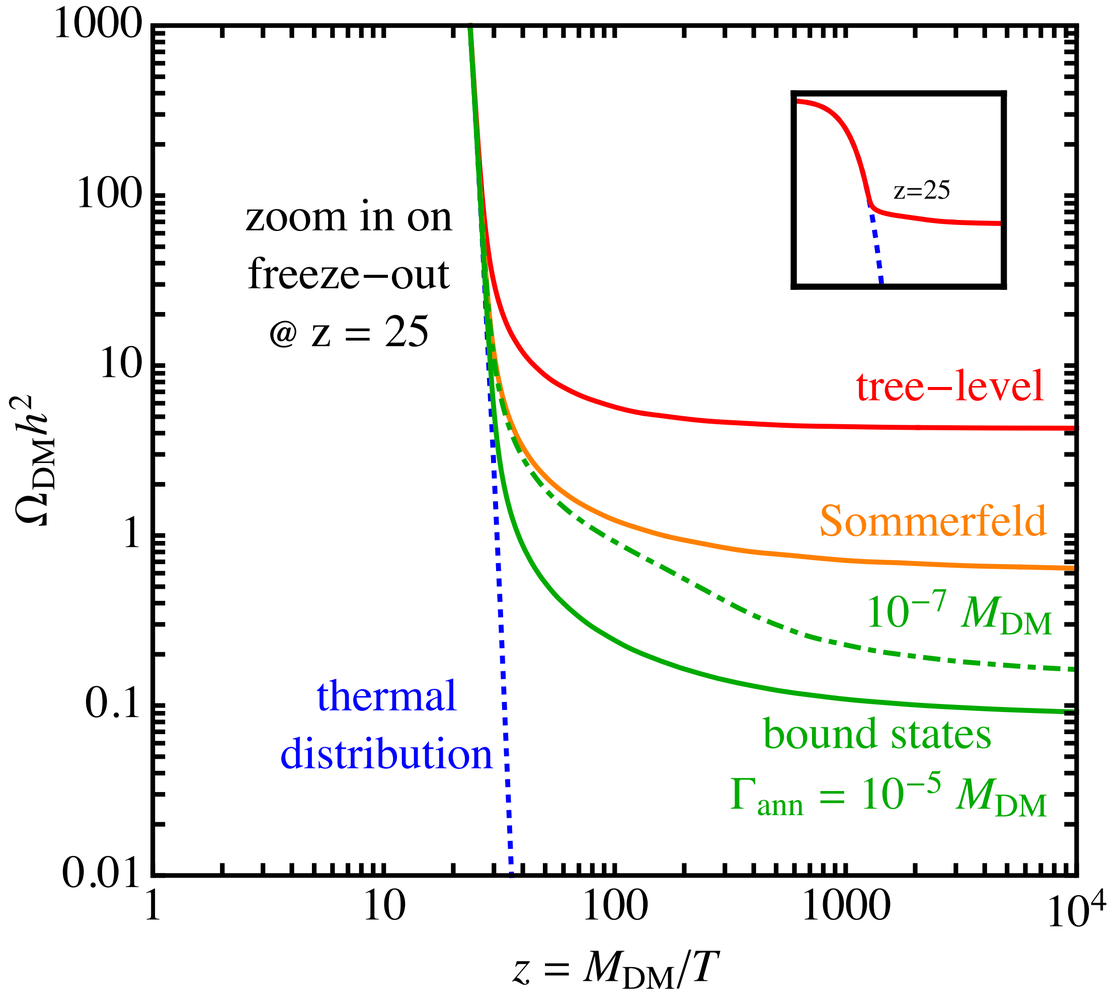
Assuming Parapositronium (J=0)

Process	Diagram	Cross-Section area	
		large velocity	small velocity
$e^+ e^- \to \gamma\gamma$			
$e^+ e^- \to P^* \to \gamma\gamma$			
$e^+ e^- \to P^* \to P\,\gamma$ $P \to \gamma\gamma$			

J. Smirnov: 2212.14361

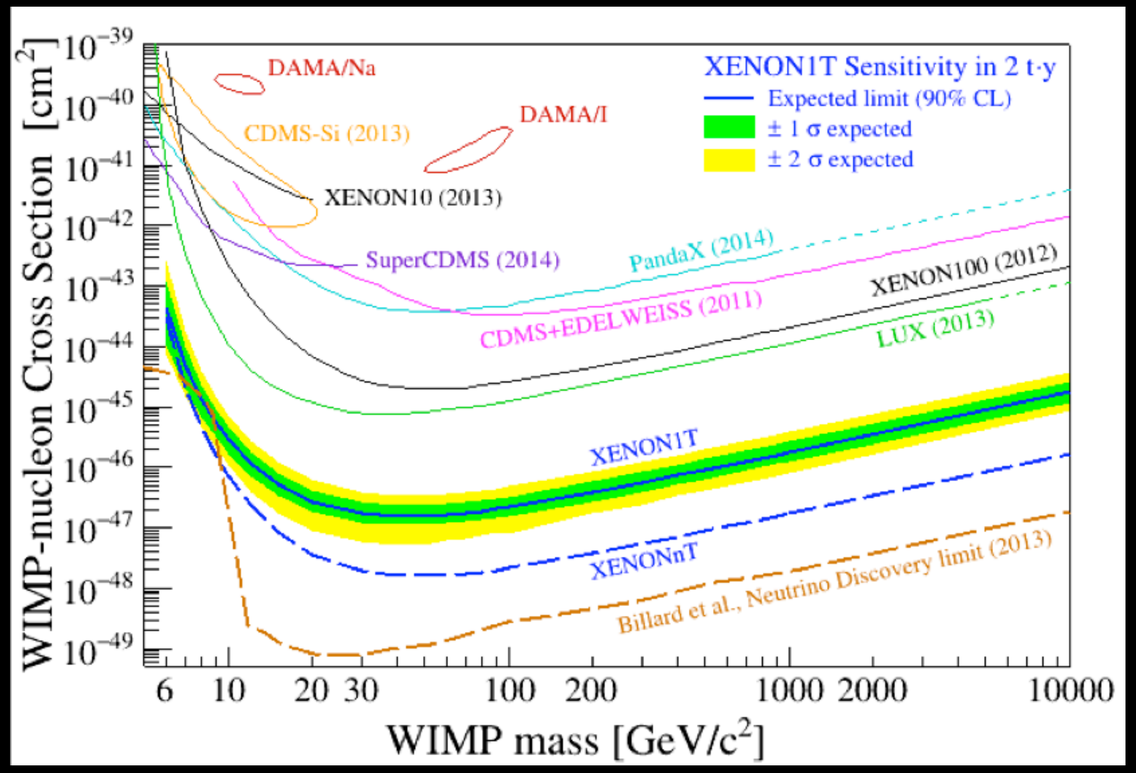
Assuming Parapositronium (J=0)

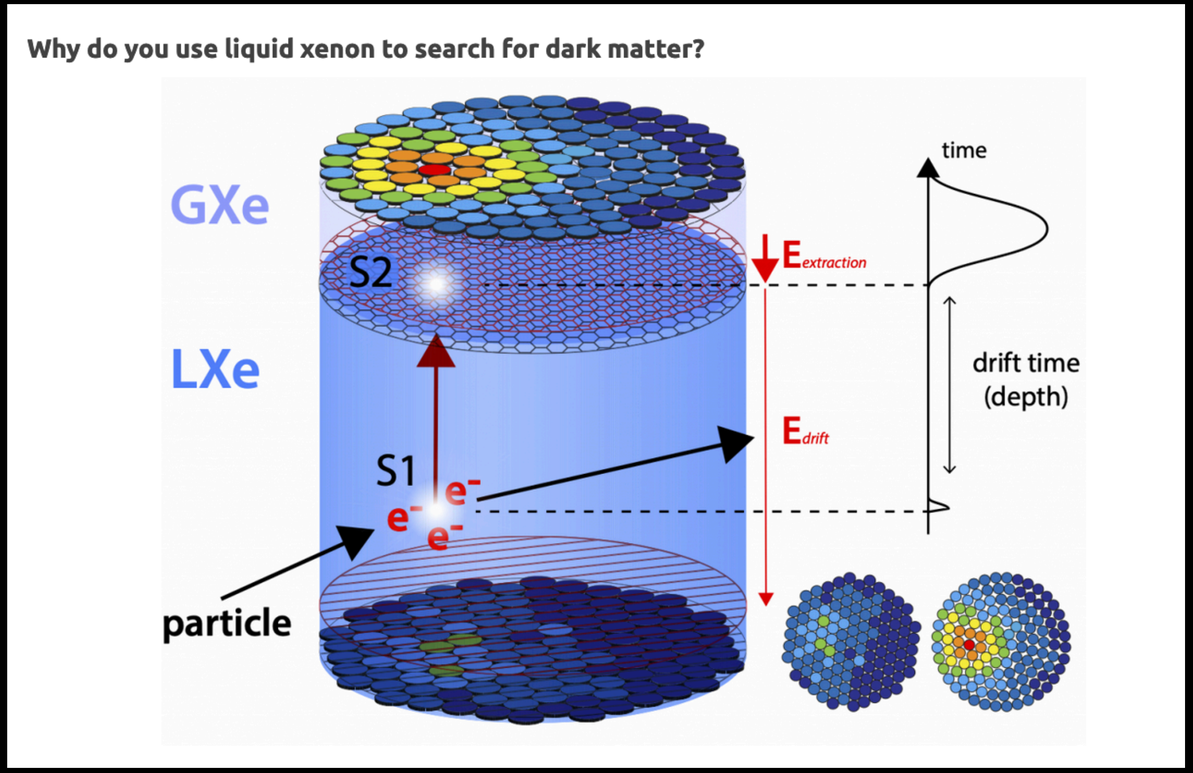
Effect on the Freezeout



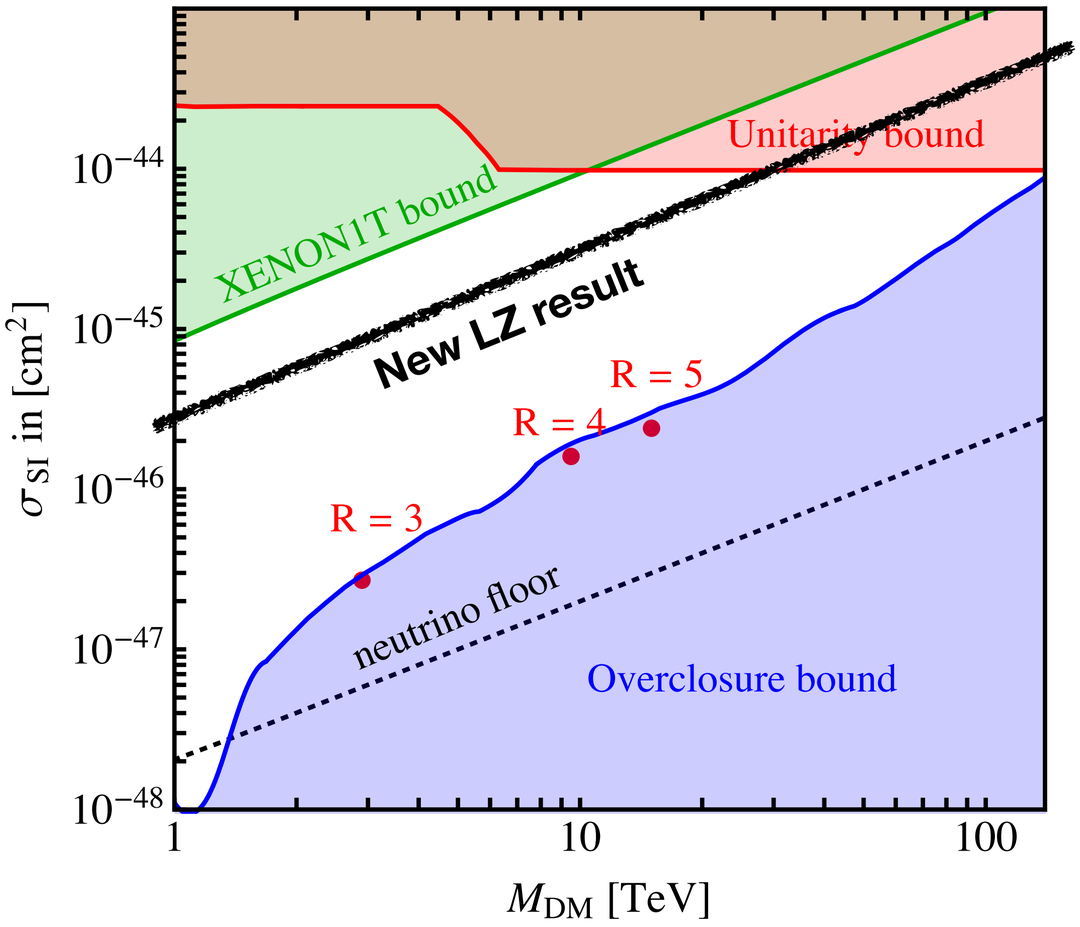
J. Smirnov, J. F. Beacom:
1904.11503

Direct Detection



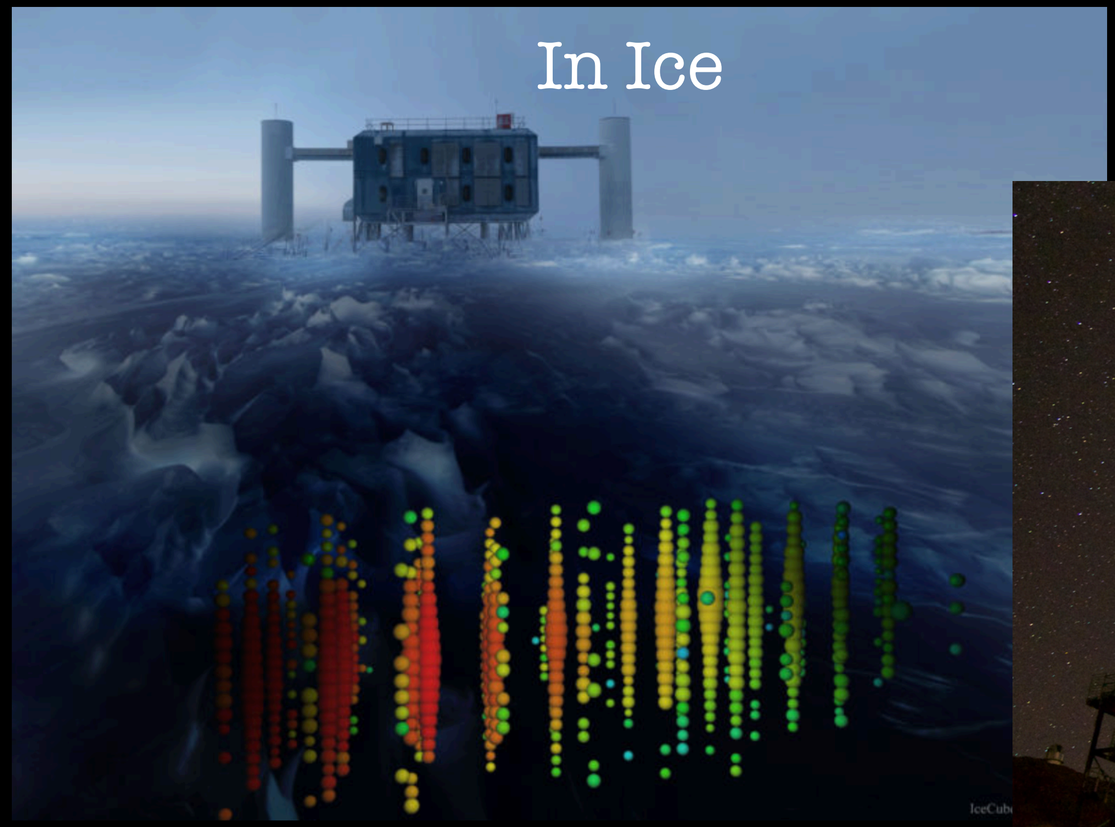


Direct Detection

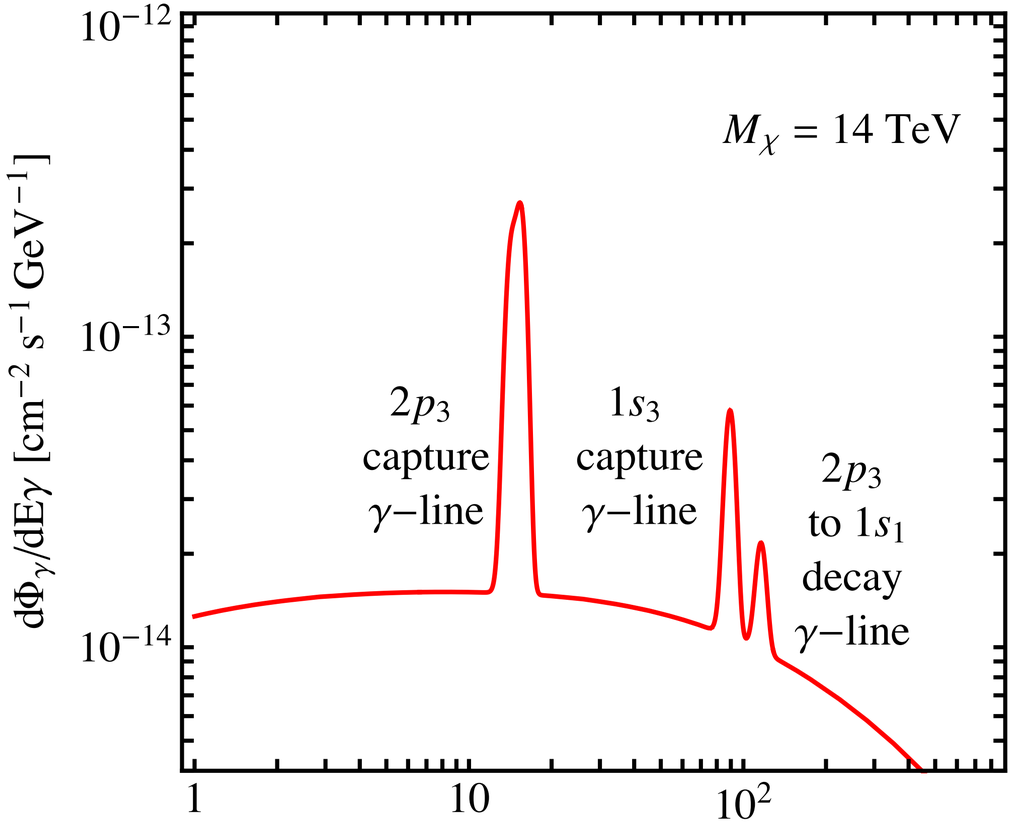


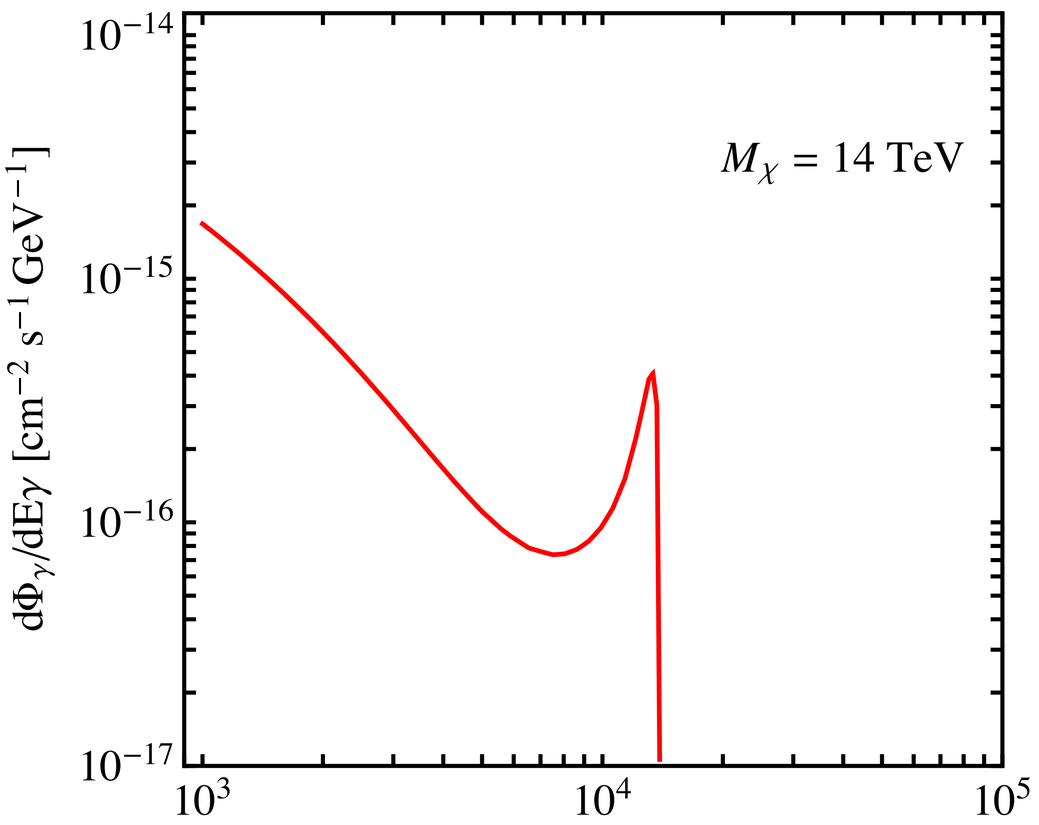
J. Smirnov, J. F. Beacom: 1904.11503

Indirect Searches for Heavy DM



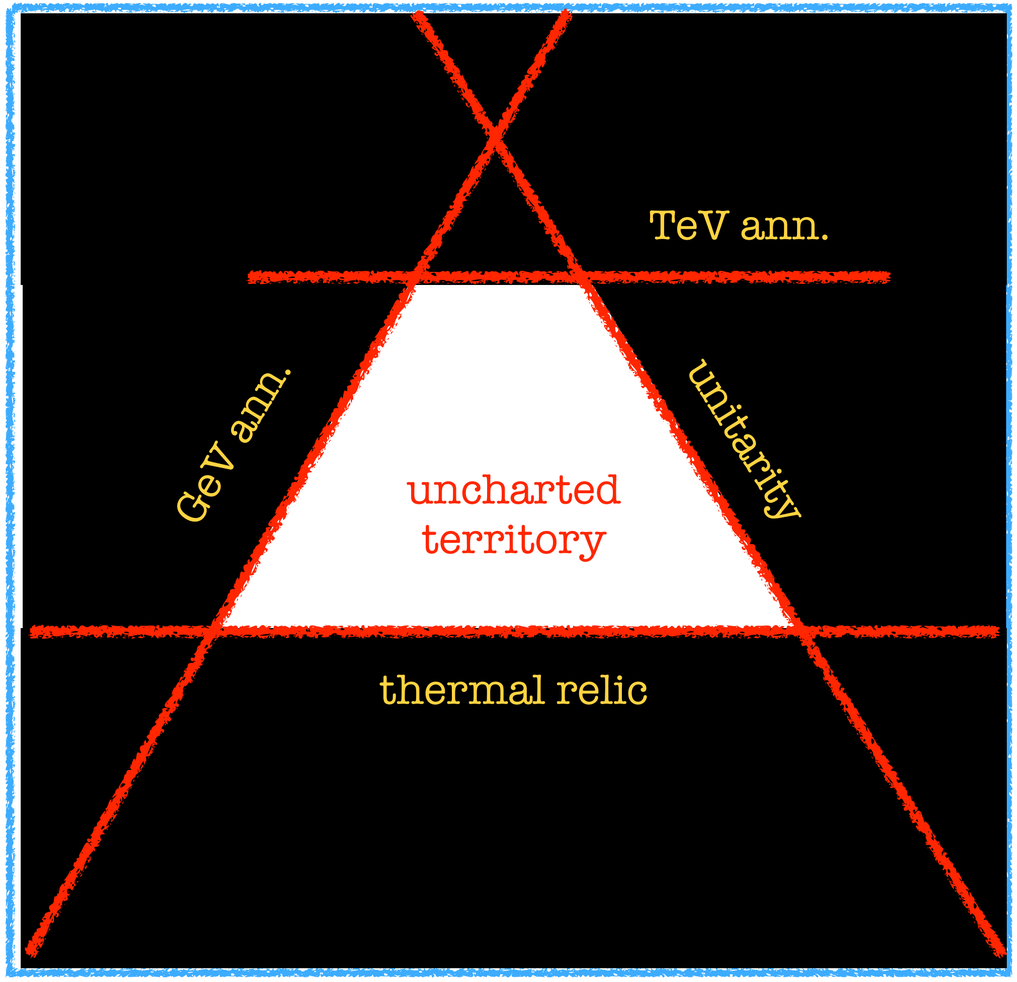
Example: DM Spectroscopy (SU(2) 5-plet)

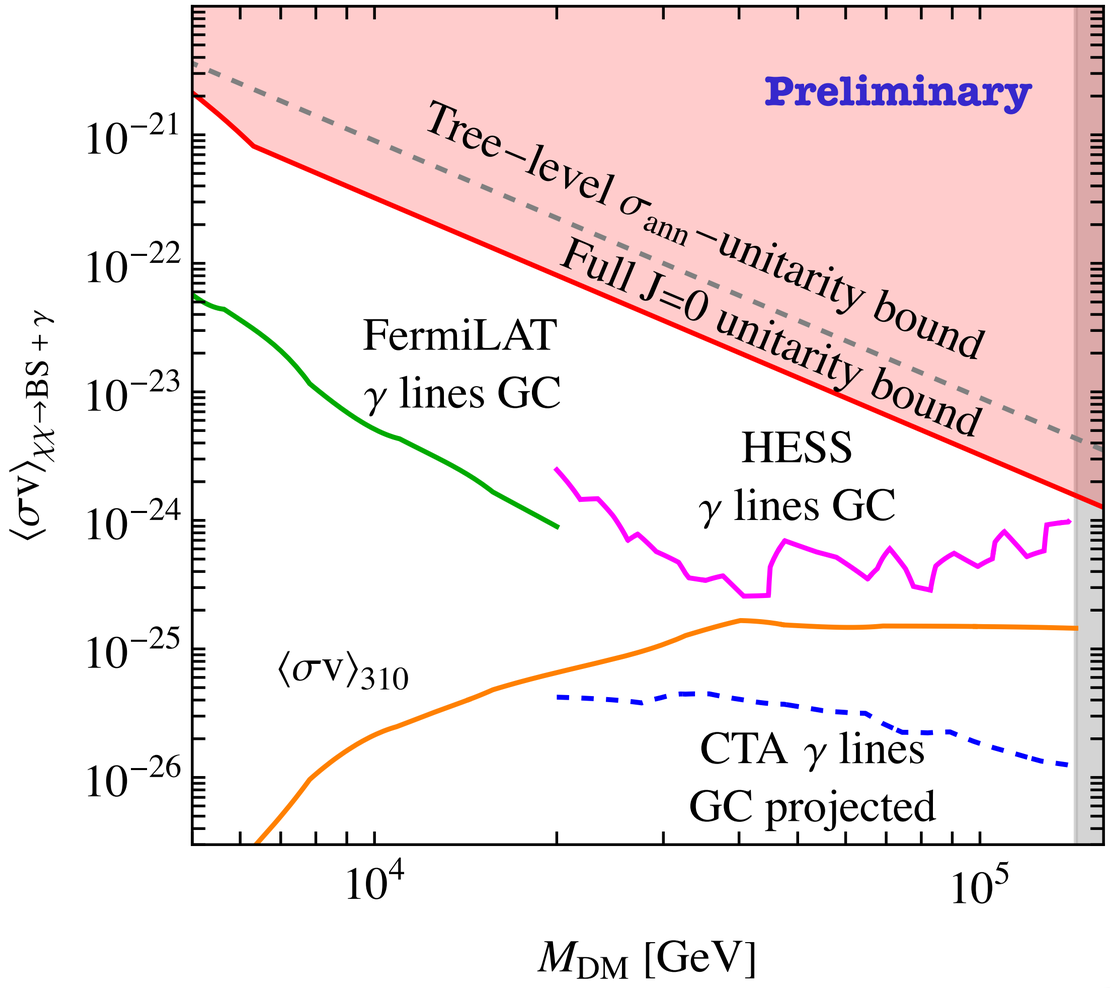




Smirnov, Beacom: 1904.11503

Sensitivity to Heavy Dark Matter





Asymptotic Safety and DM Mass

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The Dark Sector

$$\mathcal{L}_D \sim \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{gauge}}$$
$$\sim \frac{1}{2} D_\mu S D^\mu S^* + \lambda_p H^\dagger H S S^* + \lambda_S (S S^*)^2 + \frac{m_S^2}{2} S S^*$$
$$+ i\bar{\psi} \not{D} \psi + M_\psi \bar{\psi}\psi + y_\psi \, S \bar{\psi} \psi^c$$
$$+ \frac{1}{4} F^X_{\mu\nu} F_X^{\mu\nu} + \frac{\epsilon}{2} F^Y_{\mu\nu} F_X^{\mu\nu} + \frac{M_{Z'}^2}{2} \left(Z'_\mu - \partial_\mu \zeta \right)^2$$

M. Reichert, J. Smirnov: 1911.00012

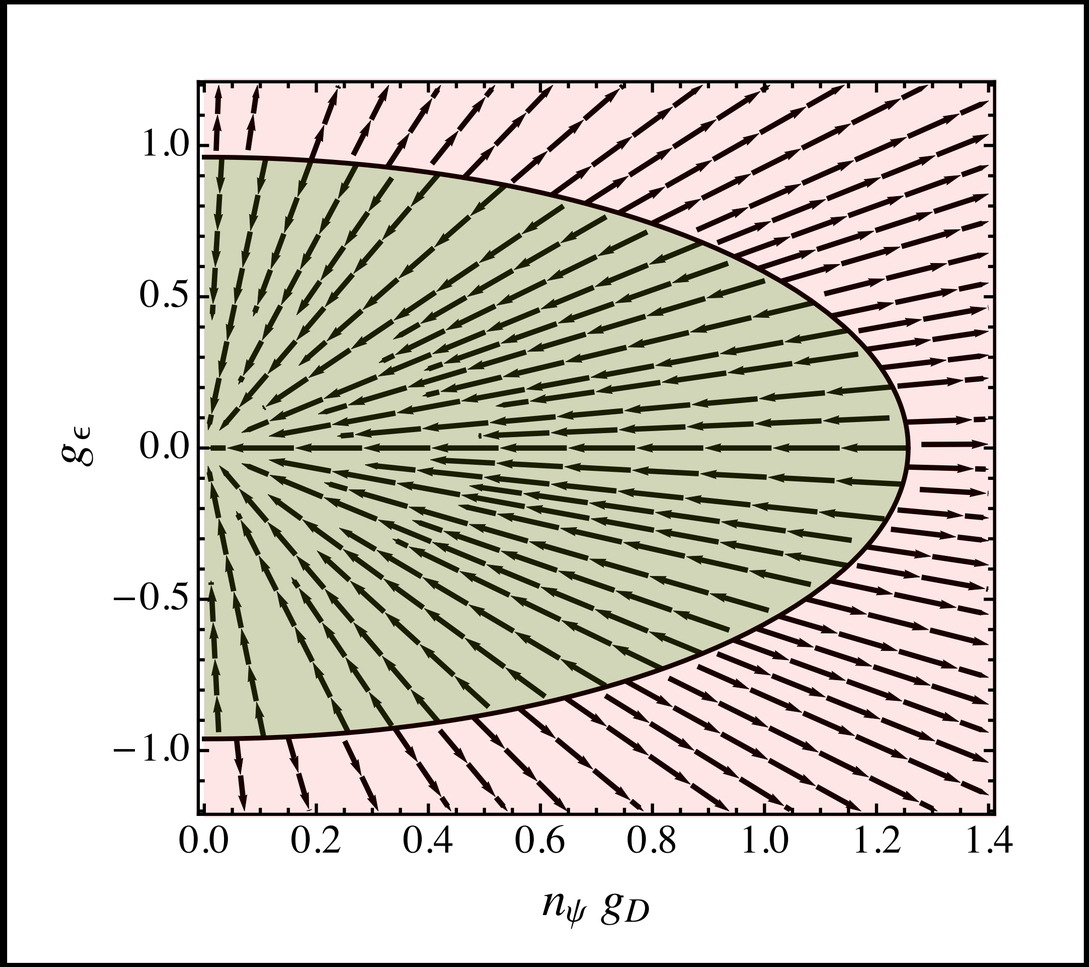
See also the talk by: Abhishek Chikkaballi

Note: Fixed-point is left invariant

$$\tilde{G}^* \approx -\frac{12\pi}{N_S + 2N_D - 4N_V - 46}$$

1) Stückelberg Mass for the Z'
2) Vector-like fermions for Vacuum Stability

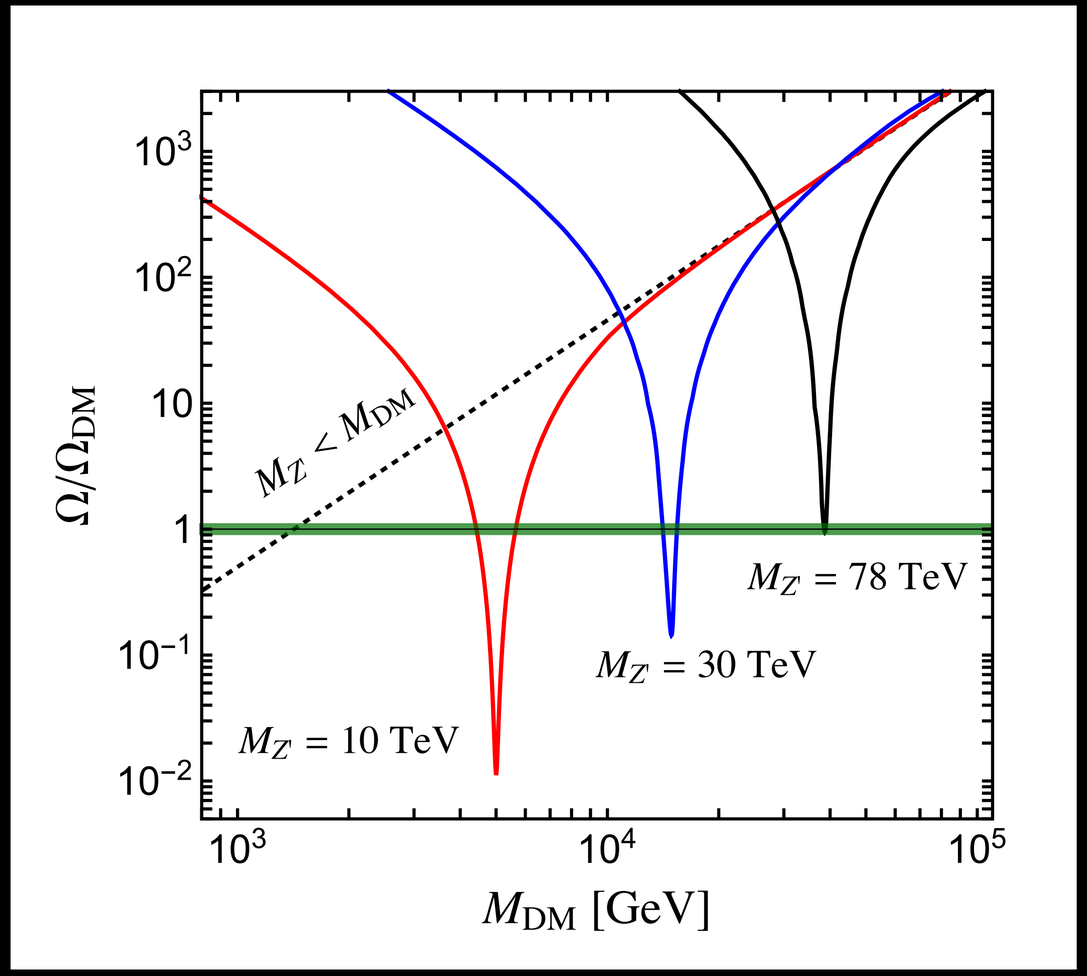
Fermion Dark Matter



M. Reichert, J. Smirnov: 1911.00012

1) Upper bound on gauge coupling and quantum number
2) Allows to derive an absolute upper bound on the DM mass

Fermion Dark Matter



$$m_\psi \approx m_{Z'}/2$$

- Resonant annihilation: leads to maximal mass
  $M_{DM} < 40$ TeV
- Non-Resonant scenario:
  $M_{DM} > M_{Z'}$
  leads to $M_{DM} < 2$ TeV

M. Reichert, J. Smirnov: 1911.00012

Beyond Weak Interactions

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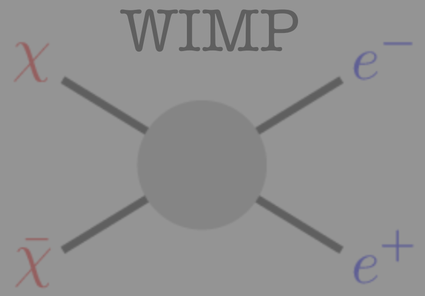
Other Types of Freezeout

WIMP



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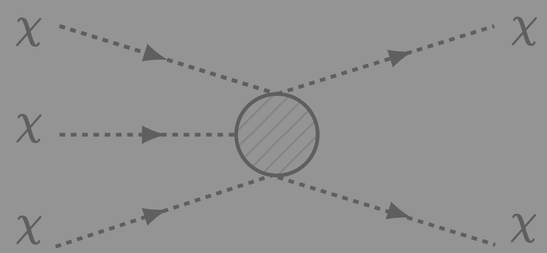

Hochberg, Kuflik, Volansky, Wacker

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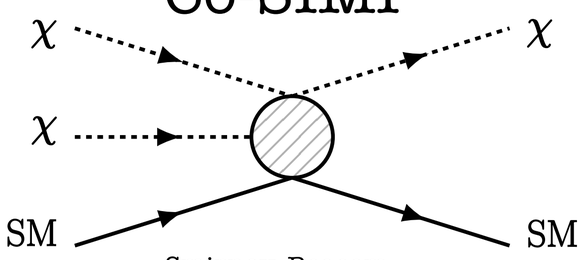
$$\Omega_{\rm DM}\, h^2 \approx \left(\frac{\rm MeV}{m_{\rm DM}}\right) \frac{0.12}{\sqrt{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, [3{\rm MeV}]^5}}$$

Co-SIMP

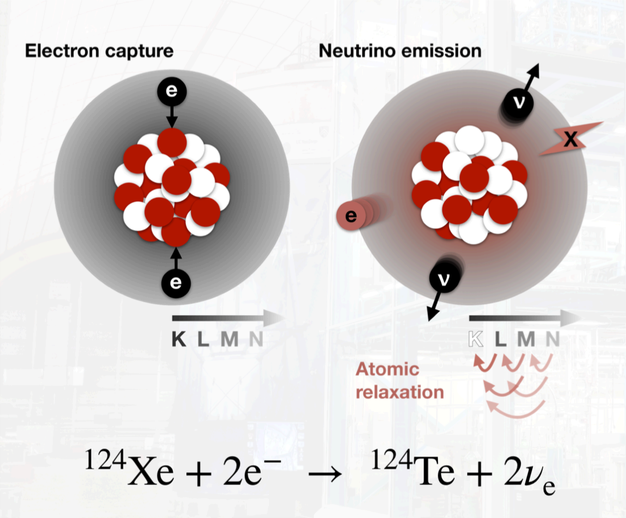


Smirnov, Beacom

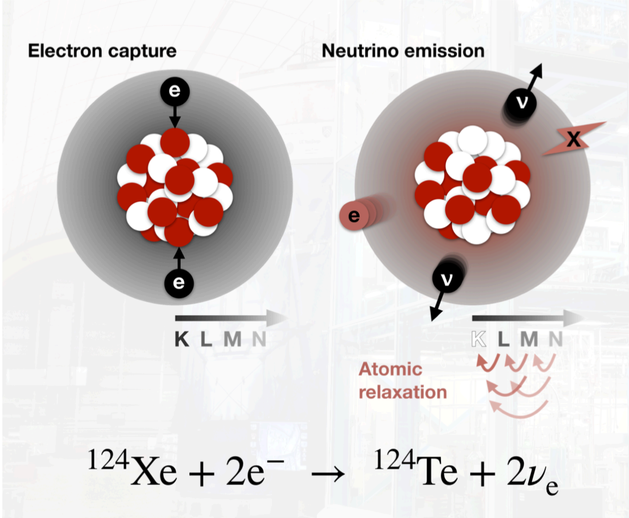
$$\Gamma_{\rm DM} = \langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle \, n_{\rm DM} n_{\rm SM} > H(T)$$

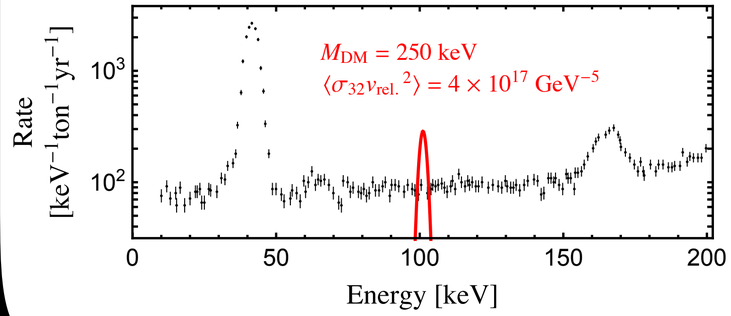
$$\Omega_{\rm DM} h^2 \approx \left(\frac{\rm MeV}{m_{DM}}\right)^3 \frac{0.12}{\langle \sigma_{3\to 2} v_{\rm rel.}^2 \rangle [100\,{\rm MeV}]^5}$$

Double Electron Capture

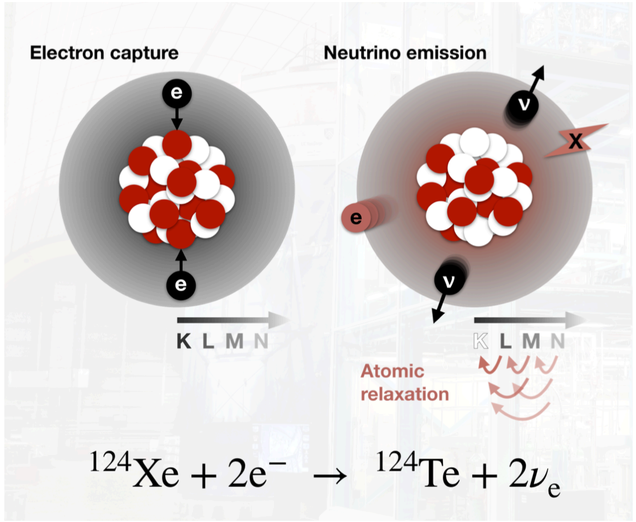


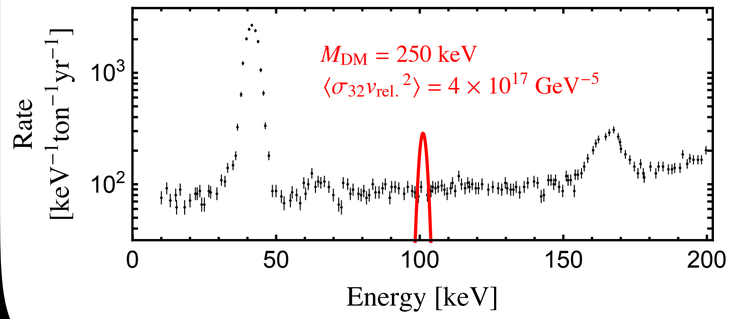
Double Electron Capture

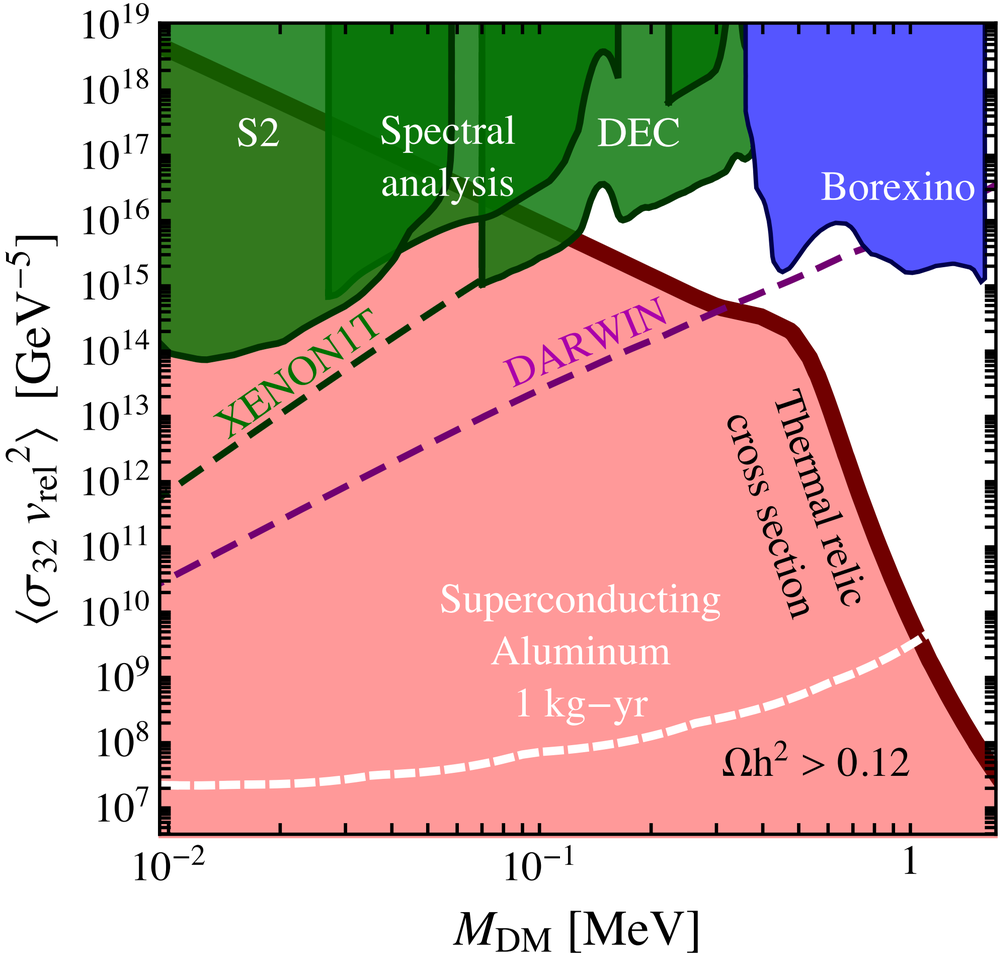




Double Electron Capture







arXiv: 2002.04038; J. Smirnov, J. Beacom

We need lower Energy Thresholds

We need lower Energy Thresholds

Superfluid He

We need lower Energy Thresholds

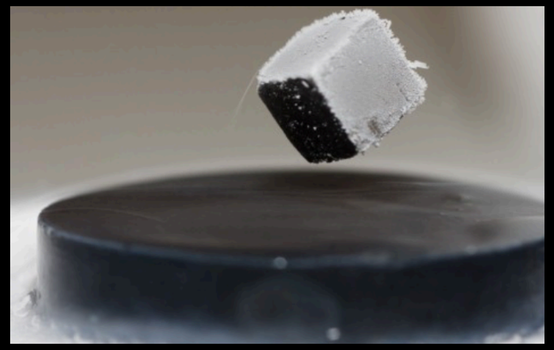
Superfluid He

Materials with Lattice Defects

We need lower Energy Thresholds

Superfluid He

Materials with Lattice Defects

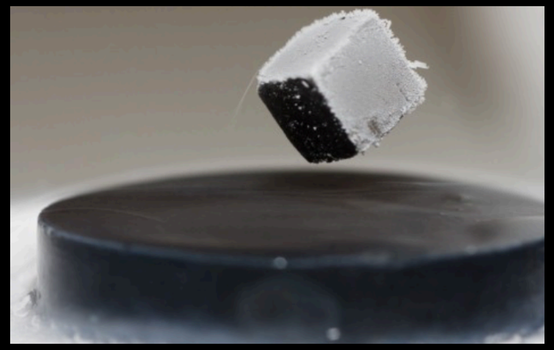


Superconductors

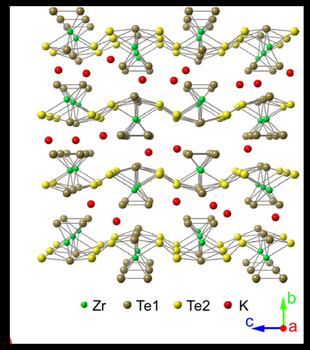
We need lower Energy Thresholds

Superfluid He

Materials with Lattice Defects



Superconductors



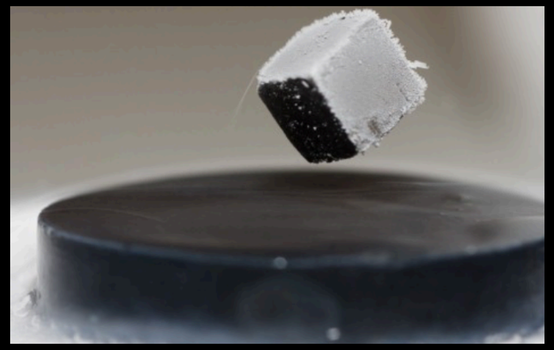
3D Dirac Materials

We need lower Energy Thresholds

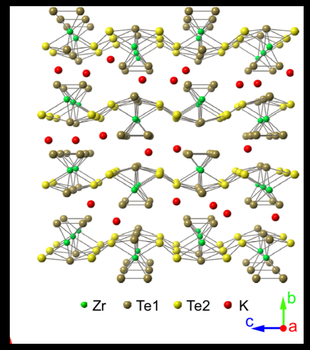
Superfluid He

Materials with Lattice Defects

Small ΔE

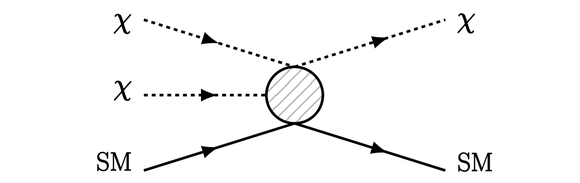


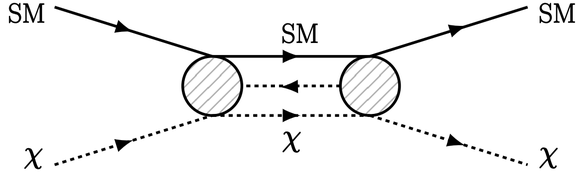
Superconductors



3D Dirac Materials

Scattering off Electrons

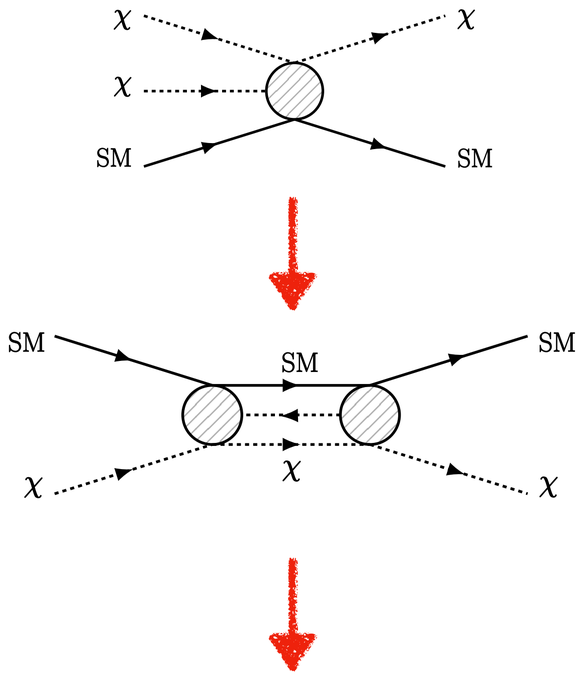




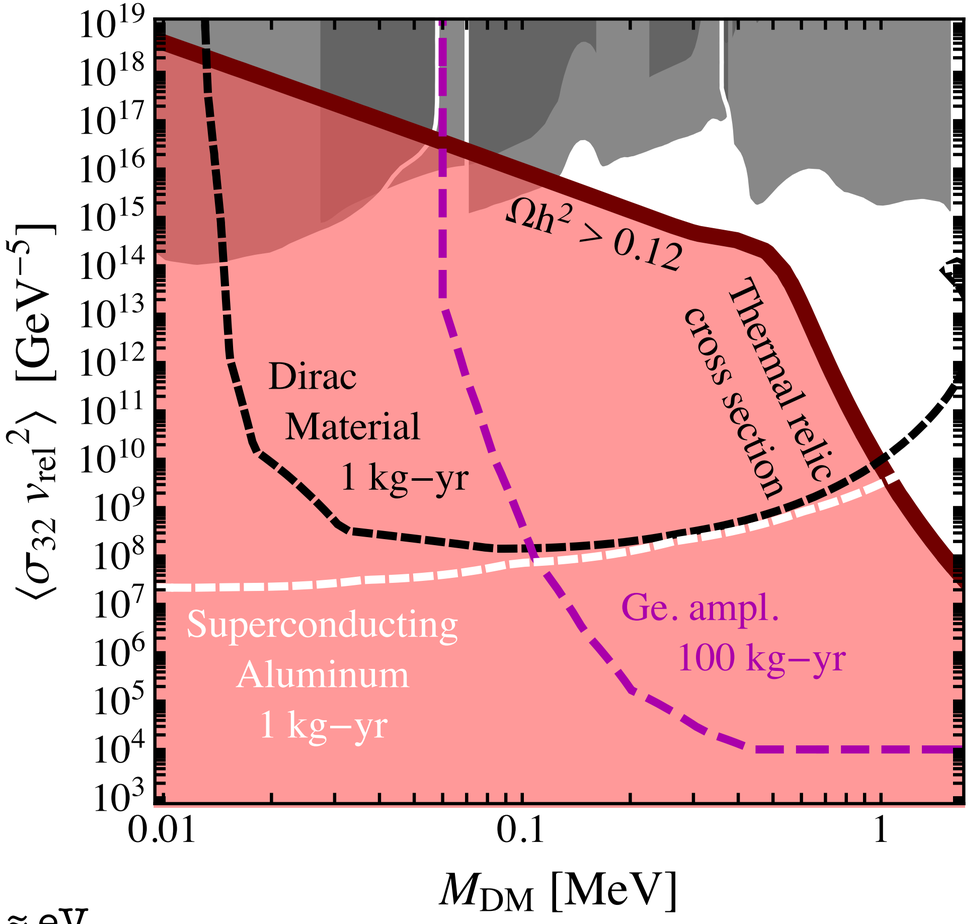
$$E_R \approx v_{\rm rel}^2 \frac{\mu^2}{M_{\rm SM}}$$

Detectors with lower energy thresholds ≈ eV

Scattering off Electrons



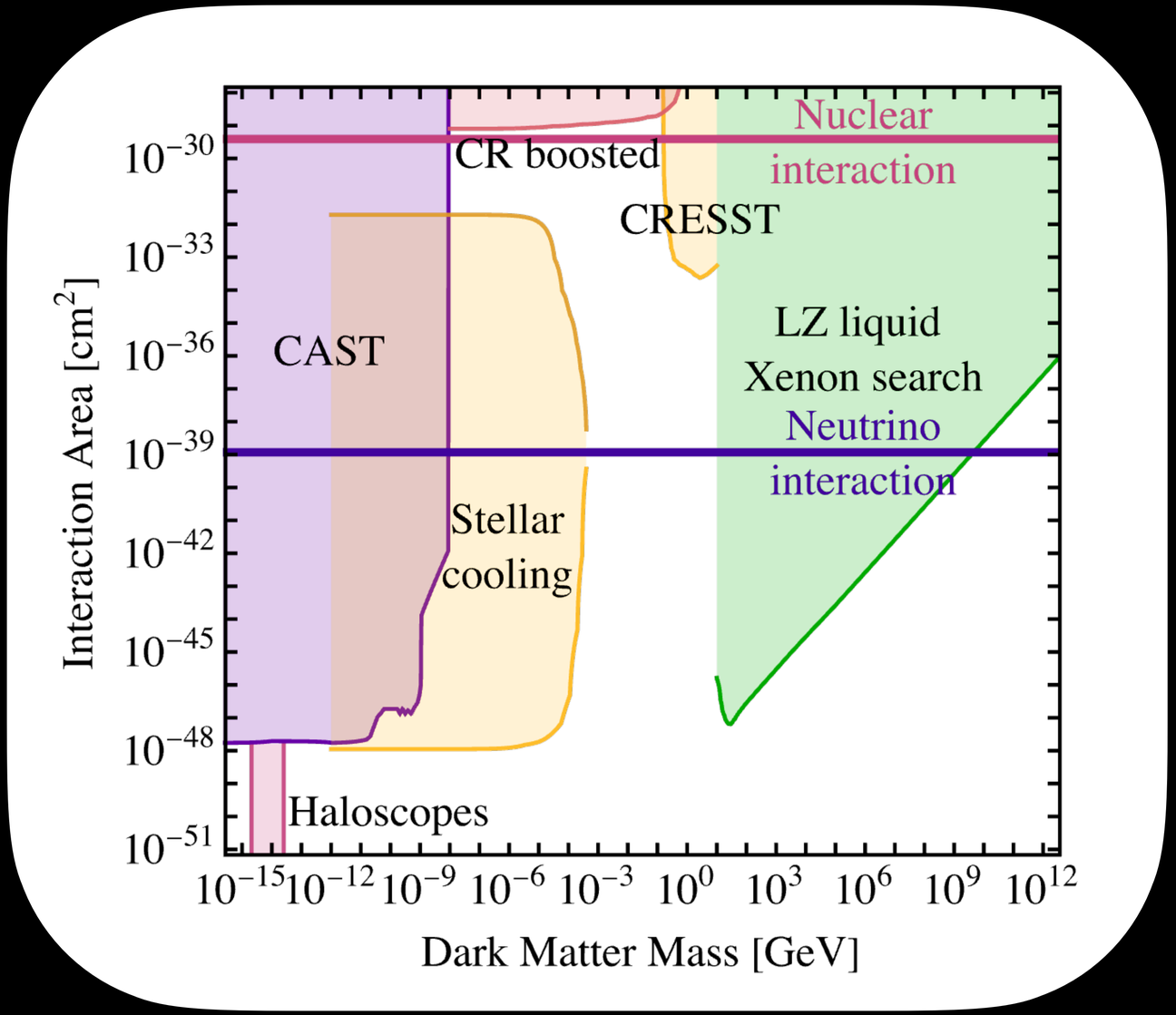
$$E_R \approx v_{\rm rel}^2 \frac{\mu^2}{M_{\rm SM}}$$



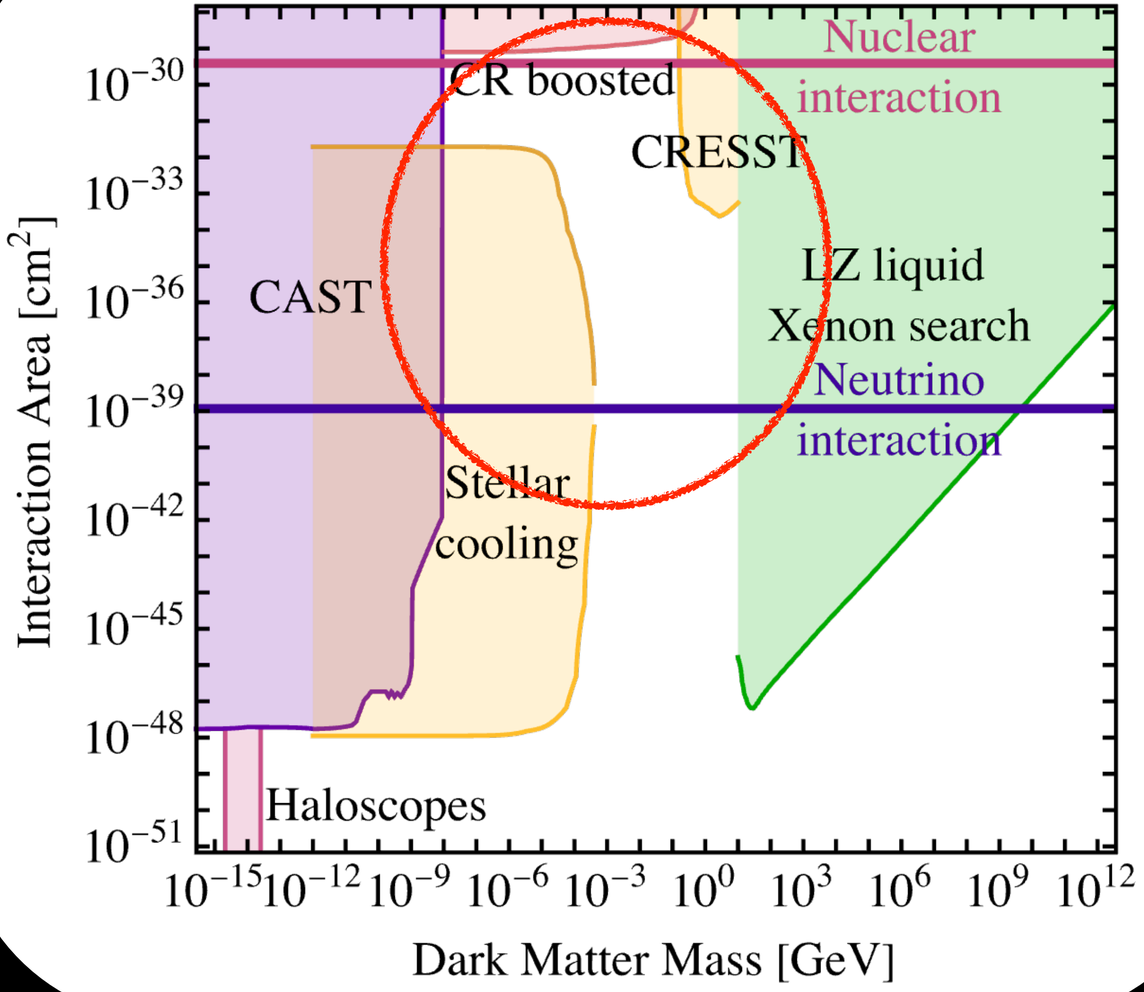
Detectors with lower energy thresholds ≈ eV

arXiv: 2002.04038; J. Smirnov, J. Beacom

Cartoon of Interaction Space



Cartoon of Interaction Space

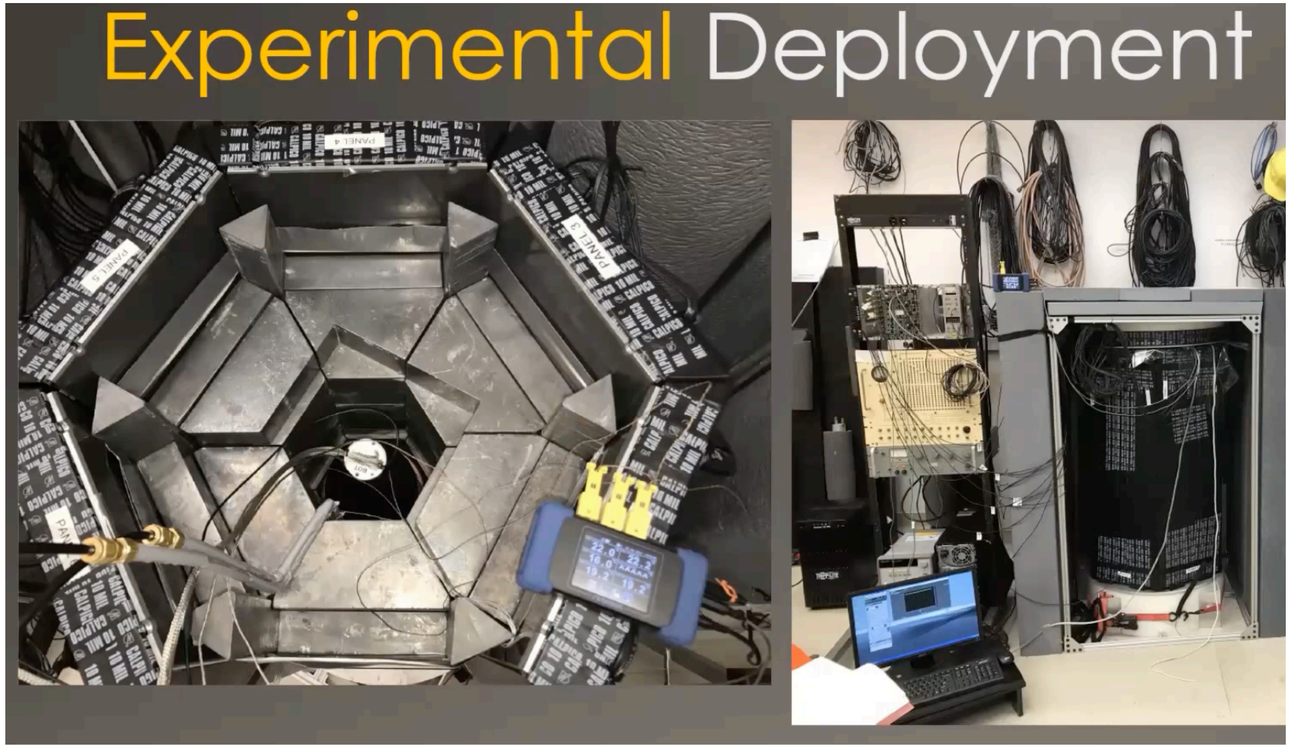


Direct Detection with Organic Molecules

Dark Matter-Electron Scattering from Aromatic Organic Targets

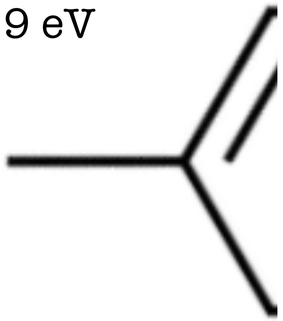
Carlos Blanco[a,b], J.I. Collar[a,b], Yonatan Kahn[c], and Benjamin Lillard[c]

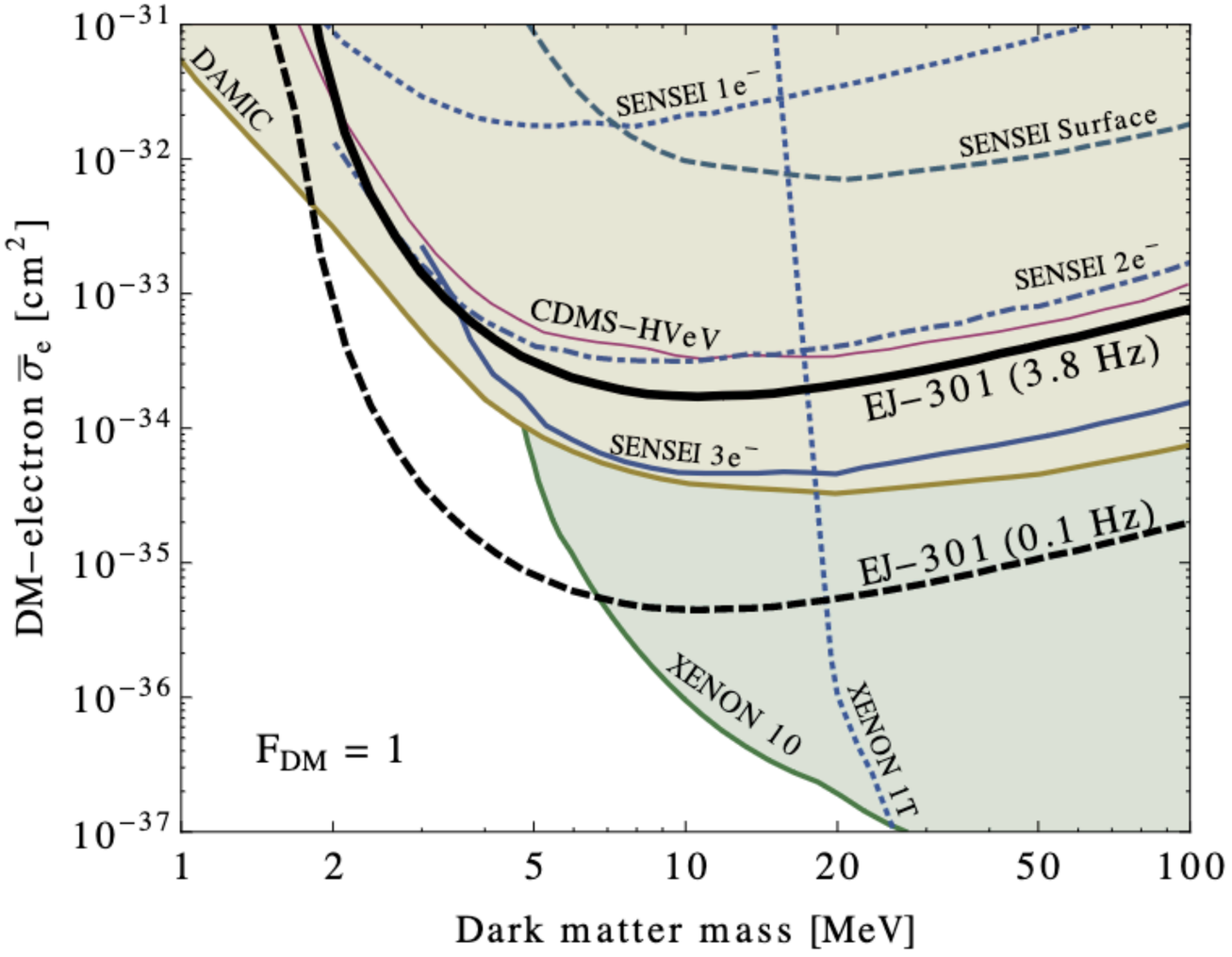
8 - 9 eV

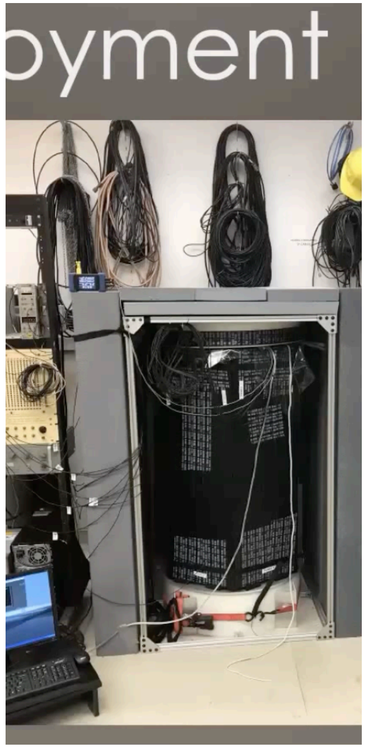


Direct Detection with Organic Molecules

8 - 9 eV

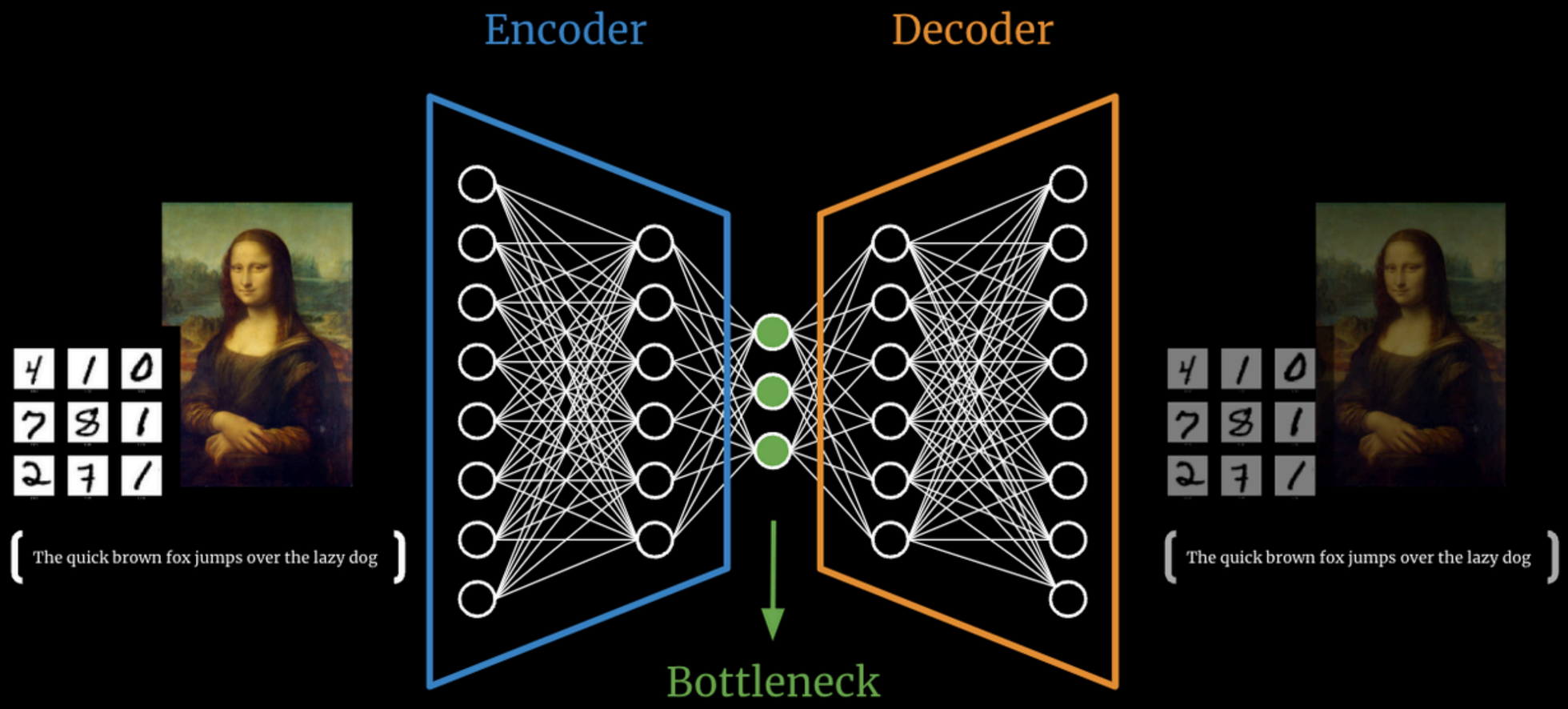






What is the optimal Target ?

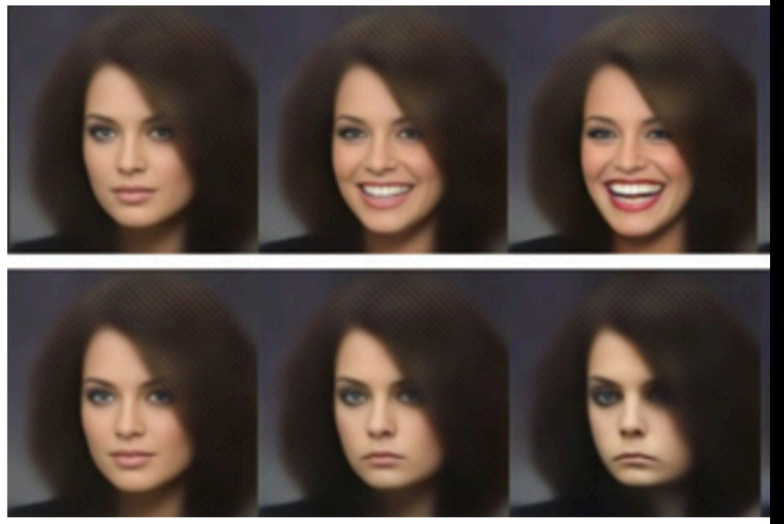
Teaching Machines Chemistry



Vectors in the Latent Space

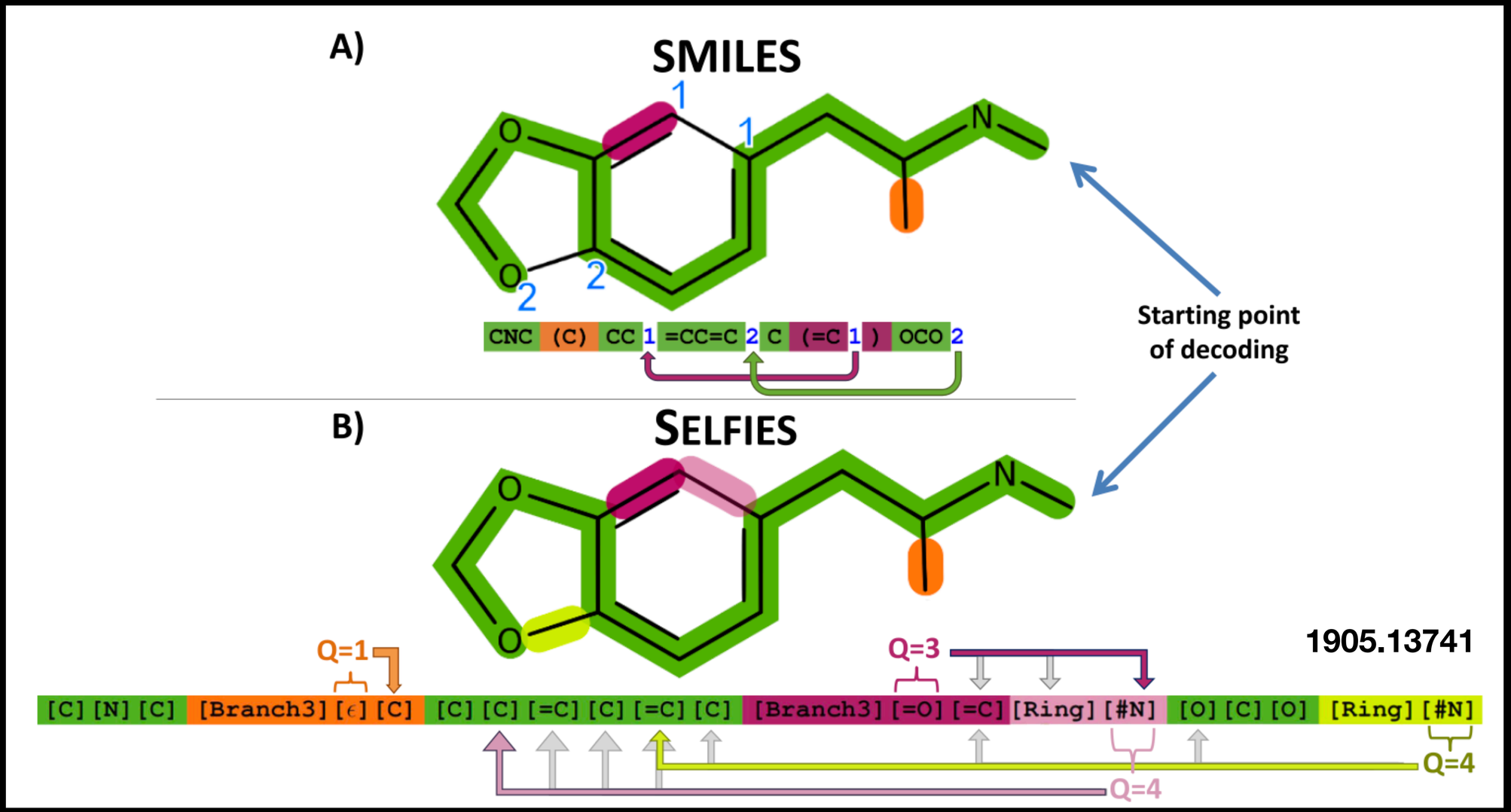
- A continuous space of faces generated by Tom White using VAEs

- The smile vector

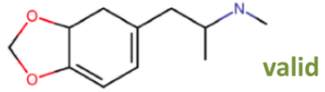
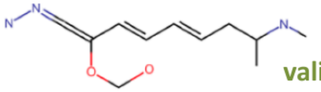
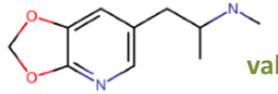
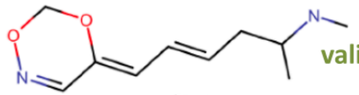
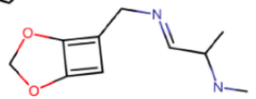
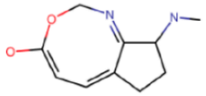
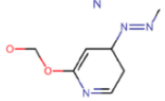


https://gaussian37.github.io/deep-learning-chollet-8-4/

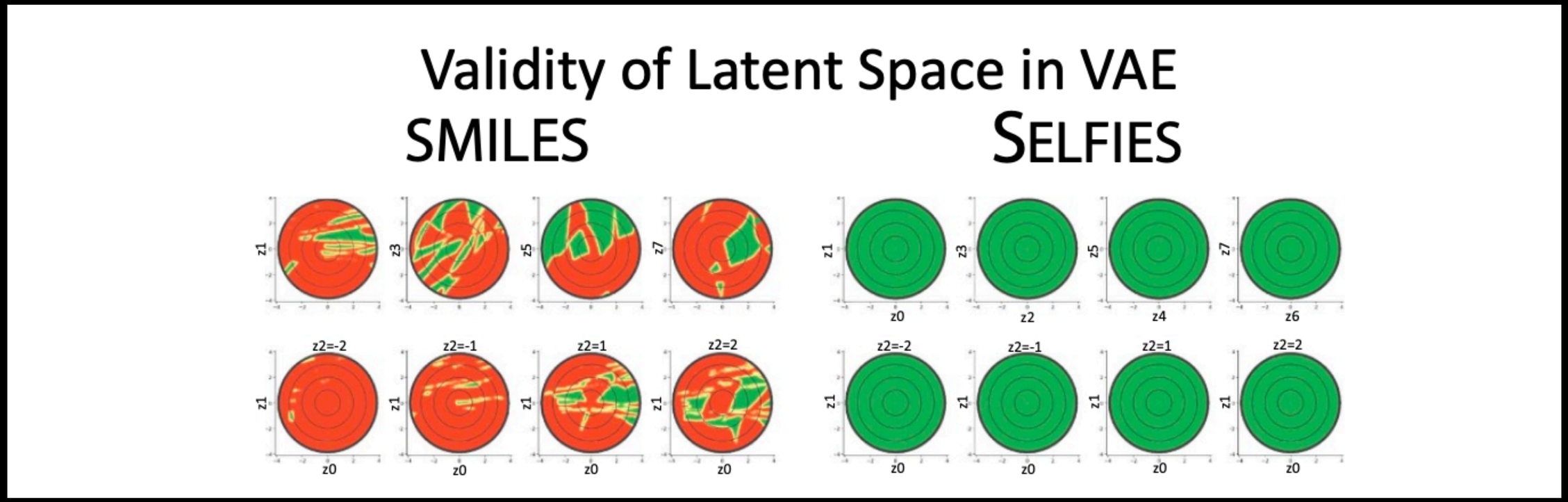
SMILES and SELFIES



Mutations and Validity

SMILES	SELFIES
A) Single Mutation	
CNC(C)CC1=CC=CNC(=C1)OCO2 syntactically invalid	 valid
CNC(C)CC1=CC=C2C(=C1FOCO2 syntactically invalid	 valid
CFC(C)CC1=CC=C2C(=C1)OCO2 semantically invalid	 valid
B) Double Mutation	
CNC(C)OC1=CC=C2C(=C1COCO2 syntactically invalid	 valid
CNC(C)CC1=CCOCCC(=C1)OCO2 syntactically invalid	 valid
CNC(C)#C1=CC=C2C(=C1)OCON syntactically & semantically invalid	 valid
C) Triple Mutation	
C=C(C#CC1=CC=C2C(=CN)OCO2 syntactically invalid	 valid
CNO(C)CC1=CC=C2C(#F1)OCO2 syntactically & semantically invalid	 valid
CNC(C)CC1=CCCC2#F=C1)OCO2 syntactically & semantically invalid	 valid

Latent Space Quality



Learning the QM9 dataset 130 kMolecules

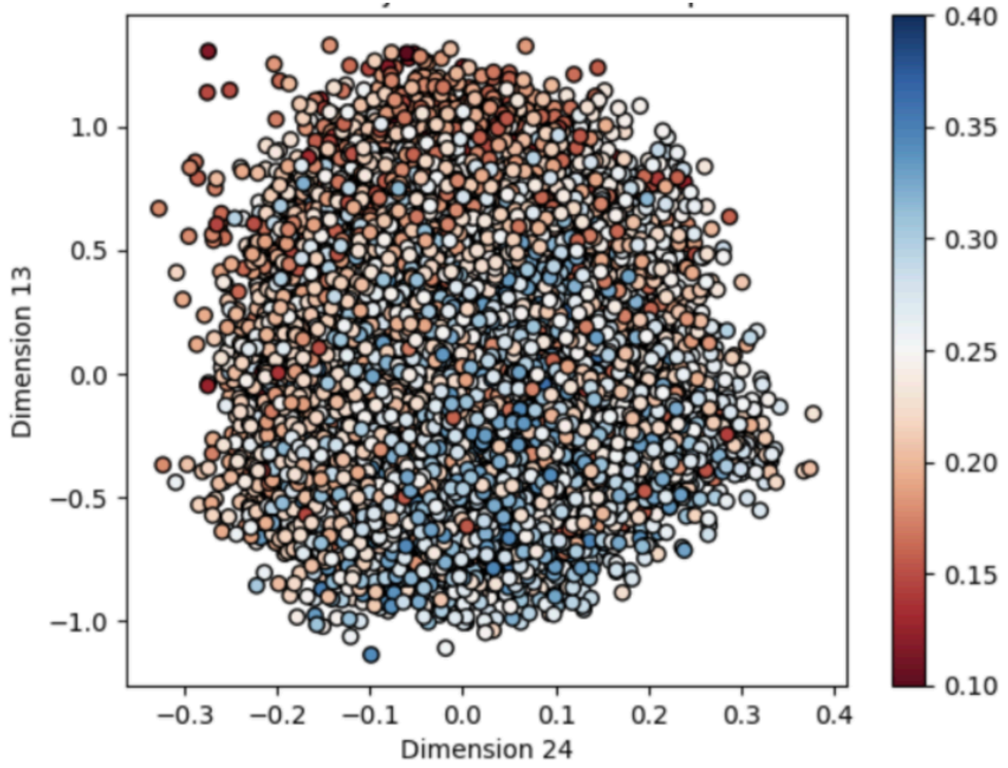


FIG. 2. A 2D projection of our latent spaces showing the intrisic separation of molecules by HOMO-LUMO gap.

Learning the QM9 dataset 130 kMolecules

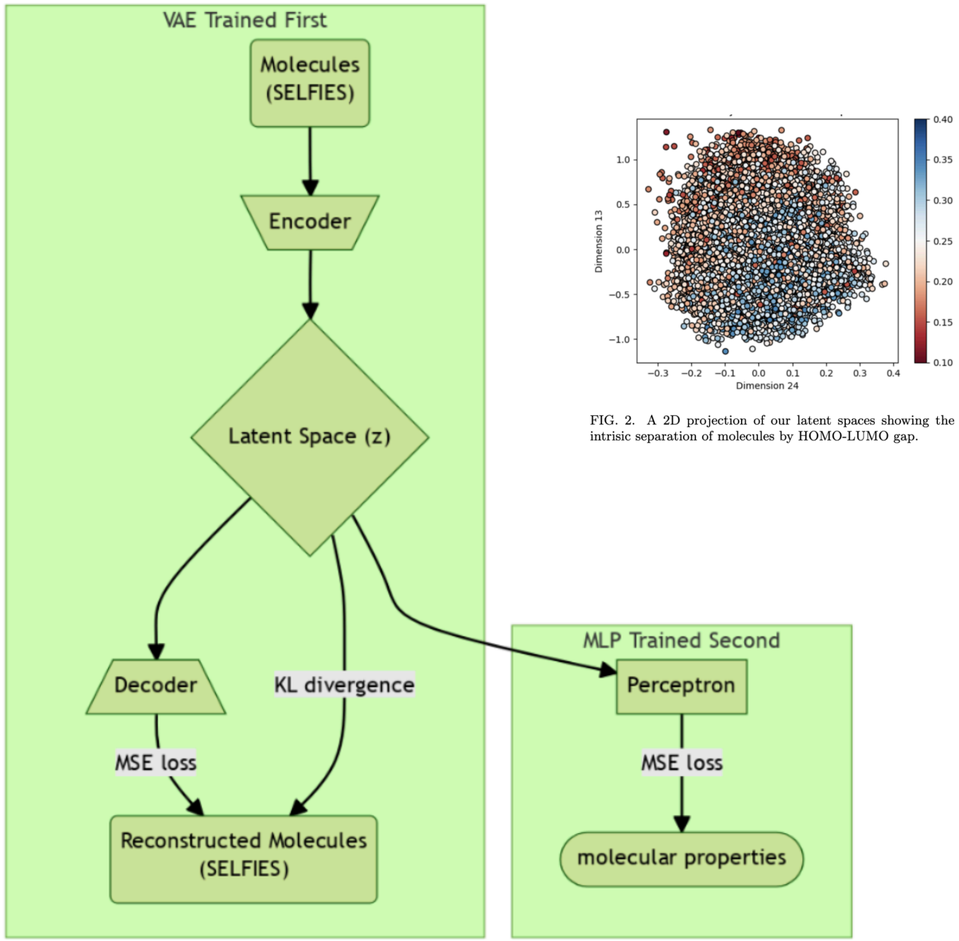


FIG. 2. A 2D projection of our latent spaces showing the intrisic separation of molecules by HOMO-LUMO gap.

Learning the QM9 dataset 130 kMolecules

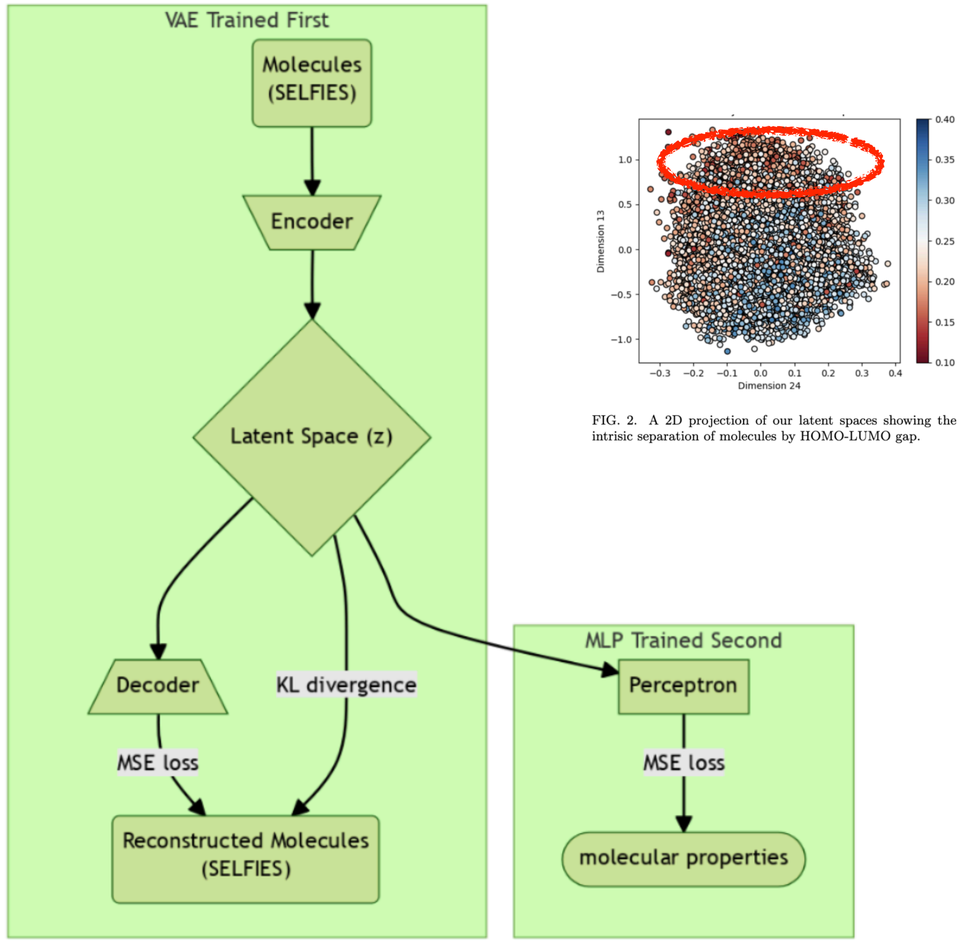
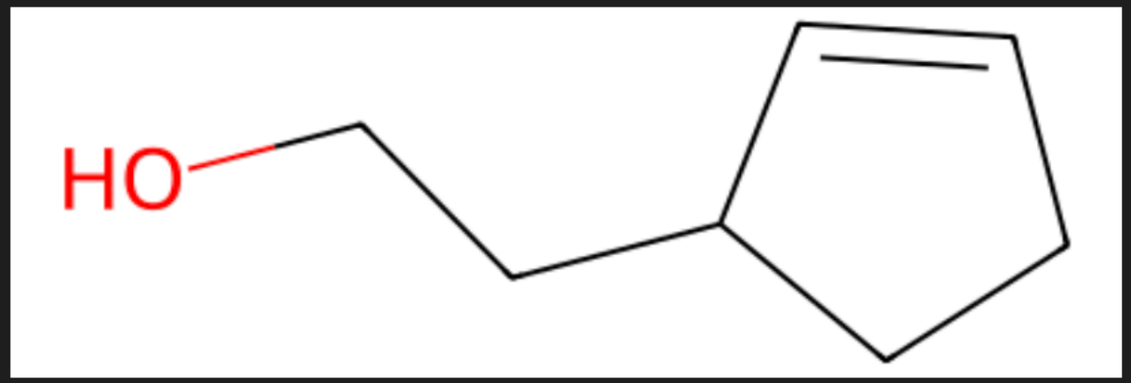


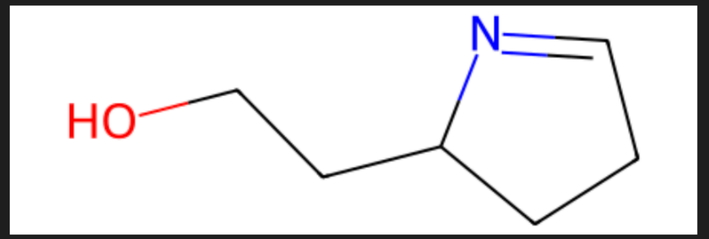
FIG. 2. A 2D projection of our latent spaces showing the intrisic separation of molecules by HOMO-LUMO gap.

Example: reconstructing in QM9

input molecule

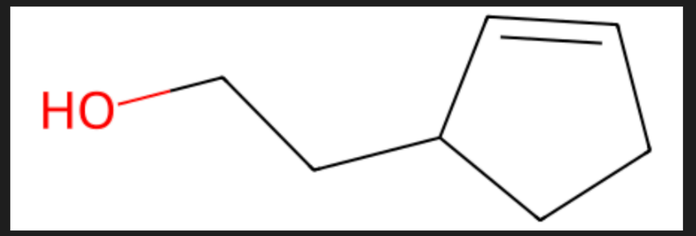


reconstructed molecule:



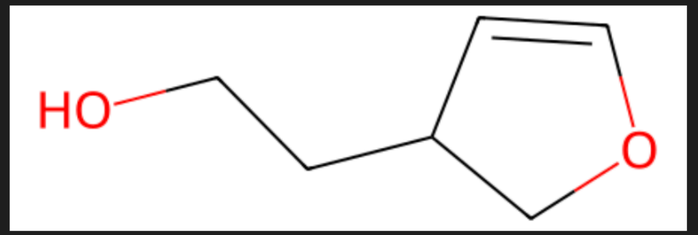
Similarity score 0.6774193548387096

reconstructed molecule:



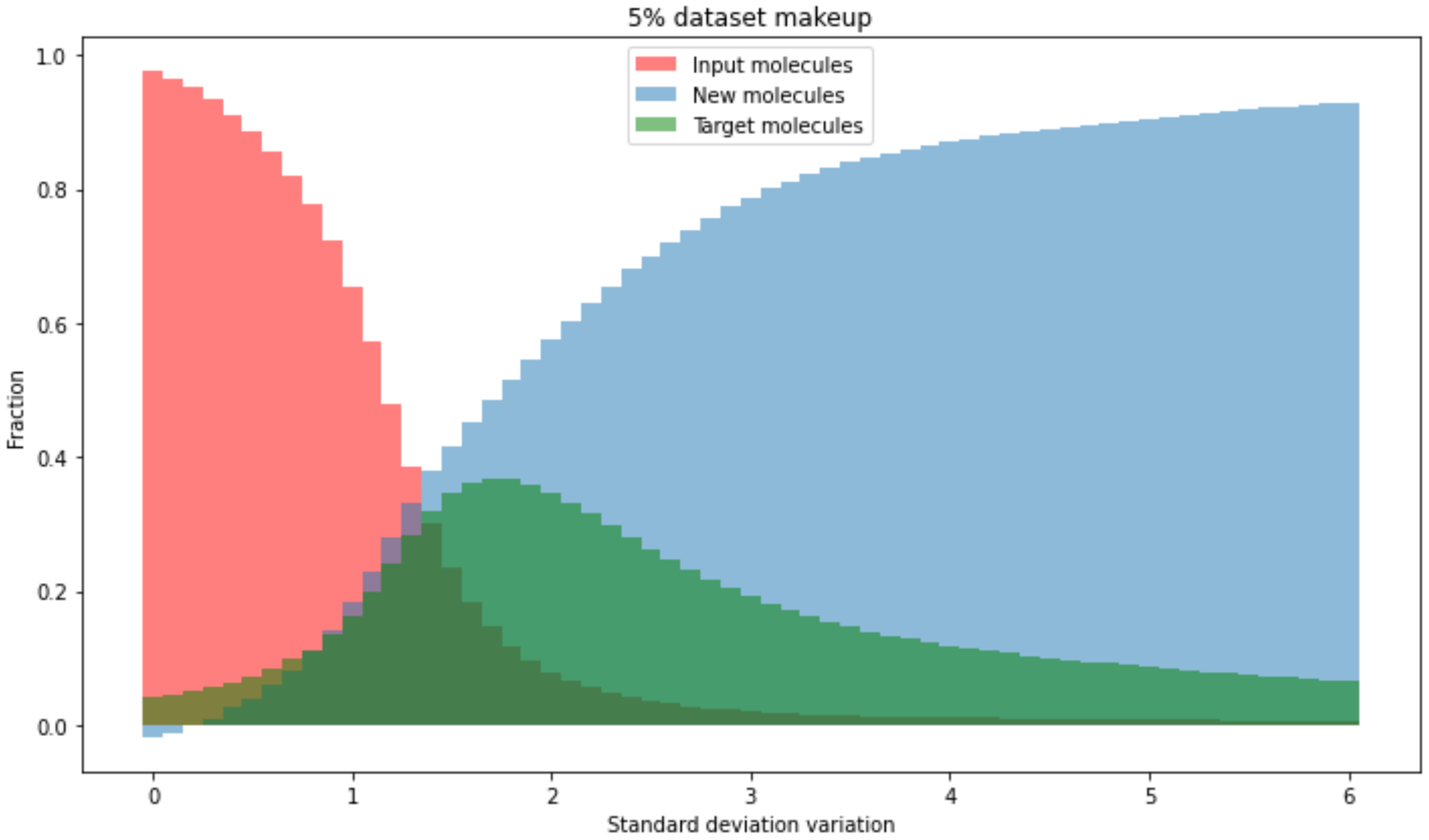
Similarity score 1.0

reconstructed molecule:

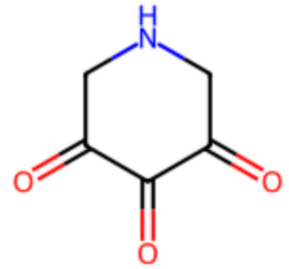


Similarity score 0.7666666666666667

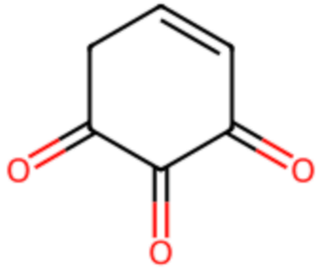
Small subset training: prove of principle



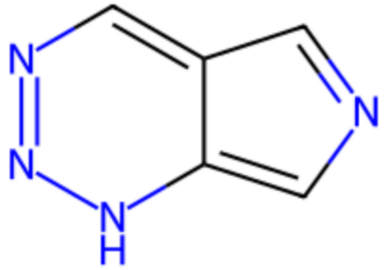
QM9 Champions



2.91 eV



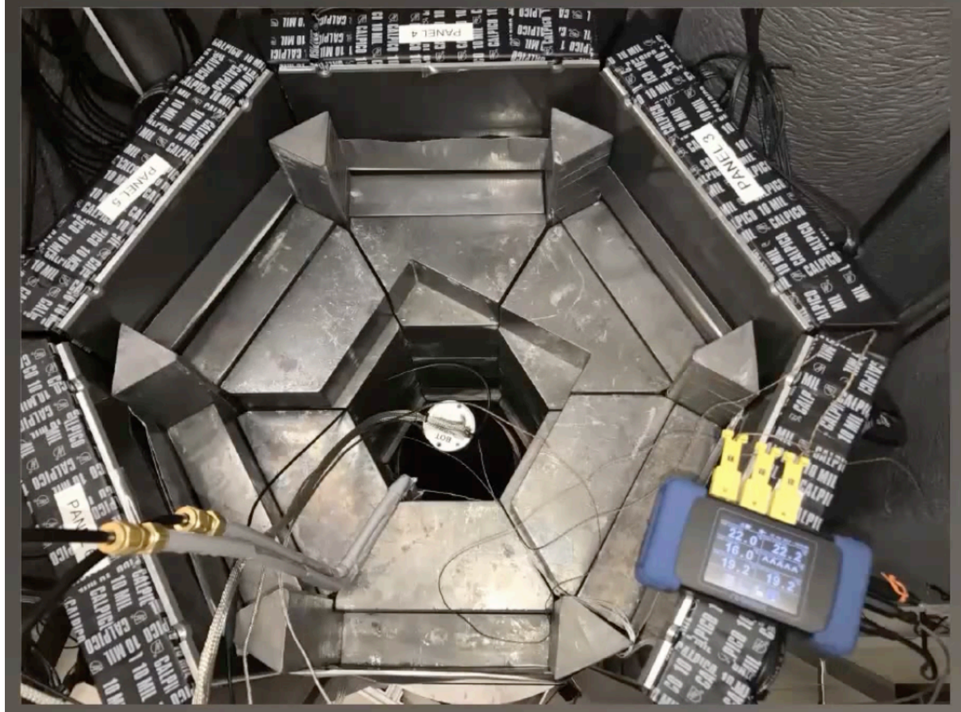
2.93 eV



3.04 eV

Moving Towards Field Tests

Experimental Deployment



Phase Transitions and Stable Dark Bound States

Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

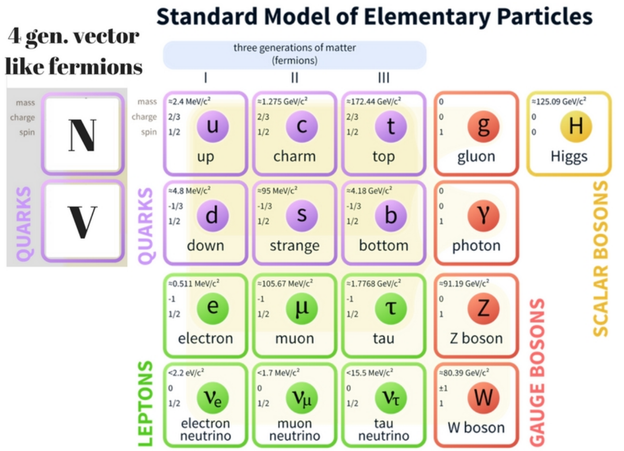
Beyond QCD:
Non-abelian Dark Sectors

Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

Extended Gauge Sector

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

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



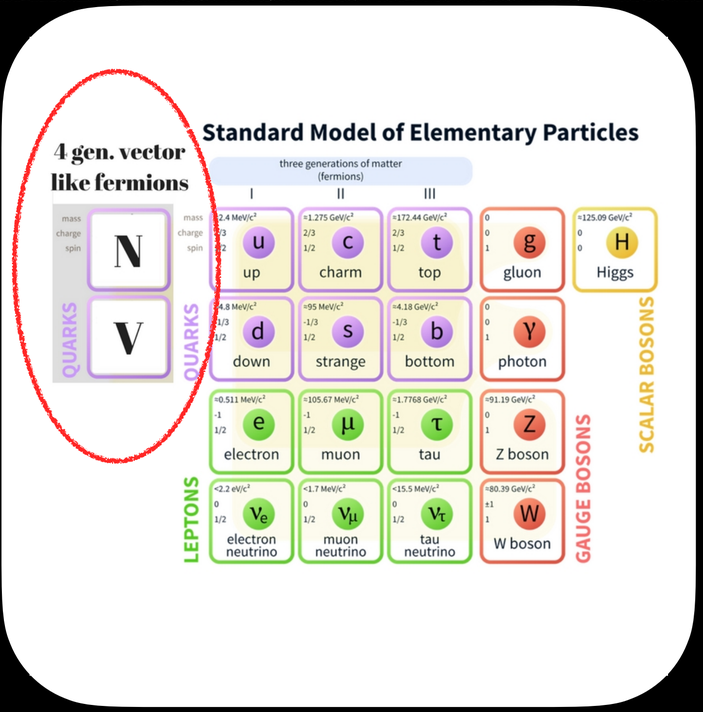
1503.08749

Extended Gauge Sector

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

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

New Baryon Number → DM candidate



1503.08749

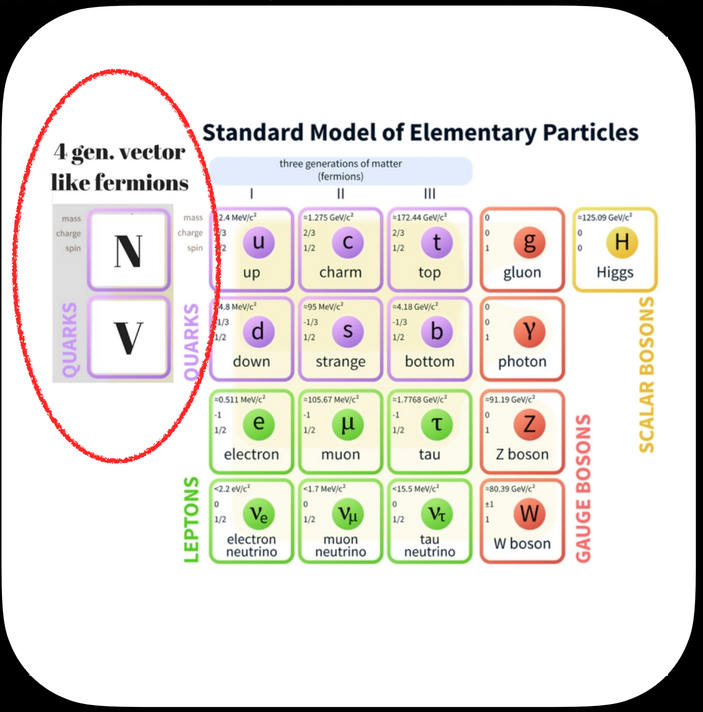
Extended Gauge Sector

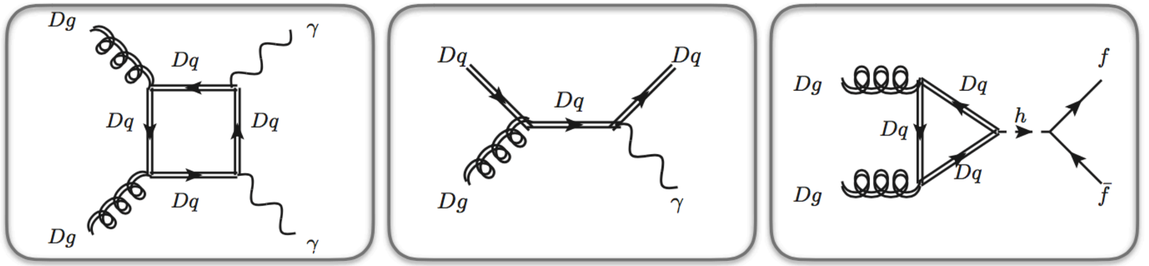
$$SU(N)_{\rm DC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$$

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

New Baryon Number → DM candidate

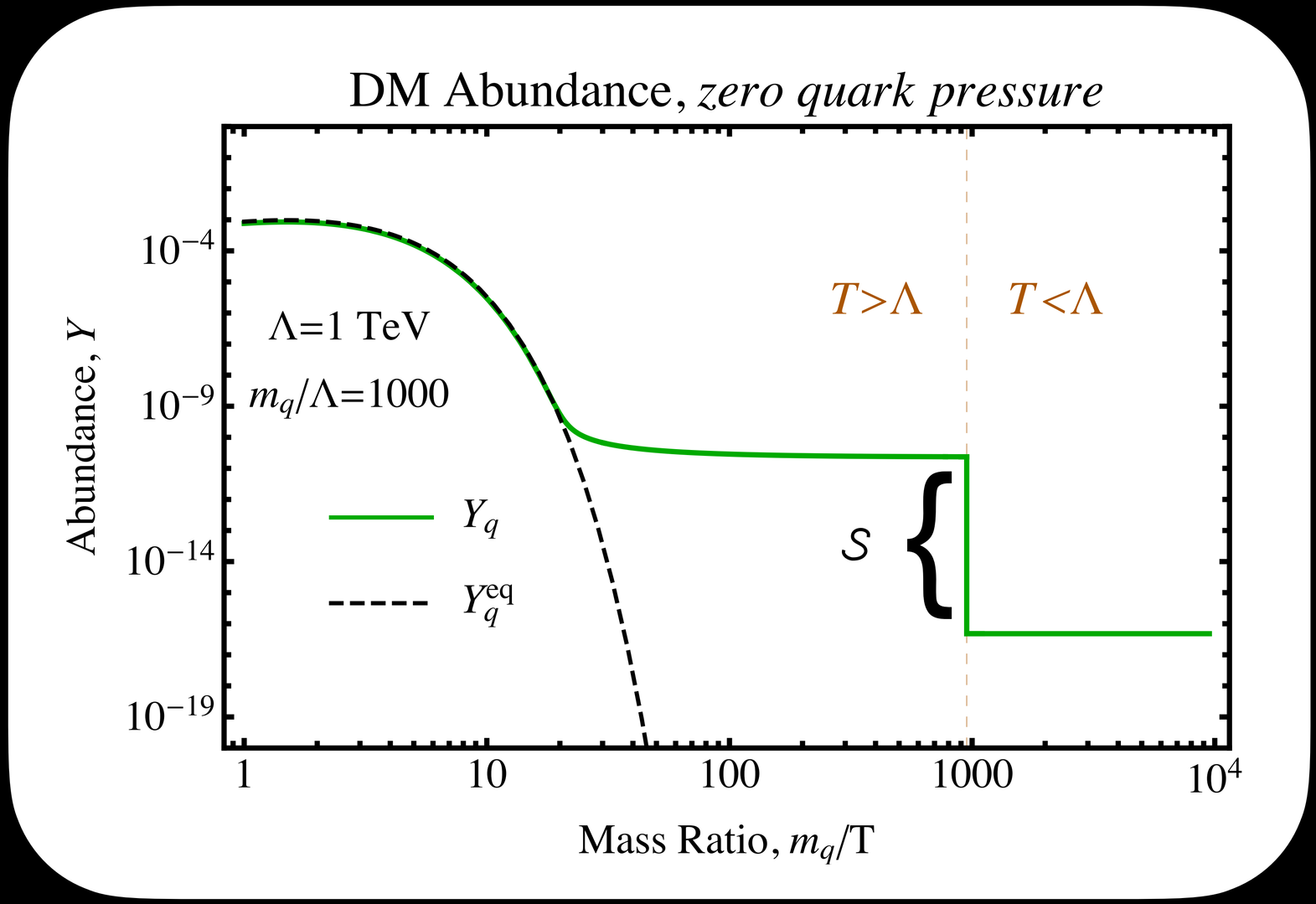
Thermal contact with the SM sector



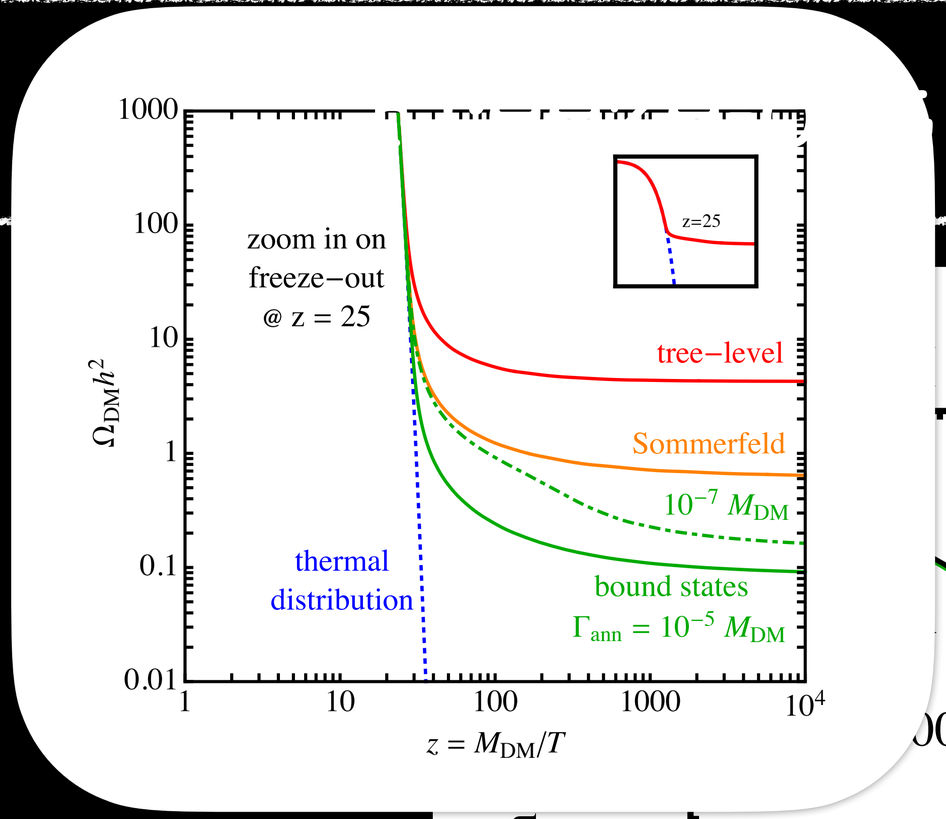


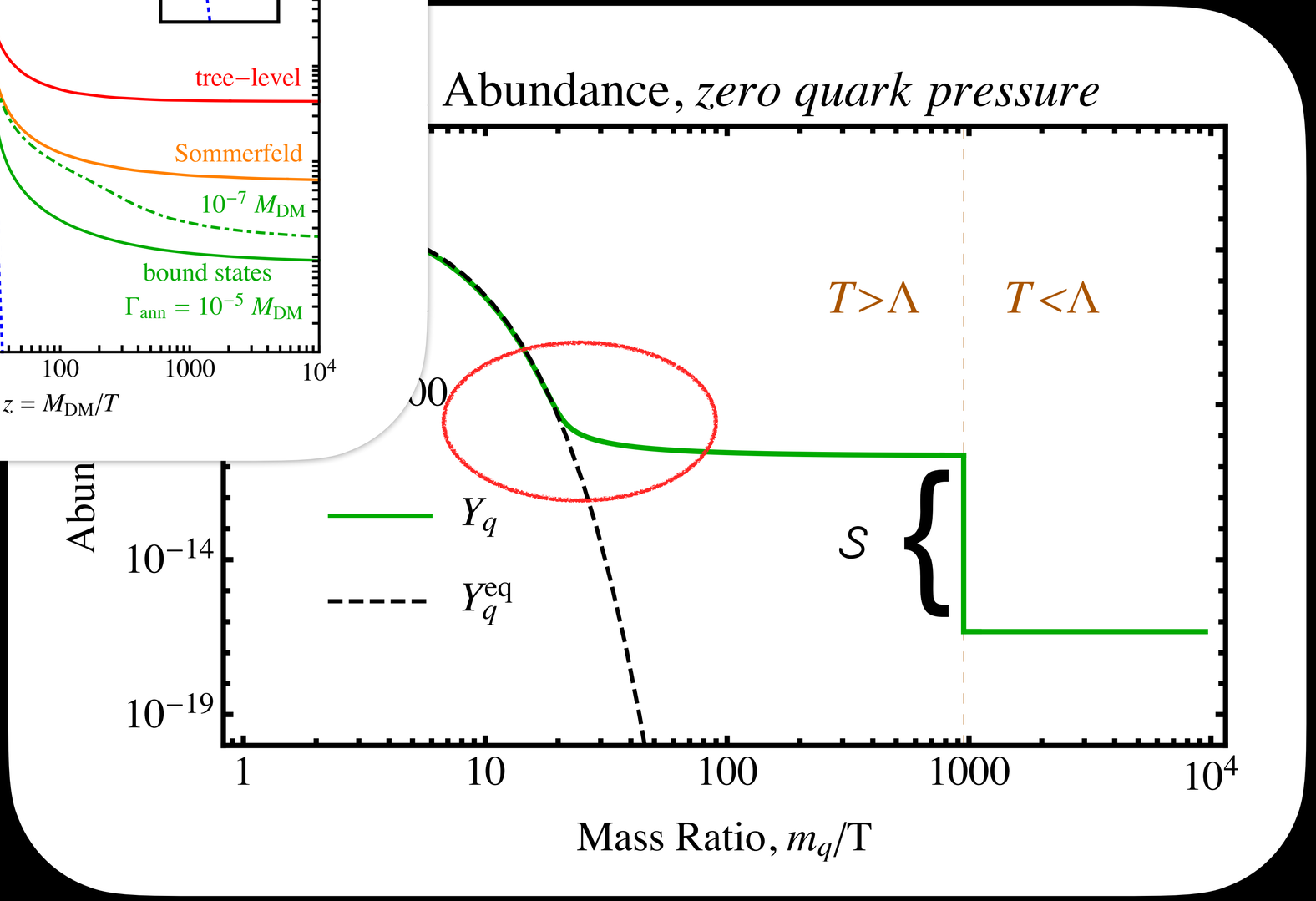
1503.08749

Freeze-out and Recombination

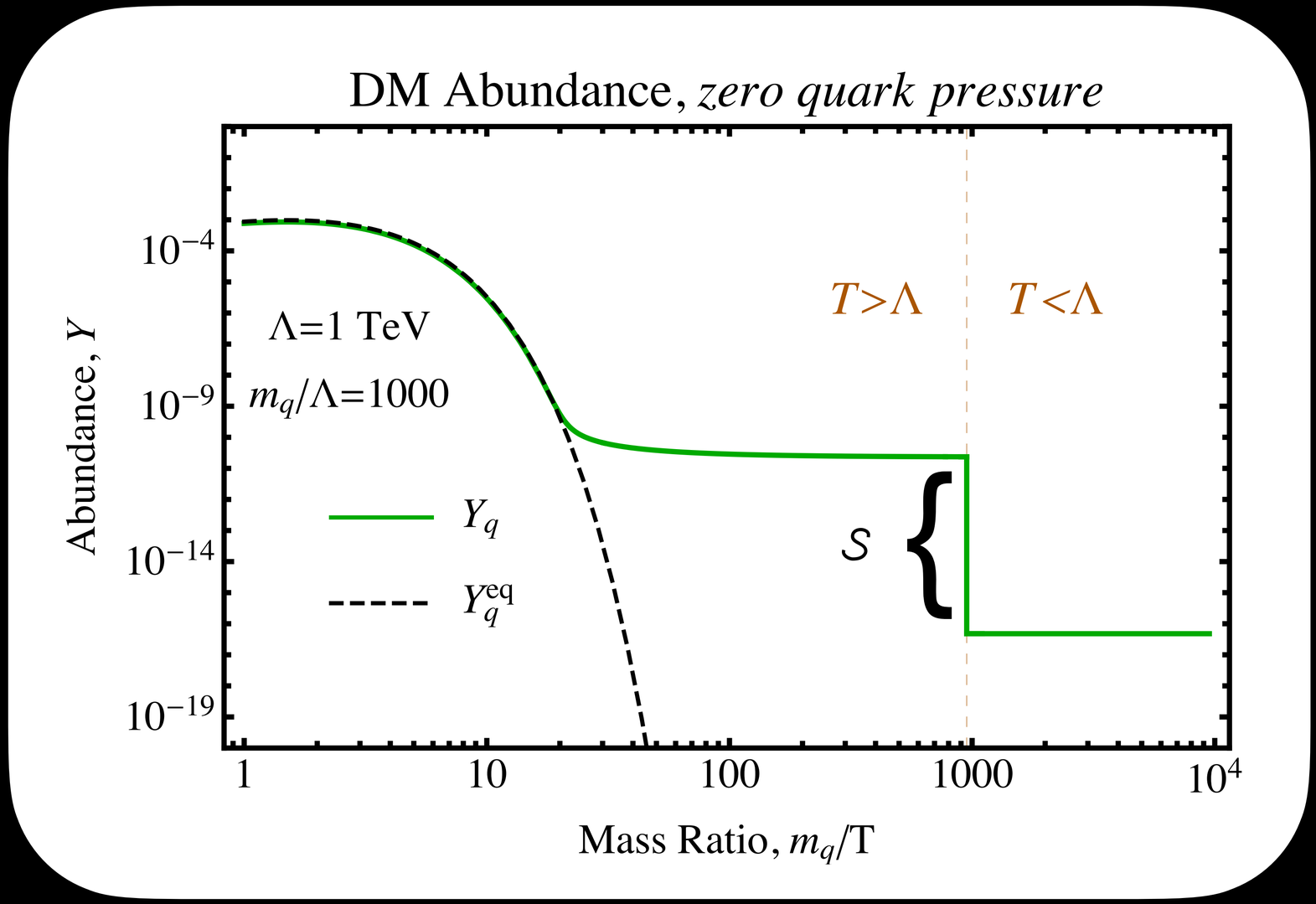


and Recombination

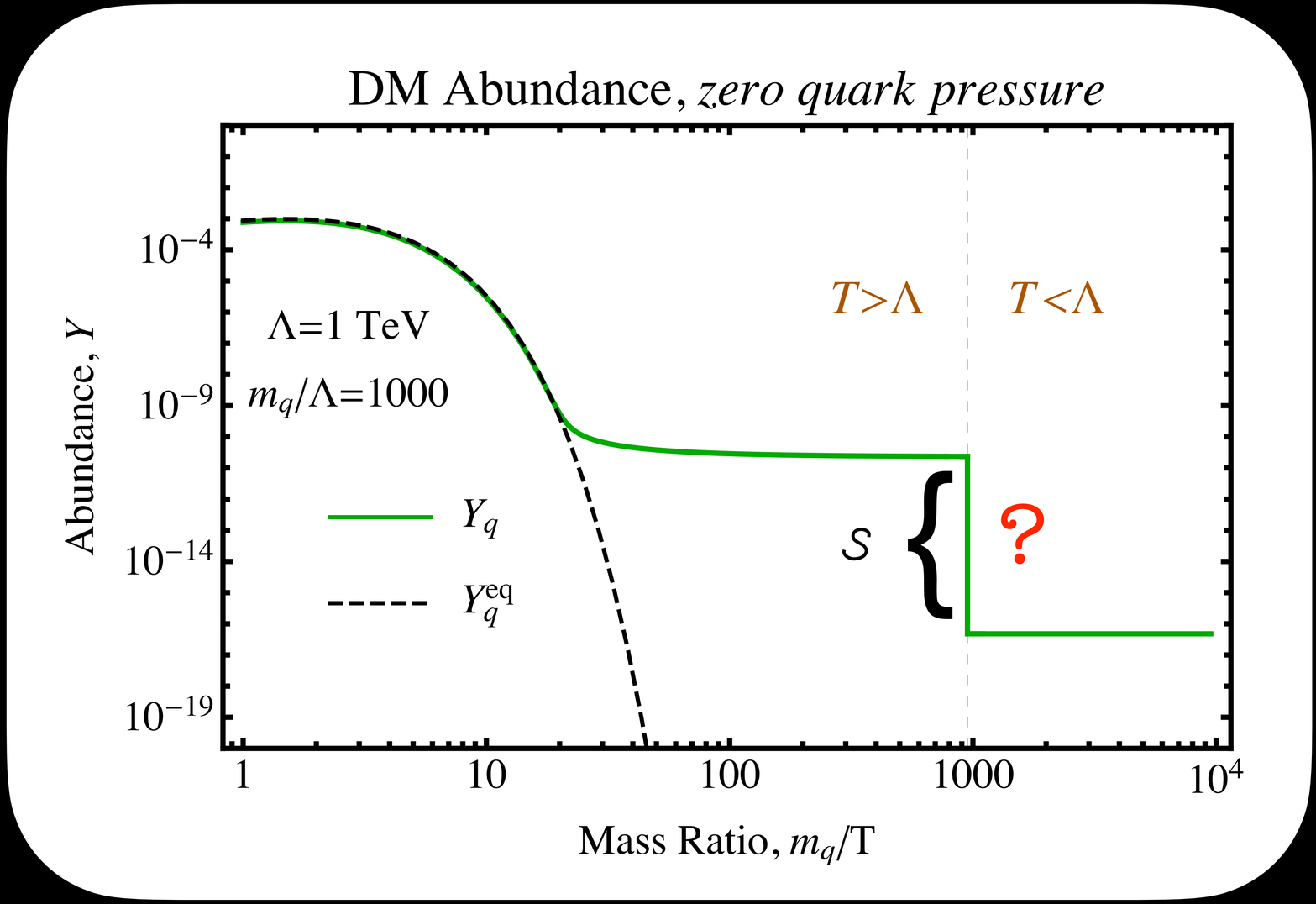




Freeze-out and Recombination



Freeze-out and Recombination



Geometric Rearrangement

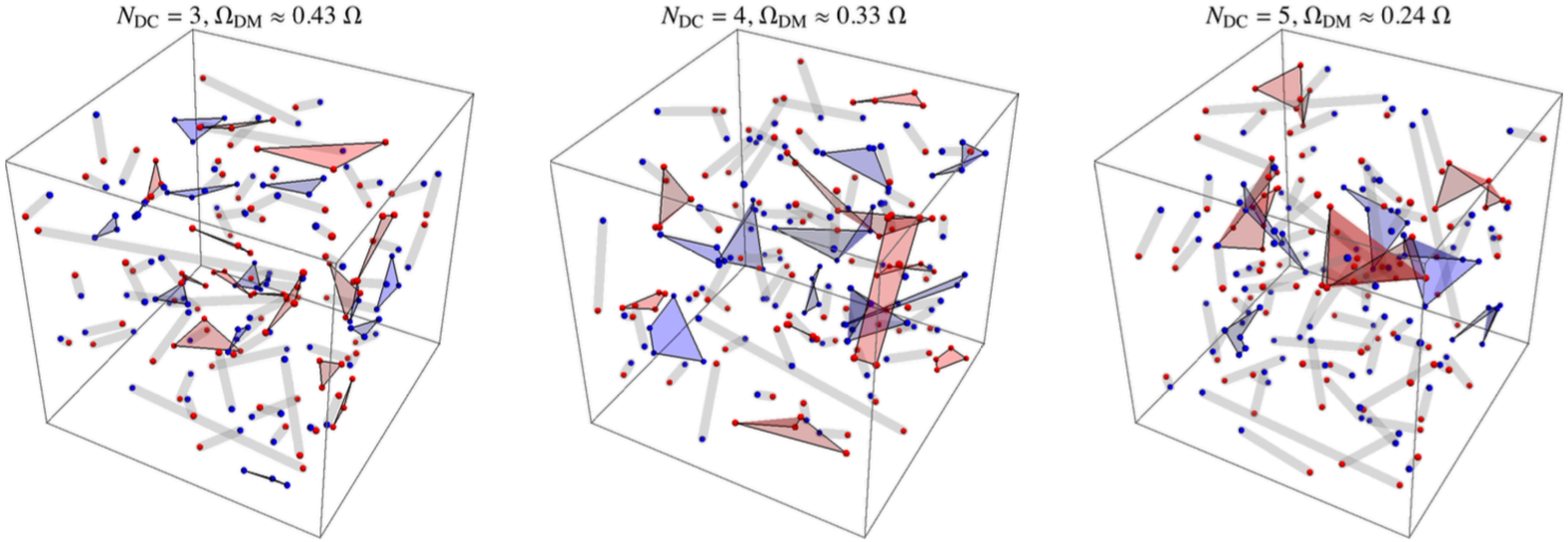
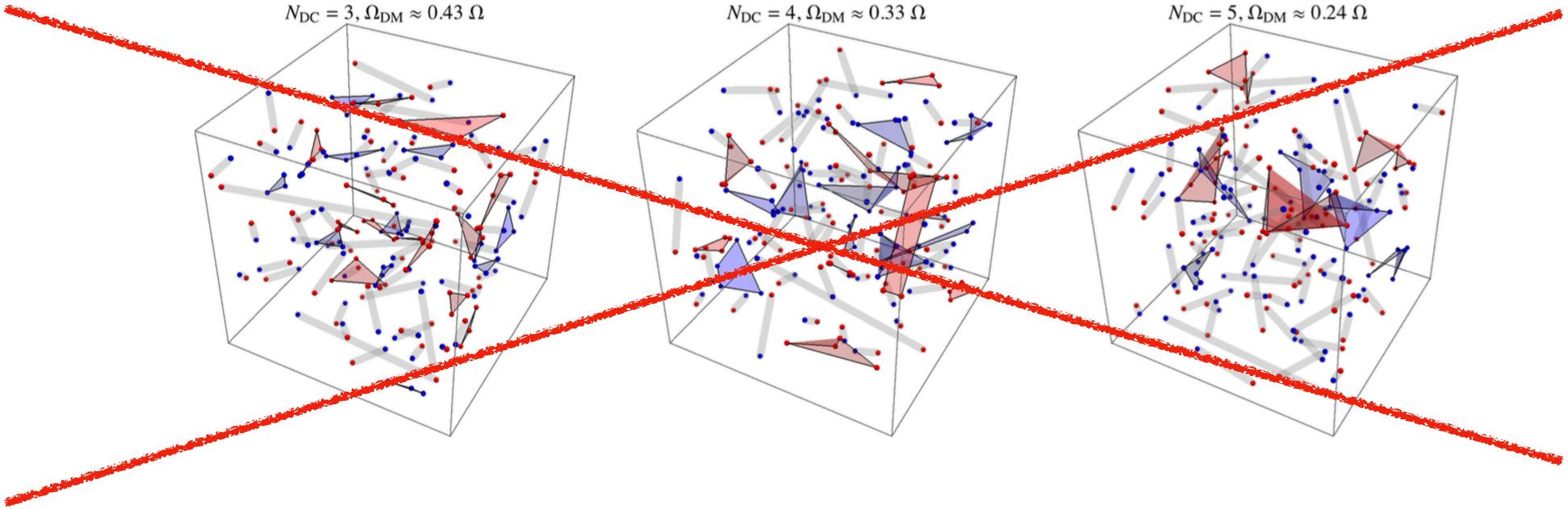


Figure 5: *Examples of dark condensation for* $N_{DC} = 3$ *(left),* 4 *(middle) and* 5 *(right). Dark quarks* $\mathcal{Q}$ *(anti-quarks* $\bar{\mathcal{Q}}$*) are denoted as red (blue) dots, placed at random positions. We assume that each DM particle combines with its dark nearest neighbour, forming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

Geometric Rearrangement



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Dark Matter as a weakly coupled Dark Baryon
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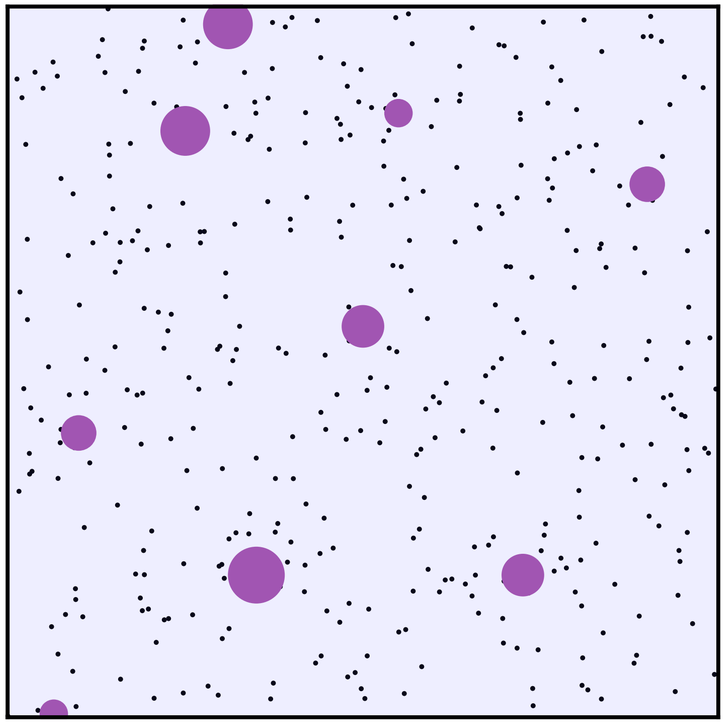
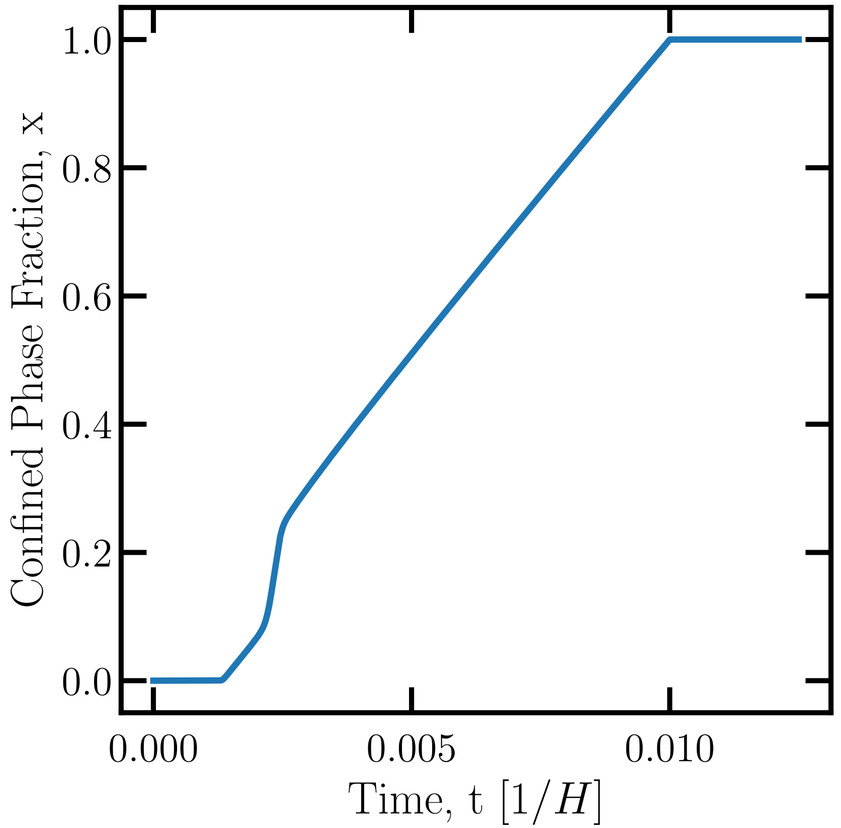
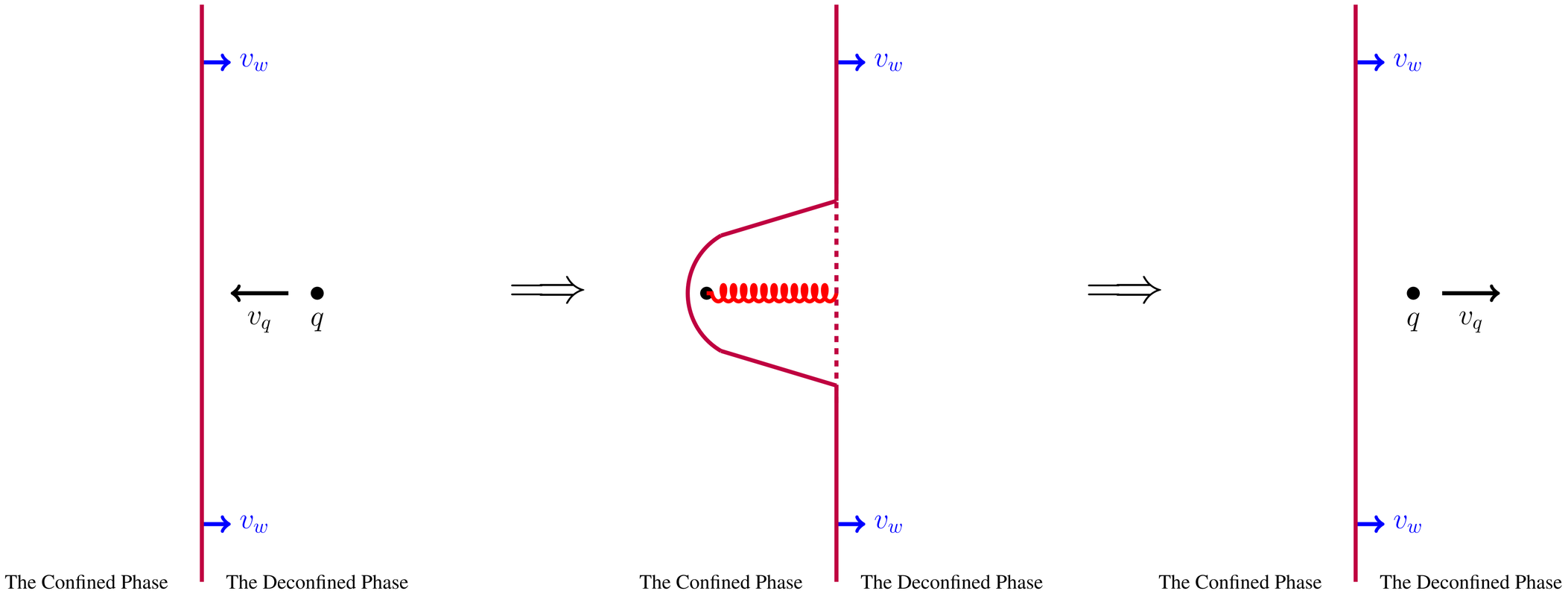
Dynamics of the Phase Transition





Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

Bubble Wall and Heavy Quarks



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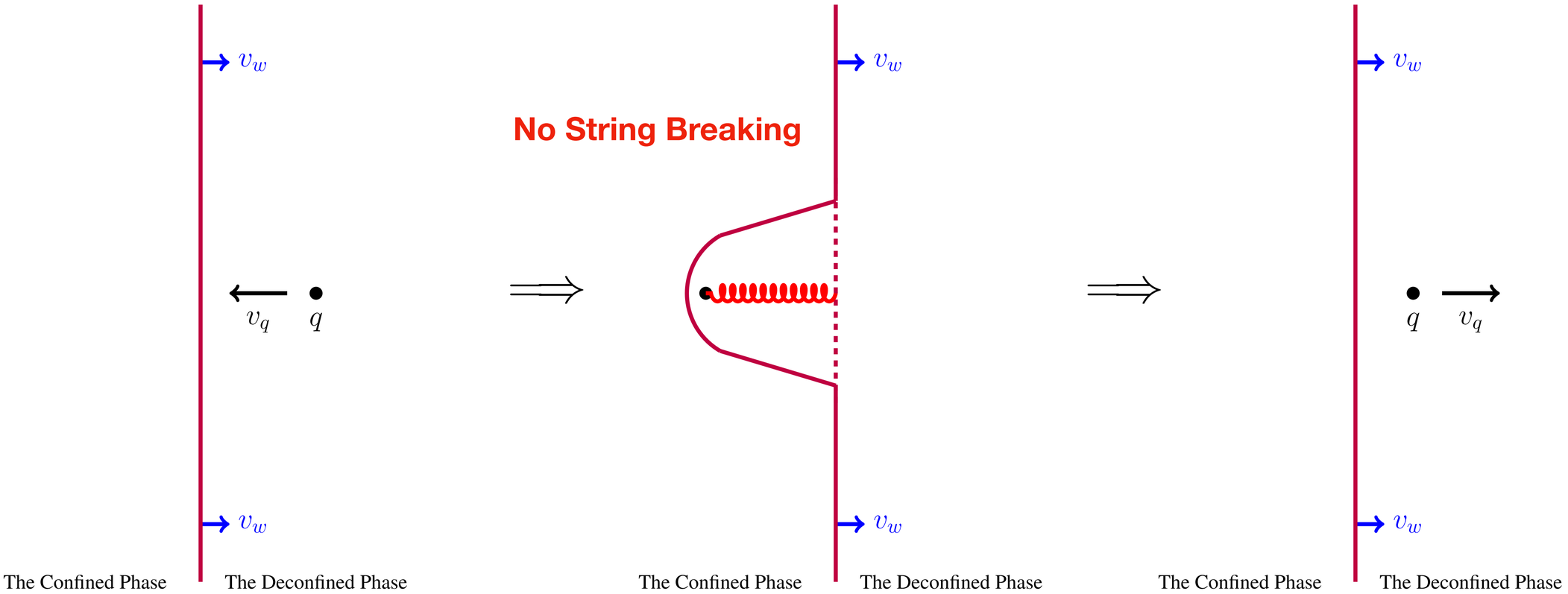
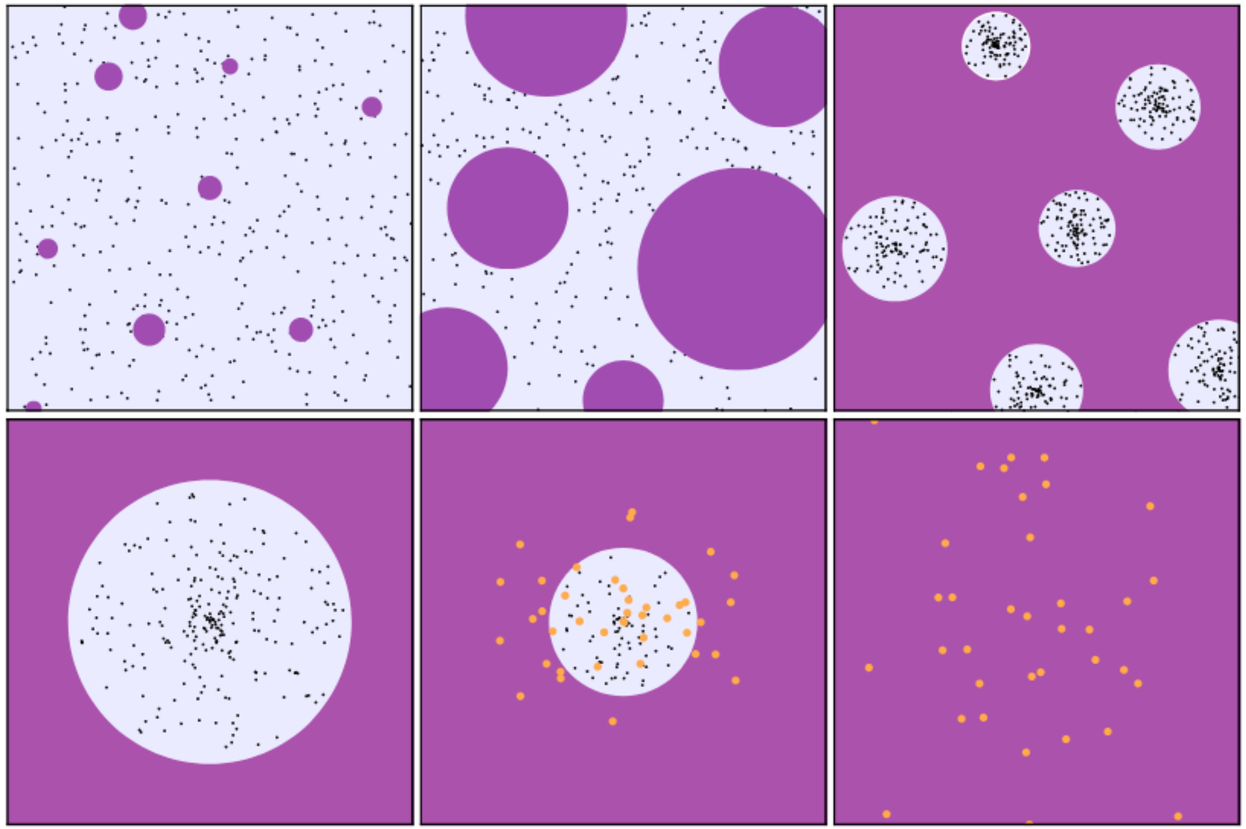
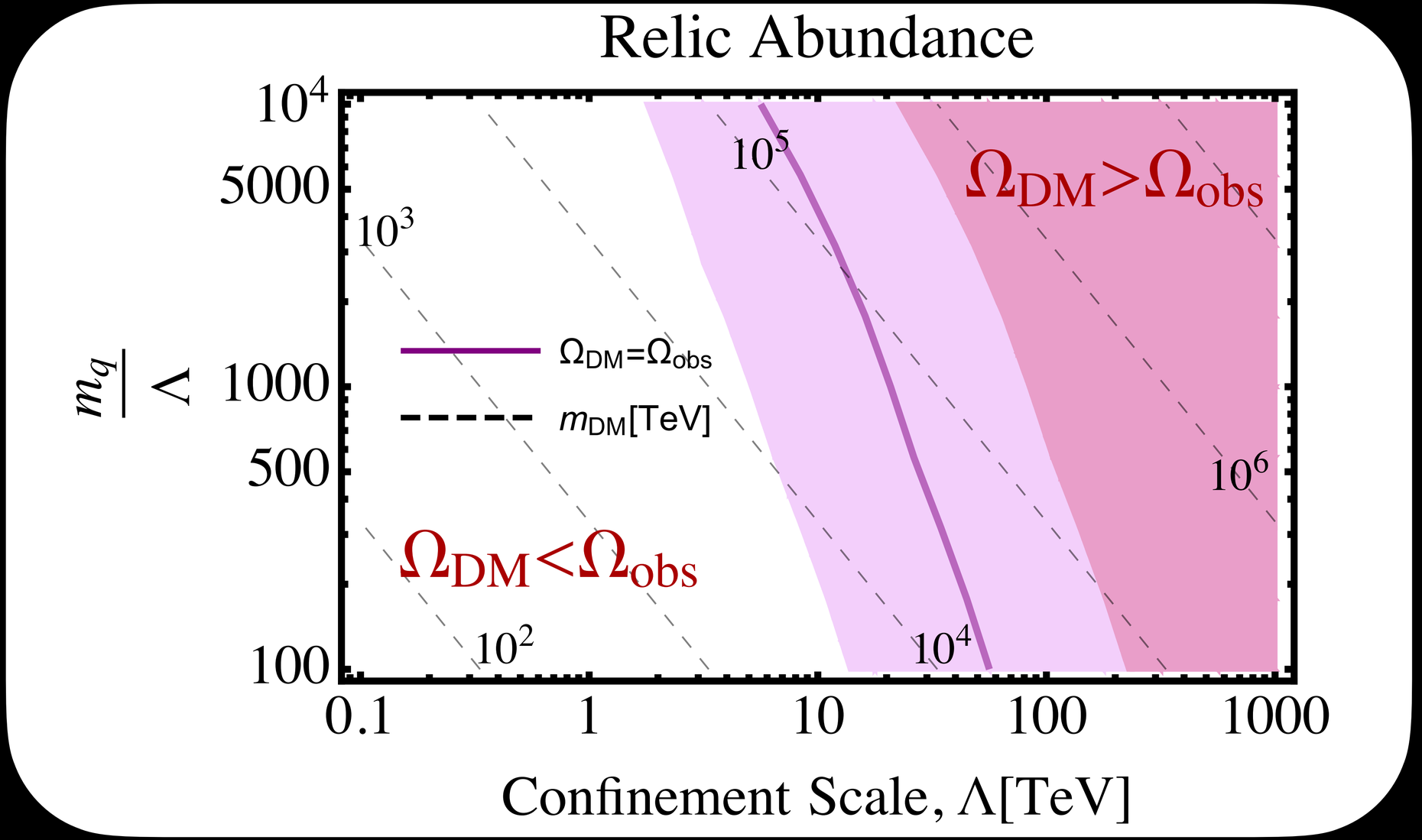


Minimal Abundance and Asymmetry



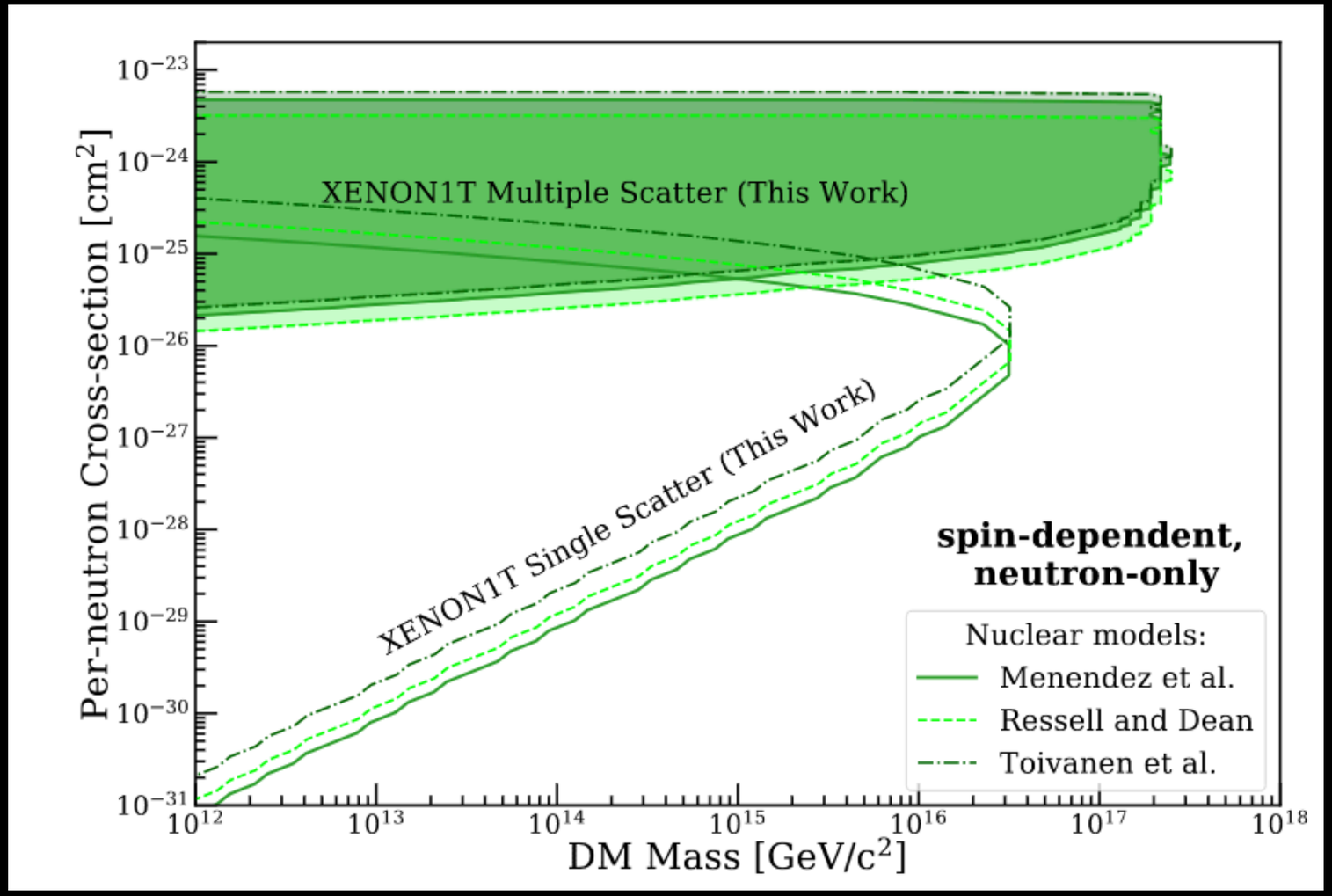
$$S_{\rm AS} = \frac{\sqrt{N_0}}{N_0} = \frac{1}{\sqrt{N_0}}$$

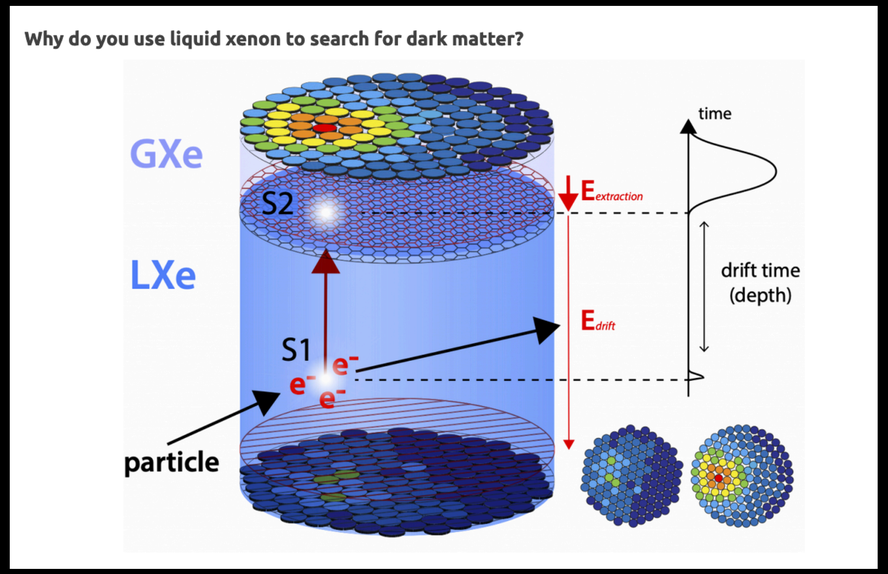
Result for Relic Abundance



P. Asidi, T. Slatyer, D. Kraemer, E. Kufik, G. Ridgway, J.Smirnov: 2103.09822

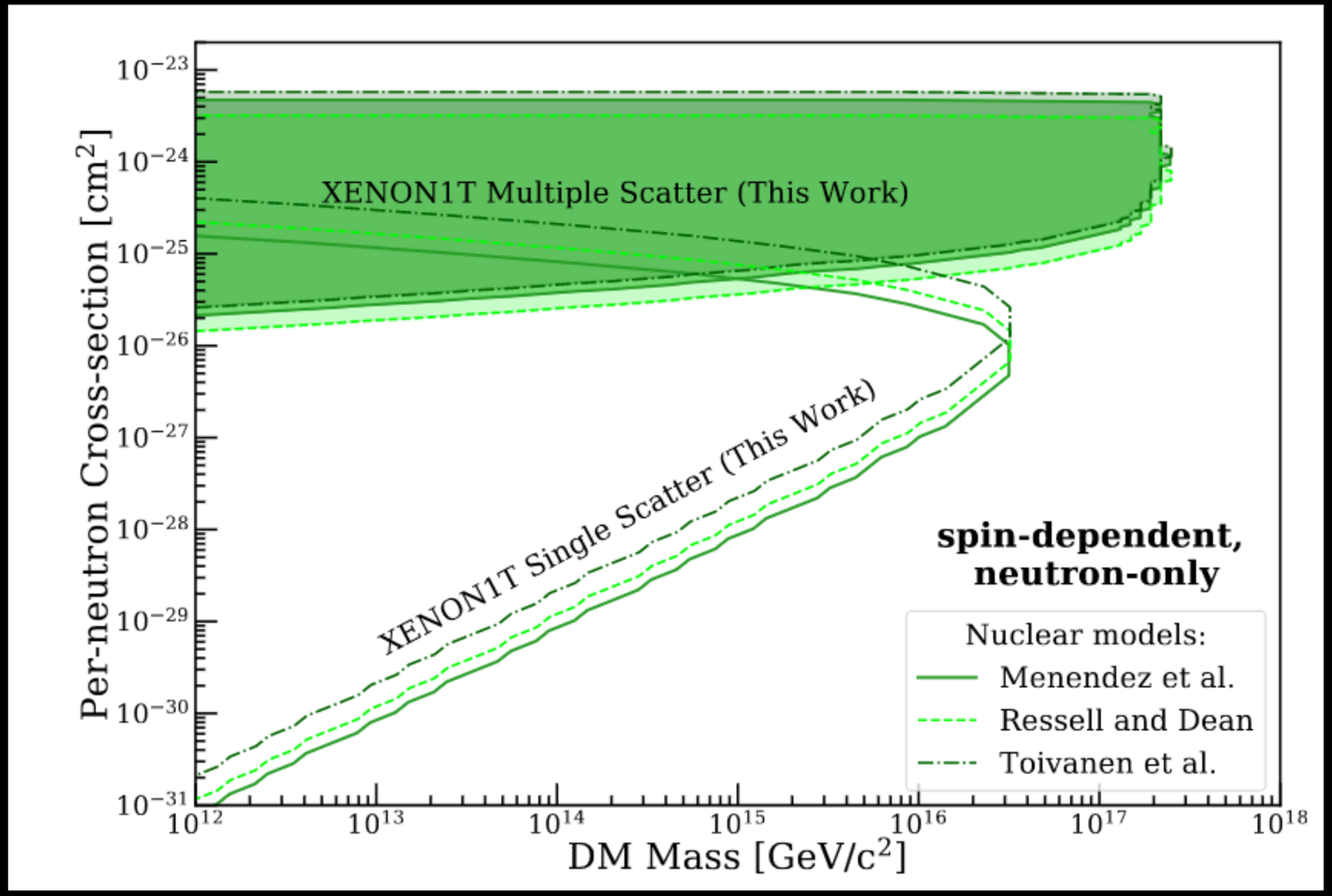
Extending the Direct Detection Range

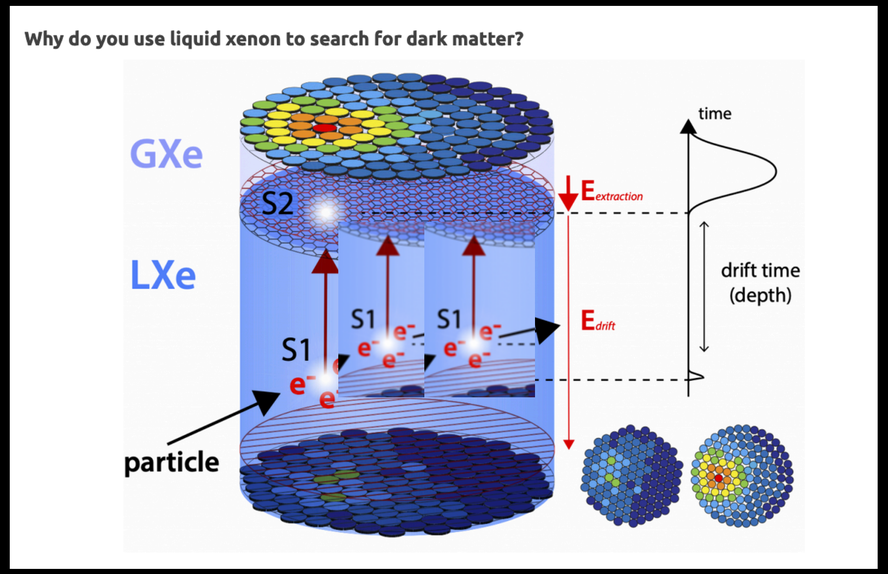




XENON Collaboration:
2304.10931

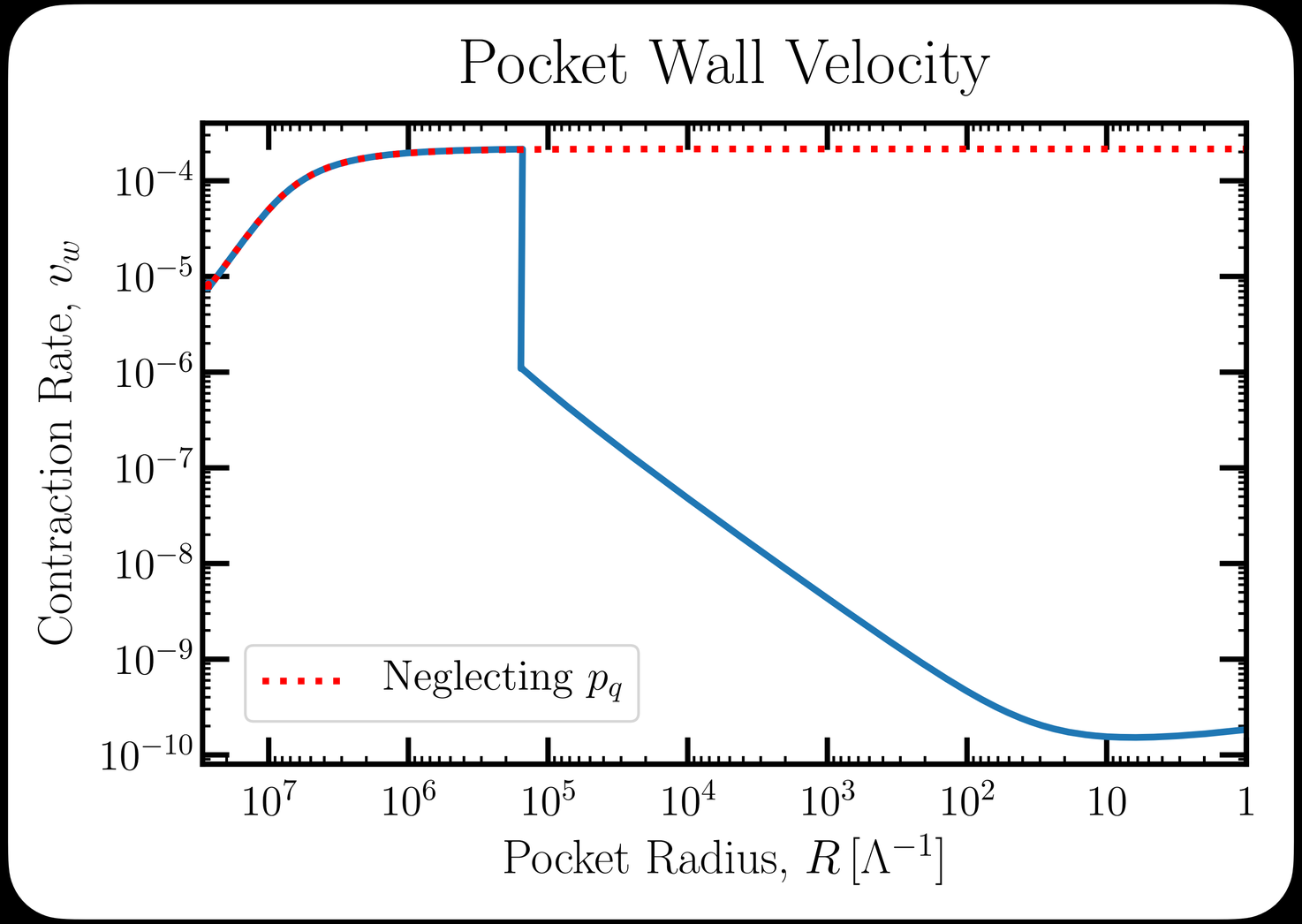
Extending the Direct Detection Range





XENON Collaboration:
2304.10931

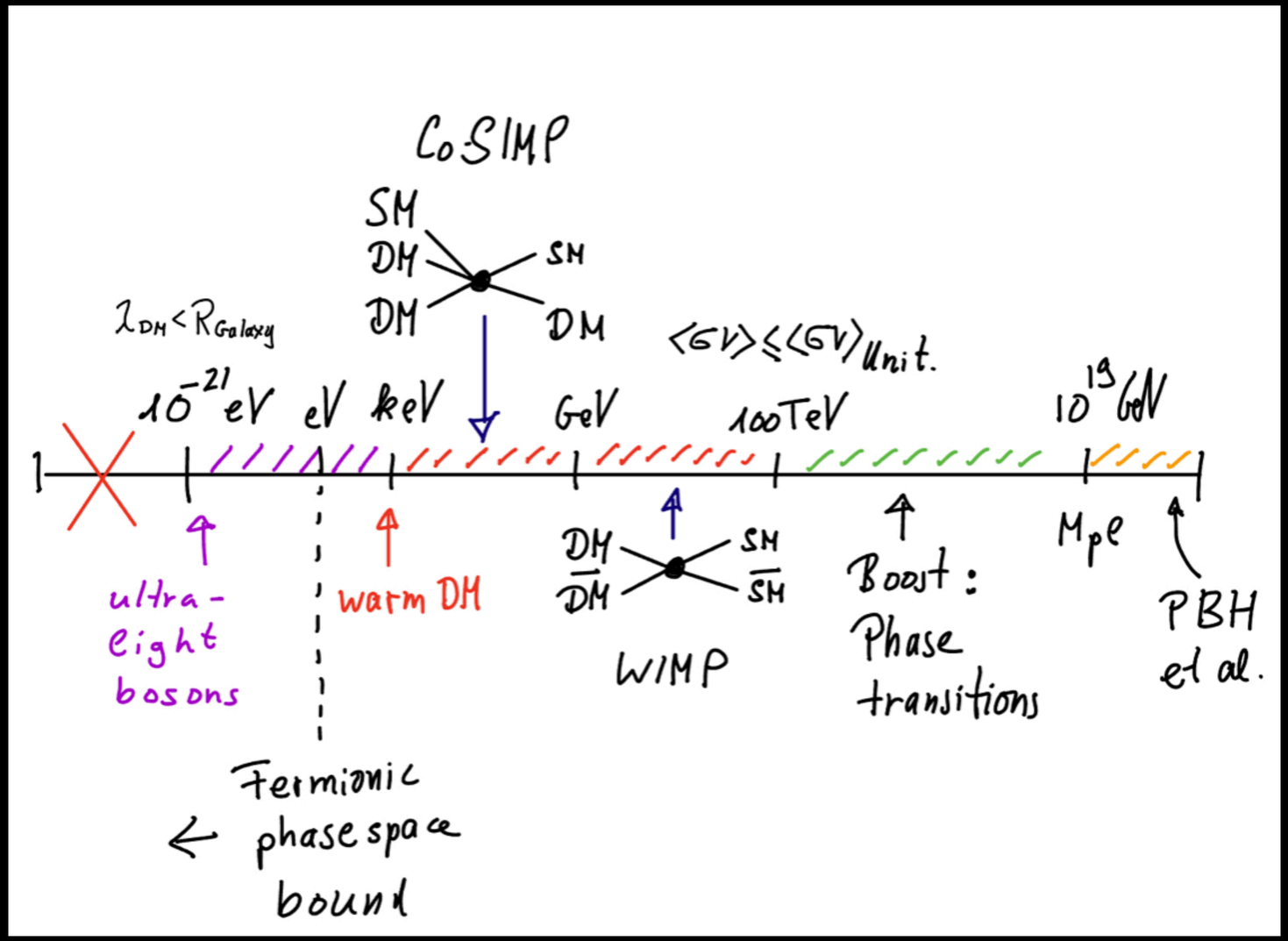
Input for Gravitational Wave Searches



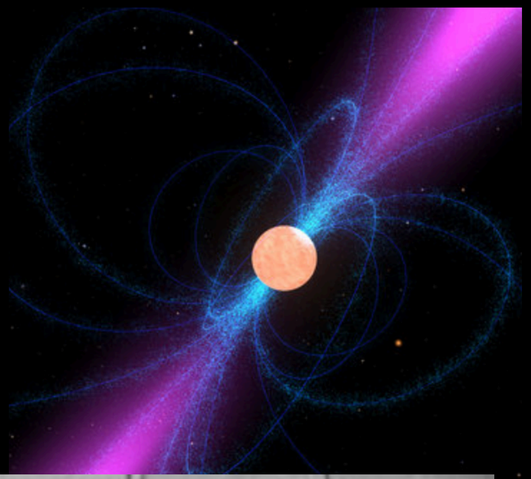
See the talk by:
Tomas Konstandin

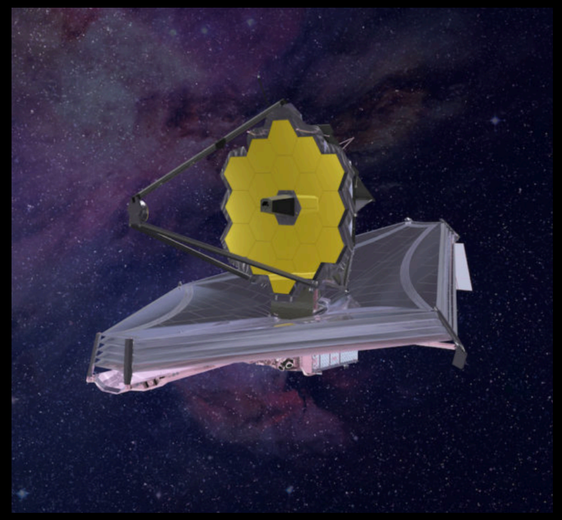
2103.09822

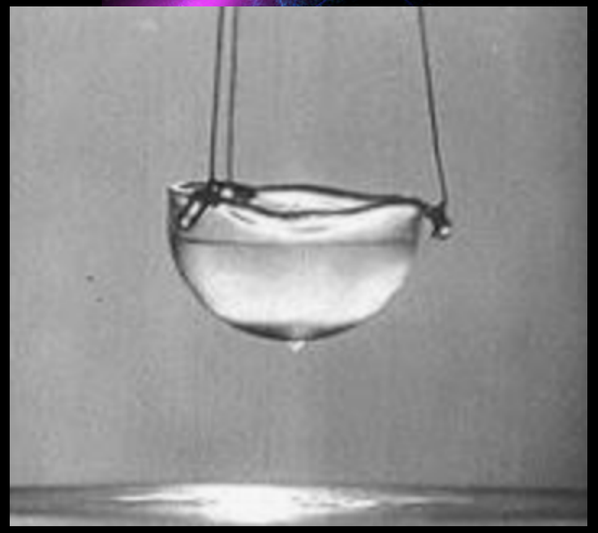
Dark Matter Landscape

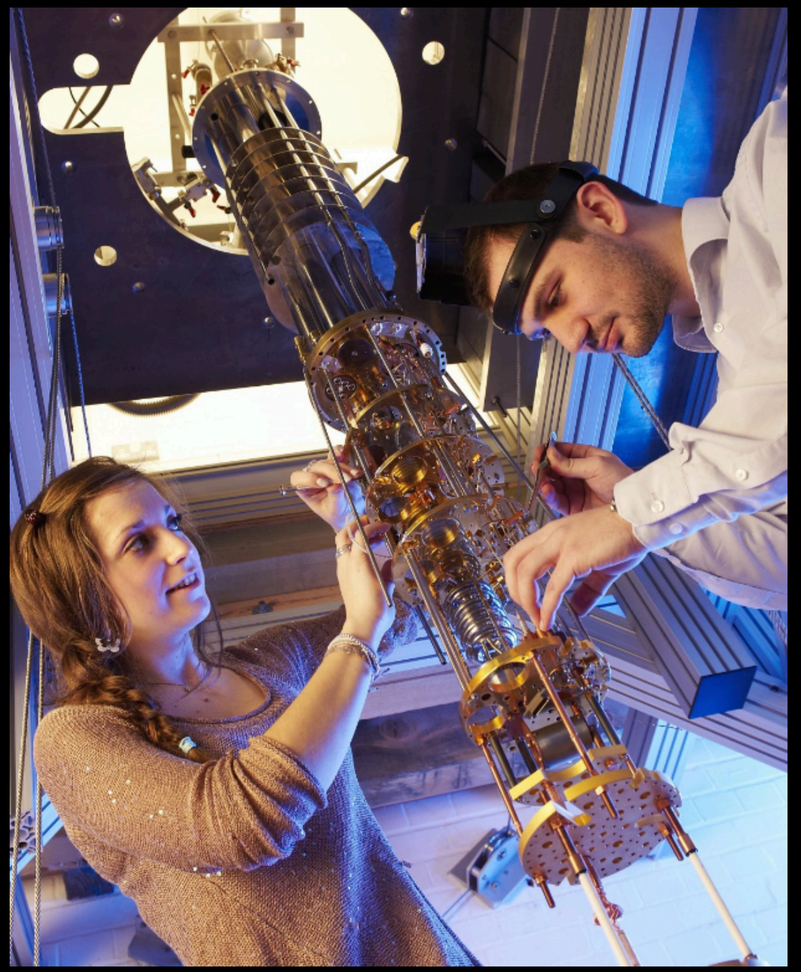


Developing field: New Ideas Welcomed

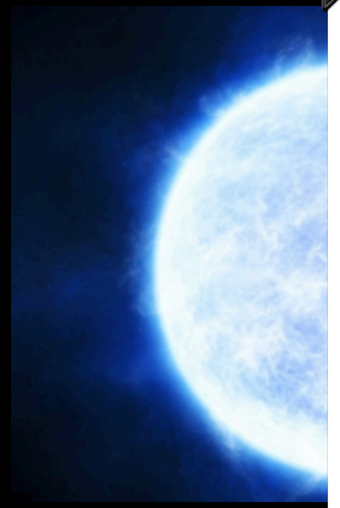


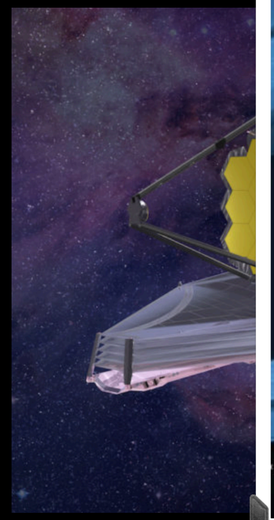


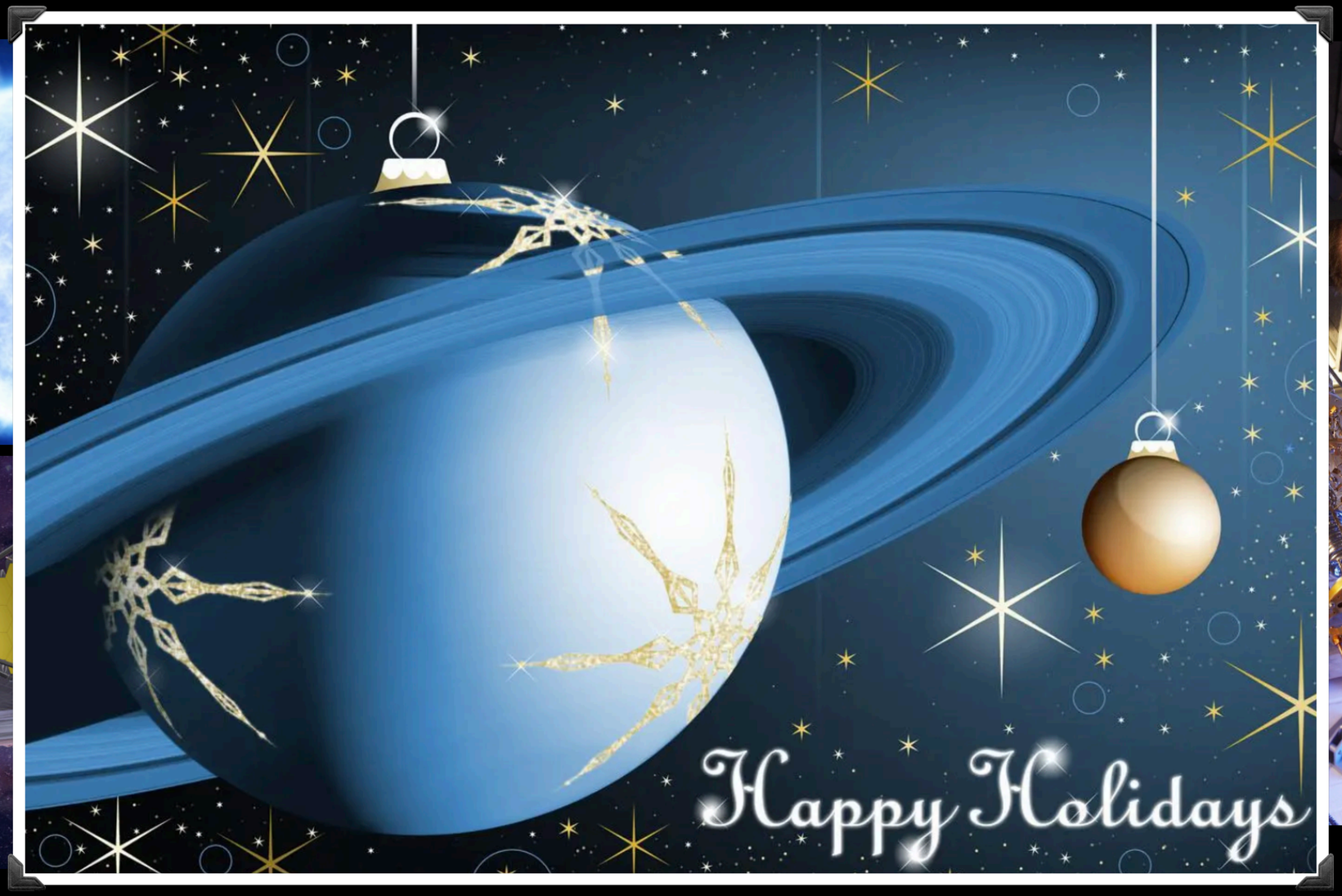


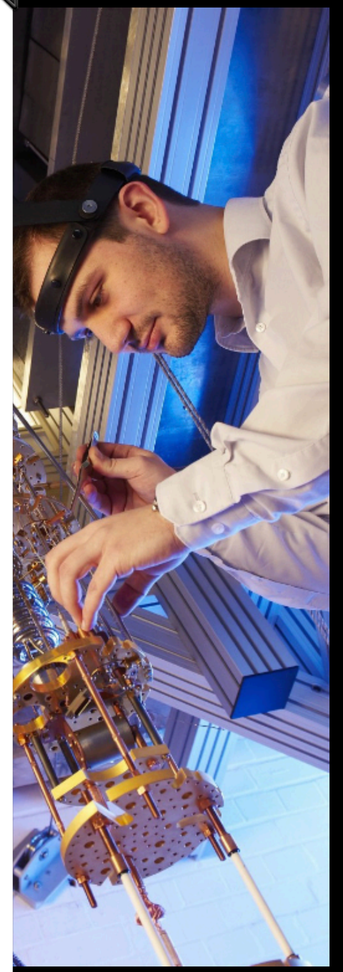


Developing field: New Ideas Welcomed









Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

Backup

QCD charged Dark Matter

Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

Color-Charged Dark Matter Model

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

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

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

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

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

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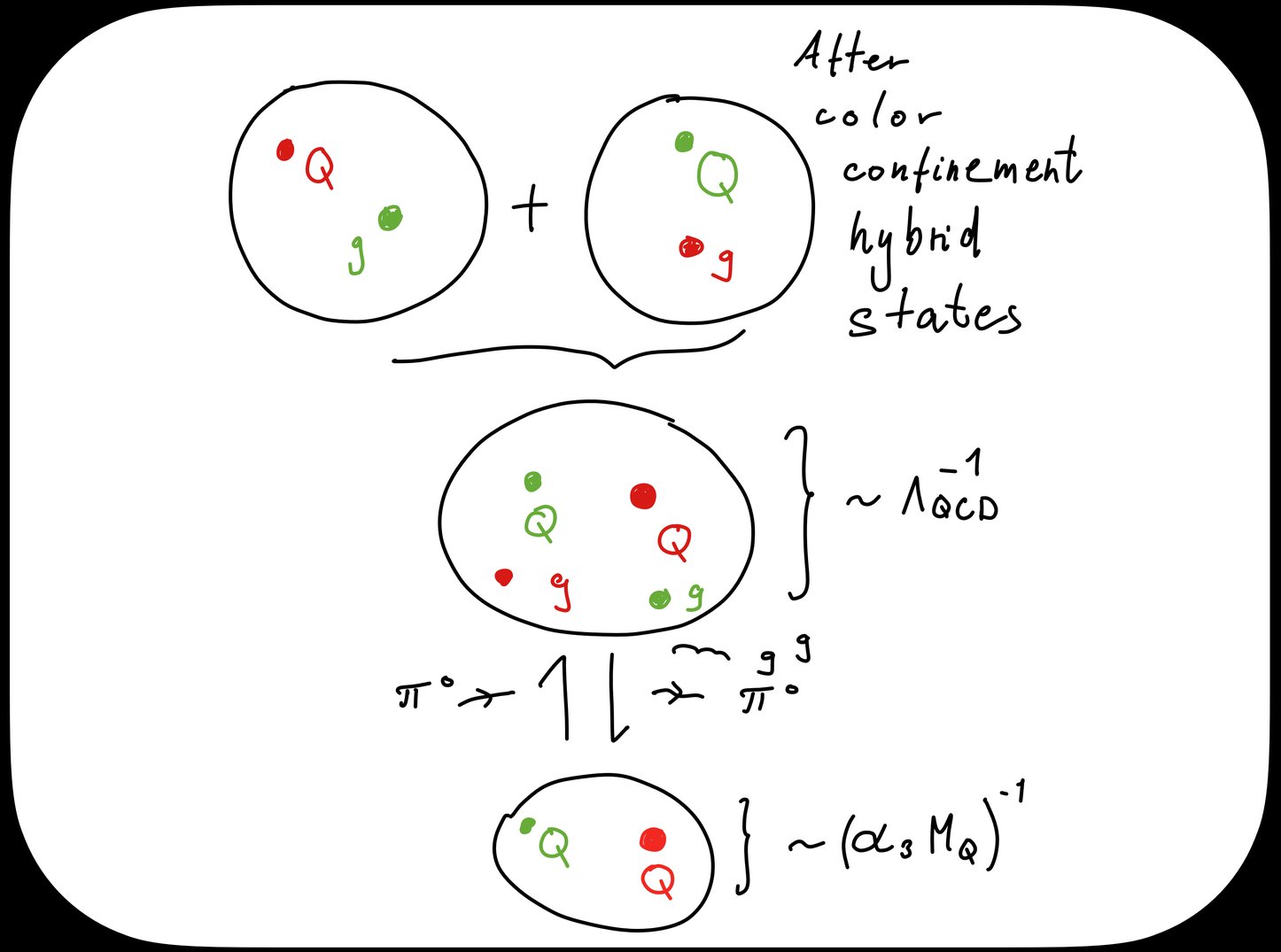
$$Q = (3, N, Y)$$

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

Idea: Chromocatalysis



Dark and not-so dark States

The Q^2

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

Binding Eenergy $\approx \alpha_3^2 M_Q$

DM candidate

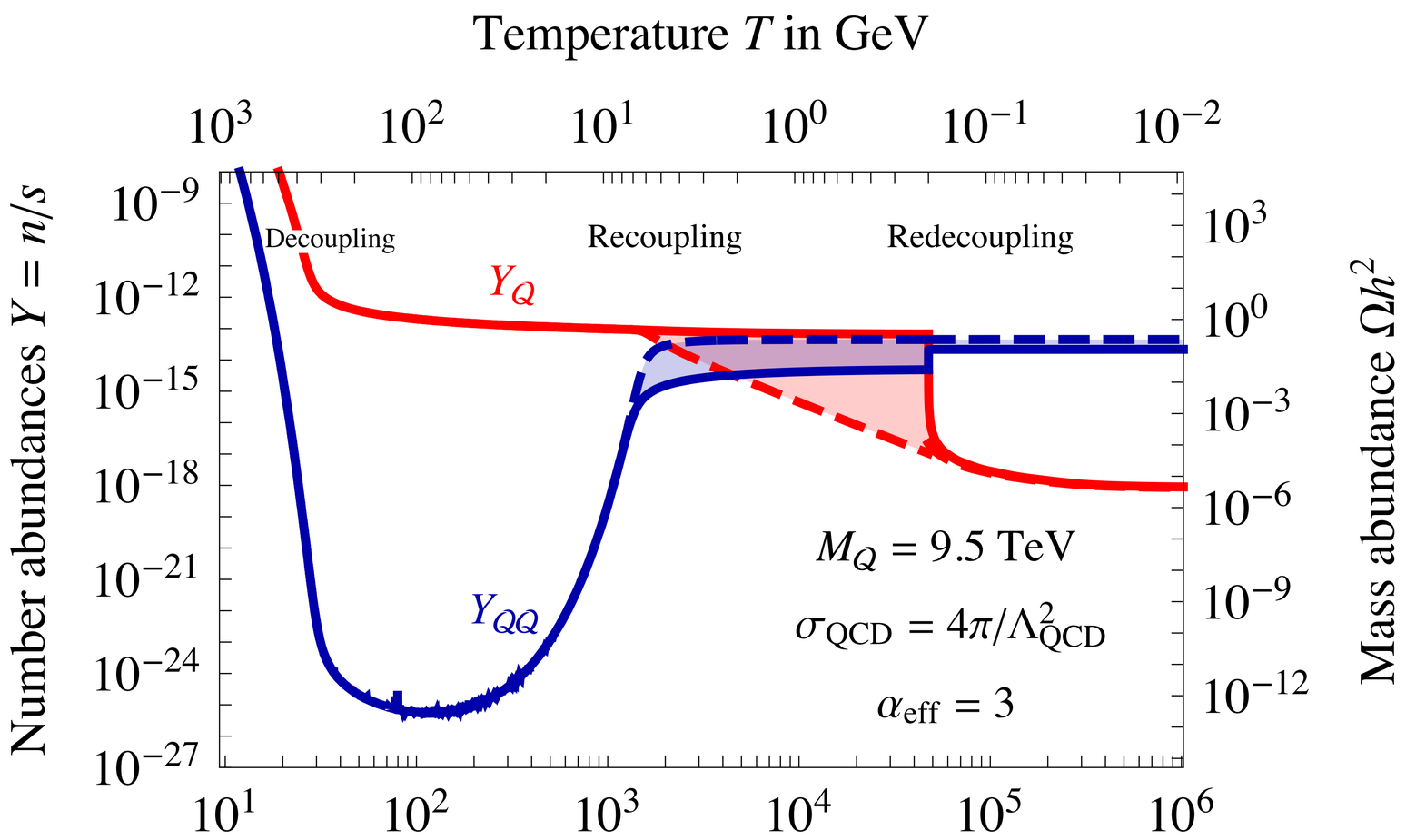
Hybrids Q g

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

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

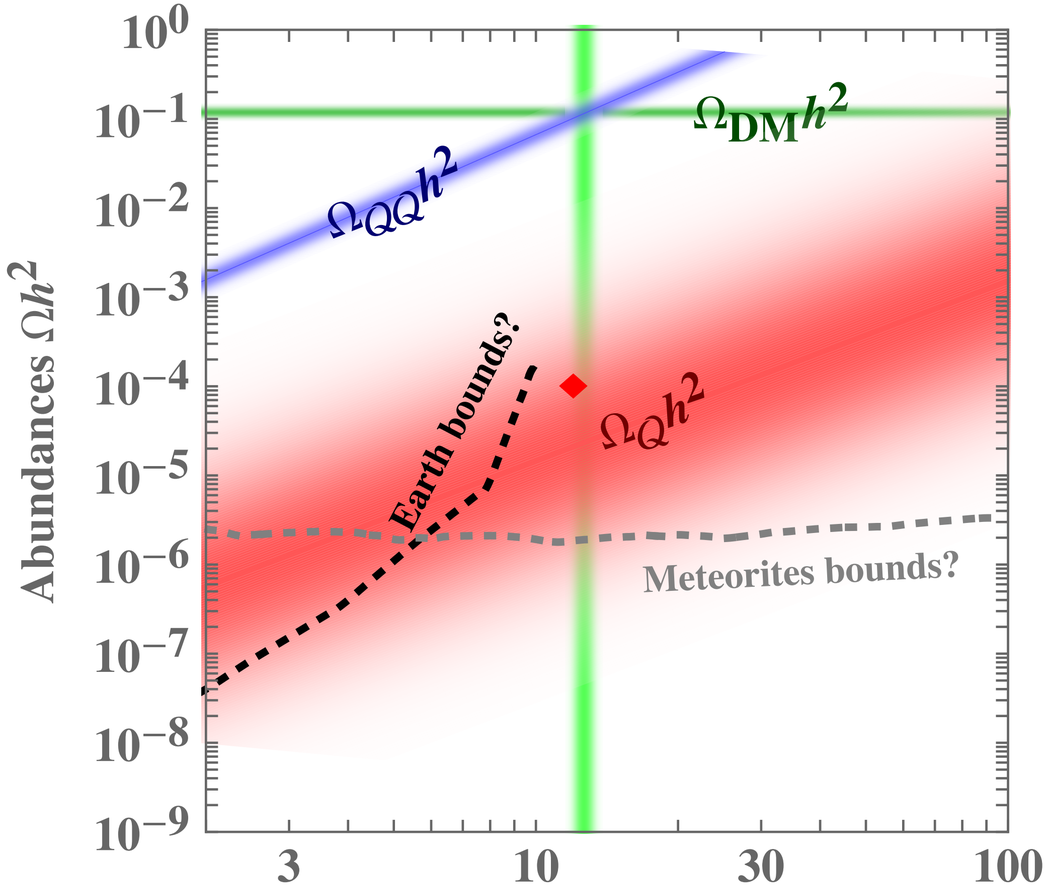
Dangerous

Chromo-catalysis in Cosmology



Mitridate, Redi, JS et al.:
1801.01135, 1811.08418

Abundances Today



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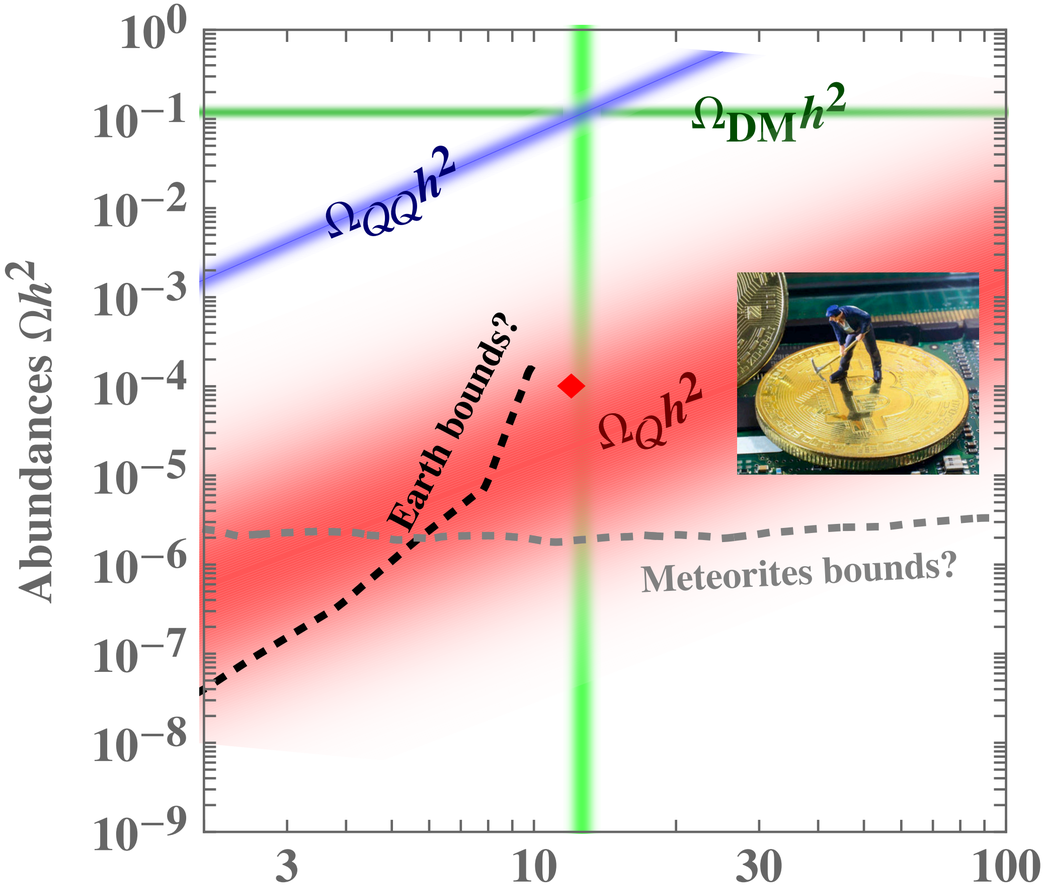
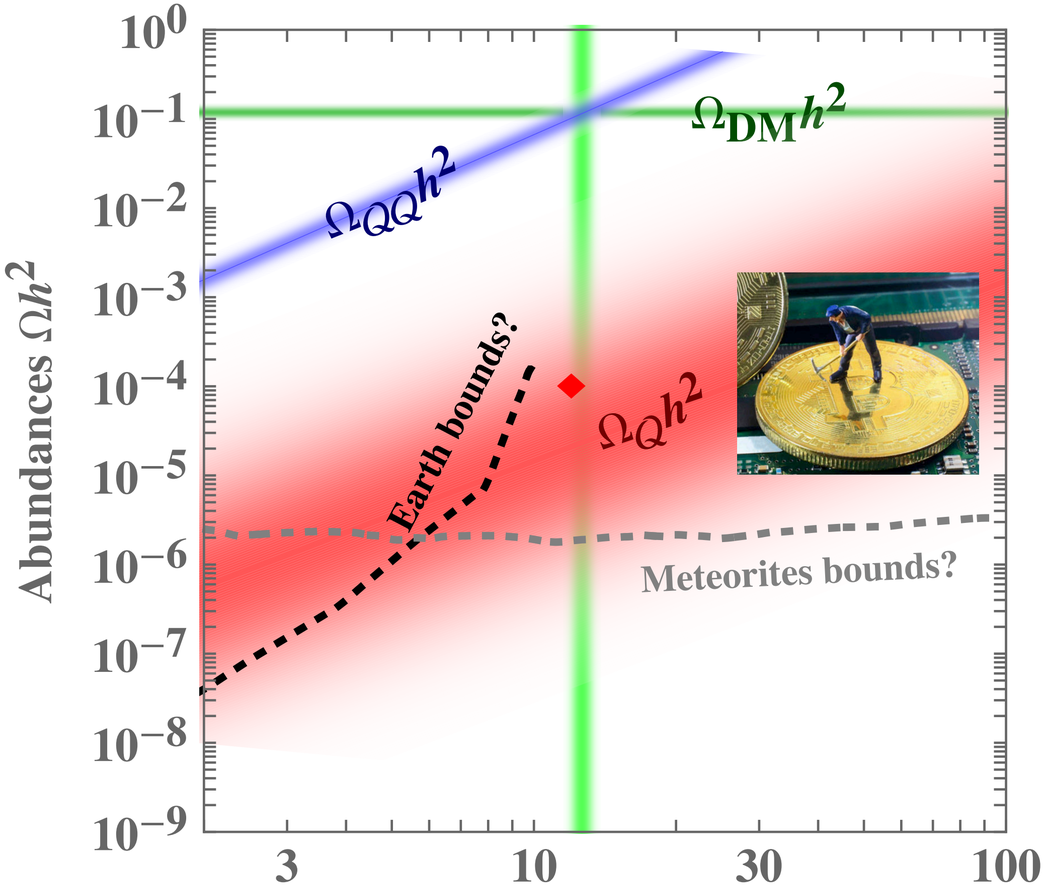
Abundances Today



Mitridate, Redi, JS et al.:
1801.01135, 1811.08418

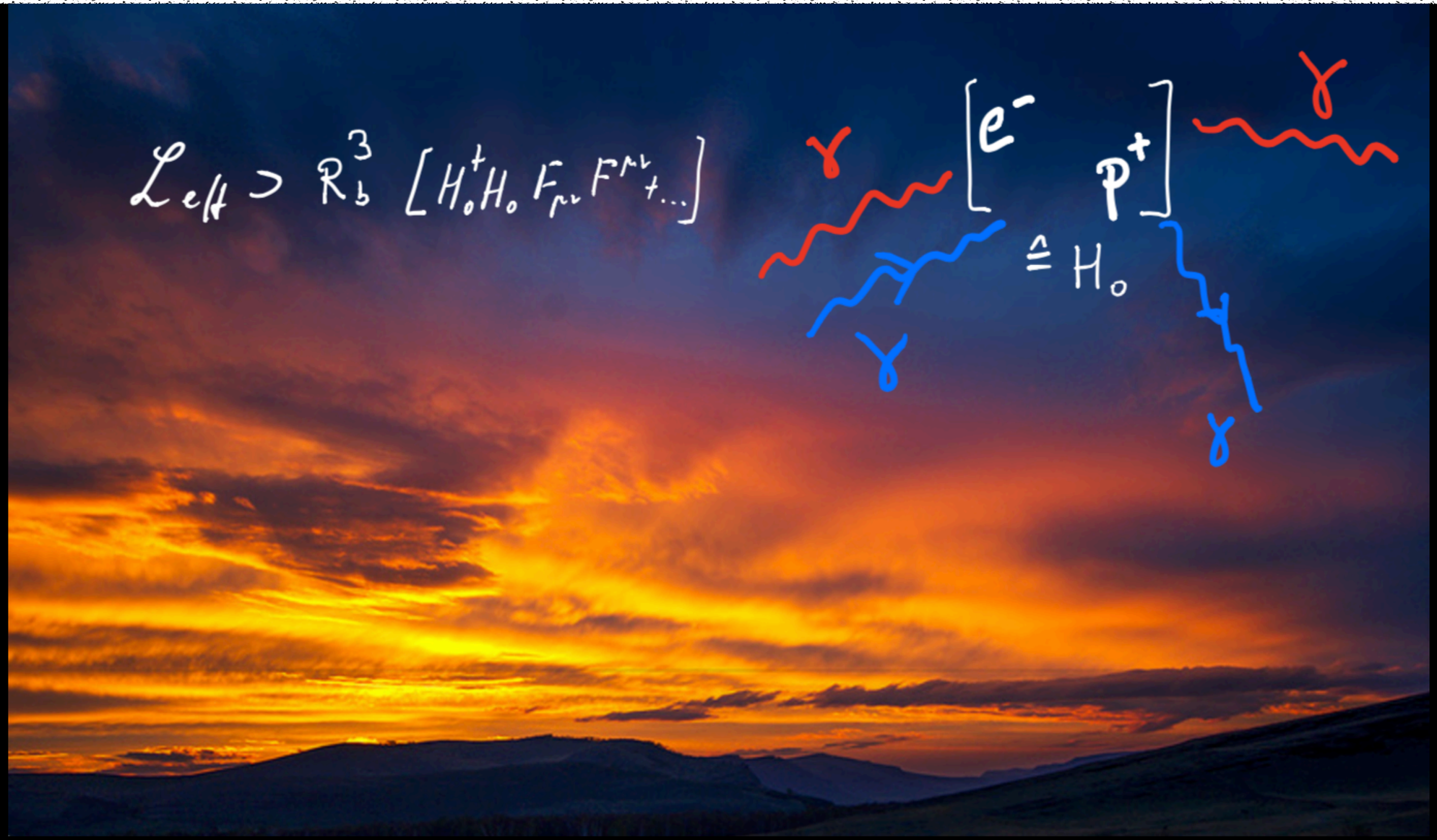
Abundances Today

Open Question:
Nuclear Binding
of Isospin = 0 ?

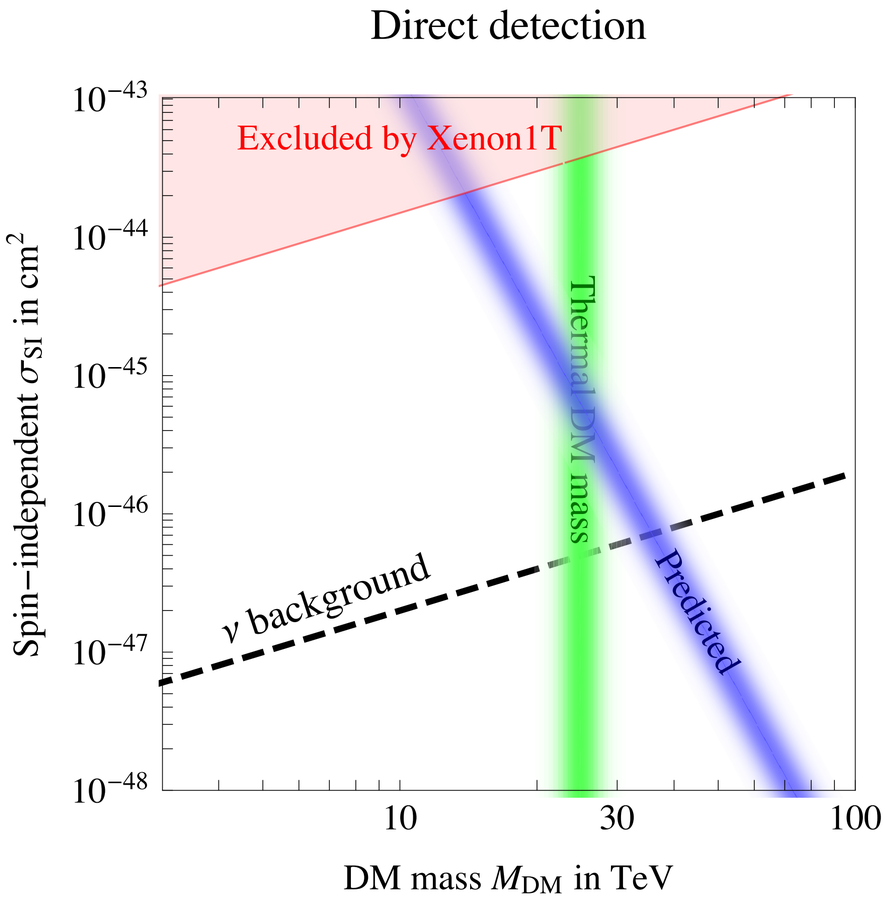


Mitridate, Redi, JS et al.:
1801.01135, 1811.08418

Direct Dectection & Chromopolarizability



Direct Dectection & Chromopolarizability



arXiv: 1801.01135

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

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

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

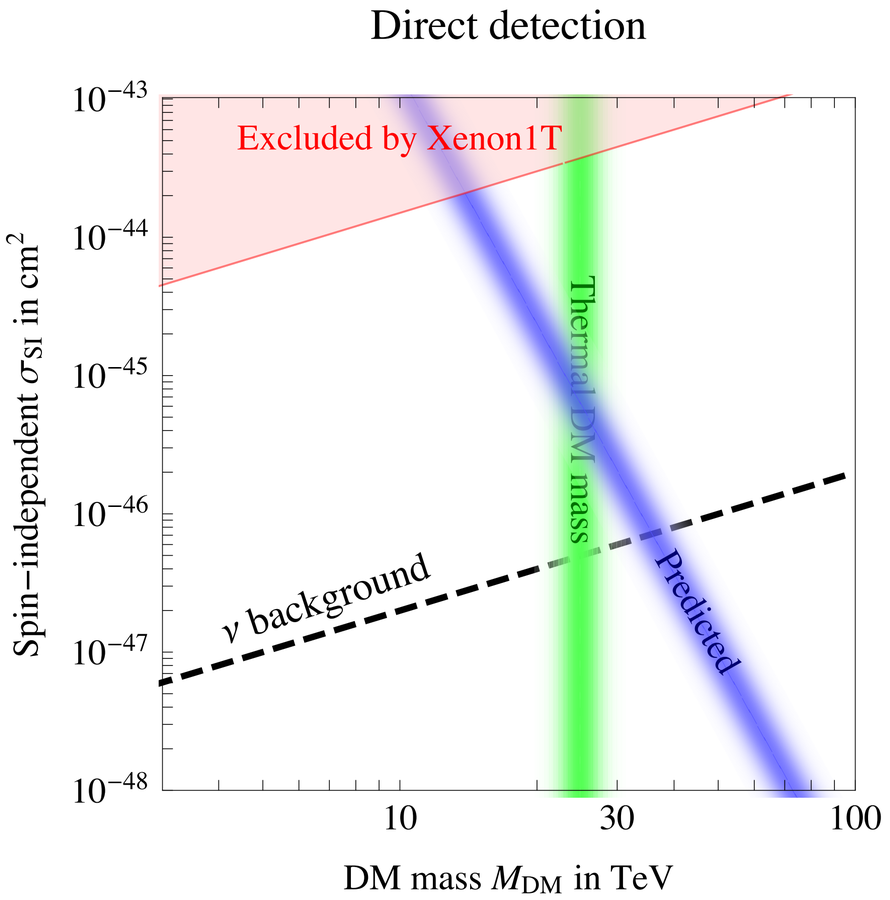
$$\sigma_{\rm SI} = \frac{f_N^2}{4\pi} \frac{m_N^2}{M_{\rm DM}^2}$$

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

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

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

Direct Dectection & Chromopolarizability



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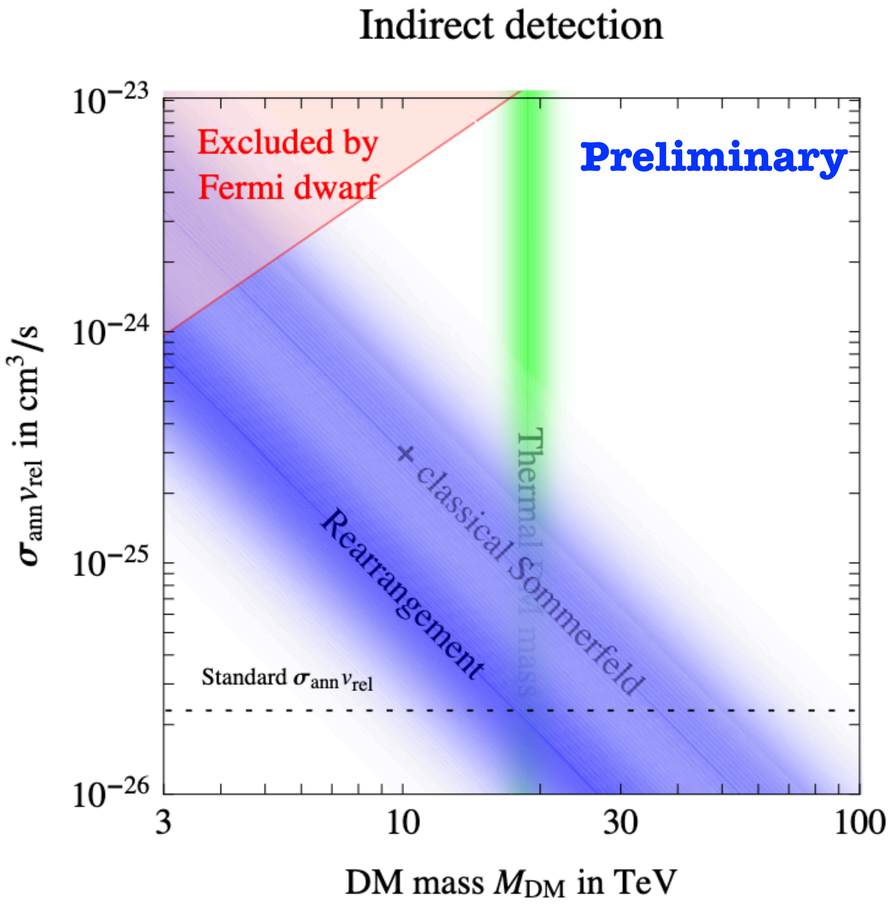
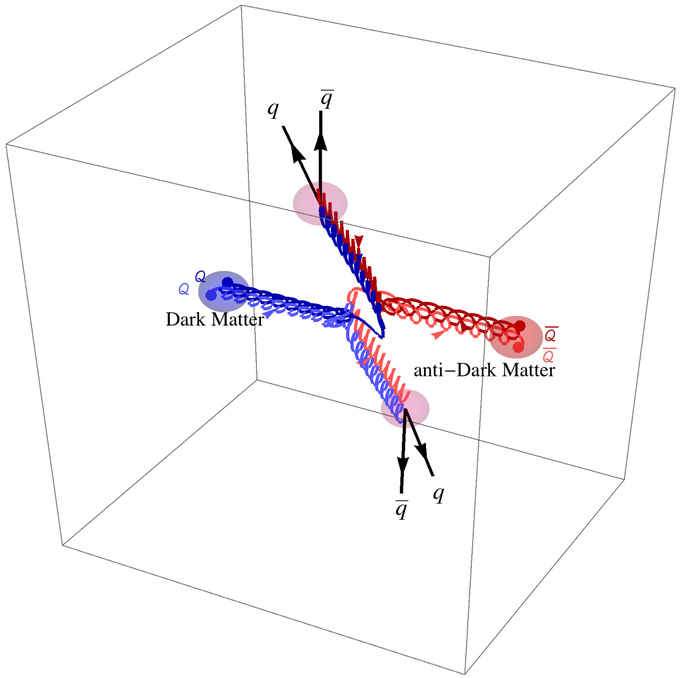
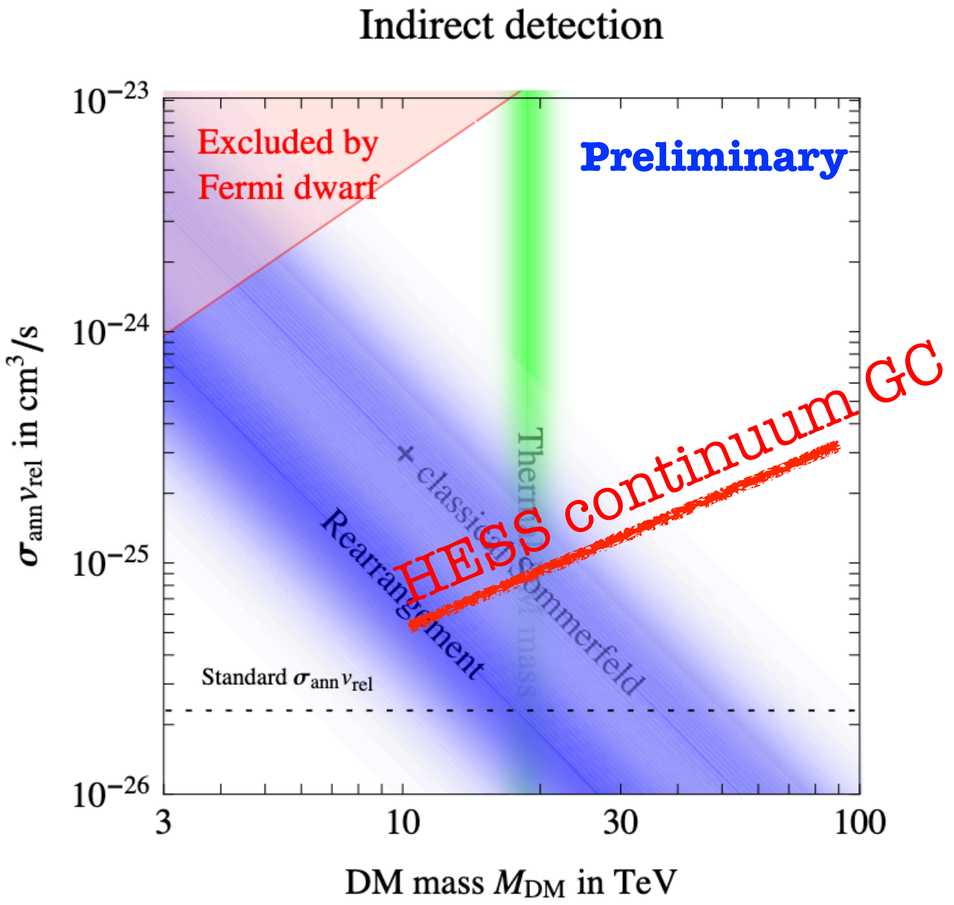
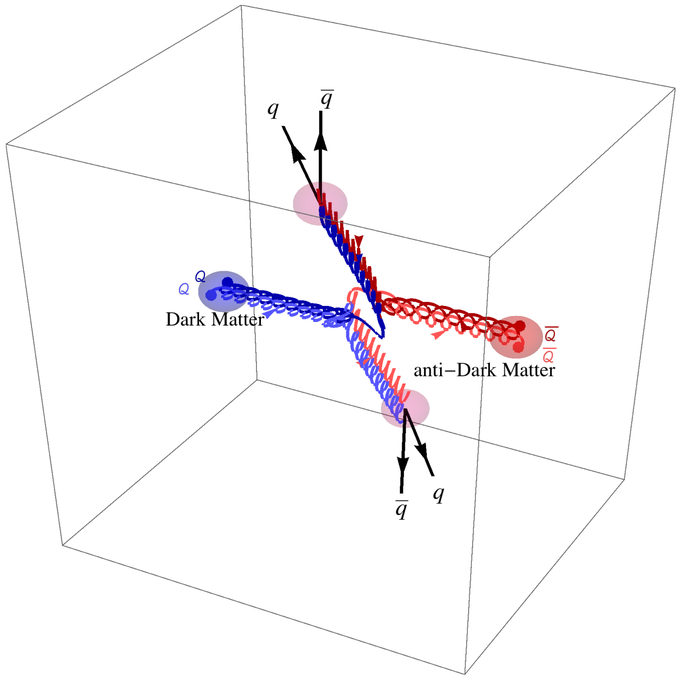
Annihilation Signals





Annihilation Signals

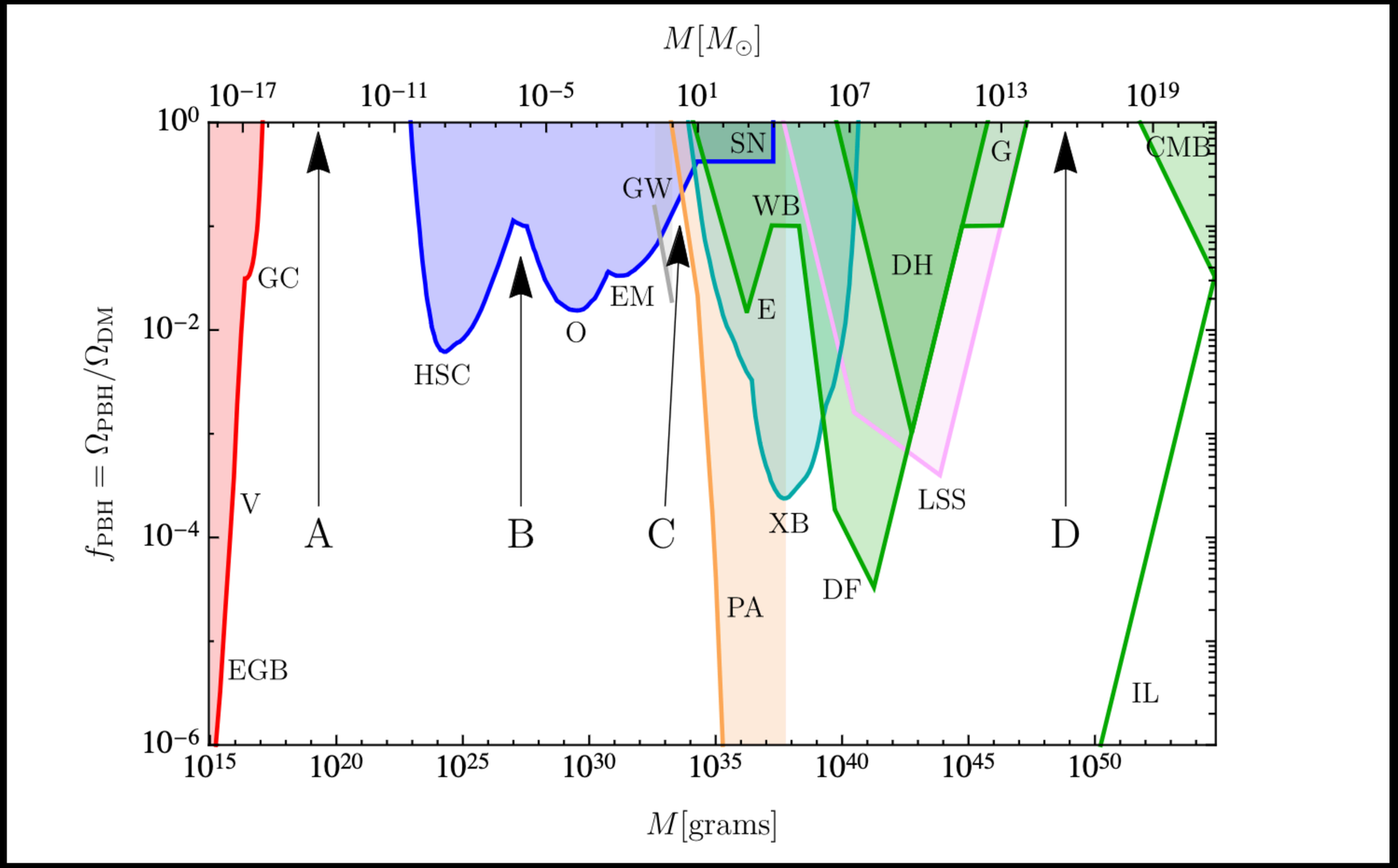




Compact Objects

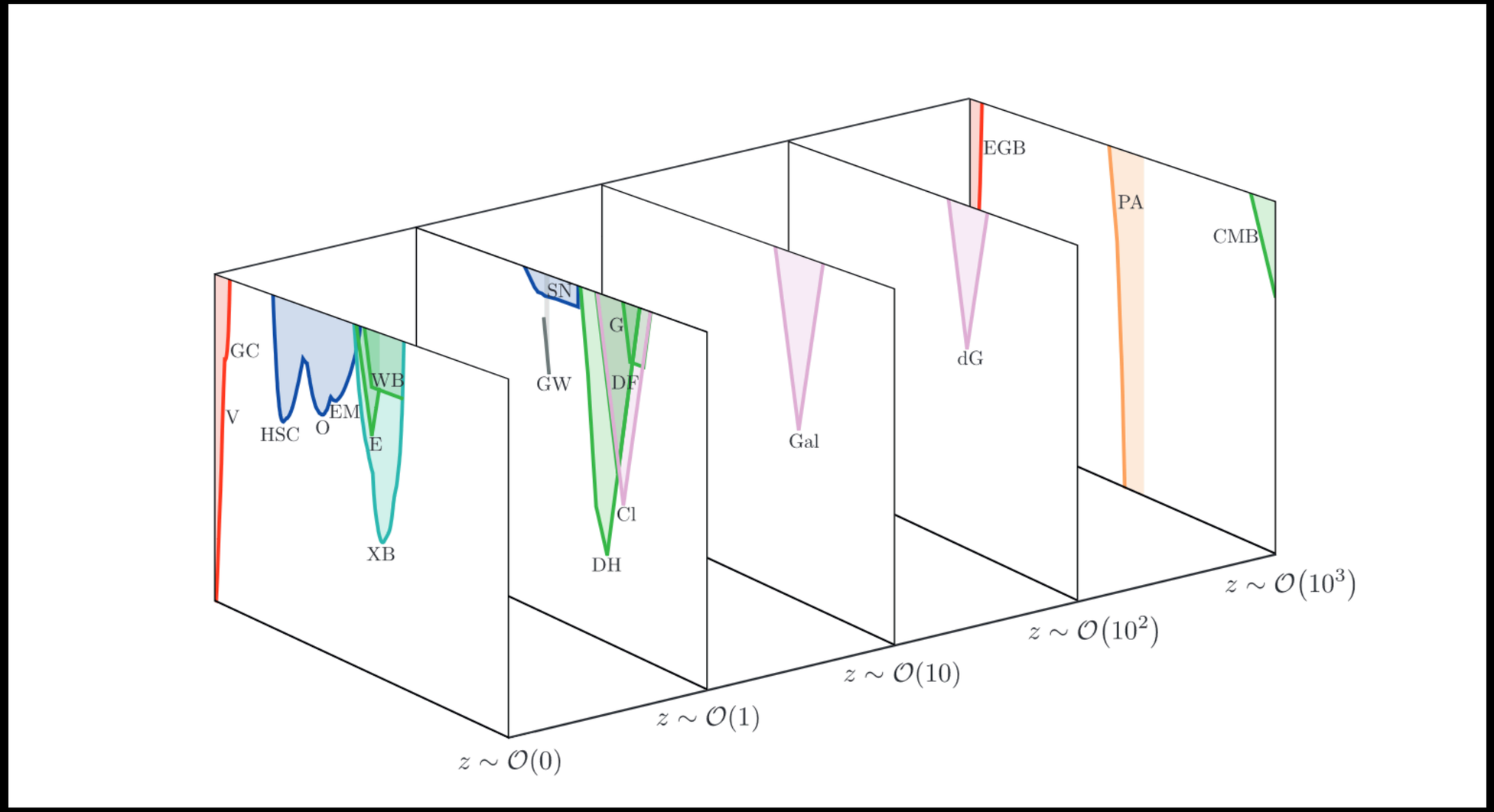
Juri Smirnov, juri.smirnov@liverpool.ac.uk; Hamburg, 21/12/23

Primordial Black Holes



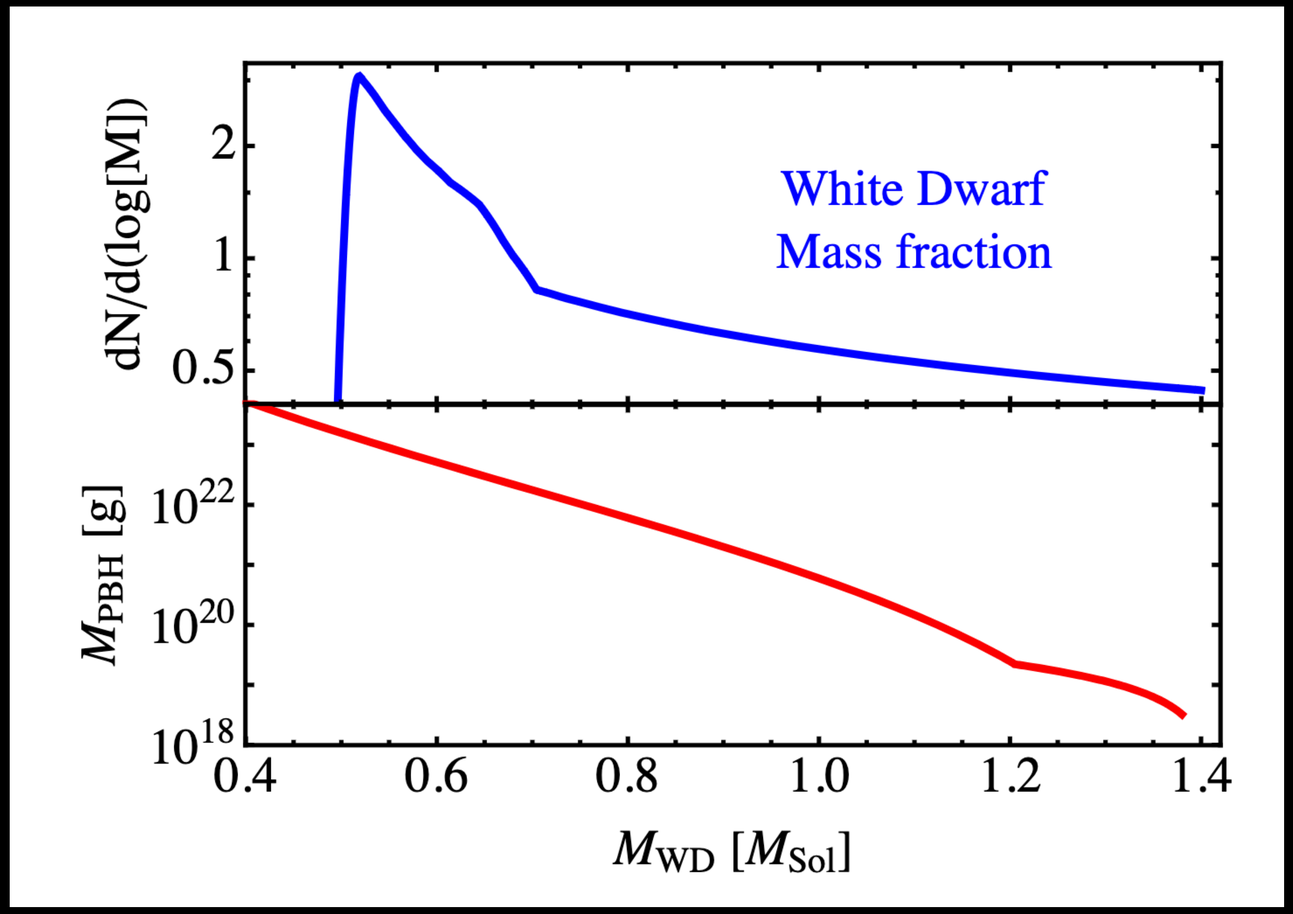
Carr & Kühnel 2021

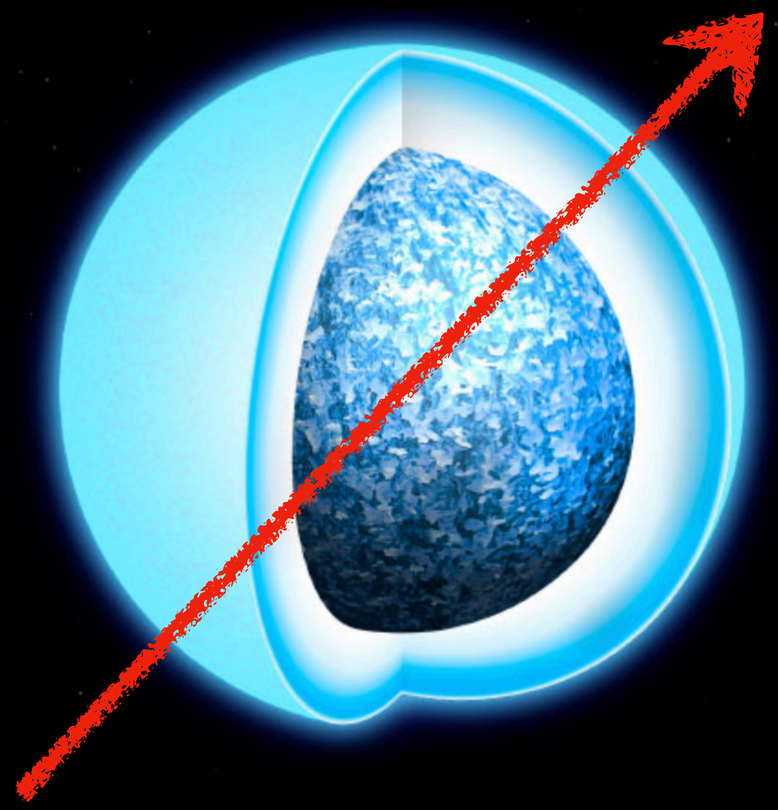
Primordial Black Holes Lookback



Carr & Kühnel 2021

Ignition Efficiency

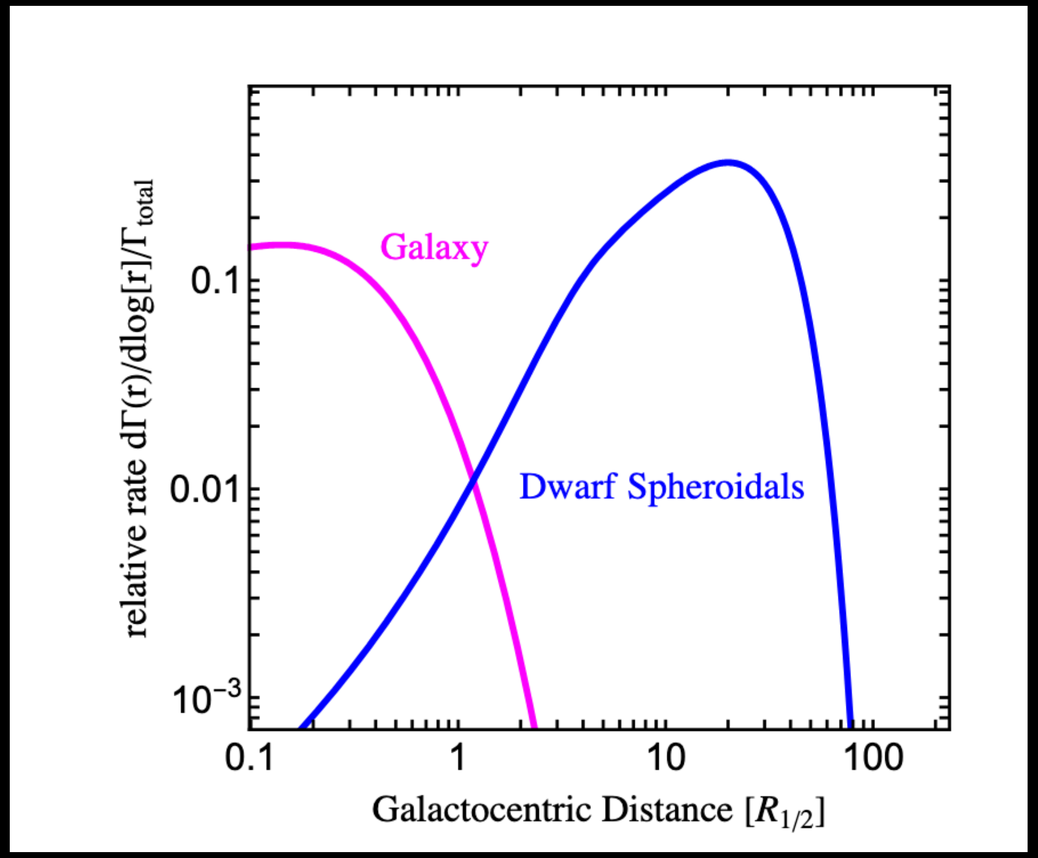


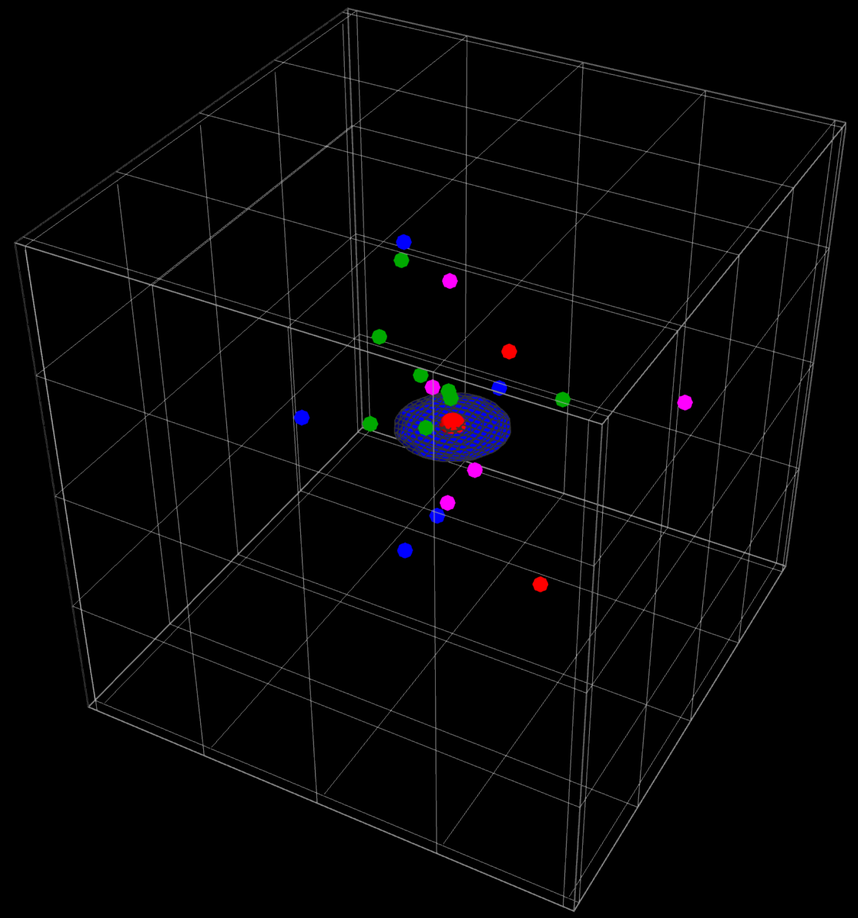


2211.00013 : **JS**, Goobar, Linden, Mörtsell

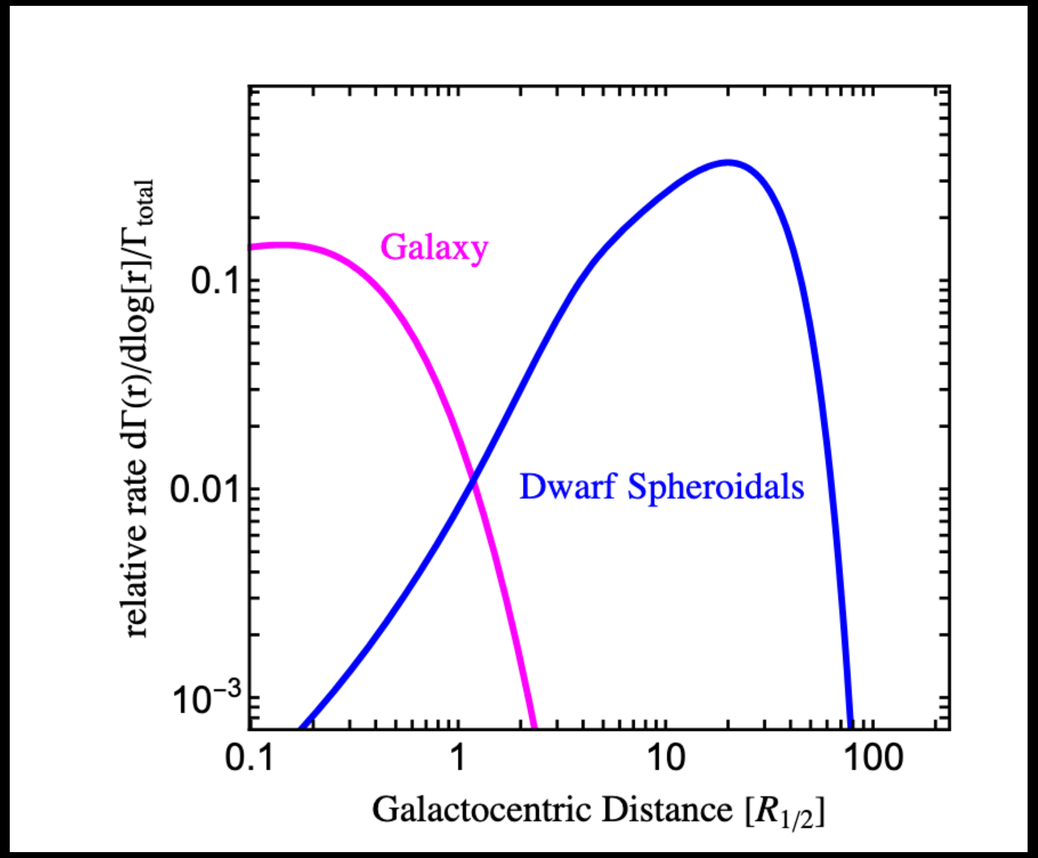
$$M_{\rm PBH} \sim R_{\rm heat} > \lambda_{\rm min}$$

Distribution in Distant Galaxies

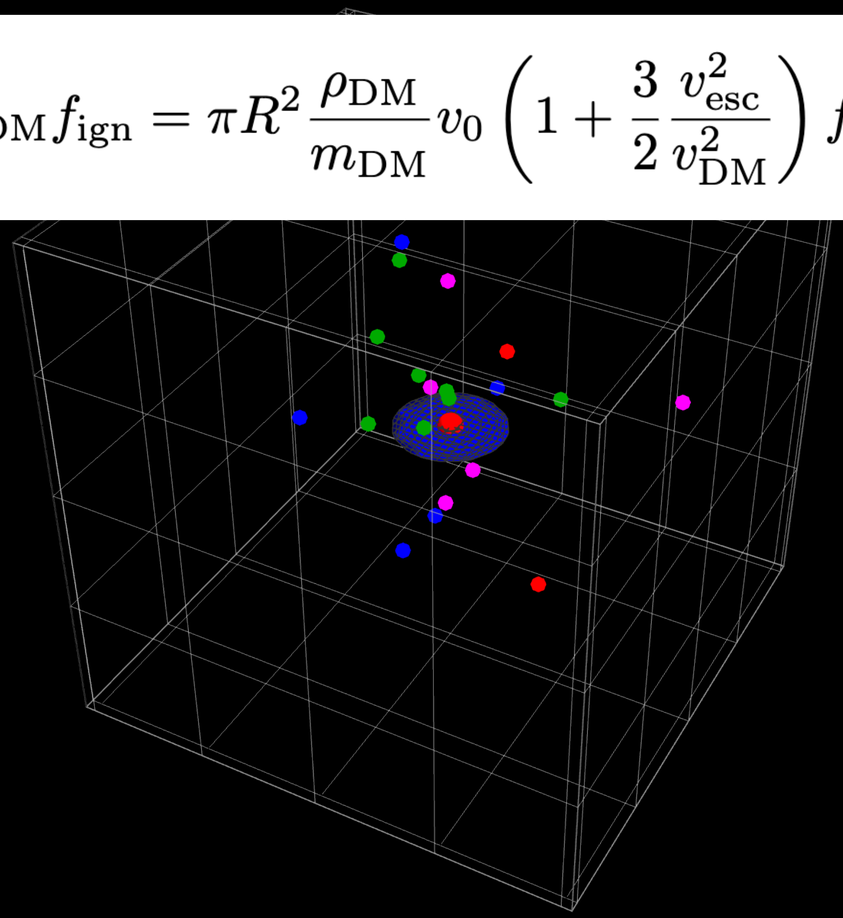




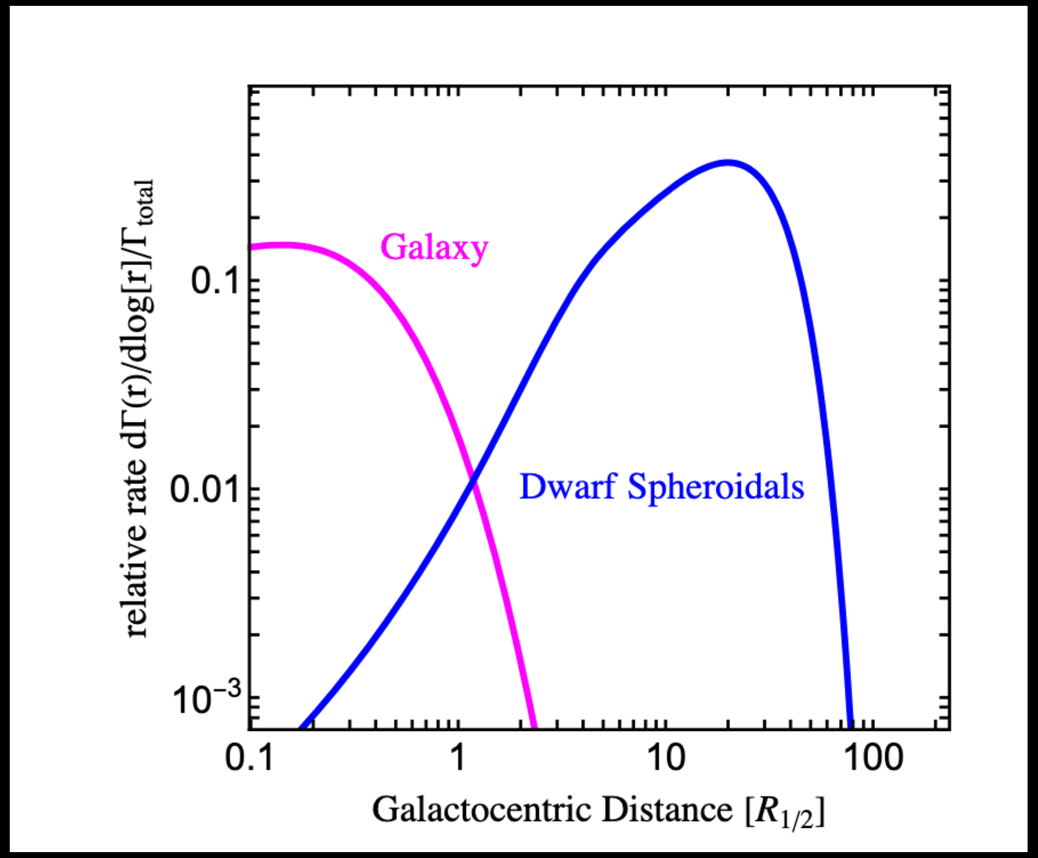
Distribution in Distant Galaxies

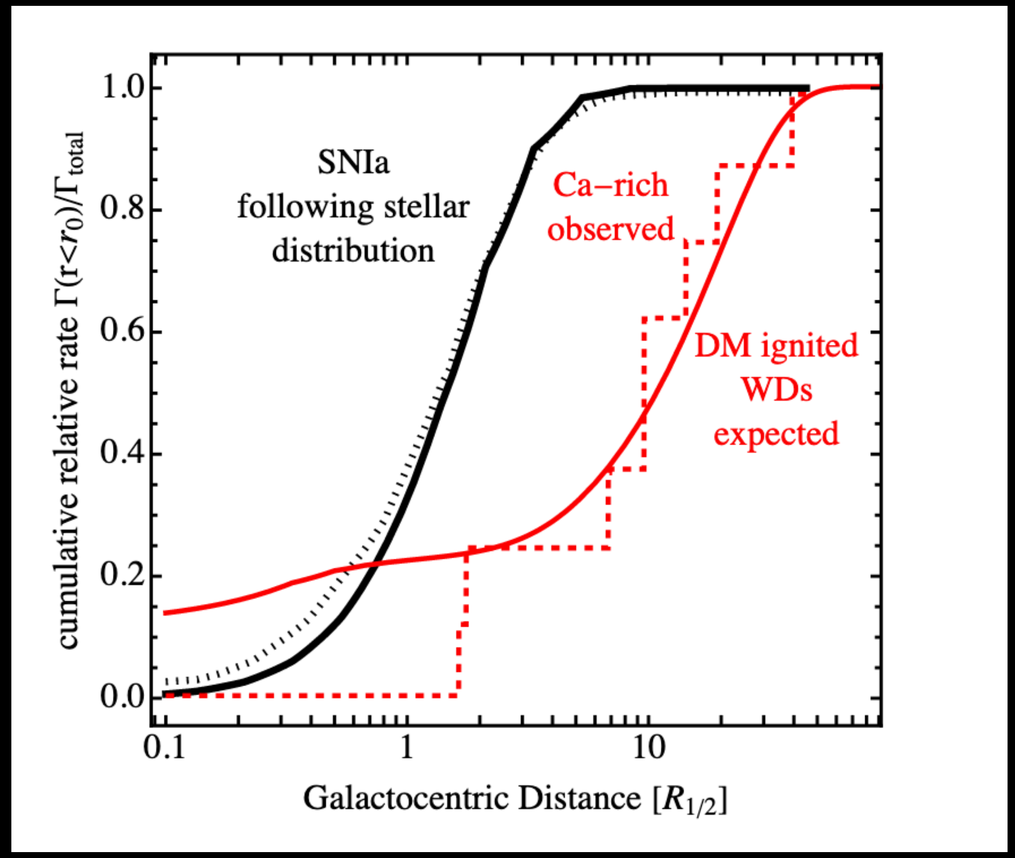


$$\Gamma_{\rm ign} = \phi_{\rm DM} f_{\rm ign} = \pi R^2 \frac{\rho_{\rm DM}}{m_{\rm DM}} v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_{\rm DM}^2}\right) f_{\rm ign}$$



Fit to the Observational Data





2211.00013 : **JS,** Goobar, Linden, Mörtsell

Minimal Benchmark Model PBHs