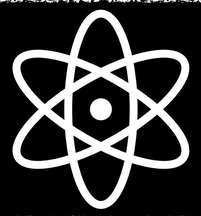
Dark Sector Phase Transitions and Dark Matter Squeezeout

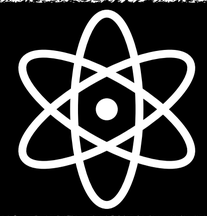
Lecturer: University of Liverpool

Seminar: Physics Department UoL
Liverpool: 24/10/23

Many thanks to my collaborators: Tracy Slatyer, Greg Ridgeway (MIT), Pouya Asadi (Oregon), Eric Kuflik, Eric D. Kramer (Hebrew U.), Tim Linden, Ariel Goobar, Edward Mörtsell (Stockholm U.)



Matter has structure



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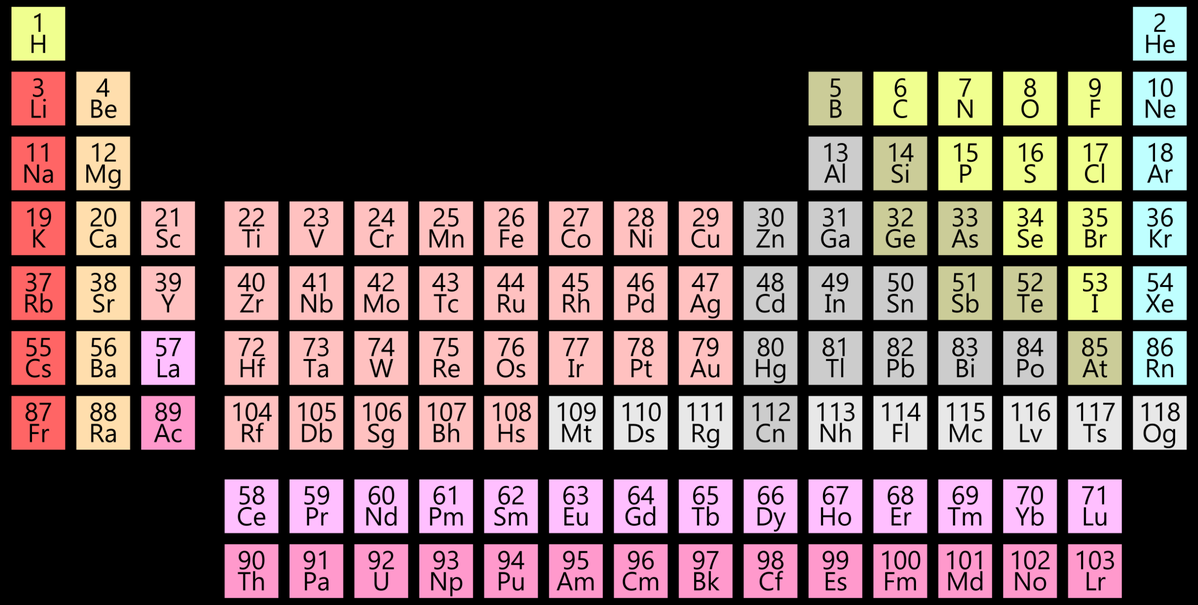

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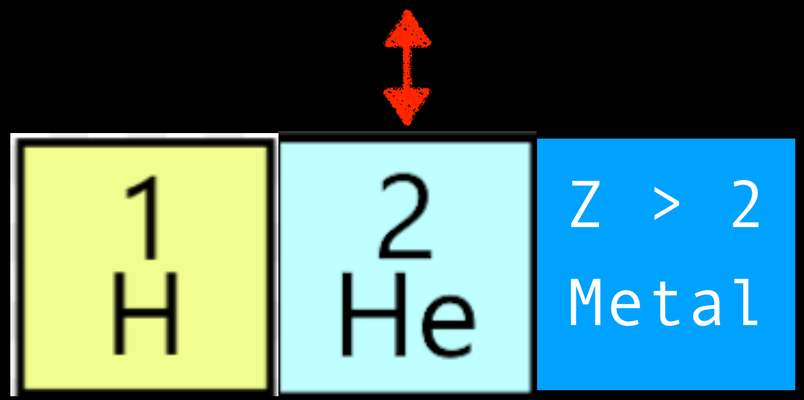
Matter has structure

1 H																2 He
3 Li	4 Be										5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
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
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	



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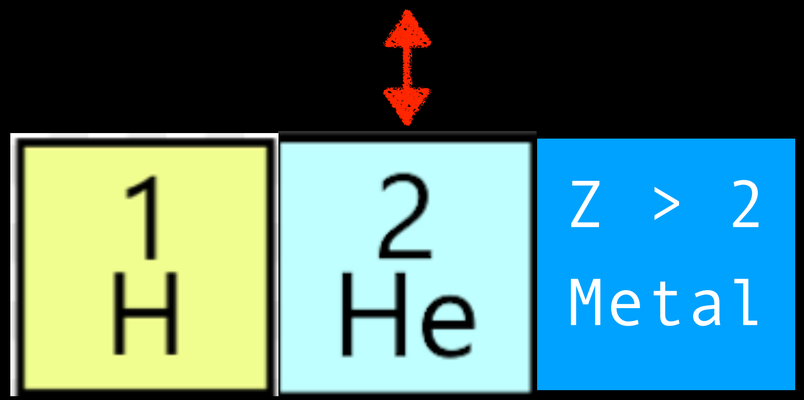

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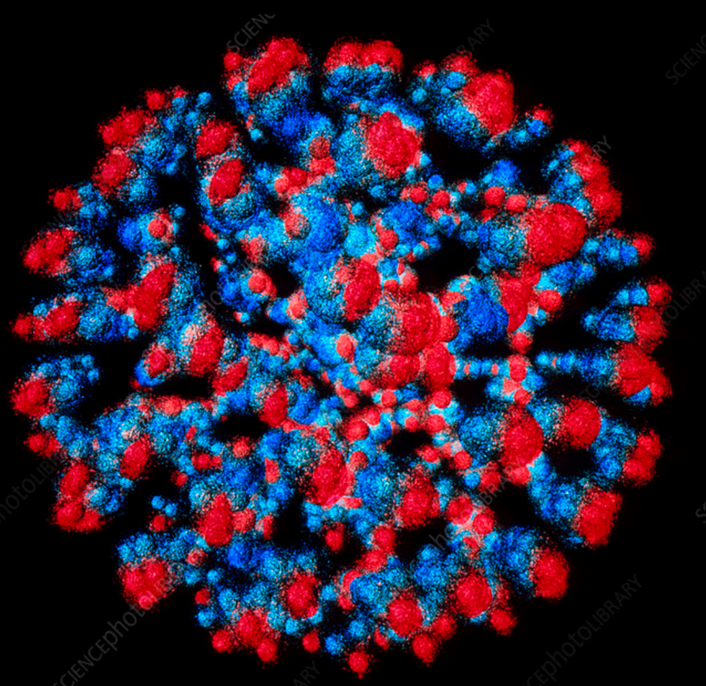

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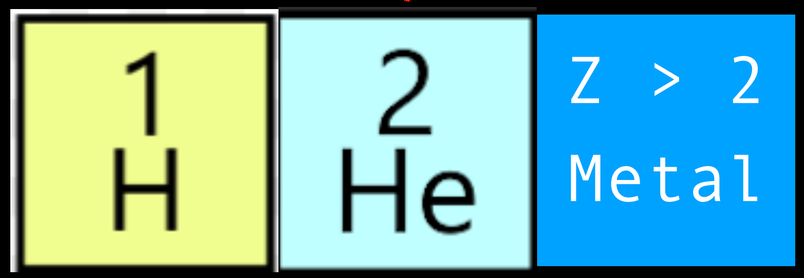

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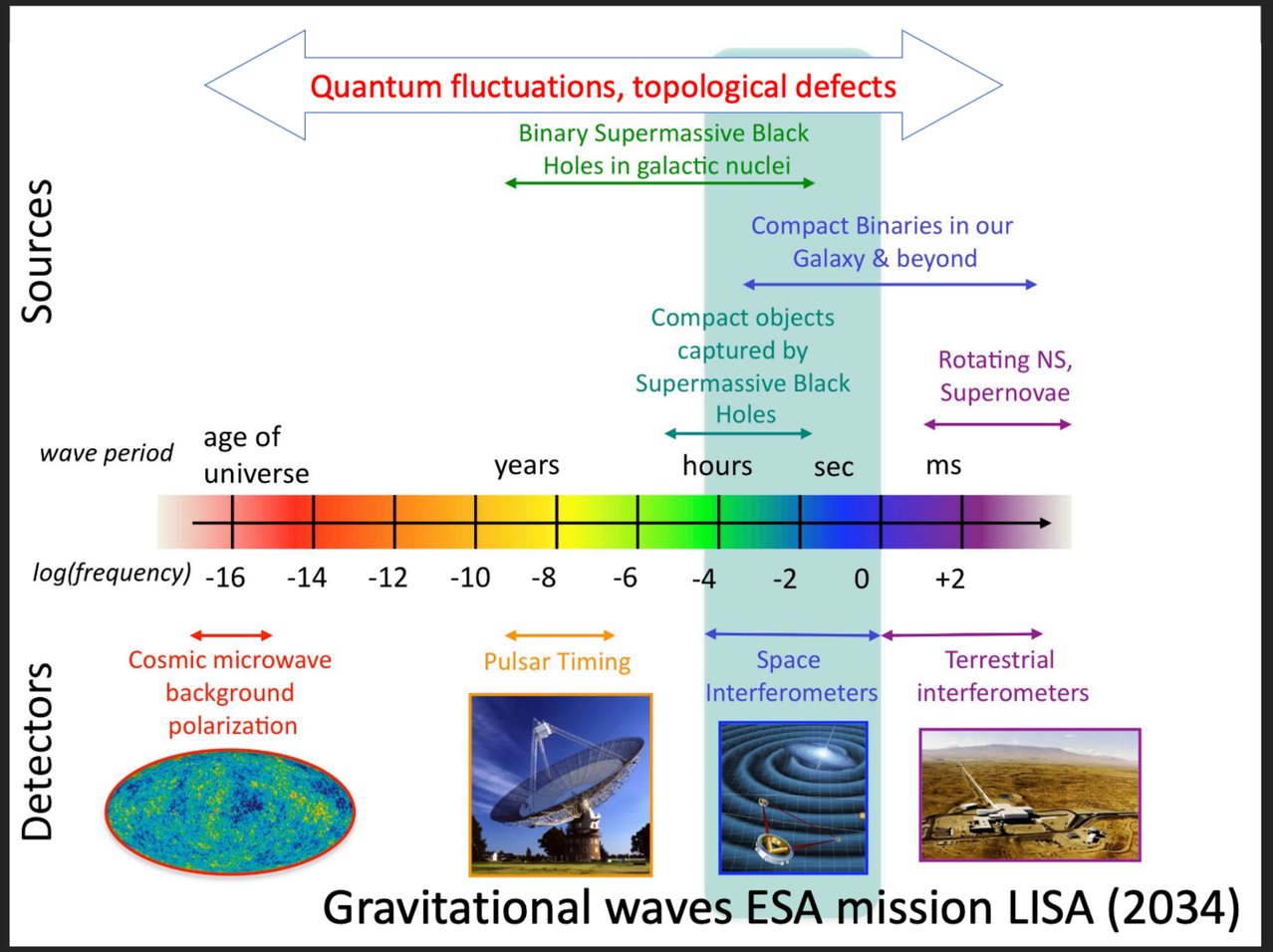
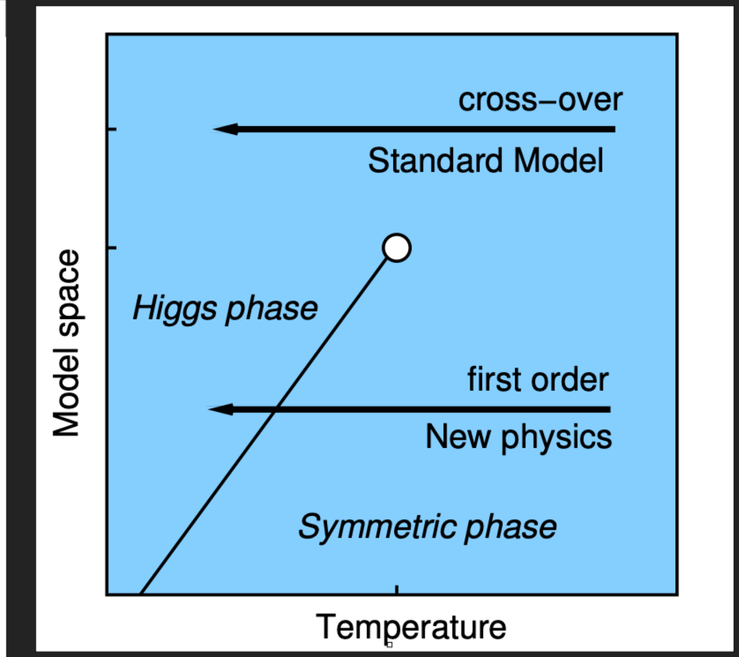
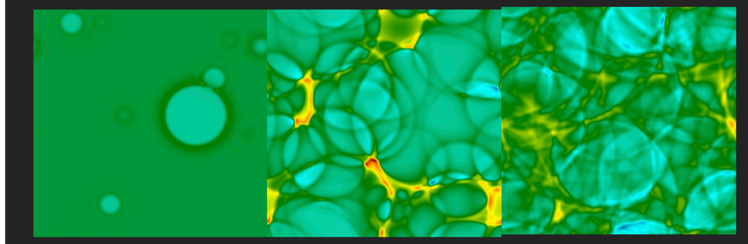
The Standard Model has Phase Transitions



Gravitational waves ESA mission LISA (2034)





Numerical simulation of a phase transition

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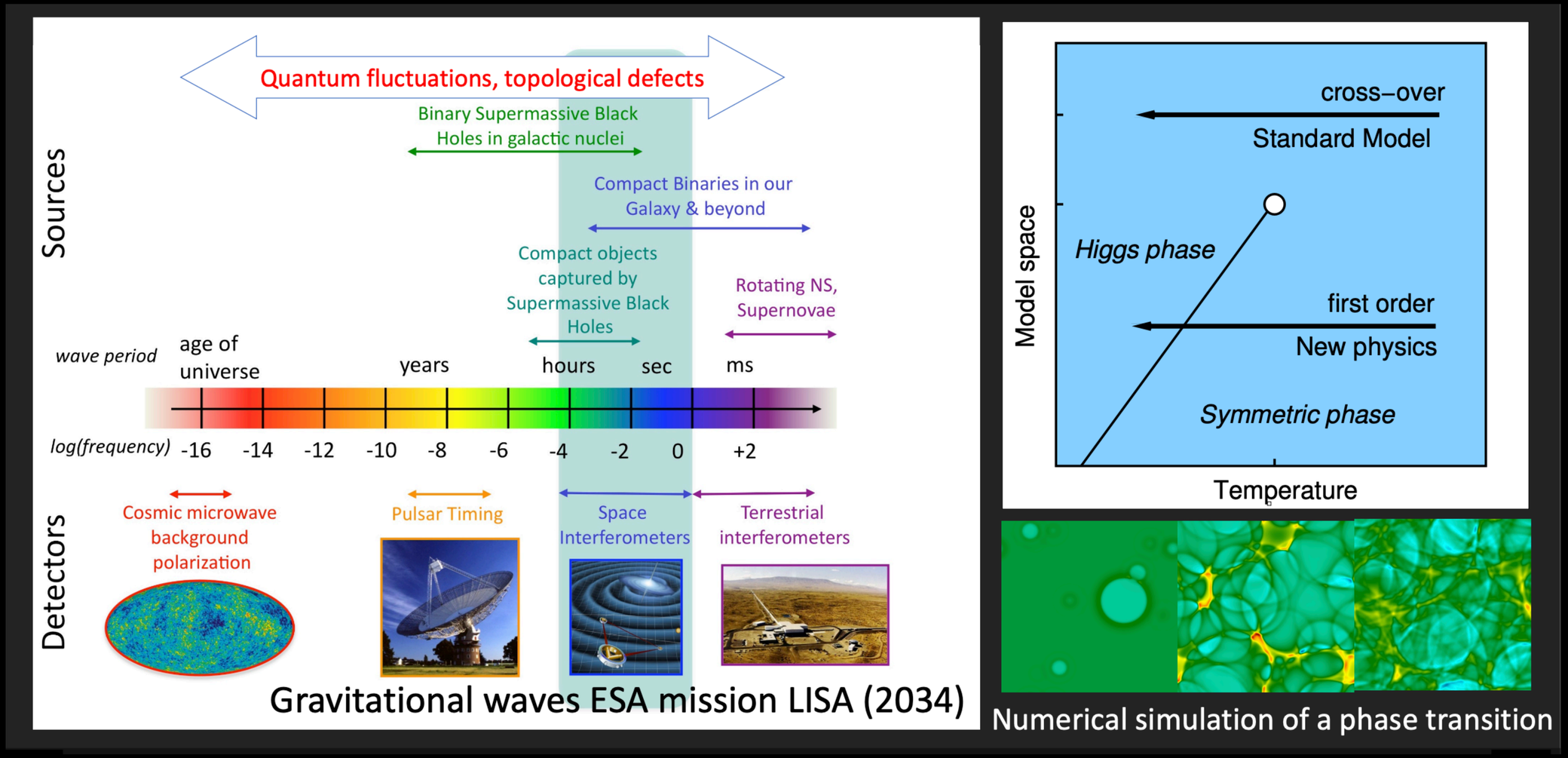

QUEST-DMC: Hindmarsh

Confinement and Stable Bound States

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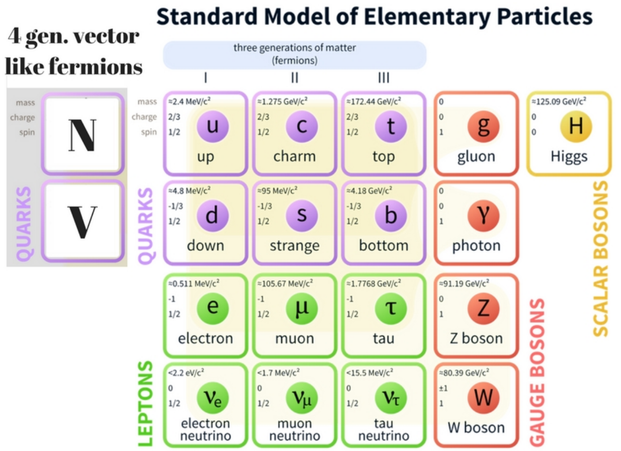
Dark Gauge Interactions

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

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



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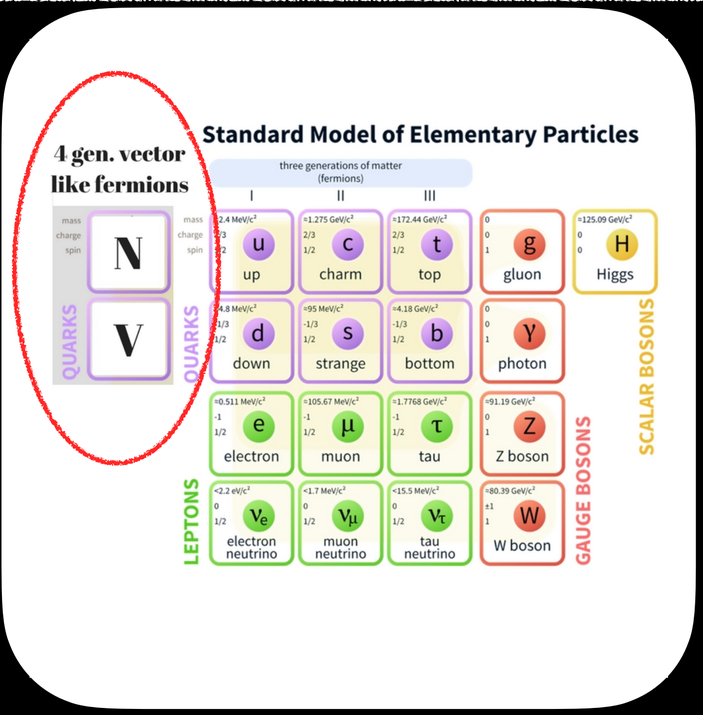
New Baryon Number → DM candidate



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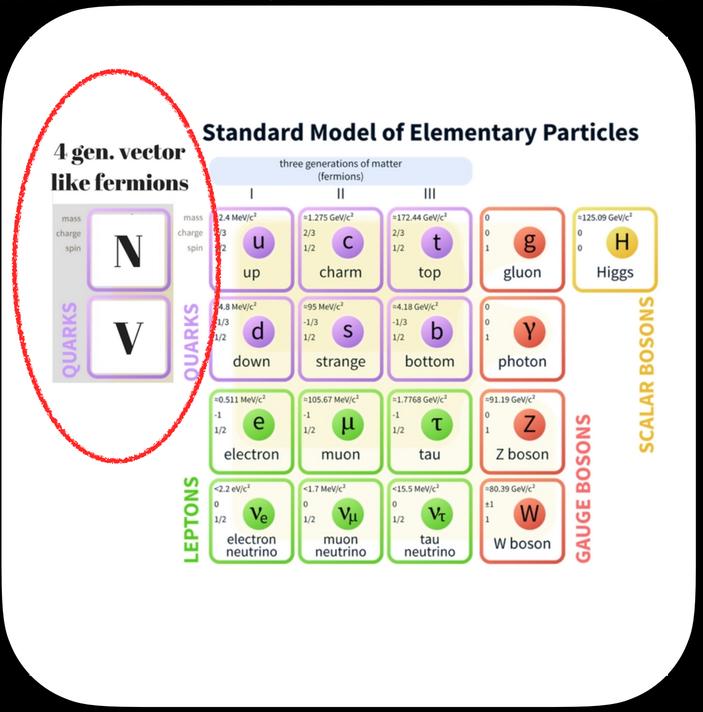
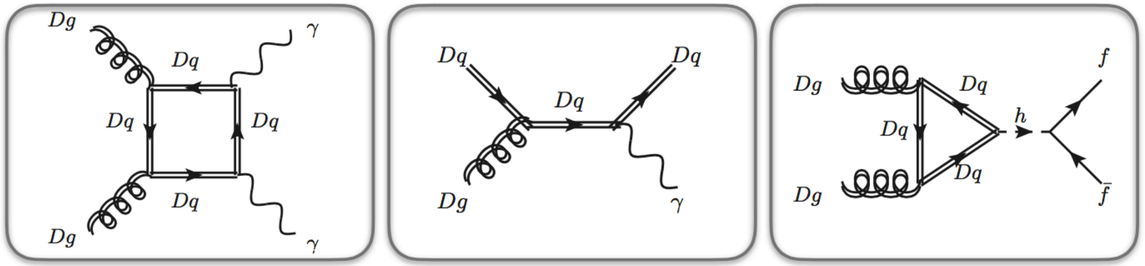
New Baryon Number → DM candidate

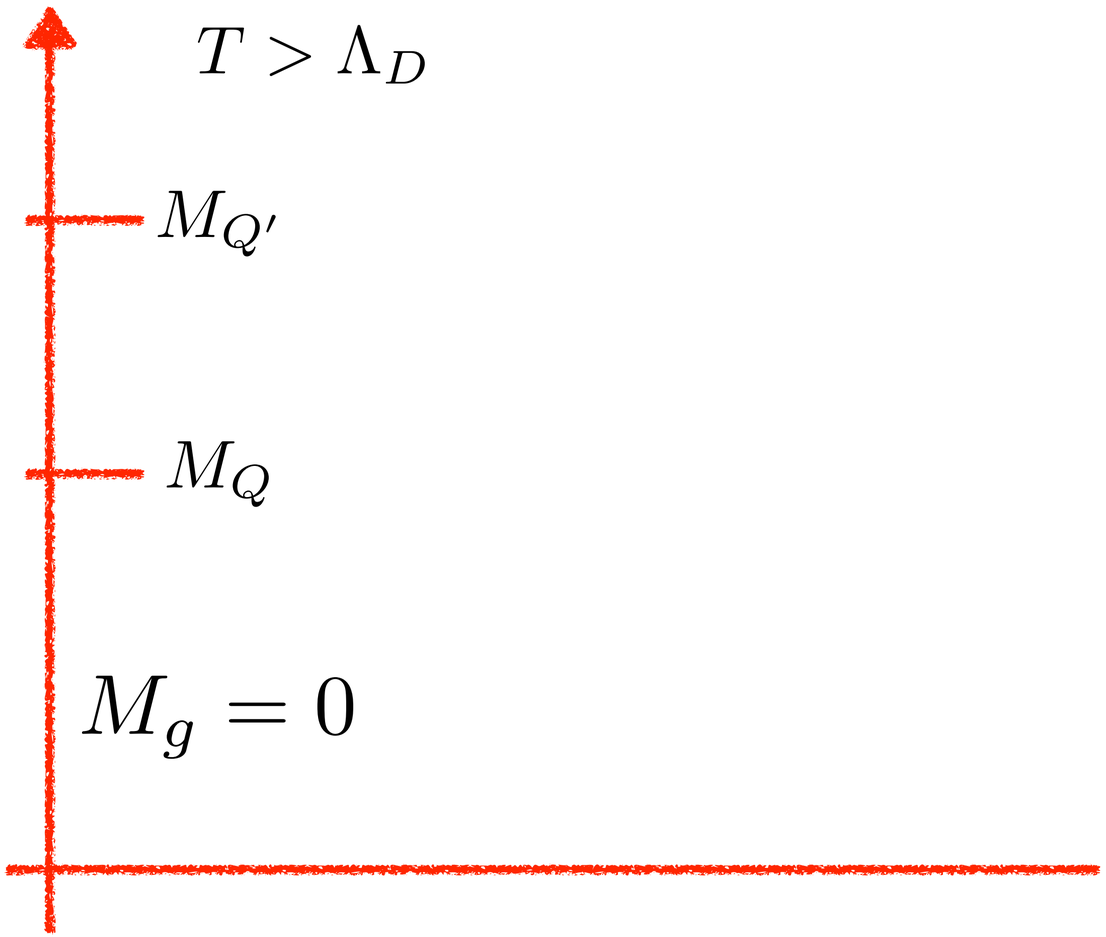
Thermal contact with the SM sector





Redi et al.
arxiv:1503.08749

Mass Spectra



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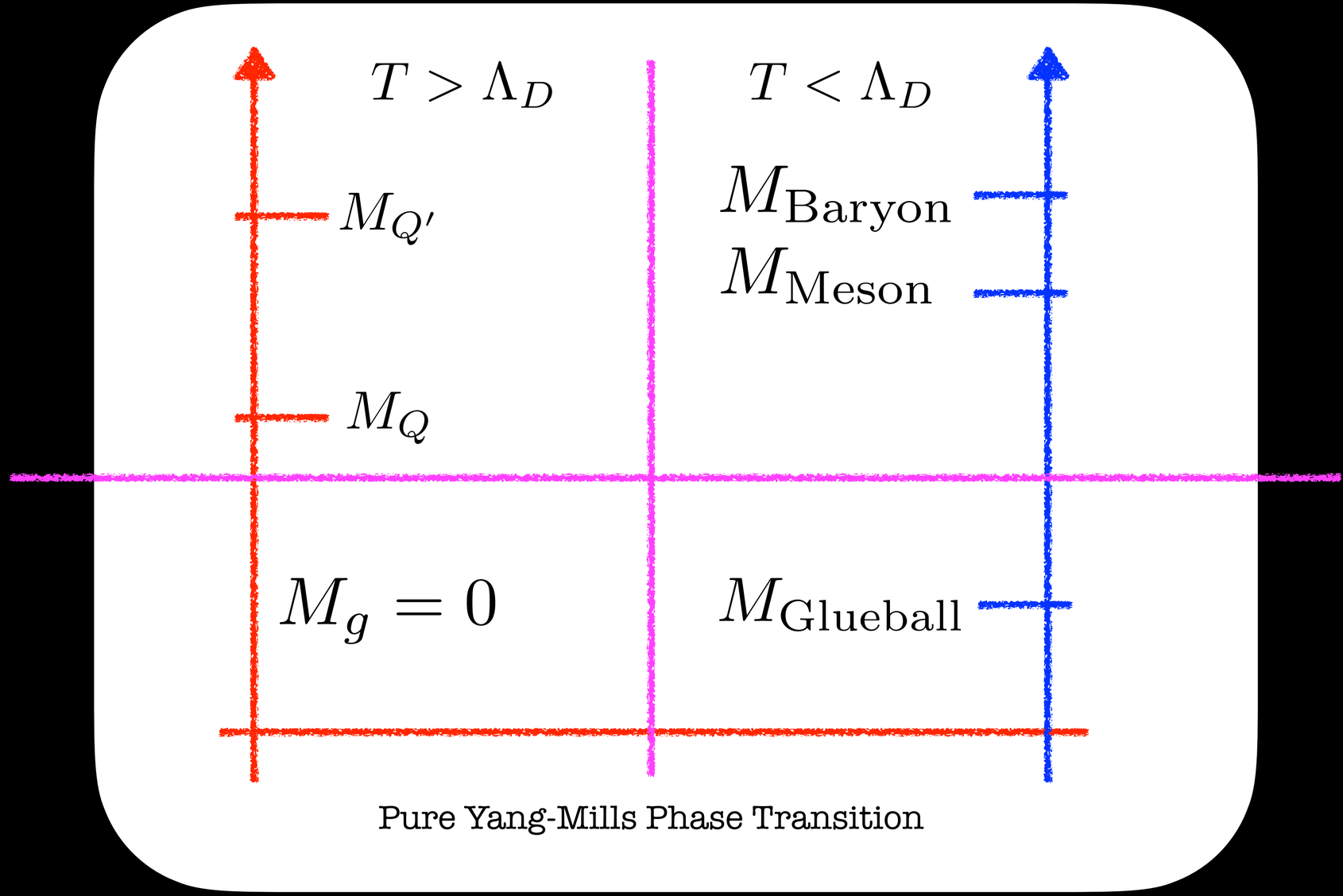

Pure Yang-Mills Phase Transition

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The Relic Abundance

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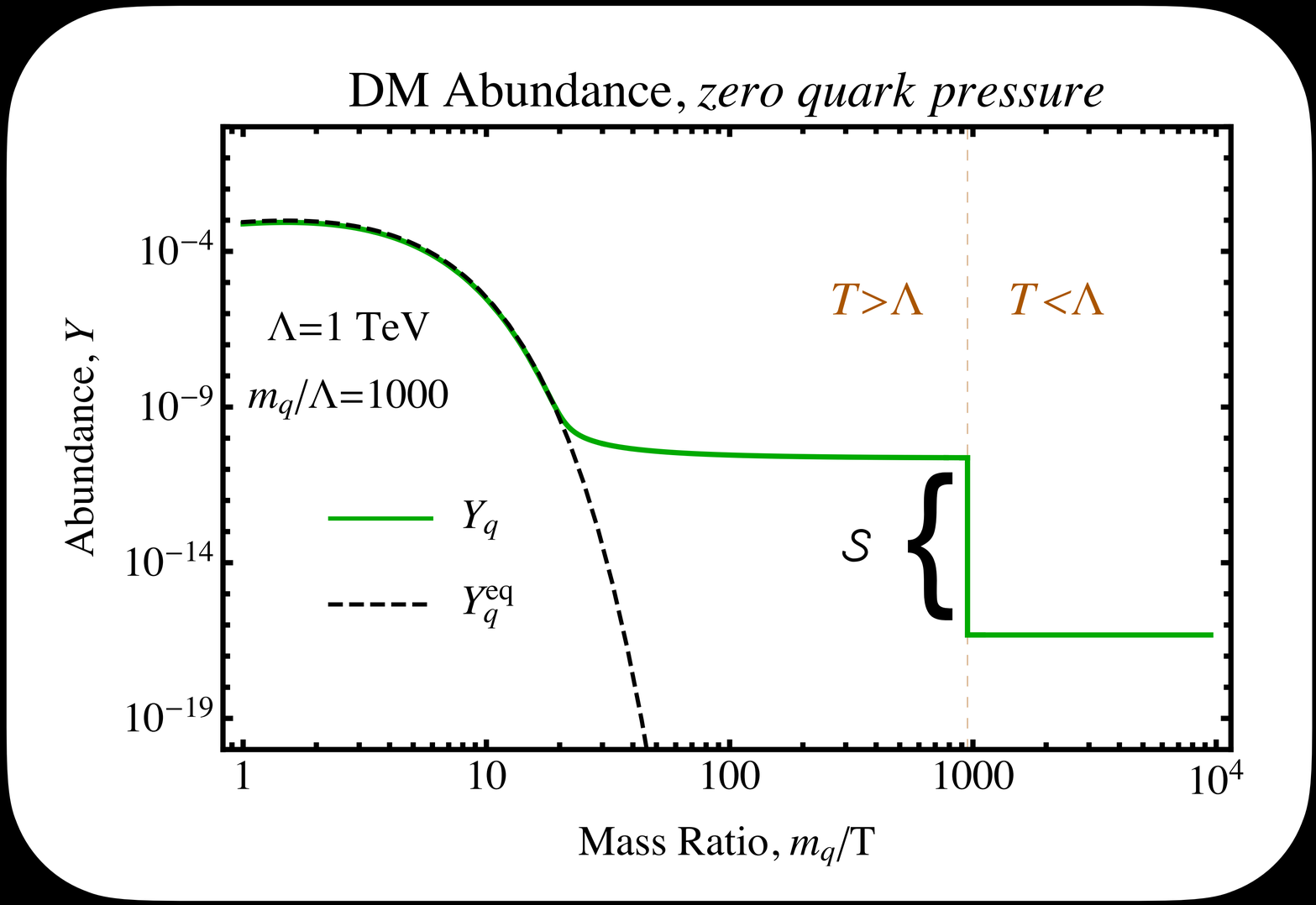
The Freezeout



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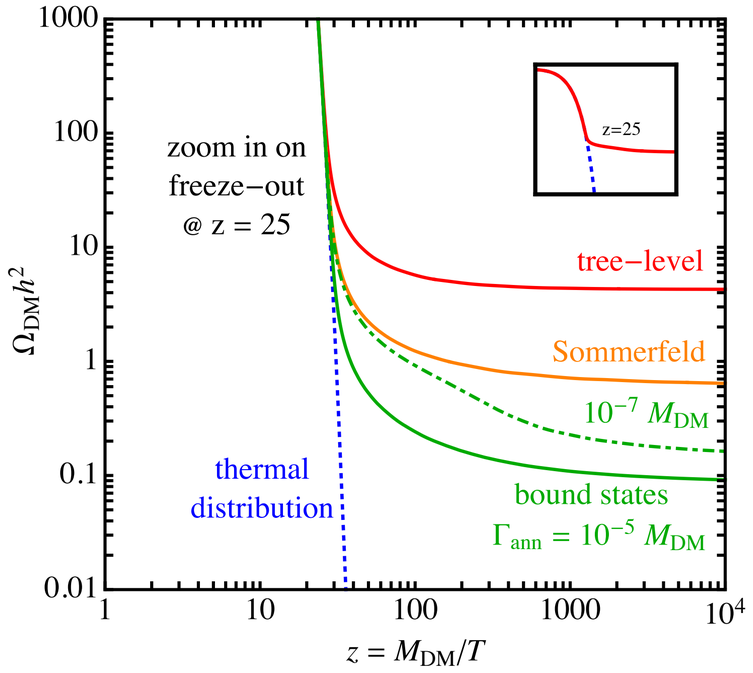
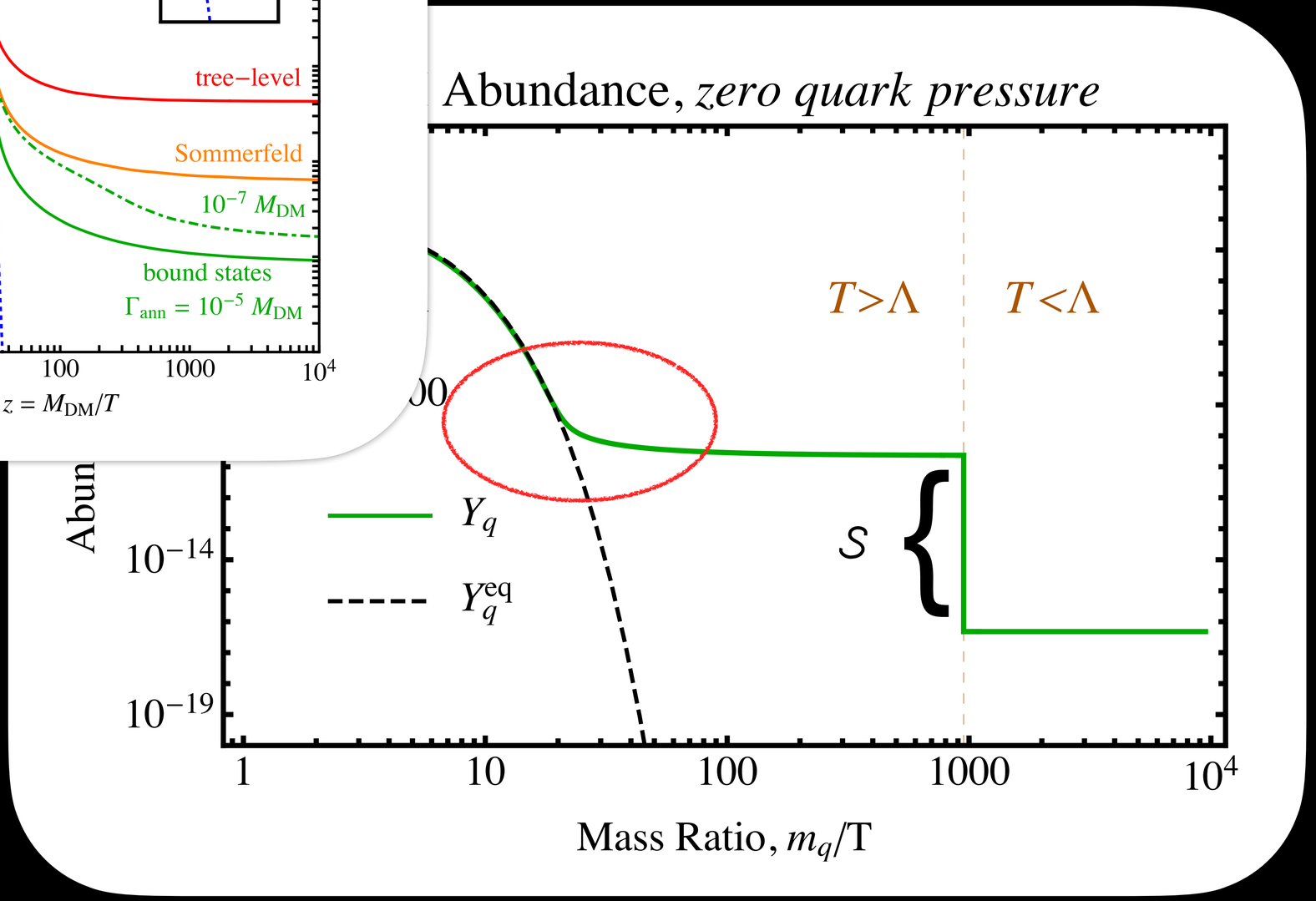
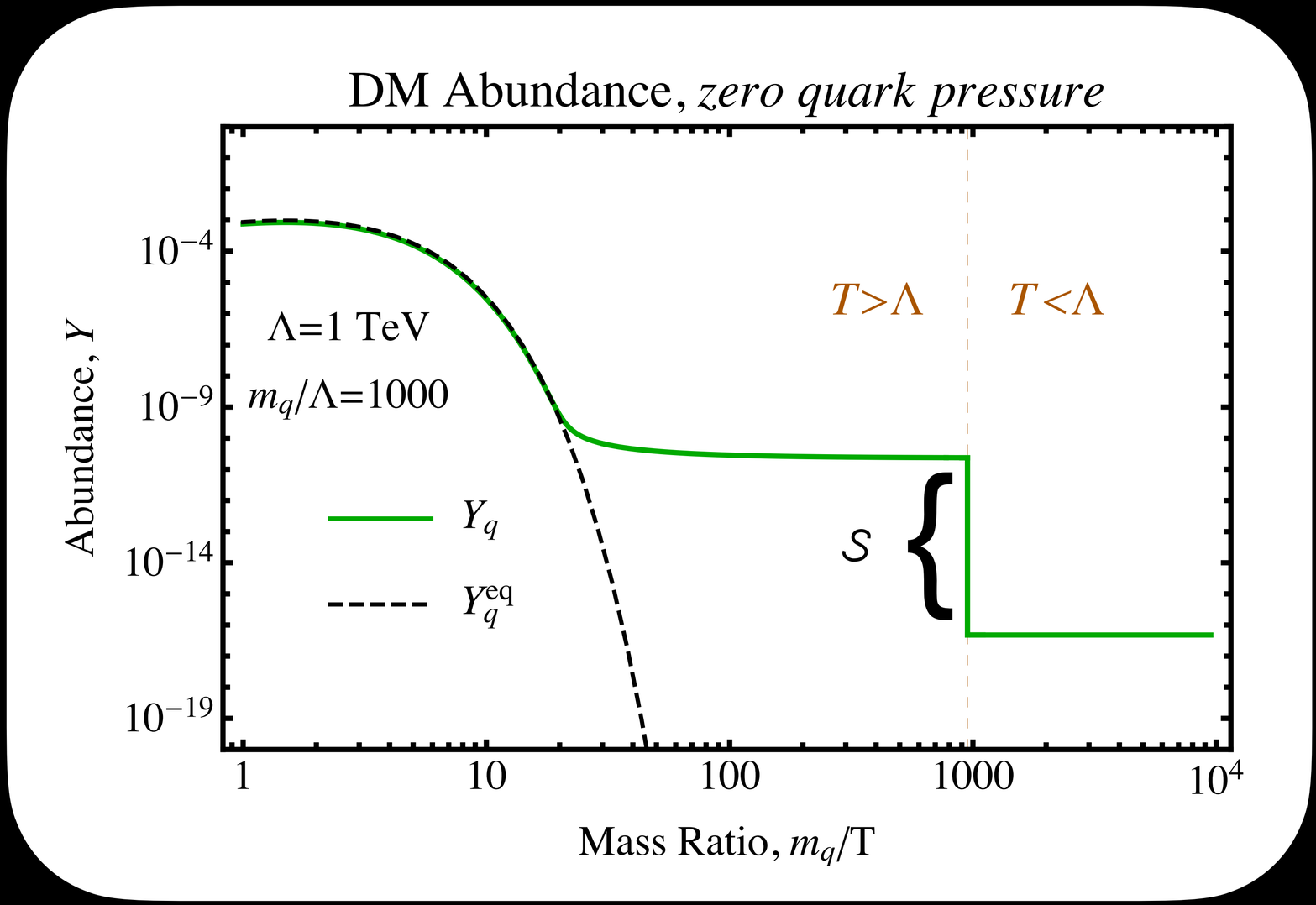

zoom in on
freeze−out
@ z = 25
z=25
tree−level
Sommerfeld
$10^{-7}\ M_{\rm DM}$
thermal
distribution
bound states
$\Gamma_{\rm ann} = 10^{-5}\ M_{\rm DM}$
$\Omega_{\rm DM}h^2$
$z = M_{\rm DM}/T$


Abundance, *zero quark pressure*
$T>\Lambda$
$T<\Lambda$
Y_q
$Y_q^{\rm eq}$
S
Mass Ratio, m_q/T

The Freezeout



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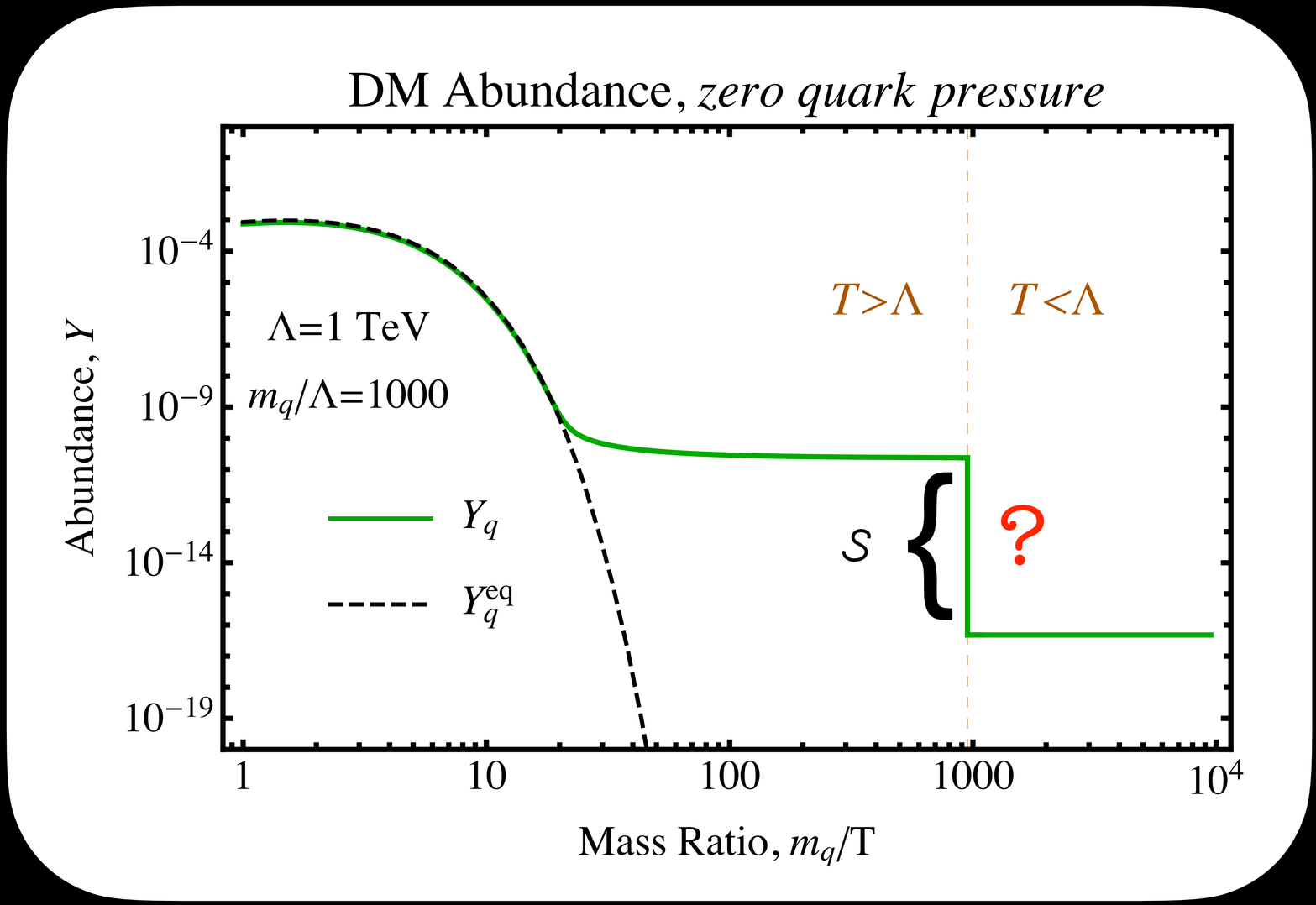

Geometric Rearrangement

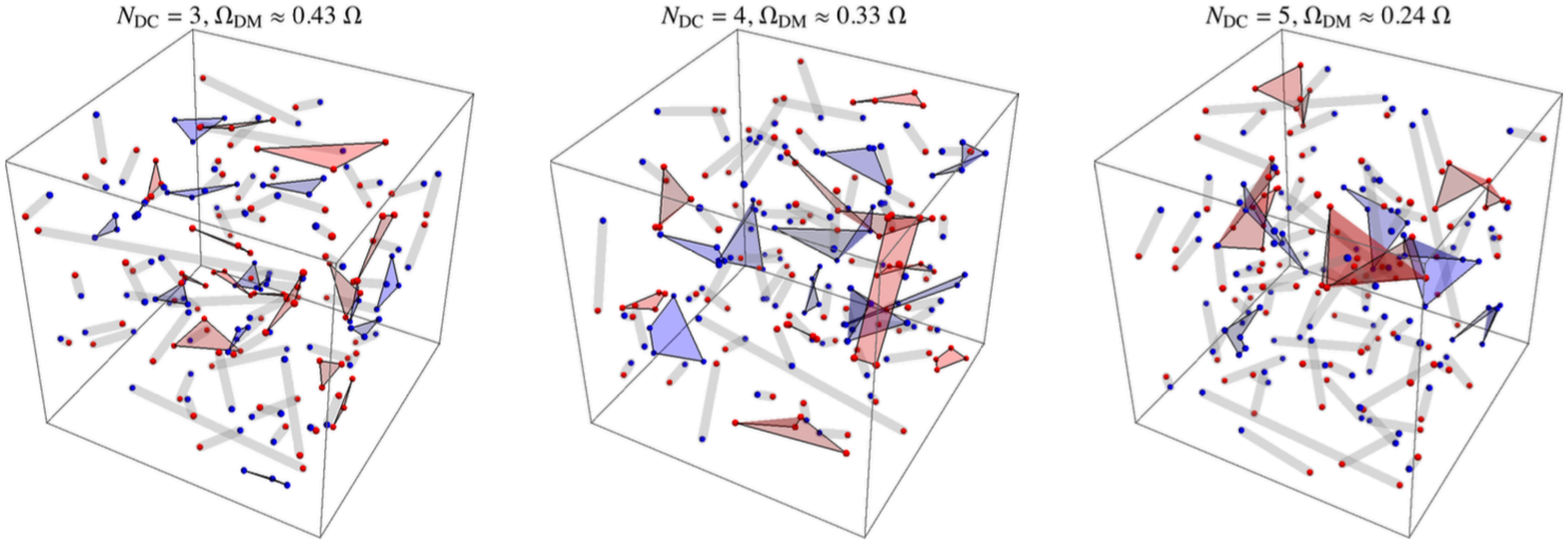

Figure 5: *Examples of dark condensation for* $N_{\rm DC} = 3$ *(left),* 4 *(middle) and* 5 *(right). Dark quarks* $\mathcal{Q}$ *(anti-quarks* $\bar{\mathcal{Q}}$*) are denoted as red (blue) dots, placed at random positions. We assume that each DM particle combines with its dark nearest neighbour, forming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

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

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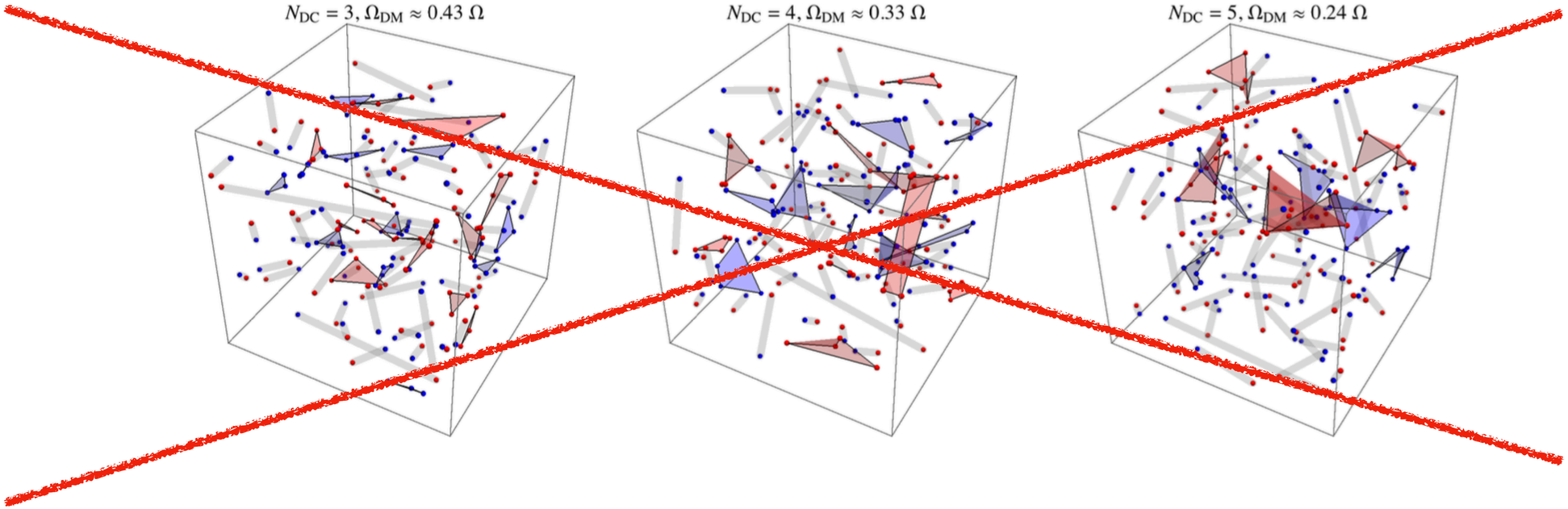

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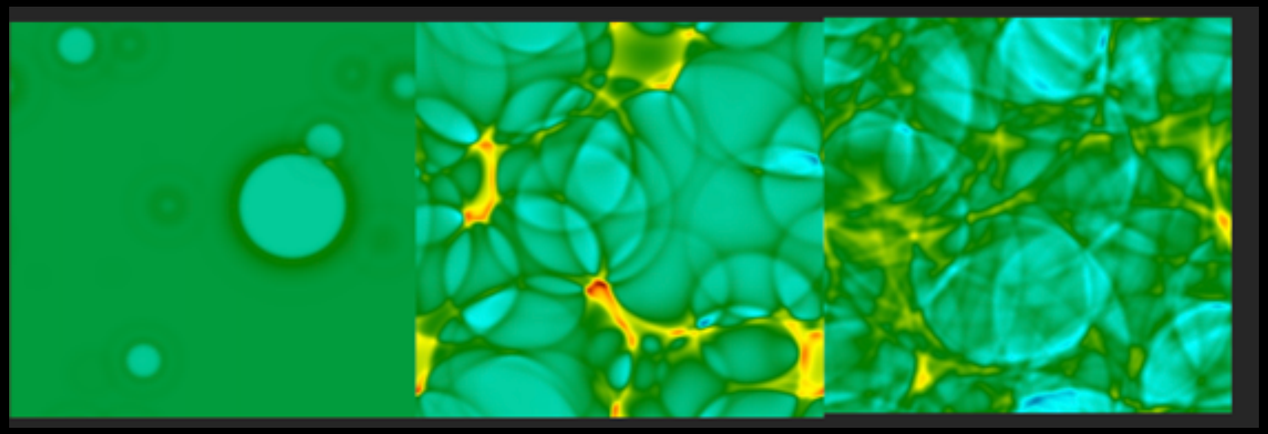
Understanding the Phase Transition



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Effectively Pure Yang-Mills PT

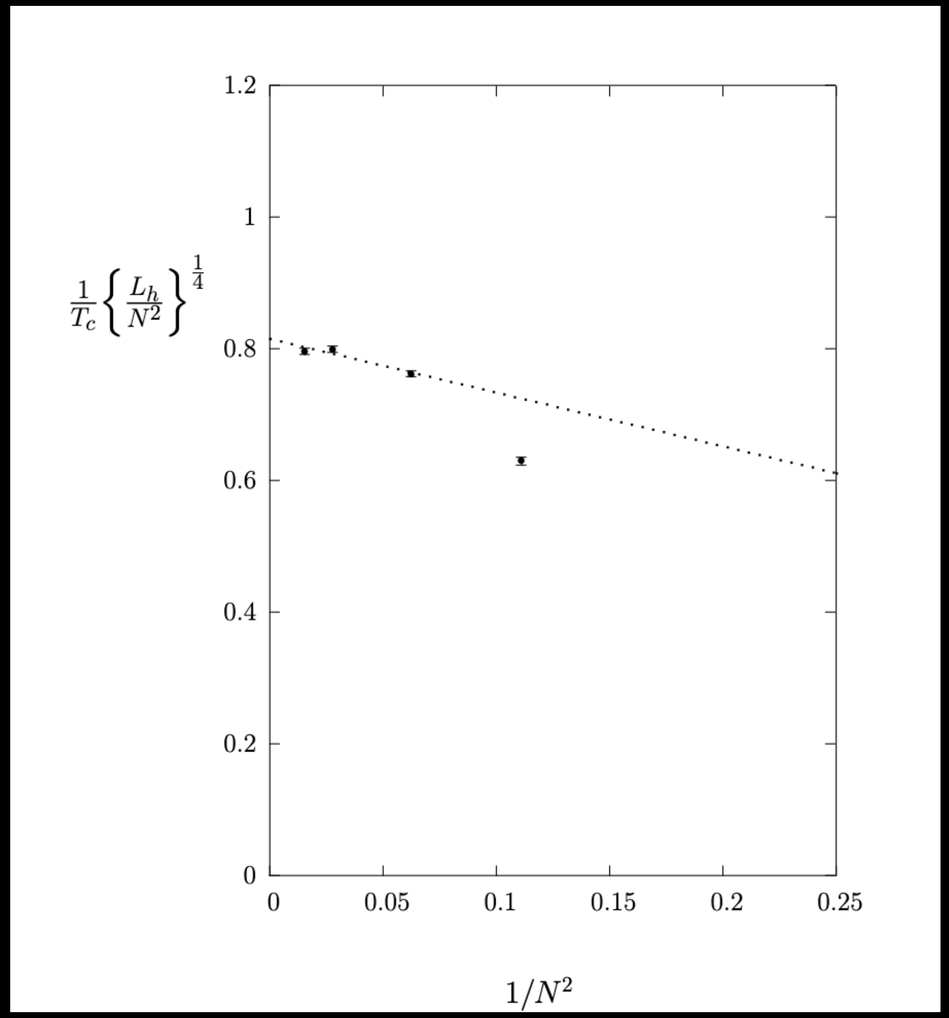
Lattice Data SU(3) :

- Latent Heat

$$L = 1.413\, T_c^4$$

- Surface tension

$$\sigma = 0.02\, T_c^3$$



B. Lucini et al. https://arxiv.org/pdf/hep-lat/0502003.pdf

Thermodynamic Considerations

Assumptions:

- Local kinetic equilibrium
- Homogeneous Pressure (1. order PT)
- Cooling due to Hubble expansion

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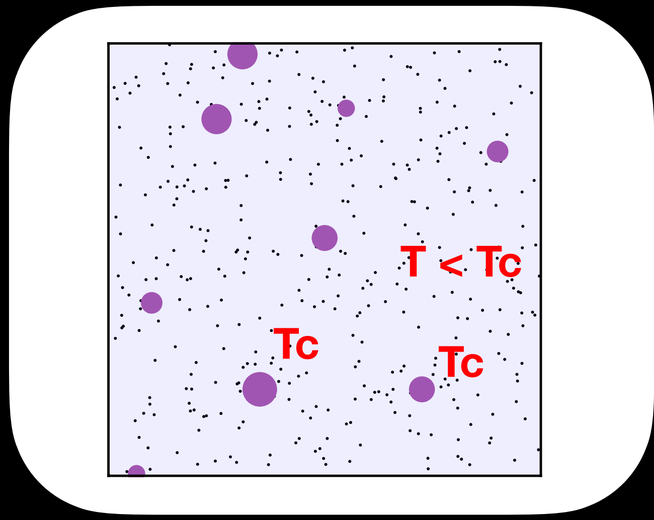
Entropy production by bubble expansion into supercool phase:



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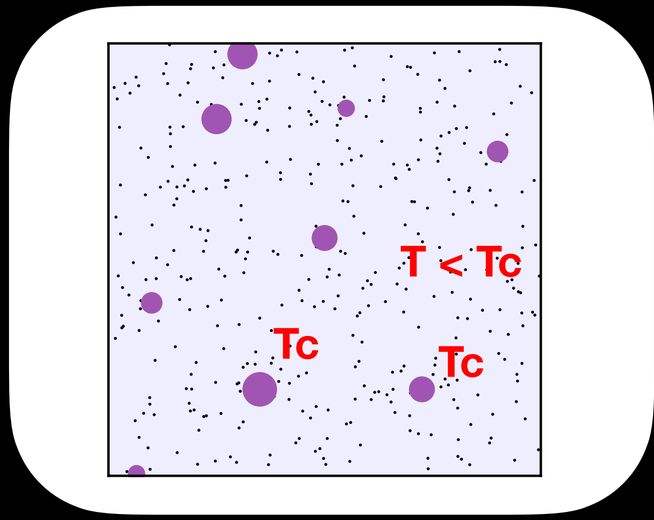

Supercooling: $\epsilon = \dfrac{T_c - T}{T_c}$

$$\Delta S = \Delta S_{\mathrm{P}} + \Delta S_{\mathrm{th.}}$$
$$= -\frac{L\Delta V}{T_c} + \frac{L\Delta V}{T} = \frac{\epsilon L \Delta V}{T}$$

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Thermodynamic Considerations II

$$TS_f = (\rho_f + P_f)V_f = (\rho_i + P_i)V_i + T\Delta S$$
$$\approx (\rho_i + P_i + \bar{\epsilon}L)V_i$$

Thermodynamic Considerations II

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$$\rho_i \approx \rho_{\rm SM} + L$$

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$\rho_i \approx \rho_{\rm SM} + L$ $\quad$ $\rho_f \approx \rho_{\rm SM}$ $\quad$ $P \approx \frac{\rho_{\rm SM}}{3}$ $\quad$ Lattice Study: L. Guisti, M. Pepe 1612.00265 $\quad$ $P_{\rm YM} \ll \rho_{\rm YM}$

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$$\left(\frac{a_f}{a_i}\right)^3 \approx 1 + \frac{3L}{4\rho_{\rm SM}} \Rightarrow \frac{a_f}{a_i} \approx 1.01$$

$\bar{\epsilon} \ll 1$

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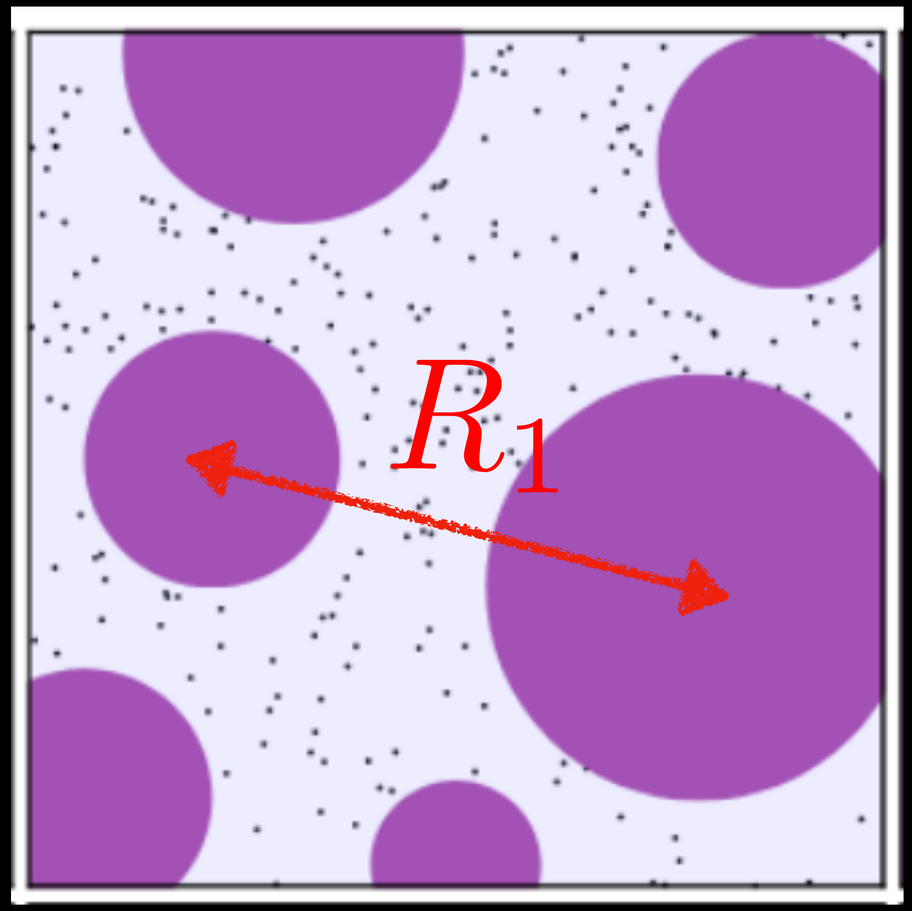
$$\left(\frac{a_f}{a_i}\right)^3 \approx 1 + \frac{3L}{4\rho_{\rm SM}} \Rightarrow \frac{a_f}{a_i} \approx 1.01$$

$$t_{\rm PT} \approx \frac{0.01}{H}$$

$\bar{\epsilon} \ll 1$

Thermodynamic Considerations III



Bubble Wall Velocity:

$$v_{\rm wall} \leq \frac{R_1}{t_{\rm PT}}$$

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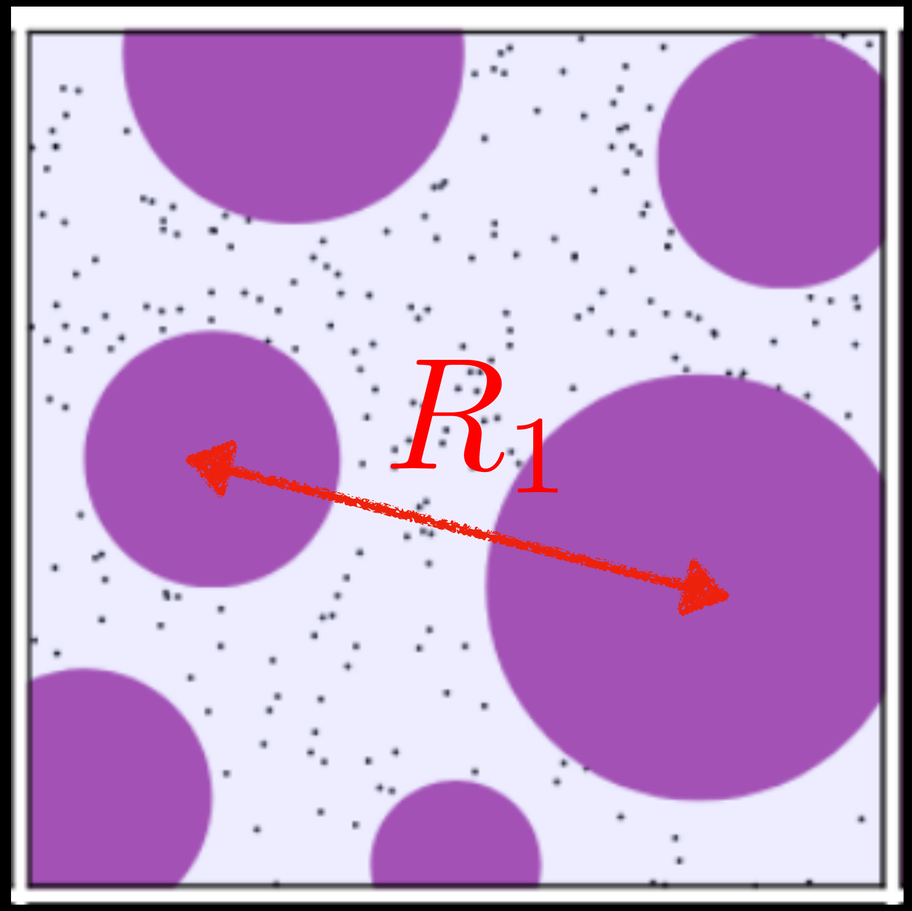
Thermodynamic Considerations III



Bubble Wall Velocity:

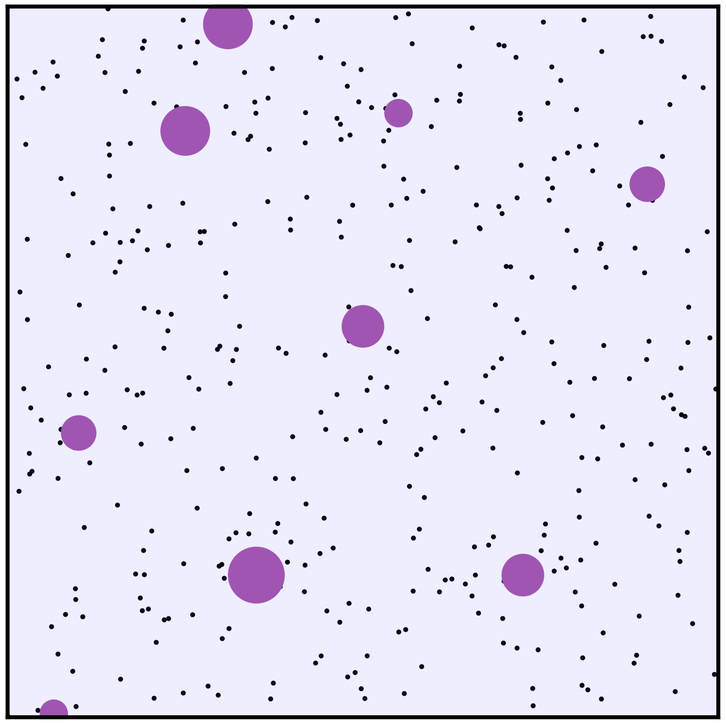
$$v_{\rm wall} \leq \frac{R_1}{t_{\rm PT}}$$

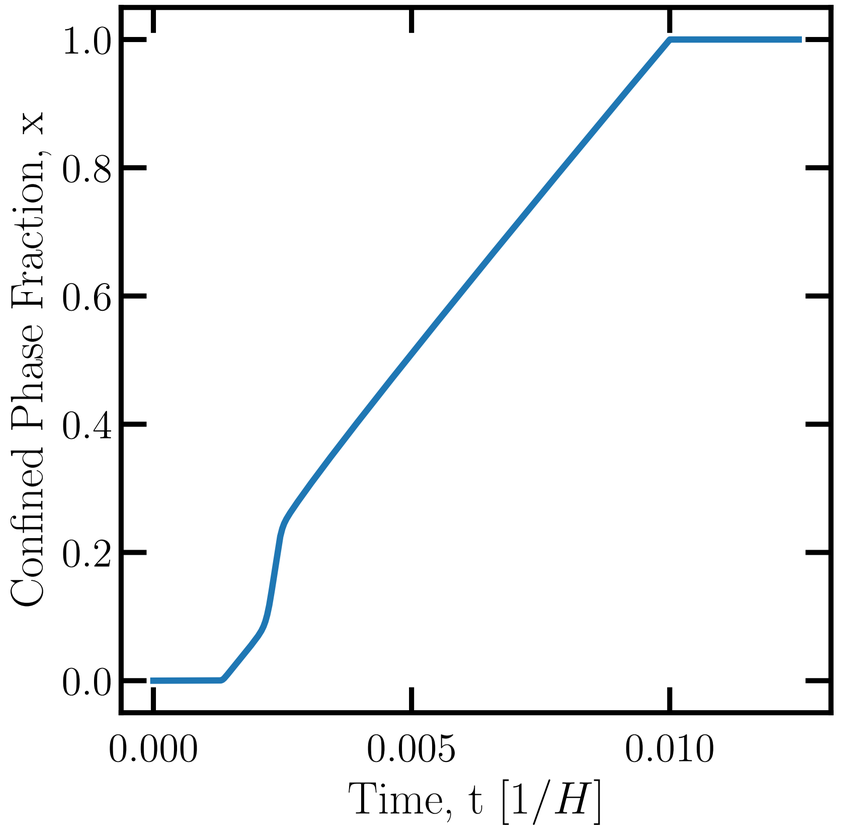
$$R_1 \approx \left(\frac{M_{\rm Pl}}{10^4 T_c}\right)^{2/3} \frac{1}{T_c}$$

$$v_{\rm wall} \leq 10^{-3}$$

2203.15813: Pouya Asadi, Eric D. Kraemer, Eric Kuflik, Tracy Slatyer, **JS**

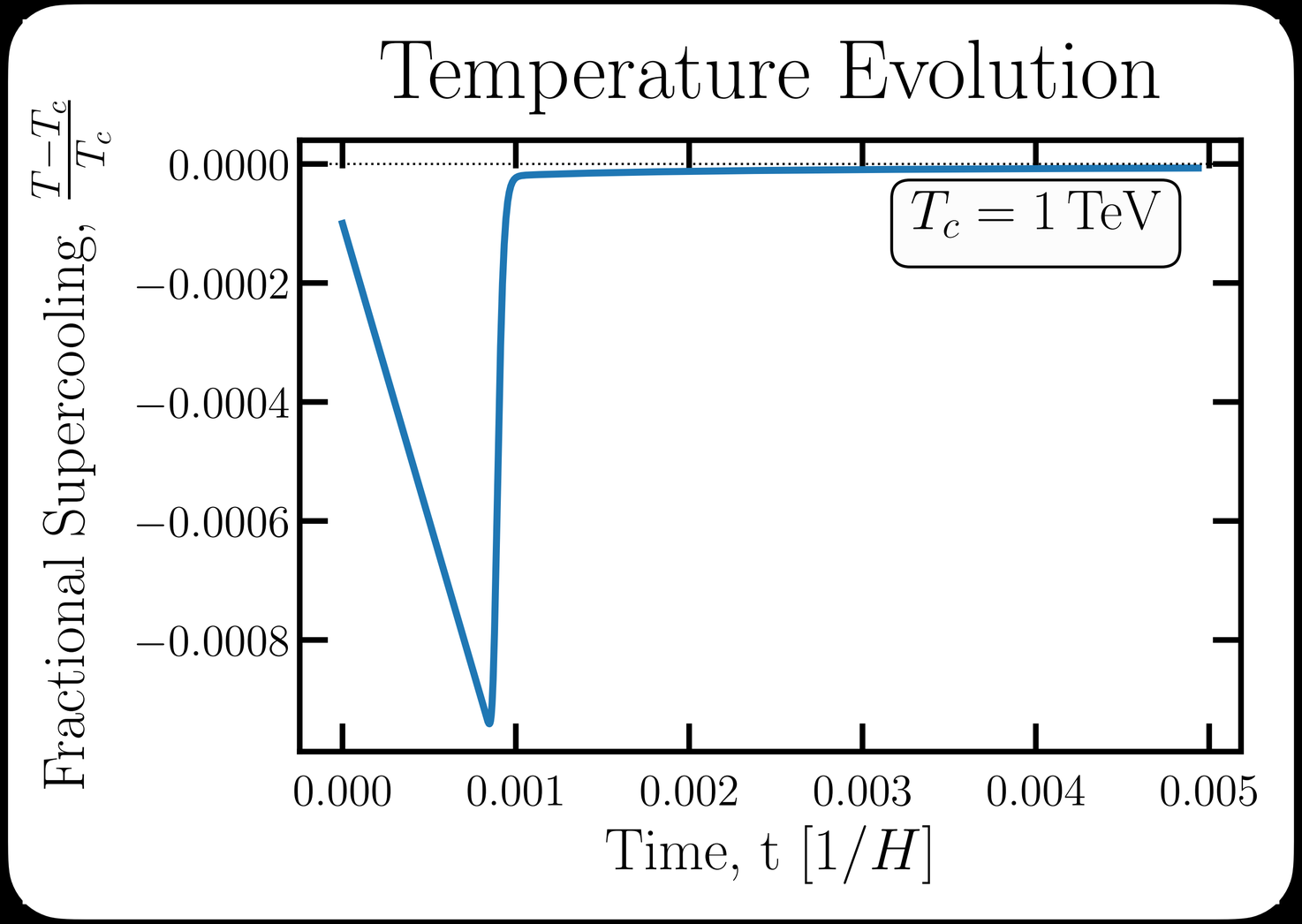
Simulating the Phase Transition I





Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Simulating the Phase Transition II



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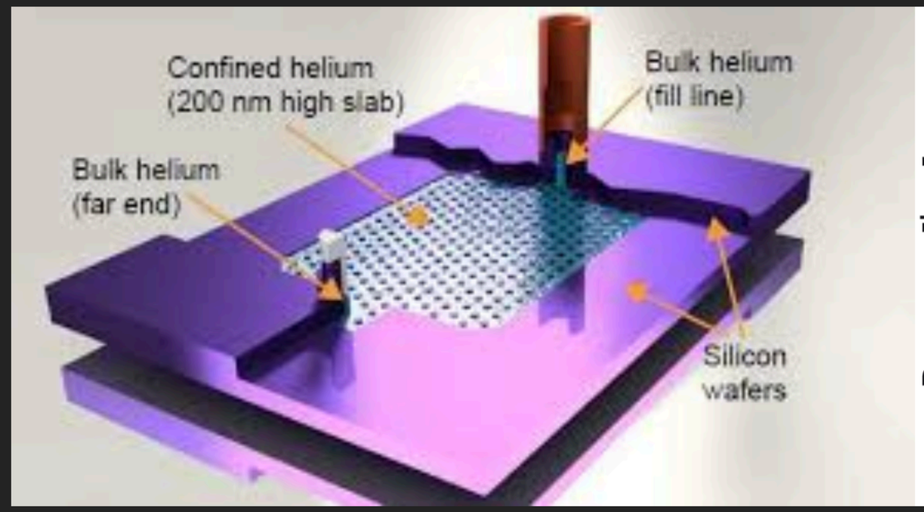
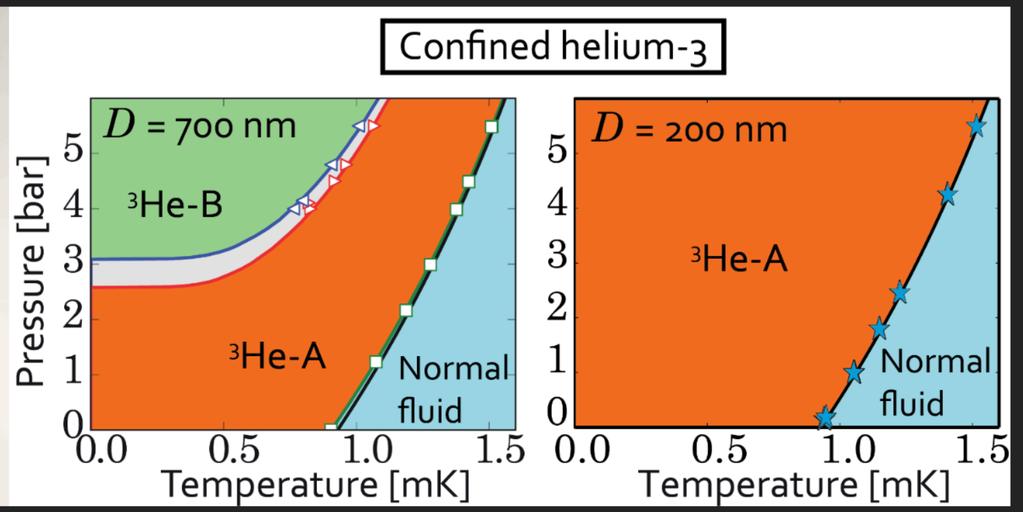
Phase Transitions in the lab: QUEST-DMC

WP2: Phase transitions in extreme matter

Prof Mark Hindmarsh

- Engineer phase transitions between superfluid ^{3}He phases of distinct symmetry (a bulk bubble away from walls, under nanoscale confinement)
- Quantum sensors to probe the nucleation and dynamics of transition, control the free energy landscape with tuning parameters.





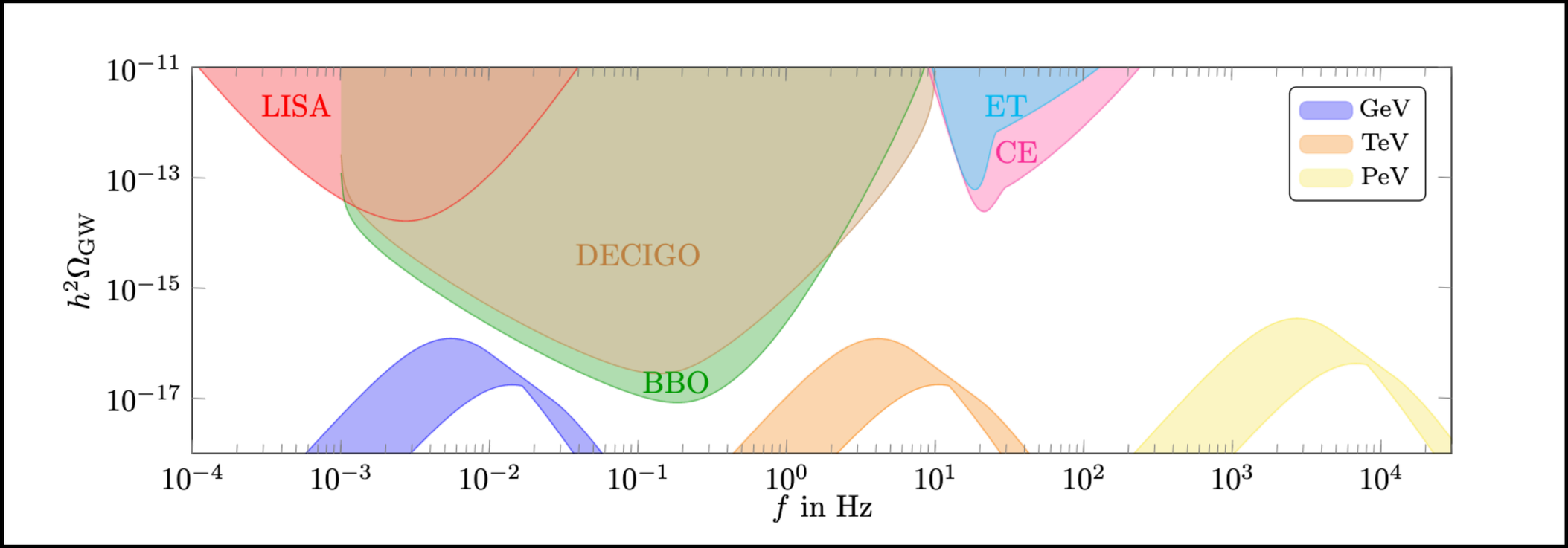
Science
AAAS

Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

L. V. Levitin,[1] R. G. Bennett,[1]* A. Casey,[1] B. Cowan,[1] J. Saunders,[1]† D. Drung,[2] Th. Schurig,[2] J. M. Parpia[3]

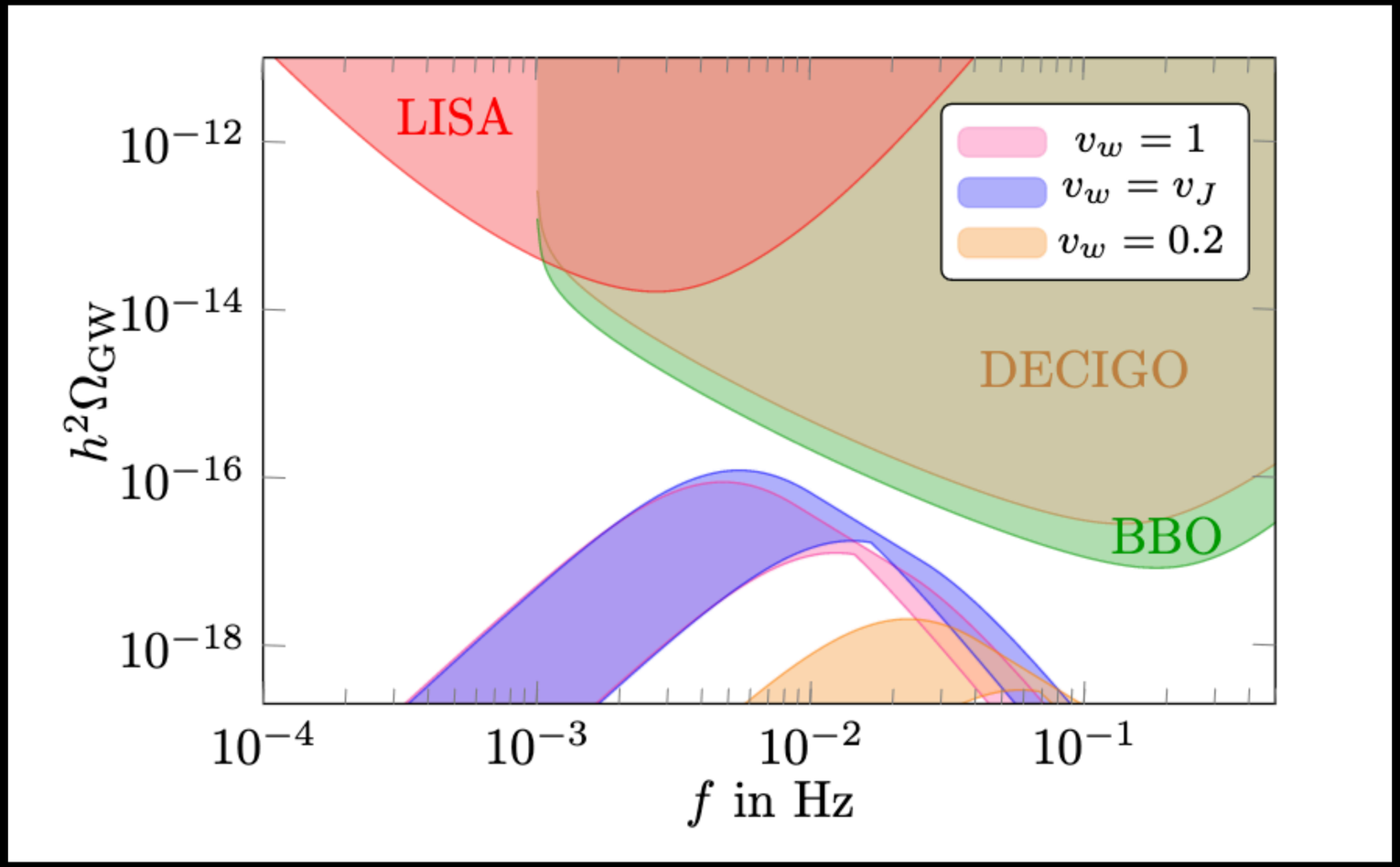
Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Gravitational Wave Sensitivity Scale



Reichert et al. arXiv:2211.08877

Gravitational Wave Sensitivity Wall Velocity



Challenging, unless alternative GW production

Reichert et al. arXiv:2211.08877

The Effect on Abundance

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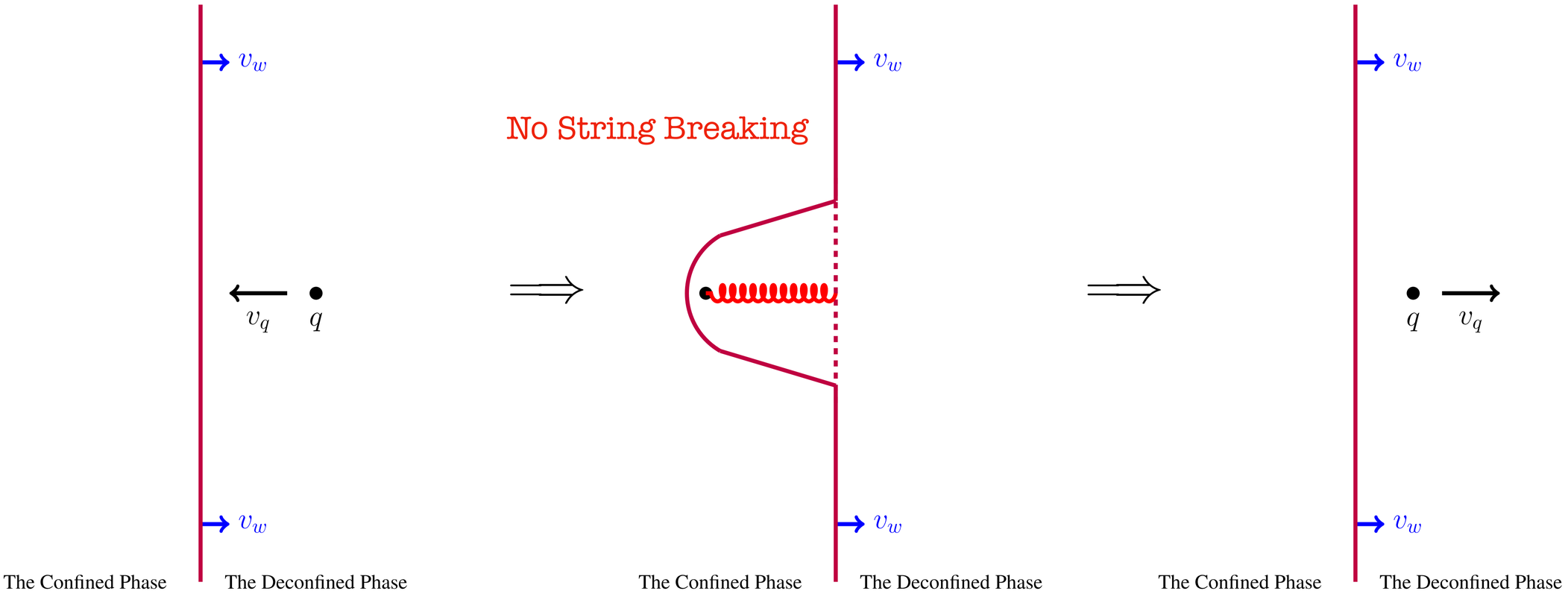
Bubble Wall Reflection



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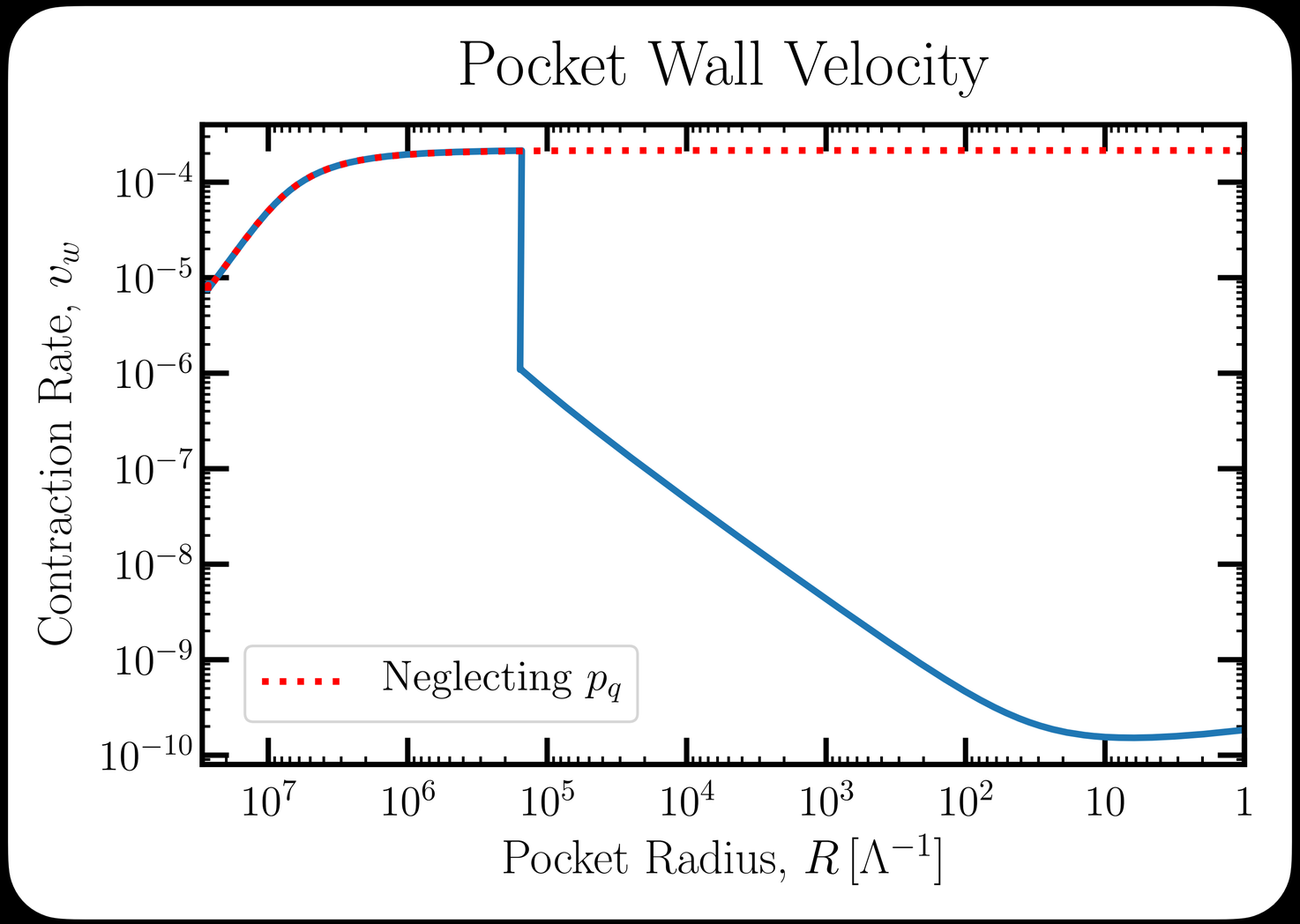
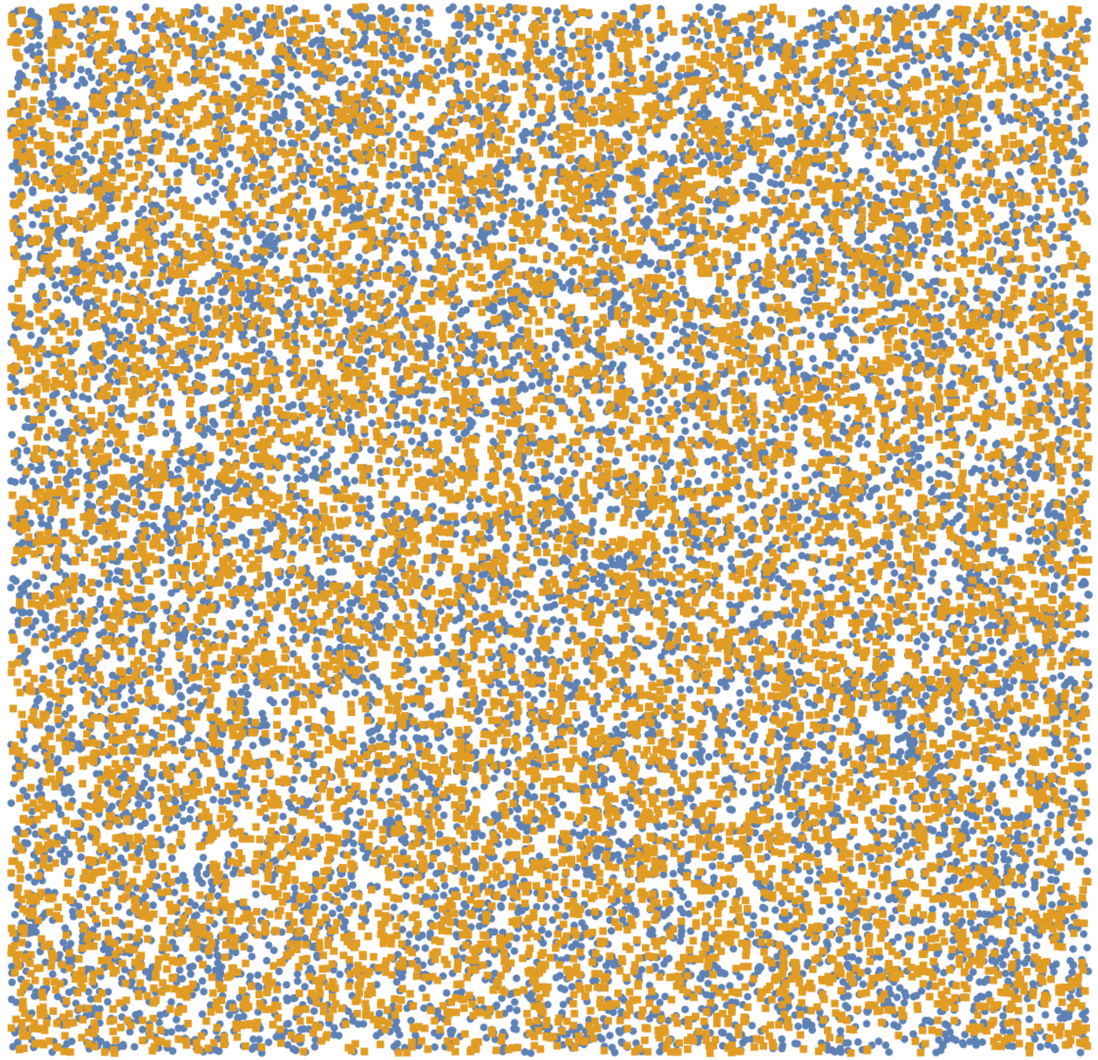
Simulating the Phase Transition III



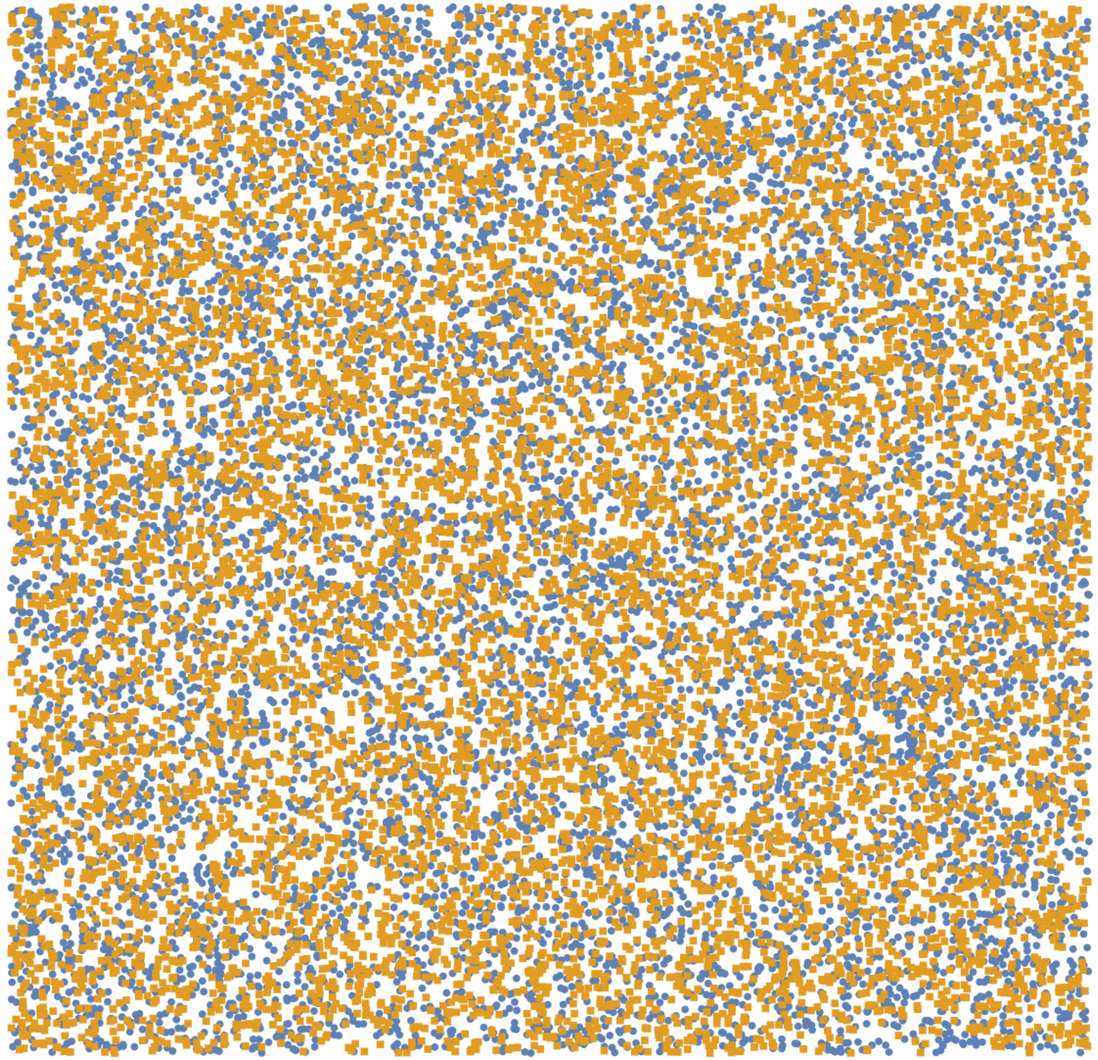
Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

The Dark Baryon Squeezeout



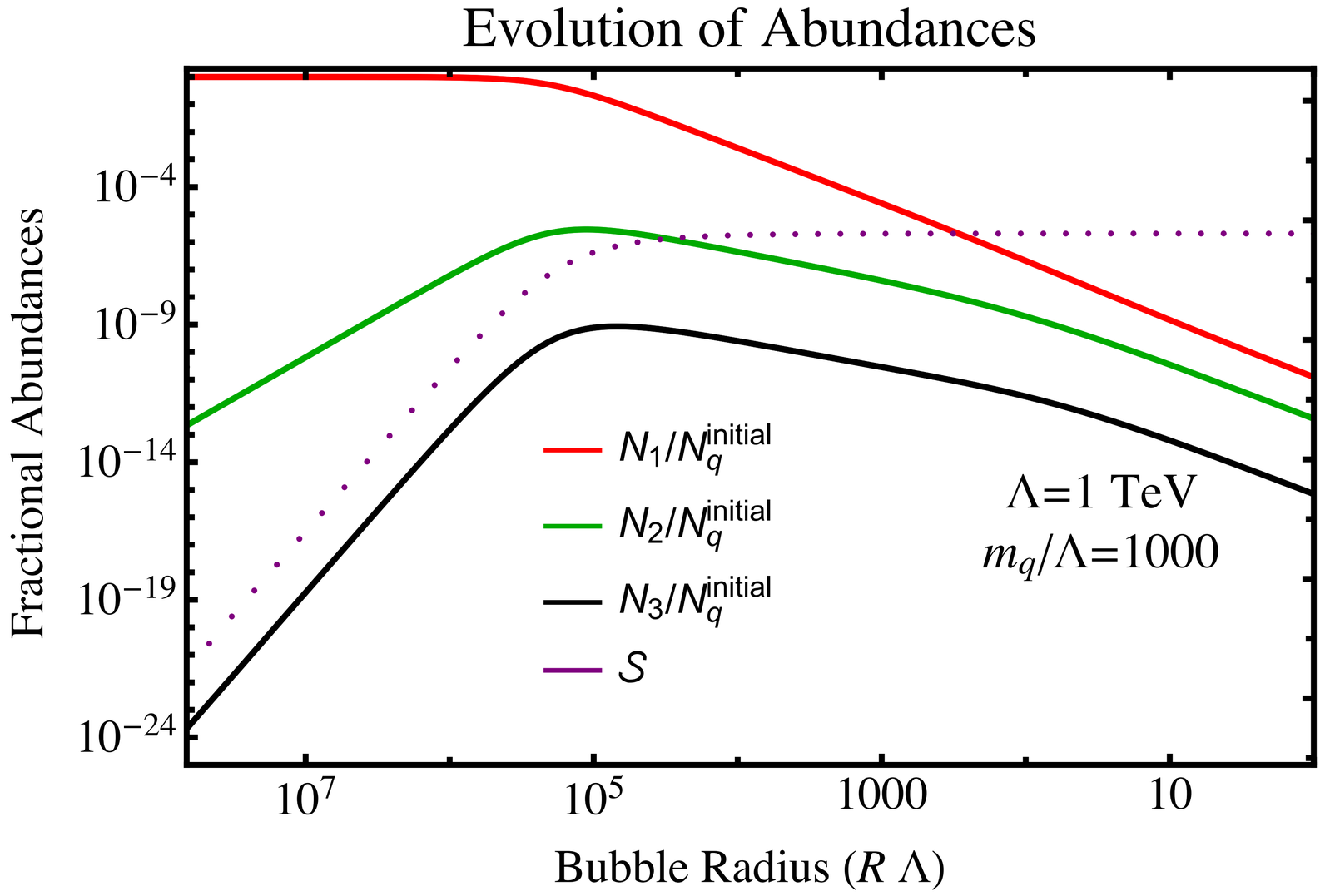
Credit: Eric Kuflik

The Dark Baryon Squeezeout



Credit: Eric Kuflik

Local Boltzmann Evolution



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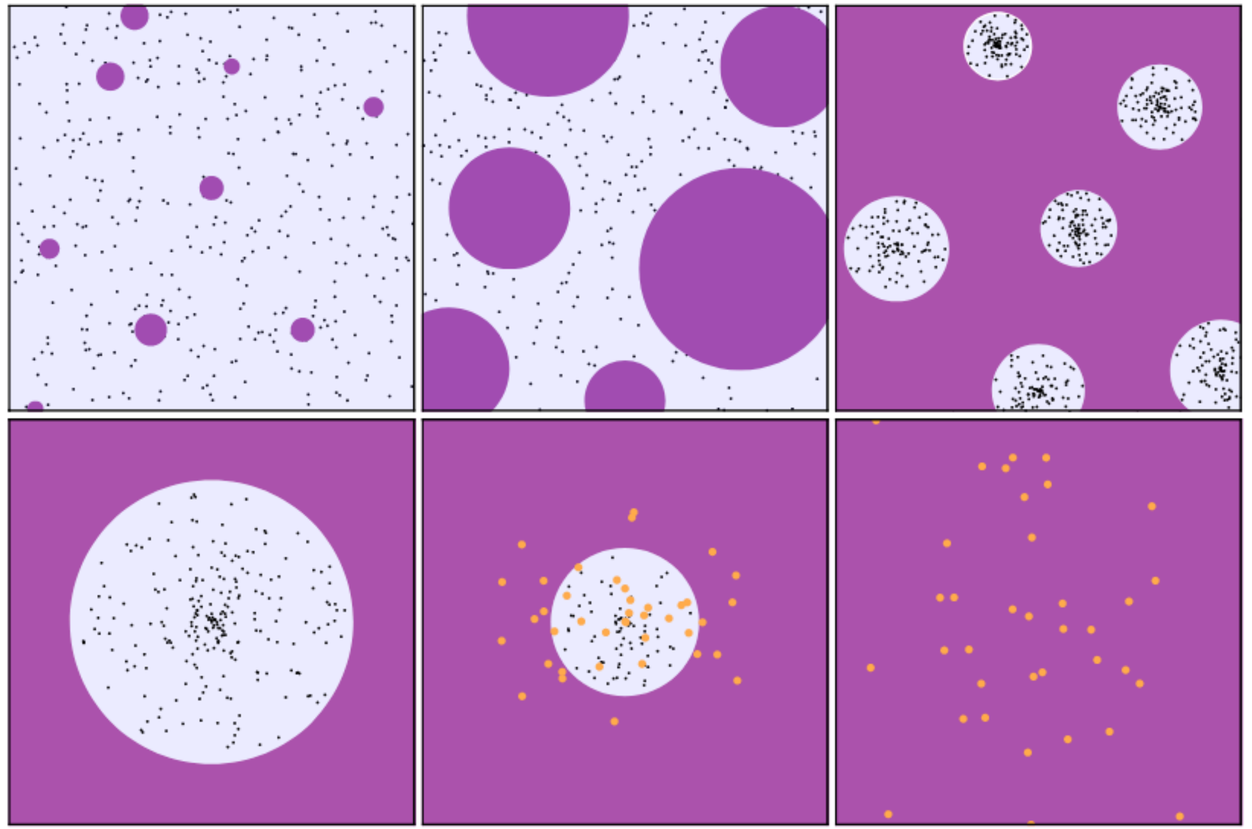
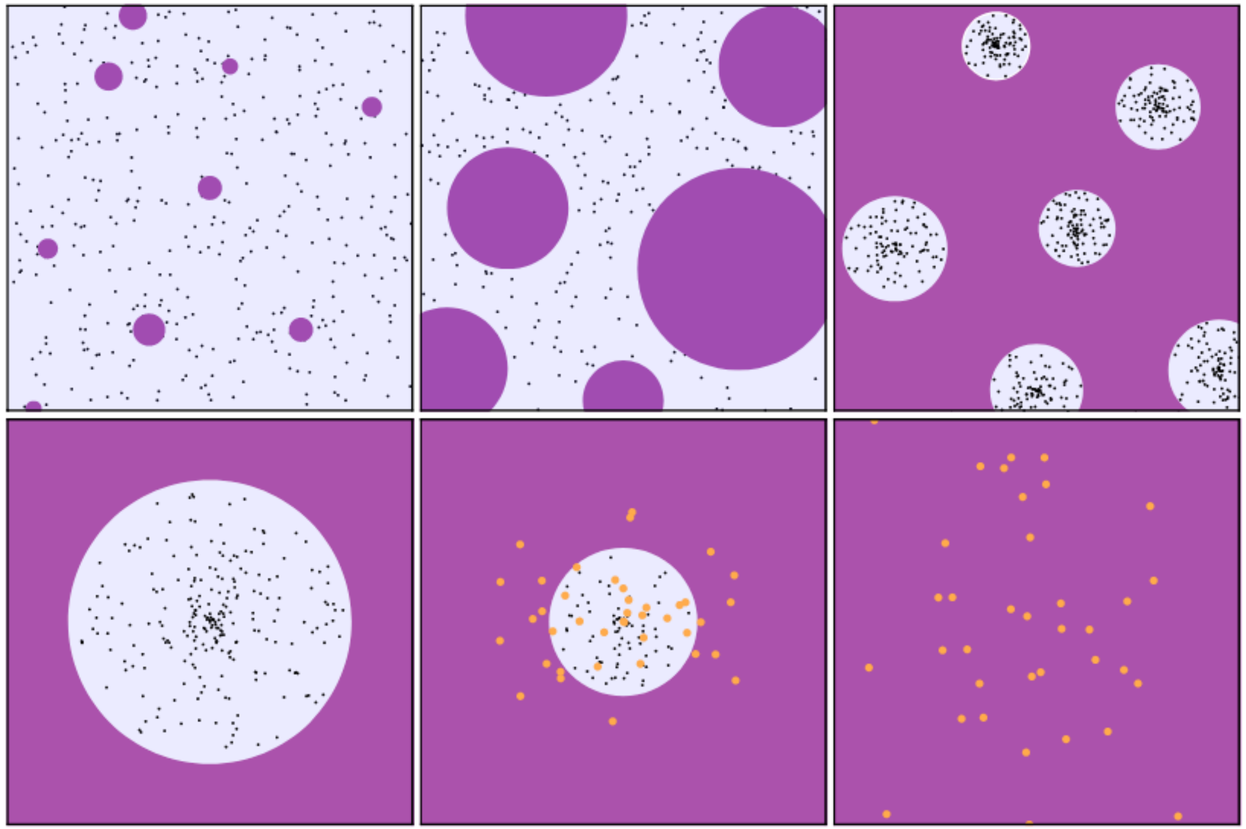
Dynamical Confinement



arxiv:2103.09822: Pouya Asadi, Greg Ridgway,
Eric D. Kraemer, Eric Kuflik, Tracy Slatyer, **JS**

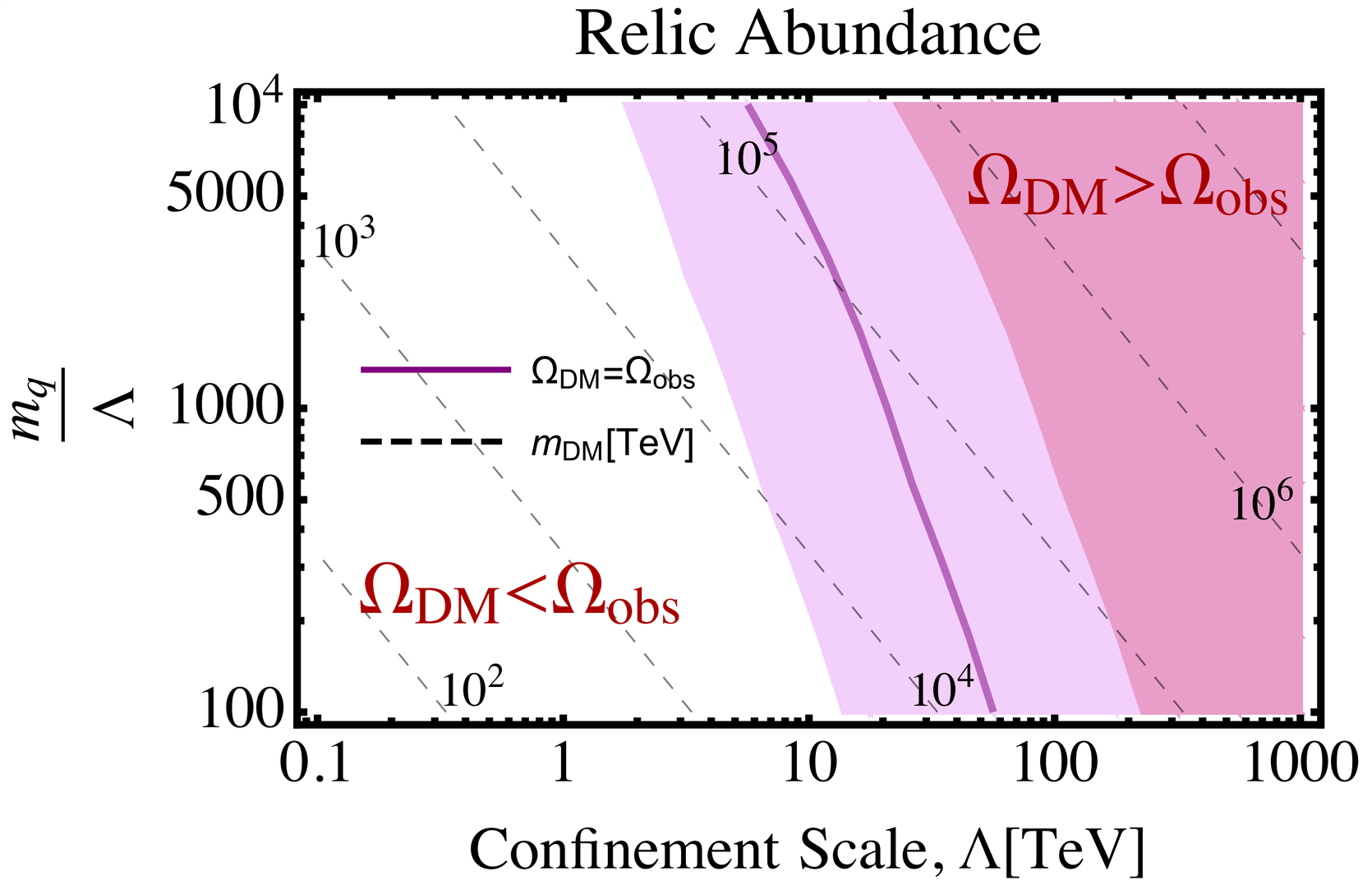
Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Minimal Abundance and Asymmetry



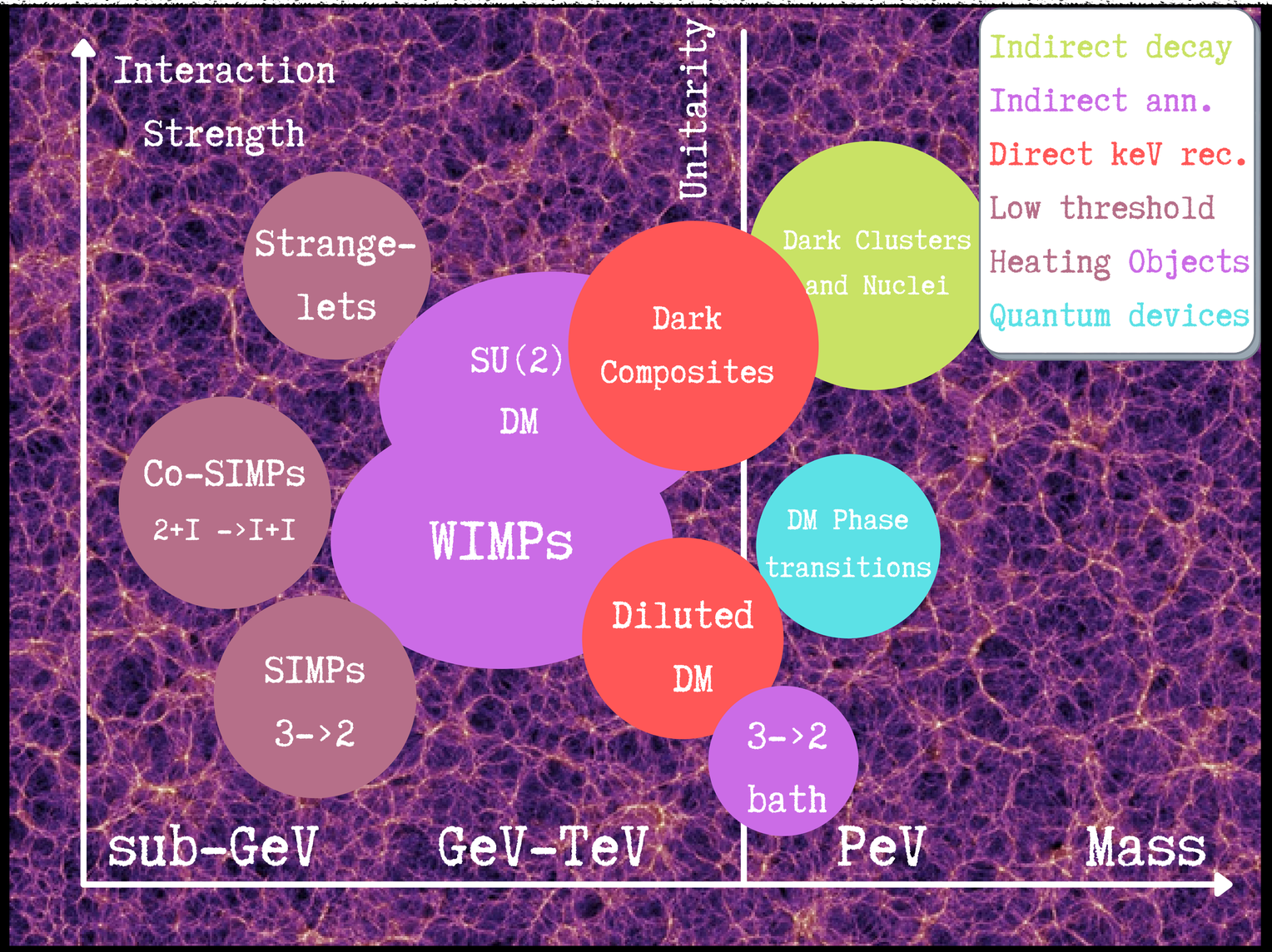
$$S_{\rm AS} = \frac{\sqrt{N_0}}{N_0} = \frac{1}{\sqrt{N_0}}$$

Result for Relic Abundance



Links to Phenomenology

Dark Matter Production Scenario Space



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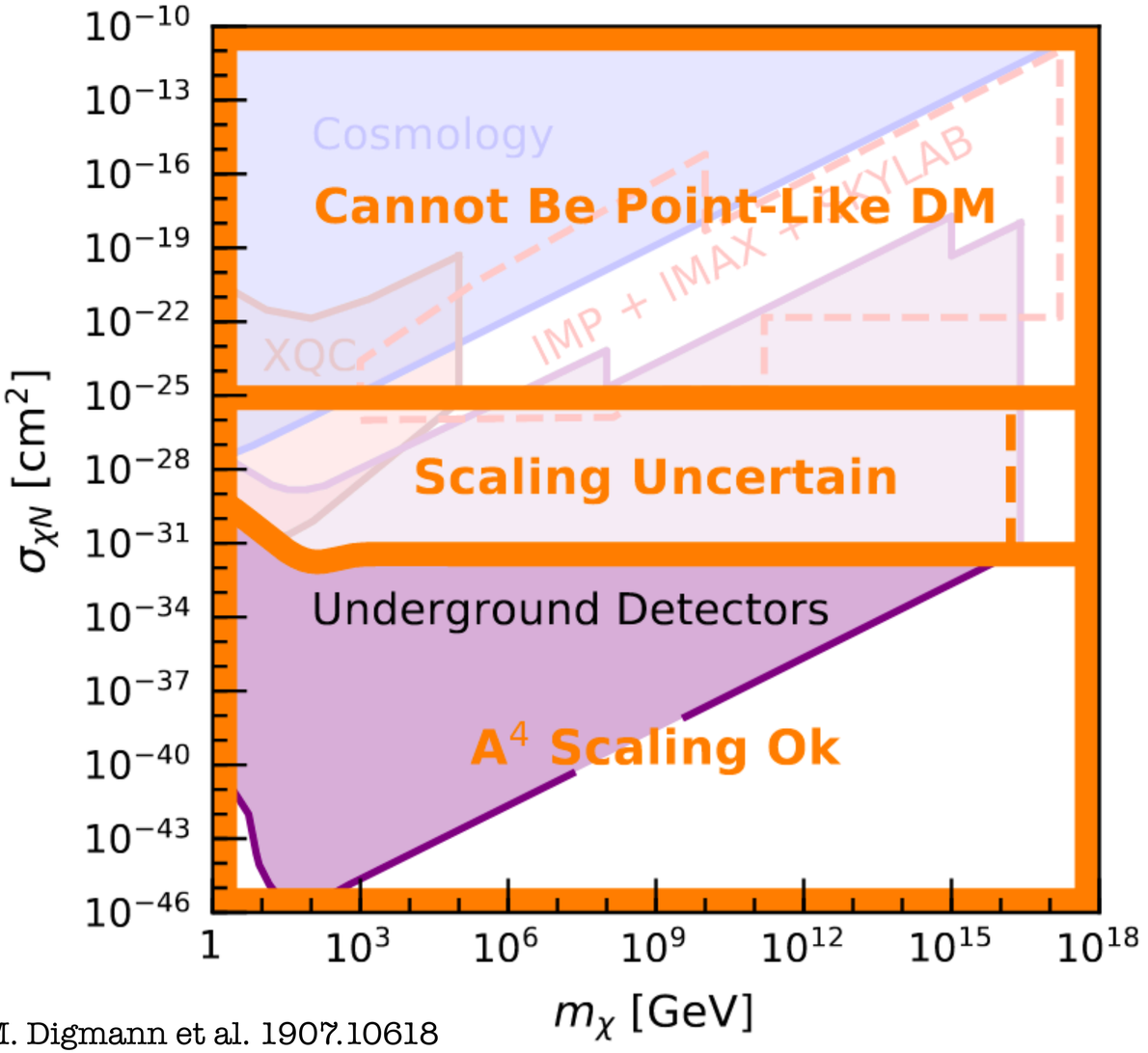
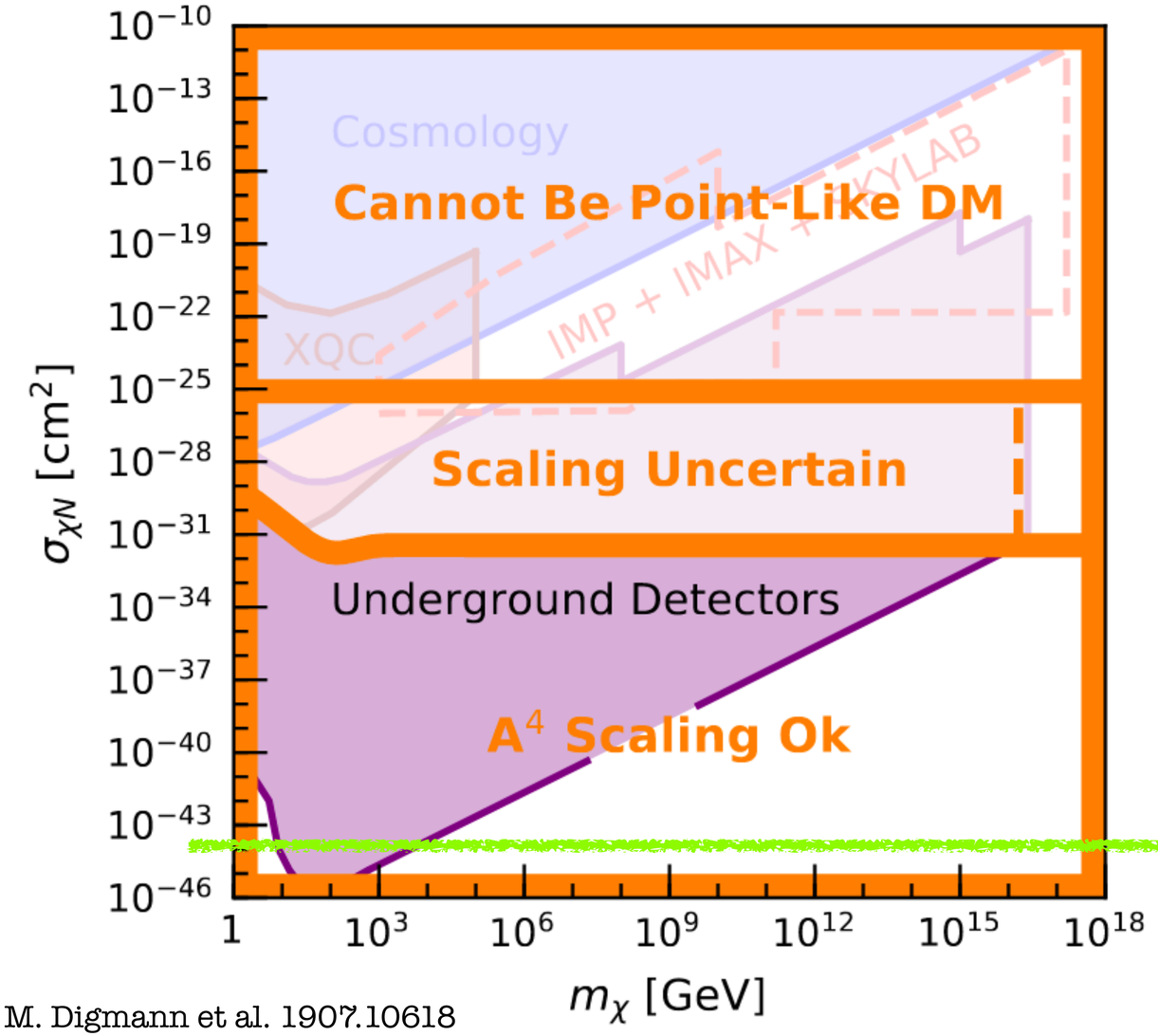
Weakly or Rarely?

Generic Feature: Residual Interactions



M. Digmann et al. 1907.10618

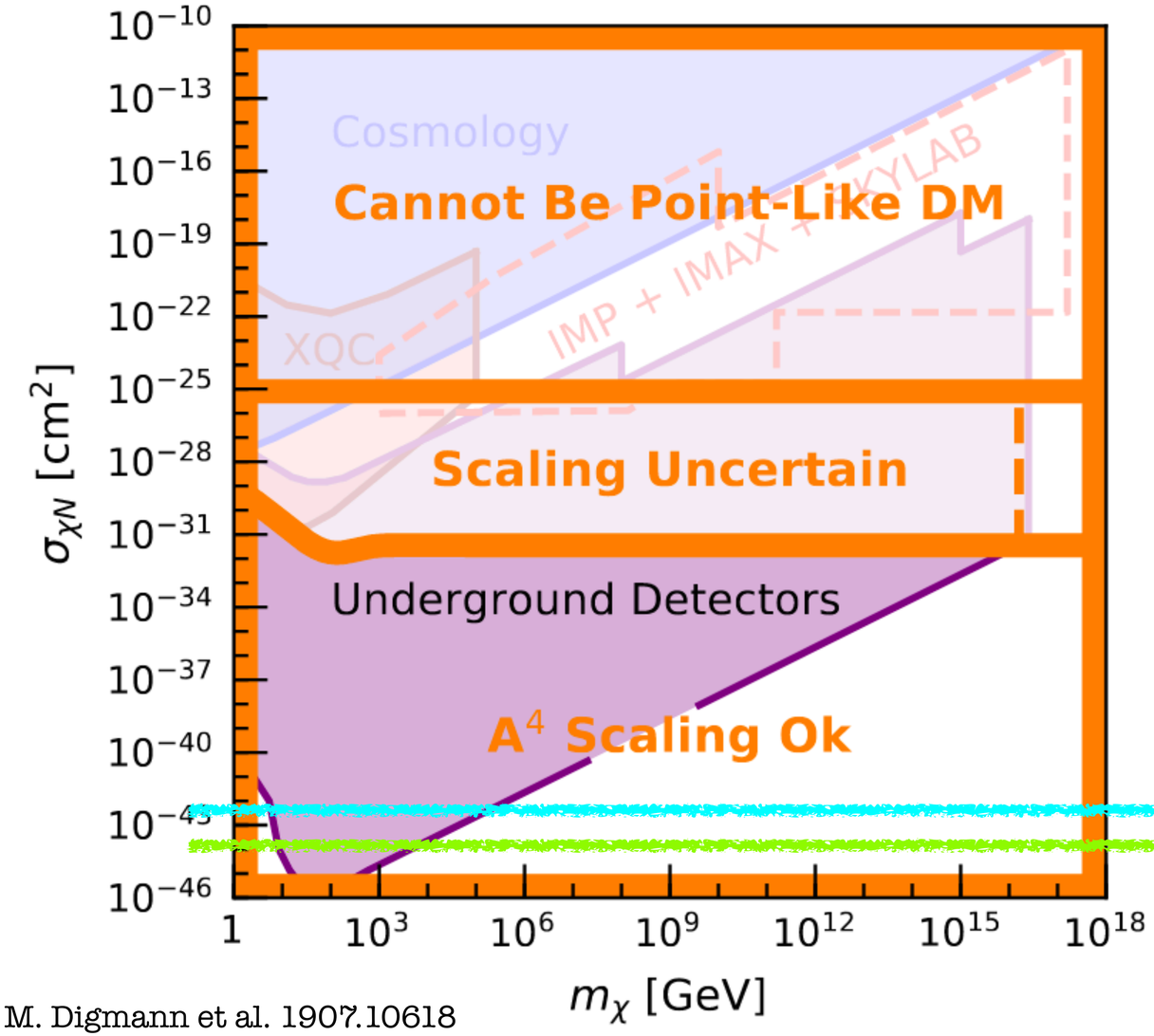
Generic Feature: Residual Interactions



EW Loops

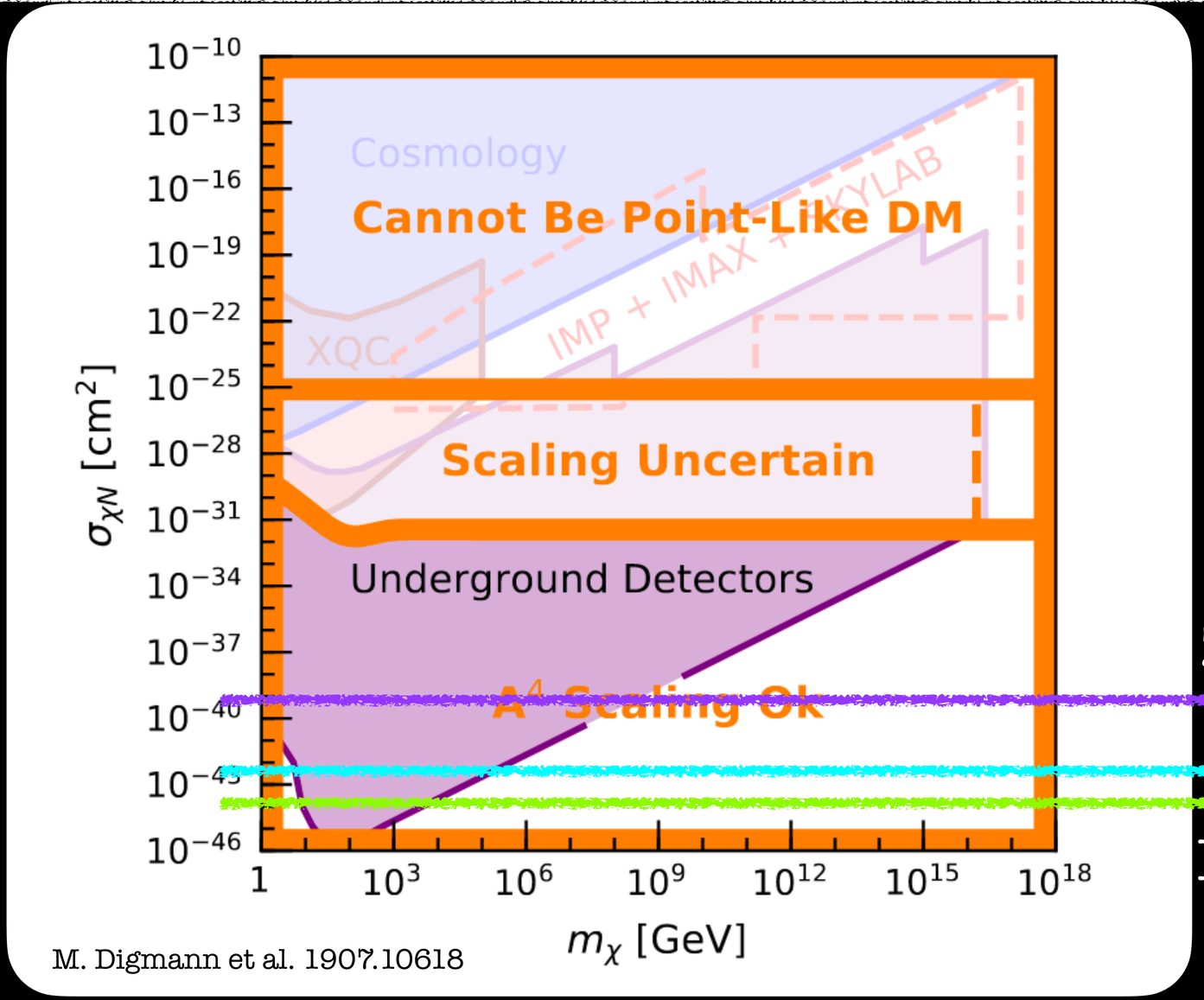
M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



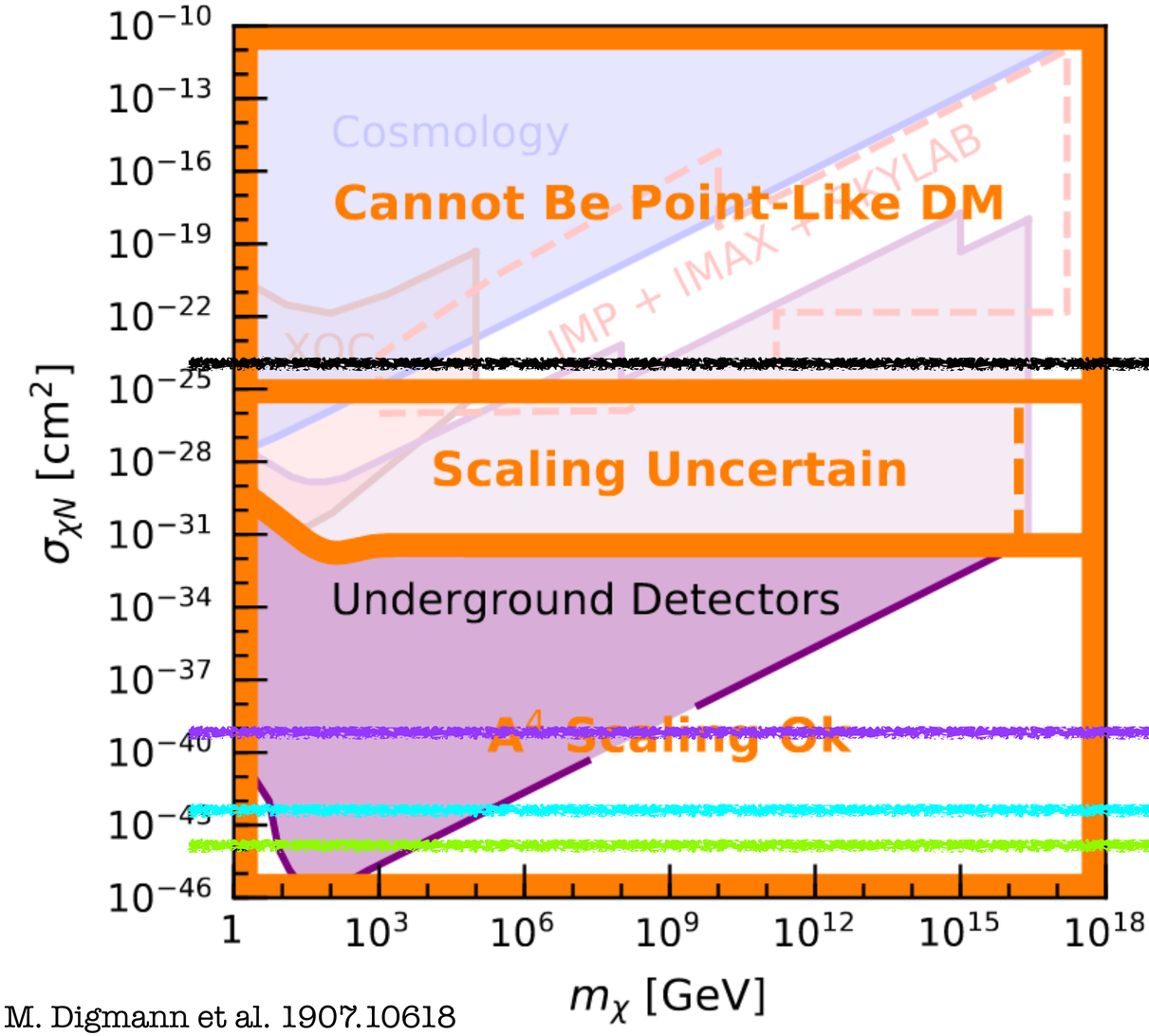
Z Boson

Higgs

EW Loops

M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



Nuclear

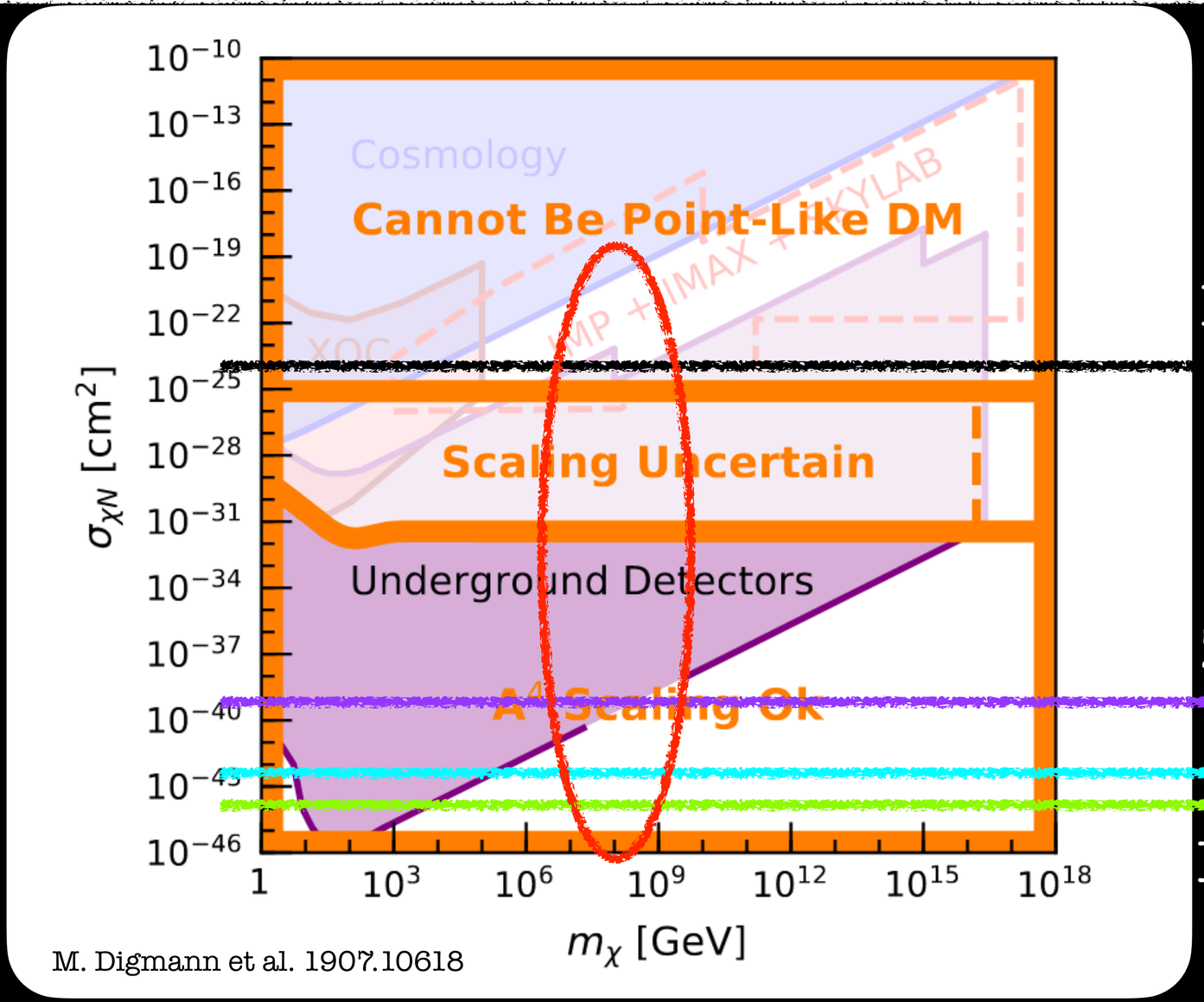
Z Boson

Higgs

EW Loops

M. Digmann et al. 1907.10618

Generic Feature: Residual Interactions



Nuclear

Z Boson

Higgs

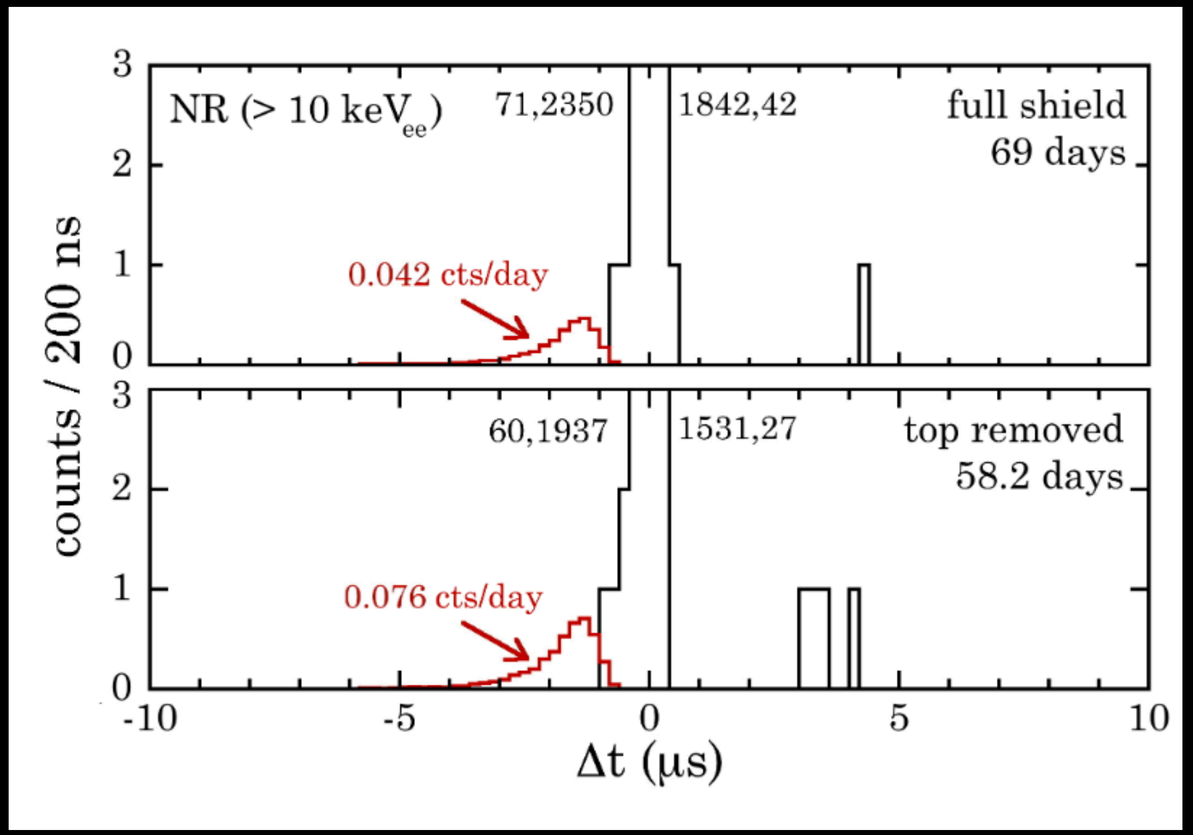
EW Loops

M. Digmann et al. 1907.10618

New Searches Microscopic DM

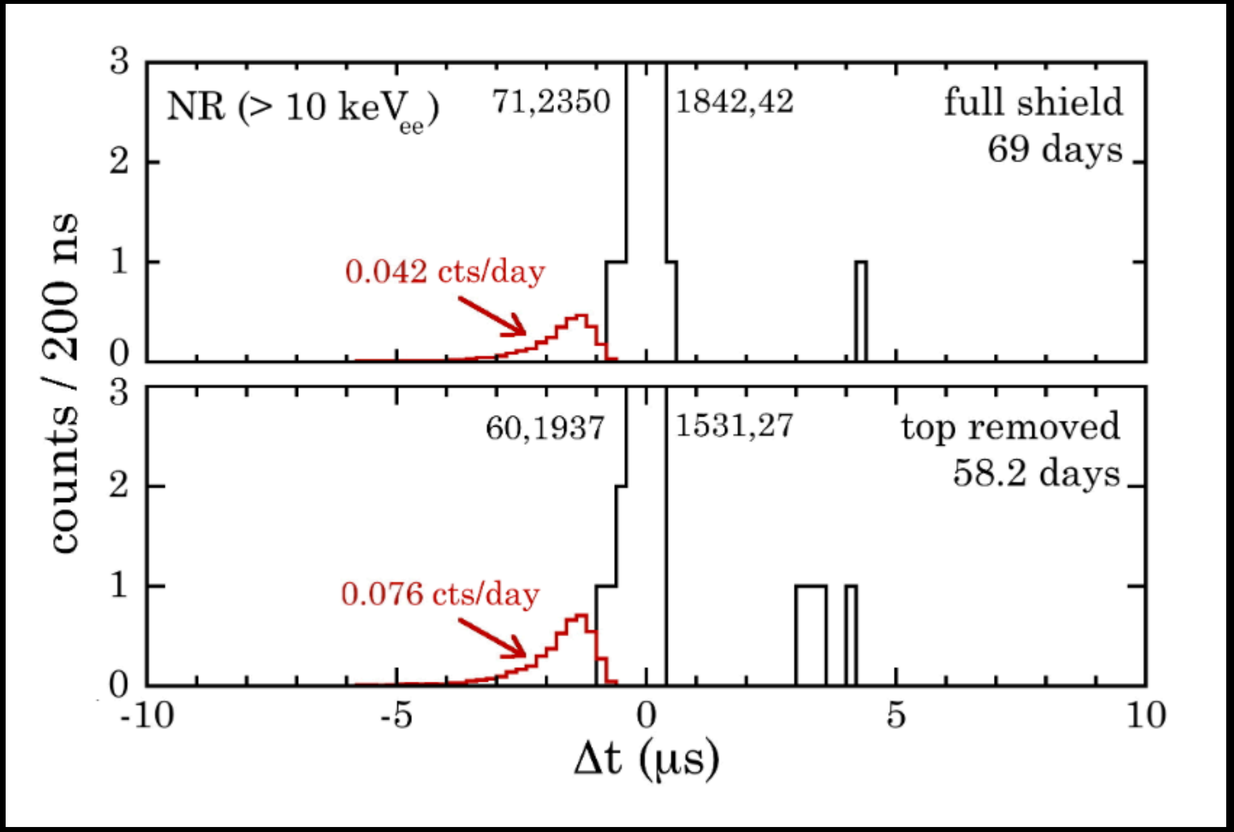
Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

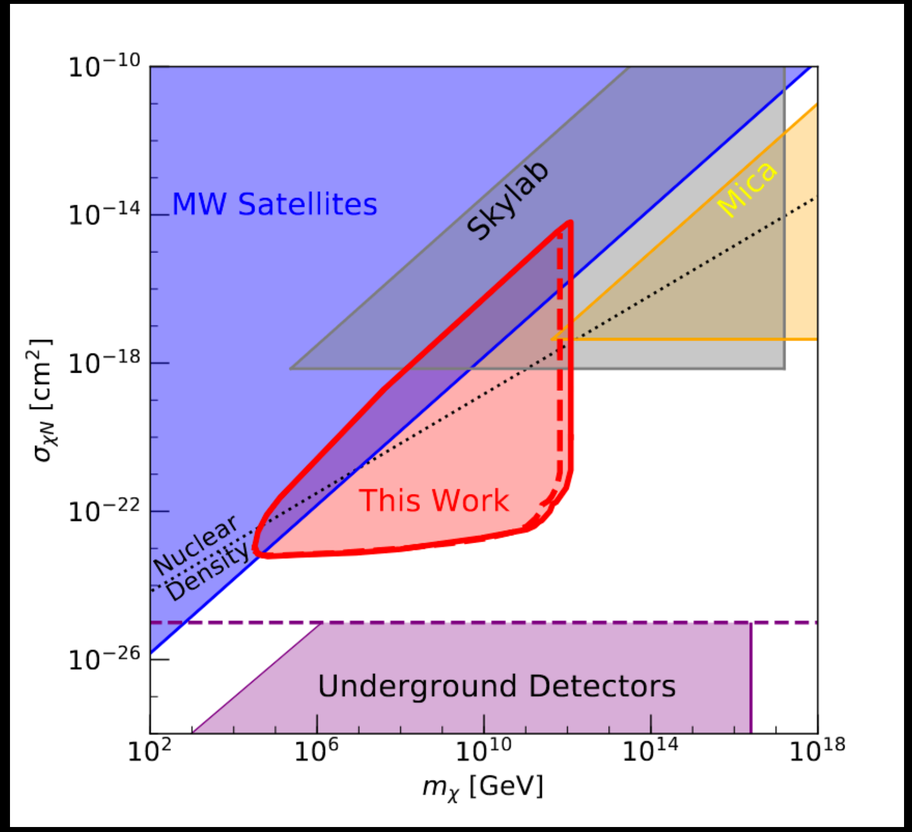
Large Scattering Cross Sections



arxiv:2008.10646: C. Cappiello et al.

Large Scattering Cross Sections





arxiv:2008.10646: C. Cappiello et al.

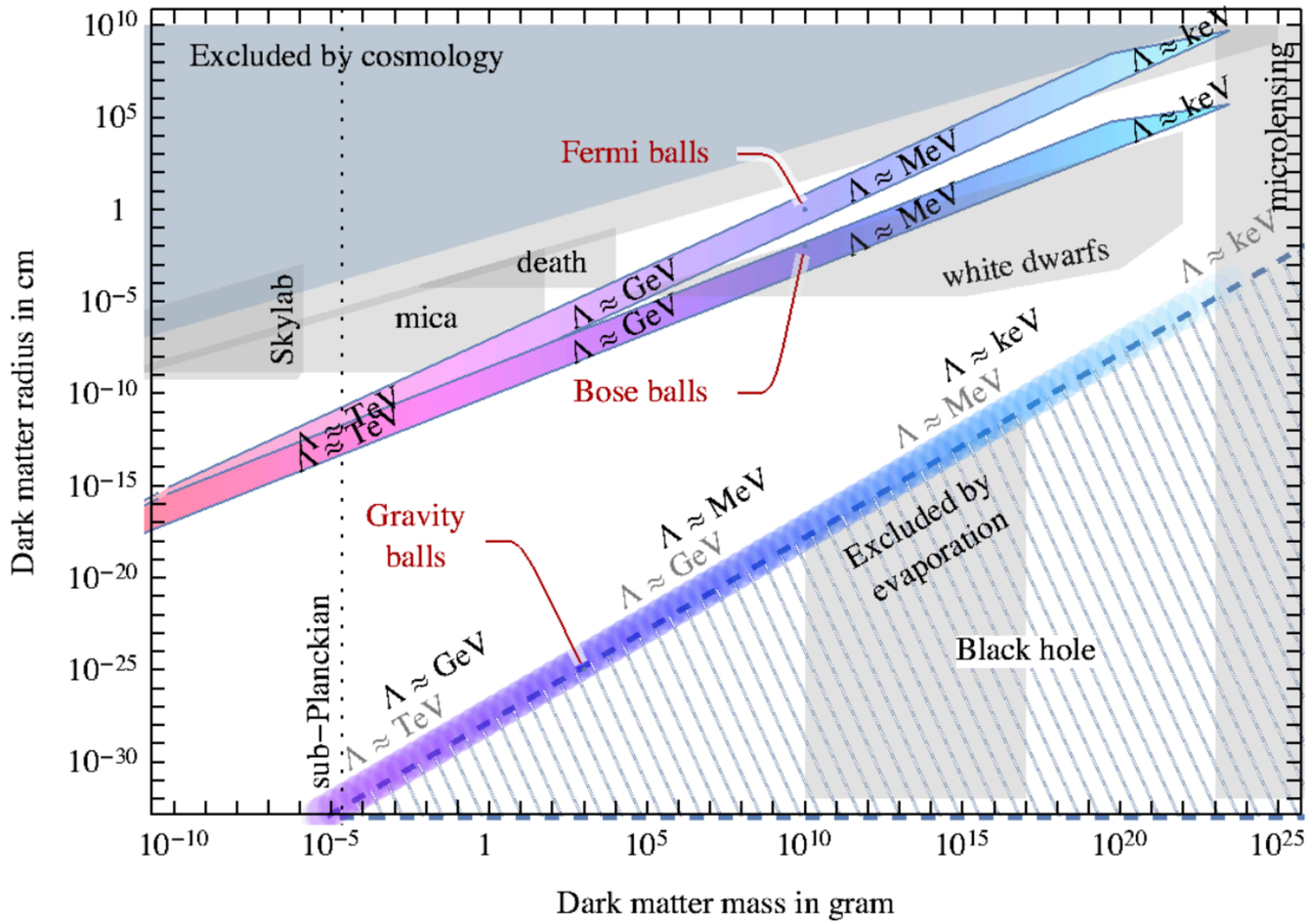
New Searches Macroscopic DM

Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Compact Objects from Phase Transitions

1) Add primordial DM asymmetry

2) Low efficiency for Baryon f ormation



2105.02840: Gross et al.

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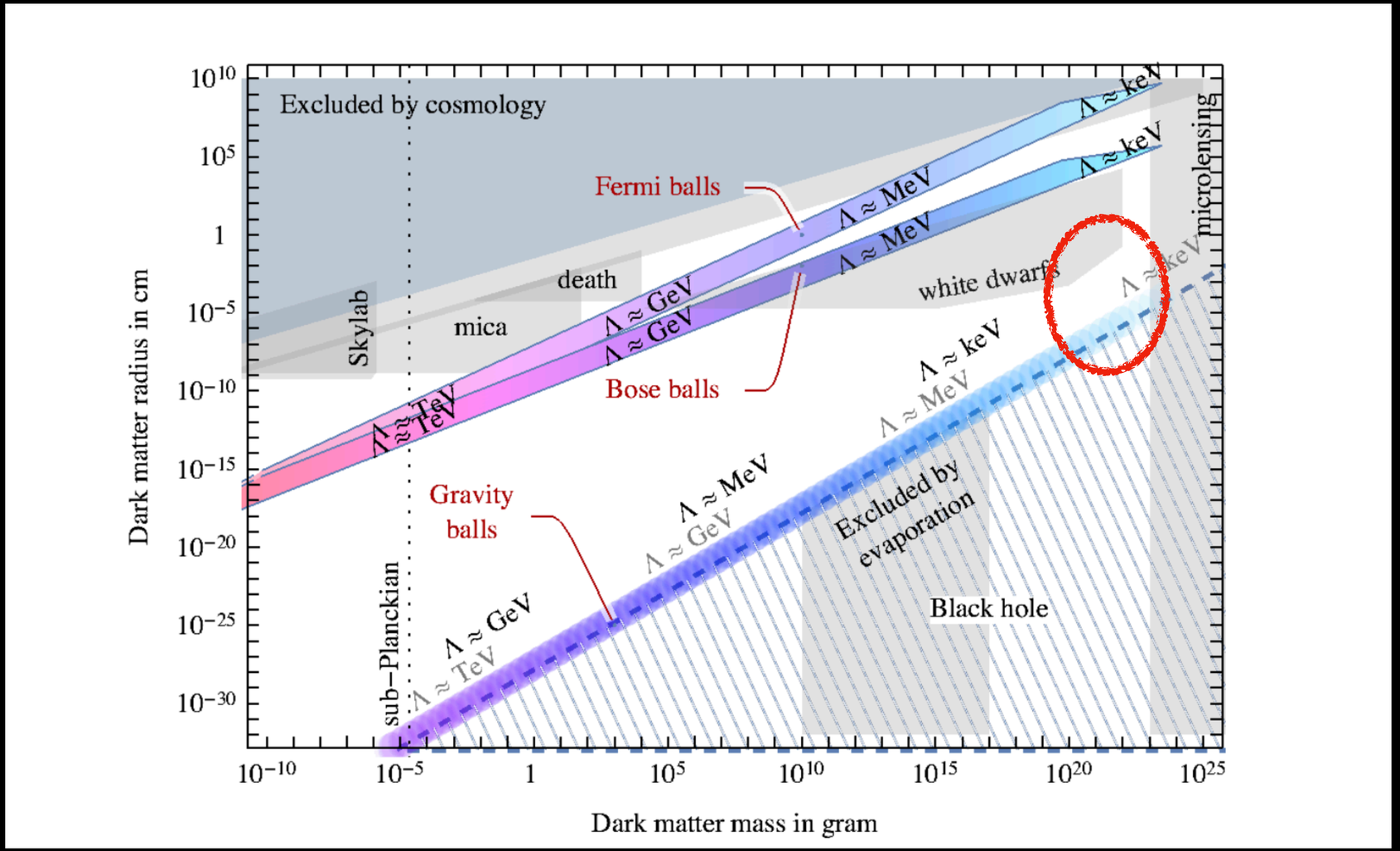
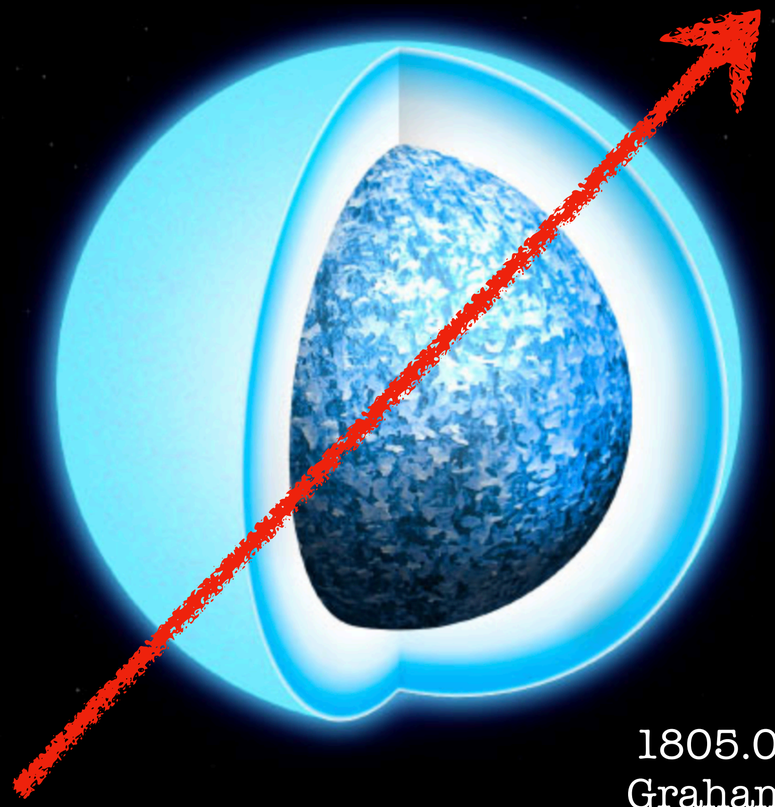


2105.02840: Gross et al.

Dark Matter Triggered Supernova

$$T > \mathrm{MeV}$$

$$\frac{\lambda_{\rm min}}{\rm cm} = \begin{cases} 2.8 \times 10^{-5} \sqrt{\frac{5 \times 10^9 \frac{\rm g}{\rm cm^3}}{\rho_{\rm WD}}}, & \frac{\rho_{\rm WD}}{\rm g/cm^3} > 1.6 \times 10^8 \\ 10^{-4} \left(\frac{2 \times 10^8 \frac{\rm g}{\rm cm^3}}{\rho_{\rm WD}} \right)^2, & \frac{\rho_{\rm WD}}{\rm g/cm^3} < 1.6 \times 10^8 \end{cases}$$



1805.07381:
Graham et al.

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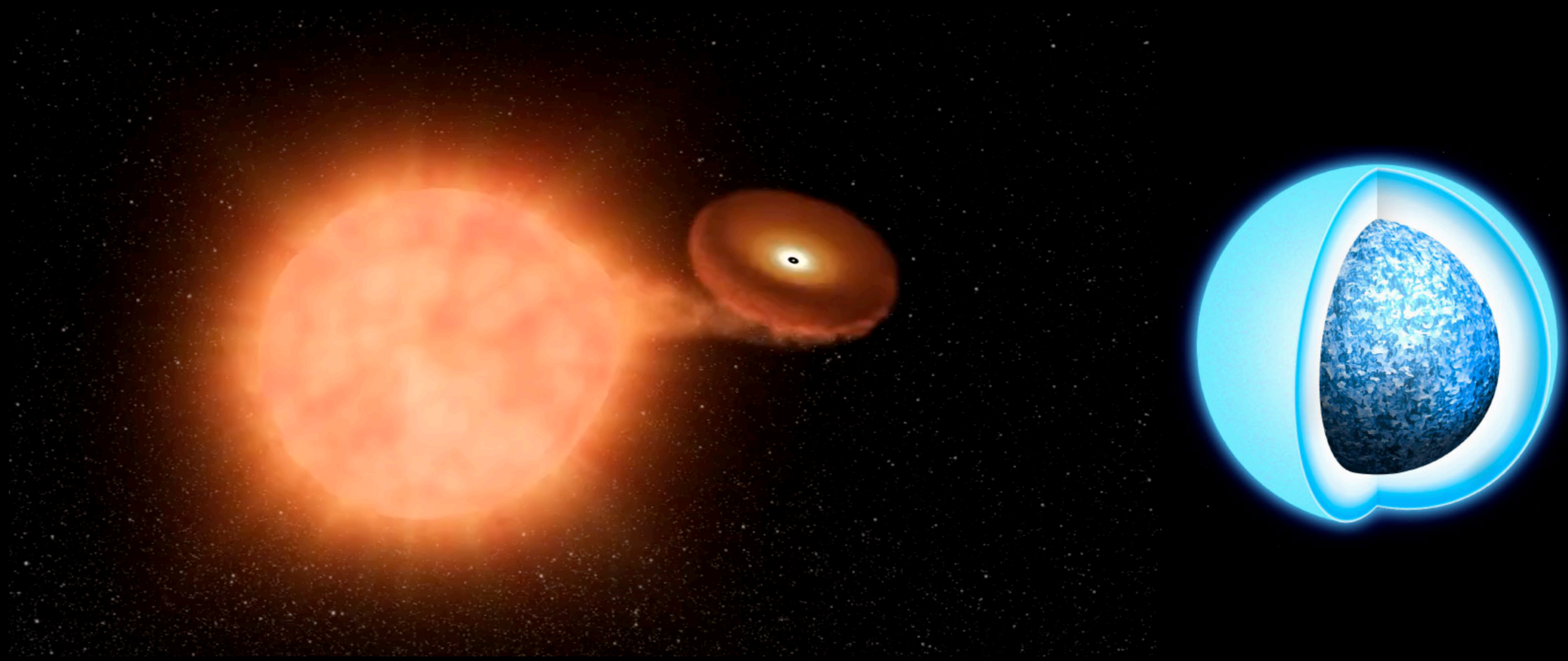
Ca-Rich Gap Transients



https://exoplanets.nasa.gov/resources/2172/type-ia-supernova/

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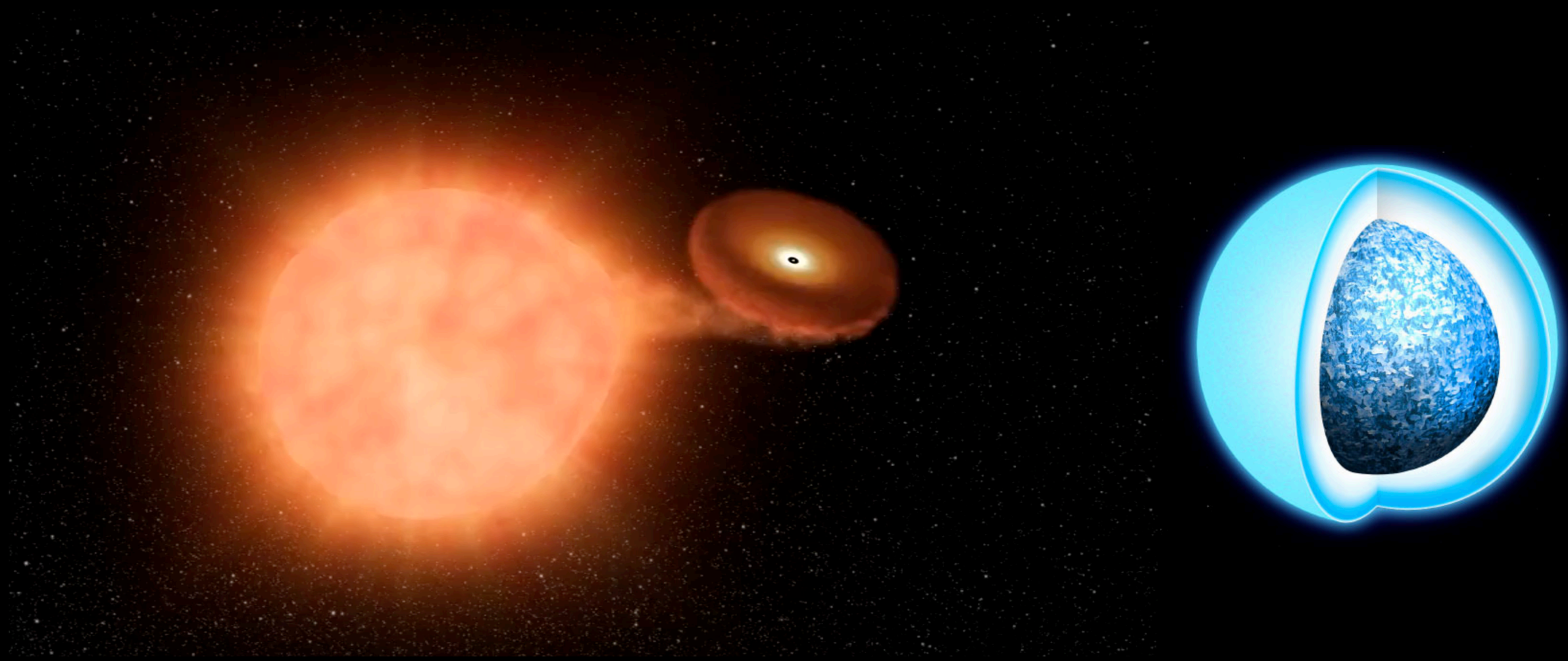
Ca-Rich Gap Transients



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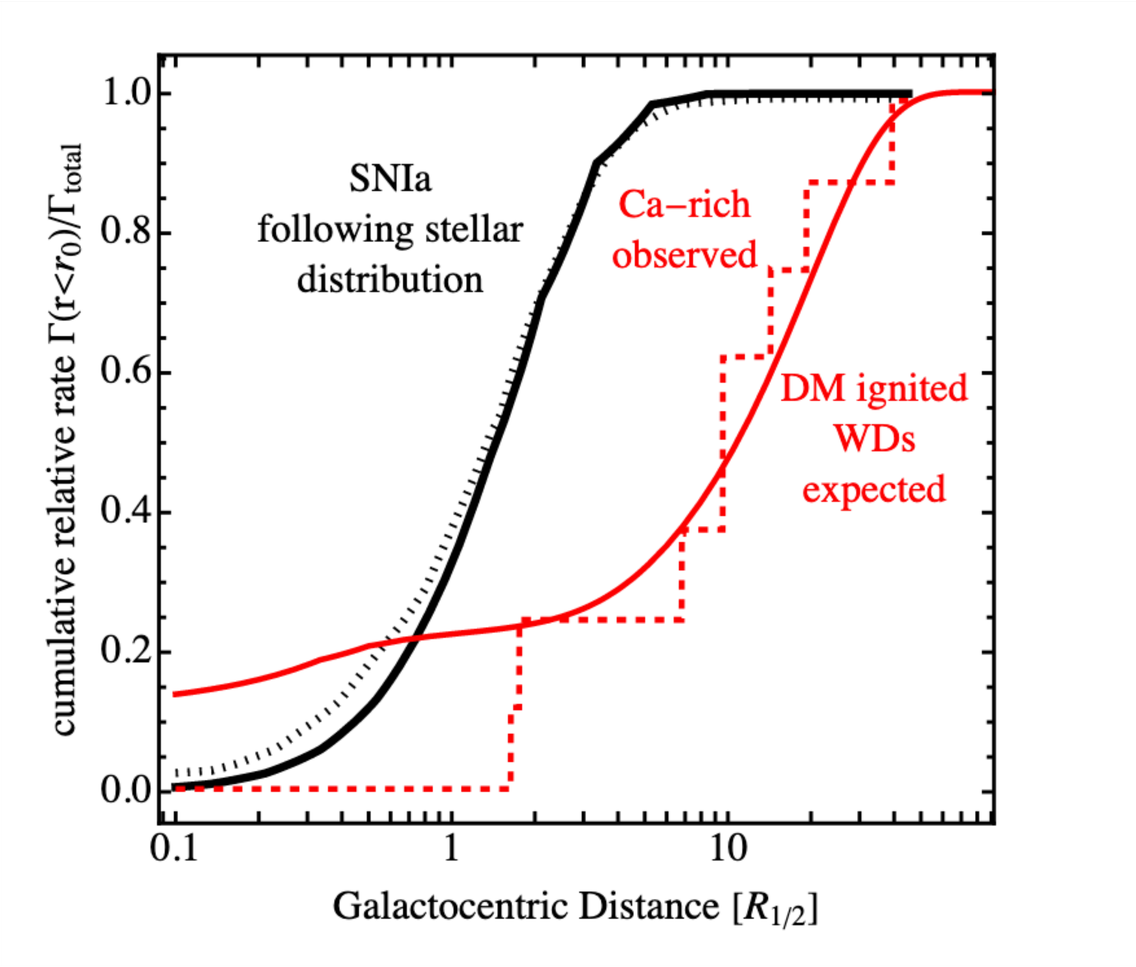
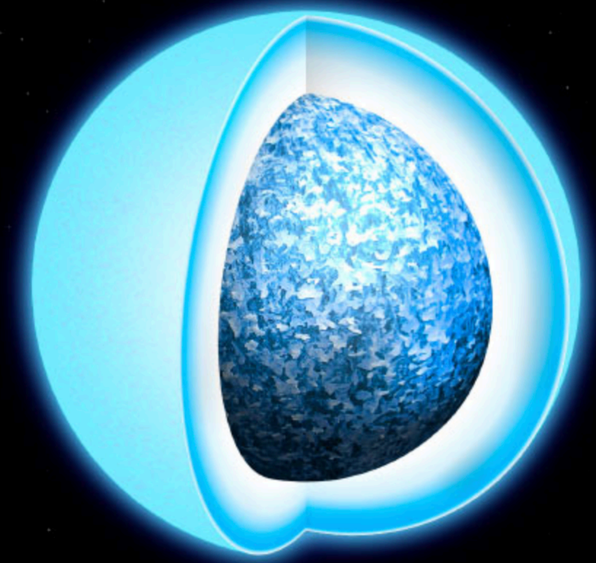
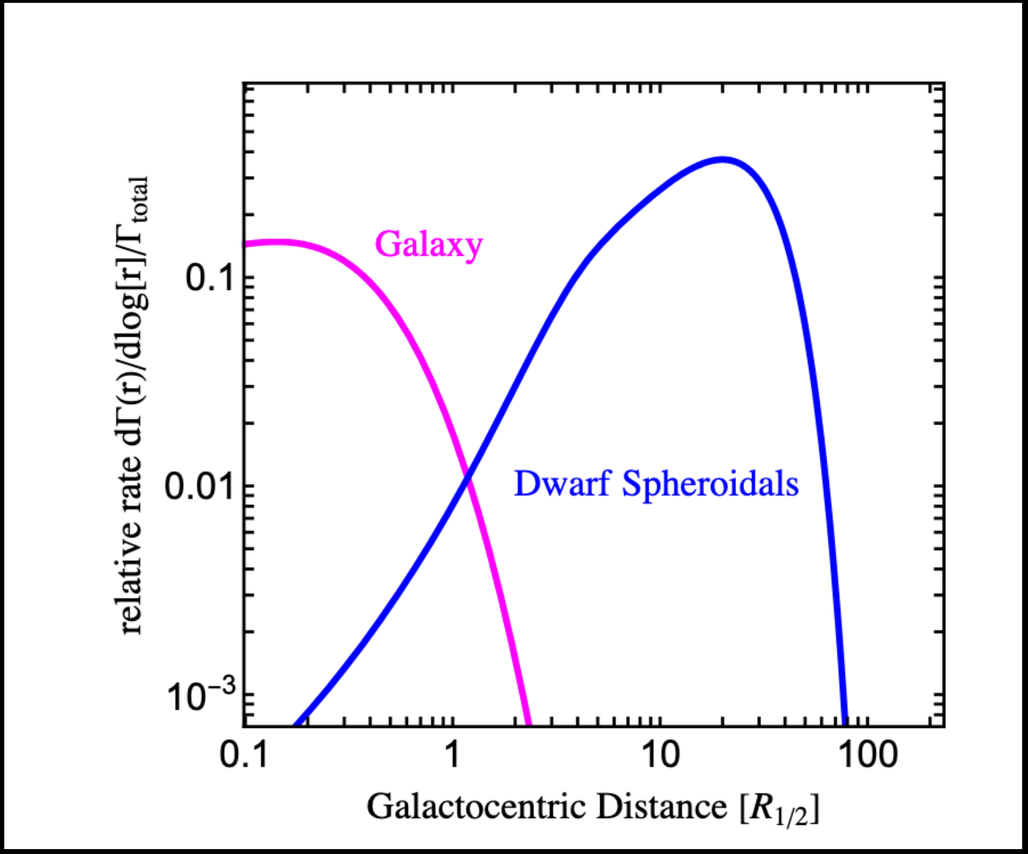
Ca-Rich Gap Transients

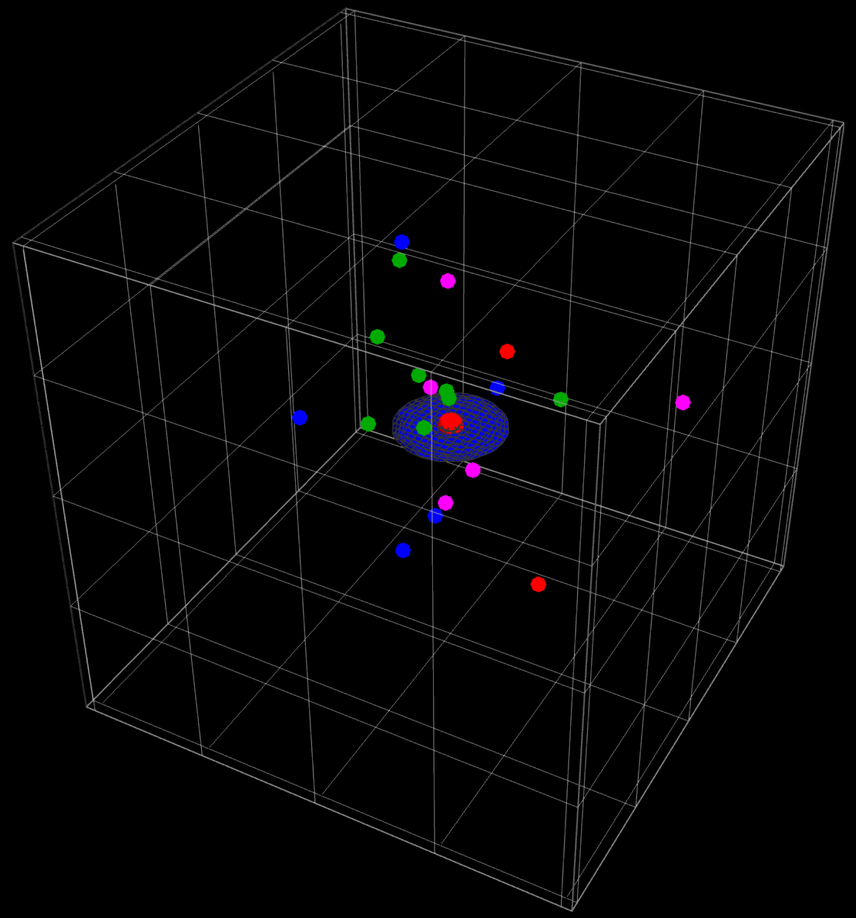




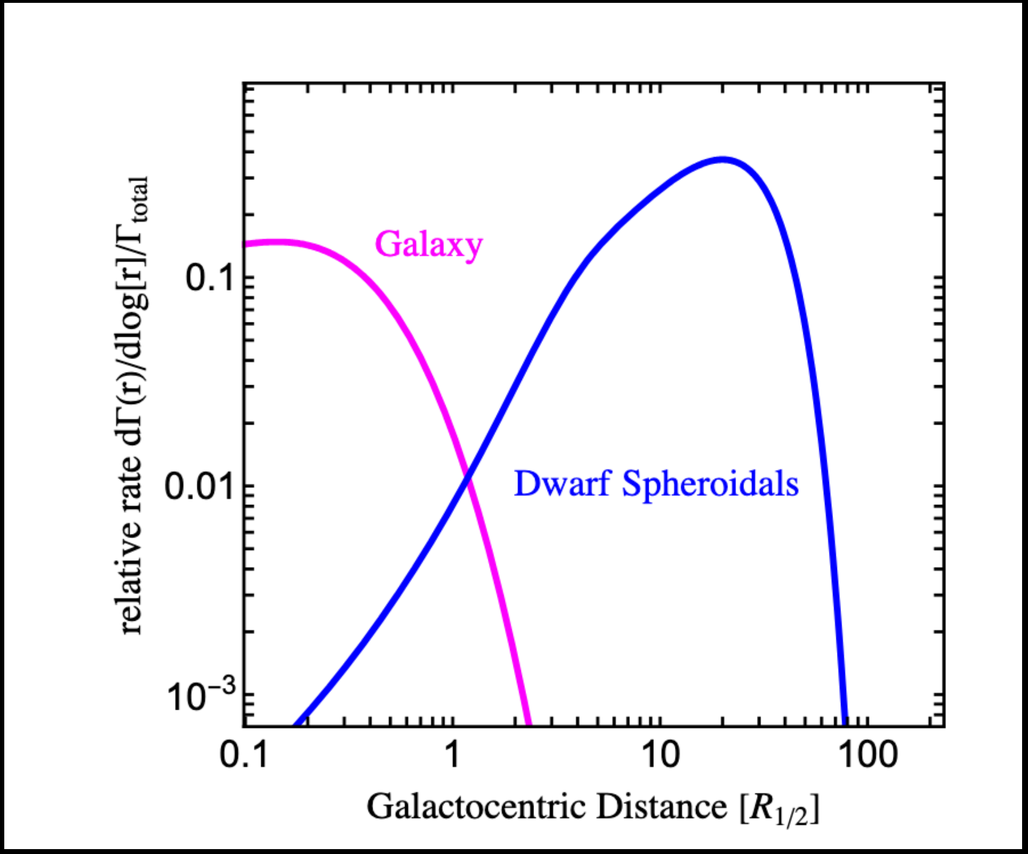
2211.00013 : **JS**, Goobar, Linden, Mörtsell

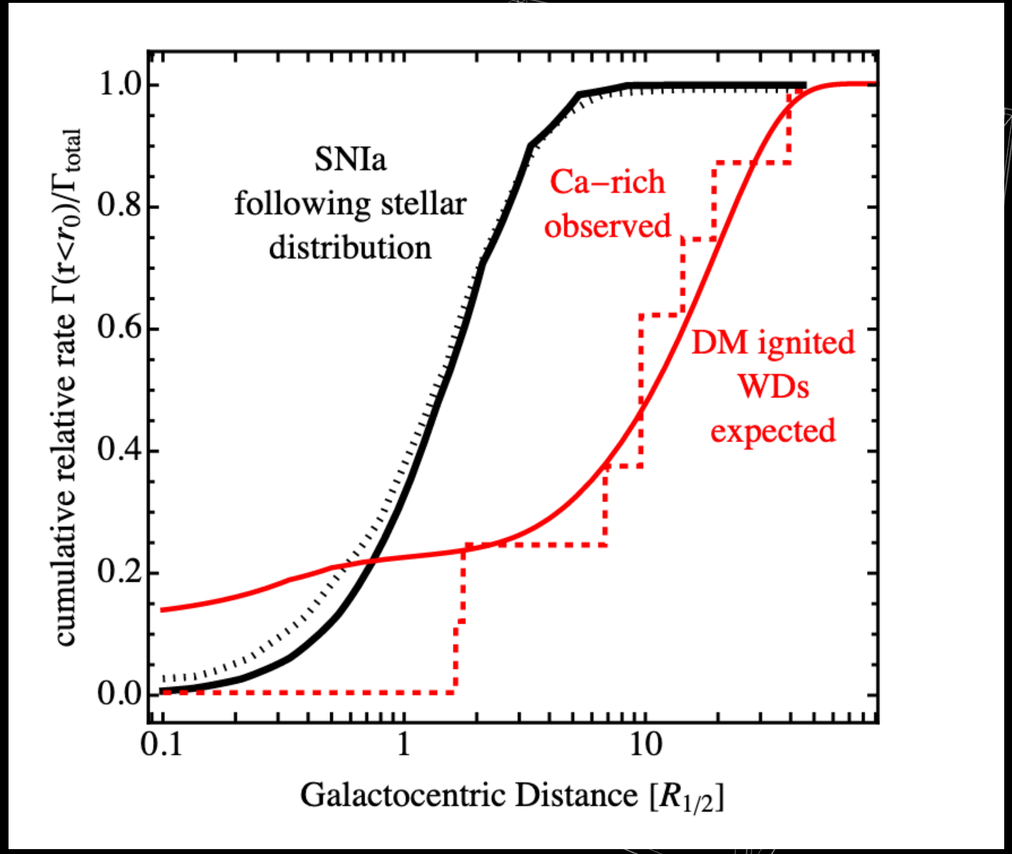
Distribution in Distant Galaxies



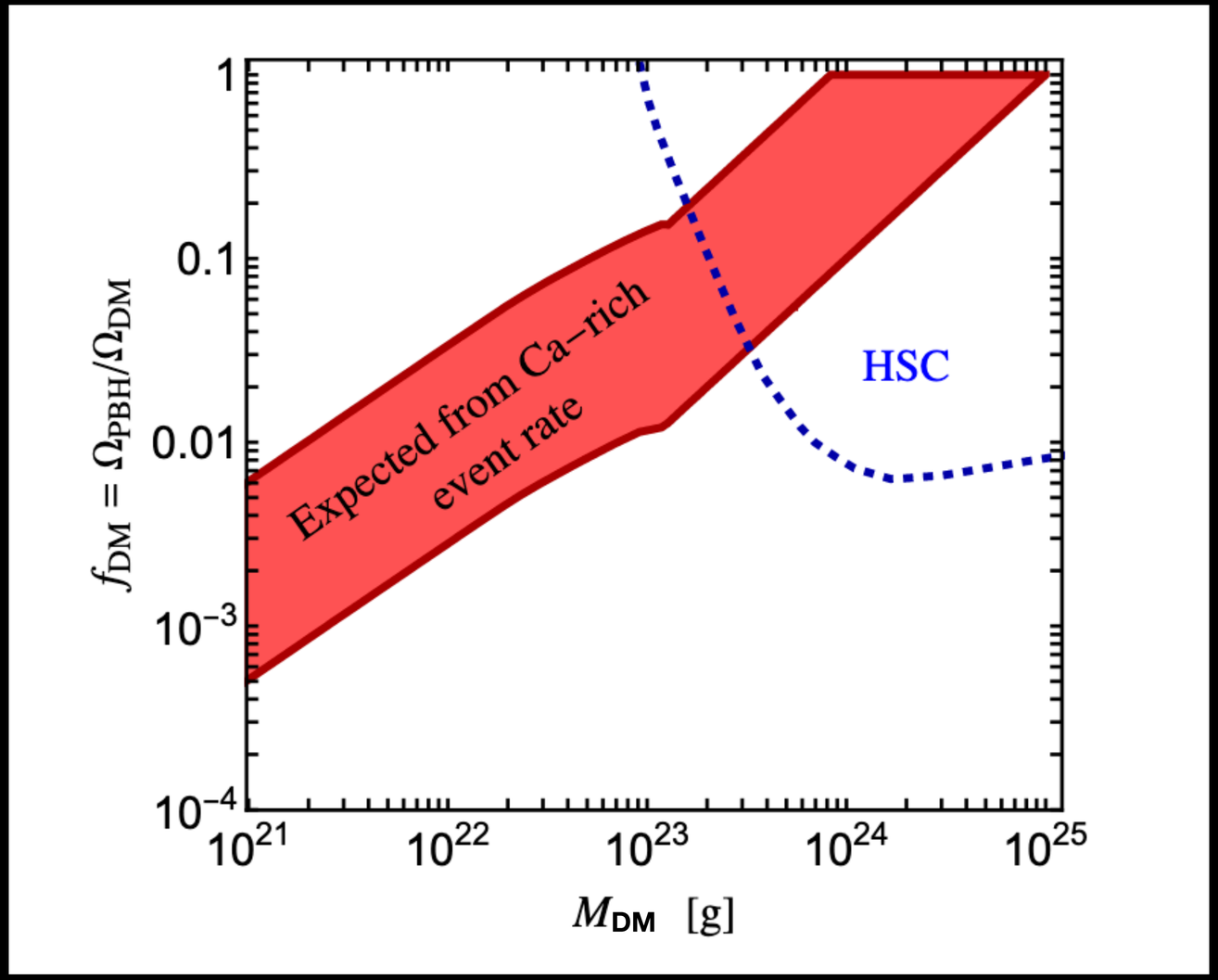


Distribution in Distant Galaxies

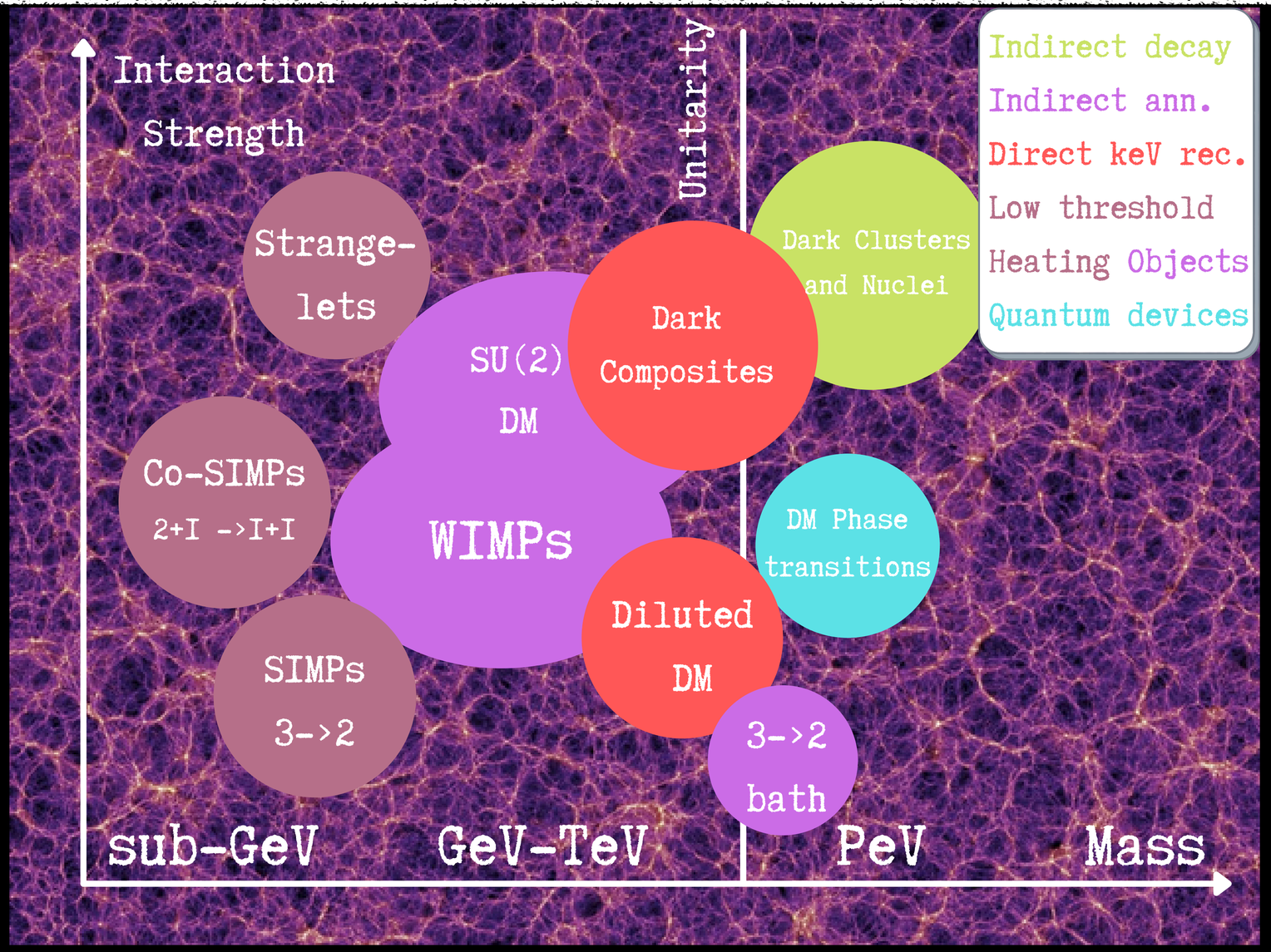




Mass and Abundance for observed Rate



Rich Scenario Space to Explore



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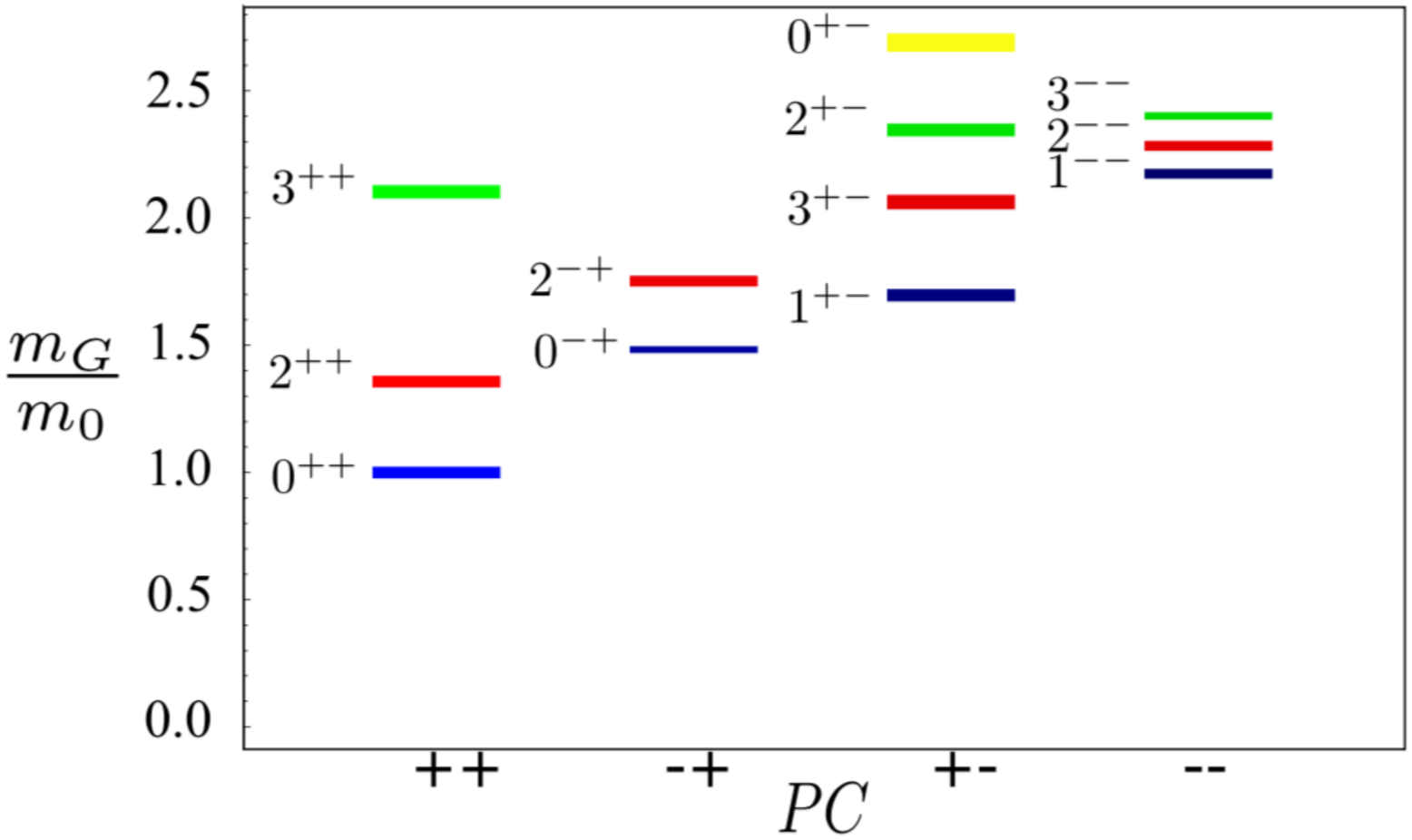
BackUp

UV Completions

Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

The Glueball Spectrum



J. Junkevich et al. : 0903.0883

Glueball Decay Channels

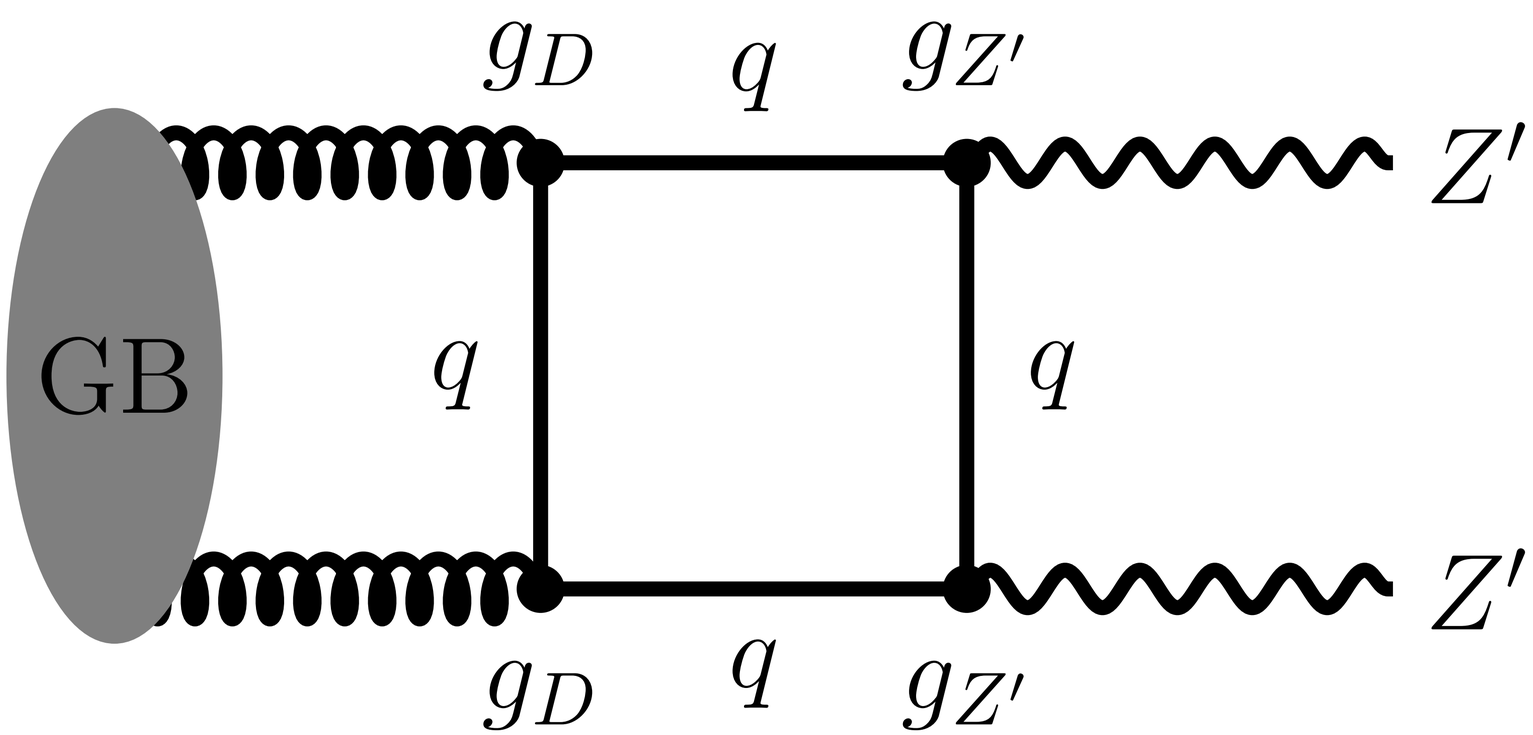
State	$D = 6$ operators	$D = 8$ operators
0^{++}	bb, W^+W^-, ZZ, hh	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
$2^{\pm+}$	$0^{\pm+}h(h^*)$	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
0^{-+}	-	gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$
3^{++}	$0^{-+}h$, $2^{\pm+}h(h^*)$	$0^{-+}gg$ $2^{++}gg$, $1^{+-}\gamma$
1^{+-}	-	$0^{\pm+}\gamma$, $2^{-+}\gamma$
1^{--}	$1^{+-}h(h^*)$	$0^{\pm+}\gamma$, $2^{\pm+}\gamma$, ff
0^{+-}, 2^{+-}, 3^{+-} 2^{--}, 3^{--}	$J^P{-}h(h^*)$	$0^{\pm+}\gamma$, $2^{\pm+}\gamma$

J. Junkevich et al. : 0903.0883

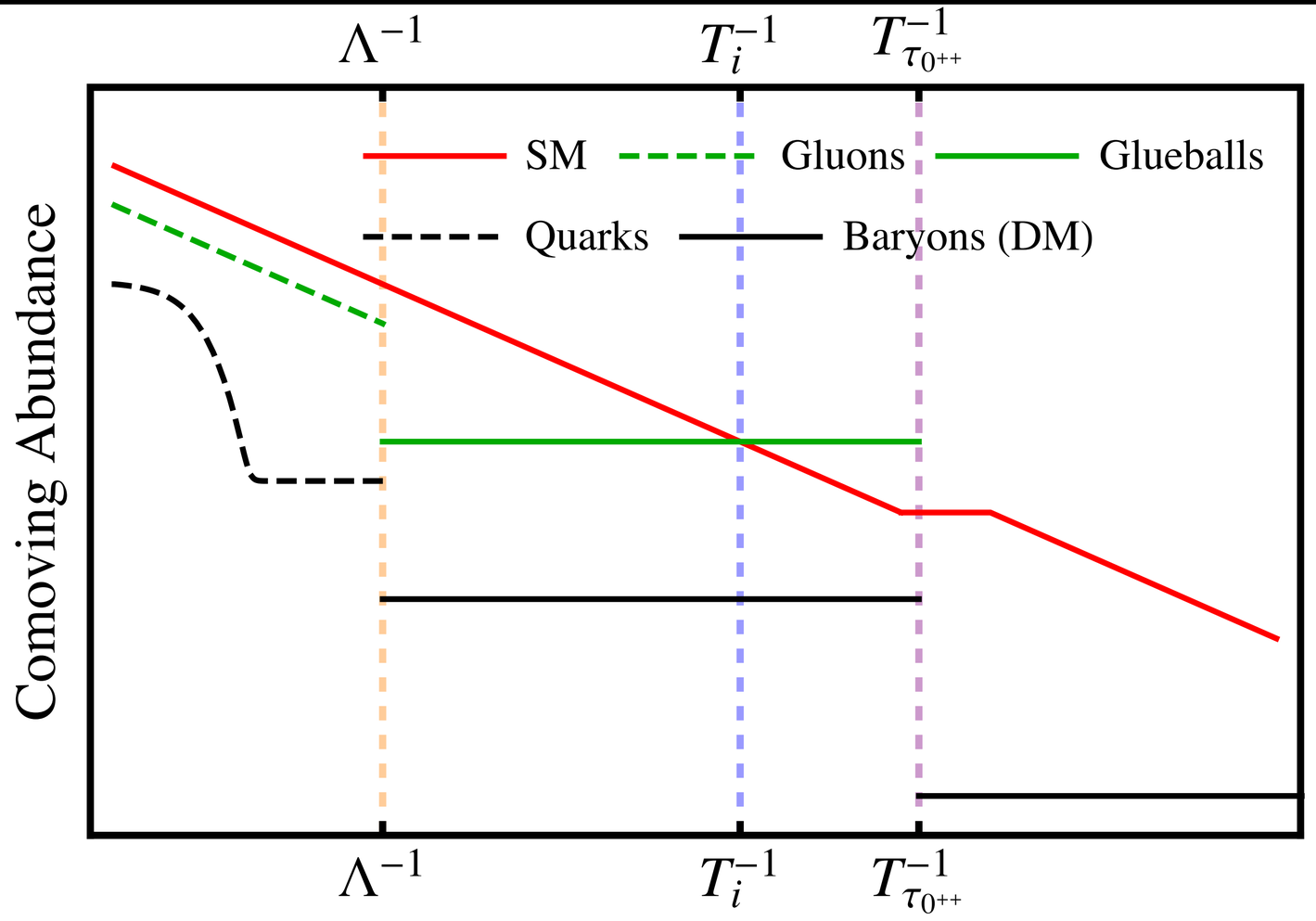
Z' Portal Model

Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Glueball Decay Diagram

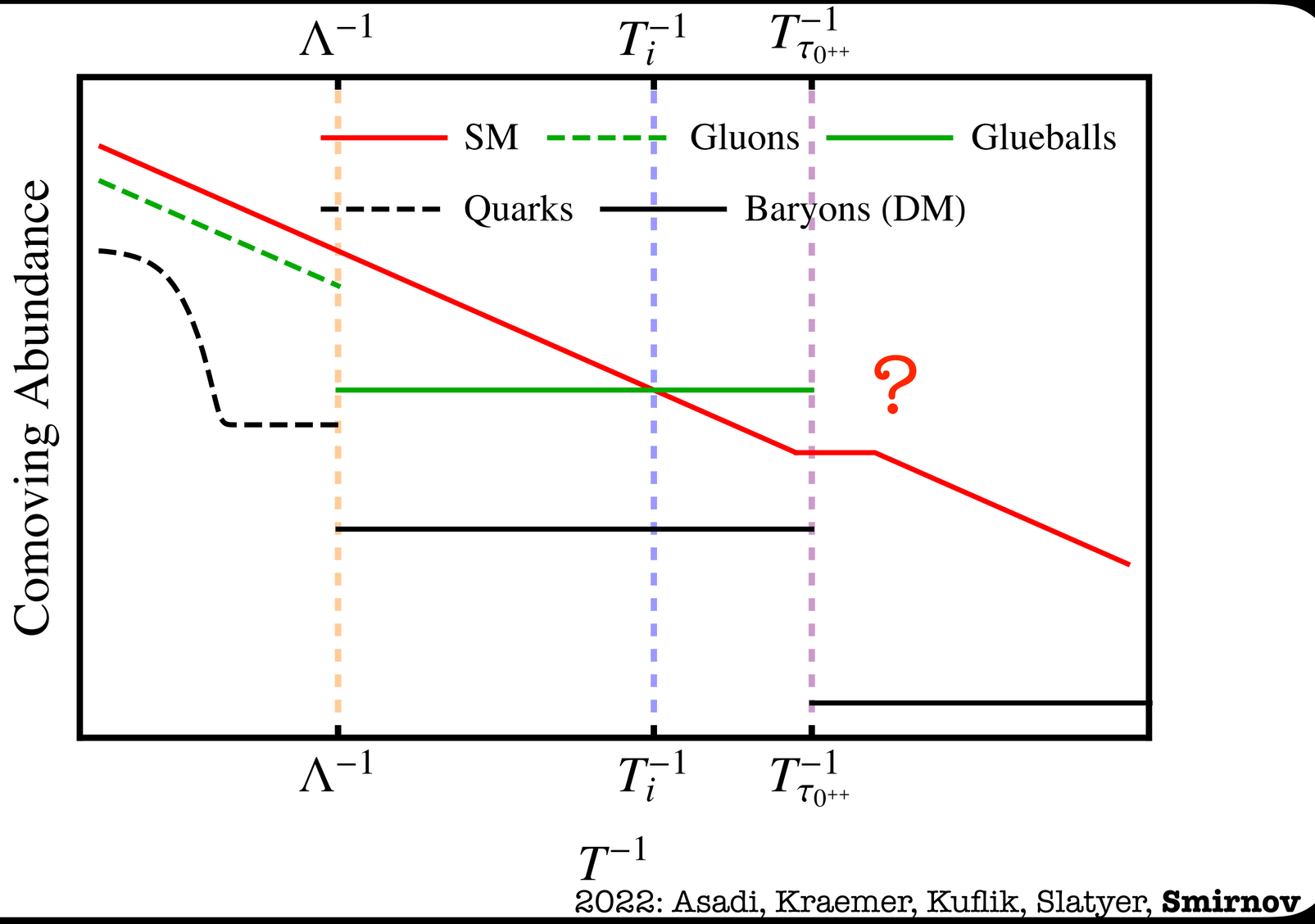


Entropy Injection



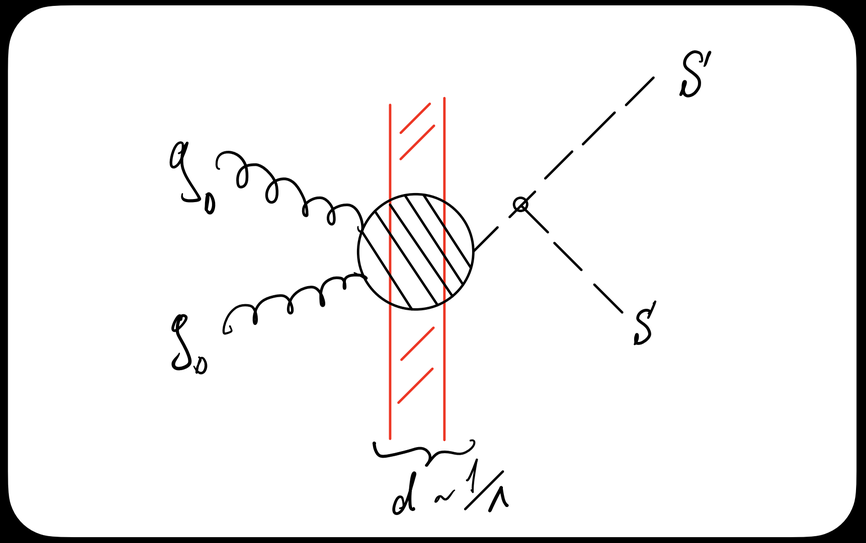
2022: Asadi, Kraemer, Kuflik, Slatyer, **Smirnov**

Entropy Injection



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

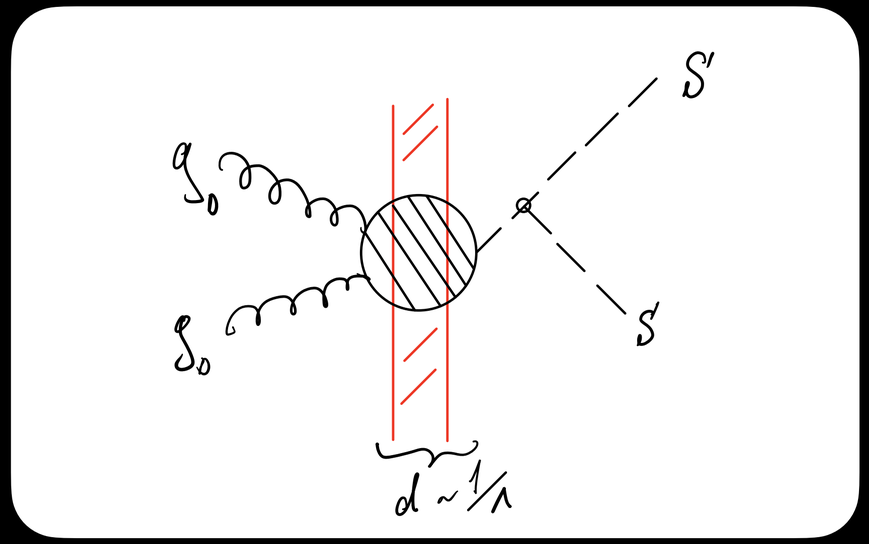
Number Density of Glueballs



$$\gamma_{\rm GB} = n_g^2 \langle \sigma_{\rm GB} v \rangle$$

$$\langle \sigma_{\rm GB} v \rangle \approx 1/T_c^2 \exp\left[-2 m_{\rm GB}/T_c\right]$$

Number Density of Glueballs



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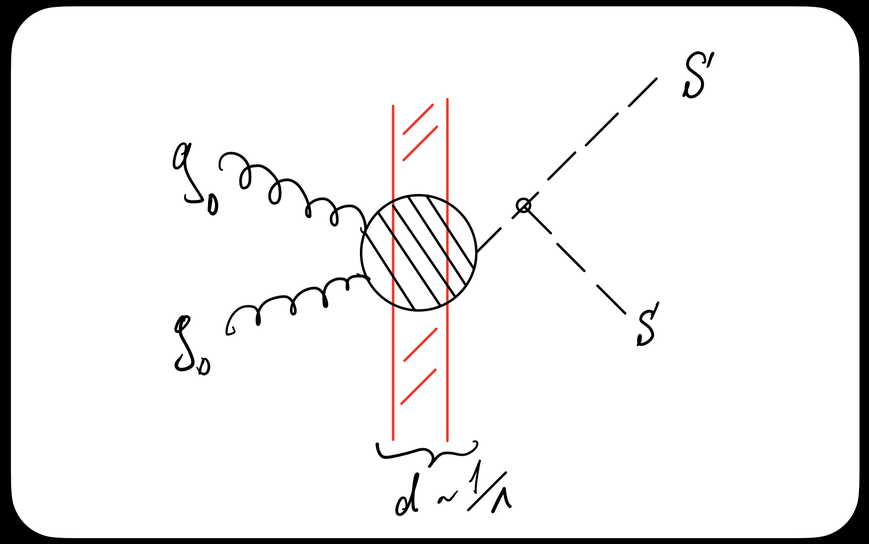
$$\langle \sigma_{\rm GB} v \rangle \approx 1/T_c^2 \exp\left[-2 m_{\rm GB}/T_c\right]$$

$$n_{\rm GB} = \gamma_{\rm GB}\, f V\, t_{\rm prod}$$

Number Density of Glueballs



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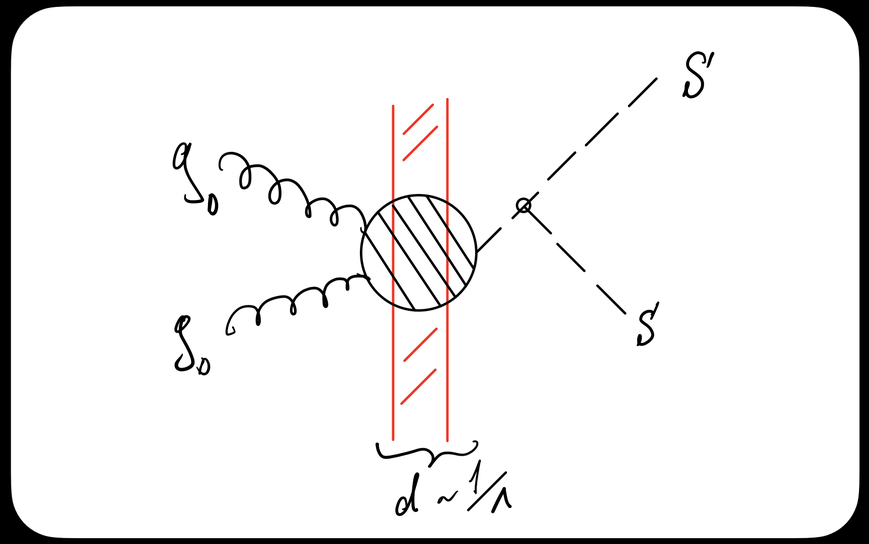
$$\langle \sigma_{\rm GB} v \rangle \approx 1/T_c^2 \exp\left[-2 m_{\rm GB}/T_c\right]$$

$$n_{\rm GB} = \gamma_{\rm GB}\, f_V\, t_{\rm prod}$$

$$f_V = \frac{V_{\rm walls}}{V_{\rm bubble}} = \frac{4\pi T_c^{-1} R_1^2}{\frac{4\pi}{3} R_1^3} \approx 3 \left(\frac{10^4\, T_c}{M_{\rm pl}}\right)^{2/3}$$

Juri Smirnov, juri.smirnov@liverpool.ac.uk;, 24/10/23

Number Density of Glueballs



$$\gamma_{\rm GB} = n_g^2 \langle \sigma_{\rm GB} v \rangle$$

$$\langle \sigma_{\rm GB} v \rangle \approx 1/T_c^2 \exp\left[-2m_{\rm GB}/T_c\right]$$

$$n_{\rm GB} = \gamma_{\rm GB}\, f_V\, t_{\rm prod}$$

$$f_V = \frac{V_{\rm walls}}{V_{\rm bubble}} = \frac{4\pi T_c^{-1} R_1^2}{\frac{4\pi}{3} R_1^3} \approx 3 \left(\frac{10^4\, T_c}{M_{\rm pl}}\right)^{2/3}$$

$$n_{\rm GB} \approx T_c^3 \frac{\exp\left[-2m_{\rm GB}/T_c\right]}{v_w}$$

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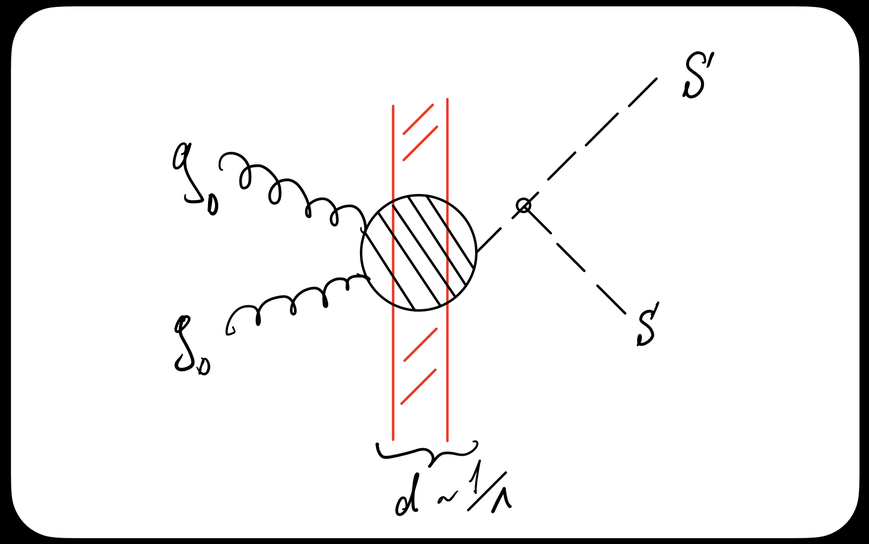

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$$n_{\rm GB} \approx T_c^3 \frac{\exp\left[-2m_{\rm GB}/T_c\right]}{v_w} \qquad n_{\rm GB} \approx 2 \cdot 10^{-6}\, T_c^3 \left(\frac{M_{\rm pl}}{T_c}\right)^{0.2}$$

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Number Density of Glueballs II

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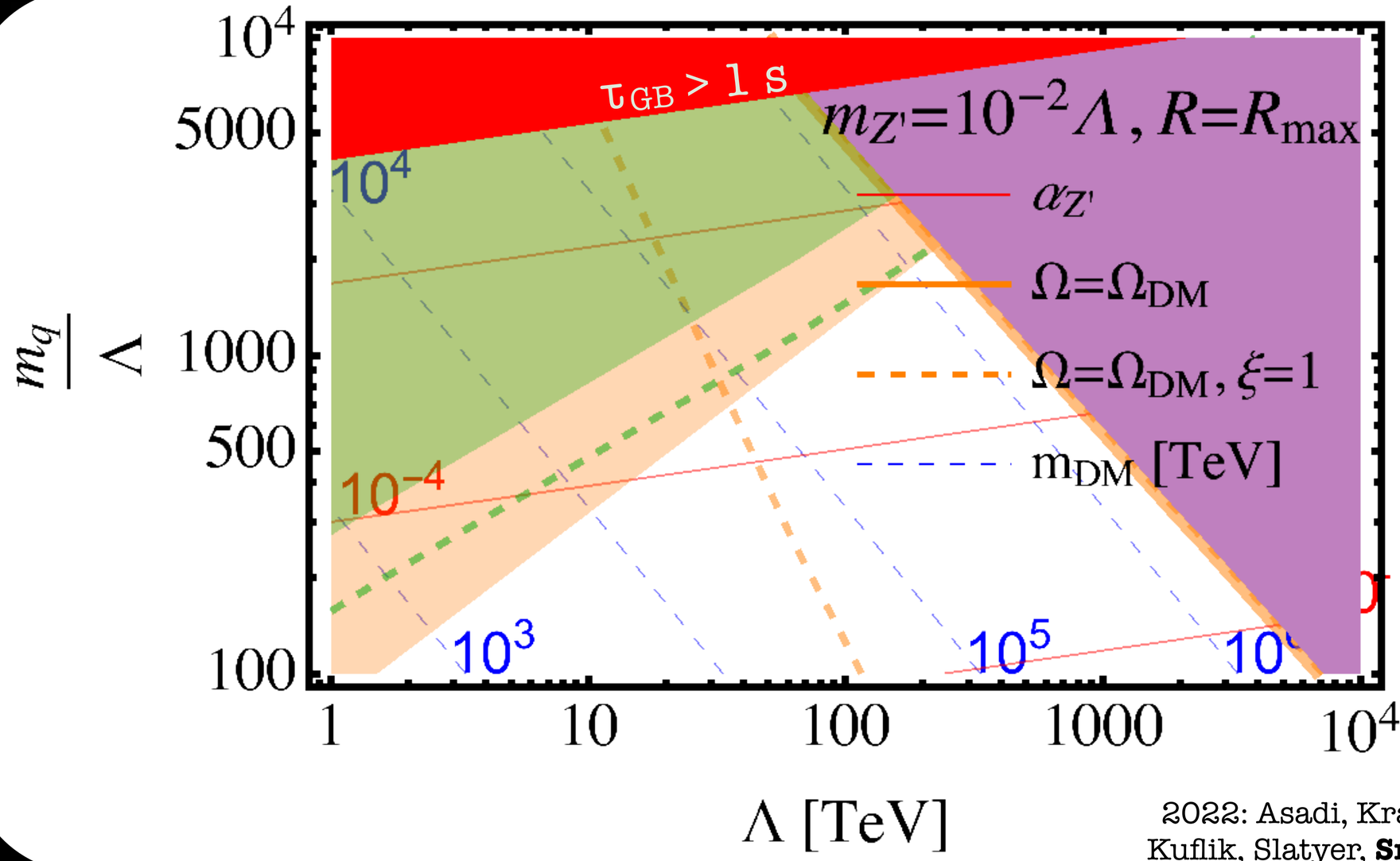
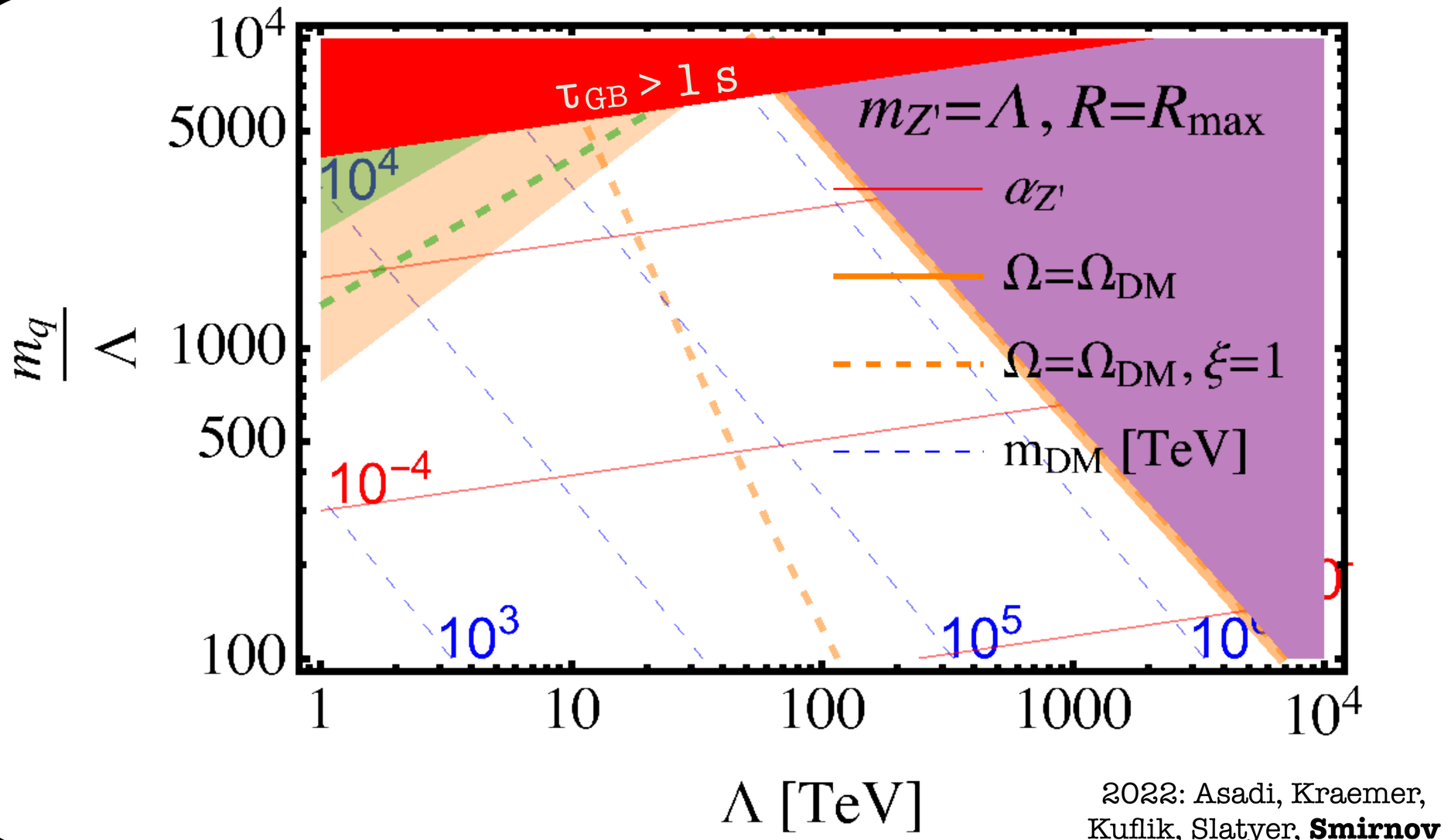
$$R \equiv \frac{s_{\rm GB}}{s_{\rm SM}} \qquad R_{\rm max} \sim 2.5 \times 10^{-4}$$

Parameter Space I



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

Parameter Space II



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