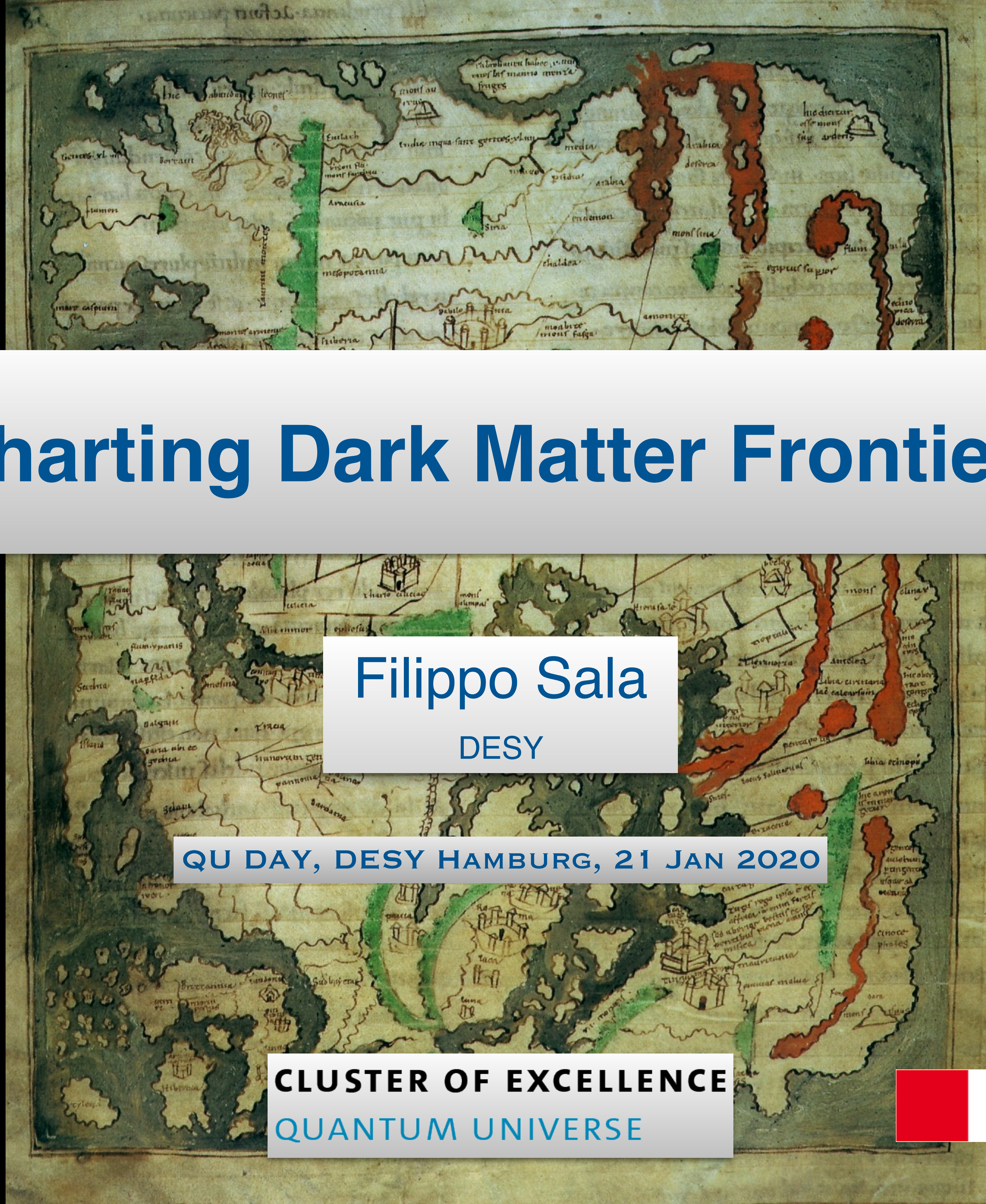


Charting Dark Matter Frontiers

Filippo Sala

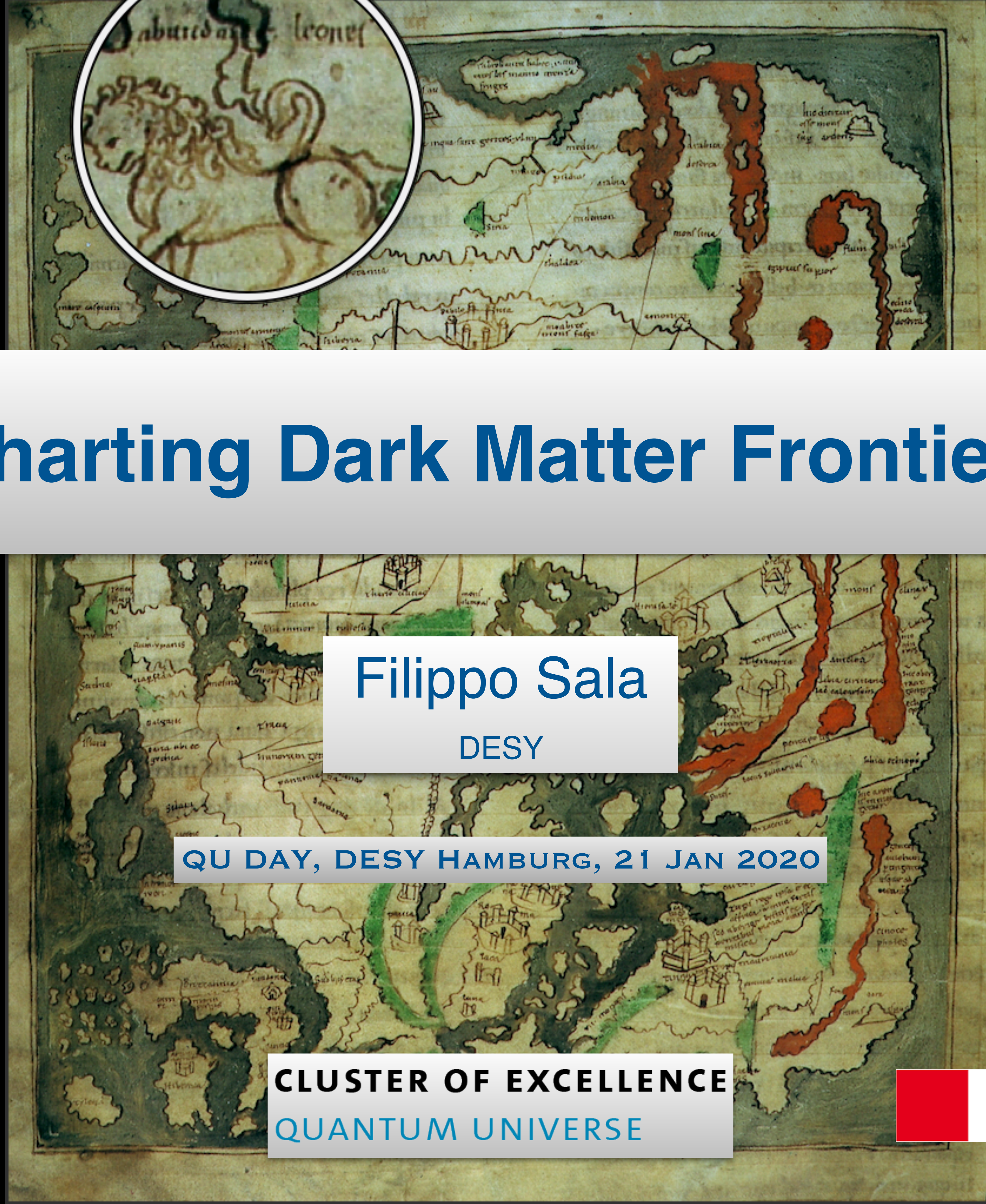
DESY

QU DAY, DESY HAMBURG, 21 JAN 2020

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

PIER



Charting Dark Matter Frontiers

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QU DAY, DESY HAMBURG, 21 JAN 2020

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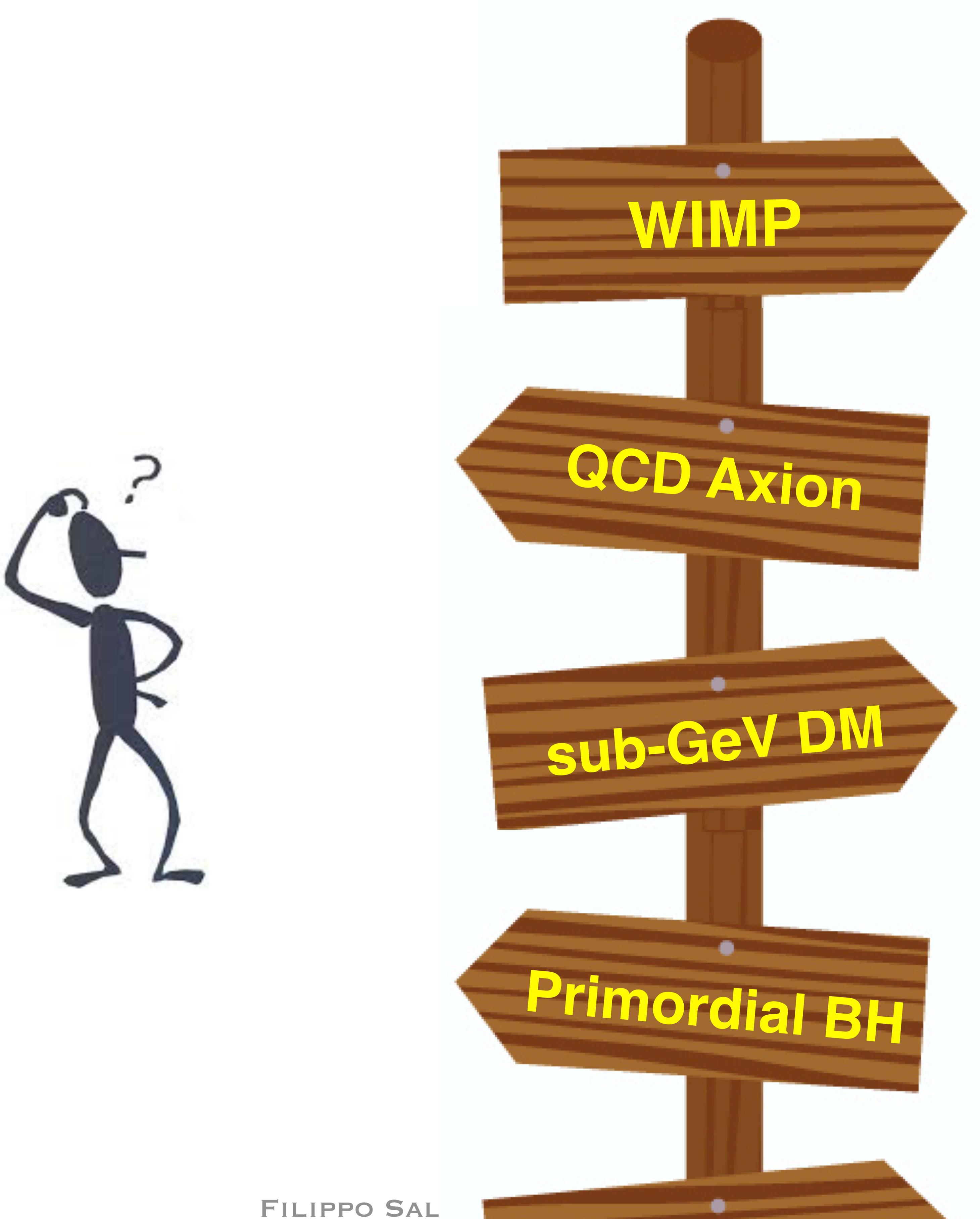
QUANTUM UNIVERSE

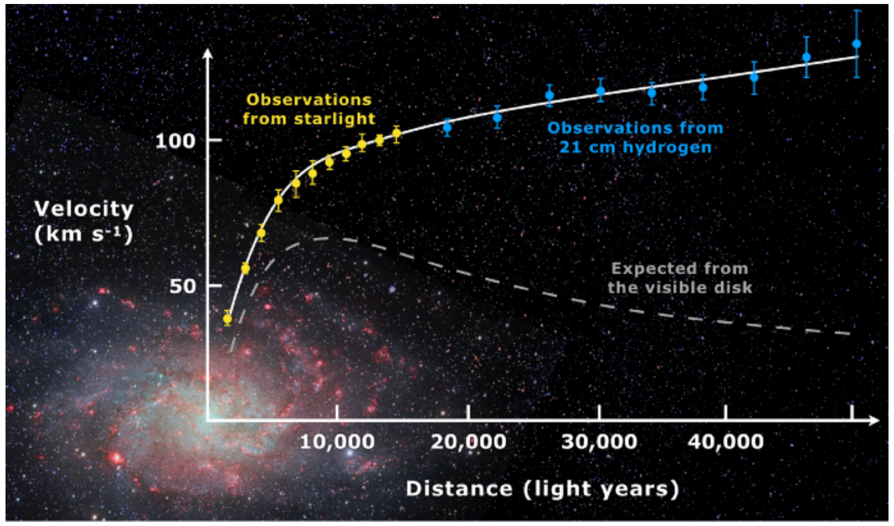
Dark Matter 2010

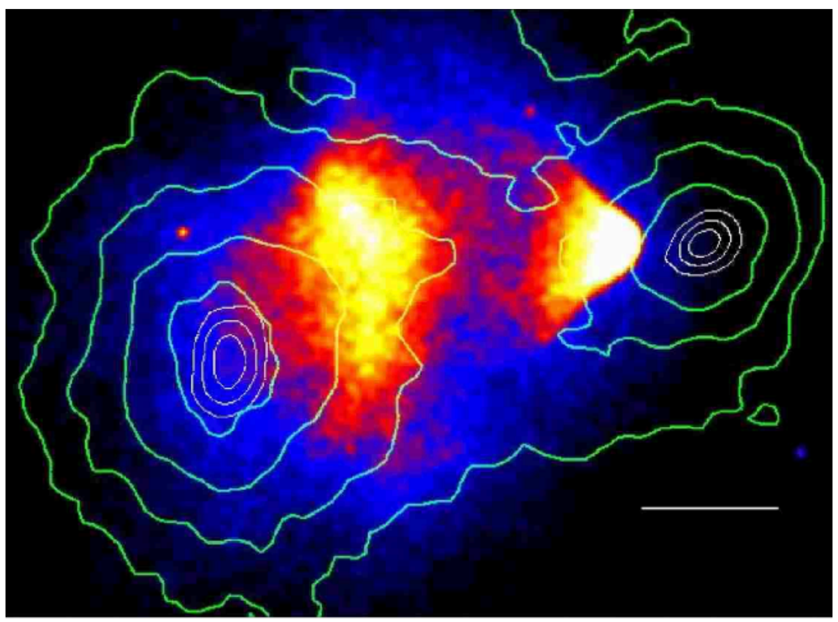
Dark Matter ~~2010~~ 2020

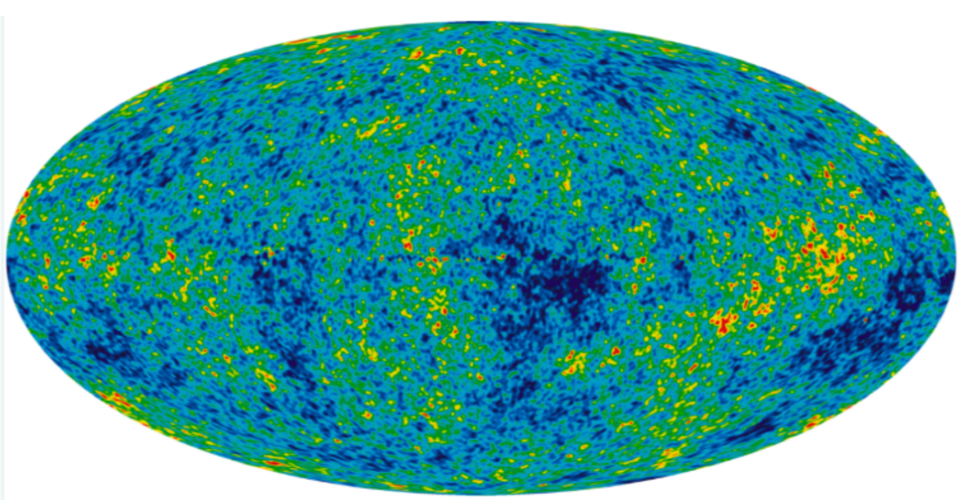


Dark Matter Map

Problems with our Model of Universe







$\sim 10's$ kpc

$\sim$ Mpc

$\sim$ 10 Gpc

Very different scales!

Dark Matter

only known hypothesis that solves all of them at once

Rules of the Dark Matter Game

"**Particle**" properties

- feels **Gravity**
- CMB (& not spoil BBN,...) = **non-baryonic**
- Invisible now = almost **electrically neutral**
- **stable** enough

"**Historical**" properties

How much? $\Omega_{\rm DM} \simeq 0.26$ $\left(\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_{\rm crit}} \quad \rho_{\rm crit} = \frac{5\ \text{protons}}{\text{meter}^3}\right)$

Since when? enough **before CMB**

How fast? **Non-relativistic**

Weakly Interacting Massive Particles

Particle properties: **massive** $U(1)_{\rm em}$**neutral** **stable** **not a baryon**

Weak = SM weak force, DM charged under $SU(2)_w \times U(1)_Y$

(or = whatever interaction with the SM, provided $\alpha = 10^{-3} - 10^{-1}$)

Weakly Interacting Massive Particles

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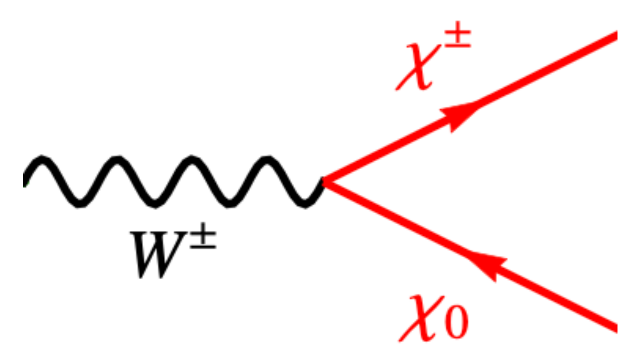
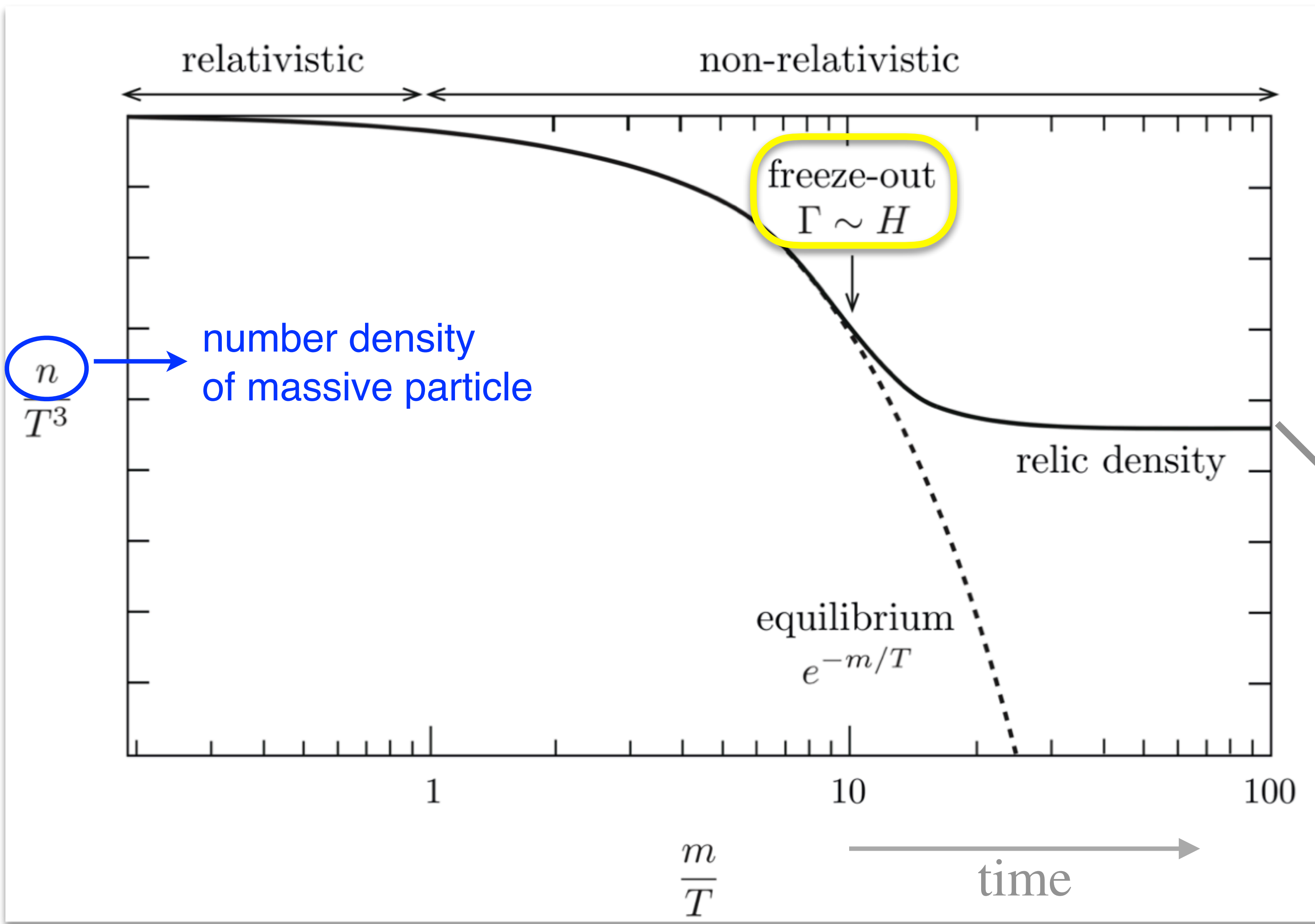
(or = whatever interaction with the SM, provided $\alpha = 10^{-3} - 10^{-1}$)

Example: DM χ as an EW multiplet

$$\mathcal{L}_\chi = \frac{1}{2}\,\bar{\chi}(i\not{D} - M_\chi)\chi$$



Cosmological History



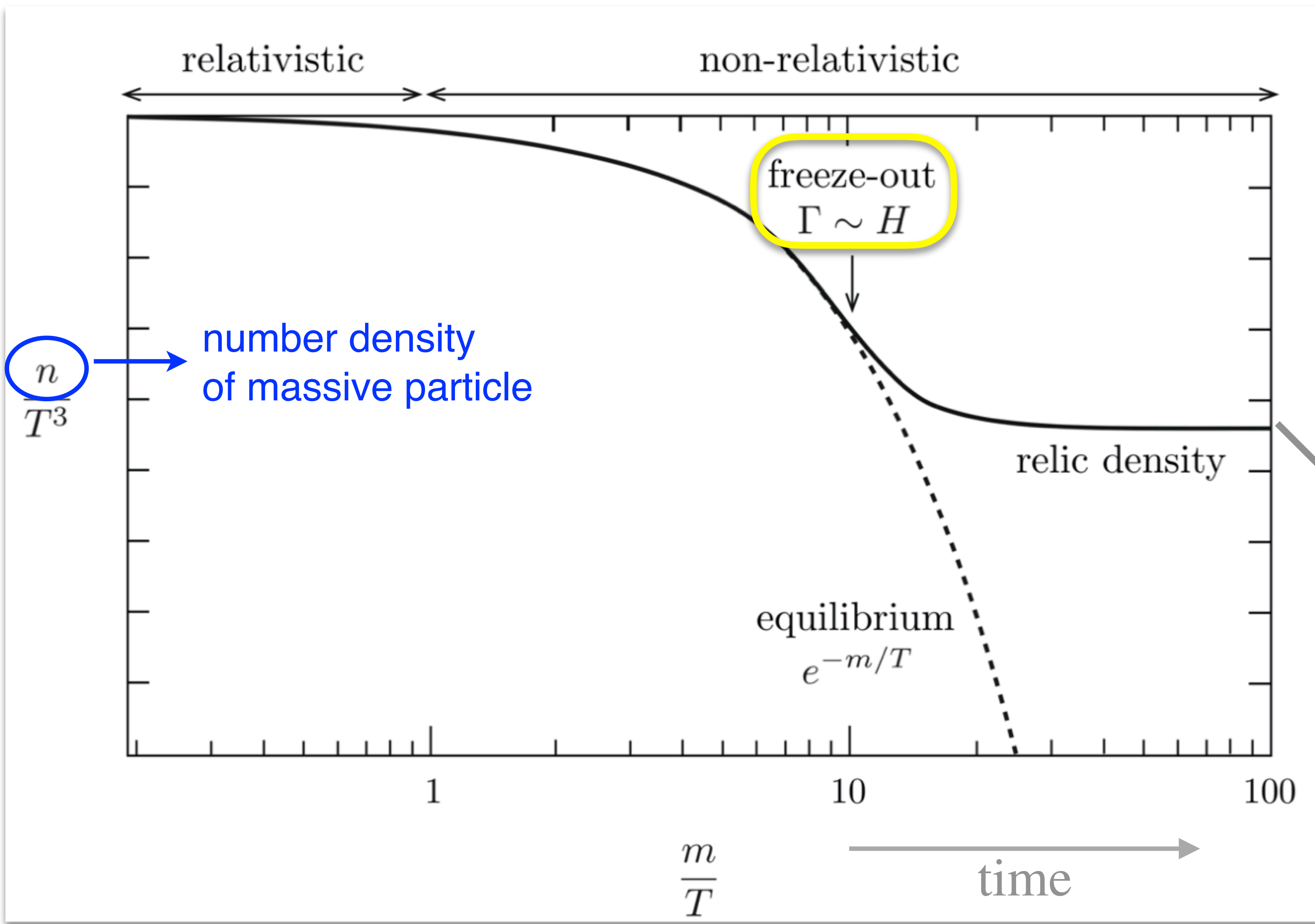
$$\Gamma = n\langle\sigma v\rangle$$

DM DM $\leftrightarrow$ SM SM

Sets today's DM abundance

$$\Omega_{\rm DM} \propto \frac{1}{\sigma v}$$

Cosmological History



$$\Gamma = n\langle\sigma v\rangle$$

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Sets today's DM abundance

$$\Omega_{\rm DM} \propto \frac{1}{\sigma v}$$

$\Omega_{\rm DM} \simeq 0.26$ from $\langle\sigma v\rangle_{\rm fo} \simeq 3 \times 10^{-26} \frac{\rm cm^3}{\rm sec}$

WIMP `Miracle'

$$\langle \sigma v \rangle_{\rm fo} \simeq \frac{1}{(20\ {\rm TeV})^2} \qquad\qquad \langle \sigma v \rangle_{\rm WIMP} \approx \frac{\alpha^2}{M_{\rm DM}^2}$$

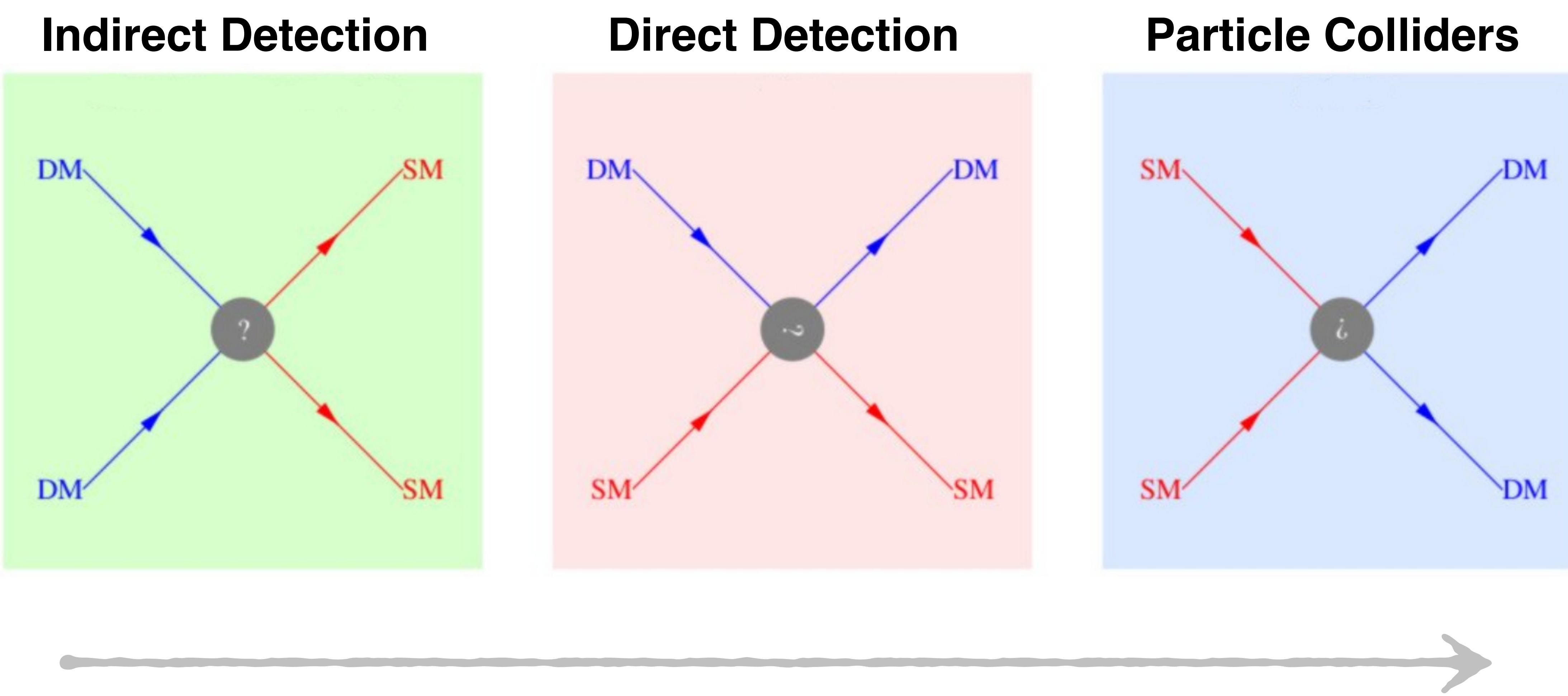
weak coupling predicts Weak scale!

New Physics at $\gtrsim$ Weak scale predicted <u>independently</u>

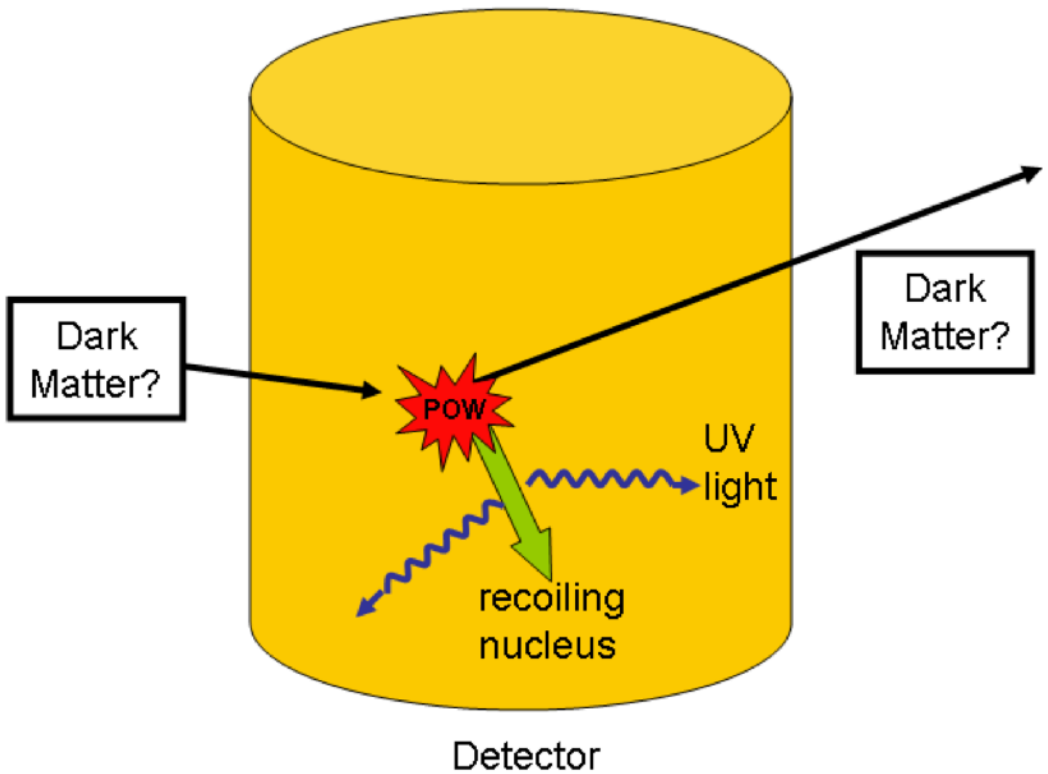
by **natural solutions to hierarchy problem**

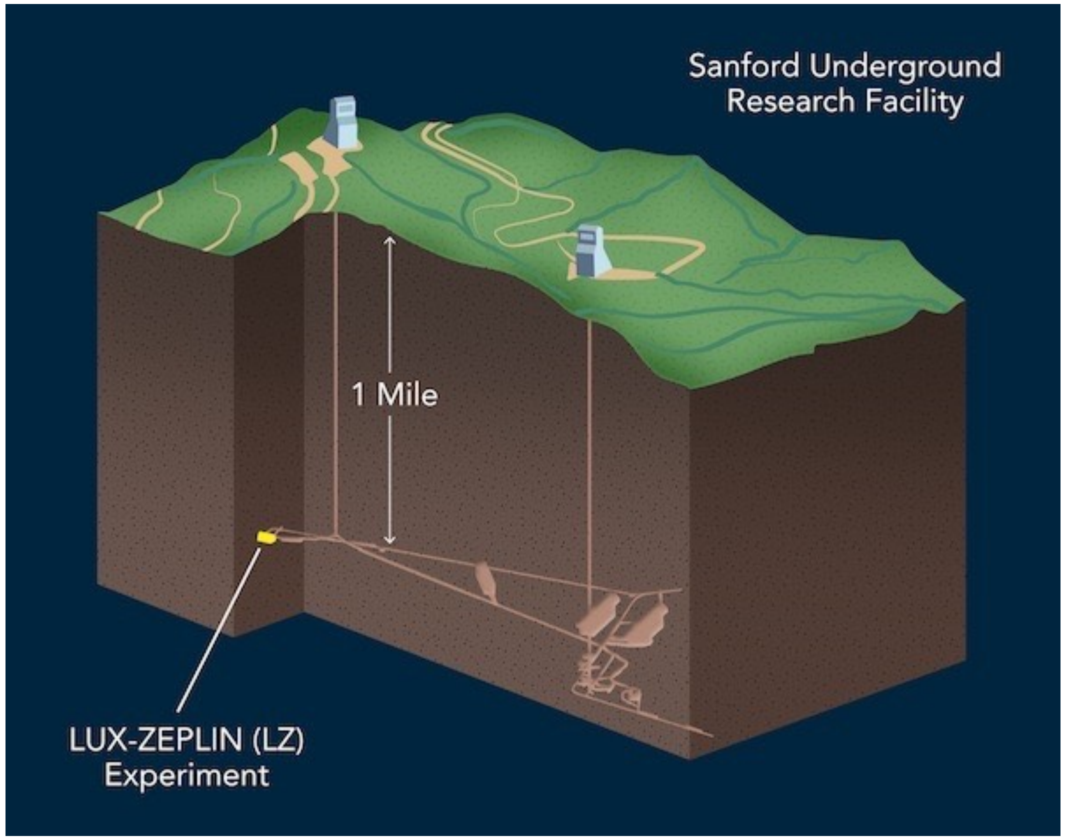
[weak-scale SUSY, Composite Higgs,…]

Seeing WIMPs

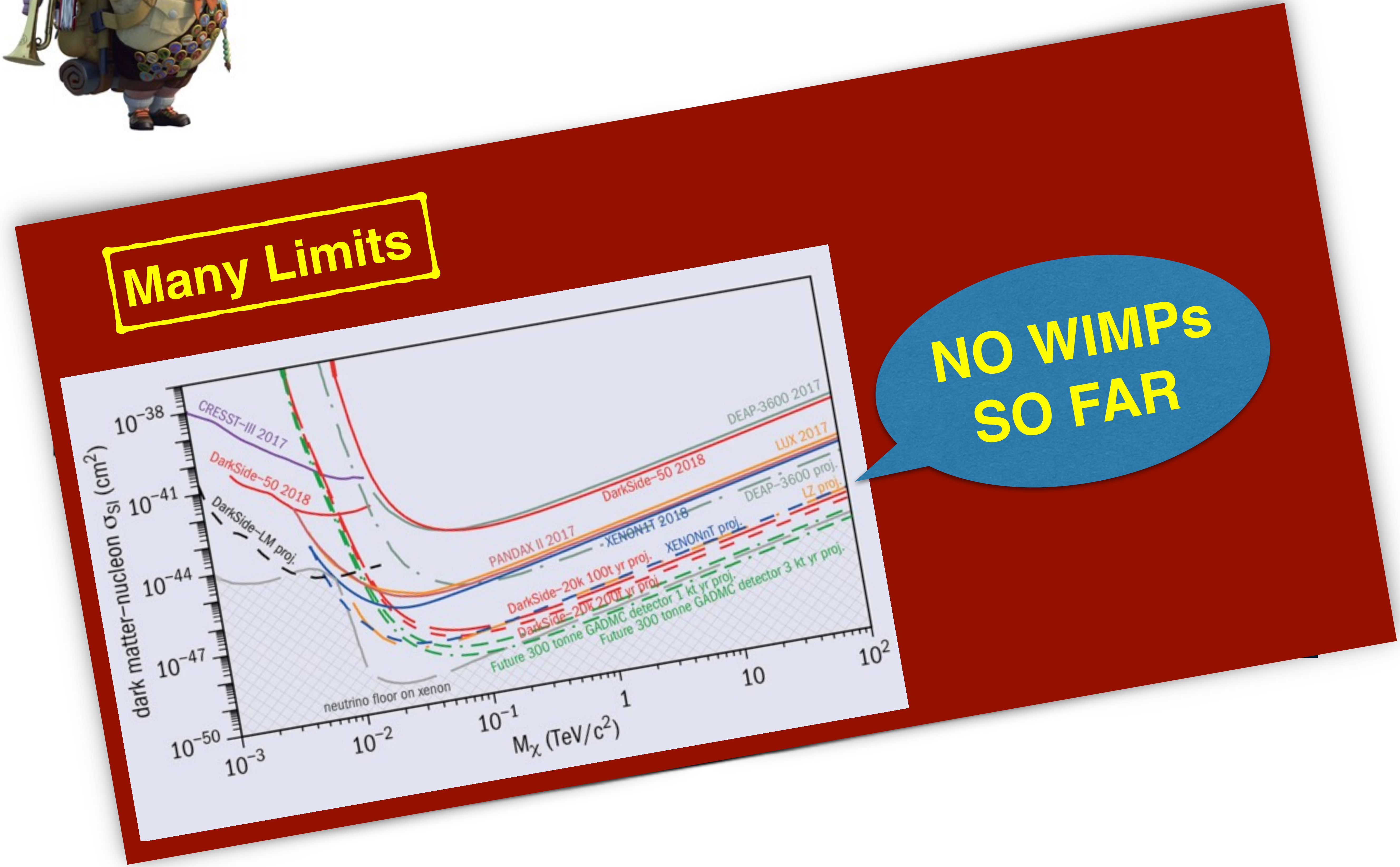


Direct Detection





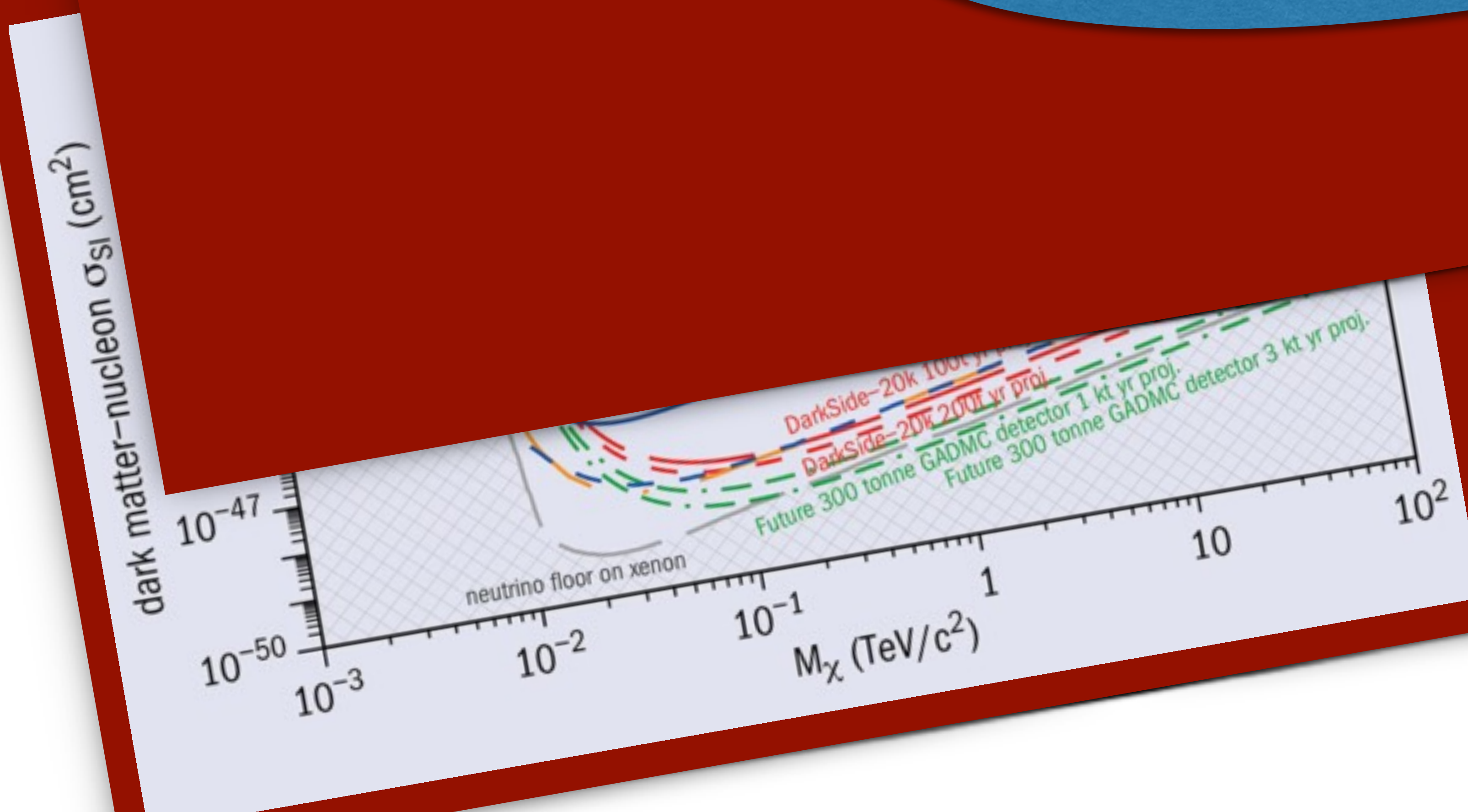
Direct Detection



Dir

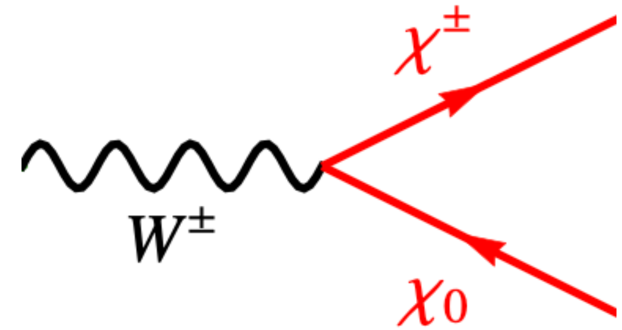
Indirect Detection and Colliders:

NO WIMPs SO FAR



A concrete example: DM as EW Triplet (Wino)

$$\mathcal{L}_\chi = \frac{1}{2}\,\bar{\chi}(i\not{D} - M_\chi)\chi$$



$$M_{\mathrm{DM}} \simeq 3\ \mathrm{TeV}$$

- Predicted in split Supersymmetry

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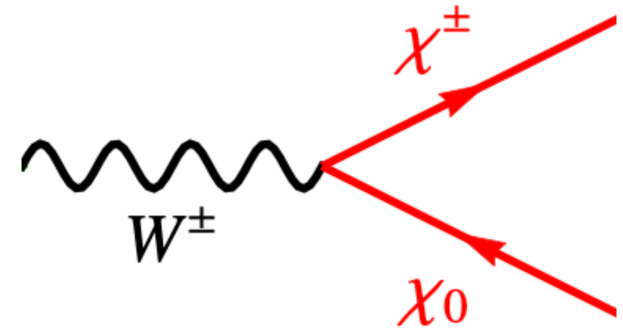
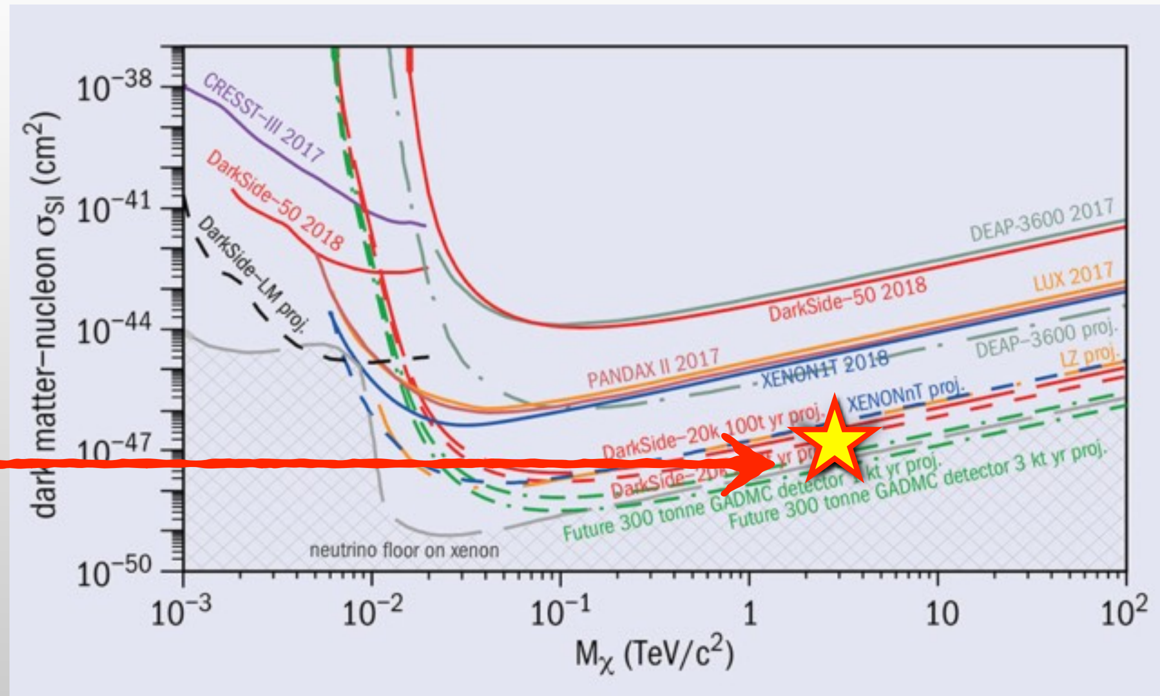


$$M_{\rm DM} \simeq 3\ \text{TeV}$$

Predicted in split Supersymmetry

Collider: wait for FCC-hh or muon

Direct Detection: Next Generation



Indirect Detection: Next Generation (?)

A concrete example: DM as EW Triplet (Wino)

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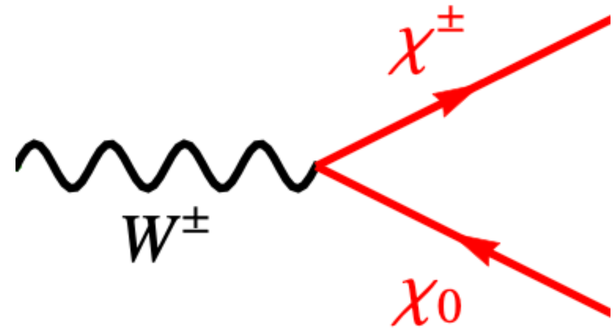

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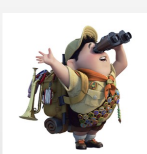

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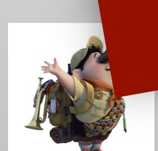
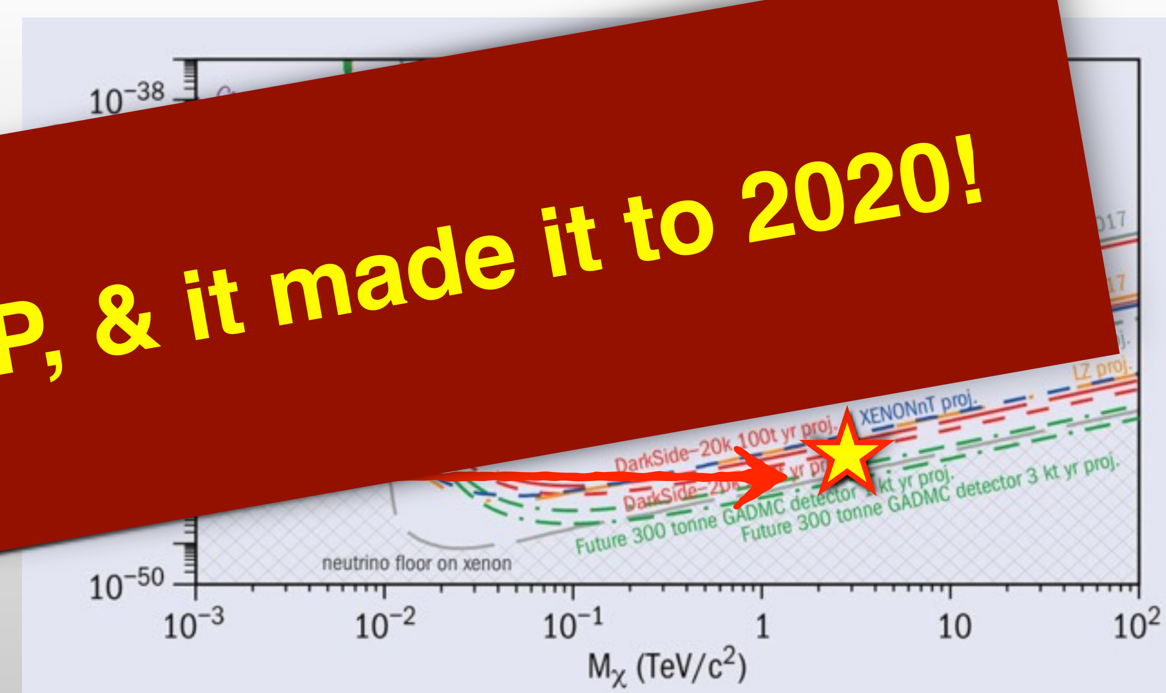


Indirect Detection: Next Generation (?)



Wino is `prototype' of WIMP, & it made it to 2020!

(My) WIMP Summary

Theoretical motivation weaker than in 2010

not weaker than theory motivation for most other candidates*

* a personal opinion

Searches now in full swing!

Not unreasonable that discovery announced this year/decade

(My) WIMP Summary

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Searches now in full swing!

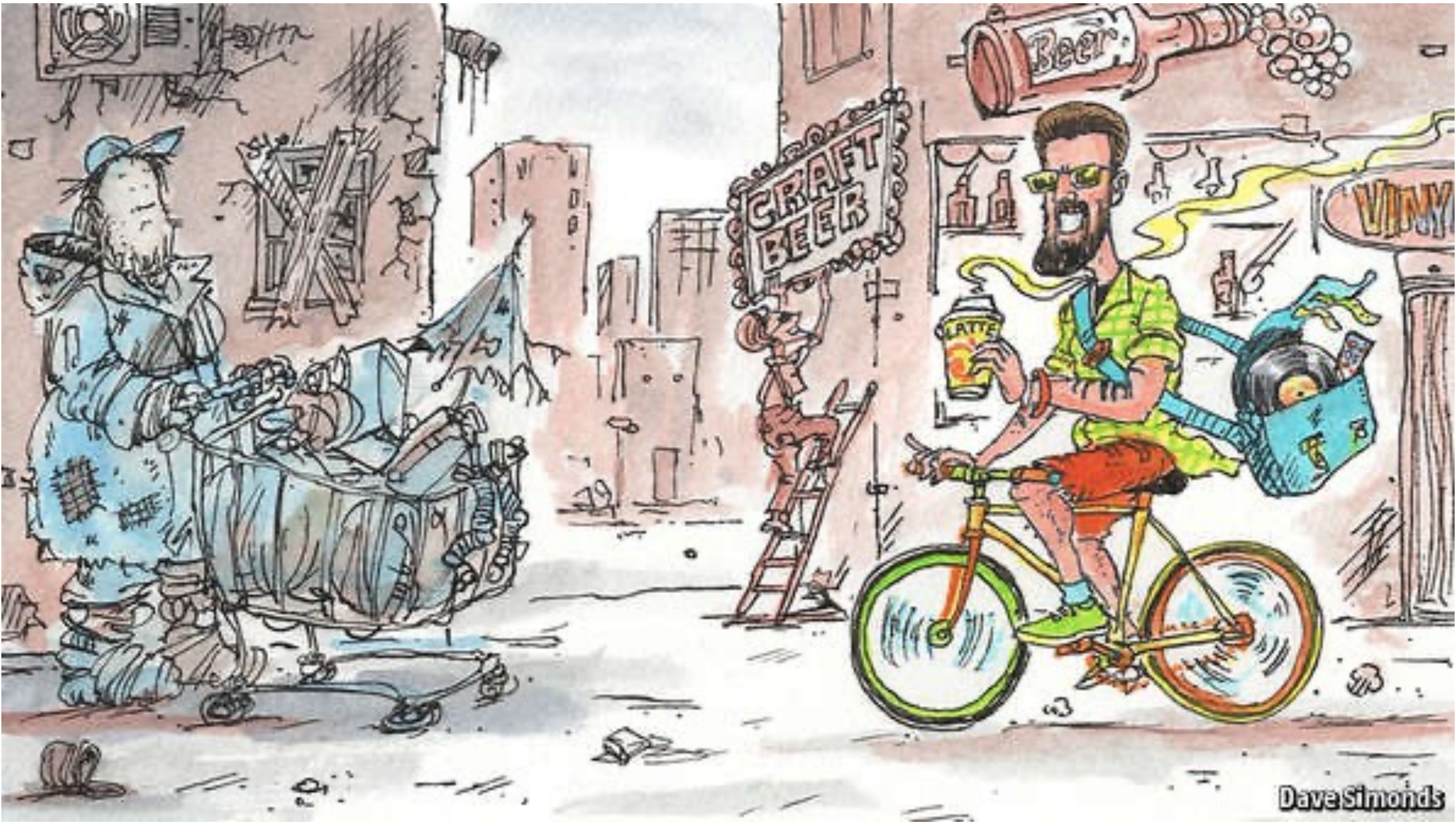
Not unreasonable that discovery announced this year/decade

Path forward seems clear → keep exploring!

Dark Matter Map

Gentrification

2010 2020



Gentrification 2010-2020

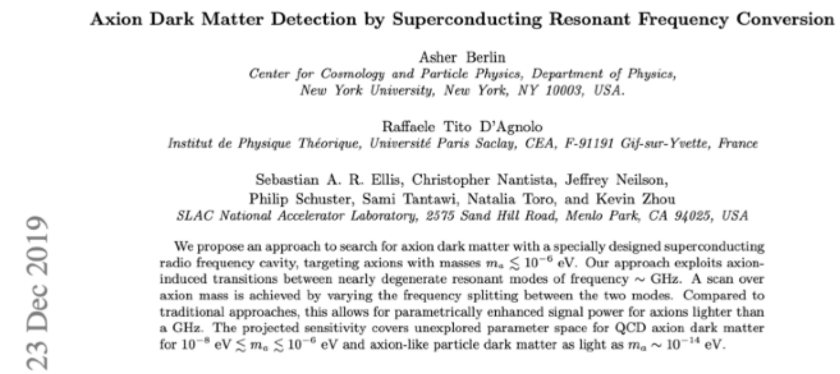
Axion Solution to Strong CP problem

ADMX

MADMAX

BRASS

...



23 Dec 2019

Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion

Asher Berlin
Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA.

Raffaele Tito D'Agnolo
Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France

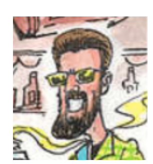
Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

We propose an approach to search for axion dark matter with a specially designed superconducting radio frequency cavity, targeting axions with masses $m_a \lesssim 10^{-6}$ eV. Our approach exploits axion-induced transitions between nearly degenerate resonant modes of frequency $\sim$ GHz. A scan over axion mass is achieved by varying the frequency splitting between the two modes. Compared to traditional approaches, this allows for parametrically enhanced signal power for axions lighter than a GHz. The projected sensitivity covers unexplored parameter space for QCD axion dark matter for 10^{-8} eV $\lesssim m_a \lesssim 10^{-6}$ eV and axion-like particle dark matter as light as $m_a \sim 10^{-14}$ eV.

Wins prize of last proposal of the decade

Less sharp links with other SM problems*

* a personal opinion (?)



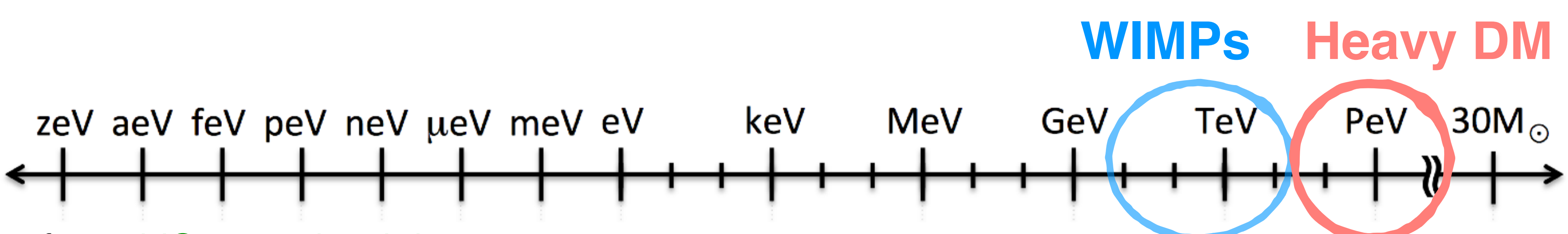
SENSEI, SuperCDMS,...

Already had one colloquium each (K. Zurek and J. Redondo)

Gentrification 2030?

Dark Matter above WIMP window

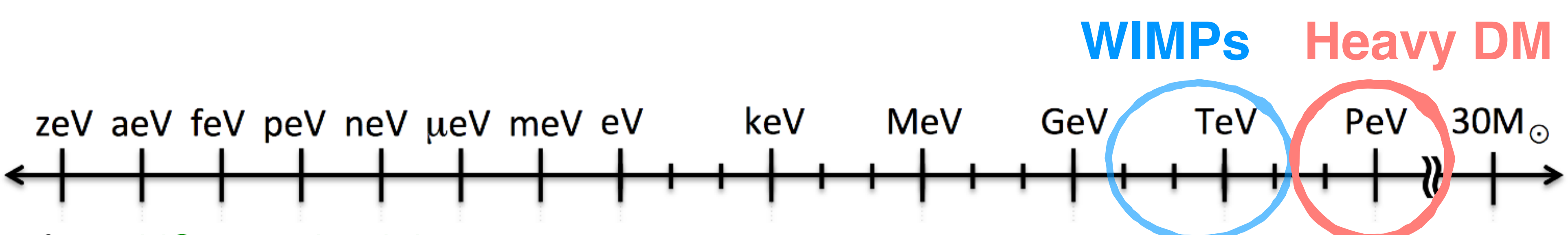
$$M_{\mathrm{DM}} > 10's\ \mathrm{TeV}$$



from US cosmic visions 1707.04591

Dark Matter above WIMP window

$$\boxed{M_{\rm DM} > 10's\ \mathrm{TeV}}$$



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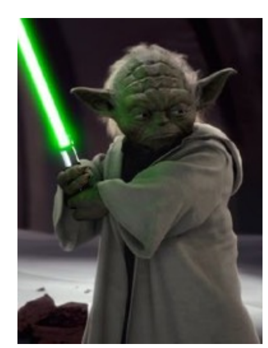
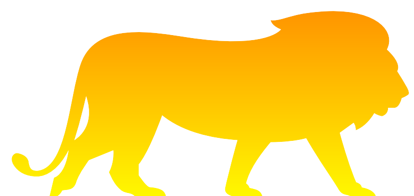


A lot to explore here!

Why Heavy Dark Matter?

Larger Energies

Experimental Access



HIC SUNT LEONES

(& DARK MATTER?)

?

~TeV

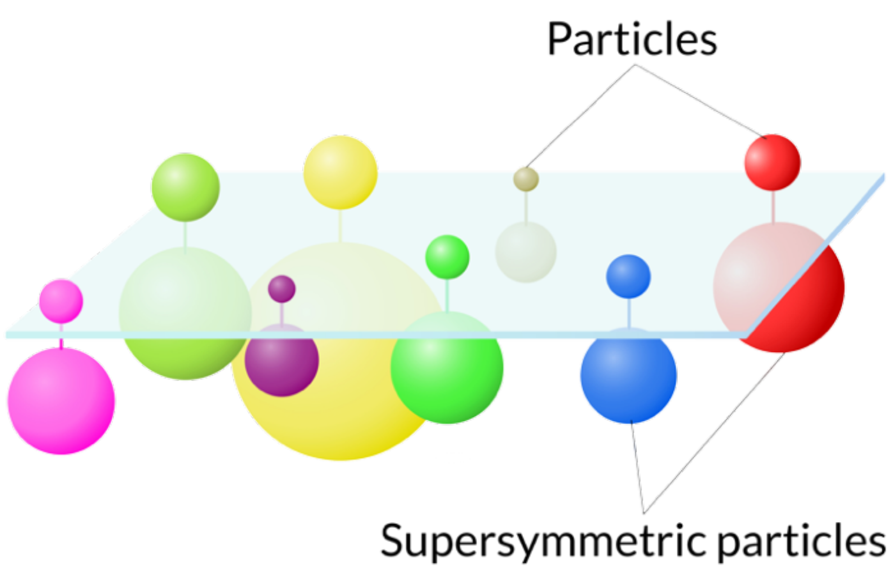
THE STANDARD MODEL

(& NO DARK MATTER)

LHC

...

Example: Heavy DM from SUSY

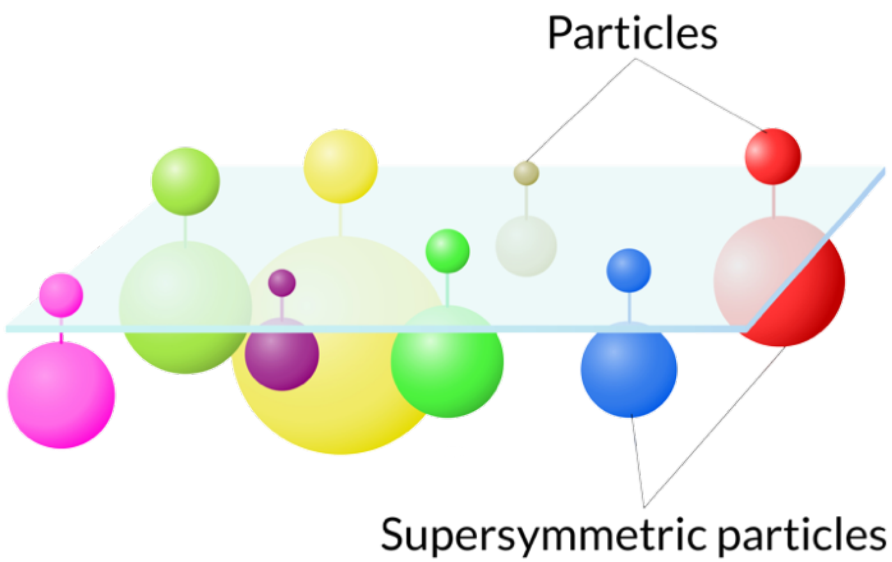


Dimopoulos Giudice Pomarol hep-ph/9607225

DM from messenger or SUSY breaking sectors

must be **>(>) 10 TeV**

Example: Heavy DM from SUSY



Dimopoulos Giudice Pomarol hep-ph/9607225

DM from messenger or SUSY breaking sectors

must be **>(>) 10 TeV**

Spectrum à la gauge mediation

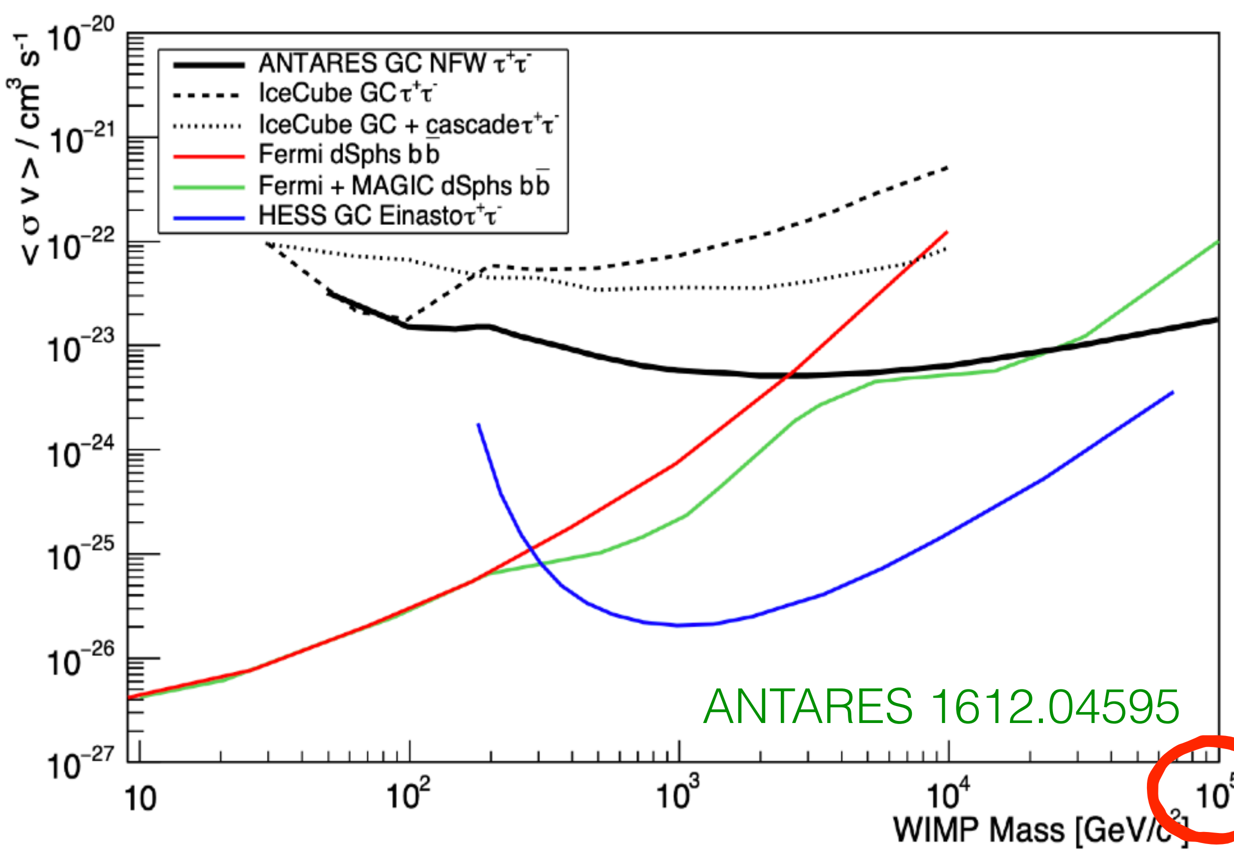
Gravitino DM $$m_{3/2} = F/(\sqrt{3}M_{\rm Pl}) \simeq 2\,{\rm eV} \times F/(100\ {\rm TeV})^2$$

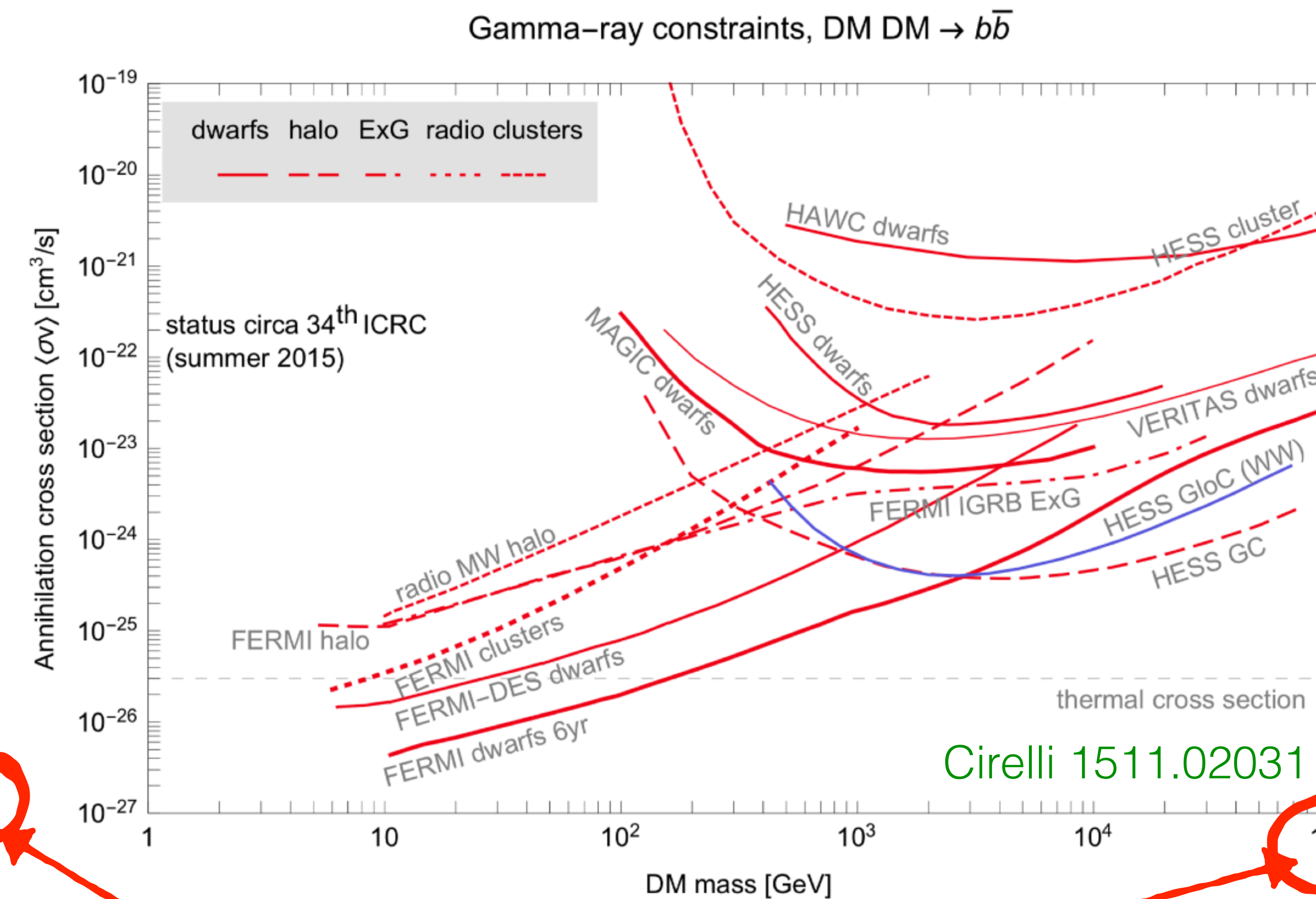
🤔 Cannot make observed DM for these values of parameter

(motivated by naturalness of Fermi scale)

🙂 Respects all bounds from cosmology and collider Osato+ 1601.07386,…

Telescopes have unique opportunity!

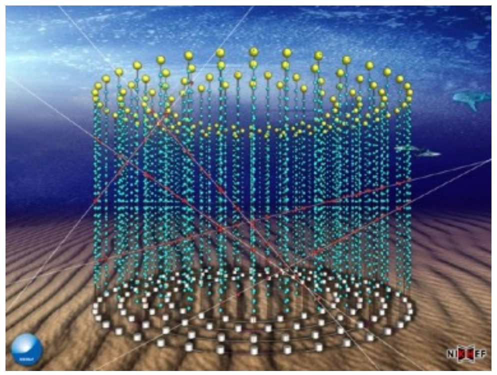




…but do not test DM annihilations beyond 100 TeV

Why not beyond 10-100 TeV?

More: 2020's race to Higher Energies



KM3NeT ν

CTA γ

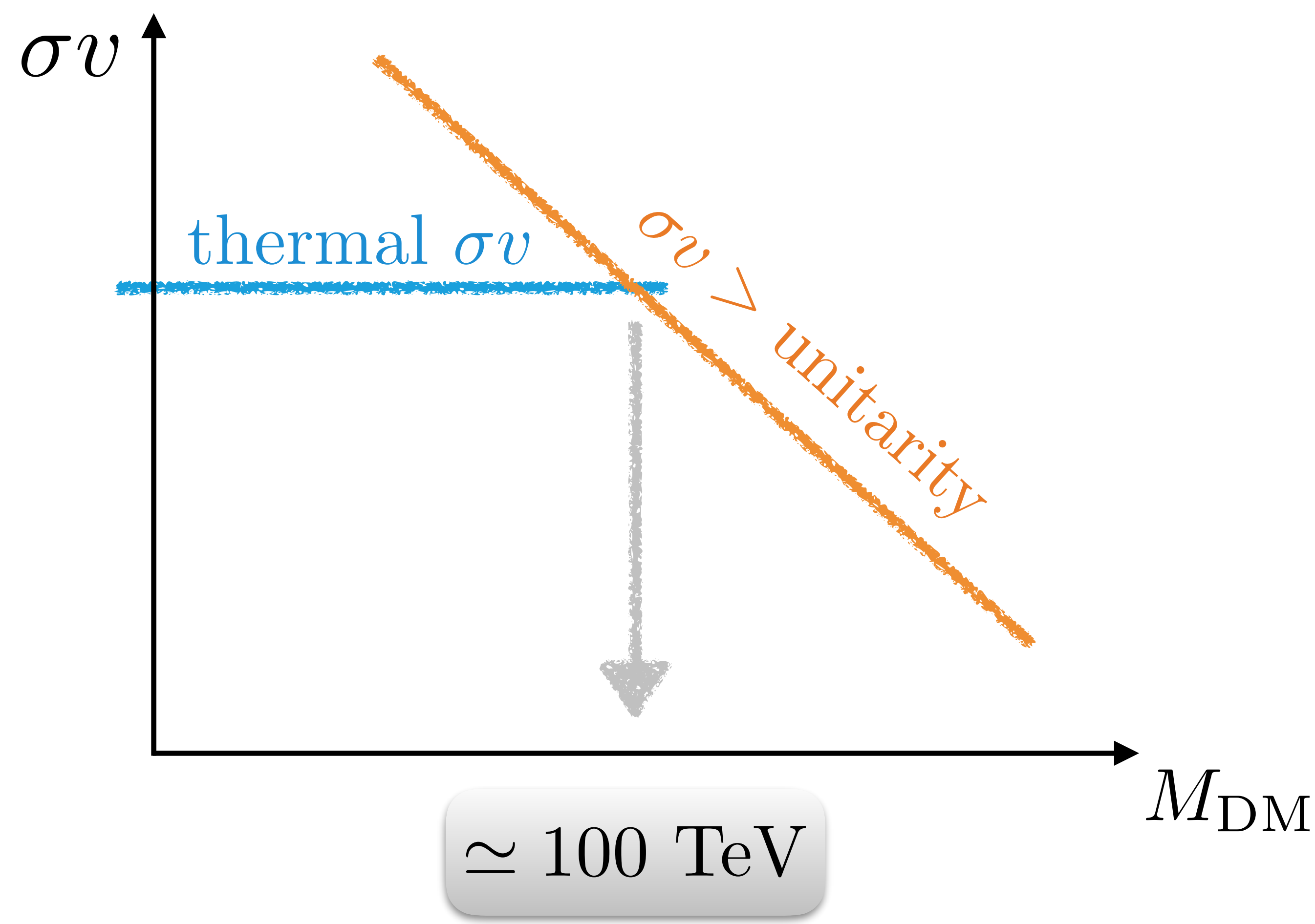
LHAASO γ

....

The Unitarity Bound

Griest Kamionkowski PRL 1990

$$SS^\dagger = 1 \quad \Rightarrow \quad \sigma^j v_{\rm rel} \leq \frac{4\pi(2j+1)}{v_{\rm rel}} \boxed{\frac{1}{M_{\rm DM}^2}}$$



Beyond the Unitarity Bound with

-> Early Matter Domination

-> Early Vacuum Energy Domination

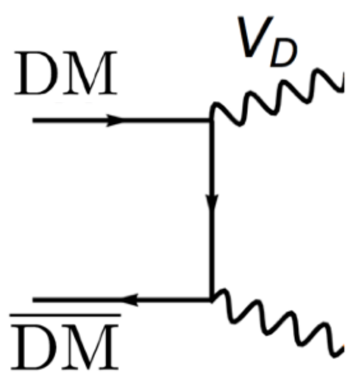
Beyond the Unitarity Bound with

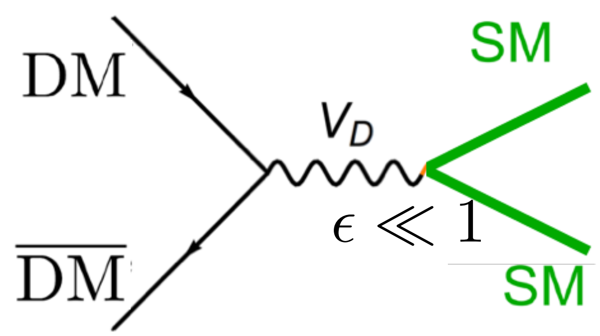
-> Early Matter Domination

Secluded Dark Matter

$$\mathcal{L} \sim g_{\rm D} V_{\rm D} \left(\overline{\rm DM}\,{\rm DM} + \epsilon\,\overline{\rm SM}\,{\rm SM} \right)$$

Thermal production possible with tiny interactions with SM Pospelov+ 0711.4866,...





~ avoid bounds from direct detection & LHC

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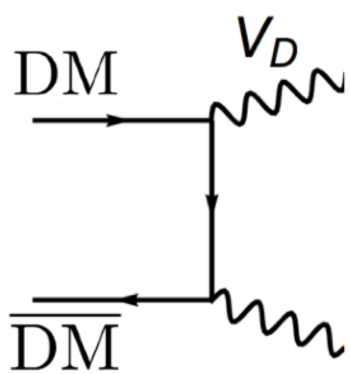
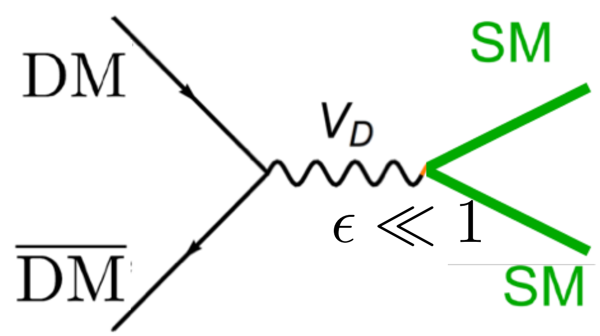




~ avoid bounds from direct detection & LHC

Explicit Example: $\mathcal{L} = \bar{X}(i\hat{D} - M_{\rm DM})X - \frac{1}{4} F_{D\,\mu\nu} F_D^{\mu\nu} - \frac{\epsilon}{2c_w} F_{D\,\mu\nu} B^{\mu\nu}$

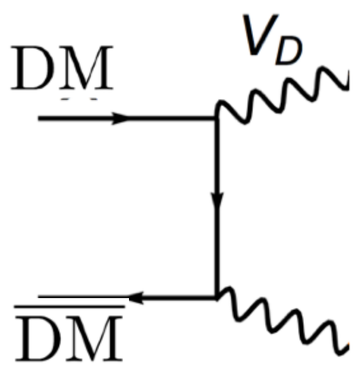
$X = {\rm DM}$ charged under a dark U(1)

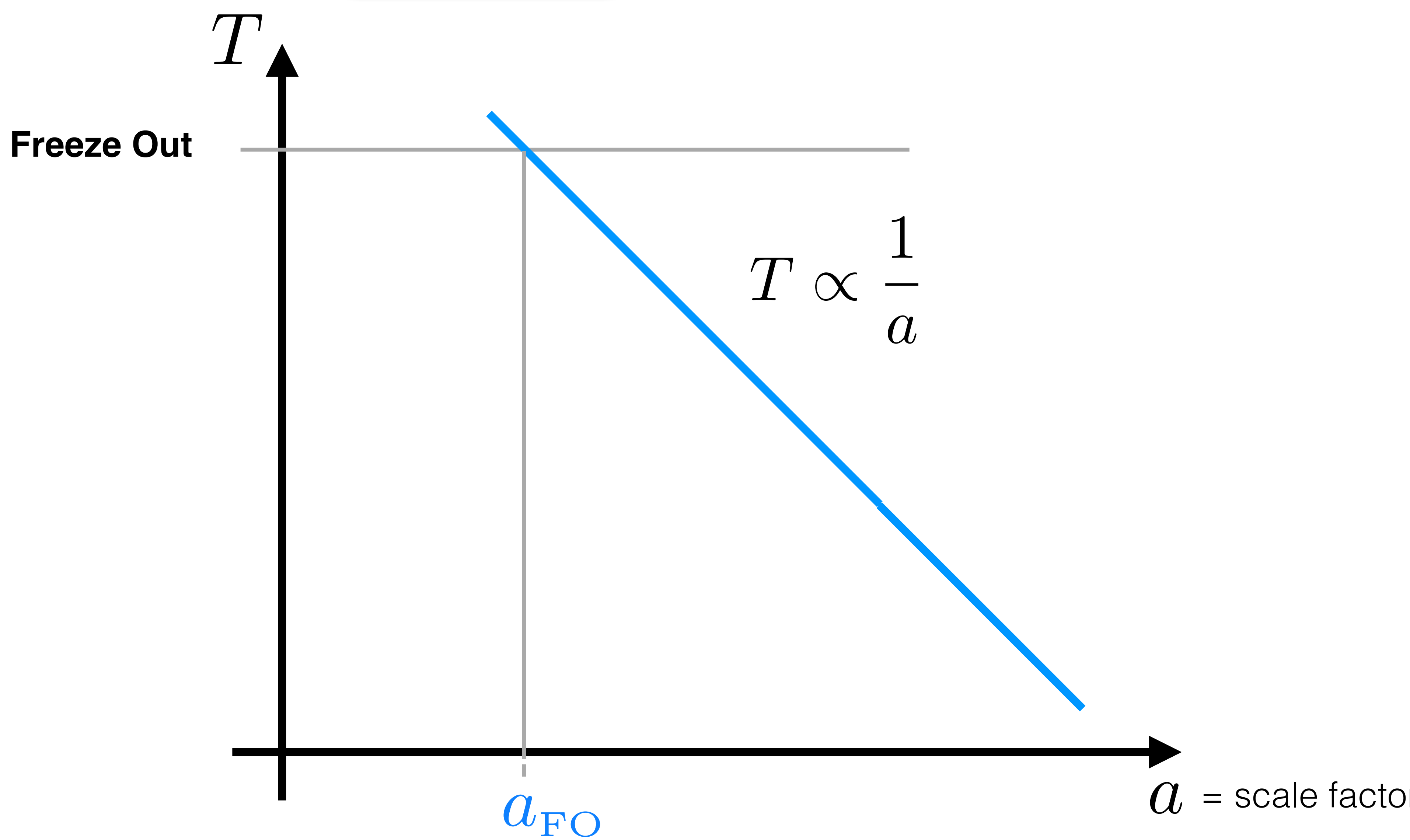
E.g. from heavy new particles charged under both U(1)'s

Secluded DM & the Unitarity Bound

Berlin+1602.08490
Cirelli+1612.07295

$$\Omega_{\mathrm{DM}} \propto \frac{1}{\sigma v}$$





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Berlin+1602.08490
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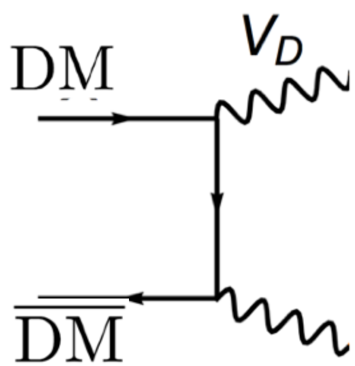
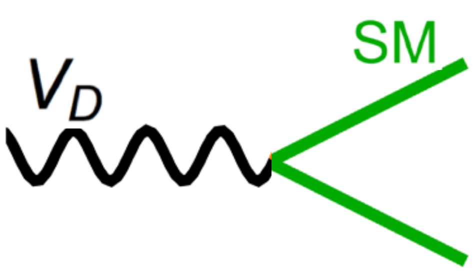


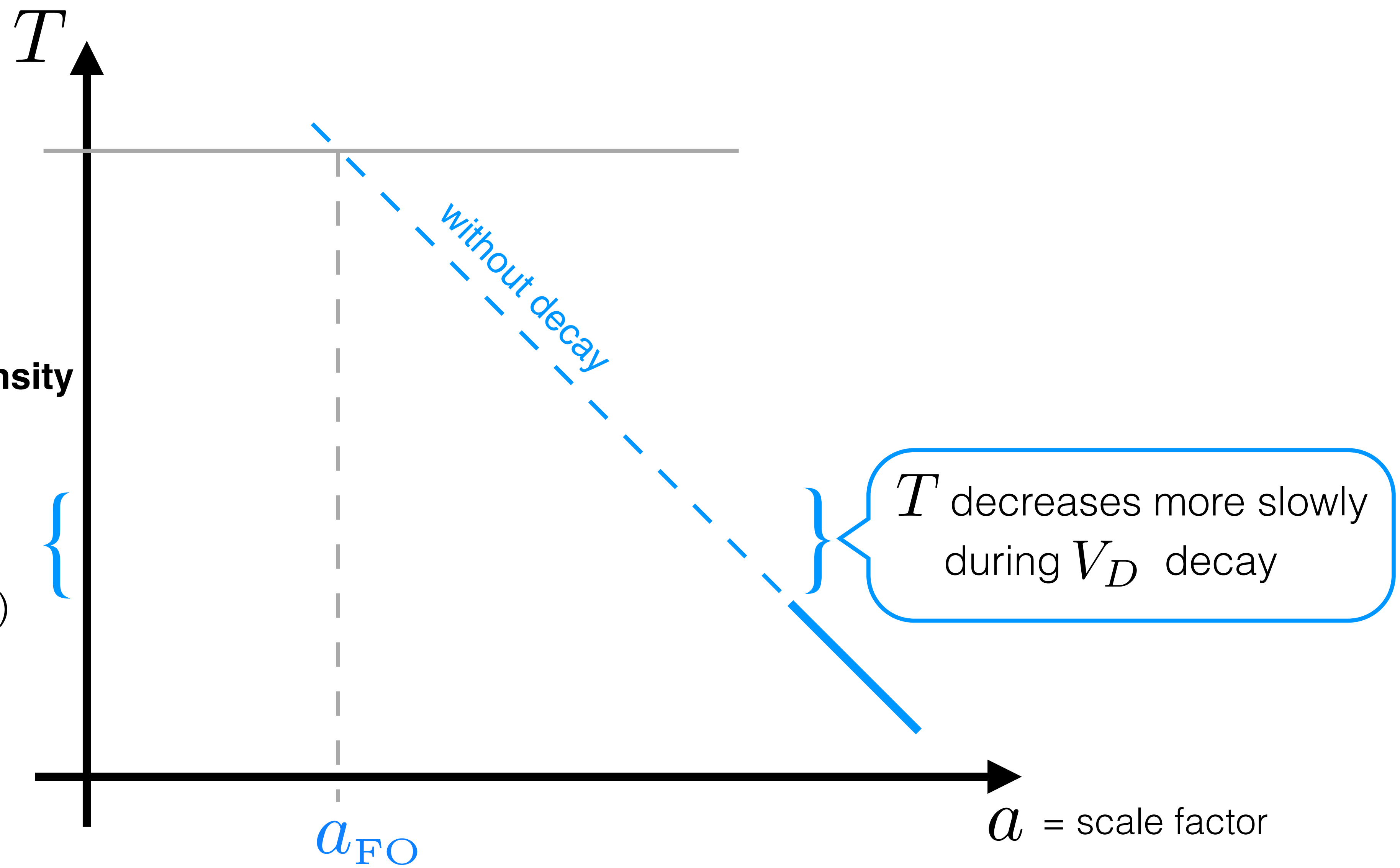
$\epsilon \lll 1$ V_D's dominate energy density



V_D's decay

(before BBN)

Freeze Out



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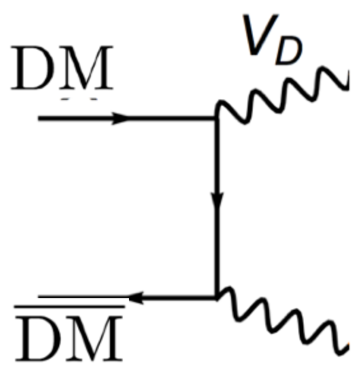
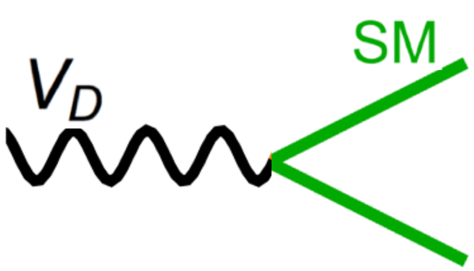


Freeze Out

$\epsilon \lll 1$ **V_D's dominate energy density**



V_D's decay
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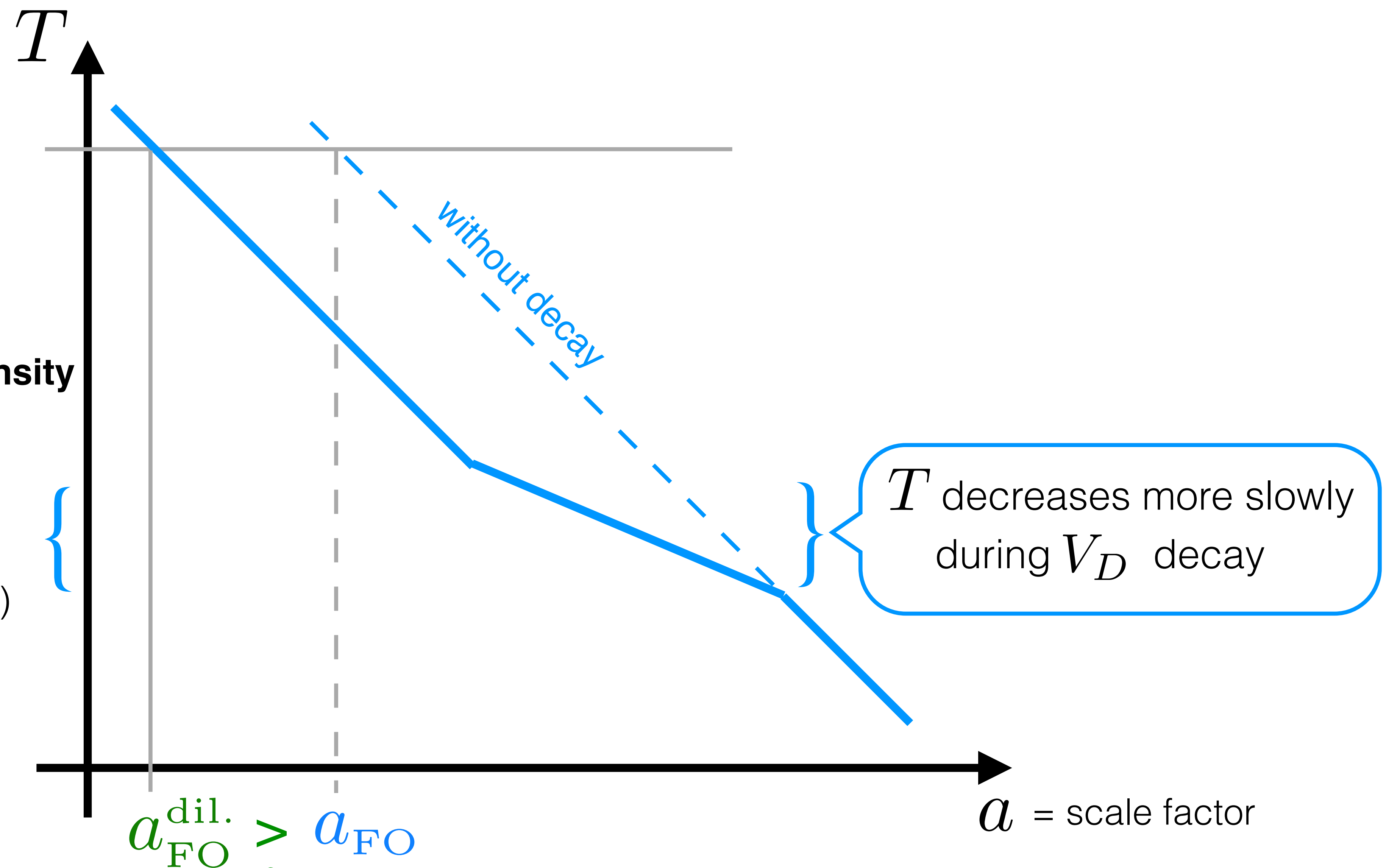


The same amount of relic DM is later more <u>diluted</u>

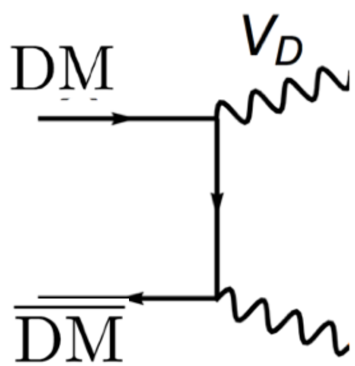
Secluded DM & the Unitarity Bound

Berlin+1602.08490
Cirelli+1612.07295

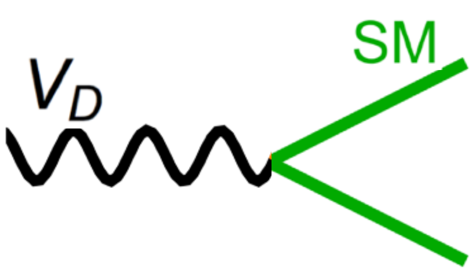
$$\Omega_{\rm DM} \propto \frac{1}{\sigma v} \frac{s_{\rm before}}{s_{\rm after}}$$

1/dilution factor
Scherrer Turner 1985

Smaller $\langle \sigma v \rangle_{\rm fo}$

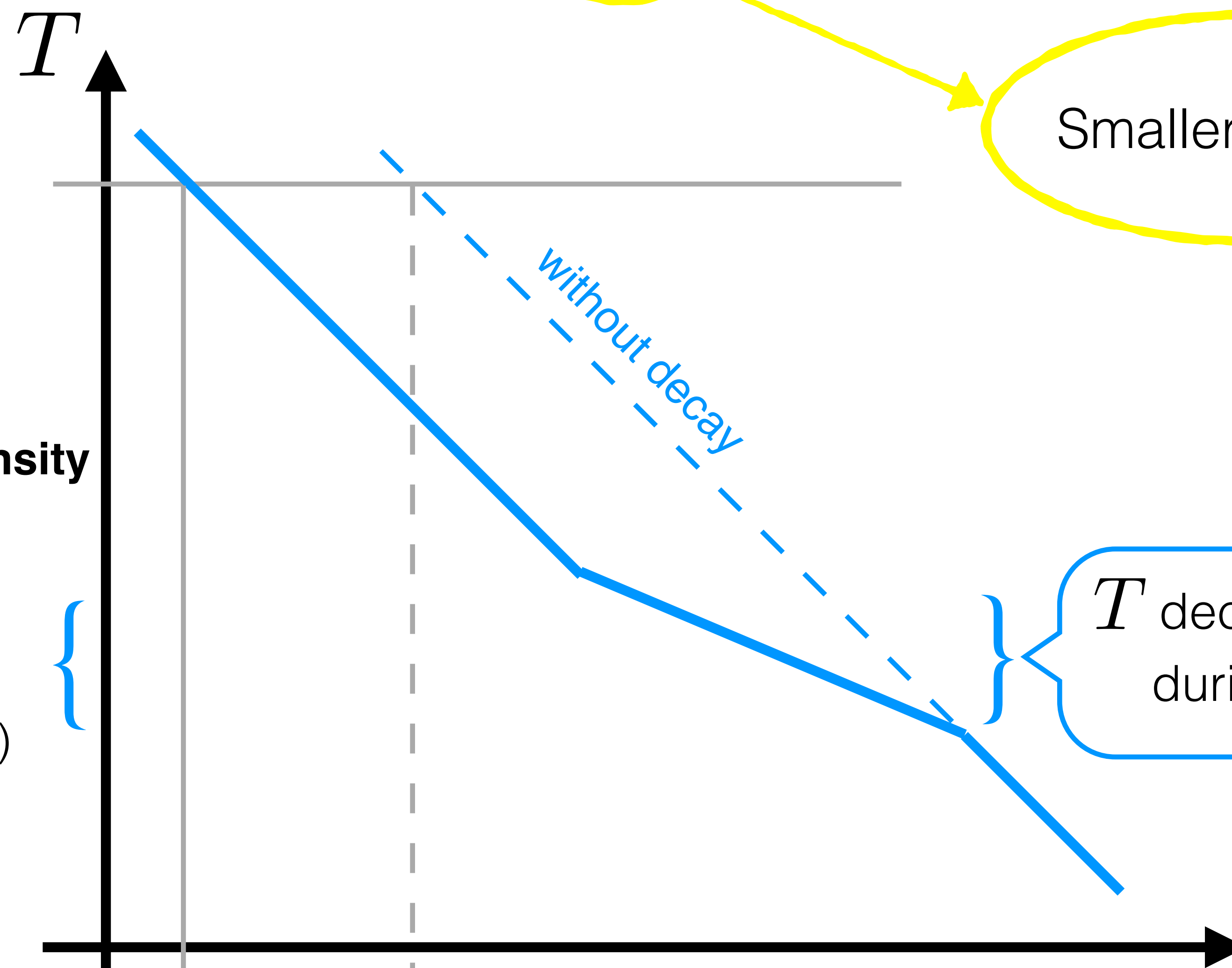


$\epsilon \lll 1$ V_D's dominate energy density



V_D's decay
(before BBN)

Freeze Out



T decreases more slowly during V_D decay

$a_{\rm FO}^{\rm dil.} > a_{\rm FO}$

a = scale factor

The same amount of relic DM is later more <u>diluted</u>

Secluded DM & the Unitarity Bound

Berlin+1602.08490
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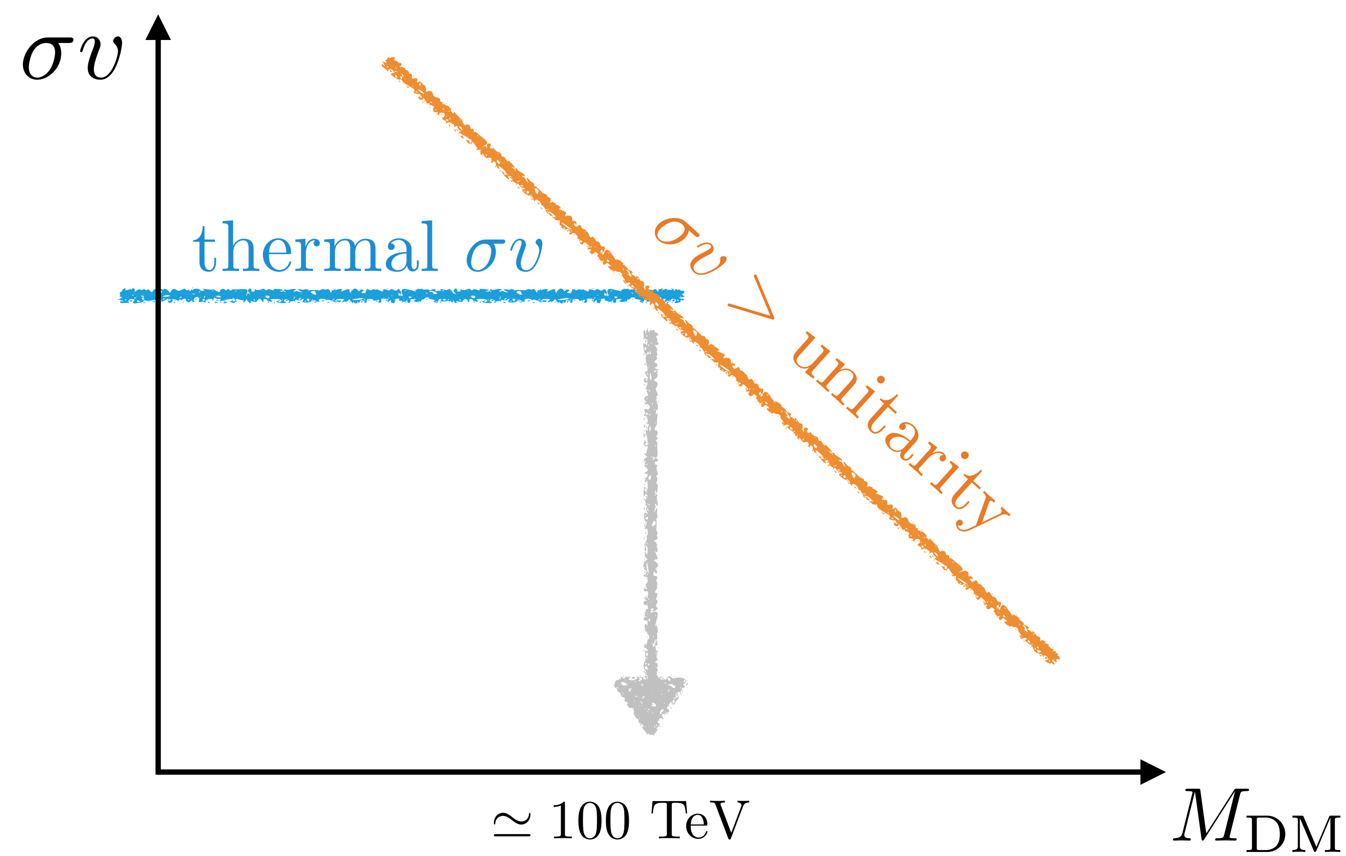
Scherrer Turner 1985

Smaller $\langle\sigma v\rangle_{\rm fo}$



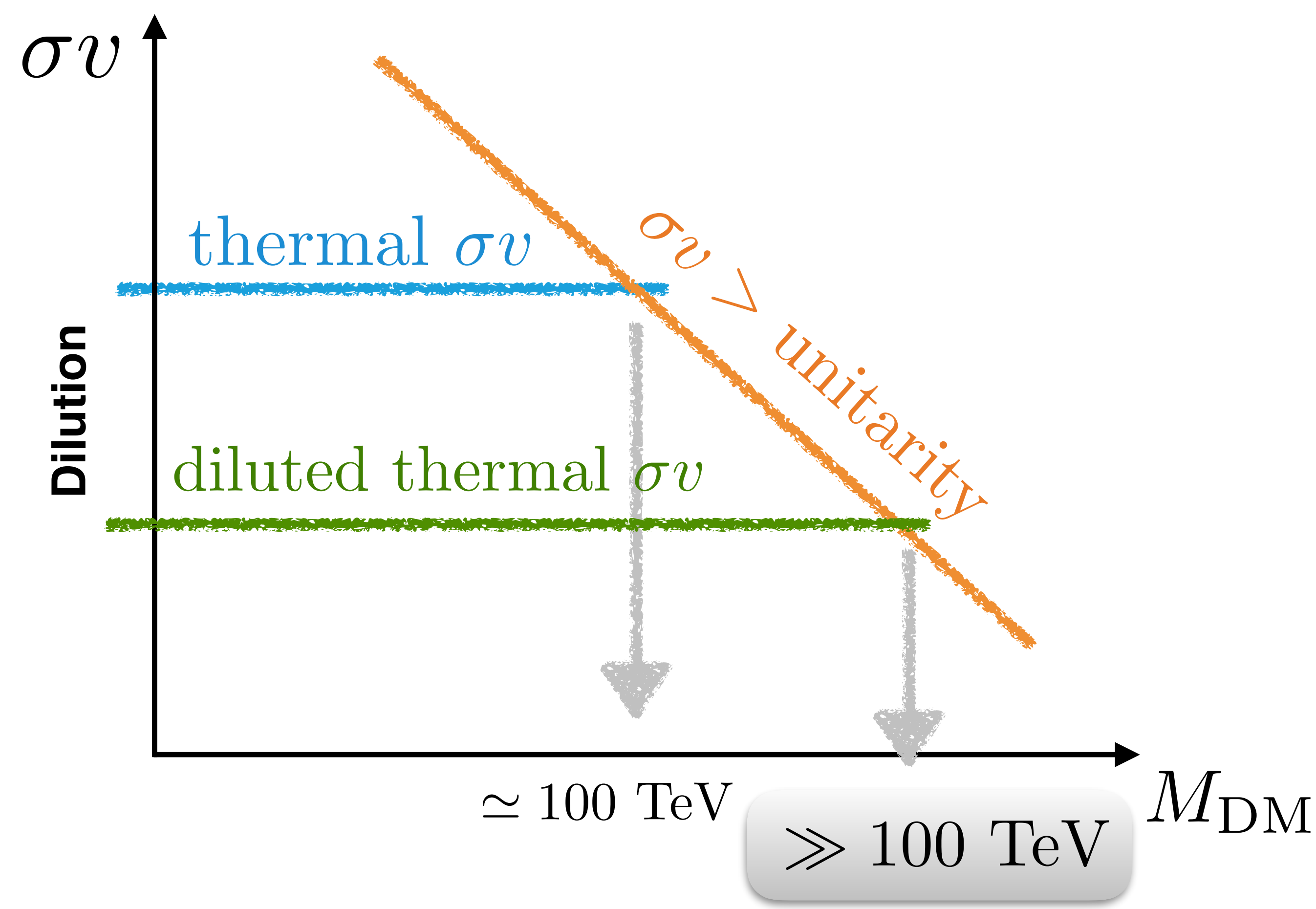
Secluded DM & the Unitarity Bound

Berlin+1602.08490
Cirelli+1612.07295

$$\Omega_{\rm DM} \propto \frac{1}{\sigma v} \frac{s_{\rm before}}{s_{\rm after}}$$

1/dilution factor
Scherrer Turner 1985

Smaller $\langle \sigma v \rangle_{\rm fo}$



*not specific of secluded DM, works for <u>any early matter domination</u>

Experimental Tests

Tiny portal with the SM + Heavy $\longrightarrow$ Direct Detection & Collider put no constraints

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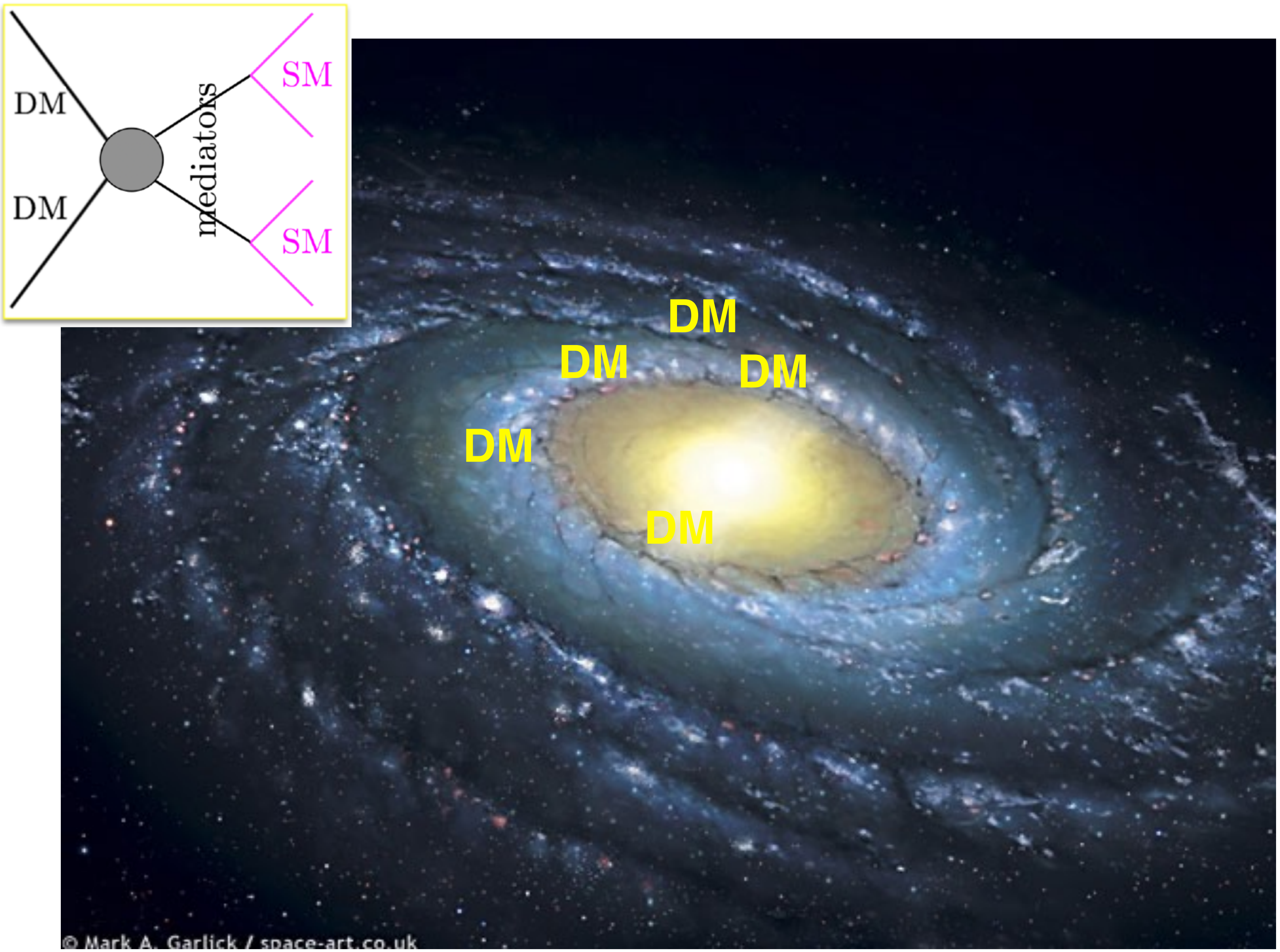

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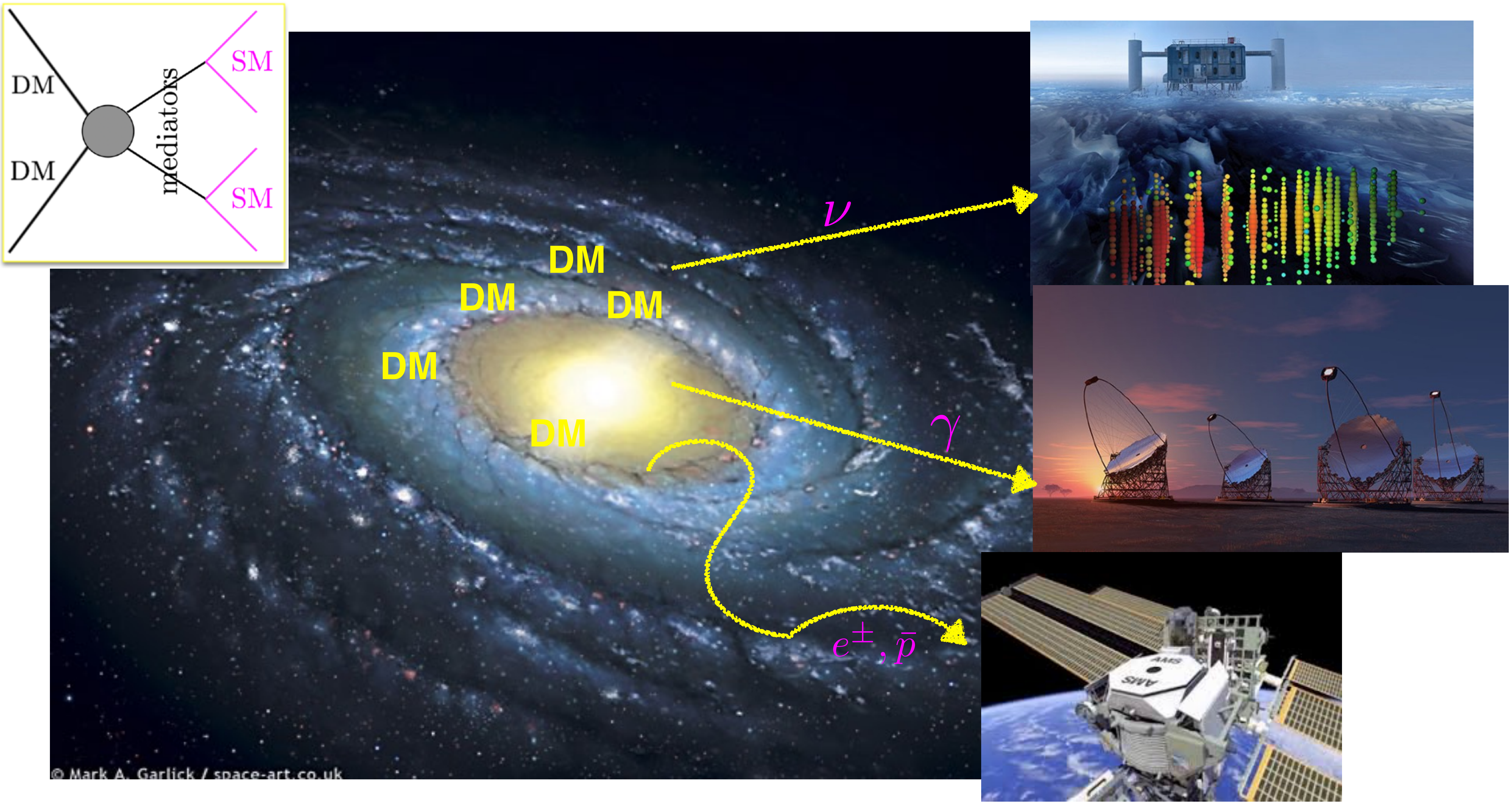
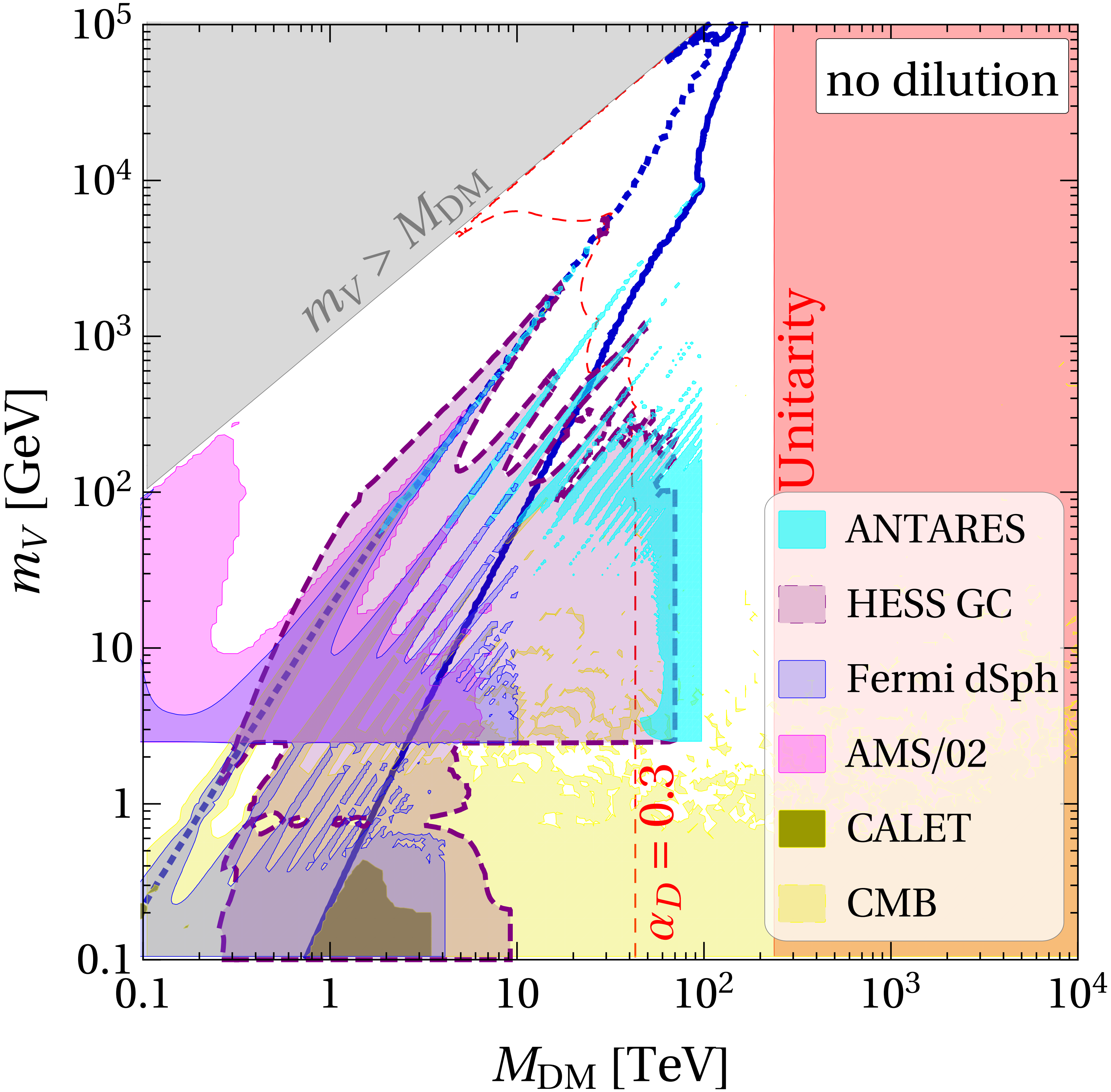


Signals of O(100) TeV DM

Cirelli Gouttenoire Petraki FS 1811.03608



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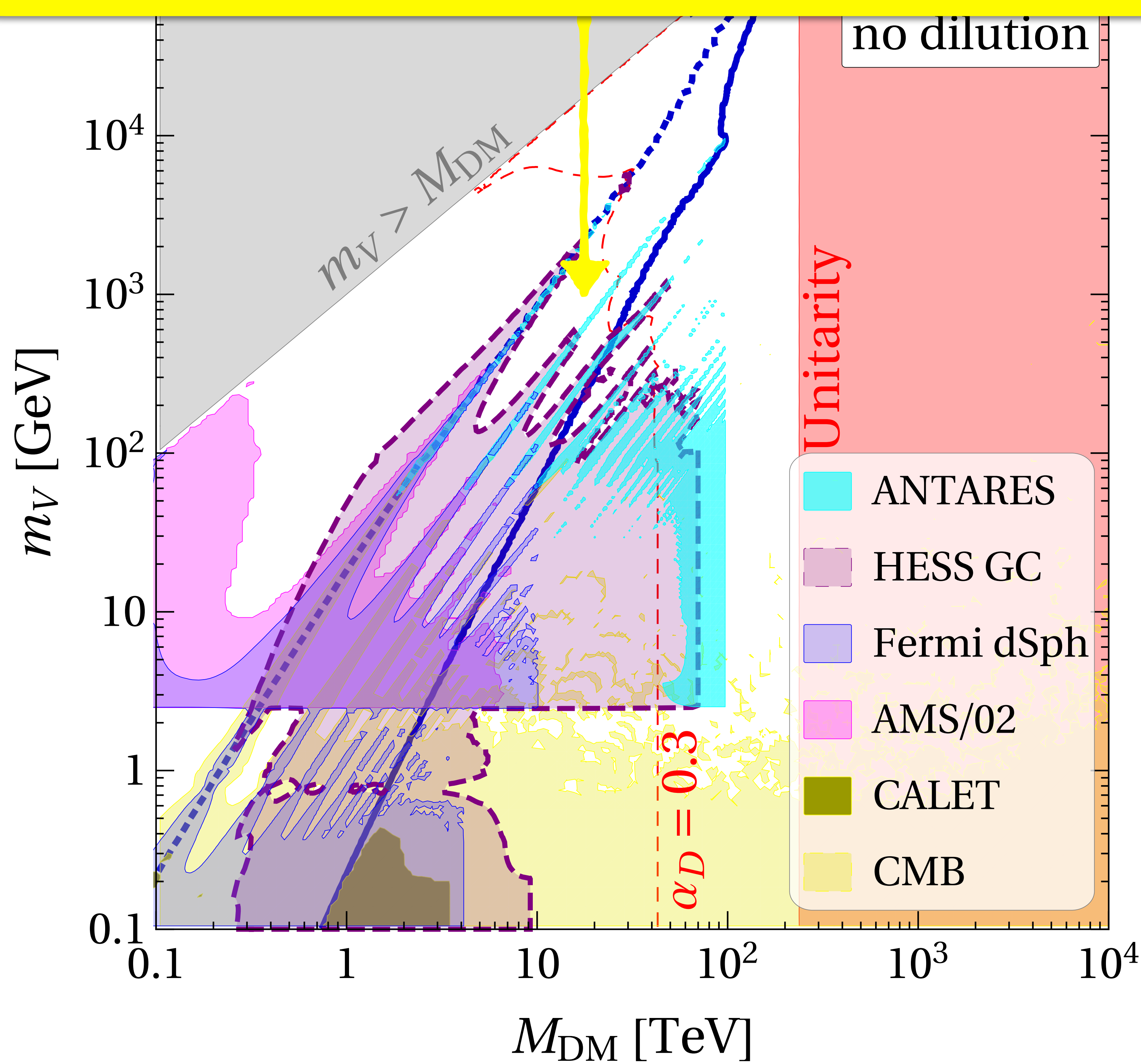
Multimessanger hunt for **Heavy DM** is possible!



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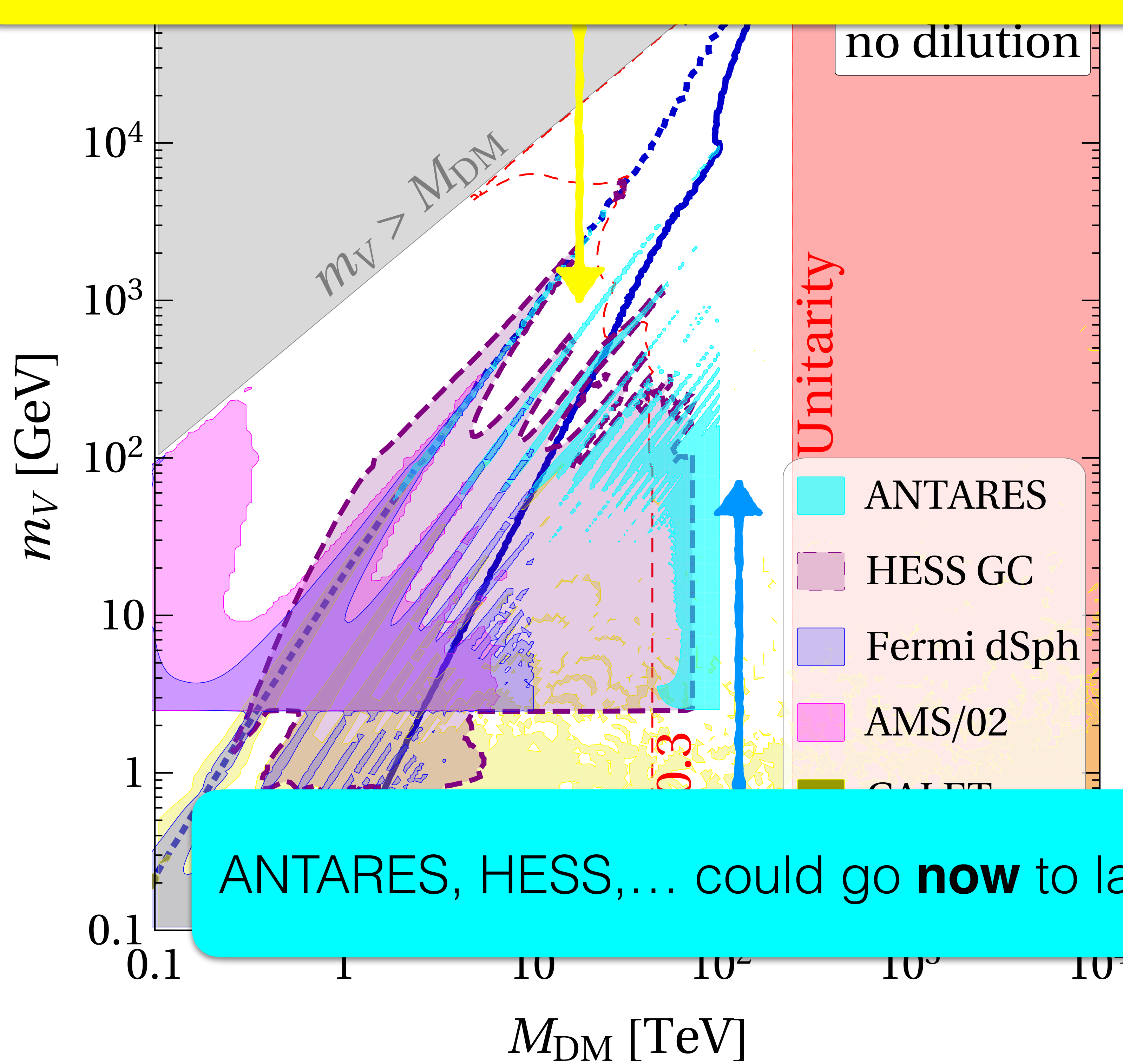
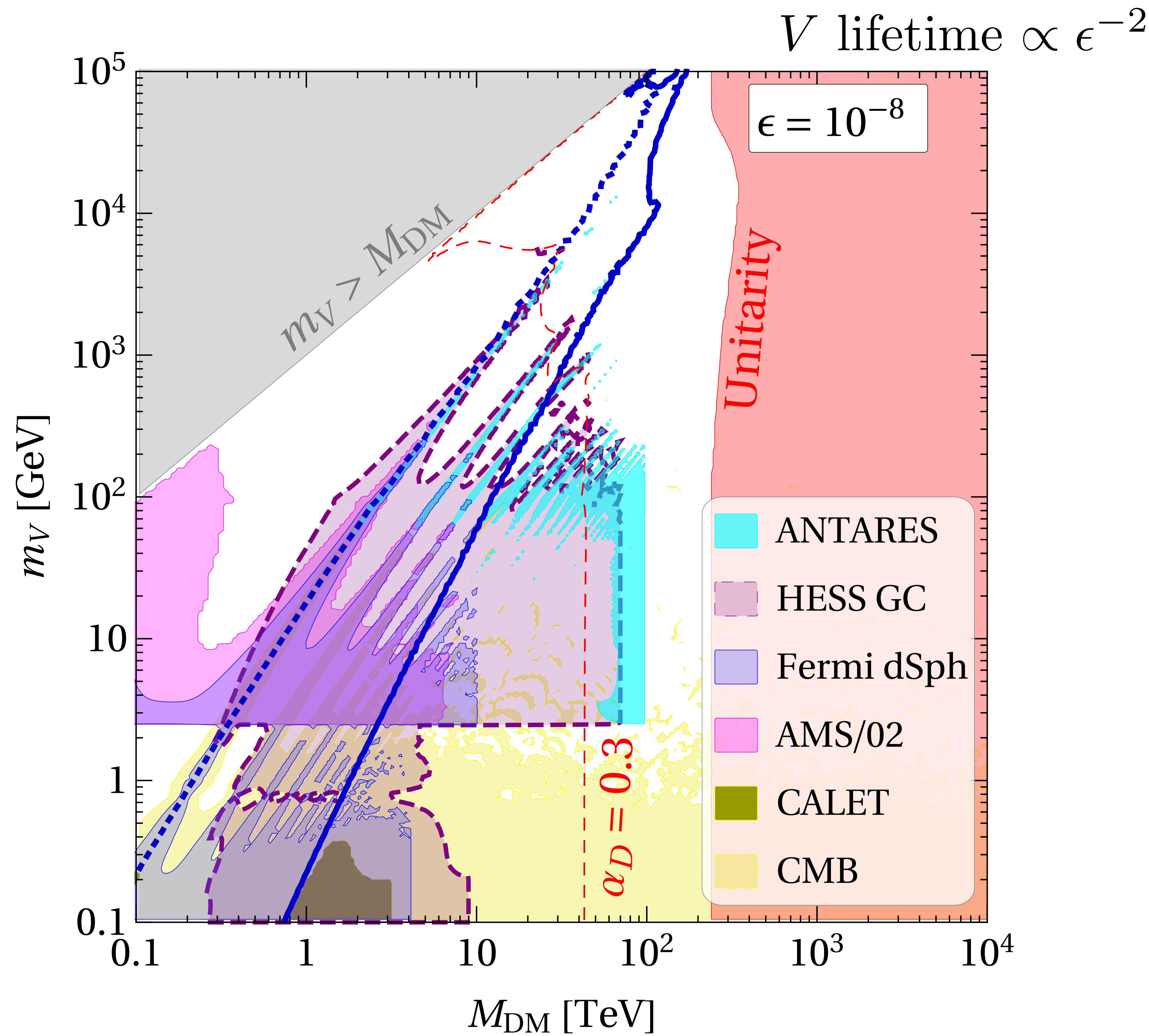


ANTARES, HESS,… could go **now** to larger DM mass

Signals of O(100) TeV DM

Cirelli Gouttenoire Petraki FS 1811.03608



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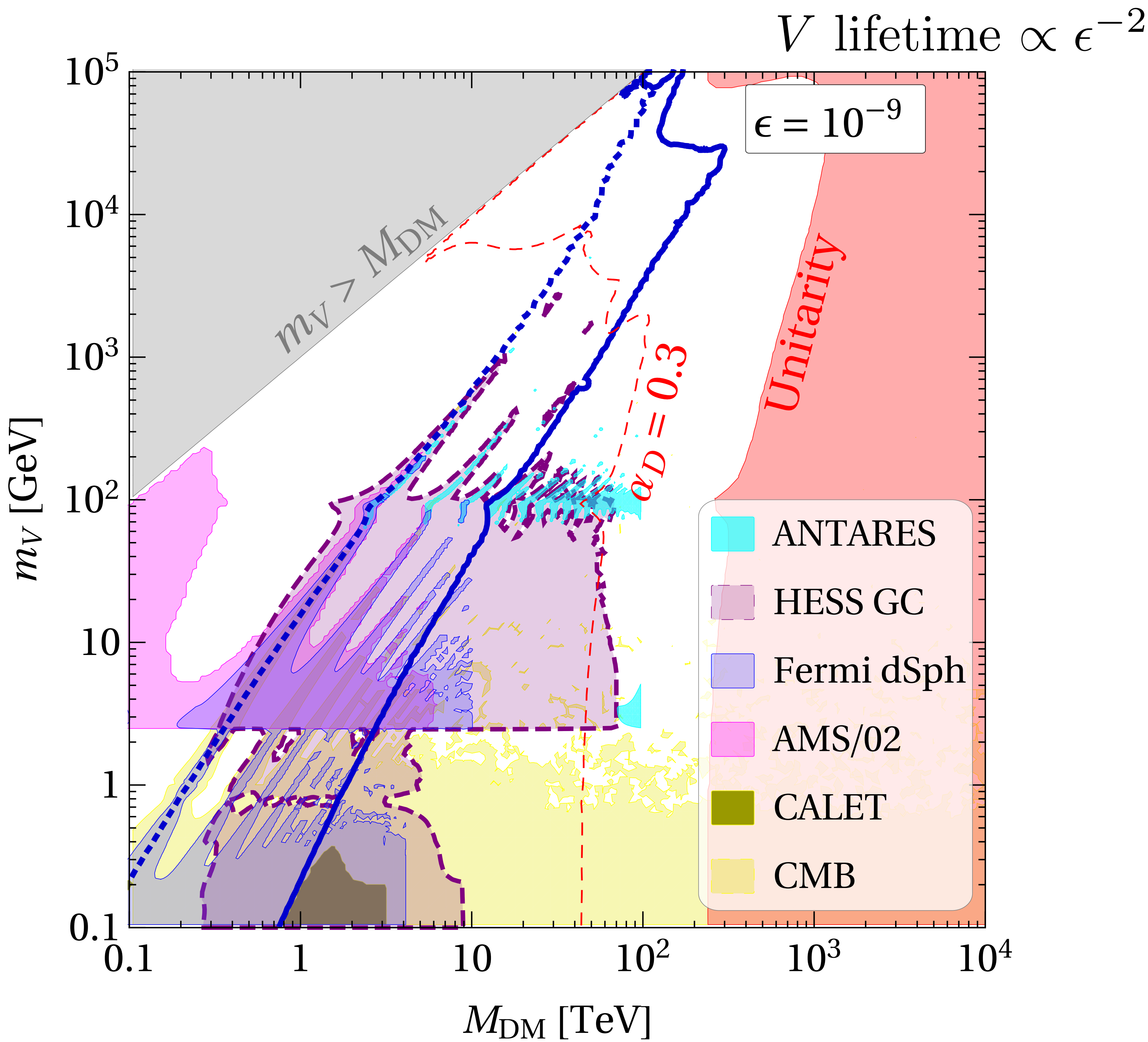

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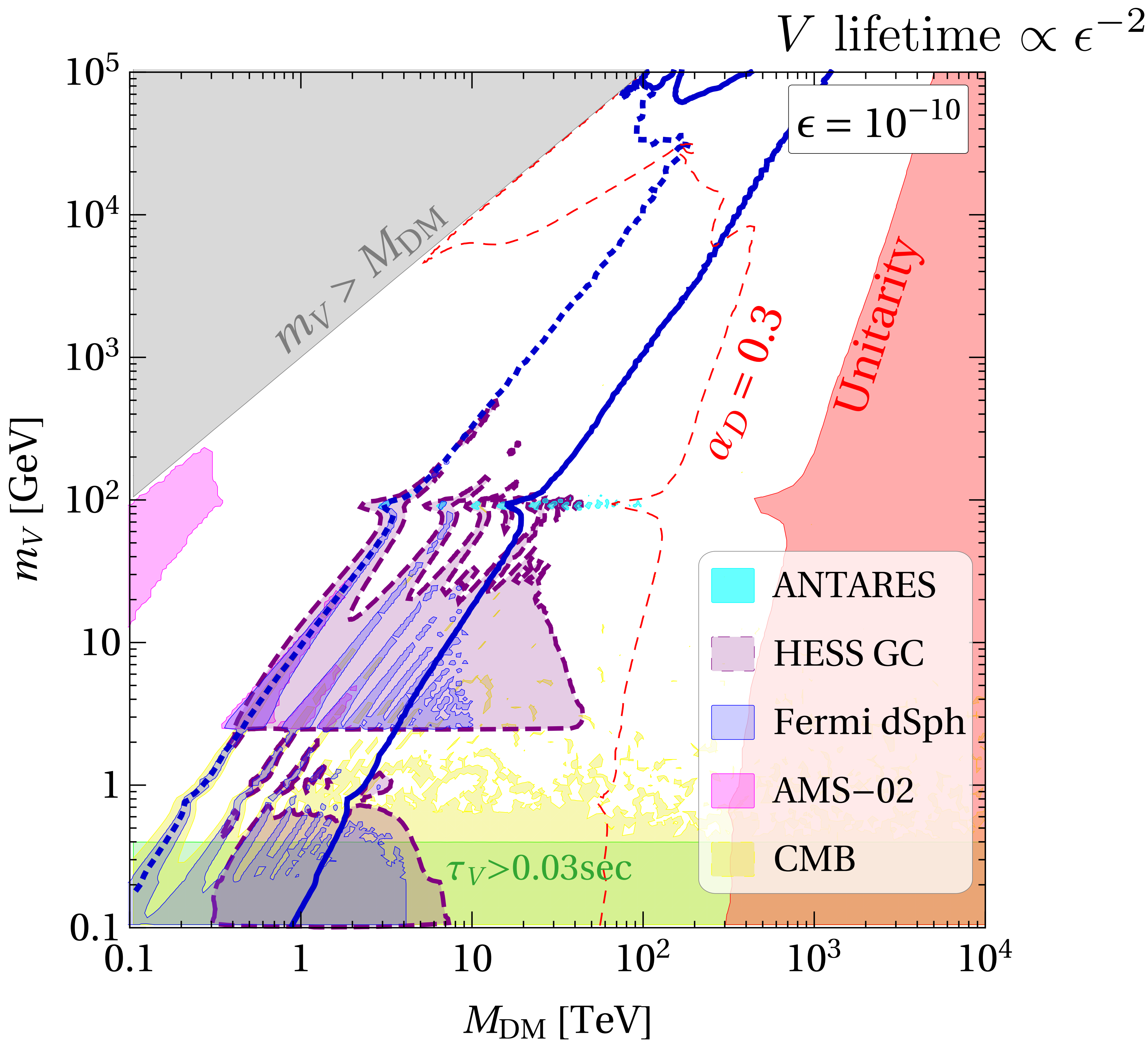

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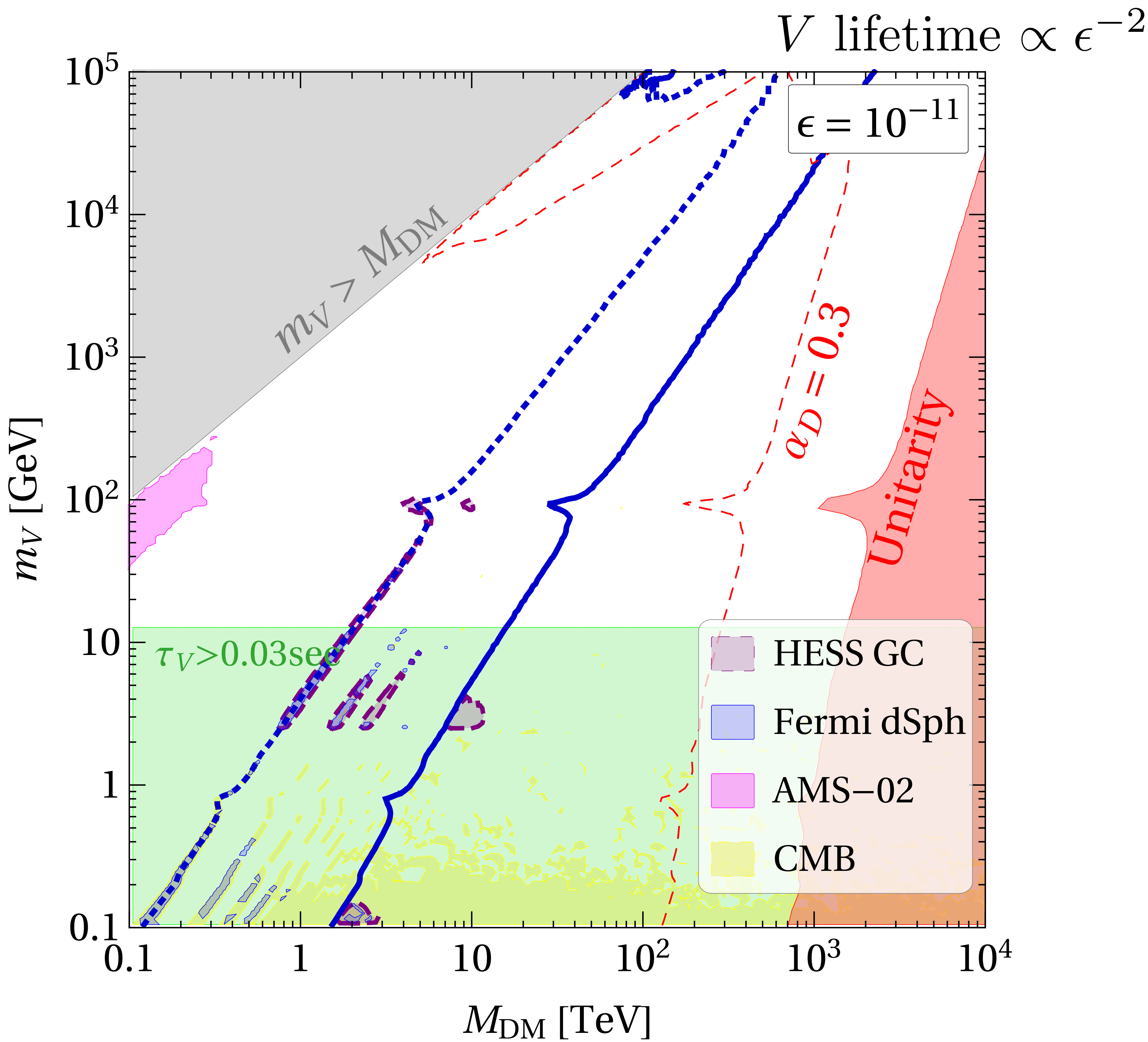

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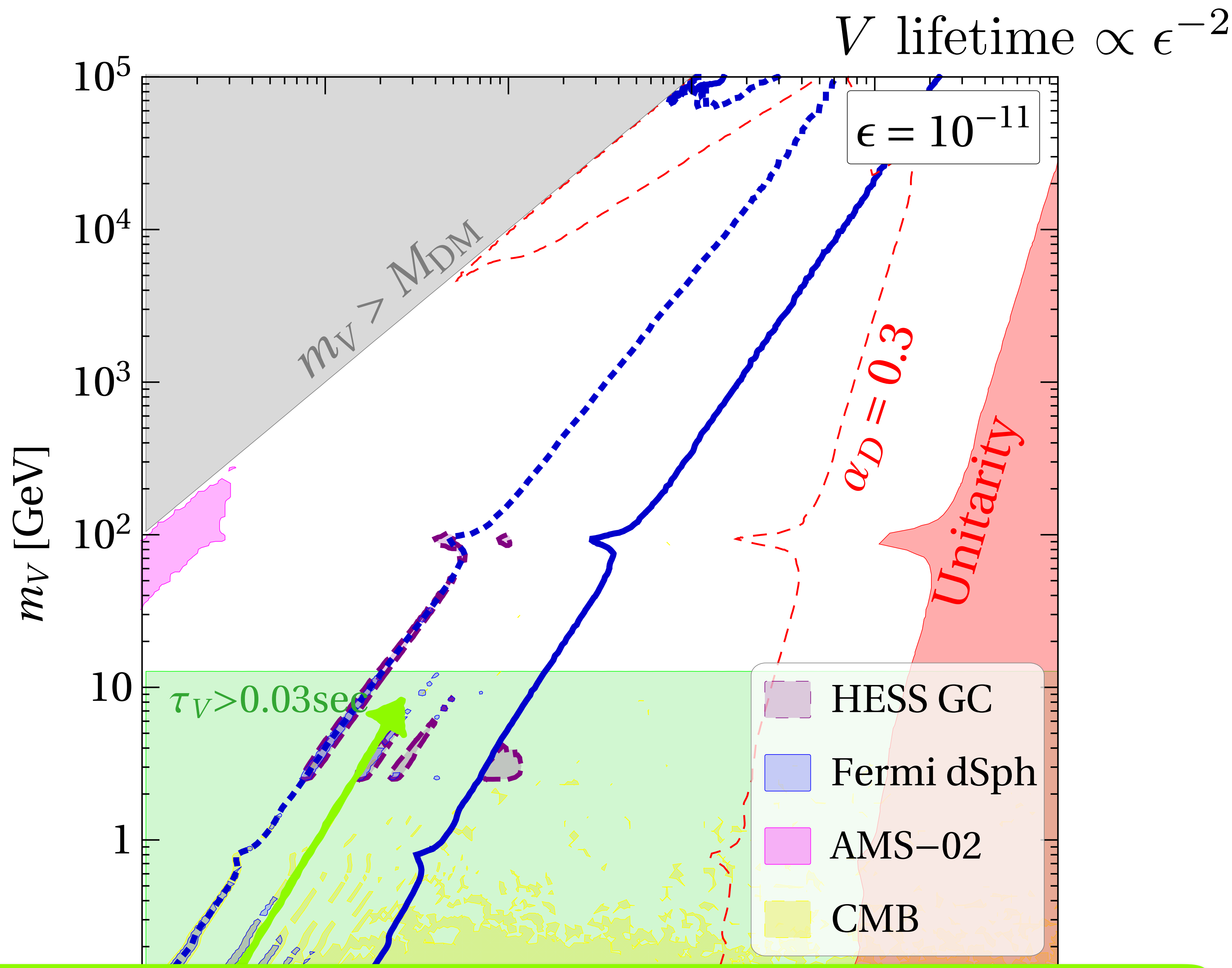

Dilution inhibits signals, but **BBN** closes quickly available space

Signals of O(100) TeV DM

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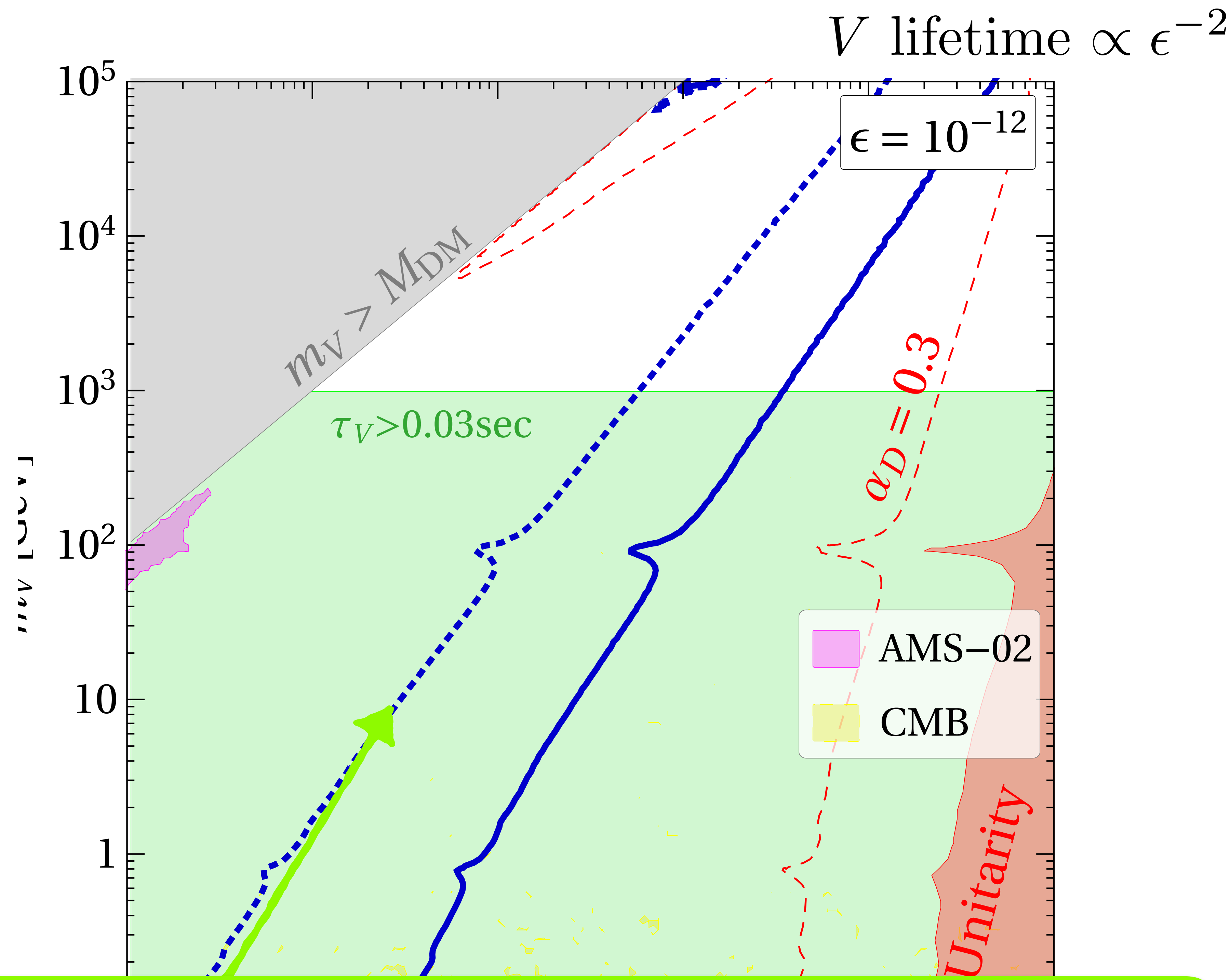


Dilution inhibits signals, but **BBN** closes quickly available space

Beyond the Unitarity Bound with

-> Early Matter Domination

Heavy Dark Matter is testable!

Lot still to do: connection with UV, DM structures, collider tests…

-> Early Vacuum Energy Domination

Beyond the Unitarity Bound with

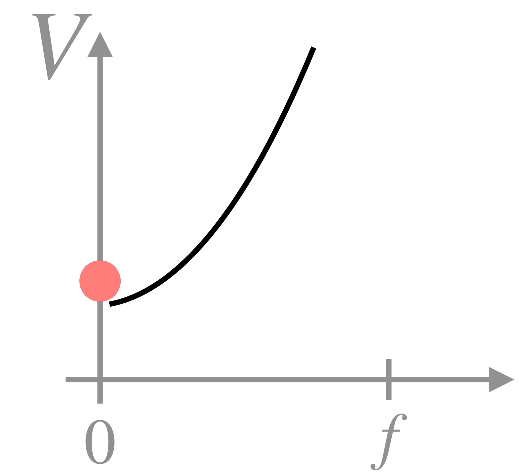
-> Early Vacuum Energy Domination

mostly based on Baldes, Gouttenoire, FS, Servant, to appear

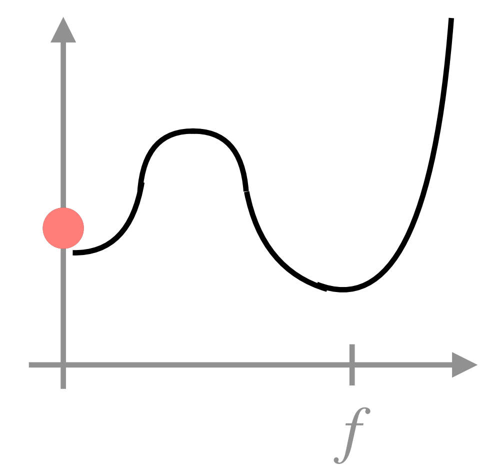
Early Universe & Confining Sectors

T

System trapped in false minimum



$m_* = g_* f$ Transition to Deeper Vacuum ?



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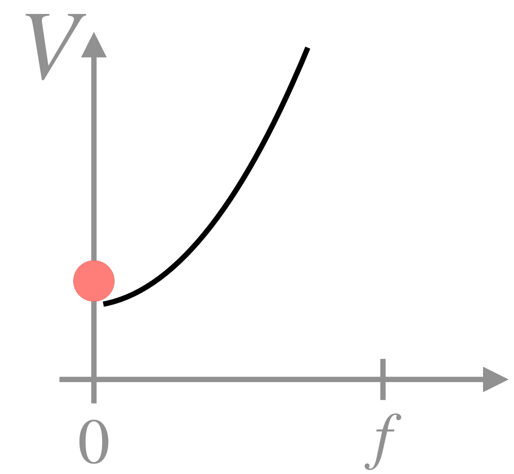

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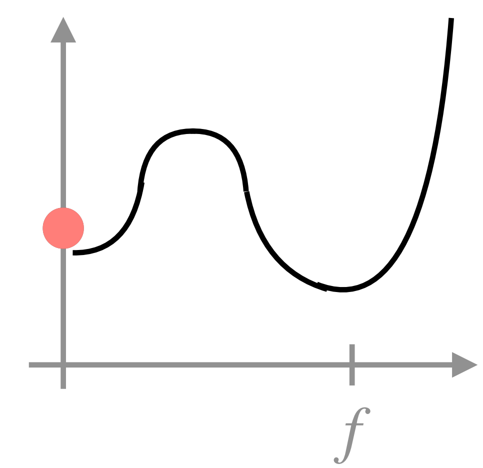
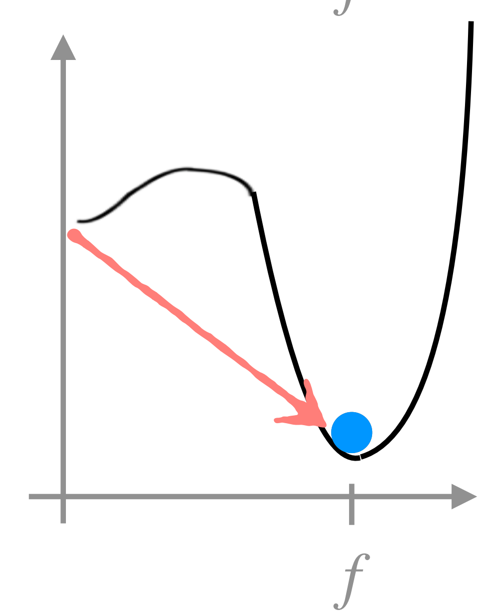


$T_{\rm nuc} \ll m_*$ SUPERCOOLING

Phase Transition happens later

if nearly flat potential in 0



Happens in Warped Extra Dimensions & in Confining Theories

Why a New Confining Sector?

Dark Matter

Antipin Redi Strumia Vigiani 1503.08749, …

EW hierarchy problem

Agashe Contino Pomarol hep-ph/0412089, …

Barbieri+ 1501.07803, Low Tesi Wang 1501.07890, …

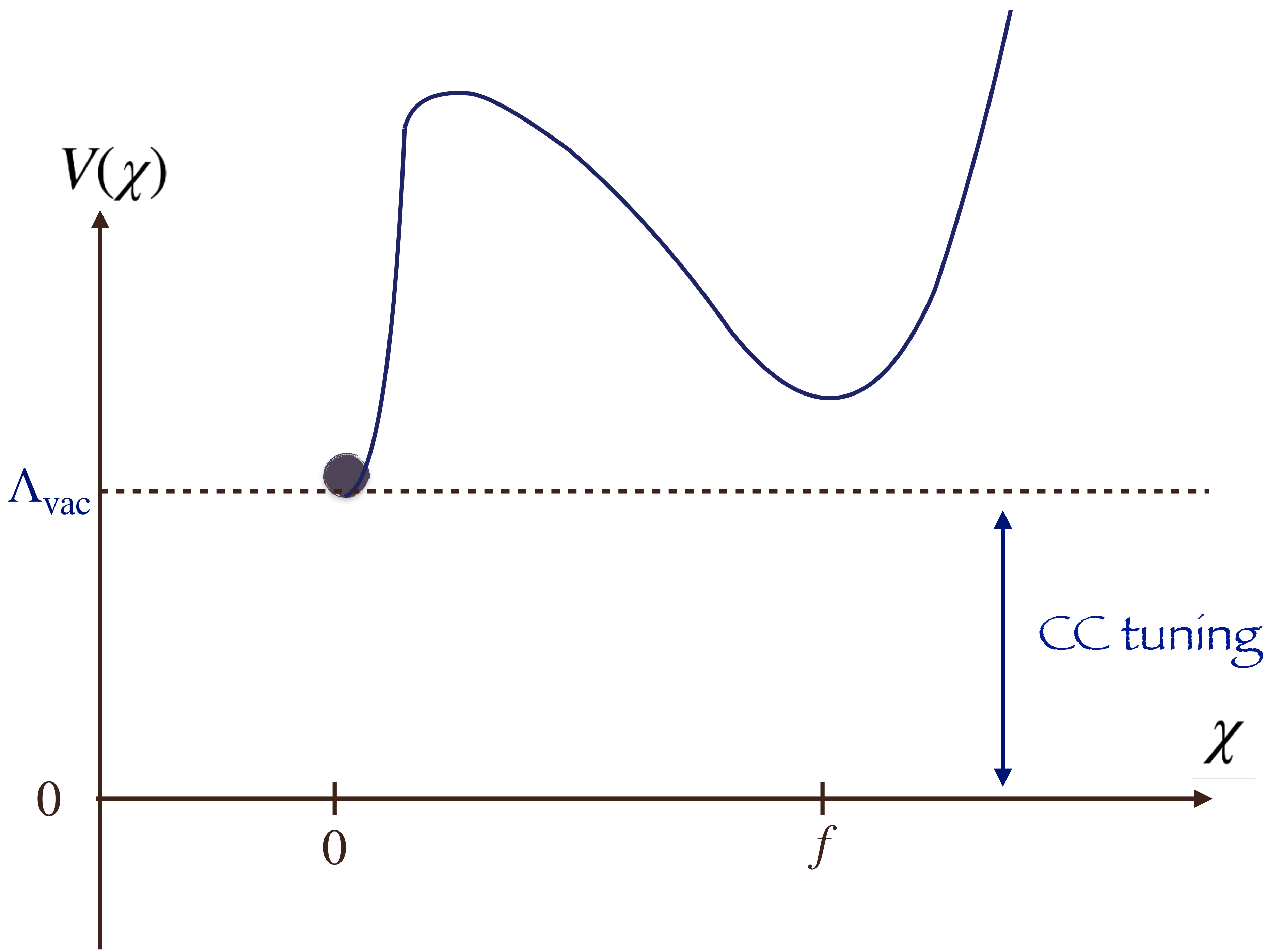
SM Flavor

Kaplan 1991,…

…& many more

animation by Yann Gouttenoire

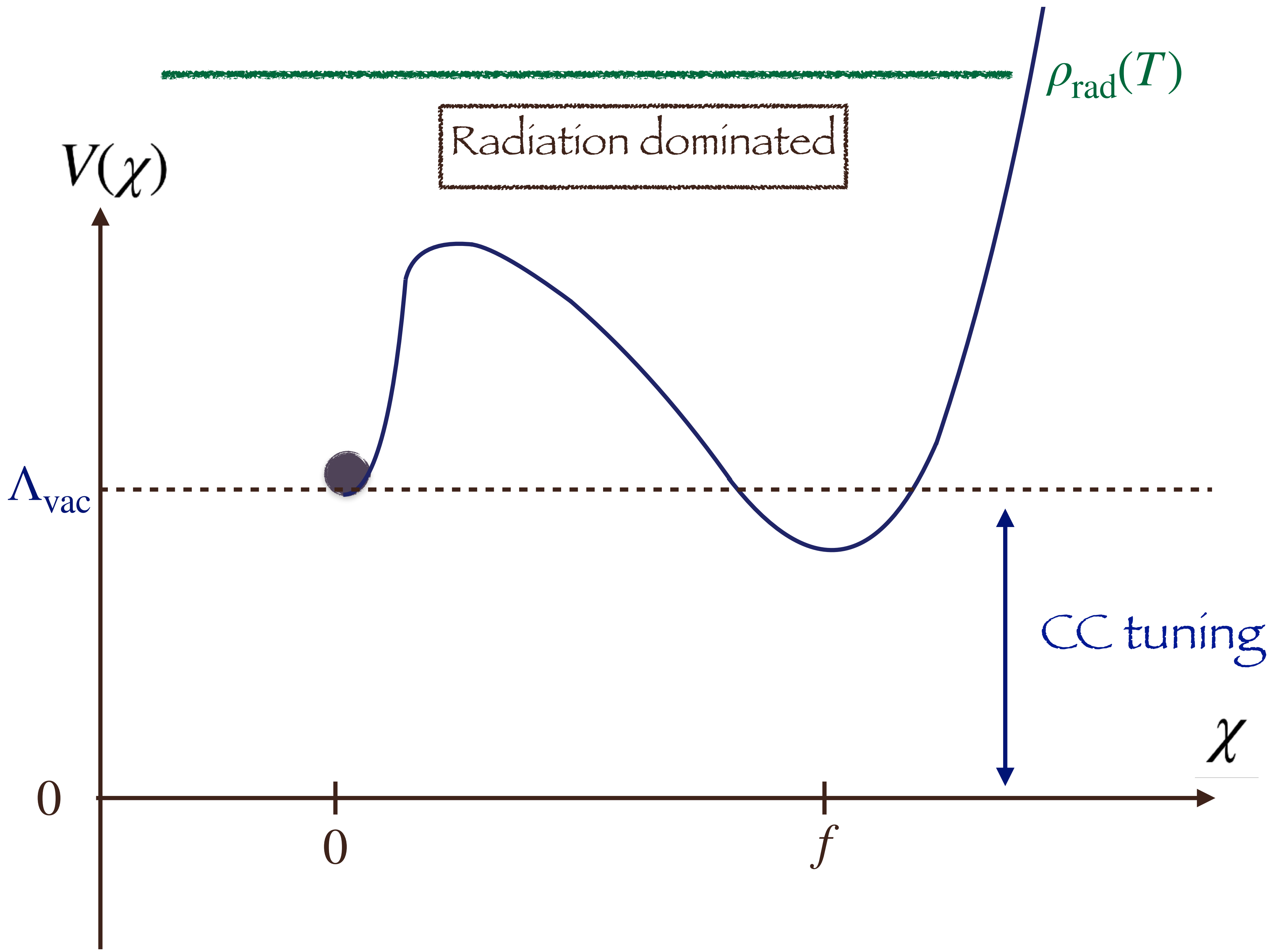
Cosmology I: Supercooling



$$H \equiv \frac{\dot a}{a} = \frac{1}{M_{\rm Pl}}\sqrt{\rho_{\rm rad} + \Lambda_{\rm vac}} \qquad \rho_{\rm rad} \approx T^4$$

animation by Yann Gouttenoire

Cosmology I: Supercooling



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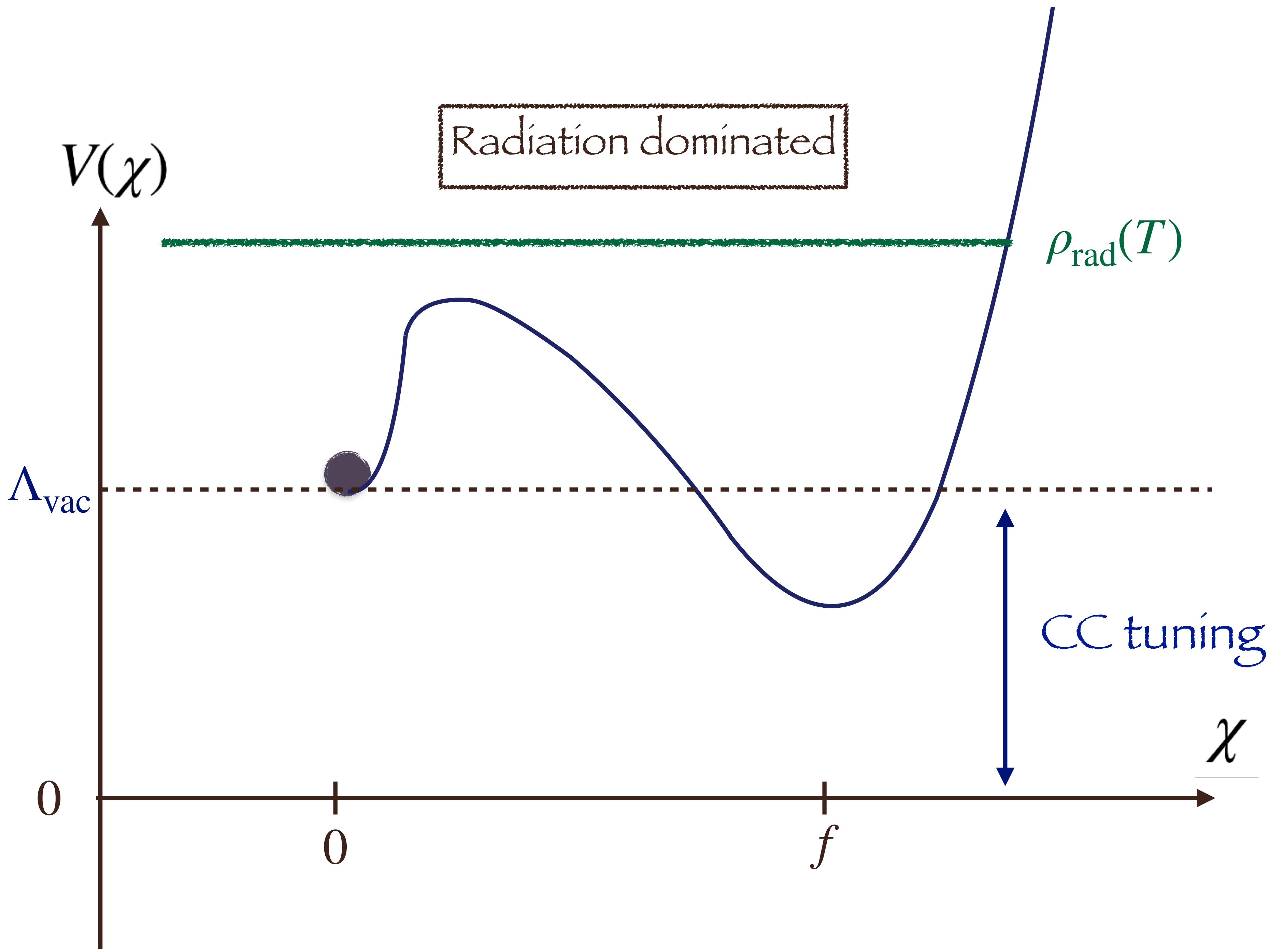

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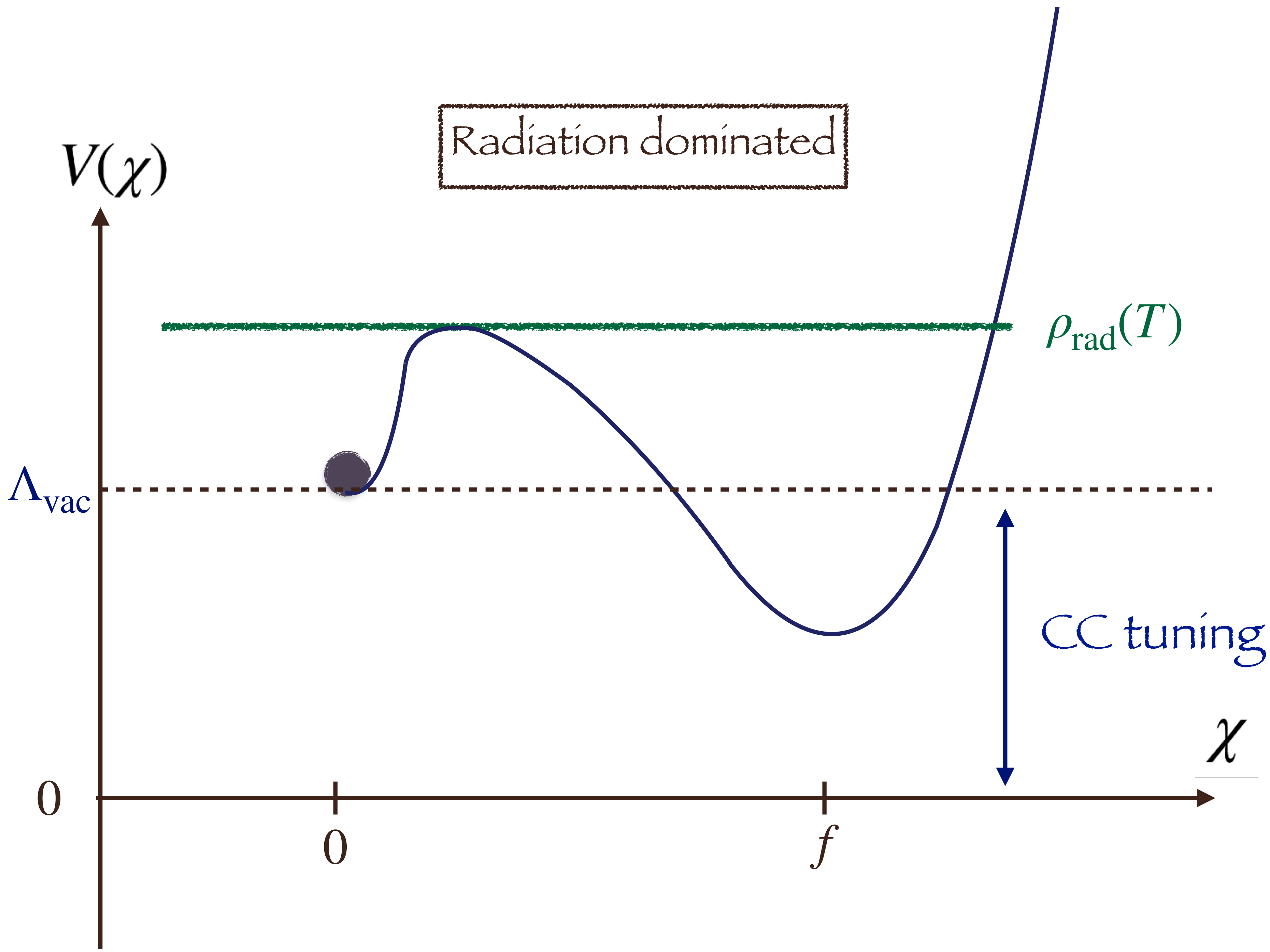

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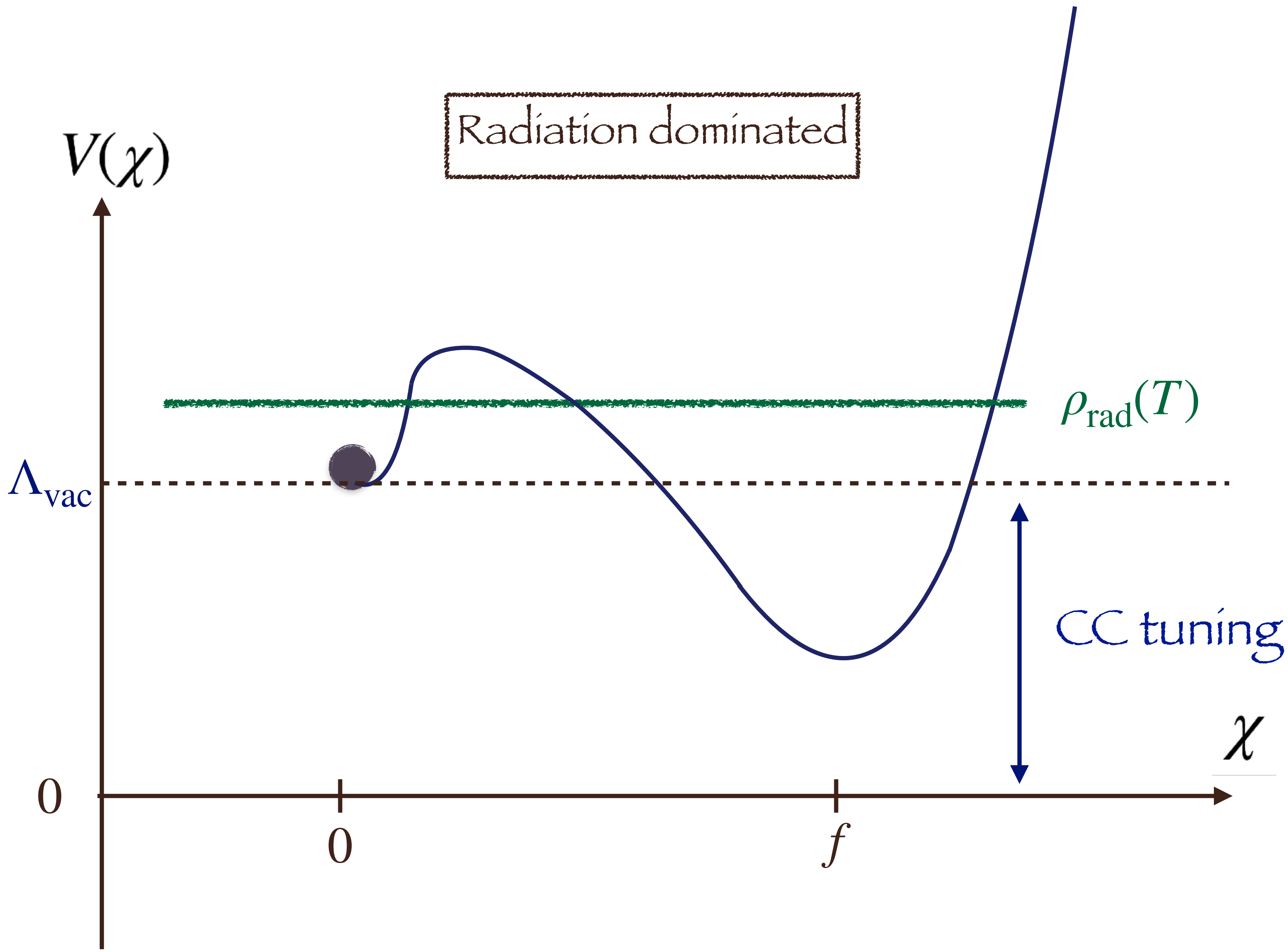

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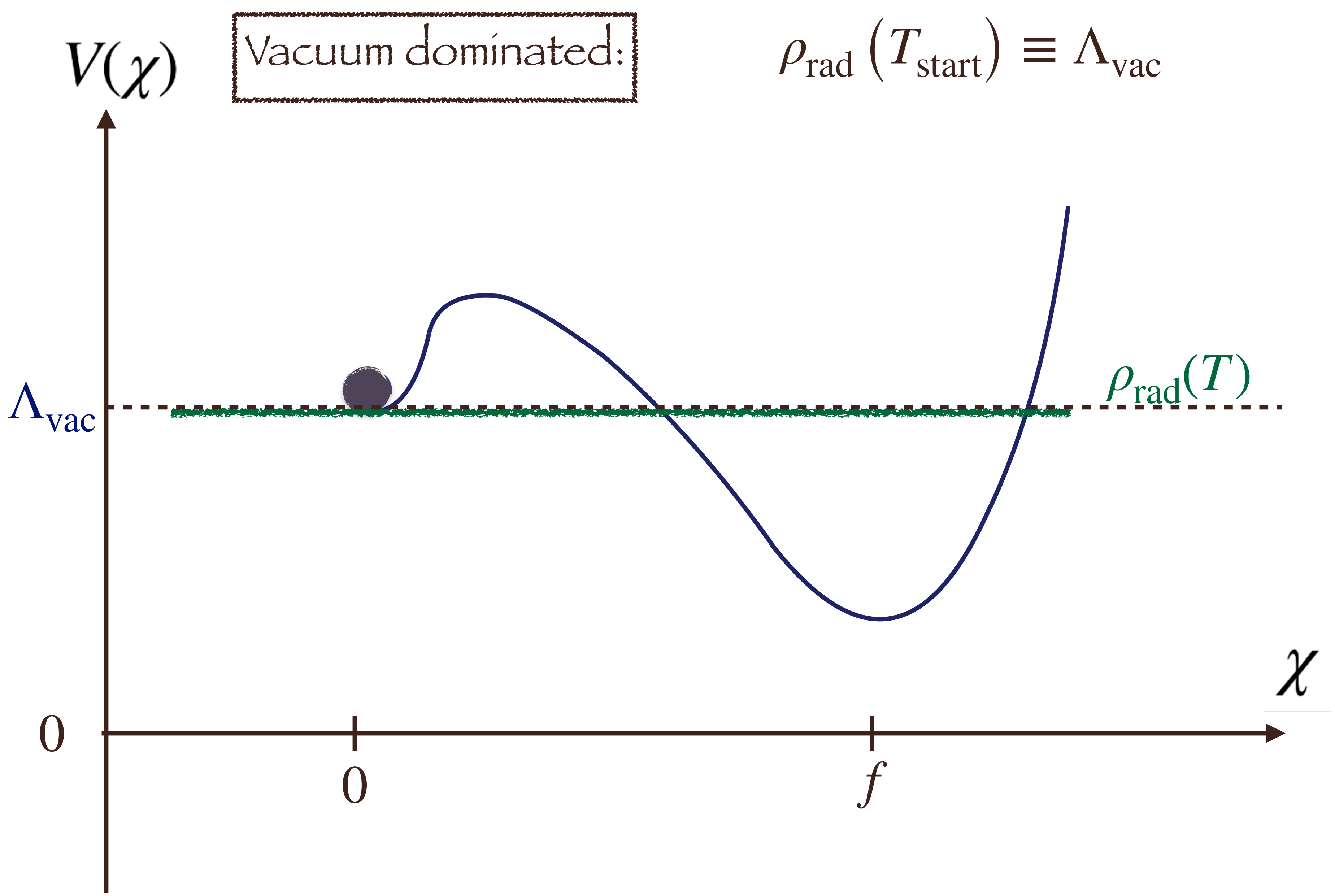

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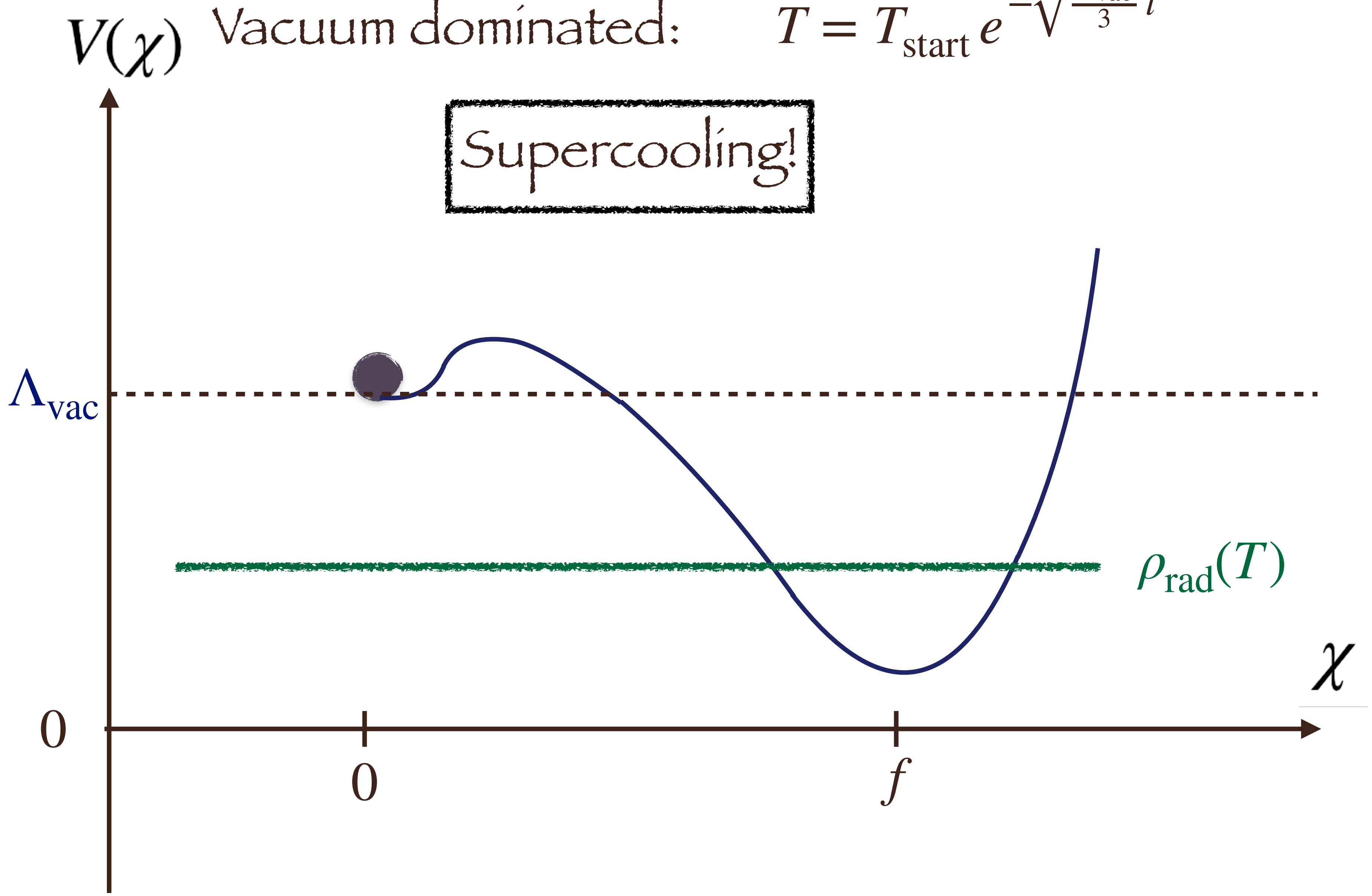
Cosmology I: Supercooling

Vacuum dominated: $T = T_{\text{start}}\, e^{-\sqrt{\frac{\Lambda_{\text{vac}}}{3}}\, t}$



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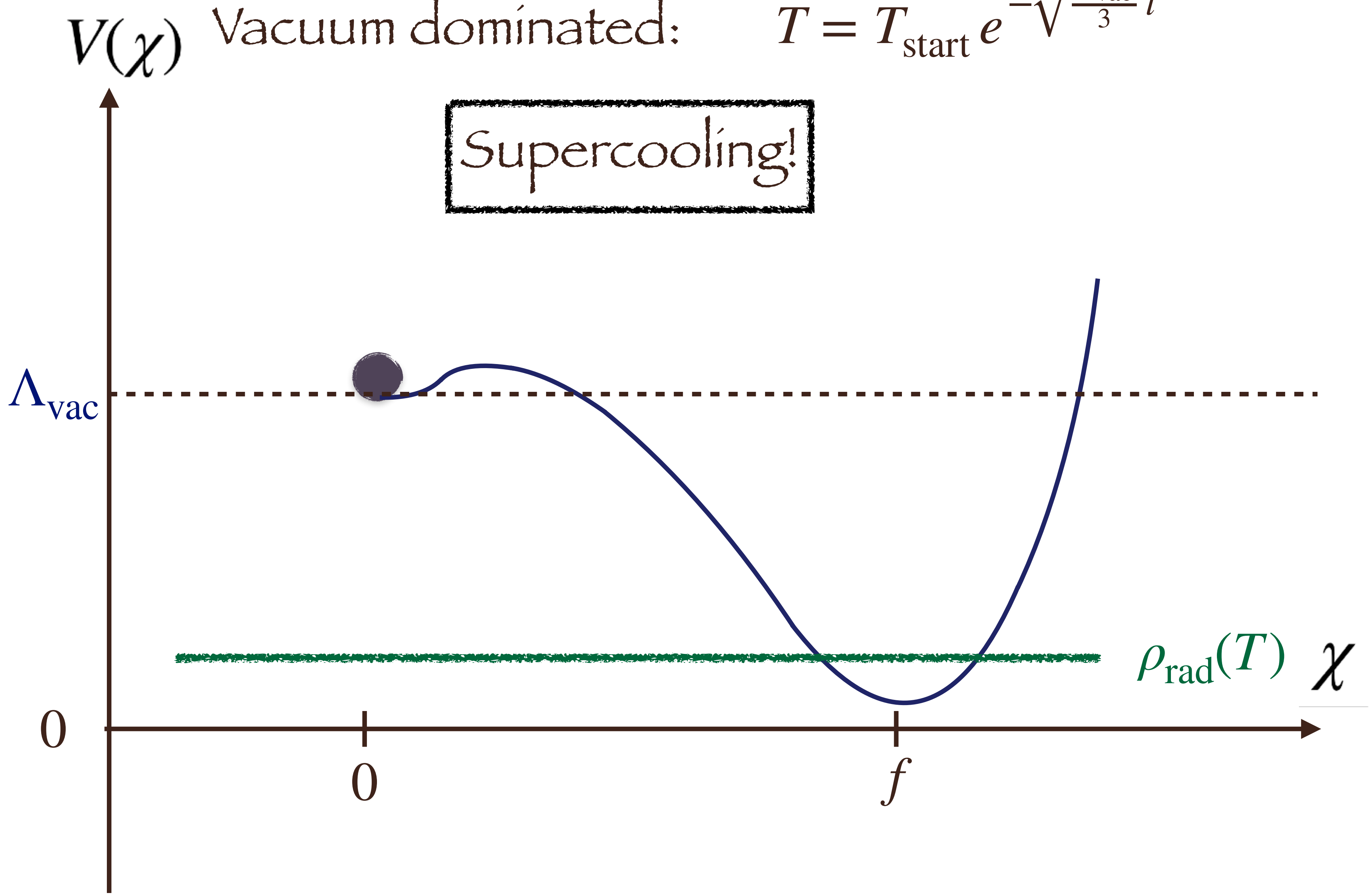

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animation by Yann Gouttenoire

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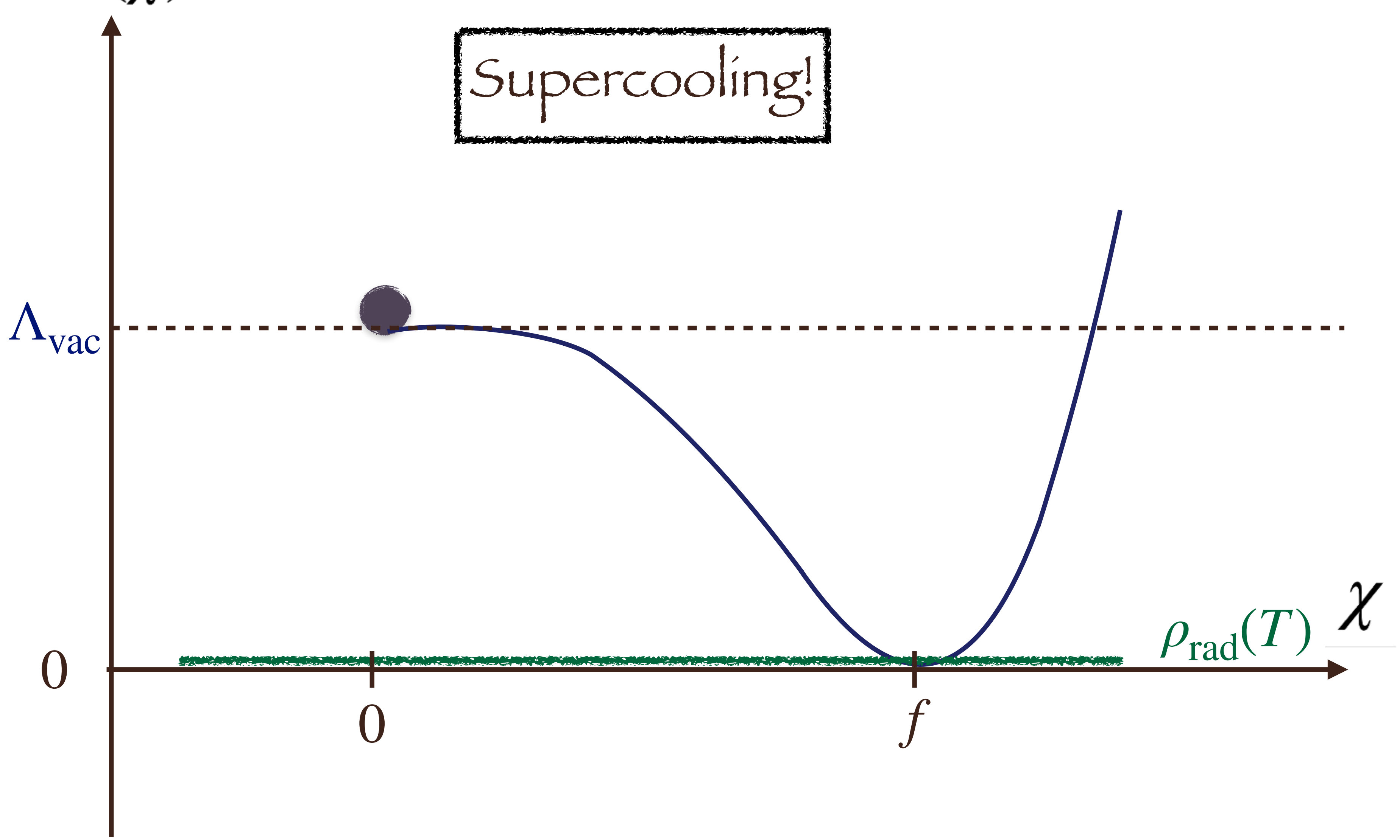
Vacuum dominated: $T = T_{\mathrm{start}}\, e^{-\sqrt{\frac{\Lambda_{\mathrm{vac}}}{3}}\,t}$

$\boxed{\text{Supercooling!}}$



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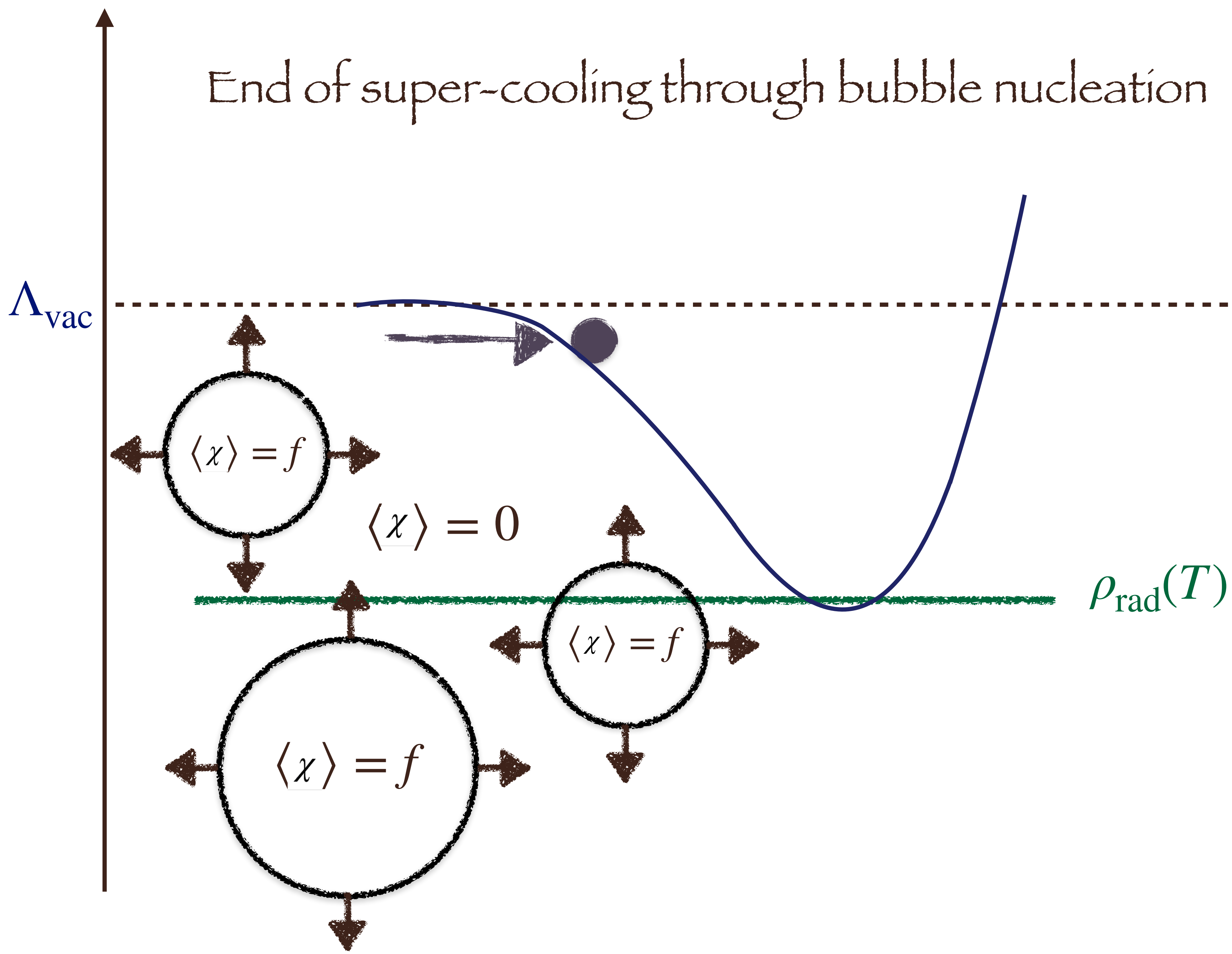
animation by Yann Gouttenoire

Cosmology II: End of Supercooling



animation by Yann Gouttenoire

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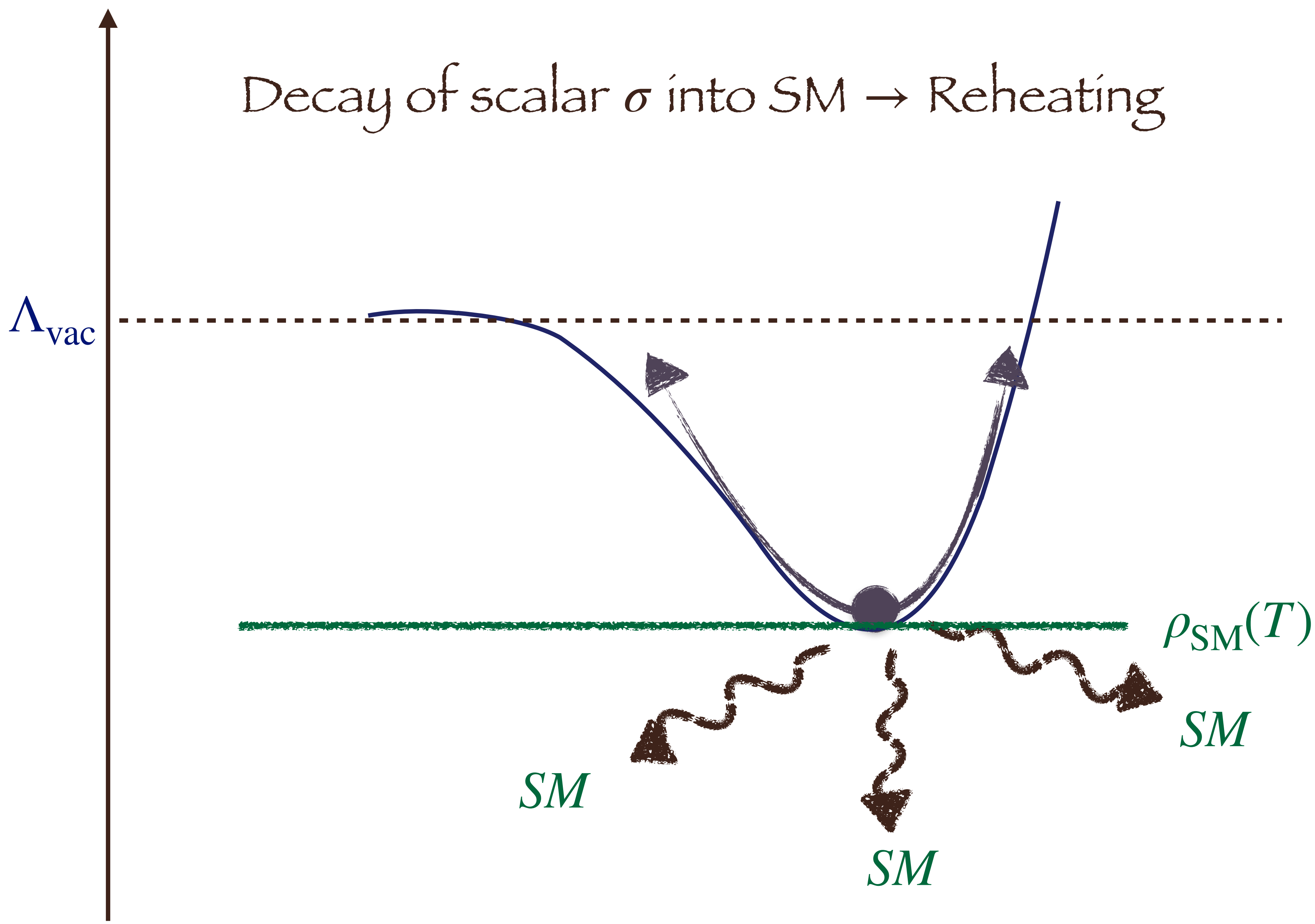

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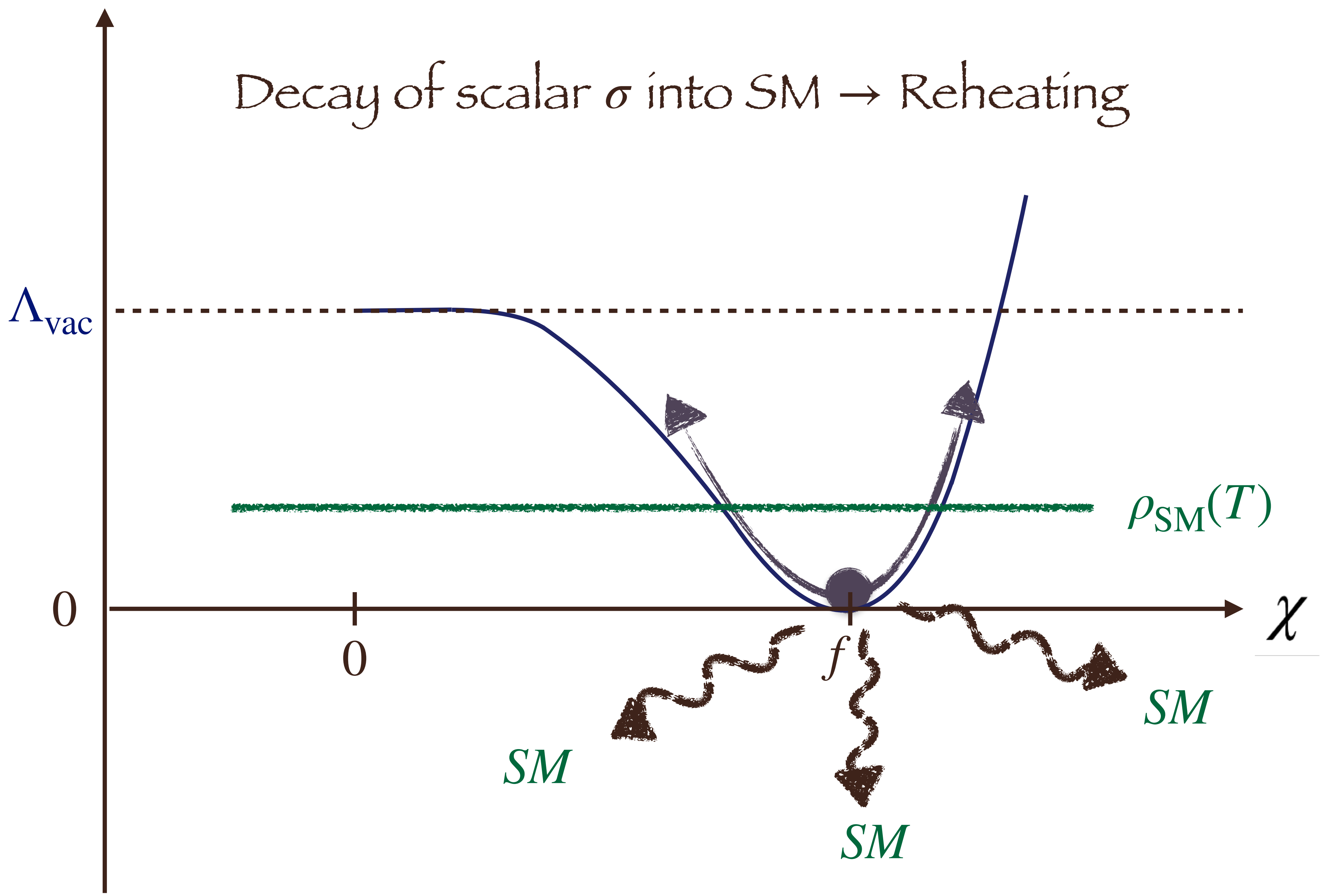

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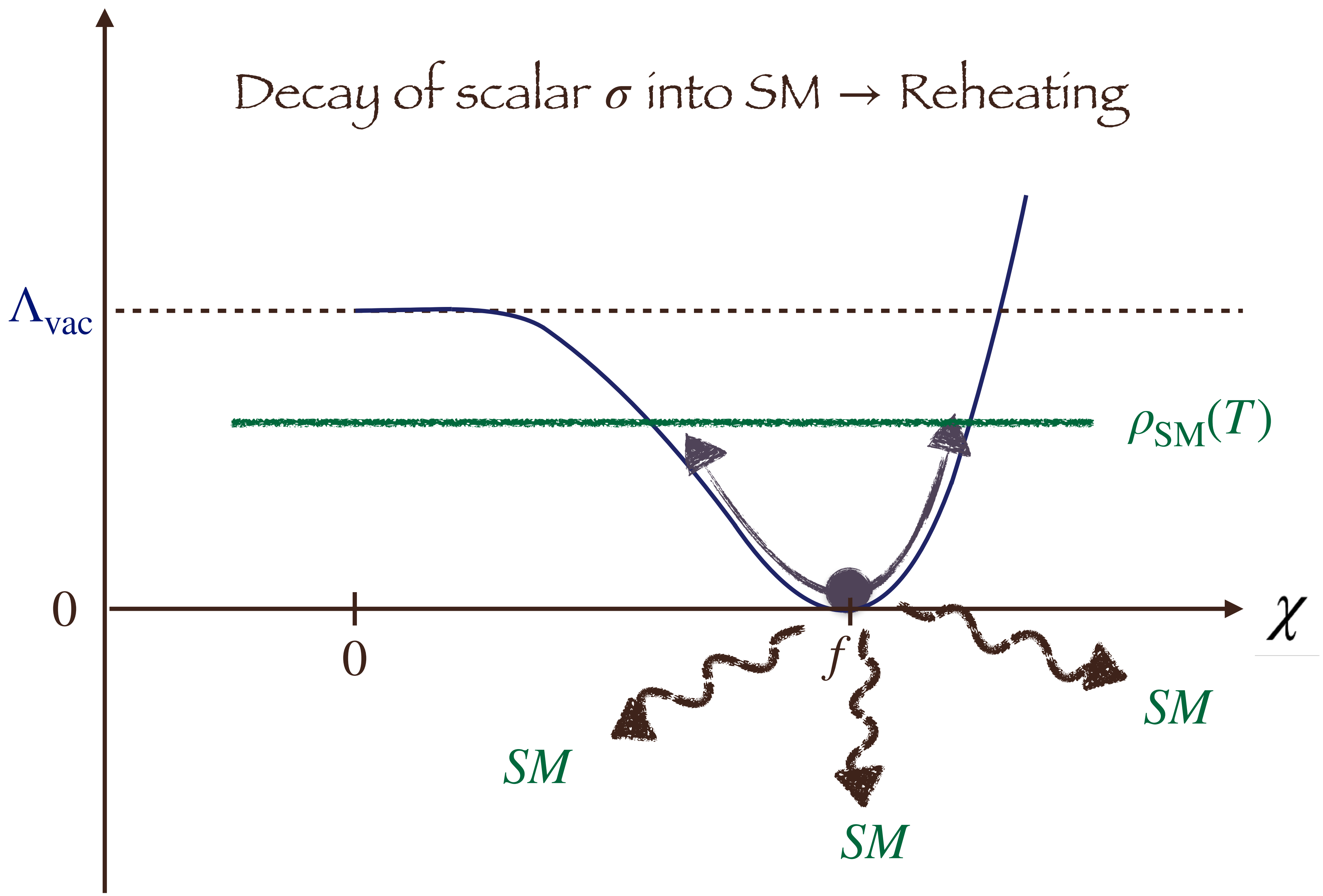

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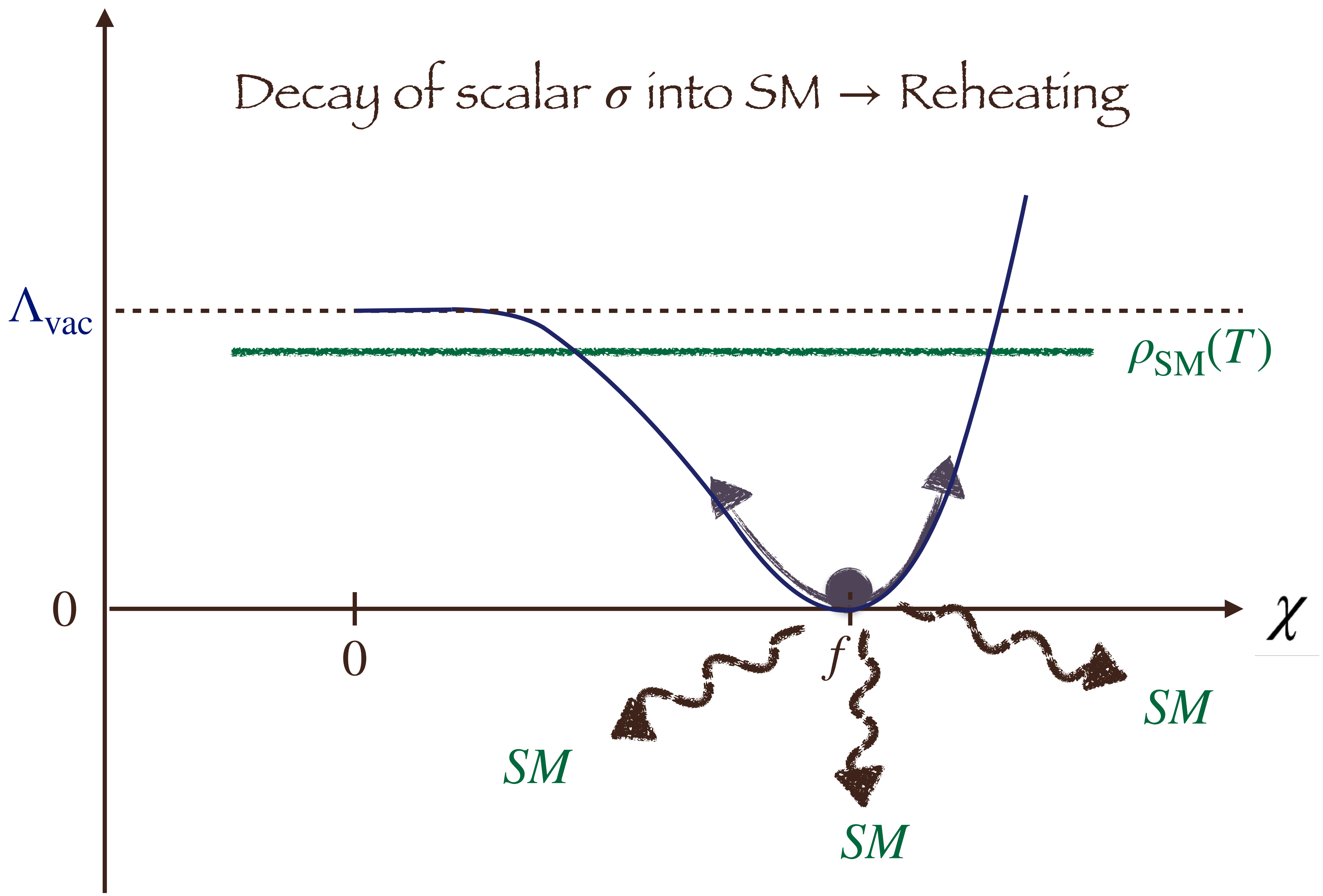
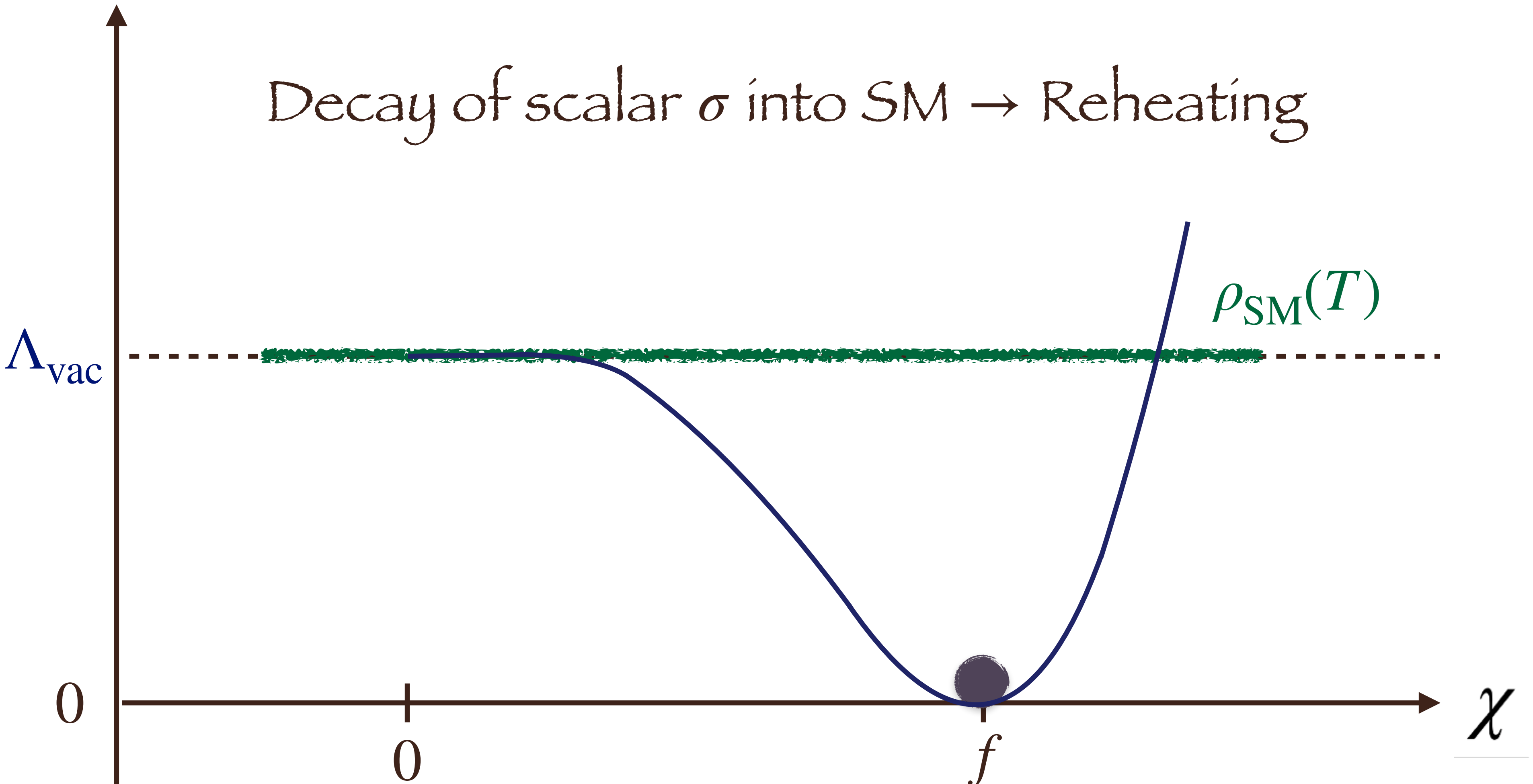


Cosmology II: End of Supercooling

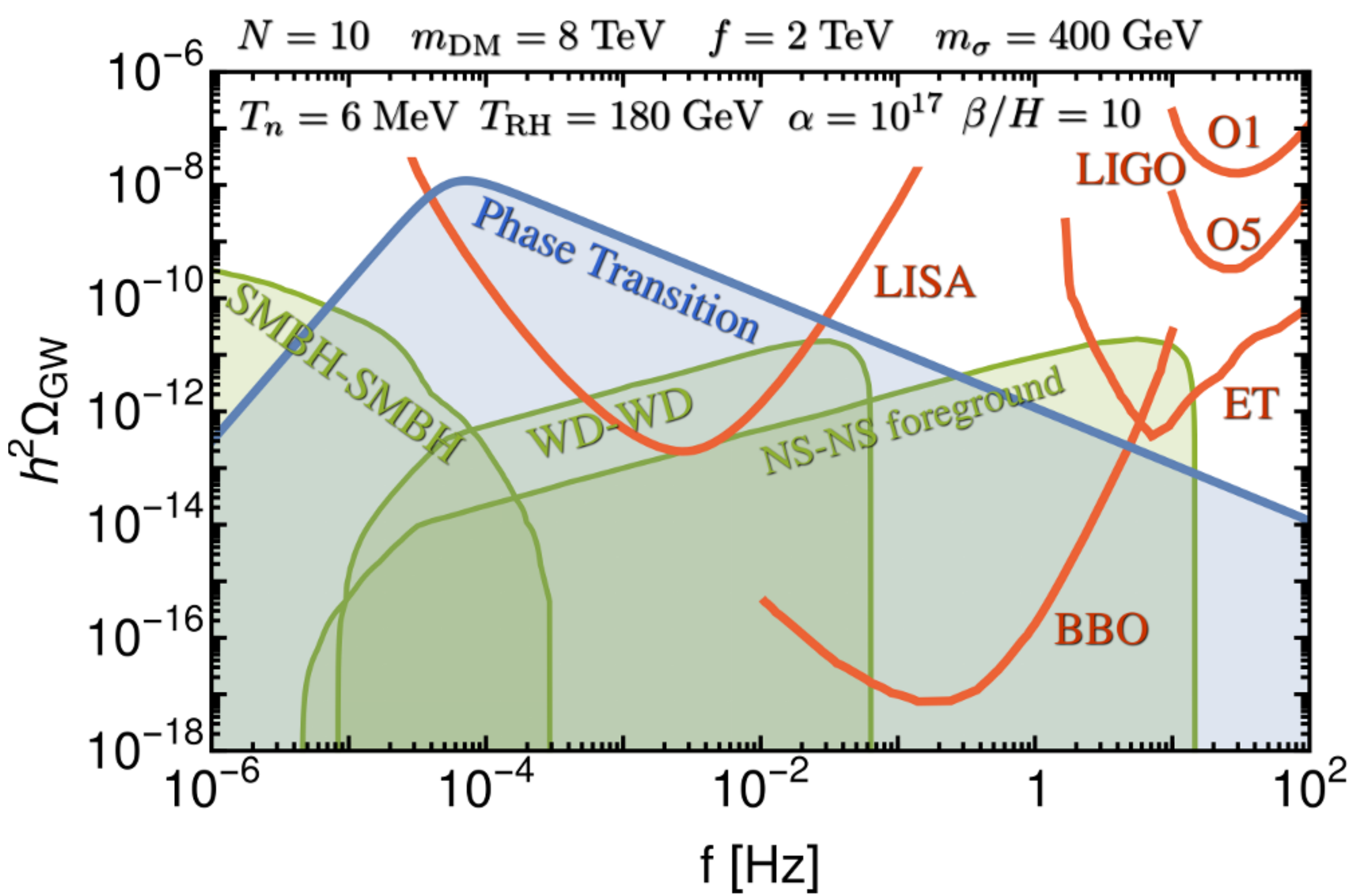
Decay of scalar σ into SM → Reheating



Instantaneous decay: $\Gamma_\sigma \gg H \quad \rightarrow \quad T_{\rm reh} \simeq T_{\rm start}$

Net effect: $\boxed{\text{dilution by } \dfrac{a_{\rm end}}{a_{\rm start}} \simeq \dfrac{T_{\rm start}}{T_{\rm end}} = \dfrac{f}{T_{\rm nuc}}}$

Gravitational Waves from Phase Transition



Dark Matter from a confining Sector

M_{UV}

$m_* = g_* f \ll M_{\text{UV}}$

Here: DM as composite resonance

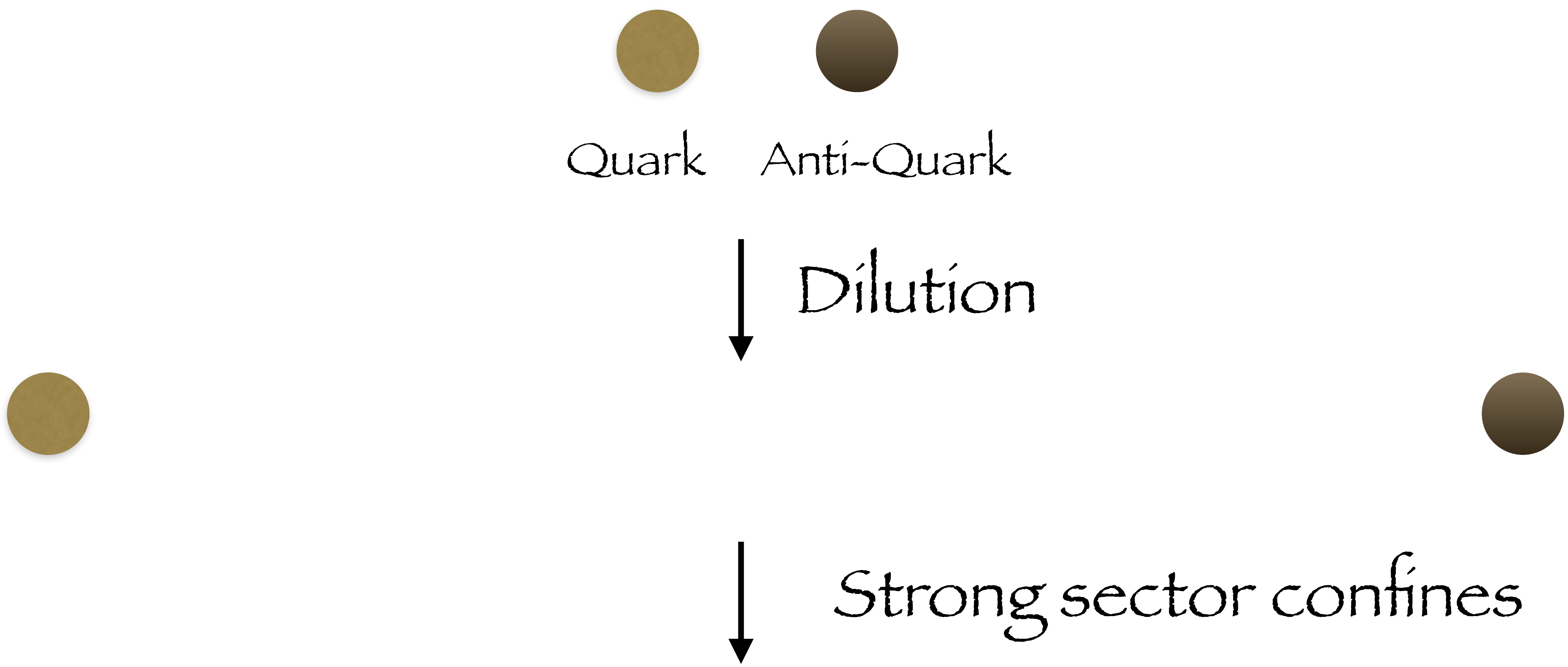
with some portal to SM

$f \sim \text{TeV}$ if linked to hierarchy problem

DM formation at Phase Transition

$\boxed{\text{Naive picture}}$

Baratella Pomarol Rompineve
1812.06996



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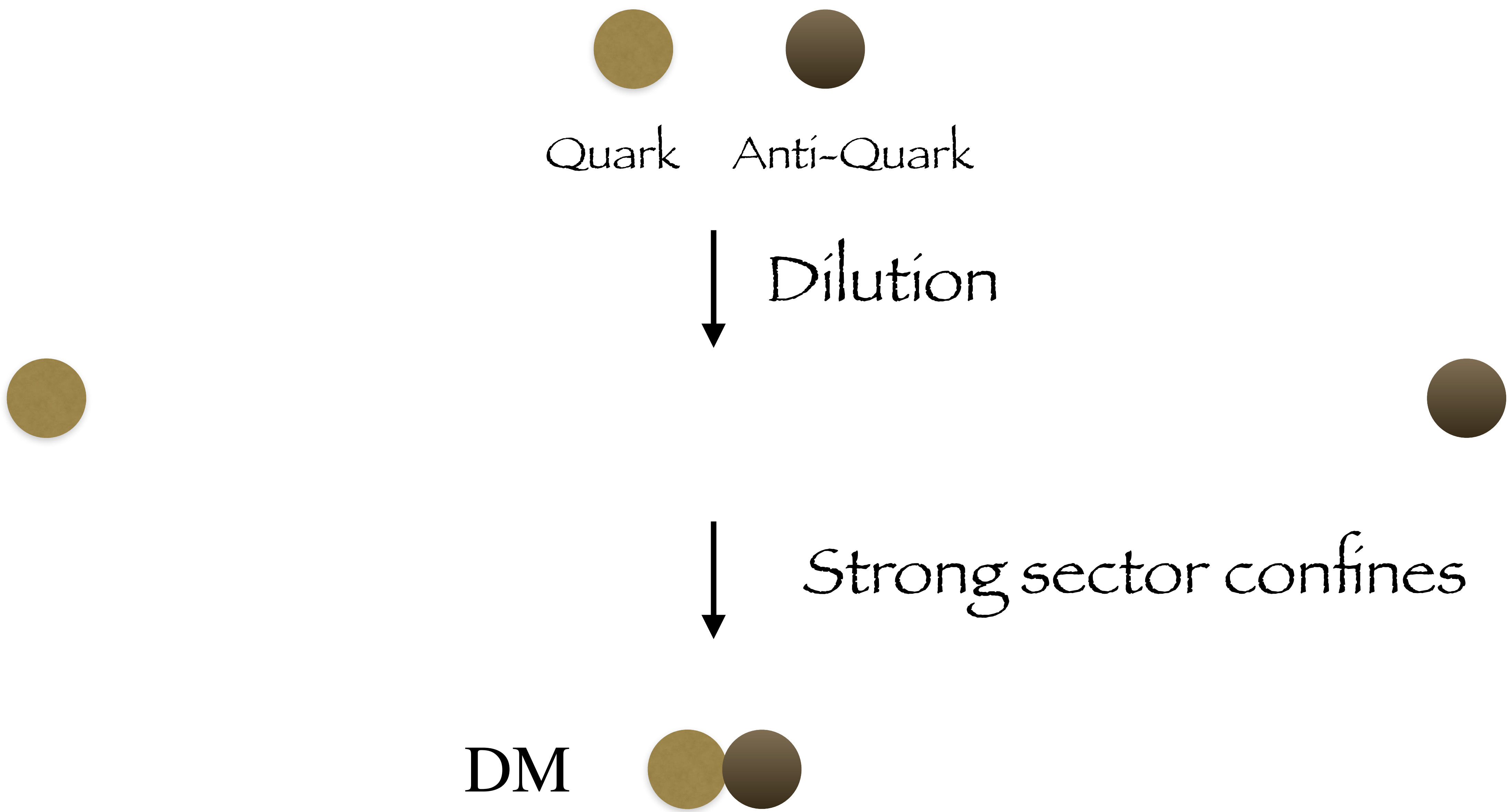

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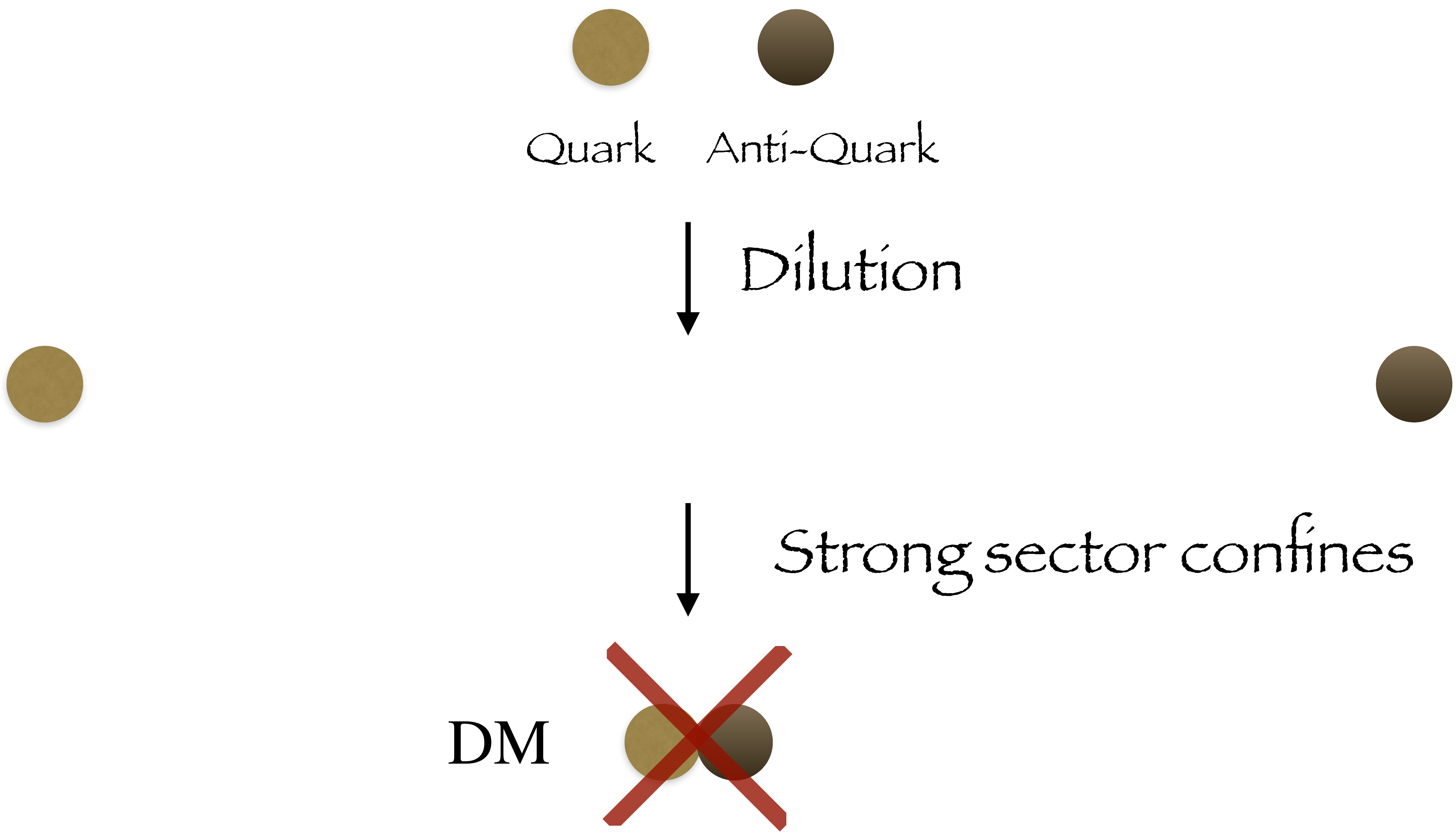


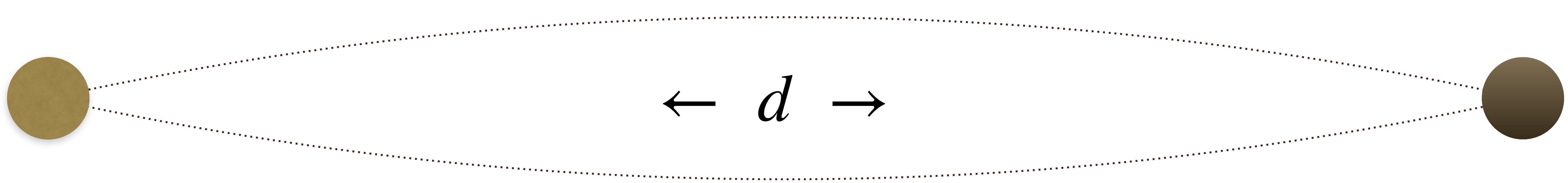
DM formation at Phase Transition

$$\boxed{\text{Include confinement effects}}$$

Quark Anti-Quark

$\downarrow$ Dilution

$E_{q\bar{q}} \simeq f^2\, d \gg f$ $\downarrow$ Strong sector confines



DM formation at Phase Transition

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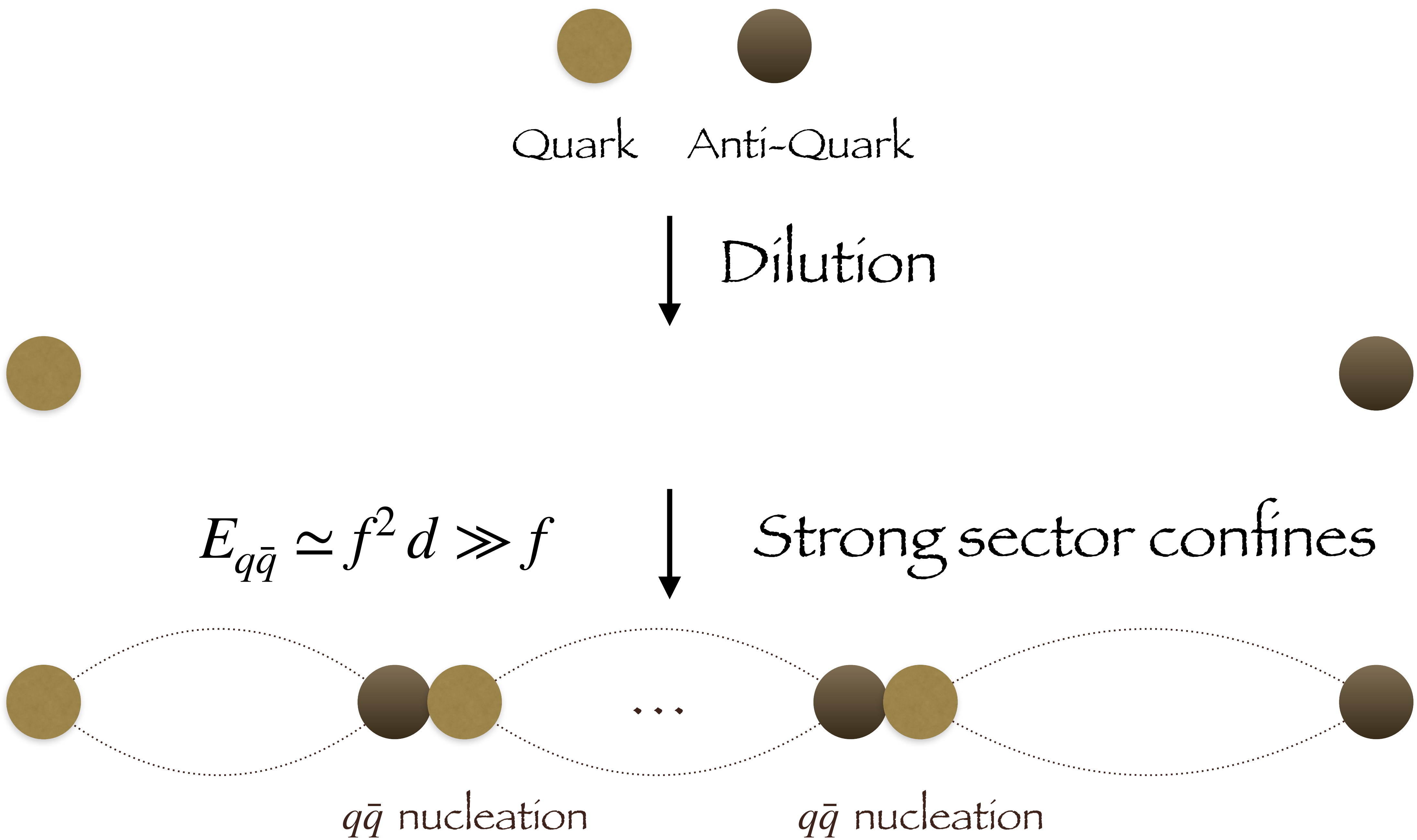
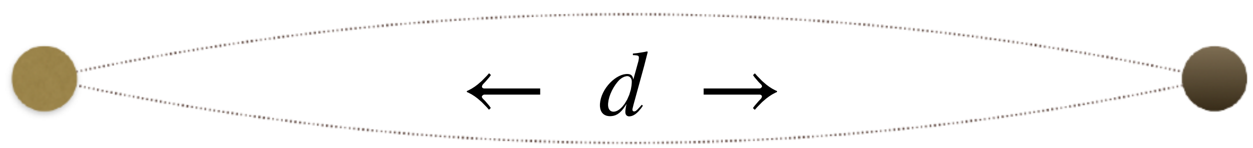


What's the relevant distance?

Assume $E_{q\bar{q}} \simeq f^2 d$ even at large distances



Naively distance from thermal quark density $d \sim n_q^{-1/3} \sim T_{\rm nuc}^{-1}$

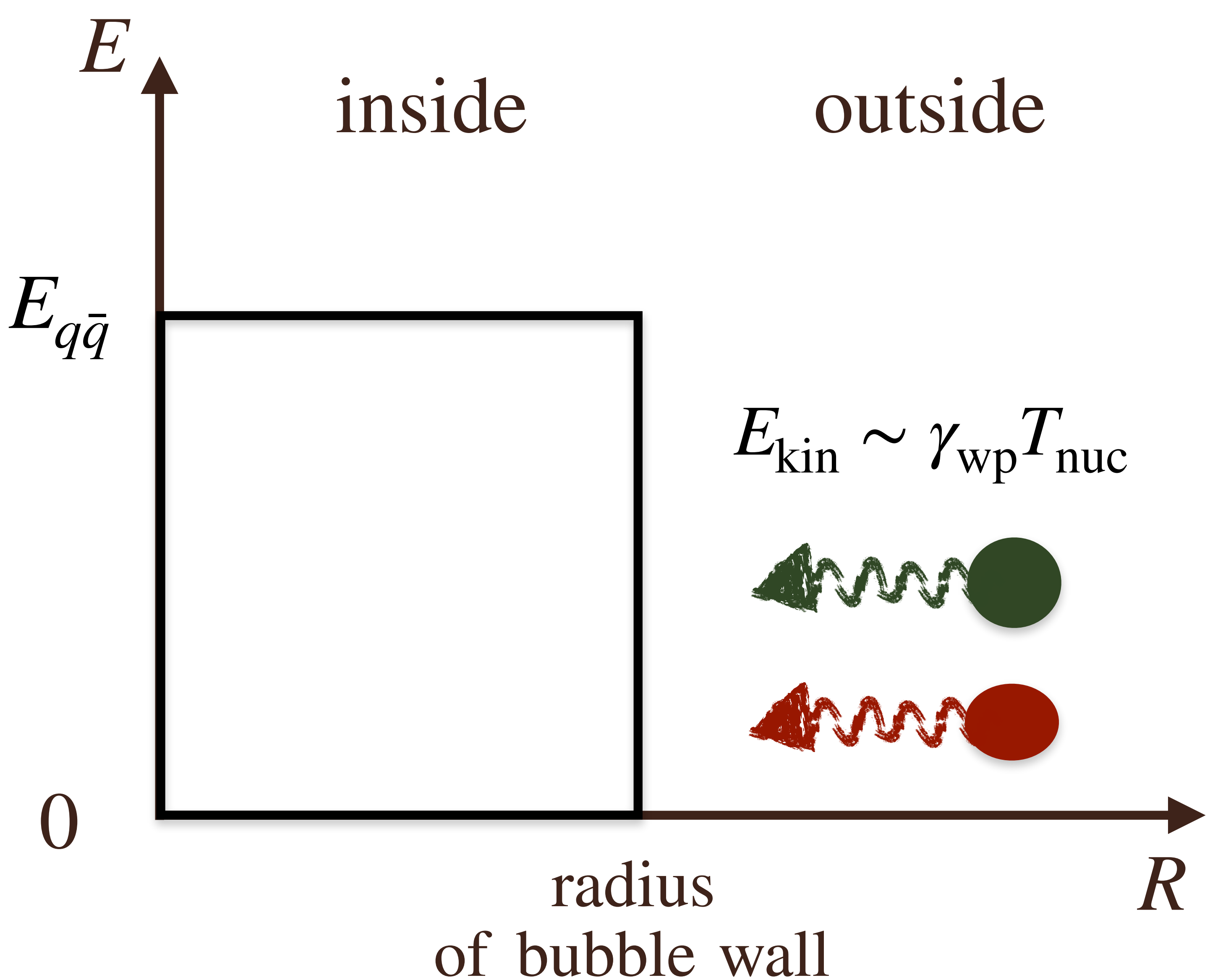
But then paradox: boost to frame of bubble wall $d \rightarrow d/\gamma^{1/3}$

$$E_{q\bar{q}} \rightarrow E_{q\bar{q}}/\gamma^{1/3}$$

$\boxed{\text{A binding energy cannot depend on the frame!}}$

Our Modelling of String Fragmentation

Treat $E_{q\bar{q}}$ as a `mass' → $d$ should be computed in `interaction frame' of quarks



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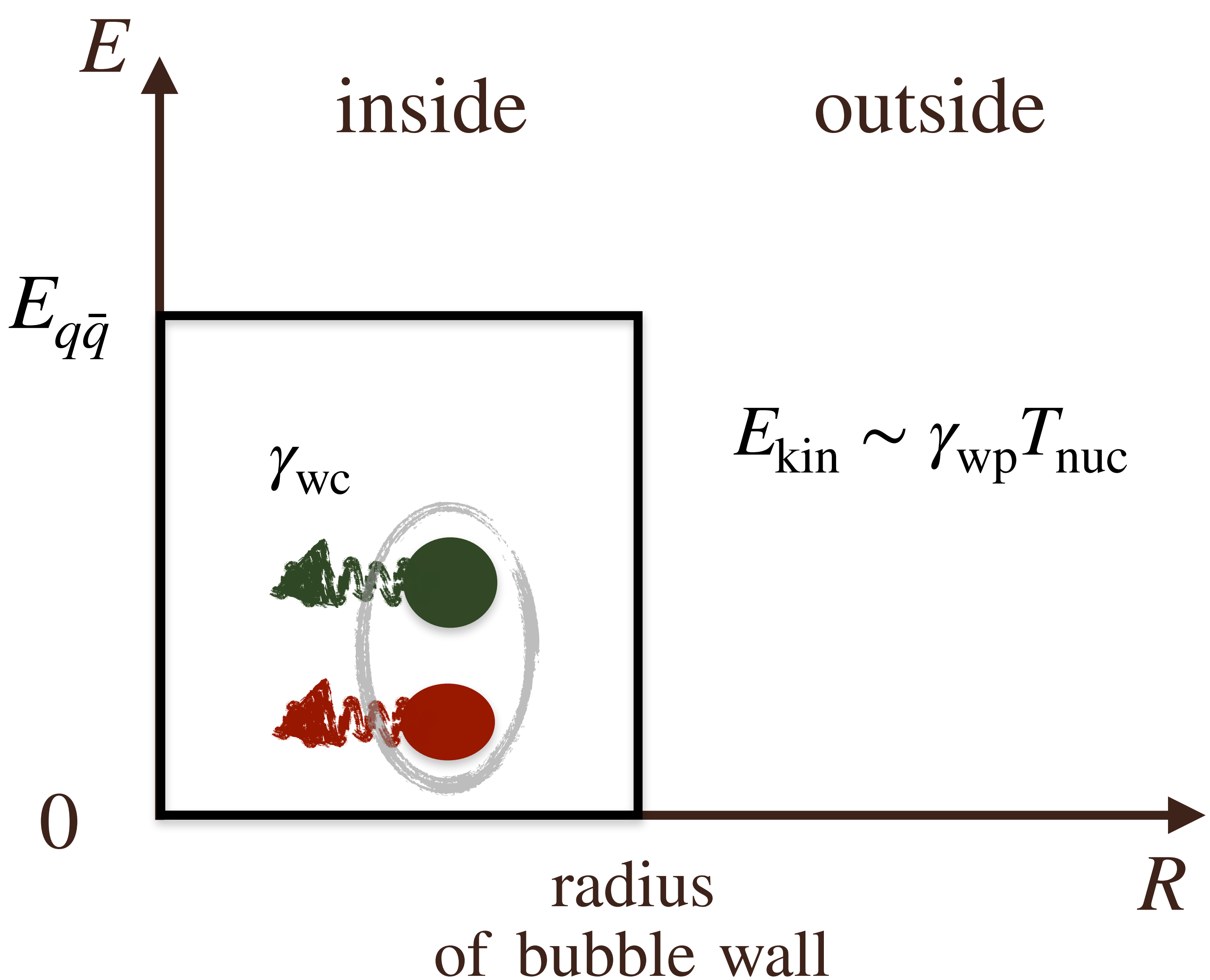

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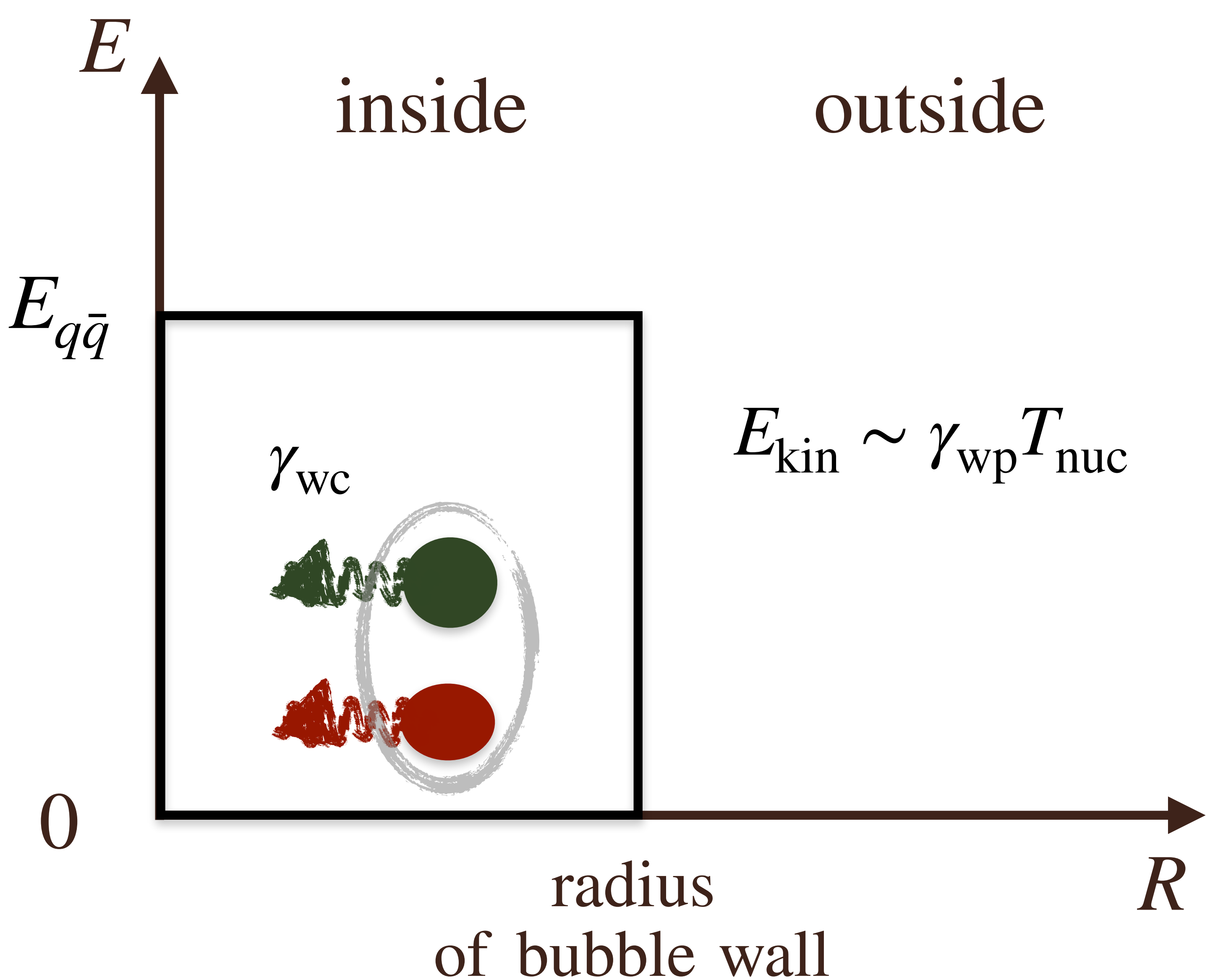
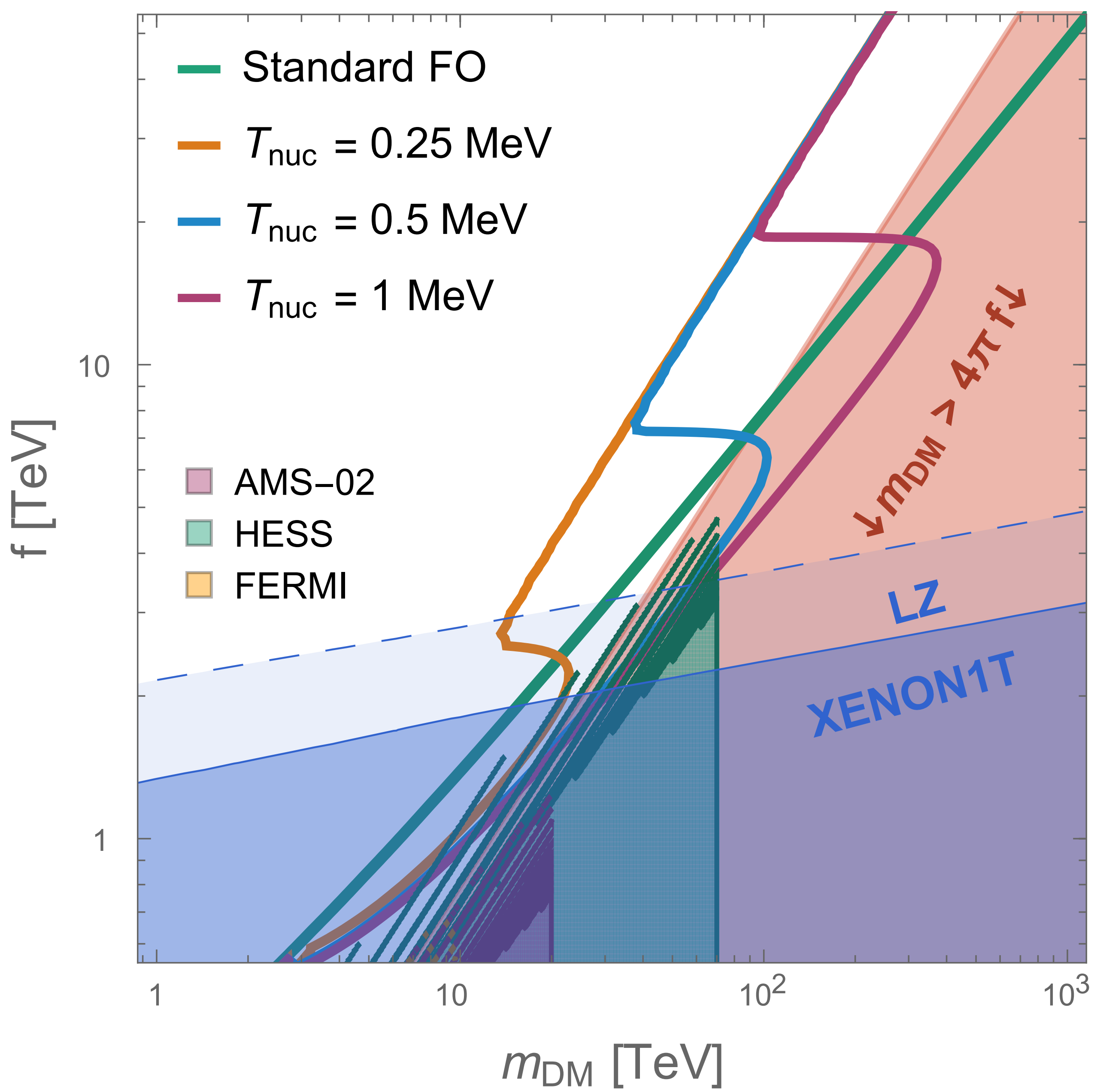


Enhancement of DM abundance

by a factor $\sim \dfrac{E_{q\bar{q}}}{m_{\rm DM}} \sim \left(\dfrac{f}{T_{\rm nuc}}\right)^{1/2}$

Pheno of Supercool Composite DM

$$\mathscr{L}_{\rm DM} = -\, m_{\rm DM}\, \bar\psi\psi\left(1+\frac{\sigma}{kf}\right) \qquad m_{\rm DM} = g_\star f$$



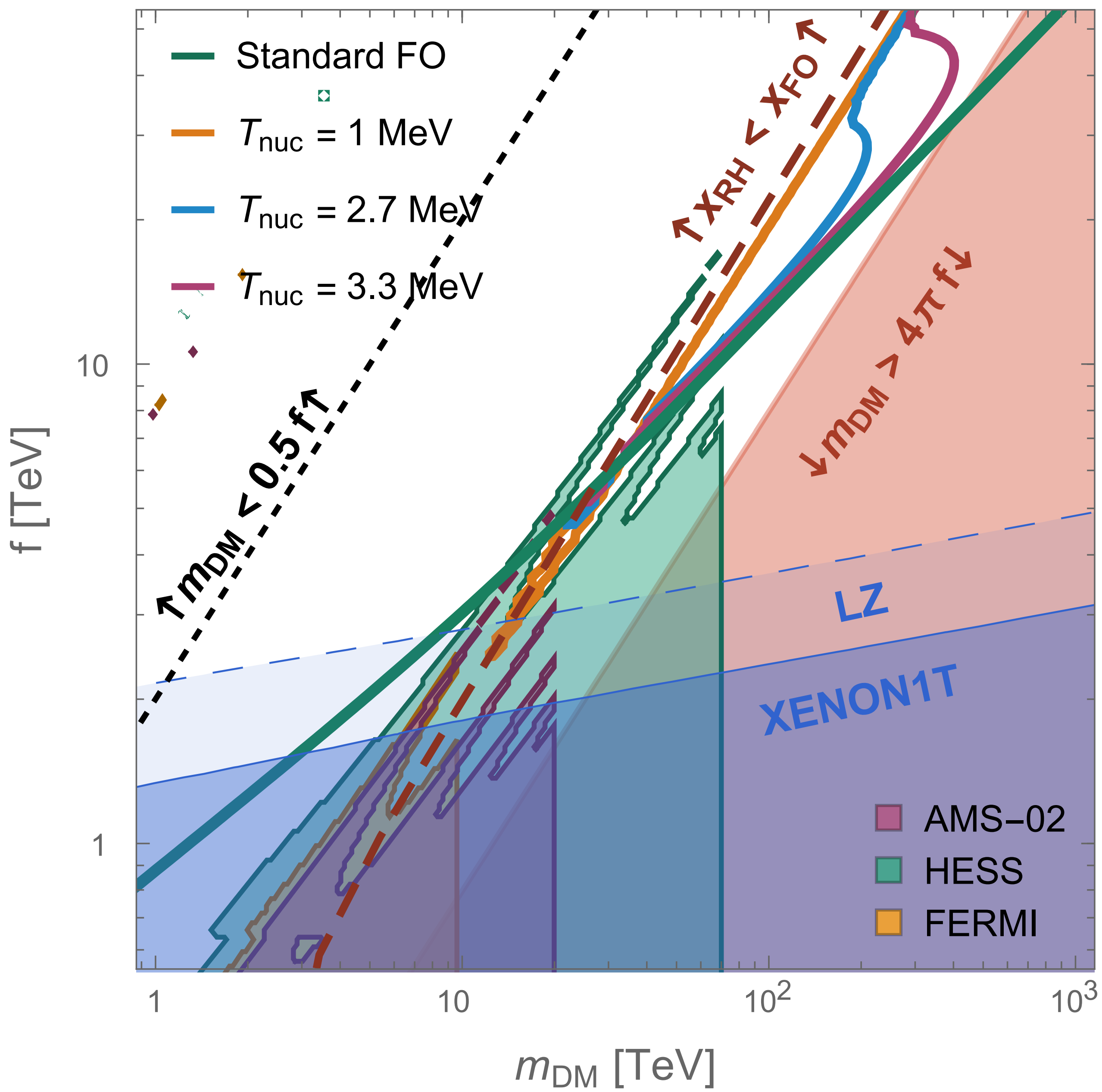
Signals as in non-supercooled DM

But available parameter space increases!

- $f \gtrsim 1.5$ TeV
- $m_{\rm DM} \gtrsim 20$ TeV

Pheno of Supercool Composite DM

Now Scalar DM



Annihilation is s-wave:

→ Thermal wash-out more efficient

→ Larger signals at Telescopes

- $f \gtrsim 1.5$ TeV
- $m_{\rm DM} \gtrsim 20$ TeV

Dark Matter above WIMP window

Larger Energies

Experimental Access

HIC SUNT LEONES
(& DARK MATTER?)

Cosmic Rays
Gravity Waves
?

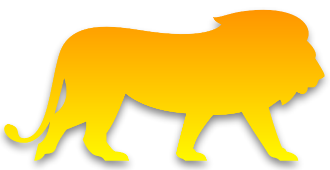
~TeV

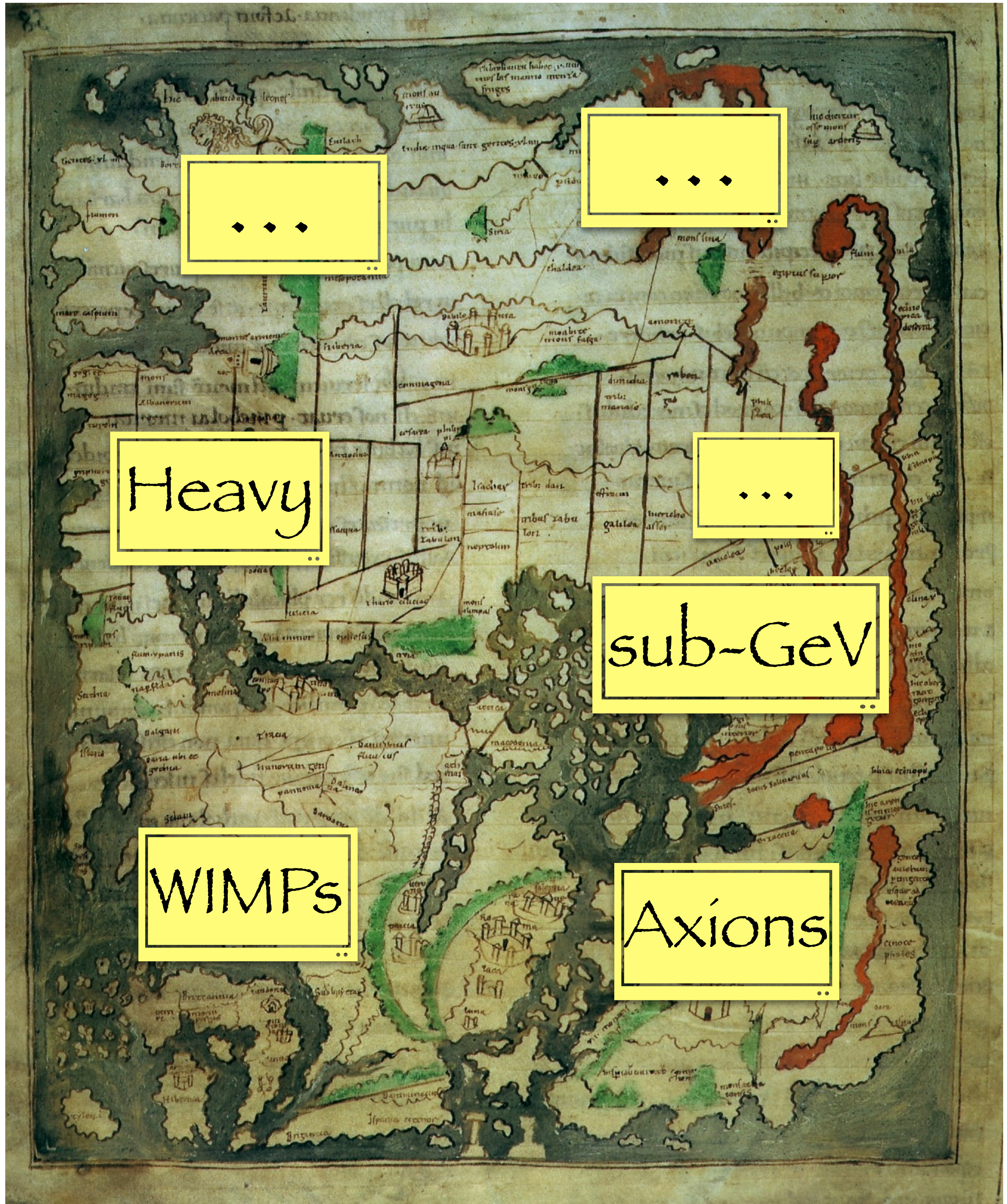
THE STANDARD MODEL
(& NO DARK MATTER)

LHC
...

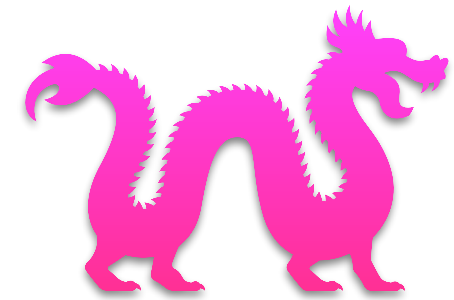
Dark Matter 2030?

???



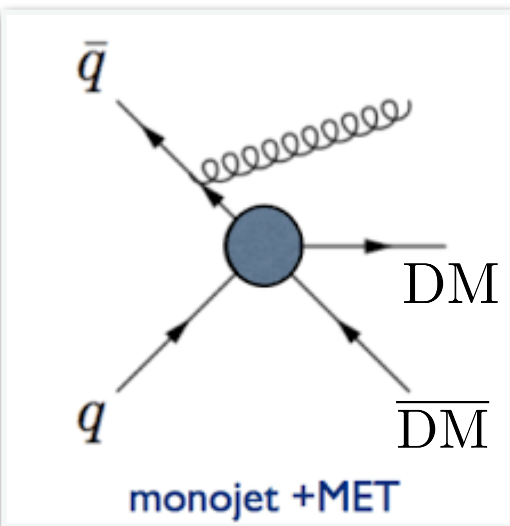


???

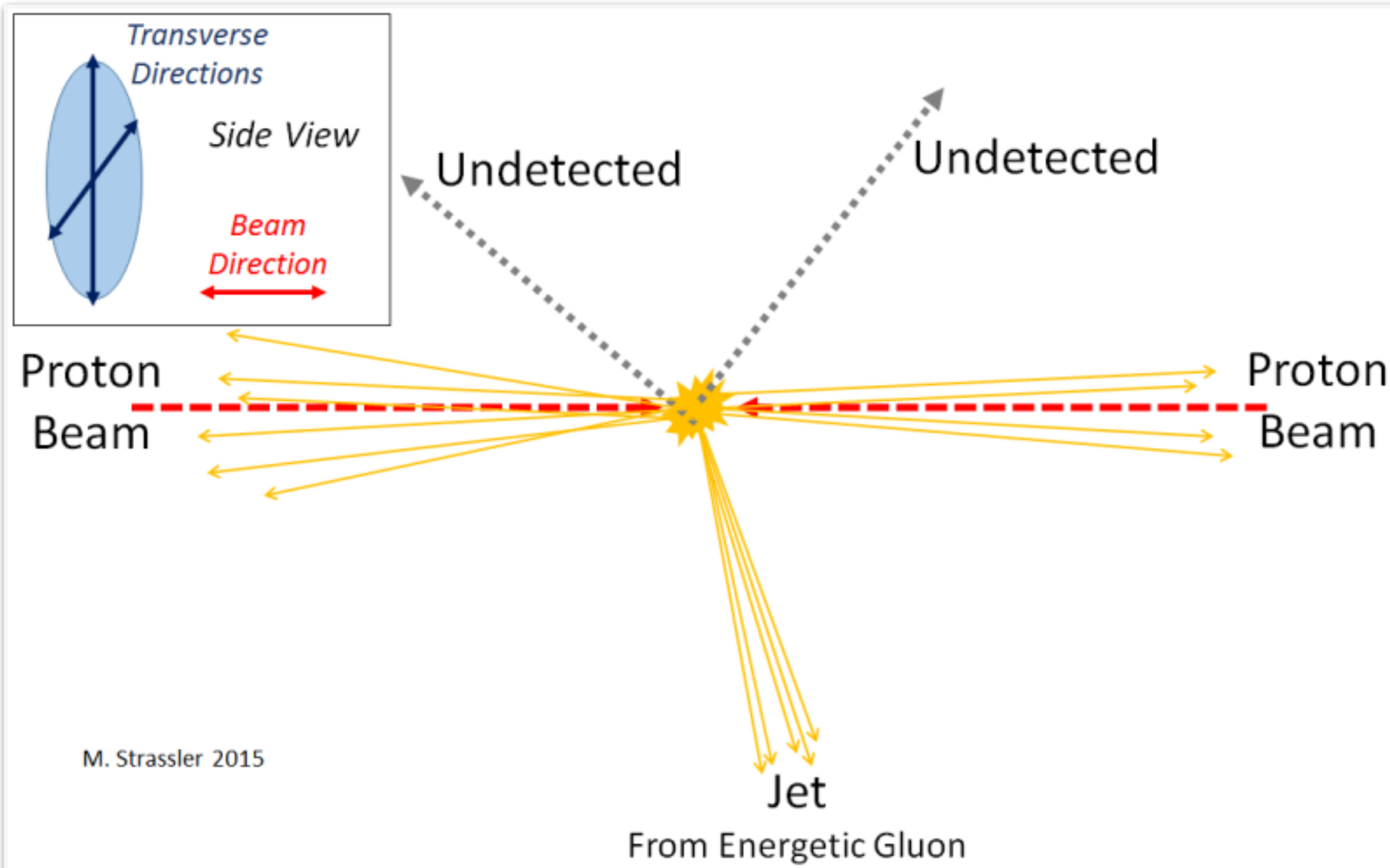


Back up

Colliders



$\bar{q}$
DM
q
$\overline{\mathrm{DM}}$
monojet +MET

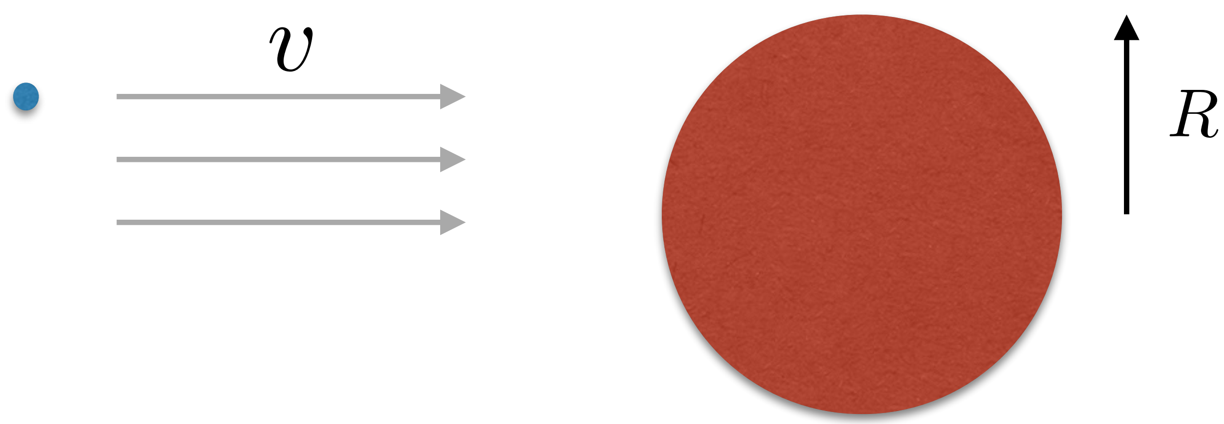


Transverse Directions
Side View
Beam Direction
Undetected
Undetected
Proton Beam
Proton Beam
M. Strassler 2015
Jet
From Energetic Gluon

Sommerfeld Enhancement

Sommerfeld 1931,
Hisano+ hep-ph0412403 (first time DM), ….
Arkani-Hamed+ 0810.0713 for nice explanation

Classical analogous



$$\sigma_0 = \pi R^2$$

If slow, gravity becomes important:

$$\boxed{\sigma = \sigma_0 \left(1 + \frac{v_{\rm esc}^2}{v^2}\right)}$$

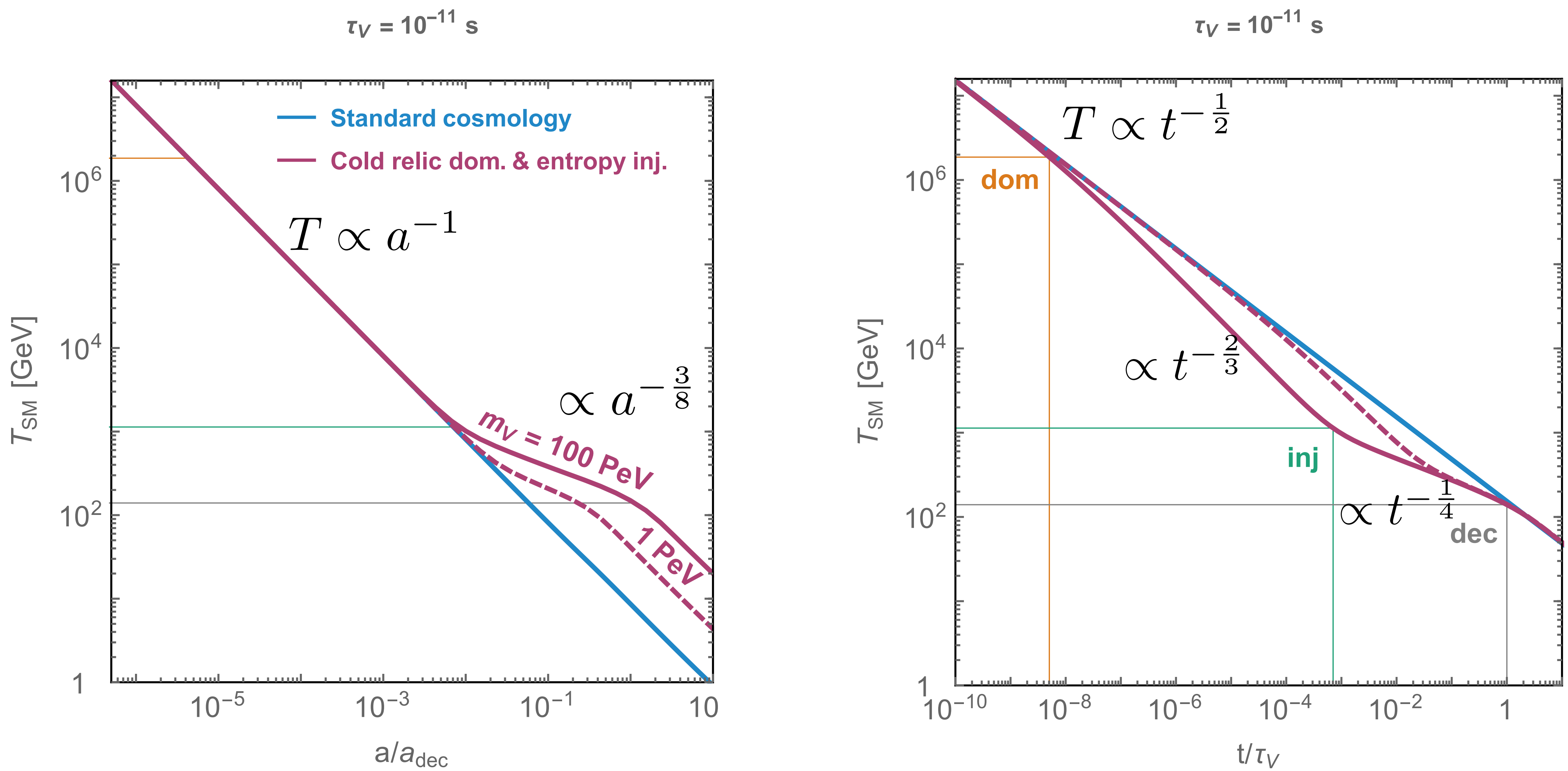
Quantum: like in classical example, to have (Sommerfeld) enhancement requires

- slow particles $v \ll c$
- long-range attractive force $M_{\rm mediator} < \alpha\, M_{\rm DM}$

DM mass for SM weak force? $\alpha_{\rm w} \sim 1/30$ $\boxed{M_{\rm DM} \gtrsim 30\, M_{W,Z} \simeq 2.5 \text{ TeV}}$

A bit more technical:
quantum field theory computations assume particles are "free" (=plain waves) at $r = +\infty$
BUT: if potential V is important also there (long-range!) you have to **solve Schroedinger eq.**

Cosmology of Secluded DM



dom: **early matter domination** starts

inj: most SM entropy comes from mediator decays

dec: matter domination ends when $t \simeq \tau_V$

Experimental Tests

Cirelli+ 1612.07295, Baldes+ 1712.07489
Cirelli Gouttenoire Petraki FS 1811.03608

Tiny portal with the SM + Heavy → Direct Detection & Collider put no constraints

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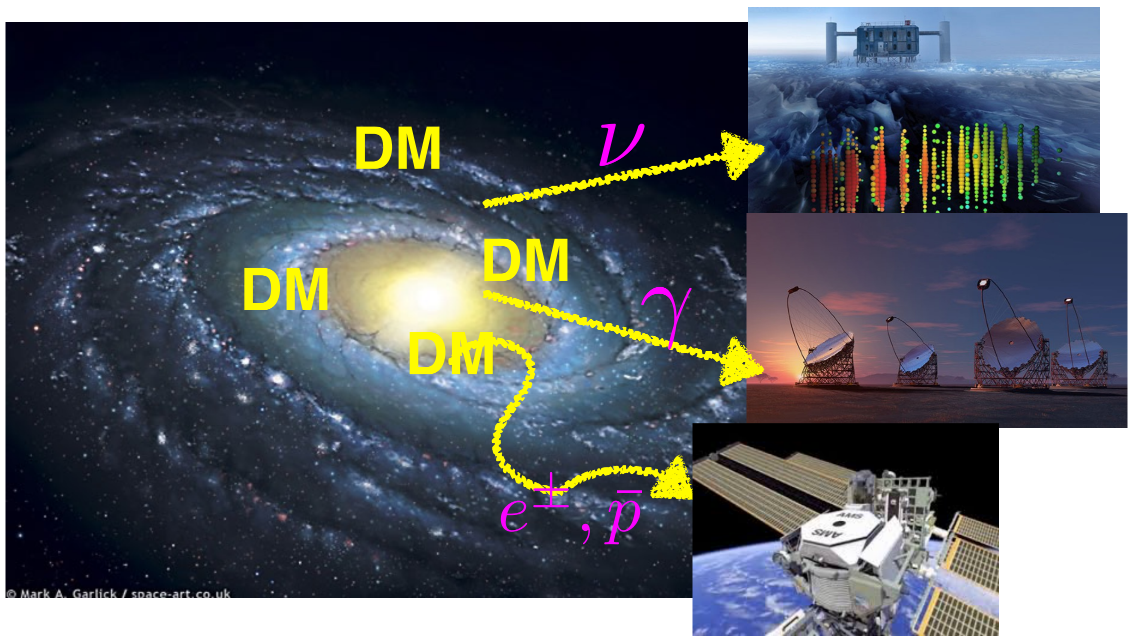

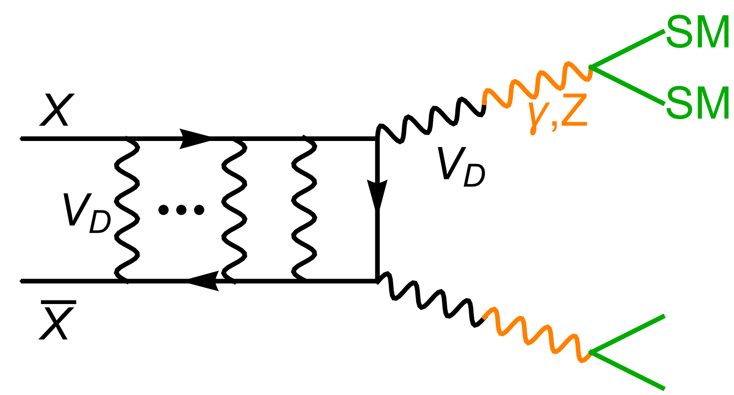

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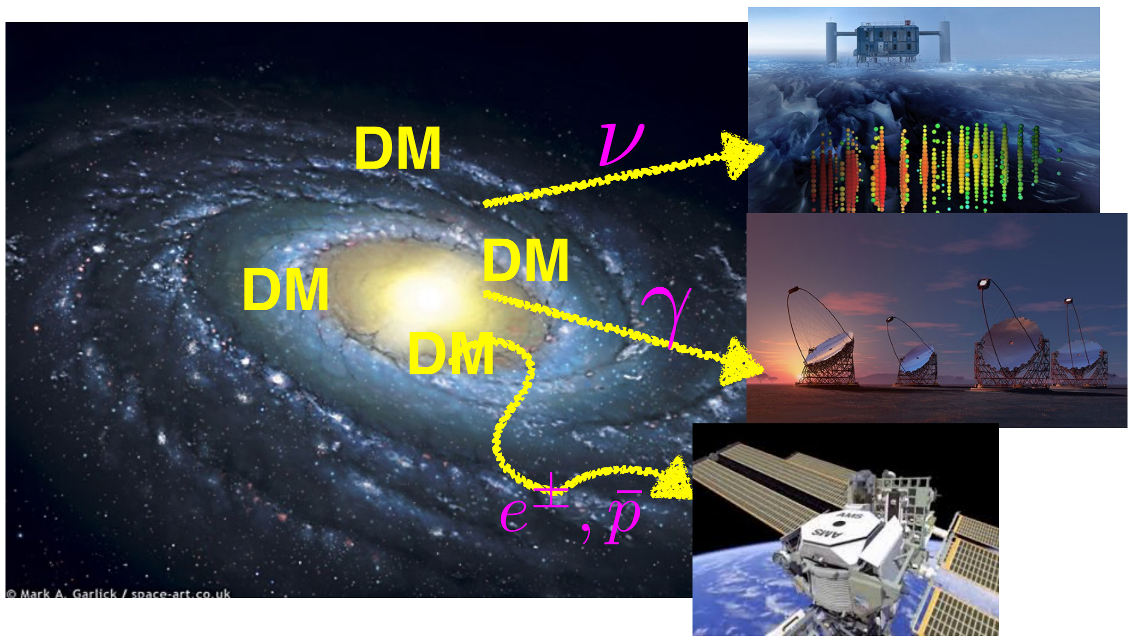

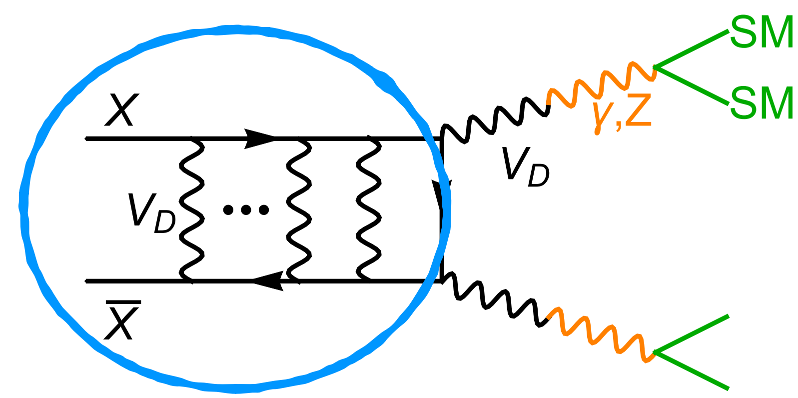

1. Sommerfeld and Bound State formation
Petraki+ 1611.01394

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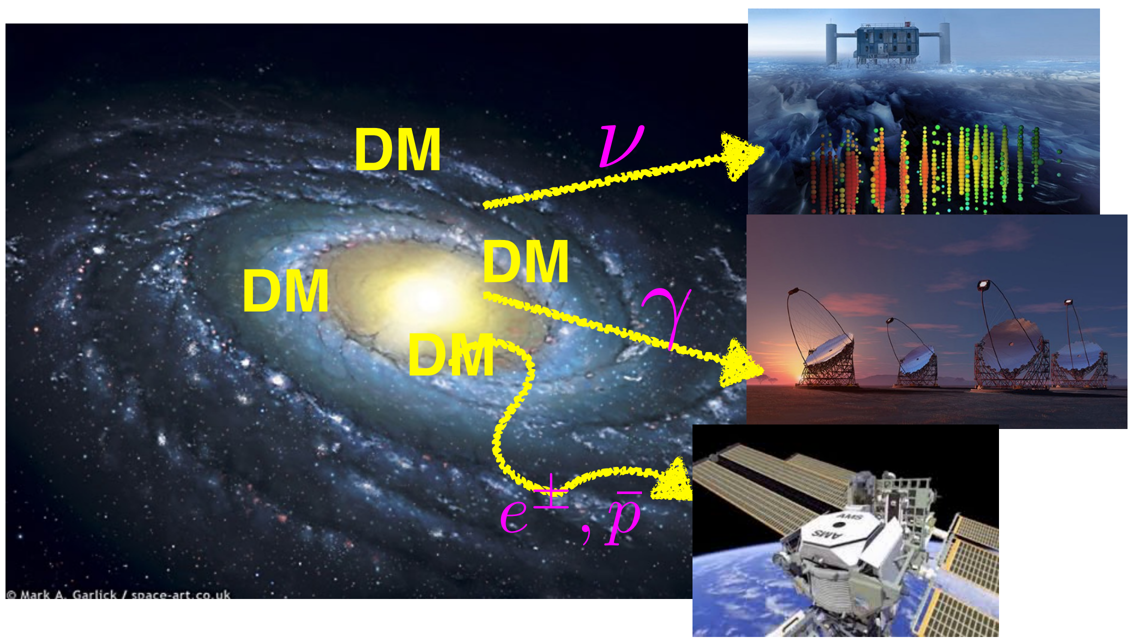

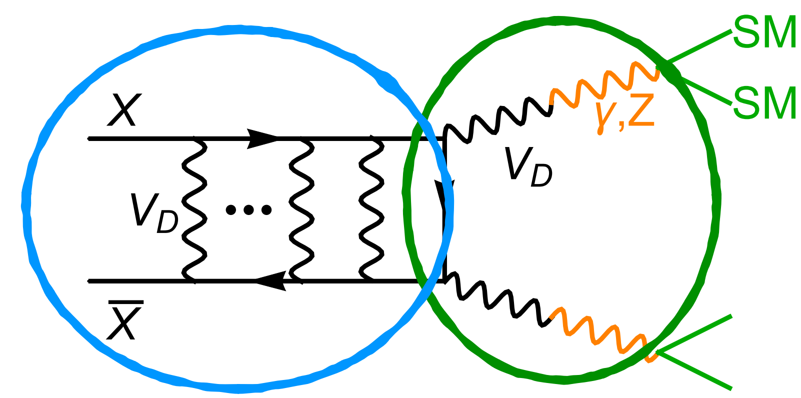

1. Sommerfeld and Bound State formation
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2. Cascade decays: one step softens the spectra
Elor Rodd Slatyer 1511.08787

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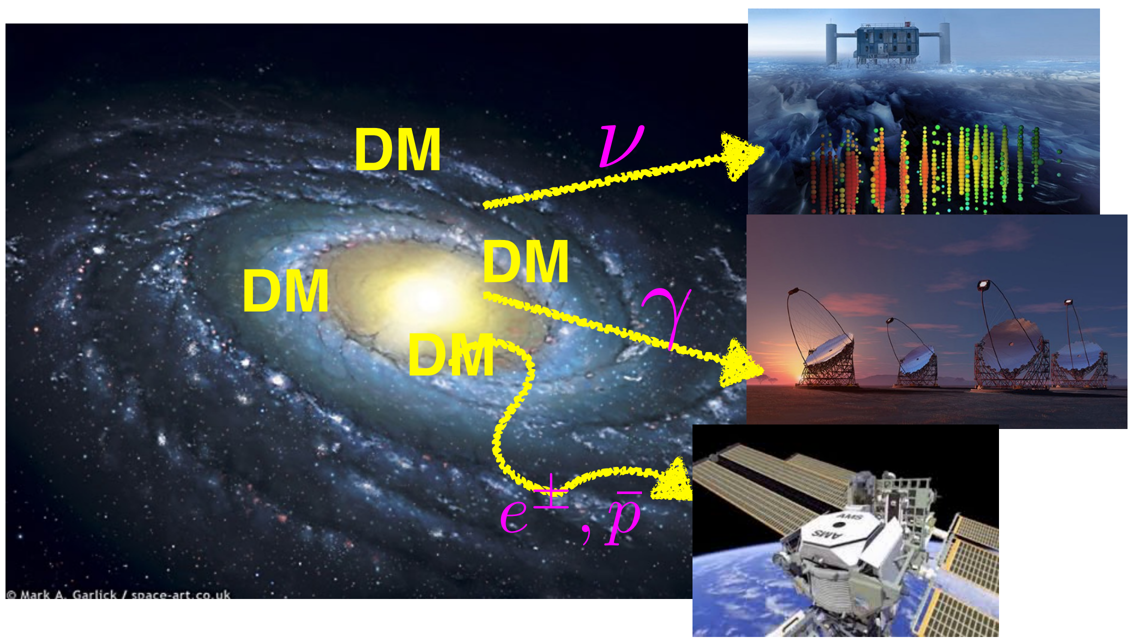
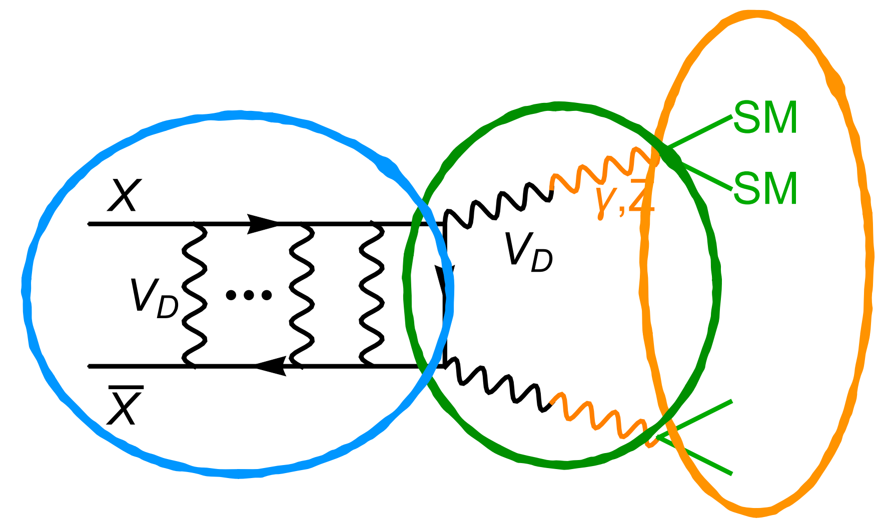
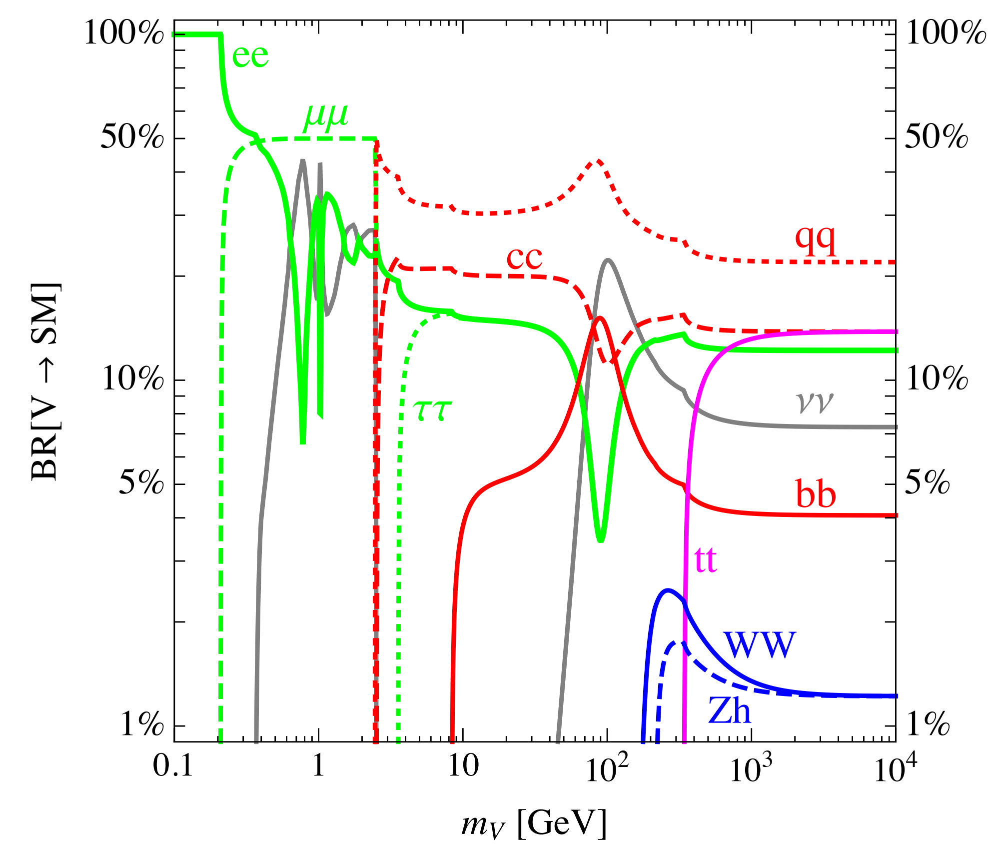




1. Sommerfeld and Bound State formation
Petraki+ 1611.01394

2. Cascade decays: one step softens the spectra
Elor Rodd Slatyer 1511.08787

3. Dark Photon decays



Supercooling

Dilaton Interactions

$$\mathscr{L}_{\rm kin} = k^2 \frac{\partial_\mu \chi^2}{2}$$ well-known in 5D, where $k^2 = 24$

see e.g.
Rattazzi Cargese2003
Nardini+ 0706.3388
Bellazzini+ 1209.3299

Redefine χ as canonically normalised, then:

$$V \simeq \frac{g_\chi^2}{k^4} \chi^4 \left[1 - \left(\frac{\chi}{k f} \right)^{\gamma_\epsilon} \right]$$

$$\text{Free Energy density} = \rho - Ts = g_* T^4 \pi^2 \left(\frac{1}{30} - \frac{2}{45}\right) = -g_* T^4 \frac{\pi^2}{90}$$

$$\lambda_{\text{peak}} = \frac{1}{\beta} v_{\text{coll}} = f_{\text{peak}}^{-1} \qquad f_{\text{peak}} \sim \frac{a_{\text{coll}}}{a} f_{\text{coll}} \simeq \frac{T_0}{T_{\text{coll}}} f_{\text{coll}} \simeq 10^{-5}\text{Hz} \frac{T_{\text{coll}}}{100\text{ GeV}} \frac{\beta}{H}$$

Potential at Finite T

Creminelli Nicolis Rattazzi hep-th/0107141,…

$T \gg m_*$ Free energy of interacting gluon gas + "usual" thermal contributions

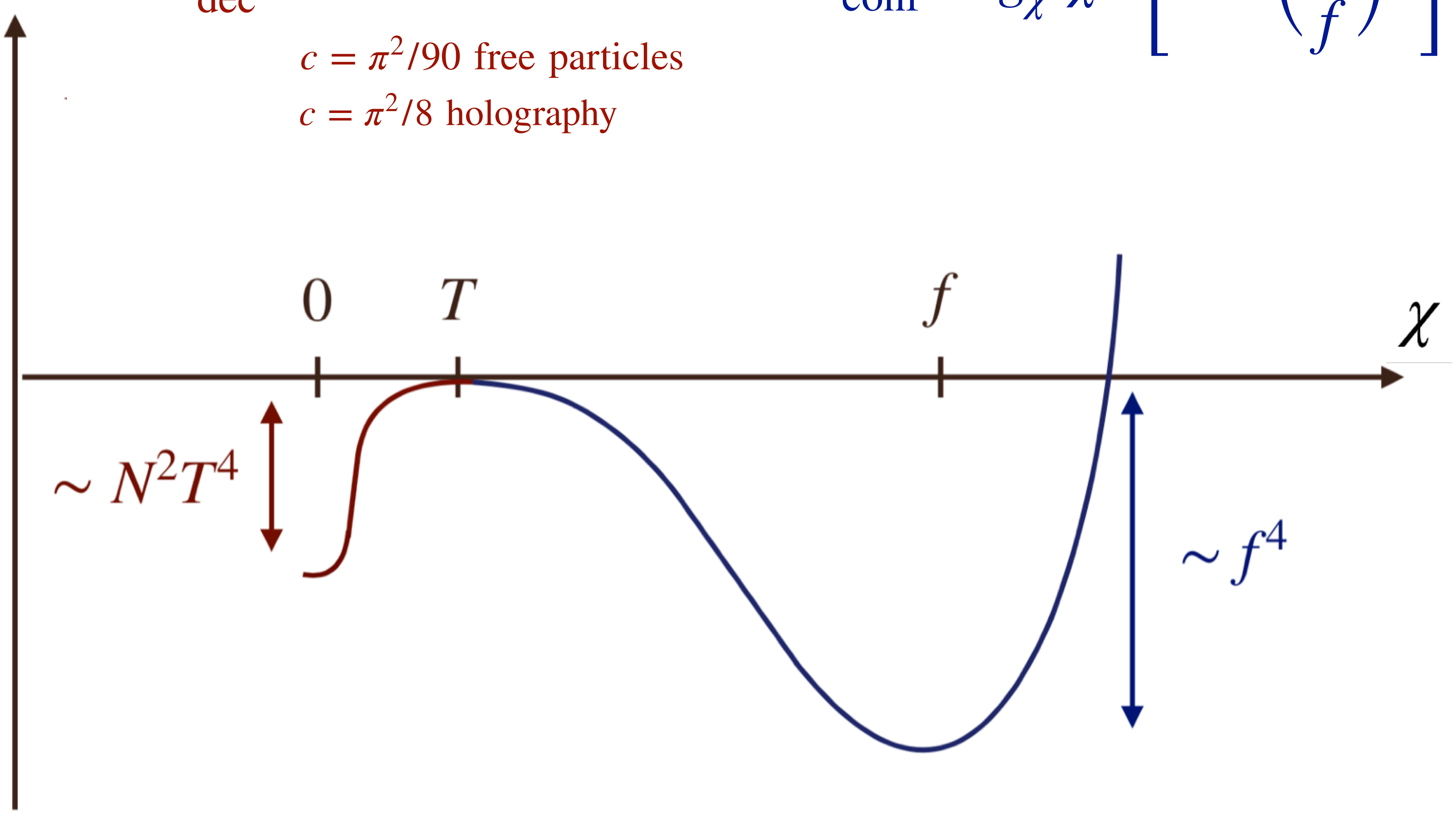
Big, only contribution necessary to describe PT!

$$V_{\text{dec}} = -\,c\,N^2T^4$$

$c = \pi^2/90$ free particles

$c = \pi^2/8$ holography

$$V_{\text{conf}} \simeq g_\chi^2\,\chi^4\left[1 - \left(\frac{\chi}{f}\right)^{\gamma_\epsilon}\right]$$

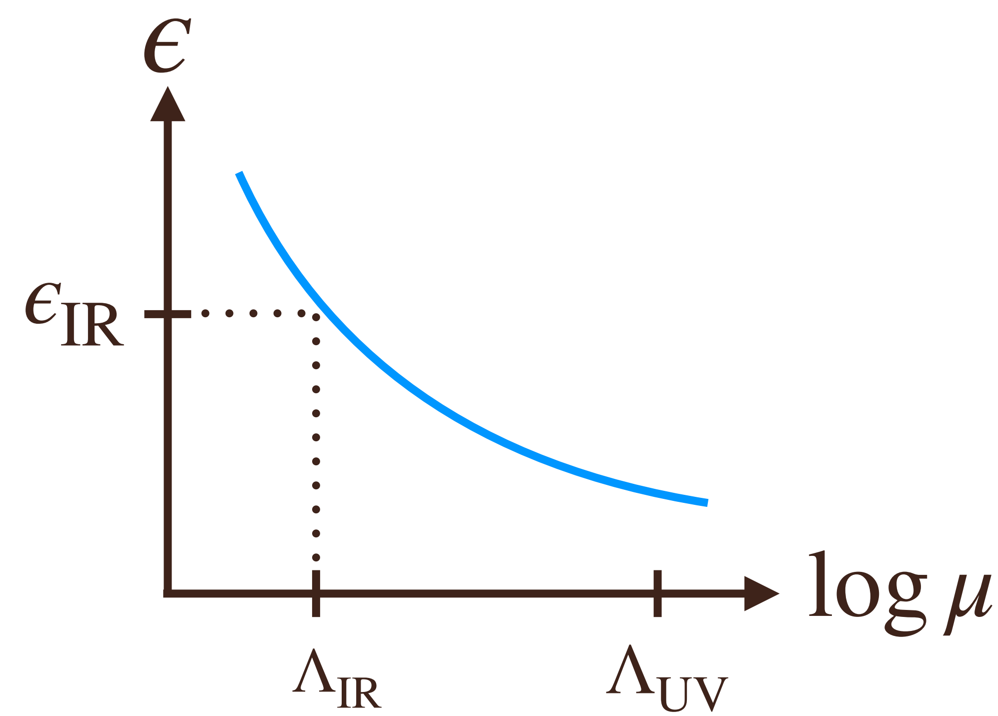


Breaking Scale Invariance

Assume

- Strongly-Interacting CFT in the UV
- Small explicit breaking of scale-invariance $\epsilon \mathcal{O}_\epsilon$ $\quad d_{\mathcal{O}} = 4 + \gamma_\epsilon \lesssim 4$

$$\frac{\partial \epsilon}{\partial \log \mu} \simeq \gamma_\epsilon \, \epsilon \longrightarrow \epsilon[\mu] \simeq \epsilon_{\rm IR} \left(\frac{\mu}{\Lambda_{\rm IR}}\right)^{\gamma_\epsilon}$$



Is this ~ a spontaneous breaking?

A Light Dilaton?

Dilaton = pseudo Goldstone Boson associated to breaking of scale invariance

$$\chi = f e^{\sigma/f} \qquad \sigma(x) \to \sigma(\lambda x) + f \ln \lambda$$

$V = g_\chi^2 \chi^4$ respects scale invariance + does not break it spontaneously

$$-\epsilon[\chi]\chi^4 \simeq g_\chi^2 \chi^4 \left[1 - \left(\frac{\chi}{f}\right)^{\gamma_\epsilon}\right]$$ spontaneous from explicit breaking

$$\boxed{m_\sigma^2 \simeq -4\,\gamma_\epsilon\, g_\chi^2 f^2}$$

QCD $\beta_{\alpha_s}(\Lambda_{\rm QCD}) \sim O(1)$ no light QCD dilaton

BSM Can γ_ϵ be made small at confinement scale? YES!

Contino Pomarol Rattazzi 2010
Bellazzini+ 1305.3919
Coradeschi+ 1306.4601

Nucleation Temperature

Supercooling begins at $T_{\rm start} \sim f$

Bubble nucleation ends SC at $\boxed{T_{\rm nuc} \sim f \exp\left(-c\,\frac{f^2}{m_\sigma^2}\right)}$

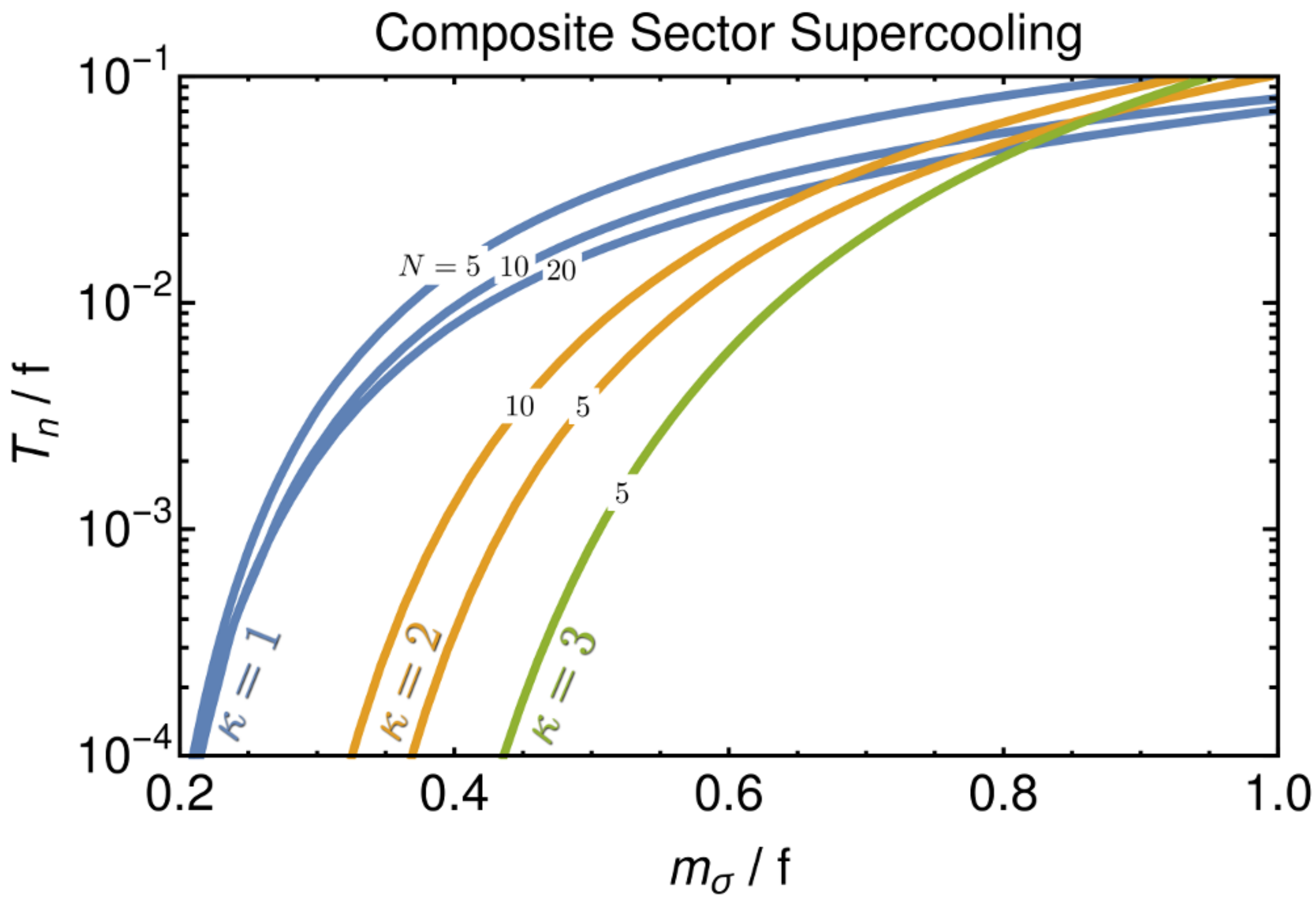
Nucleation happens when tunnelling rate ~ Hubble

$$\Gamma(T_{\rm nuc}) \sim H^4(T_{\rm nuc})$$

Bounce action $S_4 \approx 100$

Tunneling rate $\Gamma \sim T^4 \left(\frac{S_4}{2\pi}\right)^2 e^{-S_4}$

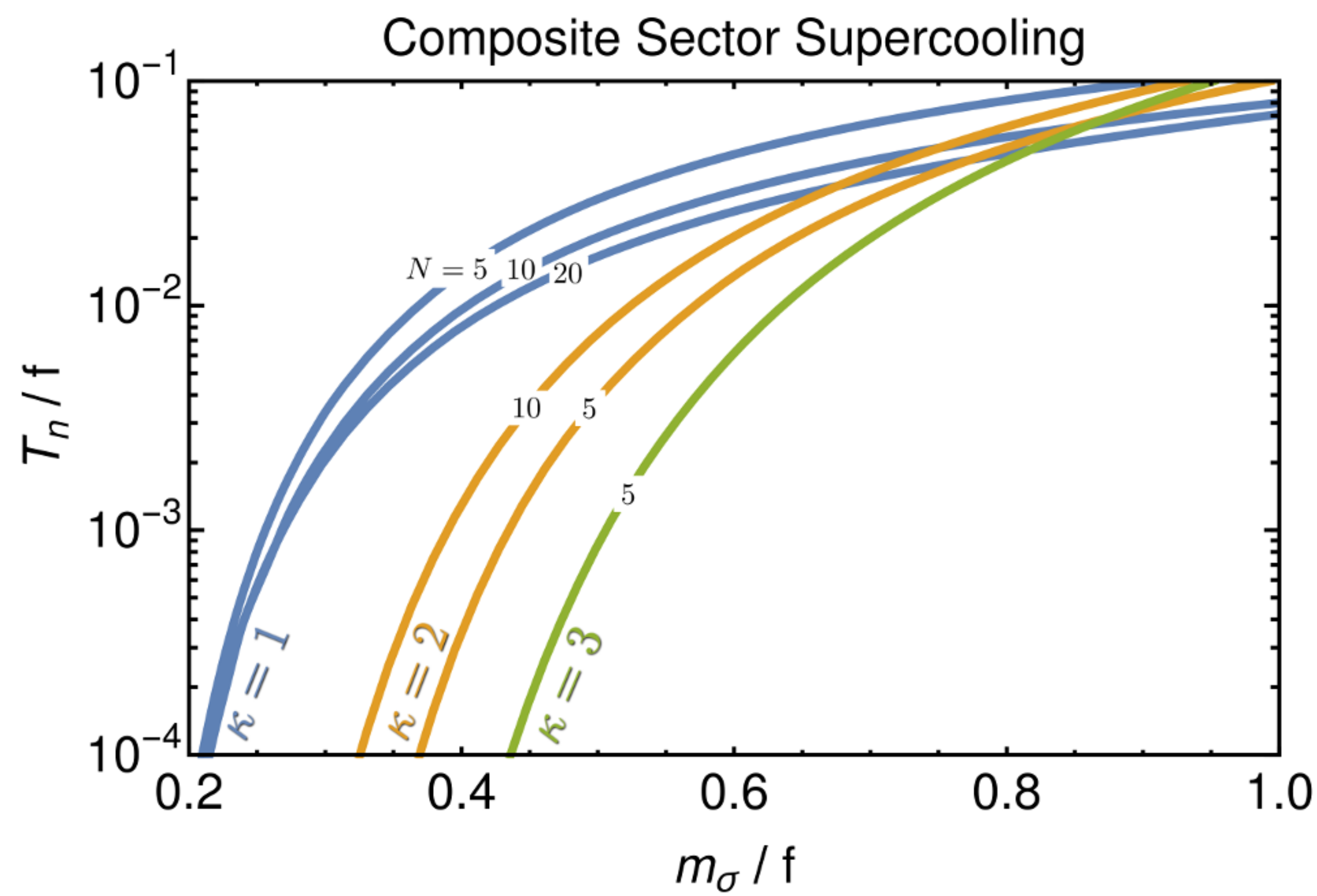
Nucleation Temperature



Effect of wave-function renormalization of the dilaton field

It can be large, e.g. $\kappa \simeq 5$ in 5D duals!

Nucleation Temperature



For small m_σ PT seem to never complete! → But then it can be triggered by QCD

Iso Serpico Shimada 1704.04955

von Harling Servant 1711.11554

$T_{\rm QCD} < 100\,{\rm MeV}$ expected, cause all quarks are massless in deconfined phase!

Gravitational Waves from Phase Transition

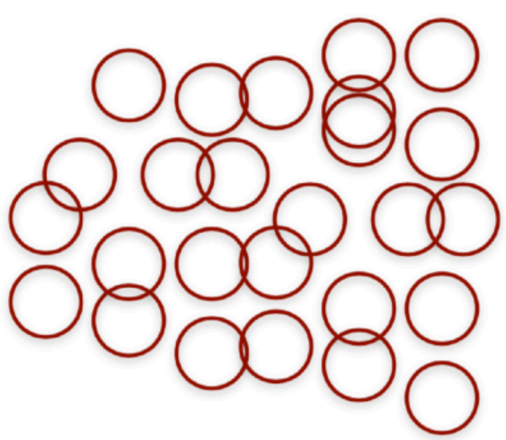
Randall Servant hep-ph/0607158,…

$$\Omega_{\mathrm{GW}} \propto \left(H/\beta\right)^2 \qquad \beta^{-1} \sim \text{duration of PT}$$

$$\frac{\beta}{H} \simeq T \frac{dS_4}{dT}\bigg|_{T_{\mathrm{nuc}}} \simeq 15 \left(\frac{10}{N_{\mathrm{e-fold}}}\right)^2$$

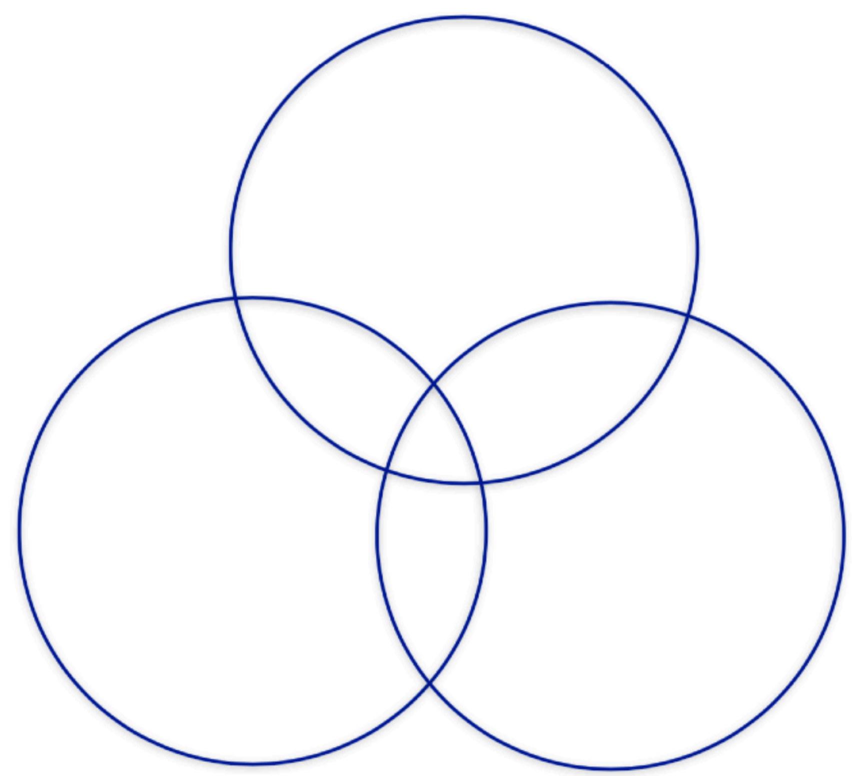
Standard 1st order PT

$\beta/H \sim 100$



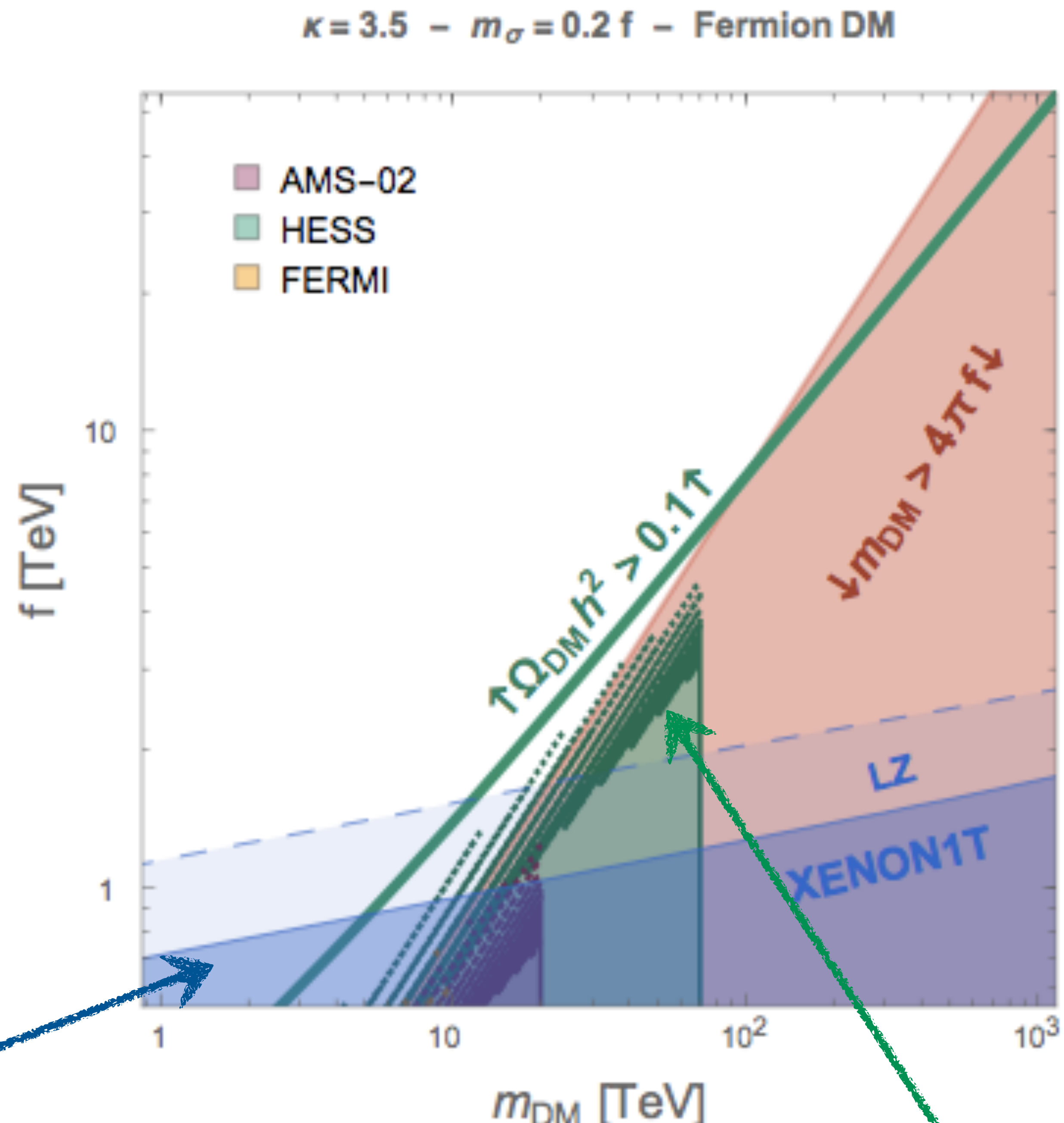
Supercooled PT

$\beta/H \sim 10$



Pheno of Composite DM

$$\mathscr{L}_{\mathrm{DM}} = -\, m_{\mathrm{DM}} \bar{\psi}\psi \left(1 + \frac{\sigma}{k f}\right)$$



DD needs assumptions on $c_G \dfrac{\alpha_s}{8\pi k f} \sigma G G$

Conservatively we choose $c_G = 1/3$

ID is p-wave

Sommerfeld enhanced

Supercool Dark Matter

$$Y = \frac{\text{number density}}{\text{entropy density}}$$

~ one-slide review of Hambye Strumia Teresi 1805.01473

Supercooling $\oplus$ Sub-thermal

→ DM massless before supercooling

$$Y_{\rm eq} = \frac{45 g_{\rm DM}}{2\pi^4 g_s}$$

→ Dilution by short inflation period

$$Y_{\rm super-co} = Y_{\rm eq} \left(\frac{T_{\rm nuc}}{T_{\rm start}}\right)^3,$$

$$SM + SM \to DM + DM$$

$$\frac{dY_{\rm DM}}{dx} = \frac{\lambda}{x^2}\left(Y_{\rm DM}^2 - Y_{\rm DM}^{2\rm eq}\right), \qquad x = \frac{m_{DM}}{T}$$

$$Y_{\rm sub-th} \propto \lambda \exp\left(-2\, x_{RH}\right)$$

WARNING: If $T_{RH} > T_{FO}$

then back to standard freeze-out!

String Potential at Finite T?

$$E_{\text{QCD}} \simeq \sigma(T)\, d \qquad \sigma(T > T_{\text{crit}}) \to 0$$

~ supported by Lattice

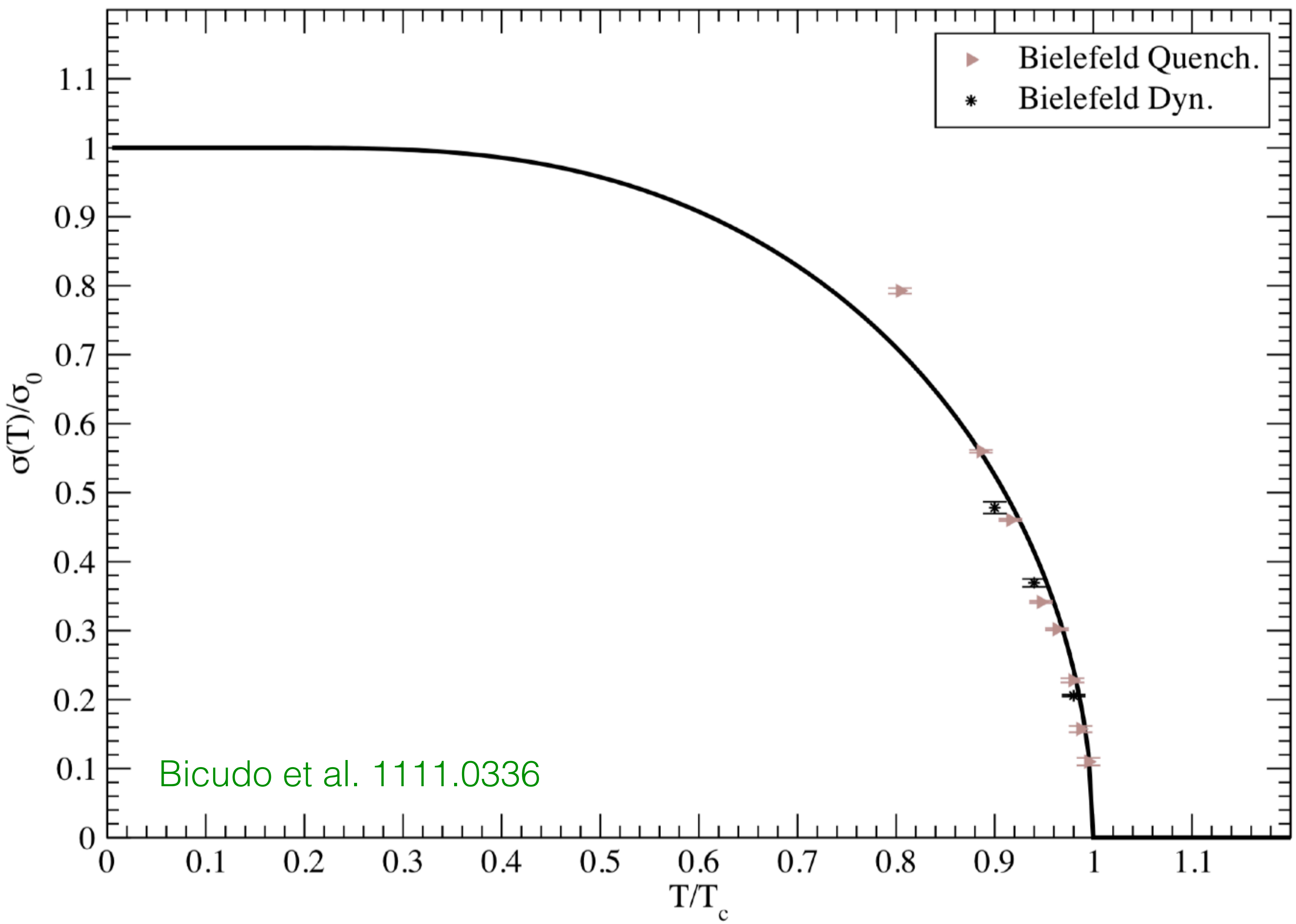
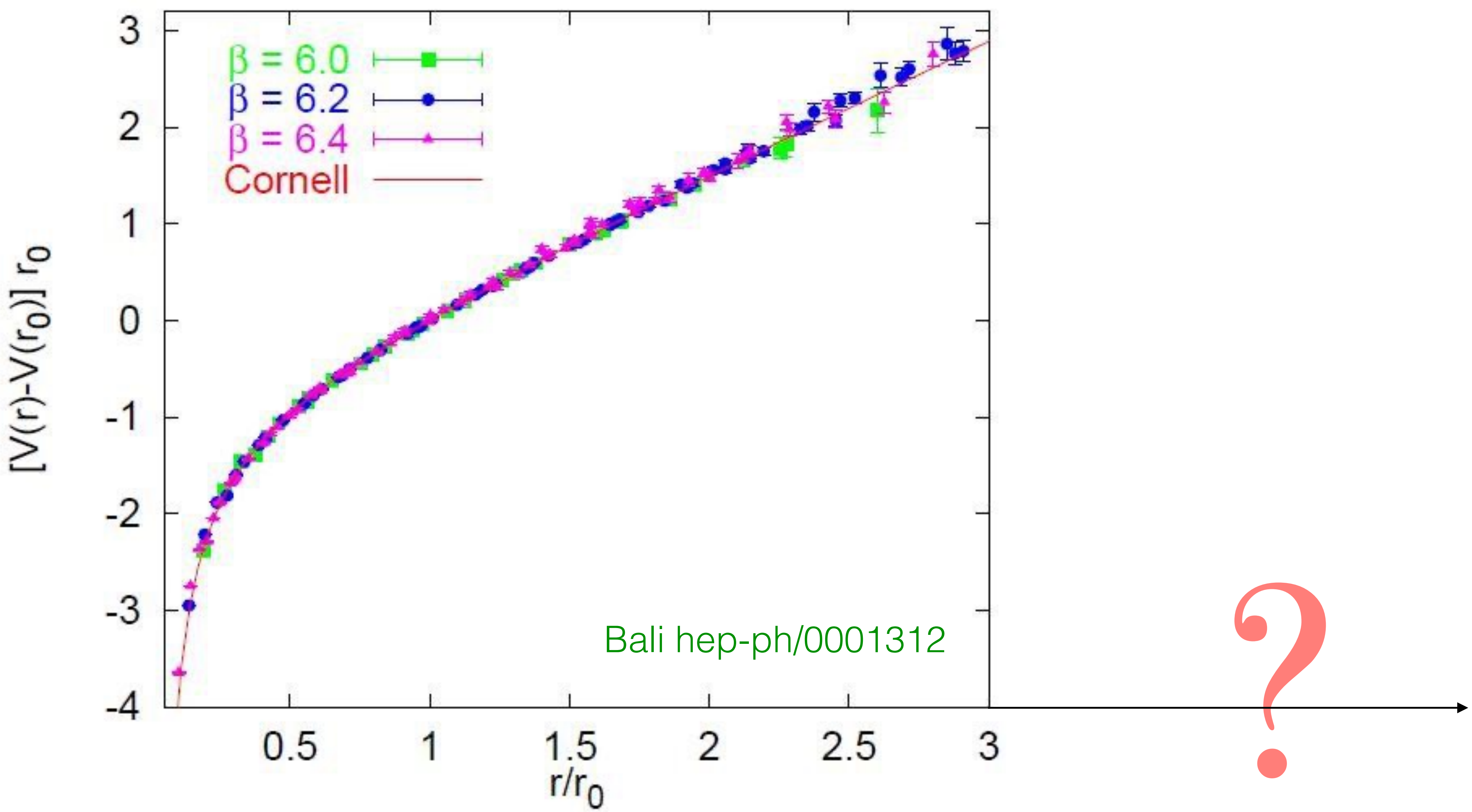


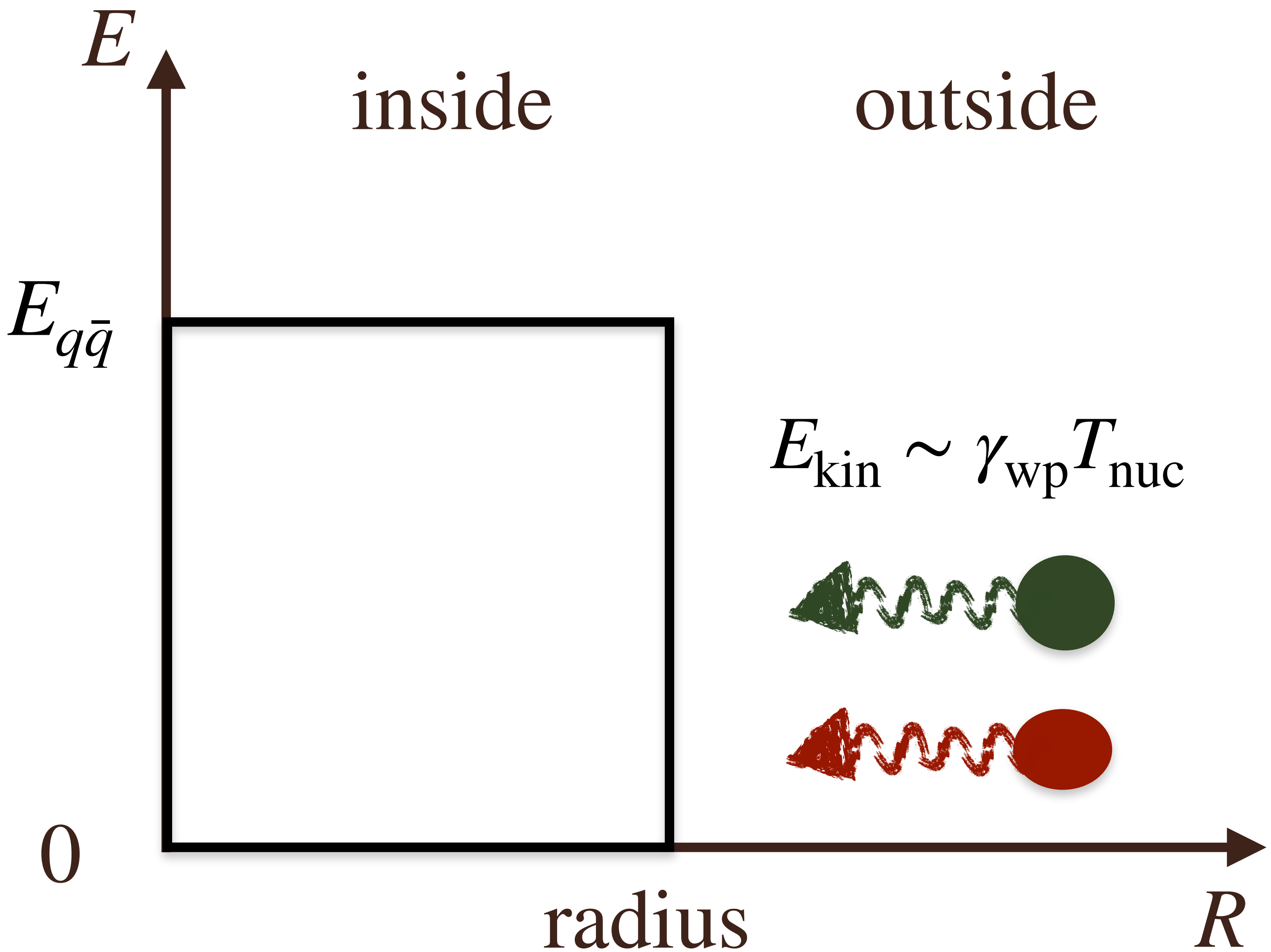
Figure 1: $\sigma(T)$ Bielefeld data and emprirical curve

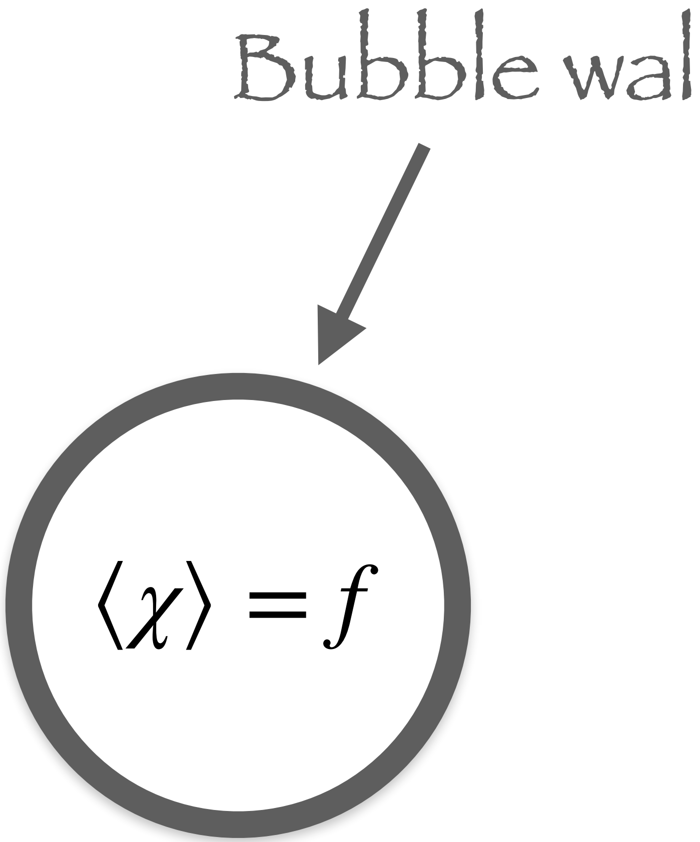
String Potential at large d?

? $$E_{q\bar{q}} \simeq f^2 d \quad \text{at} \quad d \gg f^{-1}$$?

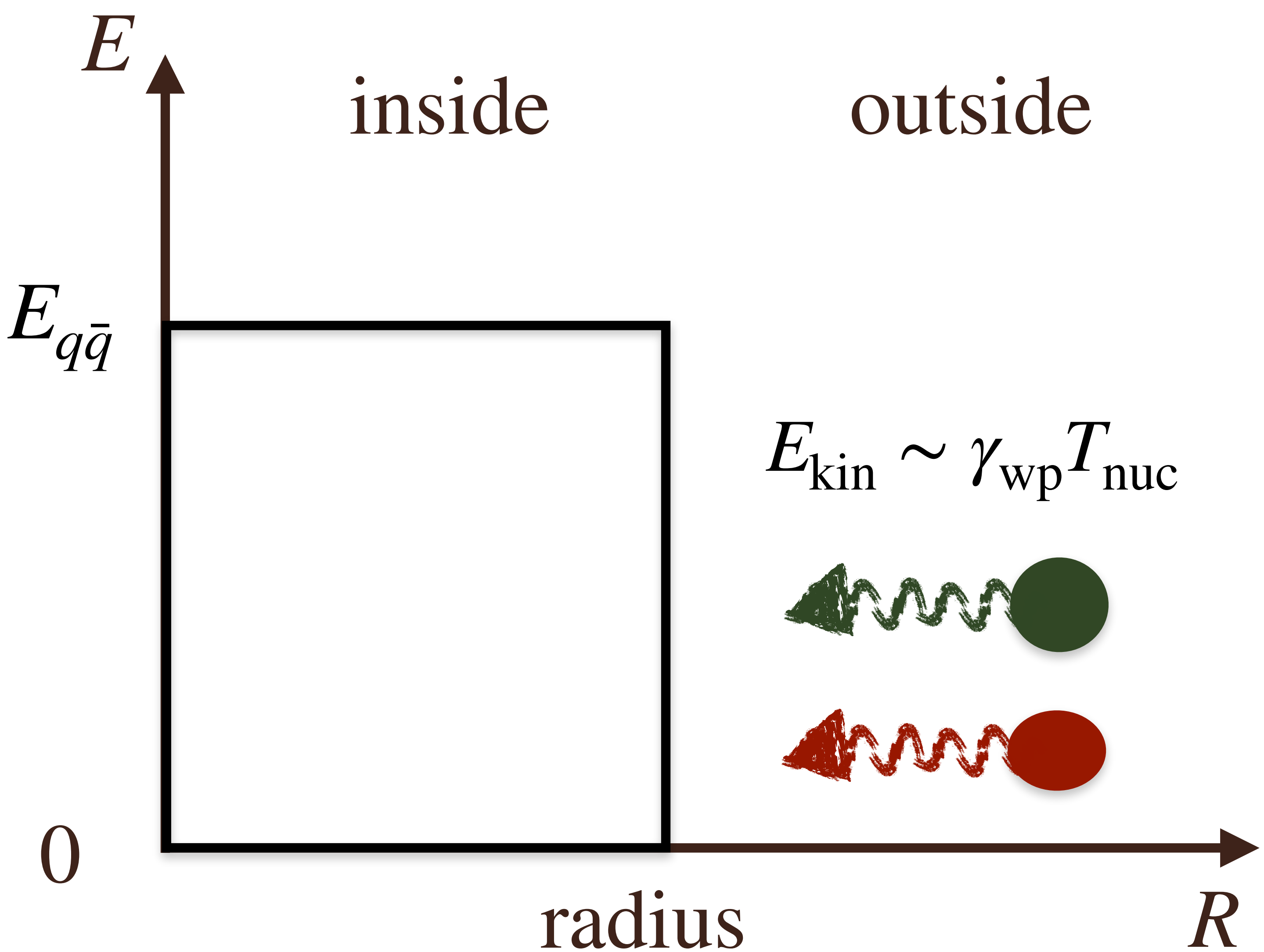


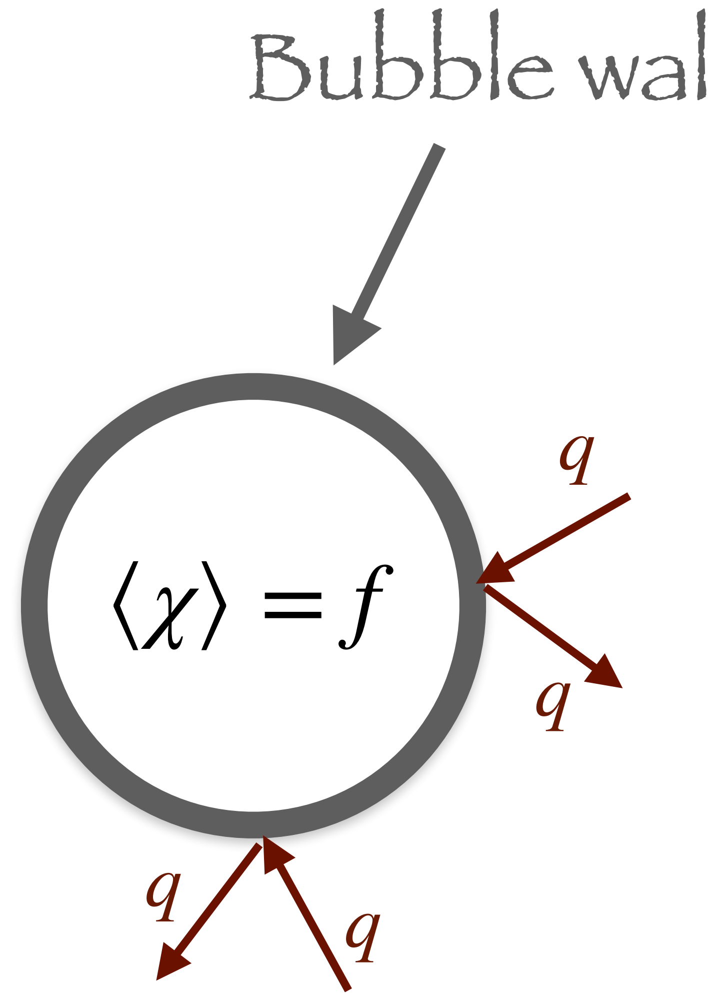
In the frame of the bubble wall





In the frame of the bubble wall





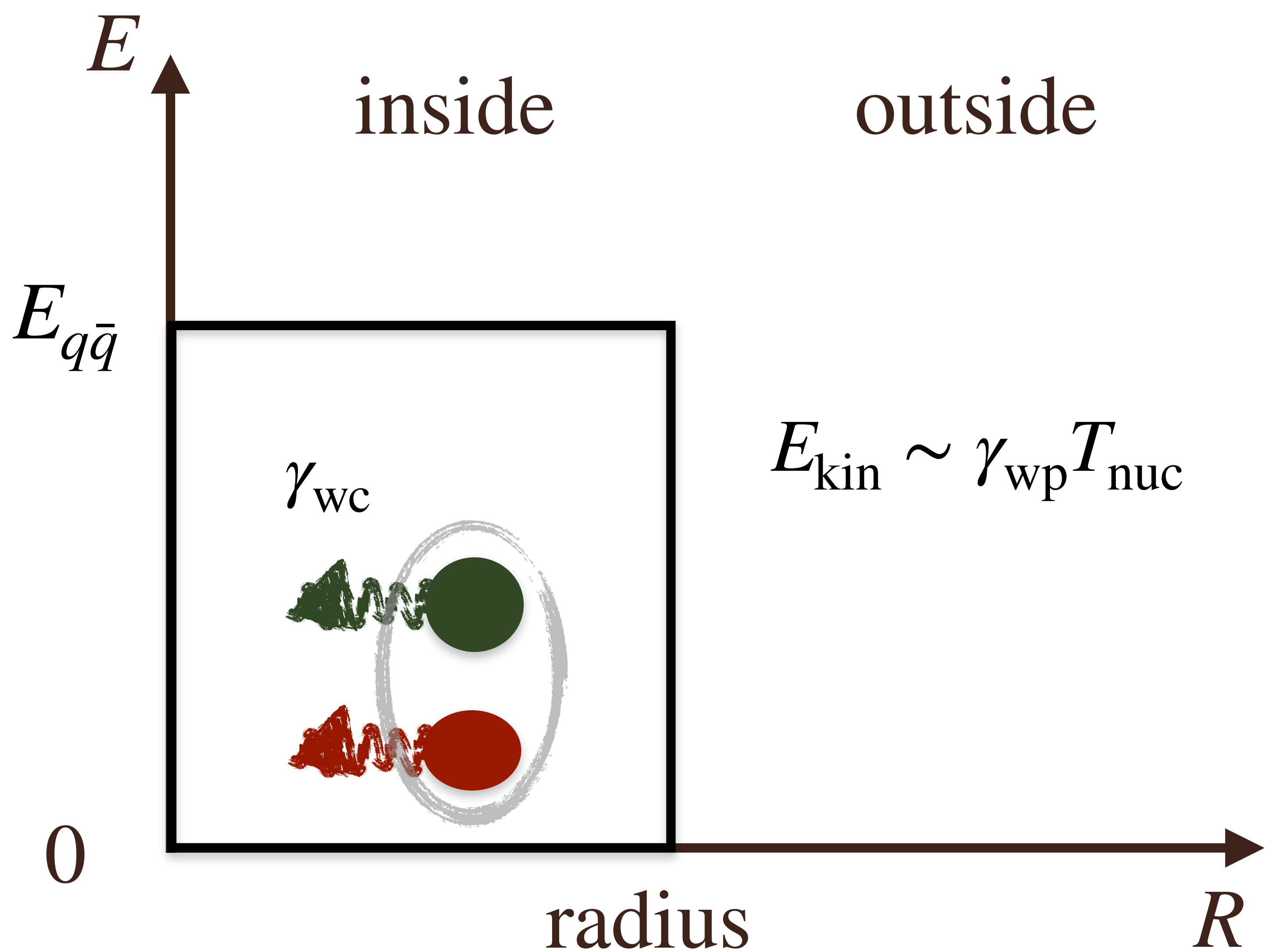
1) Pressure if all quarks bouncing back:

$\mathscr{P}_{\rm friction} \sim \Delta p\, n \sim 2\gamma T_{\rm nuc}\, \gamma T_{\rm nuc}^3$

$\mathscr{P}_{\rm Expand} \sim \Delta V \sim f^4$

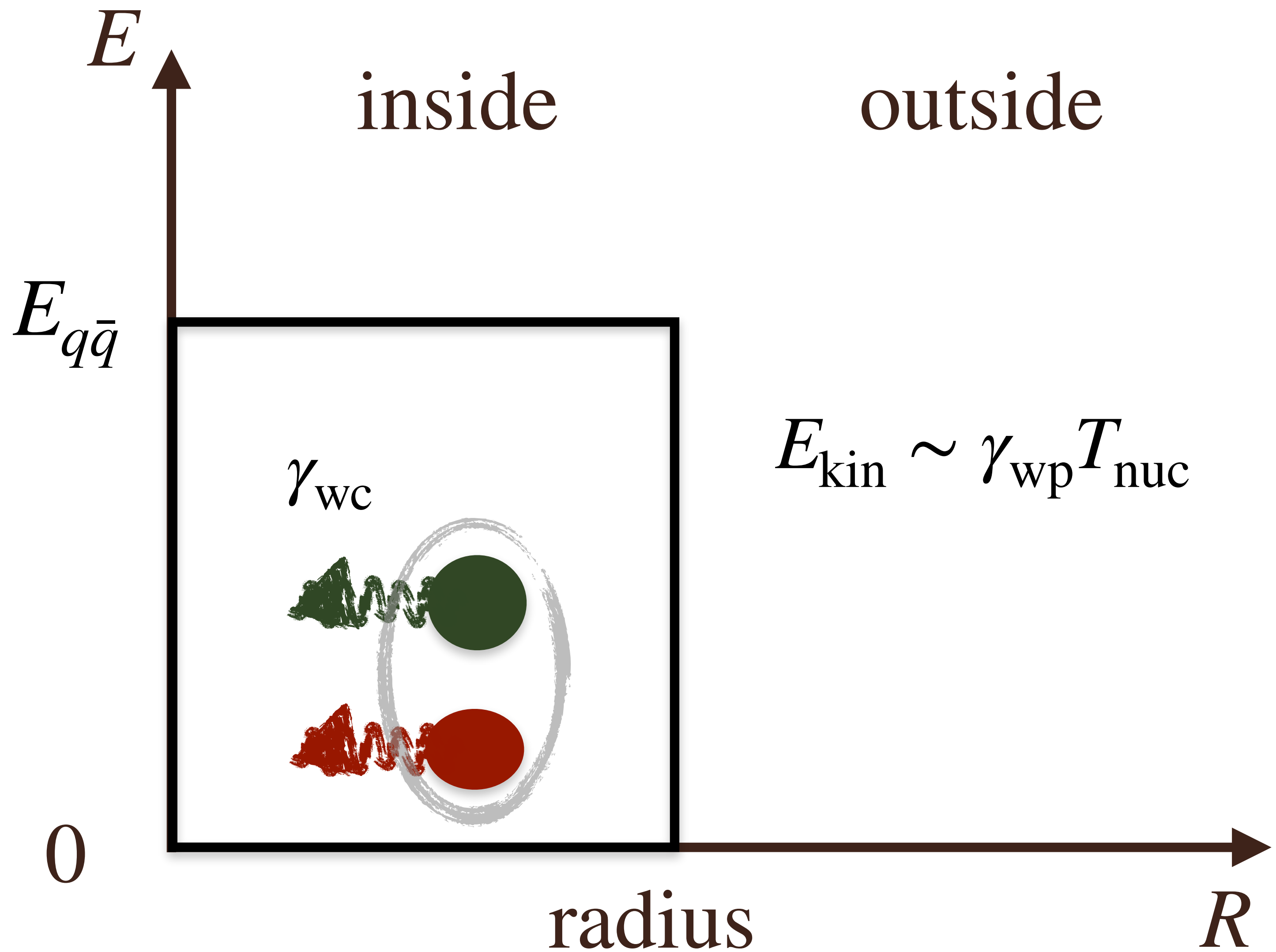
-> Terminal velocity: $\gamma_{\rm wp}^{\rm terminal} \sim \dfrac{f^2}{T_{\rm nuc}^2}$

In the frame of the bubble wall



2) Quarks enter inside the bubble when $E_{\rm kin} \gtrsim \gamma_{\rm wc} E_{q\bar{q}}$

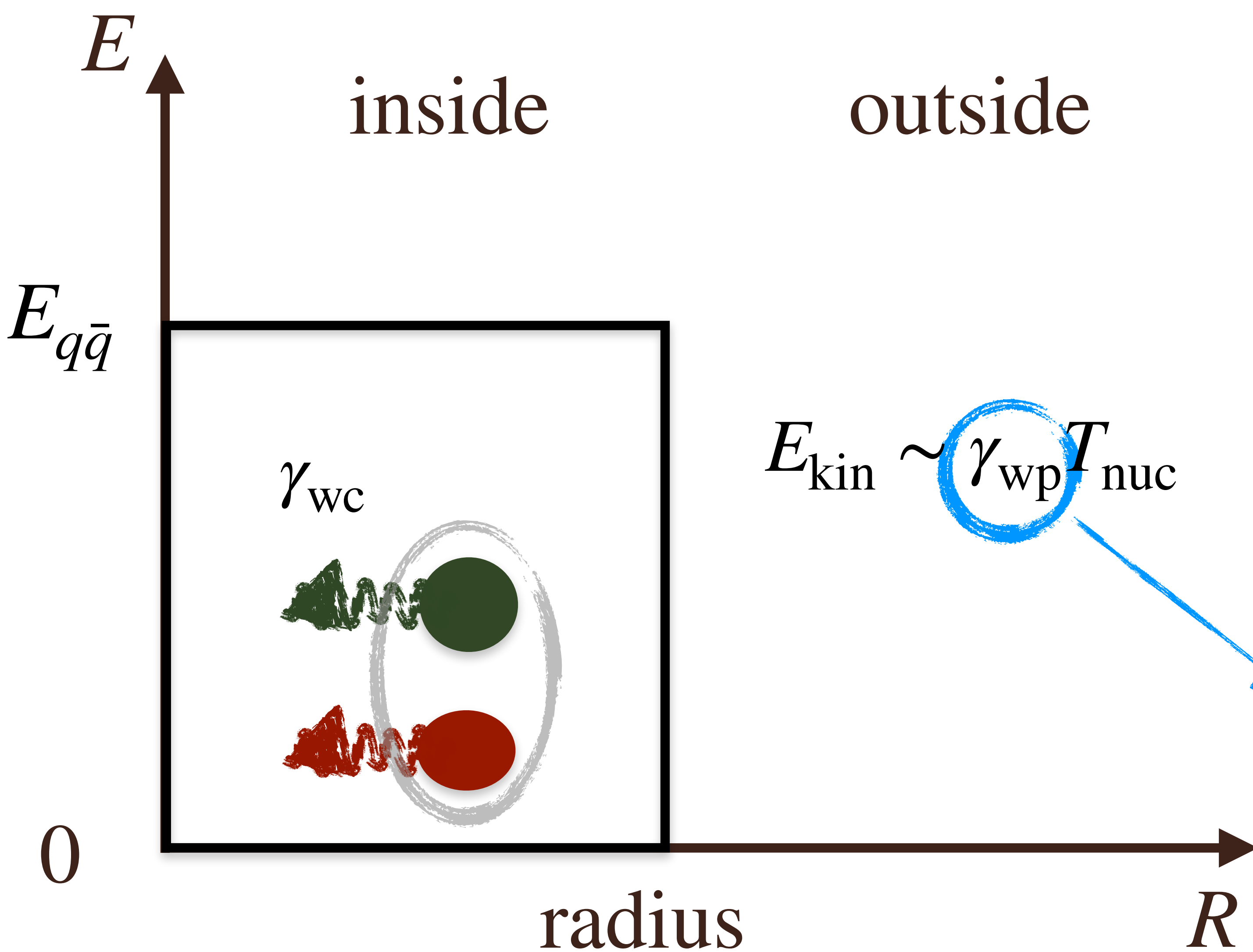
In the frame of the bubble wall



$$E_{q\bar{q}} = \frac{f^2}{\gamma_{cp}^{1/3} T_{nuc}}$$

2) Quarks enter inside the bubble when $E_{kin} \gtrsim \gamma_{wc} E_{q\bar{q}}$

In the frame of the bubble wall



$$E_{\rm kin} \sim \gamma_{\rm wp} T_{\rm nuc}$$

$$E_{q\bar{q}} = \frac{f^2}{\gamma_{\rm cp}^{1/3} T_{\rm nuc}}$$

$$\gamma_{\rm cp} \sim \left(\frac{f}{T_{\rm nuc}}\right)^{3/2}$$

2) Quarks enter inside the bubble when $E_{\rm kin} \gtrsim \gamma_{\rm wc} E_{q\bar{q}}$

-> A single string has energy $E_{q\bar{q}} \sim \left(\frac{f}{T_{\rm nuc}}\right)^{1/2} f \boxed{\gg f}$

-> Quarks enter the bubbles, $E_{q\bar{q}} \ll E_{\rm kin}^{\rm terminal}$

DM abundance after supercooling

from Hambye Strumia Teresi 1805.01473 to Baldes Gouttenoire FS Servant 1911.xxxxx

$\boxed{\text{Supercooling}} \oplus \boxed{\text{Sub-thermal}}$

DM abundance after supercooling

from Hambye Strumia Teresi 1805.01473 to Baldes Gouttenoire FS Servant 1911.xxxxx

Supercooling

→ DM massless before supercooling

$$Y_{\rm eq} = \frac{45 g_{\rm DM}}{2\pi^4 g_s}$$

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Supercooling

→ DM not yet formed
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$$Y_{\rm super-co} = Y_{\rm eq} \left(\frac{T_{\rm nuc}}{T_{\rm start}}\right)^3,$$

DM abundance after supercooling

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Supercooling

→ DM not yet formed
before supercooling

$$Y_{\rm eq}^{\rm quarks} = \frac{45 g_{\rm q}}{2\pi^4 g_{\rm s}}$$

→ Dilution by inflation +
enhancement by string breaking

$$Y_{\rm super-co} = r\, Y_{\rm eq}^{\rm quarks} \left(\frac{T_{\rm nuc}}{T_{\rm start}}\right)^{2.5},$$

DM abundance after supercooling

from Hambye Strumia Teresi 1805.01473 to Baldes Gouttenoire FS Servant 1911.xxxxx

Supercooling $\oplus$ Sub-thermal

→ DM not yet formed before supercooling

$$Y_{\rm eq}^{\rm quarks} = \frac{45 g_{\rm q}}{2\pi^4 g_{\rm s}}$$

→ Dilution by inflation + enhancement by string breaking

$$Y_{\rm super-co} = r\, Y_{\rm eq}^{\rm quarks} \left(\frac{T_{\rm nuc}}{T_{\rm start}}\right)^{2.5},$$

conceptually equivalent

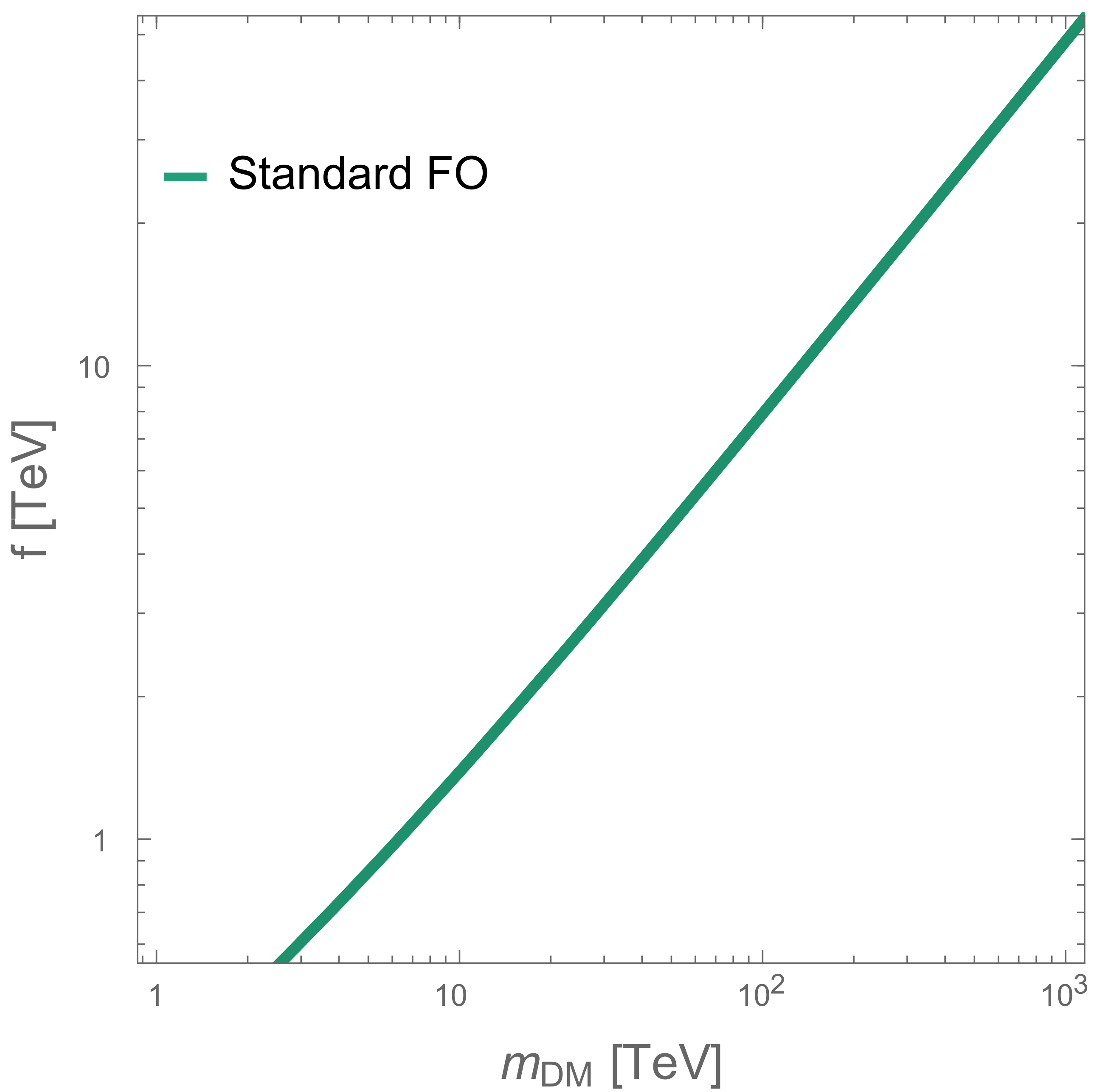
$$Y_{\rm sub-th} \propto \lambda \exp\left(-2\, x_{RH}\right)$$

WARNING: If $T_{RH} > T_{FO}$

then back to standard freeze-out!

Pheno of Supercool Composite DM

$$\mathcal{L}_{\rm DM} = -\, m_{\rm DM}\,\bar{\psi}\psi\left(1+\frac{\sigma}{kf}\right) \qquad m_{\rm DM} = g_\star f$$



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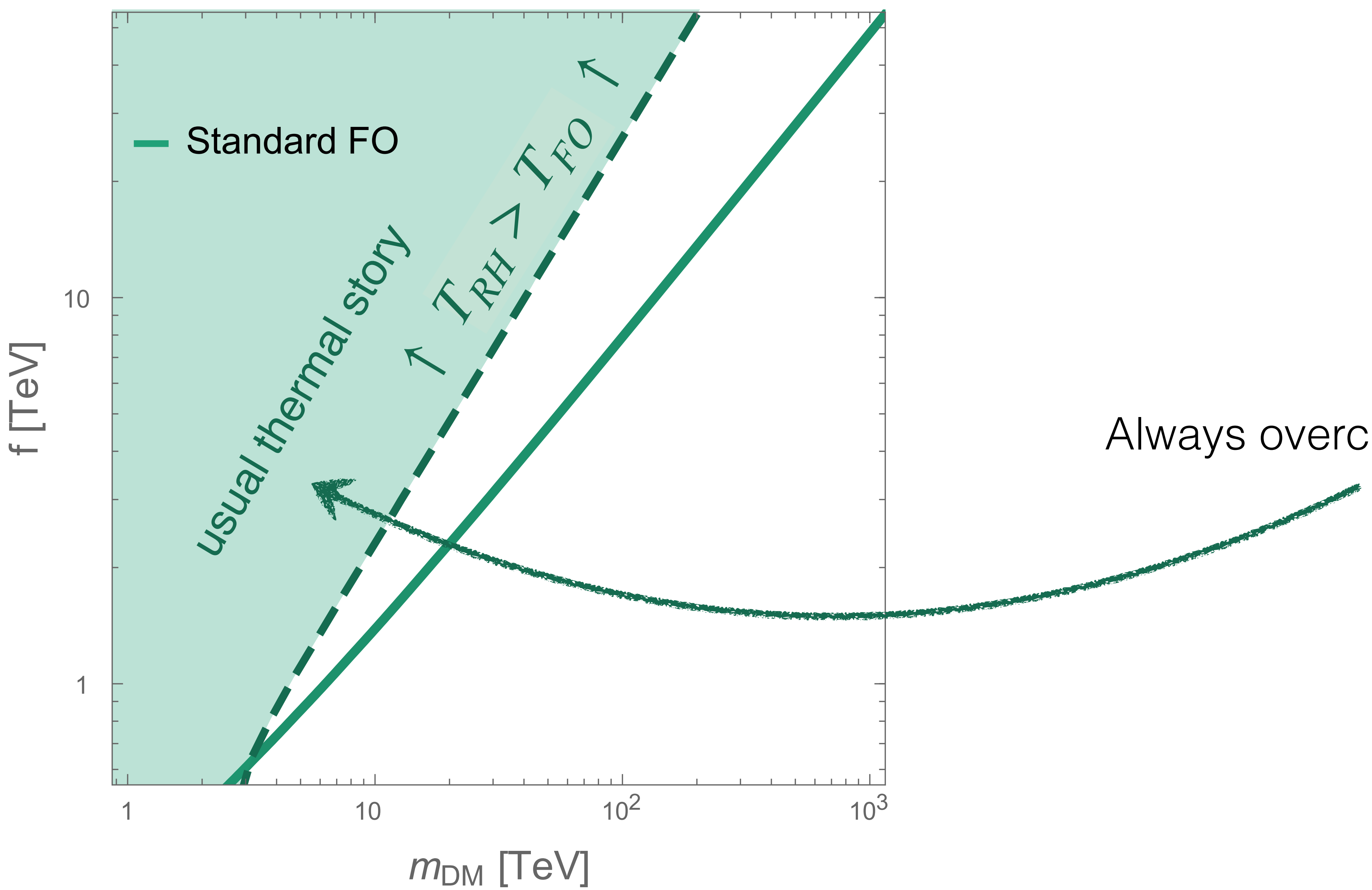

Always overclosure here!

Pheno of Supercool Composite DM

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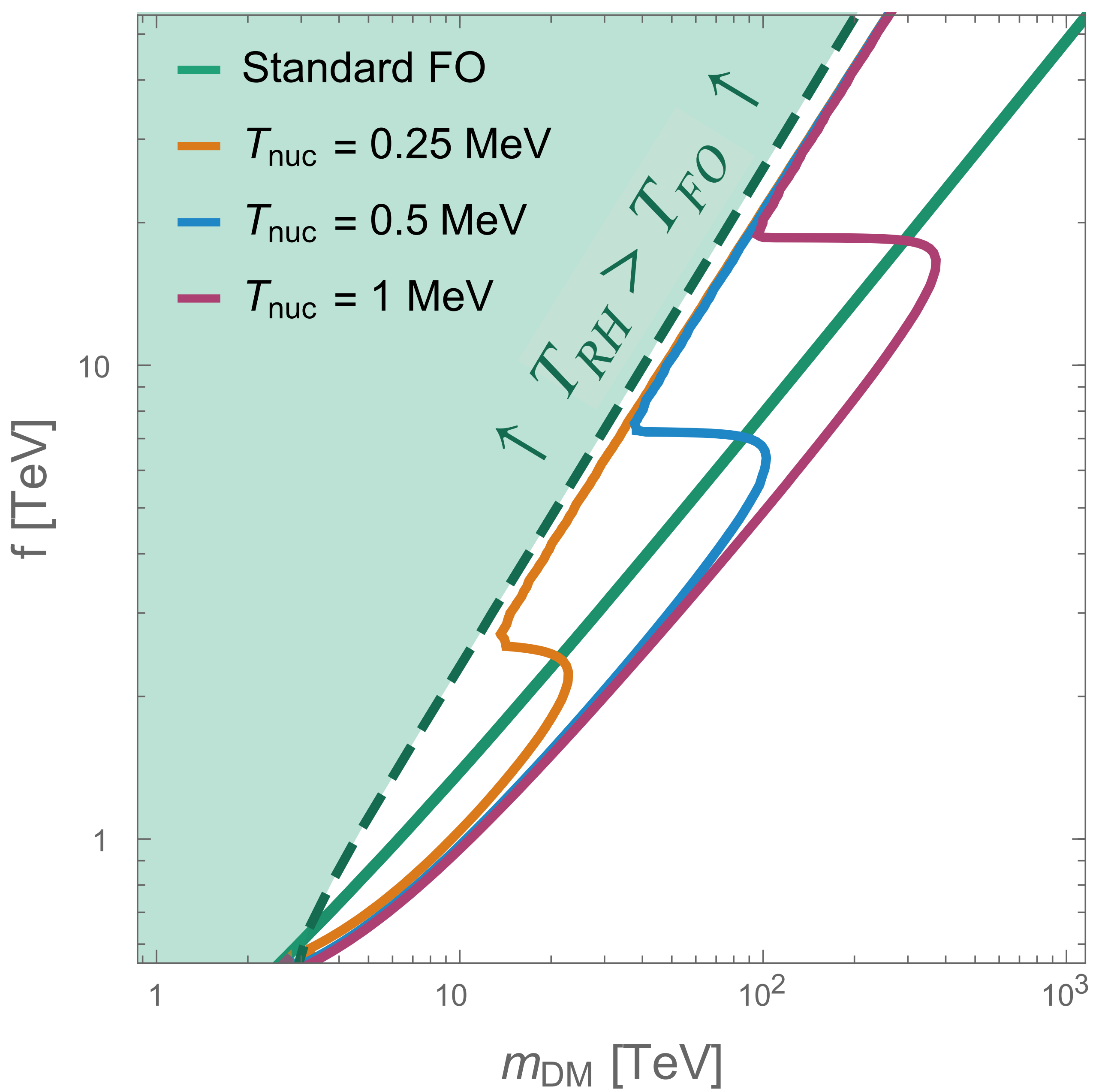

DM abundance lines

after supercooling

$$Y_{\rm super-co} = r\, Y_{\rm eq}^{\rm quarks} \left(\frac{T_{\rm nuc}}{T_{\rm start}}\right)^{2.5},$$

$$Y_{\rm sub-th} \propto \; \lambda \, \exp\left(-2\, x_{RH}\right)$$

$$\lambda \sim M_{\rm Pl}\, m_{\rm DM}\, \sigma v\, x_{\rm RH}$$