WIMP Dark Matter In An Unusual Cosmological History

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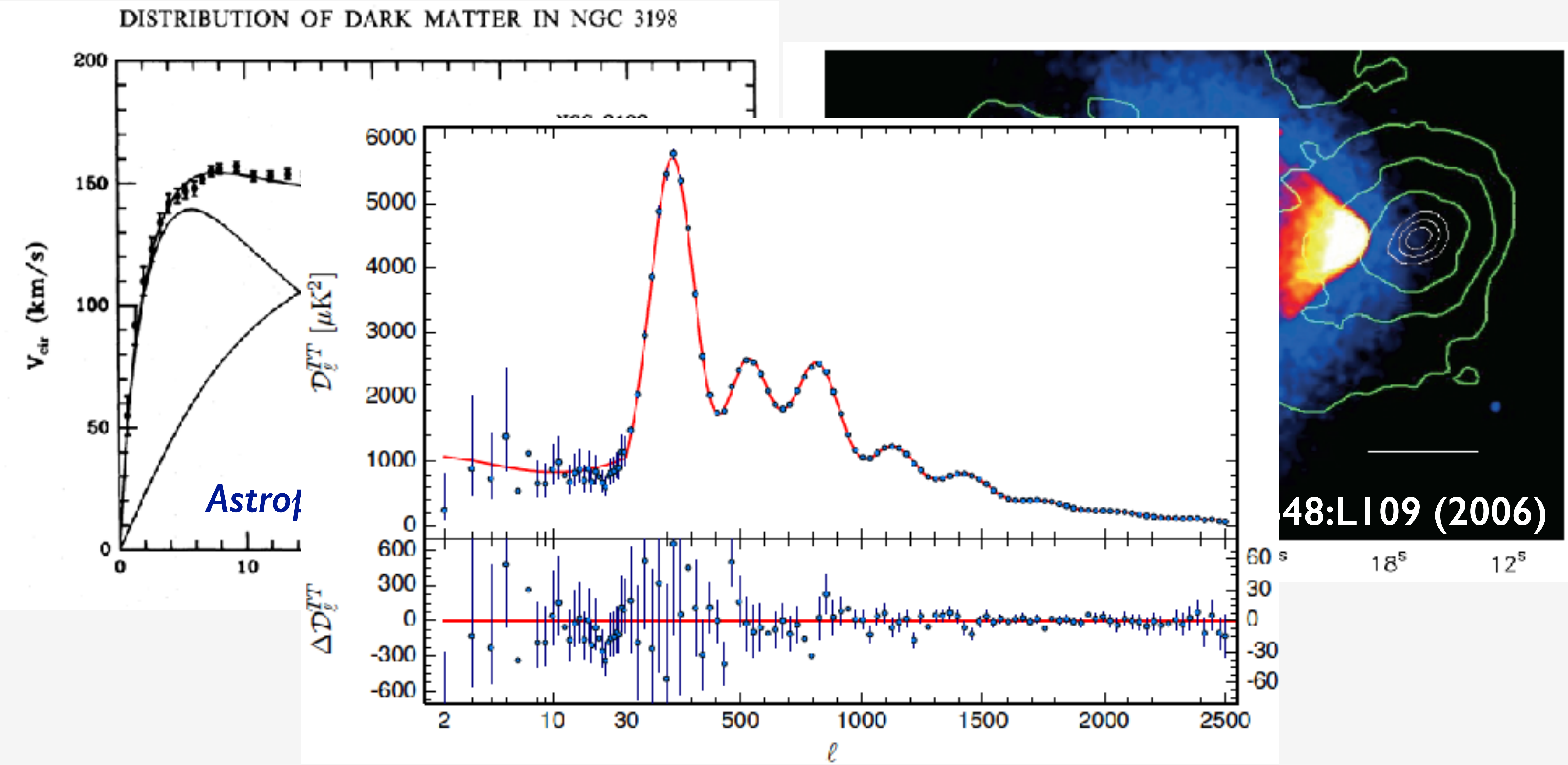
D. Berger, **SI**, T. Tait, M. Waterbury, *JHEP 07 (2020) 192*

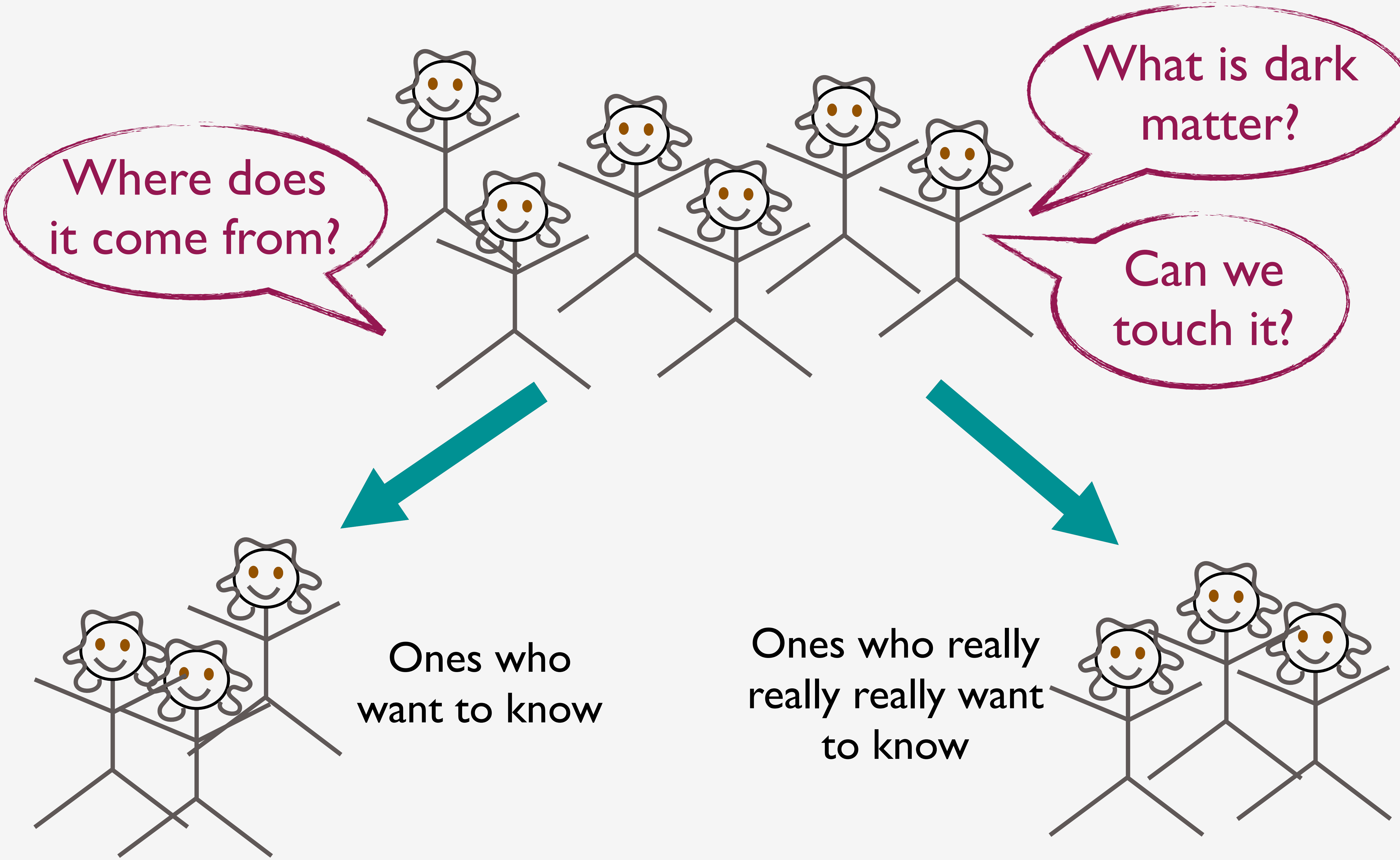
Dark Matter exists



$$\Omega_d \sim 0.27$$

$$\Omega_b \sim 0.04$$

Existential crisis?



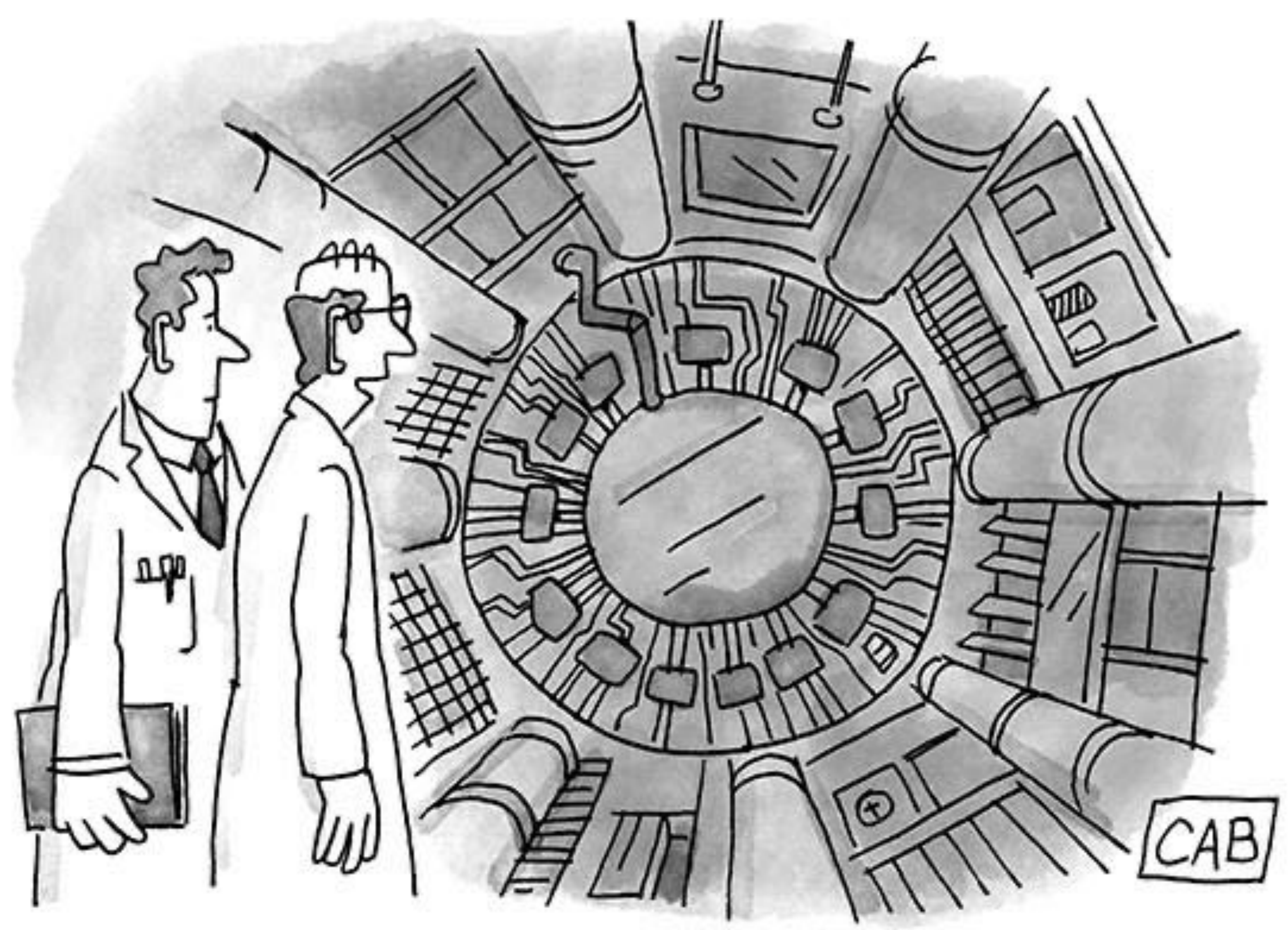
We know dark matter…

- is about 27% of the universe's energy density
- mostly (only?) interacts gravitationally
- is cold, collisionless (?)
- does not clump much (?)

These are only astrophysical observations!

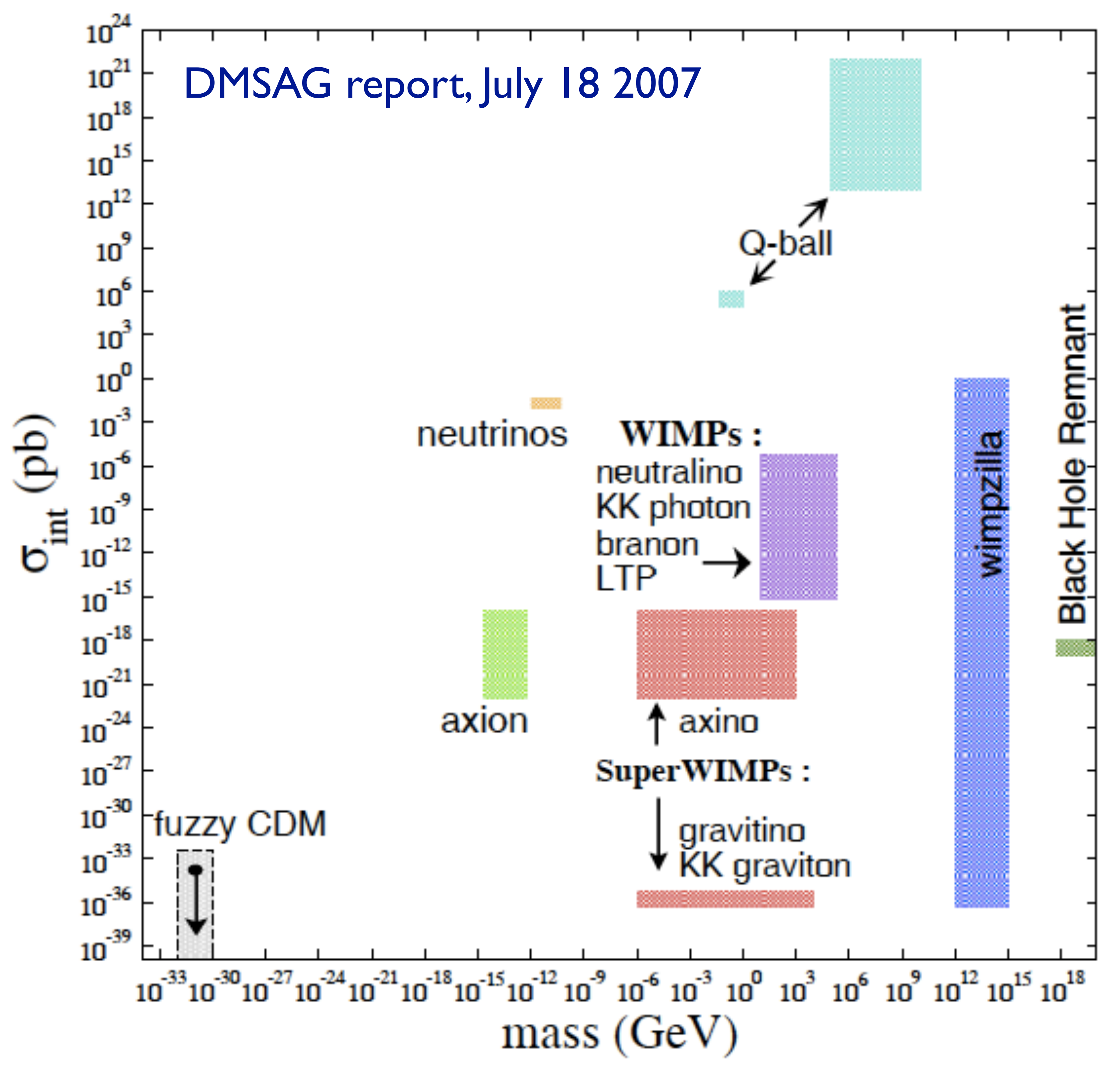
We need more to know about the "particle" properties of dark matter

Is DM an elementary particle?



"Once you have a collider, every problem starts to look like a particle."

What is Dark Matter?



Playing ground is full with good to great ideas!

dark photons?

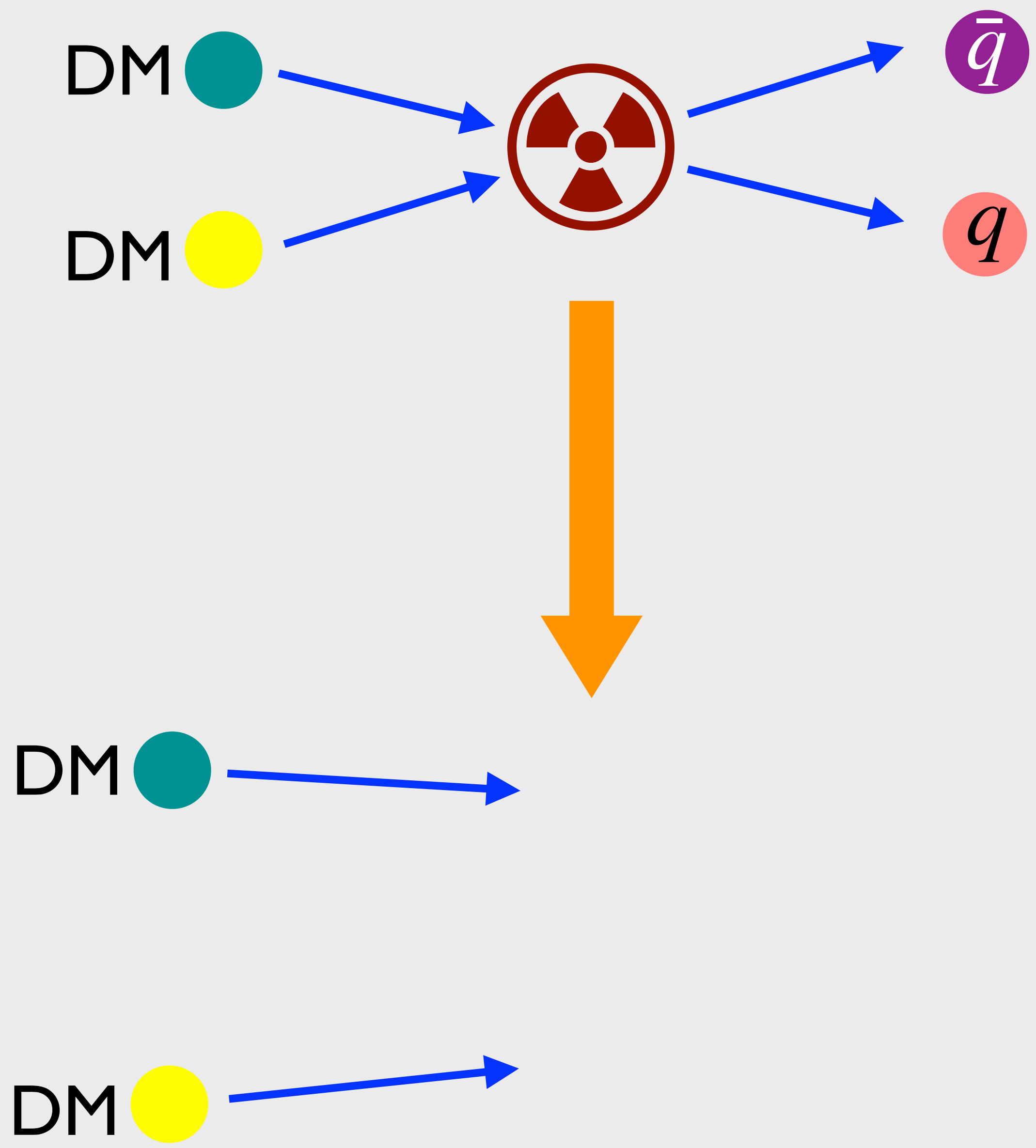
SIMPs?

FIMPs?

Non-QCD axions?

⋮

A short history of DM



DM is thermally produced in the early universe

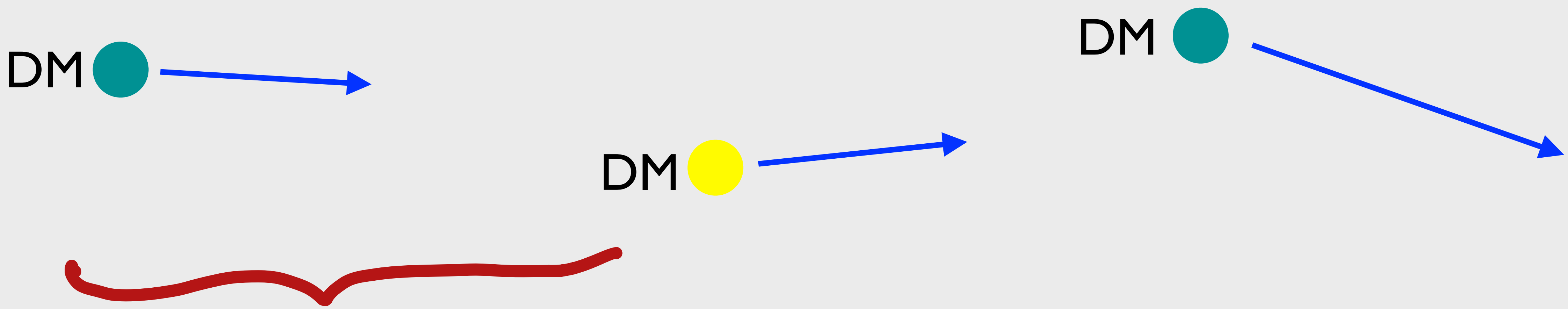
Annihilates via its interactions with the SM

Universe cools and expands

It’s harder and harder for DM particles to find each other

thermal freeze out

Thermal freezout



Annihilation "lifetime" of dark matter particles

$$\tau = \frac{1}{n_X} \frac{1}{\langle \sigma_{\rm ann} v \rangle}$$

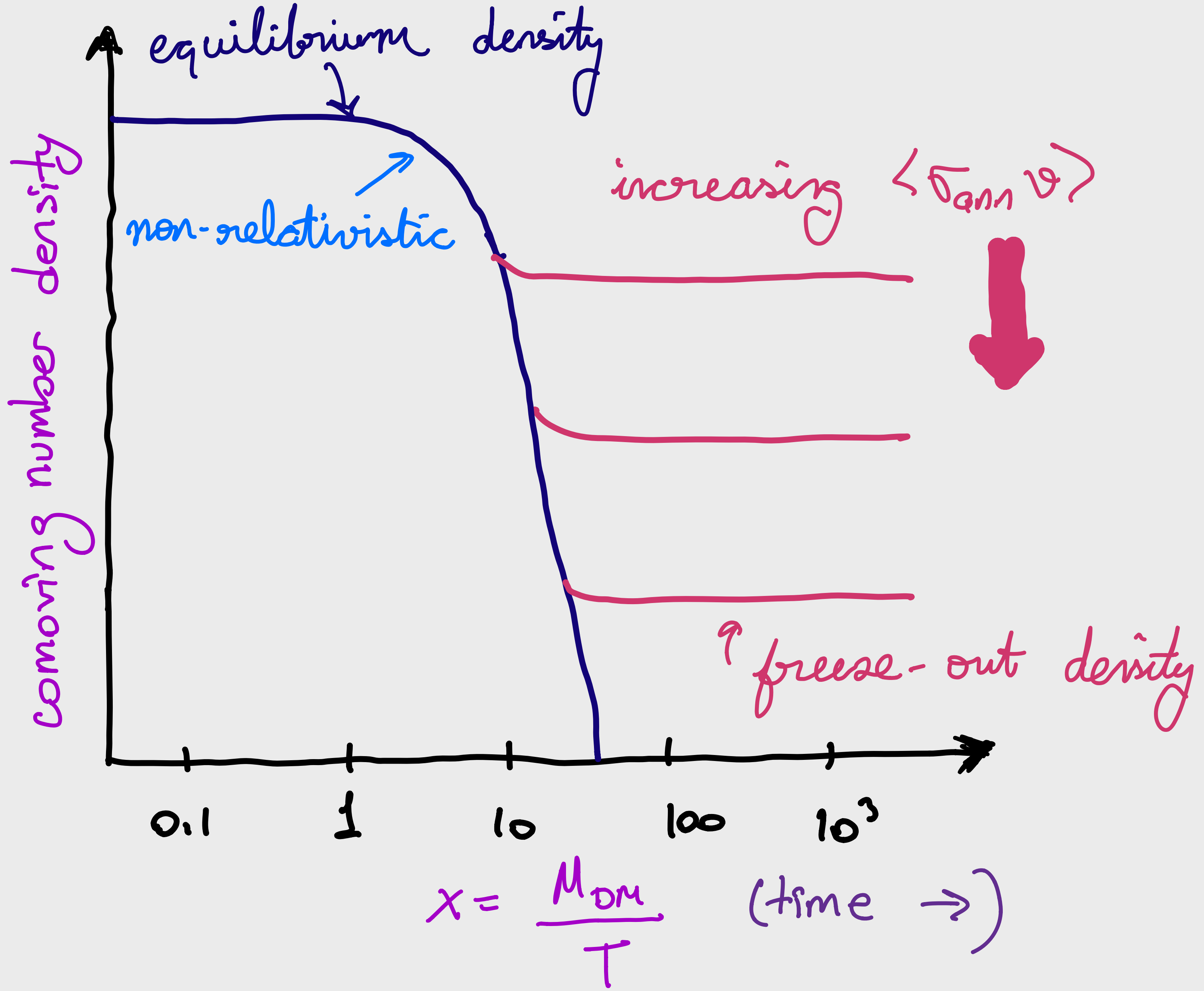
DM number density for $T < M_X$

$$n_X = g_X \left(\frac{M_X T}{2\pi} \right) \exp\left(-M_X/T\right)$$

s-wave cross section: $\sigma_{\rm ann} \propto \frac{\sigma_0}{v}$

* Annihilation switches off when $\tau = \frac{1}{H(T_f)}$

WIMP miracle



For:

$$H = \frac{T^2}{M_{\rm Pl}^*}$$

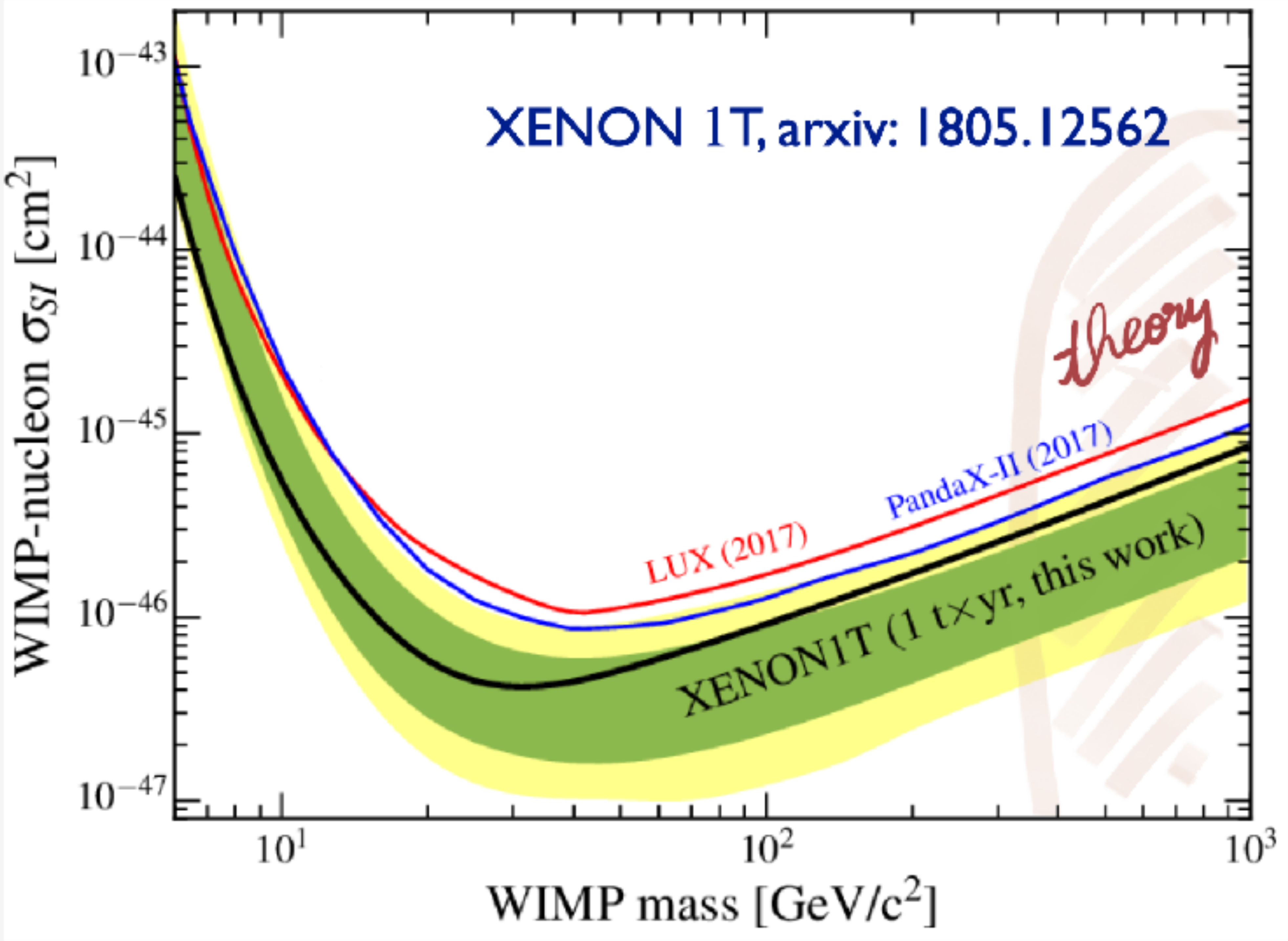
$$M_{\rm DM} \sim 100\ \text{GeV}$$

$$\sigma_0 \sim 10^{-36}\ \text{cm}^2$$

Observed DM density!

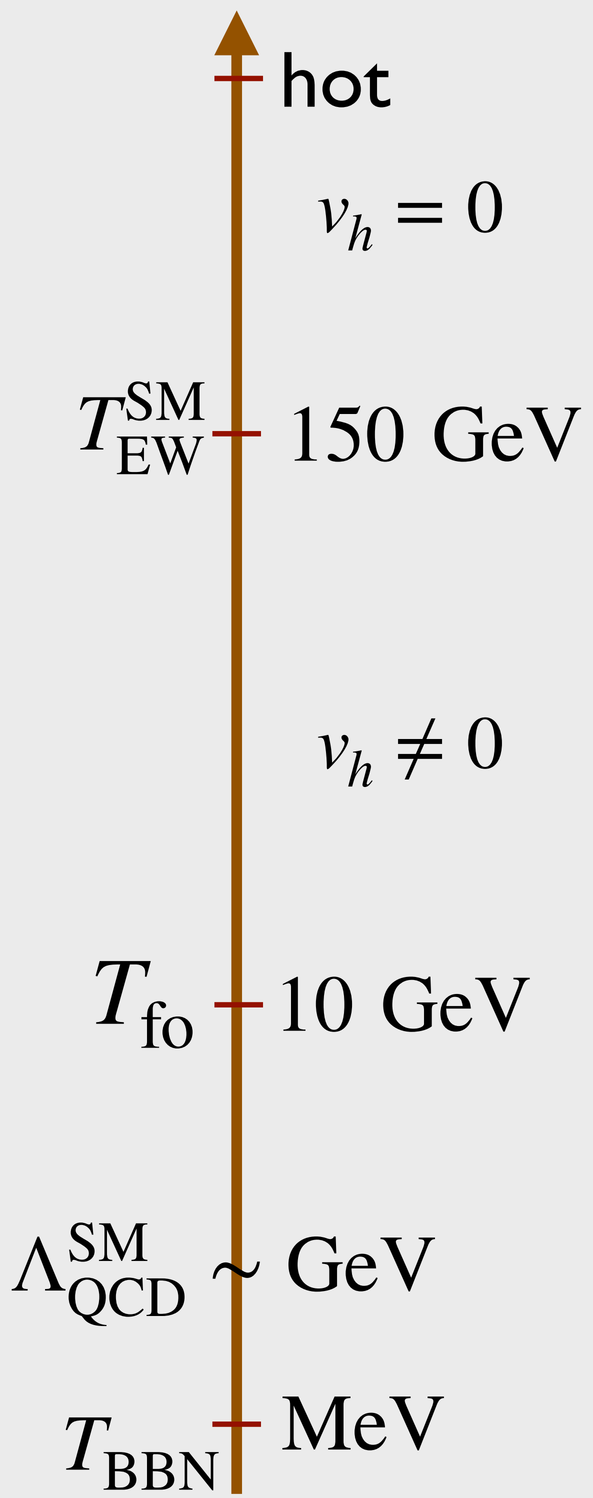
WIMP miracle

No WIMPs yet 😭



XENON 1T, arxiv: 1805.12562
theory
LUX (2017)
PandaX-II (2017)
XENON1T (1 t×yr, this work)
WIMP-nucleon σ_{SI} [cm^2]
WIMP mass [GeV/c^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^1
10^2
10^3

Assumptions

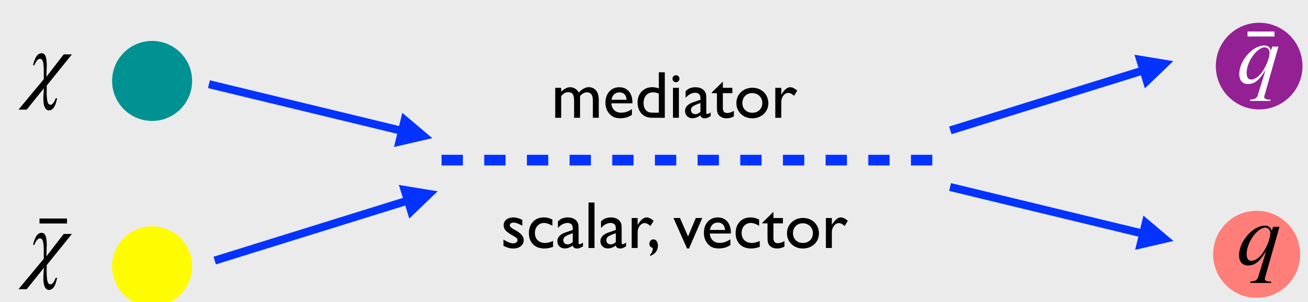


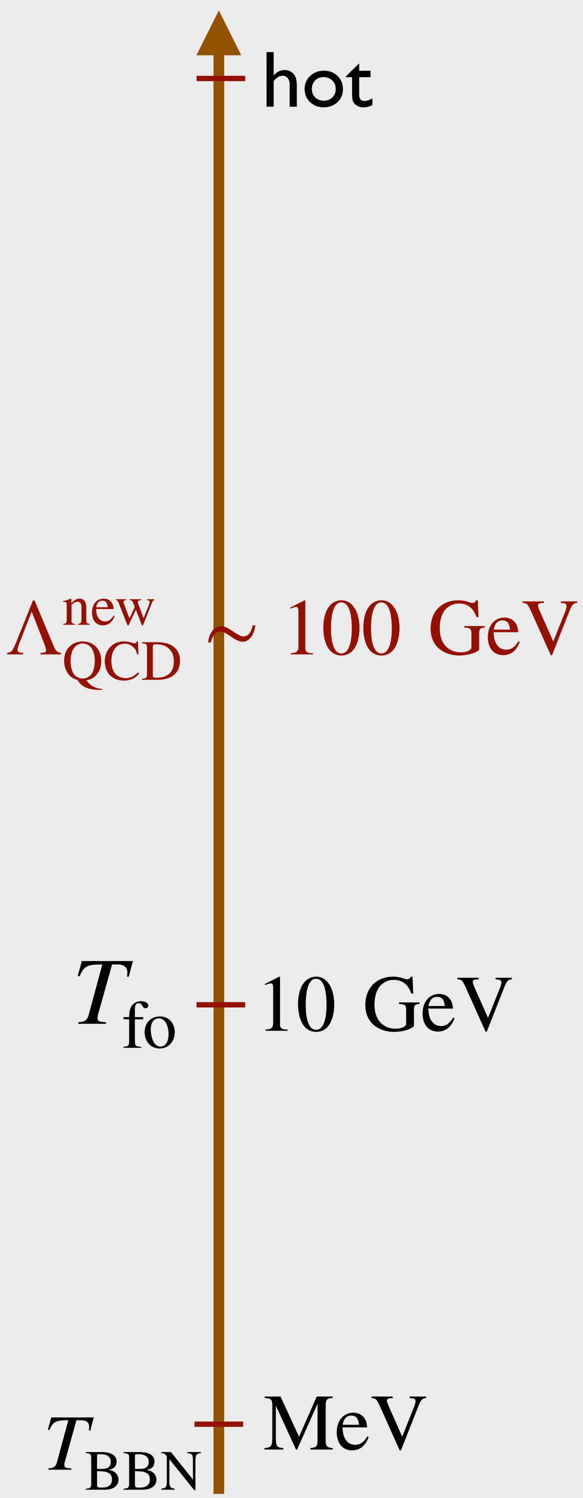
A "standard" cosmological history

includes (mostly) SM particles

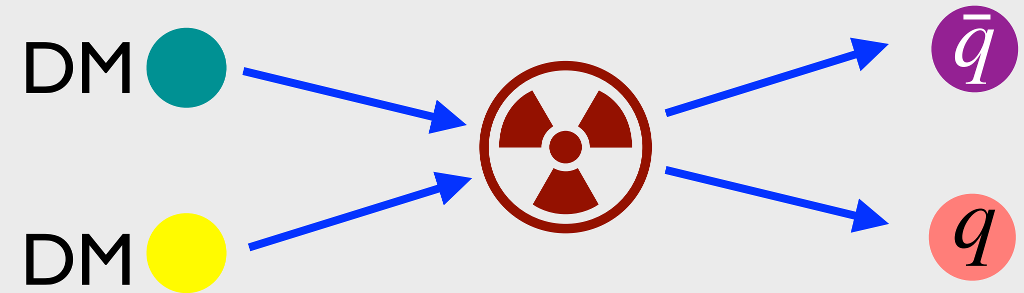
DM freezes out in radiation domination

"Standard" dark matter interactions

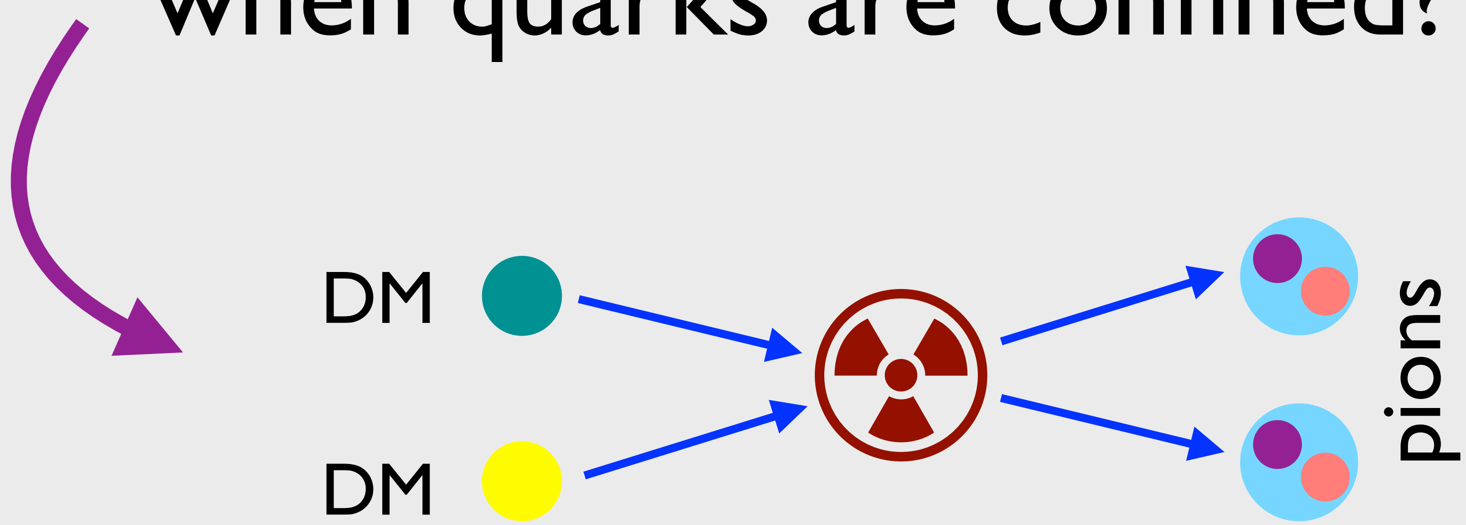




Instead of



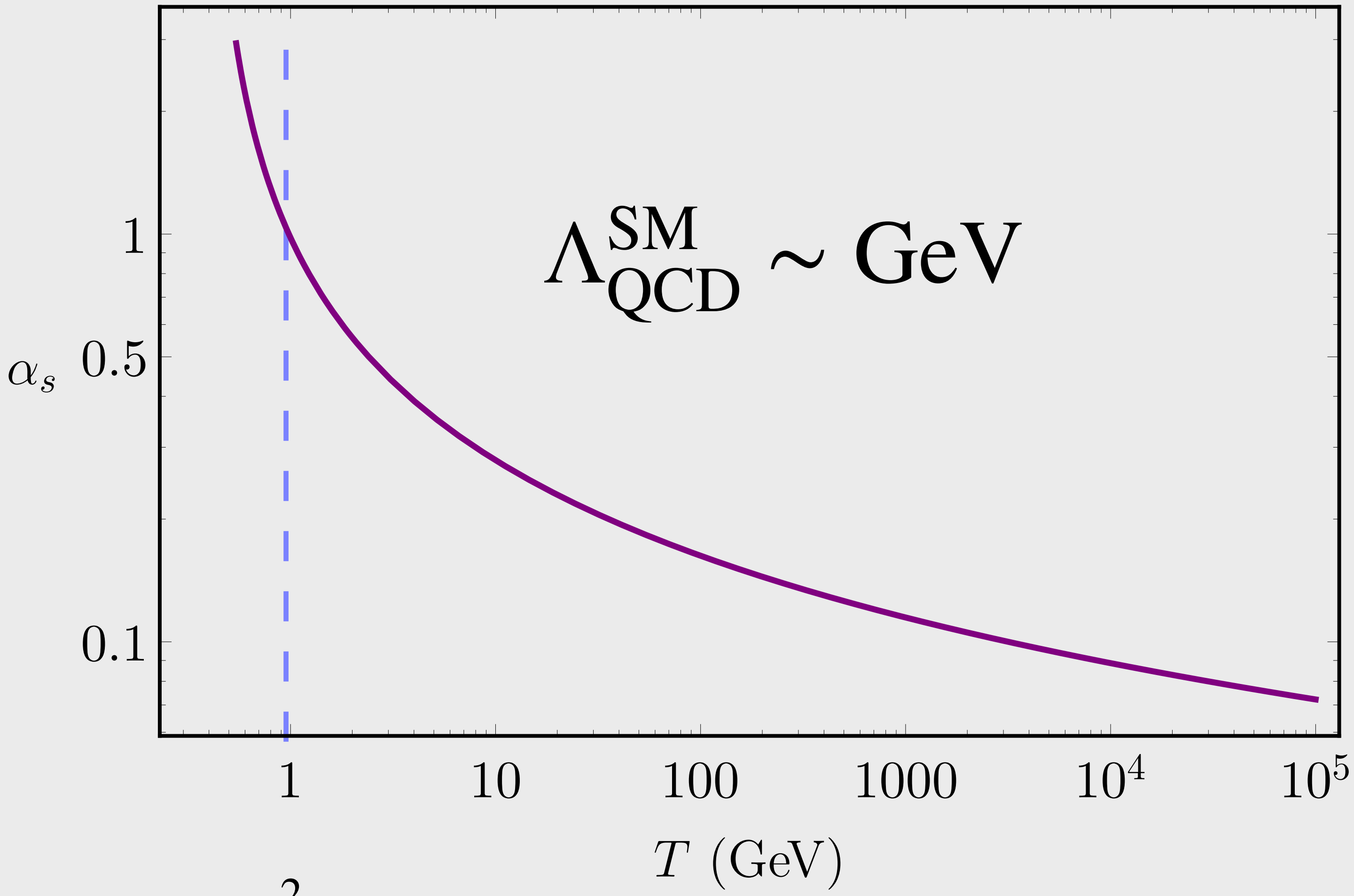
What if… DM froze out when quarks are confined?



QCD recap

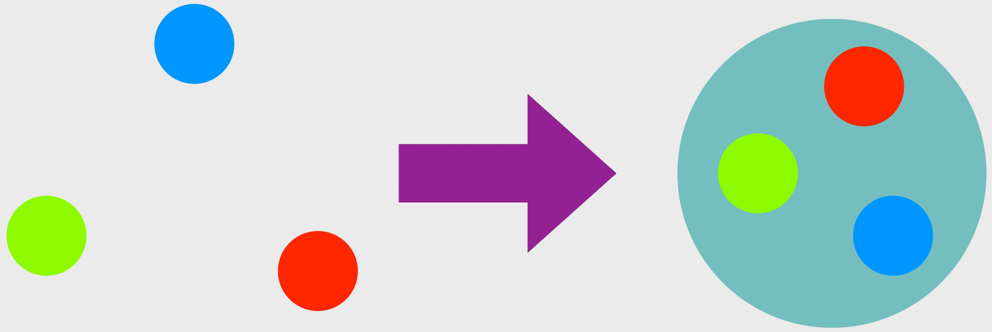
QCD phase transition

QCD is asymptotically free at high energies, but becomes strongly interacting at low energy



$\alpha_s = \frac{g_s^2}{4\pi}$: interaction strength

Quarks confine into hadrons when the strong coupling becomes "large"



QCD Phase Transition

We don't know anything about what happened before Big Bang Nucleosynthesis ($T \sim \mathrm{MeV}$, $t \sim$ sec)

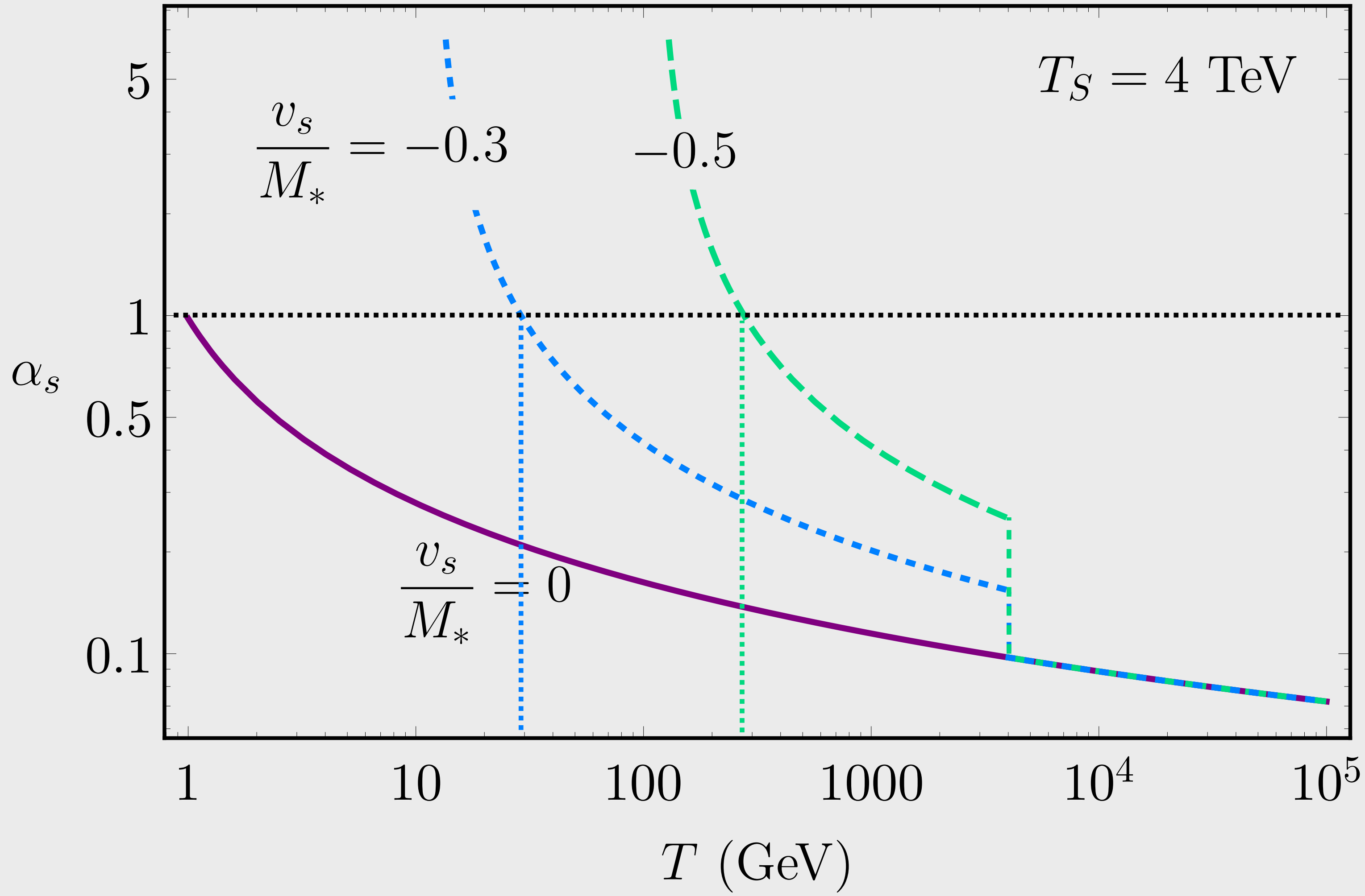
What if QCD was different in the early Universe?

SI, T. Tait, PRL (2019), 122, 112001, *arXiv: 1811.00559*

We can change QCD!

SI, T. Tait, PRL (2019), 122, 112001, *arXiv: 1811.00559*

Confinement scale changes with new particles if they interact via strong interactions!



$$\mathscr{L} \supset \left(\frac{1}{g_s^2} + \frac{\phi}{M_*}\right) G^{\mu\nu} G_{\mu\nu}$$

$$\frac{1}{g_{\text{eff}}^2} = \frac{1}{g_s^2} + \frac{v_\phi}{M_*}$$

$$\Lambda_{\text{QCD}} \simeq \Lambda_{\text{QCD}}^{\text{SM}} \times \exp\left(\frac{24\pi^2}{2N_f - 33}\frac{v_\phi}{M_*}\right)$$

currently

billions of years ago

$\Lambda_{QCD} \sim 400$ MeV

$\Lambda_{QCD} \sim 400$ GeV

Things that depend on the QCD scale will be different in the early Universe

pions ~ O(100 MeV)

pions ~ O(100 GeV)

SM QCD

confinement ~ 400 MeV

mass of up/down quarks $< \Lambda_{\rm QCD}^{\rm SM}$

pion masses: $m_{\pi 0}^2 = \dfrac{2\kappa_0(m_u + m_d)}{f_{\pi 0}^2}$

QCD quantities:

$$\kappa_0 \simeq (225 \text{ MeV})^3$$

$$f_{\pi 0} \simeq 94 \text{ MeV}$$

New physics QCD

confinement ~ 400 GeV

all quarks are lighter than $\Lambda_{\rm QCD}^{\rm new}$

pions are heavier:

Higgs vev

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{v_h}{v_h^{\rm SM}}\right) \xi$$

$$\kappa \simeq \kappa_0\, \xi^3$$

$$f_\pi \simeq f_{\pi 0}\, \xi$$

with $\xi \equiv \dfrac{\Lambda_{\rm QCD}^{\rm new}}{\Lambda_{\rm QCD}^{\rm SM}}$

The (new) confined phase

Above confinement: 6 massless quarks

Below confinement: quarks are no more! we have mesons

chiral symmetry breaking: $SU(6)_L \times SU(6)_R \to SU(6)_{\text{diag}}$

$$\mathscr{L}_{\text{ch}} \supset \frac{f_\pi^2}{4}\text{Tr}[\partial_\mu U \partial^\mu U] + \kappa \text{Tr}[U M]$$

the pion matrix $U(x) = e^{2iT^a \Pi^a(x)/f_\pi}$

$$\mathscr{L}_{\text{ch}} \supset \sqrt{2}\kappa y_t h - \frac{\kappa}{f_\pi^2}\text{tr}[\{T^a, T^b\}M]\pi^a \pi^b$$

$$M = \frac{h}{\sqrt{2}}\text{diag}\left(y_u, y_d, y_s, y_c, y_b, y_t\right)$$ quark mass matrix

What is κ ? We can find by matching to the SM QCD!

OLD

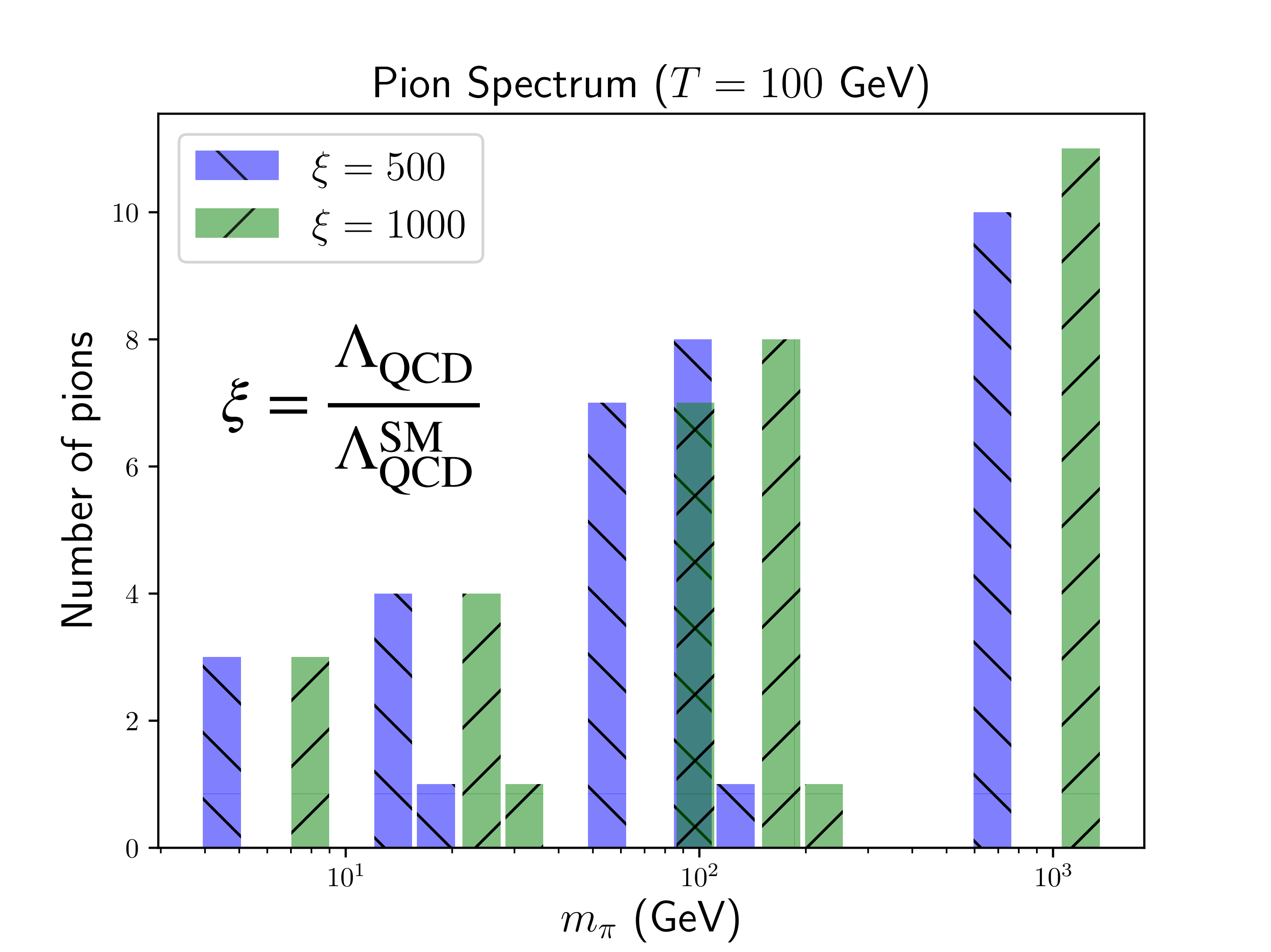
$$m_{\pi 0}^2 = \frac{2\kappa_0(m_u + m_d)}{f_{\pi 0}^2} \qquad \kappa_0 = \frac{m_{\pi 0}^2 f_{\pi 0}^2}{\sqrt{2} v_h^0 (y_u + y_d)} \simeq (224 \text{ MeV})^3$$

NEW

$$\kappa \simeq \kappa_0 \left(\frac{\Lambda_{QCD}}{\Lambda_{QCD}^{SM}} \right)^3$$

$$f_\pi \simeq f_{\pi 0} \left(\frac{\Lambda_{QCD}}{\Lambda_{QCD}^{SM}} \right)$$

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{\Lambda_{QCD}}{\Lambda_{QCD}^{SM}} \right) \left(\frac{v_h}{v_h^{SM}} \right)$$



Scalar potential in the confined phase

- Higgs gets a tadpole term from the meson mass-term

$$V_{\rm tad}(v_h) \simeq \kappa \frac{y_t}{\sqrt{2}} v_h \simeq -0.0158\ \mathrm{GeV}^3 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}\right)^3 v_h$$

- Thermal corrections to the Higgs potential from mesons

$$V_{\rm meson}(v_h, T) = \sum_{i=1\ldots35} \frac{T^4}{2\pi^2} J_B\left(\frac{m_i^2}{T^2}\right)$$

$$J_B(m^2) = \int_0^\infty dx x^2 \log\left(1 - e^{-\sqrt{x^2+m^2}}\right)$$

- The gluon condensate contributes to the singlet potential

$$\frac{\phi}{M_*}\langle GG\rangle \longrightarrow V_{\rm GC}(v_\phi) \simeq \frac{v_\phi}{4M_*}\Lambda_{\rm QCD}^4$$

Fantastic phases and where to find them

$v_h = 0$

finite temperature corrections
the usual: gauge bosons, quarks,…

T_c

$T_{\rm EW}^{\rm SM}$

QCD confined

$v_h \neq 0$

no quarks,
but hadrons!

T_d

$v_h = v_h^{\rm SM}$

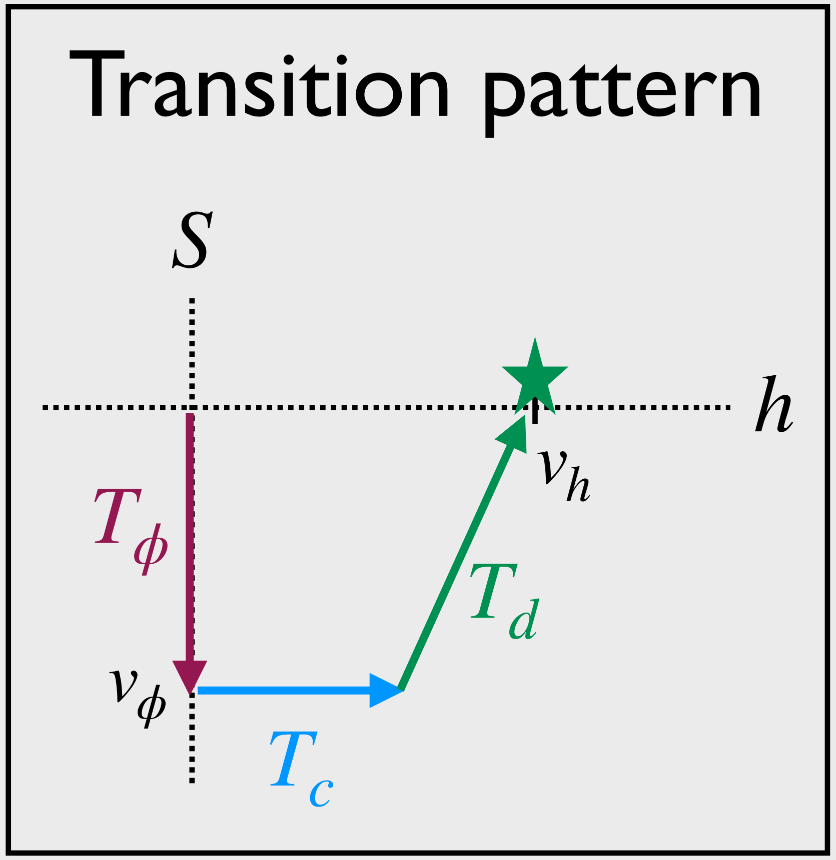
QCD deconfines

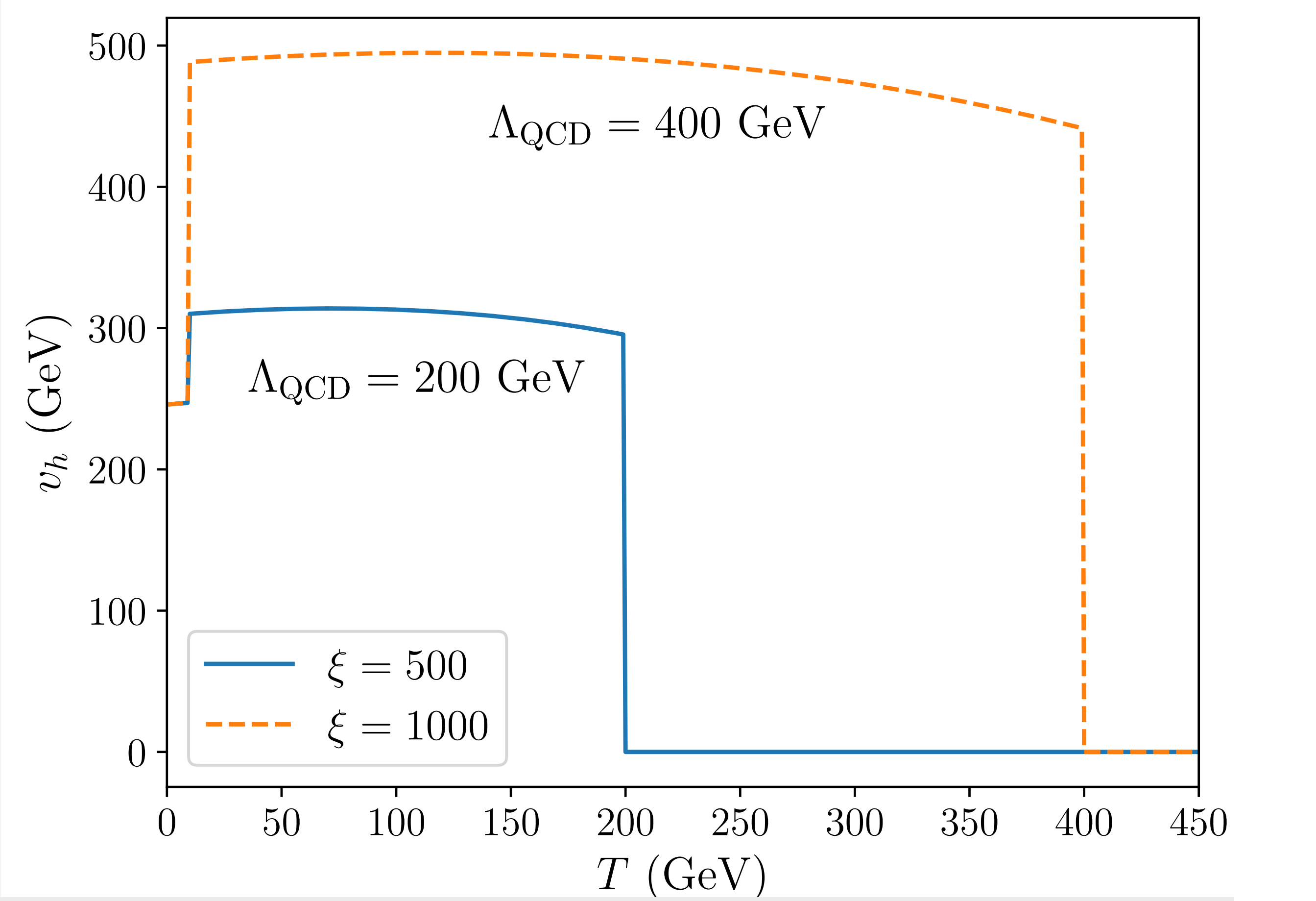
return to the SM

$\Lambda_{\rm QCD}^{\rm SM} \sim \rm GeV$

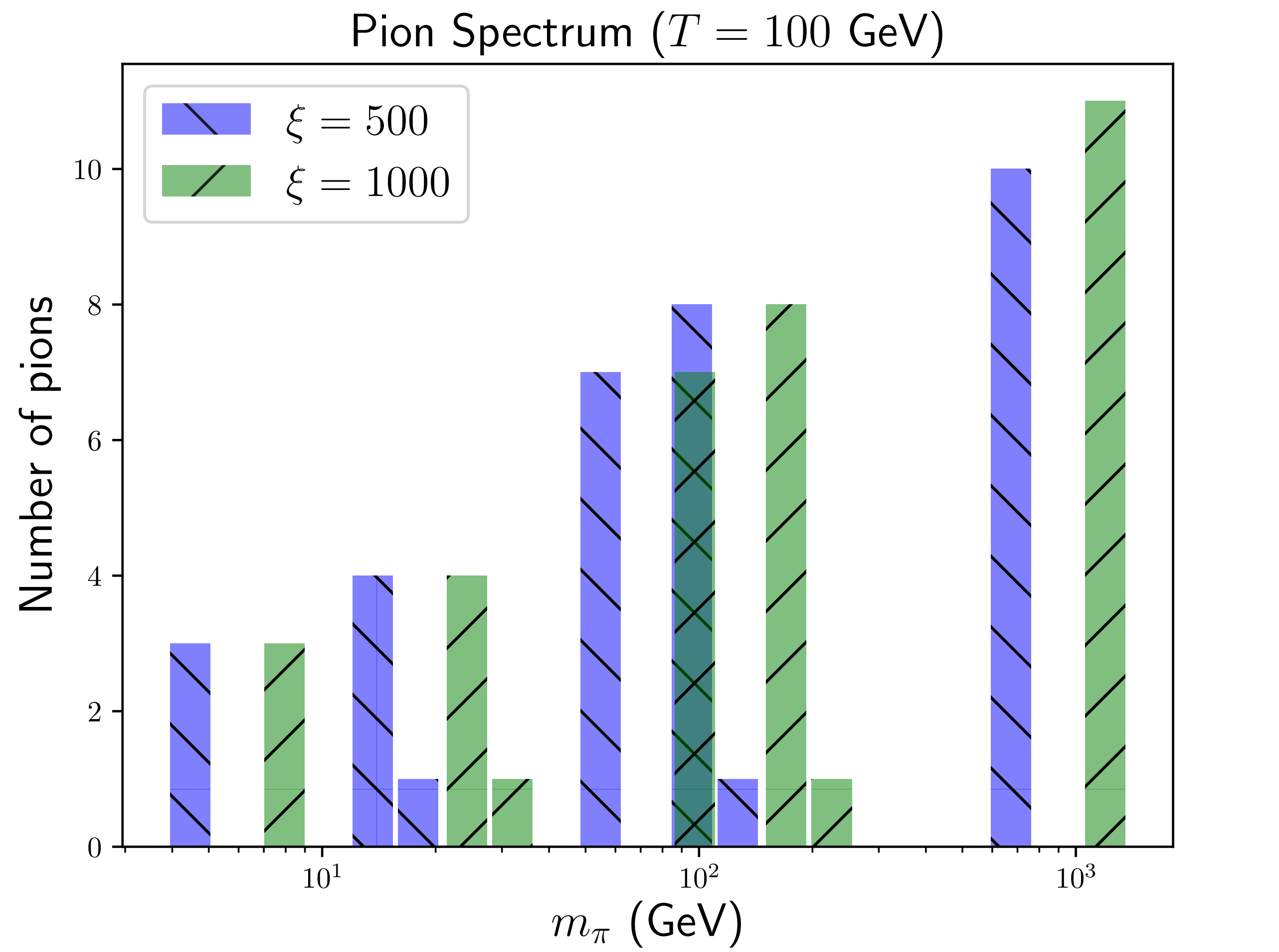
QCD confined

$T_{\rm BBN}$





Higgs vev is larger than its SM value!



$$\xi = \frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}$$

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}\right)\left(\frac{v_h}{v_h^{\rm SM}}\right)$$

New QCD cosmology

↓

Dark matter?

D. Berger, **SI**, T. Tait, M. Waterbury, *arXiv: 2004.06727*

Let's look at a generic WIMP with scalar/vector interactions

$$\mathscr{L} \supset m_\chi \chi\bar{\chi}$$

vector mediator

$$+ \frac{\lambda}{M_V^2} \bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$$

$$+ \frac{\beta}{M_S^2} \bar{\chi}\chi\,\bar{q}q$$

scalar mediator

$$\mathscr{L} \supset \left(m_\chi + \frac{2\kappa\,\mathrm{tr}[\beta]}{M_S^2} \right) \bar{\chi}\chi$$

not much change

$$+ \frac{2i}{M_V^2} f^{abc}\mathrm{tr}[T^b\lambda]\bar{\chi}\gamma^\mu\chi\,\pi^a\partial_\mu\pi^c$$

pions

$$+ \frac{2\kappa}{f_\pi^2 M_S^2}\mathrm{tr}[T^aT^b\beta]\,\bar{\chi}\chi\,\bar{\pi}^a\pi^b$$

QCD enhanced

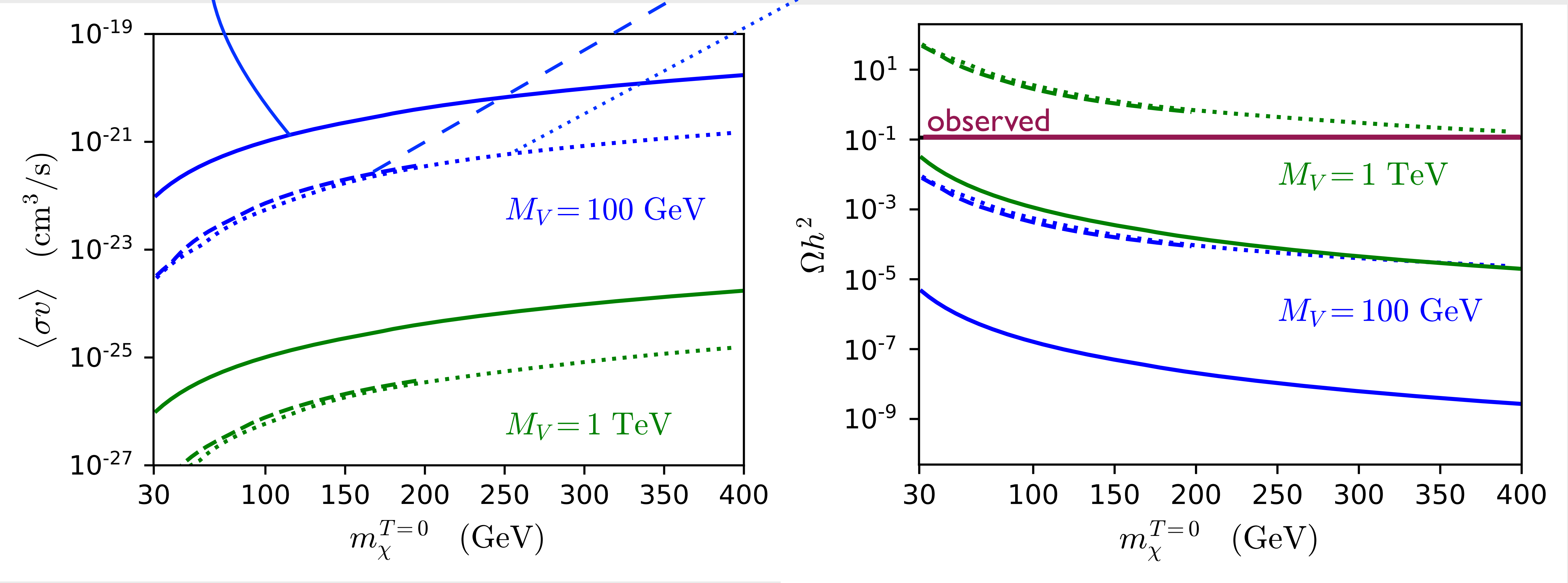
Vector Mediator

$$\frac{\lambda}{M_V^2}\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q \quad \Rightarrow \quad \frac{2i}{M_V^2} f^{abc}\mathrm{tr}[T^b\lambda]\bar{\chi}\gamma^\mu\chi\,\pi^a\partial_\mu\pi^c$$

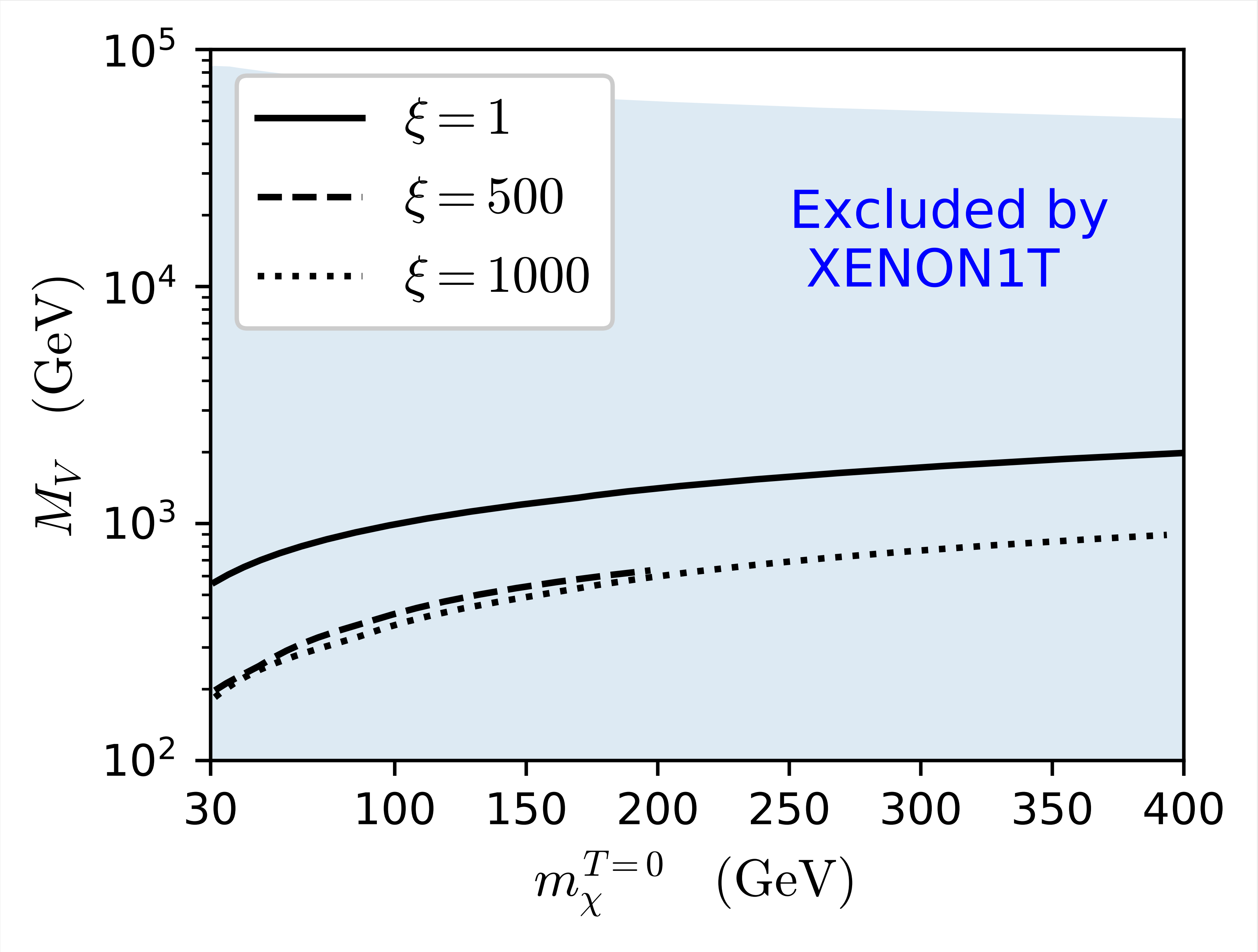
$$\xi \equiv \frac{\Lambda_{QCD}^{new}}{\Lambda_{QCD}^{SM}} = 1$$

$$\xi = 500 - 1000$$

annihilation x-section is independent of confinement scale



Vector Mediator



Vector mediated WIMP stays doomed

Scalar Mediator

$$\xi = \frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}$$

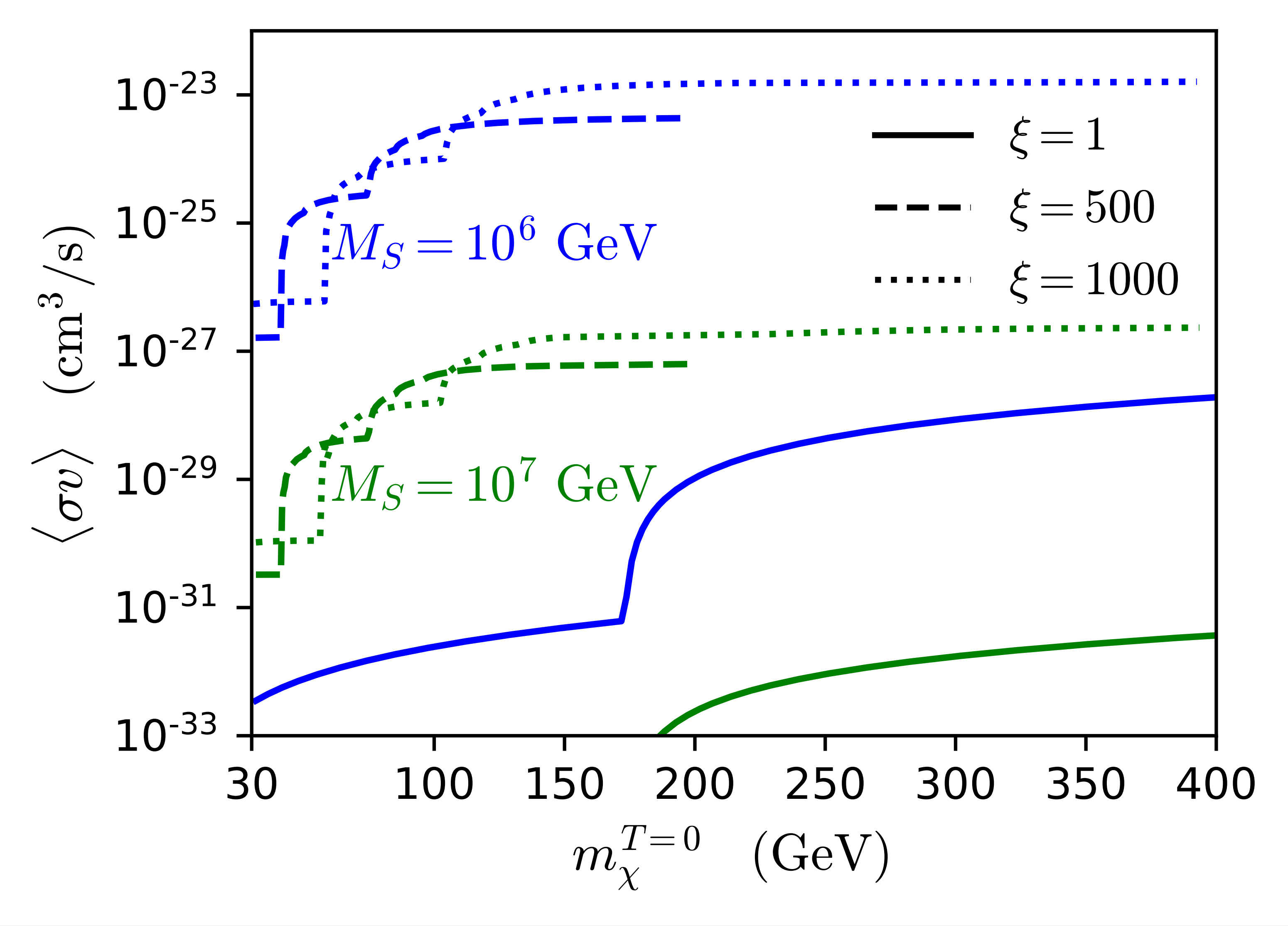
$$\frac{\beta}{M_S^2}\,\bar{\chi}\chi\,\bar{q}q$$

$$\frac{2\kappa}{f_\pi^2 M_S^2}\,\mathrm{tr}[T^a T^b \beta]\,\bar{\chi}\chi\,\bar{\pi}^a\pi^b$$

$$\frac{\kappa}{f_\pi^2} \sim \xi$$

annihilation x-section is larger than before confinement!

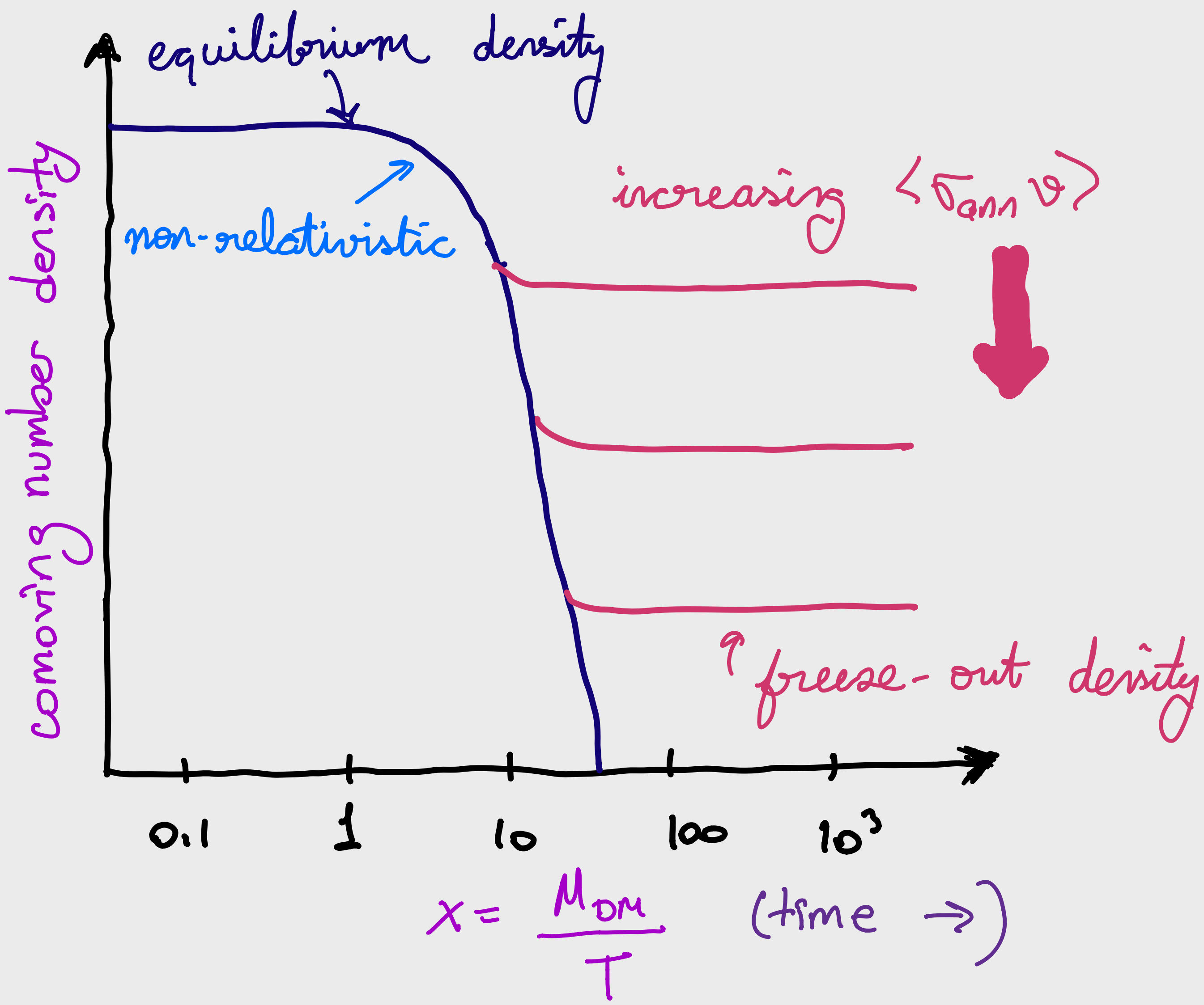
DM annihilation cross section

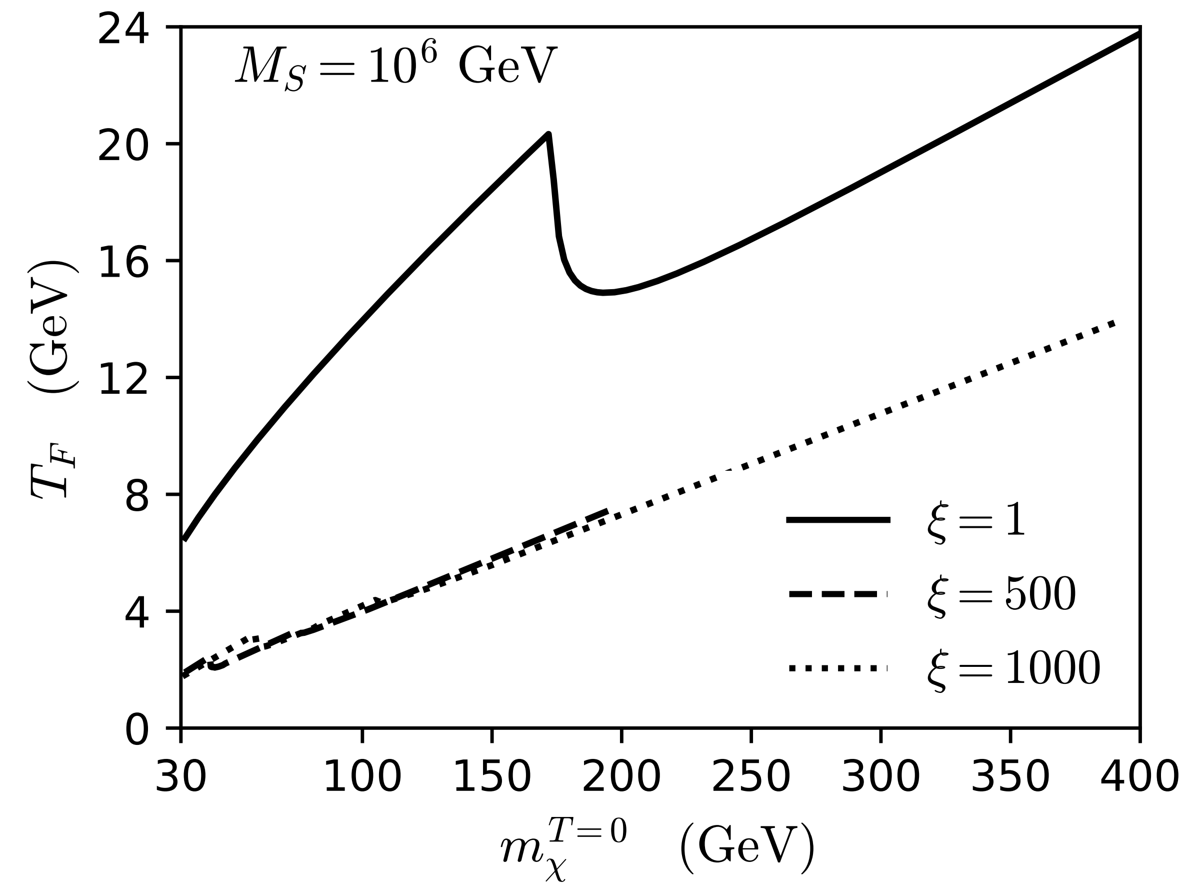


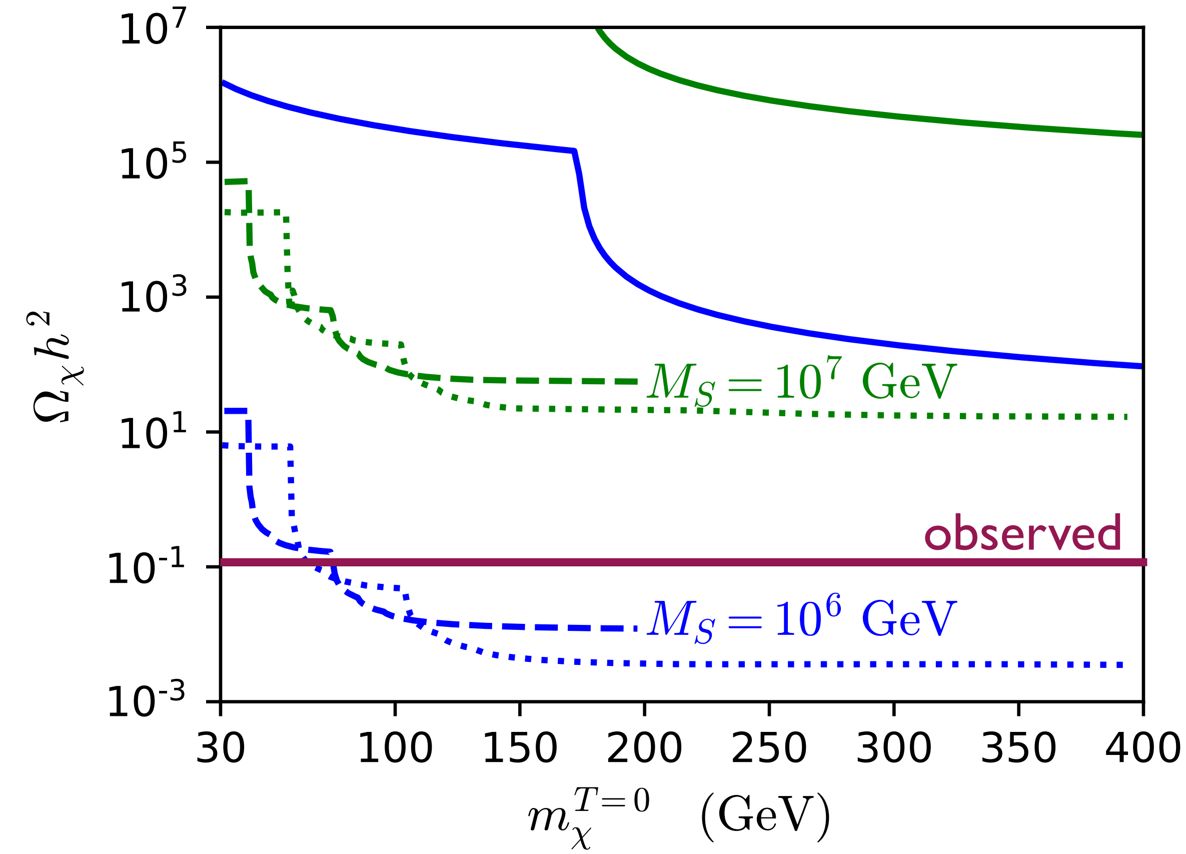
$\beta \propto y_q$ top and bottom Yukawa couplings are the largest

Scalar Mediator

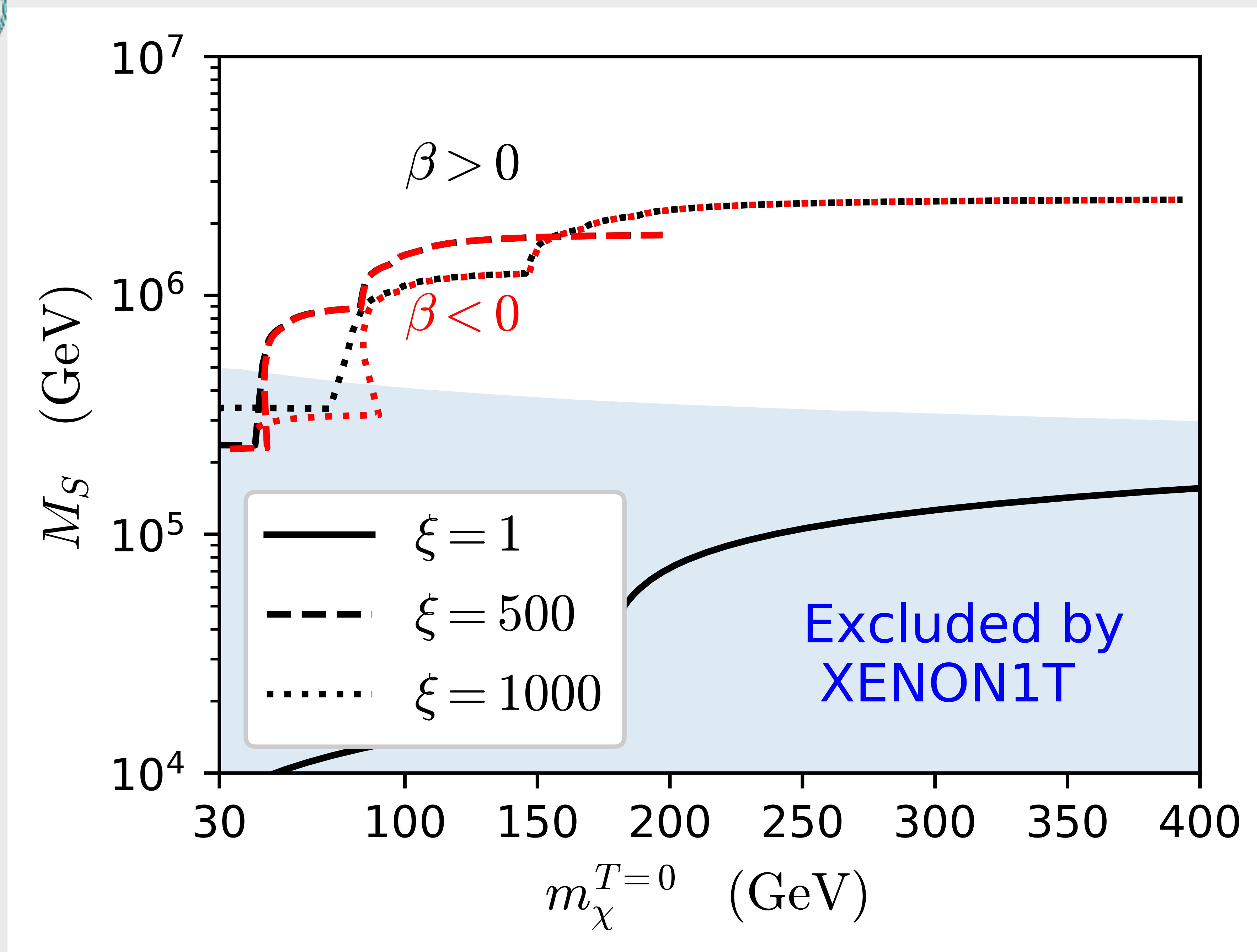
$$\xi = \frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm SM}}$$







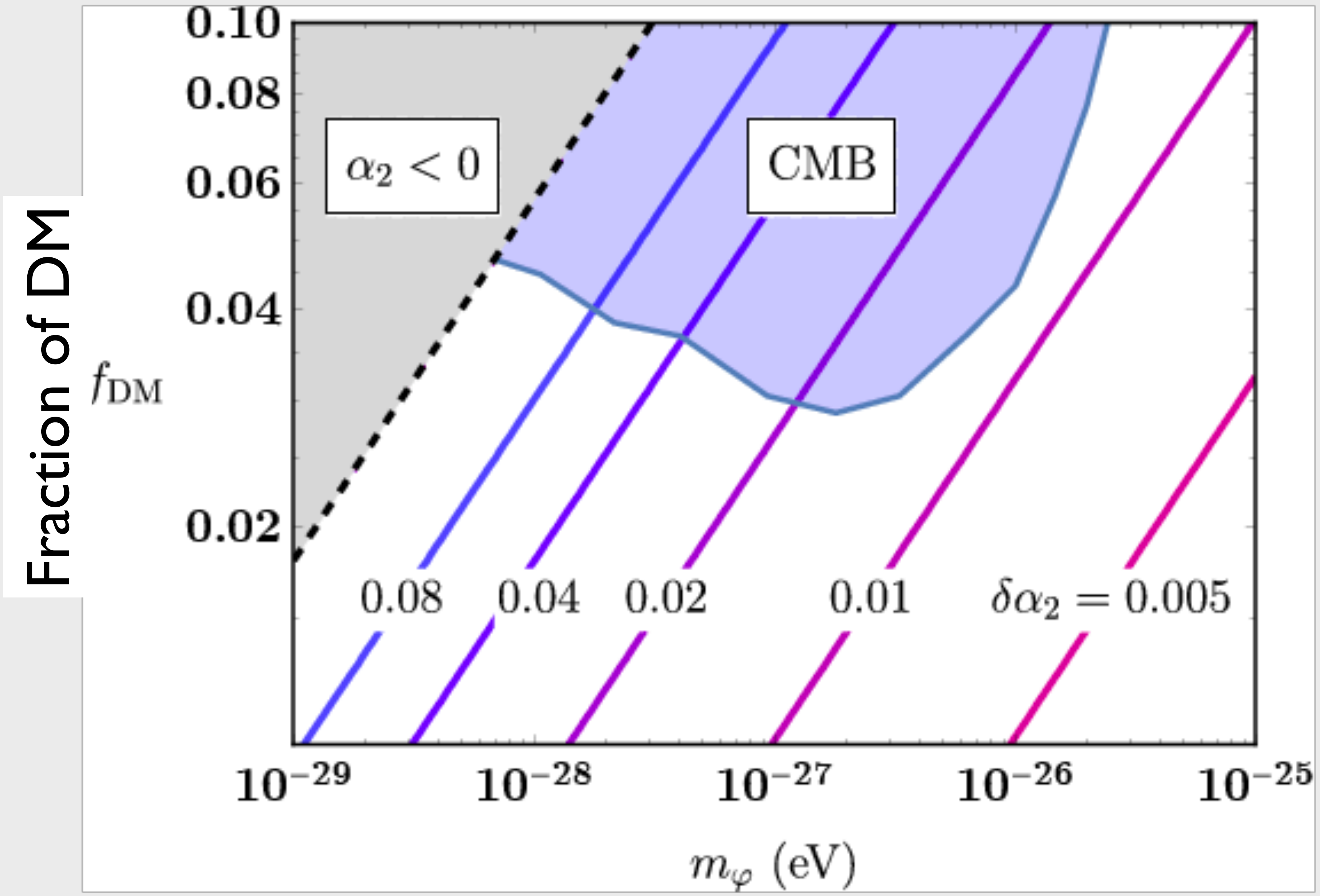
WIMP dark matter is saved!



How about other gauge couplings?

S.A.R. Ellis, **SI**, G. White, *JHEP* 08 (2019) 002, *arXiv:1905.11994*

$$\mathscr{L} \supset \left(\frac{1}{g_Y^2} + \frac{\phi}{M_{\rm Pl}}\right) B^{\mu\nu} B_{\mu\nu} + \left(\frac{1}{g_2^2} + \frac{\phi}{M_{\rm Pl}}\right) W^{\mu\nu} W_{\mu\nu}$$



New scalar can interact with the Higgs boson

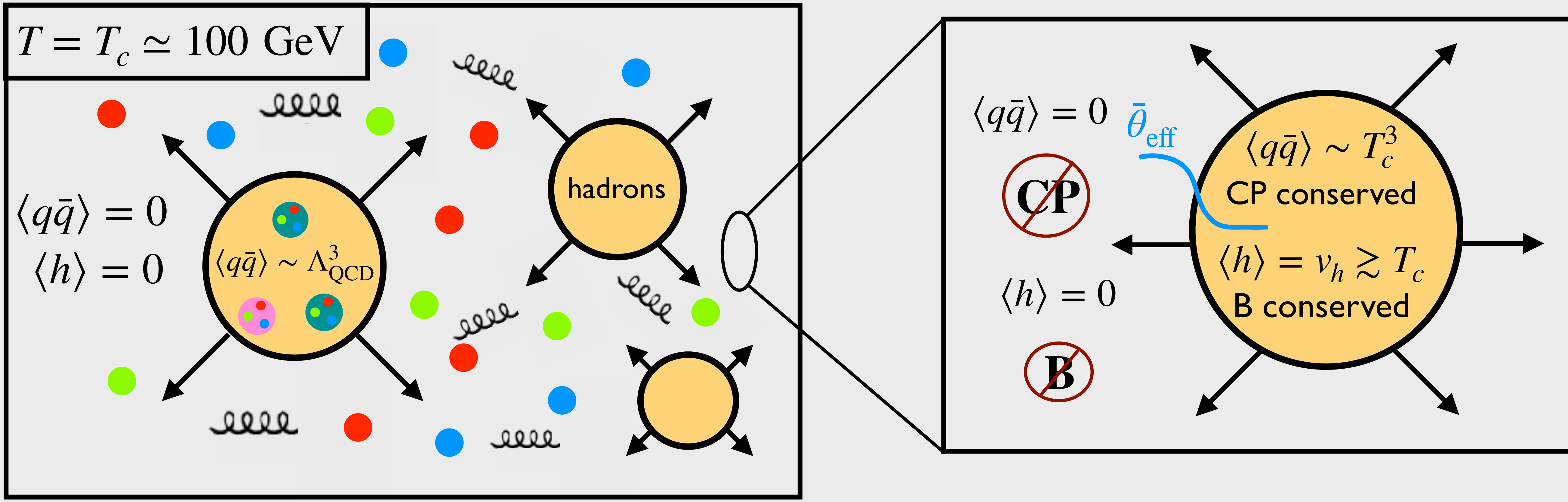
$$\begin{aligned} V_{\text{scalar}} = & -\mu^2 |H|^2 + \lambda_h |H|^4 \\ & + a_2 \phi^2 + a_3 \phi^3 + a_4 \phi^4 \\ & - b_1 \phi |H|^2 + b_2 \phi^2 |H|^2 \end{aligned}$$

New QCD cosmology

↓

Baryogenesis!

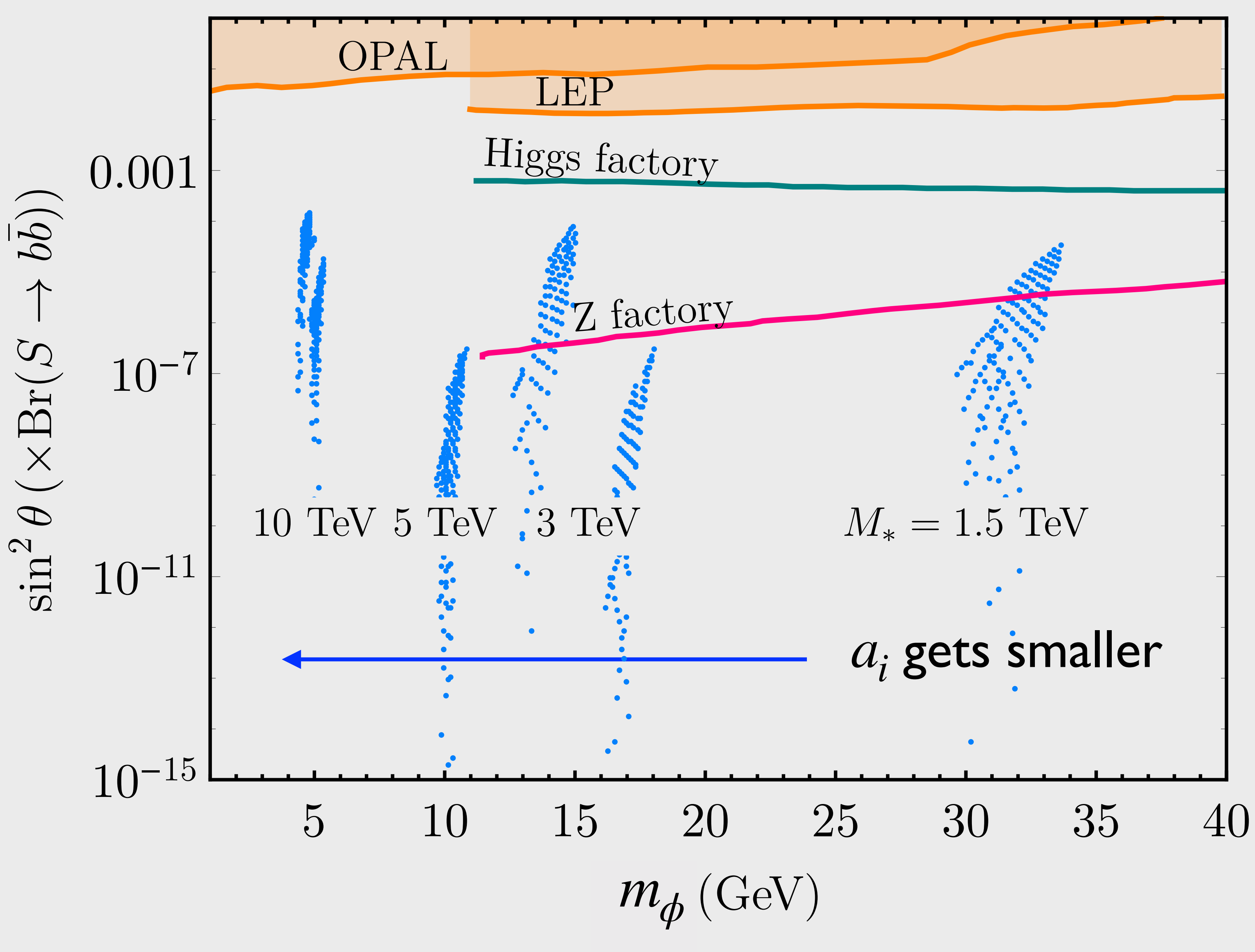
D. Croon, J. Howard, **SI**, T. Tait, *Phys.Rev.D* 101 (2020) 5, 055042 *arXiv:1911.01432*



$$\eta \sim 10^{-11} \overbrace{\sin\bar{\theta}}^{\sim 1} \overbrace{\frac{v_h}{\Lambda_{\rm QCD}}}^{\sim 4} \left(\overbrace{\frac{T_{\rm c}}{T_{\rm reh}}}^{>1}\right)^3$$

$$\eta_{\rm obs} \simeq 8.5 \times 10^{-11}$$

Constraints - Higgs mixing



Mixing angle is too small for current searches

Singlet lighter than ~10GeV is hard to constrain since it decays primarily to gluons

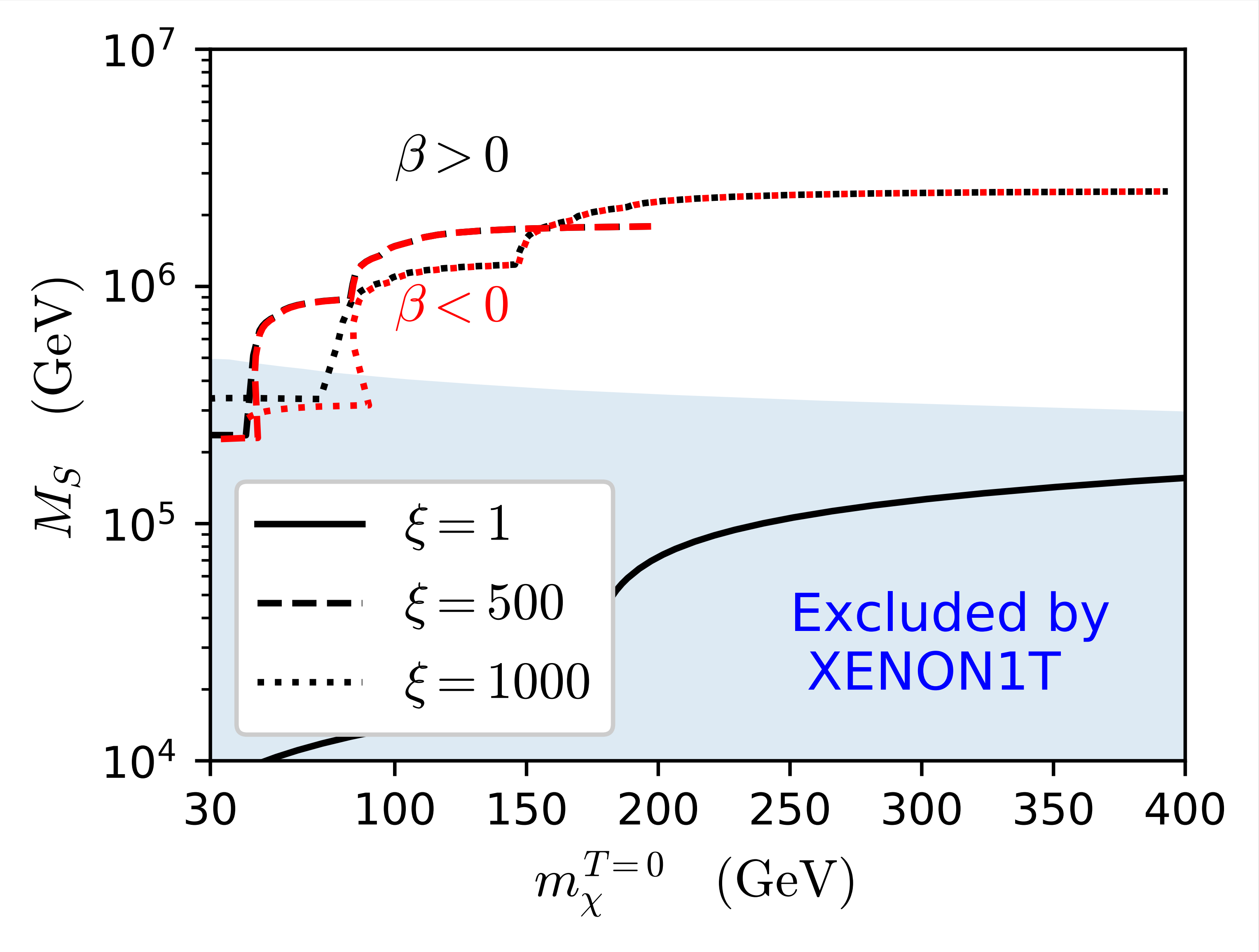
$f \sim 10^{-3}$ Hz

Multi-step $1^{\rm st}$ order phase transitions → Interesting GW signatures!

Summary & Outlook

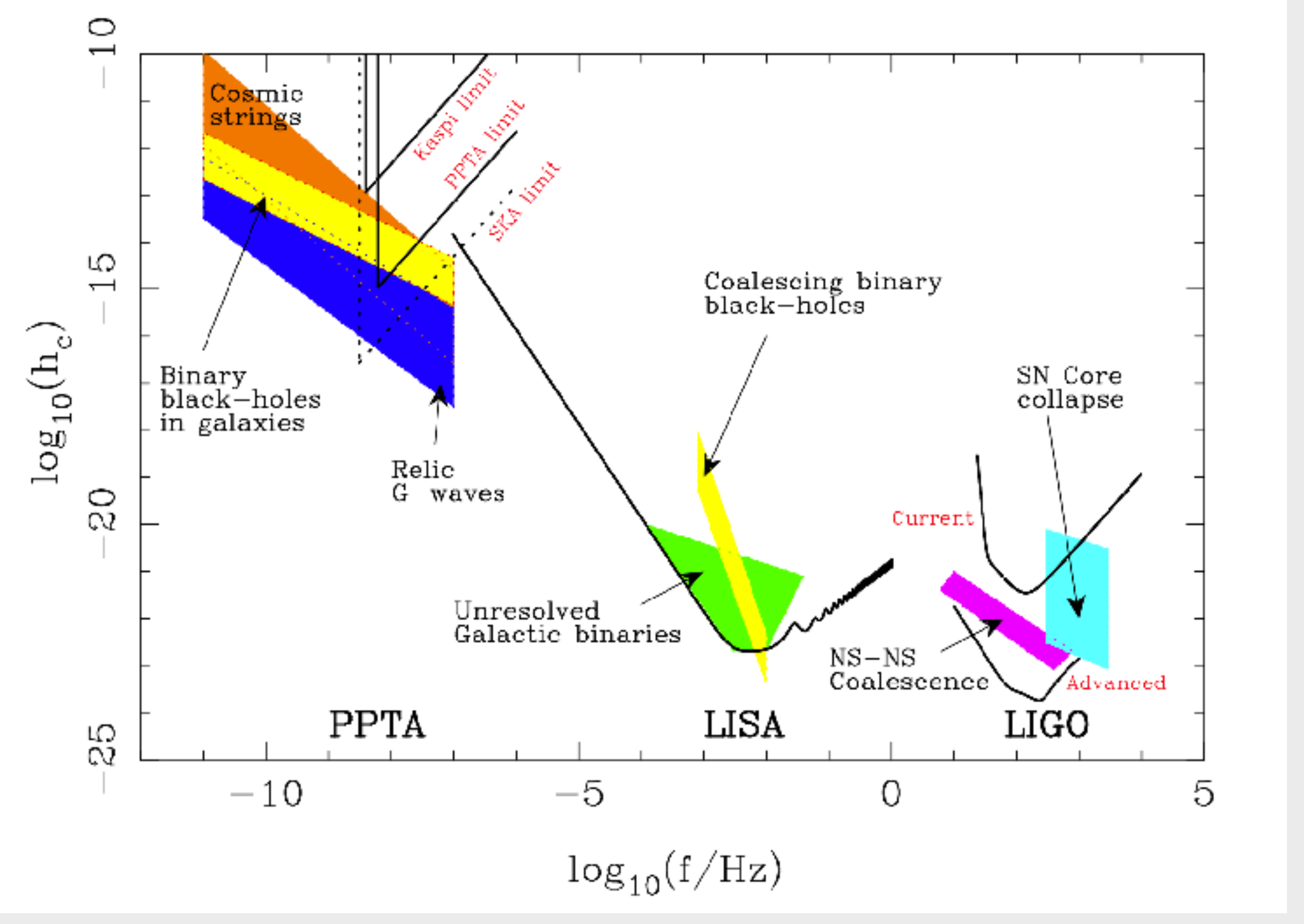
When will we know what DM is???

When will the pandemic end?



Backup slides

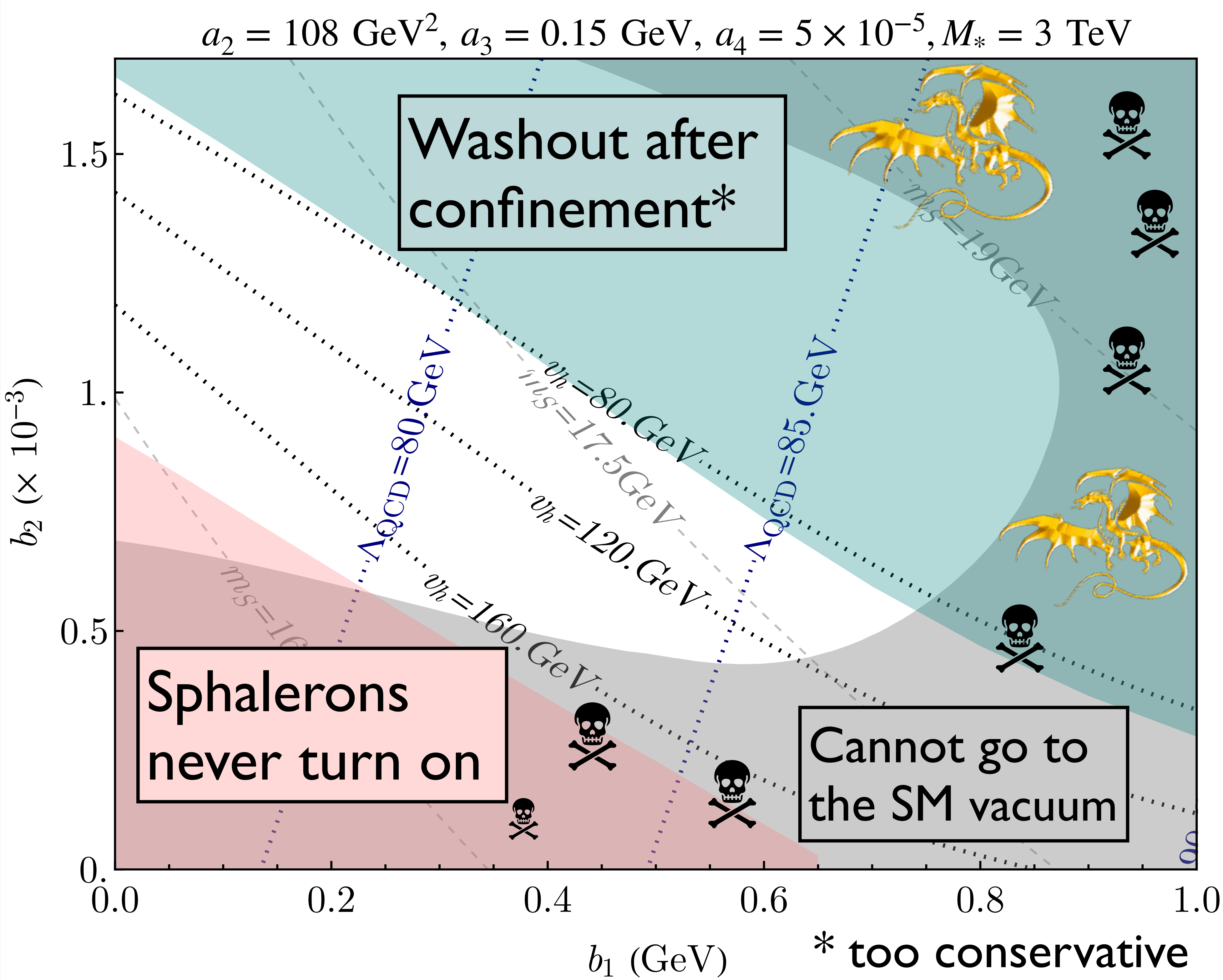
E. Thrane, etal, Phys.Rev. D88 (2013) no.12, 124032



fix (6 benchmark scenarios)

vary

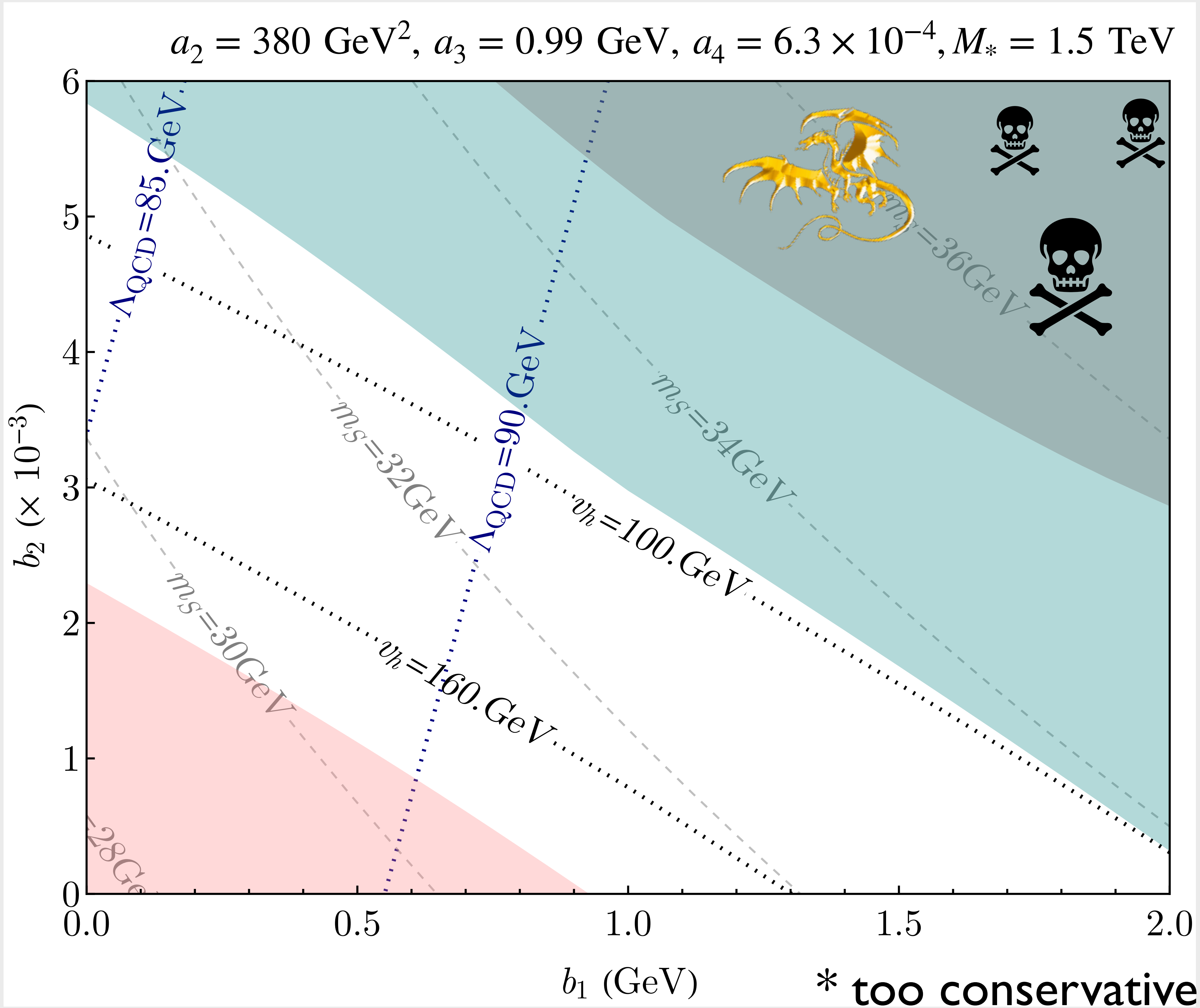
$$V_0 = -\mu^2|H|^2 + \lambda_h|H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S|H|^2 + b_2 S^2|H|^2$$



* too conservative

fix (6 benchmark scenarios) — vary

$$V_0 = -\mu^2|H|^2 + \lambda_h|H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4 - b_1 S|H|^2 + b_2 S^2|H|^2$$



* too conservative

Benchmark scenarios

	M_*	a_2/GeV^2	a_3/GeV	a_4
1.	1.5 TeV	380	9.9×10^{-1}	6.3×10^{-4}
2.	3 TeV	108	1.5×10^{-1}	5.1×10^{-5}
3.	3 TeV	44.2	6.14×10^{-2}	2.1×10^{-5}
4.	5 TeV	38.9	3.24×10^{-2}	6.6×10^{-6}
5.	10 TeV	9.72	4.05×10^{-3}	4.1×10^{-7}
6.	10 TeV	4.92	2.27×10^{-3}	2.6×10^{-7}