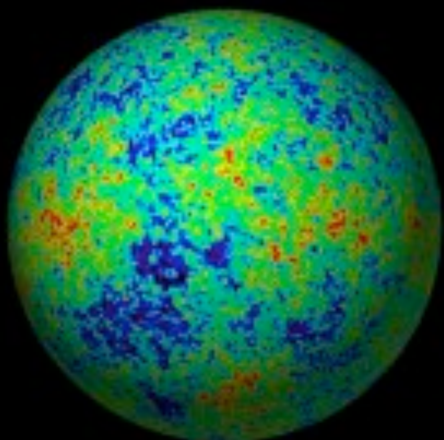
Theories of Dark Matter

Tim M.P. Tait
University of California, Irvine

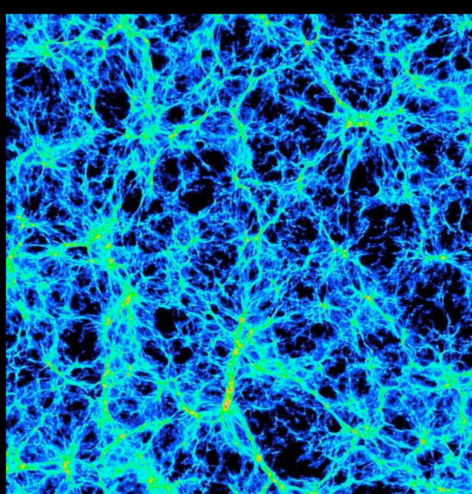
PPC 2021
University of Oklahoma
May 17, 2021

Dark Matter

CMB



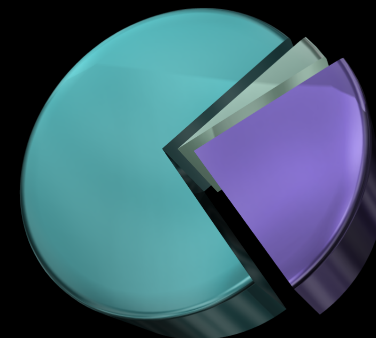
Supernova

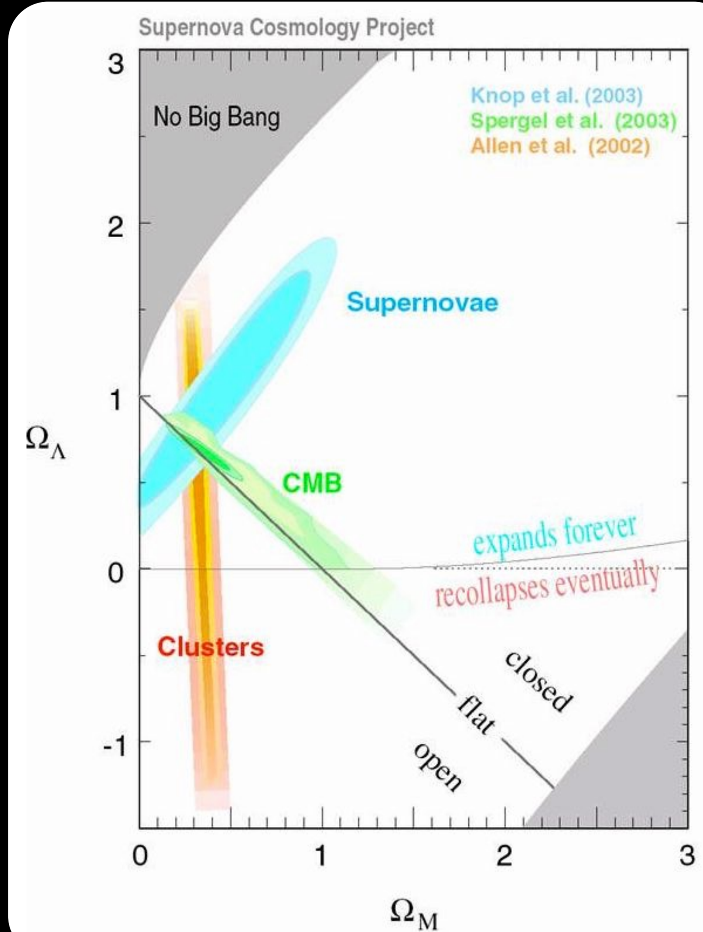


Structure

Lensing

Ordinary Matter
Dark Matter
Dark Energy





What is Dark Matter?

"Cold Dark Matter: An Exploded View" by Cornelia Parker

- A theory of dark matter is necessary to place it into the context of what we know about fundamental particles and their interactions.
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the SM has the right properties!

The Dark Matter Questionnaire

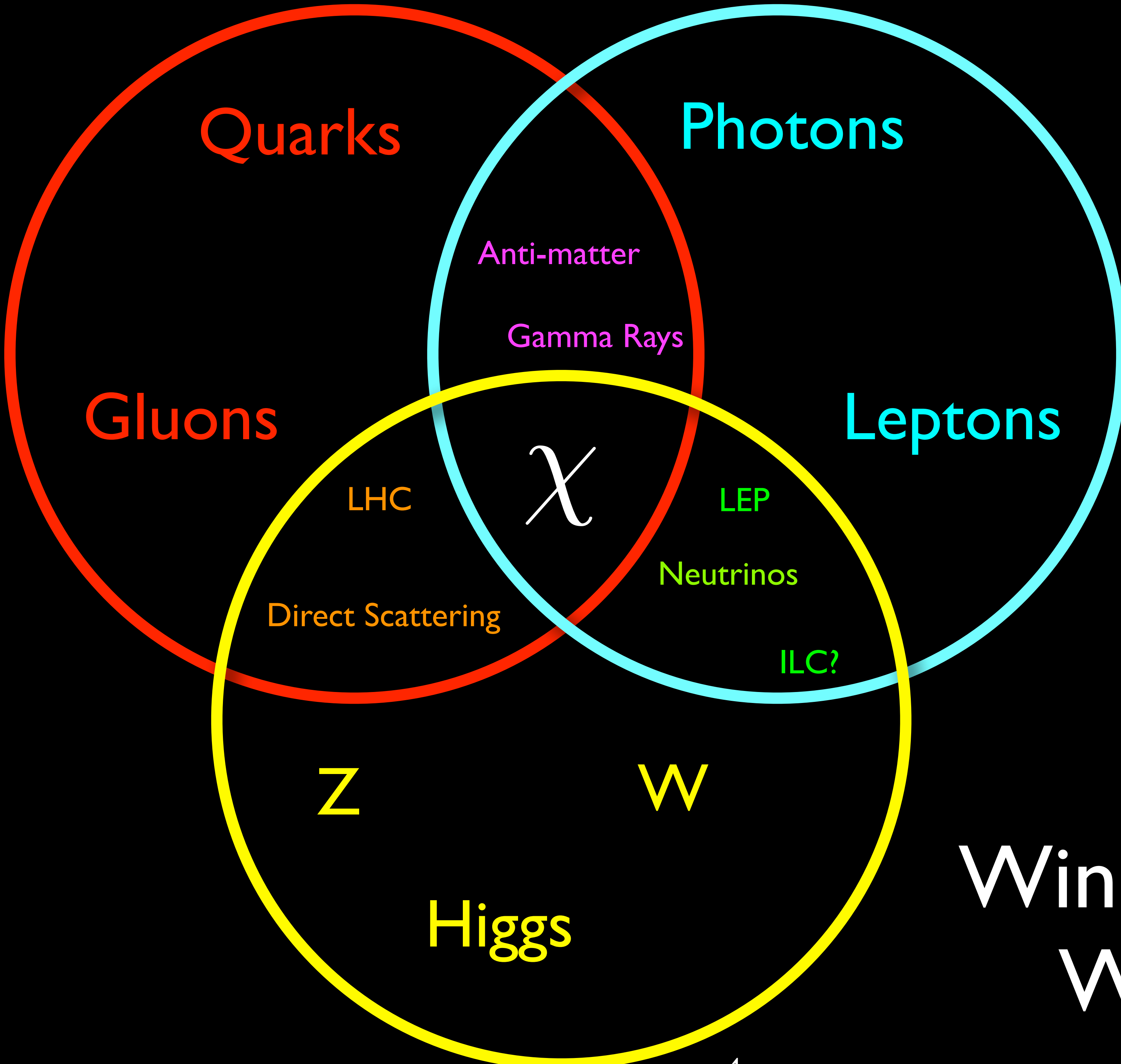
- ☐ Mass: ________
- ☐ Spin : ________
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

How was it produced?

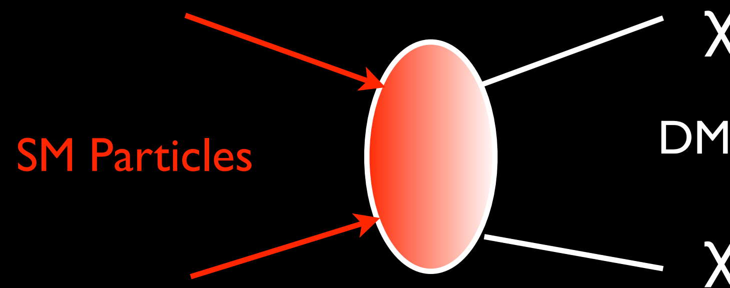
- ☐ Freeze-out ☐ Freeze-in
- ☐ Misalignment ☐ Something else



Windows on WIMPS

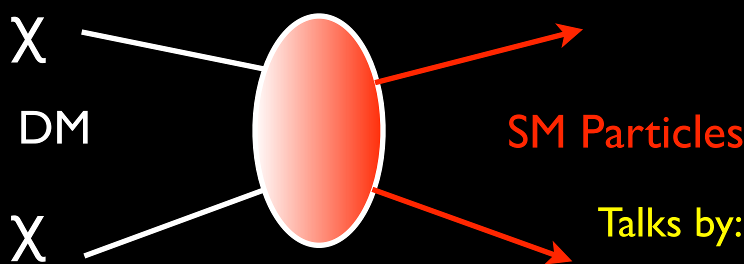
Probes of DM

Indirect Detection

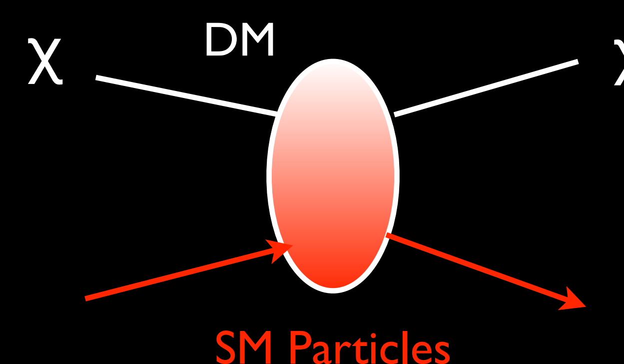


Collider Searches

Talk by:
Andrew Whitbeck

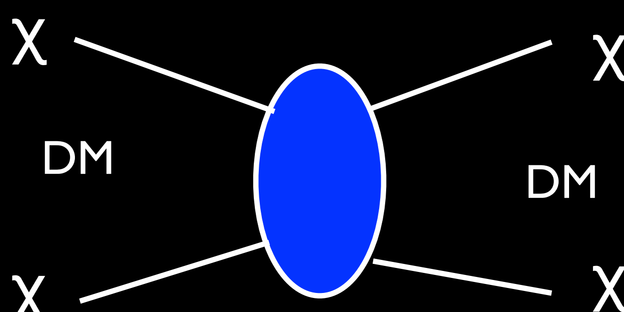


Talks by: Simona Murgia
JiJi Fan

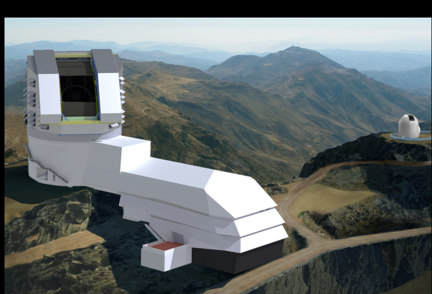


Direct Detection

Talks by: Cora Dvorkin
Sarah Shandera
Kim Boddy
Pearl Sandick
Stefano Profumo



Self-Interactions

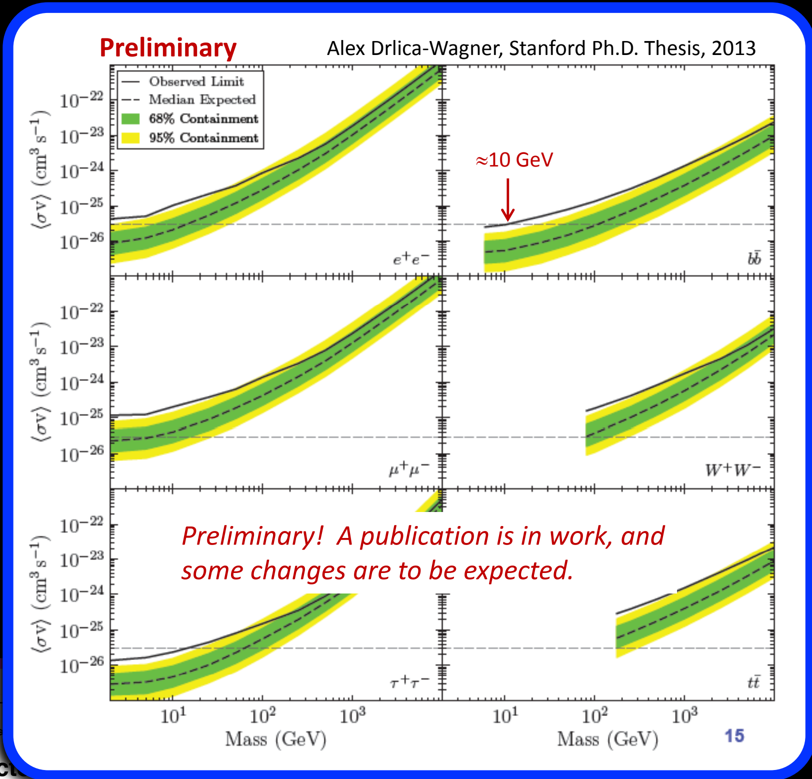


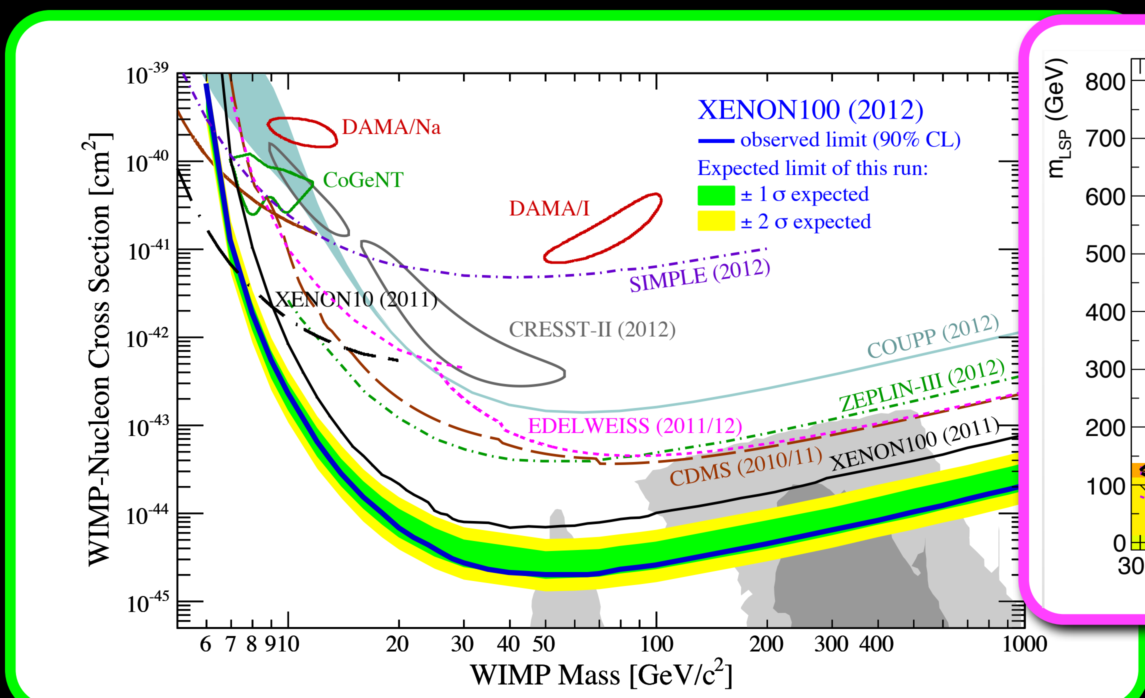
Talks by:
Rafael Lang
Rouven Essig

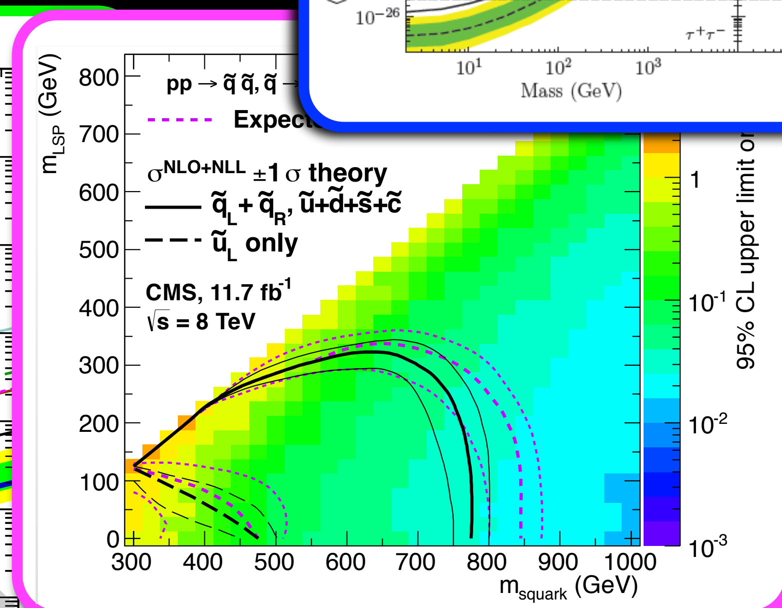
We Need (a) Theory

Individually, dark matter searches of all kinds put limits on various cross sections. Without some kind of theoretical structure, we can't compare them.

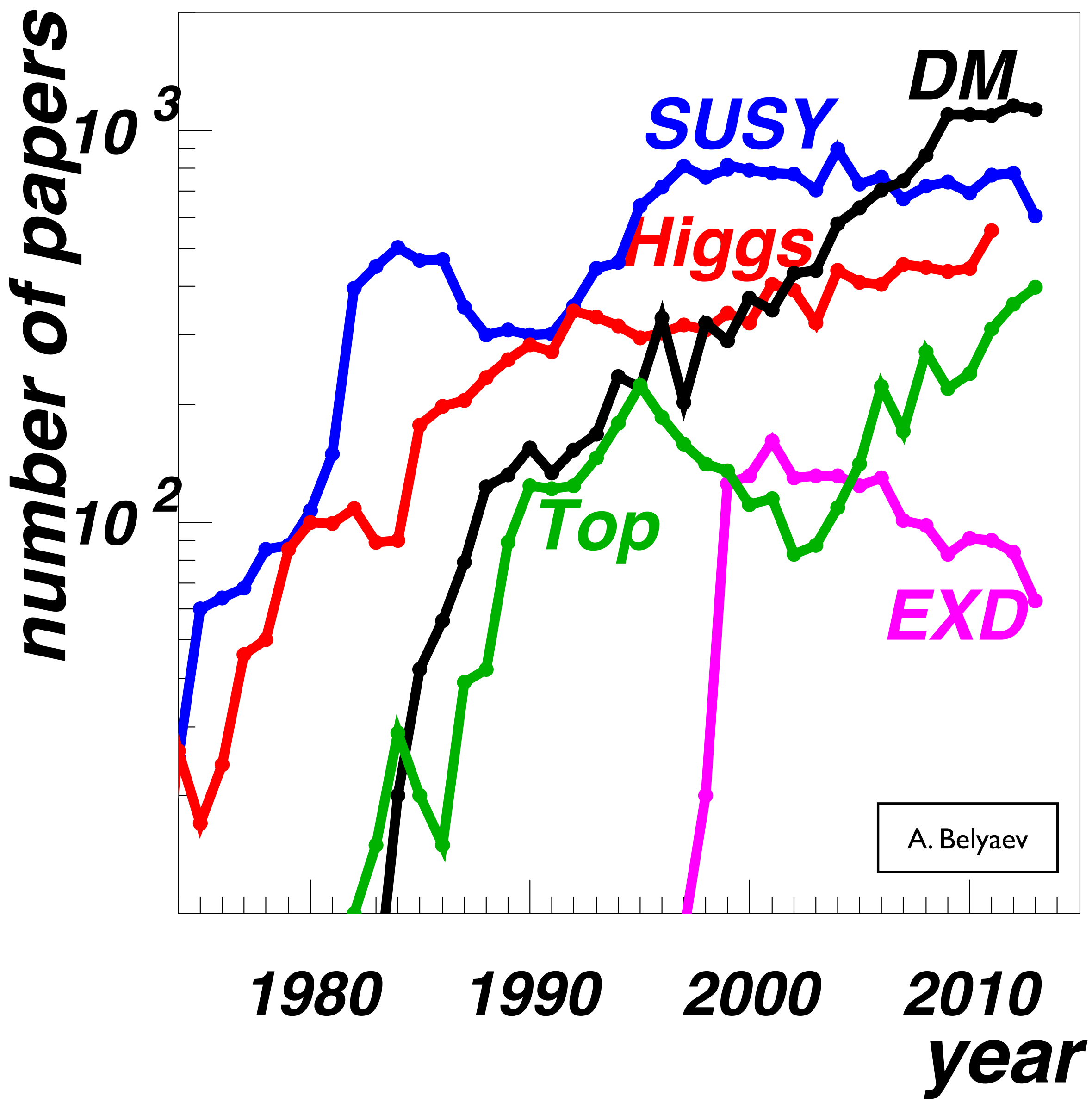
And we *know* they all descend from a single underlying theoretical framework…



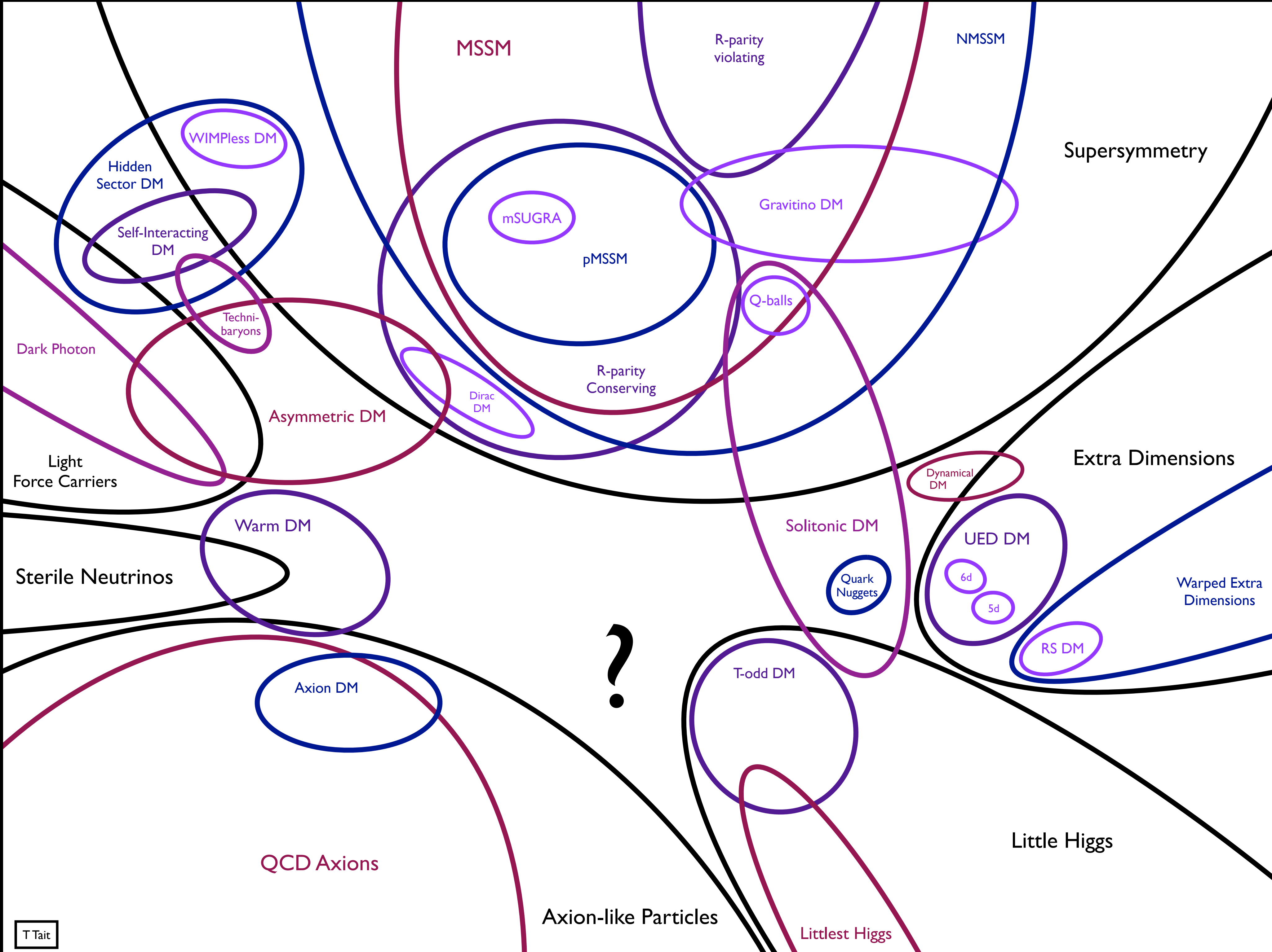


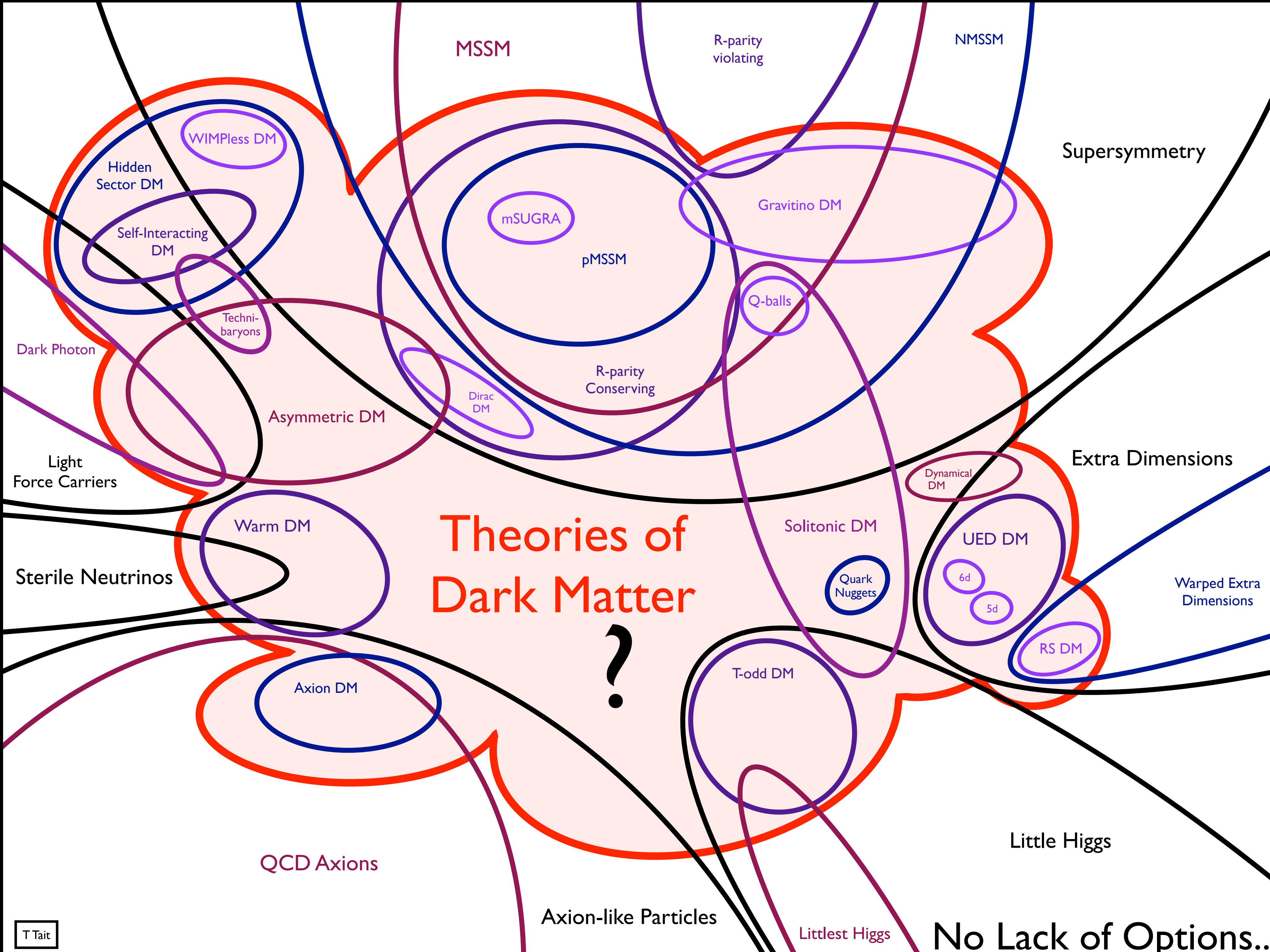


Which theory to use?



number of papers
10^3
10^2
SUSY
DM
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year


MSSM
R-parity violating
NMSSM
WIMPless DM
Hidden Sector DM
Supersymmetry
Gravitino DM
mSUGRA
pMSSM
Self-Interacting DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Extra Dimensions
Light Force Carriers
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
Warped Extra Dimensions
5d
RS DM
T-odd DM
Axion DM
?
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait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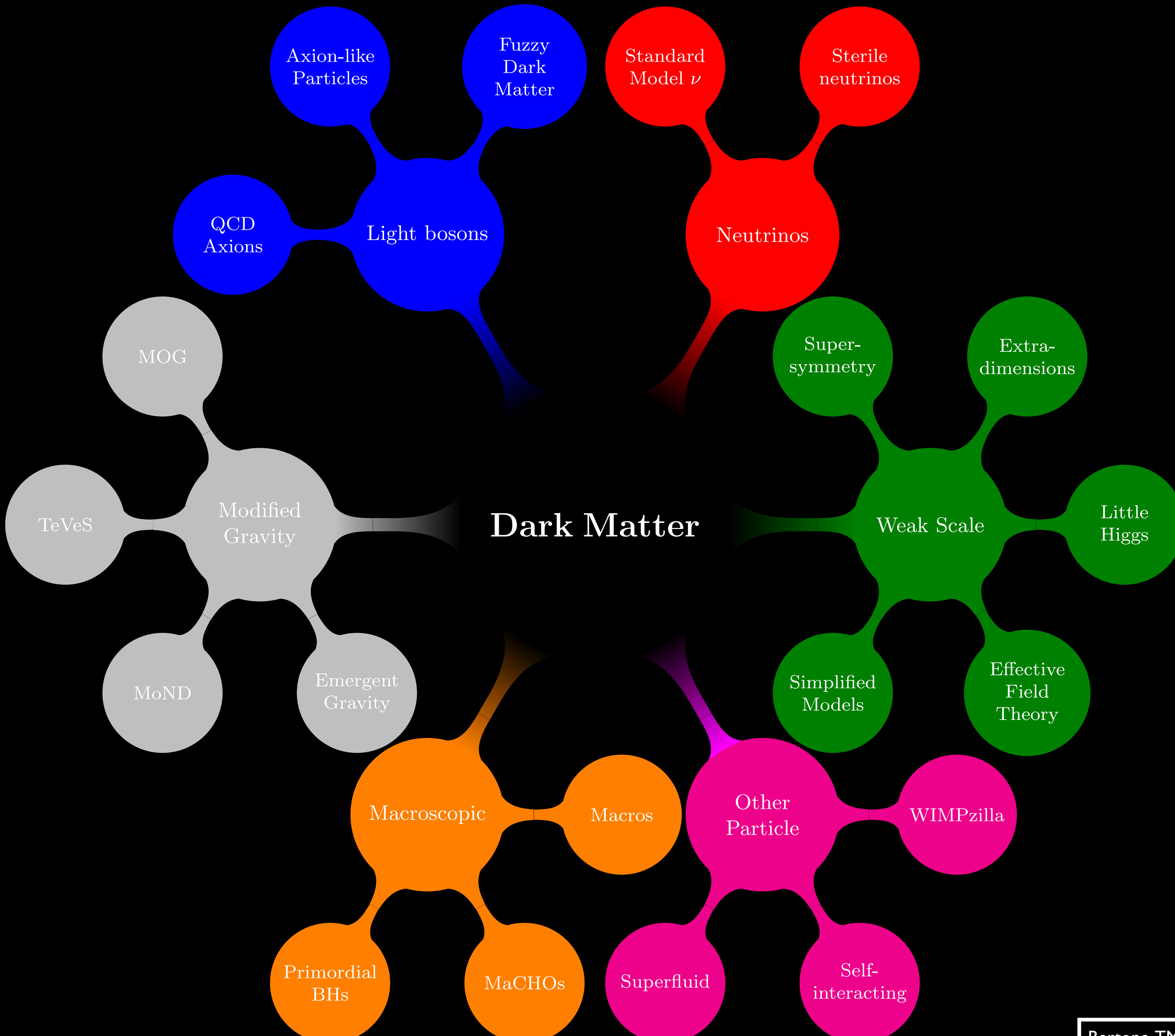
T Tait
No Lack of Options…



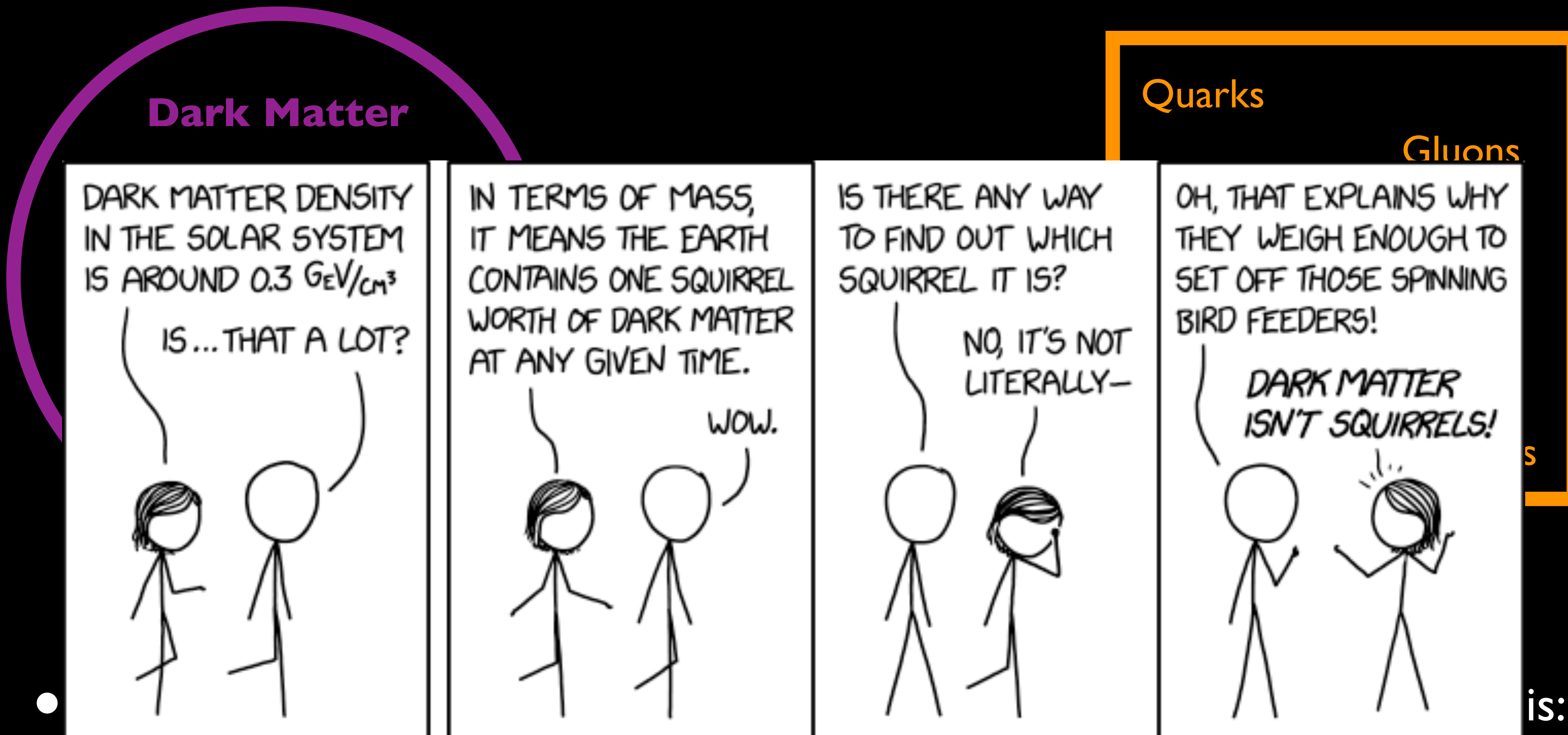
Bertone, TMPT Nature 2018

Mediators

Talks by: Stefania Gori
Bhaskar Dutta
Gordan Krnjaic
Keith Dienes
Yang Bai
Pavel Fileviez Perez

- One of the key questions that any theory of dark matter must address is: how does it interact with the Standard Model?
- Mediators could be part of the SM itself (Z, Higgs,…), new exotic particles with SM charges (e.g. squarks,…), or without (Z', dark photon, …).
- There could be an entire dark sector waiting to be discovered!

Mediators



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- There could be an entire da… to be discovered!

Cosmological Production of Dark Matter

Freeze Out: WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
    - WIMPs naturally can account for the amount of dark matter we observe in the Universe through the freeze out mechanism.
    - WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.

Talks by: Keith Olive, Gordy Kane

- WIMPs are a vision of dark matter for which we can use particle physics experimental techniques to search very effectively.
- One needs to be a little careful with the precise use of the term WIMP:
    - Some people may refer to particles which literally experience the SM electroweak SU(2) interaction.
    - Others may use the term to refer to particles with interactions and masses that are roughly electroweak sized, but may be formally unconnected to the SM weak interactions.

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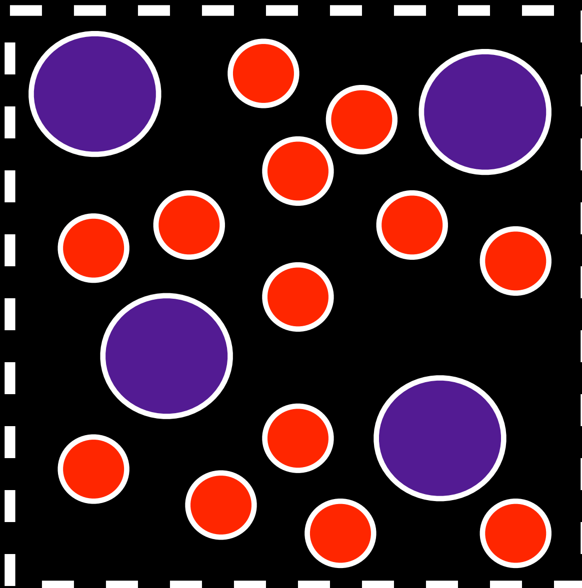
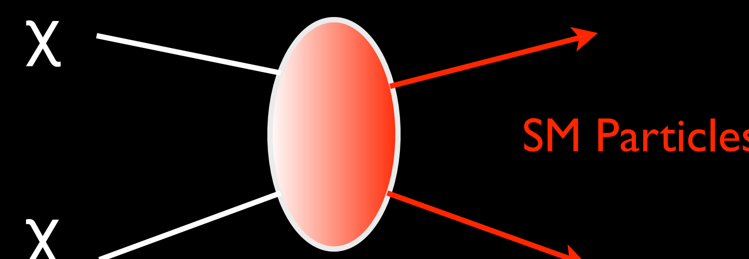
The WIMP Miracle



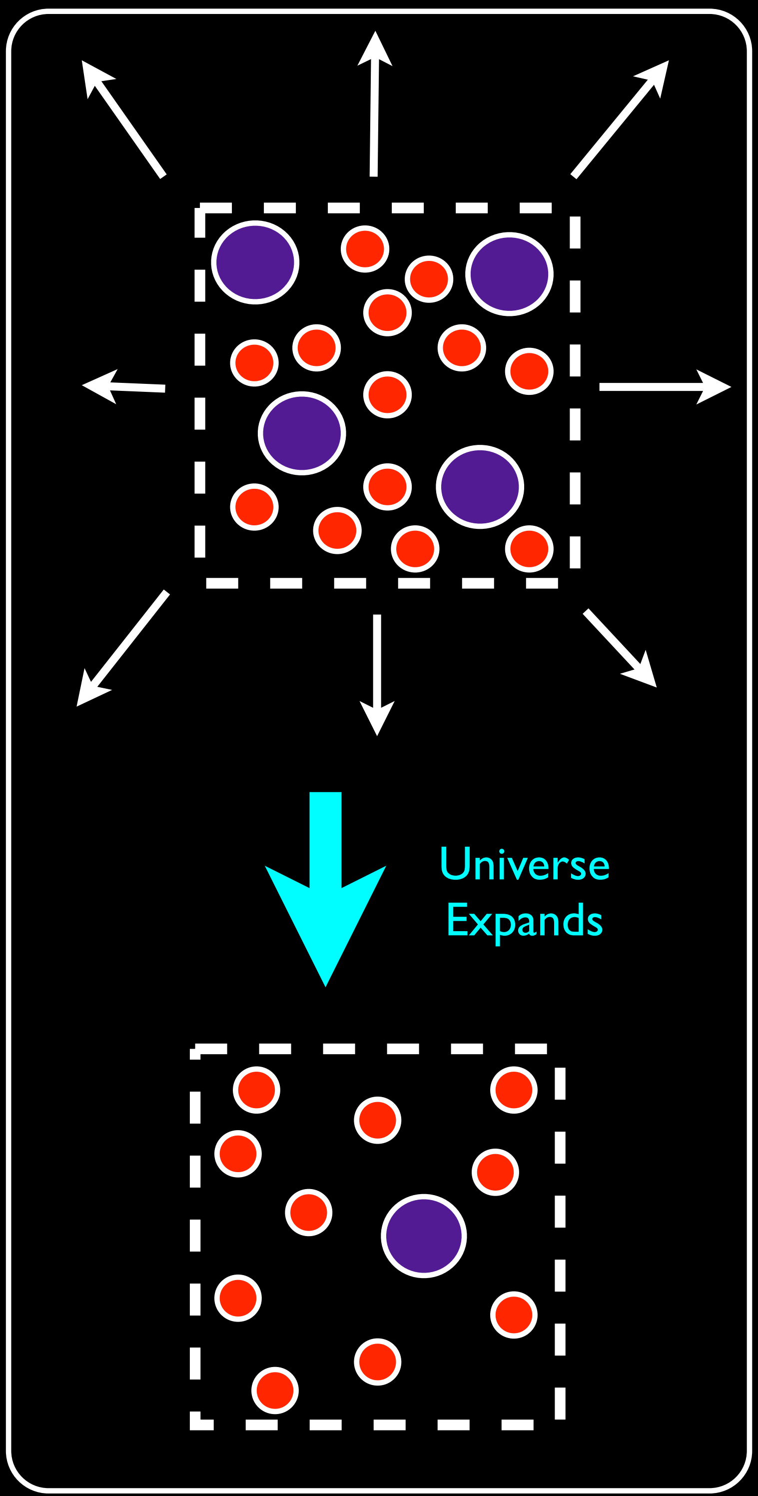
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, $\chi\chi$ -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$



Freeze-Out

- If this were the whole story, the dark matter would just keep diluting as the Universe cools, and would be irrelevant today.
- However, the expansion of the Universe eventually results in a loss of equilibrium.
- At the “freeze-out” temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on $\sigma(\chi\chi \to \text{SM})$: more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



Relic Density

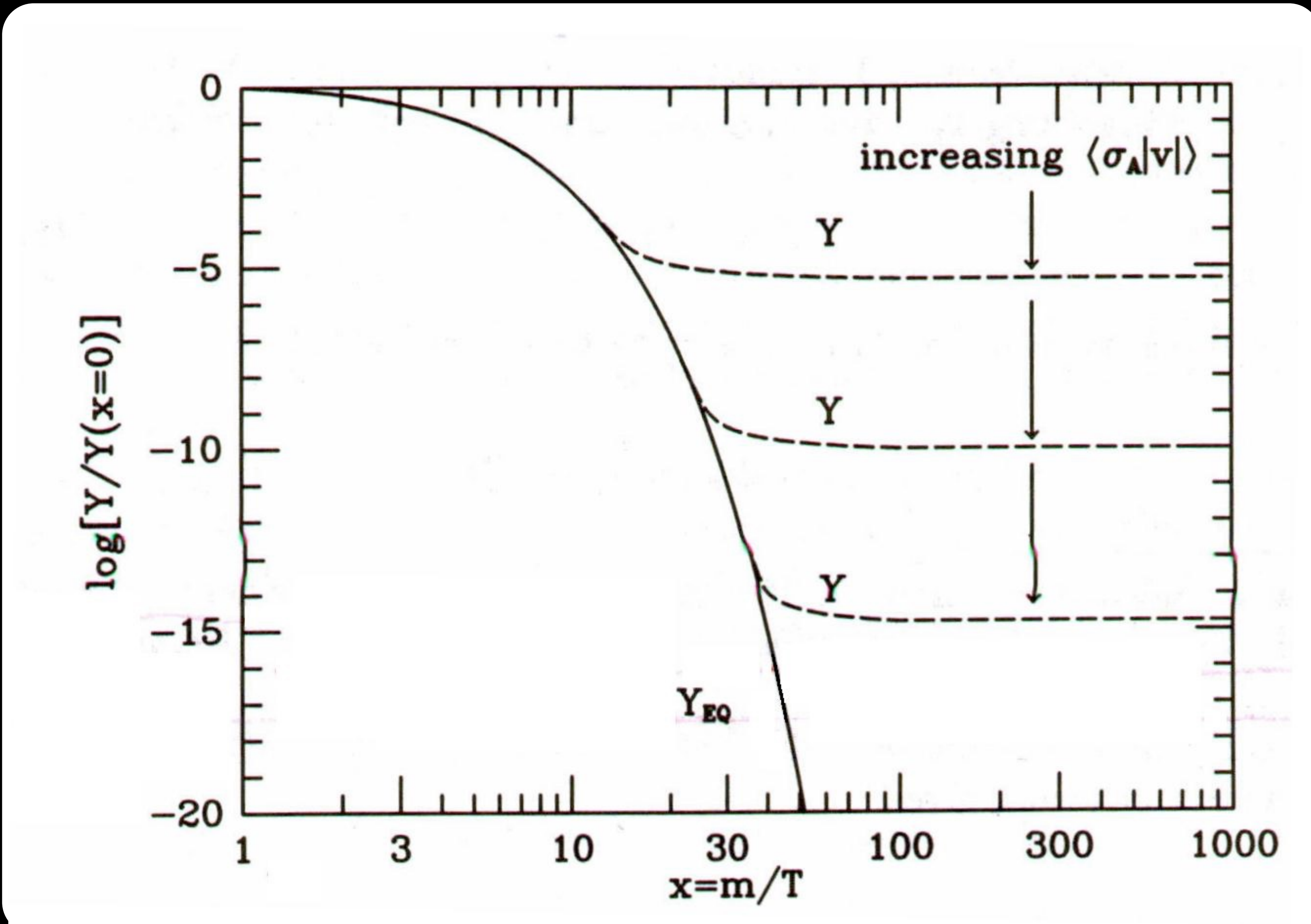


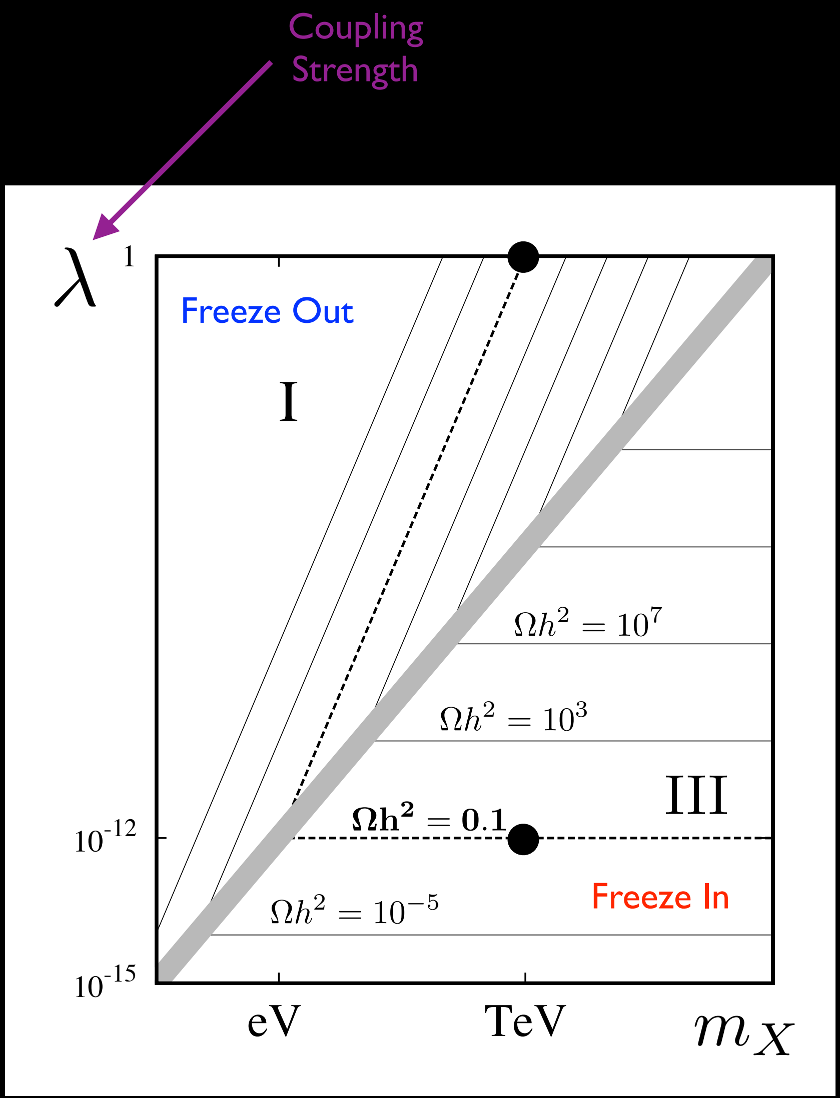
Figure from Kolb & Turner

x=m/T increasing
is
T decreasing
is
time increasing

- The observed quantity of dark matter is suggestive of a cross section for annihilation into the thermal bath (the SM + ...).

Freeze In

- Another very interesting possibility is production through freeze in.
- Freeze assumes negligible initial density, and requires small couplings, such that the particle does not reach equilibrium.
- If these couplings are small enough, the relic particle's lifetime could be large enough for it to be dark matter, even if it decays. There are many different scenarios, corresponding to different interaction types with the Standard Model.
- For example, a quartic interaction of the form χ^2 SM SM allows for an χ that is exactly stable, and interacts with a pair of SM particles in the thermal bath.

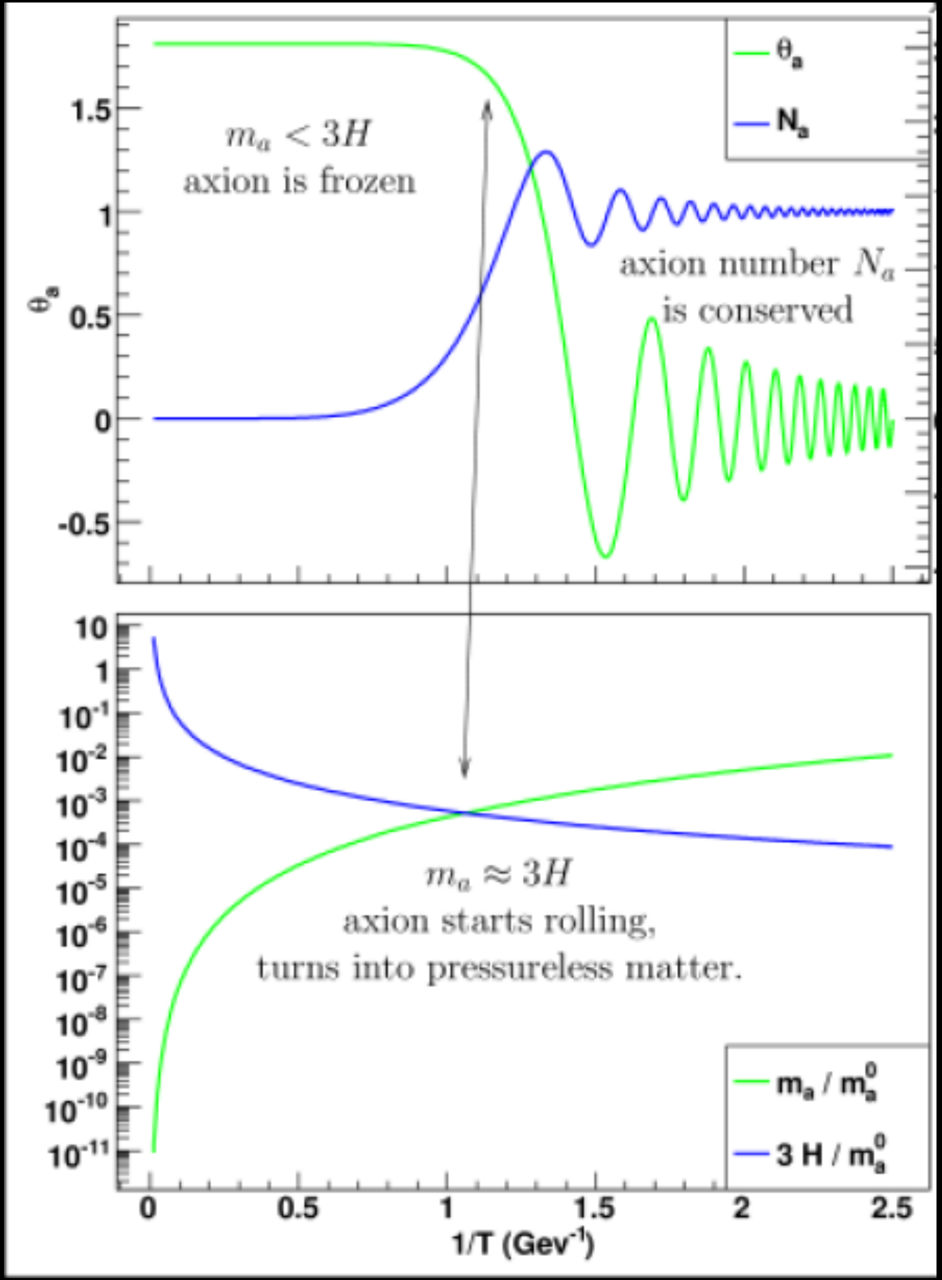


Hall, Jedamzik, Russel, West
arXiv:0911.1120

Talk by: Kyu-Jung Bae

Non-Thermal Production

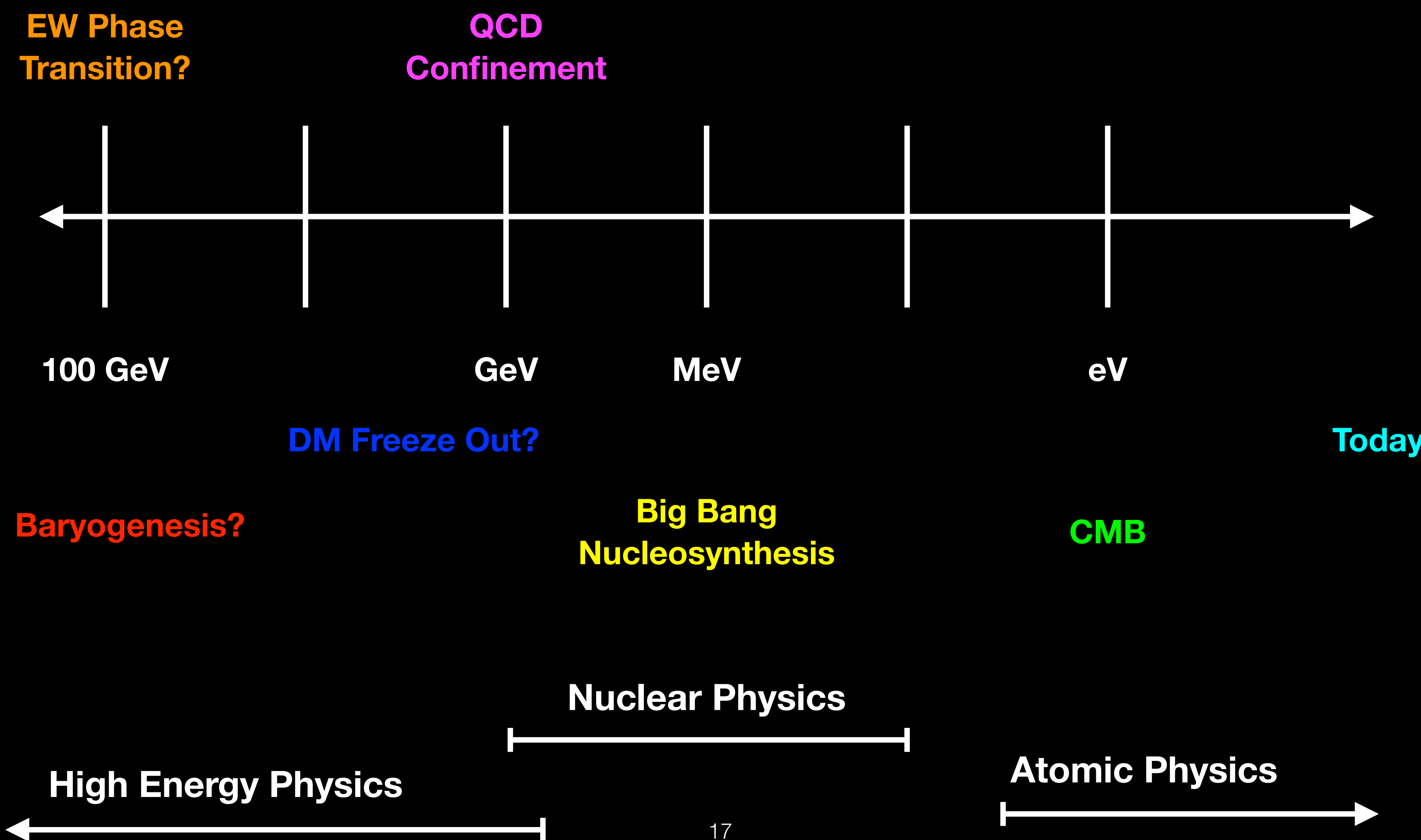
- Bosonic fields can also be produced as an initial condition of the Universe.
- For example, gravitationally at the end of inflation.
- If the masses and interactions are small enough, a field can persist as an expectation value until late times.
- When the mass of the field becomes comparable to the Hubble scale, it begins oscillating and starts behaving like a collection of particles.
- This type of production is famous in the discussion of axion dark matter (in the case where the Peccei-Quinn symmetry is broken before inflation), but also applies to other light scalar and vector particles as well.



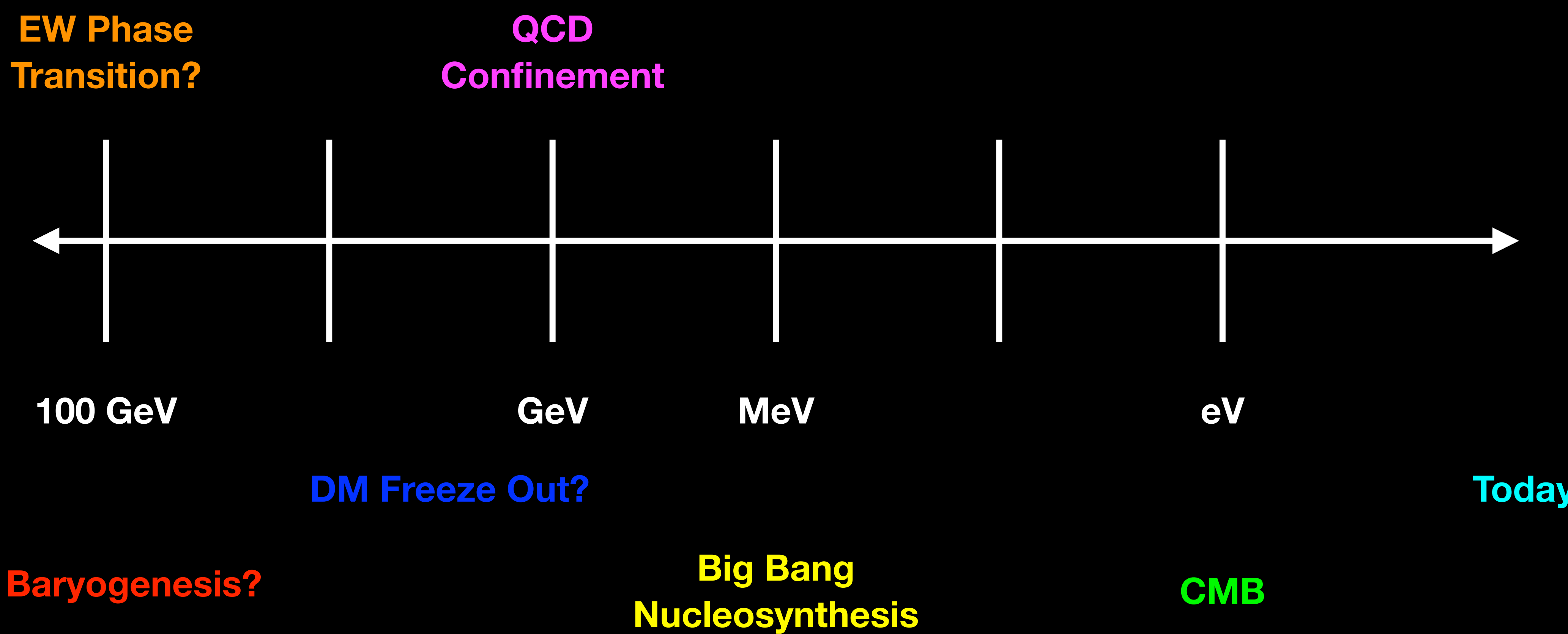
From a nice review in:
Wantz, Shellard [0910.1066]

Dark Matter Production is an Opportunity

Early Times are Uncertain



Early Times are Uncertain



Before BBN, most of what we know about the physics in the early Universe is an extrapolation based on the Standard Model + ingredients such as dark matter.

Features such as inflation, dark matter, and the existence of a baryon asymmetry are all indications that ingredients are missing at earlier times… the extrapolation is uncertain!

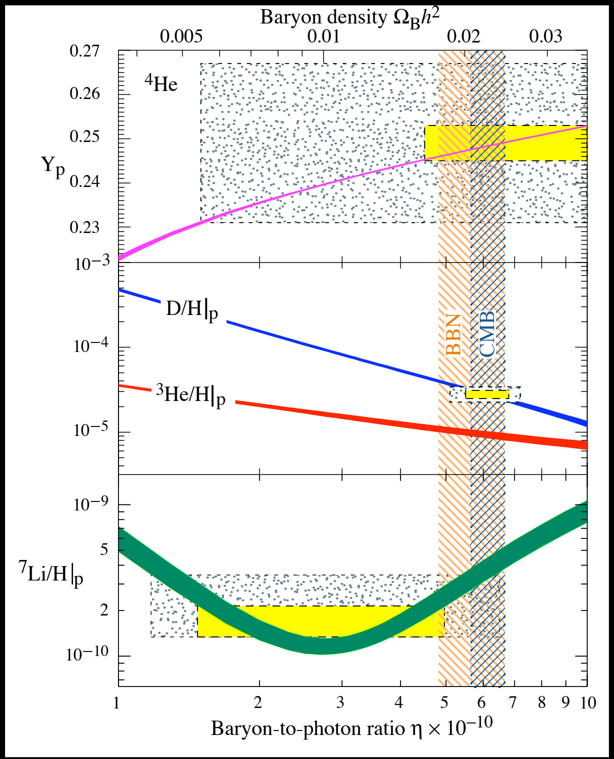
Freeze Out Relic?

As an example to illustrate this point, let's imagine things that could go wrong with the freeze out calculation.

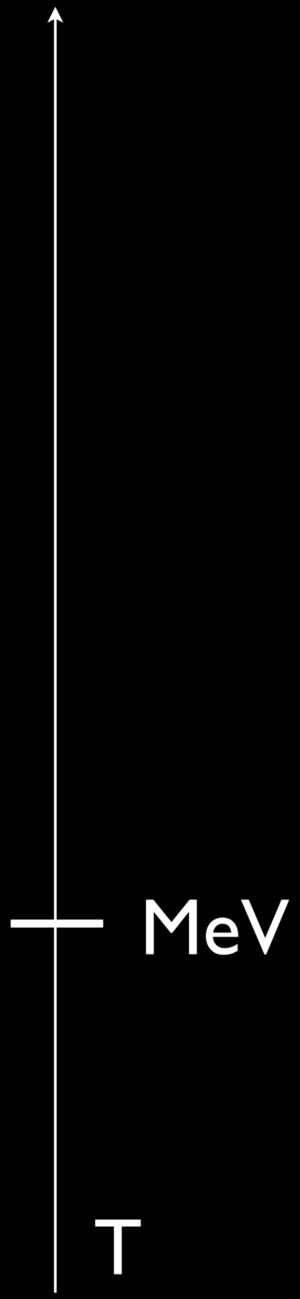
What do we *know* about the history of the Universe?

Freeze Out Relic?

What do we *know* about the history of the Universe?



We understand the Universe pretty well back to the time of Nucleosynthesis, from the abundance of isotopes of H, He, and Li.

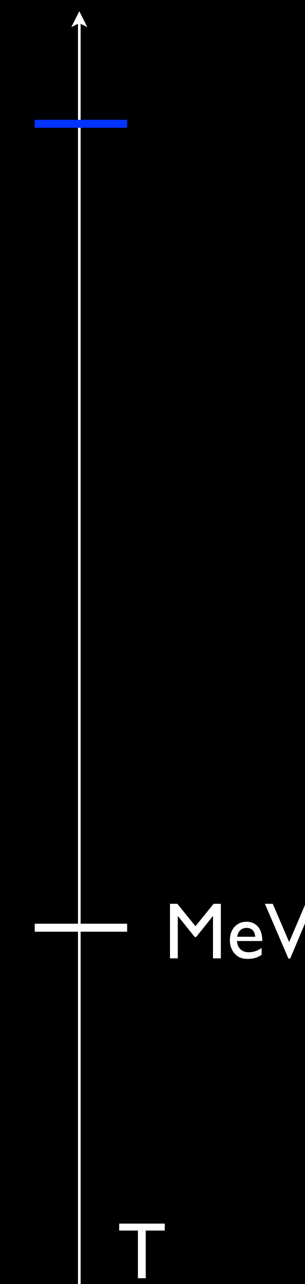


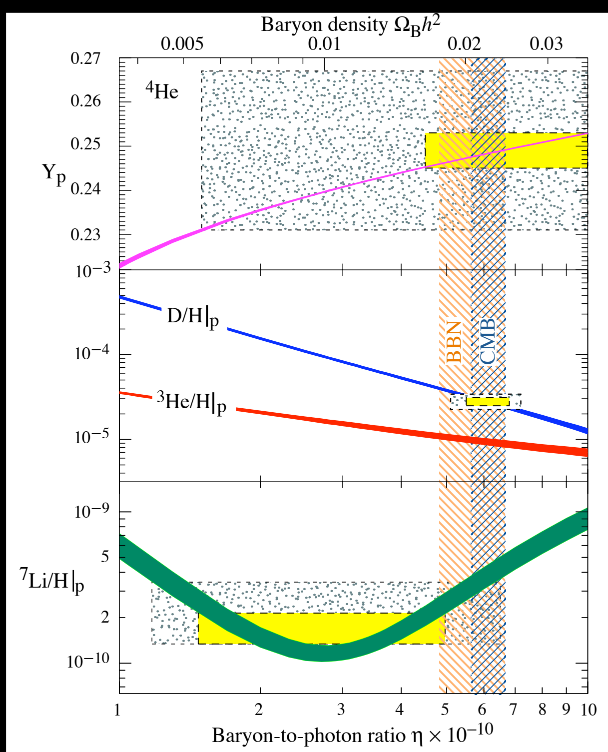
Freeze Out Relic?

What does that mean for DM?

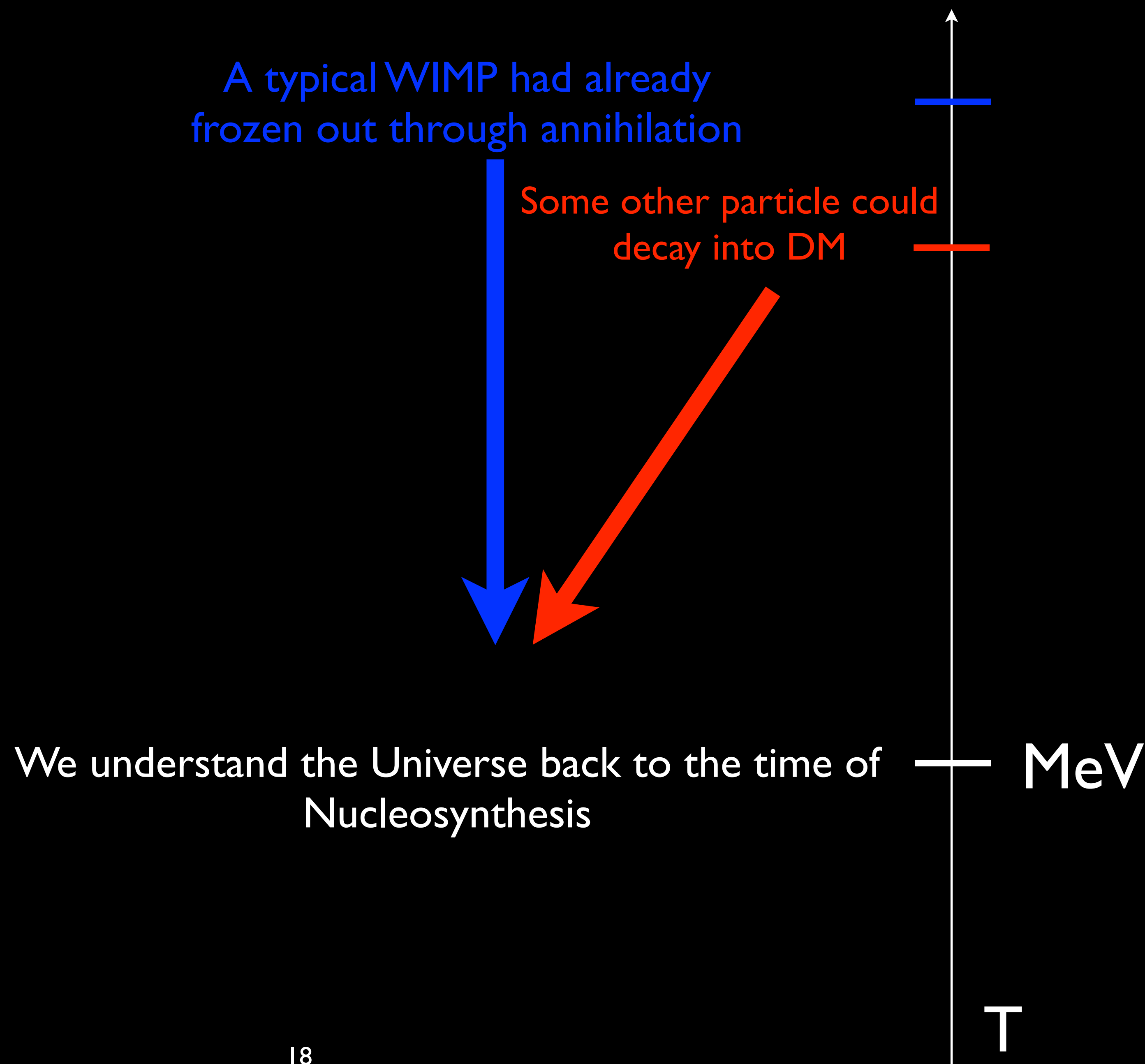
A typical WIMP had already frozen out through annihilation

We understand the Universe back to the time of Nucleosynthesis





Lots Could Happen



Lots Could Happen

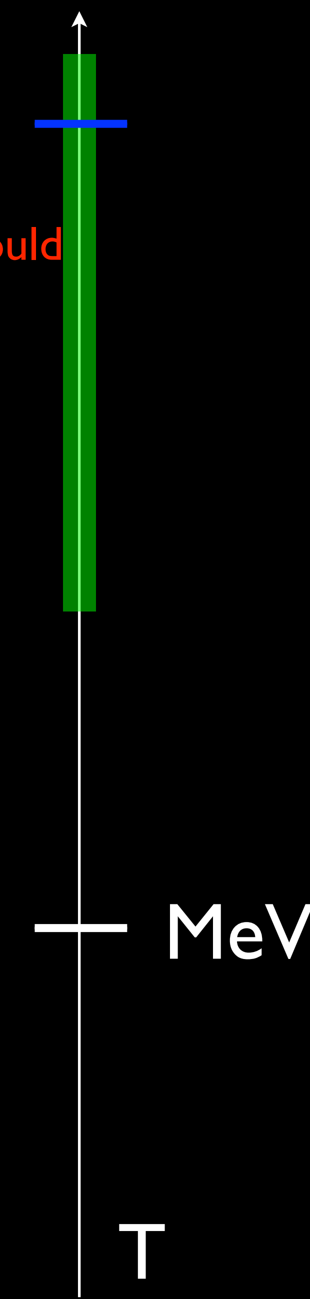
Physics could look different from our expectations (because of a VEV, etc)

Parallel Talk by:
Jessica Howard
(Wednesday 15:15 pm)

A typical WIMP had already frozen out through annihilation

Some other particle could decay into DM

We understand the Universe back to the time of Nucleosynthesis



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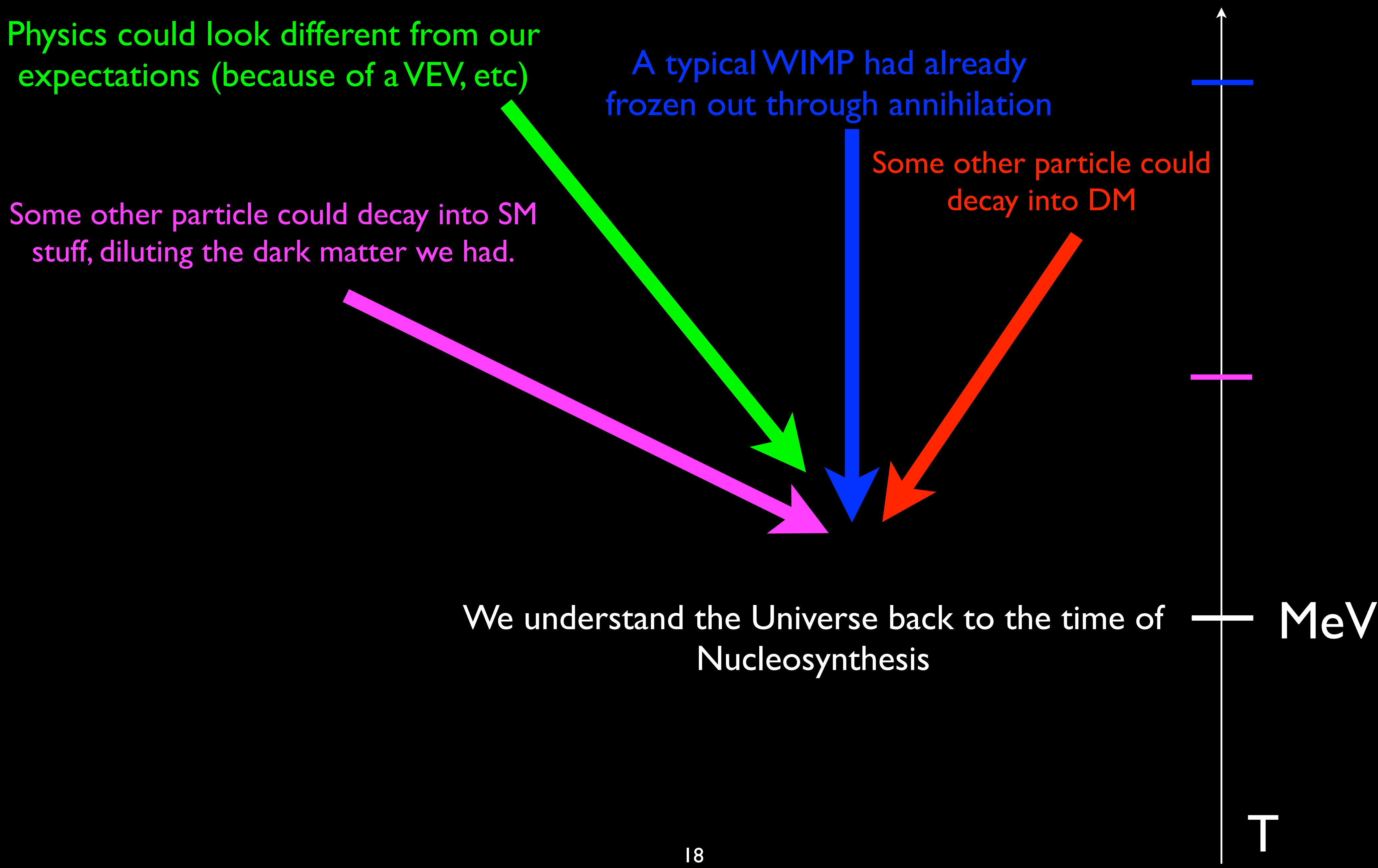


Lots Could Happen

Physics could look different from our expectations (because of a VEV, etc)

A typical WIMP had already frozen out through annihilation

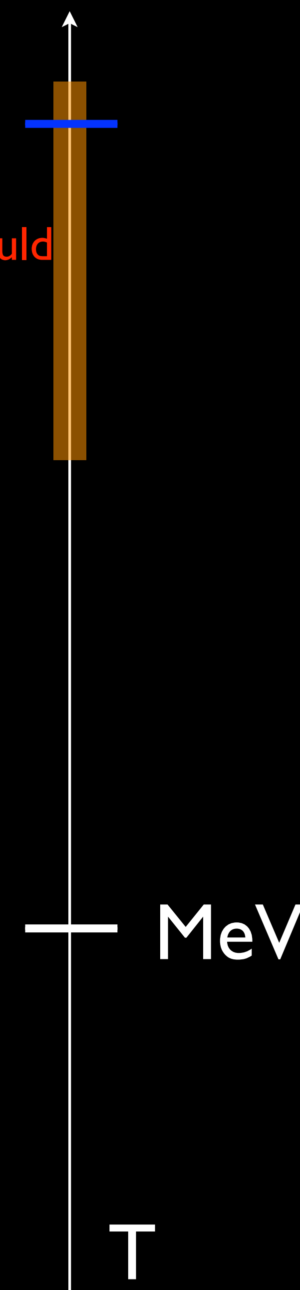
Some other particle could decay into DM

Some other particle could decay into SM stuff, diluting the dark matter we had.

There could be an unexpected early period of matter domination or inflation

Talk by:
Adrienne Erickcek

We understand the Universe back to the time of Nucleosynthesis



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There could be an unexpected early period of matter domination or inflation

This is a feature!

We understand the Universe back to the time of Nucleosynthesis

MeV

T

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

Lots Could Happen

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A typical WIMP had already frozen out through annihilation

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Some other particle could decay into SM stuff, diluting the dark matter we had.

There could be an unexpected early period of matter domination or inflation

To illustrate this point,
I have a couple of examples related to a change in QCD in the early Universe, such that it confines at an early time.

This is a feature!

We understand the Univ
Nucleos

V

Understanding the annihilation cross section could verify the WIMP miracle and push back our understanding of the Universe to earlier times.

T

Early QCD Confinement

- We introduce dynamics promoting the strong coupling to a dynamical field (denoted by ϕ):

Ipek, TMPT 1811.00559

$$-\frac{1}{4}\left(\frac{1}{g_0^2}+\frac{\phi}{M_*}\right)G^{\mu\nu}G_{\mu\nu} \qquad g_{\text{eff}}^2\left(\langle\phi\rangle\right)=\frac{g_0^2}{1+g_0^2\frac{\langle\phi\rangle}{M_*}}$$

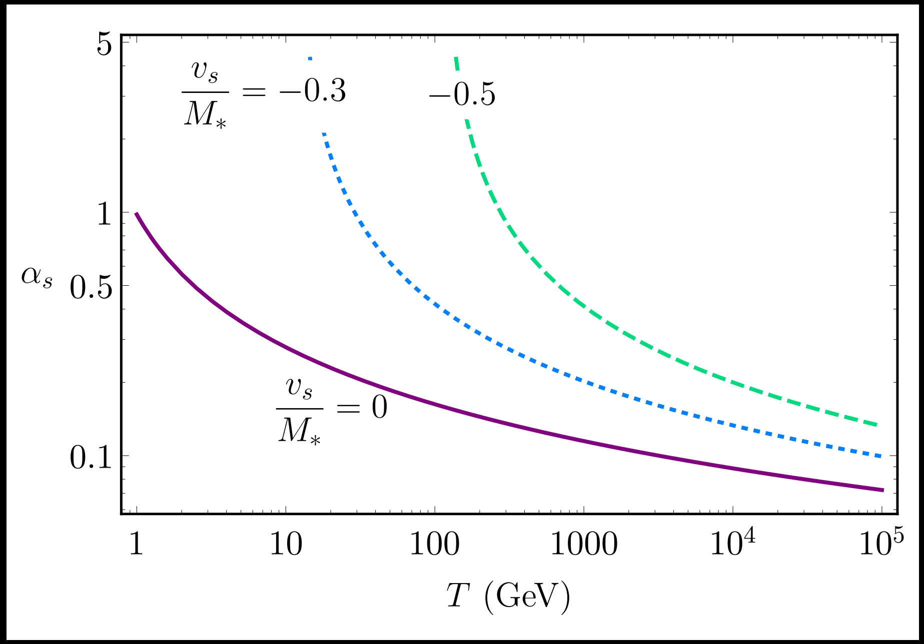
- The scale at which QCD gets strong is about:

$$\Lambda \simeq \Lambda_0 \times \text{Exp}\left(\frac{24\pi^2}{2n_f-33}\frac{\langle\phi\rangle}{M_*}\right)\equiv \xi\Lambda_0$$

- For $n_f = 6$, to get Λ ~ TeV:

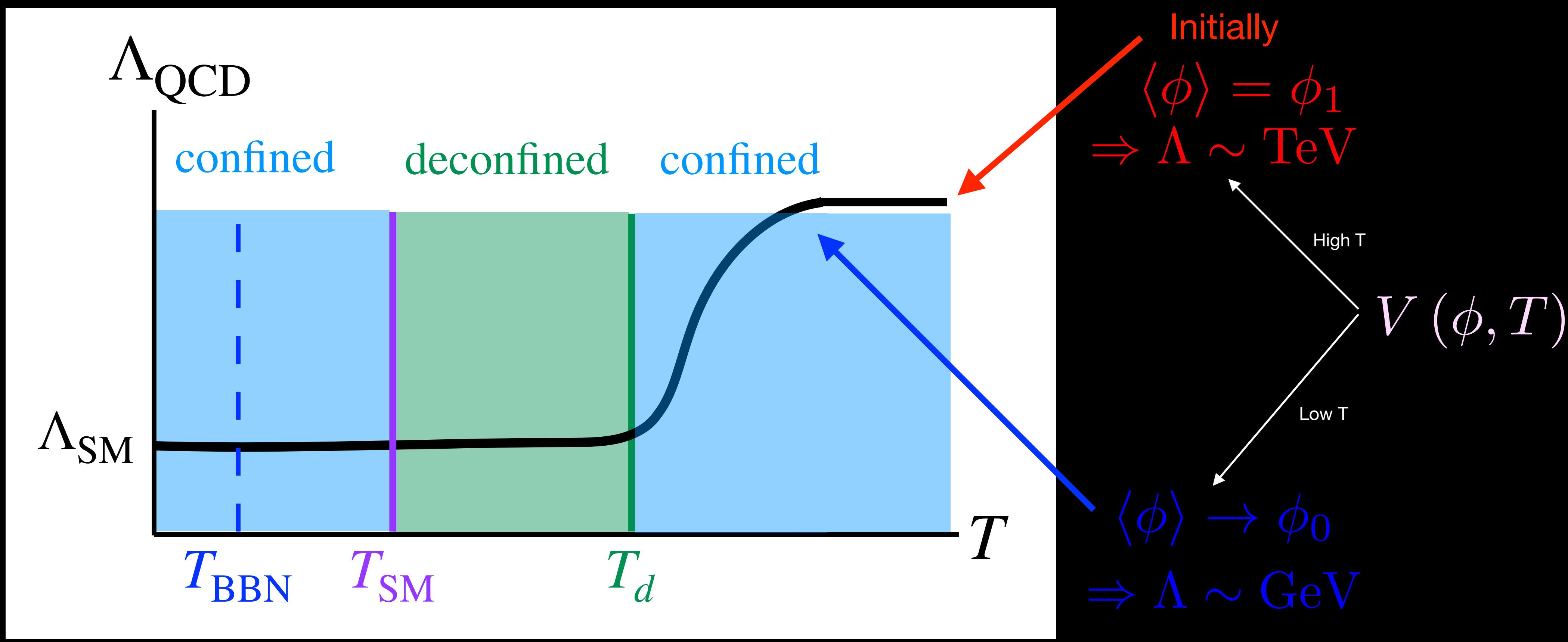
$$\frac{\Delta\langle\phi\rangle}{M_*}\simeq -0.8$$

Berger, Ipek, TMPT, Waterbury 2004.06727



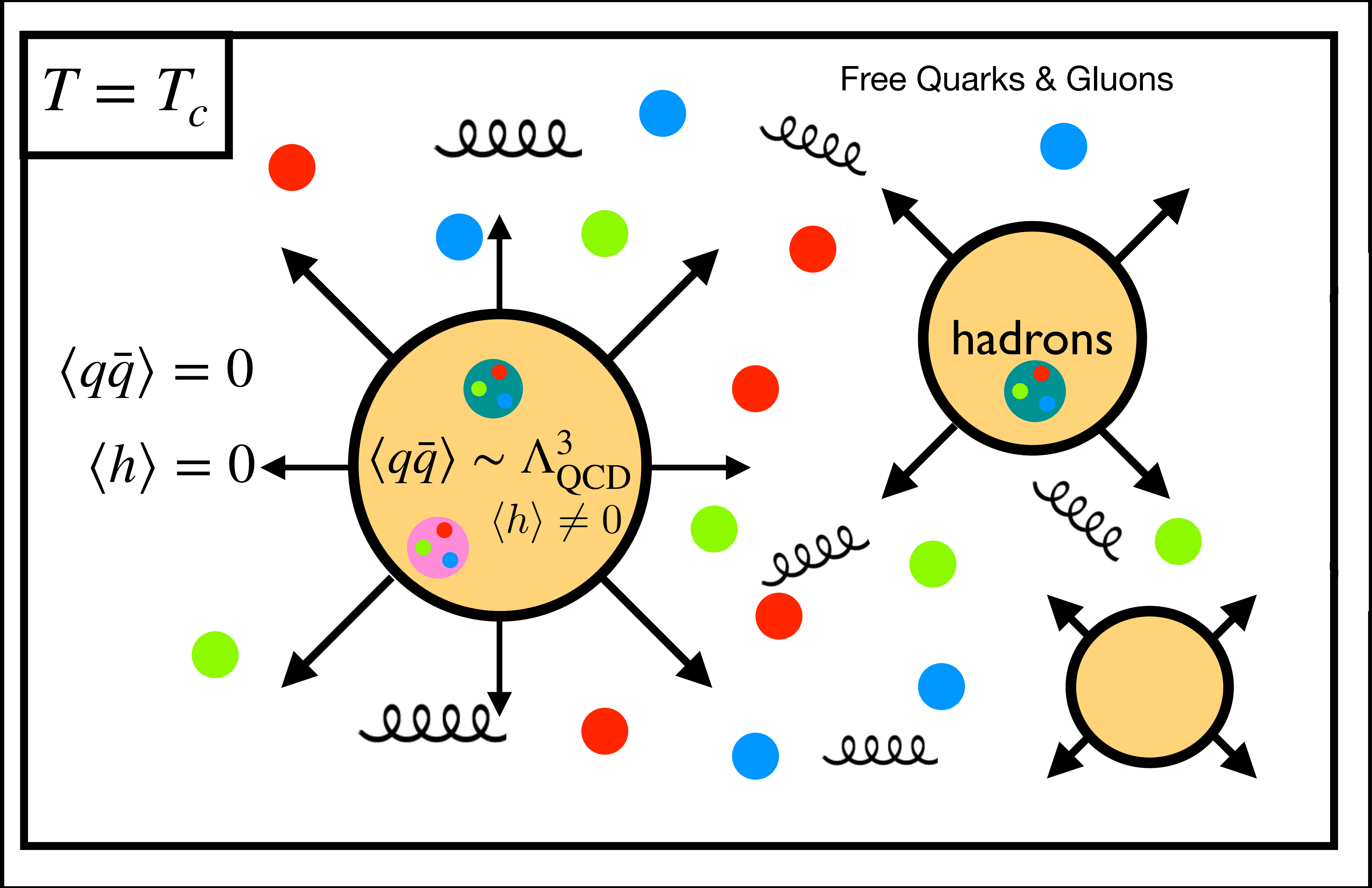
Φ Potential

- The potential for ϕ should receive temperature-dependent corrections such that <ϕ> shifts, moving from a value at high temperatures corresponding to a large Λ to a value at low temperatures matching on to Λ ~ 1 GeV.



Croon, Howard, Ipek, TMPT 1911.01432

QCD Phase Transition



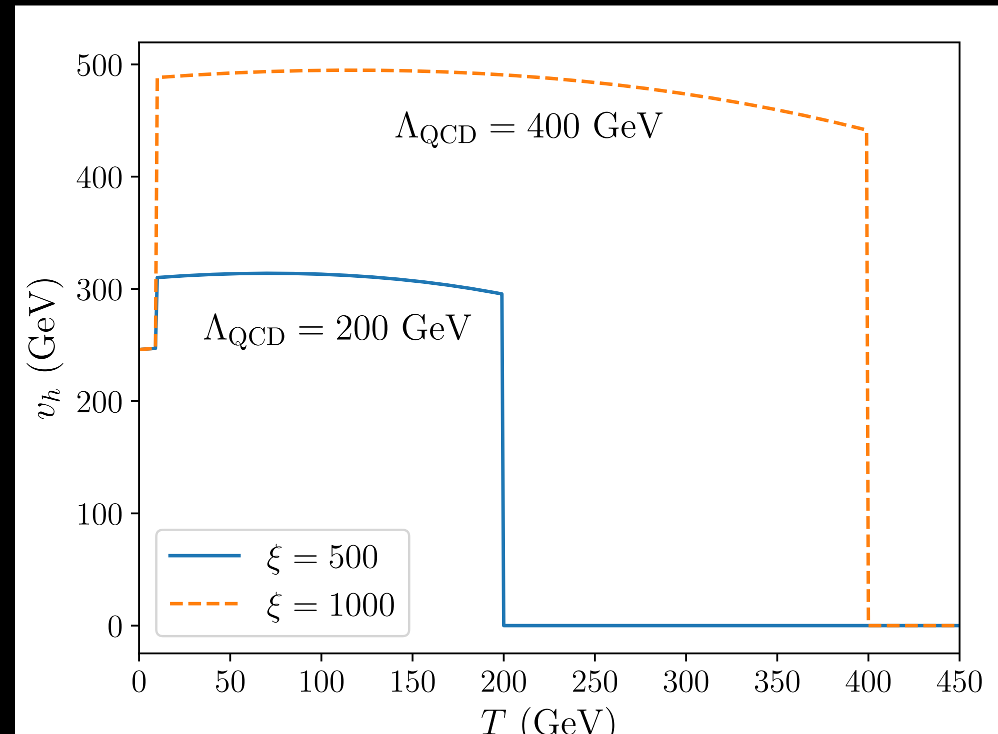
Ipek, TMPT 1811.00559

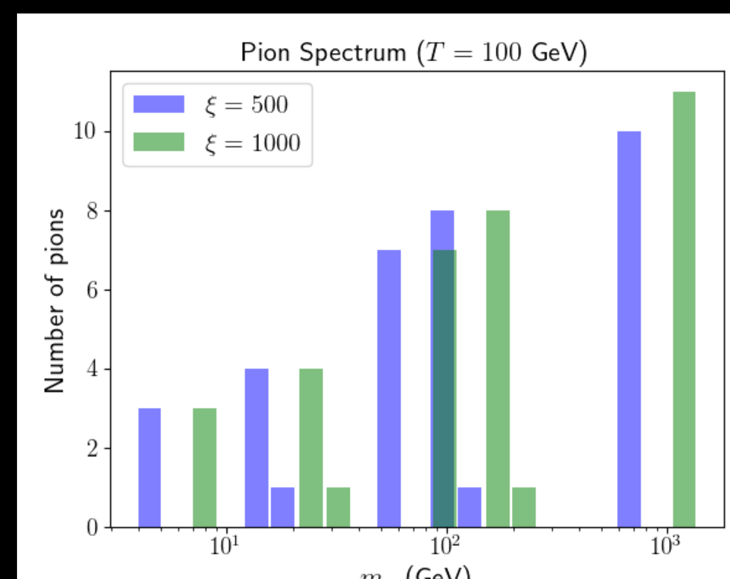
1st Order!

Confined Universe

- In the confined phase, the important active degrees of freedom are the ~35 pNGB mesons.
    - Their properties are described by chiral perturbation theory, with parameters matched to low energy QCD data, and dimensionful quantities scaled up to the high scale confinement scale.

$$\kappa \simeq (220\ \mathrm{MeV})^3\, \xi^3\ , \qquad f_\pi \simeq 94\ \mathrm{MeV}\, \xi, \qquad m_\pi^2 \simeq m_{\pi 0}^2\, \xi\, v_h / v_h^0,$$





2004.06727

- The thermal corrections to the Higgs potential are dominated by the top-flavored (or bottom-flavored) mesons rather than top/bottom quarks.

- The chiral condensate acts as a tadpole for the Higgs doublet.

$$\kappa\ \mathrm{tr}(U M_q^\dagger + M_q U^\dagger) \longrightarrow \sqrt{2}\kappa\, y_t\, h - \frac{\kappa}{f_\pi^2}\, \mathrm{tr}[\{T^a, T^b\} M]\, \pi^a \pi^b\ ,$$

DM Freeze Out

Berger, Ipek, TMPT, Waterbury 2004.06727

- Let's imagine that DM is a WIMP which is a (SM singlet) Dirac fermion that likes to interact with quarks.
- If the mediators are heavy compared to the energies of interest, this can be parameterized by a dimension six contact interaction.
- For simplicity, I will also imagine that this is a scalar interaction, and its flavor structure is minimal-flavor violating (MFV), matching the quark Yukawa interactions. (So: this is consistent with the Higgs portal).
- (If the singlet field is heavy and has some mixing with the Higgs, this is the kind of low energy interaction it would mediate).
- If the WIMP further freezes out during the confined phase, its interactions are with mesons rather than quarks, which are enhanced by Λ.
- The chiral condensate can shift the DM mass by a non-trivial amount!

$$\frac{\beta_{ij}}{M_S^2}\bar{\chi}\chi\ \bar{q}_i q_j$$

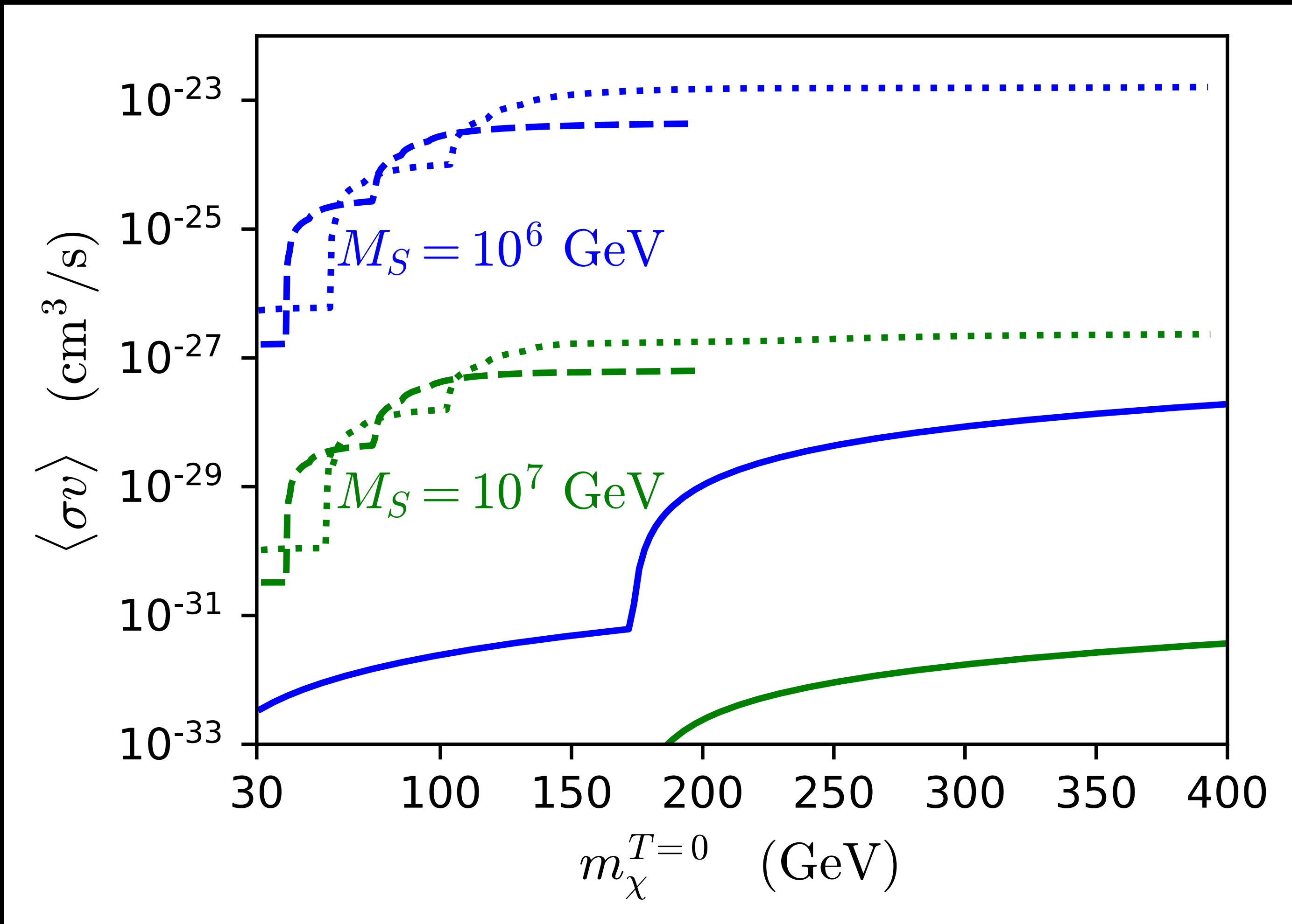
$$\beta_{ij} \equiv \pm\delta_{ij}\frac{y_i}{y_u}$$

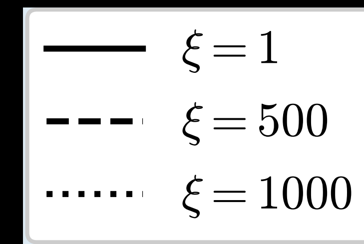
$$\frac{\kappa}{M_S^2}\ \bar{\chi}\chi\ \mathrm{tr}\left(U^\dagger\beta + U\beta^\dagger\right)$$

$$\frac{2\kappa\ \mathrm{tr}\,[\beta]}{M_S^2}\ \bar{\chi}\chi + \frac{2\kappa}{f_\pi^2}\frac{1}{M_S^2}\ \mathrm{tr}[T^a T^b \beta]\ \bar{\chi}\chi\pi^a\pi^b$$

$$m_\chi^{T=T_F} = m_\chi^{T=0} + \Delta m_\chi\ , \quad \text{where}\ \ \Delta m_\chi \simeq (2\ \mathrm{eV})\,\xi^3\left(\frac{10^6\ \mathrm{GeV}}{M_S}\right)^2$$

Freeze Out





Note the thresholds when the top channel(s) open up. Because of the WIMP mass shift induced by confinement, their location changes for different Λs.

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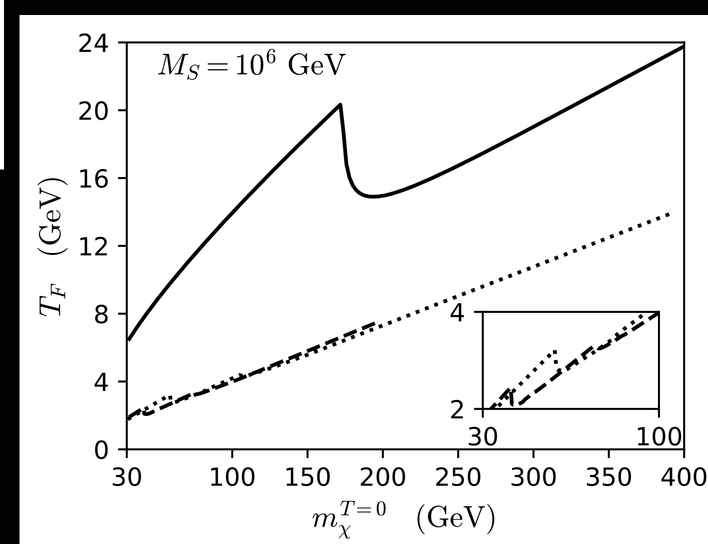
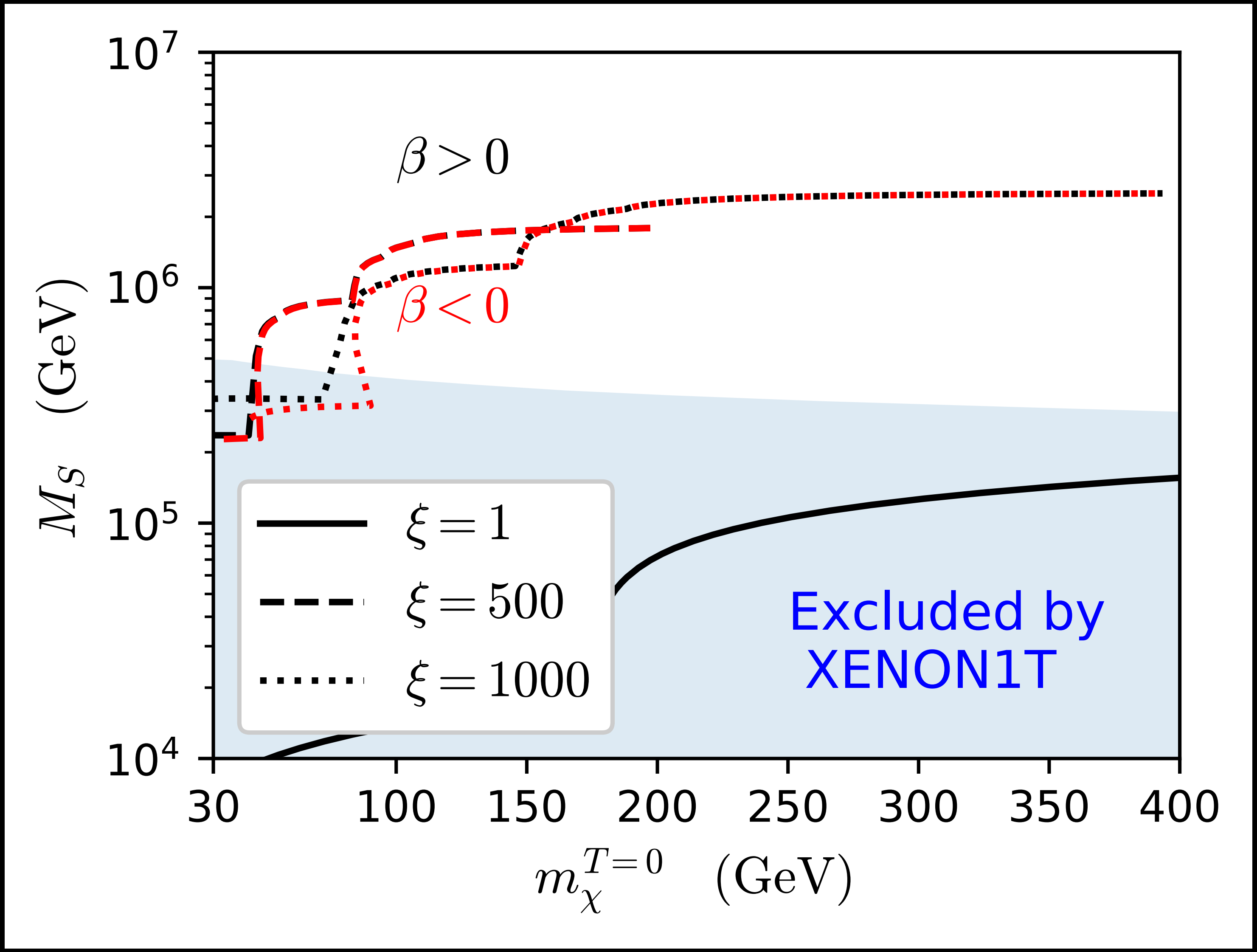


The cross sections during early confinement are enhanced by a factor of κ / f_π^2 compared to the unconfined case. This enhancement from compositeness dramatically shifts the parameter space leading to the correct relic density through freeze-out.

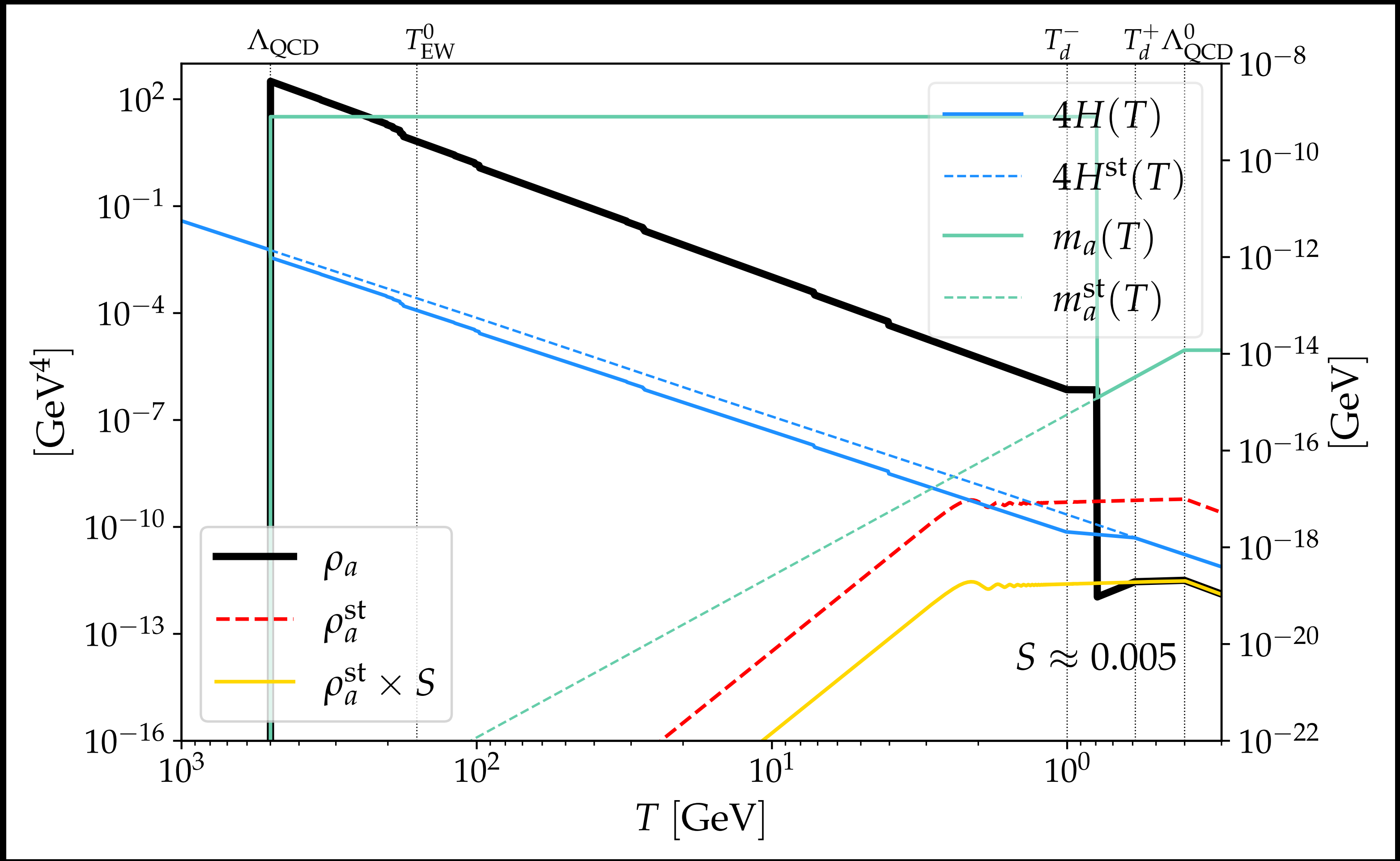
Freeze Out



Berger, Ipek, TMPT, Waterbury 2004.06727

If the dark matter had frozen out in the SM, the parameters to realize the relic density would be already excluded by Xenon-1ton. Freezing out during early confinement rescues this parameter space, reconciling Xenon with freeze out.

QCD Axion Production



- In a theory in which the QCD axion plays the role of dark matter, a period of early QCD confinement can also make a huge difference.

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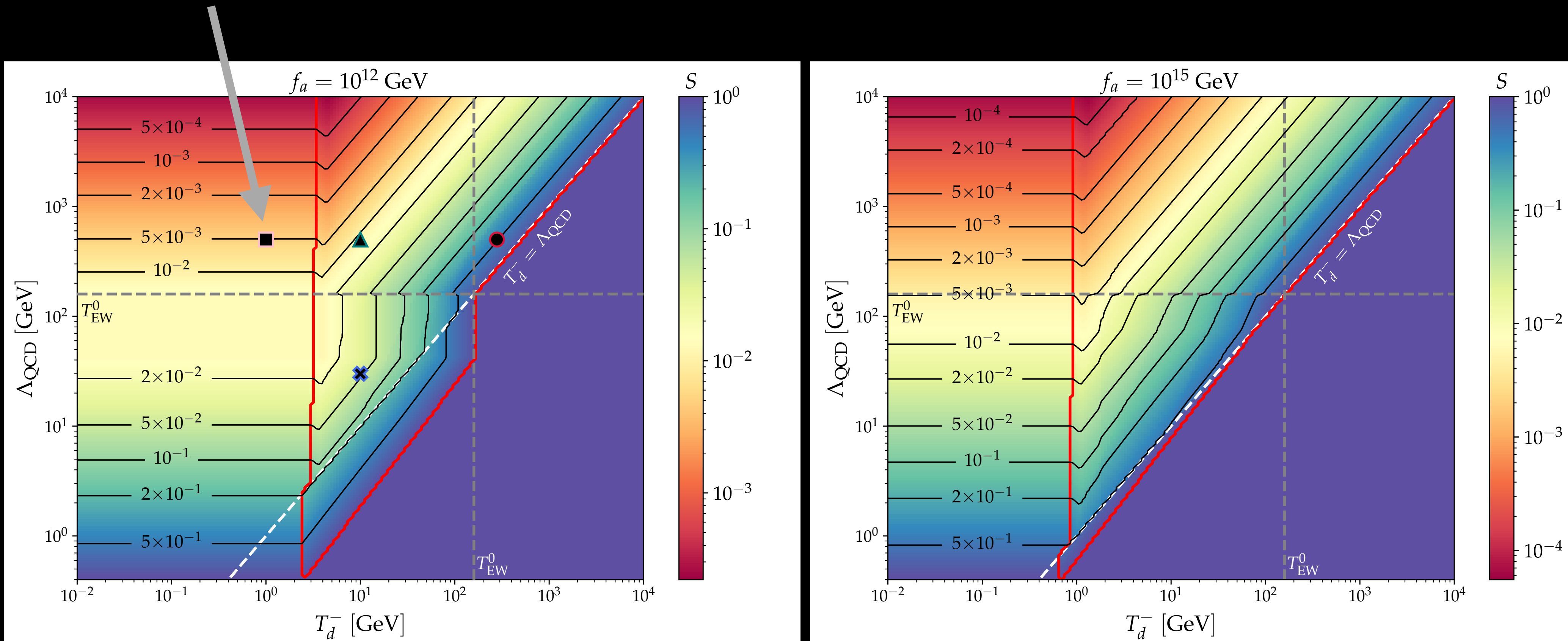
- Since the axion mass is pegged to the QCD scale, a dramatic change in Λ could cause it to start oscillating early, disrupting the usual connection between f_a, θ_0, and the final axion density expected from misalignment production.

Axion Production



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- The net result is typically a suppression of the final density of axions.
- This allows larger axion decay constants (lighter axions) to be naturally produced (from O(1) misalignment) with the correct abundance — it opens up regions of axion parameter space which would otherwise have looked very fine-tuned.

Outlook

- Theories of dark matter are necessary both to describe how dark matter (and perhaps a whole dark sector) fit into the SM and also to be able to understand how experiments work together to probe the parameter space.
- A theory of dark matter also allows us to connect the abundance of dark matter to the cosmological history of the Universe.
- Many interesting ideas exist for how we may have ended up with the abundance of dark matter that we observe. I reviewed popular visions for freeze out, freeze in, and misalignment production.
- The dependence of the dark matter density on the history of the Universe is a feature. An observation of dark matter might suggest physics beyond the Standard Model which impacts the cosmological history that might otherwise be difficult to access using our current experimental searches.
- I highlighted the example where new dynamics results in a different value for the strong coupling at early times, and showed how this can dramatically impact WIMP freeze out or axion misalignment production.