Title
From qcd to cosmology

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From QCD to the Cosmos

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Moriond
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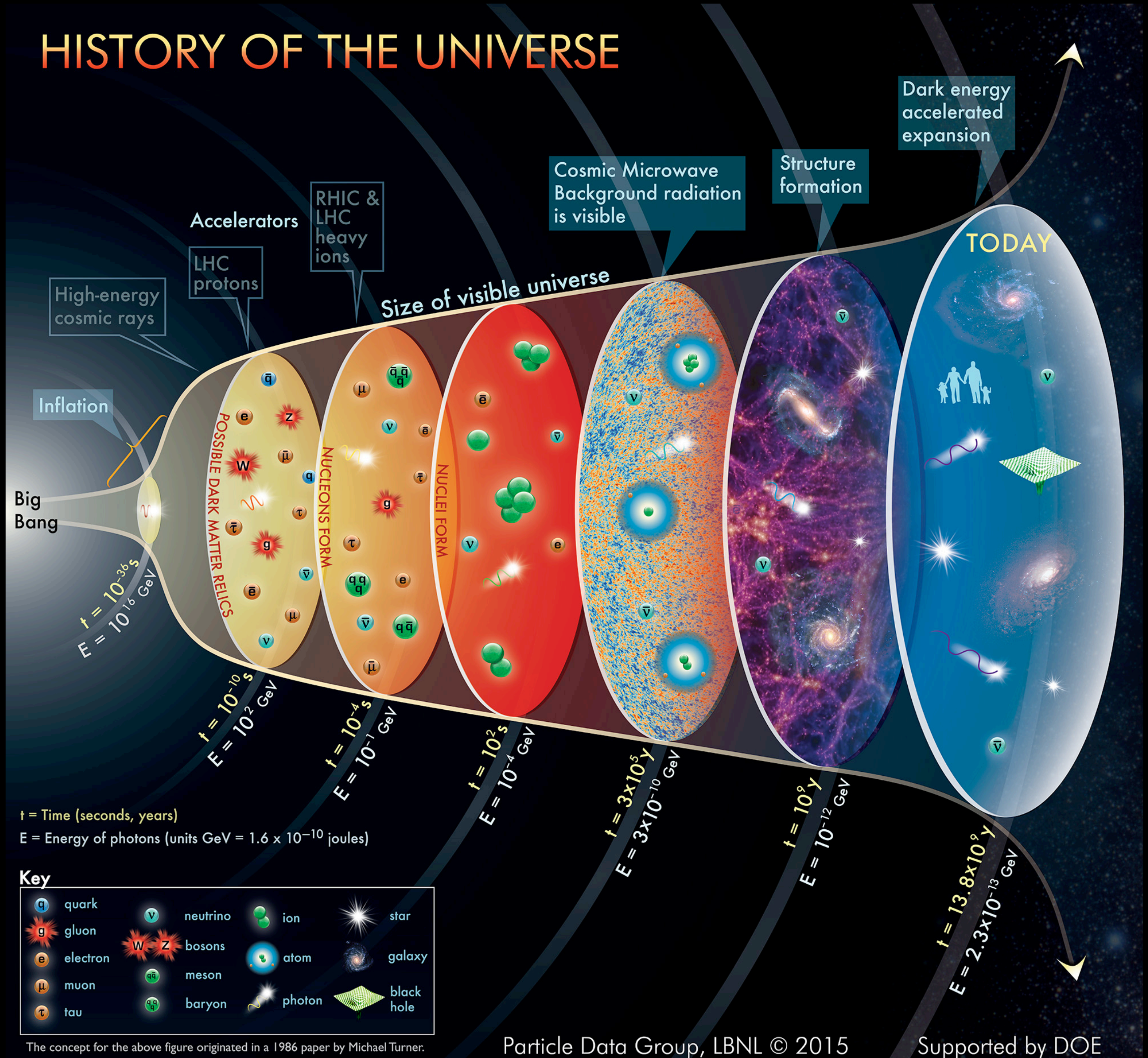
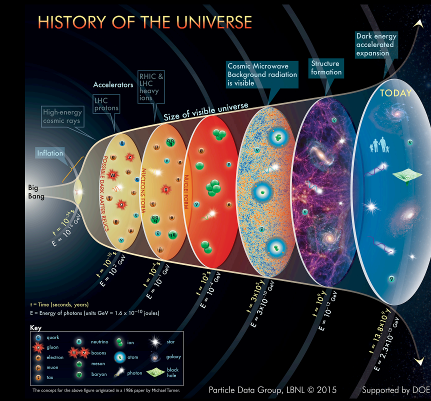
Motivation


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Motivation


HISTORY OF THE UNIVERSE
Inflation
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Particle Data Group, LBNL © 2015
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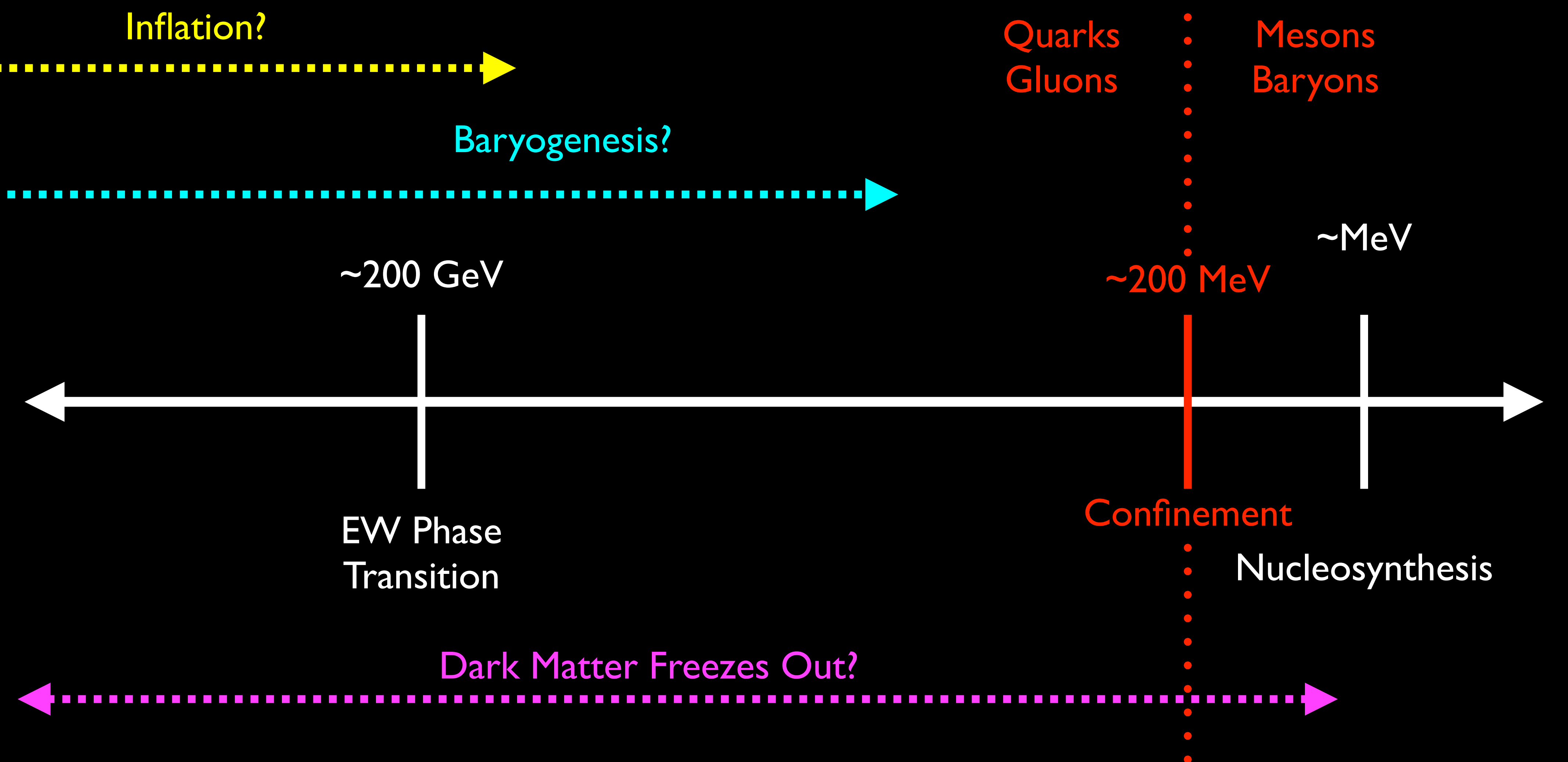
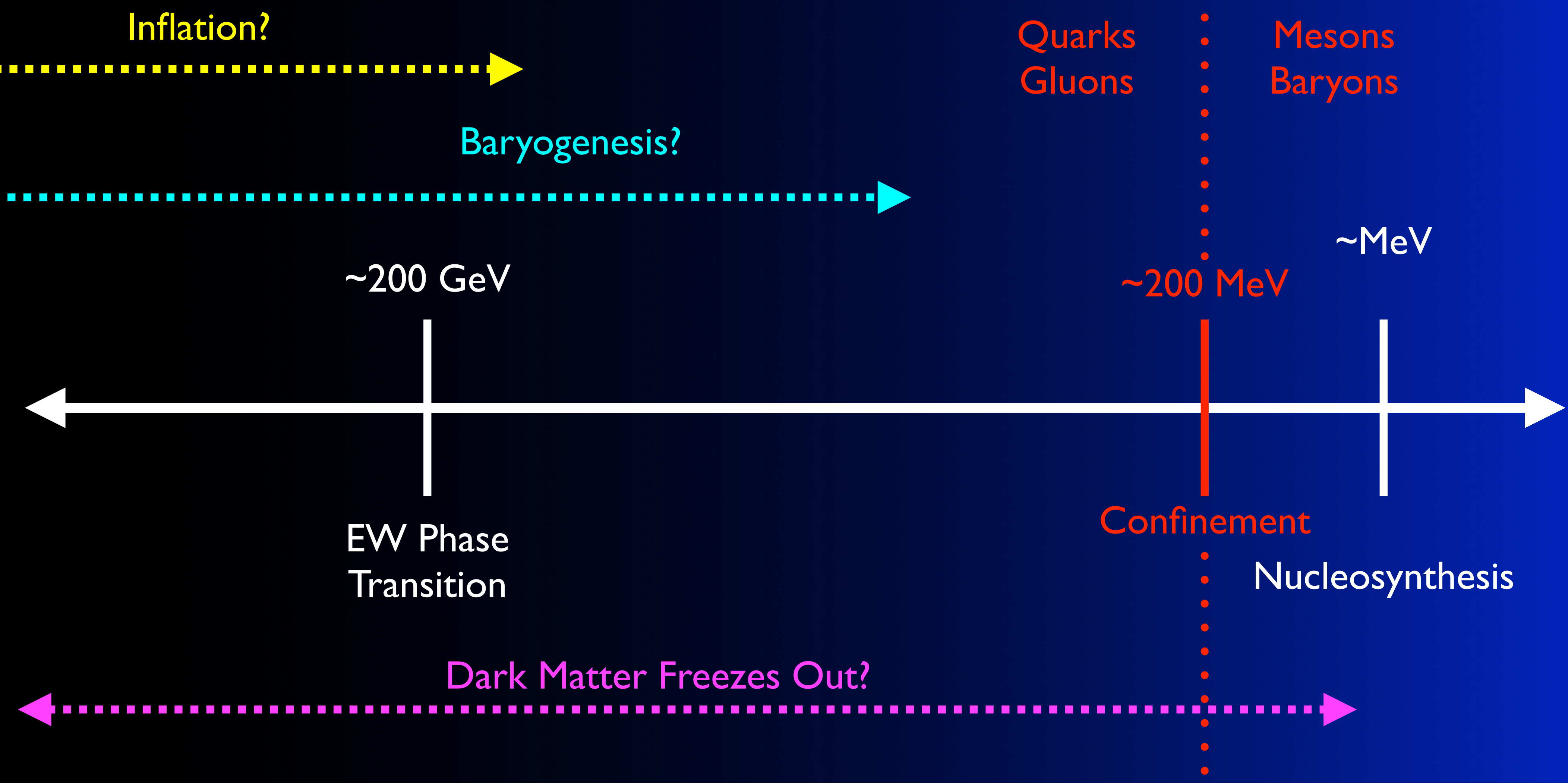

Inflation?
Baryogenesis?
Quarks
Gluons
Mesons
Baryons
~200 GeV
~200 MeV
~MeV
EW Phase
Transition
Confinement
Nucleosynthesis
Dark Matter Freezes Out?

Motivation

Experimental probes of cosmology get hazy around Nucleosynthesis



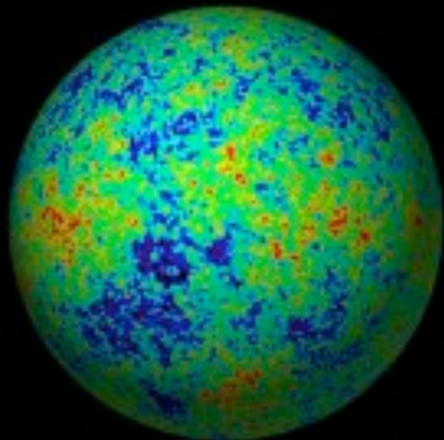
Plan

My basic plan is to start at high energy phenomena and move my way down, exploring some of the many connections that exist at different scales.

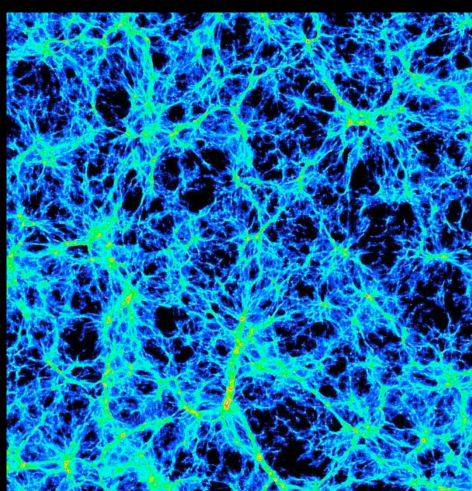
This will necessarily be idiosyncratic and incomplete!

Dark Matter

CMB



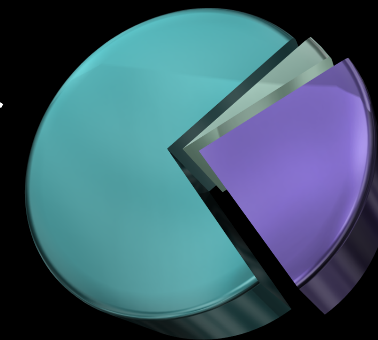
Supernova

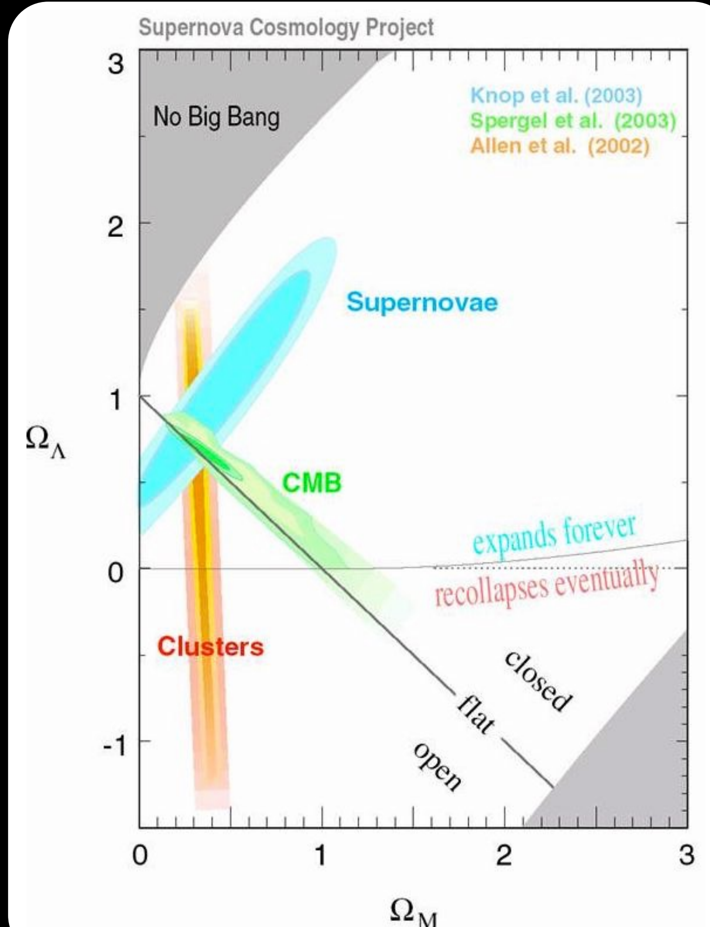


Structure

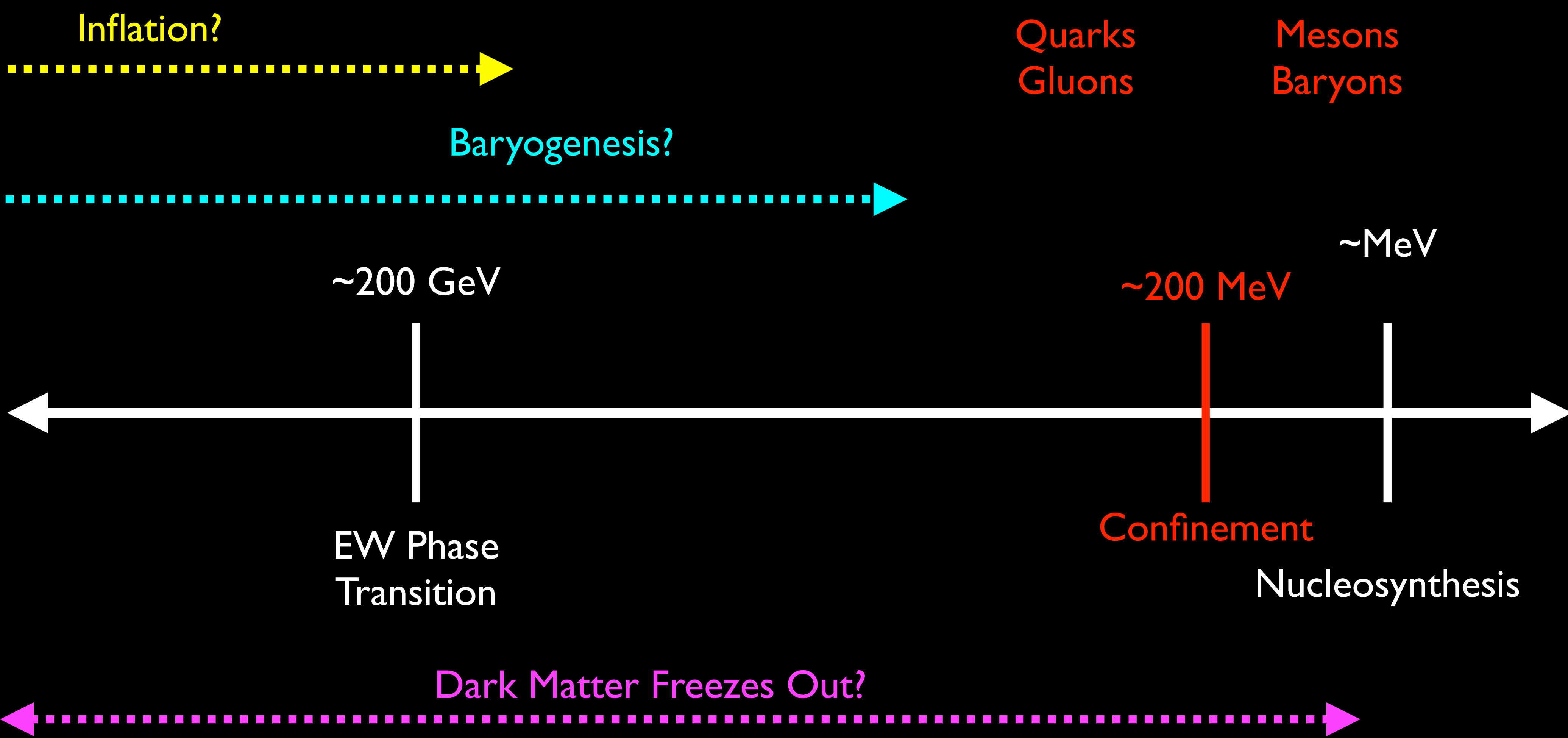
Lensing

Ordinary Matter
Dark Matter
Dark Energy





Dark Matter

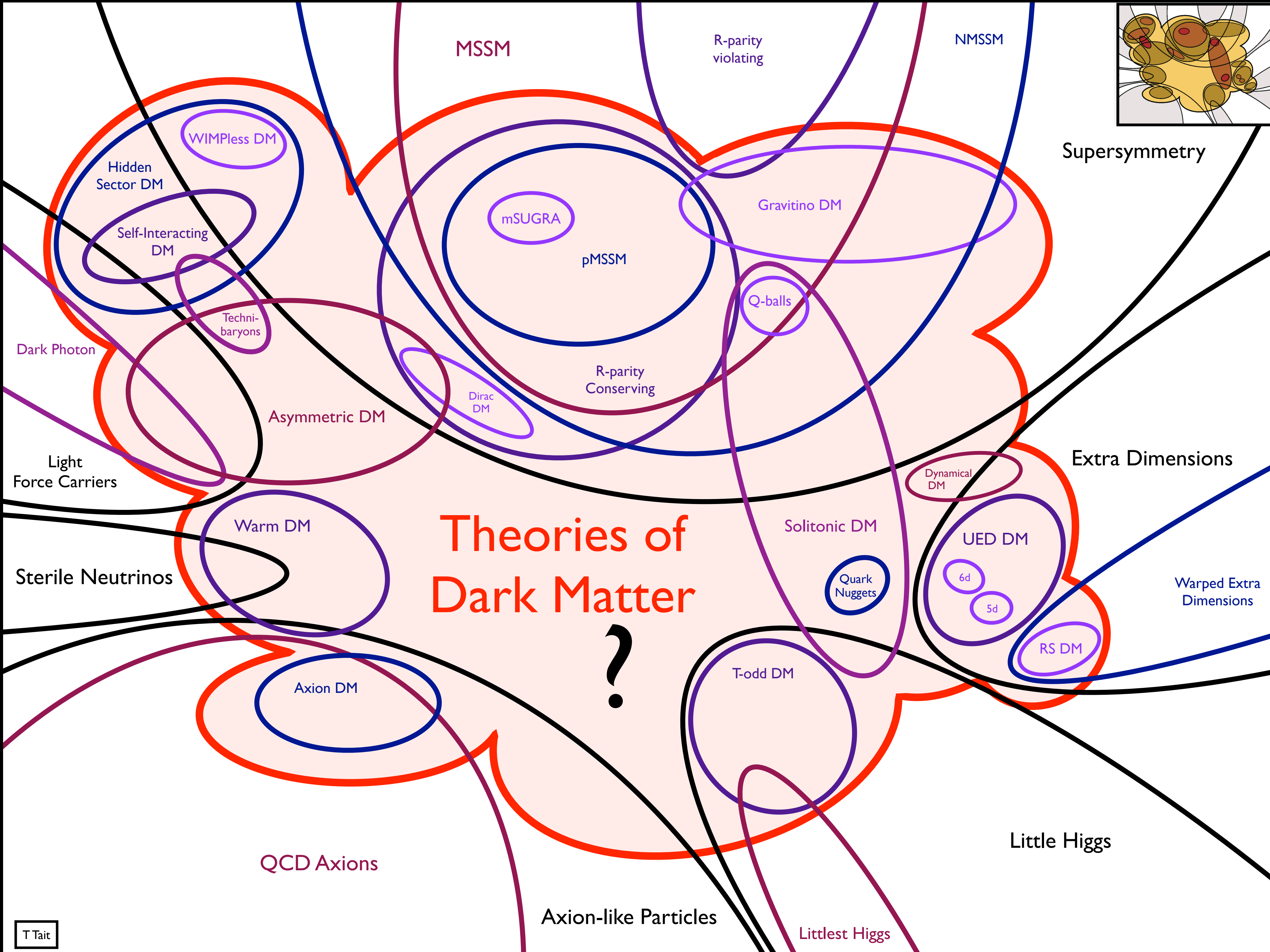


Understanding the particle physics of dark matter should allow us to reconstruct how it is produced, and potentially provides access to information about the Universe at times before nucleosynthesis.

So what is Dark Matter?

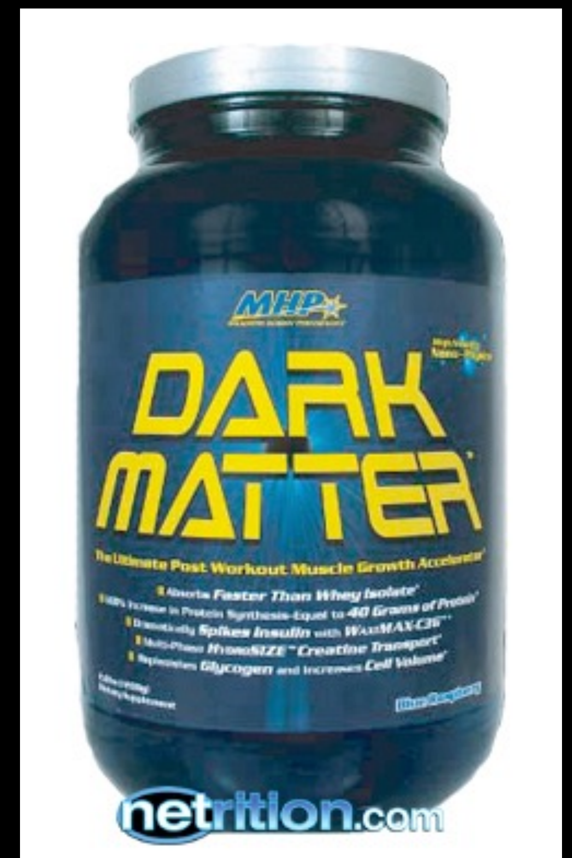
"Cold Dark Matter: An Exploded View" by Cornelia Parker

- Dark matter is a key component necessary to understand the evolution of the Universe.
- Particle physicists need to know how it fits into the Standard Model.
- Cosmologists need to know its properties such as whether it interacts, can dissipate energy, etc.
- What *do* we know about it?
  - Dark (neutral)
  - Massive
  - Still around today.


Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
Light Force Carriers
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Extra Dimensions
Dynamical DM
Warm DM
Sterile Neutrinos
Solitonic DM
Quark Nuggets
UED DM
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

WIMP Dark Matter

- One very attractive proposal 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.
    - They often occur in models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.
- QCD plays a big role in the study of WIMPs, influencing e.g. how they are produced in the early Universe, and how different particle physics probes can hope to infer their existence and properties.



59.99 Euro for 20 servings

Available in Blue Raspberry, Fruit Punch, and Grape flavors....

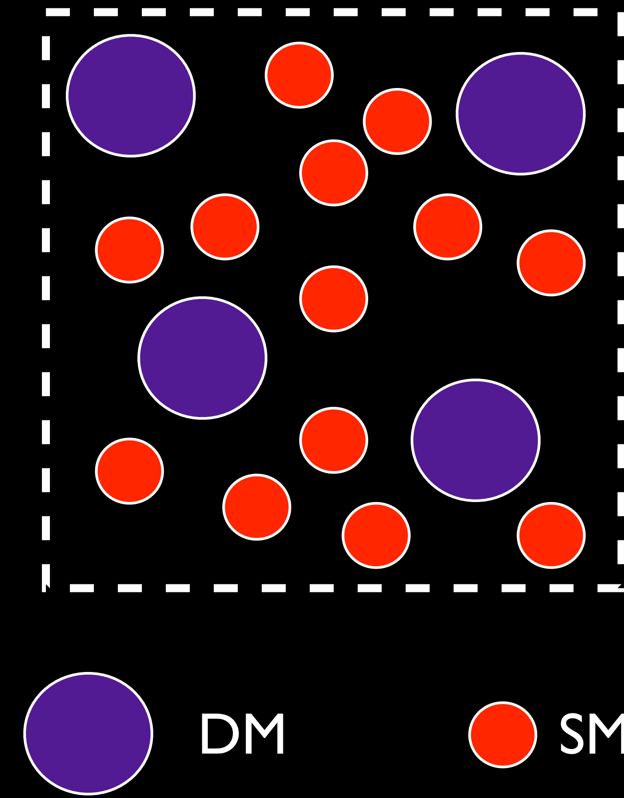
The WIMP Miracle

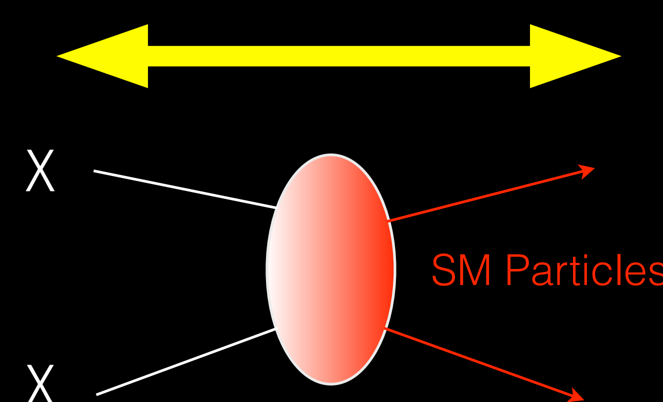
- One of the primary motivations for WIMPs is the “WIMP miracle”, an attractive picture explaining the density of dark matter in the Universe today.

- While not strictly a requirement for a successful theory of dark matter, this picture is very attractive [meaning: we think it is likely that things work this way], and so it is worth understanding the argument.

- 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 and vice-versa.

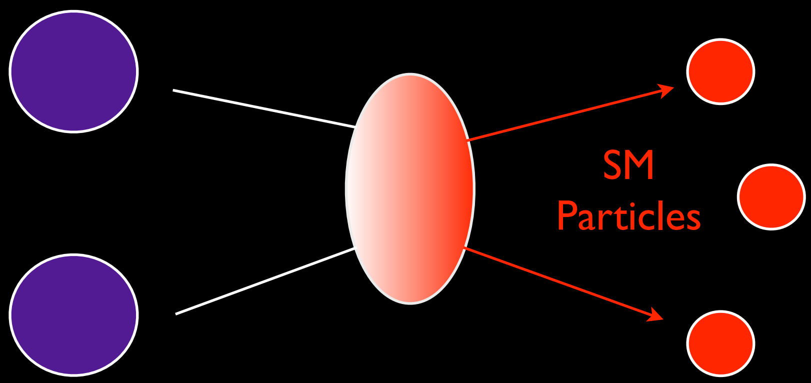




Boltzmann Equation

- The evolution of the dark matter number density (n) is controlled by a Boltzmann equation, which tracks the effect of the expansion of the Universe (H) and the creation and destruction of dark matter.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$



- A Universe where WIMPs stayed in equilibrium would be pretty boring.
    - As the temperature falls, there will be fewer and fewer WIMPs present, since the fraction of the plasma with enough energy to produce them will become smaller and smaller.
    - (Almost) Nothing would be left!

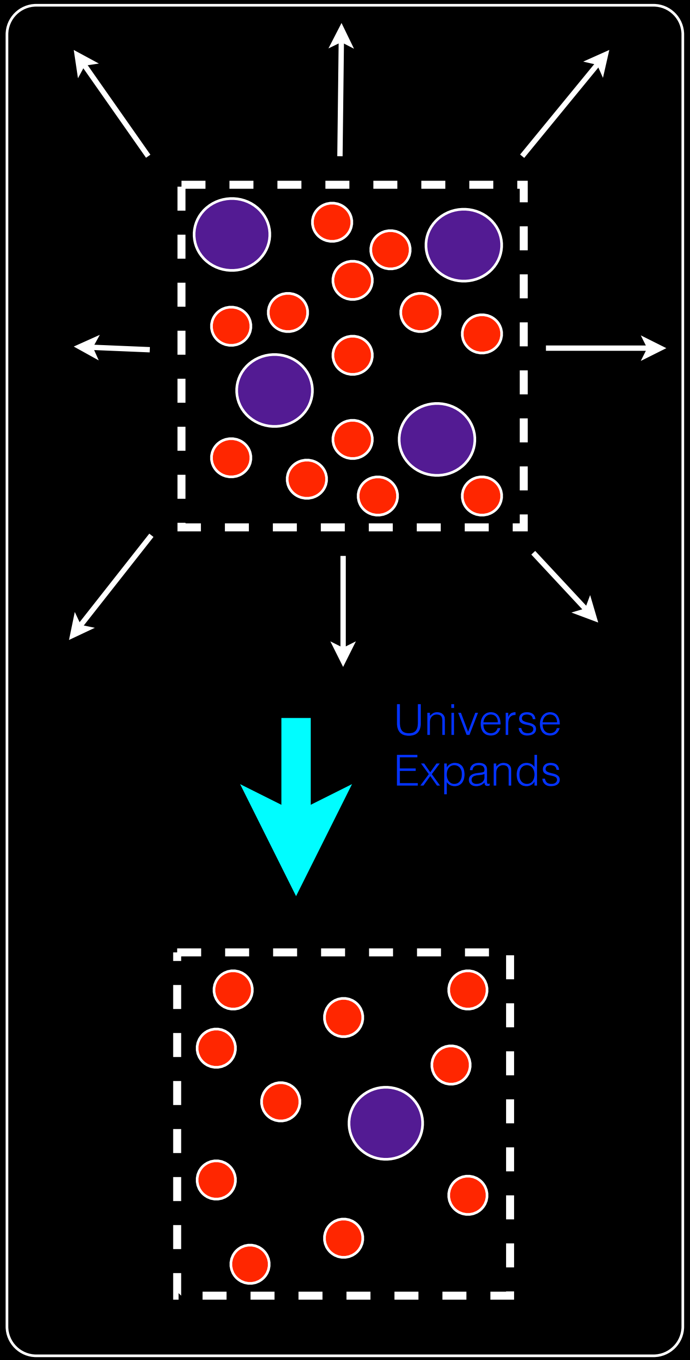
$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{Exp}\left[-m/T \right]$$

Freeze-Out

- However, the expansion of the Universe eventually results in a loss of equilibrium.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$

- When (n_{eq} <σv>) << H, the scattering that maintains equilibrium can't keep up with the expansion.
- The WIMPs become sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- Where they "freeze out" obviously depends on how big <σv> is.

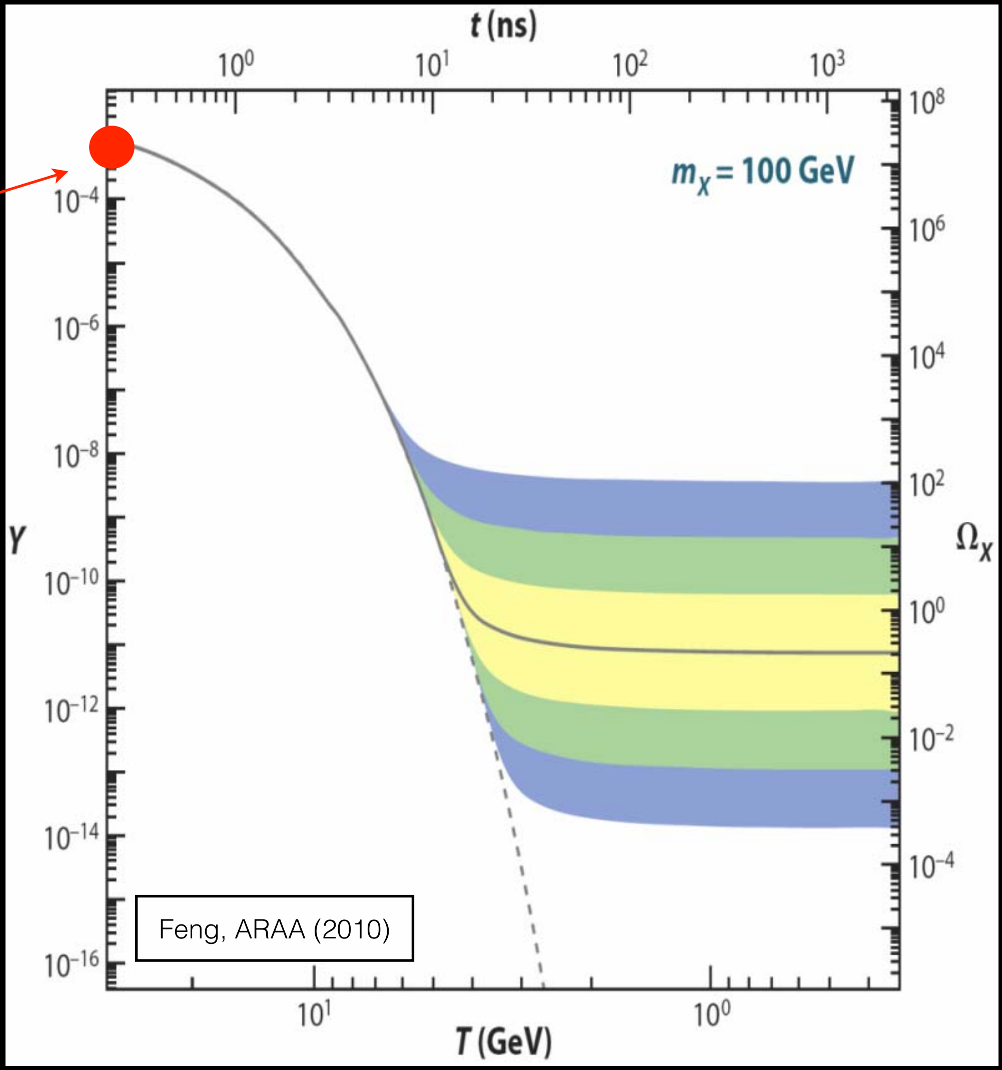


Relic Density

- The basic picture is:
  - We start out with dark matter in equilibrium with the SM plasma.
  - As the temperature falls, the number of WIMPs does too.
  - We track the equilibrium density until freeze-out:

$$n_{eq}\langle\sigma v\rangle \sim H$$

$$(mT)^{3/2}e^{-m/T} \qquad \frac{g^4}{m^2} \qquad \sim \frac{T^2}{M_{Pl}}$$



$$\frac{m}{T} \sim \log\left[\frac{M_{Pl}}{m}\right] \qquad m \sim 100\ \mathrm{GeV} : \frac{m}{T} \sim 40$$

…which determines how many WIMPs are left over.

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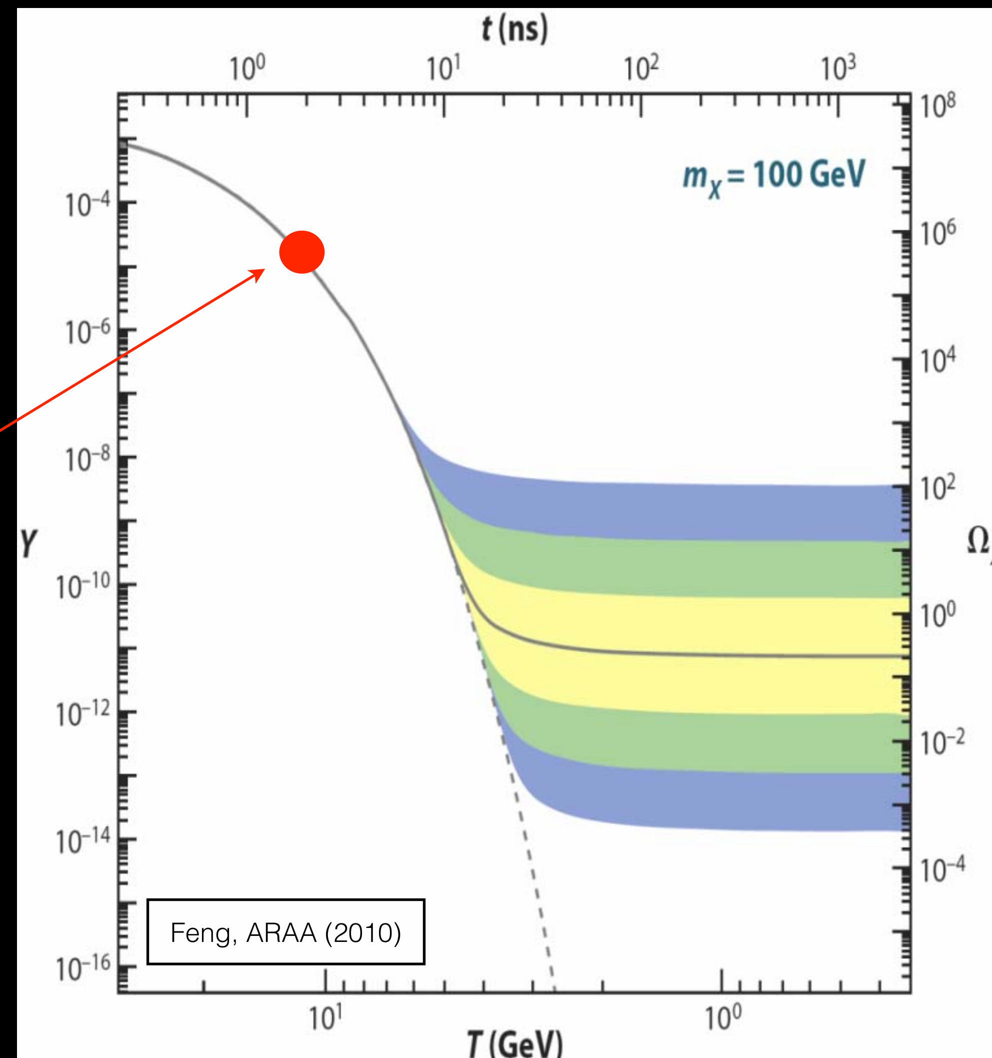

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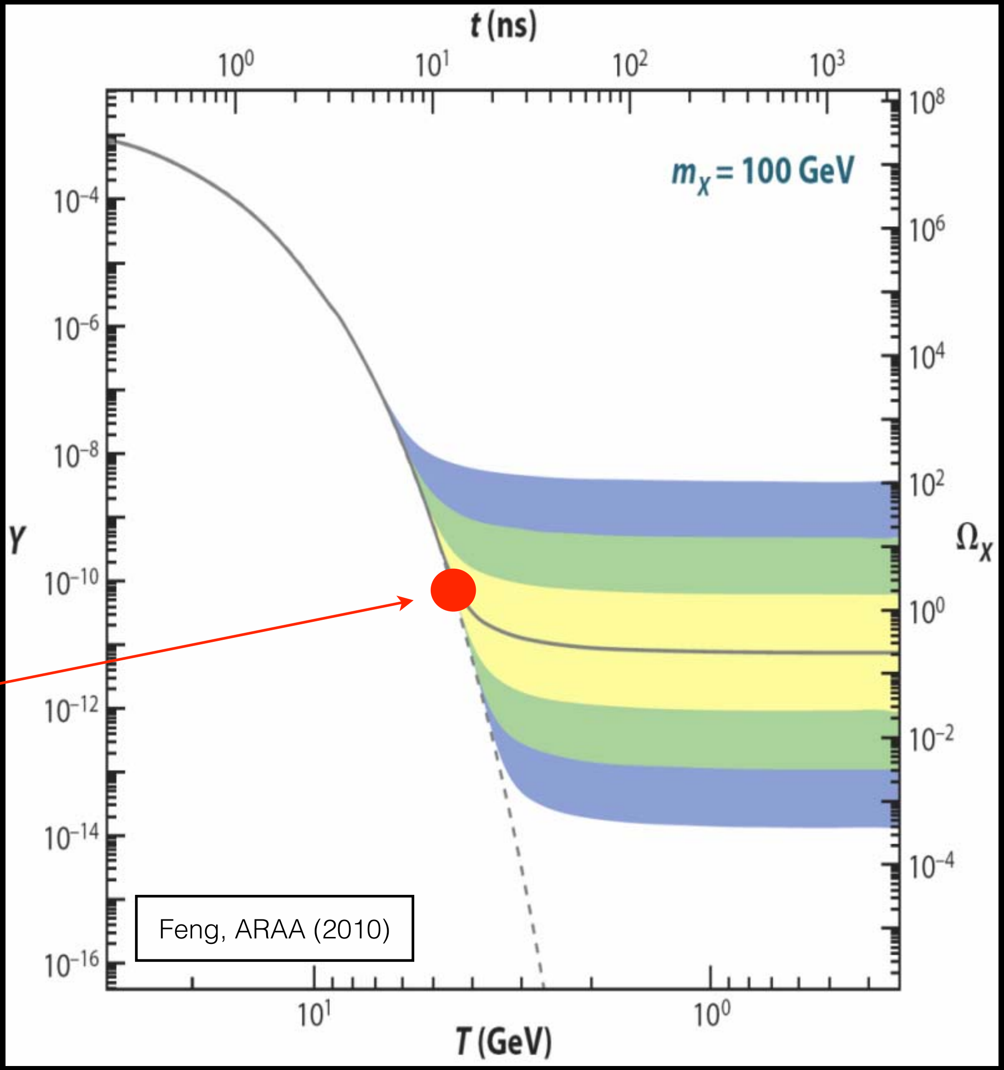

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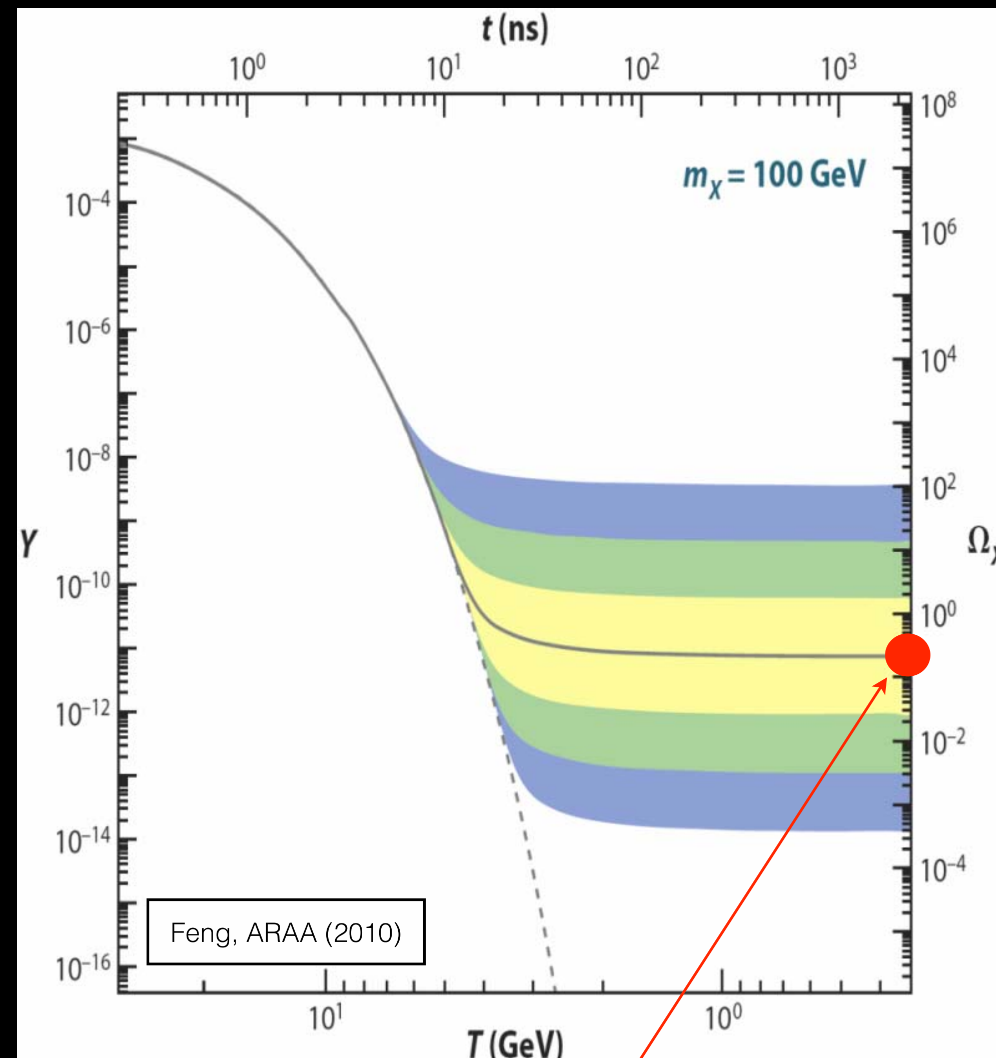

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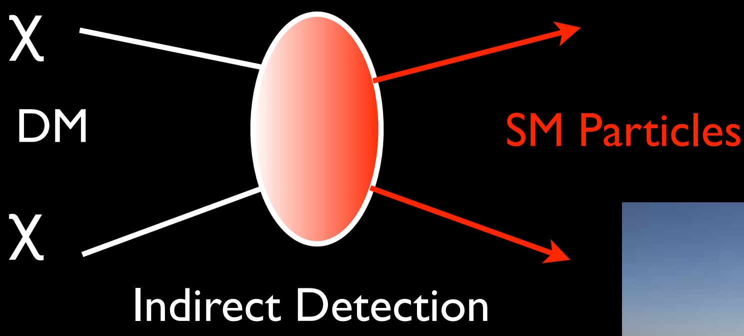
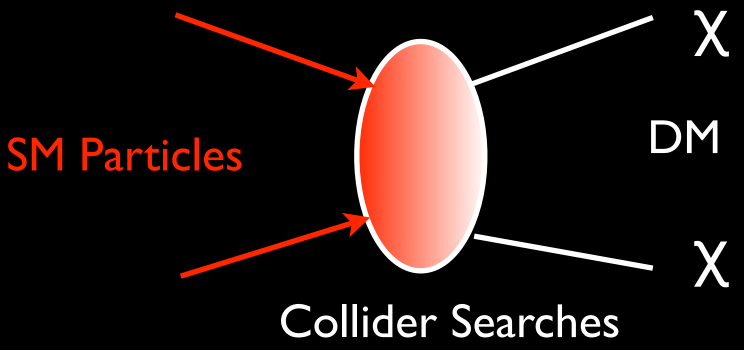
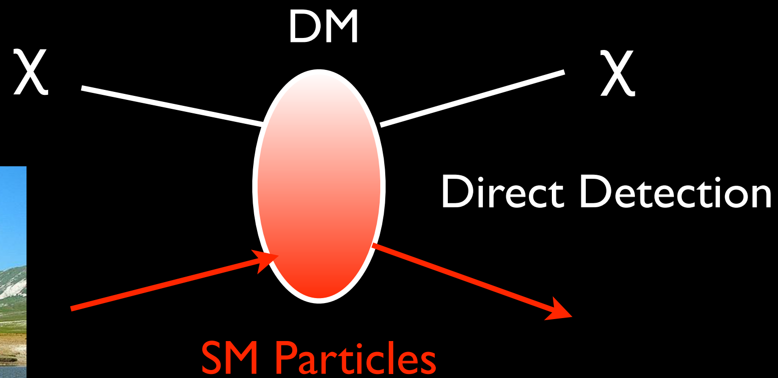
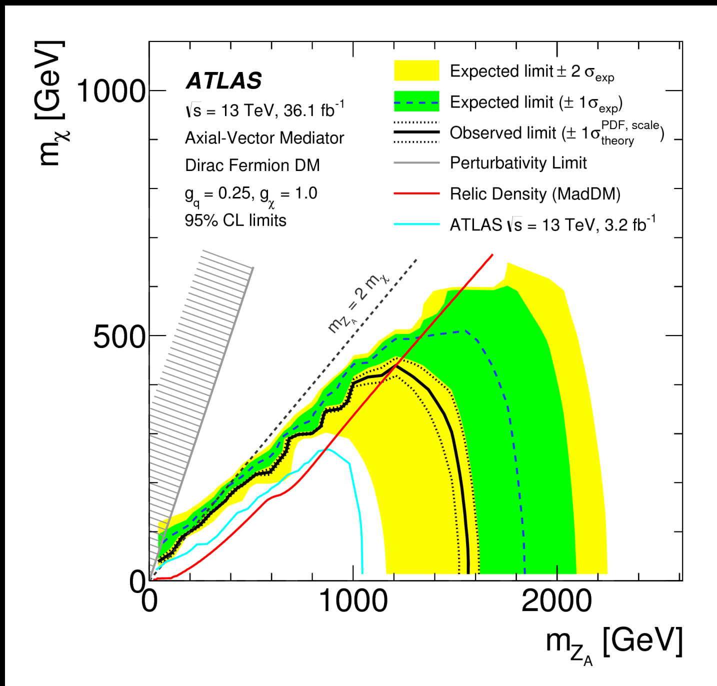
WIMP Searches

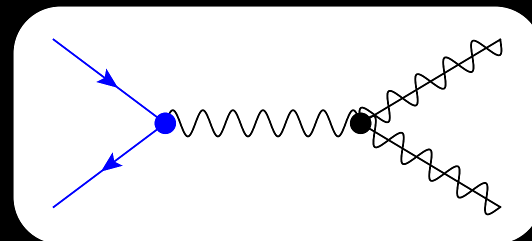


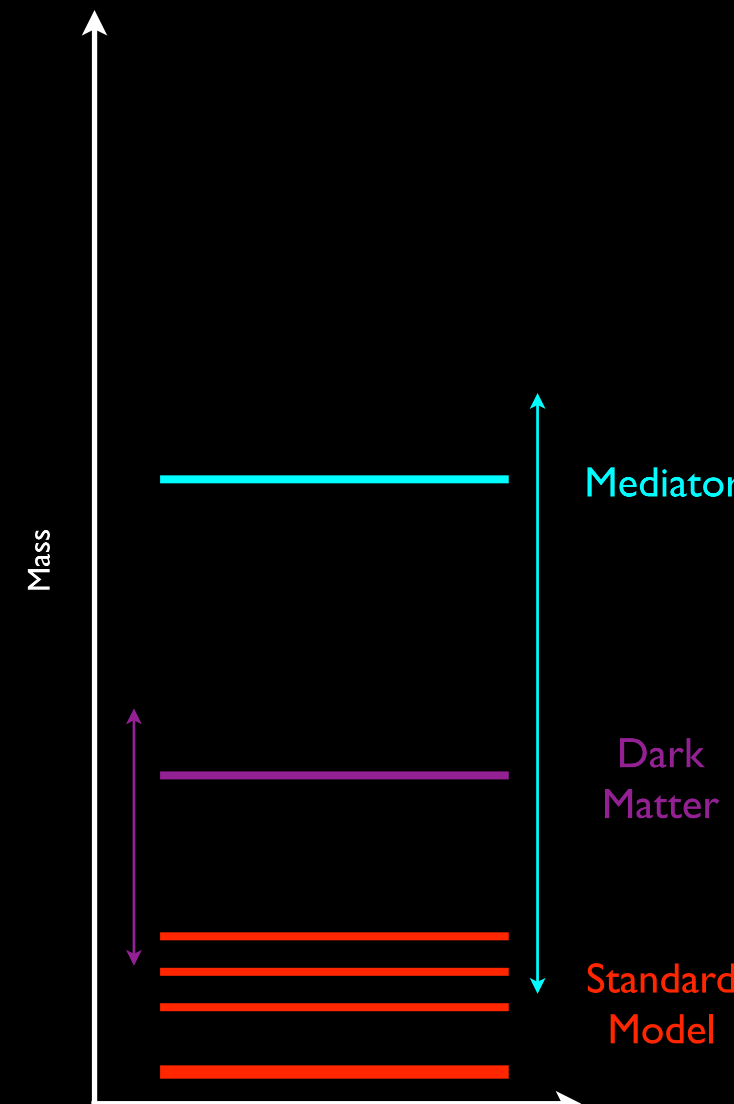


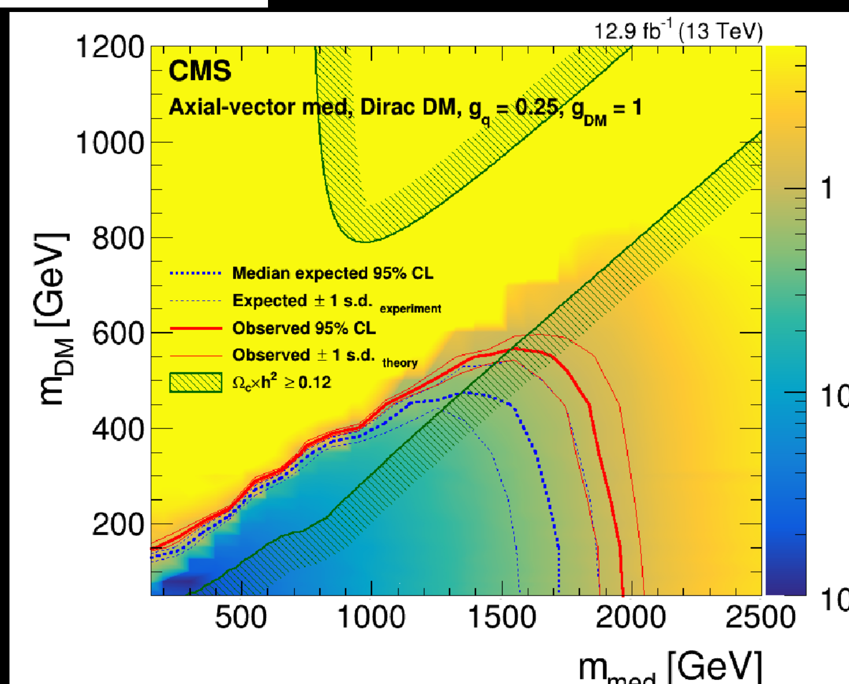


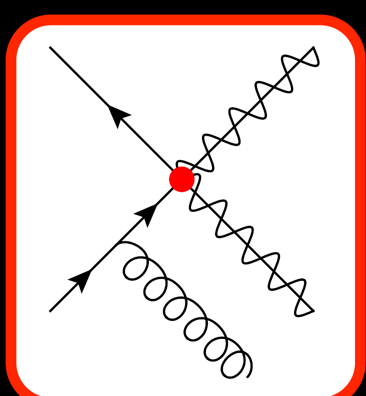
Axial Vector Mediator



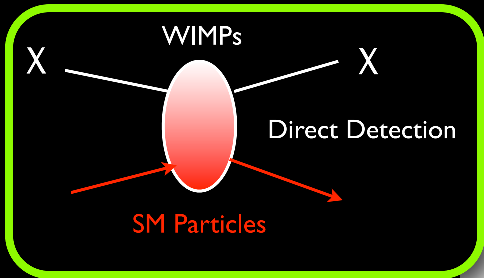


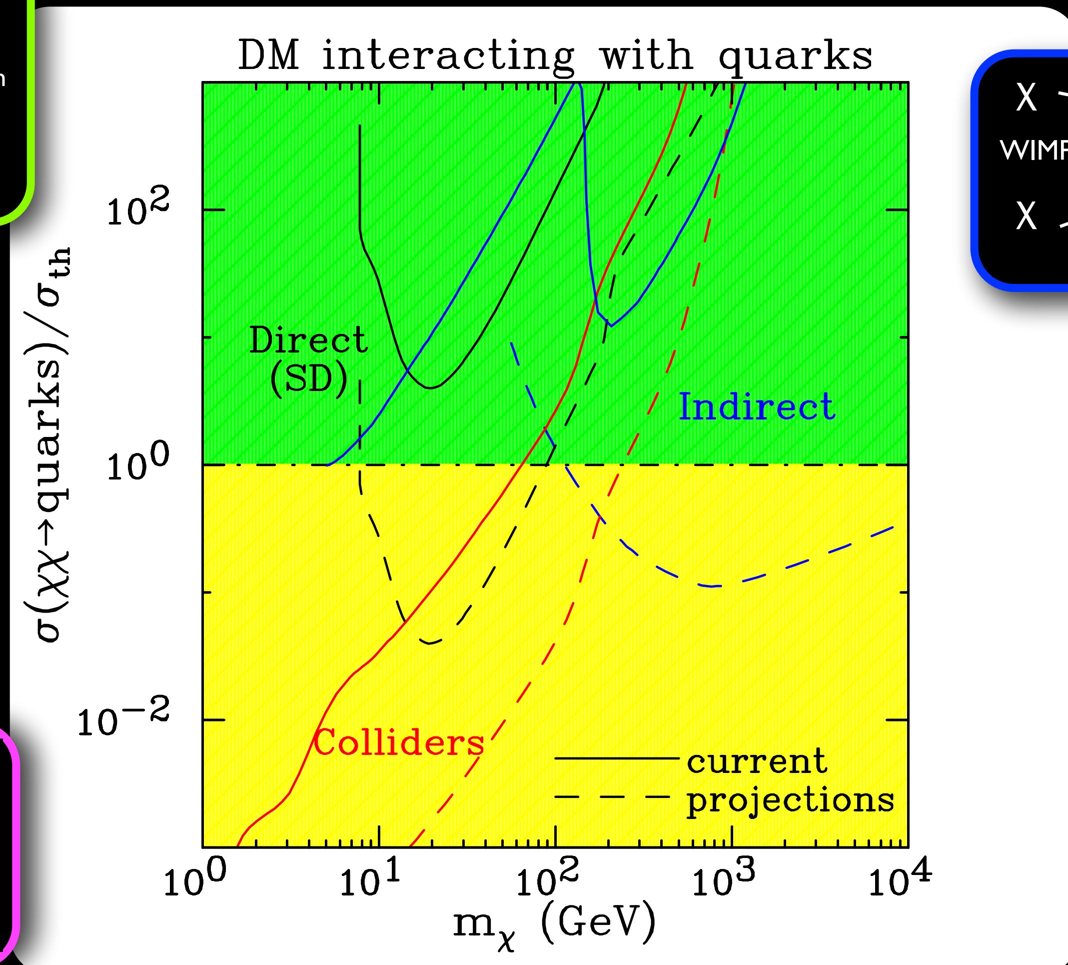


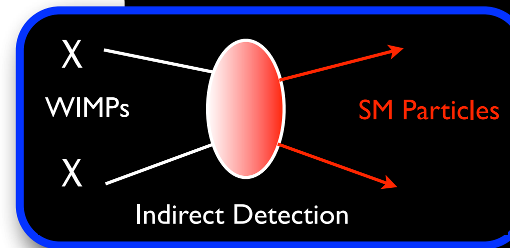


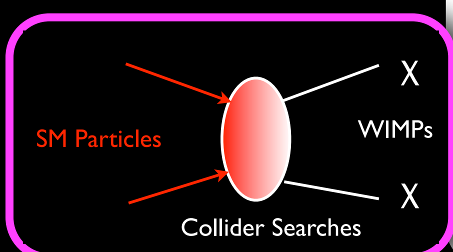


Reconstructing WIMPs









DM Complementarity, arXiv:1305.1605

Reconstructing the particle physics of a WIMP is likely to require a multi-pronged search strategy.

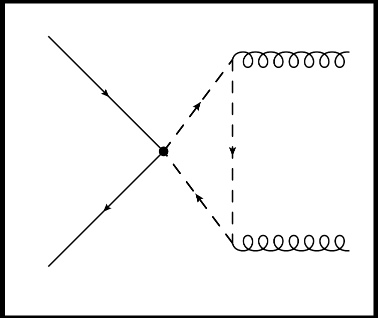
Dark Matter Coupled to Gluons

Godbole, Mendiratta, TMPT 1506.01408 & JHEP
+Shivaji 1605.04756 & JHEP
Bai, Osborne 1506.07110 & JHEP

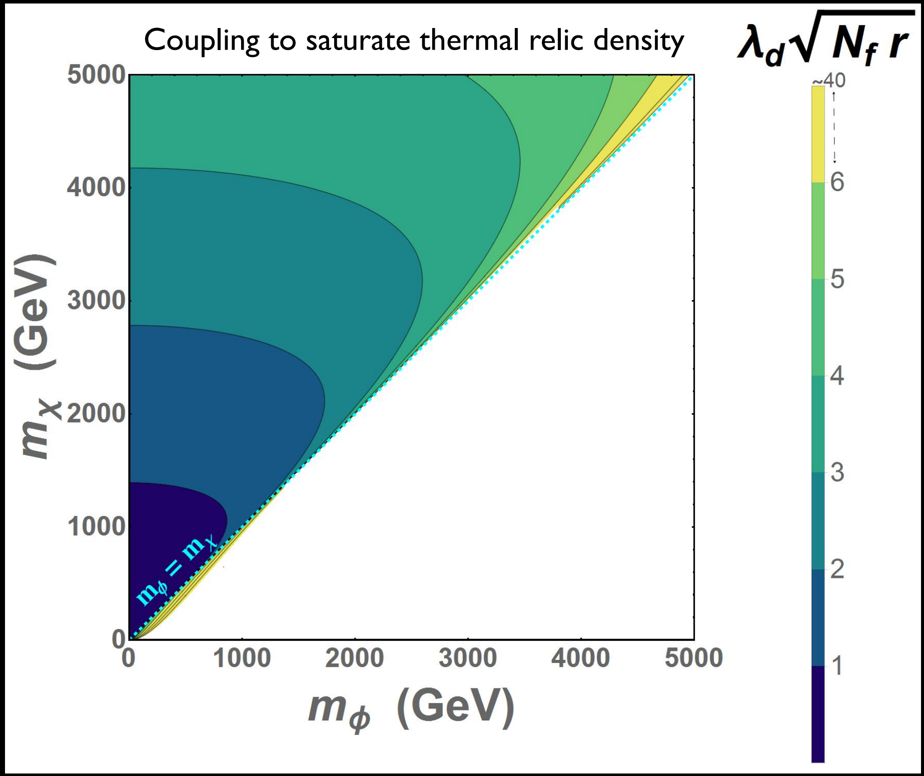
- It may be that QCD acts *directly* as the portal between the dark matter and the Standard Model.
- Scalar DM can interact with a scalar colored mediator via a quartic interaction:

$$\lambda_d \, |\chi|^2 |\phi|^2$$

- This interaction does not require the scalar to be Z_2-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (in some cases) like an R-parity violating squark.
- The color and flavor representations (r, N_f) of the mediator are parameters.
- For perturbative λ, a thermal relic actually favors $m_\phi < m_\chi$ so annihilation into $\phi\phi^*$ is open in a standard cosmology.



The dominant coupling to the SM is at one loop to gluons!

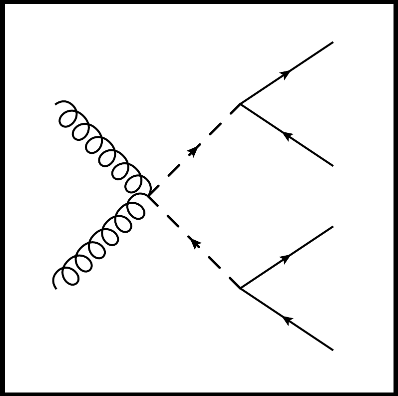


Mediator Searches

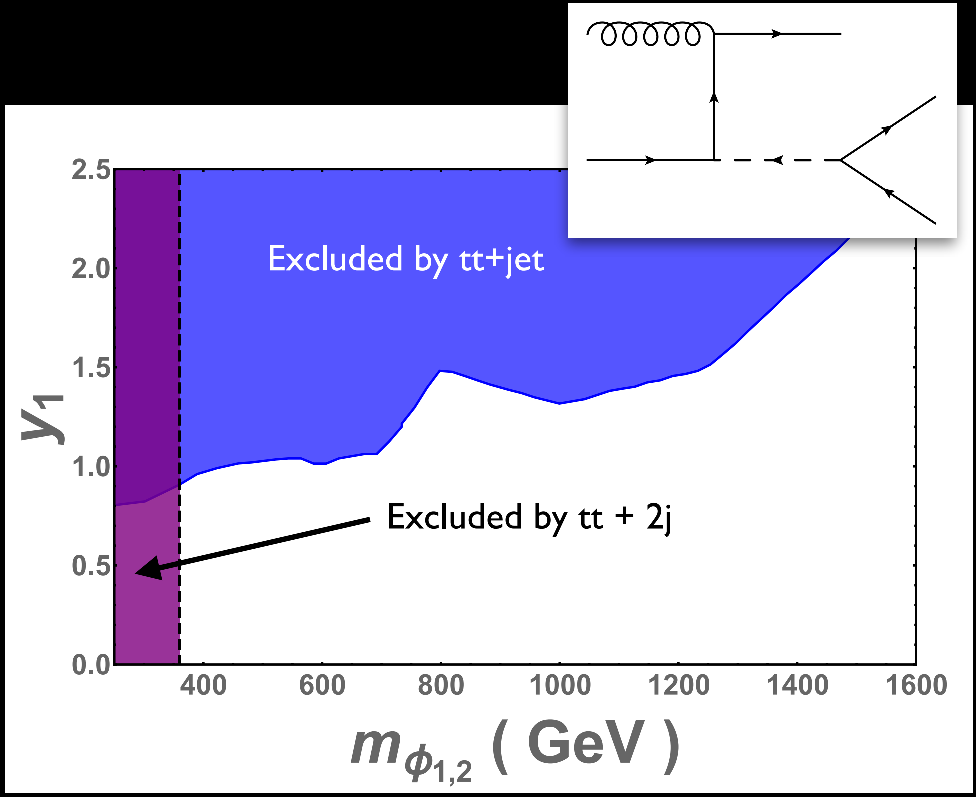
- The physics of the mediators is model-dependent, depending on their color, electroweak, and flavor representations.
- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.
- In this case, freedom from strong flavor constraints can be obtained by coupling anti-symmetrically in flavor indices:

$$y\epsilon^{ijk}\phi_i\bar{u}_j u^c_k + h.c.$$

- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints leave a lot of interesting parameter space open.

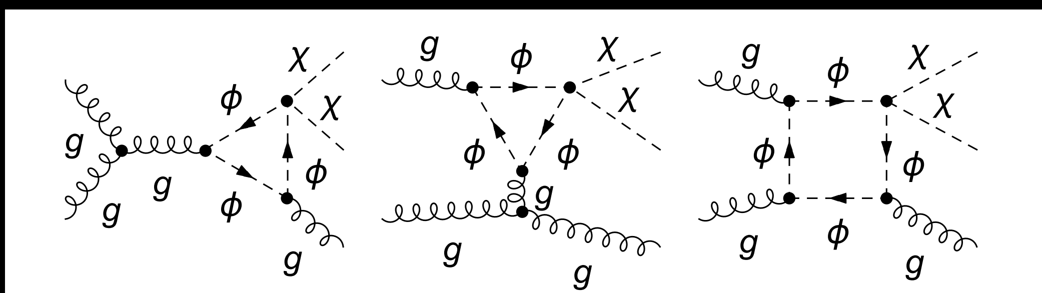


Decays into unflavored jets are bounded by m_ϕ > 350 GeV (for color triplets) from searches.

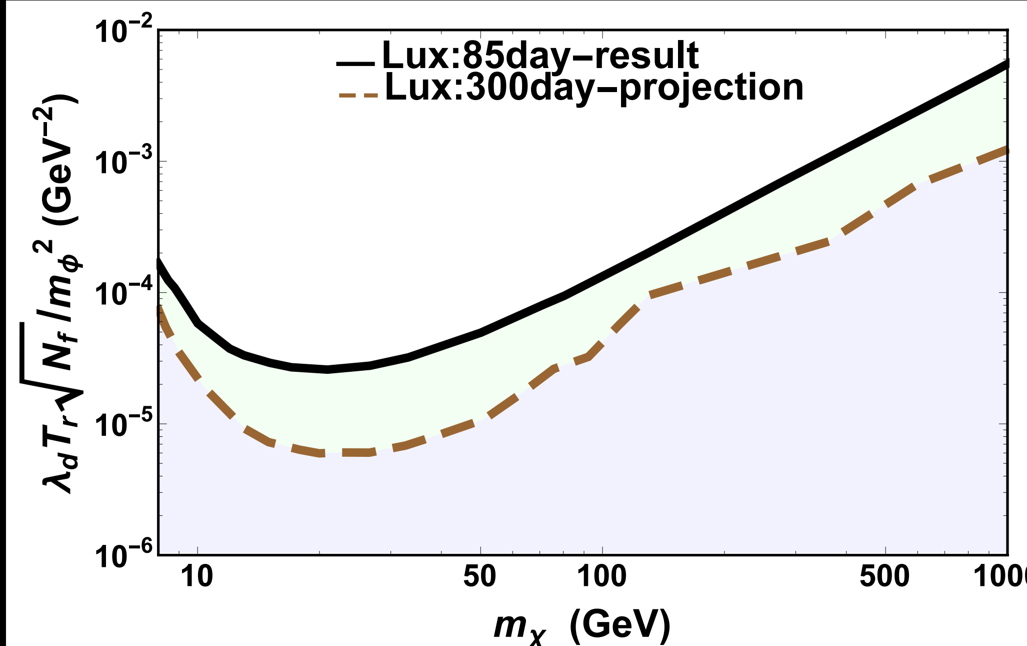


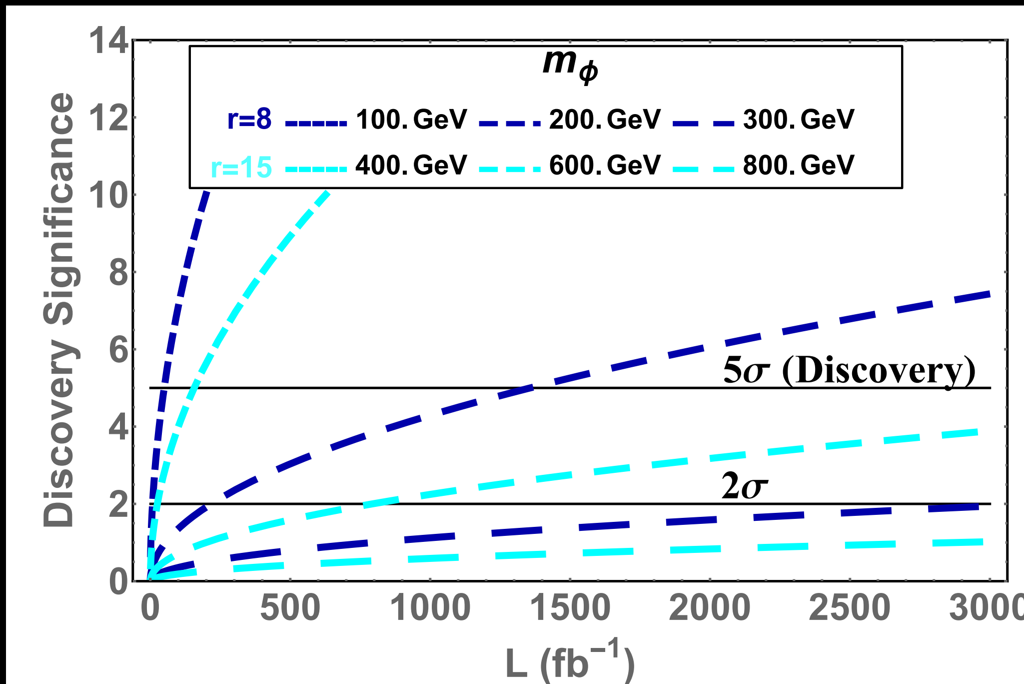
DM Searches

- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.



- As a result, prospects at the LHC are not particularly hopeful, though for large enough r and λ, it is possible to see something with a very large data set.

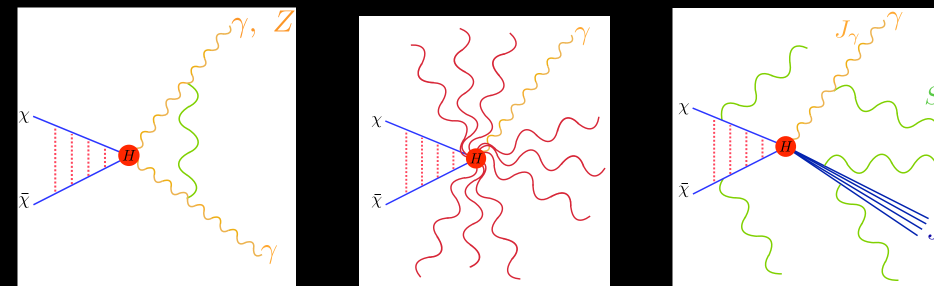




(a) $\sqrt{s} = 13$ TeV

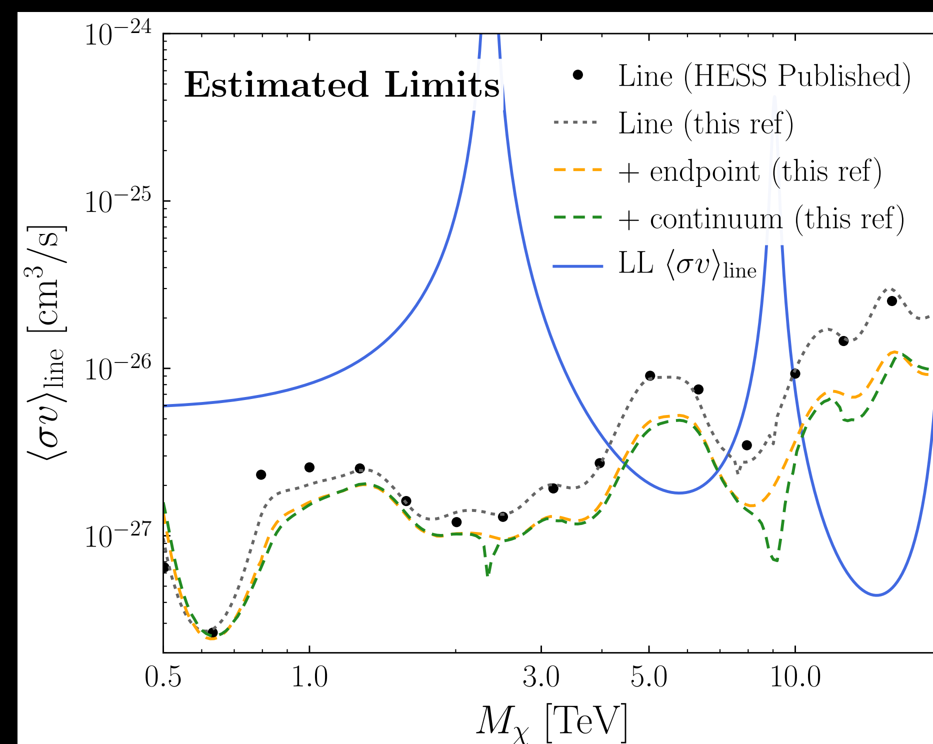
SCET for Dark Matter

- Even a more garden-variety WIMP whose interactions are governed by the weak force [such as a wino] can profit from lessons from QCD.
- When such particles are very heavy, the W and Z bosons are light enough by comparison that they look like a long range force when heavy winos annihilate.
- Techniques from QCD such as soft collinear effective theory are necessary to resum large logs.
- A series of EFTs describe the physics for wino annihilation into (e.g.) photon + X for various wino masses and photon energies.
- Theoretical techniques from QCD lead to accurate predictions for winos!



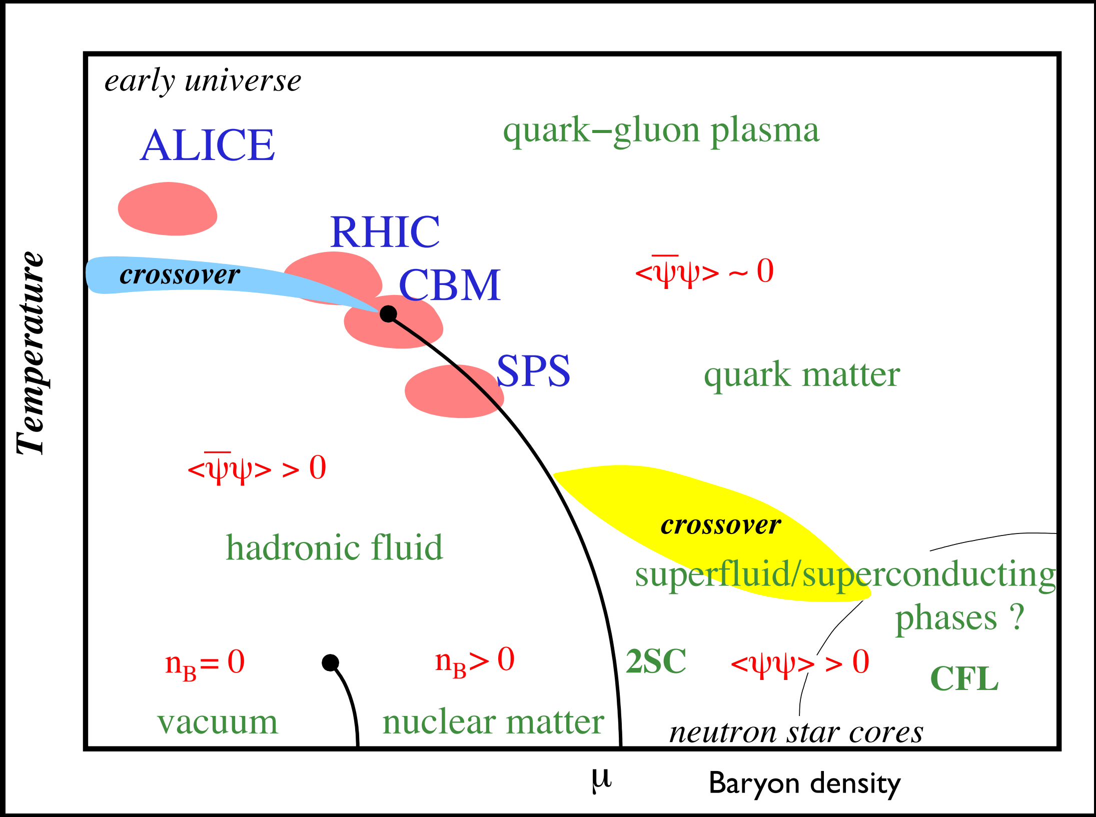
$m_X = 0$ $\qquad$ $m_X \sim M_\chi$ $\qquad$ $m_X \ll M_\chi$

Baumgart, Cohen, Mouilt, Rodd, Slatyer, Solon, Stewart, Vaidya. 1712.07656

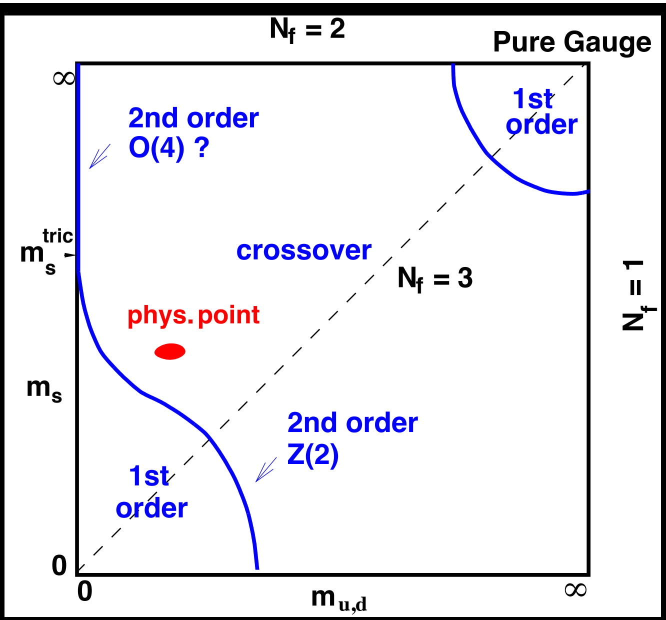


QCD Phase Transition

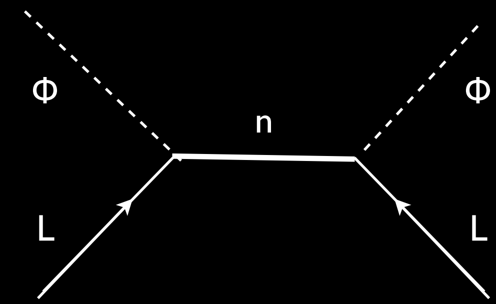
- Light dark matter may be produced at temperatures low enough that QCD has time to confine.
- The phase transition takes us from the theory of quarks and gluons to the theory of hadrons with broken chiral symmetry.
- The transition from one phase to another is still not perfectly theoretically understood, and depends on the light quark masses.
- For example, since the freeze-out calculation scaled out the expansion by normalizing to the entropy, unexpected entropy production could confuse the relic density.
- Accelerator data is a crucial input to understand the nature of the transition!



Review by Schaefer & Wagner 0812.2855

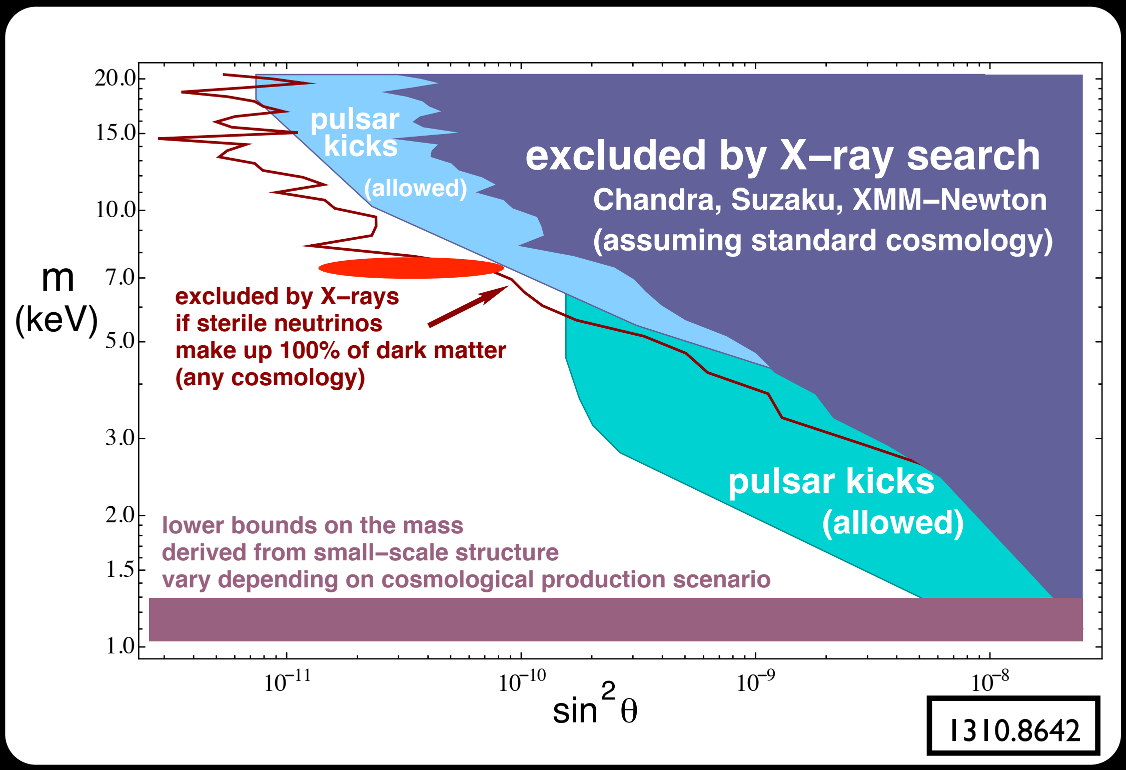


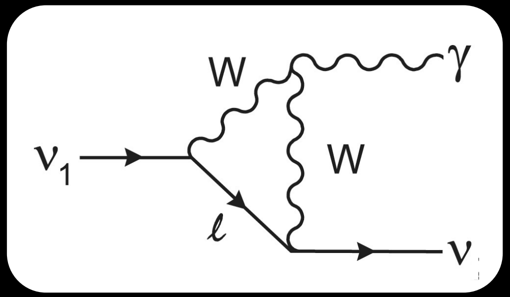
Sterile Neutrinos



- Sterile neutrinos, often invoked to explain the fact that the active neutrinos have masses and can oscillate, are an intriguing DM candidate.
- If sufficiently light and not strongly mixed with the active neutrinos, they can be stable on the scale of the age of the Universe.
- This is an interesting regime of mass where the dark matter transitions from being cold to warm enough to influence structure formation.
- It's also the regime of an intriguing X-ray excess that may come from their decay into a photon + an active neutrino.

Bulbul et al 1402.2301

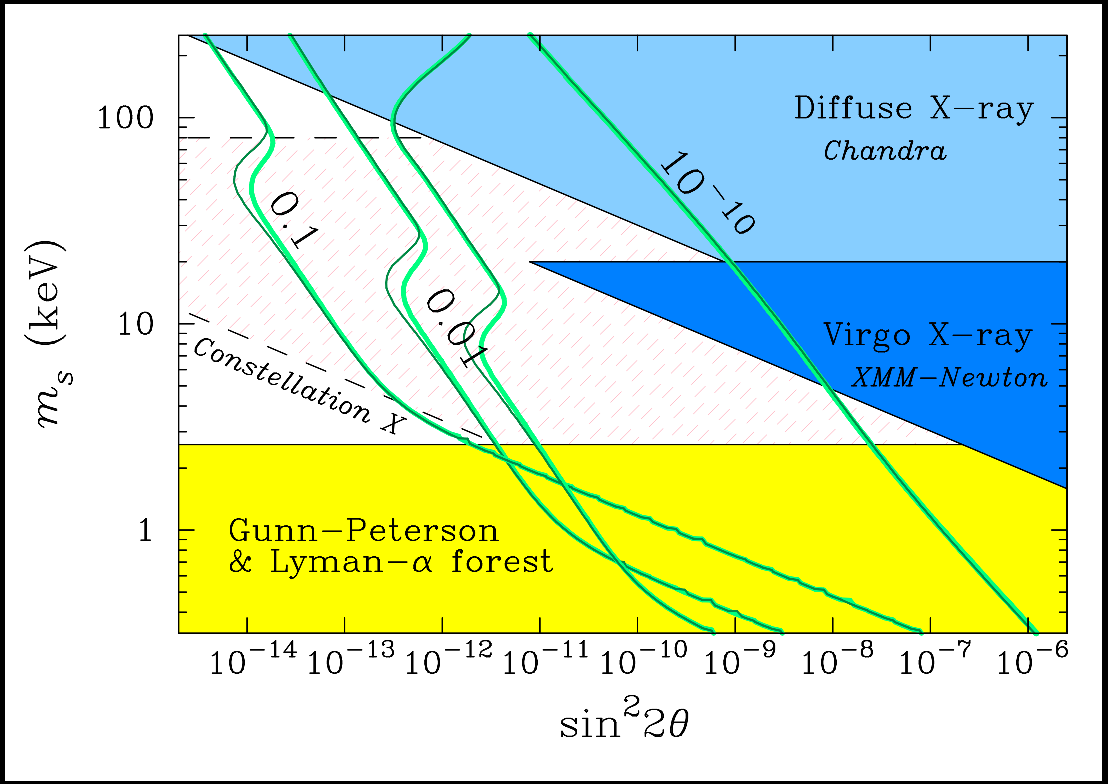




Sterile Neutrinos

- Sterile neutrinos are produced by out-of-equilibrium scattering of the active neutrinos on the background plasma.
- The final density produced depends sensitively on the net Lepton number.
- For the relevant parameters, the production peaks at temperatures around 130 MeV — right around the QCD phase transition!
- The nature of the phase transition determines how long the Universe spends at the "magic temperature" for production, the degrees of freedom in the plasma available for converting active neutrinos into dark matter, and dilution through entropy transfer into radiation.

Abazajian & Fuller astro-ph/0204294
See also: Venumadhav et al 1507.06655



Lines show contours of correct abundance for different initial lepton numbers.

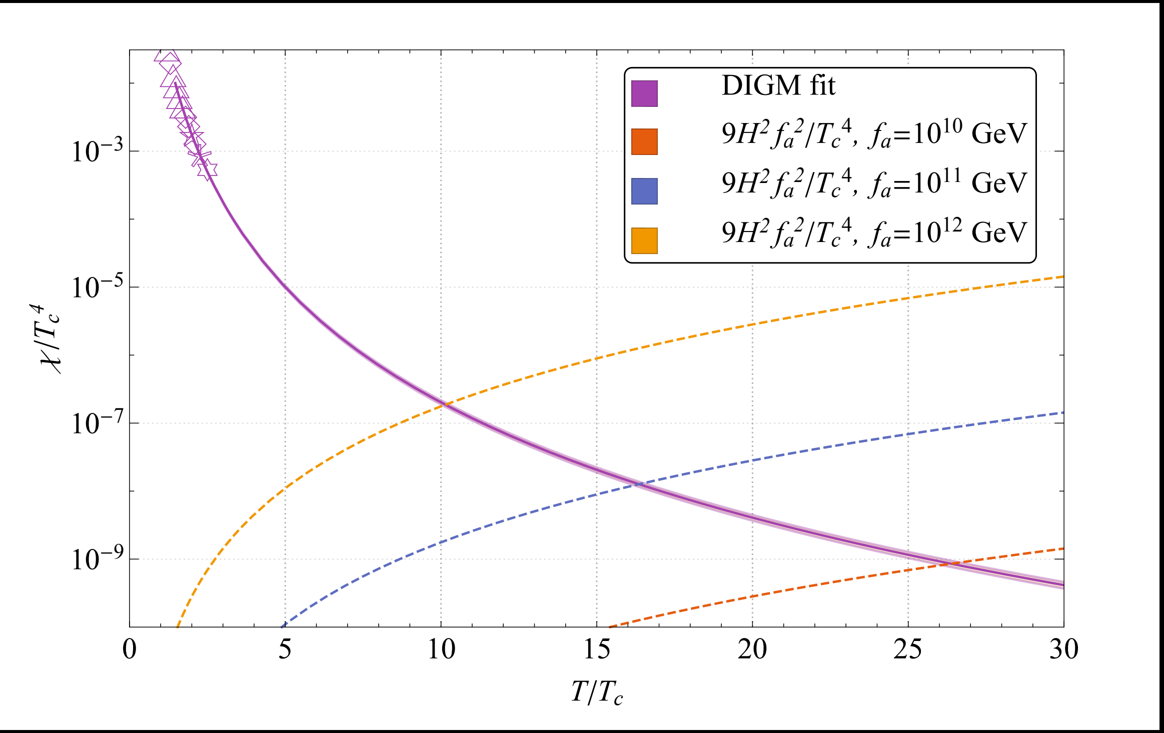
Thin: First order phase transition

Thick: Cross-over phase transition

Axions

- The axion is another light dark matter candidate, whose existence is postulated to solve the strong QCD problem.
- Its mass is a consequence of the QCD axial anomaly, related to the topological susceptibility χ, and is temperature-dependent.
- Axion production takes place roughly when 3 H(T) ~ m_a(T).
- Once produced, the axion mass increases as the temperature falls, until eventually it reaches the ~zero temperature value it has today.
- Lattice calculations can help tether models for χ(T), but are still in their early stages.

$$\chi(T) = m_a^2(T) f_a^2$$

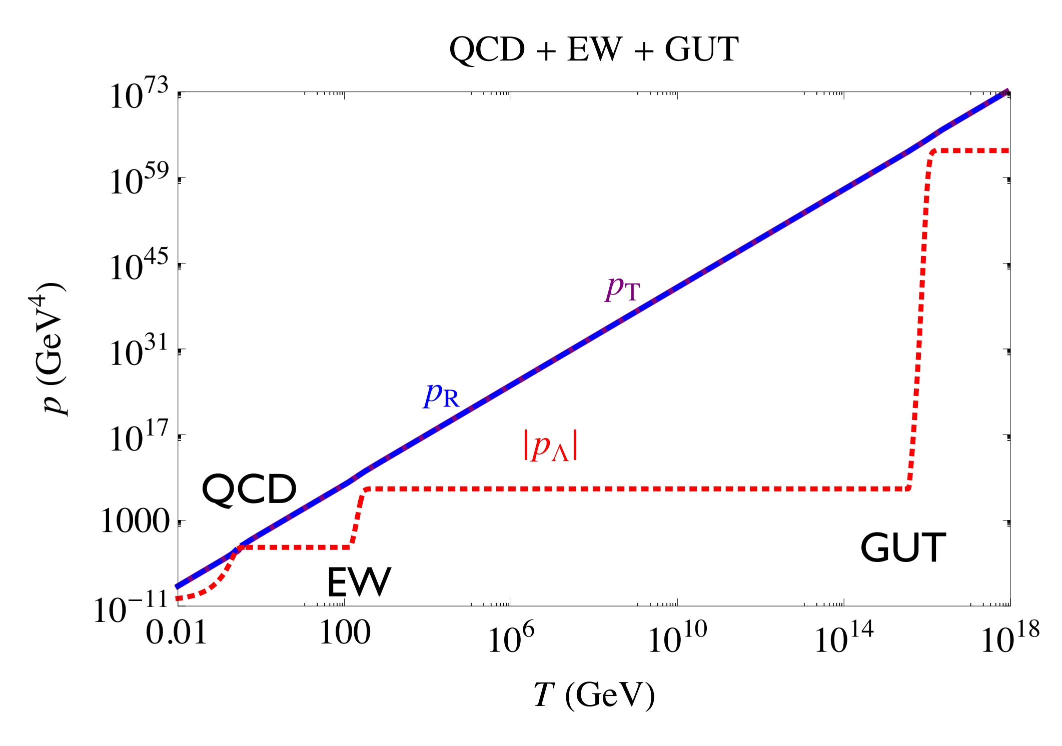


Lattice calculations at finite temperature (for a pure glue theory), fit to a dilute instanton gas model.

Berkowitz, Buchoff, Rinaldi 1505.07455
See also: Kitano, Yamada 1506.00370

QCD & Dark Energy

- The QCD phase transition also represents a puzzle with regard to dark energy.
- Naively, one expects that the vacuum energy changes by an amount of order Λ^4_{QCD} after the phase transition.
- This is obviously much larger than the observed dark energy, and is another take on the CC fine tuning problem.
- It suggests that in extreme environments such as the interior of a neutron star, where the QCD enters a different phase, there may be a non-negligible contribution to the equation of state from vacuum energy.

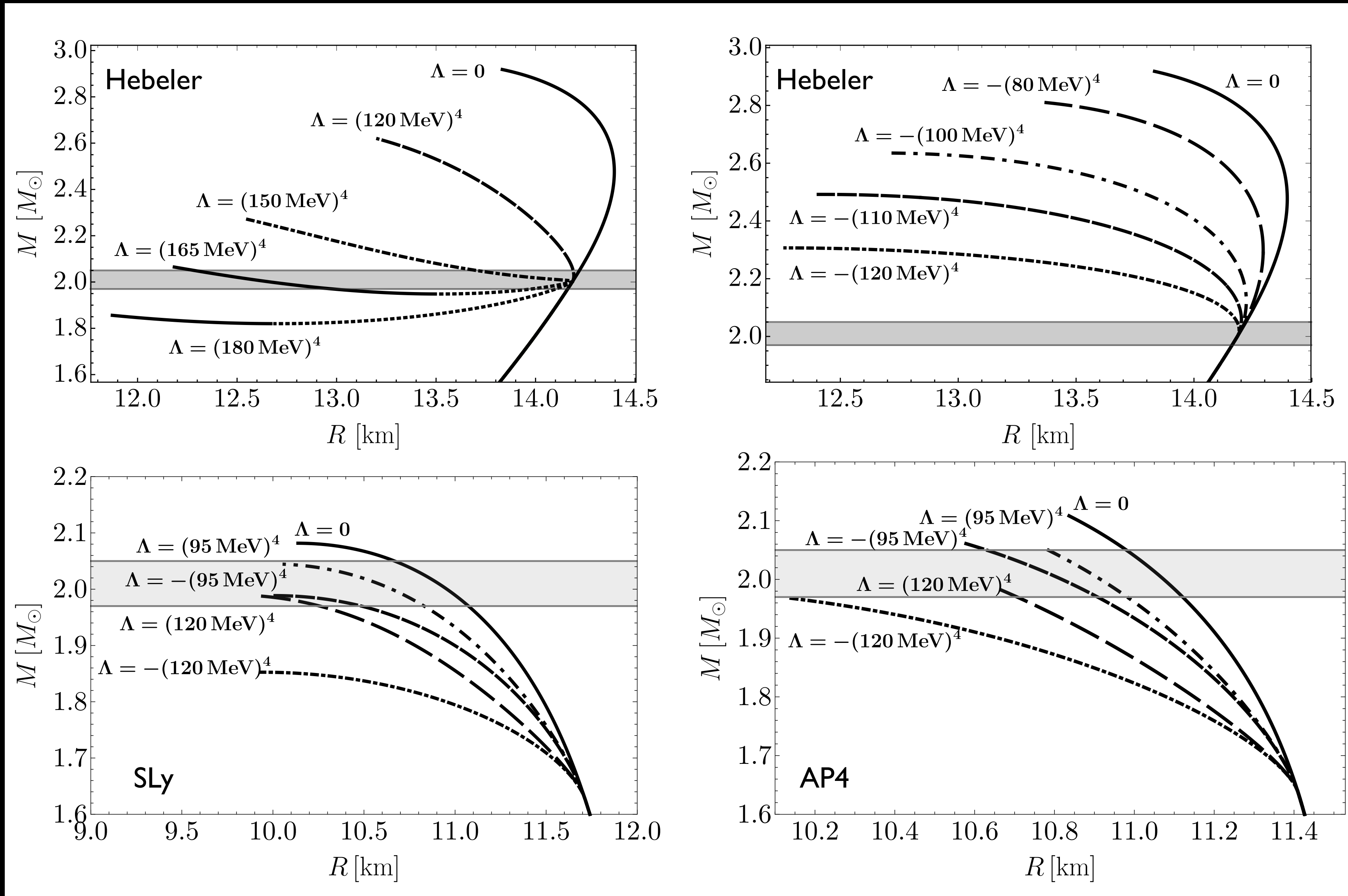


Bellazzini, Csaki, Hubisz, Serra, Terning
1502.04702

$$\Lambda_{\rm QCD}^{\rm vac} + \Lambda_{\rm bare} = \left(10^{-3}\ {\rm eV}\right)^4$$

$$\Lambda_{\rm QCD}^{\rm other} + \Lambda_{\rm bare} \sim \Lambda_{\rm QCD}$$

Neutron Stars?

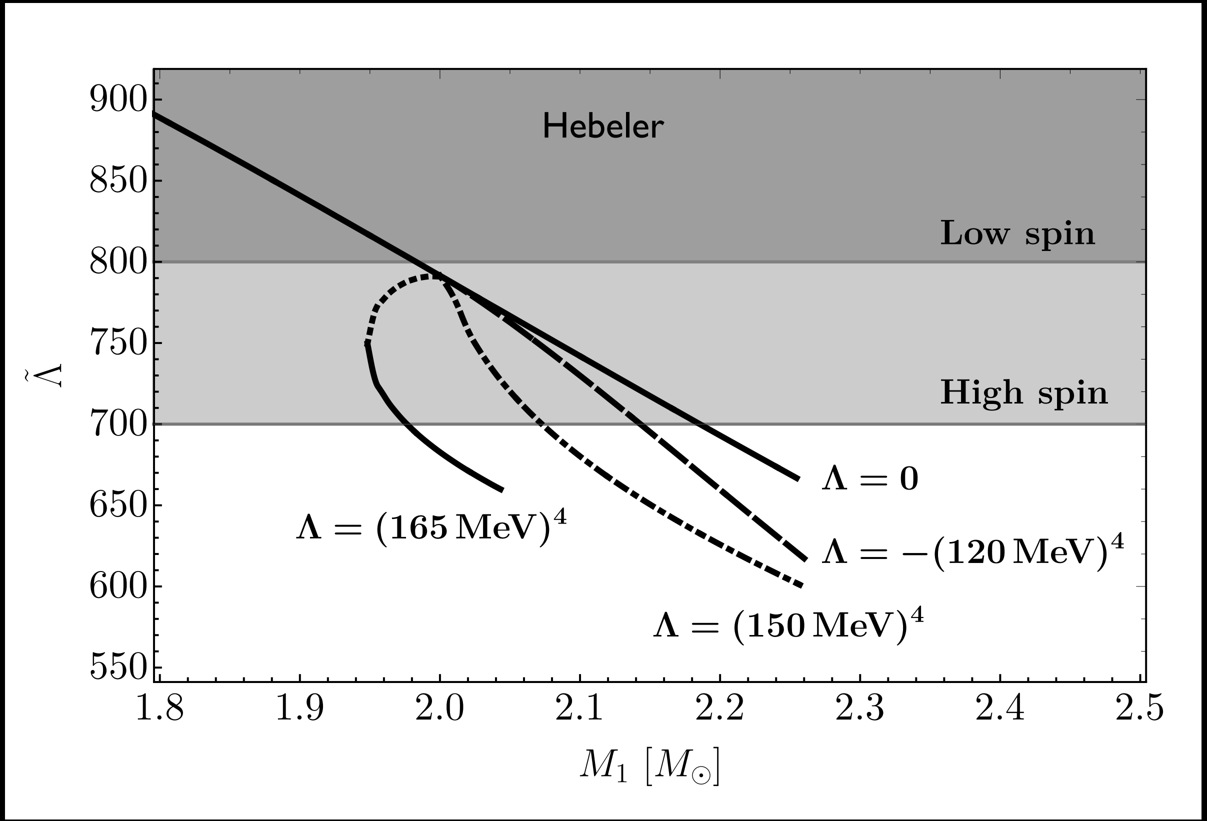


Csaki, Eroncel, Hubisz, Rigo, Terning
1802.04813

- The presence of additional vacuum energy on top of standard equations of state can significantly influence the mass-radius relation for neutron stars.
- Observations by NICER can help pin down the EoS (including vacuum energy).

Mergers

- The modified equation of state influences the interior structure, and thus the tidal forces in neutron star binary systems.
- The combined dimensionless tidal deformability ($\tilde{\Lambda}$) influences the gravitational wave form when the stars merge, and with enough statistics can provide information about the EoS.
- For GW170817, the low spin interpretation requires $\tilde{\Lambda}$ be less than about 800, whereas the high spin < 700.
- The range of allowed mass for the heavier star can be wider when vacuum energy is included.



Csaki, Eroncel, Hubisz, Rigo, Terning 1802.04813

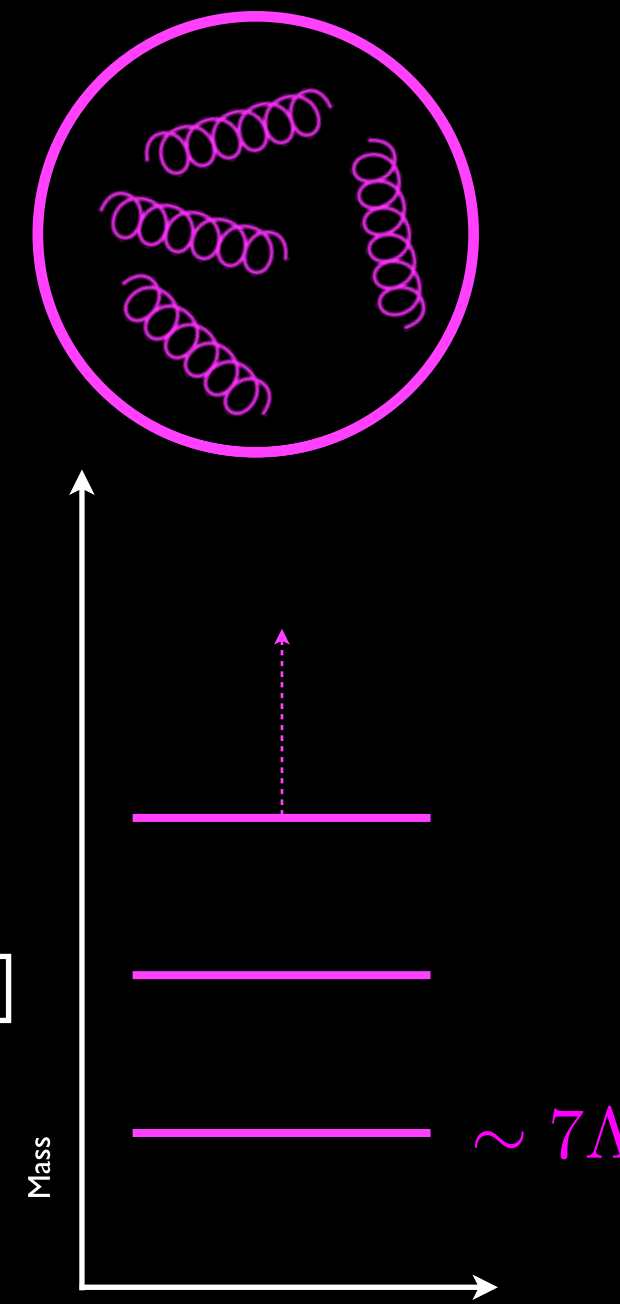
Chirp mass fixed to 1.188 M_{sun}, corresponding to GW170817

Composite Dark Matter

- It could be that QCD provides a metaphor for the nature of dark matter.
- A new confined gauge force generically produces massive composite particles which could play the role of dark matter.
- If any matter charged under the hidden gauge group and the SM is extremely heavy, there is no relevant interaction between the dark sector and the SM.
- At high energies, the theory is described by weakly coupled dark gluons.
- At low energies, the dark gluons confine into massive dark glueballs.

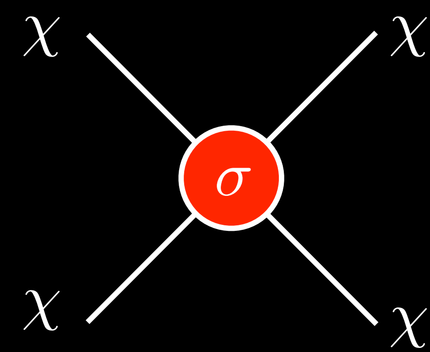
Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014

- The theory is defined by the number of colors N and confinement scale Λ, which characterizes the mass of the lowest glueball state, and the splitting between the various glueballs.



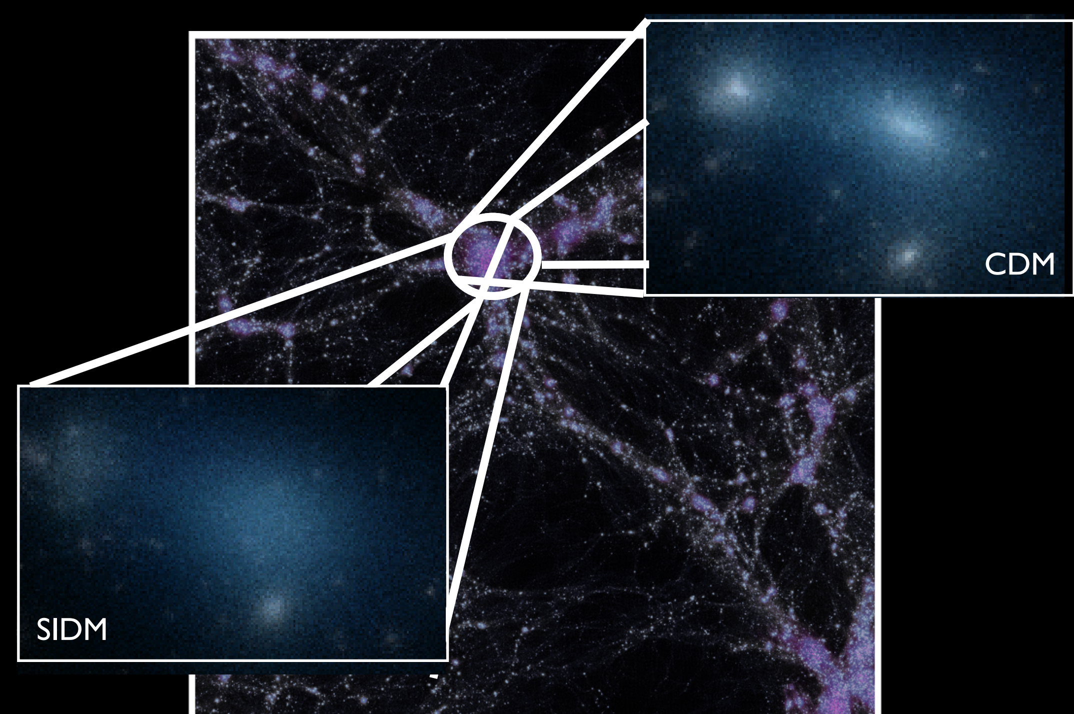
Self-Interacting DM?

- Dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- There is some (controversial) evidence that this may help simulation better describe observation.
- It could also be that the tension arises from the fact that the simulations don't properly model the impact of baryonic matter.
- Astronomy provides a unique perspective on properties that particle searches cannot probe.

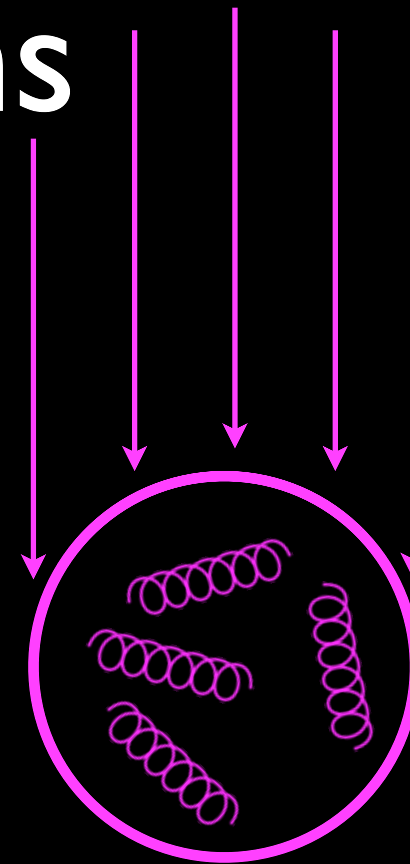


σ / m < 0.7 cm^2 / g

(at a relative speed of ~3000 km/s)

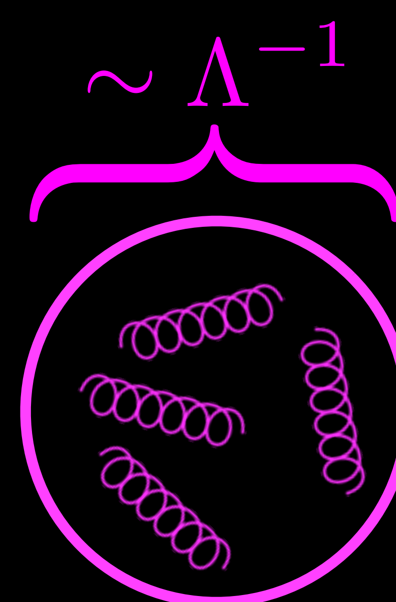


Glueball Interactions



- In this theory, nothing can be computed very reliably in perturbation theory.
  - Lattice gauge theory may be able to help.
- Nonetheless, the self-interactions of the glueballs will be roughly given by the geometric cross section for strongly coupled objects of size ~ 1 / Λ.

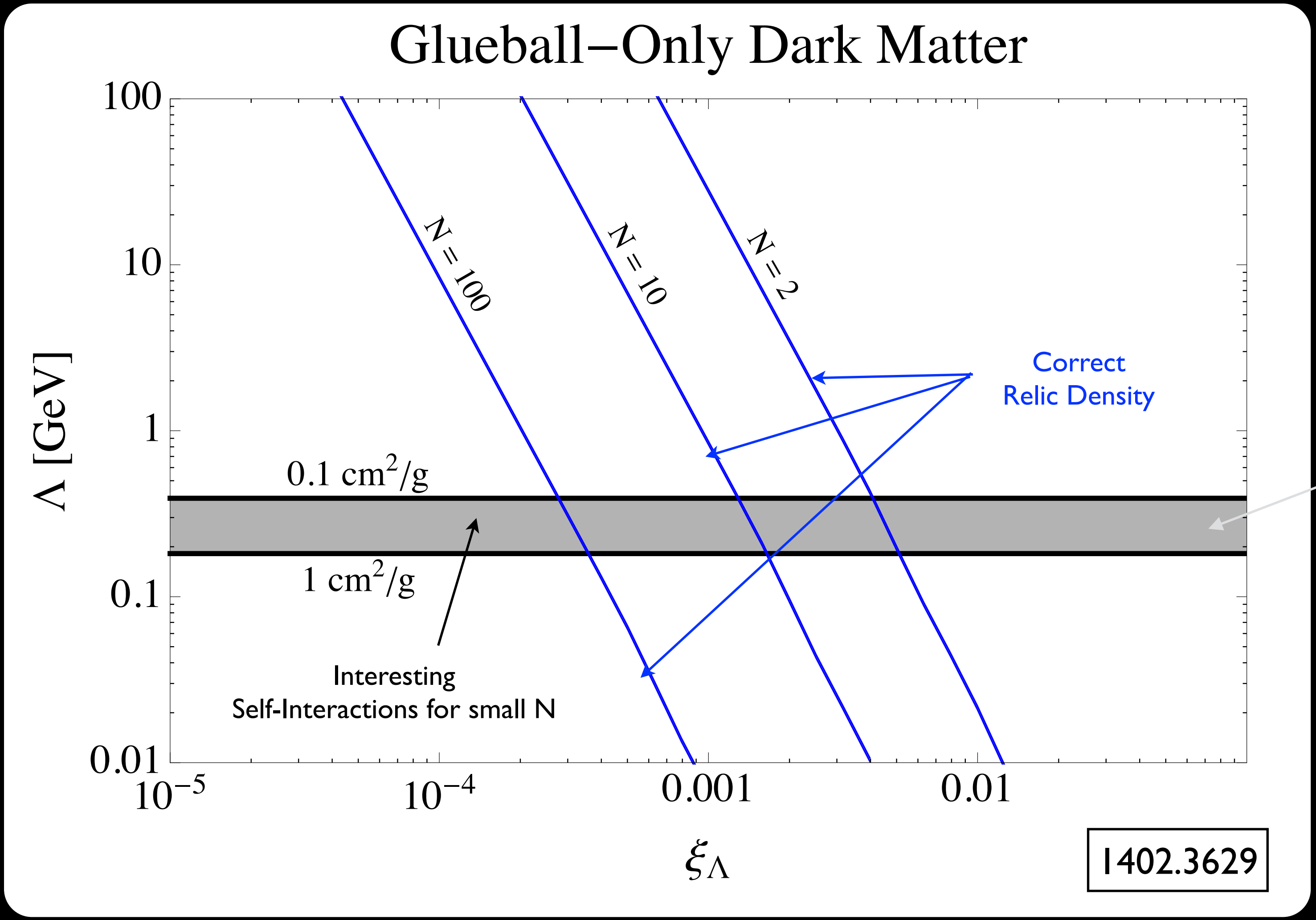
$$\sigma\,(\mathrm{gb}\ \mathrm{gb} \to \mathrm{gb}\ \mathrm{gb}) \sim \frac{4\pi}{\Lambda^2 N^2}$$



- Since the single parameter Λ controls both the mass and the cross section (for small N), arranging for an interesting value of σ/m essentially fixes Λ ~ 500 MeV.

Amusingly close to Λ_{QCD}…

Glueball Parameter Space



~ right SIDM σ for small N

Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014

- The relic density of the glueballs depends on the temperature of the hidden sector relative to the SM ($\xi = T_h / T_{SM}$). An interesting parameter space has ~ observable self-interactions and the correct relic density.

Cosmological QCD?

- What if the coupling of QCD is different in the early Universe?
- For example, if the strong coupling is controlled by a field whose value is different at early times, our expectations for when QCD confined could be simply wrong.

$$-\frac{1}{4}\left(\frac{1}{g_0^2}+\frac{\phi}{M_*}\right)G_{\mu\nu}G^{\mu\nu}$$

- As a crazy speculation, let's consider the case where QCD confines above the TeV scale.

$$g_{\text{eff}}^2=\frac{g_0^2}{1+g_0^2\frac{\langle\phi\rangle}{M_*}}$$

  - Basic quantities like the relevant degrees of freedom could be different at the time of dark matter freeze out.
  - If QCD confines early, it can trigger an electroweak breaking whose properties are disconnected from the Higgs…
- Of course, we need to make sure it relaxes back to the QCD we know in time for nucleosynthesis!

What is this good for?
Baryogenesis? Anything?
How would we tell it happened?

Outlook

- QCD and cosmology seem to have many messages for each other.
- In this talk I have tried to explore some that struck me as interesting and timely
  - Dark Matter freeze out
  - Sterile neutrinos
  - Axions
  - Neutron stars and dark energy
  - Composite dark matter and self interactions
- Of course, there are many others!
- I can’t wait to see what connections future sessions of Moriond will reveal!

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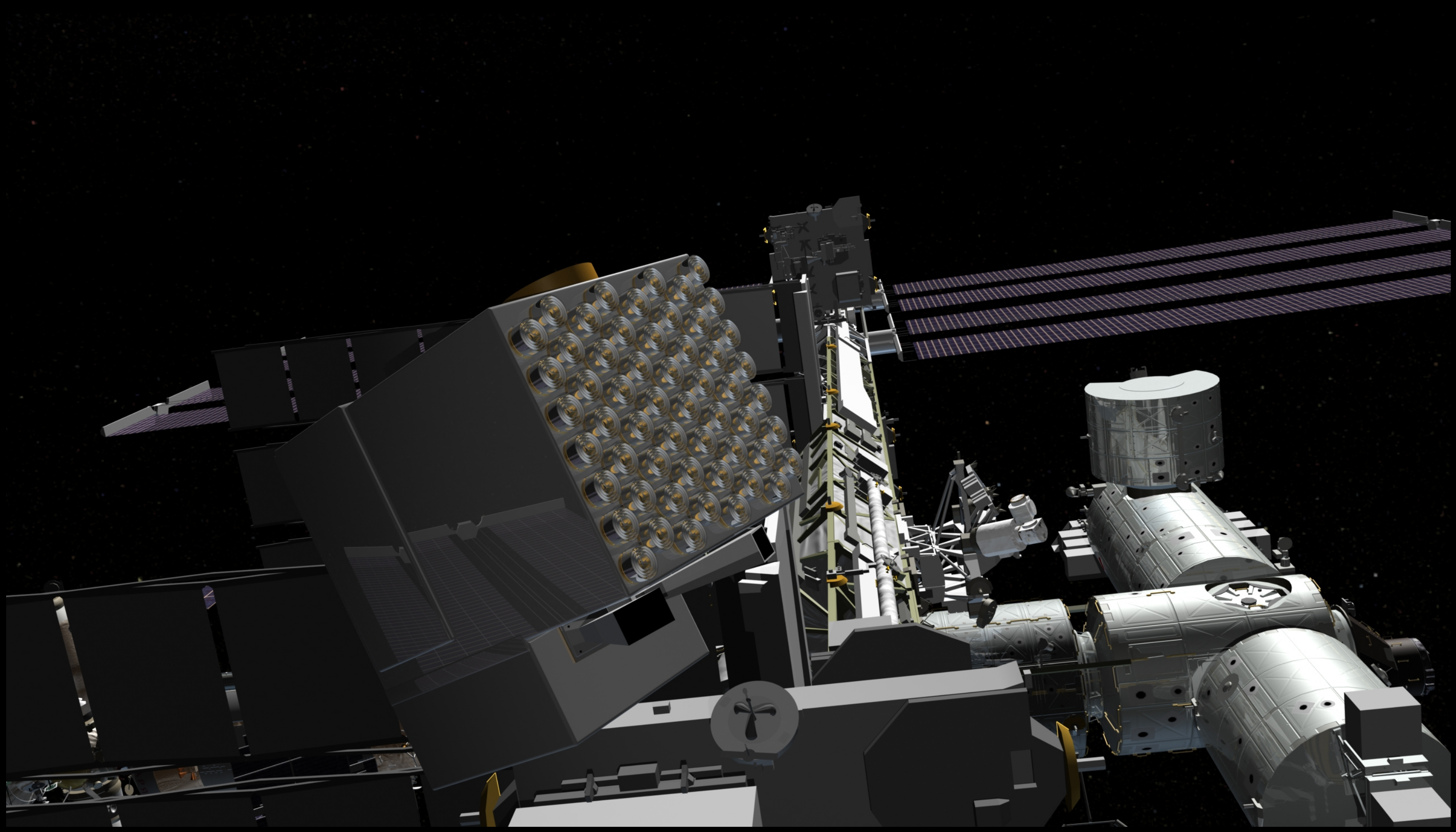
Thank you!

Bonus Material

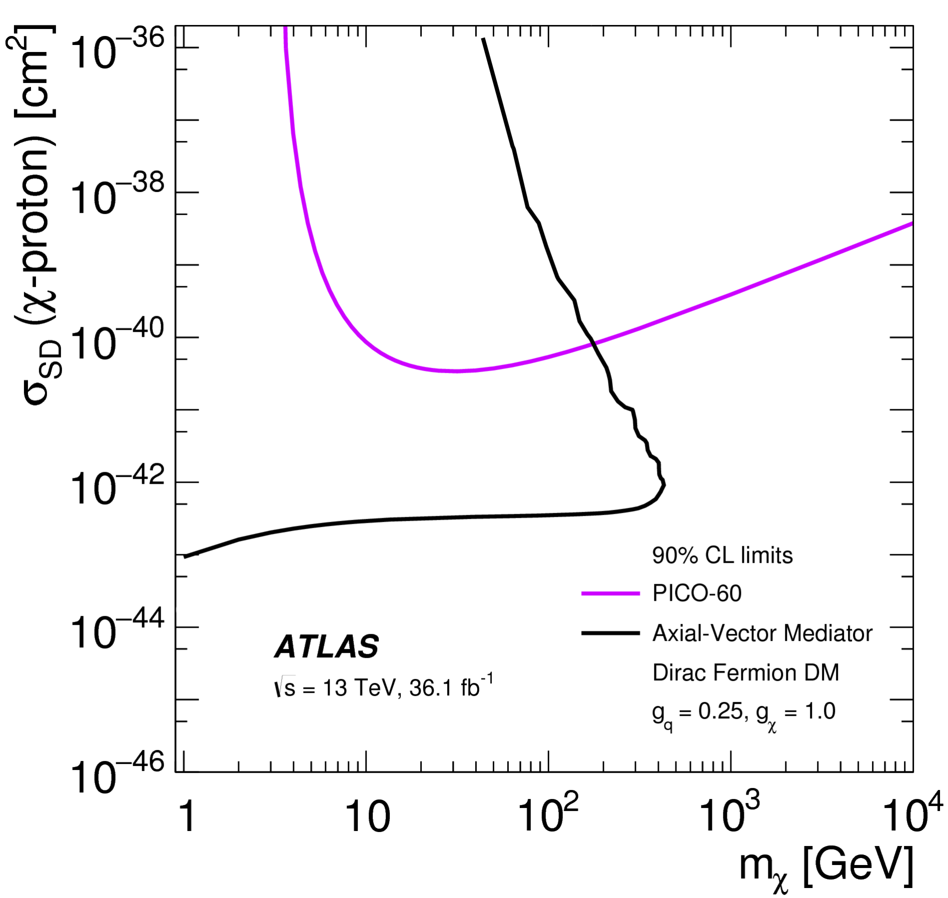
Neutron star Interior Composition ExploreR

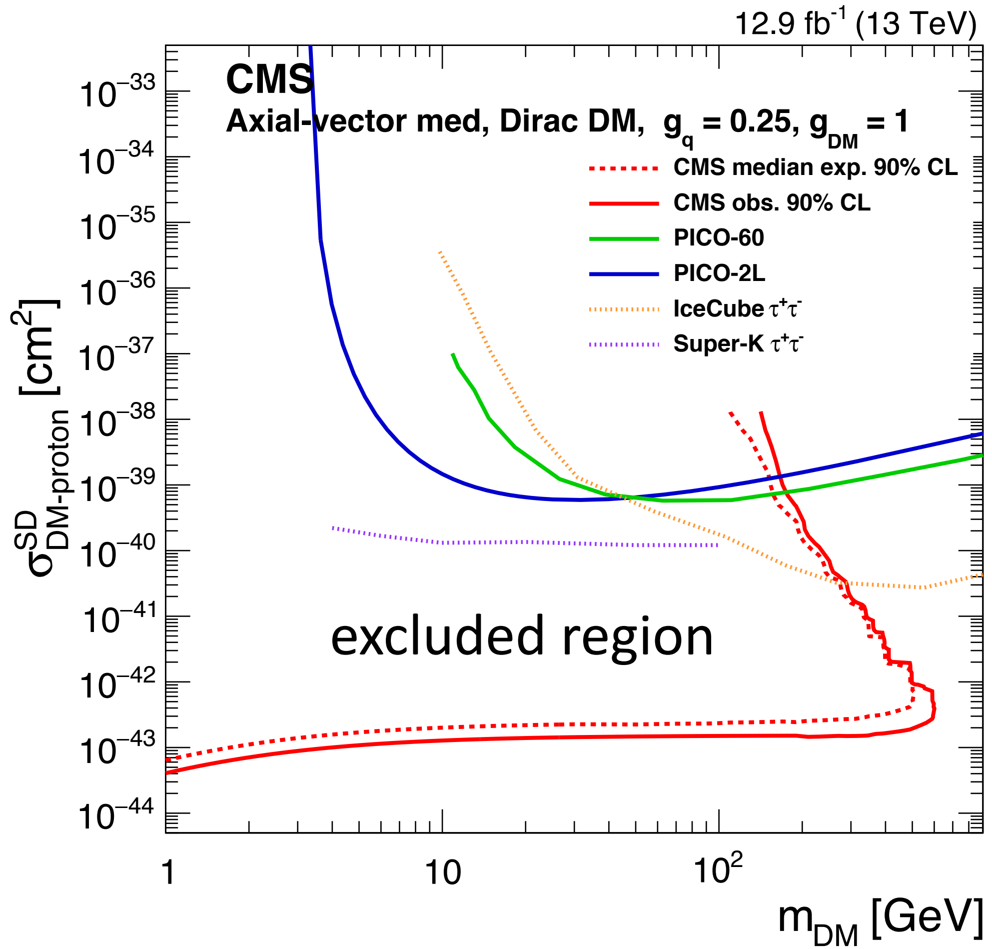


Artist's conception aboard the ISS.

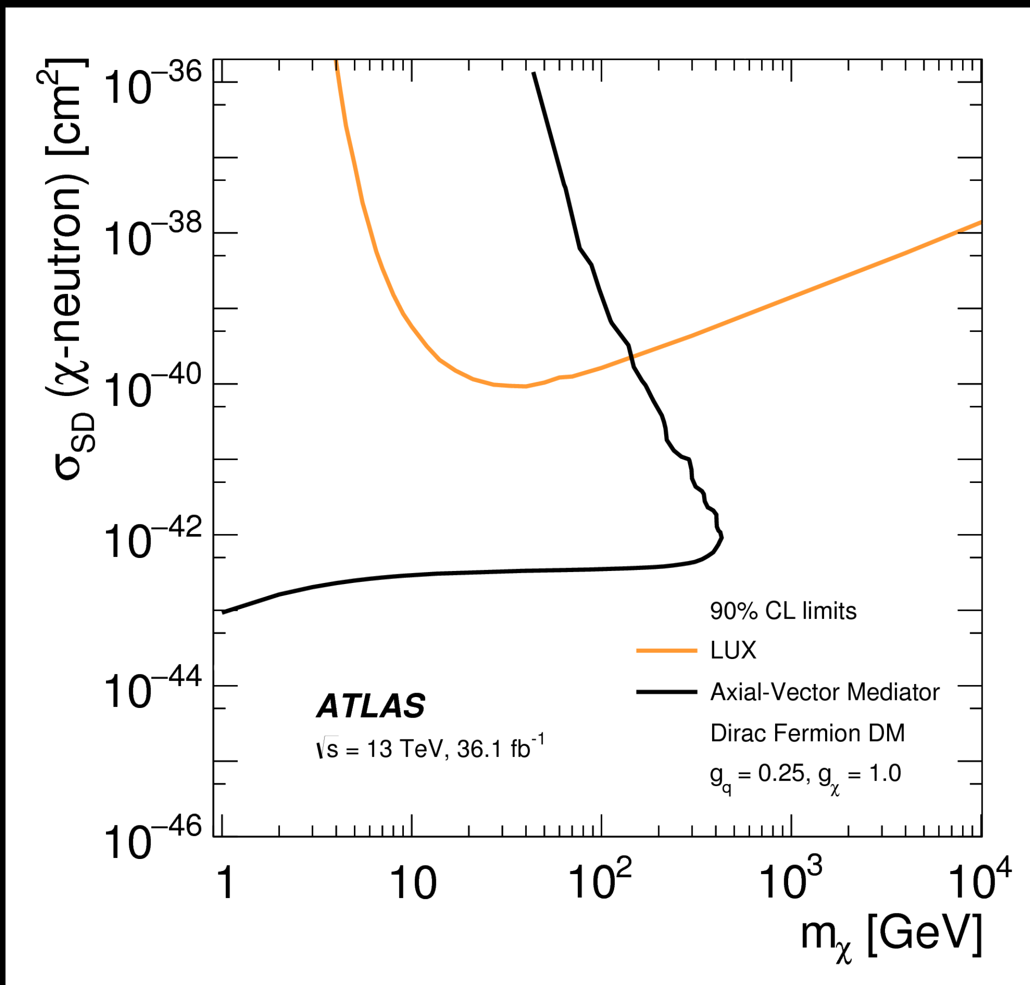
Axial Vector: Monojet Searches

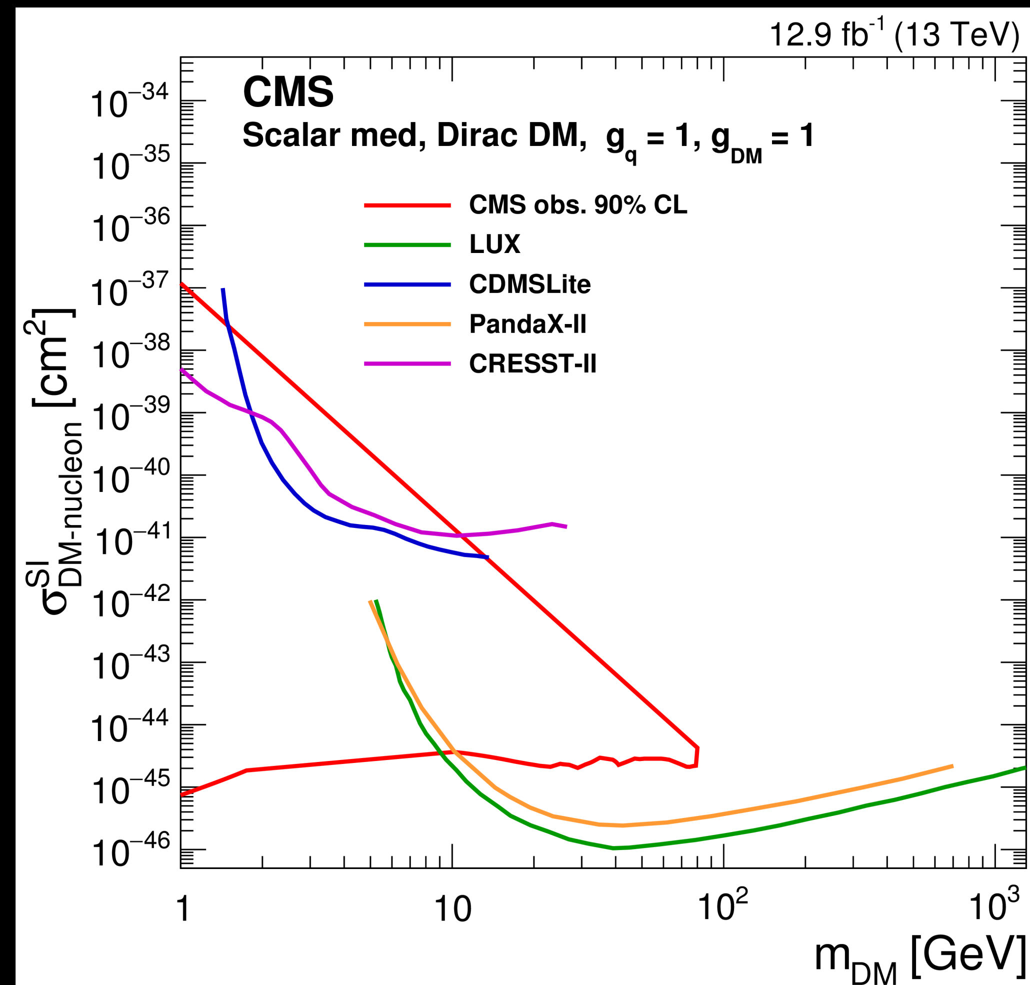
Axial vector mediator g_q=0.25, g_{DM}=1.0



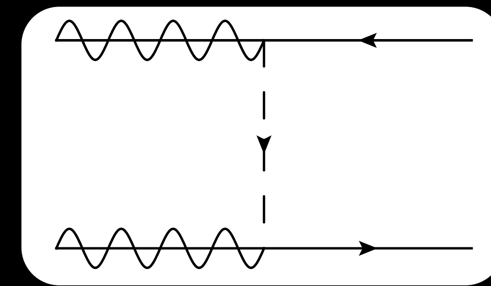


Monojet Searches: Other Interpretations

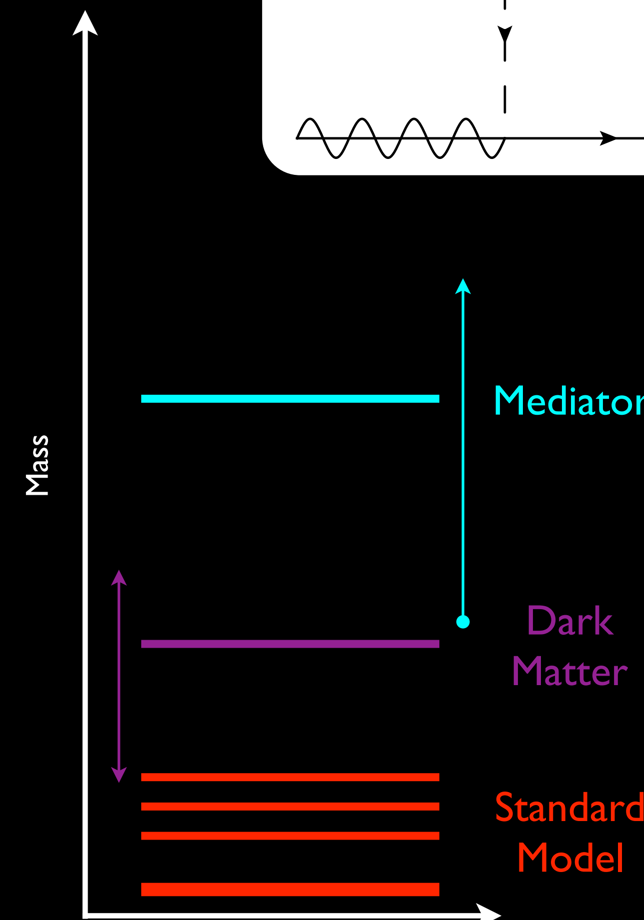




Colored Scalar



- Another construction has dark matter interacting with quarks via a colored scalar mediator.
- Minimal flavor violation suggests we consider mediators with a flavor index corresponding to {uR,cR,tR}, {dR,sR,bR}, {Q1,Q2,Q3} and/or combinations.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

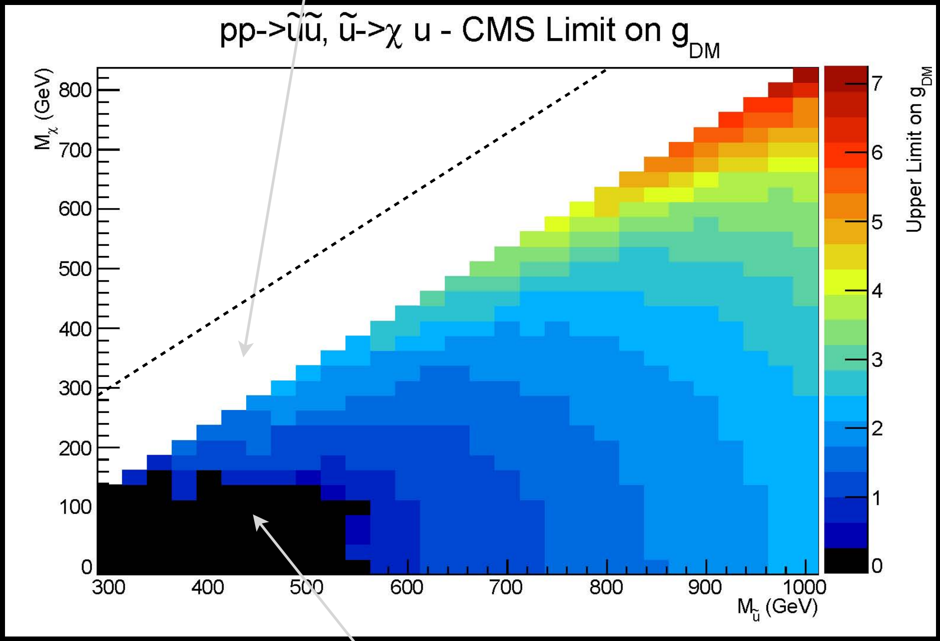


Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679

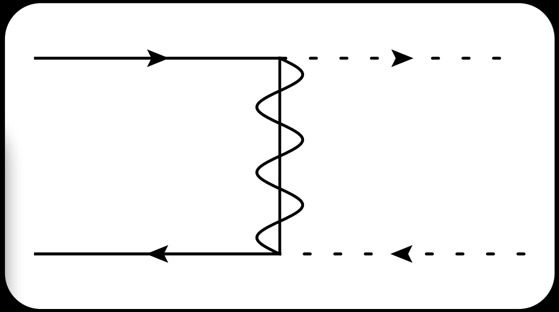
$\tilde{u}_R$ Model

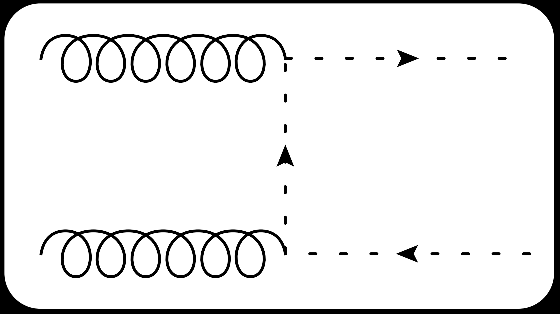
Weak bounds in the mass-degenerate region.

- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.

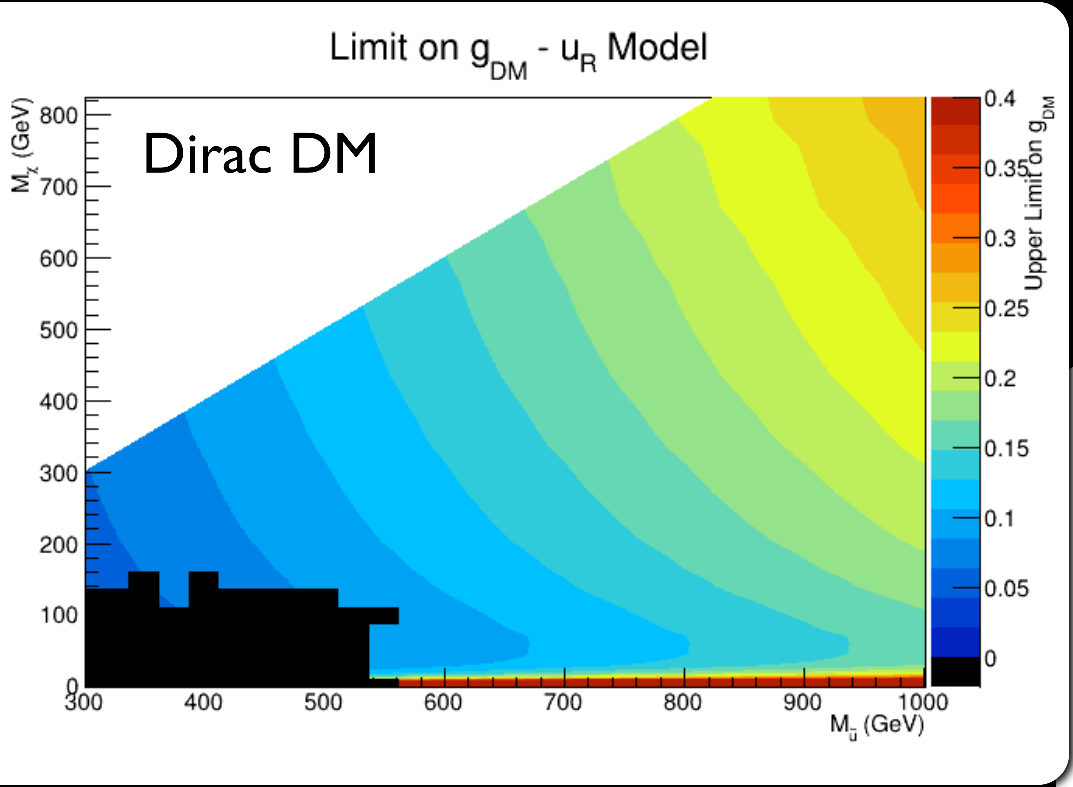


QCD production saturates the CMS limits, resulting in no allowed value of g.

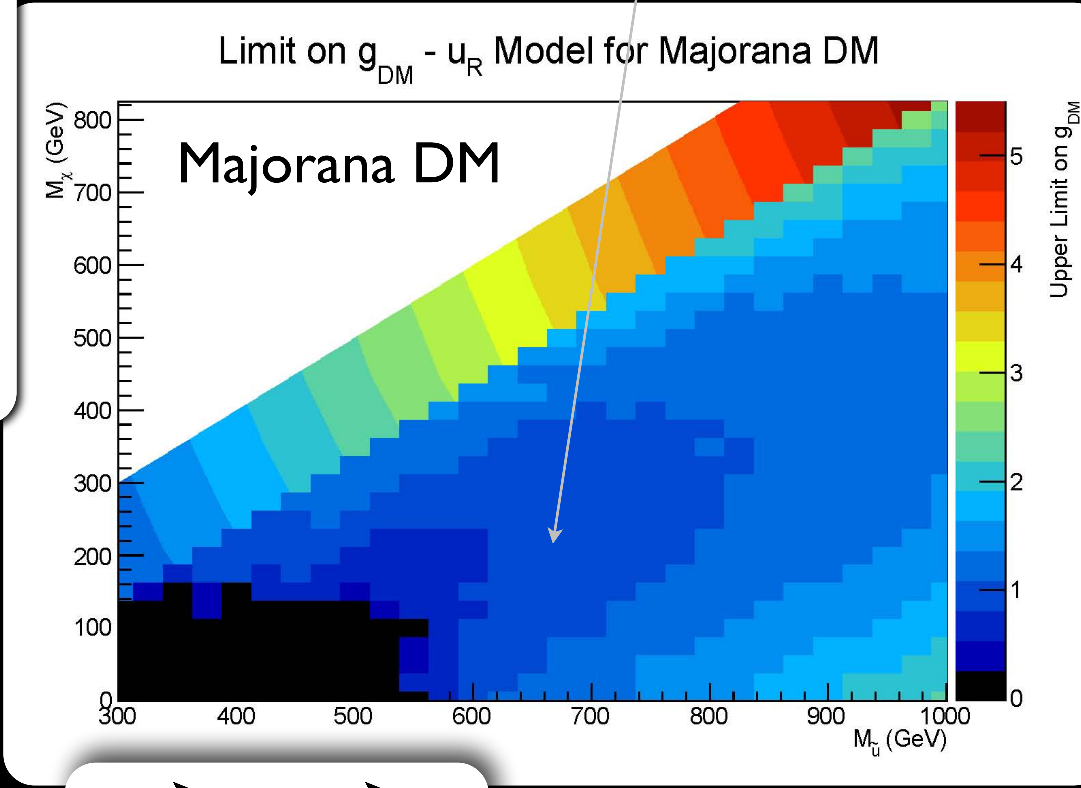




Majorana versus Dirac



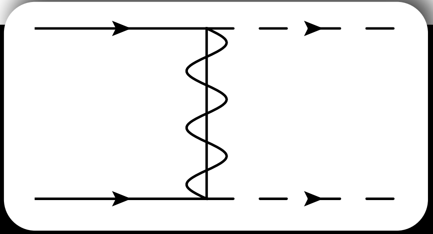
Collider bounds tend to dominate for Majorana DM.



There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

Majorana WIMPs have no tree-level spin-independent scattering in this model.

At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.



$\tilde{u}_R$ Model: Forecasts

- Similarly, we can forecast for the annihilation cross section.
- The Fermi LAT does not put very interesting constraints at the moment, but it is very close to doing so, and limits from dwarf satellite galaxies are likely to be relevant in the near future for Majorana DM.
- We can also ask where in parameter space this simple module would lead to a relic which freezes out with the correct relic density ($\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s).