Bound States in Heavy Dark Sectors: from WIMPonium to Squeezeout

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GGI Tea Break Colloquium
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with Pouya Asadi, Matthew Baumgart, Patrick Fitzpatrick & Emmett Krupczak
Phys. Rev. Lett. **127**, 211101; Phys. Rev. D **104**, 095013
with Pouya Asadi, Eric Kramer, Eric Kuflik, Gregory Ridgway, & Juri Smirnov
work in progress
with Matthew Baumgart, Nicholas Rodd & Varun Vaidya

Outline

- The puzzle of dark matter
- Motivation and background for dark-matter bound states
- WIMPonium and gamma-ray signals for heavy weakly-interacting dark matter
- Strongly interacting dark sectors and changes to the cosmological history

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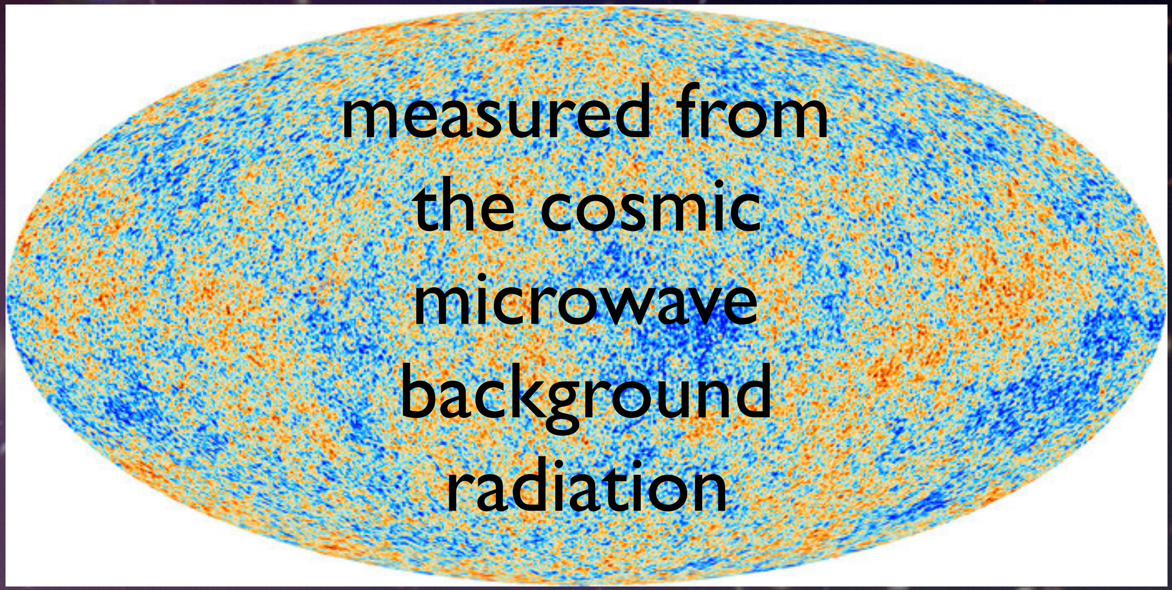

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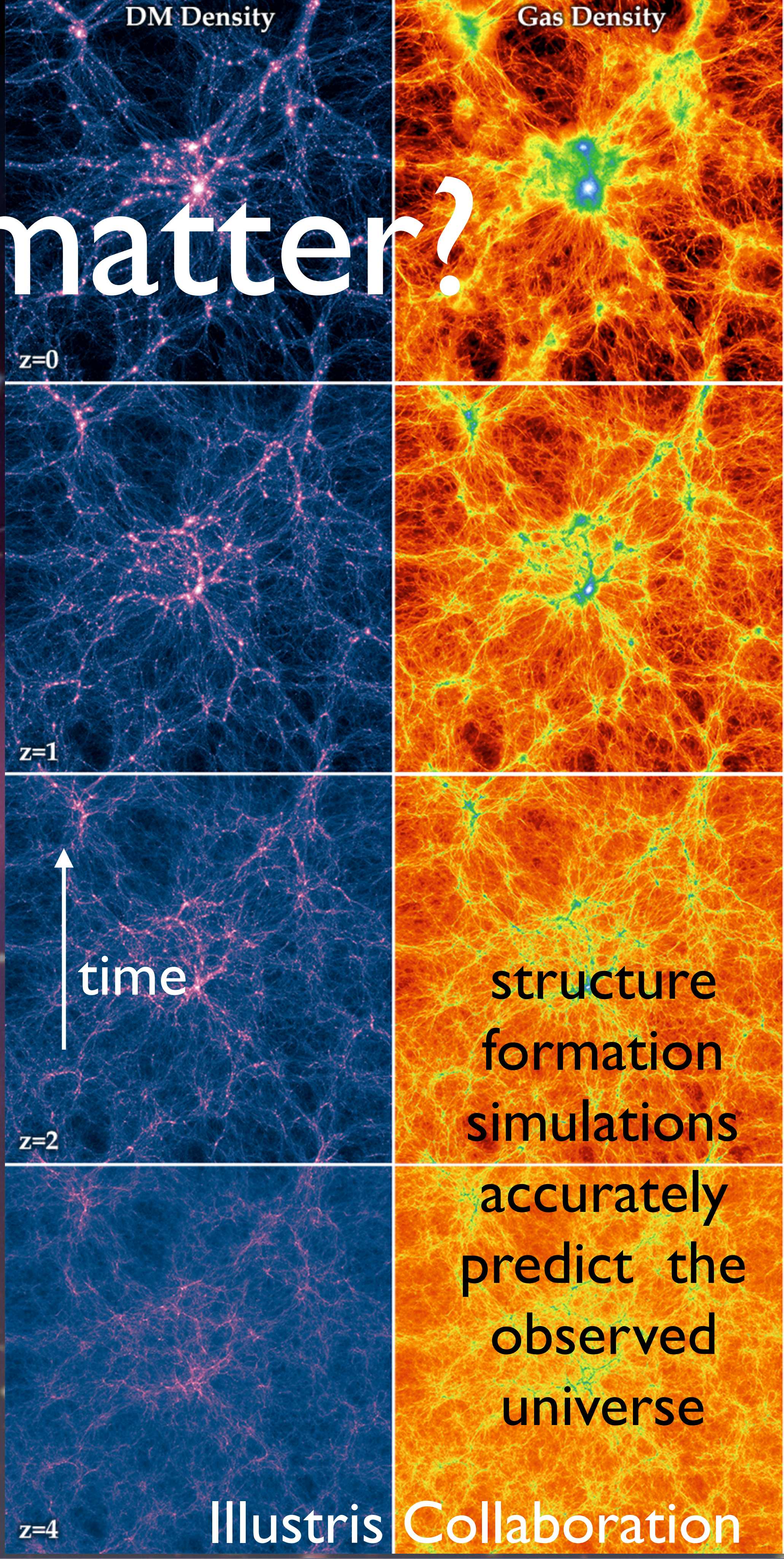

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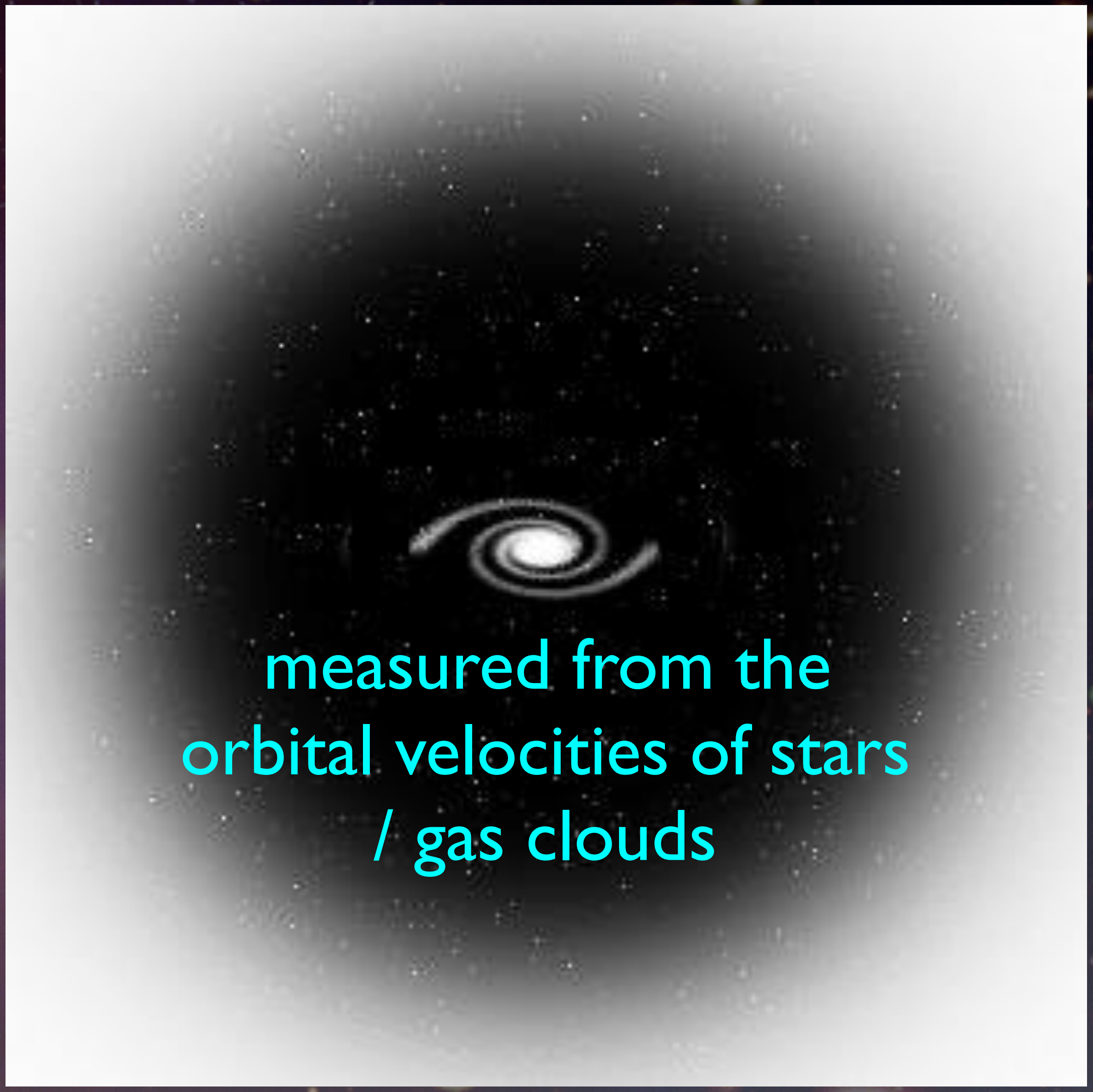

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- Forms the primordial "scaffolding" for the visible universe.
- Forms large clouds or "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

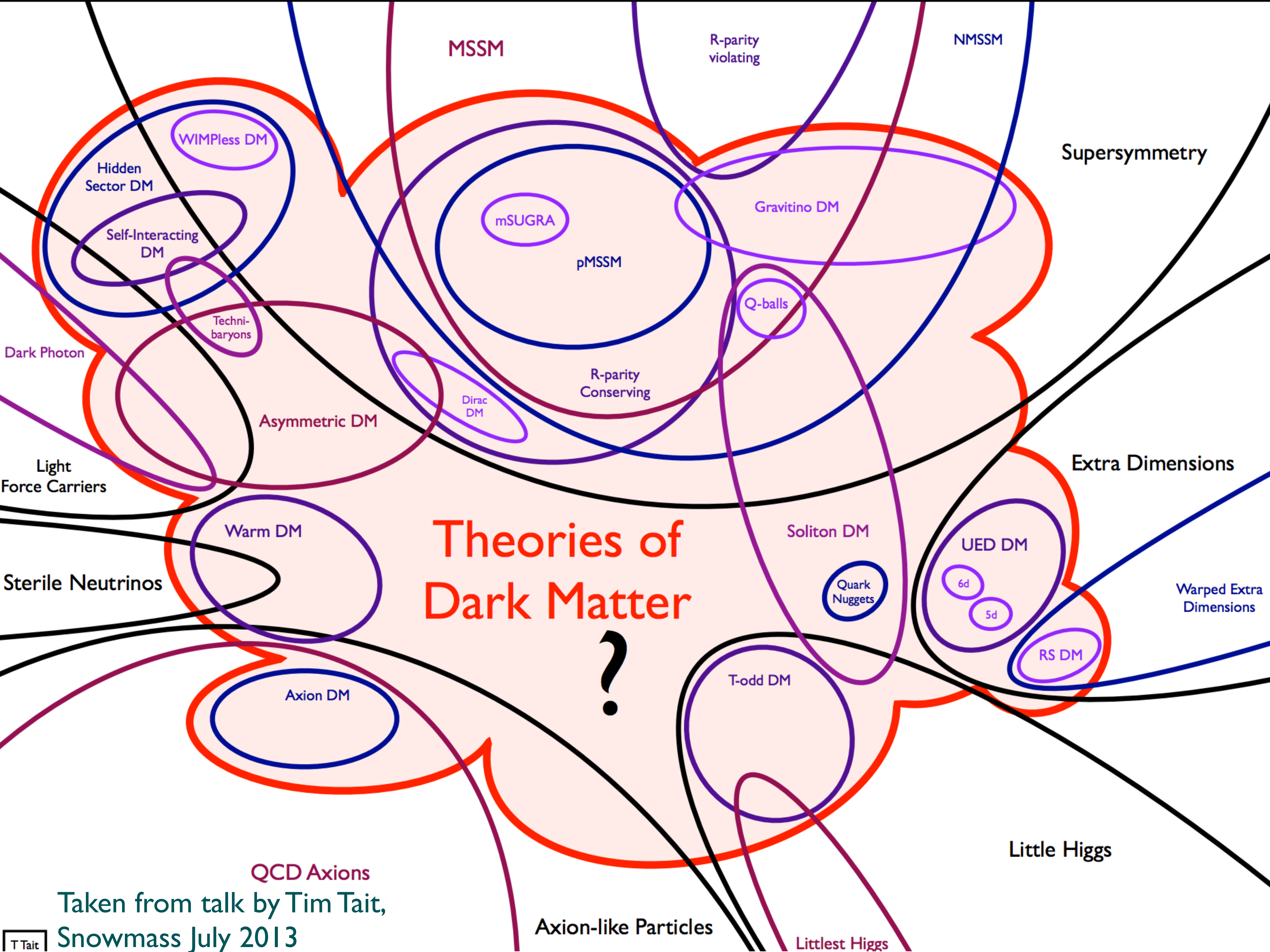
What is dark matter?

<u>We know it:</u>

- Consequently, cannot be explained by any physics we currently understand

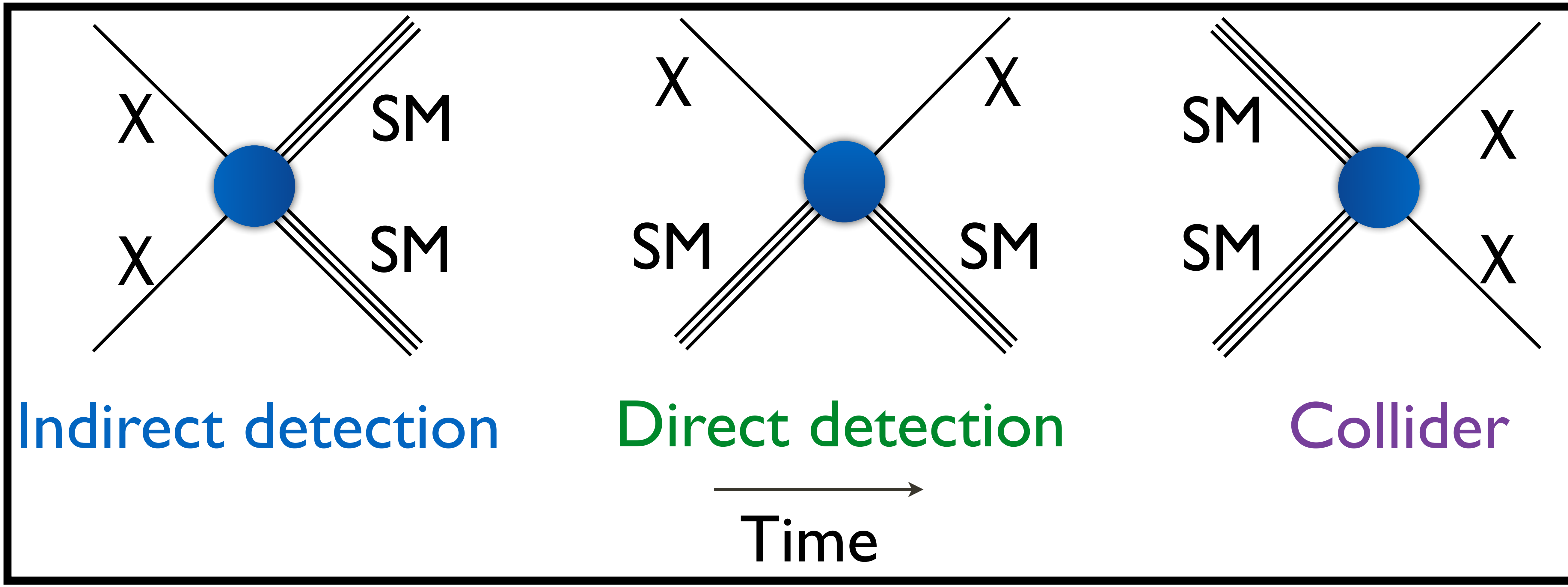
<u>We don't know:</u>

- What it's made from.
- Is it one particle, or more than one?
- How it interacts with other particles.
- Whether it's absolutely stable, or decays slowly over time.
- Why its abundance is what it is.
- If/how it's connected to other deep problems in particle physics.



Taken from talk by Tim Tait, Snowmass July 2013

Searches for dark matter



- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay.

- Direct detection: look for atomic nuclei “jumping” when struck by dark matter particles, using sensitive underground detectors.

- Colliders: produce dark matter particles in high-energy collisions, look at visible particles produced in the same collisions, check for apparent violation of energy/momentum conservation.

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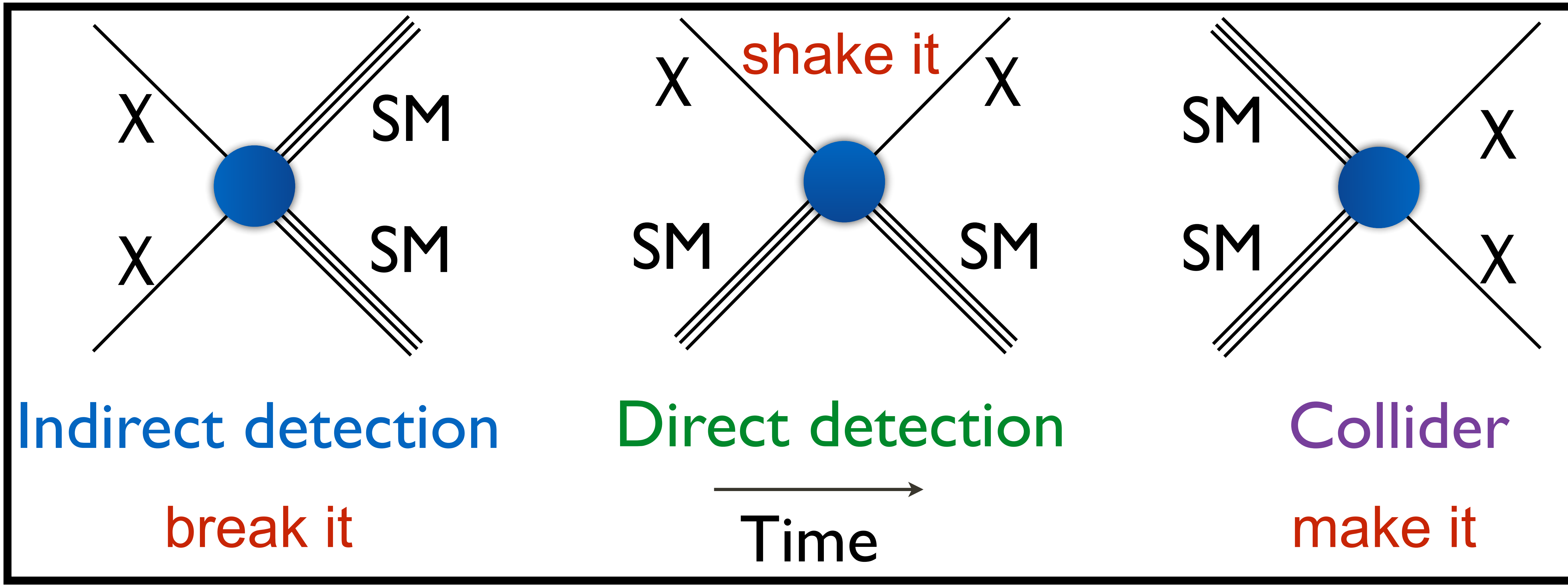

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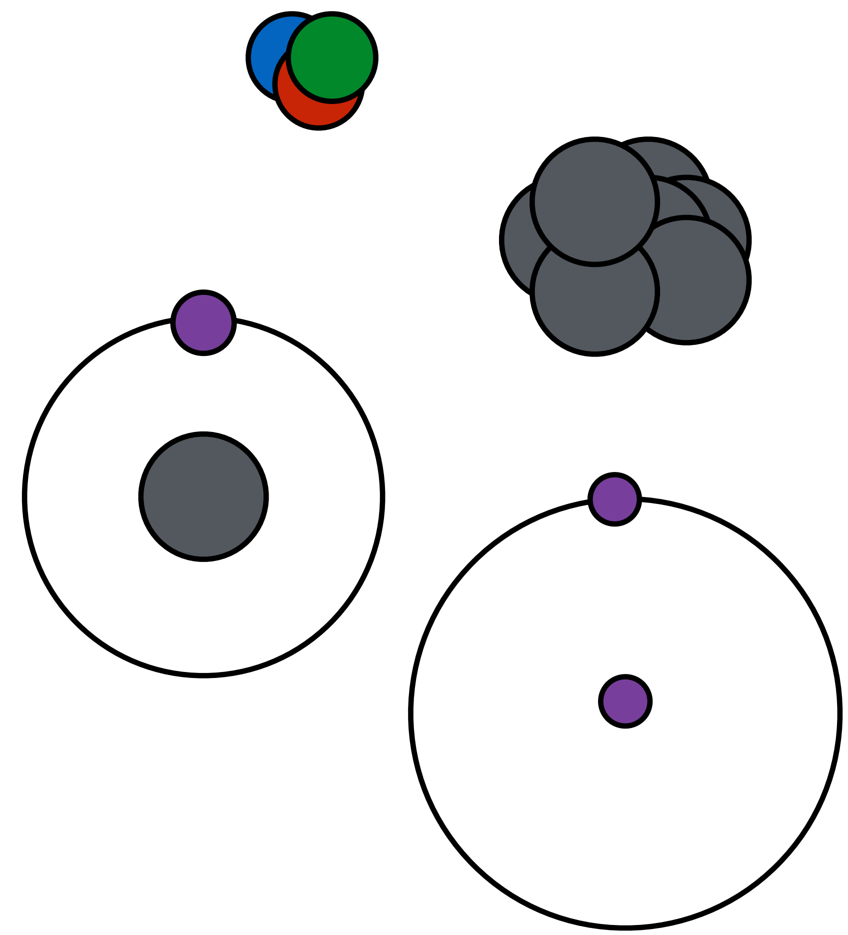
Dark matter bound states?

- Bound states are ubiquitous in the Standard Model:
  - stable bound states: nucleons (bound states of quarks), nuclei (bound states of nucleons), atoms (bound states of protons/electrons)
  - unstable bound states: mesons, particle-antiparticle bound states



- Under what circumstances can dark matter form bound states?
- If dark matter can form bound states, how would that change its observable signatures?

Ingredients for bound states

- Attractive potentials generically support bound states if they are sufficiently strong/long-range

- "Long range" means the range of the interaction should be larger than the Bohr radius of the bound state ($1/\alpha\ \mu$ where α is the relevant coupling and μ is the reduced mass)

- Potentials mediated by massive particles have a cutoff determined by the particle mass m, which should be smaller than the inverse Bohr radius:

$$m < \alpha\mu$$

- Massless particles (like the photon) give rise to infinite-range forces (electromagnetism) - infinite tower of bound states

- More massive force carriers → shorter-range potentials → finite number of bound states

Two scenarios for dark matter bound states (I)

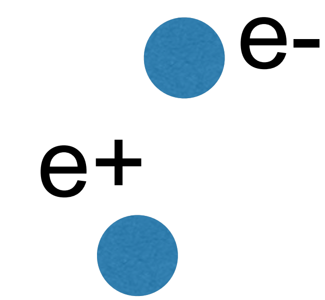
- Case 1: suppose force carrier is known already
  - possible candidate: W, Z, Higgs bosons
  - all around 100 GeV in mass
  - coupling strength $\alpha_{weak} \sim 1/30$
  - suggests we need bound state constituents to have mass around 100 GeV/α_{weak} ~ 3 TeV or heavier
  - so this scenario points to heavy weakly interacting massive particles (WIMPs)

Two scenarios for dark matter bound states (II)

- Case 2: suppose force carrier is something new - “dark force” experienced by dark matter but not ordinary matter
- Now dark matter, dark force carrier can have a wide range of masses
- “Dark-onium” would be a bound state comprised of dark matter (or related particles), bound together by the potential induced by the dark force
- The dark force could have a range of strengths, consistent with upper limits from observations

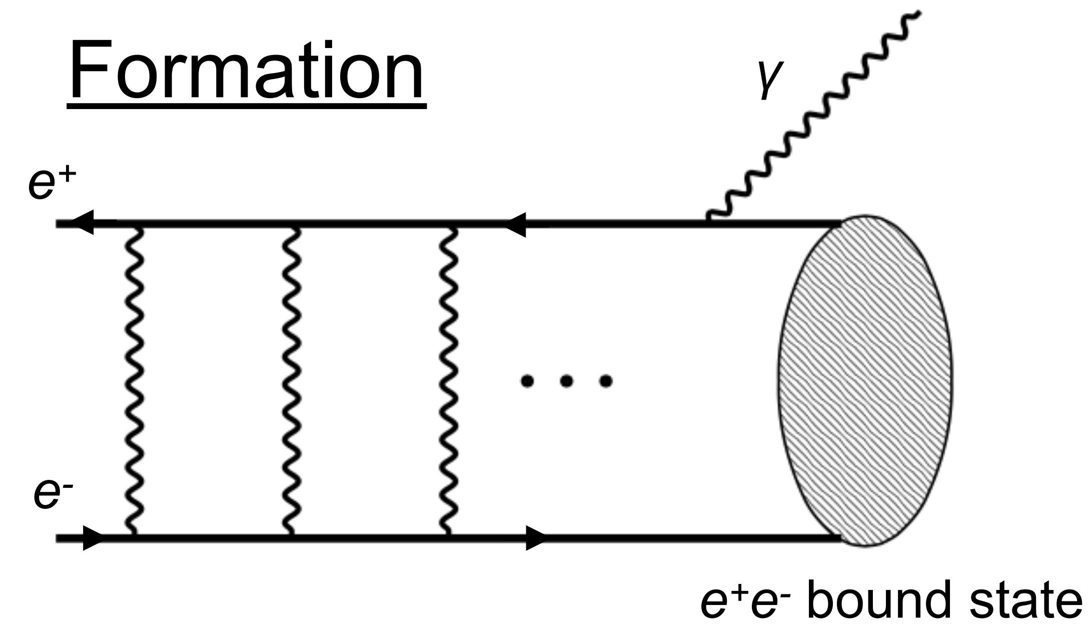
WIMPonium and indirect signals

Analogy: positronium



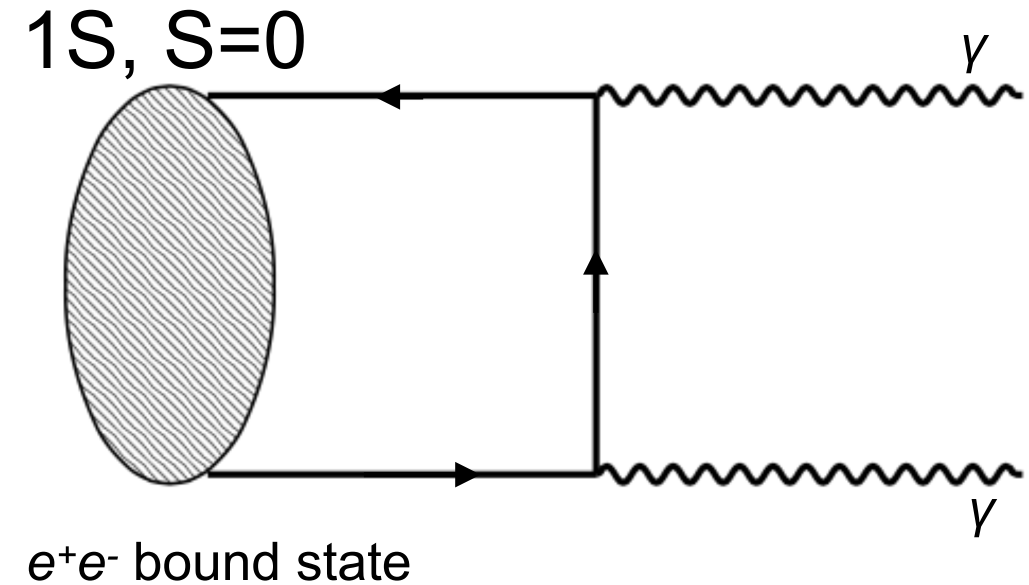
- Positronium is a bound state of an electron and its antiparticle
- It must radiate a photon to form (or scatter off another particle), by energy-momentum conservation - “radiative capture”.
- We can look for these photons or photons from the decay of the positronium via annihilation.
- At low velocities, bound state formation + decay is the dominant annihilation channel (by a factor of ~3).
- Can it be an important signal mechanism for dark matter?

Formation



Annihilation

1S, S=0



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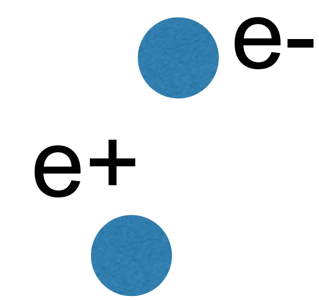

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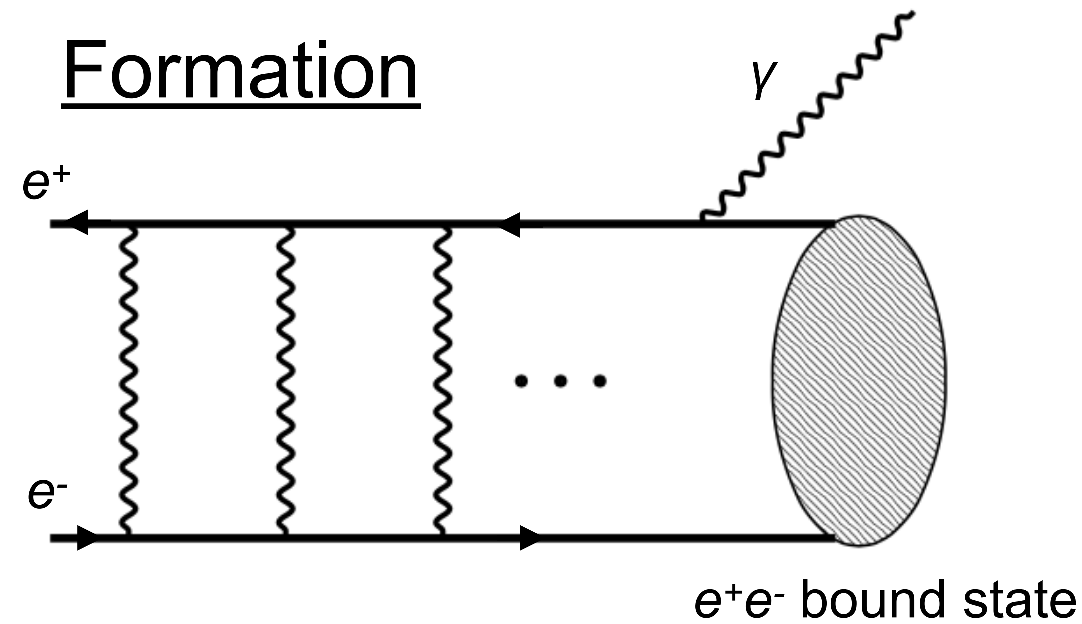

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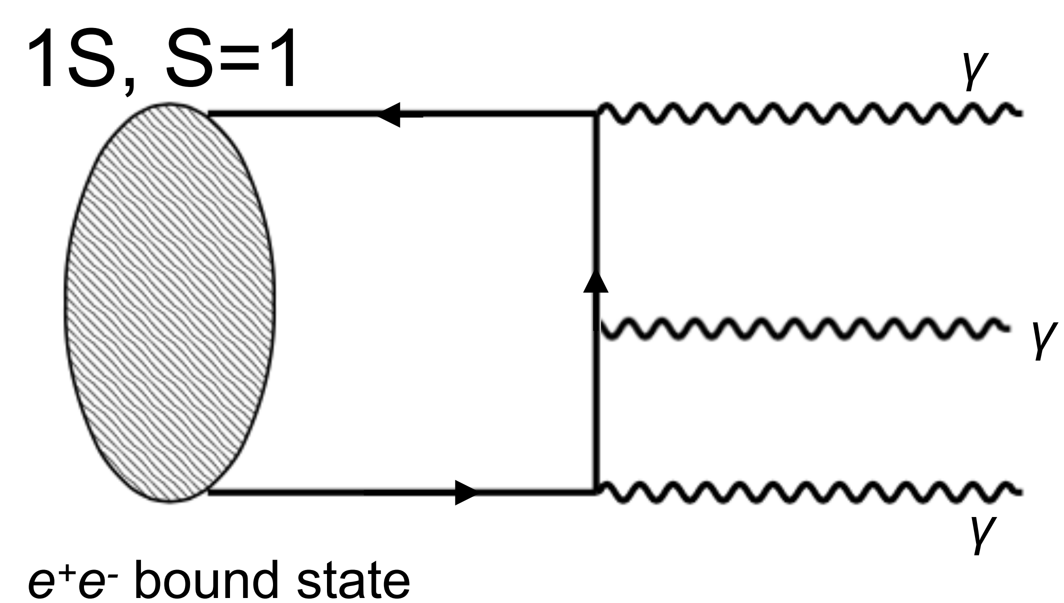


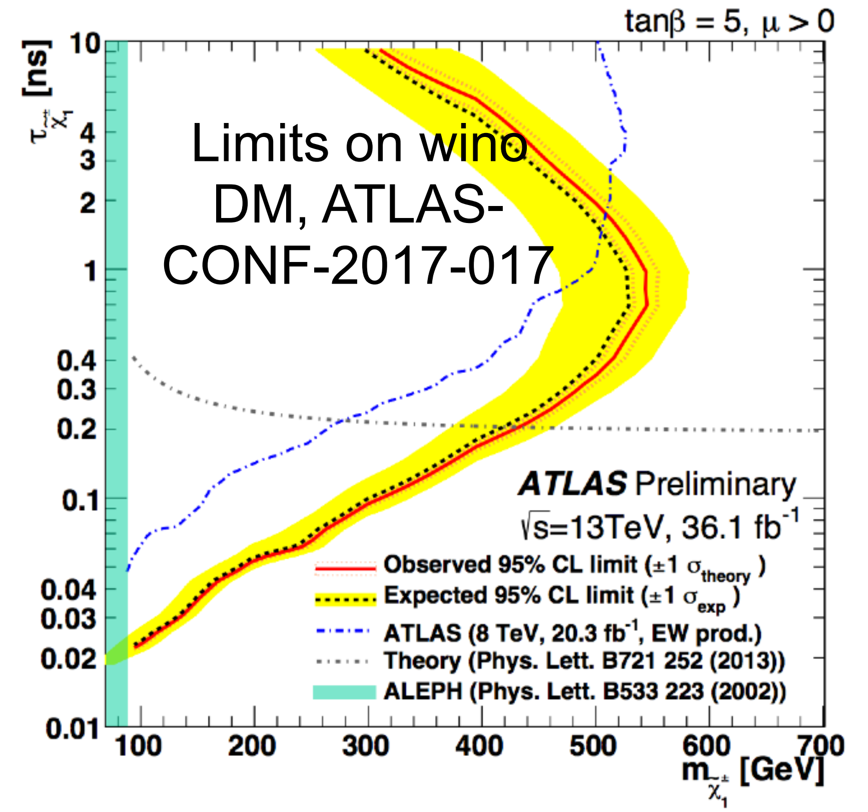
A minimal WIMPonium

- We argued the presence of bound states requires DM mass ~ 3 TeV or larger.
- One class of simple heavy dark matter models is sometimes called “minimal dark matter” [Cirelli et al ’05] - the dark matter transforms under $SU(2)_L$, the Standard Model electroweak gauge group, which means it interacts with partner “chargino” particles through the W and Z bosons.
- We can classify the possibilities by the representations of $SU(2)_L$, which determine how many partner particles there are, e.g.
  - wino - triplet fermion - 1 Majorana fermion (DM) + 1 Dirac fermion (chargino) - appears as the counterpart of the W boson in models of supersymmetry - preferred mass 3 TeV
  - quintuplet fermion - 5 Majorana degrees of freedom (DM + singly-charged Dirac fermion + doubly-charged Dirac fermion) - preferred mass 14 TeV

Detecting wino/ quintuplet dark matter

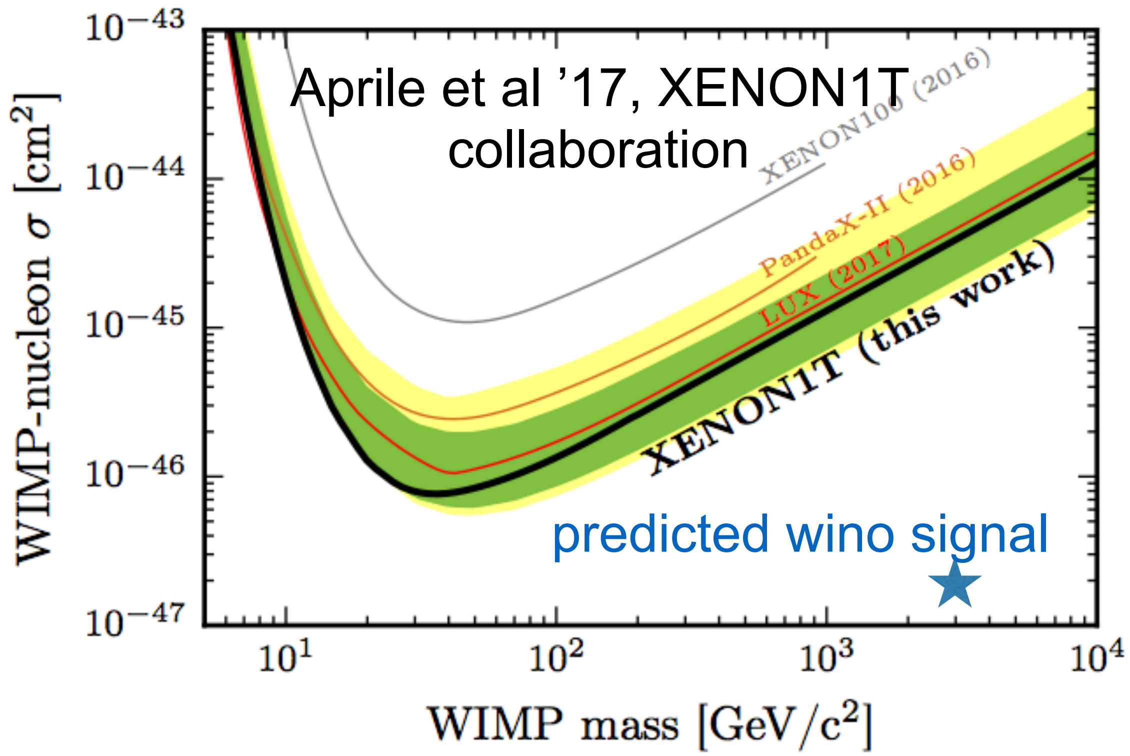
- Colliders?

  No - 3+ TeV is too heavy for even the LHC



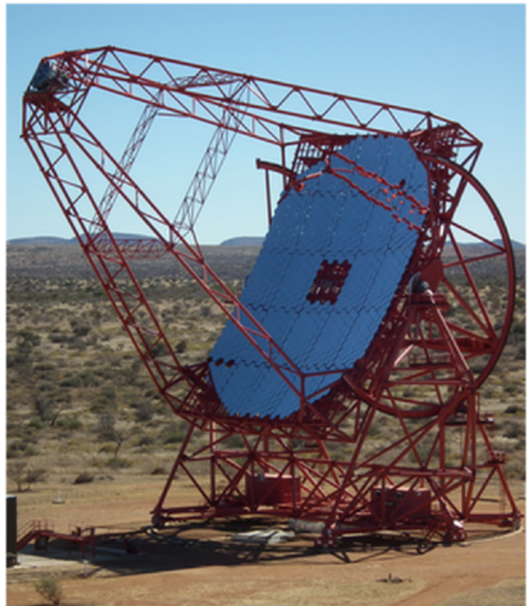
- Direct detection?

  No - predicted signal is too small



- Indirect detection?

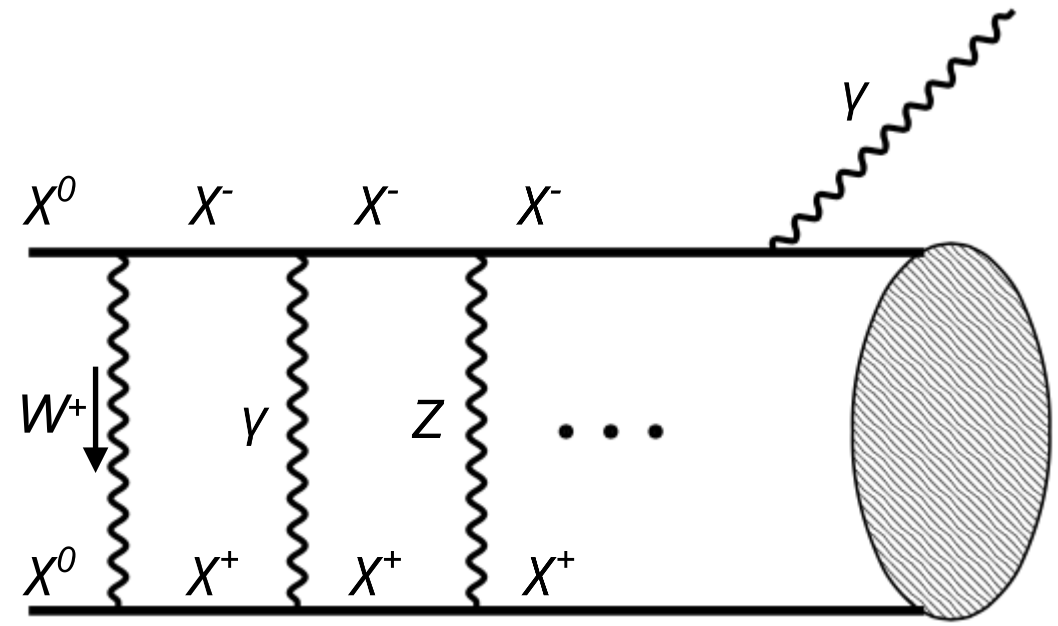
  Looks much more promising!

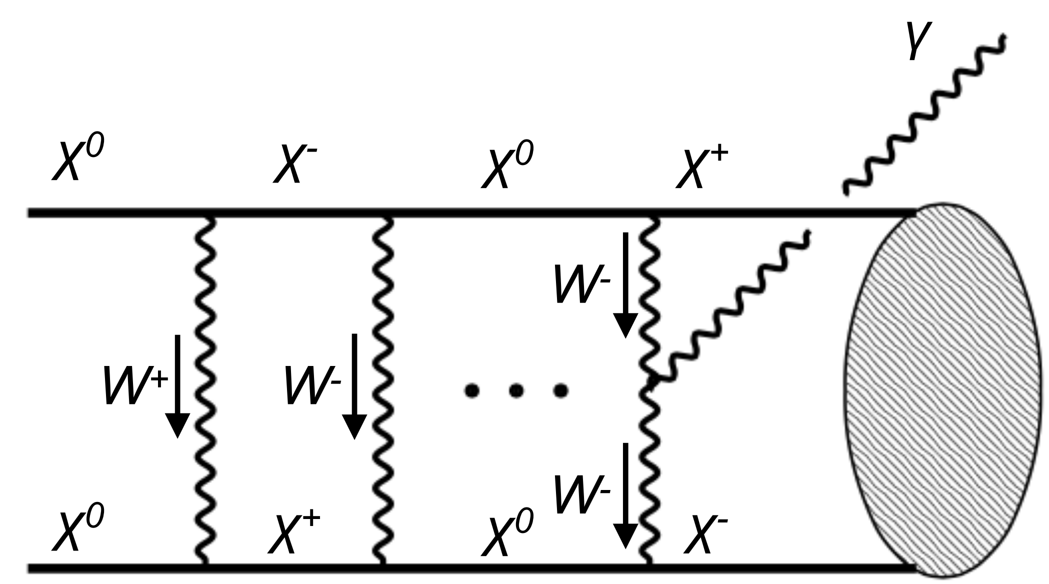


WIMPonium properties

- Bound states are a mixture of dark matter and chargino states.
- They are held together by exchange of W and Z bosons as well as photons (exchanged between the charginos).
- Bound states can form by radiation of a photon from the chargino component, even if there is not enough binding energy to radiate a W or Z
- Because the W boson is itself charged, the bound state can also form by radiating a photon from the potential.
- These features - multiple force carriers, bound states mixing different DM-like particles, new interactions - could also appear with new dark forces.

Formation of “wino-onium”

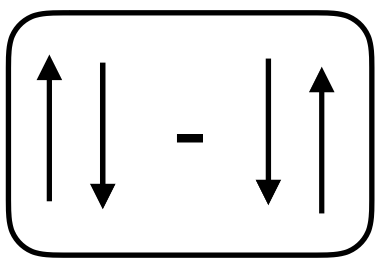




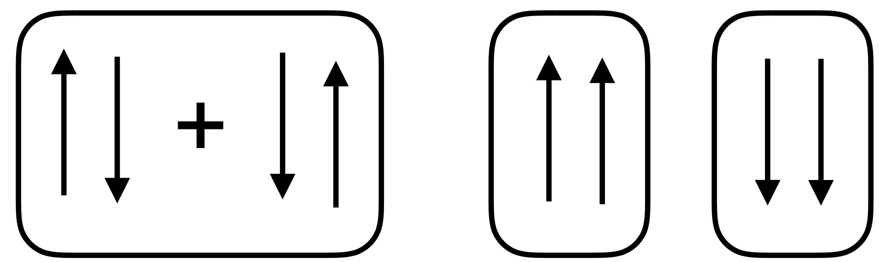
A spin-statistics subtlety

- Pauli exclusion principle: two identical spin-1/2 particles cannot occupy the same state.

- Generalization: the wavefunction describing two identical spin-1/2 particles must change sign when we swap the two particles.



“singlet” (S=0) - swapping particle spins gives minus sign



“triplet” (S=1) - swapping particle spins gives no sign change

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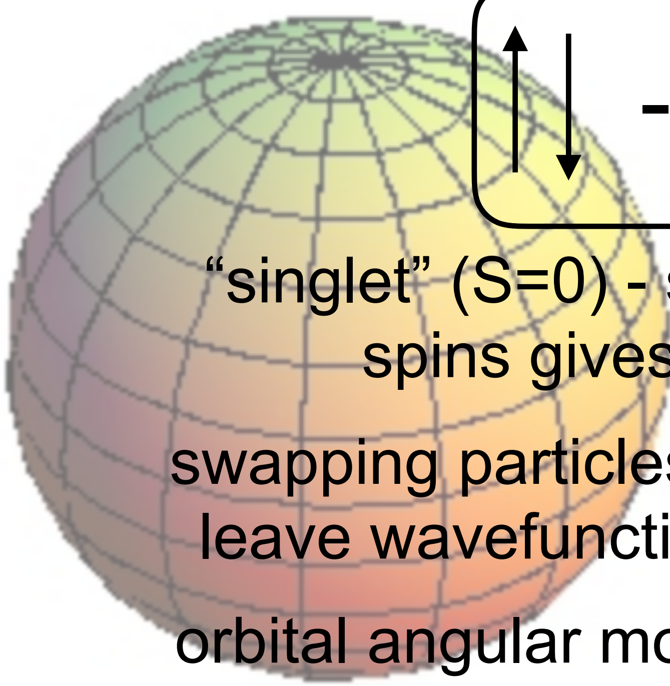

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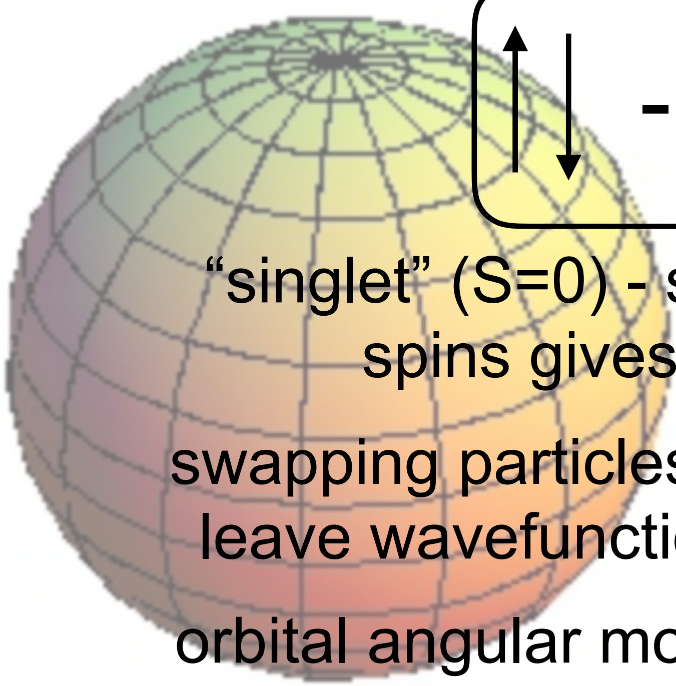

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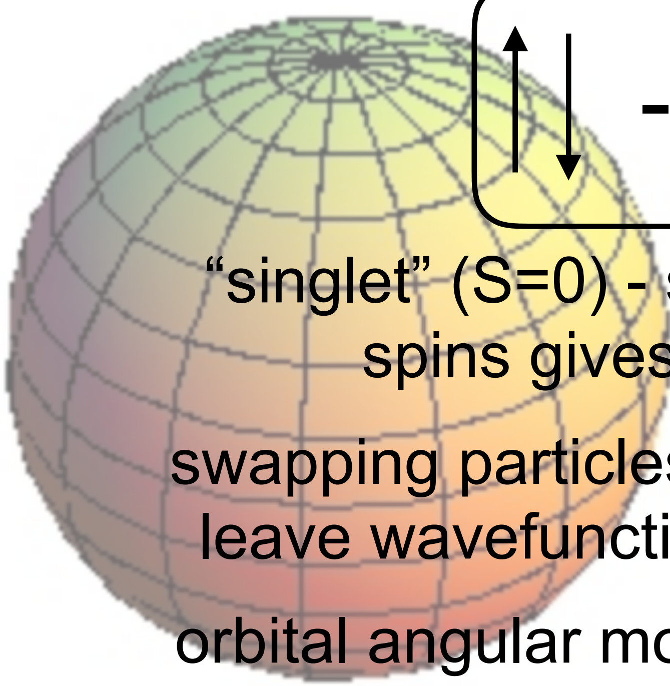

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- Thus the wavefunction can only have a non-zero $\chi^0\chi^0$ component when L+S=even.

- But dipole photon radiation gives $\Delta L = \pm 1$, $\Delta S = 0$. So if the initial DM-DM state has L+S=even, the bound state will have L+S=odd.

Finding the bound states

- Basic idea: just as for hydrogen, we solve the Schrodinger equation; we can then use quantum mechanics perturbation theory to work out formation and transition rates
- Now the potential is more complicated - must describe interactions between all 2-particle states coupled by the gauge bosons (i.e. made from DM + charginos)

$$\Psi = \begin{pmatrix} \psi_N \, (\equiv \chi^0 \chi^0) \\ \psi_C \, (\equiv \chi^+ \chi^-) \end{pmatrix} \quad \text{L+S even} \quad V(r) = \begin{pmatrix} 0 & -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} & 2\delta M - \frac{\alpha}{r} - \alpha_W c_W^2 \frac{e^{-m_Z r}}{r} \end{pmatrix}$$

- The long-range potential felt by the particles depends on L+S (L+S-odd bound states cannot include identical fermion pairs) [Cirelli, Strumia & Tamburini '07; Beneke, Hellmann & Ruiz-Femenia '15]
- For either choice of L+S, the potential is a matrix and can have multiple eigenvalues - correspond to different strengths of the force between particles for different states
- Leads to multiple towers of bound states with different energies
- L+S-dependent selection rules constrain which states can be populated by capture via single-photon emission

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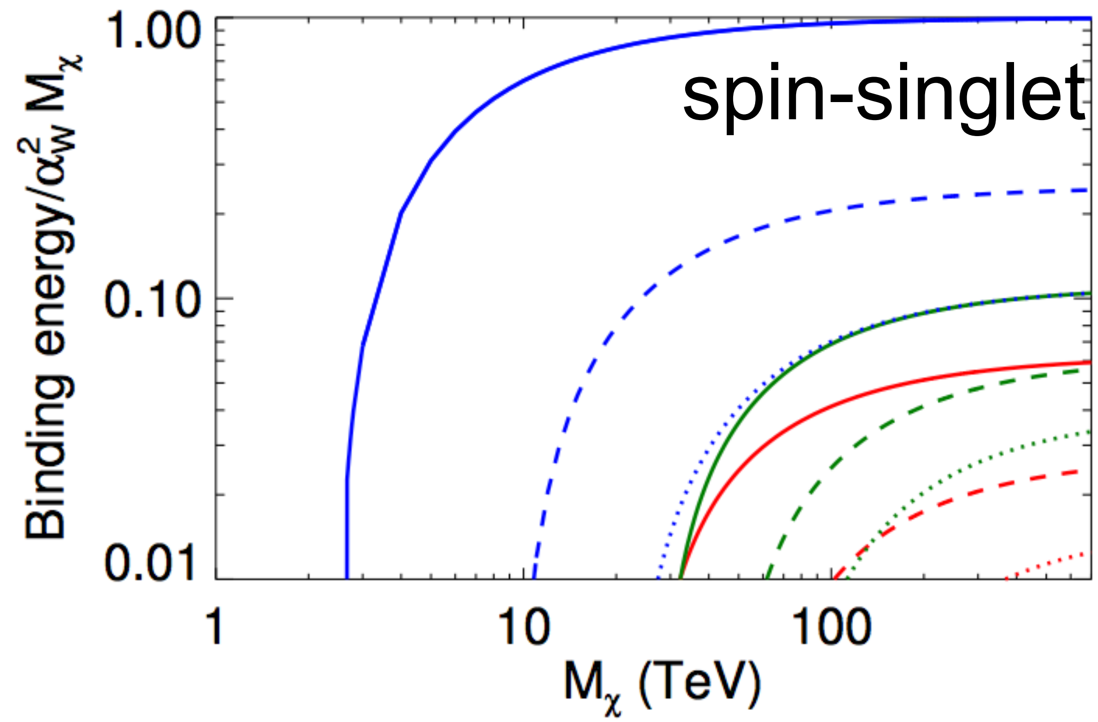
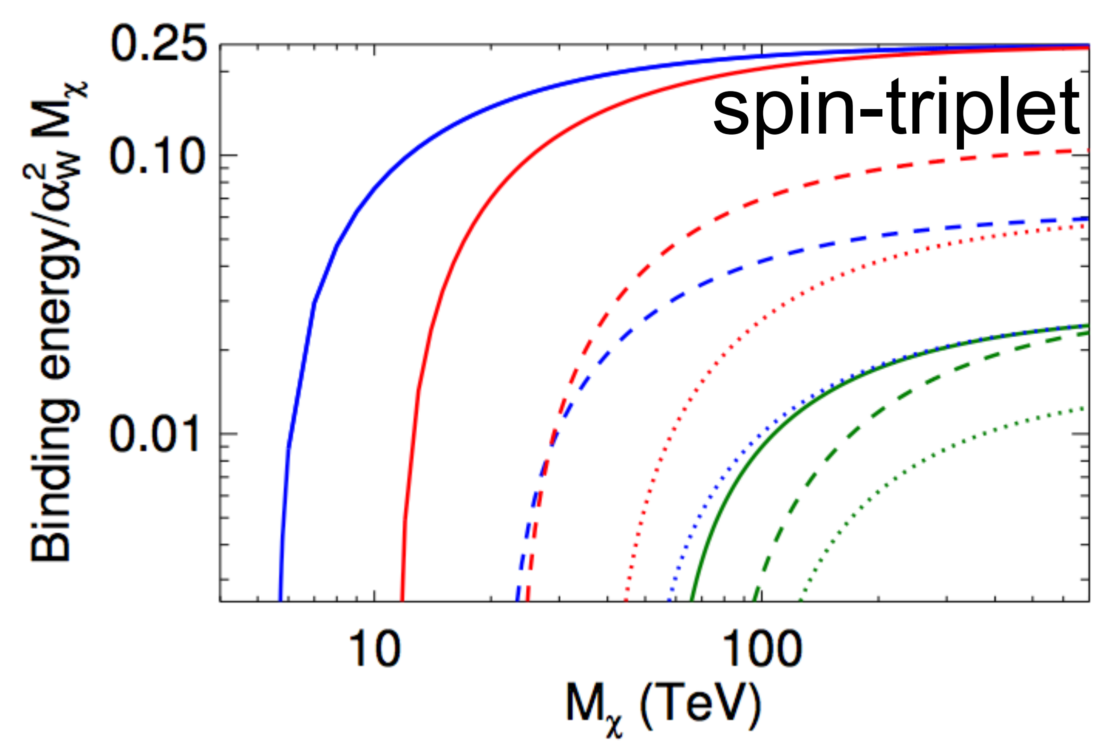
The wino: a double tower of bound states

	Spin-Singlet Spectrum	Spin-Triplet Spectru
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{144}$		6D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{100}$	5P	5D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{64}$	4P	4S 4D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{36}$	3P 6D	3S 3D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{25}$	5D	5P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{16}$	4S 2P 4D	2S 4P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{9}$	3S 3D	3P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{4}$	2S	1S 2P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = 1$	1S	





Comparison to hydrogen

	Spin-Singlet Spectrum	Spin-Triplet Spectrum
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{144}$		
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$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{64}$	4S 4P 4D	4S 4P 4D
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{36}$	3S 3P 3D	3S 3P 3D
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$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{4}$	1S	1S
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$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{36}$	3P	3S 3D
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$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{16}$	4S 4D 2P	4P 2S
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{9}$	3S 3D	3P
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = \frac{1}{4}$	2S	2P 1S
$\lvert\frac{E_n}{M_\chi \alpha_W^2}\rvert = 1$	1S	

Comparison to hydrogen

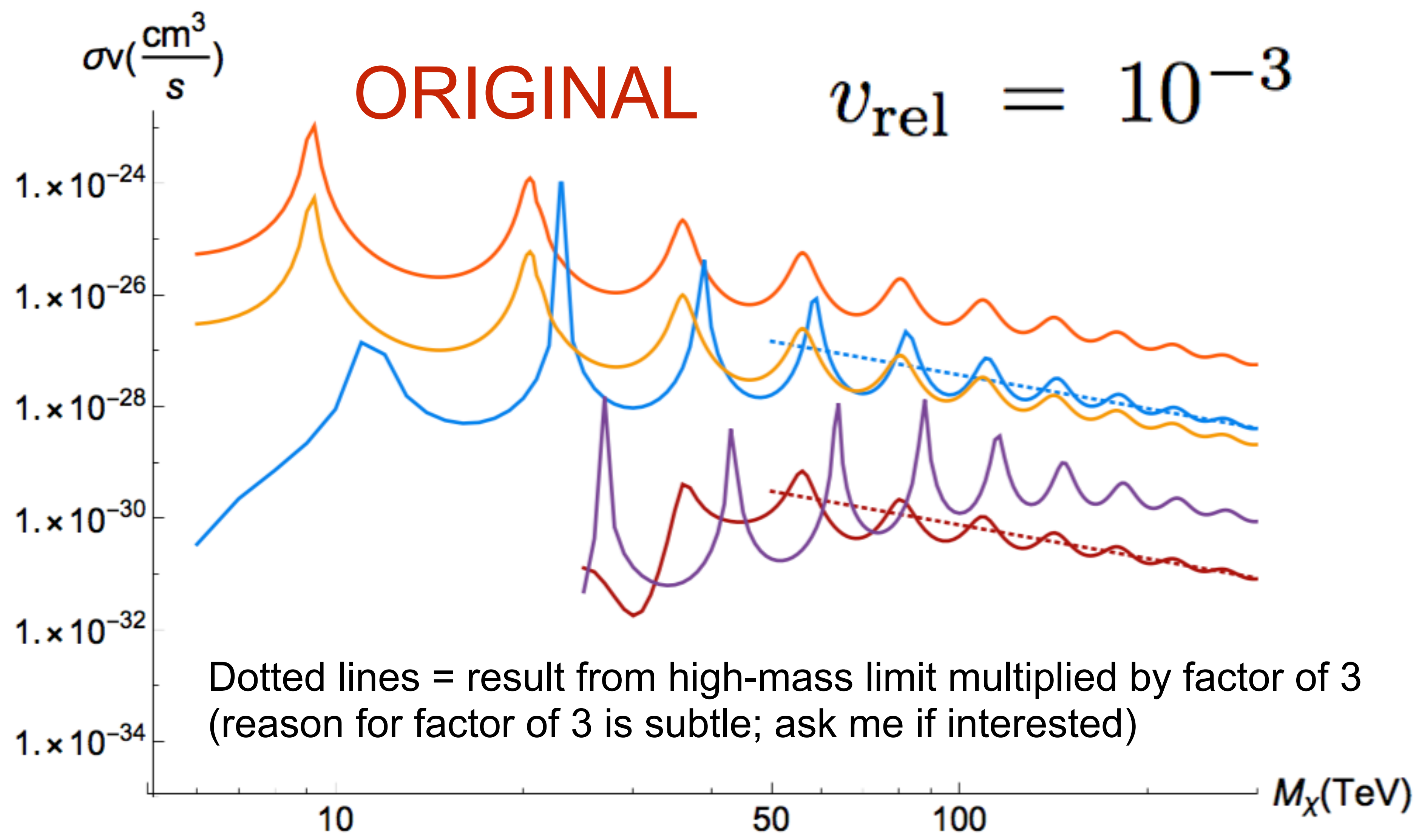
	Spin-Singlet Spectrum	Spin-Triplet Spectrum
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{144}$		6D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{100}$	5P	5D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{64}$	4P	4S 4D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{36}$	3P 6D	3S 3D
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{25}$	5D	5P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{16}$	4S 2P 4D	2S 4P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{9}$	3S 3D	3P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = \frac{1}{4}$	2S	1S 2P
$\left\lvert \frac{E_n}{M_\chi \alpha_W^2} \right\rvert = 1$	1S	

- Decay patterns of bound states are quite different to hydrogen
- Modifies which states are metastable, & energy gaps between states

Numerical results for the wino

- At the thermal mass, there are no bound states accessible by single-photon capture.
- Even considering higher masses, bound state formation is almost always highly subdominant to annihilation, unlike positronium.
- Resonances reflect onset of zero-energy bound states.
- Original paper [Asadi, TRS et al '16] had a minus sign error - erratum forthcoming, these results are updated.

Thanks to Kalliopi Petraki & Julia Harz for pointing out the error!



Sommerfeld-enhanced inclusive annihilation rate
Sommerfeld-enhanced rate for line photon production
Formation rate of 1S spin-triplet state
s-wave and d-wave contributions to formation of 2P spin-singlet bound states

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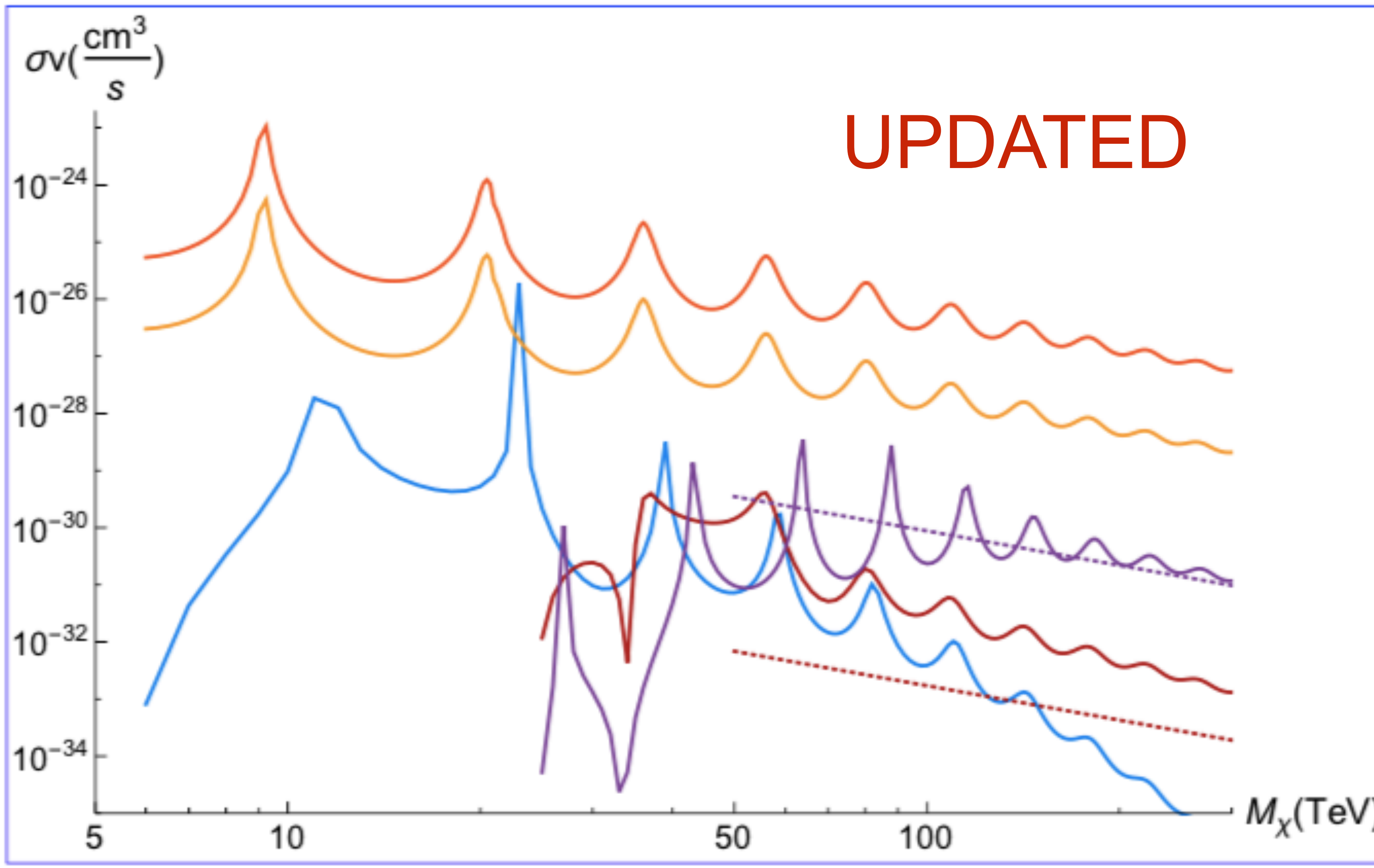

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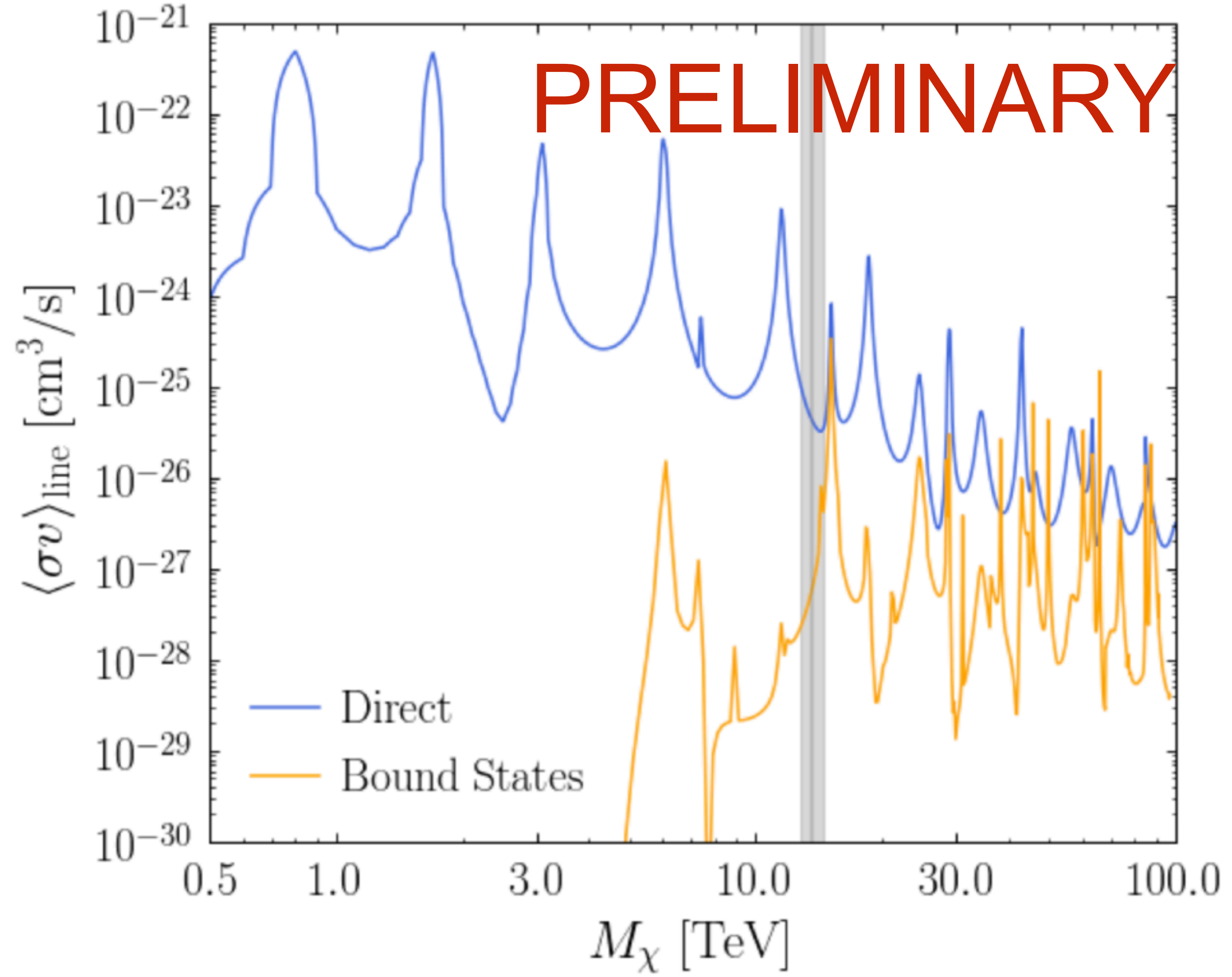
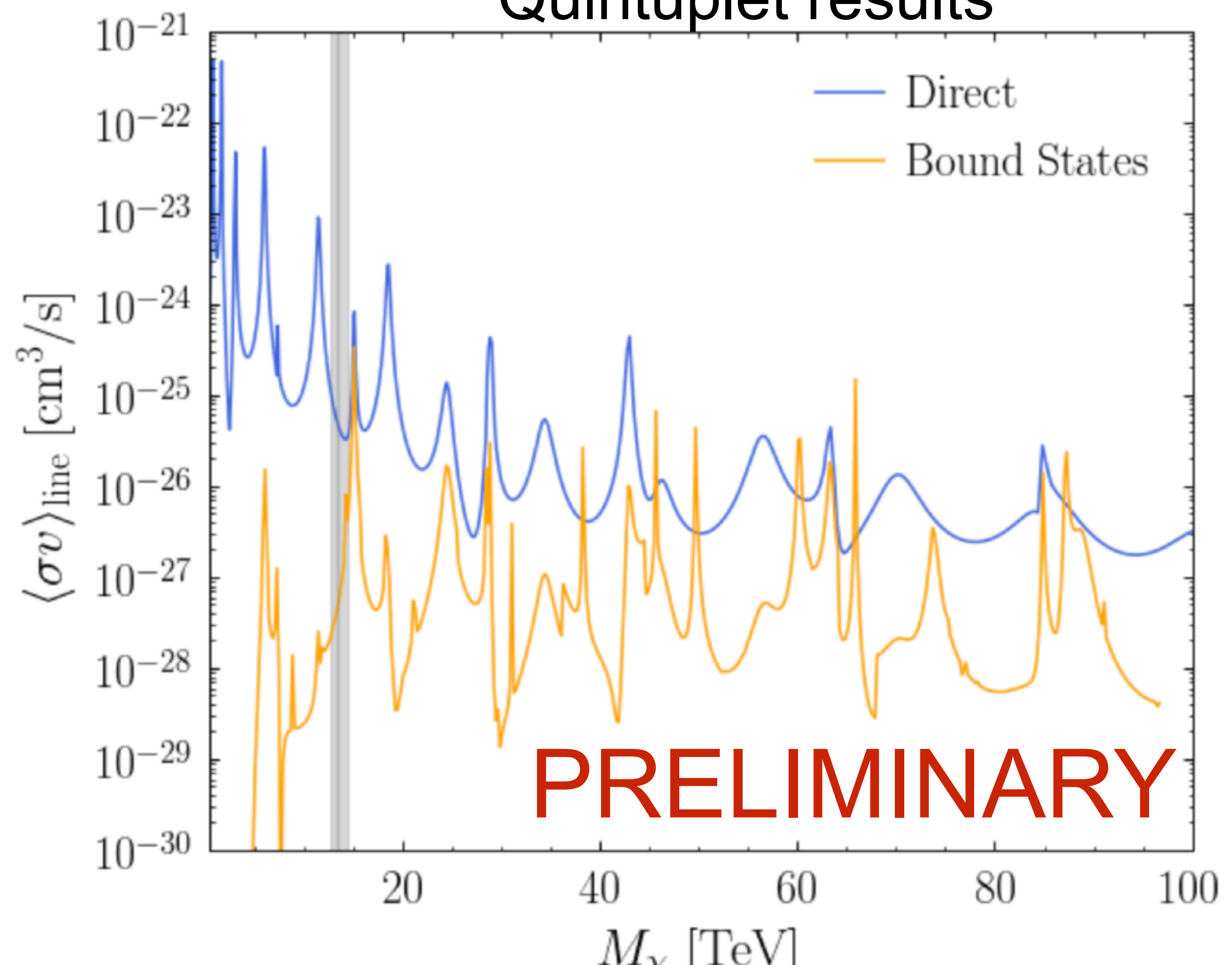
Overall indirect signal

- Computing the direct annihilation signal requires some care - large logarithmic terms appear in the usual perturbative expansion, need to re-sum them [e.g. Baumgart, TRS et al '18 for the wino], as well as including bound state effects (negligible for the wino)
- Where bound state effects matter, we compute formation and decay rates of each of the possible bound states
- Quintuplet (work in progress with Baumgart, Rodd & Vaidya): heavier mass + different representation means bound states are important, interplay is non-trivial



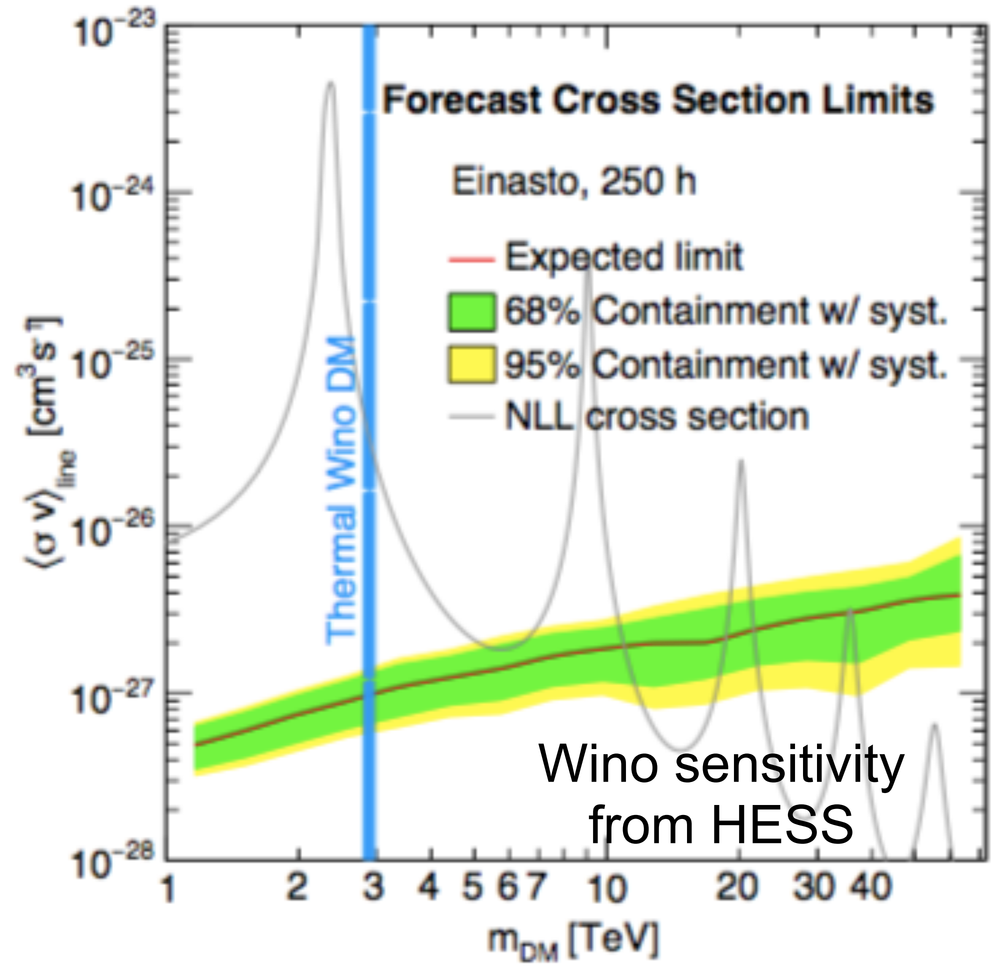
Quintuplet results



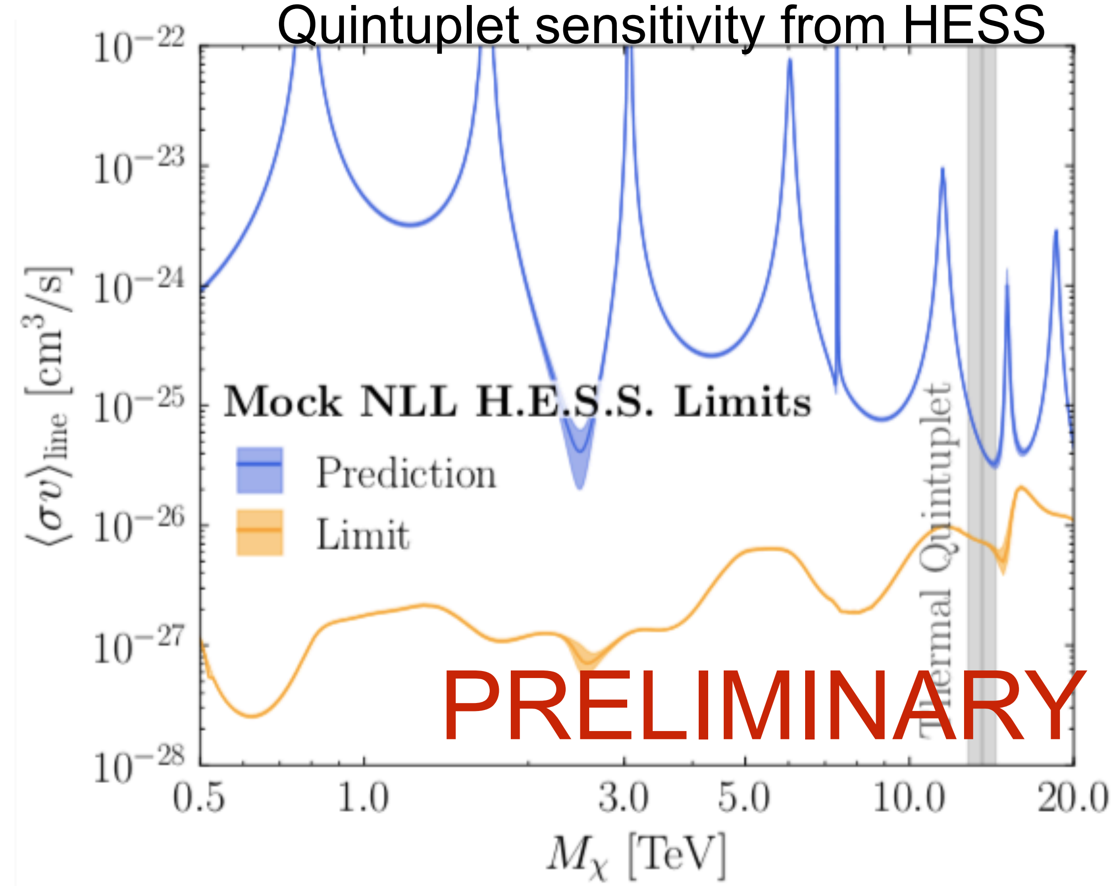
Limits from indirect detection

- Observations of gamma rays from the Galactic Center with H.E.S.S can set strong constraints on this signal
- Such limits come with a significant uncertainty on the dark matter density near the Galactic Center
- However, the wino signal is large enough that the dark matter density would need to be flat within ~2 kpc of the center (~6000 light years) to avoid exclusion
- (PRELIMINARY) For the quintuplet, even a small flattened core (<0.5 kpc) would evade detection

Rinchiuso, TRS et al '18



Quintuplet sensitivity from HESS



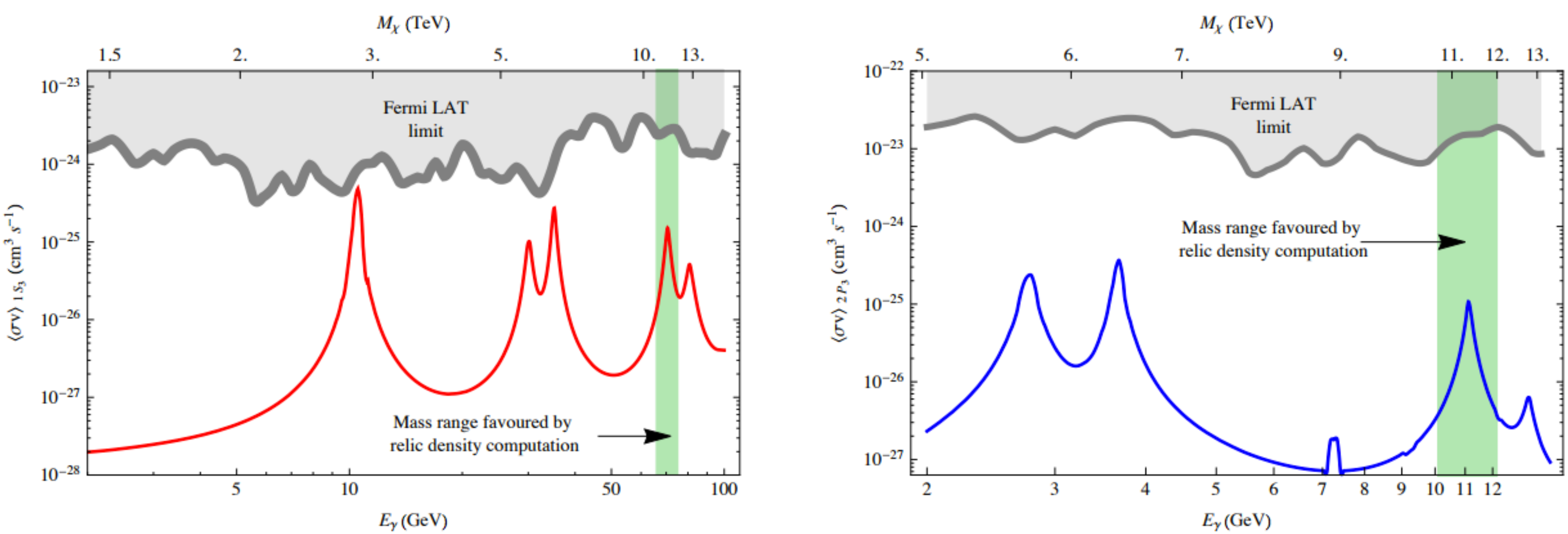
Emission/absorption lines?

- In principle, presence of bound states implies emission lines:
  - from initial recombination to form bound state
  - from decay of dark-onium excited states to ground state
- Absorption lines also possible if the bound state is stable (in particular, constituents cannot annihilate against each other) - suppressed for wino, as bound state is short-lived and thus should be rare in halo.
- Could probe gauge structure of DM / dark sector.
- Much lower energy than annihilation signal (suppressed by $\sim\alpha_W^2$ factor), could act as supplemental probe - e.g. ground-based telescopes see TeV-scale annihilation signal, space-based telescope sees correlated GeV-scale emission lines.

Emission lines for WIMPs

- For the wino, unfortunately, the rate for such transitions is too low to be detectable with space-based telescopes (roughly 10^{-4} photons/m^2/yr from the Galactic halo, for a 10 TeV wino-like particle).

- However, for thermal $SU(2)_L$ quintuplet DM, there would be a gamma-ray line at 70 GeV roughly 1 order of magnitude below current sensitivity [Mitridate et al ’17].



What would change for dark forces?

- Mass scales can be very different.
- No emission lines (would be “dark force carrier” emission - probably much harder to see than photons! see Baldes et al ‘20)
- Generic properties:
  - multiple towers of bound states with displacement in energy + modified selection rules
  - strong dependence of capture rate on the group structure (force carriers + how they couple to the dark matter)
- The degree to which bound states are important for indirect searches can vary widely between models!
- Bound states can also matter for how the observed amount of dark matter is produced in the first place

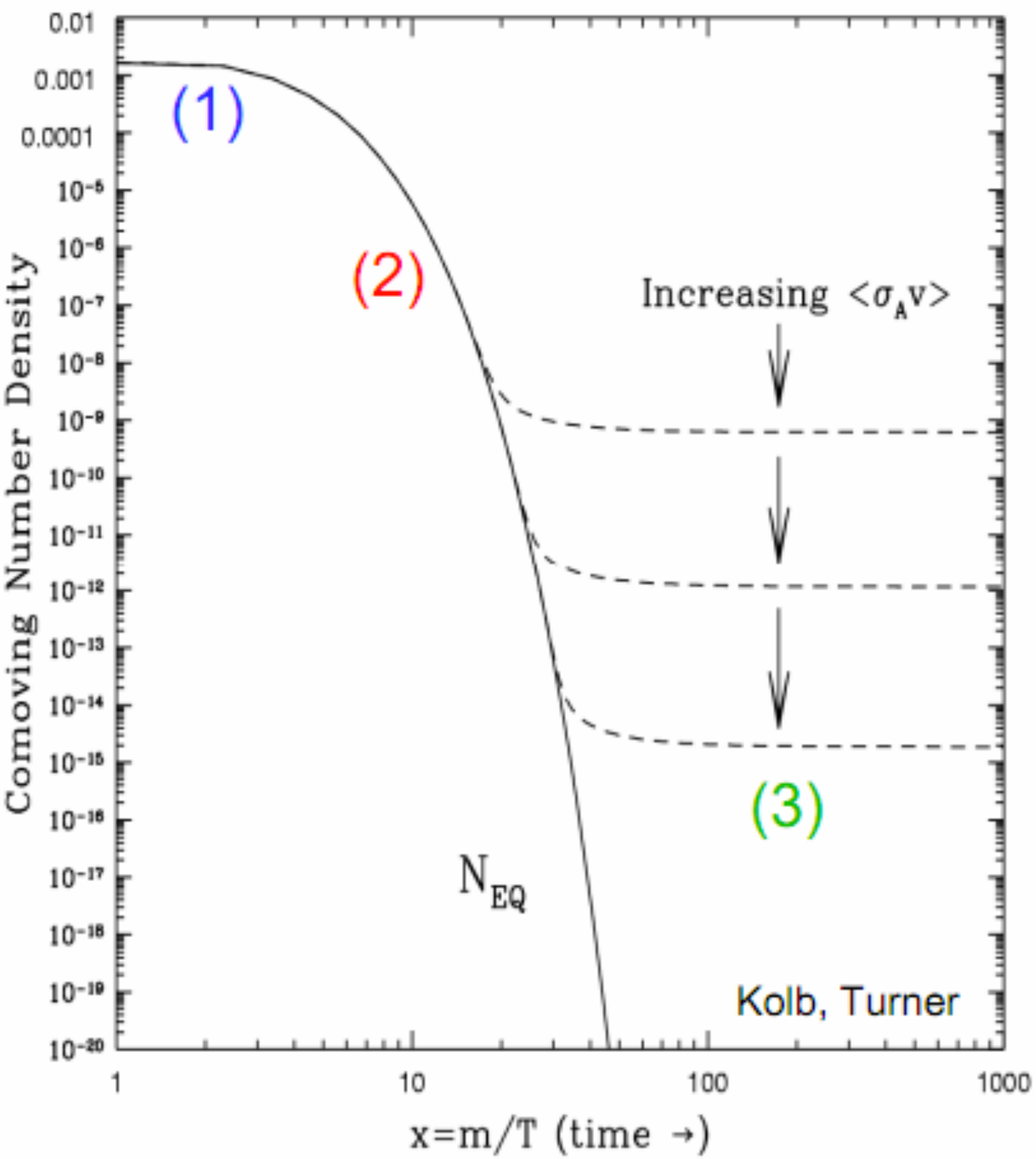
Strongly-interacting dark sectors and dark matter abundance

Thermal freezeout

- If DM particles can annihilate to visible particles, when the universe was sufficiently hot the reverse process would also occur - producing DM in thermal equilibrium with Standard Model (1)

- When the temperature fell below the DM mass, DM production would become inefficient while annihilation continued - leading to depletion (2)

- Eventually annihilation would also become inefficient relative to cosmic expansion (3), leading to a plateau <u>set by the strength of annihilation</u>



The unitarity bound

- Formation of bound states increases annihilation and thus decreases the late-time density plateau (this is important for the quintuplet)
- However there is a mass-dependent hard upper limit on the annihilation rate, based on probability conservation in quantum mechanics, even taking bound states into account
- Performing a partial-wave decomposition, the lth partial wave contributes a maximum annihilation cross section:

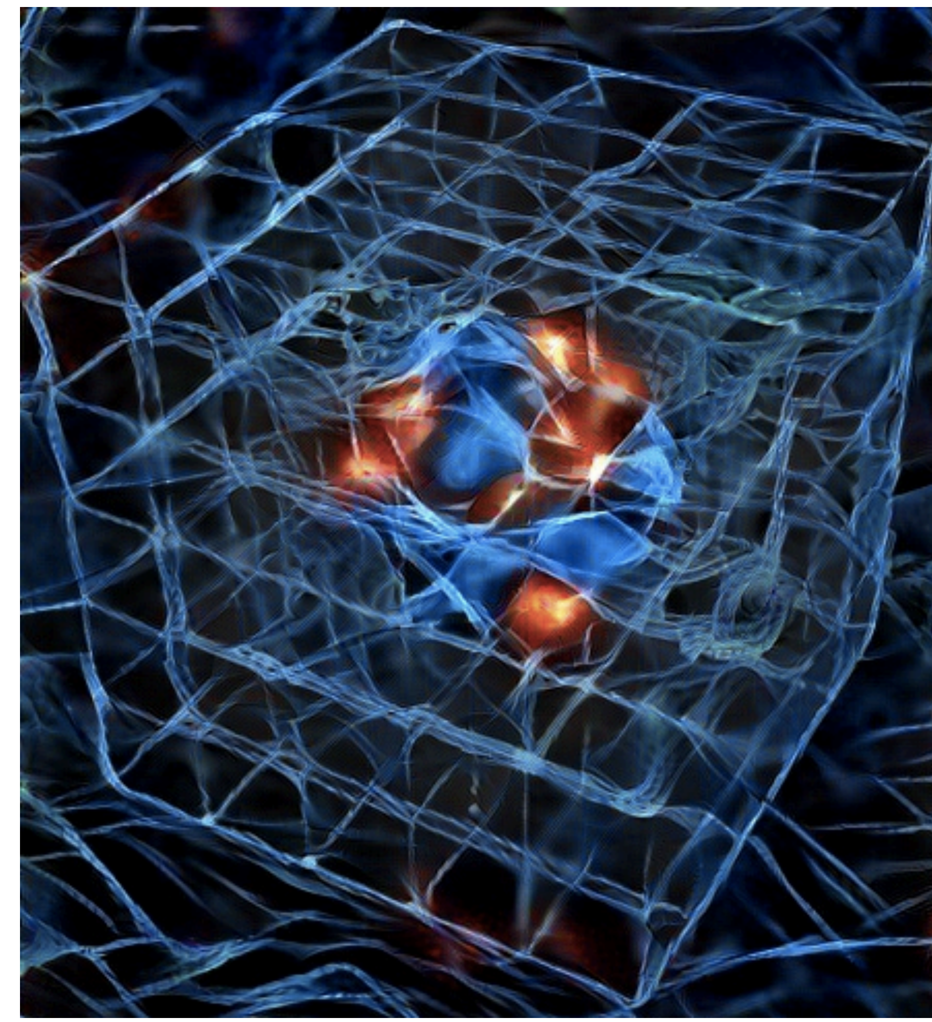
$$\sigma = \sum_{l=0}^{\infty} \sigma_l, \quad \sigma_l = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_l \leq (2l+1)\frac{4\pi}{k^2}$$

- For direct annihilation, higher partial waves are velocity-suppressed, so the leading contributions generally come from the first few partial waves (higher partial waves matter for bound states)
- This bound then becomes an upper limit on the dark matter mass around 1 PeV for composite DM (lower for pointlike DM) - heavier dark matter annihilates too slowly and would predict too much DM today [Smirnov & Beacom '19]
- Loophole: changes to the standard cosmological history

Analogy: QCD

- The strong interaction of the Standard Model is <u>confining</u>; the forces between particles become stronger as they are pulled apart (opposite to e.g. electromagnetism, gravity)

- At low energies, strongly-interacting particles - called <u>quarks</u> and <u>gluons</u> - bind tightly to each other, and cannot be separated into individual free particles

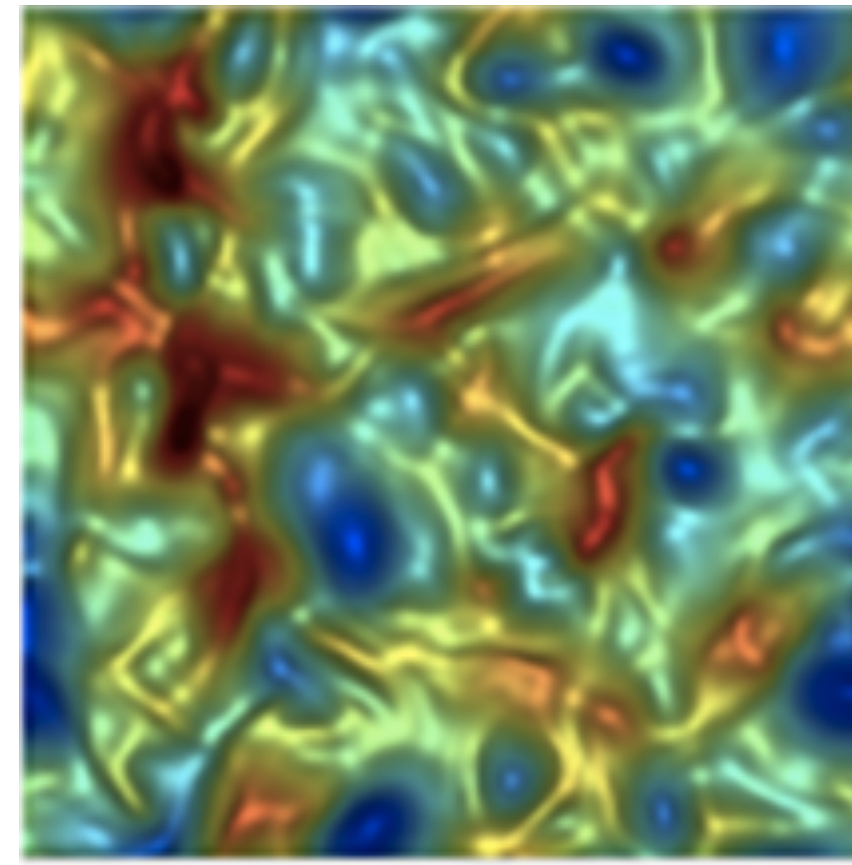


- Trying to pull them apart requires energy, and that energy goes into creating more quarks/gluons from the vacuum

- Appropriate degrees of freedom are the bound states: hadrons (containing quarks bound by gluons), glueballs (gluons only). Hadrons can be baryons (3 quarks) or mesons (quark + antiquark).

A dark quark-gluon plasma

- However, at high enough temperature and density, the quarks and gluons will not coalesce into bound states



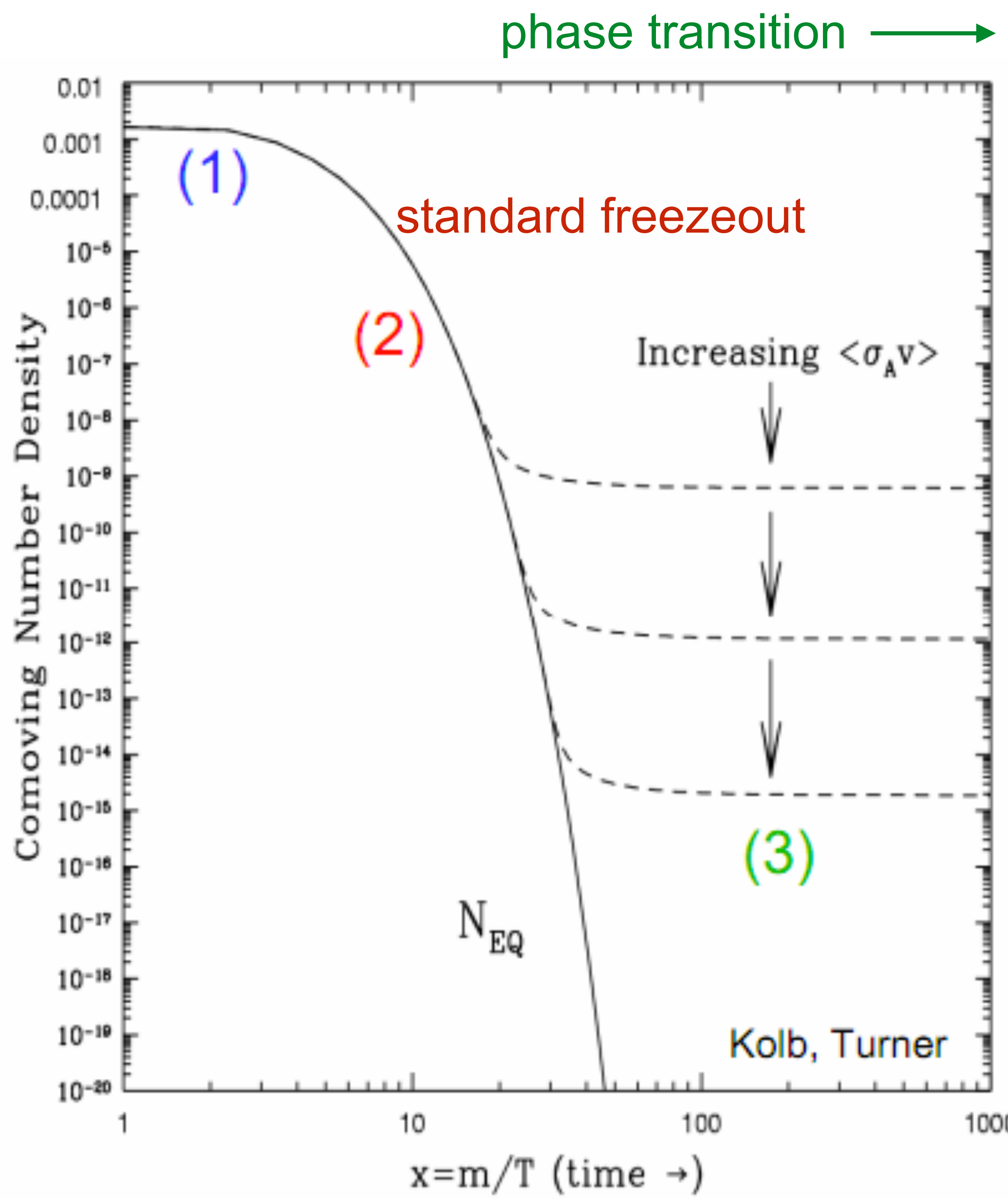
- Instead, free quarks float in a strongly-interacting sea of gluons - we call this state a quark-gluon plasma or the deconfined phase
- Suppose there are “dark quarks” and “dark gluons”, with their own strong interaction (separate from the SM interactions);
    - today the dark matter is comprised of stable dark baryons (bound states),
    - sufficiently early in cosmic history, the universe was filled with a dark quark-gluon plasma.

A dark phase transition

- In this scenario, the "dark sector” (dark quarks + dark gluons) undergoes a phase transition from deconfined to confined phases at a temperature Λ
- Let us further suppose:
  - The dark quarks/antiquarks can annihilate into dark gluons
  - Dark gluons thermalize with visible particles in the early universe (requires a portal to the Standard Model)
- This means, in the absence of the phase transition, all our arguments about freezeout would still hold (dark quarks are in equilibrium with dark gluons, which are in equilibrium with visible particles)
- Does the phase transition change anything?

Stage I: freezeout

- Assume dark quarks are much heavier than confinement scale
- Freezeout occurs as usual in the deconfined phase
- Sets initial conditions for the phase transition - stable comoving density of dark quarks + antiquarks
- If dark quarks are heavier than the unitarity bound, this density will be too high to match the relic abundance



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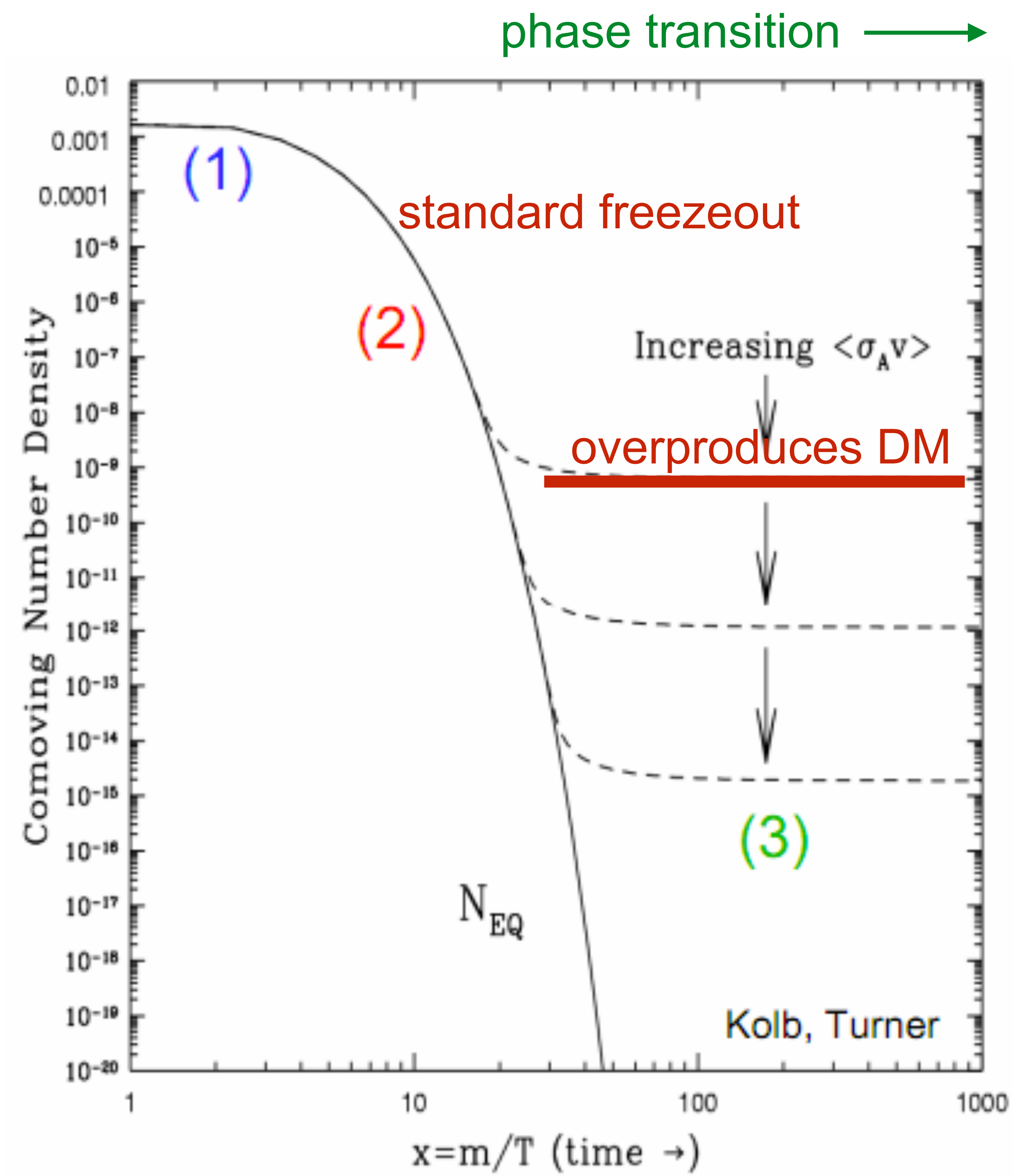
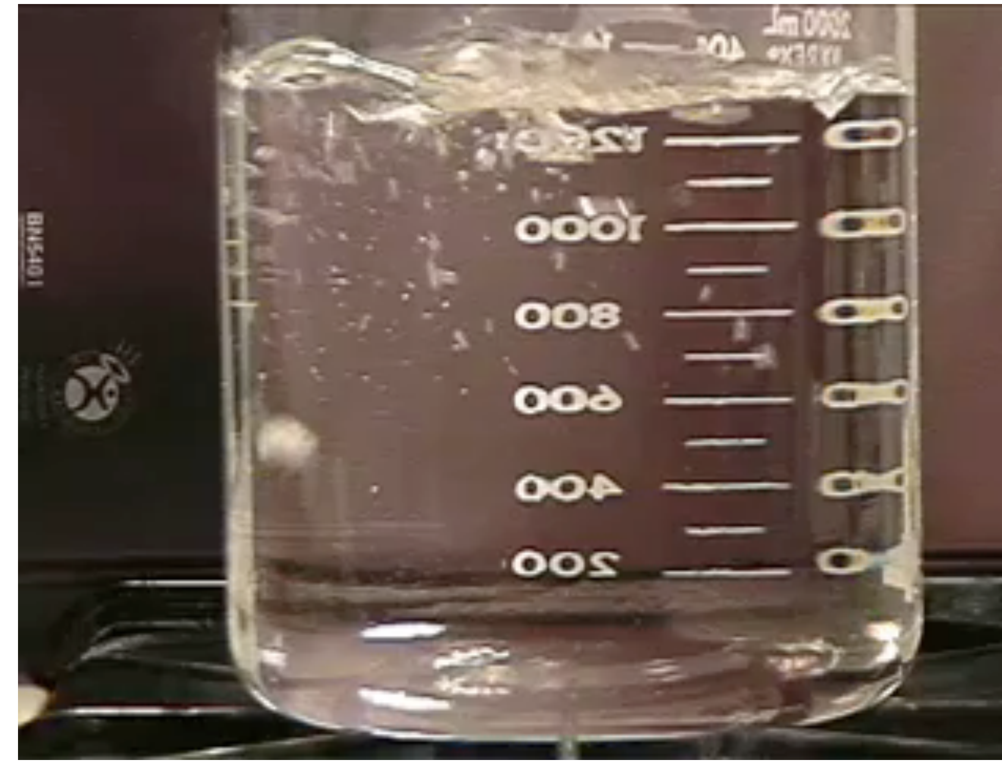


Stage 2: bubble growth

- After freezeout, once the temperature of the universe drops to Λ, bubbles of the confined phase begin to form and grow.
- These bubbles cannot form with free quarks inside, as free quarks cannot exist in the confined phase (requiring too much energy).
- Quarks (& antiquarks) must either quickly form hadrons or be shunted to the outside of the bubbles.
- Note: this is a *first-order phase transition* - expected to occur (based on lattice studies) when the quarks are sufficiently heavy. In the Standard Model, there is a smooth crossover between phases rather than an abrupt phase transition.



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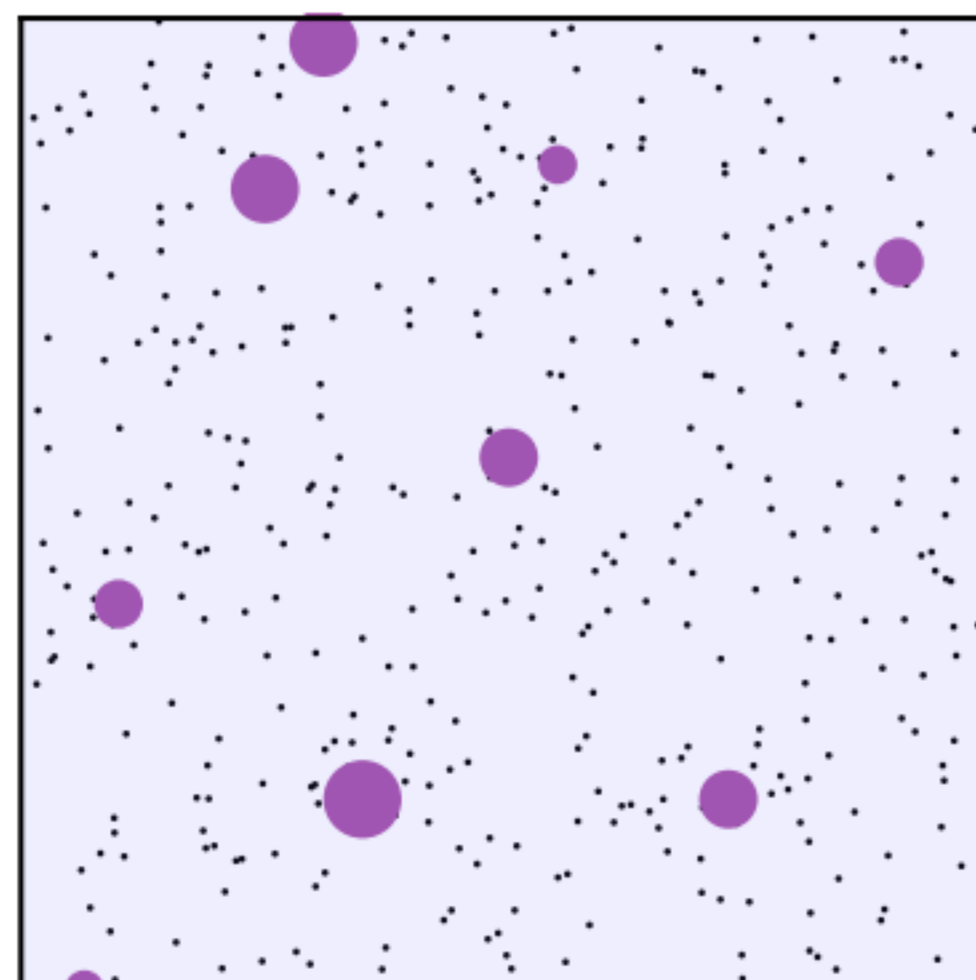

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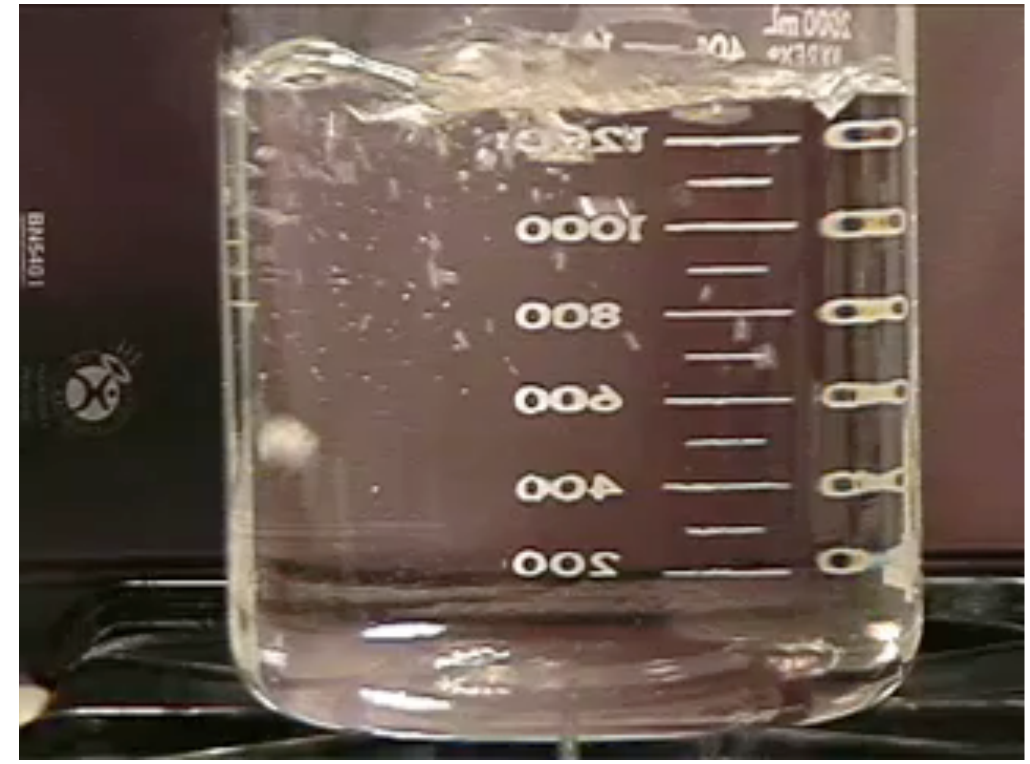

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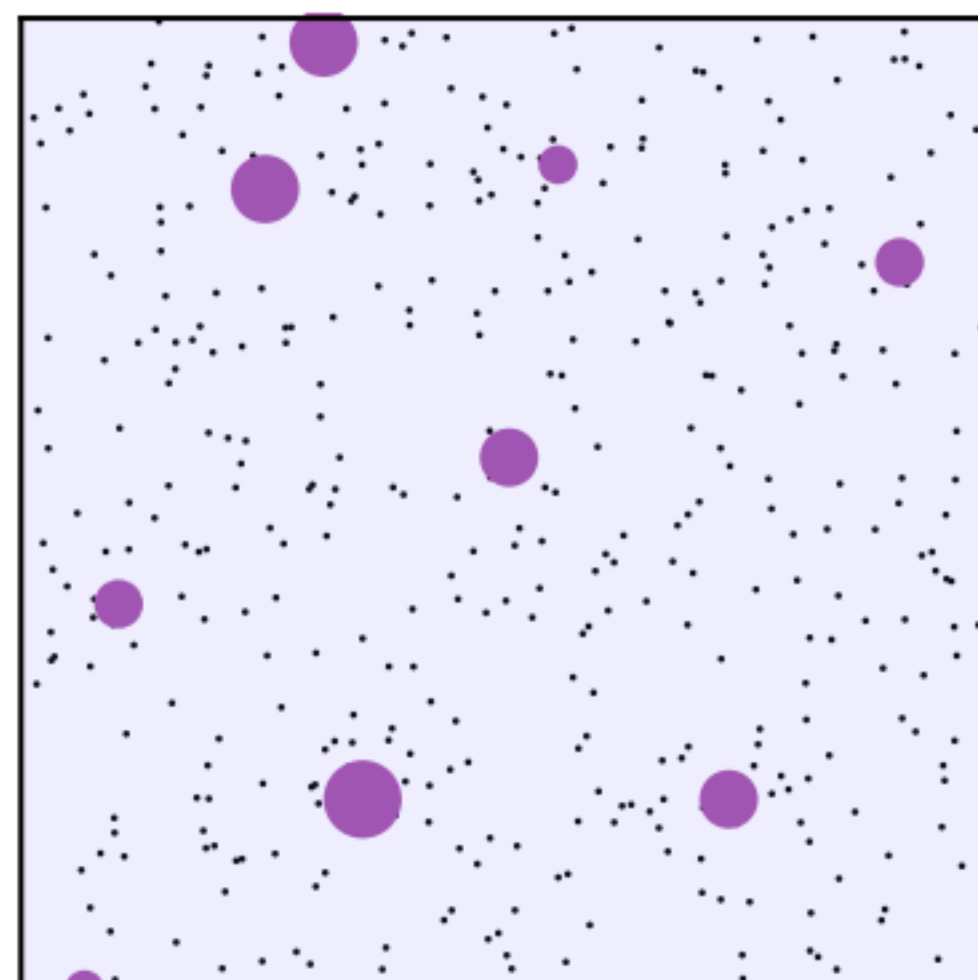

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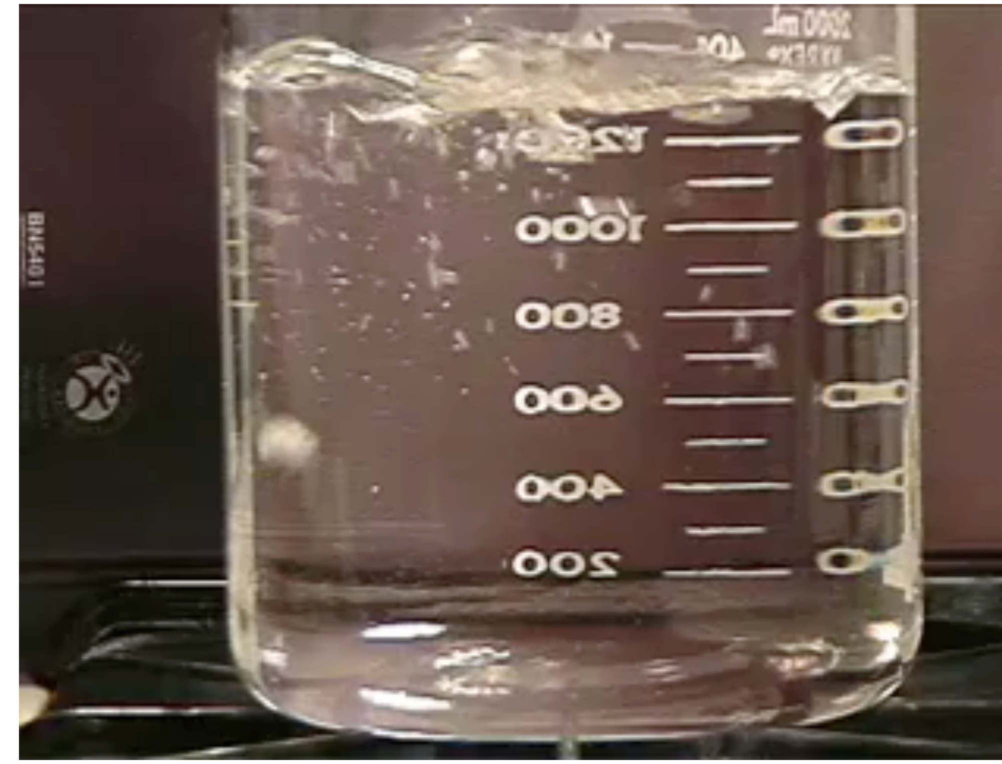

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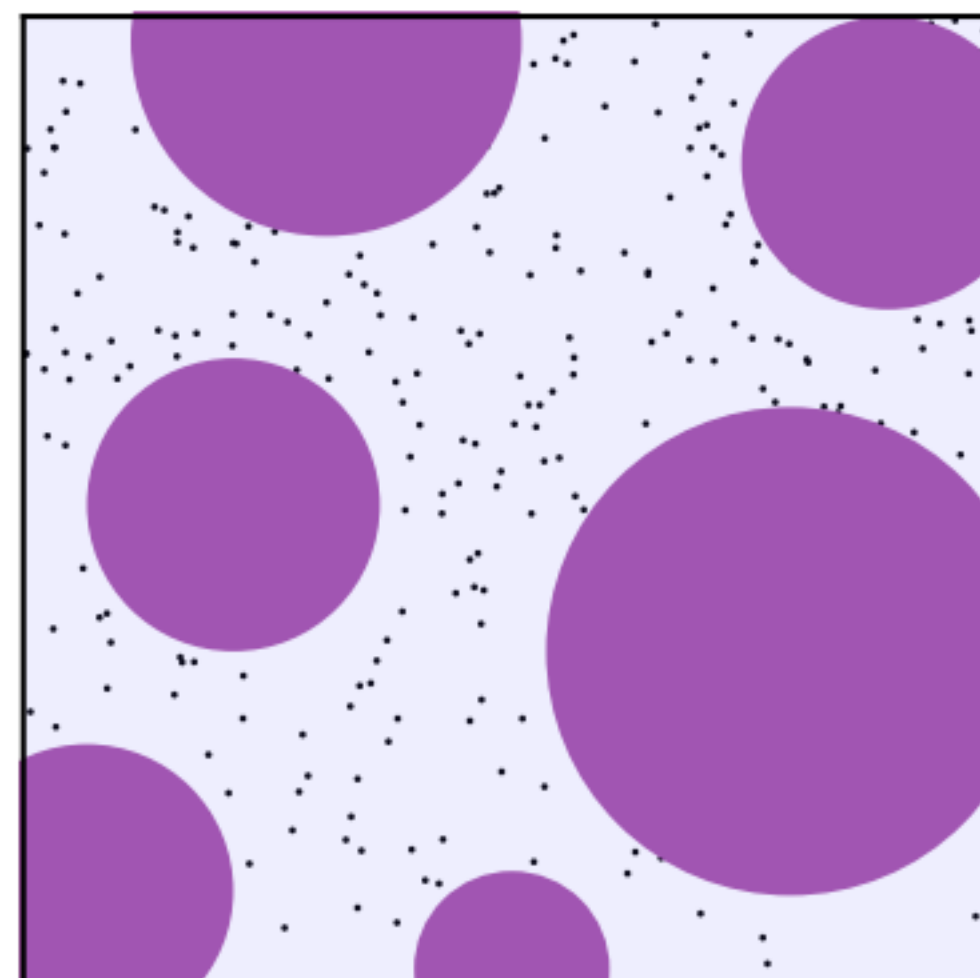
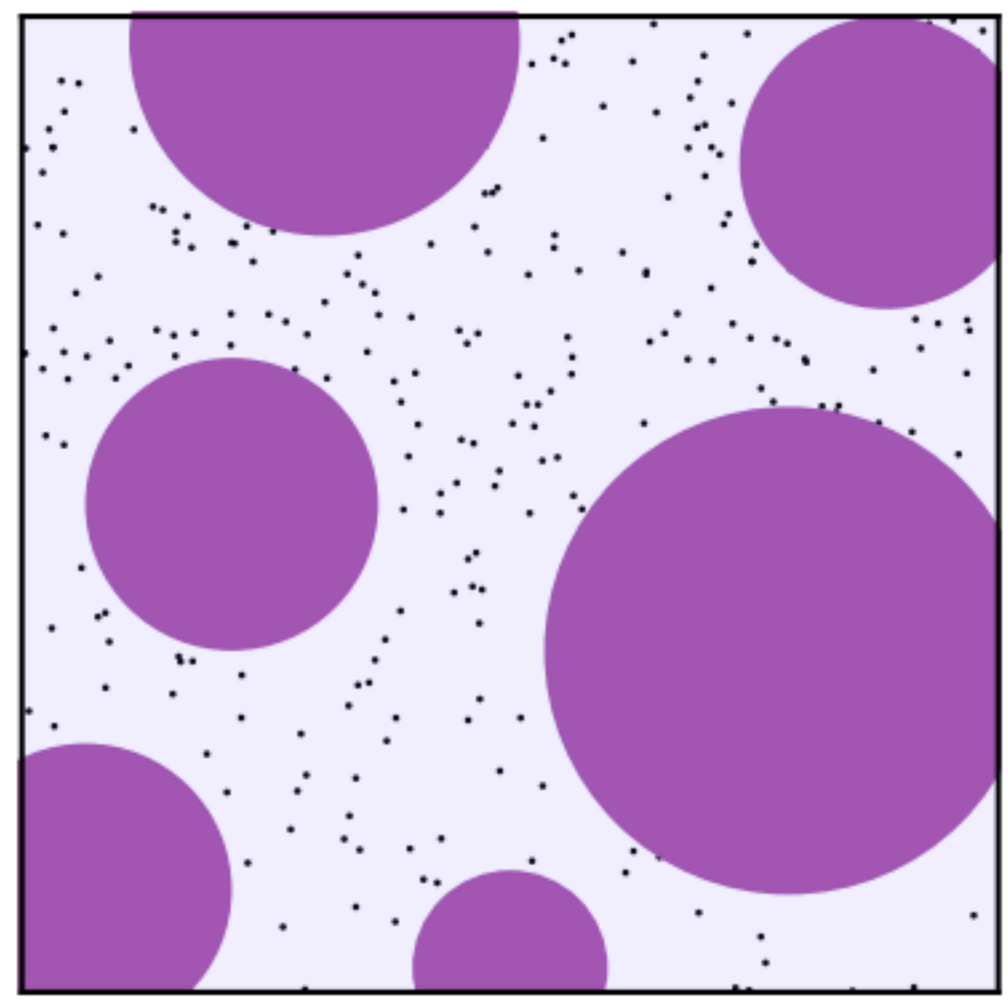


Stage 3: percolation

- As the bubbles continue to grow, eventually they will fill most of the universe - the remaining deconfined phase (gluon “sea” + heavy quarks) will occur only in isolated “pockets”
- All the heavy quarks will have been herded into these pockets by bouncing off the bubble walls
- As these pockets continue to shrink, they compress the heavy quarks to high density



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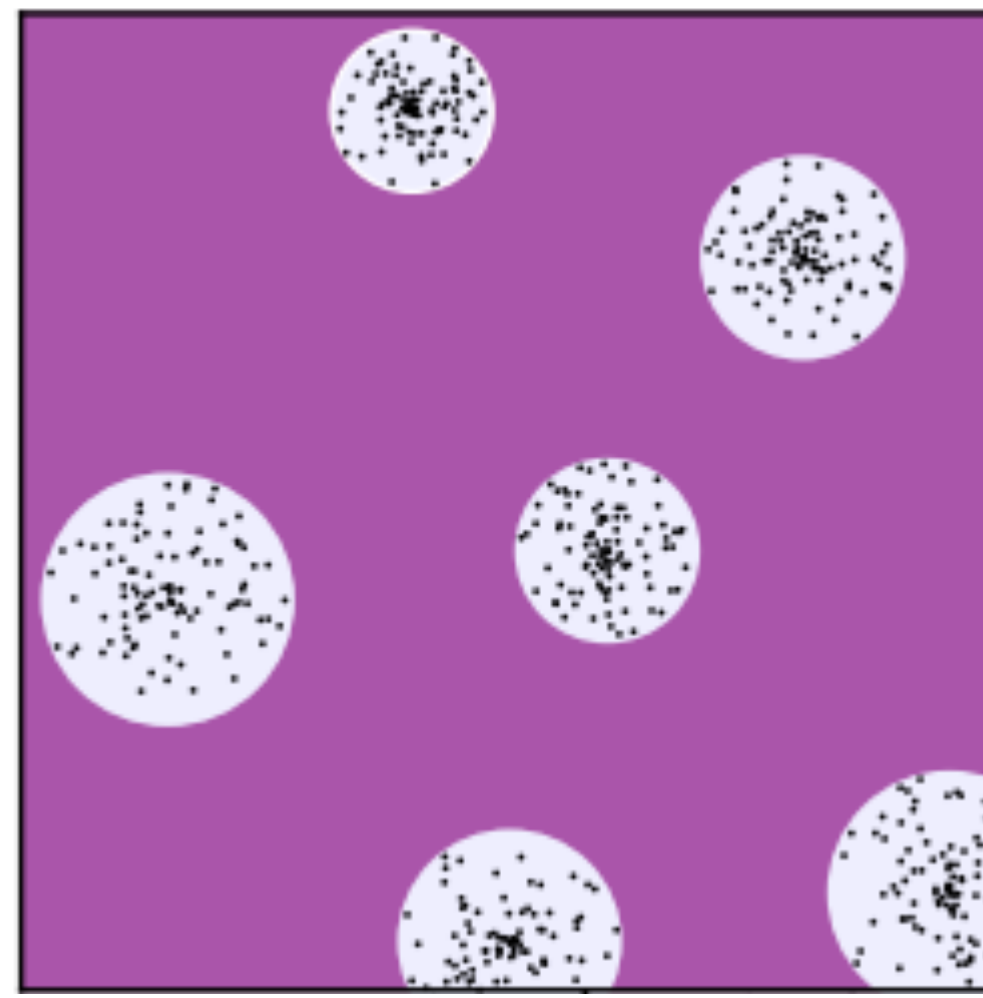
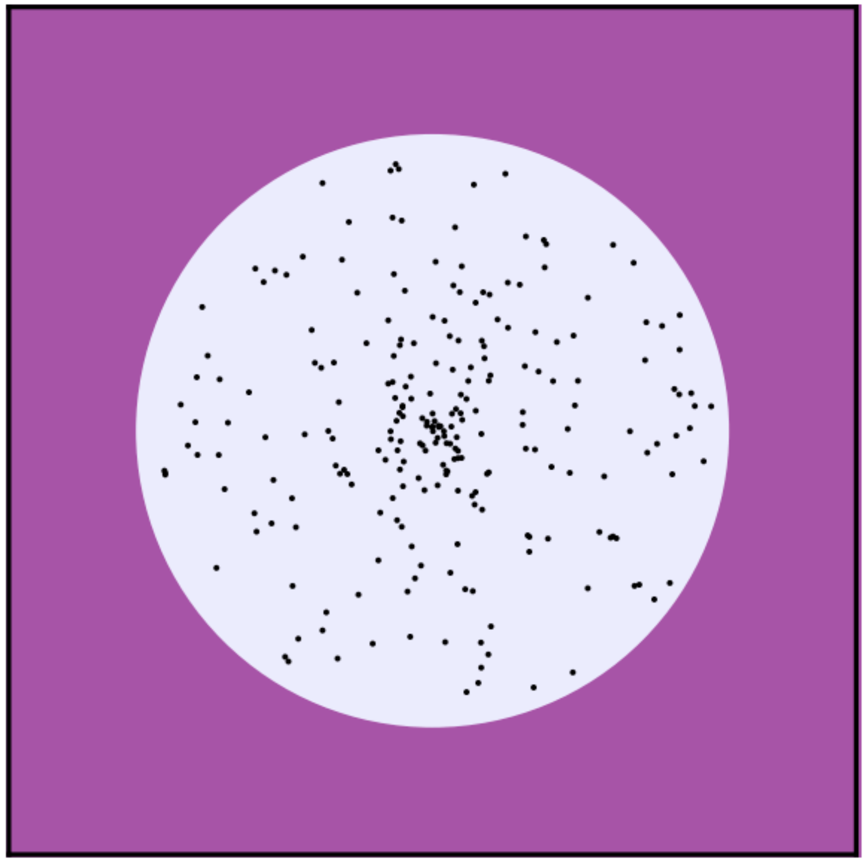


Stage 4: squeezeout

- Previously annihilation had frozen out
- But now the dark quarks are compressed into a much smaller volume, the density is high enough for it to re-start!
- At the same time, at these high densities the dark quarks can bind into dark hadrons
- Dark hadrons can leak through the shrinking pocket walls into the bulk of the universe that is now in the confined phase
- These hadrons form the dark matter at late times - DM is squeezed out of the pockets as they shrink down to zero size



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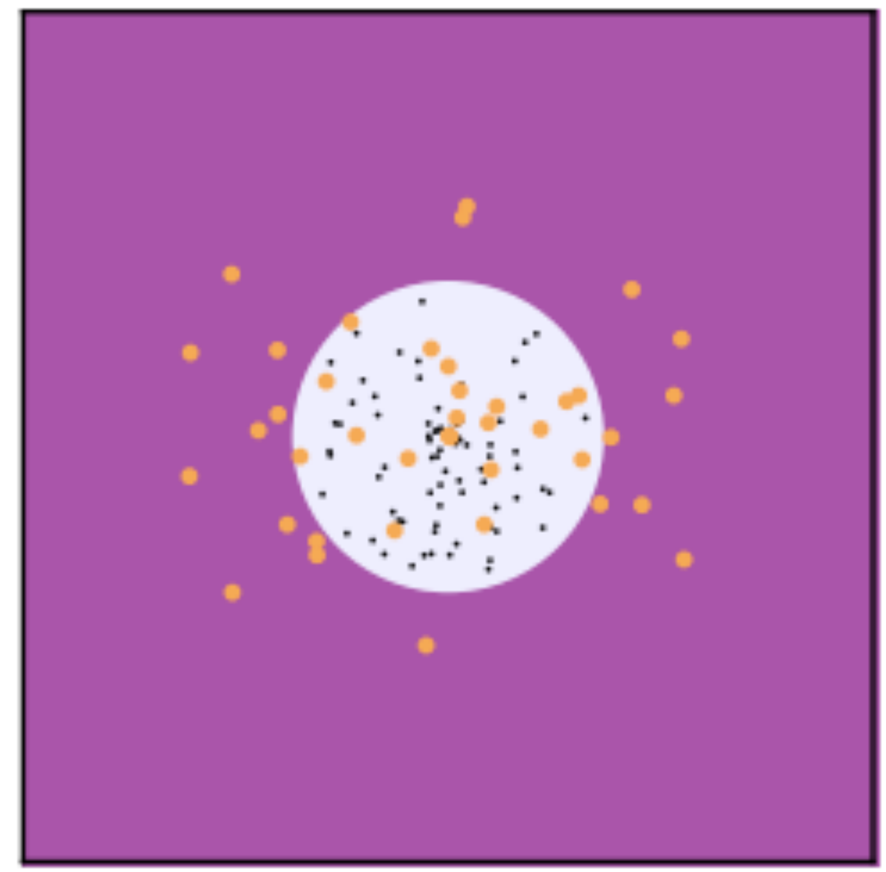

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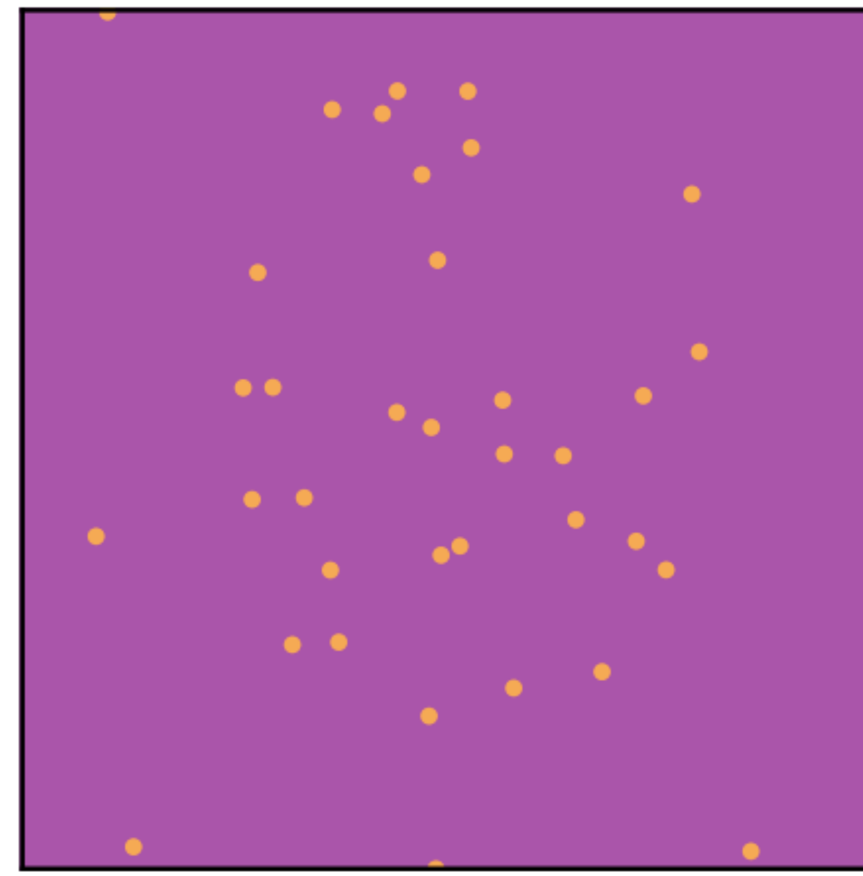

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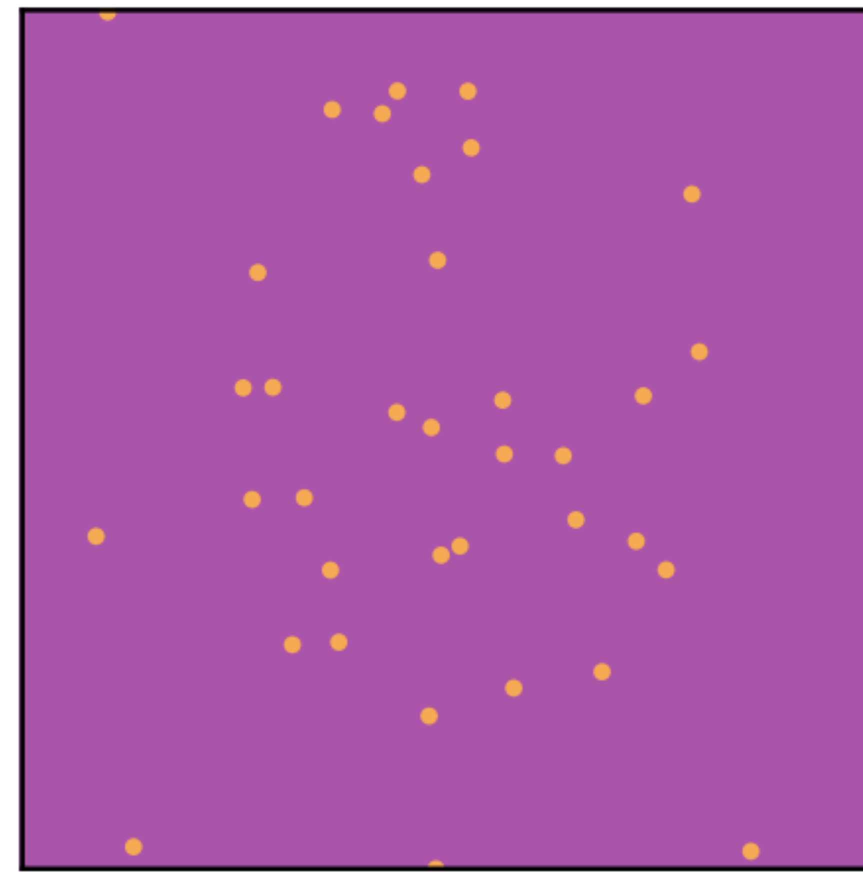
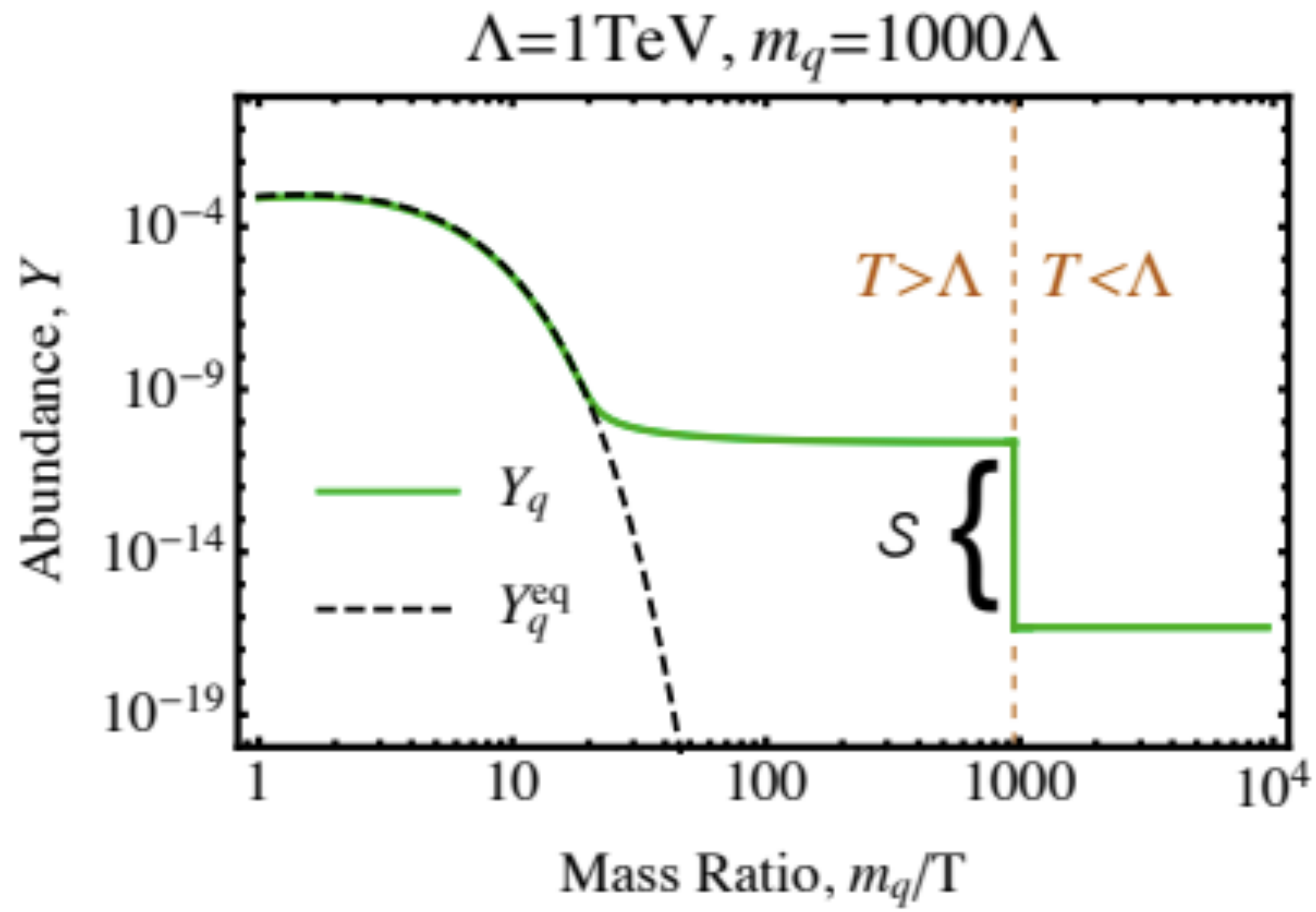


Summary of cosmic history for this scenario

- Freezeout: the dark quark abundance is depleted through annihilation as normal.
- Squeezeout: the phase transition triggers a further sharp drop in the abundance, potentially by several orders of magnitude, as the dark quarks are compressed in contracting pockets and many of them annihilate before forming hadrons.
- We find this leads to the observed relic abundance for PeV-EeV DM.



Observational signatures?

- What I have shown you so far depends almost exclusively on the dark-sector physics - most signatures would depend on the details of the portal to the Standard Model

- Any first-order dark sector phase transition could generate a stochastic gravitational wave background that could be seen in future experiments [e.g. Geller et al, PRL 2018]

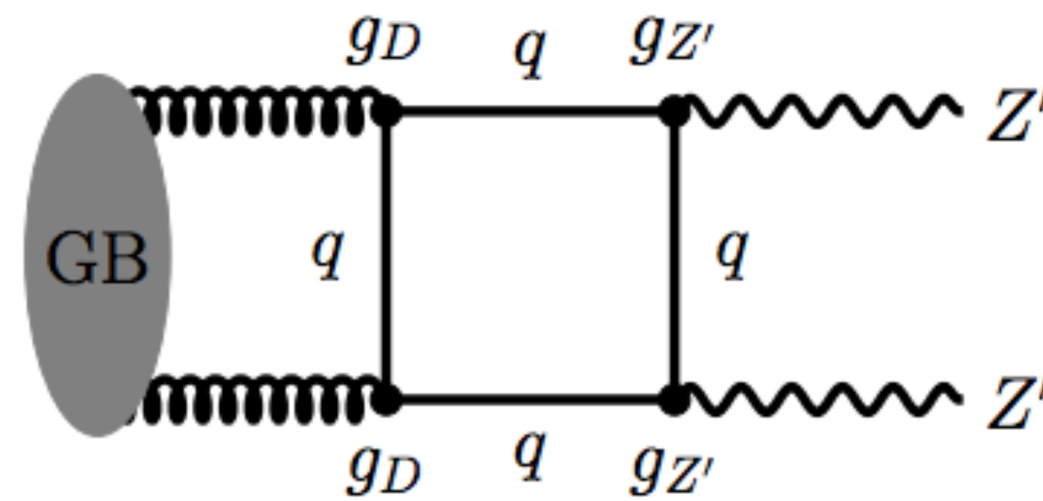
- To explore other signatures, we consider a simple $U(1)_{B-L}$ portal to the Standard Model [2203.15813, Asadi, Kramer, Kuflik, TRS & Smirnov]

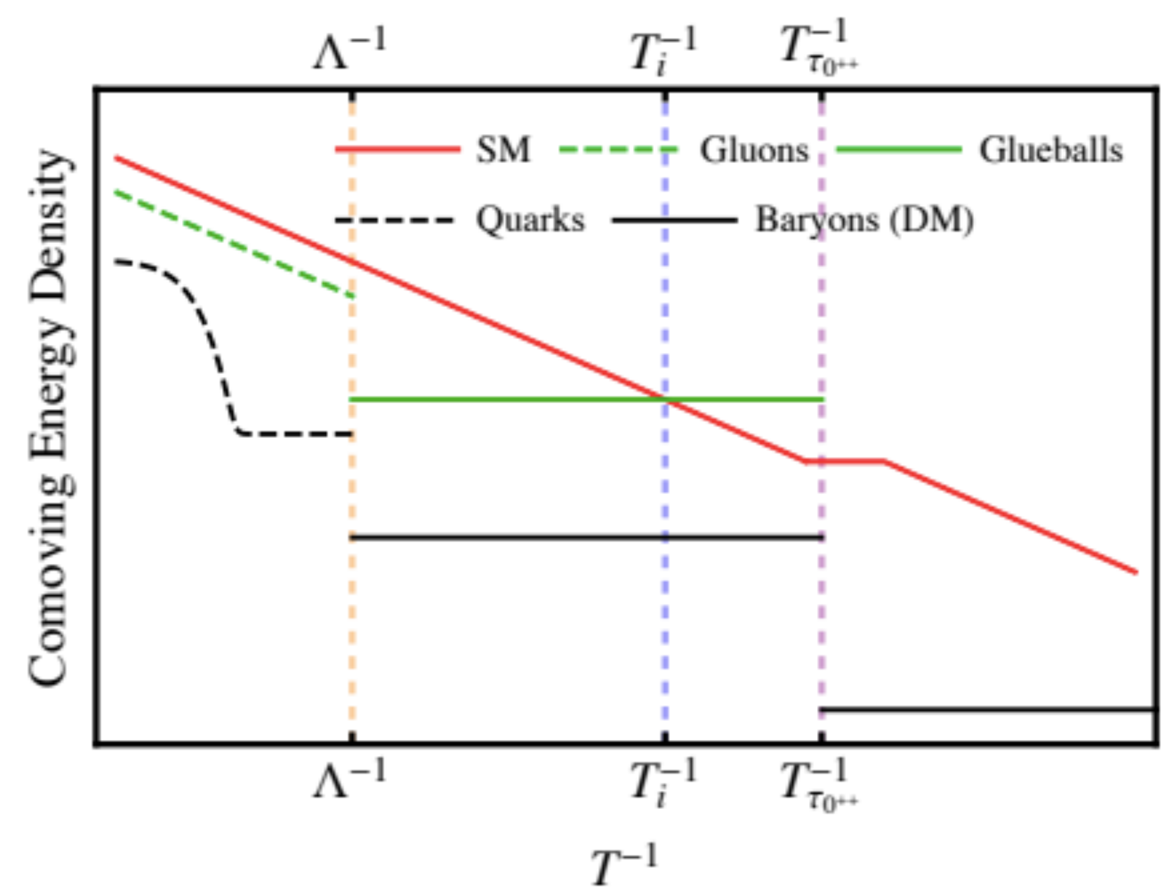
- Gauge B-L symmetry giving rise to a new Z' gauge boson, charge dark quarks under B-L (q_q=1)

- Adds two new parameters: the mass of the Z' and the gauge coupling for $U(1)_{B-L}$

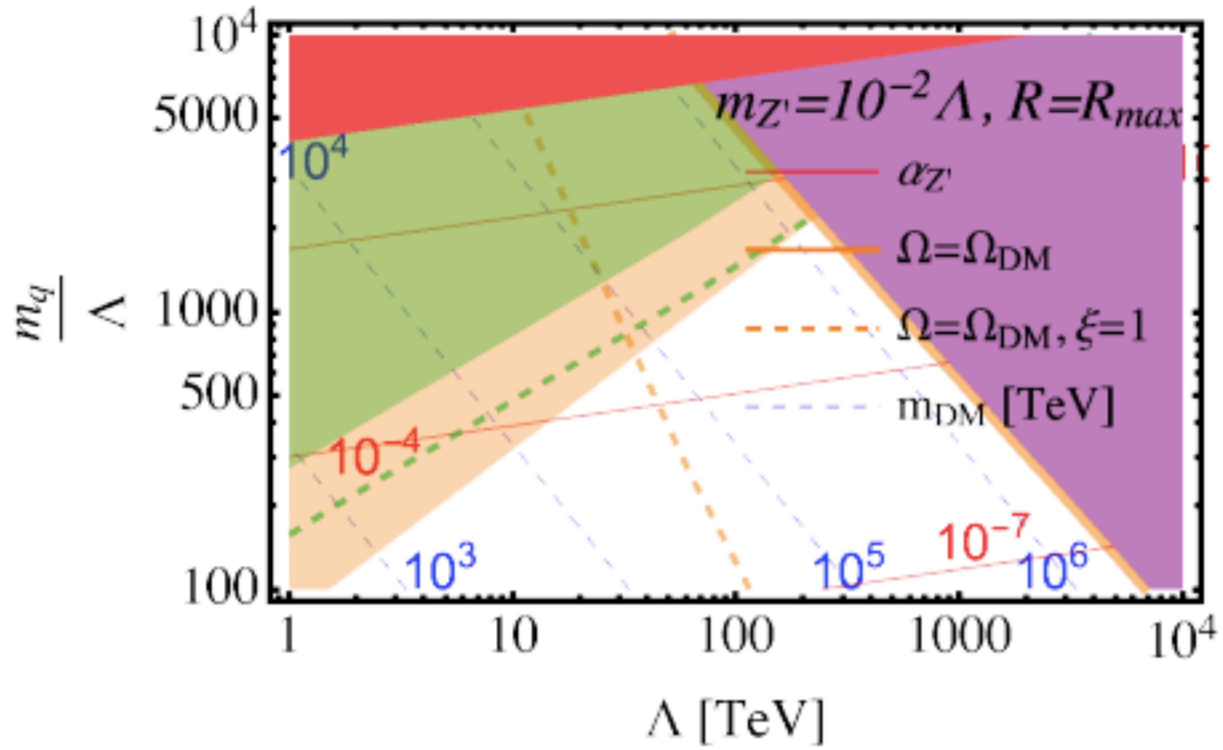
The importance of glueballs

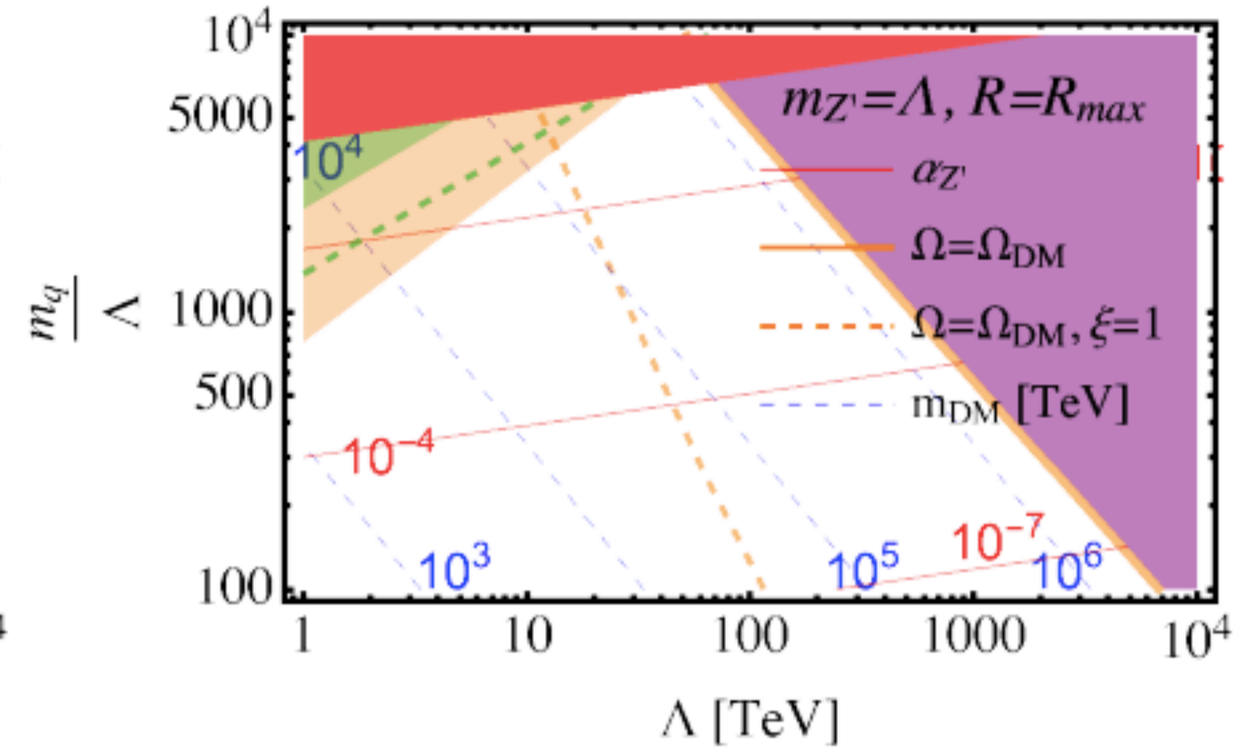
- Dark glueballs = bound states of the dark gluons
- If they are stable, would make up the DM - requires a portal to the Standard Model so they can decay
- But we found it is quite generic for some glueballs to be metastable, decaying with a long lifetime
- In parts of parameter space the glueballs are long-lived enough to dominate the energy density before they decay → early matter domination
- When they do decay, large entropy injection into the SM → further dilution of the DM abundance
- Can drive (parts of) the allowed parameter space to even heavier DM masses





Constraints on the Z' model





- In this plot we adjust the coupling to the Standard Model the value that allows the maximal glueball lifetime consistent with constraints. In the red region this value becomes nonperturbative.
- Dashed and solid orange lines show the shift in parameters yielding the correct relic density due to glueball decay
- Green, orange, purple regions show constraints on model due to direct detection (dashed green = neutrino floor), collider searches for the Z', and overclosure

Summary

- Dark matter is more than 80% of the matter in the universe, and we don't know what it is.
- Dark matter could potentially have complex structure, similar to the Standard Model; like the Standard Model particles, dark matter could form bound states.
- If the dark sector is non-Abelian (=multiple force carriers), the resulting bound states would have a modified spectral structure and different decay processes / selection rules compared to their closest Standard Model analogs.
- Dark bound states could enhance existing searches for dark matter and open up new detection channels, in particular if the dark matter inhabits a complex "dark sector".
- If the dark sector undergoes a confinement phase transition, that phase transition and subsequent decay of dark-sector bound states can dramatically reduce the dark matter abundance, allowing much heavier dark matter to be thermally coupled to the Standard Model and consistent with present-day observations