Structure formation

Standard lore: after photons decouple from baryons, perturbative overdensities continue to grow under gravity, eventually collapsing into virialized structures

"Cold" (non-relativistic) DM – small clumps form first, accrete to form larger structures, "cosmic web"

"Hot" (relativistic) DM – free-streaming erases early small-scale structure, largest structures form first, then fragment – clusters would be oldest structures in the universe

2nd option is excluded by observations of galaxy/cluster ages, + the fact that we see small dwarf galaxies – HDM predicts few small galaxies, cutoff in "matter power spectrum"

Neutrinos are HDM, so cannot be 100% (or large fraction) of DM.

Limits on subdominant HDM (Archidiacono et al '13), neutrinos (3 fermions) $\Sigma m_\nu < 0.27$ eV

$\Omega_\nu \approx 0.02 (\Sigma m_\nu)/\text{eV}$

Warm DM – DM has non-negligible free-streaming length during structure formation, erases structure on v small scales, albeit not on scales lage enough to prevent galaxies from forming

Can constrain by matter power spectrum

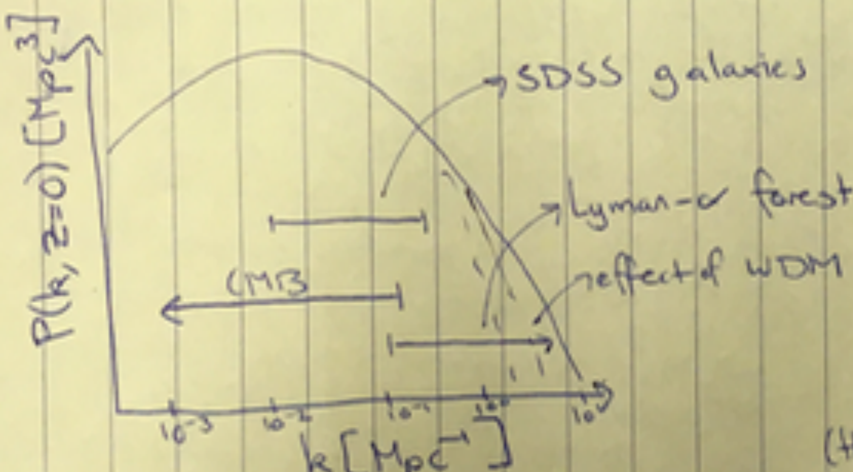
axion (1 scalar)
$m_a < 0.67$ eV
$\Omega_a \approx 0.01 m_a/\text{eV}$
HDM should be at most $O(1\%)$

The matter power spectrum

Define $\delta(\vec{r}) = \frac{\rho(\vec{r}) - \bar{\rho}}{\bar{\rho}}$ – fractional density fluctuations

Fourier transform: $\delta(\vec{k}) = \frac{1}{(2\pi)^3}\int \delta(\vec{x})\, e^{-i\vec{k}\cdot\vec{x}}\, d^3\vec{x}$

Power spectrum: $P(k) = \langle |\delta(\vec{k})|^2 \rangle$ – describes power in density enhancements at a given scale



Hlozek et al '12

k = comoving inverse distance scale

– corresponds to comoving scale of original mode that formed a given structure, not physical size of collapsed structure today

(thermally coupled to SM) ~~while relativistic~~ decouples while relativistic)

Warm DM induces cutoff at $k_{FS} \sim 5\,\mathrm{Mpc}^{-1} \left(\frac{m_\chi}{1\,\mathrm{keV}}\right)\left(\frac{T_\nu}{T_\chi}\right)$

crude estimate

Simulation gives 50% suppression of matter power at $k_{1/2} \sim 6.5\,\frac{h}{\mathrm{Mpc}}\left(\frac{m_{WDM}}{1\,\mathrm{keV}}\right)^{1.11}\left(\frac{\Omega_{DM}}{0.25}\right)^{-0.11} \times \left(\frac{h}{0.7}\right)^{1.22}$ Viel et al 1306.2314

Strongest constraints on WDM come from "Lyman-α forest" – distant quasars emit radiation, absorbed by clouds of hydrogen – can map matter overdensities at intermediate redshifts. Probes matter power spectrum at $z \sim 2-6$, scales as small as $k \sim 10\,h/\mathrm{Mpc}$. Viel et al 1702.01764, $m_X \gtrsim 5.3\,\mathrm{keV}$ if thermal.

What could DM be?

- Last time, briefly discussed BH DM
- This time, consider possibility that DM represents 1 or more new particles

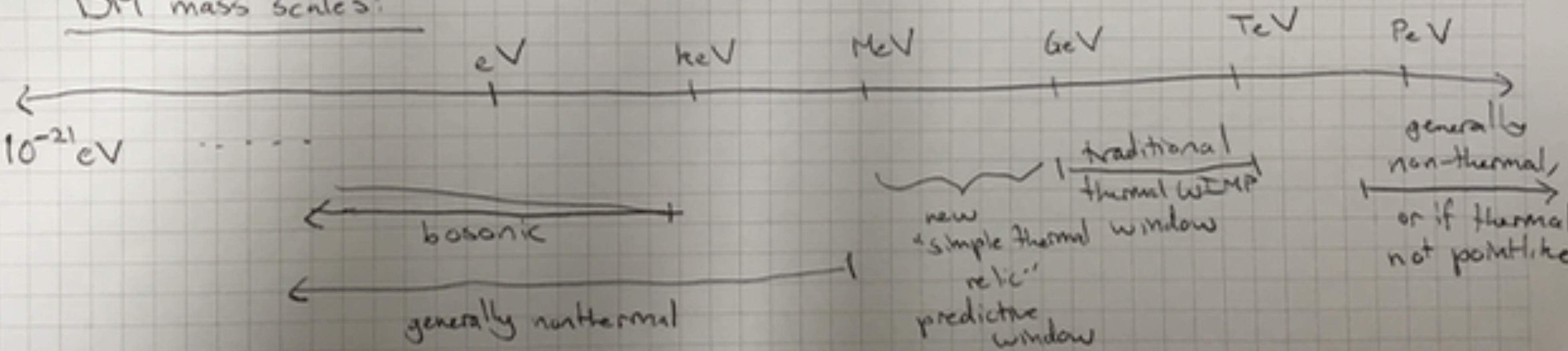
Note no SM particles work - only neutral, stable particle is neutrino, & it is HDM

(from last time: DM should be cold, stable & not interact too strongly)

~~Stability: DM could be absolutely~~

- What is DM mass?
- Is it absolutely stable? If not, what is its lifetime?
- How do we explain observed abundance (~5x greater than baryonic matter)?

DM mass scales:



10^{-21} eV - meV: regard DM as oscillating field, search for continuous wave signals

Regard DM as particle, can be absorbed or scattered on targets

thermal = was once in thermal contact with SM (or at least affects) DM-SM interactions determine relic abundance

Another kind of CMB limit: n_{eff} bounds

Nucleosynthesis, CMB set constraints on the number of effective relativistic degrees of freedom - affects energy density of radiation field, modifies the ~~at BBN timing~~ universe's expansion rate

$$\rho_{radiation} = \rho_\gamma + (3+\Delta N_\nu)\rho_\nu = \rho_\gamma\left(1+\frac{7}{8}\left(\frac{11}{4}\right)^{4/3} n_{eff}\right)$$

↳ number of effective neutrinos

$$n_{eff} \equiv 3\left[\frac{11}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3\right]^{4/3}\left(1+\frac{\Delta N_\nu}{3}\right)$$

↳ late-time ratio, after neutrino decoupling

If neutrino-photon decoupling is instantaneous, as discussed last week, & e^+e^- become non-relativistic well after decoupling, then $T_\gamma = \left(\frac{11}{4}\right)^{1/3} T_\nu$ at late times, $n_{eff} = 3+\Delta N_\nu$

In full calculation, $(n_{eff})_{SM} = 3.046$. From Planck (2015), $(n_{eff})_{observed} = 3.15 \pm 0.23$.

→ Can constrain light DM directly - temperature of the universe at BBN is ~1 MeV, if DM or something new particle to which it couples is ~~this light~~ ≲ MeV, can be in tension w/ n_{eff} limits: $\Delta n_{eff} \lesssim 1$ from BBN (1103.1261)

Furthermore, even if DM is substantially colder than SM (alleviating n_{eff} limits as the contribution to ρ scales as T^4 for a relativistic species), DM decay/annihilation that produces SM photons OR neutrinos after neutrino decoupling can change $\frac{T_\nu}{T_\gamma}$, also modifying n_{eff}. (See Berlin & Blinov '17 for a caveat.)

⇒ Thermal DM is challenging below ~MeV temperatures. At ~keV temperatures, warm dark matter limits

Generic constraints

If DM mass $\lesssim 10^{-21}$ eV, de Broglie wavelength is $\gtrsim$ 1 kpc – comparable to size of dwarf galaxies. Would suppress all structure below this scale.

Irsic et al, Armengaud et al '17: $m_\chi \gtrsim 2\text{–}3 \times 10^{-21}$ eV

Tremaine–Gunn bound:

Phase space density $\sim \frac{n}{p^3} \sim \frac{\rho}{m_\chi (m_\chi v)^3} \lesssim 2$ for fermions

$$\Rightarrow \quad m_\chi \gtrsim \left(\frac{\rho}{v^3}\right)^{1/4} \sim \left(\frac{1\ \mathrm{GeV/cm^3}}{(10^{-3})^3}\right)^{1/4}$$

$$\sim (10^{-26}\ \mathrm{GeV}^4)^{1/4}$$

$$\sim 10^{-6.5}\ \mathrm{GeV}$$

$\sim$ few hundred eV

$1\ \mathrm{cm} \sim 10^{13}\ \mathrm{fm} \sim 10^{13}\left(\frac{1}{0.2\ \mathrm{GeV}}\right)$

$\sim 5 \times 10^{13}\ \mathrm{GeV}^{-1}$

$1\ \mathrm{GeV/cm^3} \sim \frac{1}{(5\times 10^{13})^3}\ \mathrm{GeV}^4$

$\sim 10^{-41}\ \mathrm{GeV}^4$

Particle DM below this scale <u>must</u> be bosonic.

Furthermore, as discussed last time, DM in early thermal contact (until becomes NR) with SM generally too warm if $m_\chi \lesssim$ few keV, and can be in tension with N_{eff} bounds if $m_\chi \lesssim$ MeV, depending on details of model.

Suggests two broad classes of scenarios (1) light, cold, bosonic fields with sub-keV mass, non-thermal origin; (2) heavier (keV+), fermionic or bosonic, possibly thermal particle DM. Classic examples are axions (1) & WIMPs (2).

Consider evolution of DM number density in early universe

No annihilation: $\frac{d}{dt}(na^3) = 0$

$$\Rightarrow a^3 \frac{dn}{dt} + 3a^2 n \frac{da}{dt} = 0$$

$$\Rightarrow \frac{dn}{dt} + 3 \underbrace{\frac{\dot{a}}{a}}_{H} n = 0$$

With annihilation: $\frac{dn}{dt} + 3Hn = \underbrace{-\frac{n^2}{2}\langle\sigma v\rangle \times 2}_{\text{annihilation rate, 2 particles removed per annihilation}} + \left(\text{n-independent contribution from DM production processes}\right)$

In equilibrium, LHS $= 0$, $n = n_{eq}$ $\Rightarrow$ $= \langle\sigma v\rangle n_{eq}^2$

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

Equilibrium density n_{eq} set by Boltzmann distribution

$n_{eq} \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$, $T \ll m_\chi$ non-relativistic

$\sim T^3$, $T \gg m_\chi$ relativistic

When $\langle\sigma v\rangle \to 0$, n evolves as $\frac{1}{a^3}$

When $\langle\sigma v\rangle$ is large, forces n exponentially close to n_{eq}

Crossover when $\langle\sigma v\rangle n^2 \sim Hn$ i.e $\underbrace{n\langle\sigma v\rangle}_{\text{inverse timescale for annihilation}} \sim \underbrace{H}_{\text{inverse timescale for expansion}}$ – "freeze out"

For full solution, solve Boltzmann equation including changing degrees of freedom, etc.

But as an approximation, OK to define: T_f = temperature when $n\langle\sigma v\rangle = H$

$$x_f = \frac{m_X}{T_f}$$

$n_{\text{late-time}}\, a^3_{\text{late-time}} \sim \underbrace{n_f}_{=(n_{eq})_{\text{freeze-out}}} a_f^3$ i.e comoving density at late times

= comoving density at freeze-out

= comoving <u>equilibrium</u> density at freeze-out

$$s = \frac{2\pi^2}{45} g_{*s} T^3 \propto a^{-3}$$
$$\Rightarrow T \propto \frac{1}{a} g_{*s}^{-1/3}$$

First case: hot relic, freeze-out while relativistic

$$(n_{eq})_{f.o}\, a_f^3 \sim T_f^3 a_f^3$$

$$n_{\text{late-time}} \sim \frac{(T_f a_f)^3}{a^3_{\text{late-time}}}$$

Note $T_f \sim \frac{1}{a_f}$, i.e $n_{\text{late-time}}$ nearly independent of freeze-out temperature

number density comparable to that of photons, unless no. of effective d.o.f (g_*) changes drastically between freeze-out & today

Second case: cold relic, freeze-out when non-relativistic

At freezeout, $H \sim \underbrace{(m_\chi T)^{3/2} e^{-m/T}}_{n_{eq} \sim n} \langle \sigma v \rangle$

In radiation-dominated epoch, $H^2 \propto \rho \propto T^4 \Rightarrow T \propto \sqrt{H} \propto t^{-1/2}$

Write $H = \underbrace{H(T=m)}_{H(m)} x^{-2}$, $x = \frac{m}{T}$

$\Rightarrow H(m_\chi) x_f^{-2} \sim (m_\chi^2)^{3/2} x_f^{-3/2} e^{-x_f} \langle \sigma v \rangle$

$\Rightarrow e^{-x_f} = \dfrac{x_f^{-1/2}}{\left(\frac{m_\chi^3 \langle \sigma v \rangle}{H(m)}\right)}$

Approx solution:

$x_f \sim \ln\left(\frac{m_\chi^3 \langle \sigma v \rangle}{H(m_\chi)}\right)$

Note: only log dependence on mass, xsec

density of DM ~~after~~ at freezeout:

$n_\chi \sim m_\chi^3 x_f^{-3/2} e^{-x_f} \sim H(m_\chi) x_f^{-2} / \langle \sigma v \rangle$

Note: # density of photons at freezeout

$n_\gamma \sim T_f^3 \sim \frac{m_\chi^3}{x_f^3}$

both then scale $\sim$ as $\frac{1}{a^3}$, ignoring entropy dumps

$\Rightarrow \frac{n_\chi}{n_\gamma} \sim \left[\frac{H(m_\chi)}{m_\chi^2}\right] \times \left(\frac{x_f}{m_\chi}\right) \times \frac{1}{\langle \sigma v \rangle}$

independent of m_χ

$\frac{m_\chi n_\chi}{n_\gamma}$ both directly constrained today

$\sim \frac{x_f}{\langle \sigma v \rangle} \left[\frac{H(m_\chi)}{m_\chi^2}\right]$

- Thus late-time DM mass density, & hence Ω_c, has only log dependence on mass, mostly just ~~set by~~ $\propto \frac{1}{\langle \sigma v \rangle}$

To get numbers, note $H(m_\chi) \sim \frac{m_\chi^2}{m_{PL}}$

$$\Rightarrow \frac{m_\chi n_\chi}{n_\gamma} \sim \frac{x_f}{\langle \sigma v \rangle} \frac{1}{m_{PL}}$$

DM mass density $\sim 5 \times$ baryon mass density ~ 5 GeV $\times$ baryon number density

$$\sim 5 \times n_\gamma \times \underbrace{5 \times 10^{-10}}_{\text{baryon/photon ratio}} \text{ GeV}$$

$m_{PL} \sim 10^{19}$ GeV

To match data, we want

$$\Rightarrow \frac{m_\chi n_\chi}{n_\gamma} \sim 3 \times 10^{-9} \text{ GeV} \sim \frac{x_f}{\langle \sigma v \rangle} 10^{-19} \text{ GeV}^{-1}$$

$$\Rightarrow \langle \sigma v \rangle \sim x_f \cdot 10^{-10.5} \text{ GeV}^{-2}$$

First guess: take $x_f \sim 1$, as it's a log quantity

$$\Rightarrow \langle \sigma v \rangle \sim 10^{-10.5} \text{ GeV}^{-2}$$

~~Natural mass~~ If $\langle \sigma v \rangle \sim \frac{\alpha^2}{m_\chi^2}$, $\alpha \sim 10^{-2}$, $\Rightarrow m_\chi \sim 10^3$ GeV

Now take $x_f \sim \ln(m_\chi m_{PL} \langle \sigma v \rangle) \sim \ln(10^{22} (\text{GeV})^2 \times 10^{-10.5} (\text{GeV})^{-2})$
$\sim \ln(10^{11.5}) \sim 25$

Substituting this back in gives

$\langle\sigma v\rangle \sim 10^{-9}\,\text{GeV}^{-2} \sim 10^{-26}\,\text{cm}^3/\text{s}.$

More careful calculation gives $\langle\sigma v\rangle \sim 2\text{-}3\times10^{-26}\,\text{cm}^3/\text{s}$, nearly independent of mass - "thermal relic cross section".

We can write this in an even simpler way (that generalizes easily to n-body annihilation with $n>2$):

As before, $\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{eq}^2)$

At freezeout, $H_f \sim \langle\sigma v\rangle n_f$.

At temperature of matter-radiation equality, T_{eq}, $\rho_{DM} \sim \rho_{rad}$ (ignoring baryons), i.e. $n\, m_\chi \sim T_{eq}^4$. But $n \sim n_f \times \left(\frac{T_{eq}}{T_f}\right)^3$ if $T_{eq} < T_f$ (i.e. freezeout happens during radiation domination) - governed by expansion.

So we can write $n_f\, m_\chi \sim T_{eq} T_f^3 \Rightarrow n_f \sim T_{eq} m_\chi^2$, taking $T_f \sim m_\chi$ (setting $x_f \sim 1$)

Since during radiation domination $H \sim \frac{T^2}{m_{PL}}$, we have

$\frac{T_f^2}{m_{PL}} \sim \langle\sigma v\rangle n_f \sim \langle\sigma v\rangle T_{eq} m_\chi^2$, i.e. $\langle\sigma v\rangle \sim \frac{1}{m_{PL} T_{eq}}$ - set 100% by known params

$T_{eq} \sim 1\,\text{eV} \sim 10^{-9}\,\text{GeV}$, $m_{PL} \sim 10^{19}\,\text{GeV}$, so

$\Rightarrow \langle\sigma v\rangle \sim \frac{1}{(100\,\text{TeV})^2} \sim \left(\frac{10^{-2}}{1\,\text{TeV}}\right)^2$

Suggests TeV mass scale for $\alpha \sim 10^{-2}$, $m_\chi \lesssim 100$ TeV for perturbative α.

$\boxed{\text{Careful unitarity bound calculation finds } m_\chi \lesssim \text{ few hundred TeV}}$ (1407.7874)

Natural scale thus lines up with electroweak masses + couplings - suggestive, but basic mechanism works for ~ MeV - 100 TeV DM.

Can be realized in SUSY models, where DM is lightest neutralino (wino/higgsino/bino admixture) - couples to ~~Z~~ SM via W/Z/Higgs, mass scale can be naturally 100s of GeV to TeVs

DM stabilized by R-parity: lightest R-odd particle (superpartner) cannot decay.

e.g pure wino DM has correct xsec for $m_\chi \sim 3$ TeV

" higgsino " " " " for $m_\chi \sim 1$ TeV.

(Note: freezeout can be more complicated in full SUSY model as other particles near-degenerate with DM may be involved.)

Variations:

- Velocity-dependent $\langle \sigma v \rangle$ - p-wave ($\propto v^2$) or Sommerfeld-enhanced ($\propto \frac{1}{v}$ or $\propto \frac{1}{v^2}$)
- Coannihilation multiple species involved
- Forbidden/Impeded DM - annihilation to kinematically forbidden state
- SIMPs/n-body annihilation - more than 2-body processes important
- Annihilation into dark sector, not SM directly
- Scattering w/ SM decouples before annihilation, ELDERs
- Freeze-in - never reaches complete equilibrium, DM-SM interactions create abundance, don't deplete it

⋮ etc

Dark Matter
Lecture 2: Theoretical Models

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ICTP Summer School on Cosmology
Trieste
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Goals (Lecture 2)

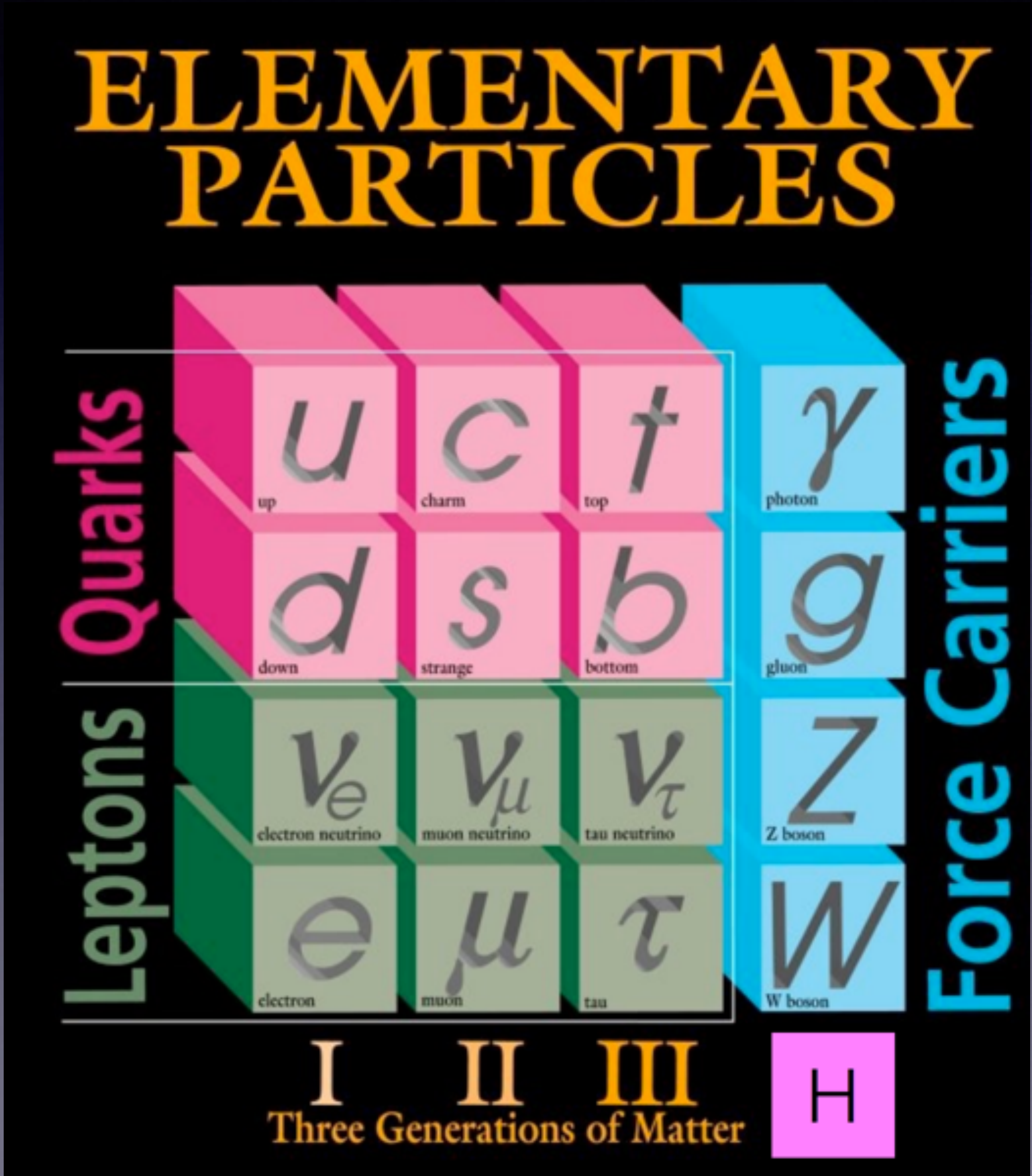
- Describe characteristics needed for a dark matter particle, and their implications:
  - Stabilization
  - Relic density
- Outline and explain the cosmology and key properties of the following scenarios:
  - Weakly Interacting Massive Particles (WIMPs)
  - Axions

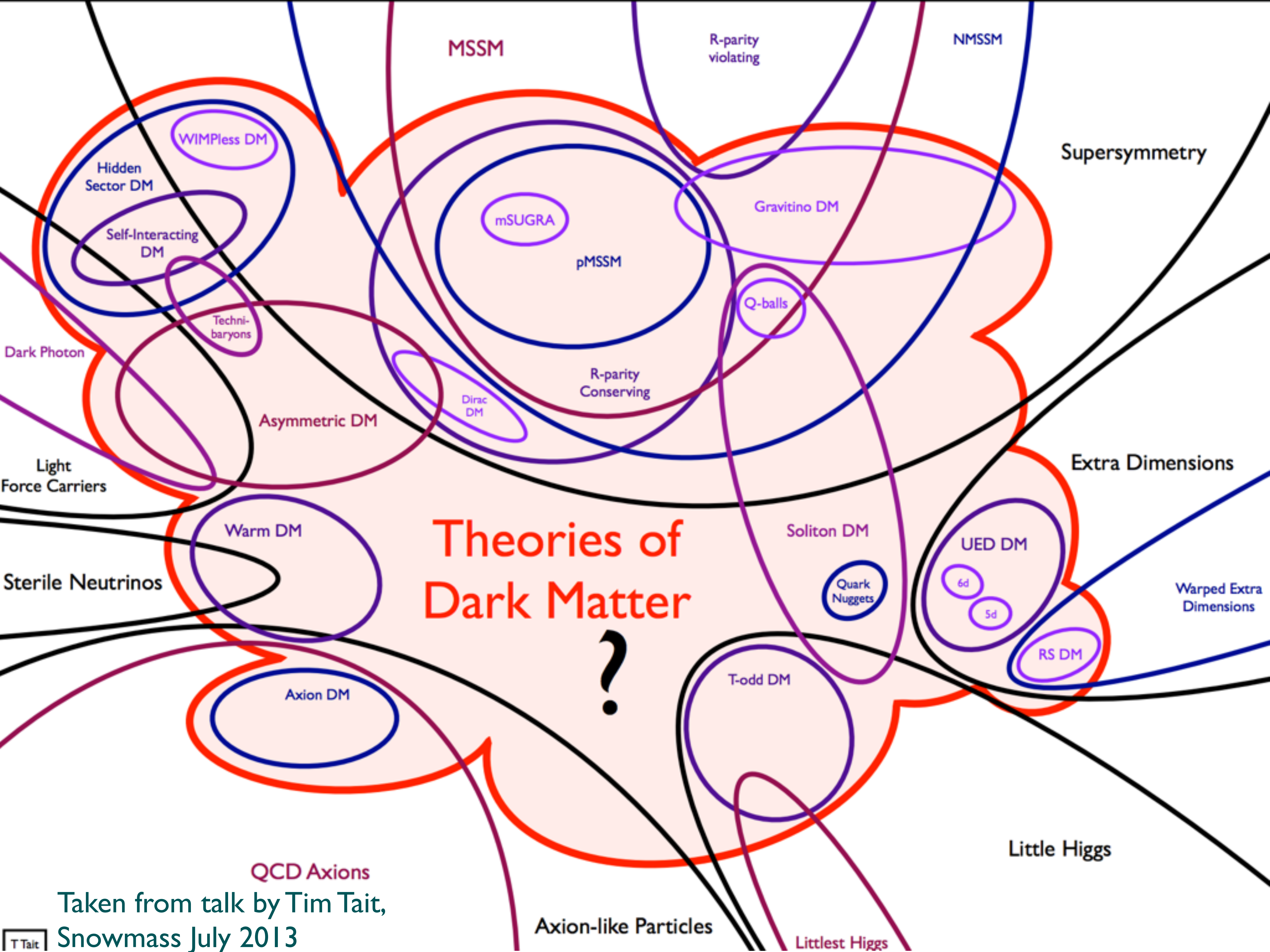
Recap from Lecture 1

- The distribution and gravitational effects of dark matter can be a powerful probe of dark-matter properties and interactions, independent of any interaction with the known particles.
- We know that dark matter is:
    - Still around today, i.e. stable on timescales ~age of the universe (rotation curves)
    - “Collisionless” - electrically neutral and interactions are fairly weak (Bullet Cluster)
    - “Cold” / slightly warm - small free-streaming length in epoch of structure formation (matter power spectrum, Lyman-alpha forest)
- No particle in the Standard Model of particle physics (the “SM”) matches these properties.

Beyond the SM

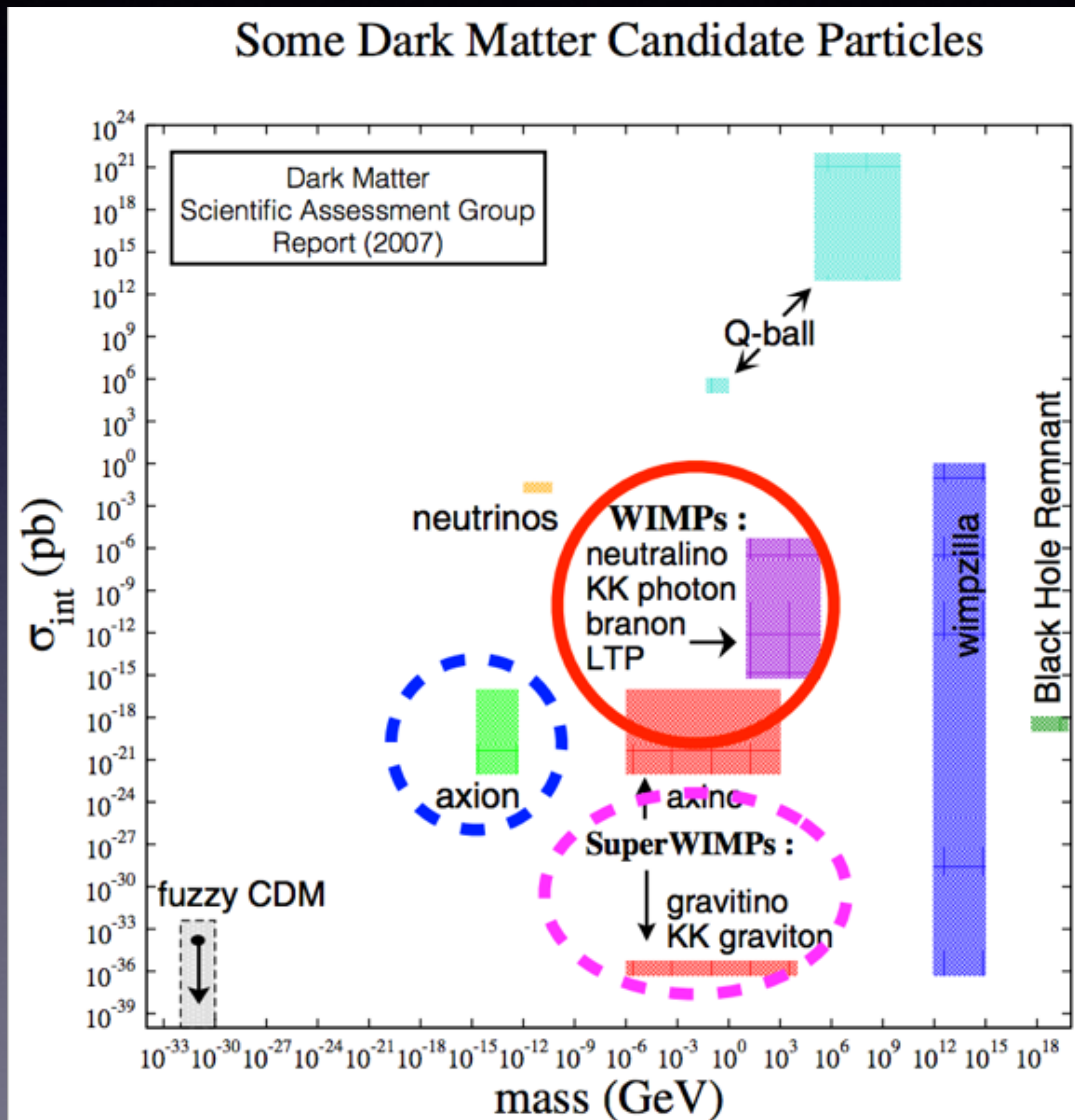
- Photons, leptons, hadrons and W bosons shine too brightly / are charged.
- Z and Higgs bosons are neutral but short-lived.
- Neutrinos are neutral and stable, but too light. They would be hot dark matter - cannot comprise all DM.





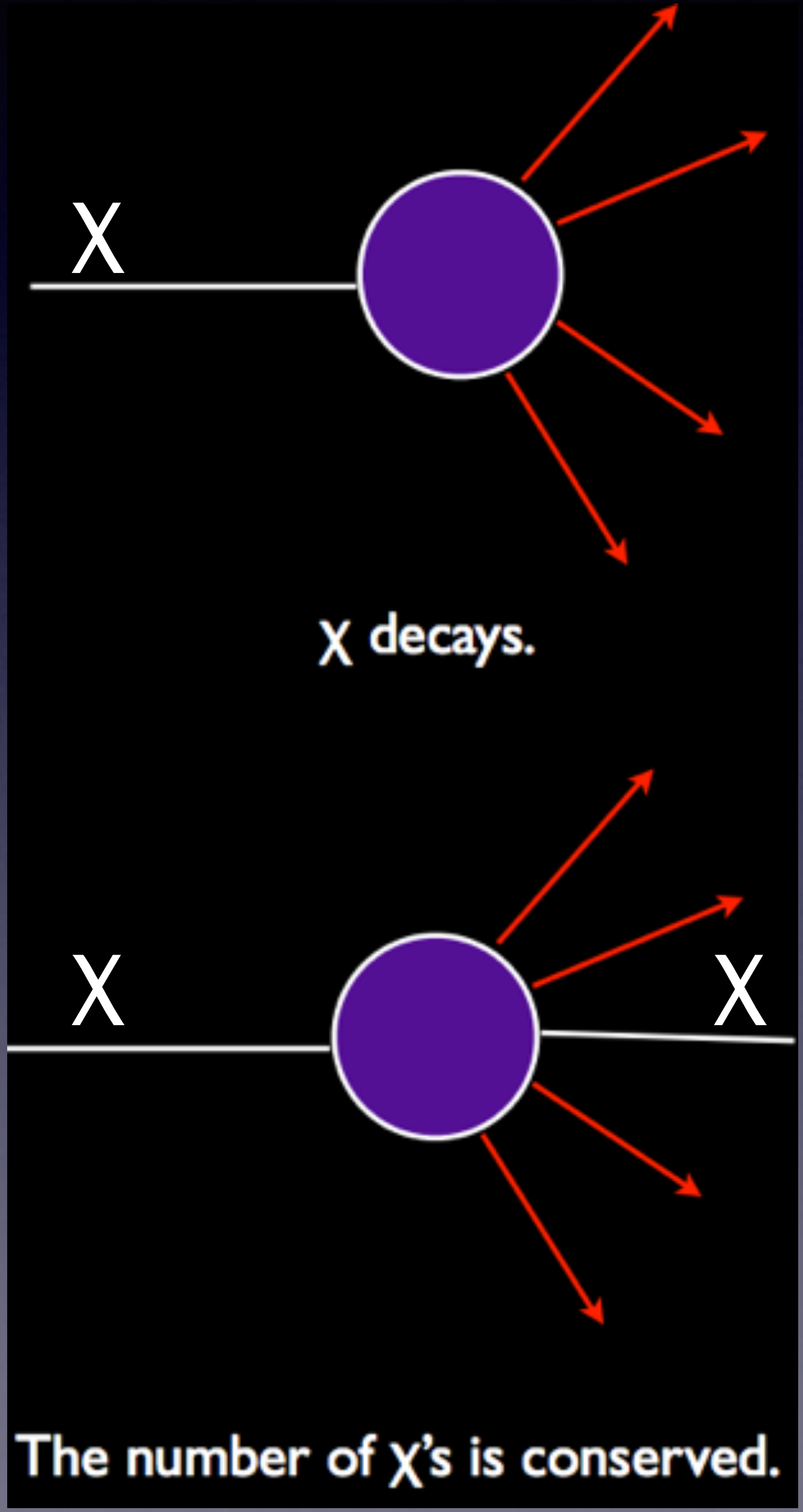
Taken from talk by Tim Tait, Snowmass July 2013

Huge range of possibilities



Stability

- One mystery is why dark matter is stable - especially if it is heavy enough to be "cold" in the early universe
- Sets stringent limits on DM-SM interactions:
  - Easiest route: impose some kind of symmetry to prevent DM from decaying
  - Simplest example is a new kind of "parity" - Z_2 discrete symmetry, forces coupling to SM fields to involve pairs of DM particles.
  - Many more examples!



The dark matter abundance

- Any DM model must explain the abundance of dark matter at the epoch of last scattering, precisely measured (from the CMB) to be:

$$\Omega_c h^2 = 0.1186 \pm 0.0020 \qquad h = H_0/(100\mathrm{km/s/Mpc}) = 0.6781 \pm 0.0092$$

Q: THERMAL OR NON-THERMAL?

Was the dark matter in thermal equilibrium with the Standard Model during the radiation-dominated epoch?

THERMAL

Explain how the early abundance of dark matter was depleted

-Asymmetric: small asymmetry between dark matter and antiparticle sets final abundance

-Symmetric: interactions set final abundance

NON-THERMAL

Explain how the required amount of dark matter was produced

-Initial condition from reheating?

-Misalignment mechanism

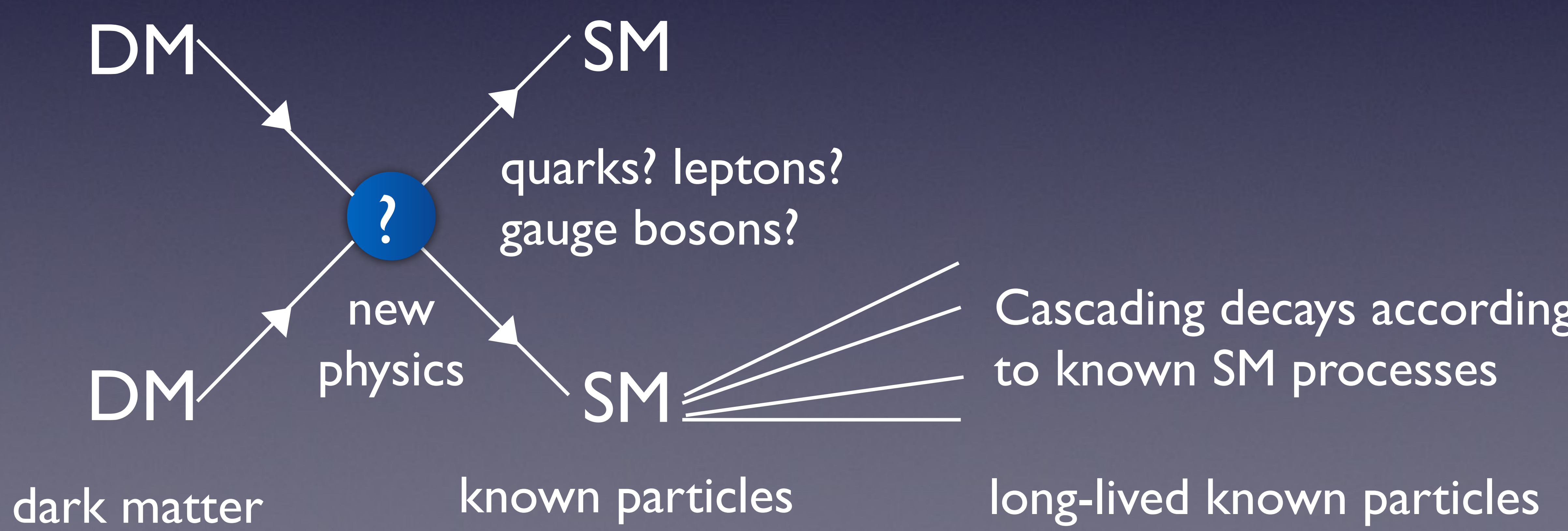
-Phase transition

-Thermal parent - interactions with state in thermal equilibrium determine its abundance

Weakly Interacting Massive Particles (WIMPs)

Thermal abundance

- Suppose dark matter:
  - can annihilate to Standard Model particles
  - was at some point kept in thermal equilibrium with the Standard Model by annihilation



Thermal freezeout

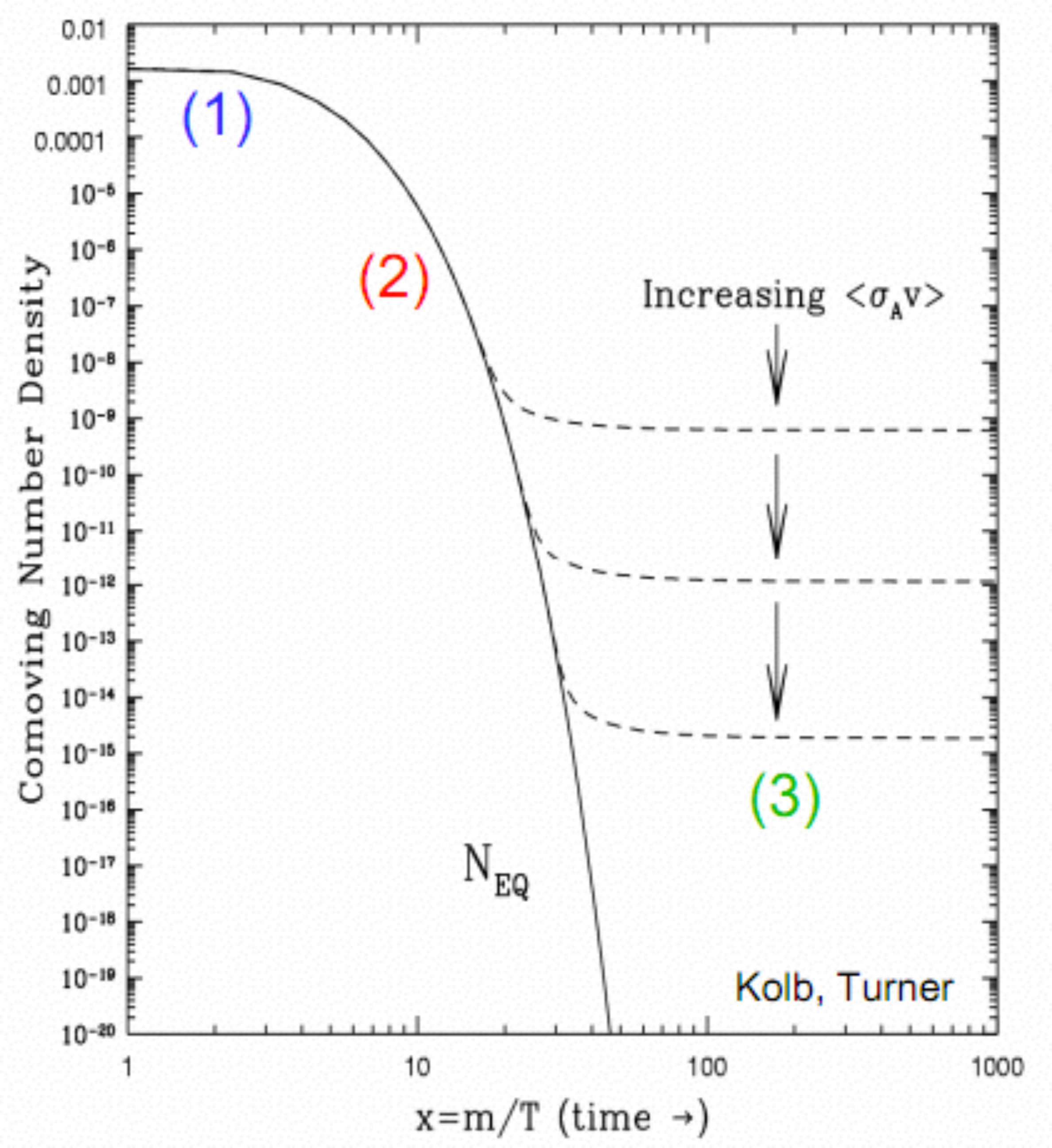
- In the early universe, let the DM particle be thermally coupled to the SM. Can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM\,SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\begin{aligned}\chi\chi &\rightarrow \mathrm{SM\,SM} \\ \chi\chi &\not\leftarrow \mathrm{SM\,SM}\end{aligned} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then freezes out.



So (known) late-time density is set by annihilation rate.

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

Outline of calculation

- Ingredients: annihilation rate for identical particles given by

  $$\text{annihilations / dt / dV} = n^2 \langle \sigma v \rangle / 2$$

- Boltzmann equation:

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

- Equilibrium density (Boltzmann distribution):

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

- Temperature of universe (assume radiation domination):

  $$H^2 \propto \rho \propto T^4 \Rightarrow T \propto \sqrt{H} \propto t^{-1/2}$$

Estimating freezeout

- For precision solution, can solve this differential equation numerically
- But we can get a simple estimate of important quantities analytically.
  - Freezeout occurs when timescale for expansion ~ timescale for collision: $H \sim n\langle\sigma v\rangle$
  - Up to freezeout, $n \sim n_{eq}$, so we require $H \sim g(mT/2\pi)^{3/2} e^{-m/T}\langle\sigma v\rangle$
- Defining x=m/T, we have $H(m)x^{-2} = g(m^2/2\pi)^{3/2} x^{-3/2} e^{-x}\langle\sigma v\rangle$
- Transcendental equation $e^{-x} = x^{-1/2}/C$ has approximate solution

$$x \sim \ln C \sim \ln\left(g(m^2/2\pi)^{3/2}\langle\sigma v\rangle/H(m)\right)$$

note: only depends on m and cross section logarithmically

Estimating freezeout II

- Abundance at freeze-out:

$$n \sim g(m^2/2\pi)^{3/2} x^{-3/2} e^{-x} \sim H(m) x_f^{-2} / \langle \sigma v \rangle$$

- For comparison, photon abundance at freezeout:

$$n_\gamma \sim T^3 \sim m^3 / x_f^3 \Rightarrow n/n_\gamma \sim \left(H(m)/m^2\right) (x_f/m) / \langle \sigma v \rangle$$

- To match measurements of DM mass density from CMB (comparable to critical density and baryon density), DM number density ~9 orders of magnitude below photon number density if $m_{DM} = m_{proton}$. At higher DM mass, number density must be lower (keeping mass density = mass x number density fixed).

$$H(m) \sim m^2/m_{\rm Pl} \Rightarrow 10^{-9}{\rm GeV}\, m_{\rm Pl} \sim x_f/\langle \sigma v \rangle \Rightarrow \langle \sigma v \rangle \sim x_f 10^{-10}{\rm GeV}^{-2}$$

- Taking x_f ~ 1 as a first approximation (since x_f is a log quantity, can't be too large) gives us a first estimate for cross section.

Cross section & mass scale

- Let us estimate $\langle\sigma v\rangle \sim \alpha^2/m^2,\ \alpha \sim 10^{-2}$
- Then from first estimate for cross section, natural mass scale is m~1000 GeV.
- Plug this back into formula for x_f; we find x_f~25.

$$x_f \sim \ln\left(g/(2\pi)^{3/2} m m_{\mathrm{Pl}} \langle\sigma v\rangle\right)$$

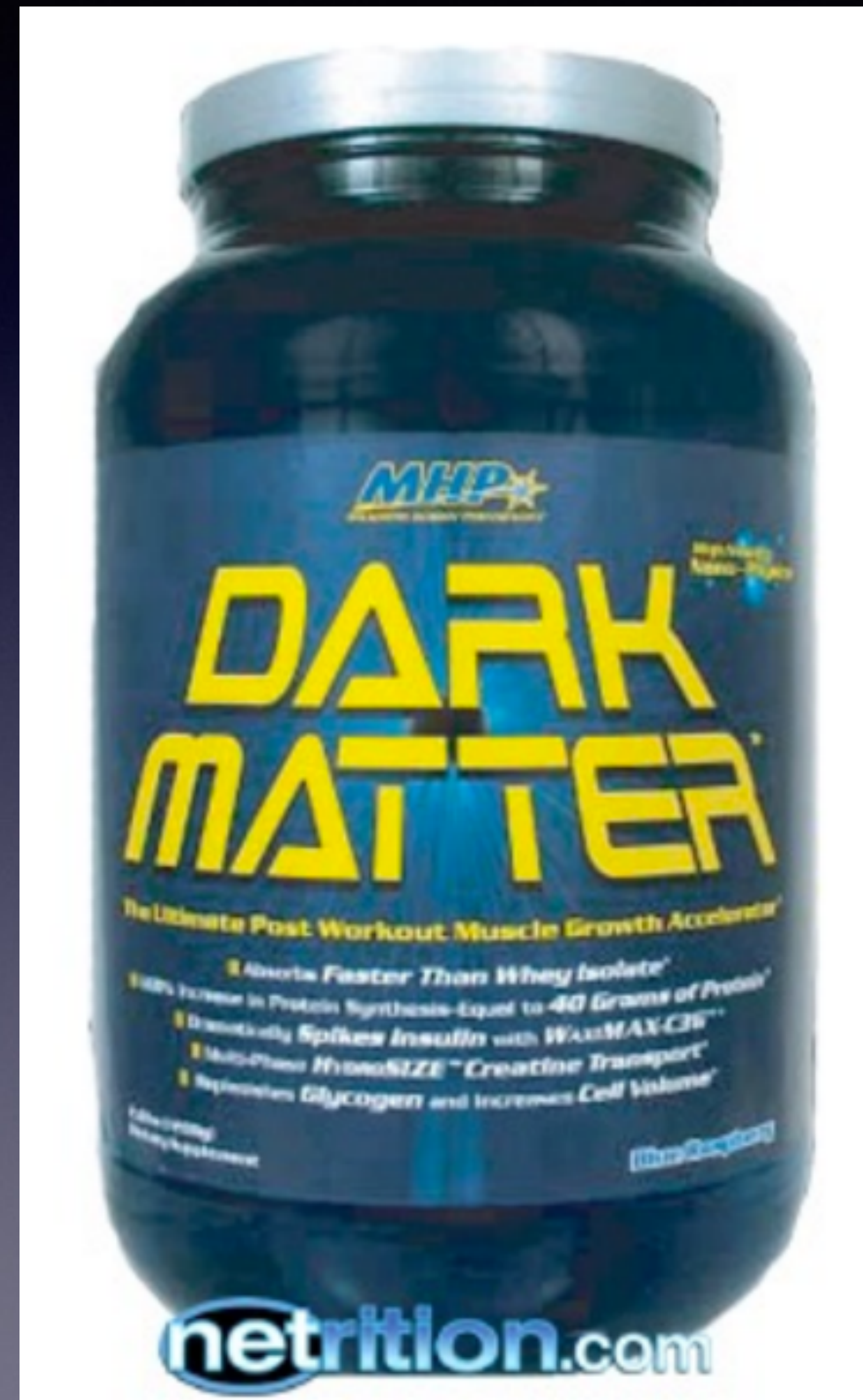
- This gives us a better cross section estimate:

$$\langle\sigma v\rangle \sim 2\times 10^{-9}\mathrm{GeV}^{-2} \approx 2\times 10^{-26}\mathrm{cm}^3/\mathrm{s}$$

- Corresponds to mass scale of a few hundred GeV, details depending on coupling and prefactors.

The WIMP miracle

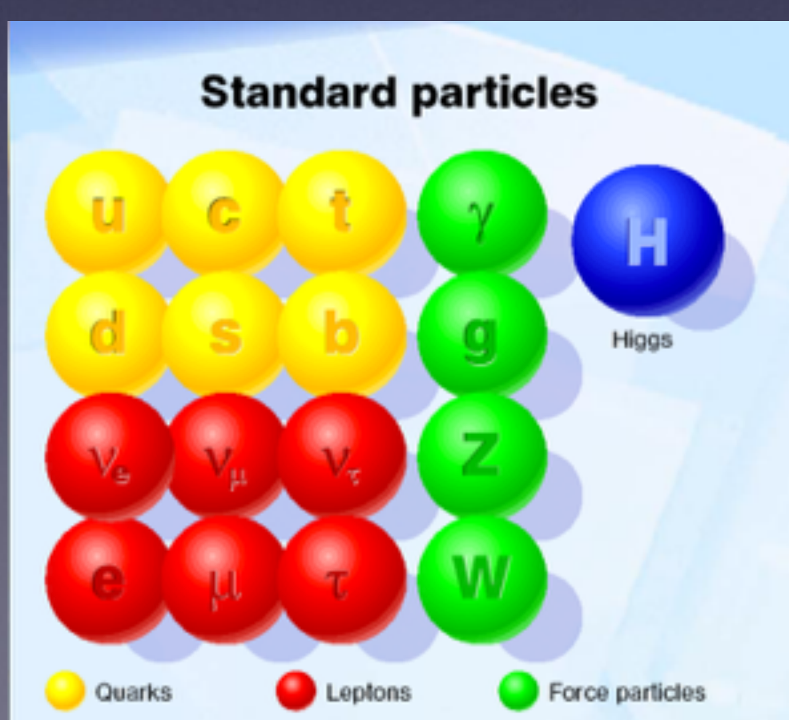
- In a thermal scenario, weak-scale annihilation cross section naturally yields the observed abundance of dark matter.
- Suggestive of new physics not too far above the weak scale.
- Stable WIMPs automatically occur in many scenarios for physics beyond the Standard Model, in particular in supersymmetry.
- However, simplest scenarios are challenged by lack of detection on other fronts; often need some extra ingredient to get the correct abundance.

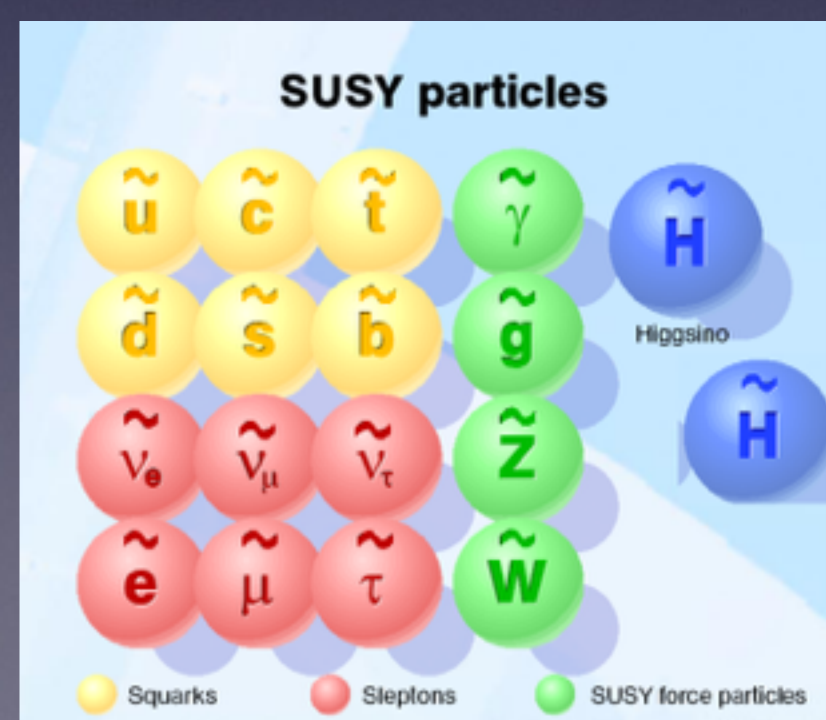


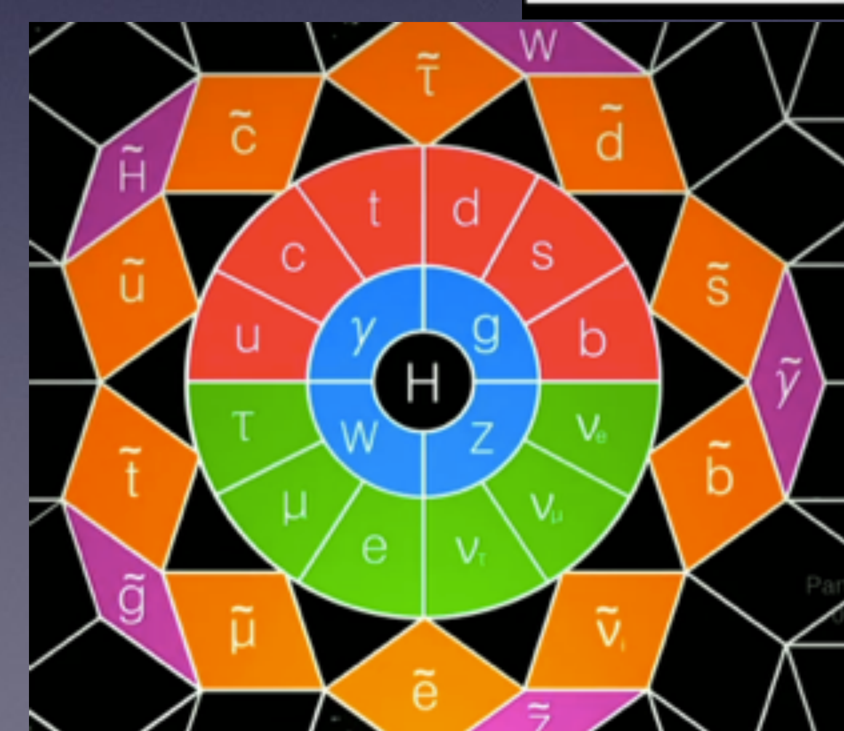
Supersymmetry (SUSY)

- Most famous dark matter candidate is the Lightest Supersymmetric Particle (LSP).
- In supersymmetric theories, every particle has a superpartner.
- Fermions have boson superpartners and vice versa.
- These additional particles cancel what would otherwise be very large predicted contributions to the Higgs mass - motivated independently of DM.
- For an in-depth introduction to SUSY, see e.g. Martin hep-ph/9709356.

Particle Fever
D.E. Kaplan

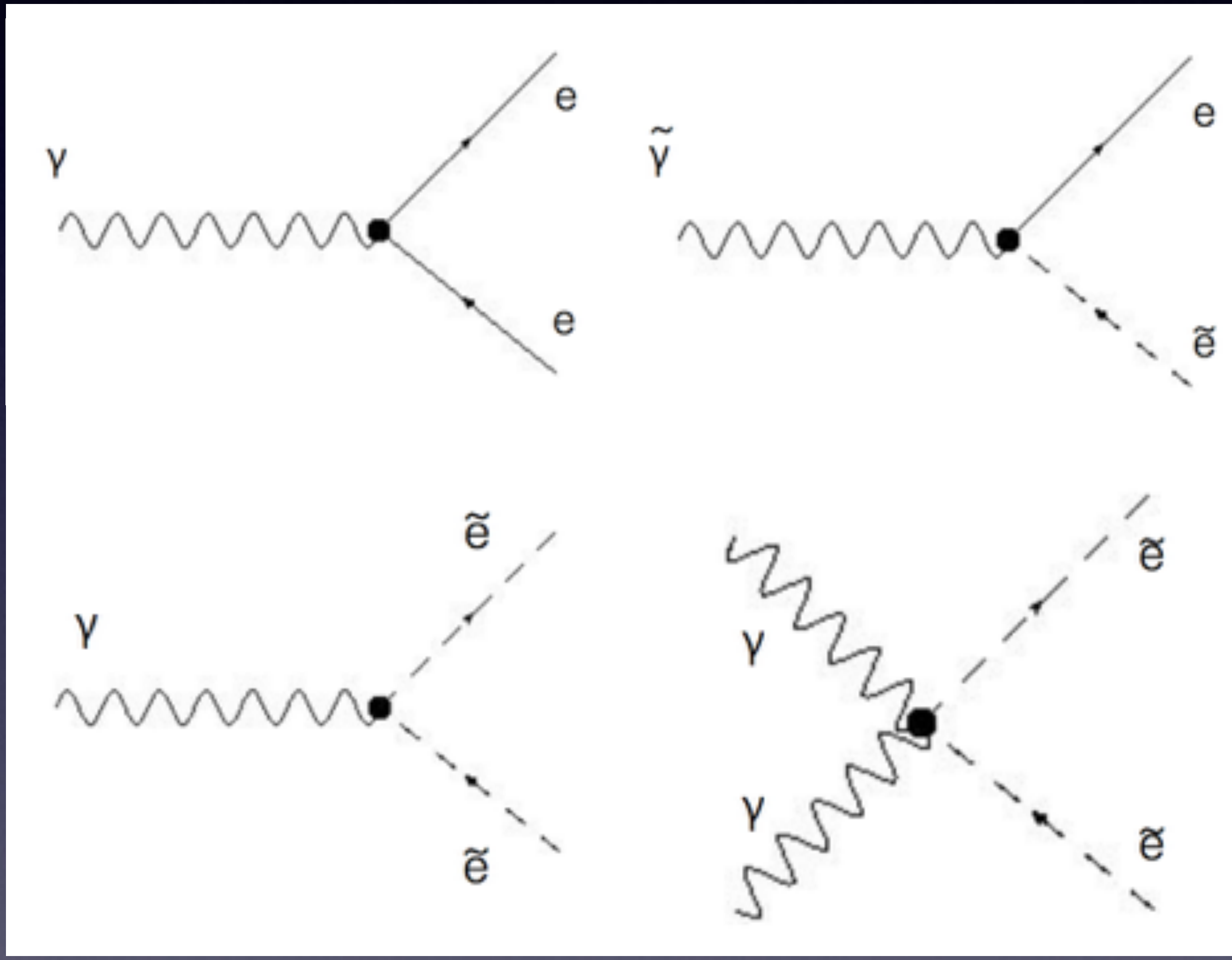






Supersymmetry (II)

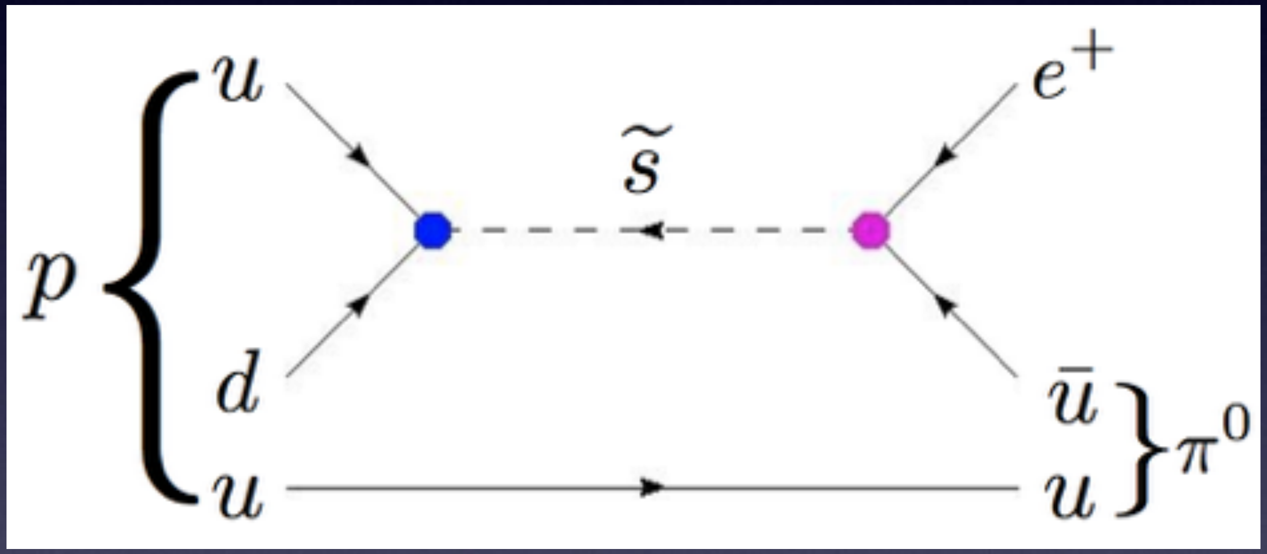
- In <u>unbroken</u> supersymmetry, particles and superpartners have same mass and closely related interactions.
- This symmetry must be broken as clearly superpartners do not have mass equal to their (known) counterparts!
- But if we break it "softly", while masses are separated, interactions remain fixed by supersymmetry.
- SUSY theories also inherit huge structure from the Standard Model.
- Consequently many quantities in SUSY theories can be calculated from just the masses of the superpartners.



Example of interactions related by supersymmetry - taken from talk by Tim Tait, August '15

R-parity

- These SUSY interactions naively imply some peculiar behavior!
- For example, they could make protons decay quickly:



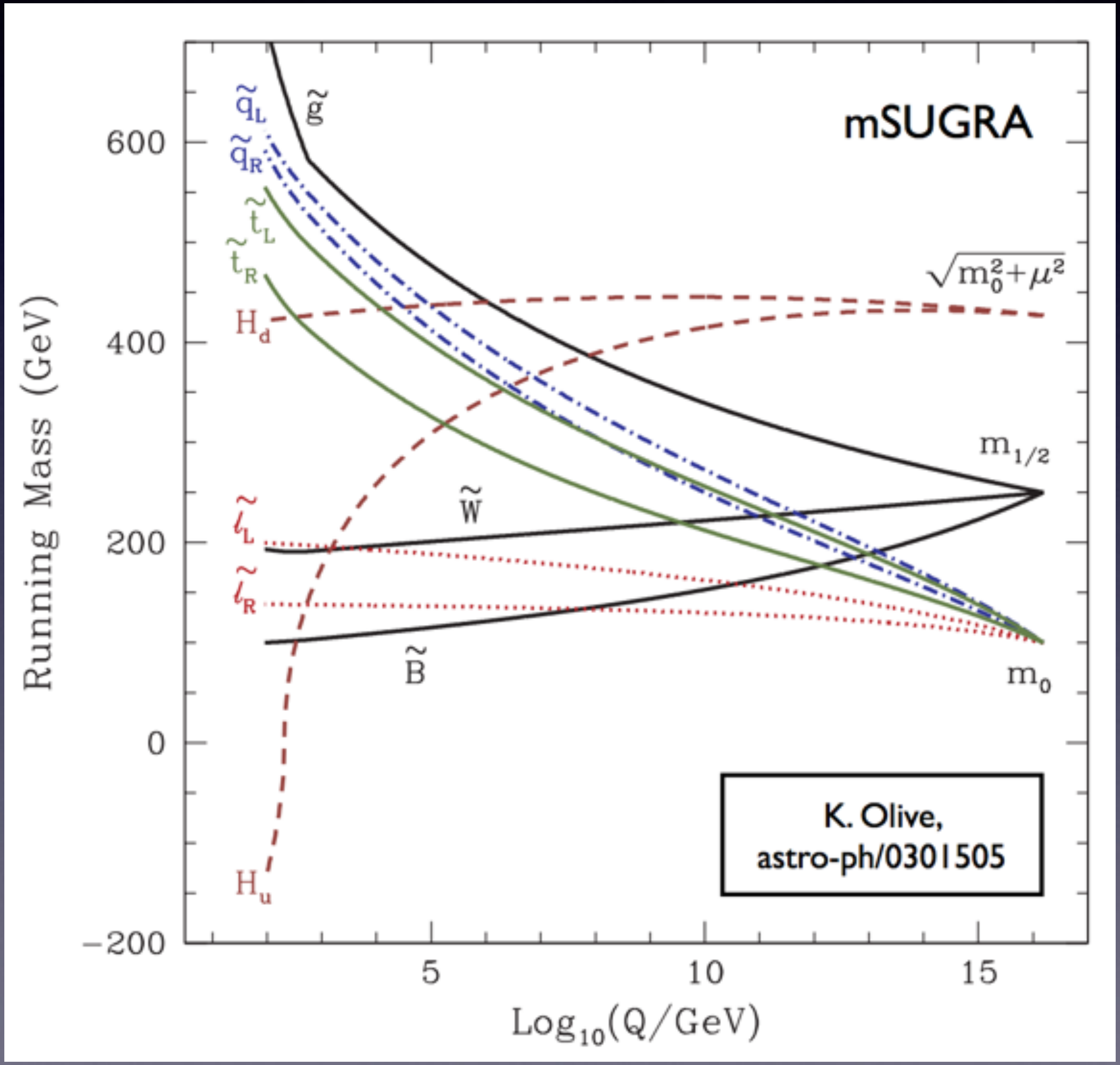
- This is pretty clearly not observed (experimental limit: lifetime $>10^{33}$ years).
- Usual approach is to impose a symmetry called R-parity, so the superpartners can only couple in pairs to the ordinary particles.
  - Superpartners have R-parity = -1
  - Ordinary particles have R-parity = +1
  - Product of R-parities before and after an interaction must be conserved

The LSP

- But then lightest particle with R-parity odd (i.e. = -1) cannot decay
  - can't produce any other particles with R-parity -1 (kinematically forbidden)
  - can't decay just to SM particles (violates R-parity)
- Avoiding proton decay gives us a stable DM candidate!
- Furthermore, any R-parity-odd particles in the early universe must eventually produce stable R-parity-odd particles by decays.
- But does the LSP satisfy other requirements for DM?

The LSP as dark matter

- First question: is it neutral?
- SUSY models in general have many parameters and the model of supersymmetry breaking matters.
- For a given model, we can compute the spectrum of superpartners, identify the lightest particle, and check its properties.



Neutralino dark matter

- Neutral fermionic superpartners = superpartners of the neutral gauge bosons
  - Higgsino = superpartner of the Higgs(es)
  - Wino = corresponds to electrically neutral gauge boson of electroweak SU(2) gauge group (there is also a "chargino" which corresponds to the charged components)
  - Bino = corresponds to gauge boson of the electroweak U(1) gauge group
- In general the physical states (of definite mass) correspond to mixtures of these - details depend on the model
- The lowest-mass such admixture determines the interactions of the DM candidate

The problem with binos

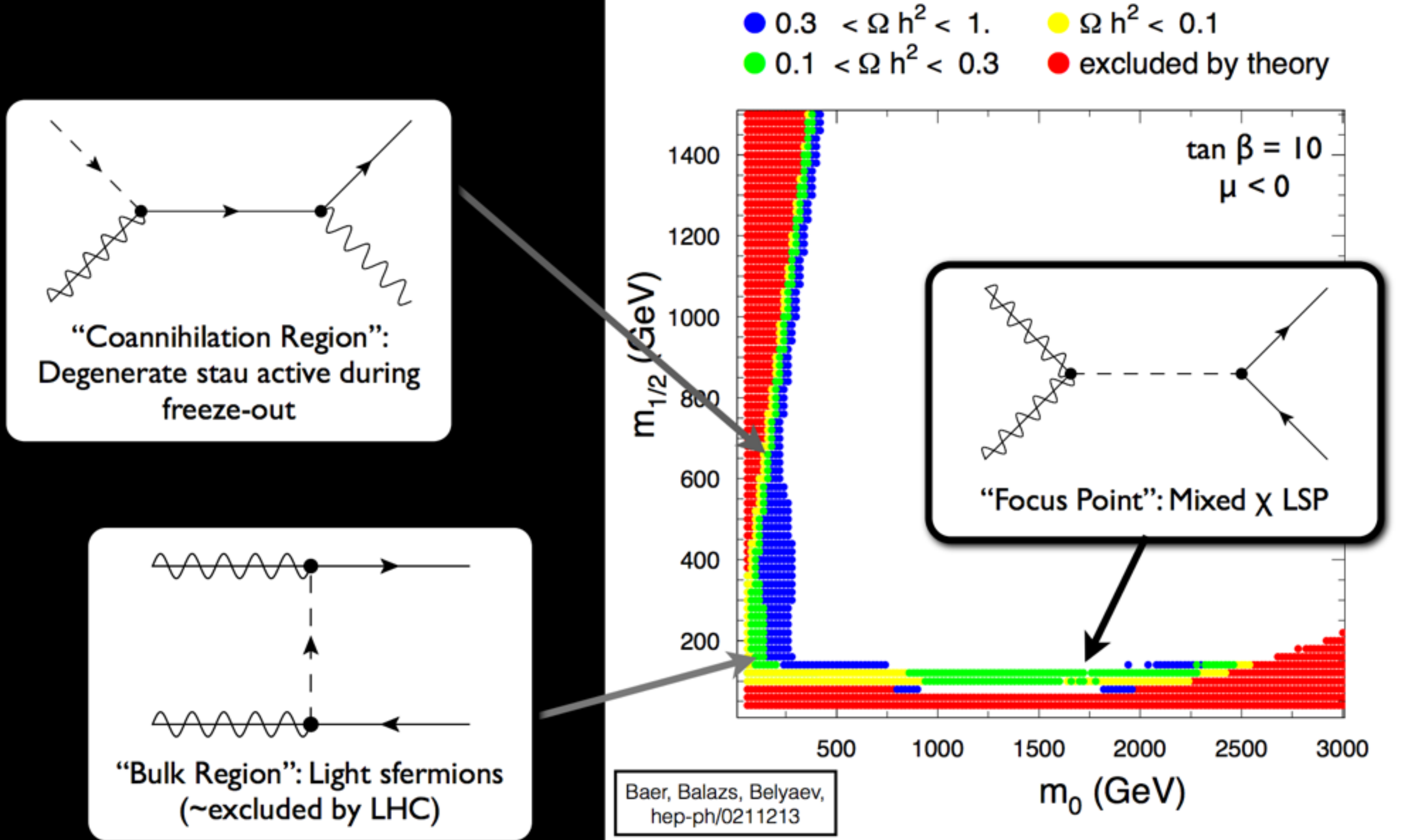
- A common (not universal) situation is for the LSP to behave mostly like a bino (with small wino/higgsino components)
  - Interactions with SM then mostly involve the scalar partners of the fermions ("sfermions")
  - Main annihilation channels for binos produce SM fermions, via interactions with sfermions.
  - But these annihilations are <u>suppressed</u> by m_f^2/m_{DM}^2 - smaller than "typical" weak-scale cross section.
- Low annihilation cross sections mean there is typically <u>too much dark matter</u> in the late universe - WIMP miracle doesn't hold up, despite weak-scale masses, due to parametric suppression.

Relic density from SUSY

- Four standard ways to fix this problem in mSUGRA, simplified example SUSY model:
  - “bulk region” - make sfermions light (larger annihilation cross sections)
  - “focus point” - reduce bino fraction so other, unsuppressed annihilation modes dominate
  - “funnel region” - annihilation through Higgs, near twice mass of DM, gives alternative, unsuppressed decay mode
  - “coannihilation region” - DM is not the only particle involved in freeze-out, need to include interactions with other near-degenerate particles

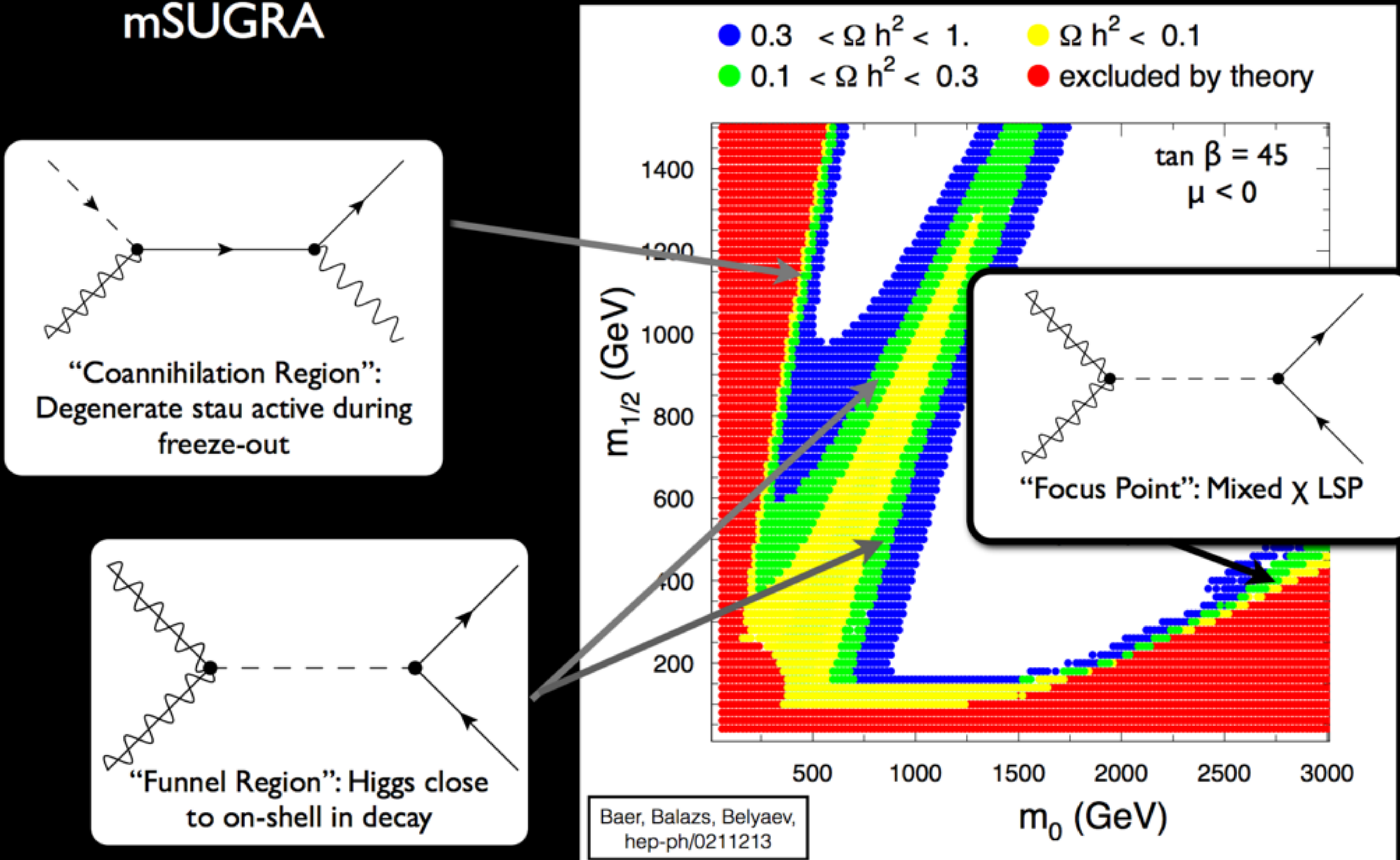
Credit to Tim Tait for these slides

mSUGRA

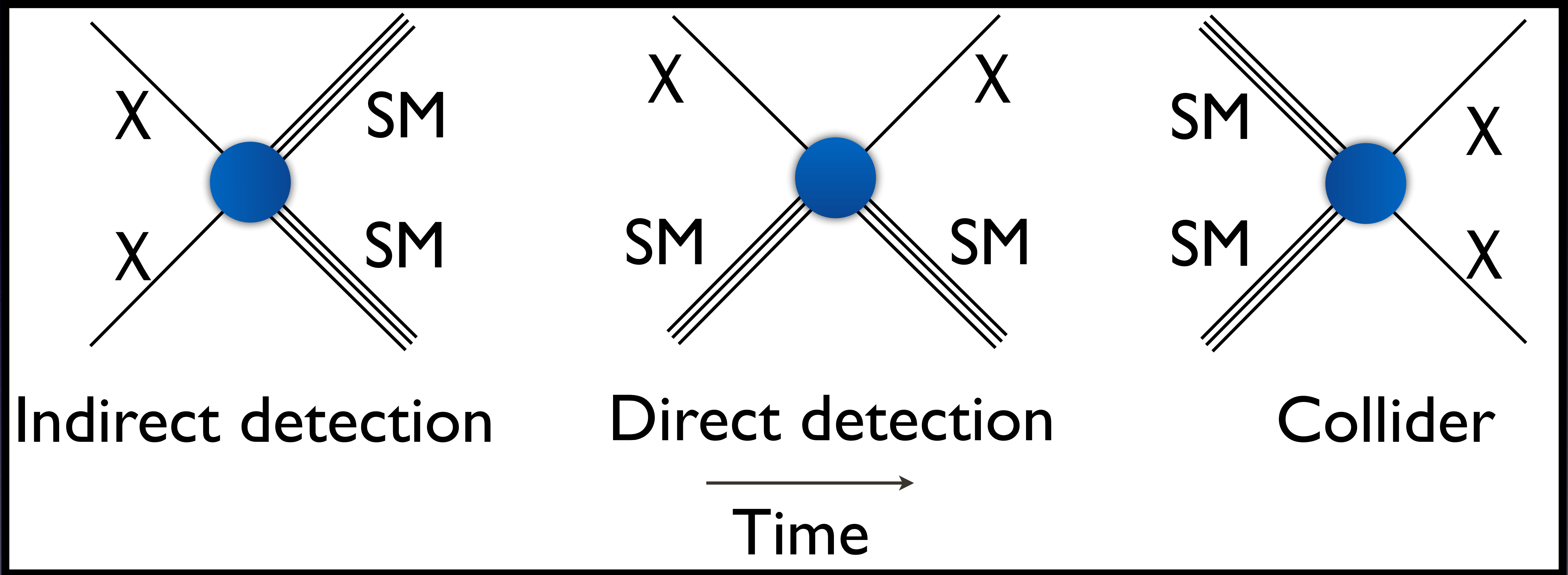


Credit to Tim Tait for these slides

mSUGRA



Hunting the WIMP



- Beyond motivations from SUSY and thermal freezeout, WIMPs are popular candidates because they have <u>many observable signatures</u>.
- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced in WIMP collisions or decay, with sensitive telescopes.
- Direct detection: look for nuclear recoils from WIMPs hitting SM particles with sensitive underground detectors.
- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

Axion dark matter

The strong CP problem

- The Standard Model Lagrangian, describing all known particle interactions, in principle should have a term of the form:

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$ gluon field strength

- A term like this can be generated by CP violation elsewhere in the Standard Model, in the terms describing the quarks - no reason for it to vanish.
- But this term induces a neutron electric dipole moment:

$$d_n = 5.2 \times 10^{-16} \mathrm{e\,cm}$$

- Experimentally, we know that:

$$d_n < 3 \times 10^{-26} \mathrm{e\,cm} \qquad \Rightarrow \theta \lesssim 10^{-10}$$

- Why is this value so small?

The axion proposal

- Replace the parameter θ by a dynamical field, call it (by convention) a/f_a where a is the field and $1/f_a$ a coupling.
- Now we just need to explain why a would evolve toward a very small value.
- But the energy stored in this field depends on the value of a - potential energy changes as a evolves.
- We can work out this effective potential (I won't give the calculation here - see e.g. Dine's TASI lectures hep-ph/0011376 for much more detail on the strong CP problem) and find:

$$V(a) = -m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos(a/f_a)$$

$$f_\pi \approx 93\mathrm{MeV}$$

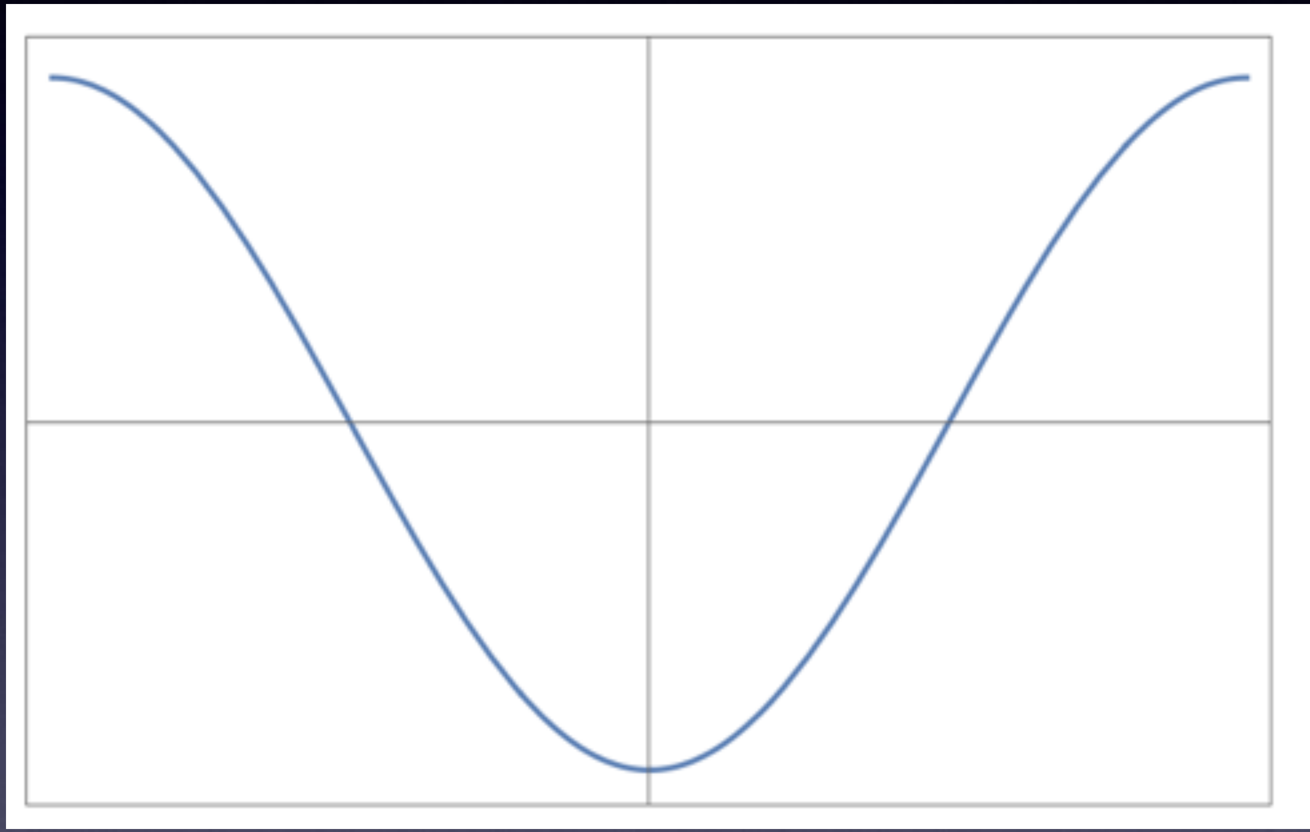
pion decay constant

$$m_\pi \approx 135\mathrm{MeV}$$

pion mass

The axion potential

- Field should evolve toward small values of this potential.
- Minima occur at $a/f_a = 2n\pi$; let's look at n=0.
- The potential is parabolic - coefficient of a^2 term gives axion mass.



$$V(a) = m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \frac{1}{2} a^2 \left(\frac{f_\pi}{f_a}\right)^2 m_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \mathcal{O}(a^4)$$

$$m_a = \frac{f_\pi m_\pi}{f_a} \left(\frac{m_u m_d}{(m_u + m_d)^2}\right)^{1/4} \approx 0.6\text{meV} \left(\frac{10^{10}\text{GeV}}{f_a}\right)$$

Axion properties

- Axion coupling to Standard Model fields is controlled by the coupling f_a, although exact couplings depend on details of model.
  - "DFSZ axion" - axion couples to photons, gluons, leptons, quarks
  - "KSVZ axion / hadronic axion" - axion couples to photons and gluons, but at lowest order no coupling to leptons or light quarks
- Axion mass is inversely proportional to their coupling to Standard Model fields - weakly coupled axions can be <u>very</u> light.
- One might think this makes them poor DM candidates - too hot?

Thermal axions

- Coupling for axions can be very weak
  - In contrast to WIMPs, question is not “when did they fall out of equilibrium” but “were they ever in equilibrium”?
- Axions produced in early universe by interactions of photons, pions
- Axions can also decay - and are produced singly, not in pairs (no symmetry keeping them stable)
  - Need to check lifetime is >> age of universe
  - Solve Boltzmann equation including decay + all production processes

Thermal axions as hot dark matter

- Timescale for decay to photons is approximately given by:

$$\tau \sim 10^{24} s \left(\frac{m_A}{\mathrm{eV}}\right)^{-5}$$

- Age of universe ~ 10^{10} yr ~ $\pi \times 10^{17}$ s => for axions to be around today, must be lighter than ~20 eV (unless decay suppressed in specific model)
  - Side note: at axion masses between about 20 eV and 300 keV, the photons from this process would disrupt nucleosynthesis!
- Solving Boltzmann equation, axions could attain thermal equilibrium if $m_a > 10^{-3}$-10^{-2} eV
- In this case, very roughly, fraction of critical density in axions:

$$\Omega_{\mathrm{axions}} \sim \mathcal{O}\left(\frac{m_a}{100\mathrm{eV}}\right)$$

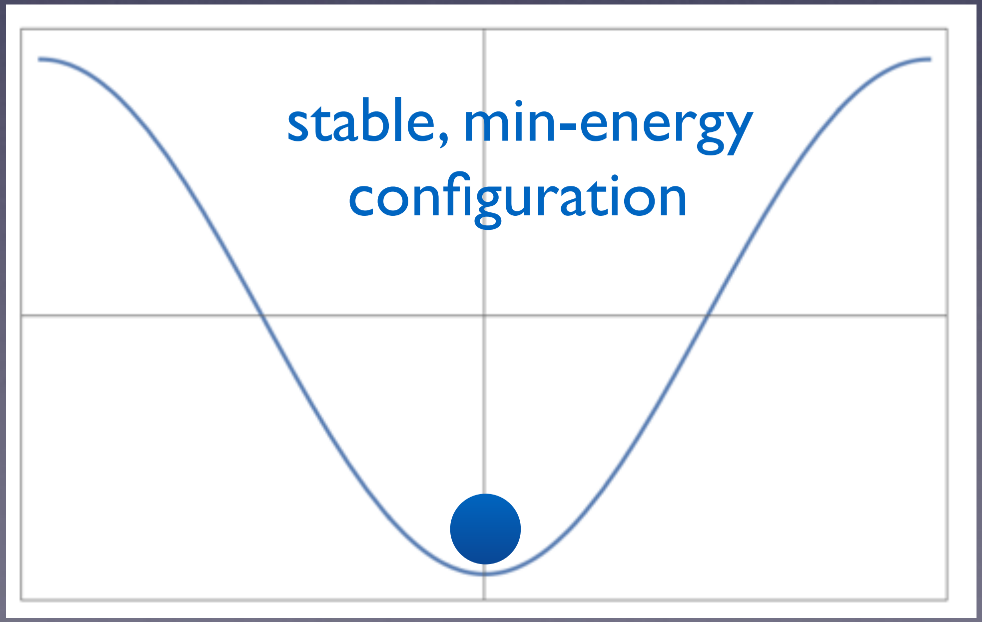
hot dark matter - needs to be small fraction of total DM
m_a < 1 eV is OK

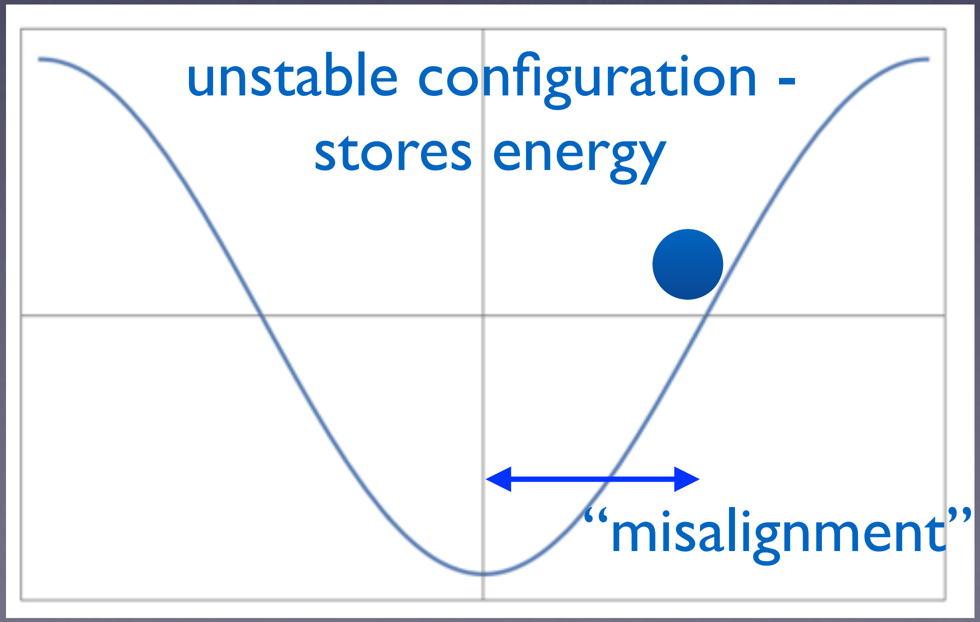
Non-thermal axions as cold dark matter

- But what if axions never equilibrate with SM?
- Sufficiently cold, light axions behave like a classical scalar field, evolving in axion potential - not individual particles

Q: How does the field evolve?

A: If initially displaced from minimum of potential (by some "misalignment angle"), must "roll" toward that minimum





An evolving scalar field

$$\frac{d^2a}{dt^2} + 3H\frac{da}{dt} + m_a^2 a = 0$$

equations of motion for scalar field in FRW
note here *a* = axion field, not scale factor

describes shape of potential near minimum

- For $m_a << H$, approximate solution with d*a*/dt = 0 - field does not evolve
- For $m_a > H$, field begins to oscillate in potential - like simple harmonic oscillator with H-dependent friction term ("Hubble friction"). For large t solution has approximate form:

$$a(t) = \Theta_0 f(t) \cos(m_a t)$$

f(t) slowly varying compared to oscillations

misalignment angle

- Solving for f(t) we find that in both radiation and matter-dominated epochs, f(t) scales like $1/(\text{scale factor})^{3/2}$.
- Energy density stored in axion field falls off like $f(t)^2 \sim 1/(\text{scale factor})^3$. Same behavior as matter - can act as cold dark matter.

Axion relic density

- Careful relic density calculation requires solving equation of motion including temperature dependence of axion mass, QCD phase transition, etc.
- Fraction of critical density:

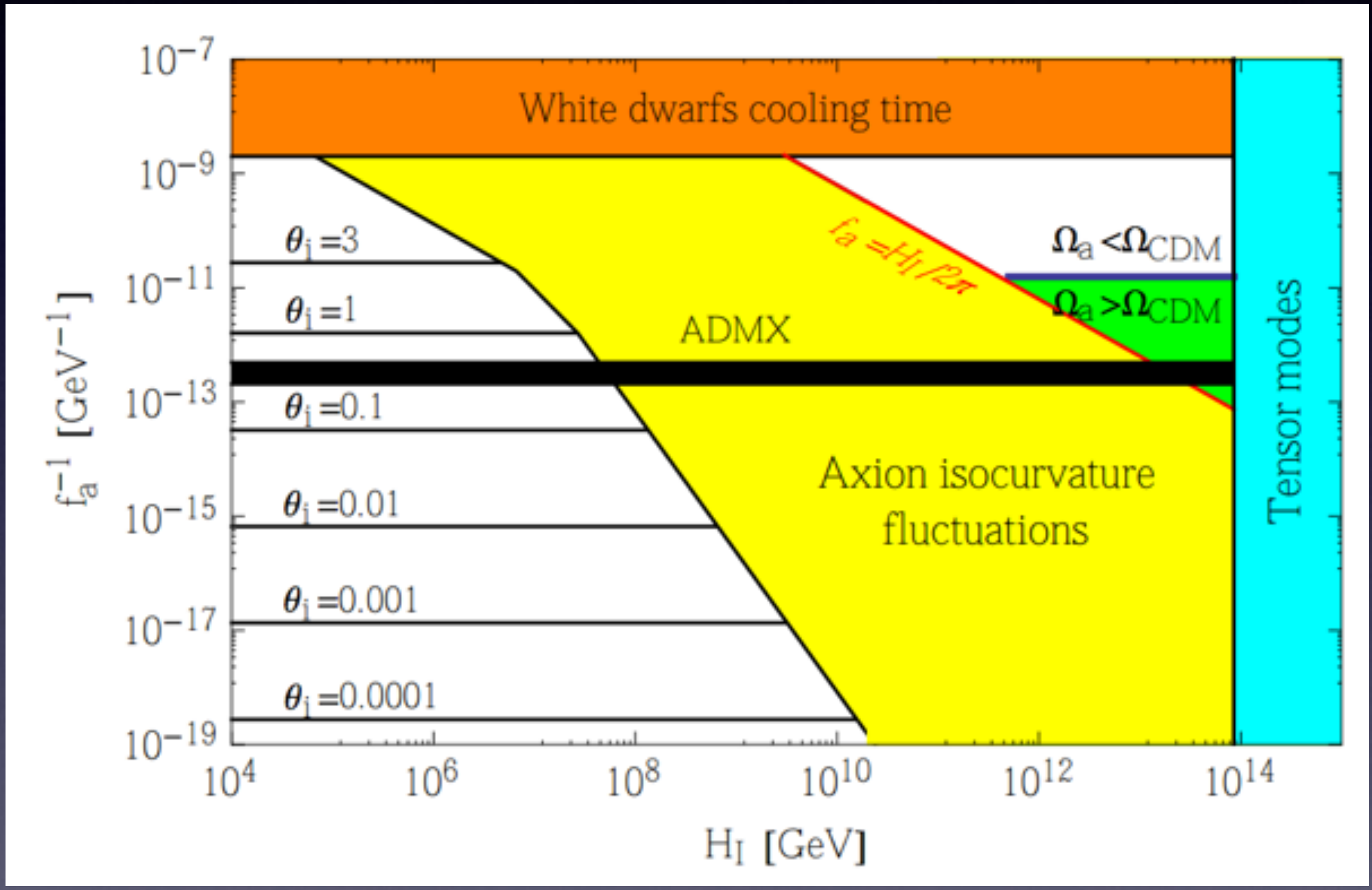
$$\Omega_{\rm axions} \approx \Omega_{\rm DM} \Theta_0^2 \left(\frac{f_a}{5 \times 10^{11} \mathrm{GeV}} \right)^{1.184}$$

- Lighter axions = higher f_a = more weakly coupled = larger relic density
- Relic density can always be suppressed by small initial misalignment angle
- But misalignment angle cannot be much larger than 1 - axions must have f_a of order 10^{11} GeV or higher (m_a~0.1 meV or smaller) to be all the DM.

Axions and inflation

Baer '15 (1510.07501)

- What value should we expect the misalignment angle to take?
- If axions are produced / misalignment angle is set only <u>after</u> inflation, i.e. $H_I >> f_a$, different patches of cosmos likely have different misalignment angles - take average of random sample
- If misalignment angle is set (in patches) <u>before</u> inflation, each such patch gets blown up at inflation - everywhere in our Hubble volume should have same angle
  - "anthropic axion"?



H_I = Hubble scale of inflation

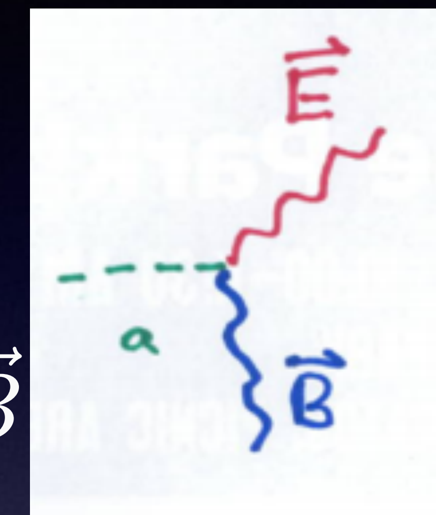
There are stringent constraints on scenarios where axion is all the DM and the energy scale of inflation is high - see Hertzberg, Tegmark & Wilczek '08
Learning about inflation may tell us about axions! (or vice versa)

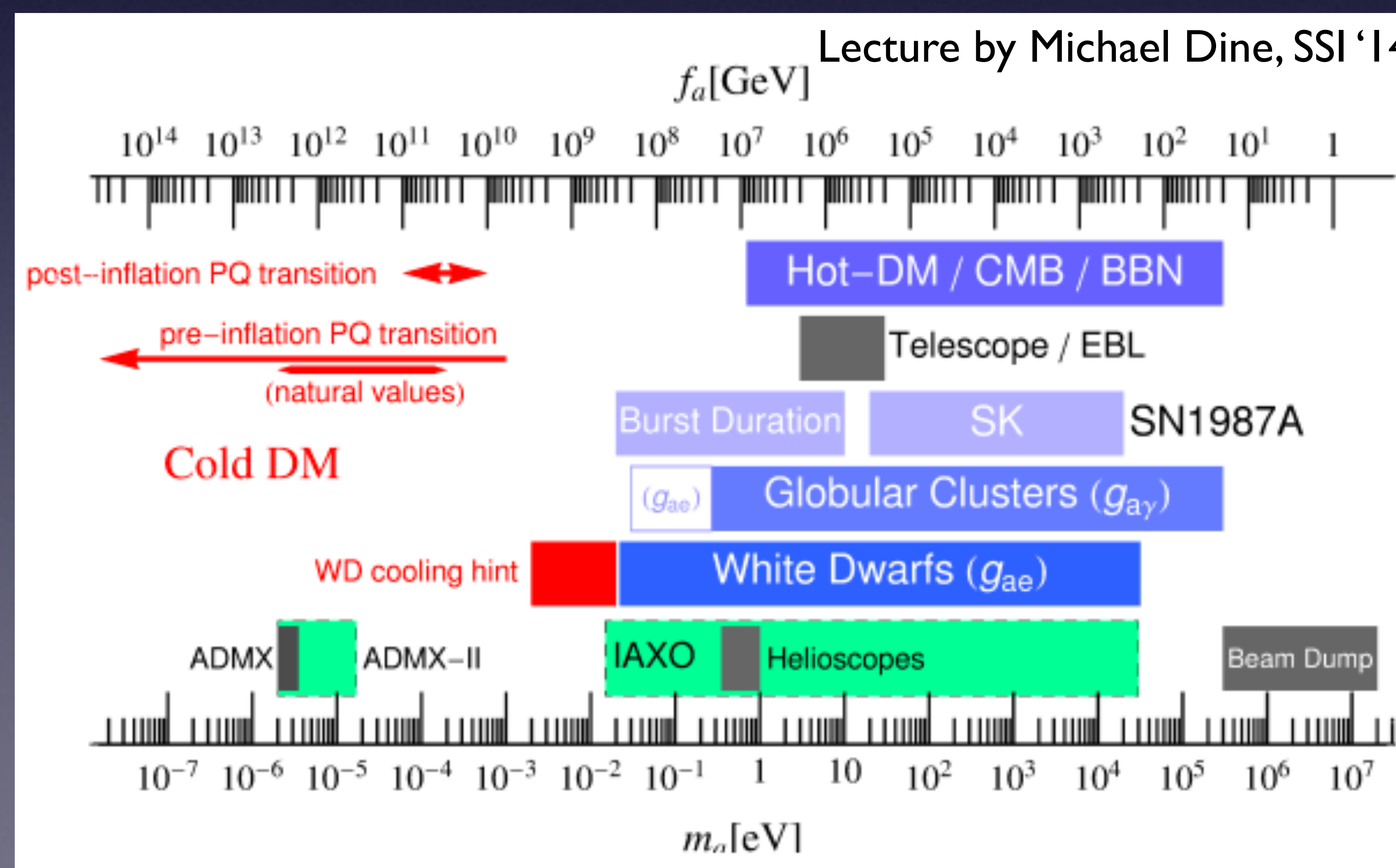
Searching for axions

- Main observable property of axions (except possibly for gravitational effects) is their coupling to the photon
- Axions can convert <u>into</u> photons in the presence of a magnetic field
- Axions interact much more weakly than photons - can carry energy through regions where photons would be absorbed
  - Can induce strong B-field, look for signs of axion production
  - Or study astrophysical systems where photon absorption is high

axion-photon interaction in presence of magnetic field

$$G_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} = G_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$





Lecture by Michael Dine, SSI ‘14

Summary

- We have discussed the basic properties and cosmology of two major categories of DM models
  - Weakly Interacting Massive Particles (WIMPs)
  - axions
- These furnish examples of non-thermal vs thermal production of the observed relic density
- Very different mass scales (<meV vs GeV-TeV)
- Very different couplings to known particles + detection methods (to be discussed in more depth in later lectures)
- These are not all-encompassing examples! There are (many) models which don't fit into either category - but these two broad scenarios are most popular, and give a sense of the scope of possibilities.