OUTLINE

LECTURE 1

Essential Cosmology: Contents and History of the Universe

LECTURE 2

WIMP Dark Matter: Candidates and Methods of Detection

LECTURE 3

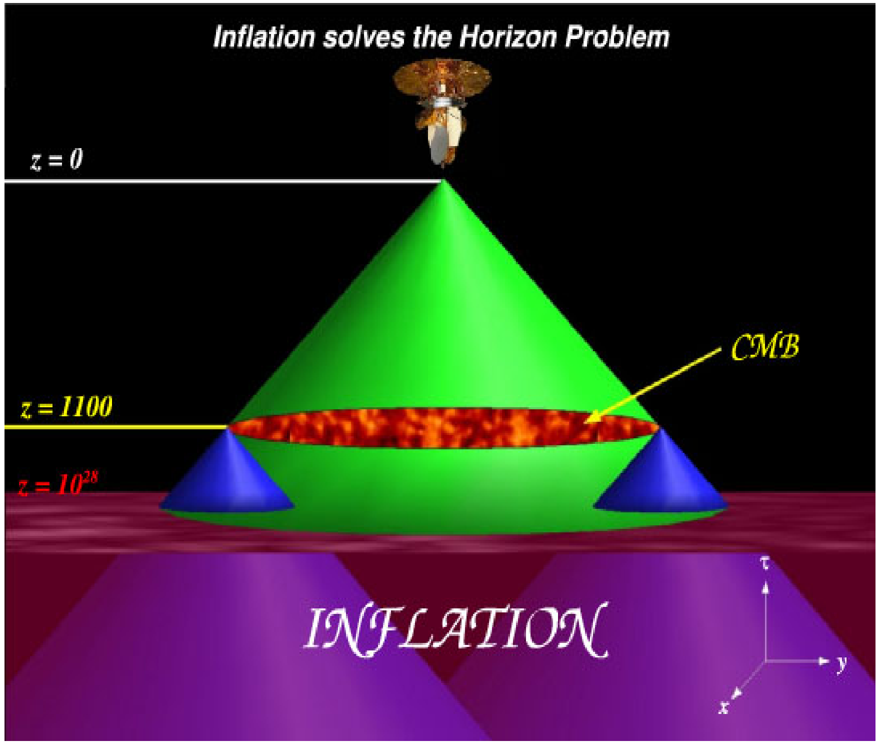
Inflation, Gravitinos, and Hidden Sectors

INFLATION

- The standard model of cosmology includes not just the hot Big Bang we have described, but also an earlier period of inflation with vacuum-dominated expansion:

$$\text{VD}: \rho \propto a^0 \Rightarrow \dot{a}^2 \propto a^2 \Rightarrow a \propto e^{ct}$$

- Inflation has many motivations. One is the horizon problem: Why do causally-disconnected parts of the CMB have the same temperature?
- With inflation, these regions of the Universe had the same origin, are causally connected



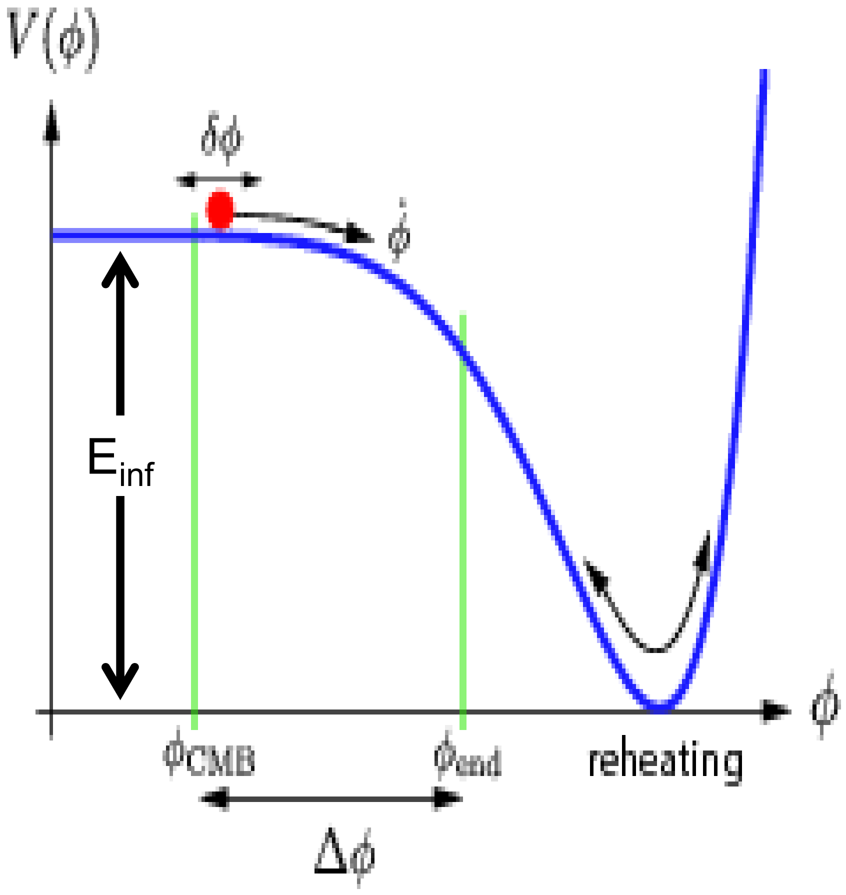
INFLATION

- There are many models of inflation, but the basic picture is simple:

- Initially, the inflaton stays at high potential energy E_{inf} and the Universe expands exponentially

- Eventually the scalar field rolls down, its potential energy is transferred to the SM particles

- The hot Big Bang begins with *reheat temperature* $T_{RH} < E_{inf}$



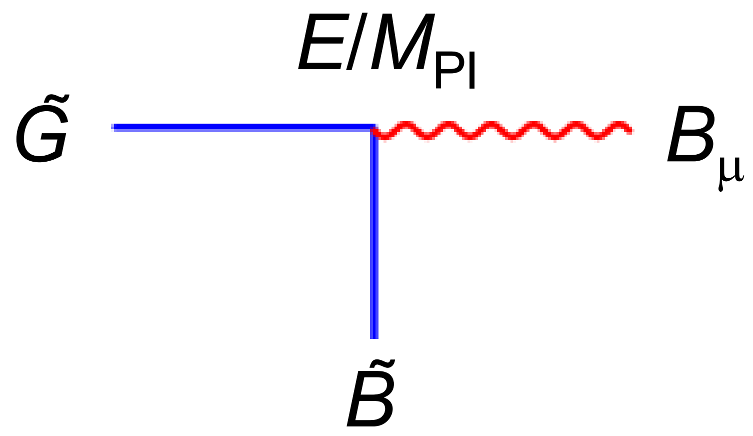
GRAVITINO DARK MATTER

- WIMPs are not the only DM candidates; they are not even the only ones predicted by SUSY: gravitinos provide a nice case study of *very* weakly interacting dark matter
- SUSY: graviton G → gravitino $\tilde{G}$, spin 3/2
- Mass $m_{\tilde{G}} \sim F/M_{\mathrm{Pl}}$, where $F^{1/2}$ is the scale of SUSY breaking
    - Ultra-light (GMSB): $F \sim (100\ \mathrm{TeV})^2$, $m_{\tilde{G}} \sim$ eV
    - Light (GMSB): $F \sim (10^7\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ keV
    - Heavy (SUGRA): $F \sim (10^{11}\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ TeV
    - Obese (AMSB): $F \sim (10^{12}\ \mathrm{GeV})^2$, $m_{\tilde{G}} \sim$ 100 TeV
- The gravitino interaction strength ~ $1/F$
- A huge range of implications for cosmology and HEP

HEAVY GRAVITINOS

- $m_{\tilde{G}} \sim F/M_{\text{Pl}} \sim$ TeV, same scale as the other superpartners
- $\tilde{G}$ interactions: $-\frac{i}{8M_{\text{Pl}}}\bar{\tilde{G}}_\mu \left[\gamma^\nu, \gamma^\rho\right] \gamma^\mu \tilde{B} F_{\nu\rho}$

Couplings grow with energy, but are typically extremely weak



OPTION 1: GRAVITINOS FROM REHEATING

- Inflation dilutes all pre-existing particle densities. But at the end of inflation, the Universe reheats and can regenerate particles. Assume the reheat temperature is between the TeV and Planck scales.

- What happens? A question of rates:

$$\sigma_{\mathrm{SM}} n \sim T \gg H \sim \frac{T^2}{M_{\mathrm{Pl}}} \gg \sigma_{\tilde{G}} n \sim \frac{T^3}{M_{\mathrm{Pl}}^2}$$

SM interaction rate >> expansion rate >> $\tilde{G}$ interaction rate

- Thermal bath of MSSM particles X: occasionally they interact to produce a gravitino: X X → X $\tilde{G}$

GRAVITINO RELIC DENSITY

- The Boltzmann equation:

$$\frac{dn}{dt} = \underset{\substack{\uparrow \\ \text{Dilution from} \\ \text{expansion}}}{-3Hn} - \langle \sigma v \rangle \left[\underset{\substack{\uparrow \\ f\tilde{G} \to f\bar{f}}}{\cancelto{0}{n^2}} - \underset{\substack{\nwarrow \\ f\bar{f} \to f\tilde{G}}}{n_{\text{eq}}^2} \right]$$

- Change variables:
  Entropy density s ~ T^3

$$t \to T \qquad n \to Y \equiv \frac{n}{s}$$

- New Boltzmann equation:

$$\frac{dY}{dT} = -\frac{\langle \sigma_{\tilde{G}} v \rangle}{HTs} n^2 \sim \langle \sigma_{\tilde{G}} v \rangle \frac{T^3 T^3}{T^2 T T^3}$$

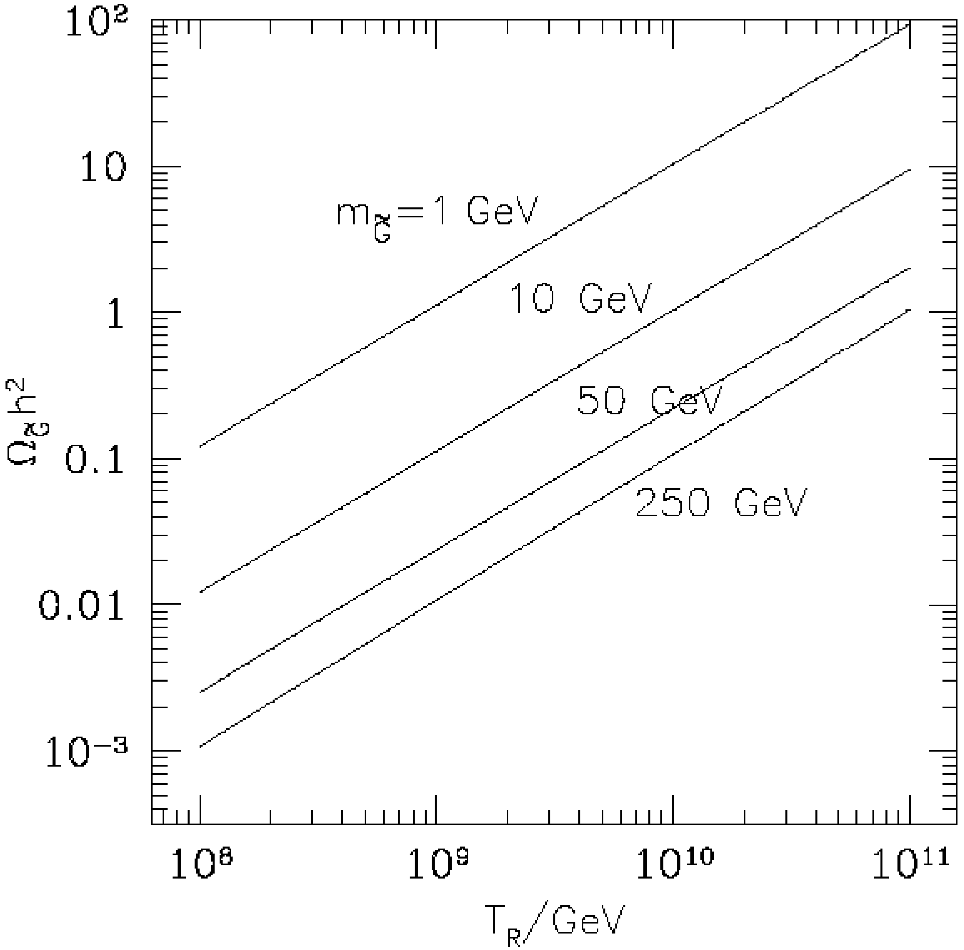
- Simple: Y ~ reheat temperature T_{RH}

BOUNDS ON T_{RH}

- $\langle\sigma v\rangle$ for important production processes:

	process i	$\lvert\mathcal{M}_i\rvert^2/\frac{g^2}{M^2}\left(1+\frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right)$
A	$g^a + g^b \longrightarrow \tilde{g}^c + \tilde{G}$	$4(s+2t+2\frac{t^2}{s})\lvert f^{abc}\rvert^2$
B	$g^a + \tilde{g}^b \longrightarrow g^c + \tilde{G}$	$-4(t+2s+2\frac{s^2}{t})\lvert f^{abc}\rvert^2$
C	$\tilde{q}_i + g^a \longrightarrow q_j + \tilde{G}$	$2s\lvert T^a_{ji}\rvert^2$
D	$g^a + q_i \longrightarrow \tilde{q}_j + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
E	$\bar{\tilde{q}}_i + q_j \longrightarrow g^a + \tilde{G}$	$-2t\lvert T^a_{ji}\rvert^2$
F	$\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \tilde{G}$	$-8\frac{(s^2+st+t^2)^2}{st(s+t)}\lvert f^{abc}\rvert^2$
G	$q_i + \tilde{g}^a \longrightarrow q_j + \tilde{G}$	$-4(s+\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
H	$\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \tilde{G}$	$-2(t+2s+2\frac{s^2}{t})\lvert T^a_{ji}\rvert^2$
I	$q_i + \bar{q}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$-4(t+\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$
J	$\tilde{q}_i + \bar{\tilde{q}}_j \longrightarrow \tilde{g}^a + \tilde{G}$	$2(s+2t+2\frac{t^2}{s})\lvert T^a_{ji}\rvert^2$

- $T_{\mathrm{RH}} < 10^8 - 10^{10}$ GeV; constrains inflation
- $\tilde{G}$ may be all of DM if bound saturated

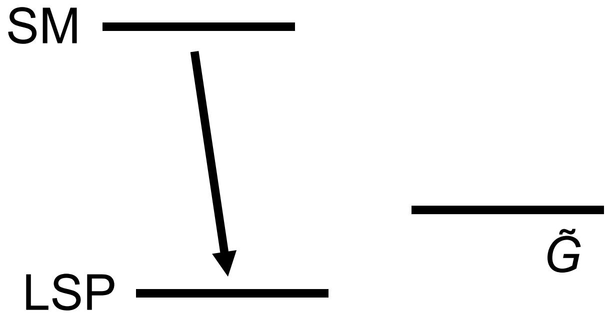


Bolz, Brandenburg, Buchmuller (2001)

OPTION 2: GRAVITINOS FROM LATE DECAYS

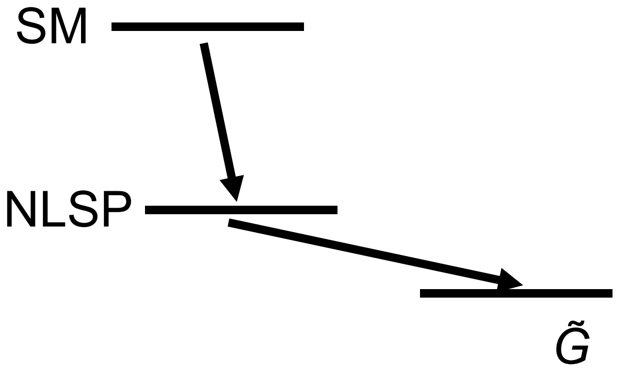
- What if gravitinos are diluted by inflation, and the universe reheats to low temperature? No “primordial” relic density

- $\tilde{G}$ not LSP



- No impact – implicit assumption of most of the literature

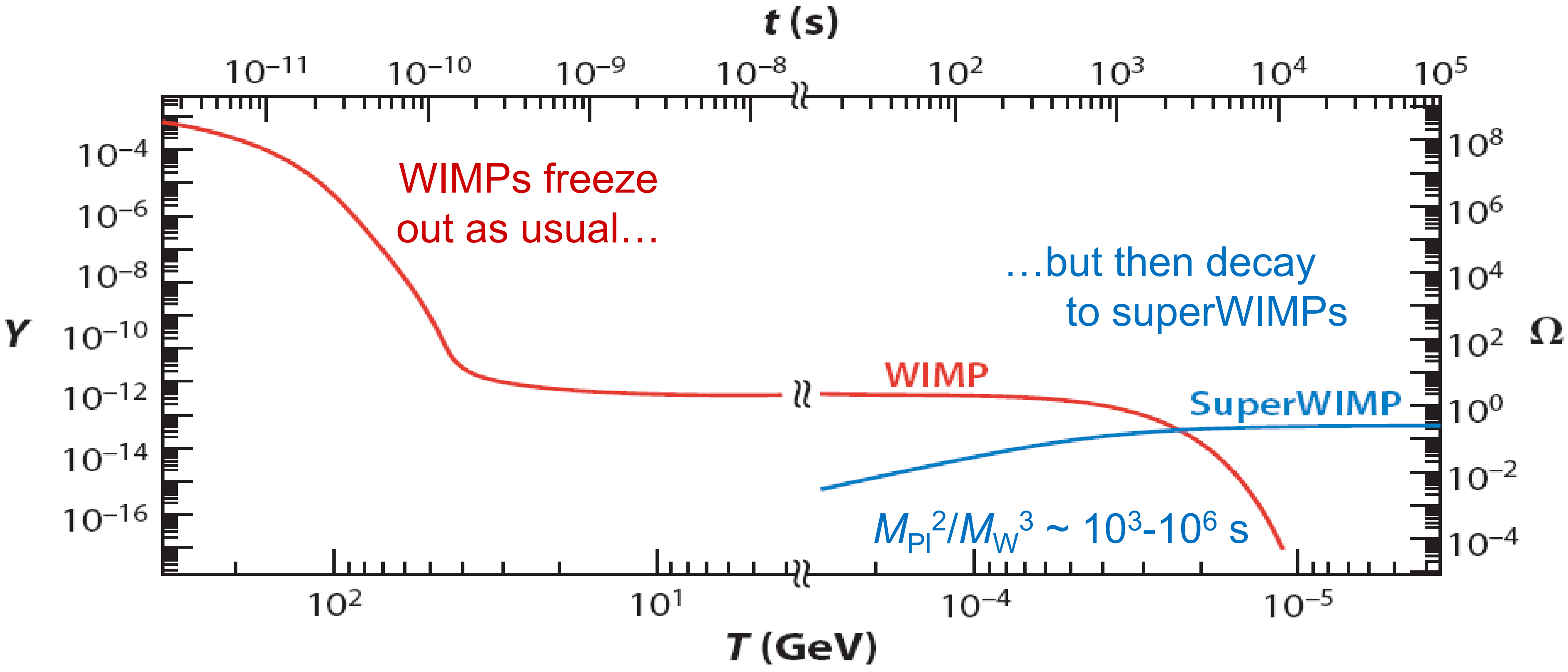
- $\tilde{G}$ LSP



- Completely different particle physics and cosmology

FREEZE OUT WITH SUPERWIMPS

Feng, Rajaraman, Takayama (2003)



WIMPs freeze out as usual…

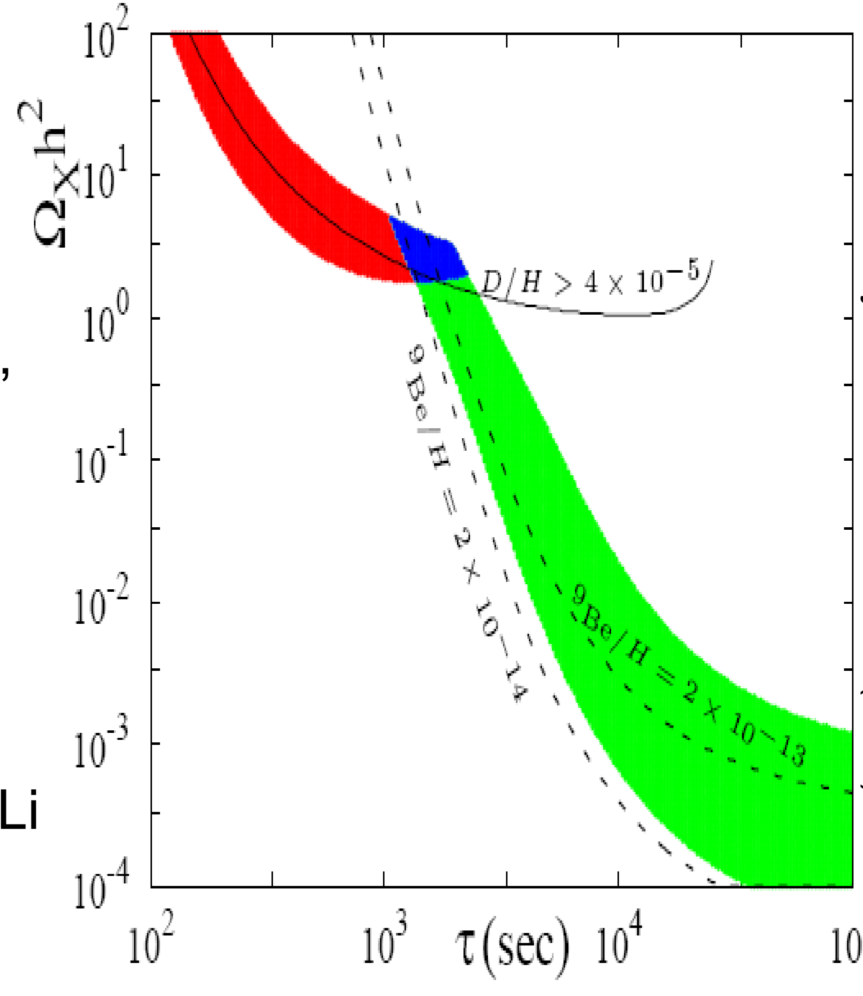
…but then decay to superWIMPs

$M_{Pl}^2/M_W^3 \sim 10^3\text{-}10^6$ s

SuperWIMPs naturally inherit the right density (WIMP miracle), share all the motivations of WIMPs, but are superweakly interacting

LATE DECAYS AND BBN

- Late decays deposit energy into the Universe, potentially destroy the light elements
- Simple way around this is to make decays before T ~ MeV, t ~ 1s
- More ambitious: as we saw previously, ^{7}Li does not agree with standard BBN prediction
  - Too low by factor of 3, ~5σ at face value
  - May be solved by convection in stars, but then why so uniform?
- Also the standard BBN prediction for ^{6}Li may be too low
- Decays after 1 s can possibly fix both



Bailly, Jedamzik, Moultaka (2008)

COSMIC MICROWAVE BACKGROUND

- Late decays may also distort the black body CMB spectrum
- For 10^5 s < τ < 10^7 s, get "μ distortions":

$$\frac{1}{e^{E/(kT)+\mu}-1}$$

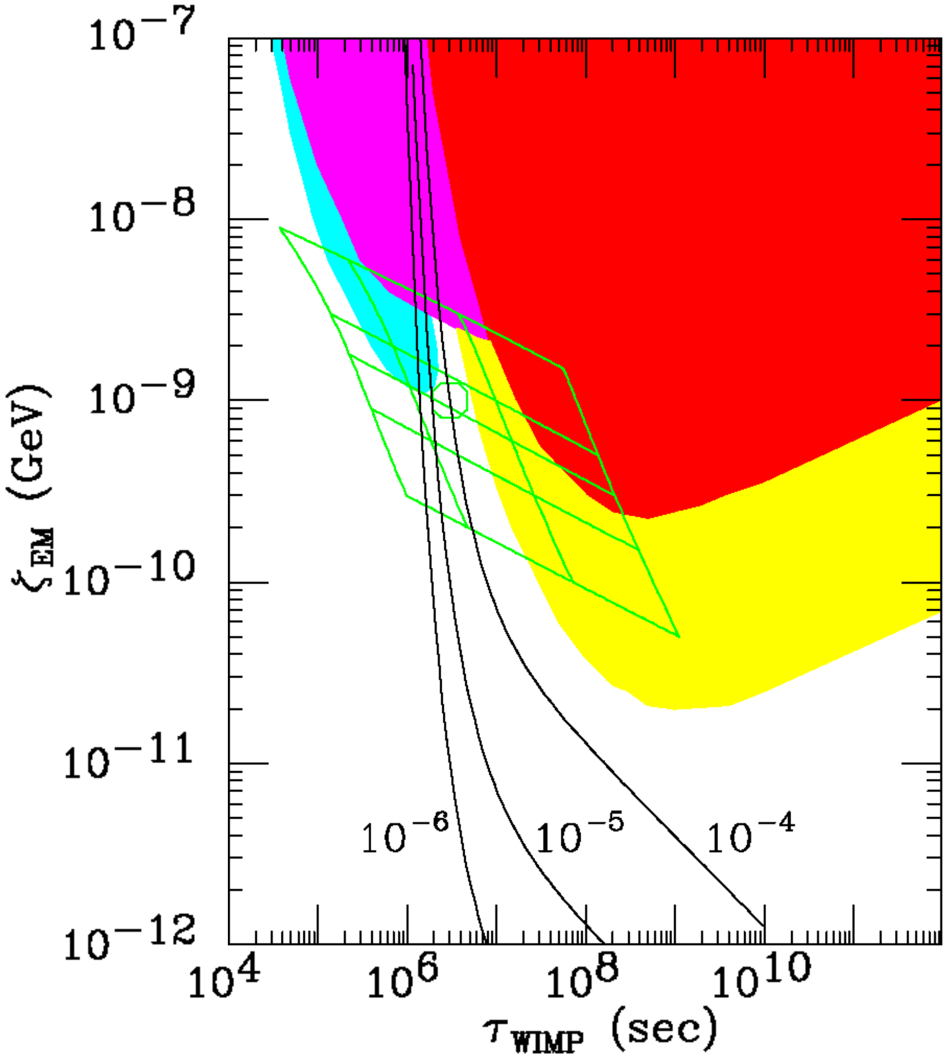
μ=0: Planckian spectrum

$\mu \neq 0$: Bose-Einstein spectrum

Hu, Silk (199

- Current bound: $|\mu| < 9 \times 10^{-5}$

Future: possibly $|\mu| \sim 5 \times 10^{-8}$



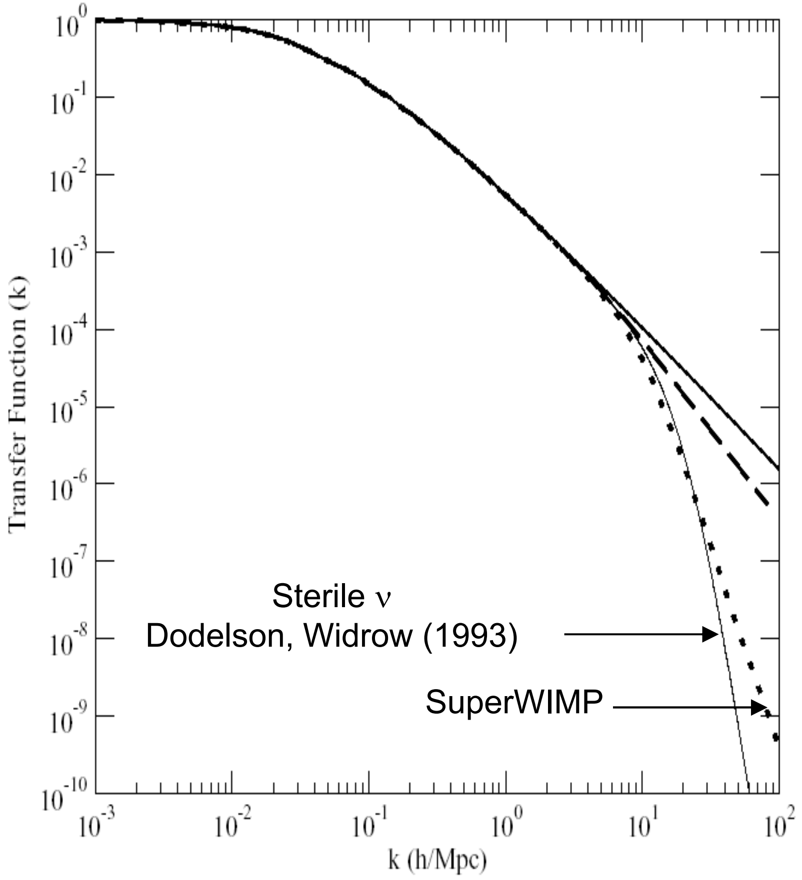
Feng, Rajaraman, Takayama (2003)

WARM DARK MATTER

- SuperWIMPs are produced in late decays with large velocity (0.1c – c)
- This motion prevents them from forming potential wells, suppresses small scale structure
- Hot DM, like active neutrinos, is excluded, but SuperWIMPs could be warm. This is quantified by the free-streaming scale

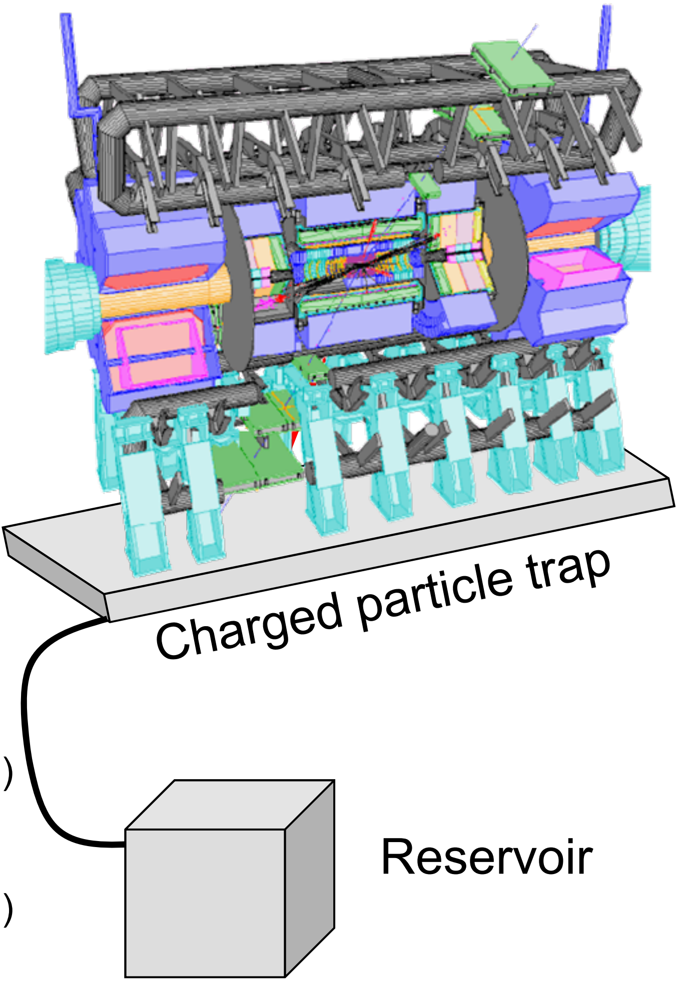
$$\lambda_{\mathrm{FS}} = \int_{\tau_X}^{t_{\mathrm{EQ}}} \frac{v(t)dt}{a(t)}$$

- Warm DM with cold DM pedigree



Kaplinghat (2005)

IMPLICATIONS FOR THE LHC



- SuperWIMP DM → metastable particles, may be charged
- Signature of new physics is “stable”, charged, massive particles, not misssing E_T
- If stable on timescales of s to months, can collect these particles and study their decays. Several ideas
  - Catch sleptons in a 1m thick water tank

    Feng, Smith (2004)
  - Catch sleptons in LHC detectors

    Hamaguchi, Kuno, Nakawa, Nojiri (2004)
  - Dig sleptons out of detector hall walls

    De Roeck et al. (2005)

WHAT WE COULD LEARN FROM CHARGED PARTICLE DECAYS

$$\tau(\tilde{l} \rightarrow l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of τ , $m_{\tilde{l}}$ and E_l → $m_{\tilde{G}}$ and G_N
  - Probes gravity in a particle physics experiment
  - Measurement of G_N on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines F : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

LIGHT GRAVITINO DM

- The original SUSY DM scenario
  - Universe cools from high temperature
  - Gravitinos decouple while relativistic, $\Omega_{\tilde{G}} h^2 \approx m_{\tilde{G}} / 800$ eV
  - Favored mass range: keV gravitinos

Pagels, Primack (1982)

- This minimal scenario is now excluded
  - $\Omega_{\tilde{G}} h^2 < 0.1 \rightarrow m_{\tilde{G}} < 80$ eV
  - Gravitinos not too hot → $m_{\tilde{G}} >$ few keV
  - keV gravitinos are now the most disfavored

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)
Seljak, Makarov, McDonald, Trac (2006)

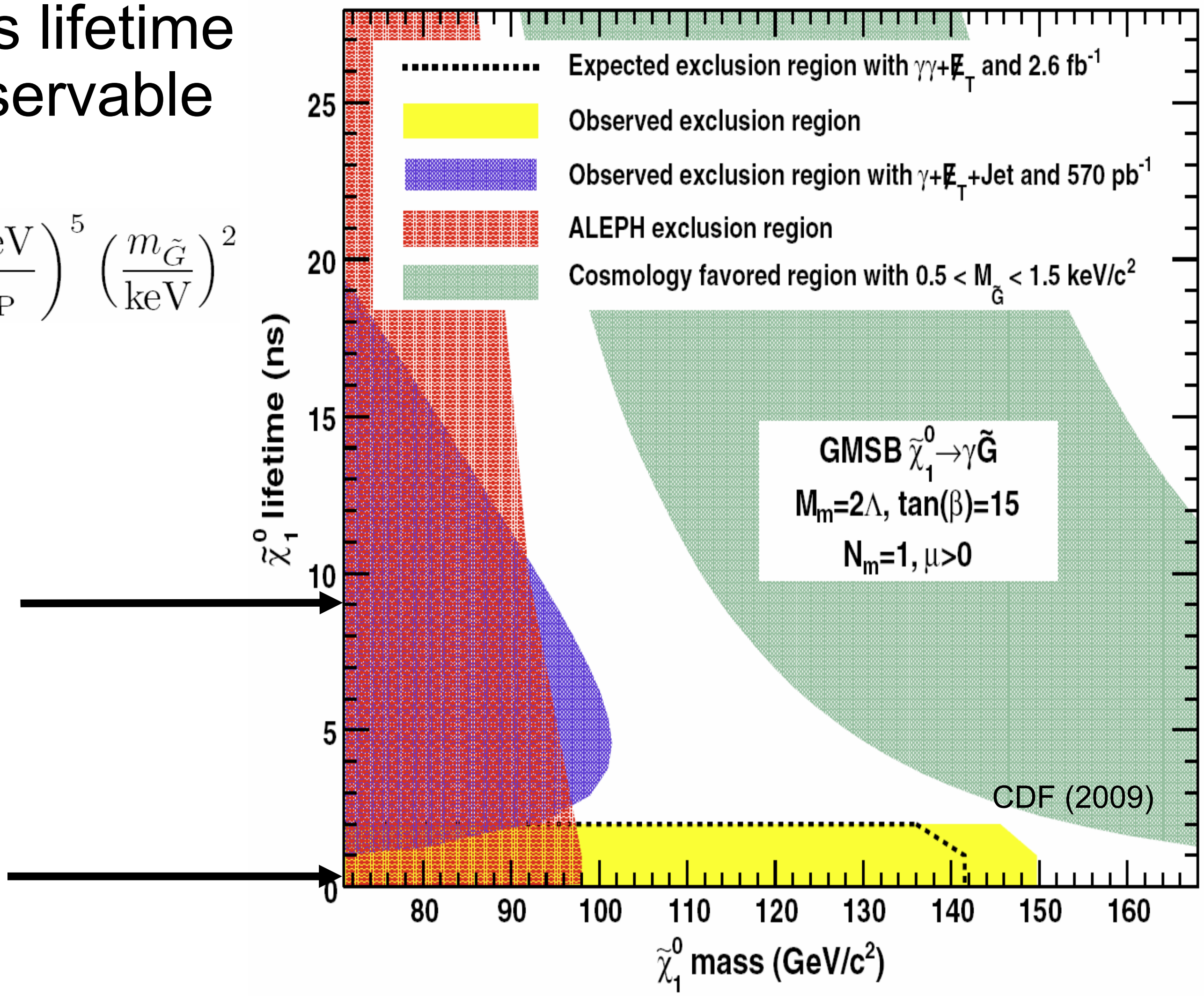
- Two ways out
  - ΛWDM: $m_{\tilde{G}} >$ few keV. Gravitinos are all the DM, but thermal density is diluted, e.g., by low reheating temperature
  - ΛWCDM: $m_{\tilde{G}} < 16$ eV. Gravitinos are only part of the DM, mixed warm-cold scenario

CURRENT BOUNDS

- Remarkably, this lifetime difference is observable at colliders!

$$c\tau_{\rm NLSP} \approx 50 \text{ cm} \left(\frac{200 \text{ GeV}}{m_{\rm NLSP}} \right)^5 \left(\frac{m_{\tilde{G}}}{\rm keV} \right)^2$$

- $m_{\tilde{G}}$ > few keV: Delayed photon signatures
- $m_{\tilde{G}}$ < 16 eV: Prompt photon signatures



HIDDEN SECTORS

- All current evidence for DM is gravitational. Perhaps DM is in a hidden sector, composed of particles with no SM strong, weak, or electromagnetic interactions

- *A priori* there are both pros and cons
  - Lots of freedom: can have interesting new phenomena
  - Too much freedom: no connections to the problems of particle physics we would like to solve, WIMP miracle, ...

HIDDEN SECTOR INTERACTIONS

- There are many ways the hidden particles could couple to us. How should we think about this?

- Use effective operators as an organizing principle:

$$\mathcal{L} = \mathcal{O}_4 + \frac{1}{M}\mathcal{O}_5 + \frac{1}{M^2}\mathcal{O}_6 + \ldots$$

  where the operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [$F_{\mu\nu}$] = 2

- *M* is a (presumably) large "mediator mass," so we expect high-dimension operators to be suppressed. There are not too many possibilities at dimension 4.

HIGGS PORTAL

Patt, Wilczek (2006)

- One possibility is

$$h^\dagger h \phi_h^\dagger \phi_h$$

where the *h* subscript denotes "hidden"

- When EW symmetry is broken, h → v + h, this leads to invisible Higgs decays

- A leading motivation for precision Higgs studies and future colliders, such as ILC, CLIC, FCC

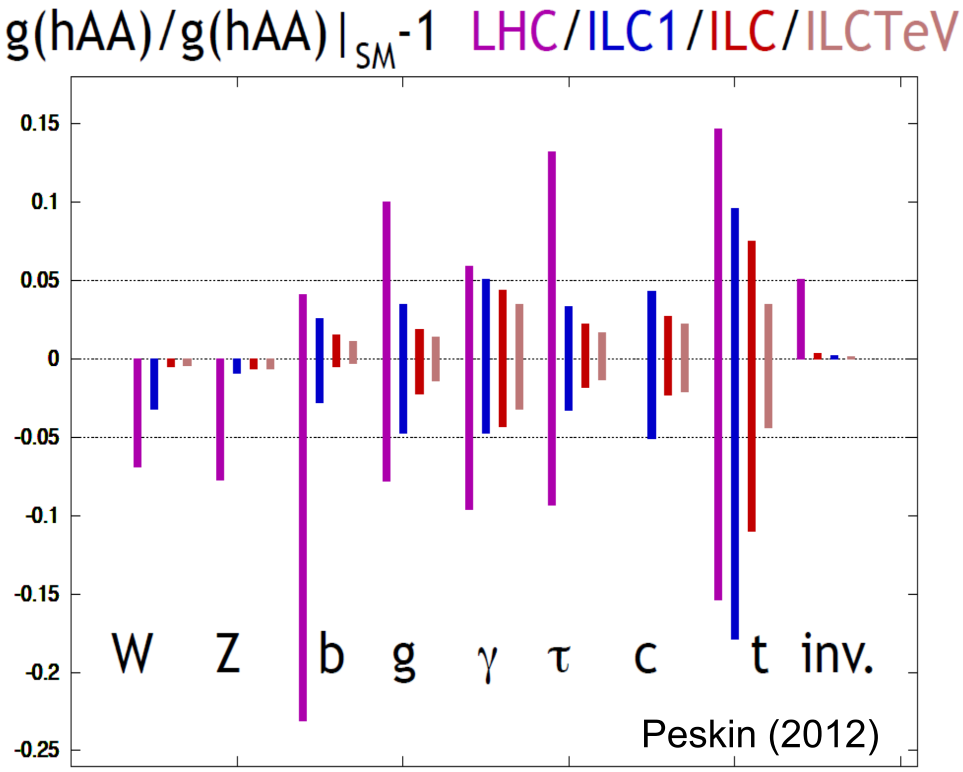


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

HIDDEN PHOTONS

Holdom (1986)

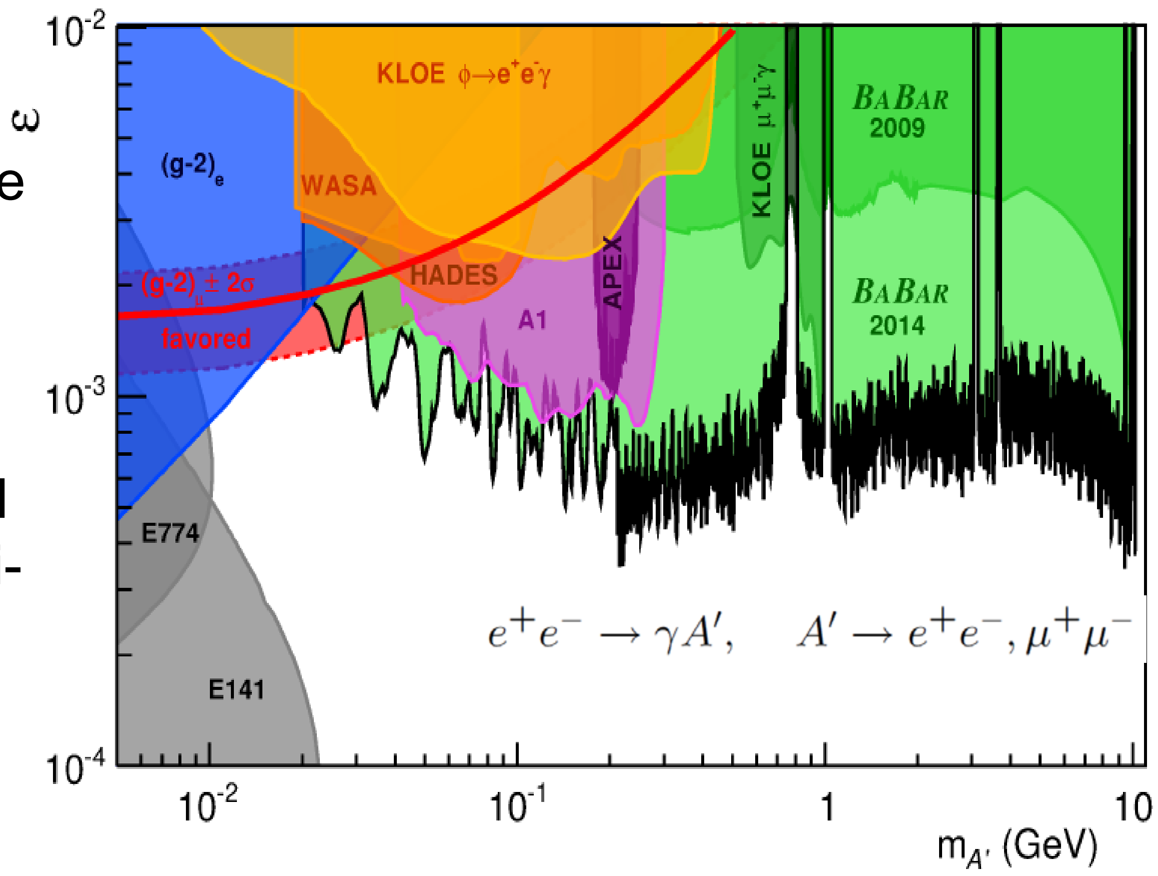
- Another possibility is $$\epsilon F_{\mu\nu} F_h^{\mu\nu}$$

  which leads to mixing between the SM photon γ and a hidden photon A’, which must have a mass

- The hidden photon cannot be the DM, but may be a portal to the dark sector

- Diagonalizing the mass matrix, one finds that the SM particles have a hidden “milli-charge” proportional to ε

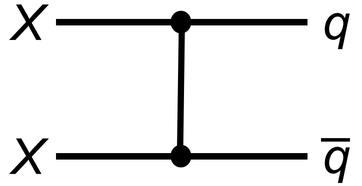
- Motivates searches at the “intensity frontier”



HIDDEN SECTOR FREEZEOUT

- The thermal relic density

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

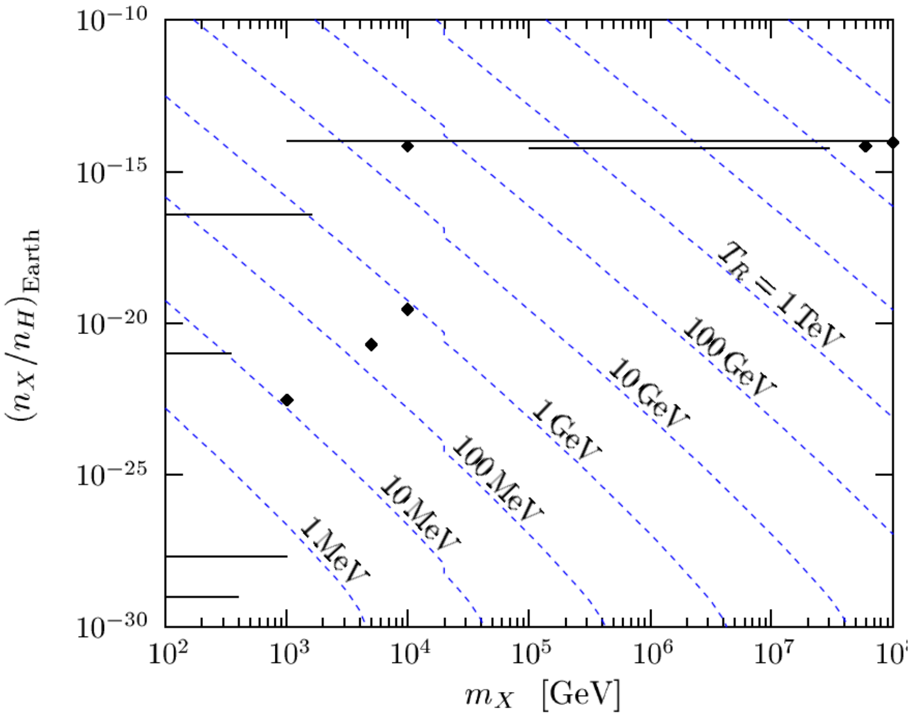


constrains only one combination of mass and coupling

- In the SM, however, we only have a few choices
  - Weak coupling: $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$
  - EM and strong: highly constrained

CHARGED STABLE RELICS

- Charged stable relics create anomalously heavy isotopes
- Severe bounds from sea water searches
- Inflation can dilute this away, but there is an upper bound on the reheating temperature



Kudo, Yamaguchi (2001)

Masses < TeV are excluded by T_{RH} > 1 MeV,
but masses > TeV are allowed

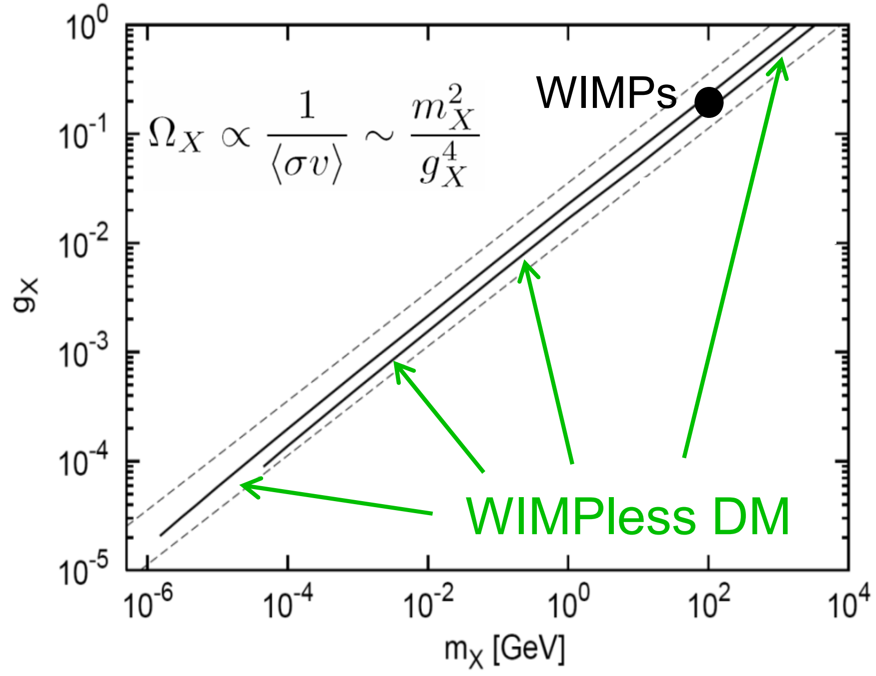
THE WIMPLESS MIRACLE

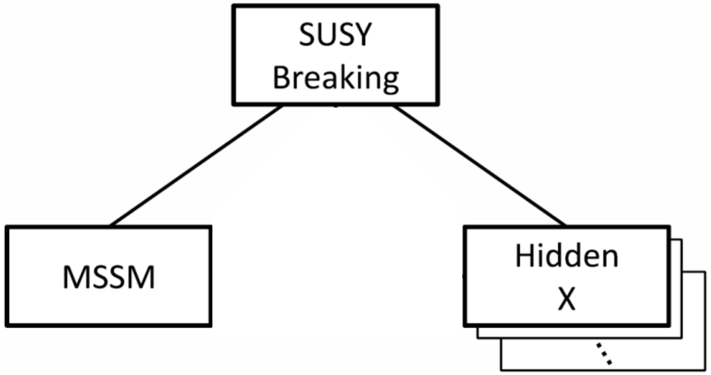
Feng, Kumar (2008); Feng, Tu, Yu (2009); Feng, Shadmi (2011)

- In a hidden sector, we can have other couplings
- In fact, in many SUSY models, to avoid unseen flavor effects, superpartner masses satisfy

$$m_X \sim g_X^2$$

- If this holds in a hidden sector, we have a "WIMPless Miracle": hidden sectors of these theories automatically have DM with the right Ω (but they aren't WIMPs)
- Is this what the new physics flavor problem is telling us?

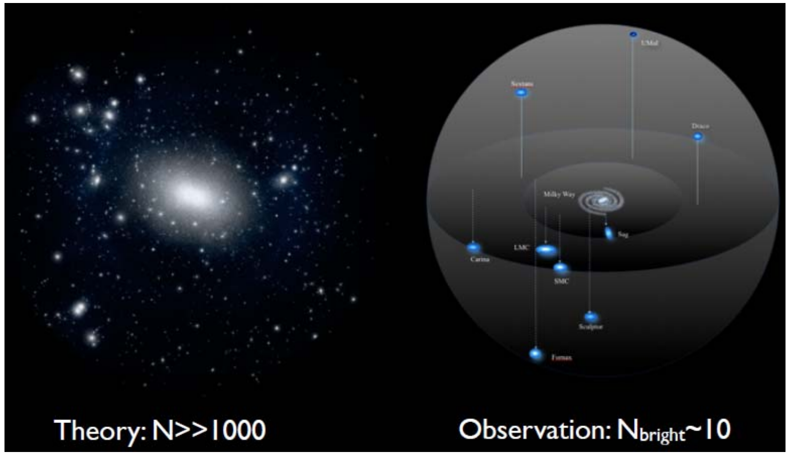


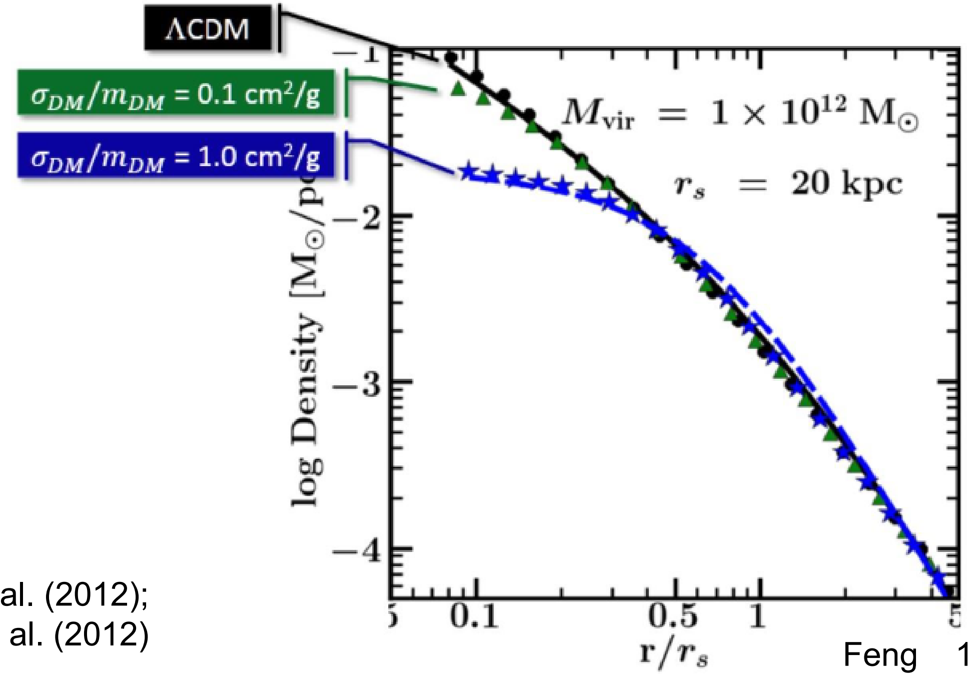


SELF-INTERACTING DARK MATTER

- If dark matter is completely hidden, can we learn anything about it?
- The Bullet Cluster provided evidence for dark matter. But the fact that dark matter passed through unperturbed →

  $\sigma_T/m < 1\ \mathrm{cm}^2/\mathrm{g}$ (or barn/GeV)
- But there are indications that the self-interactions may be near this limit
  - Cusps vs. cores
  - Number of visible dwarf galaxies





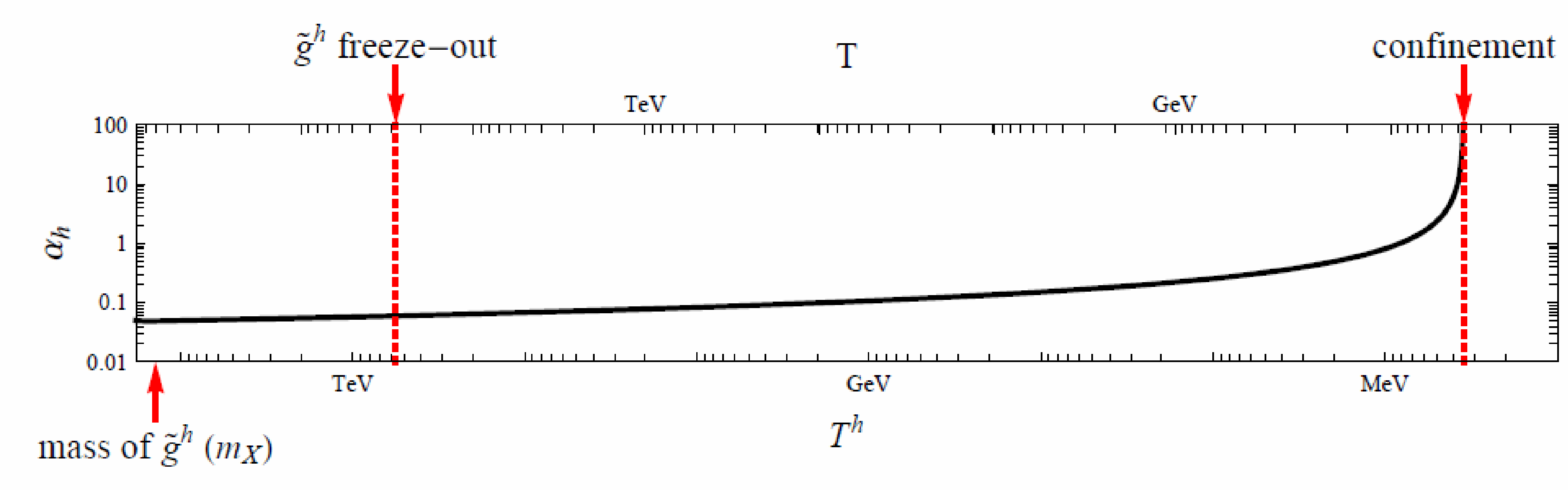
Rocha et al. (2012), Peter et al. (2012); Vogelsberger et al. (2012); Zavala et al. (2012)

DARK MATTER FROM HIDDEN QCD

Feng, Shadmi (2011), Boddy, Feng, Kaplinghat, Tait (2014)

- A simple example: pure SU(N) with hidden gluons g and gluinos $\tilde{g}$
- At early times, interaction is weak, ~10 TeV $\tilde{g}$ freezeout with correct Ω

  At late times, interaction is strong, glueballs (gg) and glueballinos ($g\tilde{g}$) form and self-interact with σ_T/m ~ 1 cm^2/g ~ 1 barn/GeV



- WIMP-like: TeV-masses with correct thermal relic density
- But completely different: self-interacting, multi-component dark matter

LECTURE 3 SUMMARY

- In addition to WIMPs, there are many other attractive DM candidates with similar motivations, but completely different implications for cosmology and HEP

- Examples: long-lived charged particles, prompt photons, invisible Higgs decays, hidden photons, …

- Is any of this right? LHC will be running soon, direct and indirect detection, astrophysical probes are improving rapidly – we will see soon