Warm Dark Matter and the LHC

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Warm dark matter = less power at small scales

Non-negligible initial velocity dispersion of dark matter particles

Free streaming

At time t free streaming length

$$l_{fs}(t) \sim v(t) \cdot t$$

Particle velocity

$$v = \frac{p}{m} = \frac{p}{T}\frac{T}{m}$$

At radiation-matter equality (beginning of rapid growth of perturbations)

$$l_{fs}(t_{eq}) \sim \frac{p}{T}\frac{T_{eq}t_{eq}}{m}$$

Perturbations at smaller scales are suppressed.

Present size

$$l_0 \sim (1+z_{eq}) \cdot \frac{p}{T} \frac{T_{eq} t_{eq}}{m}$$

- $\frac{p}{T} \simeq 3$ (if relativistic thermal-like distribution at decoupling)
- $z_{eq} \simeq 3000$, $T_{eq} \simeq 1$ eV, $t_{eq} \simeq 60$ kyr $\simeq 20$ kpc $\Longrightarrow$

$$l_0 \sim 200 \text{ kpc} \cdot \frac{1 \text{ keV}}{m}$$

Mass of less abundant objects

$$M \lesssim \rho_{DM} \cdot \frac{4}{3} \pi l_0^3 \sim 10^9 M_\odot \cdot \left(\frac{1 \text{ keV}}{m} \right)^3$$

Cf. dwarf galaxies, $M_{dwarf} \sim 10^8 \div 10^9 M_\odot$.

NB: In fact, it is sufficient to suppress perturbations at radiation domination epoch only, so this is underestimate of M.

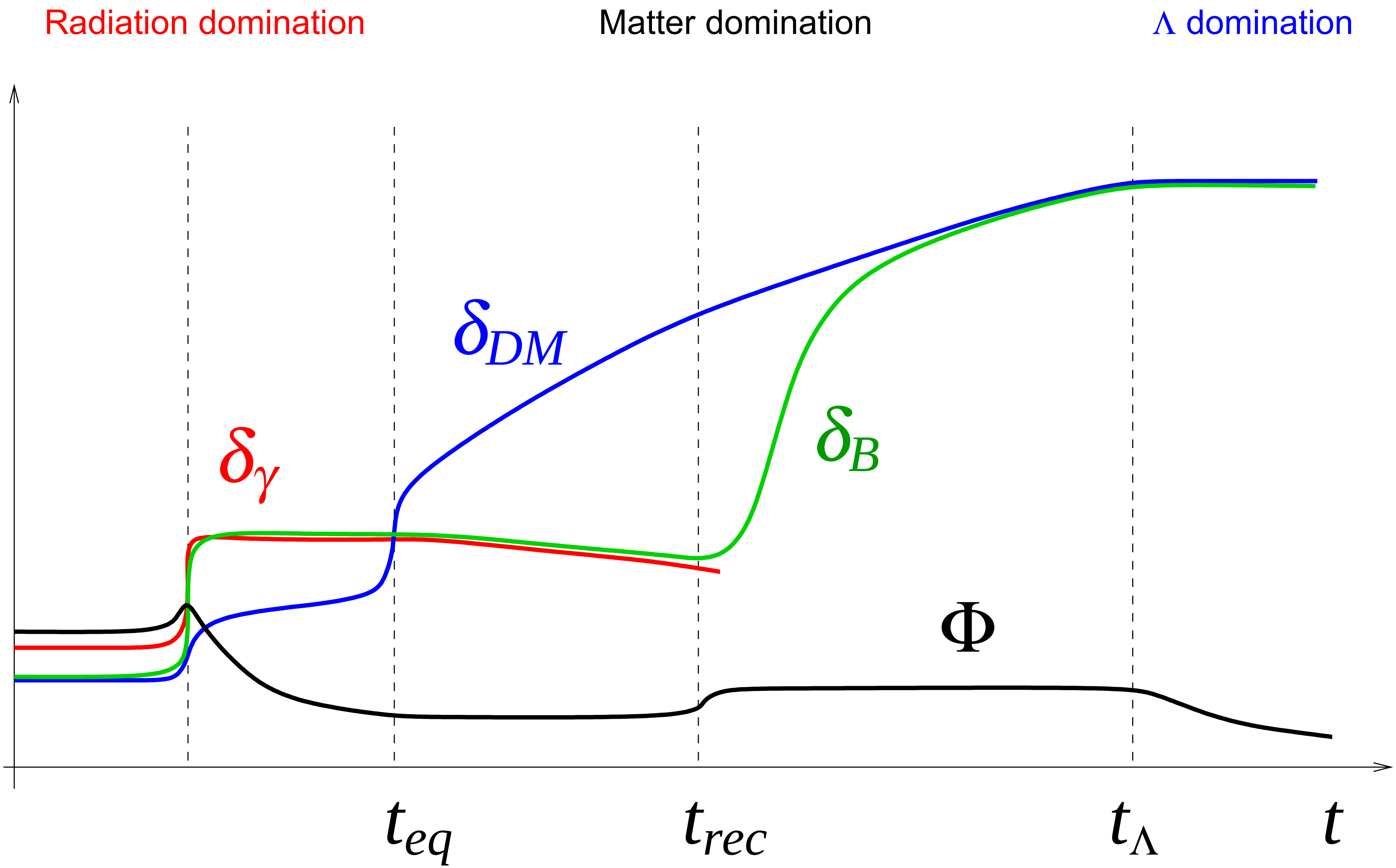
Matter domination epoch: matter perturbations grow as
$\frac{\delta\rho}{\rho}(t) \propto a(t) \propto T^{-1}$

$$\Longrightarrow \qquad \delta(t_0) \equiv \left(\frac{\delta\rho}{\rho}\right)_{today} \simeq 3000 \times \delta(t_{eq})$$

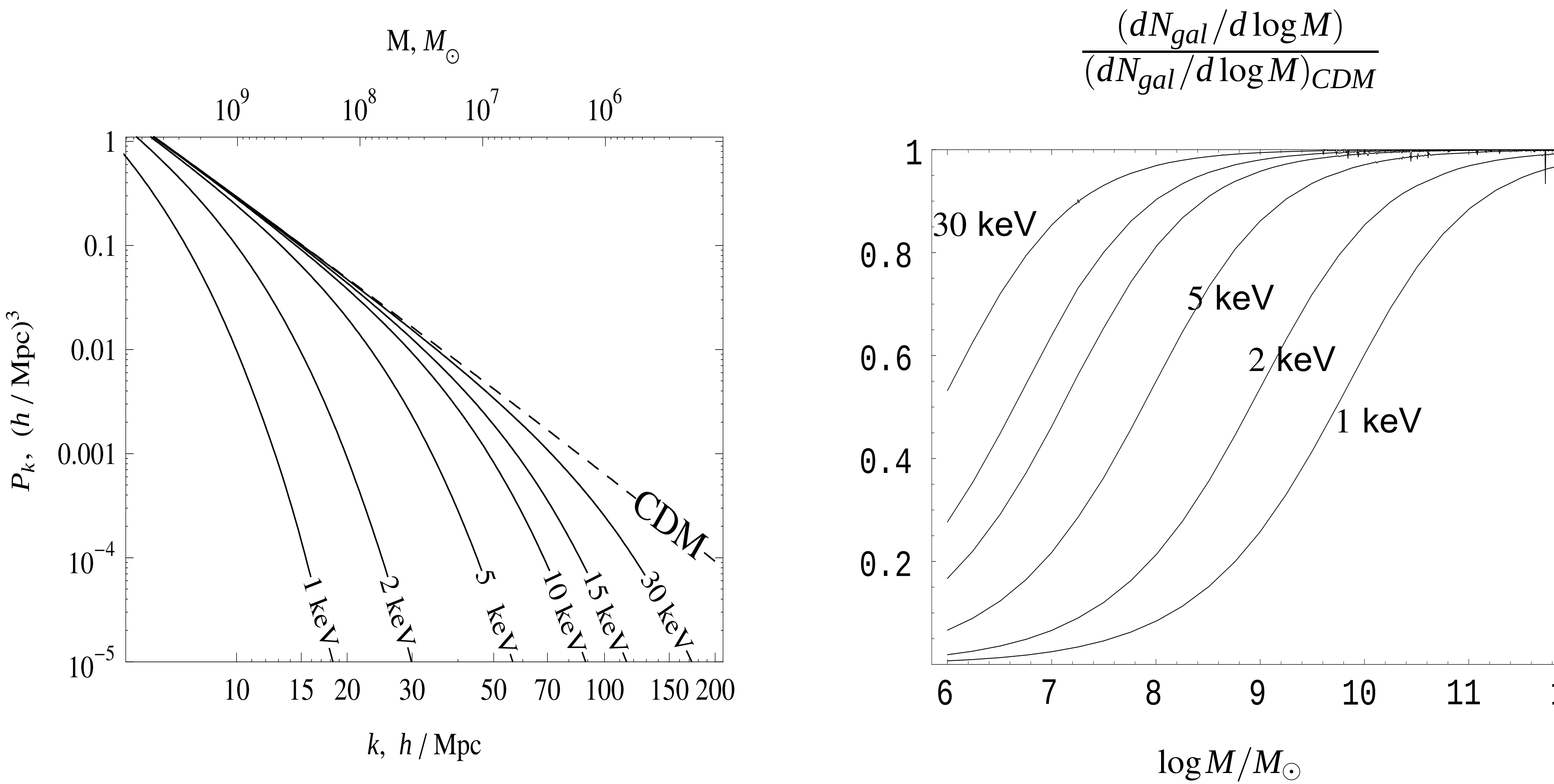
Cf. primordial perturbations $\delta_i \sim 3 \cdot 10^{-5}$ (CMB).

Additional growth factor comes from radiation domination epoch

Growth of perturbations (linear regime)



Power spectrum of perturbations

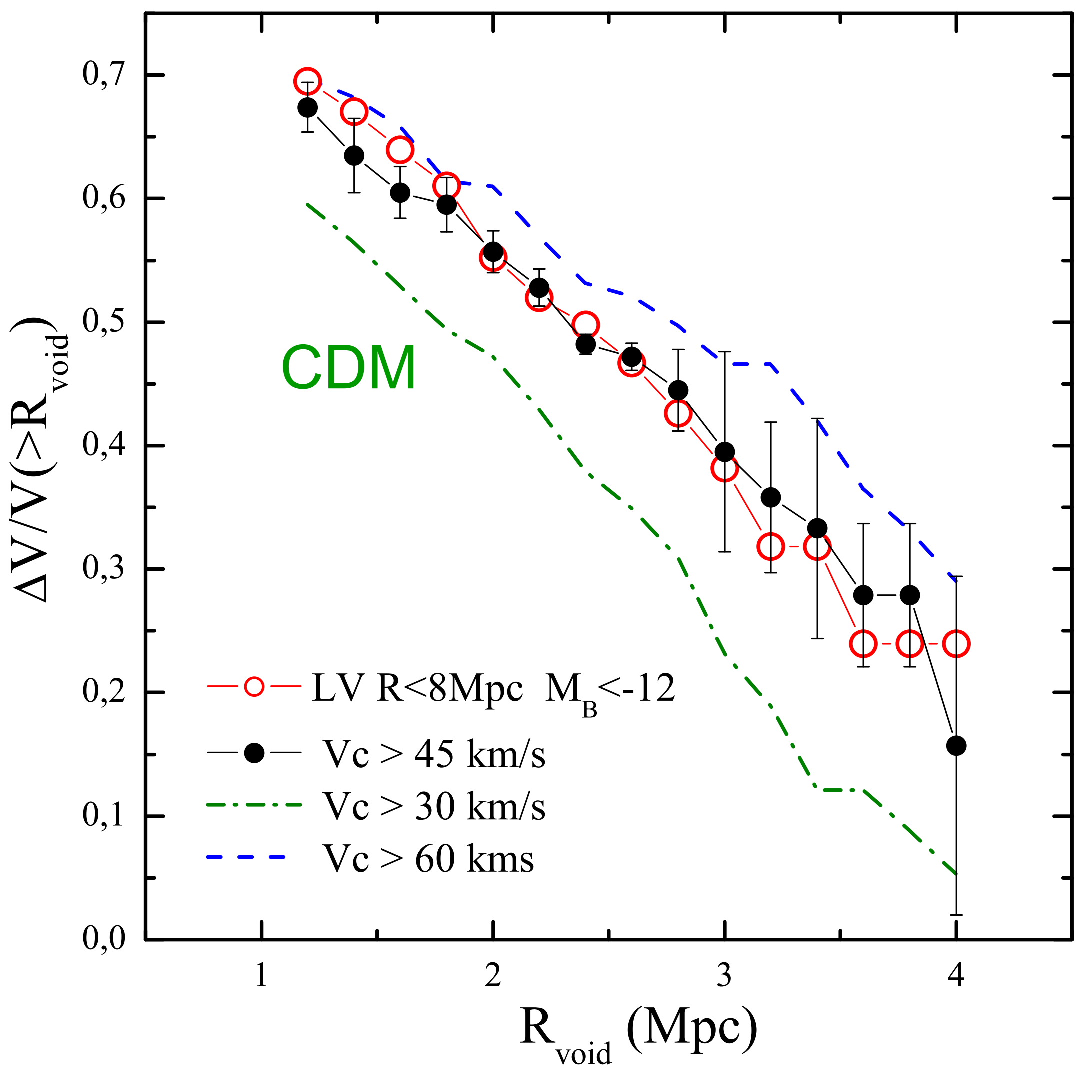


Assuming thermal primordial distribution normalized to $\Omega_{DM} \simeq 0.2$.

WDM may even be better than CDM

Distribution of voids in our neighbourhood

Tikhonov, Klypin



CDM appears to produce too many dwarf galaxies

Still unclear

Warm dark matter: phase space bounds

Tremaine, Gunn
Hogan, Dalcanton;
Boyanovsky et.al., ...

- Initial phase space density of dark matter particles: $f(\vec{p})$, independent of $\vec{x}$.

  Fermions:

$$f(\vec{p}) \leq \frac{1}{(2\pi)^3} \quad \text{by Pauli principle}$$

NB: Thermal distribution: $f_{max} = \frac{1}{2(2\pi)^3}$

Expect maximum initial phase space density somewhat (maybe considerably) below $(2\pi)^{-3}$

- Non-dissipative motion of particles, gravitatonal interactions only: particles tend to penetrate into empty parts of phase space $\Longrightarrow$ coarse grained distribution decreases in time;

  maximum phase space density also decreases in time.

  initial $f_{max} >$ present $f_{0,max}$

- Observable:

$$Q(\vec{x}) = \frac{\rho_{DM}(\vec{x})}{\langle v_{||}^2 \rangle^{3/2}}$$

$\rho_{DM}(\vec{x}) \Longleftrightarrow$ gravitational potential
$\langle v_{||}^2 \rangle \Longleftrightarrow$ velocities of stars along line of sight.

Assume dark matter particles have same velocities as stars (e.g., virialized)

$$Q \simeq m^4 \frac{n(\vec{x})}{\langle \frac{1}{3} p^2 \rangle^{3/2}} \simeq 3^{3/2} m^4 f_0(\vec{x}, \vec{p})$$

Mass bounds from primordial phase space distribution:

$$m^4 f_{max} > 3^{-3/2} Q_{max}$$

- Largest observed: dwarf galaxies

$$Q_{dwarf} = \left(3 \cdot 10^{-3} \div 2 \cdot 10^{-2}\right) \frac{M_{\odot}/\text{pc}^3}{(\text{km/s})^3}$$

With $M_{\odot} \simeq 1 \cdot 10^{63}$ keV, 1 pc$= 1.5 \cdot 10^{26}$ keV^{-1}, km/s$= 3 \cdot 10^{-6}$

$$\begin{aligned} Q_{dwarf} &= 0.03 \div 0.2 \text{ keV}^4 \\ &< 3^{3/2} \cdot m^4 f_{max} \simeq 3^{3/2} \cdot m^4 \frac{\#}{(2\pi)^3} \end{aligned}$$

$$\Longrightarrow \quad m \gtrsim 1 - 5 \text{ keV} \,,$$

depending on initial distribution function.

Interestingly, ends just meet. For thermal primordial distribution (normalized to Ω_{DM}), dark matter is barely warm, $m \gtrsim 5$ keV

- How many particles should have so high phase space density?

Assume

$$\frac{\text{Dark matter in dwarfs}}{\text{Total dark matter}} \sim 10^{-5}$$

$\Longrightarrow 10^{-5}$ of dark matter particles must have initial $f(\mathbf{p})$ greater than $f_{0,\,dwarf} \simeq Q_{dwarf}/m^4$.

Statistical estimates/bounds for strongly peaked initial distribution functions $f(\mathbf{p})$.

Look into most populated corners of primordial phase space

Madsen

NB: Works for bosons as well

Gravitinos

- One of the best motivated WDM candidates
- Mass $m_{3/2} \simeq F/M_{Pl}$
  $\sqrt{F} =$ SUSY breaking scale.
  $\Longrightarrow$ Gravitinos light for low SUSY breaking scale.
  E.g. gauge mediation
- Light gravitino = LSP $\Longrightarrow$ Stable if R-parity conserved
- Decay width of superpartners into gravitino + SM particles

$$\Gamma_{\tilde{S}} \simeq \frac{M_{\tilde{S}}^5}{F^2}$$

$$\Longrightarrow \qquad \Gamma_{\tilde{S}} = \frac{M_{\tilde{S}}^5}{6\, m_{3/2}^2 M_{Pl}^2}$$

$M_{\tilde{S}}$ = mass of superpartner $\tilde{S}$

Gravitino production in decays of superpartners

Moroi, Murayama; ...

$$\frac{d(n_{3/2}/s)}{dt} = \frac{n_{\tilde{S}}}{s}\Gamma_{\tilde{S}}$$

$s =$ entropy density

$n_{\tilde{S}}/s =$ const $\sim g_*^{-1}$ for $T \gtrsim M_{\tilde{S}}$, while $n_{\tilde{S}} \propto$ e$^{-M_{\tilde{S}}/T}$ for $T \ll M_{\tilde{S}}$
$\Longrightarrow$ production most efficient at $T \sim M_{\tilde{S}}$ (slow cosmological expansion with unsuppressed $n_{\tilde{S}}$)

$$\frac{n_{3/2}}{s} \simeq \frac{\Gamma_{\tilde{S}}}{g_* H(T \sim M_{\tilde{S}})} \simeq \frac{M_{Pl}^*}{g_* M_{\tilde{S}}^2} \cdot \frac{M_{\tilde{S}}^5}{m_{3/2}^2 M_{Pl}^2}$$

Mass-to-entropy ratio

$$\frac{m_{3/2} n_{3/2}}{s} \simeq \frac{M_{\tilde{S}}^3}{m_{3/2}} \frac{1}{g_*^{3/2} M_{Pl}}$$

$$\frac{m_{3/2} n_{3/2}}{s} \simeq \sum_{\tilde{S}} \frac{M_{\tilde{S}}^3}{m_{3/2}} \frac{1}{g_*^{3/2} M_{Pl}}$$

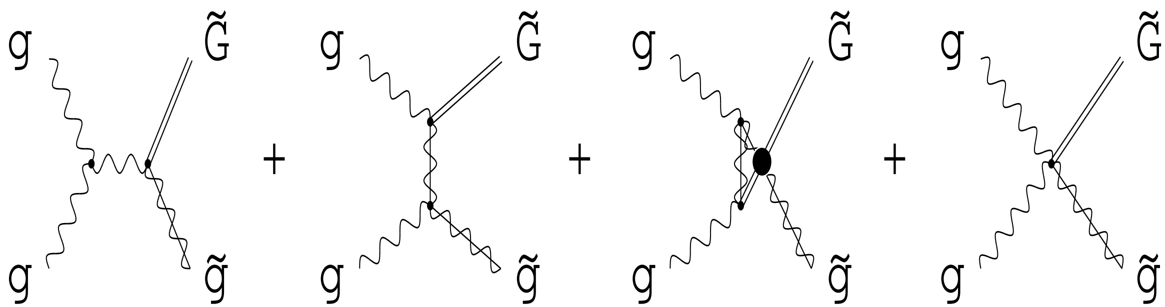
For $m_{3/2} =$ a few keV, mass-to-entropy$= 3 \cdot 10^{-10}$ GeV

$M_{\tilde{S}} \simeq 100 \div 300$ GeV

Need light superpartners

Production in scattering

Moroi et.al.; Boltz et. al.; Pradler; Rychkov, Strumia;...



Gravitino (goldstino) coupling to gauginos, dominant at high temperatures:

$$L_{int} = \frac{M_{\tilde{g}}}{F} \tilde{G}[\gamma^\mu, \gamma^\nu] \tilde{g} F_{\mu\nu} = \frac{M_{\tilde{g}}}{M_{Pl} m_{3/2}} \tilde{G}[\gamma^\mu, \gamma^\nu] \tilde{g} F_{\mu\nu}$$

Gravitinos produced at temperature T (modulo soft logs):

$$\left(m_{3/2} \frac{n_{3/2}}{s} \right)_T \sim g^2 \frac{M_{\tilde{g}}^2}{M_{Pl}^2 m_{3/2}} \frac{n_g}{s} \cdot n_g H^{-1}(T) \propto g^2 \frac{M_{\tilde{g}}^2}{m_{3/2}} T$$

Maximum production at highest possible temperature:

$$\Omega_{\tilde{G}} = \# \cdot g^2 \left(\frac{M_{\tilde{g}}}{100 \text{ GeV}} \right)^2 \cdot \left(\frac{1 \text{ keV}}{m_{3/2}} \right) \cdot \left(\frac{T_R}{1 \text{ TeV}} \right)$$

Need low maximum temperature in the Universe, $T_R \lesssim 1$ TeV to avoid overproduction in collisions.

Rather contrived scenario, but generating warm dark matter is always contrived

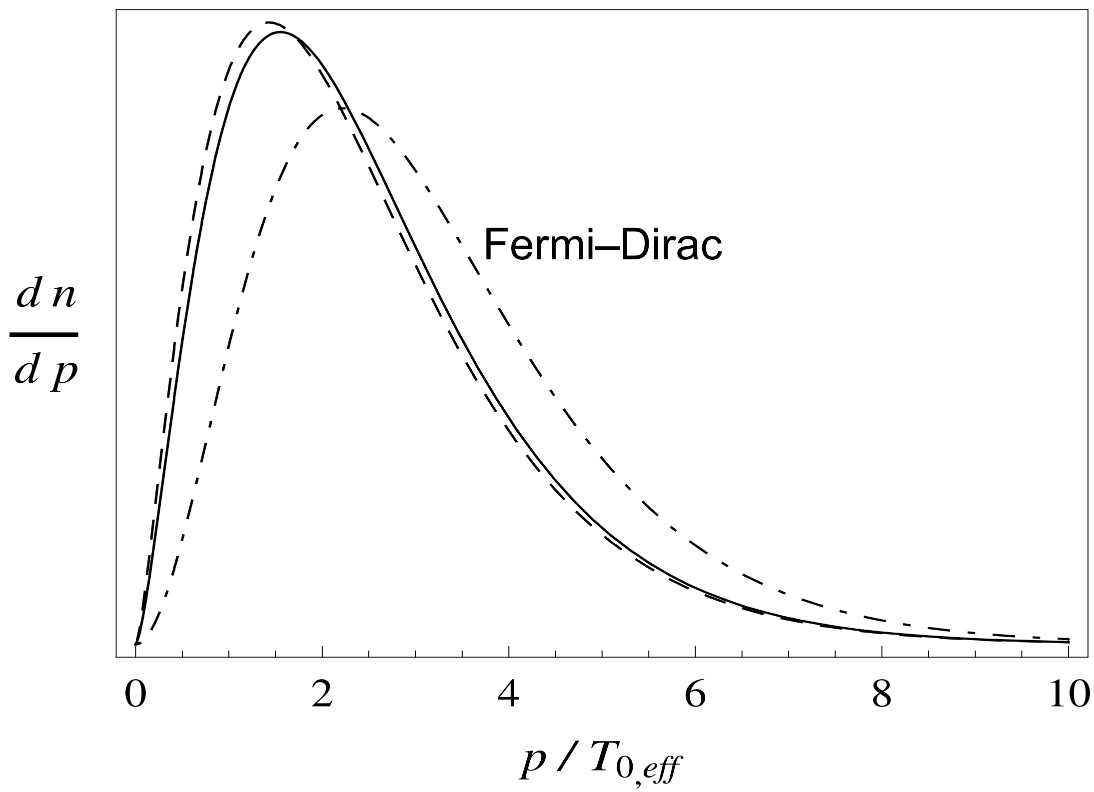
NB: $\Gamma_{NLSP} \simeq \frac{M_{\tilde{S}}^5}{m_{3/2}^2 M_{Pl}^2} \Longrightarrow c\tau_{NLSP} = \text{a few} \cdot \text{mm} \div \text{a few} \cdot 100 \text{ m}$

for $m_{3/2} = 1 \div 10$ keV, $M_{\tilde{S}} = 100 \div 300$ GeV

Longer lifetime for heavier gravitino (CDM candidate)

Can gravitino be really warm?

Overall primordial distribution function similar to thermal

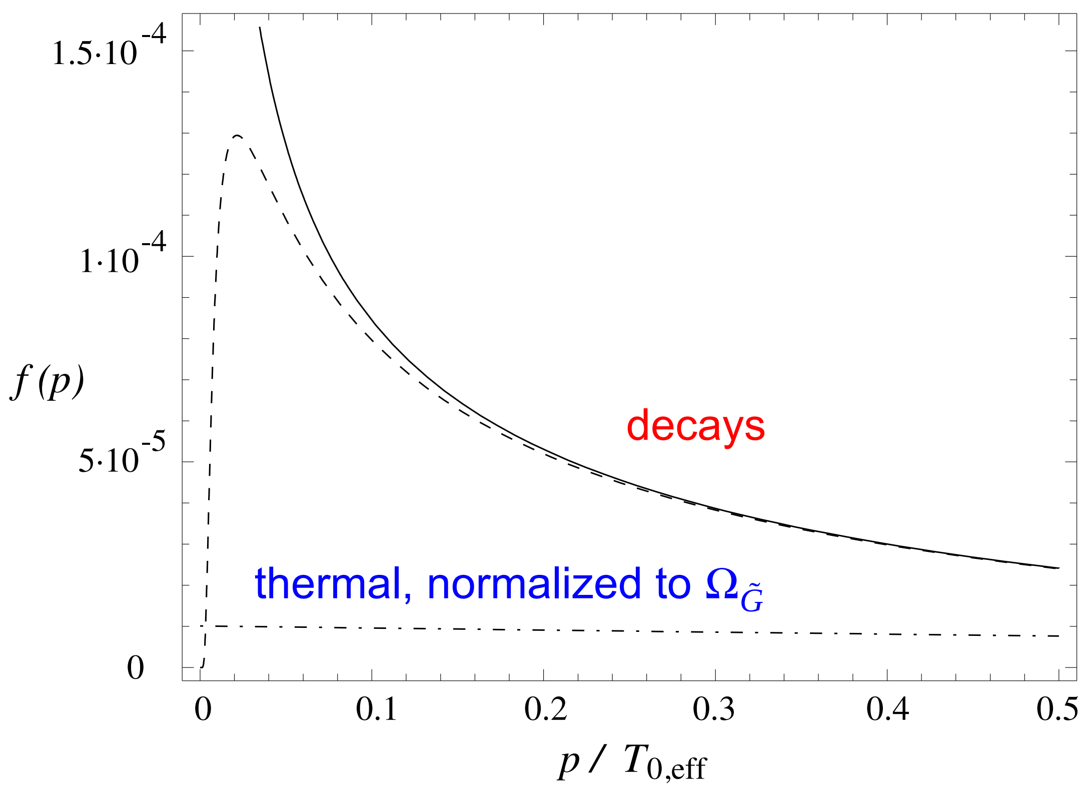


Corner in phase space

Low momentum gravitino produced in decays of heavy superpartners.

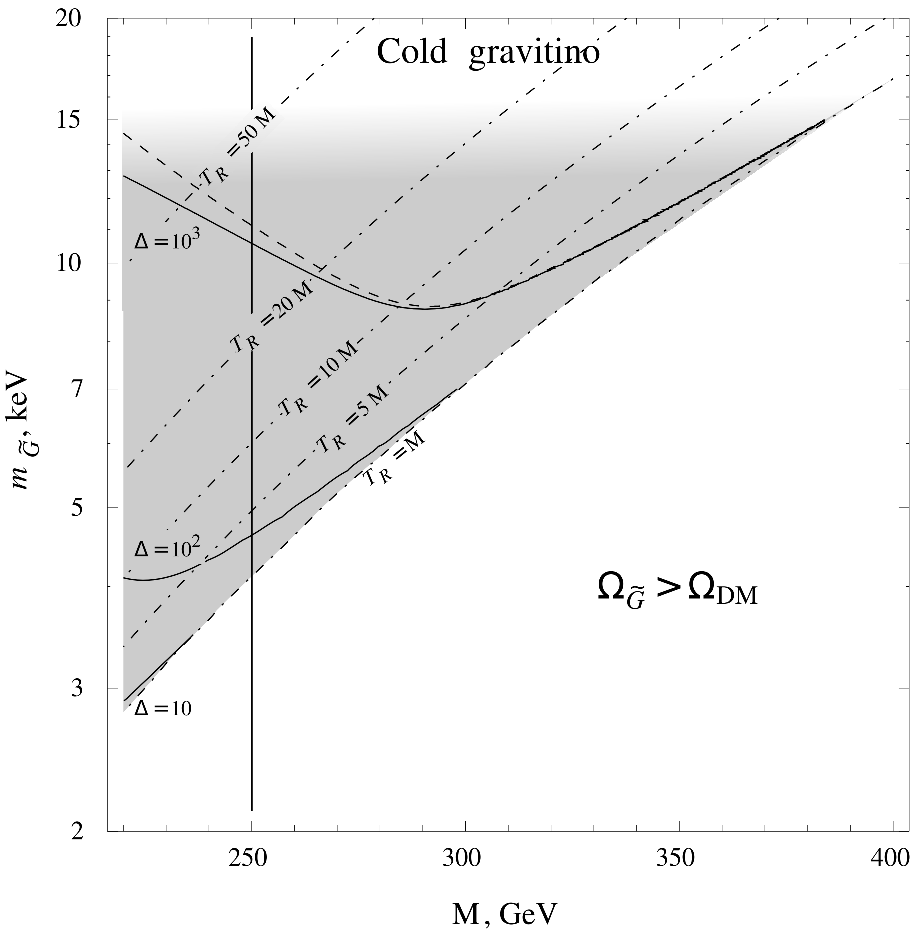
How is that possible?

Fast moving $\tilde{S}$, decaying backwards.



Scenario 1

All superpartners have the same mass M.



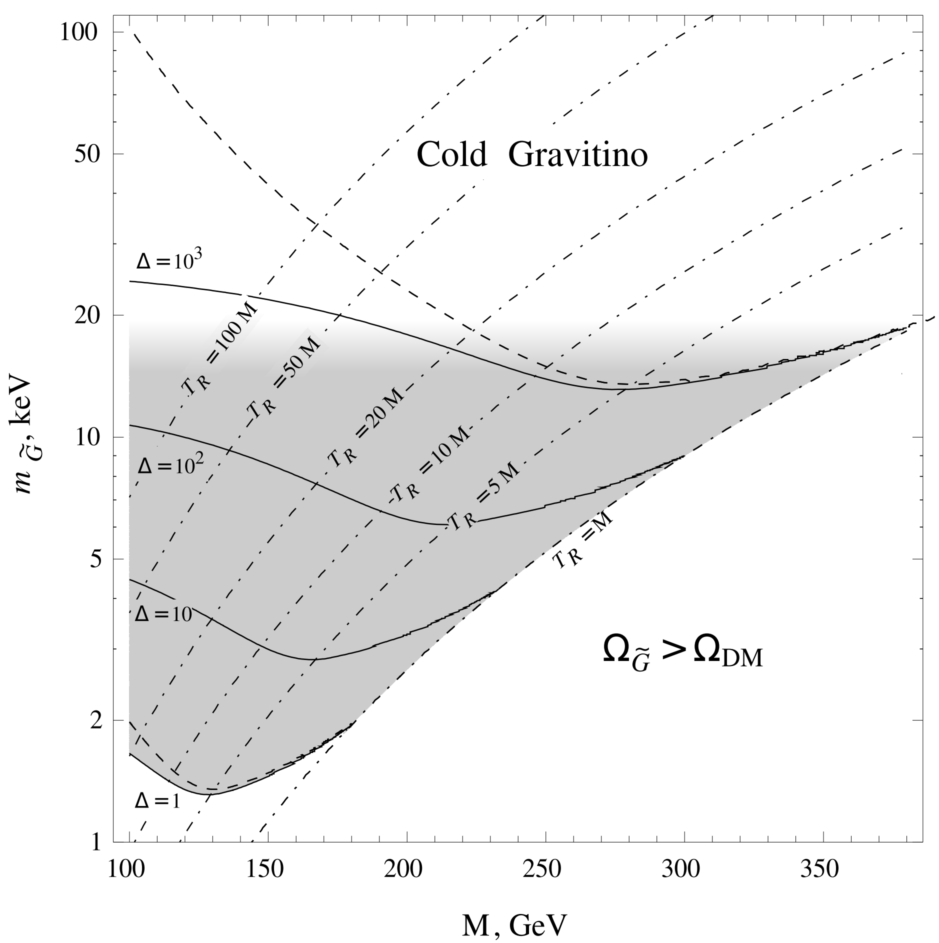
$$\Delta = \frac{f_{max}}{f_{0,\,max}}\,,$$

dilution factor

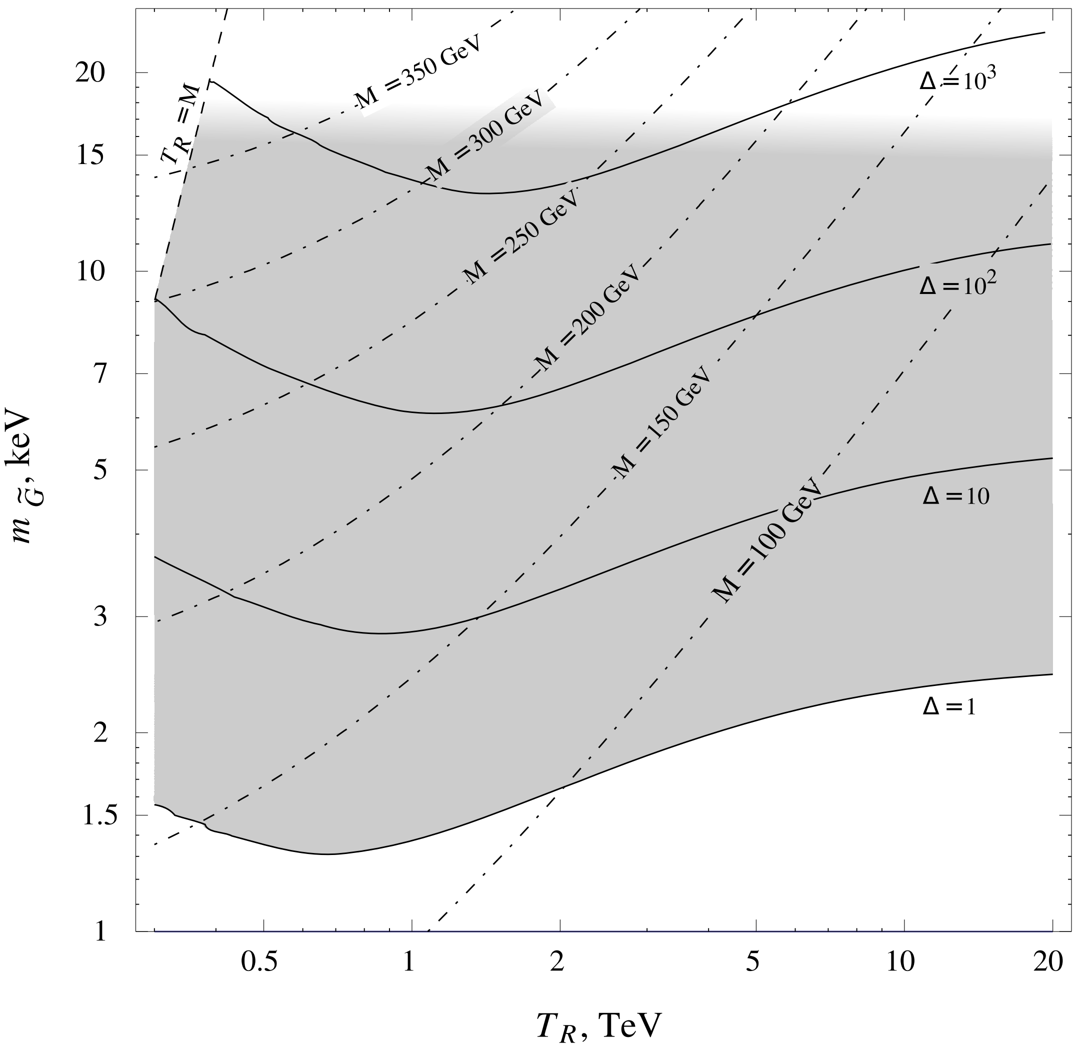
Scenario 2

Gluinos and squarks heavier than T_R,
never existed in cosmic plasma.

Electroweak sparticles relevant only



Reheating temperature must be low



To summarize:

- Particle physicist's viewpoint:
  - WDM is an interesting alternative to CDM.
  - Needs unconventional particle physics and cosmology
- Is it really useful for structures?
- Presently: considerable uncertainty in estimates of parameters even for known primordial phase space distributions.
- Gravitinos are still warm dark matter candidates
- Possible only if superpartners are light,

$$M \lesssim 300 \text{ GeV}$$

Will soon be ruled out (or confirmed) by LHC