Making and Detecting Dark Matter Particles

Manuel Drees

Bonn University

Contents

Contents

Contents

Contents

Contents

Contents

Introduction: the need for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

Introduction: the need for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\rm DM} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$ (?)

Introduction: the need for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\rm DM} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$ (?)

- Models of structure formation, X ray temperature of clusters of galaxies, ...

Introduction: the need for Dark Matter

Several observations indicate existence of non-luminous Dark Matter (DM) (more exactly: missing force)

- Galactic rotation curves imply $\Omega_{\rm DM} h^2 \geq 0.05$.

Ω: Mass density in units of critical density; $\Omega = 1$ means flat Universe.
h: Scaled Hubble constant. Observation: $h = 0.72 \pm 0.07$ (?)

- Models of structure formation, X ray temperature of clusters of galaxies, . . .
- Cosmic Microwave Background anisotropies (WMAP) imply $\Omega_{\rm DM} h^2 = 0.105^{+0.007}_{-0.013}$ **Spergel et al., astro–ph/0603449**

Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis $\rightarrow$ talk by K. Olive

Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis $\longrightarrow$ talk by K. Olive
- Analyses of CMB data

Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis$\longrightarrow$ talk by K. Olive
- Analyses of CMB data

Consistent result: $\Omega_{\rm bar} h^2 \simeq 0.02$

Need for non–baryonic DM

Total baryon density is determined by:

- Big Bang Nucleosynthesis$\longrightarrow$ talk by K. Olive
- Analyses of CMB data

Consistent result: $\Omega_{\rm bar} h^2 \simeq 0.02$

$\Longrightarrow$ Need non–baryonic DM!

Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly $\Longrightarrow \Omega_\nu h^2 \lesssim 0.01$

Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly $\Longrightarrow \Omega_\nu h^2 \lesssim 0.01$

$\Longrightarrow$ Need exotic particles as DM!

Need for exotic particles

Only possible non–baryonic particle DM in SM: light neutrinos!

Make hot DM: do not describe structure formation correctly $\Longrightarrow \Omega_\nu h^2 \lesssim 0.01$

$\Longrightarrow$ Need exotic particles as DM!

Possible loophole: primordial black holes; not easy to make in sufficient quantity sufficiently early.

What we need

Since $h^2 \simeq 0.5$: Need $\sim 20\%$ of critical density in

- Matter (with negligible pressure, $w \simeq 0$)

What we need

Since $h^2 \simeq 0.5$: Need $\sim 20\%$ of critical density in

- Matter (with negligible pressure, $w \simeq 0$)
- which still survives today (lifetime $\tau \gg 10^{10}$ yrs)

What we need

Since $h^2 \simeq 0.5$: Need $\sim 20\%$ of critical density in

- Matter (with negligible pressure, $w \simeq 0$)
- which still survives today (lifetime $\tau \gg 10^{10}$ yrs)
- and has (strongly) suppressed coupling to elm radiation

Remarks

- Precise “WMAP” determination of DM density hinges on assumption of “standard cosmology”, including assumption of nearly scale–invariant primordial spectrum of density perturbations: almost assumes inflation!

Remarks

- Precise “WMAP” determination of DM density hinges on assumption of “standard cosmology”, including assumption of nearly scale–invariant primordial spectrum of density perturbations: almost assumes inflation!
- Evidence for $\Omega_{\rm DM} \gtrsim 0.2$ much more robust than that! (Does, however, assume standard law of gravitation.)

Possible problems with cold DM

Simulations of structure formation show some discrepancies with observations on (sub–)galactic length scales:

- Too many sub–halos are predicted: Might well be "dark dwarves" (w/o baryons; perhaps blown out by first supernovae)

Possible problems with cold DM

Simulations of structure formation show some discrepancies with observations on (sub–)galactic length scales:

- Too many sub–halos are predicted: Might well be "dark dwarves" (w/o baryons; perhaps blown out by first supernovae)
- Simulations seem to over–predict DM density near centers of galaxies ("cusp problem"). Warning: many things going on in these regions!

DM is collisionsless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas

DM is collisionless!

Observation of merging cluster 1E0657-56 ("bullet cluster"):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass

DM is collisionsless!

Observation of merging cluster 1E0657-56 ("bullet cluster"):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass

Result: Collision shock slows down the (ionized) gas, but *not* the Dark Matter

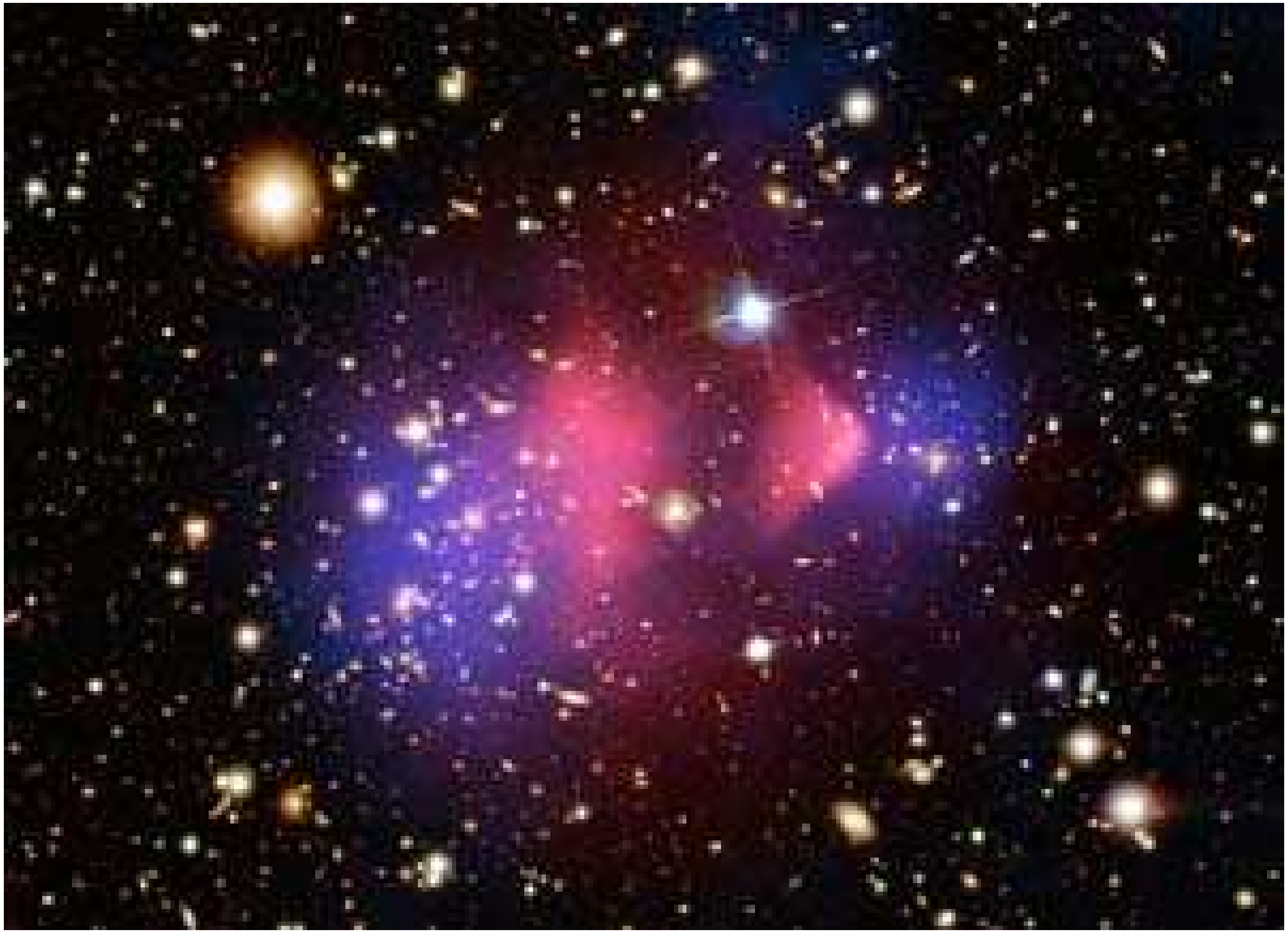
DM is collisionsless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas
- Using gravitational lensing: observes mass

Result: Collision shock slows down the (ionized) gas, but *not* the Dark Matter
Resulting bound on DM–DM scattering cross section constrains models of interacting DM! Markevitch et al., astro–ph/0309303

Bullet cluster



Sterile keV neutrinos

- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino

Sterile keV neutrinos

- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino
- Have some independent motivation:

Sterile keV neutrinos

- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino
- Have some independent motivation:
  - Are warm (or “cool”) DM: can solve cusp problem

Sterile keV neutrinos

- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino
- Have some independent motivation:
  - Are warm (or “cool”) DM: can solve cusp problem
  - Can explain pulsar kicks (through resonant oscillation in presence of strong magnetic field)

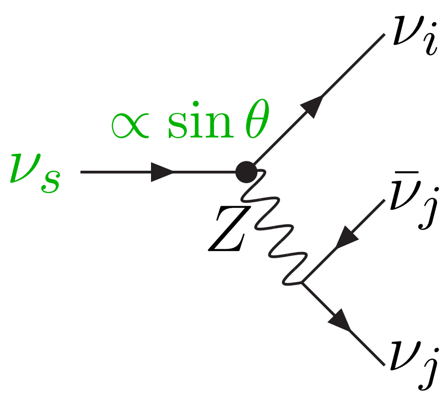
Sterile keV neutrinos

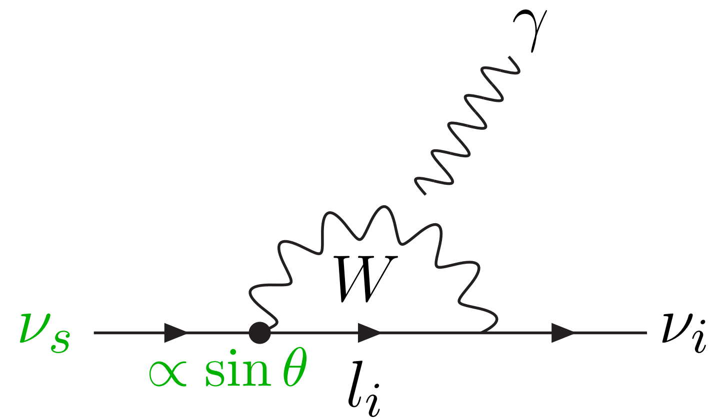
- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino
- Have some independent motivation:
  - Are warm (or “cool”) DM: can solve cusp problem
  - Can explain pulsar kicks (through resonant oscillation in presence of strong magnetic field)
  - Can lead to early re–ionization of Universe (no longer a problem?)

Sterile keV neutrinos

- Are SM gauge singlets, with small mixing angle θ to (at least) one SM neutrino
- Have some independent motivation:
  - Are warm (or “cool”) DM: can solve cusp problem
  - Can explain pulsar kicks (through resonant oscillation in presence of strong magnetic field)
  - Can lead to early re–ionization of Universe (no longer a problem?)
- Are unstable!

Decays of “sterile” neutrinos

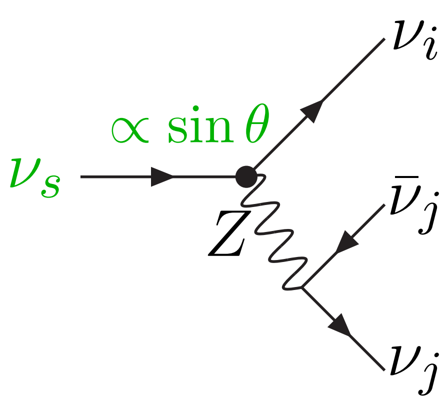


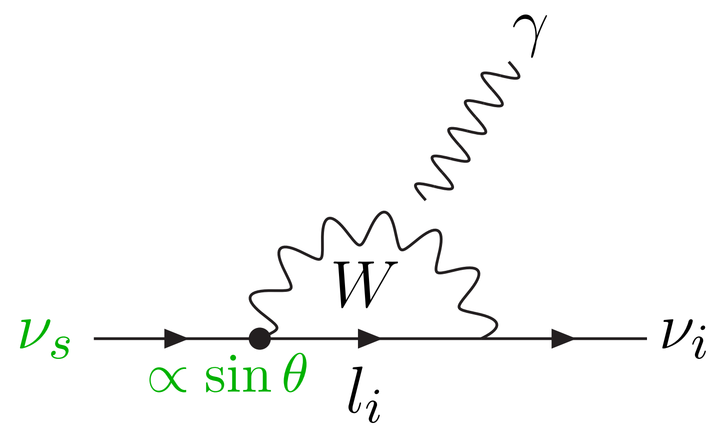


$$\Gamma(\nu_s) = \frac{G_F^2 m_s^5}{192\pi^3} \sin^2\theta$$

$$B(\nu_s \to \gamma\nu_i) \simeq 1\%$$

Decays of “sterile” neutrinos



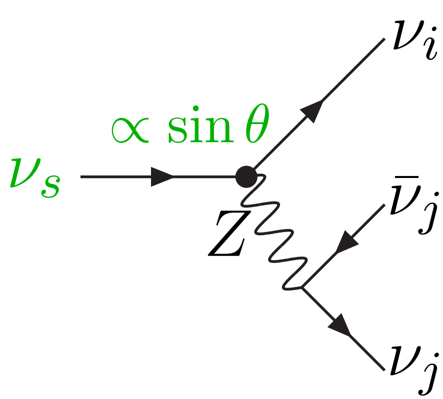


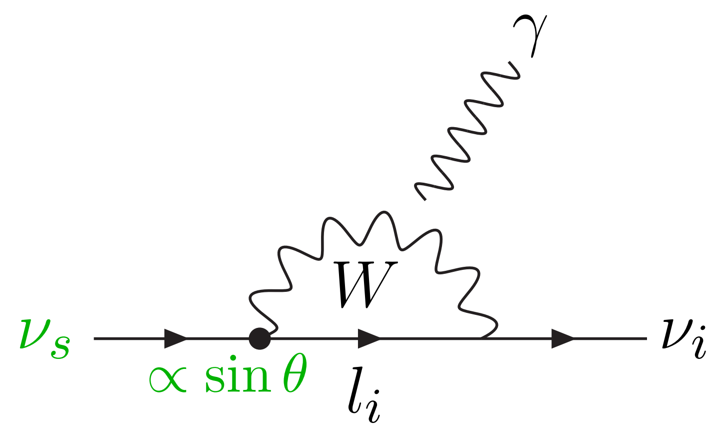
$$\Gamma(\nu_s) = \frac{G_F^2 m_s^5}{192\pi^3}\sin^2\theta \qquad\qquad B(\nu_s \to \gamma\nu_i) \simeq 1\%$$

Crossed version of left diagram contributes to production:

$$\nu_i + f \to \nu_s + f\,; \quad \nu_i + f \to \nu_s + f'$$

Decays of “sterile” neutrinos





$\Gamma(\nu_s) = \frac{G_F^2 m_s^5}{192\pi^3} \sin^2\theta$ $B(\nu_s \to \gamma\nu_i) \simeq 1\%$

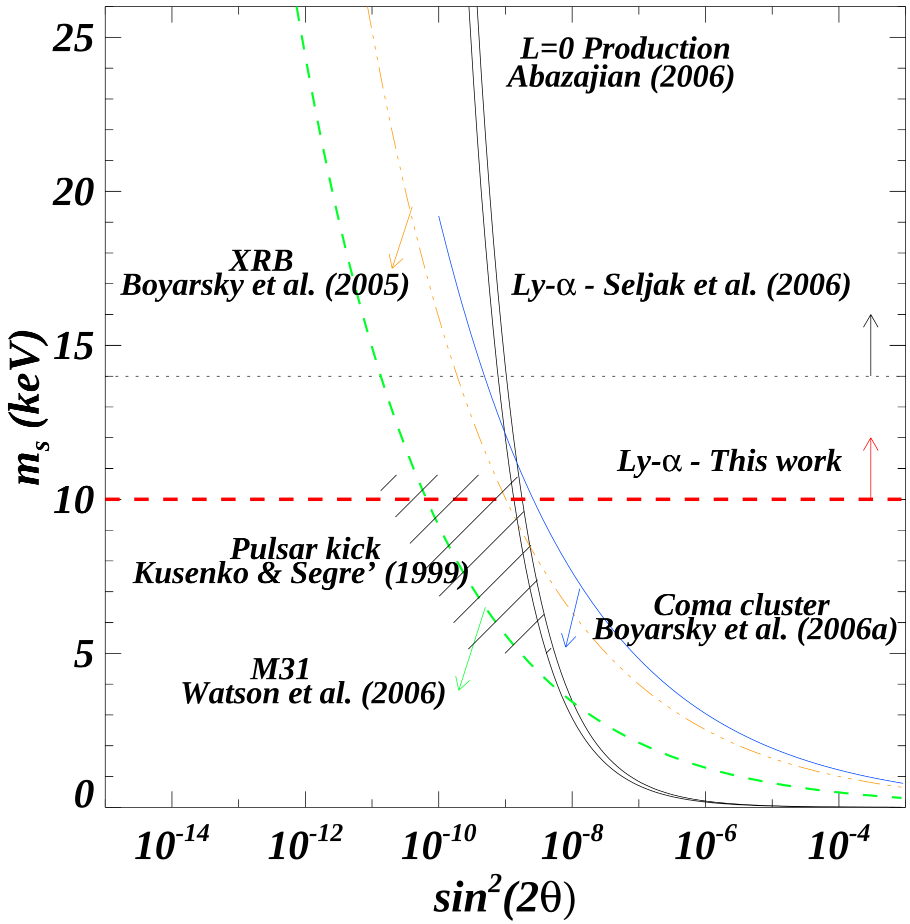
Crossed version of left diagram contributes to production:

$\nu_i + f \to \nu_s + f\ ; \quad \nu_i + f \to \nu_s + f'$

Right diagram gives only way to detect ν_s: monochromatic (X–ray) photon at $E_\gamma = m_{\nu_s}/2$.

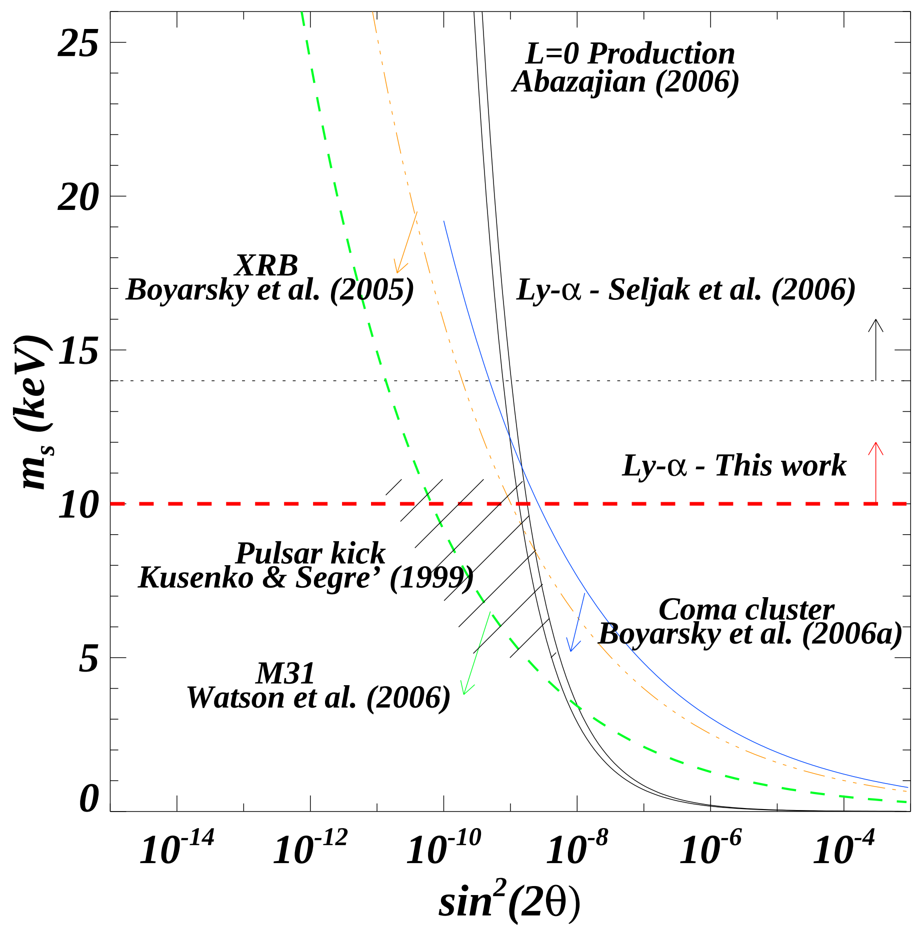
Standard sterile neutrinos are excluded!

Viel et al., astro-ph/0605706



Standard sterile neutrinos are excluded!

Viel et al., astro-ph/0605706



Loophole: Use non–standard production mechanism: large lepton asymmetry ($\Delta L \sim 0.1$), ν_s coupling to inflaton, ...

Super–/E–WIMPs

Are massive particles whose interactions with ordinary matter are much weaker than weak

- Well motivated candidates exist: gravitino, axino

Super–/E–WIMPs

Are massive particles whose interactions with ordinary matter are much weaker than weak

- Well motivated candidates exist: gravitino, axino
- Two production mechanisms: (→ parallel talk Steffen)

Super–/E–WIMPs

Are massive particles whose interactions with ordinary matter are much weaker than weak

- Well motivated candidates exist: gravitino, axino
- Two production mechanisms: (→ parallel talk Steffen)
  - Thermal production: E.g. $g + g \to \tilde{g} + (\tilde{G} \text{ or } \tilde{a})$:

$$\Omega_{\tilde{G}} h^2 \simeq 0.1 \left(\frac{M_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \frac{1 \text{ GeV}}{m_{\tilde{G}}} \frac{T_R}{2.4 \cdot 10^7 \text{ GeV}}$$

T_R : re–heat temperature of Universe

Super–/E–WIMPs

Are massive particles whose interactions with ordinary matter are much weaker than weak

- Well motivated candidates exist: gravitino, axino
- Two production mechanisms: (→ parallel talk Steffen)
  - Thermal production: E.g. $g + g \to \tilde{g} + (\tilde{G} \text{ or } \tilde{a})$:
    $$\Omega_{\tilde{G}} h^2 \simeq 0.1 \left(\frac{M_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \frac{1 \text{ GeV}}{m_{\tilde{G}}} \frac{T_R}{2.4 \cdot 10^7 \text{ GeV}}$$
    T_R : re–heat temperature of Universe
  - From NLSP decay: E.g. $\tilde{\tau}_1 \to \tau + \tilde{G} \text{ or } \tilde{a}$:
    $$\Omega_{\tilde{G} \text{ or } \tilde{a}} h^2 = \widetilde{\Omega}_{\text{NLSP}} h^2 \frac{m_{\tilde{G} \text{ or } \tilde{a}}}{m_{\text{NLSP}}}$$

Super–/E–WIMPs (cont.d)

- Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^0=\mathrm{LSP}} h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G} \text{ or } \tilde{a}} = \frac{0.1}{\Omega_{\tilde{\chi}_1^0} h^2} m_{\tilde{\chi}_1^0}$, and low T_R

Super–/E–WIMPs (cont.d)

- Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^0=\mathrm{LSP}} h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G} \text{ or } \tilde{a}} = \frac{0.1}{\Omega_{\tilde{\chi}_1^0} h^2} m_{\tilde{\chi}_1^0}$, and low T_R
- NLSP $\longrightarrow (\tilde{G} \text{ or } \tilde{a}) + X$ decays tend to mess up BBN: nearly as problematic as inverse decays

Super–/E–WIMPs (cont.d)

- Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^0=\mathrm{LSP}} h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G} \text{ or } \tilde{a}} = \frac{0.1}{\Omega_{\tilde{\chi}_1^0} h^2} m_{\tilde{\chi}_1^0}$, and low T_R
- NLSP $\rightarrow (\tilde{G} \text{ or } \tilde{a}) + X$ decays tend to mess up BBN: nearly as problematic as inverse decays
- DM Super–/E–WIMPs cannot be detected

Super–/E–WIMPs (cont.d)

- Can make SUSY scenarios giving $\Omega_{\tilde{\chi}_1^0=\mathrm{LSP}} h^2 \gg 0.1$ DM safe, by setting $m_{\tilde{G} \text{ or } \tilde{a}} = \frac{0.1}{\Omega_{\tilde{\chi}_1^0} h^2} m_{\tilde{\chi}_1^0}$, and low T_R
- NLSP $\longrightarrow (\tilde{G} \text{ or } \tilde{a}) + X$ decays tend to mess up BBN: nearly as problematic as inverse decays
- DM Super–/E–WIMPs cannot be detected
- Allow charged NLSP, e.g. $\tilde{\tau}_1$. In this case, scenario might be testable if NLSP is sufficiently long–lived, by collecting NLSPs producted at colliders and carefully measuring their decays. Hamaguchi et al., hep-ph/0409248; Feng & Smith, hep-ph/0409278; Brandenbyrg et al., hep-ph/0501287; Baltz et al., hep-ph/0602187. However, BBN?? ($\longrightarrow$ talk Olive)

WIMPs

- Exist in well–motivated extensions of the SM: SUSY, (Little Higgs with $T-$Parity), ((Universal Extra Dimension))

WIMPs

- Exist in well–motivated extensions of the SM: SUSY, (Little Higgs with $T-$Parity), ((Universal Extra Dimension))
- Can also (trivially) write down “tailor–made” WIMP models

WIMPs

- Exist in well–motivated extensions of the SM: SUSY, (Little Higgs with $T-$Parity), ((Universal Extra Dimension))
- Can also (trivially) write down “tailor–made” WIMP models
- Roughly weak cross section automatically gives roughly right relic density for thermal WIMPs! (On logarithmic scale)

WIMPs

- Exist in well–motivated extensions of the SM: SUSY, (Little Higgs with $T-$Parity), ((Universal Extra Dimension))
- Can also (trivially) write down “tailor–made” WIMP models
- Roughly weak cross section automatically gives roughly right relic density for thermal WIMPs! (On logarithmic scale)
- Roughly weak interactions may allow both *direct* and *indirect* detection of WIMPs

WIMP production

Let χ be a generic DM particle, n_χ its number density (unit: GeV^3). Assume $\chi = \bar{\chi}$, i.e. $\chi\chi \leftrightarrow$SM particles is possible, but single production of χ is forbidden by some symmetry.

WIMP production

Let χ be a generic DM particle, n_χ its number density (unit: GeV^3). Assume $\chi = \bar{\chi}$, i.e. $\chi\chi \leftrightarrow$SM particles is possible, but single production of χ is forbidden by some symmetry.

Evolution of n_χ determined by Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\rm ann} v\rangle \left(n_\chi^2 - n_{\chi,\,\rm eq}^2\right) + \sum_{X,Y} n_X \Gamma(X \to \chi + Y)$$

$H = \dot{R}/R$: Hubble parameter
$\langle \ldots \rangle$: Thermal averaging
$\sigma_{\rm ann} = \sigma(\chi\chi \to \text{SM particles})$
v : relative velocity between χ's in their cms
$n_{\chi,\,\rm eq}$: χ density in full equilibrium

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Requires

$$n_\chi \langle \sigma_{\rm ann} v \rangle > H$$

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Requires

$$n_\chi \langle \sigma_{\rm ann} v \rangle > H$$

For $T < m_\chi: \; n_\chi \simeq n_{\chi,\,\rm eq} \propto T^{3/2} e^{-m_\chi/T}, \; H \propto T^2$

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Requires

$$n_\chi \langle \sigma_{\rm ann} v \rangle > H$$

For $T < m_\chi : \; n_\chi \simeq n_{\chi,\,{\rm eq}} \propto T^{3/2} e^{-m_\chi/T}, \; H \propto T^2$

Inequality cannot be true for arbitrarily small T; point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature T_F.

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Requires

$$n_\chi \langle \sigma_{\rm ann} v \rangle > H$$

For $T < m_\chi: \; n_\chi \simeq n_{\chi,\,\rm eq} \propto T^{3/2} e^{-m_\chi/T}, \; H \propto T^2$

Inequality cannot be true for arbitrarily small T; point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature T_F.

For $T < T_F$: WIMP production negligible, only annihilation relevant in Boltzmann equation.

Thermal WIMP

Assume χ was in full thermal equilibrium after inflation.

Requires

$$n_\chi \langle \sigma_{\rm ann} v \rangle > H$$

For $T < m_\chi : \; n_\chi \simeq n_{\chi,\,\rm eq} \propto T^{3/2} e^{-m_\chi/T}, \; H \propto T^2$

Inequality cannot be true for arbitrarily small T; point where inequality becomes (approximate) equality defines decoupling (freeze–out) temperature T_F.

For $T < T_F$: WIMP production negligible, only annihilation relevant in Boltzmann equation.

Gives

$$\Omega_\chi h^2 \propto \frac{1}{\langle v \sigma_{\rm ann} \rangle} \sim 0.1 \text{ for } \sigma_{\rm ann} \sim \text{pb}$$

Thermal WIMPs: Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders

Thermal WIMPs: Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders
- No entropy production after χ decoupled: Not testable at colliders

Thermal WIMPs: Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders
- No entropy production after χ decoupled: Not testable at colliders
- H at time of χ decoupling is known: partly testable at colliders

Thermal WIMPs: Assumptions

- χ is effectively stable, $\tau_\chi \gg \tau_{\rm U}$: partly testable at colliders
- No entropy production after χ decoupled: Not testable at colliders
- H at time of χ decoupling is known: partly testable at colliders
- Universe must have been sufficiently hot: $T_R > T_F \simeq m_\chi/20$

Low temperature scenario

Assume $T_R \lesssim T_F,\ n_\chi(T_R) = 0$

Low temperature scenario

Assume $T_R \lesssim T_F, \; n_\chi(T_R) = 0$

Introduce dimensionless variables

$$Y_\chi \equiv \frac{n_\chi}{s}, \quad x \equiv \frac{m_\chi}{T}$$

(s: entropy density).

Use non–relativistic expansion of cross section:

$$\sigma_{\rm ann} = a + bv^2 + \mathcal{O}(v^4) \Longrightarrow \langle \sigma_{\rm ann} v \rangle = a + 6b/x$$

Low temperature scenario

Assume $T_R \lesssim T_F,\ n_\chi(T_R) = 0$
Introduce dimensionless variables

$$Y_\chi \equiv \frac{n_\chi}{s}, \quad x \equiv \frac{m_\chi}{T}$$

(s: entropy density).

Use non–relativistic expansion of cross section:

$$\sigma_{\rm ann} = a + b v^2 + \mathcal{O}(v^4) \Longrightarrow \langle \sigma_{\rm ann} v \rangle = a + 6b/x$$

Using explicit form of $H,\ Y_{\chi,{\rm eq}}$, Boltzmann eq. becomes

$$\frac{dY_\chi}{dx} = -f \left(a + \frac{6b}{x} \right) x^{-2} \left(Y_\chi^2 - c x^3 {\rm e}^{-2x} \right) .$$

$f = 1.32\, m_\chi M_{\rm Pl} \sqrt{g_*},\ c = 0.0210\, g_\chi^2 / g_*^2$

Low temperature scenario (cont.'d)

For $T_R \ll T_F$: Annihilation term $\propto Y_\chi^2$ negligible: defines $0-$th order solution $Y_0(x)$, with

$$Y_0(x \to \infty) = fc\left[\frac{a}{2} x_R \mathrm{e}^{-2x_R} + \left(\frac{a}{4} + 3b\right)\mathrm{e}^{-2x_R}\right] .$$

Note: $\Omega_\chi h^2 \propto \sigma_{\rm ann}$ in this case!

Low temperature scenario (cont.'d)

For $T_R \ll T_F$: Annihilation term $\propto Y_\chi^2$ negligible: defines $0-$th order solution $Y_0(x)$, with

$$Y_0(x \to \infty) = fc\left[\frac{a}{2} x_R \mathrm{e}^{-2x_R} + \left(\frac{a}{4} + 3b\right) \mathrm{e}^{-2x_R}\right] \, .$$

Note: $\Omega_\chi h^2 \propto \sigma_{\rm ann}$ in this case!

For intermediate temperatures, $T_R \lesssim T_F$: Define 1st–order solution

$$Y_1 = Y_0 + \delta \, .$$

$\delta < 0$ describes pure annihilation:

$$\frac{d\delta}{dx} = -f\left(a + \frac{6b}{x}\right) \frac{Y_0(x)^2}{x^2} \, .$$

$\delta(x)$ can be calculated analytically: $\delta \propto \sigma_{\rm ann}^3$

Low temperature scenario (cont.'d)

For $T_R \ll T_F$: Annihilation term $\propto Y_\chi^2$ negligible: defines $0-$th order solution $Y_0(x)$, with

$$Y_0(x \to \infty) = fc \left[\frac{a}{2} x_R \mathrm{e}^{-2x_R} + \left(\frac{a}{4} + 3b \right) \mathrm{e}^{-2x_R} \right] .$$

Note: $\Omega_\chi h^2 \propto \sigma_{\mathrm{ann}}$ in this case!

For intermediate temperatures, $T_R \lesssim T_F$: Define 1st–order solution

$$Y_1 = Y_0 + \delta .$$

$\delta < 0$ describes pure annihilation:

$$\frac{d\delta}{dx} = -f \left(a + \frac{6b}{x} \right) \frac{Y_0(x)^2}{x^2} .$$

$\delta(x)$ can be calculated analytically: $\delta \propto \sigma_{\mathrm{ann}}^3$

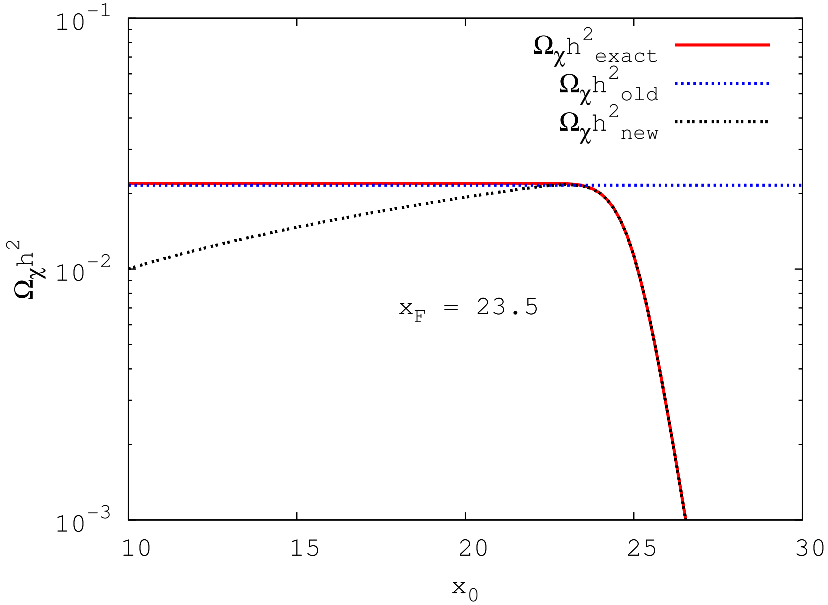
Get good results for $\Omega_\chi h^2$ for all $T_R \leq T_F$ through "resummation":

$$Y_1 = Y_0 \left(1 + \frac{\delta}{Y_0} \right) \simeq \frac{Y_0}{1 - \delta / Y_0} \equiv Y_{1.r}$$

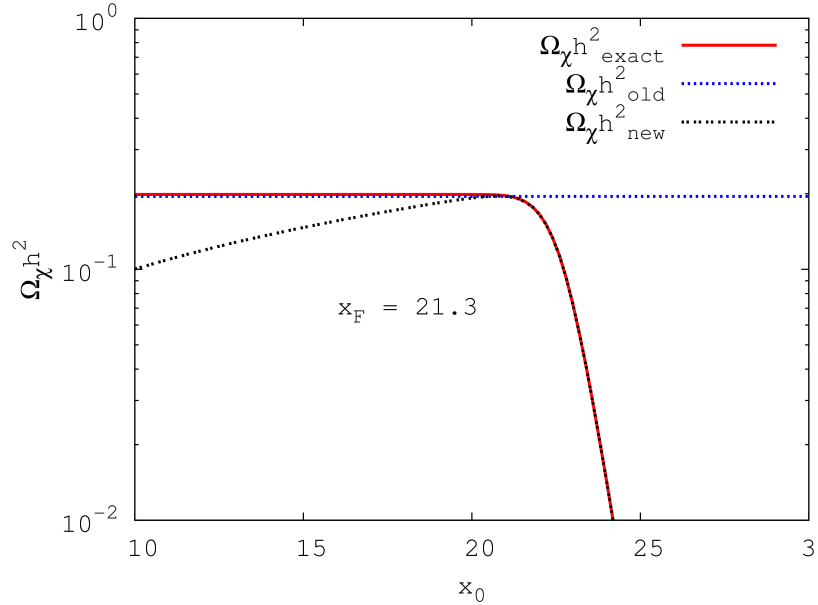
$Y_{1,r} \propto 1/\sigma_{\mathrm{ann}}$ for $|\delta| \gg Y_0$ MD, Imminniyaz, Kakizaki, hep-ph/0603165

Numerical comparison: $b = 0$

MD, Imminniyaz, Kakizaki, hep-ph/0603165



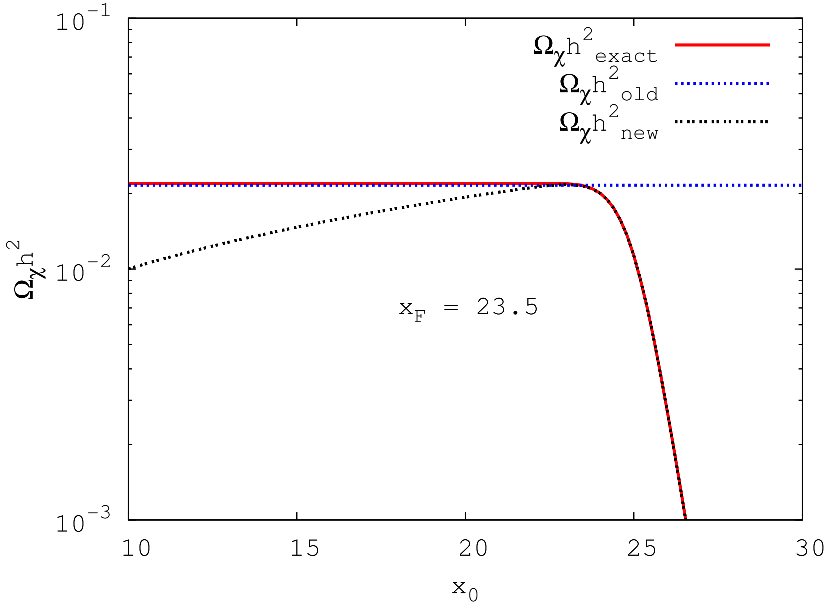
$a = 10^{-8}$ GeV^{-2}



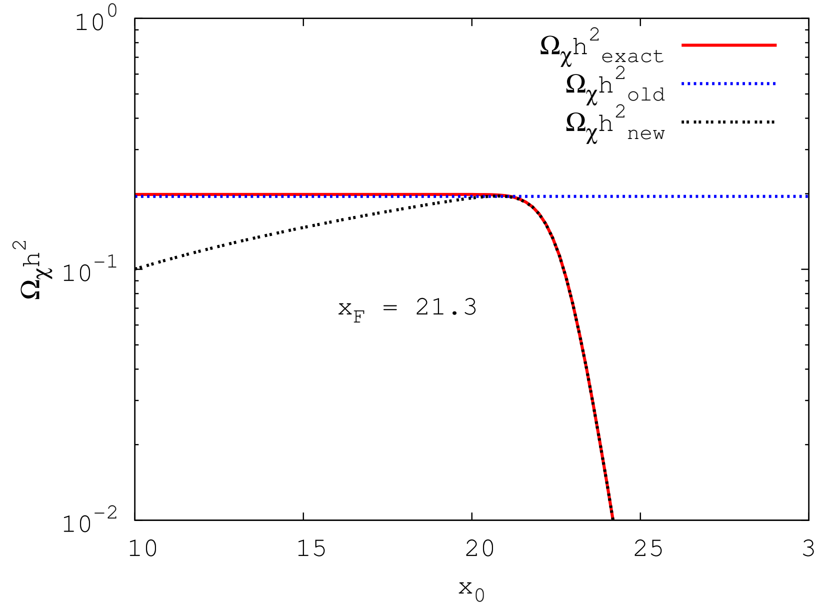
$a = 10^{-9}$ GeV^{-2}

Numerical comparison: $b = 0$

MD, Imminniyaz, Kakizaki, hep-ph/0603165



$a = 10^{-8}$ GeV^{-2}

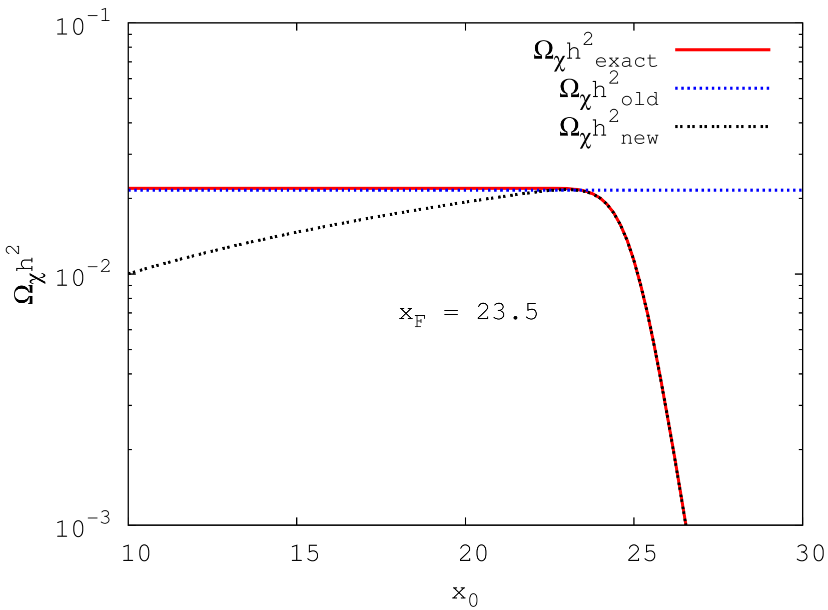


$a = 10^{-9}$ GeV^{-2}

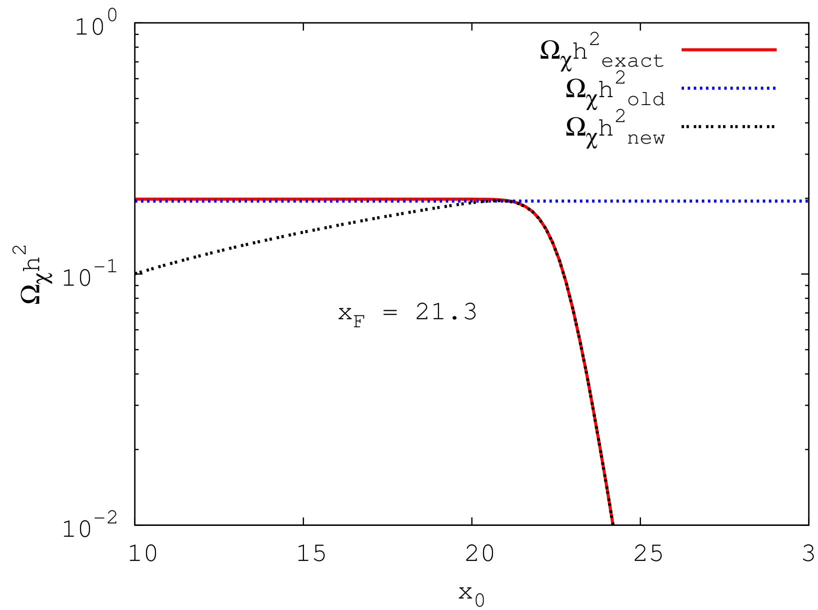
Can extend validity of new solution to all T, including $T \gg T_R$, by using $\Omega_\chi(T_{\rm max})$ if $T_R > T_{\rm max} \simeq T_F$

Numerical comparison: $b = 0$

MD, Imminniyaz, Kakizaki, hep-ph/0603165



$a = 10^{-8}$ GeV^{-2}



$a = 10^{-9}$ GeV^{-2}

Can extend validity of new solution to all T, including $T \gg T_R$, by using $\Omega_\chi(T_{\rm max})$ if $T_R > T_{\rm max} \simeq T_F$

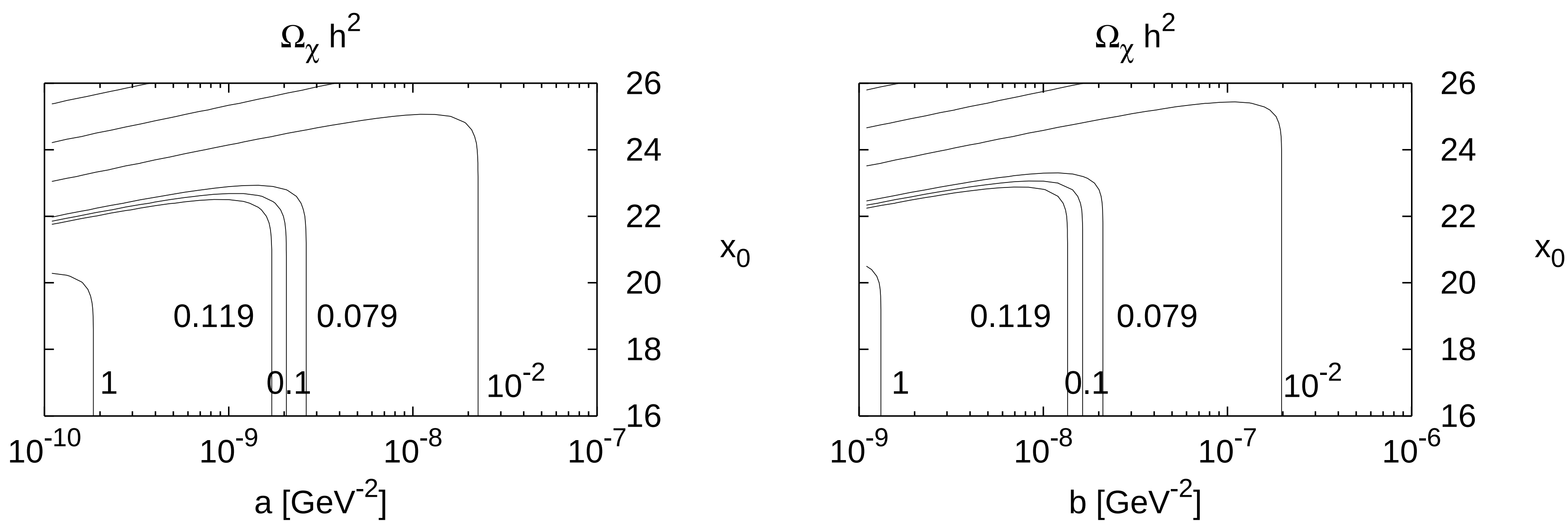
Note: $\Omega_\chi(T_R) \leq \Omega_\chi(T_R \gg T_F)$

Application: lower bound on T_R for thermal WIMP

If $n_\chi(T_R) = 0$, demanding $\Omega_\chi h^2 \simeq 0.1$ imposes lower bound on T_R:

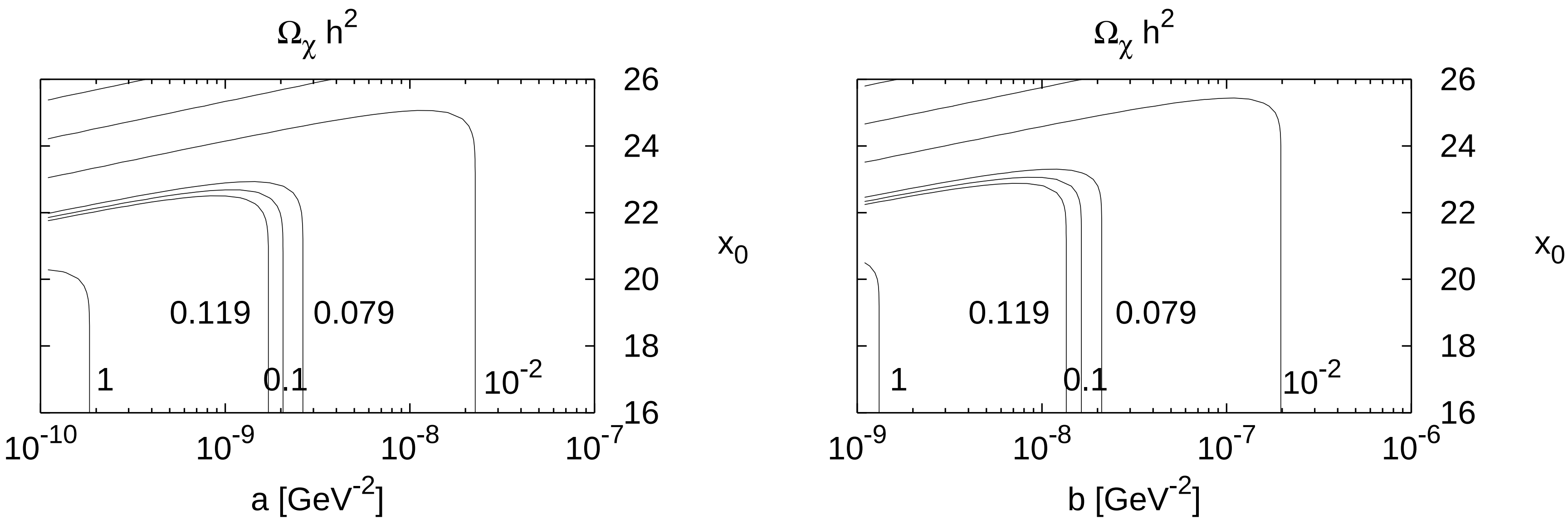
Application: lower bound on T_R for thermal WIMP

If $n_\chi(T_R) = 0$, demanding $\Omega_\chi h^2 \simeq 0.1$ imposes lower bound on T_R:



Application: lower bound on T_R for thermal WIMP

If $n_\chi(T_R) = 0$, demanding $\Omega_\chi h^2 \simeq 0.1$ imposes lower bound on T_R:



$$\Longrightarrow T_R \geq \frac{m_\chi}{23}$$

Holds independently of $\sigma_{\rm ann}$!

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections
- HLS theorem: biggest allowed symmetry of $S-$matrix is product of gauge group and SUSY

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections
- HLS theorem: biggest allowed symmetry of $S-$matrix is product of gauge group and SUSY
- Local SUSY closely related to gravity (hence Supergravity, SUGRA)

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections
- HLS theorem: biggest allowed symmetry of $S-$matrix is product of gauge group and SUSY
- Local SUSY closely related to gravity (hence Supergravity, SUGRA)
- Related to superstring theory: best candidate TOE

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections
- HLS theorem: biggest allowed symmetry of $S-$matrix is product of gauge group and SUSY
- Local SUSY closely related to gravity (hence Supergravity, SUGRA)
- Related to superstring theory: best candidate TOE
- Allows one–step unification of gauge couplings

Best motivated WIMP: neutralino $\tilde{\chi}_1^0$

- Weak–scale Supersymmetry stabilizes hierarchy against radiative corrections
- HLS theorem: biggest allowed symmetry of $S-$matrix is product of gauge group and SUSY
- Local SUSY closely related to gravity (hence Supergravity, SUGRA)
- Related to superstring theory: best candidate TOE
- Allows one–step unification of gauge couplings
- In simplest (R_p-invariant) version: LSP is stable: can be good candidate for DM particle! (Free bonus, *not* related to original motivation.)

Minimal Supergravity, mSUGRA

- SUSY needs to be broken; no “standard model of SUSY breaking” exists

Minimal Supergravity, mSUGRA

- SUSY needs to be broken; no “standard model of SUSY breaking” exists
- Most general soft breaking of MSSM introduces ~ 100 new free parameters! Most of this vast parameter space excluded by FCNC constraints, unless $m_{\tilde{f}} \gg 1$ TeV.

Minimal Supergravity, mSUGRA

- SUSY needs to be broken; no "standard model of SUSY breaking" exists
- Most general soft breaking of MSSM introduces ~ 100 new free parameters! Most of this vast parameter space excluded by FCNC constraints, unless $m_{\tilde{f}} \gg 1$ TeV.
- Way out: Postulate universal spectrum at GUT scale ("universal boundary conditions"): Spectrum parameterized by universal scalar mass m_0; universal gaugino mass $m_{1/2}$; universal trilinear scalar term A_0; ratio of Higgs vevs $\tan\beta$; sign of higgsino mass, sign(μ). (mSUGRA/CMSSM boundary conditions)

Advantages of mSUGRA

- FCNC small (but $b \to s\gamma,\ B_s \to \mu^+\mu^-$ do constrain parameter space)

Advantages of mSUGRA

- FCNC small (but $b \to s\gamma,\ B_s \to \mu^+\mu^-$ do constrain parameter space)
- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive

Advantages of mSUGRA

- FCNC small (but $b \to s\gamma,\ B_s \to \mu^+\mu^-$ do constrain parameter space)
- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive
- Over much of parameter space, $\tilde{\chi}_1^0$ is stable LSP!

Thermal mSUGRA Dark Matter

Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1^0} h^2$ from standard cosmology comes out too large in mSUGRA.

Regions with too small $\Omega_{\tilde{\chi}_1^0} h^2$ also exist.

Thermal mSUGRA Dark Matter

Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1^0} h^2$ from standard cosmology comes out too large in mSUGRA.
Regions with too small $\Omega_{\tilde{\chi}_1^0} h^2$ also exist.

Several DM–allowed regions do exist:

- $\tilde{\tau}_1$ co–annihilation region: $m_{1/2}^2 \gg m_0^2$

Thermal mSUGRA Dark Matter

Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1^0} h^2$ from standard cosmology comes out too large in mSUGRA. Regions with too small $\Omega_{\tilde{\chi}_1^0} h^2$ also exist.

Several DM–allowed regions do exist:

- $\tilde{\tau}_1$ co–annihilation region: $m^2_{1/2} \gg m_0^2$
- $m_0^2 \gg m^2_{1/2}$: $\tilde{\chi}_1^0$ has sizable higgsino component

Thermal mSUGRA Dark Matter

Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1^0} h^2$ from standard cosmology comes out too large in mSUGRA. Regions with too small $\Omega_{\tilde{\chi}_1^0} h^2$ also exist.

Several DM–allowed regions do exist:

- $\tilde{\tau}_1$ co–annihilation region: $m_{1/2}^2 \gg m_0^2$
- $m_0^2 \gg m_{1/2}^2$: $\tilde{\chi}_1^0$ has sizable higgsino component
- $\tan\beta \gg 1$: $m_A \simeq 2 m_{\tilde{\chi}_1^0}$ possible ("$A-$pole"; similar, smaller, "$h-$pole" also [barely] exists)

Thermal mSUGRA Dark Matter

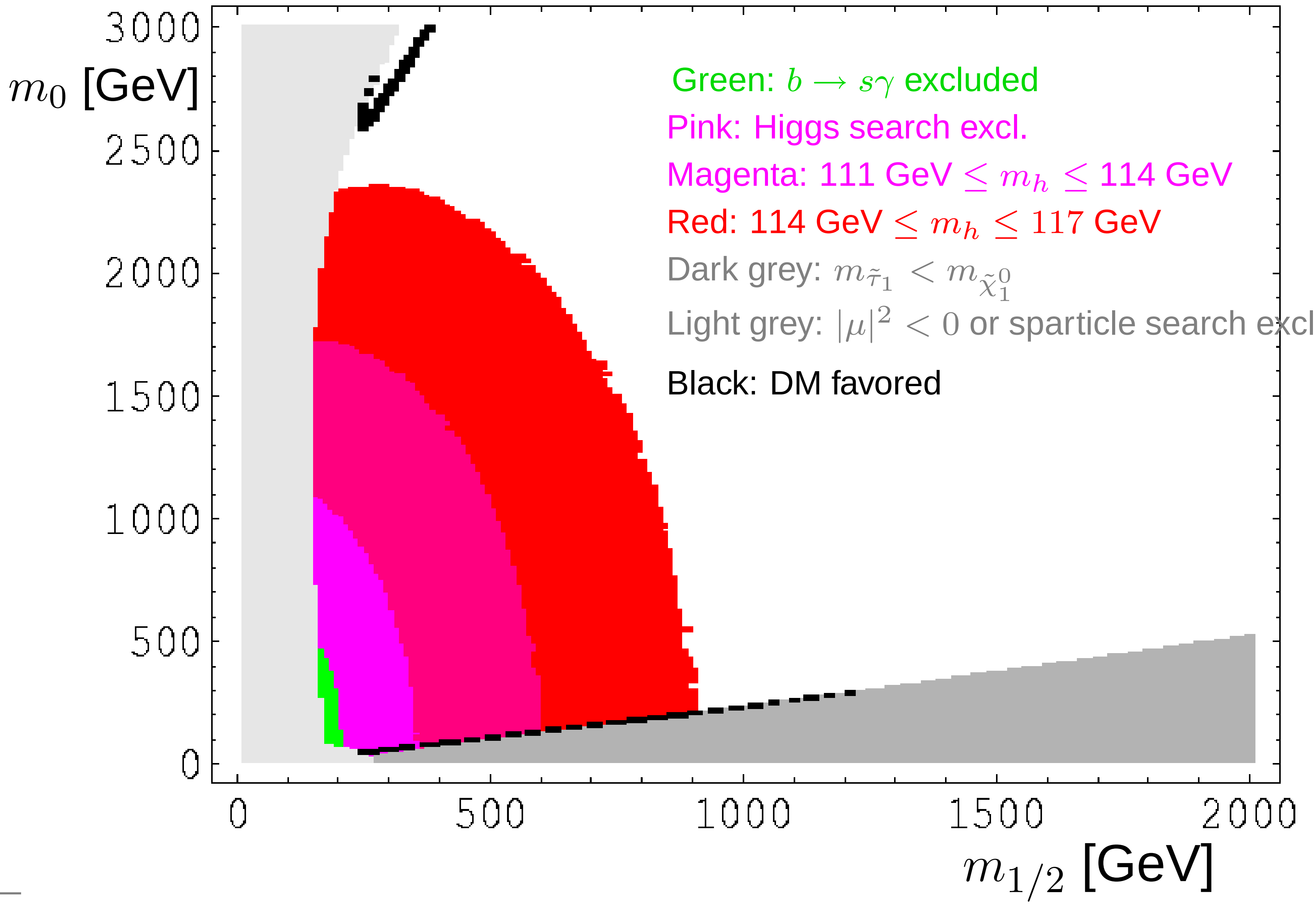
Over most of collider–allowed parameter space, $\Omega_{\tilde{\chi}_1^0} h^2$ from standard cosmology comes out too large in mSUGRA. Regions with too small $\Omega_{\tilde{\chi}_1^0} h^2$ also exist.

Several DM–allowed regions do exist:

- $\tilde{\tau}_1$ co–annihilation region: $m^2_{1/2} \gg m_0^2$
- $m_0^2 \gg m^2_{1/2}$: $\tilde{\chi}_1^0$ has sizable higgsino component
- $\tan\beta \gg 1$: $m_A \simeq 2 m_{\tilde{\chi}_1^0}$ possible ("$A-$pole"; similar, smaller, "$h-$pole" also [barely] exists)

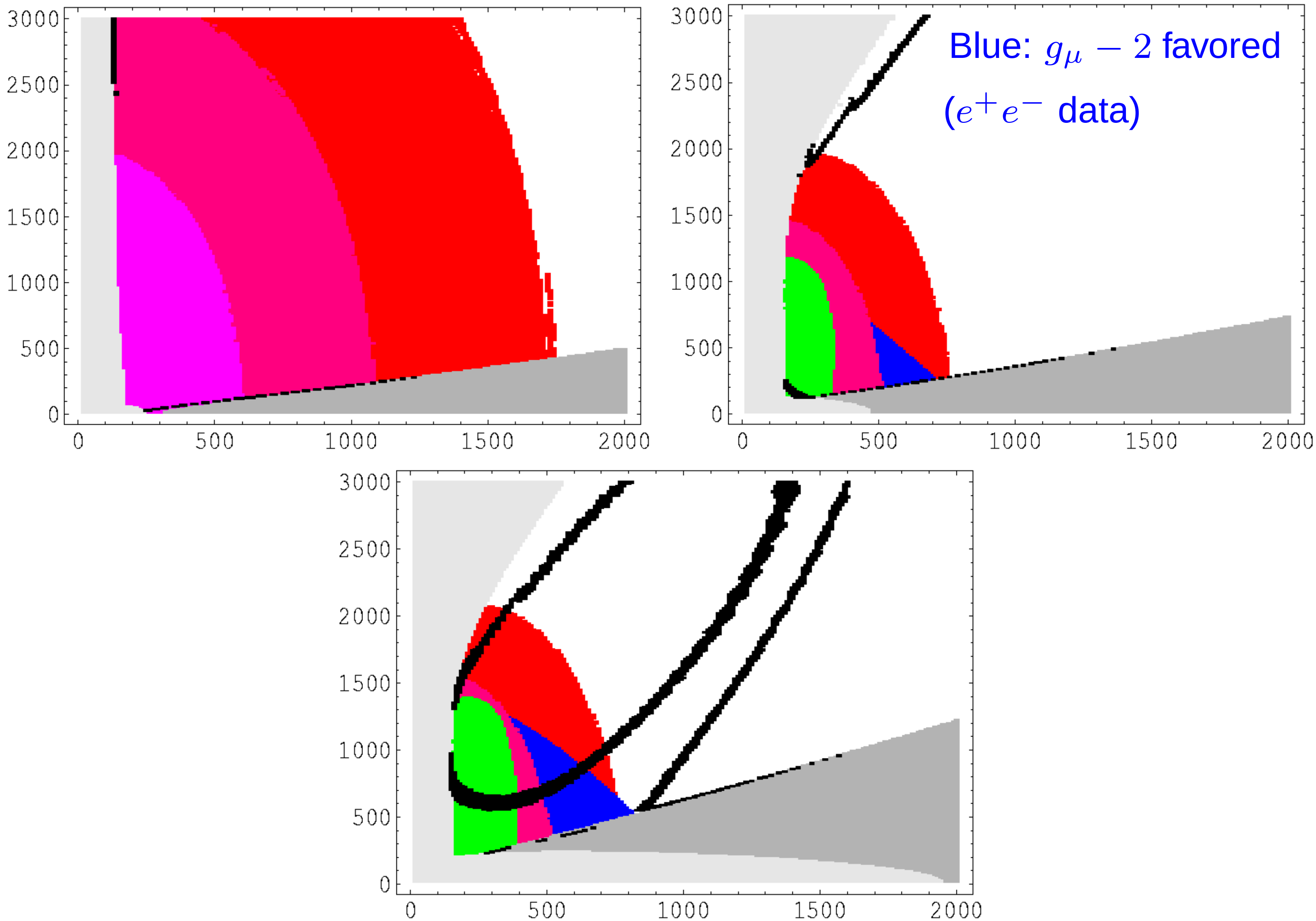
Following examples from Djouadi, MD, Kneurr, hep-ph/0602001

Example: $m_t = 172.7$ **GeV,** $\tan\beta = 10,\ A_0 = 0,\ \mu > 0$



Effect of varying $\tan\beta$

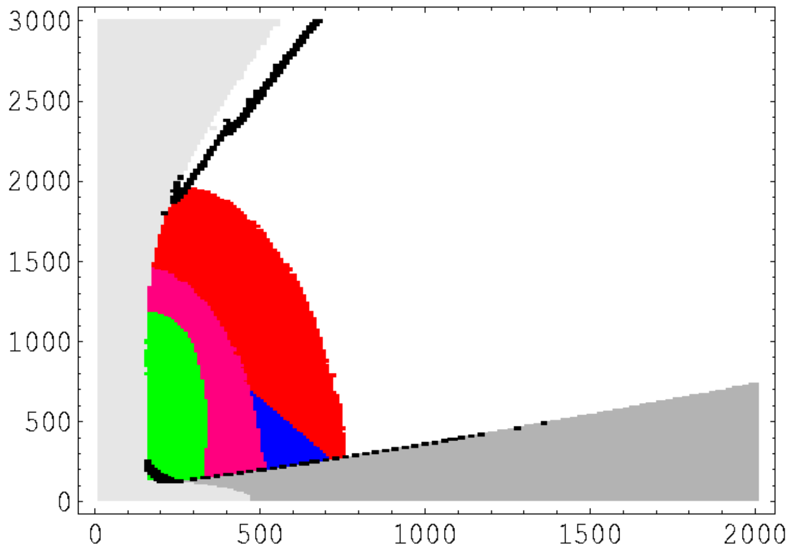
$\tan\beta = 5$ $\tan\beta = 30$



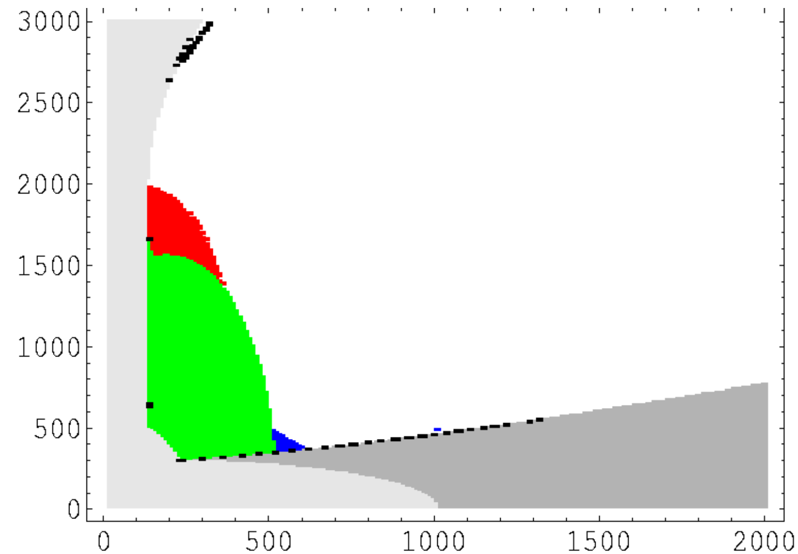
$\tan\beta = 50$

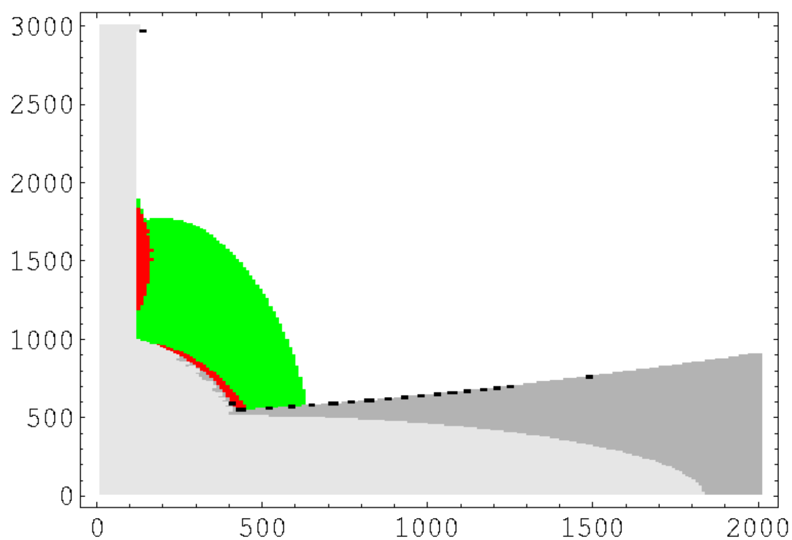
Varying A_0**:** $m_t = 172.7$ **GeV,** $\tan\beta = 30,\ \mu > 0$

$A_0 = 0$



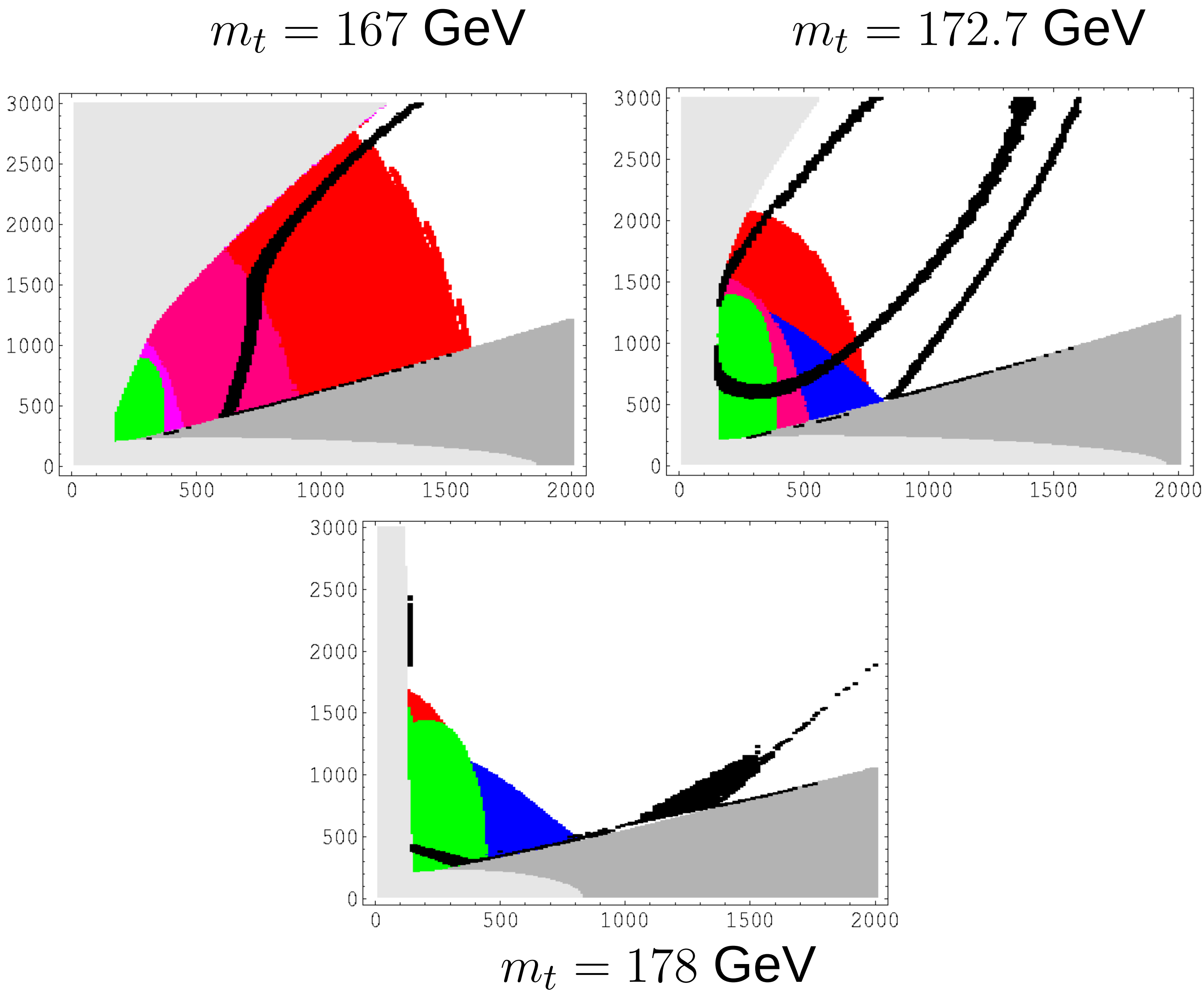
$A_0 = -1$ TeV





$A_0 = -2$ TeV

Varying m_t: $\tan\beta = 50,\ A_0 = 0,\ \mu > 0$



Mass Bounds

More meaningful than “size of allowed parameter space”

mSUGRA, all parameters scanned over allowed region

particle	minimal mass [GeV]			min, max mass	
	basic	incl. $b \to s\gamma$	incl. DM	aggr. a_μ	incl. DM
$\tilde{\chi}_1^0$	52	52	53	53, 359	55, 357
$\tilde{\chi}_1^\pm$	105	105	105	105, 674	105, 667
$\tilde{\chi}_3^0$	135	135	135	135, 996	292, 991
$\tilde{\tau}_1$	99	99	99	99, 1020	99, 915
h	91	91	91	91, 124	91, 124
$H^\pm$	128	128	128	128, 979	128, 960
$\tilde{g}$	359	380	380	399, 1880	412, 1870
$\tilde{d}_R$	406	498	498	498, 1740	498, 1740
$\tilde{t}_1$	102	104	104	231, 1440	244, 1440

Indirect WIMP detection

- WIMPs are everywhere!

Indirect WIMP detection

- WIMPs are everywhere!
- In regions with increased WIMP density: WIMPs can annihilate into SM particles even today:

Indirect WIMP detection

- WIMPs are everywhere!
- In regions with increased WIMP density: WIMPs can annihilate into SM particles even today:
  - In halo of galaxies

Indirect WIMP detection

- WIMPs are everywhere!
- In regions with increased WIMP density: WIMPs can annihilate into SM particles even today:
  - In halo of galaxies
  - Near center of galaxies

Indirect WIMP detection

- WIMPs are everywhere!
- In regions with increased WIMP density: WIMPs can annihilate into SM particles even today:
  - In halo of galaxies
  - Near center of galaxies
  - Inside the Sun or Earth

Indirect WIMP detection: signals

- Slow $\bar{p}$, fast e^+: background? Propagation?

Indirect WIMP detection: signals

- Slow $\bar{p}$, fast e^+: background? Propagation?
- Slow $\bar{d}$: Propagation?

Indirect WIMP detection: signals

- Slow $\bar{p}$, fast e^+: background? Propagation?
- Slow $\bar{d}$: Propagation?
- Photons: Background?

Indirect WIMP detection: signals

- Slow $\bar{p}$, fast e^+: background? Propagation?
- Slow $\bar{d}$: Propagation?
- Photons: Background?
- GeV Neutrinos: Low rate

Indirect WIMP detection: signals

- Slow $\bar{p}$, fast e^+: background? Propagation?
- Slow $\bar{d}$: Propagation?
- Photons: Background?
- GeV Neutrinos: Low rate

Further discussion: talks by de Boer, Mannheim

Direct WIMP detection

- WIMPs are everywhere!

Direct WIMP detection

- WIMPs are everywhere!
- Can elastically scatter on nucleus in detector:
$$\chi + N \rightarrow \chi + N$$
Measured quantity: recoil energy of N

Direct WIMP detection

- WIMPs are everywhere!
- Can elastically scatter on nucleus in detector:
  $$\chi + N \to \chi + N$$
  Measured quantity: recoil energy of N
- Detection needs ultrapure materials in deep–underground location; way to distinguish recoils from β, γ events; neutron screening; ...

Direct WIMP detection

- WIMPs are everywhere!
- Can elastically scatter on nucleus in detector:

  $$\chi + N \to \chi + N$$

  Measured quantity: recoil energy of N
- Detection needs ultrapure materials in deep–underground location; way to distinguish recoils from β, γ events; neutron screening; ...
- Is being pursued vigorously around the world!

Direct WIMP detection: theory

Counting rate given by

$$\frac{dR}{dQ} = AF^2(Q)\int_{v_{\rm min}}^{v_{\rm esc}} \frac{f_1(v)}{v} dv$$

Q: recoil energy

$A$$= \rho\sigma_0/(2m_\chi m_r) =$ const.

$F(Q)$: nuclear form factor

v: WIMP velocity in lab frame

$v^2_{\rm min} = m_N Q/(2m_r^2)$

$v_{\rm esc}$: Escape velocity from galaxy

$f_1(v)$: normalized one–dimensional WIMP velocity distribution

Direct WIMP detection: theory

Counting rate given by

$$\frac{dR}{dQ} = AF^2(Q) \int_{v_{\rm min}}^{v_{\rm esc}} \frac{f_1(v)}{v} dv$$

Q: recoil energy

$A = \rho\sigma_0/(2m_\chi m_r) =$ const.

$F(Q)$: nuclear form factor

v: WIMP velocity in lab frame

$v_{\rm min}^2 = m_N Q/(2m_r^2)$

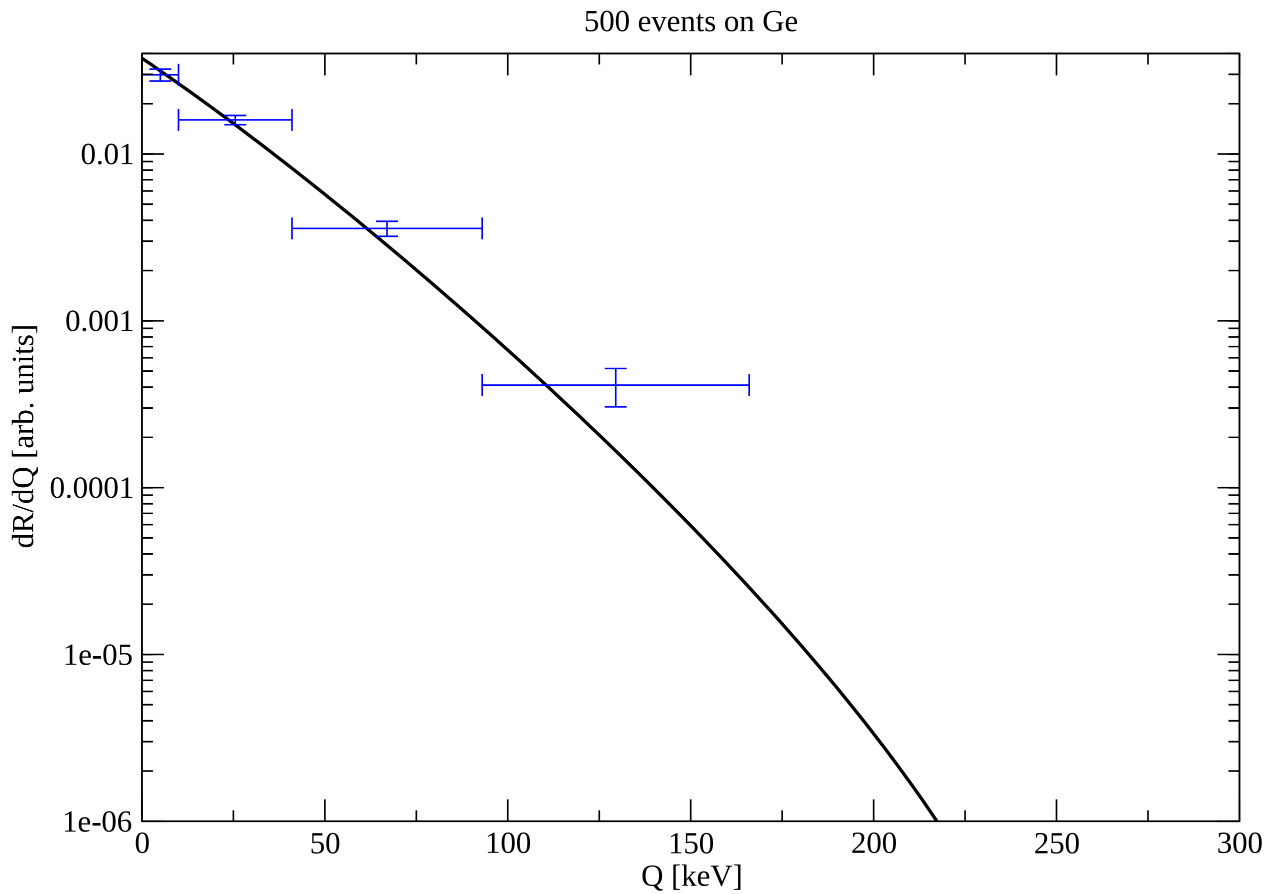
$v_{\rm esc}$: Escape velocity from galaxy

$f_1(v)$: normalized one–dimensional WIMP velocity distribution

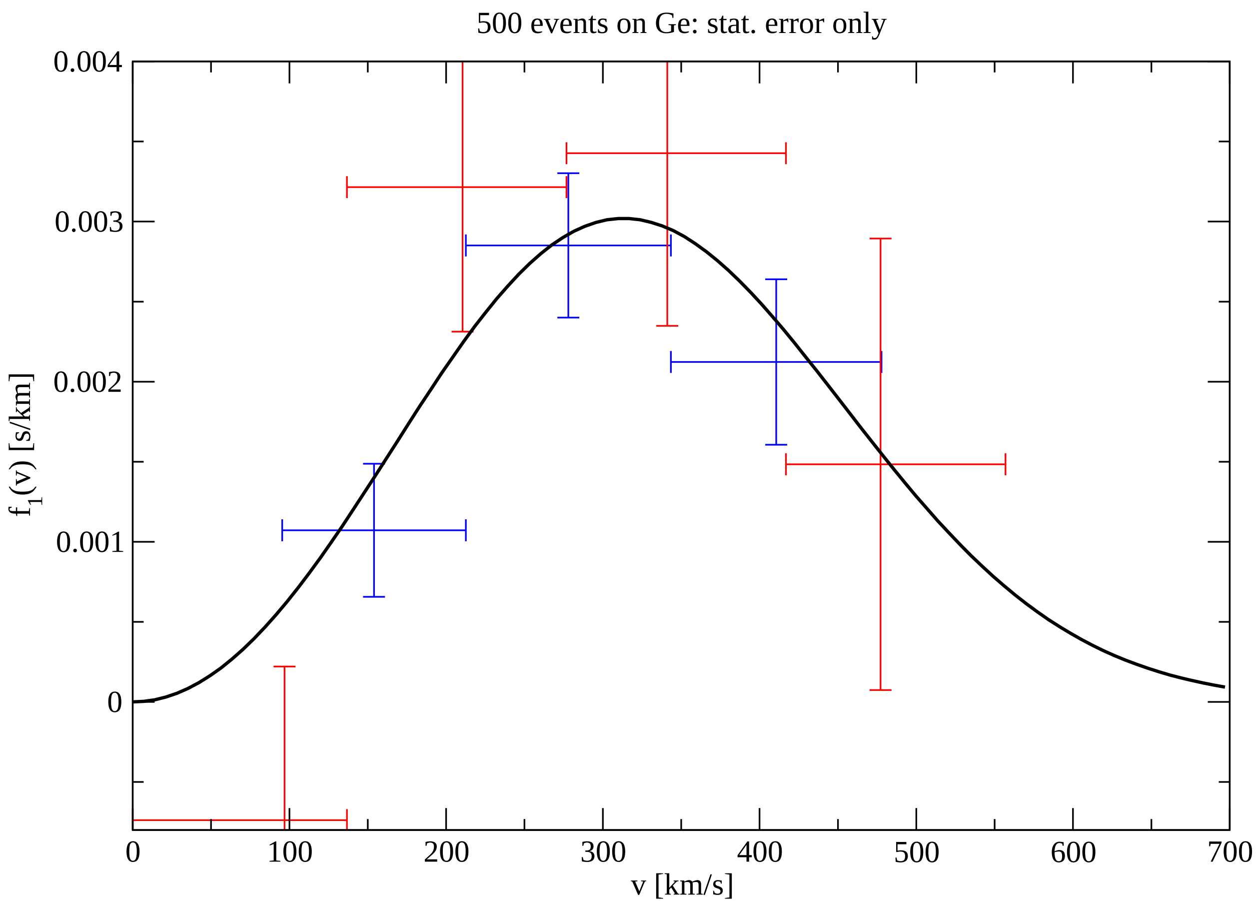
In principle, can invert this relation to measure $f_1(v)$!

Recoil spectrum: prediction and simulated measurement

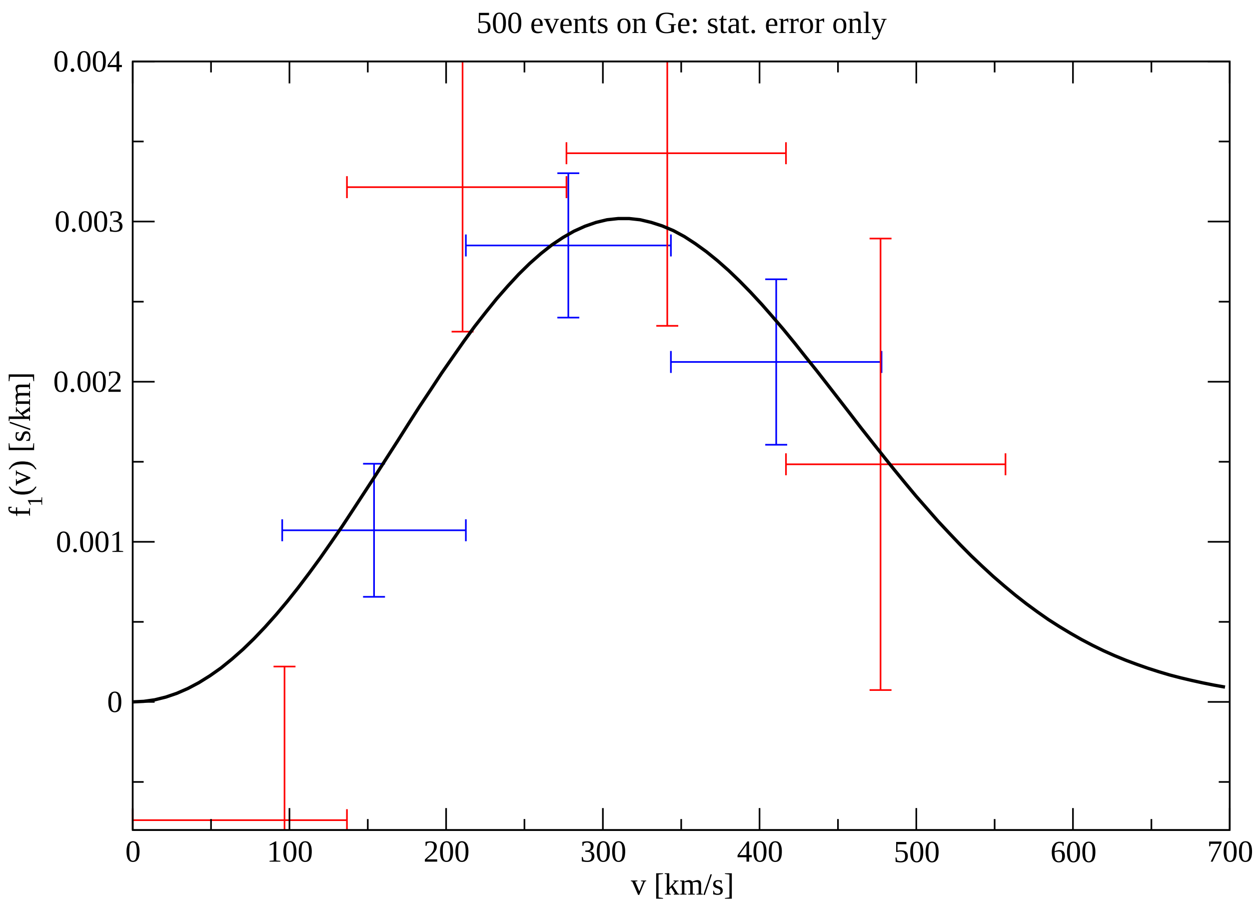
MD, Shan, in progress



$f_1(v)$: prediction and simulated measurement



$f_1(v)$: prediction and simulated measurement

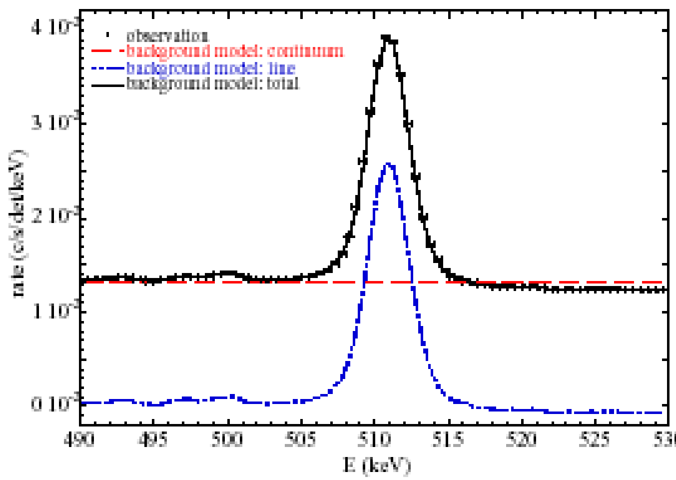


A few moments of $f_1(v)$ may be measurable with relatively few events

MeV Dark Matter

Motivated by excess of 511 keV photons observed from direction of galactic center, by everyone who looked; most recently, by INTEGRAL satellite.

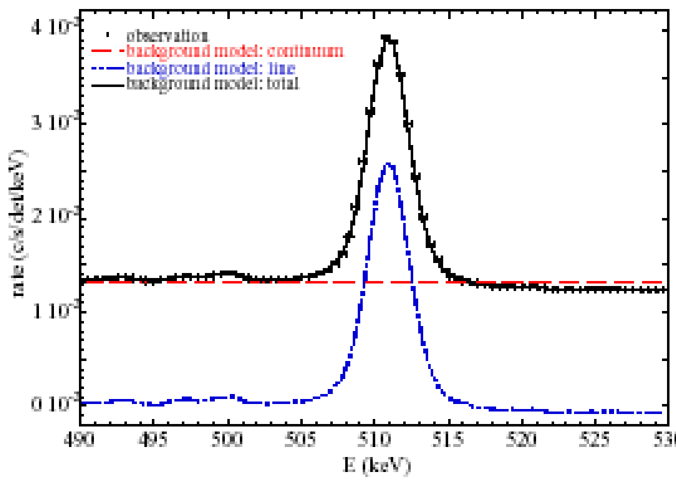
INTErnational Gamma Ray Astrophysical Laboratory: observes sky in γ rays from highly eccentric orbit (perigee 10,000 km, aphogee 152,000 km, orbital period 3 days)



MeV Dark Matter

Motivated by excess of 511 keV photons observed from direction of galactic center, by everyone who looked; most recently, by INTEGRAL satellite.

INTErnational Gamma Ray Astrophysical Laboratory: observes sky in γ rays from highly eccentric orbit (perigee 10,000 km, aphogee 152,000 km, orbital period 3 days)

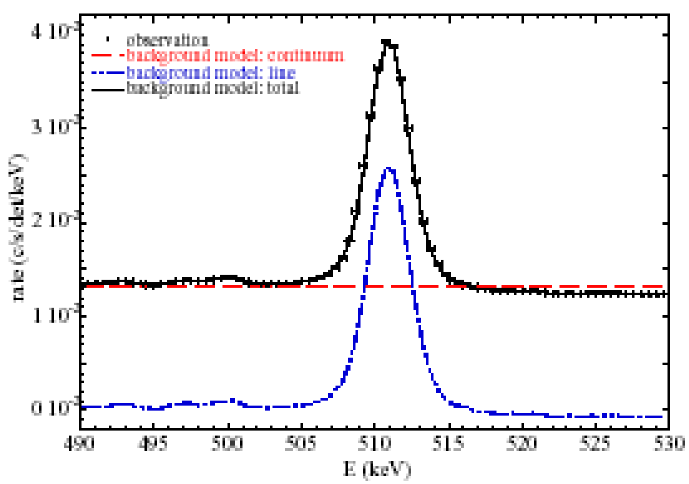


Line width (FWHM) $\simeq 3$ keV; resolution $\simeq 2.2$ keV

MeV Dark Matter

Motivated by excess of 511 keV photons observed from direction of galactic center, by everyone who looked; most recently, by INTEGRAL satellite.

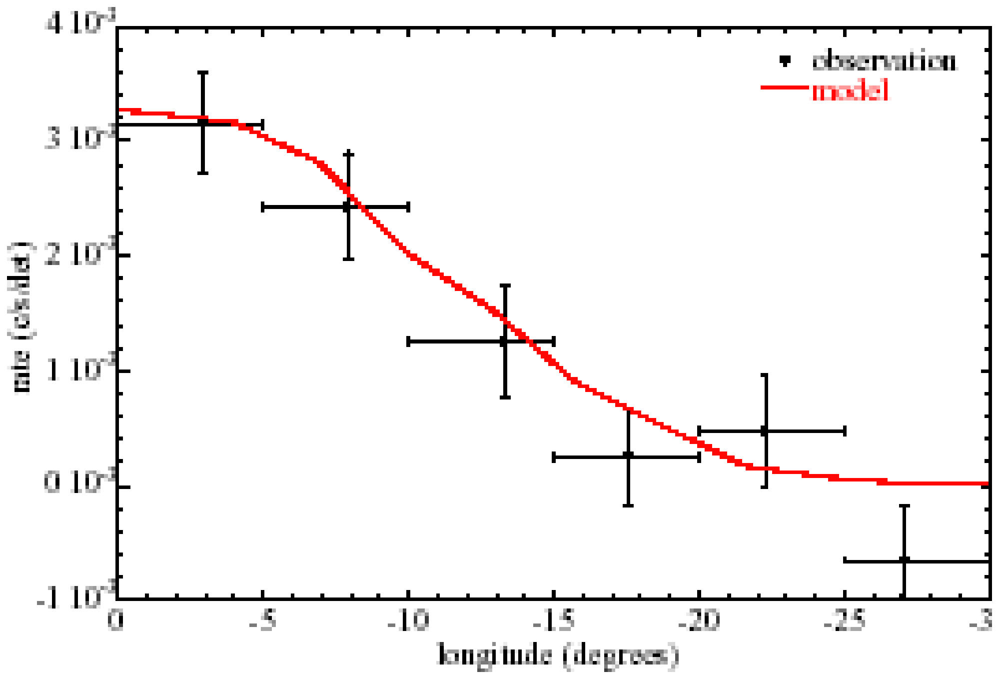
INTErnational Gamma Ray Astrophysical Laboratory: observes sky in γ rays from highly eccentric orbit (perigee 10,000 km, aphogee 152,000 km, orbital period 3 days)



Line width (FWHM) $\simeq 3$ keV; resolution $\simeq 2.2$ keV
Background: continuum plus CR-induced 511 keV line (from empty sky region)

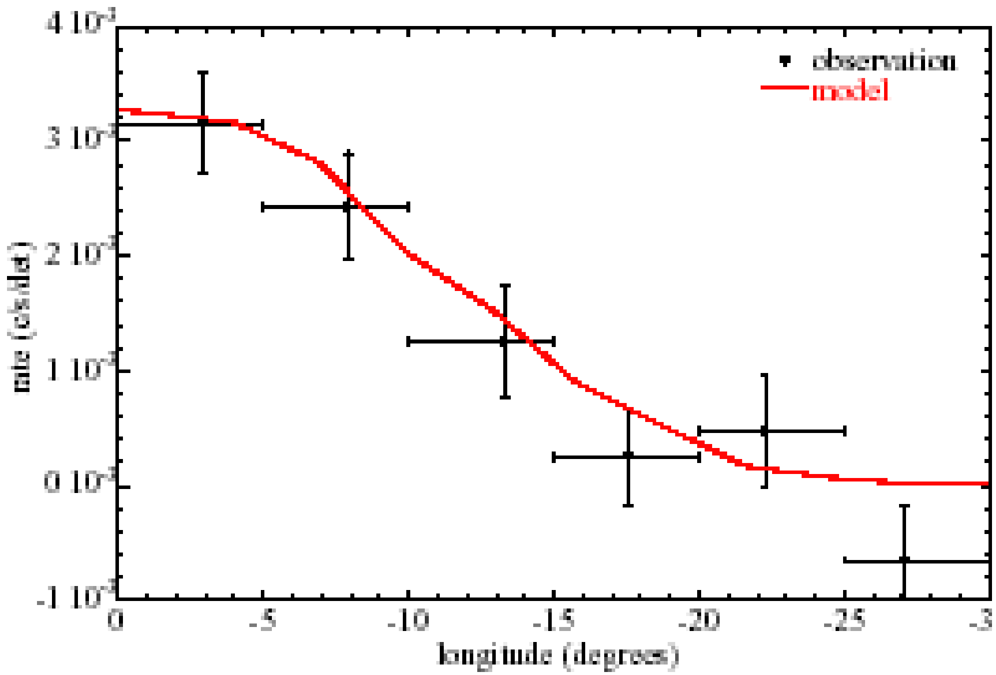
INTEGRAL results (cont'd)

Source is extended



INTEGRAL results (cont'd)

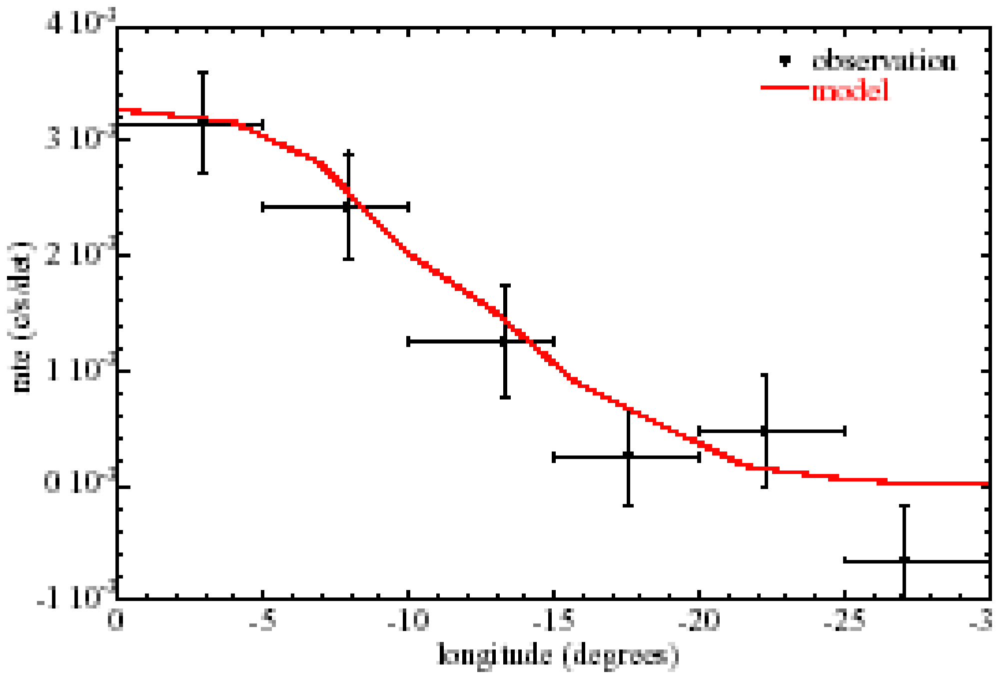
Source is extended



Angular width (FWHM) $\simeq 10^\circ$; resolution $\simeq 2^\circ$

INTEGRAL results (cont'd)

Source is extended



Angular width (FWHM) $\simeq 10^\circ$; resolution $\simeq 2^\circ$

No evidence for substructure

Interpretation

- Line is quite sharp $\Longrightarrow$ must come from annihilation of non–relativistic e^+e^-

Interpretation

- Line is quite sharp $\Longrightarrow$ must come from annihilation of non–relativistic e^+e^-
- Astrophysical sources (novae, supernovae, hypernovae, stellar flares):

Interpretation

- Line is quite sharp $\Longrightarrow$ must come from annihilation of non–relativistic e^+e^-
- Astrophysical sources (novae, supernovae, hypernovae, stellar flares):
  - rate of positron production uncertain

Interpretation

- Line is quite sharp $\Longrightarrow$ must come from annihilation of non–relativistic e^+e^-
- Astrophysical sources (novae, supernovae, hypernovae, stellar flares):
  - rate of positron production uncertain
  - difficulty filling entire bulge

Interpretation

- Line is quite sharp $\Longrightarrow$ must come from annihilation of non–relativistic e^+e^-
- Astrophysical sources (novae, supernovae, hypernovae, stellar flares):
  - rate of positron production uncertain
  - difficulty filling entire bulge
- Dark Matter $\to e^+e^-$ annihilation: Can work!! Boehm, Hooper, Silk, Casse, Paul, astro–ph/0309686, Phys. Rev. Lett 92, 101301 (2004)

Interpretation in terms of MeV DM

- DM particles χ annihilate: $\chi\bar{\chi} \to e^+e^-$ ($\chi \equiv \bar{\chi}$ is possible.)

Interpretation in terms of MeV DM

- DM particles χ annihilate: $\chi\bar{\chi} \rightarrow e^+e^-$ ($\chi \equiv \bar{\chi}$ is possible.)
- If $m_\chi \leq 100$ MeV: positrons get slowed down sufficiently fast before annihilating; main mechanism: ionization of neutral atoms

Interpretation in terms of MeV DM

- DM particles χ annihilate: $\chi\bar{\chi} \to e^+e^-$ ($\chi \equiv \bar{\chi}$ is possible.)
- If $m_\chi \leq 100$ MeV: positrons get slowed down sufficiently fast before annihilating; main mechanism: ionization of neutral atoms
- Magnetic fields keep positrons within ~ 1 pc of their origin

Interpretation in terms of MeV DM

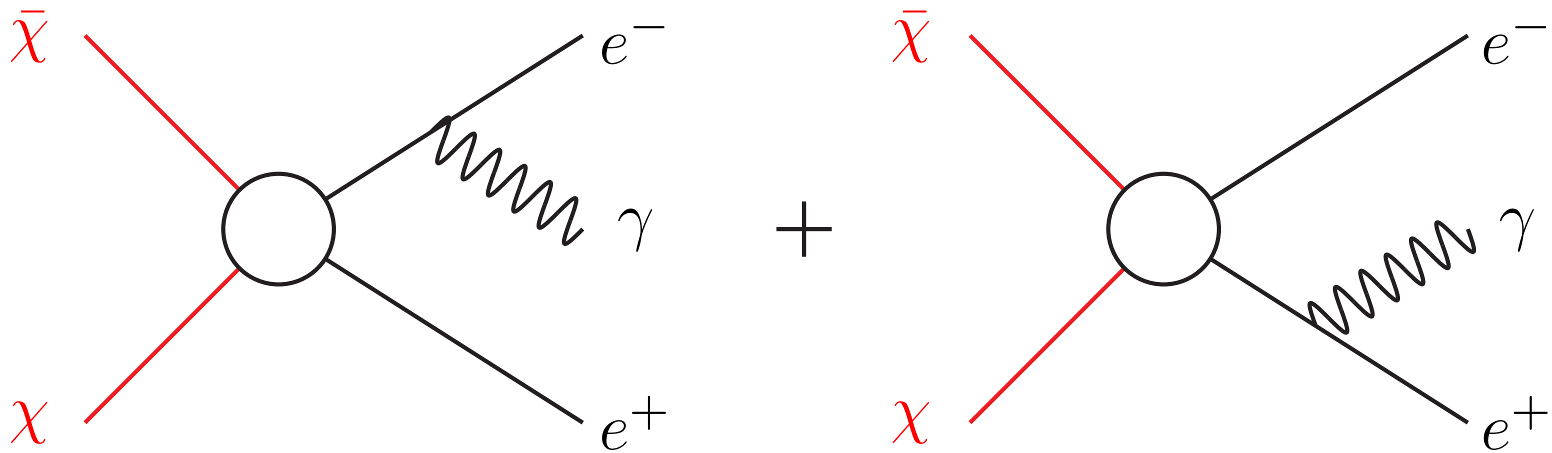
- DM particles χ annihilate: $\chi\bar{\chi} \rightarrow e^+e^-$ ($\chi \equiv \bar{\chi}$ is possible.)
- If $m_\chi \leq 100$ MeV: positrons get slowed down sufficiently fast before annihilating; main mechanism: ionization of neutral atoms
- Magnetic fields keep positrons within ~ 1 pc of their origin
- $\Longrightarrow$ Flux of 511 keV photons $\propto n_\chi^2$!

Interpretation in terms of MeV DM

- DM particles χ annihilate: $\chi\bar{\chi} \to e^+e^-$ ($\chi \equiv \bar{\chi}$ is possible.)
- If $m_\chi \leq 100$ MeV: positrons get slowed down sufficiently fast before annihilating; main mechanism: ionization of neutral atoms
- Magnetic fields keep positrons within ~ 1 pc of their origin
- $\Longrightarrow$ Flux of 511 keV photons $\propto n_\chi^2$!
- In this case, DM distribution according to galactic models can reproduce angular distribution of signal reasonably well; less so, if flux $\propto n_\chi$ (decaying DM models)

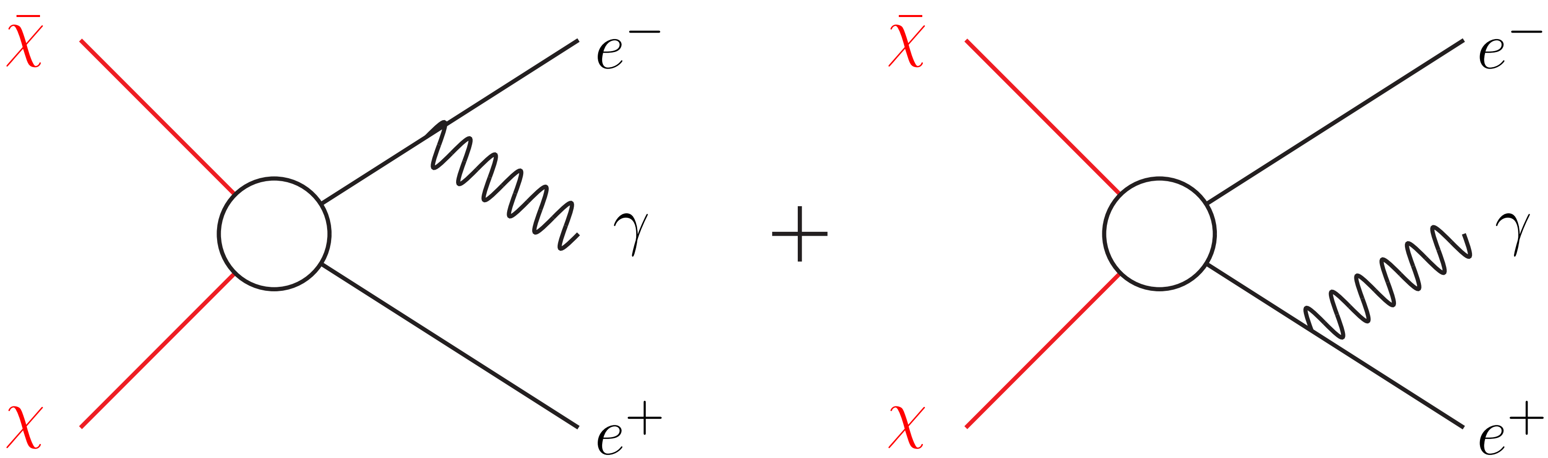
Additional astrophysical constraints

Come from higher-order (radiative) process:



Additional astrophysical constraints

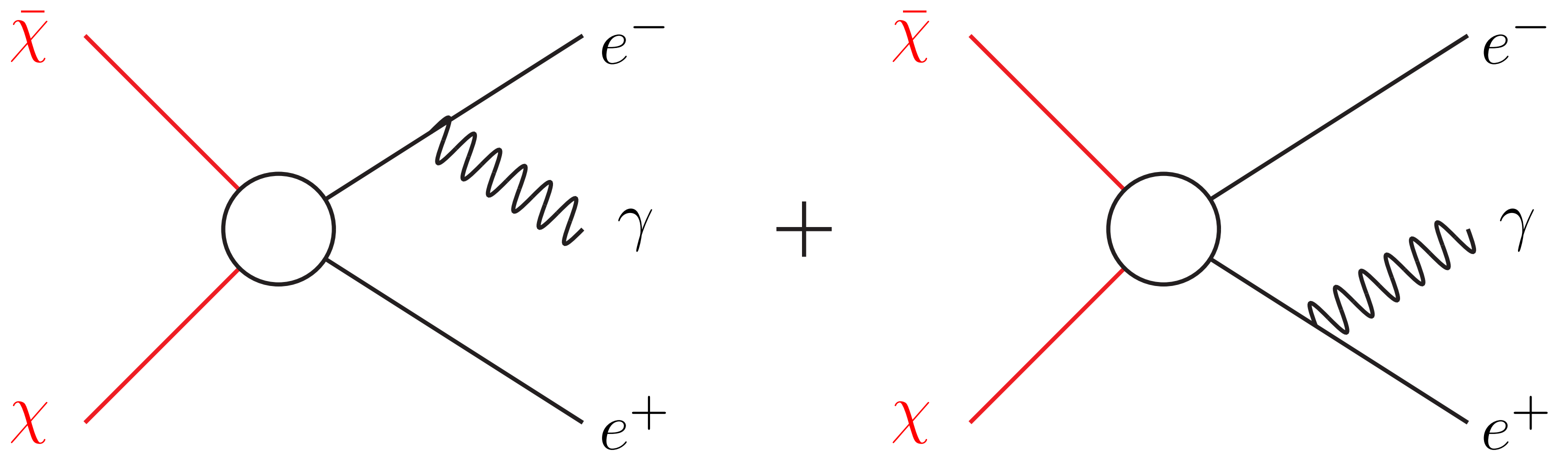
Come from higher-order (radiative) process:



Cross section $\sigma_{\rm rad} \propto \alpha \ln \frac{m_\chi}{m_e} \cdot \sigma(\chi\bar{\chi} \to e^+ e^-)$, $E_\gamma \propto m_\chi$

Additional astrophysical constraints

Come from higher-order (radiative) process:



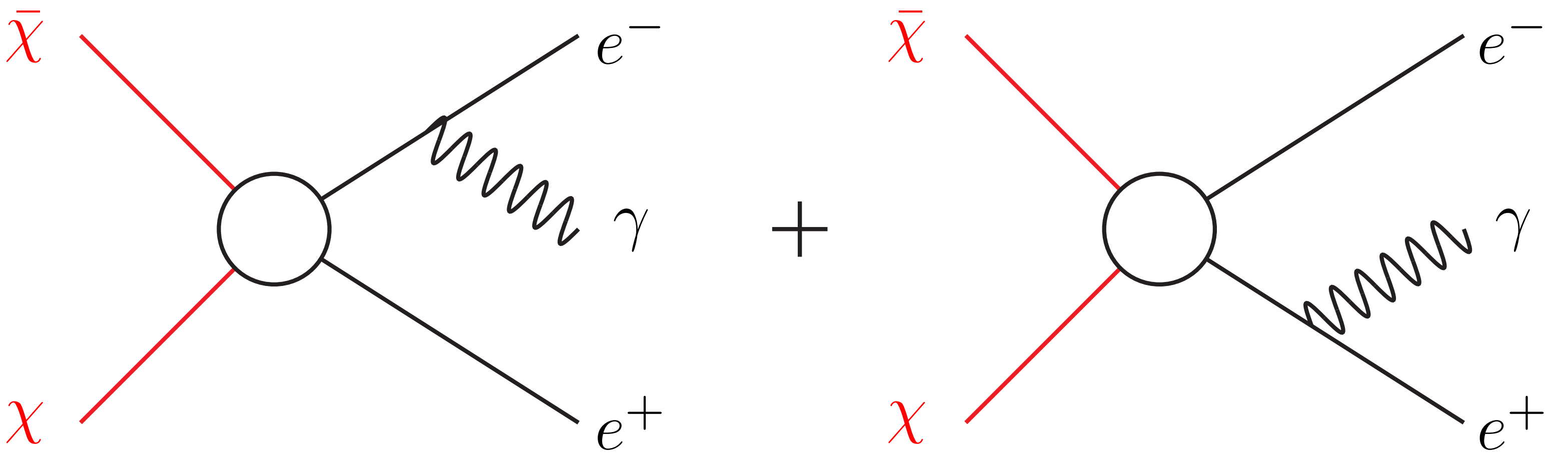
Cross section $\sigma_{\rm rad} \propto \alpha \ln \frac{m_\chi}{m_e} \cdot \sigma(\chi\bar{\chi} \to e^+e^-)$, $E_\gamma \propto m_\chi$

- To avoid overproduction of MeV photons: $m_\chi \leq 20$ MeV!

  Beacom, Bell, Bertone, Phys. Rev. Lett 94, 171301 (2005)

Additional astrophysical constraints

Come from higher-order (radiative) process:



Cross section $\sigma_{\rm rad} \propto \alpha \ln \frac{m_\chi}{m_e} \cdot \sigma(\chi\bar{\chi} \rightarrow e^+e^-)$, $E_\gamma \propto m_\chi$

- To avoid overproduction of MeV photons: $m_\chi \leq 20$ MeV!

  Beacom, Bell, Bertone, Phys. Rev. Lett 94, 171301 (2005)

- Bound reduced to ~ 3 MeV if photons produced during slow–down of $e^\pm$ are included. Beacom & Yuksel, Phys. Rev. Lett. 97, 071102 (2006)

Particle physics model

- To explain flux of 511 keV photons: need

$$10^{-3}\ \mathrm{fb} \le v\sigma(\chi\bar{\chi} \to e^+e^-) \cdot \left(\frac{1\ \mathrm{MeV}}{m_\chi}\right)^2 \cdot \kappa \le 1\ \mathrm{fb}$$

$\kappa = 1\ (2)$ if $\chi = \bar{\chi}$ ($\chi \neq \bar{\chi}$). Expanded range in Boehm et al. by factor 10 in both directions. Note: ρ_χ fixed from galactic modelling $\Longrightarrow n_\chi \propto 1/m_\chi$.

Particle physics model

- To explain flux of 511 keV photons: need

$$10^{-3}\ \mathrm{fb} \leq v\sigma(\chi\bar{\chi} \to e^+e^-) \cdot \left(\frac{1\ \mathrm{MeV}}{m_\chi}\right)^2 \cdot \kappa \leq 1\ \mathrm{fb}$$

  $\kappa = 1\ (2)$ if $\chi = \bar{\chi}$ ($\chi \neq \bar{\chi}$). Expanded range in Boehm et al. by factor 10 in both directions. Note: ρ_χ fixed from galactic modelling $\Longrightarrow n_\chi \propto 1/m_\chi$.

- Mass range for DM particle χ:

$$m_e \leq m_\chi \leq 20\ \mathrm{MeV}$$

Particle physics model

- To explain flux of 511 keV photons: need

$$10^{-3} \text{ fb} \le v\sigma(\chi\bar{\chi} \to e^+e^-) \cdot \left(\frac{1 \text{ MeV}}{m_\chi}\right)^2 \cdot \kappa \le 1 \text{ fb}$$

  $\kappa = 1\ (2)$ if $\chi = \bar{\chi}$ ($\chi \ne \bar{\chi}$). Expanded range in Boehm et al. by factor 10 in both directions. Note: ρ_χ fixed from galactic modelling $\Longrightarrow n_\chi \propto 1/m_\chi$.

- Mass range for DM particle χ:

$$m_e \le m_\chi \le 20 \text{ MeV}$$

- Taken together, these constraints imply that χ was in thermal equilibrium (using $T_R > 0.7$ MeV from BBN; Guidice et al. 2001)

Particle physics model (cont'd)

- To get right thermal relic density, χ annihilation cross section at decoupling must have been *much* higher than the current cross section into e^+e^- pairs

Particle physics model (cont'd)

- To get right thermal relic density, χ annihilation cross section at decoupling must have been *much* higher than the current cross section into e^+e^- pairs
- Strongly hints at annihilation from $P-$wave only: $v\sigma \propto v^2$. Note: $v^2_{\text{dec.}} \sim 0.1, \; v^2_{\text{now}} \sim 10^{-6}$.

Particle physics model (cont'd)

- To get right thermal relic density, χ annihilation cross section at decoupling must have been *much* higher than the current cross section into e^+e^- pairs
- Strongly hints at annihilation from $P-$wave only: $v\sigma \propto v^2$. Note: $v^2_{\rm dec.} \sim 0.1, \ v^2_{\rm now} \sim 10^{-6}$.
- Simplest realization: χ annihilation mediated by exchange of spin–1 Boson U; χ is complex scalar or Majorana spin–$1/2$ fermion. (Dirac fermion would annihilate from $S-$wave!)

Particle physics model (cont'd)

- To get right thermal relic density, χ annihilation cross section at decoupling must have been *much* higher than the current cross section into e^+e^- pairs
- Strongly hints at annihilation from $P-$wave only: $v\sigma \propto v^2$. Note: $v^2_{\text{dec.}} \sim 0.1,\ v^2_{\text{now}} \sim 10^{-6}$.
- Simplest realization: χ annihilation mediated by exchange of spin–1 Boson U; χ is complex scalar or Majorana spin–$1/2$ fermion. (Dirac fermion would annihilate from $S-$wave!)
- Relic density essentially fixes product $g^2_\chi \left(g^2_{e_R} + g^2_{e_L} \right)$ of $U-$boson couplings.

Model building aspects

- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave

Model building aspects

- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave
- $g_e - 2$ constraint implies $g_\chi > g_{e_R}, g_{e_L}$

Model building aspects

- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave
- $g_e - 2$ constraint implies $g_\chi > g_{e_R}, g_{e_L}$
- $g_\chi \gg g_{e_R}, g_{e_L}$ natural if U couples to electrons only through mixing with γ, Z!

Model building aspects

- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave
- $g_e - 2$ constraint implies $g_\chi > g_{e_R}, g_{e_L}$
- $g_\chi \gg g_{e_R}, g_{e_L}$ natural if U couples to electrons only through mixing with γ, Z!
- If total gauge group $G = G_{\rm SM} \times G_U$: $SU(2)$ invariance implies $g_{e_L} = g_{\nu_e}$: took $g_{e_L} = 0$ most of the time.

Model building aspects

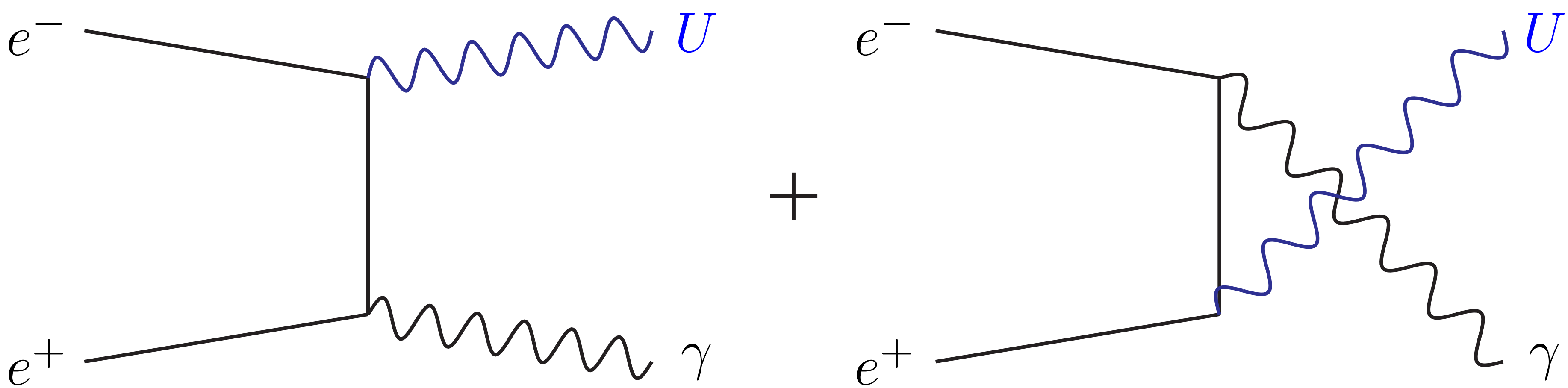
- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave
- $g_e - 2$ constraint implies $g_\chi > g_{e_R}, g_{e_L}$
- $g_\chi \gg g_{e_R}, g_{e_L}$ natural if U couples to electrons only through mixing with γ, Z!
- If total gauge group $G = G_{\rm SM} \times G_U$: $SU(2)$ invariance implies $g_{e_L} = g_{\nu_e}$: took $g_{e_L} = 0$ most of the time.
- DM and $g_e - 2$ constraints are compatible only for $M_U \lesssim 0.2$ GeV!

Model building aspects

- For most purposes, scalar $\chi \simeq$ Majorana χ with $g_{e_L} = g_{e_R}$: both are pure $P-$wave
- $g_e - 2$ constraint implies $g_\chi > g_{e_R}, g_{e_L}$
- $g_\chi \gg g_{e_R}, g_{e_L}$ natural if U couples to electrons only through mixing with γ, Z!
- If total gauge group $G = G_{\rm SM} \times G_U :\ SU(2)$ invariance implies $g_{e_L} = g_{\nu_e}$: took $g_{e_L} = 0$ most of the time.
- DM and $g_e - 2$ constraints are compatible only for $M_U \lesssim 0.2$ GeV!
- Did not attempt to build full (renormalizable) model.

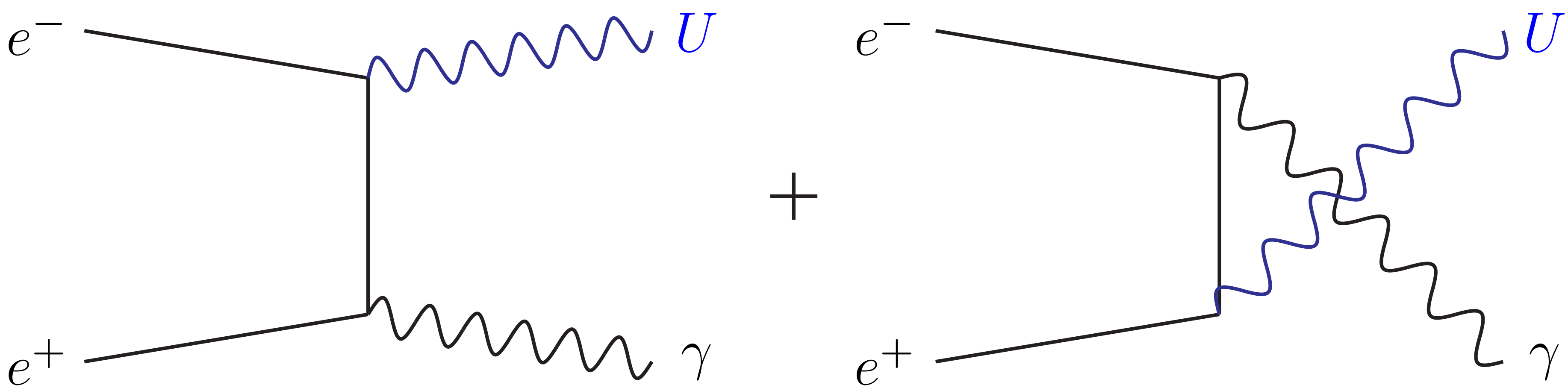
Tests at low energy e^+e^- colliders

$U-$boson must couple to electrons: can be produced at e^+e^- colliders!



Tests at low energy e^+e^- colliders

$U-$boson must couple to electrons: can be produced at e^+e^- colliders!



$$\frac{d\sigma(e^+e^- \to U\gamma)}{d\cos\theta} = \frac{\alpha\left(g_{e_L}^2 + g_{e_R}^2\right)}{4s\,(1-y)\sin^2\theta}\left[2\left(1+y^2\right) - \sin^2\theta\,(1-y)^2\right]$$

$y = \frac{M_U^2}{s} < 0.04$ even at DAΦNE.

Remarks

- Cross section $\propto 1/s \Longrightarrow$ lower energy is in principle better!

Remarks

- Cross section $\propto 1/s \Longrightarrow$ lower energy is in principle better!
- However: $\left.\frac{\int \mathcal{L}dt}{s}\right|_{\mathrm{DA\Phi NE}} < \left.\frac{\int \mathcal{L}dt}{s}\right|_{B-\mathrm{factories}}$: $B-$factories should have better chance

Remarks

- Cross section $\propto 1/s \Longrightarrow$ lower energy is in principle better!
- However: $\left.\frac{\int \mathcal{L} dt}{s}\right|_{\mathrm{DA\Phi NE}} < \left.\frac{\int \mathcal{L} dt}{s}\right|_{B-\mathrm{factories}}$: $B-$factories should have better chance
- Two possible final states:

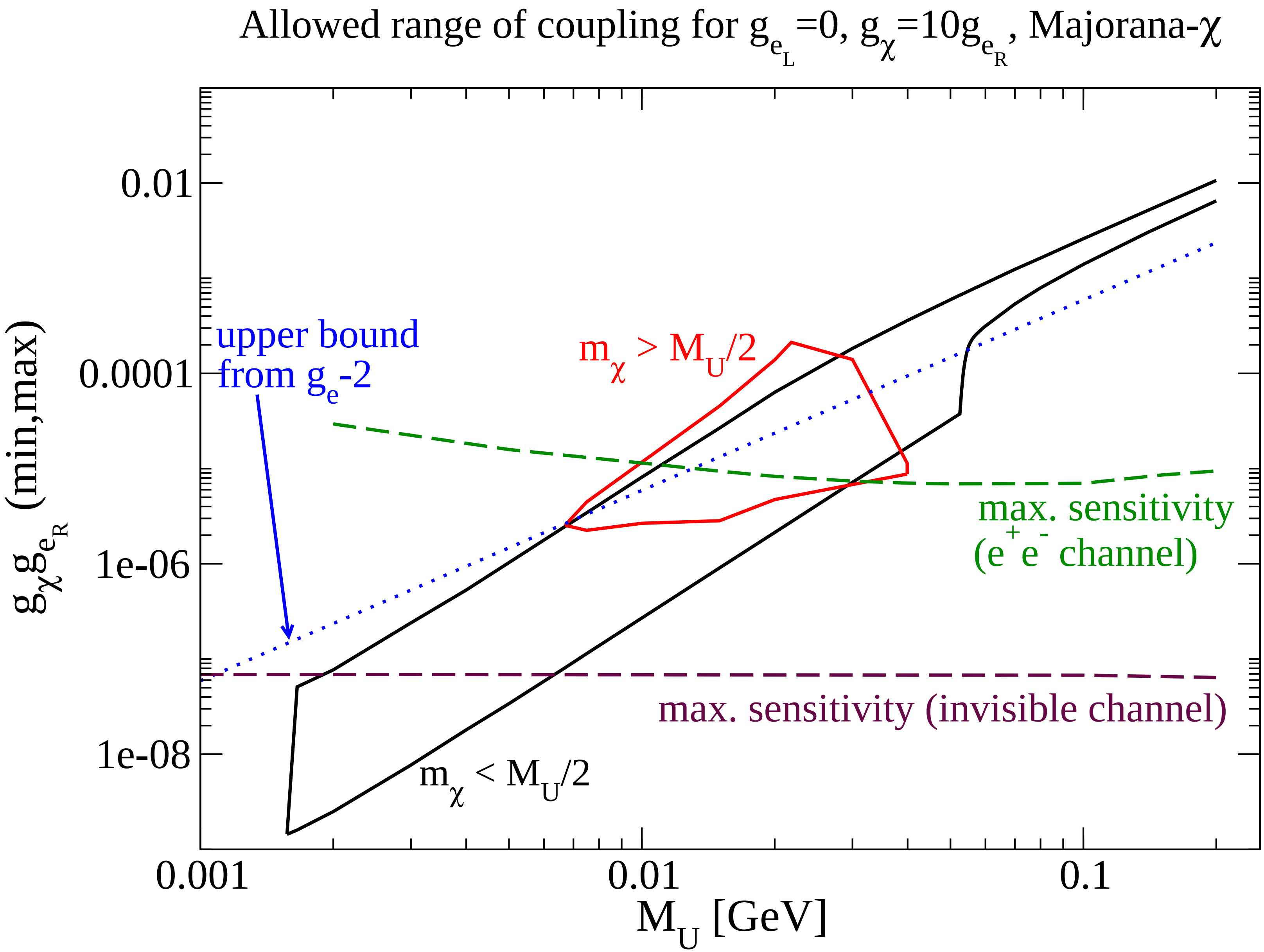
Remarks

- Cross section $\propto 1/s \Longrightarrow$ lower energy is in principle better!
- However: $\left.\frac{\int \mathcal{L}dt}{s}\right|_{\mathrm{DA\Phi NE}} < \left.\frac{\int \mathcal{L}dt}{s}\right|_{B-\mathrm{factories}}$: $B-$factories should have better chance
- Two possible final states:
  - $U \to e^+e^-$: have $e^+e^-\gamma$ final state

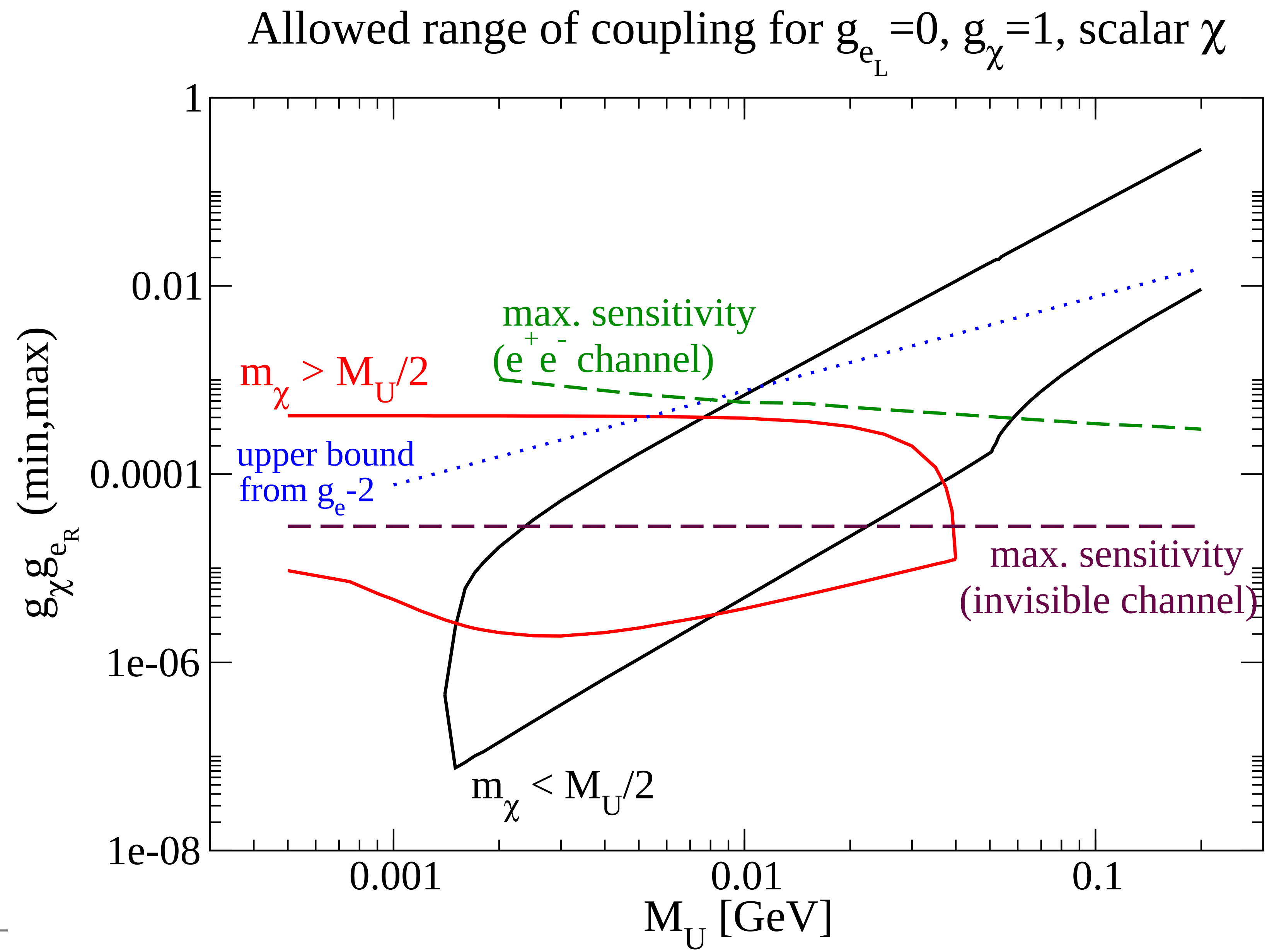
Remarks

- Cross section $\propto 1/s \Longrightarrow$ lower energy is in principle better!
- However: $\left.\frac{\int \mathcal{L} dt}{s}\right|_{\mathrm{DA\Phi NE}} < \left.\frac{\int \mathcal{L} dt}{s}\right|_{B-\mathrm{factories}}$: $B-$factories should have better chance
- Two possible final states:
  - $U \to e^+e^-$: have $e^+e^-\gamma$ final state
  - $U \to \nu\bar{\nu},\ \chi\bar{\chi}$: have $\gamma+$ ‘nothing’ final state (trigger??)

Reach for DAΦNE



Reach for $B-$factories



Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible

Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible
- Neutralinos in mSUGRA remain well motivated, viable candidate

Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Standard sterile ν's probably excluded; MeV DM testable at low energy colliders; gravitino/axino DM constrained by BBN

Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Standard sterile ν's probably excluded; MeV DM testable at low energy colliders; gravitino/axino DM constrained by BBN
- Thermal production of DM particles is most attractive mechanism: least dependent on details of cosmology

Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Standard sterile ν's probably excluded; MeV DM testable at low energy colliders; gravitino/axino DM constrained by BBN
- Thermal production of DM particles is most attractive mechanism: least dependent on details of cosmology
- If DM is made from thermal WIMPs: lower bound on T_R increases by factor $\sim 10^4$

Summary

- Lots of different particle DM candidates have been suggested; not all are equally plausible
- Neutralinos in mSUGRA remain well motivated, viable candidate
- Standard sterile ν's probably excluded; MeV DM testable at low energy colliders; gravitino/axino DM constrained by BBN
- Thermal production of DM particles is most attractive mechanism: least dependent on details of cosmology
- If DM is made from thermal WIMPs: lower bound on T_R increases by factor $\sim 10^4$
- WIMPs can be detected in a variety of ways; once detected, allow new probes of Universe