Light Higgses and Dark Matter

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~~Light~~ Low-Mass Dark Matter

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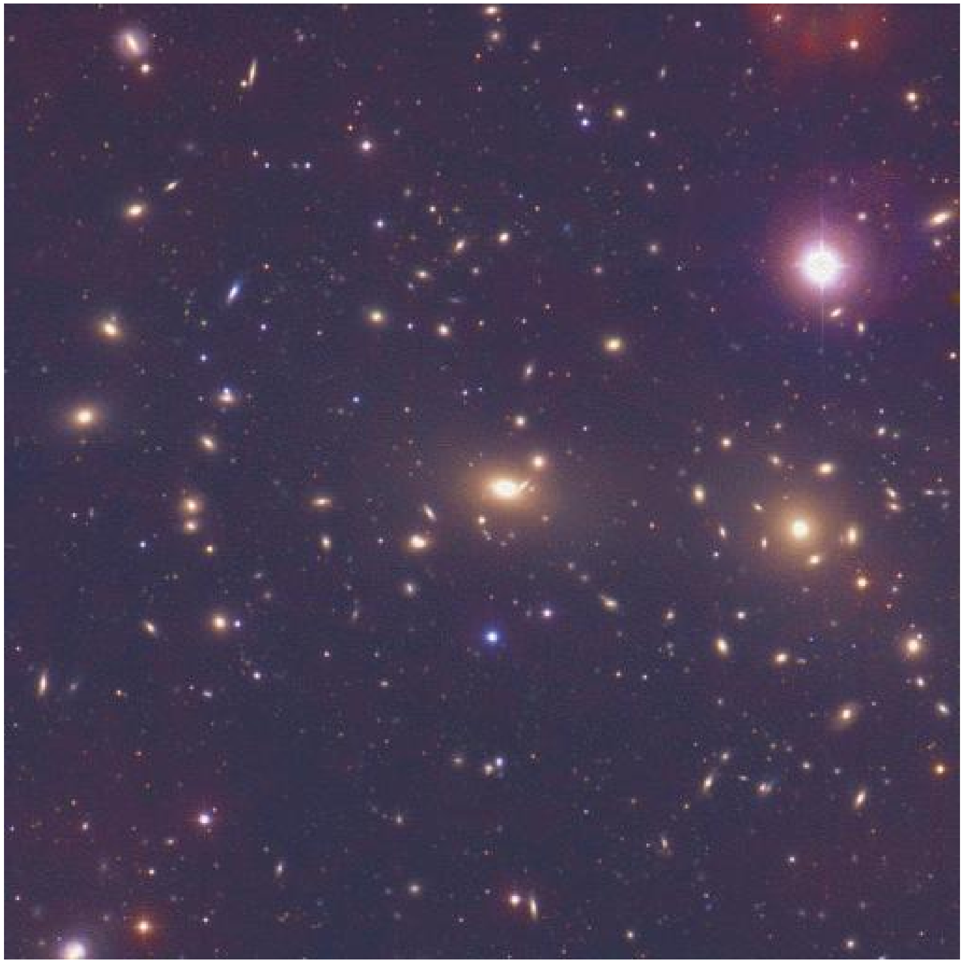
Outline

- A Brief History of Dark Matter
- A Model Independent Approach
- Motivations and Expectations for Light Dark Matter
- Invisible Quarkonium Decays
- Light Dark Matter from SUSY
- Detection of the Mediator, or a Higgs?
- Conclusion

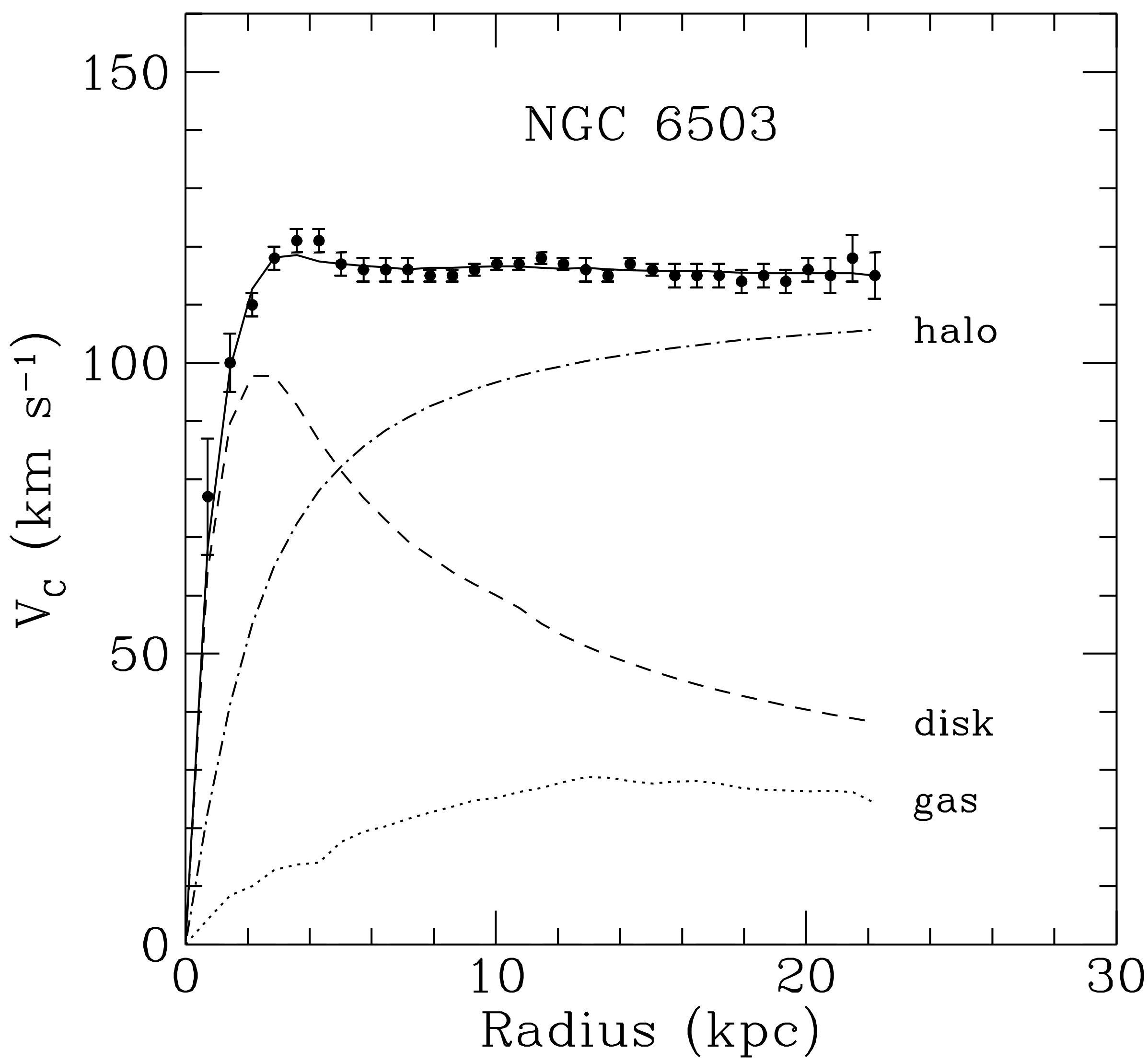
A Brief History of Dark Matter

1933 Fritz Zwicky calculates the mass of the Coma cluster using the Virial Theorem using galaxies on the outer edge, and comes up with a number 400 times larger than the expected mass.



A Brief History of Dark Matter

1975 Vera Rubin notices the rotation curves of galaxies are flat at large radii. (Jungman, Kamionkowski, Griest)



A Brief History of Dark Matter

There are two broad classes of solutions by looking at Einstein's equation

$$G_{ab} = 8\pi G_N T_{ab}$$

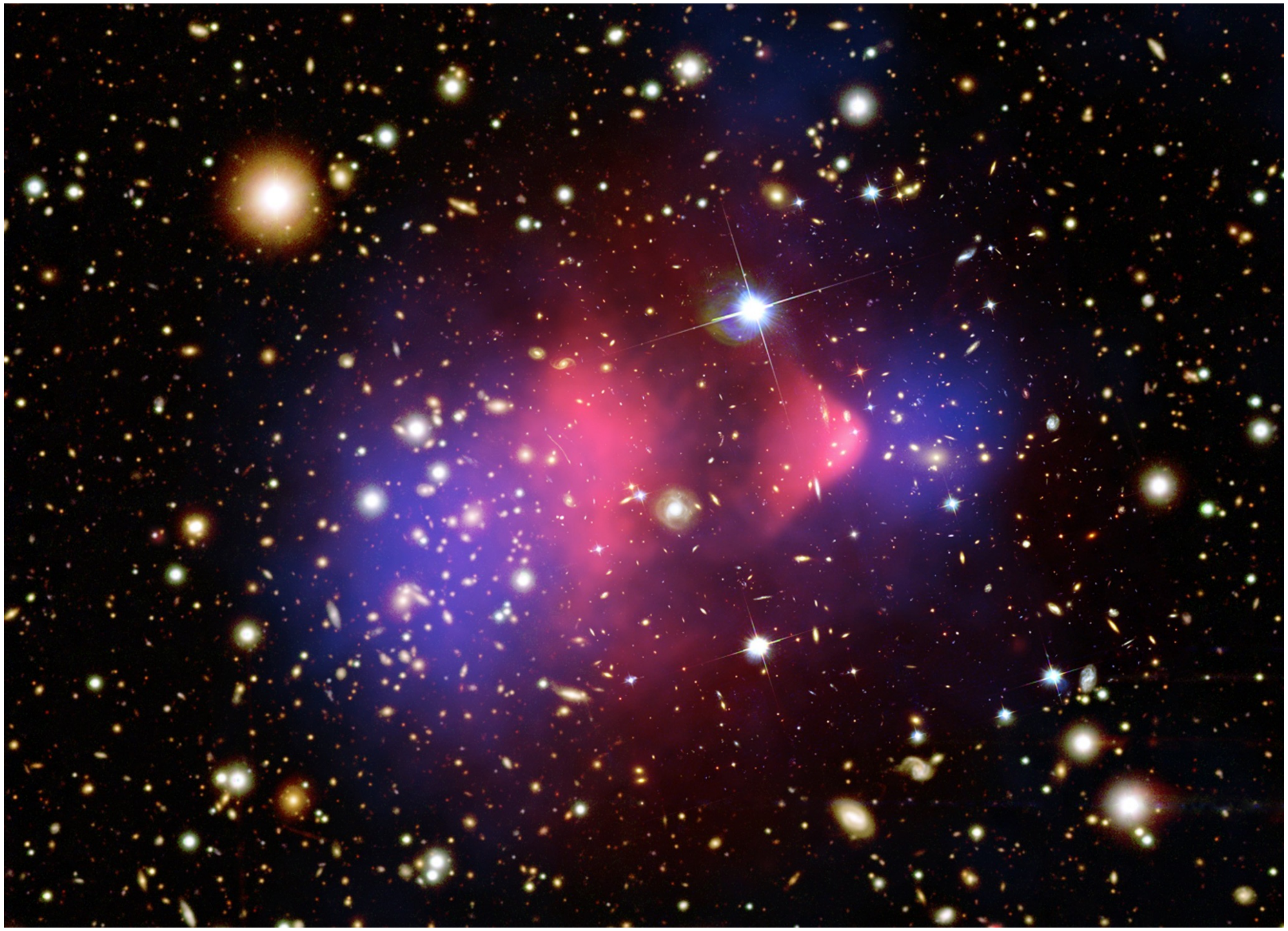
- Modifications to the left-side of gravity. e.g. MOdified Newtonian Dynamics (MOND), TeVeS (Tensor Vector Scalar theory). Now disfavored by Bullet Cluster observations of X-Ray gas [`astro-ph/0608407`].

- Modifications to the right-side of gravity

  – Massive Compact Halo Objects (e.g. black holes and rogue Jupiter-sized objects in interstellar space) Now ruled out for $10^{-7} < M/M_\odot < 5$ (EROS-2 Collaboration) [`hep-ph/0607207`]

  – Particle Dark Matter

A Brief History of Dark Matter



X-ray gas, gravitational potential [Clowe et al. astro-ph/0608407]; Note the claim of disproving MOND is disputed: [Angus, Famaey, Zhao astro-ph/0606216] requires addition of Hot Dark Matter: 2 eV neutrinos.

Dark Matter Status

Cold Particle Dark Matter is the *most favored* solution.

Theorists quickly noticed that Supersymmetry *already contains* a Dark Matter candidate particle (the lightest neutralino, or sneutrino).

This has lead the Dark Matter community to search for *candidates*, and to Dark Matter candidates tied to the solutions of other problems, such as Electroweak Symmetry Breaking.

A "candidate" is: A particle in a theory designed to solve a *different* problem.

The solution to the *Dark Matter* problem may have nothing to do with *Electroweak Symmetry Breaking*.

Perhaps by solving the Dark Matter problem, this will teach us something about these other problems. Let's try to solve the Dark Matter problem, *by itself.*

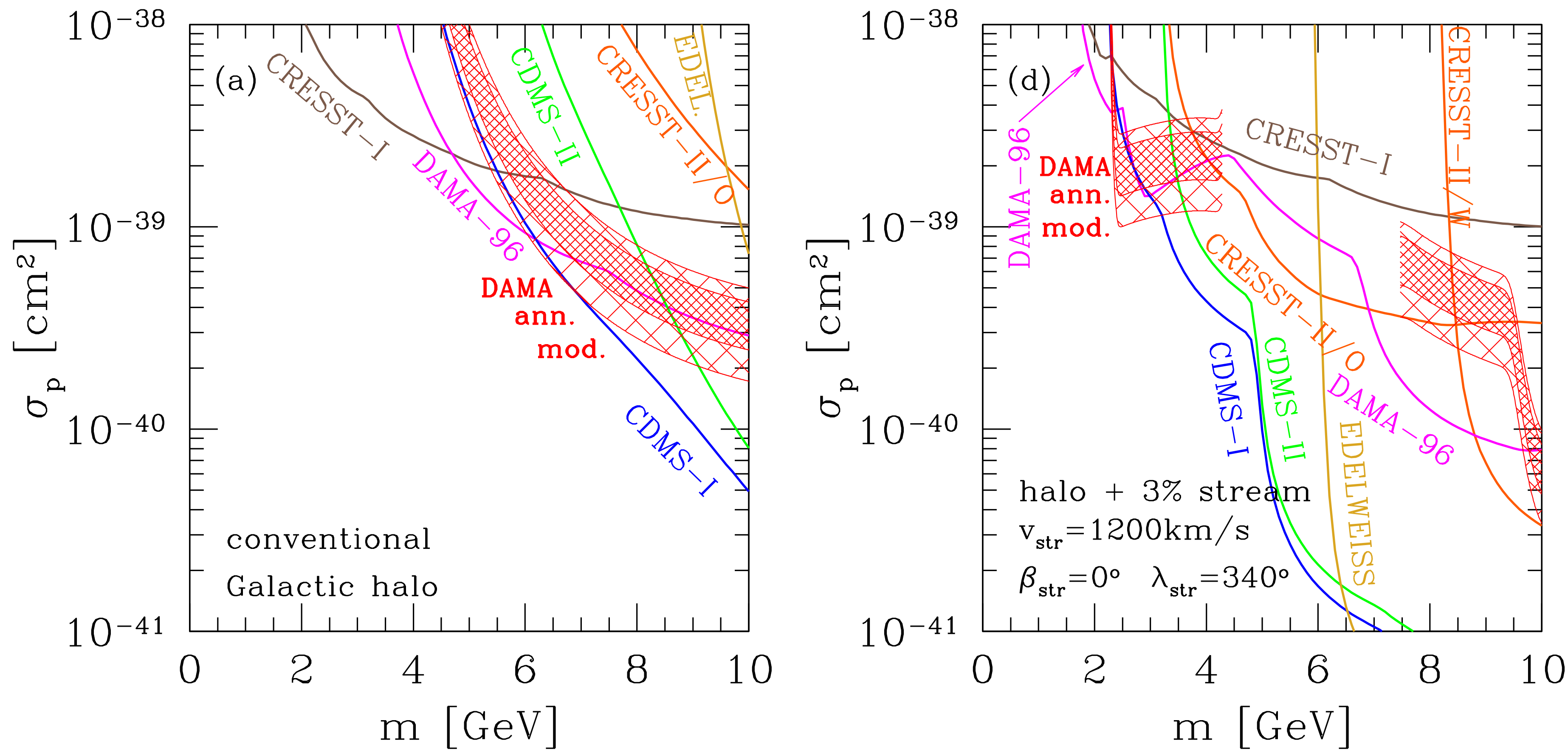
DAMA Evidence

DAMA is a 100kg NaI detector. They observed an annual modulation signal consistent with a WIMP with mass $M_{\chi^0} = 52^{+10}_{-8}$ GeV and a cross section $\sigma = 7.2^{+0.4}_{-0.9} \times 10^{-6}$ pb. [Phys.Lett.B480:23-31,2000]

This is inconsistent with recent CDMS results using Si and Ge. [astro-ph/0405033]

It was pointed out that Na has a lower detection threshold than Si and Ge, making DAMA more sensitive to light dark matter. Furthermore, a "wind" passing through our local region can make DAMA and CDMS compatible. [Gondolo, Gelmini, Savage, Freese]

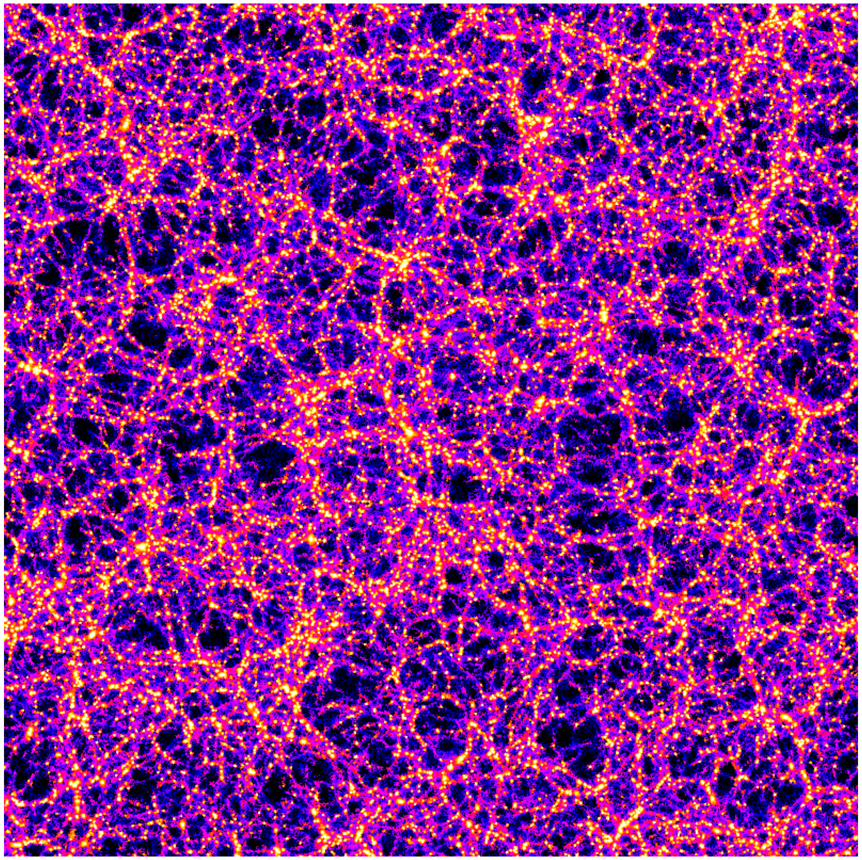
DAMA/CDMS Compatability



[Gondolo, Gelmini, hep-ph/0504010]

Dark Matter Map

An isotropic distribution as often used with $\rho_\chi = 0.3\text{GeV/cm}^3$ is probably too naïve.



[University of Washington, N-Body simulations, 100 MPc slice]

INTEGRAL Evidence

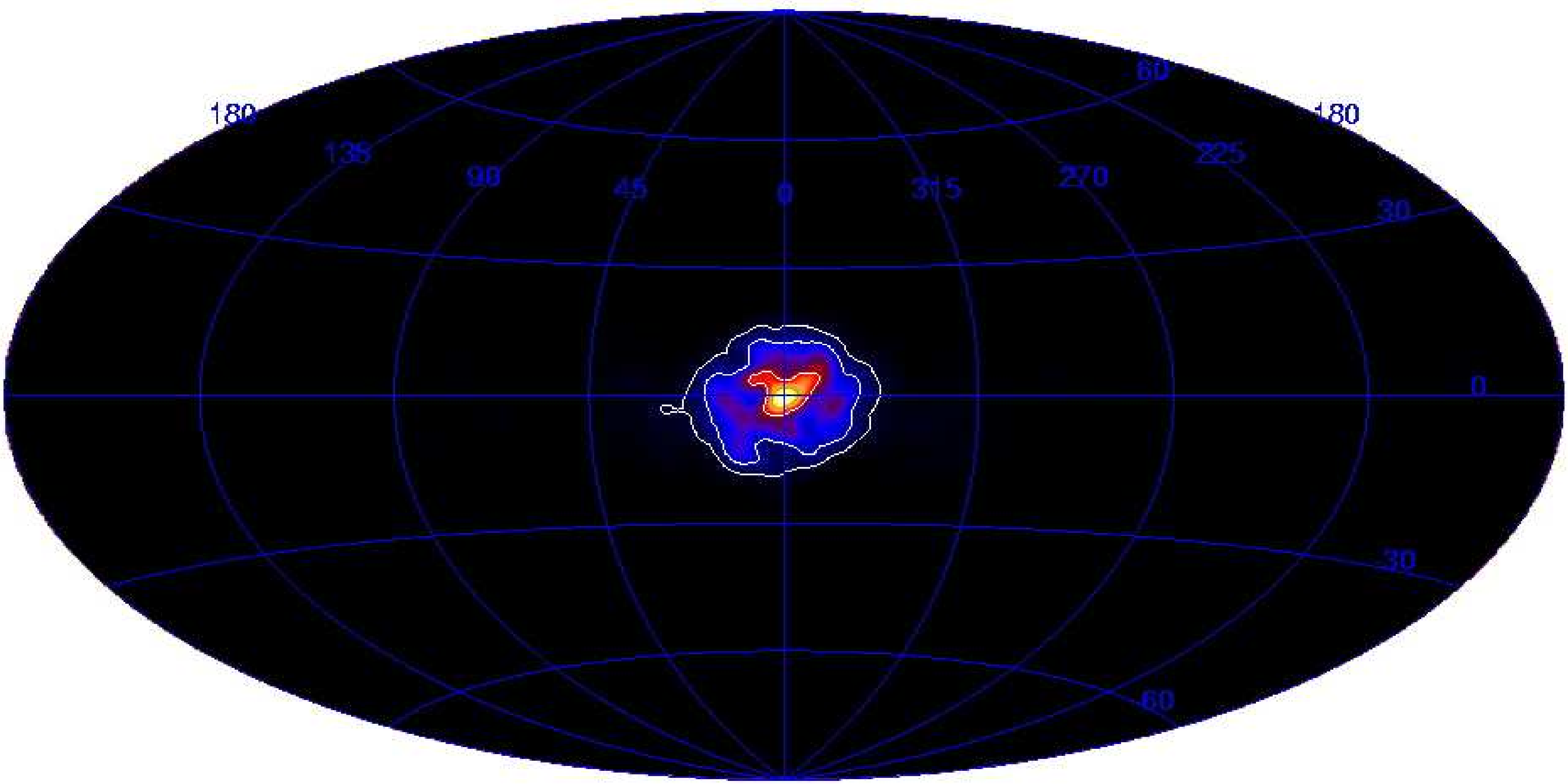
The SPI spectrometer aboard the INTEGRAL satellite observes a gaussian profile of 511 keV γ-rays coming from the inner kiloparsec of our galaxy. Attempt to explain this from astrophysical sources have failed thus far.

If this is coming from dark matter annihilation, the dark matter must be in the range $m_e < m_{\chi^0} < 20$ MeV (and possibly as low as 3 MeV: Yuksel [`astro-ph/0609139`]). This annihilation must not produce any π^0 or high-energy photons from $e^+e^-\gamma$ final state, due to COMPTEL and EGRET limits on gamma rays.

Annihilation through Z^0 and MSSM higgses is not efficent enough to prevent a neutralino this light from over-closing the universe.

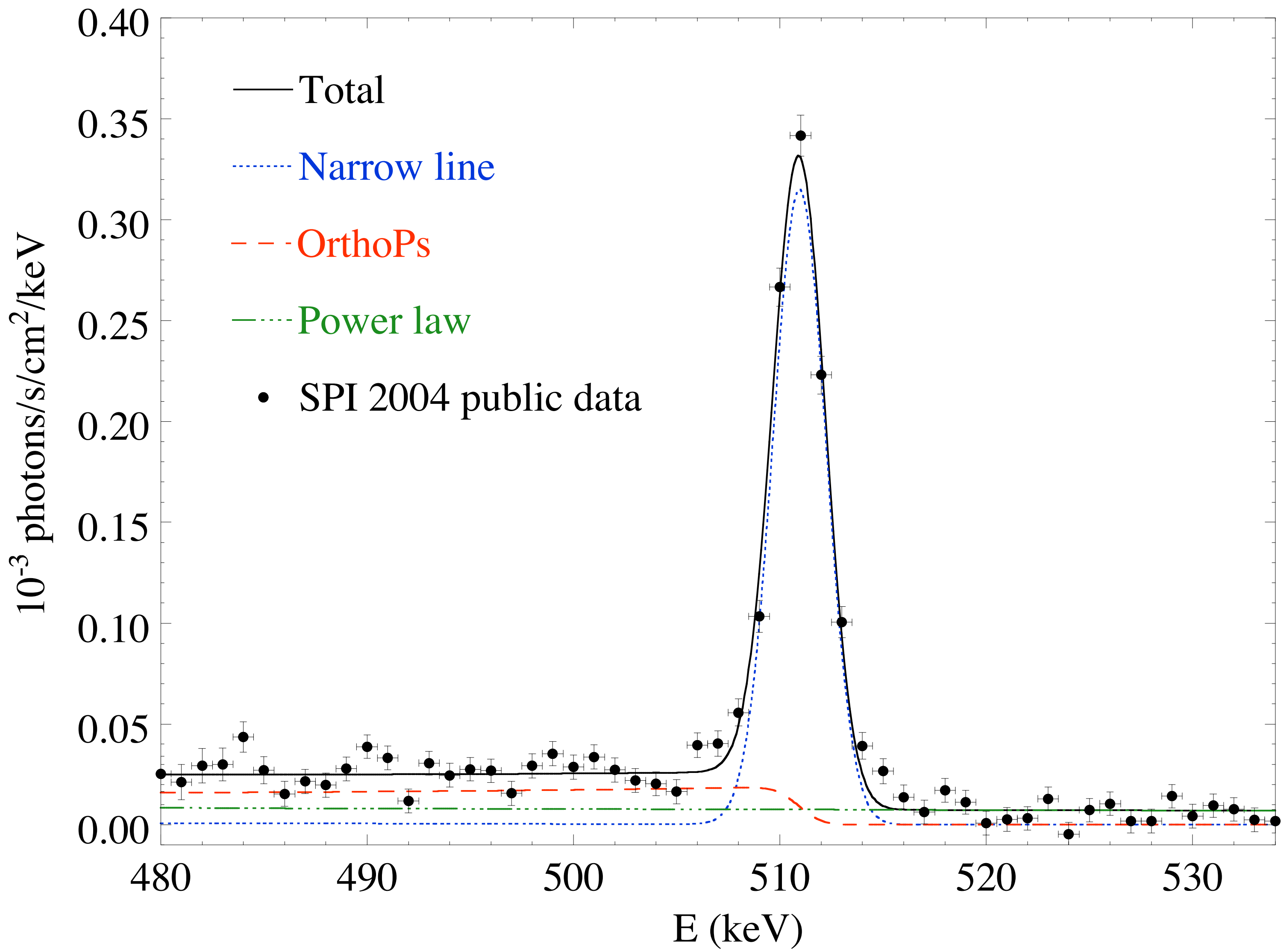
$\Rightarrow$ A new SM-DM annihilation mediator is required.

INTEGRAL Spectrum



[Knödlseder et. al. astro-ph/0506026]

INTEGRAL Spectrum



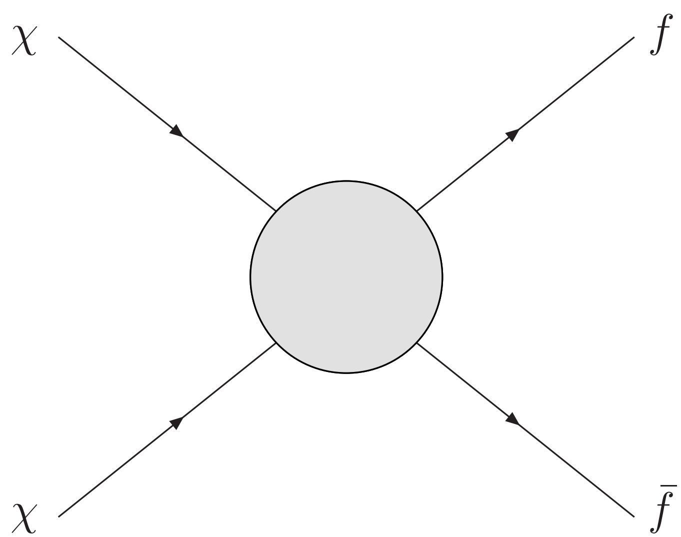
[Jean et. al. astro-ph/0509298]

What do we know?

- If Dark Matter is decoupled, we could never discover it.

- If not, we assume it was in thermal equilibrium at some point.

- WMAP has measured the relic density, and therefore, the *annihilation cross section*.



How light can Dark Matter be?

Let us concentrate on the region that can be tested by BaBar, BESIII, and similar experiments: $M_\chi < 5$ GeV.

Such light Dark Matter *must not couple significantly to the Z boson*. For SUSY theories this means the Higgsino component of the lightest neutralino $\epsilon_u^2 - \epsilon_d^2 < 6\%$. Binos and neutral Winos do not couple to the Z. Here:

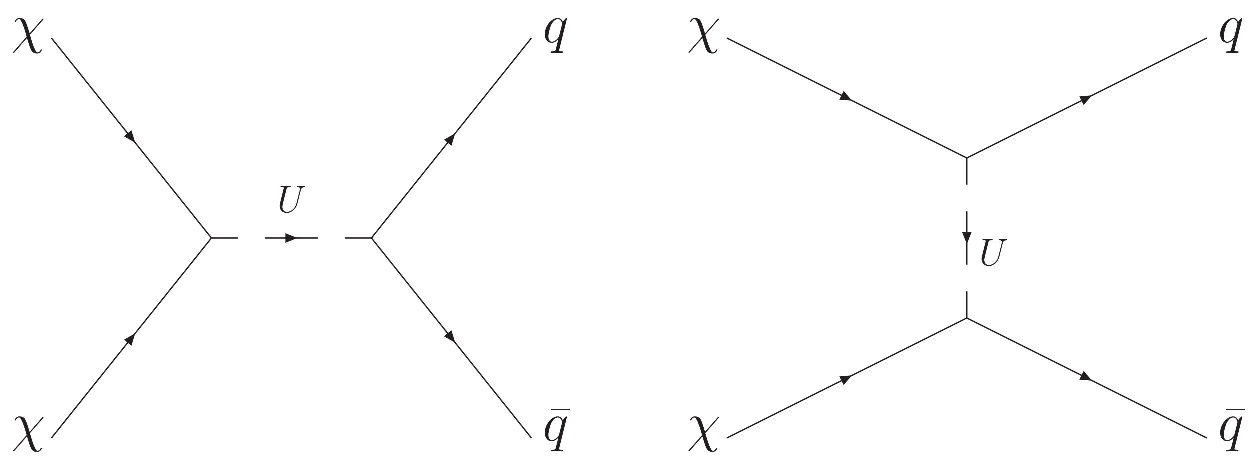
$$\chi_1^0 = \epsilon_u \widetilde{H}_u + \epsilon_d \widetilde{H}_d + \epsilon_B \widetilde{B} + \epsilon_W \widetilde{W}^0 + \ldots$$

$BR(Z \to \text{invisible}) = 20.00 \pm 0.06\%$ is well measured, and consistent with SM expectation of $N_\nu = 3$.

The Z and MSSM Higgses do not generally provide a strong enough annihilation to get the correct relic density if $M_\chi < 20$ GeV.

Annihilation Mediators

Light dark matter requires a new *annihilation mediator* U in addition to the Dark Matter itself.



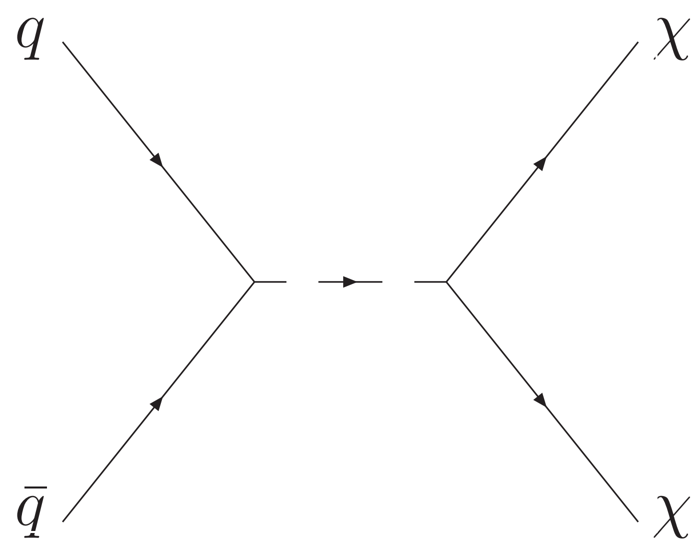
If the annihilation mediator appears in the t-channel (right), *must carry Standard Model quantum numbers*. Such as, squarks, sleptons, charginos, etc.

Let's assume we have not missed any charged or colored states with $M \lesssim 100$ GeV.

In the s-channel, the parameter space consists of the couplings $g_{U\chi\chi}$ and $g_{Uf\bar{f}}$, and masses M_χ and M_U.

$t \to -t$

The time-reversed annihilation diagram corresponds to the *invisible decay of particle -onia*.



Measuring an invisible decay gives direct sensitivity to the J^{CP} of the mediator!

We have many $f\bar{f}$ bound states: π^0, ρ, η, ω, η', J/Ψ, χ_c, χ_b, Υ, η_b, etc.

Model Independence

Assume:

- Dark Matter annihilates in pairs (rather than a single particle with very small coupling like the axion)

Then we are forced to consider:

- Scalar or fermion Dark Matter particle

- Scalar, pseudoscalar, or vector particle mediates the SM-DM interaction

- If it is measured in $f\bar{f}$ -onia decays, it must be light.

Naïve Branching Ratio Expectations

Using the WMAP measurement $\Omega h^2 = 0.113$ and

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma v \rangle}$$

Where v is the average velocity at freeze-out, $v = T = m_\chi/20$. The invisible width of a hadron composed dominantly of $q\bar{q}$ is given by:

$$\Gamma(H \to \chi\chi) = f_H^2 M_H \sigma(q\bar{q} \to \chi\chi)$$

and $\sigma(q\bar{q} \to \chi\chi) \simeq \sigma(\chi\chi \to q\bar{q})$. This gives

$$BR(\Upsilon(1S) \to \chi\chi) \simeq 0.61\% \qquad BR(J/\Psi \to \chi\chi) \simeq 0.036\%$$

$$BR(\eta \to \chi\chi) \simeq 0.0074\%$$

New measurement from BES! [hep-ex/0607006] $BR(\eta \to \chi\chi) < 0.065\%$

Scalars and Pseudoscalars tend to have very small branching ratios ($\lesssim 10^{-7}$) because they are wider. These expectations are maximal given these *naïve assumptions*. We lose by factors of 2 if χ is Majorana instead of Dirac, or a scalar. But treating the relic density properly introduces much larger variation than this.

Dark Matter in Particle Decays

In order to see an invisible decay of a hadron H, we must *tag* the state so that we know that H was created.

One way to do this: radiative decays.

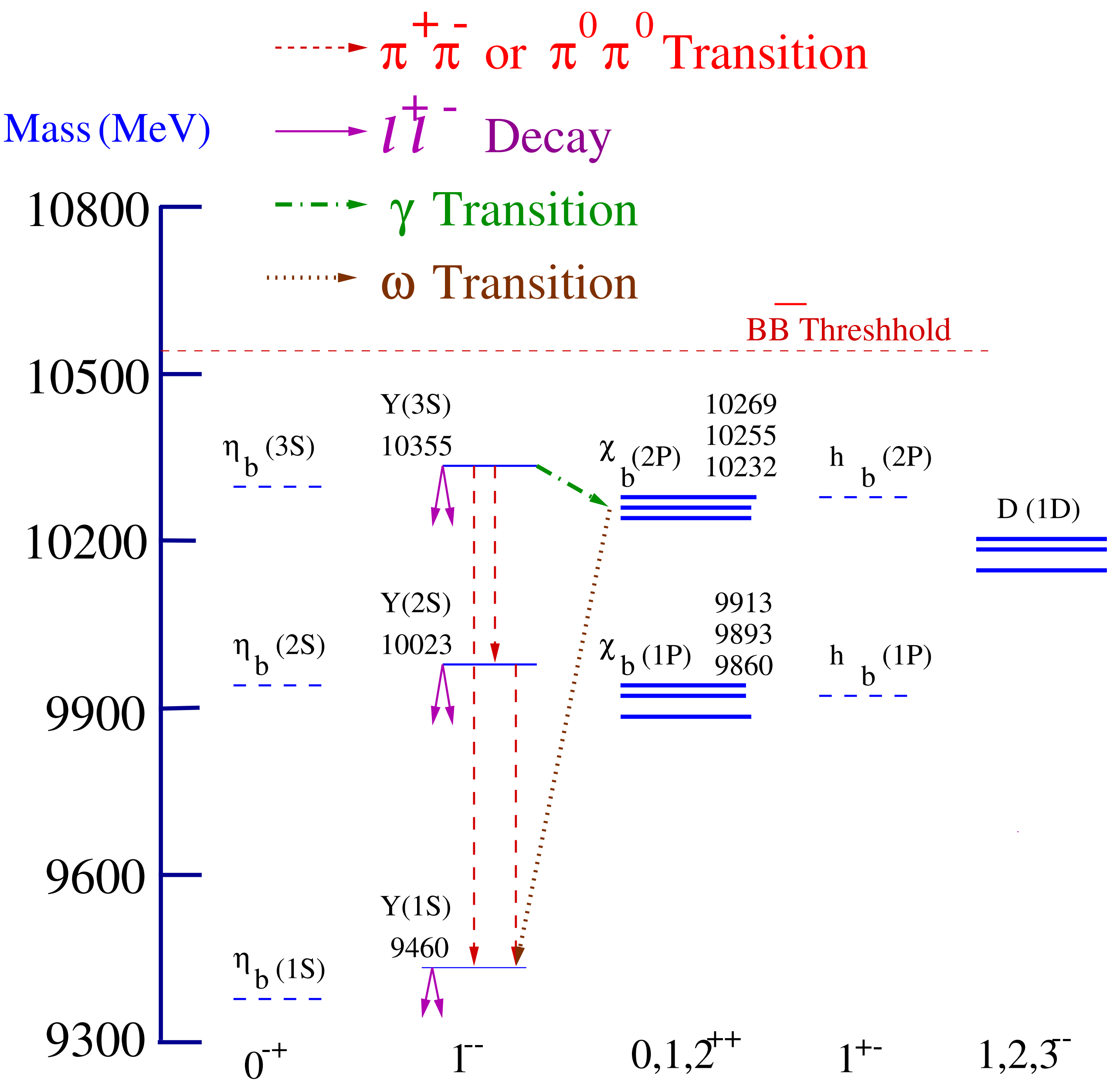
Many particles have radiative decays from excited states involving a $\pi^+\pi^-$ pair. e.g. $\Psi(2S) \to J/\Psi\pi^+\pi^-$, $\eta' \to \eta\pi^+\pi^-$.

Knowledge that two narrow resonances were formed gives us strong kinematic constraints.

We have B-factories running at the $\Upsilon(4S)$, so I studied $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ (where $n = 2, 3$).

Belle had a better idea: run on the $\Upsilon(3S)$. Almost the same analysis, but signal is enhanced by $\mathcal{O}(10^4)$.

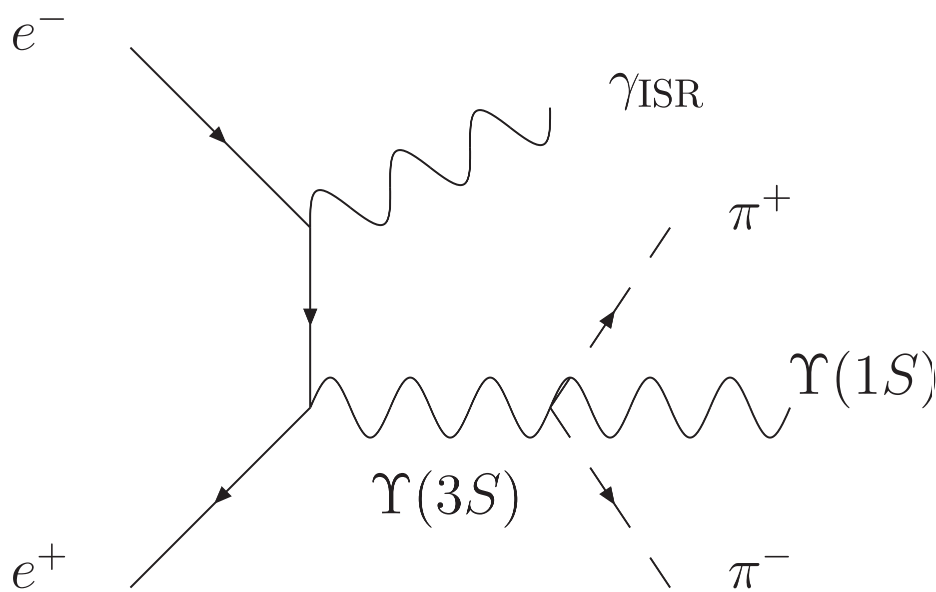
Bottomonium Spectra



How to measure invisible branching ratios

Create heavier quarkonia e.g. $\Upsilon(3S)$ or $\Upsilon(2S)$ via ISR

ISR photons are monochromatic in the CM frame, and inside the detector volume about 16% of the time.

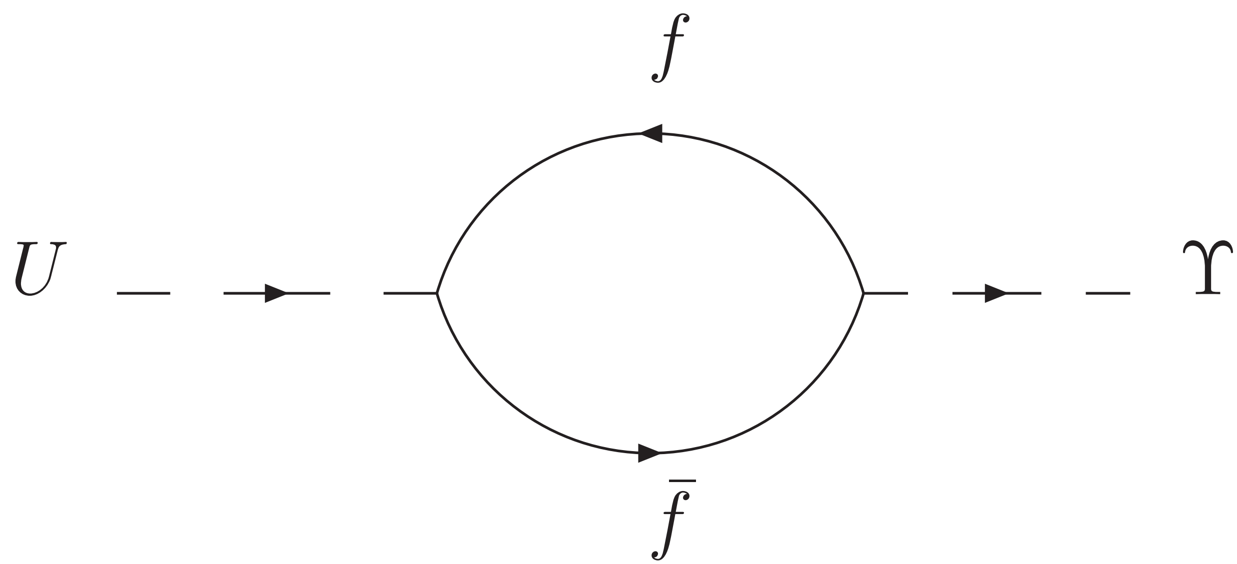


Allow quarkonia to decay radiatively to lighter quarkonia (perhaps multiple radiative decays)

Radiative decays are *overconstrained*

Invisible Decays

Until recently, only *two* particles have any limit on their invisible width: π^0 and Z.



These are the first collider measurements of invisible meson decay

$$\begin{aligned}
BR(\Upsilon \to \text{invisible}) &< 0.25\%(\text{Belle}[\mathtt{hep-ex/0611041}]) \\
BR(\Upsilon \to \text{invisible}) &< 0.39\%(\text{CLEO}[\mathtt{hep-ex/0612051}]) \\
BR(\eta \to \text{invisible}) &< 0.065\%(\text{BESII}[\mathtt{hep-ex/0607006}]) \\
BR(\eta' \to \text{invisible}) &< 0.14\%(\text{BESII}[\mathtt{hep-ex/0607006}])
\end{aligned}$$

Invisible Decay vs. Single Photon

Single photon methods were used to measure the invisible width of the Z, and to look for invisible particles via $\Upsilon \to \gamma +$ invisible [CLEO, Phys. Rev. D **51**, 2053 (1995); Phys. Rev. D **33**, 300 (1986)] *these experiments need to be repeated with the larger datasets at CLEO, BaBar, and Belle*

Single photon counting is fundamentally limited by calorimiter resolution, and backgrounds from ISR, diphoton events.

We need a better handle to remove backgrounds.

The BaBar $\Upsilon \to$ invisible effort was done on the $4S$ (as I suggested [hep-ph/0506151]) but has been significantly hampered by unexpected backgrounds (mostly photon fusion, and beam). [S. Sekula]

Conclusion: *radiative decays are required to suppress backgrounds in invisible decay searches.*

An Effective Theory for Dark Matter

Minimal elements required: a mediator boson U and DM candidate χ.

$$\begin{aligned}
\mathcal{L}_V &= \frac{1}{g^2} U^{\mu\nu} U_{\mu\nu} + \mu\phi^2 + \lambda\phi^4 + \overline{\chi}(\not{D} + M_\chi)\chi \\
\mathcal{L}_S &= \mu U^2 + \lambda U^4 + \overline{\chi}(\not{D} + M_\chi)\chi \\
&\quad + a U_r \overline{f} f + ib U_i \overline{f}\gamma_5 f + c U_r \overline{\chi}\chi + id U_i \overline{\chi}\gamma_5\chi
\end{aligned}$$

Resulting in annihilation cross sections

$$\sigma_S = \frac{\left(\left(a^2 + b^2\right) s - 4\, a^2 M_\chi^2\right)\left(\left(c^2 + d^2\right) s - 4\, c^2 M_f^2\right)}{16\pi E_1 E_2 \left((s - M_U^2)^2 + M_U^2 \Gamma_U^2\right)} \sqrt{\frac{s - 4\, M_f^2}{s - 4 M_\chi^2}}$$

$$\sigma_V = \frac{a^2 c^2 (s + 2M_\chi^2)(s + 2M_f^2)}{12\pi E_1 E_2 \left((s - M_U^2)^2 + M_U^2 \Gamma_U^2\right)} \sqrt{\frac{s - 4\, M_f^2}{s - 4 M_\chi^2}}$$

Annihilation cross section can be enhanced by a small Γ_U.

Annihilation cross section also enhanced by narrow width of hadrons, where U mixes with hadrons.

Parameter Space

There are 3 essential parameters:

- The product of couplings a^2c^2 or b^2d^2.
- The masses M_U and M_χ.

a and b cannot be very large or the mediator would have been discovered in SM processes.

Another option: $a = b = 0$ for light fermions u,d,e but $a, b > 0$ for second or third generation. Gauge-invariant couplings a, b imply that a scalar U mixes with the SM Higgs.

Thresholds ($s \simeq 4{M_\chi}^2$) and resonances ($s \simeq M_U^2$) can significantly enhance or suppress the annihilation cross section and/or invisible branching fraction.

Relic Density Constraint

One of these is fixed by the relic density constraint (let us take this to be the couplings a^2c^2 or b^2d^2).

This constraint is complicated to evaluate properly (in progress). It comes from the Friedmann-Robertson-Walker (FRW) cosmology

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

n = number density, H = Hubble constant, $\langle \sigma v \rangle$ thermally-averaged cross section, n_{eq} = equilibrium number density at temperature T.

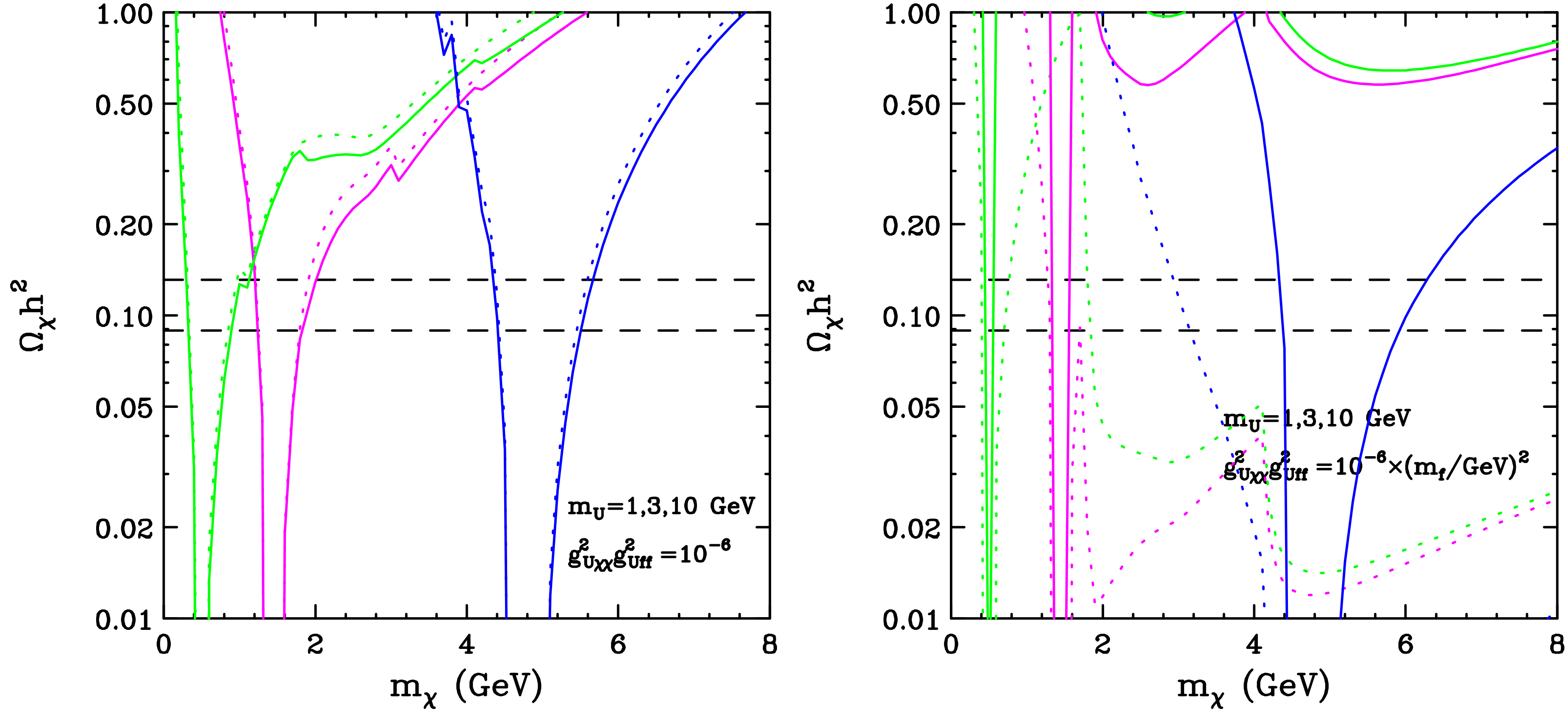
This can be rewritten

$$\frac{dY(x)}{dx} = -\sqrt{\frac{\pi}{45 G_N}} \times \frac{g_*^{1/2}(x) M_\chi}{x^2} \langle \sigma v \rangle (x) \left(Y(x)^2 - Y_{\text{eq}}^2(x) \right)$$

where $x = M_\chi / T$.

The parameter $g_*^{1/2}(x)$ encodes the "number of relativistic degrees of freedom" at a given temperature. [Hindmarsh, Philipsen `hep-ph/0501232`]
This is the limiting factor for accuracy due to QCD phase transition!

Relic Density Calculation



(left solid) scalar DM, vector mediator
(left dotted) scalar DM, axial vector mediator
(right solid) fermion DM, scalar mediator
(right dotted) fermion DM, pseudoscalar mediator

[D. Hooper, B. McElrath, to appear]

Invisible Widths of Quarkonium

The DM invisible width of a hadron H is

$$\Gamma_S = \frac{f_H^2\sqrt{1-4M_\chi^2/M_U^2}}{8\pi M_U}\left[\frac{\left((a^2+b^2)s-4a^2M_\chi^2\right)\left((c^2+d^2)s-4c^2M_f^2\right)}{(s-M_U)^2-M_U^2\Gamma_U^2}\right]$$

$$\Gamma_V = \frac{f_H^2\sqrt{1-4M_\chi^2/M_U^2}}{6\pi M_U}\left[\frac{a^2c^2(s+2M_f^2)(s+2M_\chi^2)}{(s-M_U)^2-M_U^2\Gamma_U^2}\right]$$

- Invisible widths are enhanced if M_U happens to lie near M_H. (But: important mixing effects must be taken into account)

- Invisible widths are suppressed if $M_H \simeq 2M_\chi$

- The *partial width* is determined by Dark Matter considerations. Try to measure invisible decays of narrow resonances first.

The NMSSM and μ-solvable models

The NMSSM was originally designed to solve the μ problem in the MSSM by adding a single chiral supermultiplet that is uncharged under SM gauge symmetries. Its superpotential is

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \tag{1}$$

when the scalar compnent of S gets a vev, $\mu = \lambda \langle S \rangle$ is dynamically generated, solving the μ problem.

The matter spectrum is extended to have one extra neutralino (called the singlino), one extra CP-even higgs, and one extra CP-odd higgs.

After SUSY is broken, trilinears and soft masses are generated for S:

$$V_{\text{soft}} \subset A_\lambda \lambda S H_u H_d + A_\kappa \kappa S^3 + m_S^2 S^2 \tag{2}$$

There are other ways to add a singlet and also solve the μ problem. (e.g. MNSSM, singlets to break extra gauge groups, etc) We take the NMSSM to be a prototype for "μ-solvable" models. The necessary features for light dark matter should be found in any μ-solvable model.

Light Neutralinos in the NMSSM

The MSSM can allow a massless neutralino. Solving $\det M_{\chi^0} = 0$:

$$M_1 = \frac{M_Z^2 \sin^2\theta_W \sin(2\beta) M_2}{M_2\mu - M_W^2 \sin(2\beta)} \tag{3}$$

This gives $80\text{MeV} < M_1 < 16\text{GeV}$ for reasonable parameters.

By a similar analysis, the NMSSM can also allow a massless neutralino (with M_1 as large as 55 GeV).

To evade $Z \to invisible$ constraints, a neutralino lighter than $M_Z/2 \simeq$ 45 GeV must be mostly bino or mostly singlino.

The lightest neutralino (LSP) can be any linear combination of bino and singlino, since for a given singlino mass we can tune M_1 to be near it, and therefore get any singlino-bino mixing angle we want.

Light A_1 in the NMSSM

There are two CP-odd A bosons in the NMSSM. After removing the goldstone corresponding to the Z, we can write the lightest as:

$$A_1 = \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_S. \quad (4)$$

In either the large $\tan\beta$ limit or large $\langle S\rangle$ limits, $M^2_{A_1} \simeq 3\kappa A_\kappa \langle S\rangle$. (Alternatively: $M^2_{A_1} = 3\frac{\kappa}{\lambda} A_\kappa \mu$)

Thus, A_1 will be light and mostly singlet in the small κ and/or small A_κ limits.

The light A_1 can also be MSSM-like if the angle $\cos\theta_A$ is large. This is possible but constrained. For $M_{\chi^0} < 5$ GeV:

$\cos\theta_A \tan\beta < 5$	LEP $Z \to b\bar{b}b\bar{b}$ or $\tau^+\tau^-\tau^+\tau^-$
$\cos\theta_A \tan\beta < 3$	$b \to s\gamma$, $B_s \to \mu\mu$, and $(g-2)_\mu$
$\cos\theta_A \tan\beta < 0.5$	$\Upsilon \to \gamma\chi^0\chi^0$ ($M_{\chi^0} < 1.5$ GeV)

$U(1)$ symmetries give a small M_A

$$W = \lambda S H_u H_d + \kappa S^3 \qquad V_{soft} = \lambda A_\lambda S H_u H_d + \kappa A_\kappa S^3 \tag{5}$$

Peccei-Quinn symmetry is approximate in $\kappa \ll 1, A_\kappa \ll M_{SUSY}$ limit. [Miller, Moretti, Nevzorov, `hep-ph/0501139` (among others)]

R-symmetry (not respected by supersymmetry): is approximate in $\kappa A_\kappa, \lambda A_\lambda \ll M_{SUSY}$ limit. [Matchev, Cheng, `hep-ph/0008192`]

In *both* cases, A_1 is the PNGB of the broken symmetry.

In "Secluded Sector" models with a gauged $U(1)'$, the $Z - Z'$ mass hierarchy can also generate a small M_A:

$$m_{A_1}^2 \simeq m_{SS_i}^2 \frac{v_s v_{si}}{v_{si}^2 + v_{s3}^2} \tag{6}$$

[Erler, Langacker, Li, `hep-ph/0205001`; Han, Langacker, McElrath `hep-ph/0405244`; Barger, Langacker, Lee, Shaughnessy `hep-ph/0603247`]

The gaugino-mediated connection

In gaugino-mediated SUSY breaking, gauginos get soft masses M_{SUSY} first, and transmit SUSY breaking to the rest of the theory at 1-loop.

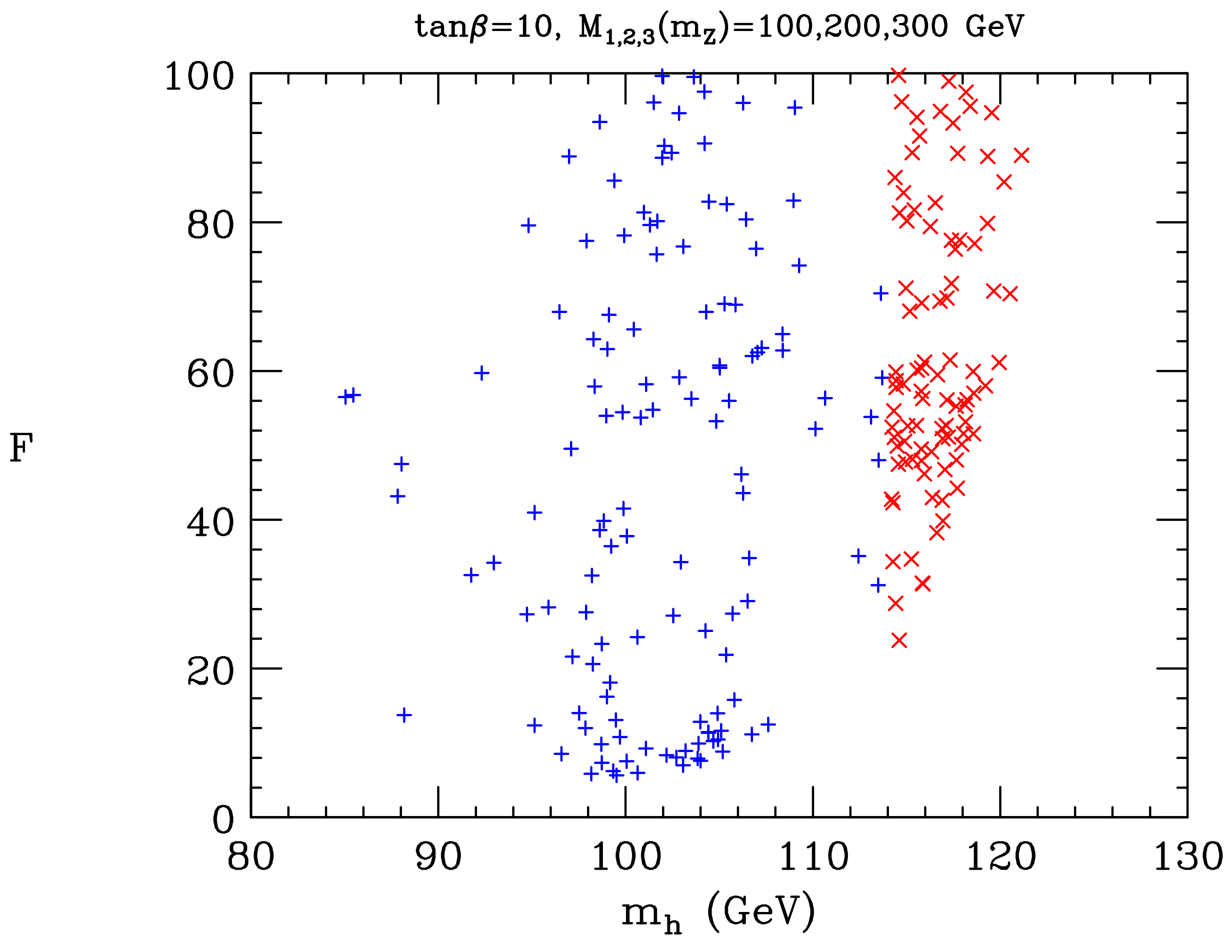
H_u and H_d are charged under $SU(2)_L$ and $U(1)_Y$, therefore we expect $A_\lambda \simeq M_{SUSY}/4\pi$.

S is *uncharged* under SM gauge symmetries. Therefore we expect $A_\kappa \simeq M_{SUSY}/16\pi^2$.

Other SUSY breaking scenarios generate small trilinears.

We *want* a light A_1

A light A_1 can eliminate the fine-tuning problem in the MSSM.



Dermisek, Gunion, `hep-ph/0502105`

Indirect Constraints

Binos, winos and singlinos do not couple to the Z directly. $\Rightarrow Z \to$ *invisible* only constrains the higgsino component of the LSP. Given an LSP with an eigenvector:

$$\chi^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}, \tag{7}$$

the invisible Z decay constraint limits $|\epsilon_u^2 - \epsilon_d^2| \lesssim 6\%$.

The wino component of the LSP is limited by direct chargino searches, which force M_2 large. $\Rightarrow$ The LSP must be a linear combination of bino and singlino.

We computed $(g-2)_\mu$, $b \to s\gamma$, $B_s \to \mu\mu$, Z invisible width, all LEP constraints on higgses, and $\Upsilon \to A_1\gamma$ where the A_1 decays visibly or invisibly, in a 2-body or 3-body decay.

Constraints generally limit the product $\cos\theta_A \tan\beta$, but a light A_1 or bino generally have small effects that can be compensated or cancelled by other things in the theory (e.g. squarks, H^+, χ^+, etc).

Trade-off: lighter A_1/χ^0 or improved constraints $\Rightarrow$ must be closer to relation $M_{A_1} \simeq 2M_{\chi^0}$.

Other Rare Decays with Dark Matter

$B^+ \to K^+ + invisible$ also provides a constraint. In scalar dark matter scenarios, this may be 50 times larger than the SM process. [Bird, Jackson, Kowalewski, Pospelov, hep-ph/0401195] [Bird, Kowalewski, Pospelov, hep-ph/0601090]

$\Upsilon \to \gamma + invisible$ can provide a measurable signal *and* the correct relic density [Gunion, Hooper, McElrath, hep-ph/0509024]

The $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio was recently measured by the E787 and E949 experiments to be $BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, which is nearly twice the value predicted in the Standard Model, $(0.67^{+0.28}_{-0.27}) \times 10^{-10}$ [hep-ex/0403036].

Υ and J/Ψ Decays

If kinematically allowed, vector resonances can decay into a photon and A_1.

$$\frac{\Gamma(V \to \gamma A)}{\Gamma(V \to \mu\mu)} = \frac{G_F m_b^2}{\sqrt{2}\alpha\pi}\left(1 - \frac{M_H^2}{M_V^2}\right) \cos^2\theta_A x^2. \tag{8}$$

where $x = \tan\beta$ for Υ and $x = \cot\beta$ for J/Ψ.

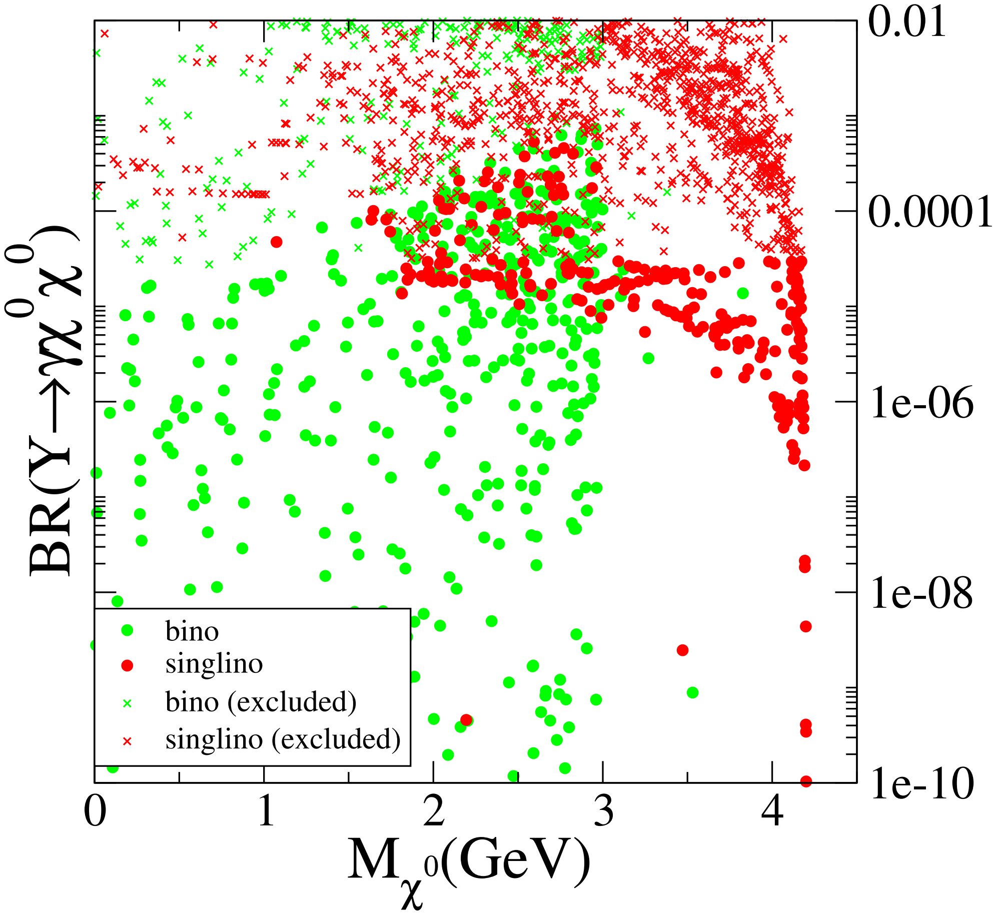
The 3-body decay $\Upsilon \to \chi^0\chi^0\gamma$ is also measured.

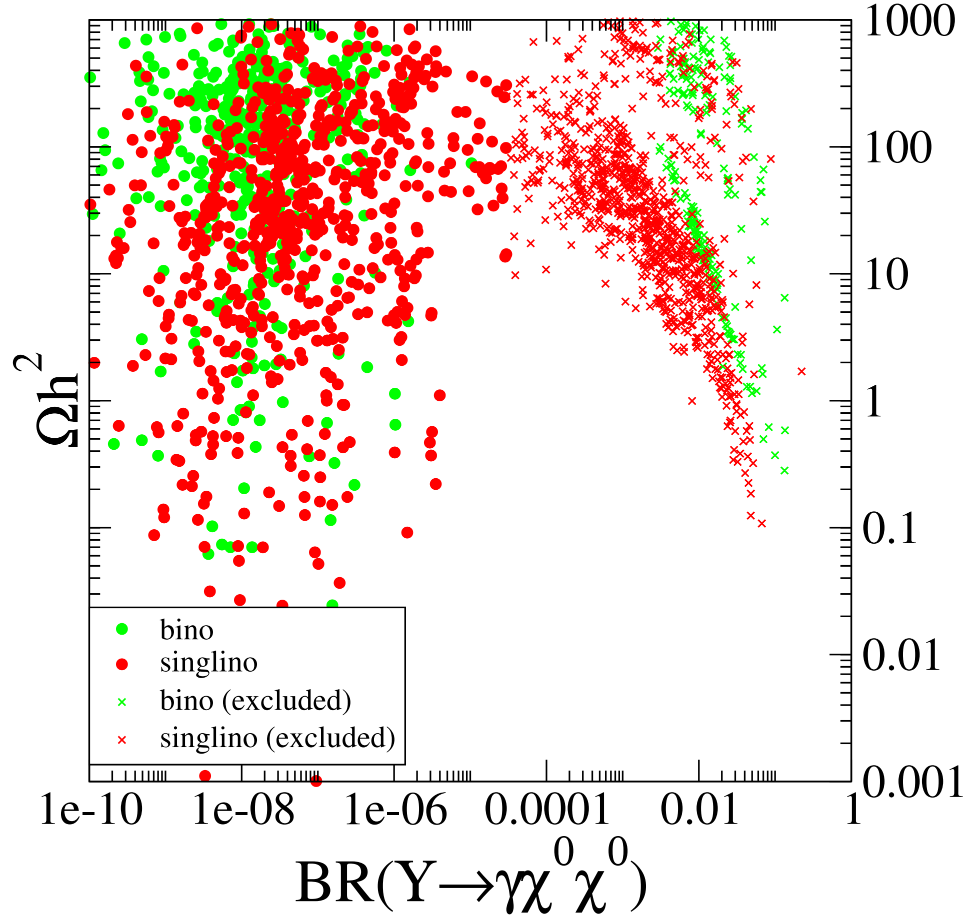
It is claimed that by measuring both $\Upsilon \to A_1\gamma$ and $J/\Psi \to A_1\gamma$, the standard axion is ruled out. However

$$BR(\Upsilon \to A_1\gamma) \times BR(J/\Psi \to A_1\gamma) \propto \cos^4\theta_A \tag{9}$$

which is generally quite small. Thus we can evade these limits even for $M_\chi^0 < M_{J/\Psi}/2$.

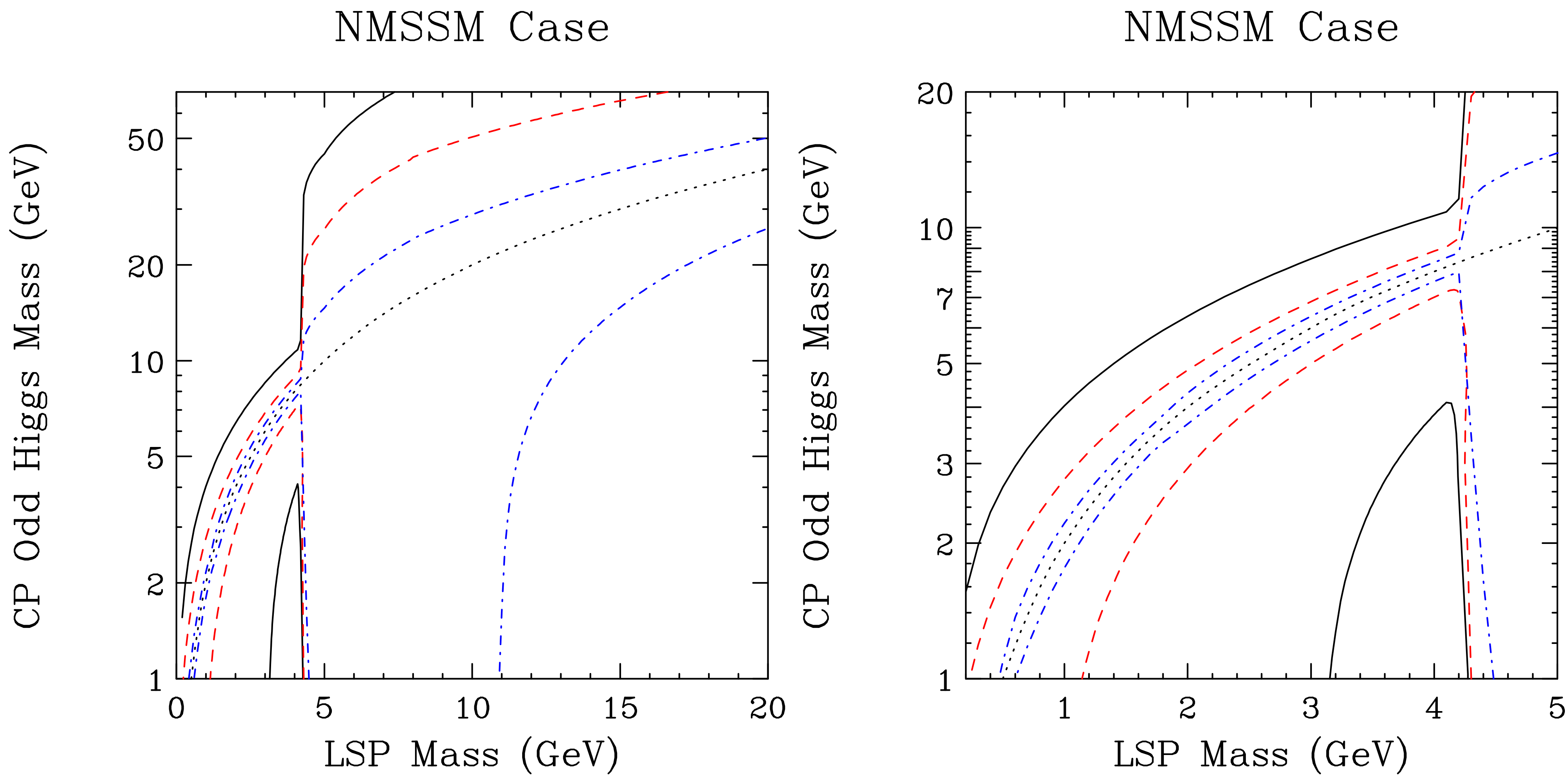
Υ decays and relic density





CLEO limits are $BR(\Upsilon \to \gamma\chi^0\chi^0) \simeq 3 \times 10^{-5}$ for $M_{\chi^0} < 1.5$ GeV.
CLEO used only 48 pb^{-1} of data (about 1M $\Upsilon(1S)$). They have 20 times this recorded. BaBar and Belle have produced about 5M $\Upsilon(1S)$ each with ISR.
This measurement can be drastically improved with existing data!

Relic Density figures



These results are for ($\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$). $\tan\beta$=(50, 15 and 3) are shown as solid black, dashed red, and dot-dashed blue lines, respectively. Also shown as a dotted line is the contour corresponding to $2m_{\chi^0} = m_A$. For each set of lines, we have set $\cos^2\theta_A = 0.6$.

Back to the MSSM

$M_\chi = 0$ is *allowed* by collider experiments in the MSSM. It requires the neutralino to only have a small higgsino component $\epsilon_u^2 - \epsilon_d^2 < 6\%$, and no assumption of gaugino mass unification. ($M_\chi \simeq M_1$)

It was shown [Gondolo, Gelmini, Nuc.Phys.B360,145 (1991)] that Z^0, plus enhancement from the Υ resonances, is insufficent to obtain the correct relic density.

The lightest allowable M_χ is 6 GeV [Bottino, Donato, Fornengo, Scopel `hep-ph/0304080`] *excluding* effects of hadronic resonances. This is done by tuning the CP-odd higgs, A as light as possible (90 GeV). (A has an s-wave annihilation cross section) If A mixes with a singlet, it can be made much lighter (i.e. NMSSM), and all M_χ are allowed.

Once pseudoscalar resonances η_b, η_c etc are taken into account, The MSSM *should* admit neutralinos $M_\chi < 5$ GeV.

Best measurements for this are those involving b's: $B \to K + invisible$, $\Upsilon \to \gamma + invisible$. ($\eta_b \to invisible$ is probably impossible to measure)

A solution to INTEGRAL?

Anihilation to electrons requires $M_{\chi^0} < 20$ MeV from gamma-ray considerations [Beacom]. Since annihilation mediator is a higgs, annihilation is extremely inefficent due to small electron Yukawa.

Consider instead annihilation to muons, which decay to electrons. Need $M_\mu < M_{\chi^0} < M_{\pi^+} + M_{\pi^0}/2$ or 106MeV $< M_{\chi^0} <$ 207 MeV.

Therefore 212MeV $\lesssim M_A \lesssim$ 414MeV.

Also need $\cos\theta_A \tan\beta < 0.13$ to evade $\Upsilon \to A_1\gamma$.

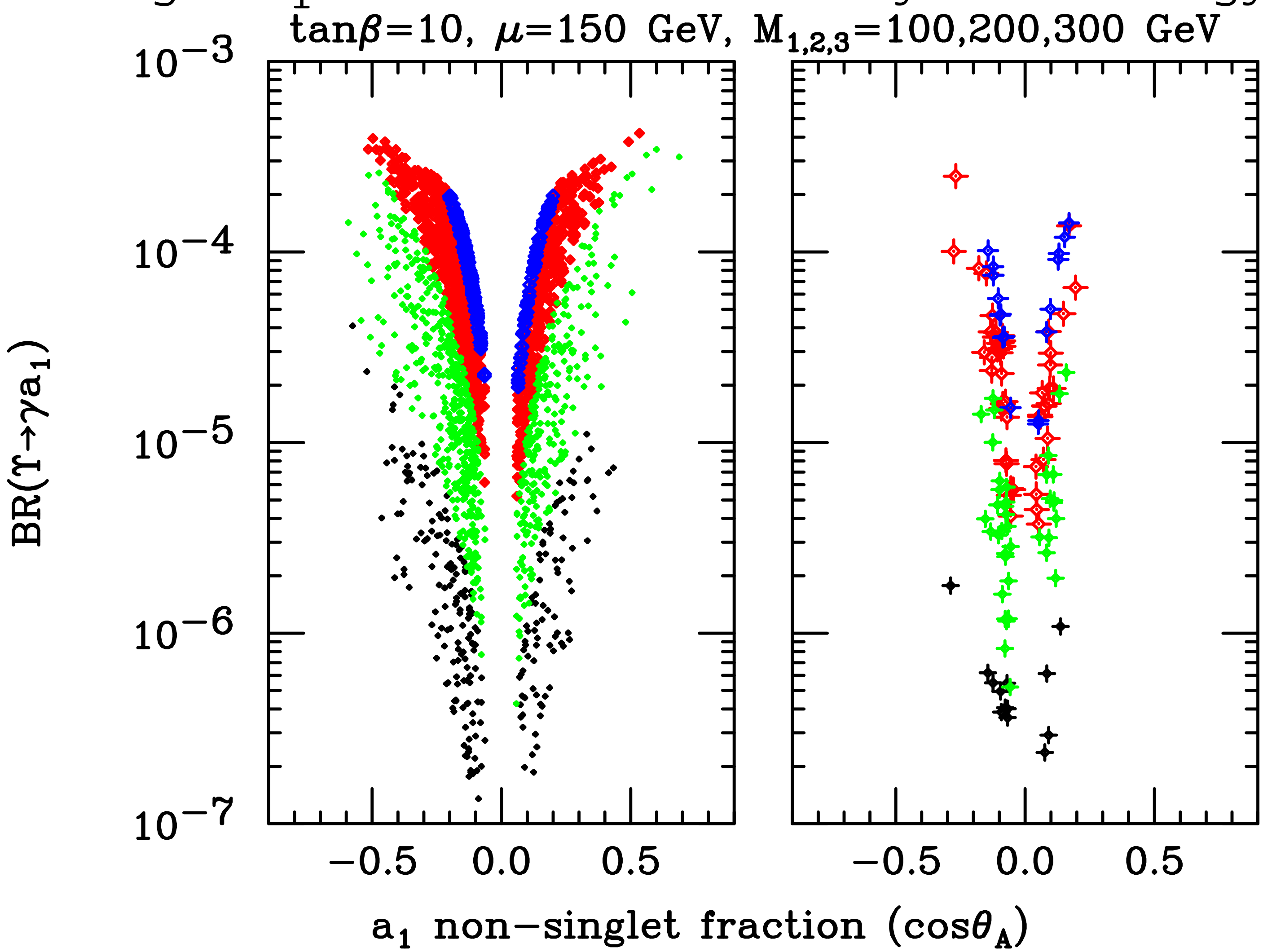
Correct relic density can be obtained for $M_{A_1} \simeq 2M_{\chi^0} \pm 10$ MeV.

Can be confirmed by improving the $\Upsilon \to A_1\gamma$ measurement with existing data from CLEO, BaBar, Belle!

More recent papers claim $M_A < 3MeV$ [Yuksel, Beacom `astro-ph/0609139`]

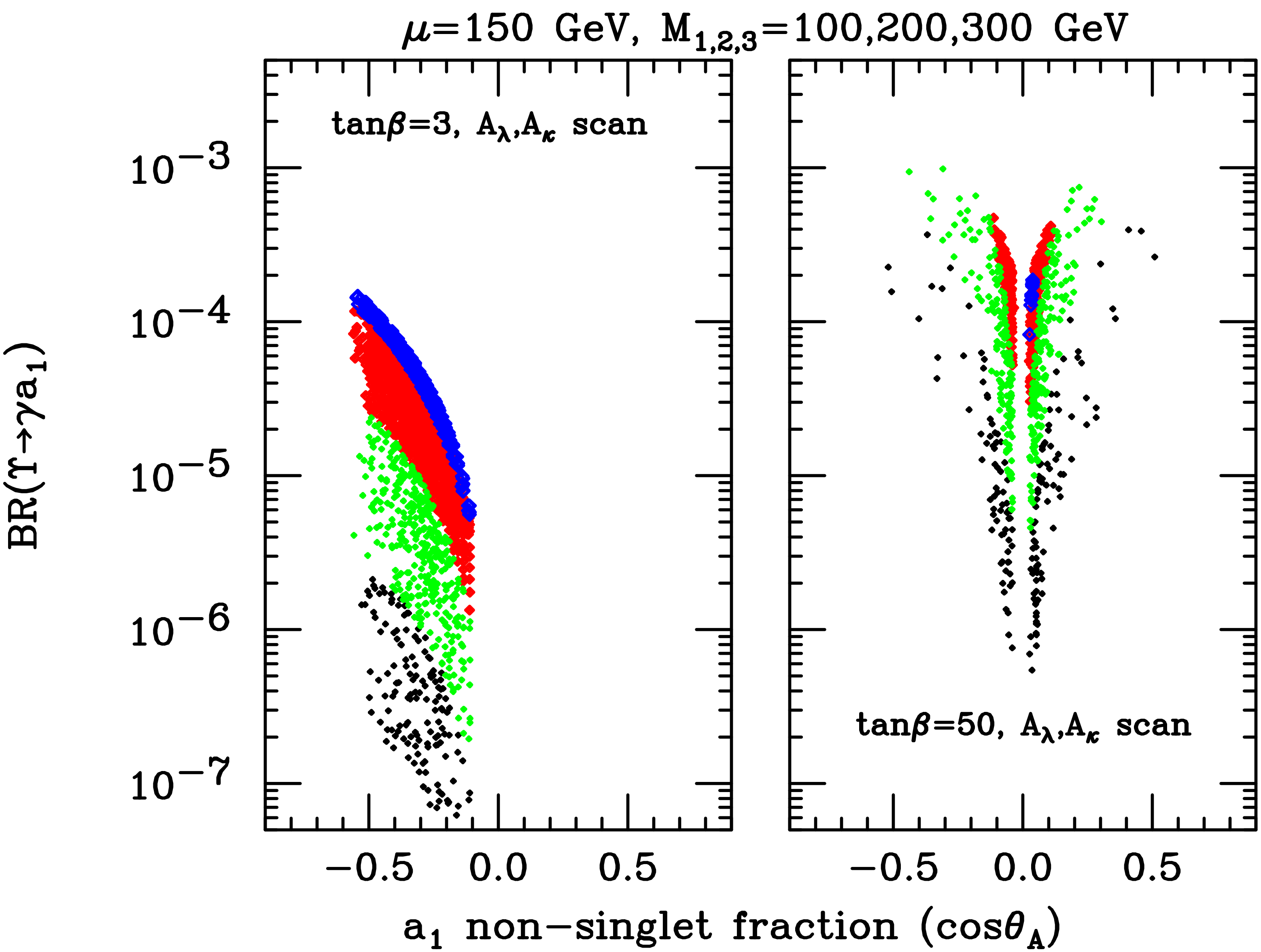
Direct Mediator Detection

The light A_1 can be detected directly at low-energy machines.



[Dermisek, Gunion, McElrath, hep-ph/0612031]

Direct Mediator Detection



Direct detection experiments

CRESST: Cryogenic Rare Event Search using Superconducting Technology: threshold may be as low as 500 eV (but background $e^-/\gamma/\alpha$ discrimination requires a bit more energy)

COUPP: Chicago Observatory for Underground Particle Physics

Conclusion(s)

Interesting new physics measurements sensitive to dark matter or singlet higgses are:

$$\begin{aligned} \Upsilon &\to invisible & \quad J/\Psi &\to invisible \\ \eta &\to invisible & \quad \Upsilon &\to \gamma + invisible \\ B^+ \to K^+ &+ invisible & \quad \Upsilon &\to \gamma A_1, A_1 \to \tau^+\tau^- \\ K^+ \to \pi^+ &+ invisible & \quad J/\Psi &\to \gamma A_1 \end{aligned}$$

Current B-Factories can limit $BR(\Upsilon \to invisible) < 0.1\%$.

We should attempt to measure *all* invisible branching ratios that are practical to measure. Invisible widths can be strongly enhanced if they happen to lie near the mediator mass!

All possible values for the mediator U and DM χ should be considered, unless they're excluded by data.

Direct detection prospects for light DM look bleak unless H_1 is light.

We propose a *model-independent* effective Lagrangian that can be used for light DM studies.

Conclusions

An arbitrarily light A_1 and χ^0 are allowed.

A light bino/singlino in the NMSSM can reconcile DAMA and CDMS-II, especially if there is some “wind” of dark matter through our local area, and the H_1 is also light.

A light bino/singlino can explain the INTEGRAL observation.

$\Upsilon \to \gamma A_1$ and invisible decays of quarkonia should be pursued immediately at colliders such as BaBar, Belle, and CLEO to discover such light dark matter.

Direct detection prospects look bleak unless H_1 is very light.

Reference Formulae

$$M_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}g'v\sin\beta & 0 \\ 0 & M_2 & \frac{1}{\sqrt{2}}gv\cos\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & 0 \\ -\frac{1}{\sqrt{2}}g'v\cos\beta & \frac{1}{\sqrt{2}}gv\cos\beta & 0 & -\lambda x & -\lambda v\sin\beta \\ \frac{1}{\sqrt{2}}g'v\sin\beta & -\frac{1}{\sqrt{2}}gv\sin\beta & -\lambda x & 0 & -\lambda v\cos\beta \\ 0 & 0 & -\lambda v\sin\beta & -\lambda v\cos\beta & 2\kappa x \end{bmatrix}$$

$$M_A^2 = \begin{bmatrix} \frac{2\lambda x(\kappa x + A_\lambda)}{\sin 2\beta} & -2\lambda v\kappa x + \lambda A_\lambda v \\ -2\lambda v\kappa x + \lambda A_\lambda v & \left(2\kappa\lambda v^2 + \lambda A_\lambda \frac{v^2}{2x}\right)\sin 2\beta + 3\kappa A_\kappa x \end{bmatrix}$$

$$\tan 2\theta_A = \frac{4\sin(2\beta)\lambda v x(2\kappa x - A_\lambda)}{2x^2(2\lambda\kappa x - 3\kappa A_\kappa \sin(2\beta) + 2\lambda A_\lambda) - \lambda v^2 \sin^2(2\beta)(4\kappa x + A_\lambda)}$$

Relic Density Calculation

The relic density is given by:

$$\langle \sigma v \rangle = \frac{1}{m_{\chi^0}^2}[1 - \frac{3T}{m_{\chi^0}}]\omega(s)|_{s \to 4m_{\chi^0}^2 + 6m_{\chi^0}T} + \mathcal{O}(T^2),$$

The squared amplitudes for the processes, $\chi^0\chi^0 \to A \to f\bar{f}$ and $\chi^0\chi^0 \to H \to f\bar{f}$, averaged over the final state angle are given by:

$$\omega_{f\bar{f}}^A = \frac{C_{ffA}^2 C_{\chi^0\chi^0 A}^2}{(s - m_A^2)^2 + m_A^2 \Gamma_A^2} \frac{s^2}{16\pi} \sqrt{1 + \frac{4m_f^2}{s}},$$

where

$$\begin{aligned}
C_{\chi^0\chi^0 A} &= \cos\theta_A \left[(g_2\epsilon_W - g_1\epsilon_B)(\epsilon_d \cos\beta - \epsilon_u \sin\beta)\right] \\
&+ \cos\theta_A \left[\sqrt{2}\lambda\epsilon_s(\epsilon_u \sin\beta + \epsilon_d \cos\beta)\right] \\
&+ \sin\theta_A \sqrt{2}\left[\lambda\epsilon_u\epsilon_d - \kappa\epsilon_s^2\right] \\
C_{ffA} &= \frac{m_f}{\sqrt{2}v}\cos\theta_A \tan\beta. \\
A_1 &= \cos\theta_A A_{\mathrm{MSSM}} + \sin\theta_A A_s \\
\chi^0 &= \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}
\end{aligned}$$