Particle Dark Matter

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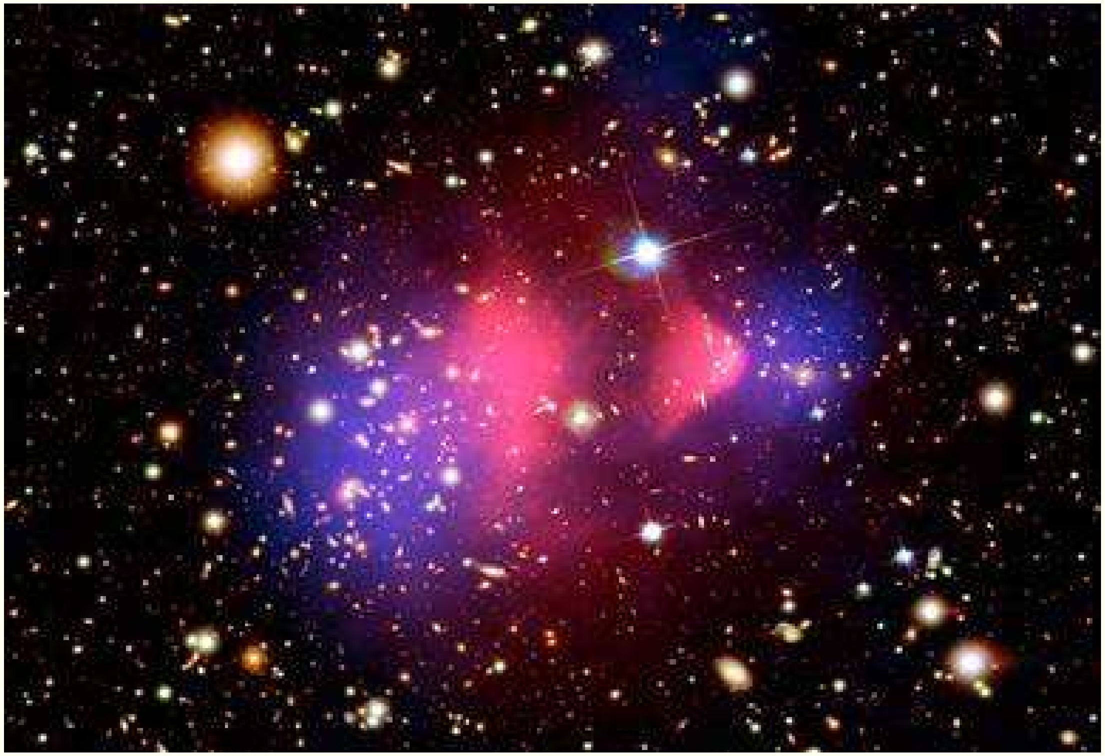
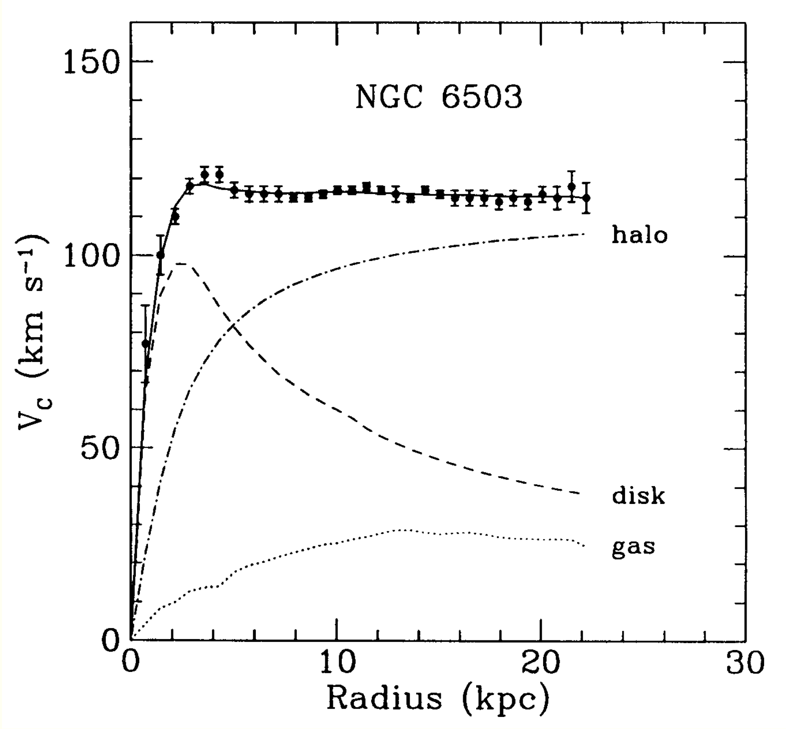
- ⋆ Evidence
- ⋆ Candidates
- ⋆ Axions
  - detection
- ⋆ WIMPs
  - direct
  - indirect
  - collider



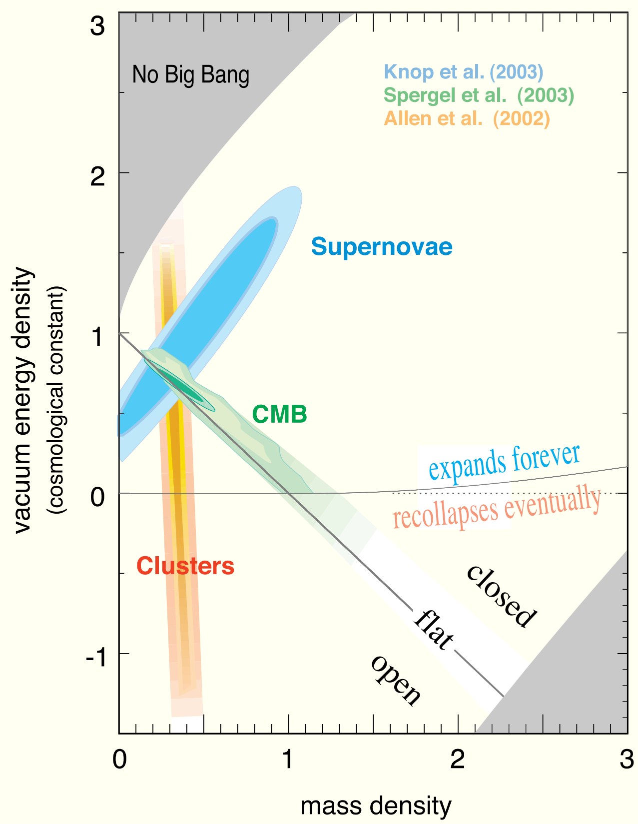
Evidence for Dark Matter

- ⋆ Binding of clusters
- ⋆ Galactic rotation curves
- ⋆ Gravitational lensing
- ⋆ Hot gas in clusters
- ⋆ CMB fluctuations
- ⋆ Large scale structure
- ⋆ flatness/BBN



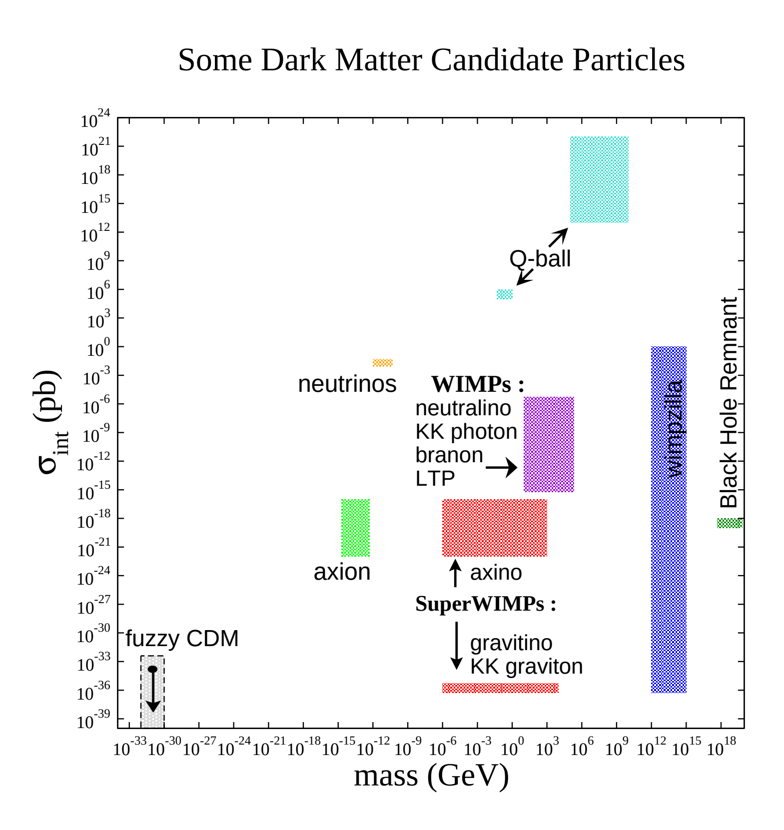
Best fit cosmology: concordance (ΛCDM) model

- $\Omega_B h^2 = 0.022 \pm 0.001$
- $\Omega_\nu h^2 < 0.007 \;\; 95\% \; CL$
- $\Omega_\Lambda h^2 \sim 0.38 \pm 0.03$
- $\Omega_{CDM} h^2 = 0.105 \pm 0.01$



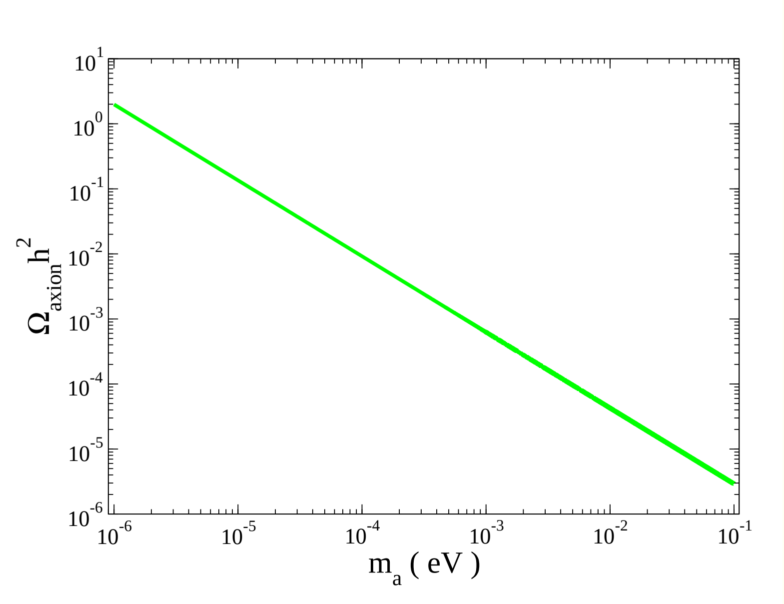
Candidates for Dark Matter

- ⋆ unseen baryons, e.g. BHs, brown dwarves, stellar remnants
  - – inconsistent with BBN element abundance calc'n
  - – limits from MACHO, EROS, OGLE
- ⋆ light neutrinos ($= HDM$)
- ⋆ axions
- ⋆ WIMPS
- ⋆ superWIMPS
- ⋆ Q-balls
- ⋆ axinos
- ⋆ primordial BHs



Axions

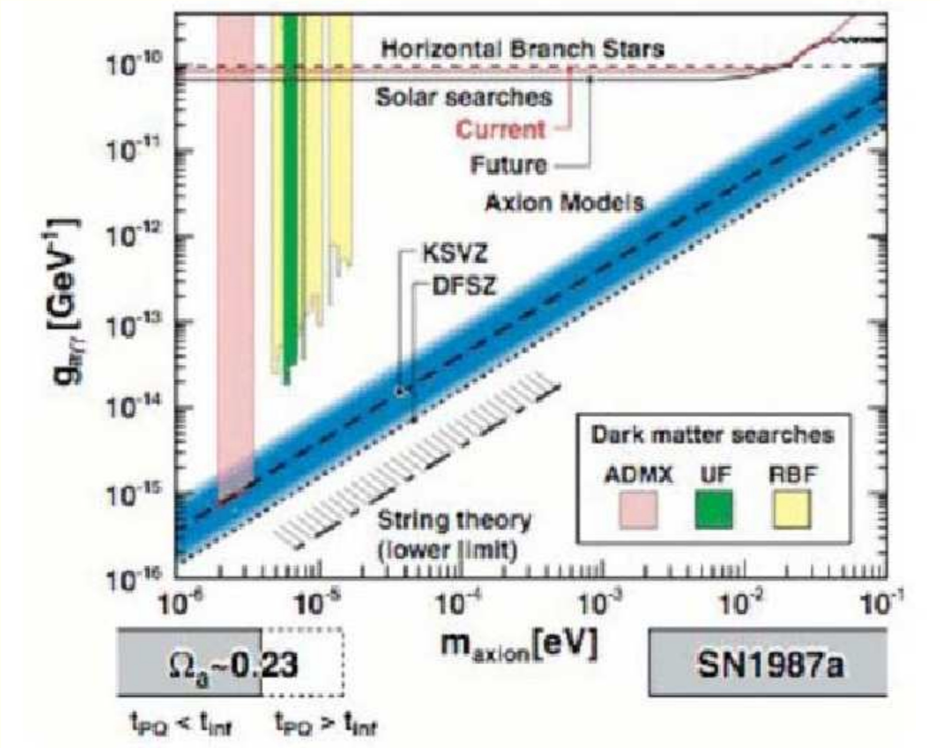
- ⋆ PQ solution to strong CP problem in QCD
- ⋆ pseudo-Goldstone boson from PQ breaking at scale f_a
- ⋆ non-thermally produced via vacuum mis-alignment
  - $m_a \sim \Lambda_{QCD}^2/f_a \sim 10^{-6} - 10^{-1} eV$
  - $\Omega_a h^2 \sim \frac{1}{2}\left[\frac{6\times 10^{-6} eV}{m_a}\right]^{7/6} h^2$
  - astro bound: stellar cooling $\Rightarrow m_a < 10^{-1} eV$
  - a couples to EM field: $a - \gamma - \gamma$ coupling (Sikivie)
  - axion microwave cavity searches



Axion microwave cavity searches

⋆ ongoing searches: ADMX experiment

- Livermore⇒ U Wash.
- Phase I: probe KSVZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- Phase II: probe DFSZ
  for $m_a \sim 10^{-6} - 10^{-5}\ eV$
- beyond Phase II:
  probe higher values m_a

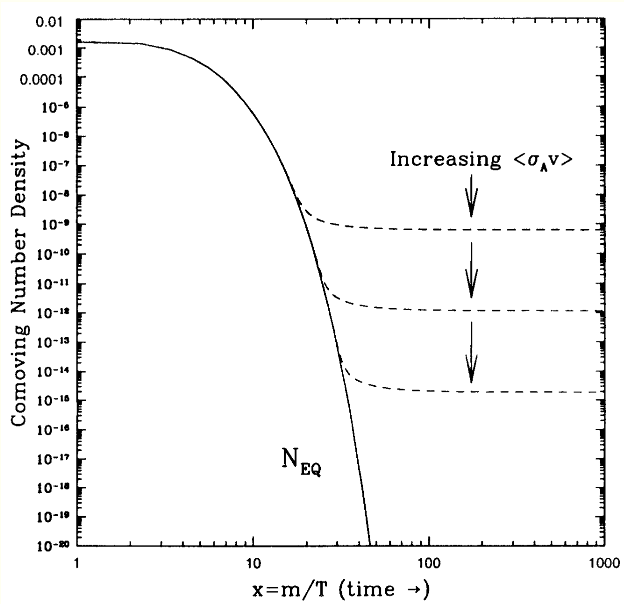


WIMPs: the WIMP miracle!

- Weakly Interacting Massive Particles
- assume in thermal equil'n in early universe
- Boltzman eq'n:

$$-\ dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$$

- $\Omega h^2 = \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{x_f}{M_{Pl}}\frac{1}{\langle\sigma v\rangle}$
- $\sim \frac{0.1\ pb}{\langle\sigma v\rangle} \sim 0.1\left(\frac{m_{wimp}}{100\ GeV}\right)^2$
- thermal relic $\Rightarrow$ new physics at M_{weak}!



Some WIMP candidates

- ⋆ 4th gen. Dirac ν (excluded)
- ⋆ SUSY neutralino (χ or $\widetilde{Z}_1$)
- ⋆ UED excited photon B_μ^1
- ⋆ little Higgs photon B_H
- ⋆ little Higgs (theory space) N_1 (scalar)
- ⋆ warped GUTS: LZP KK fermion
- ⋆ branons
- ⋆ ...

Most work done for SUSY theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stable see-saw mechanism for neutrino mass
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis
  - most analyses: mSUGRA model
    - $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  - lots and lots of other models

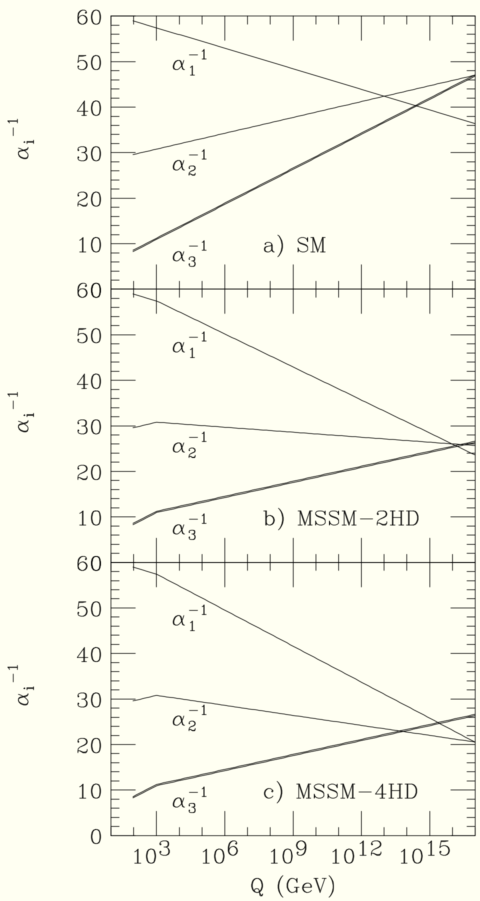
Supersymmetry: fermions⇔ bosons

★ MSSM: doubling of spectra

- spin-0 squarks, sleptons
- spin-$\frac{1}{2}$ charginos, neutralinos, gluino
- extra Higgses: $h,\ H,\ A,\ H^{\pm}$
- R-parity cons'n: LSP is stable

★ LSP candidates

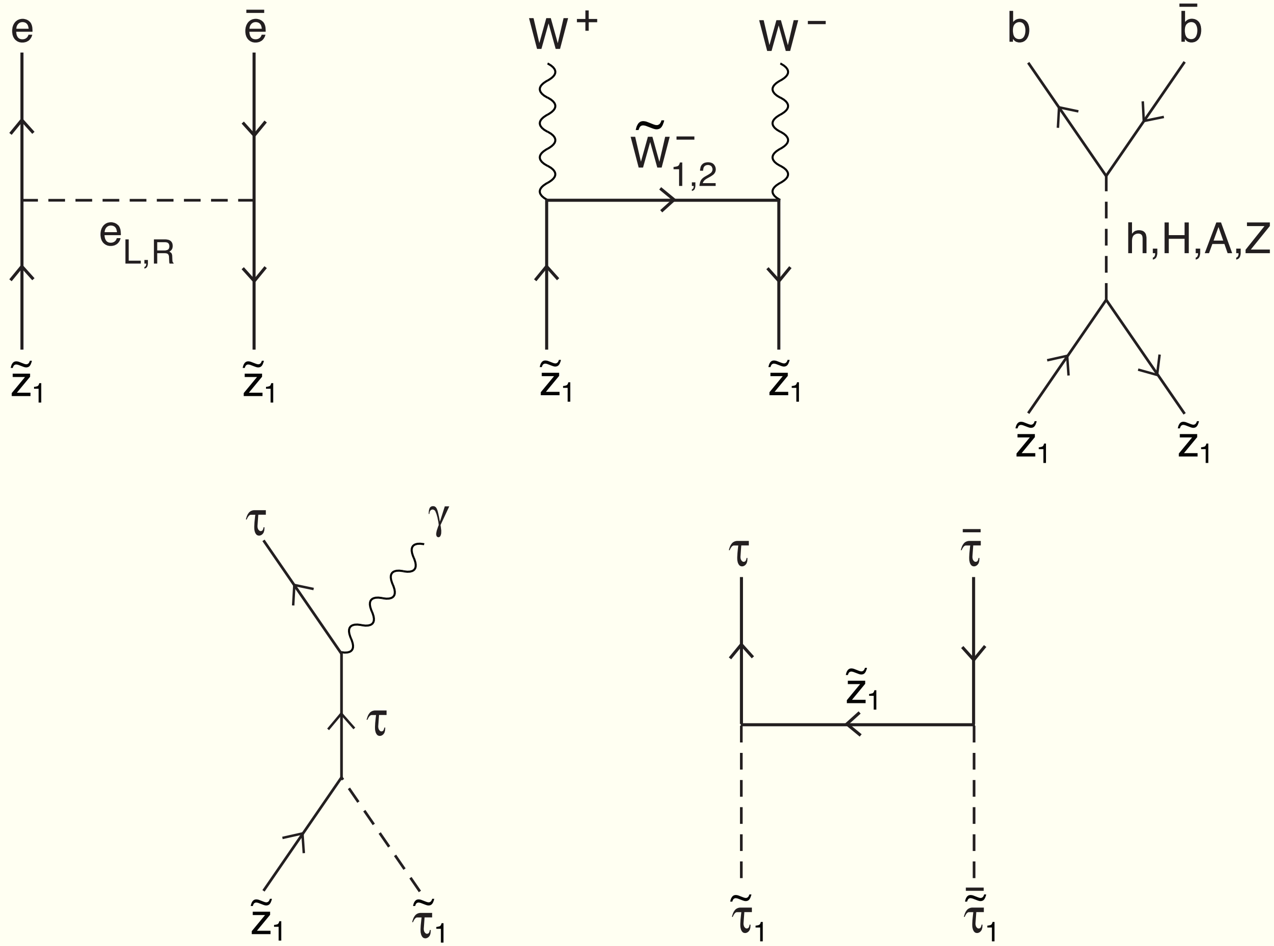
- sneutrinos (excluded)
- gravitinos (superWIMPs)
- neutralinos
- GMSB messengers
- hidden sector states
- axino/saxion



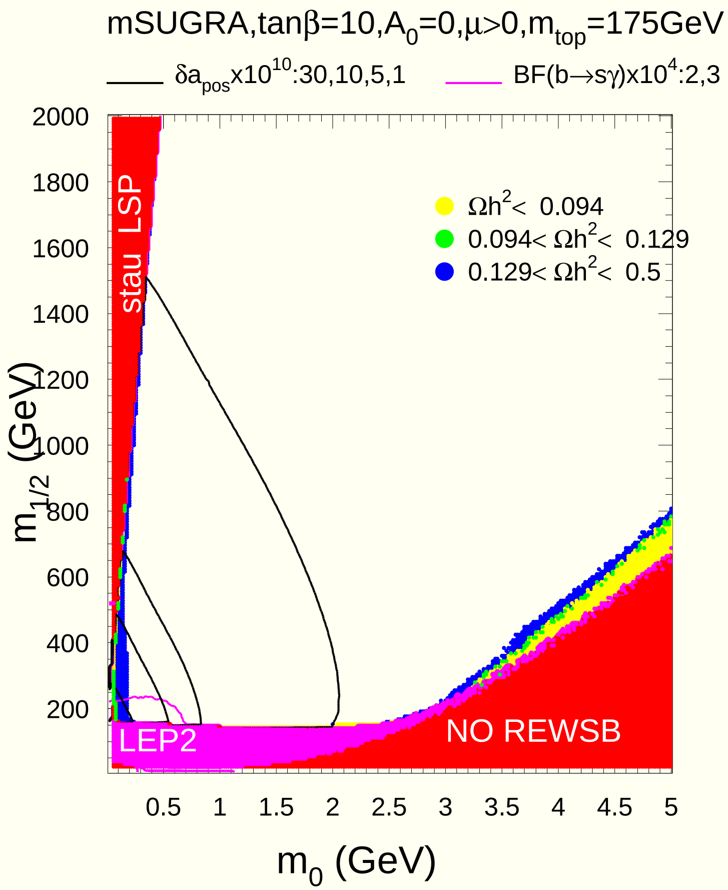
Neutralino dark matter

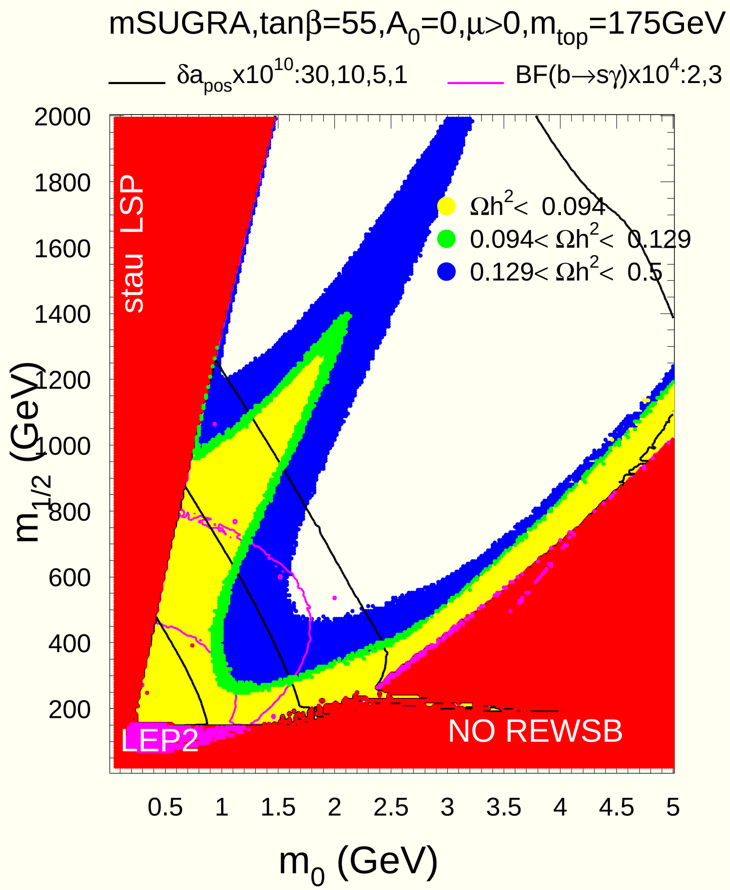
- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ several computer codes available
  - DarkSUSY, Micromegas, IsaReD (part of Isajet)

Some neutralino (co)annihilation processes



Relic density in minimal SUGRA model





HB, A. Belyaev, T. Krupovnickas and A. Mustafayev

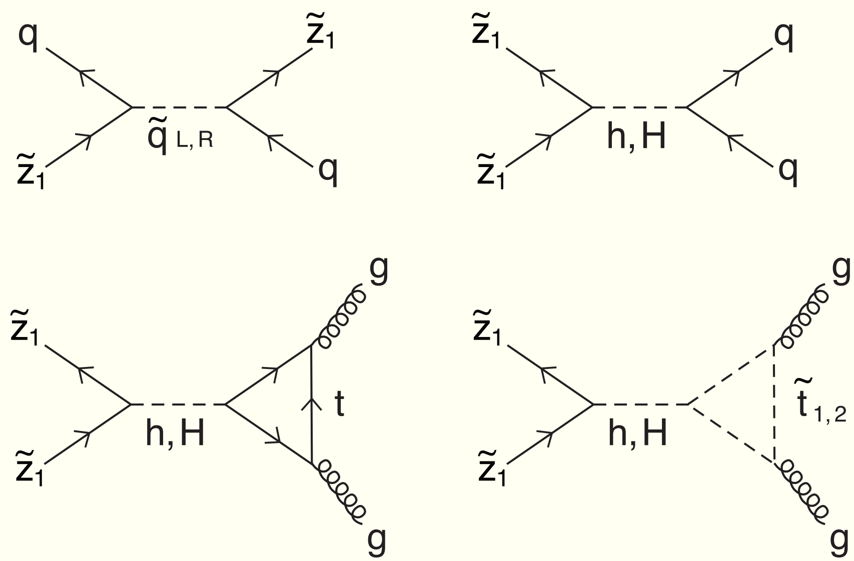
Main mSUGRA regions consistent with WMAP

- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \rightarrow small$)
- ⋆ A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

Direct detection of SUSY DM

⋆ Calculate neutralino-nucleus scattering

- calculate $\widetilde{Z}_1 - q$ or $\widetilde{Z}_1 - g$ scattering: take $v \to 0$ limit
  - ∗ spin-dependent cross section couples to spin of nucleus: cancel
  - ∗ spin-independent cross section $\propto A^2$: add
  - ∗ results usually quoted in terms of $\sigma_{SI}(\widetilde{Z}_1 p)$ so results from different target nuclei can be compared



Direct detection of SUSY DM

scan over mSUGRA space ($\Omega_{CDM}h^2 \sim 0.11$) :

★ Stage 1:

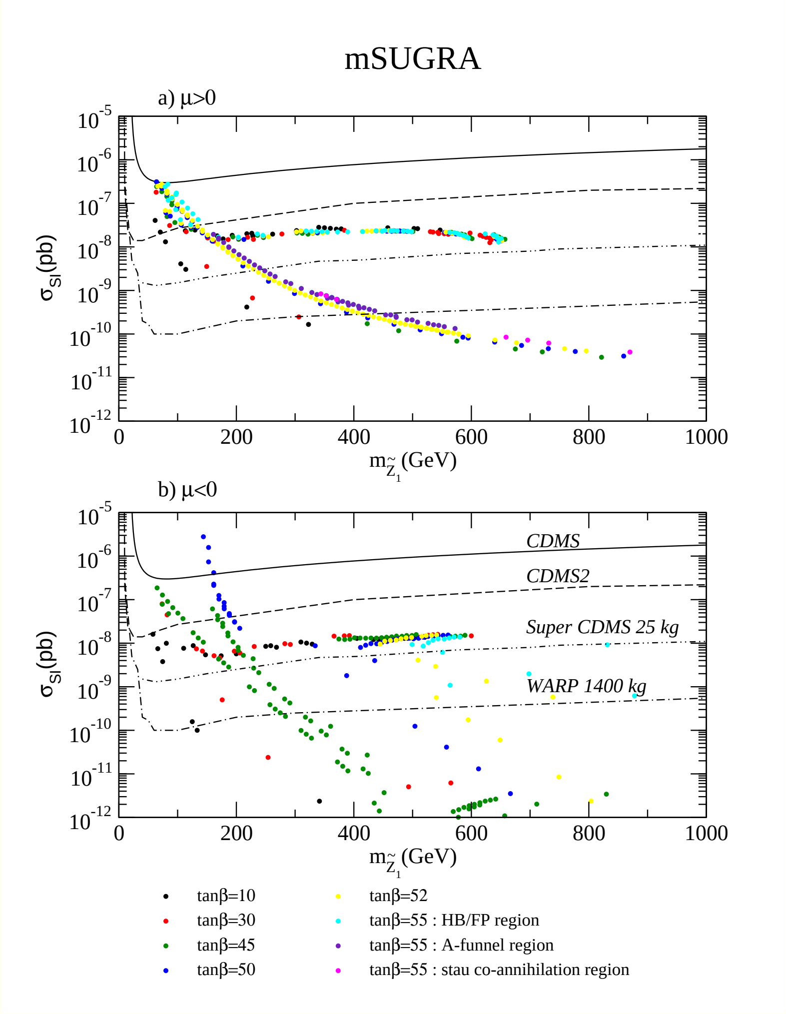
- CDMS1, Edelweiss, Zeplin1

★ Stage 2:

- CDMS2, CRESST2, Edelweiss2
- Zeplin2, Xenon-10

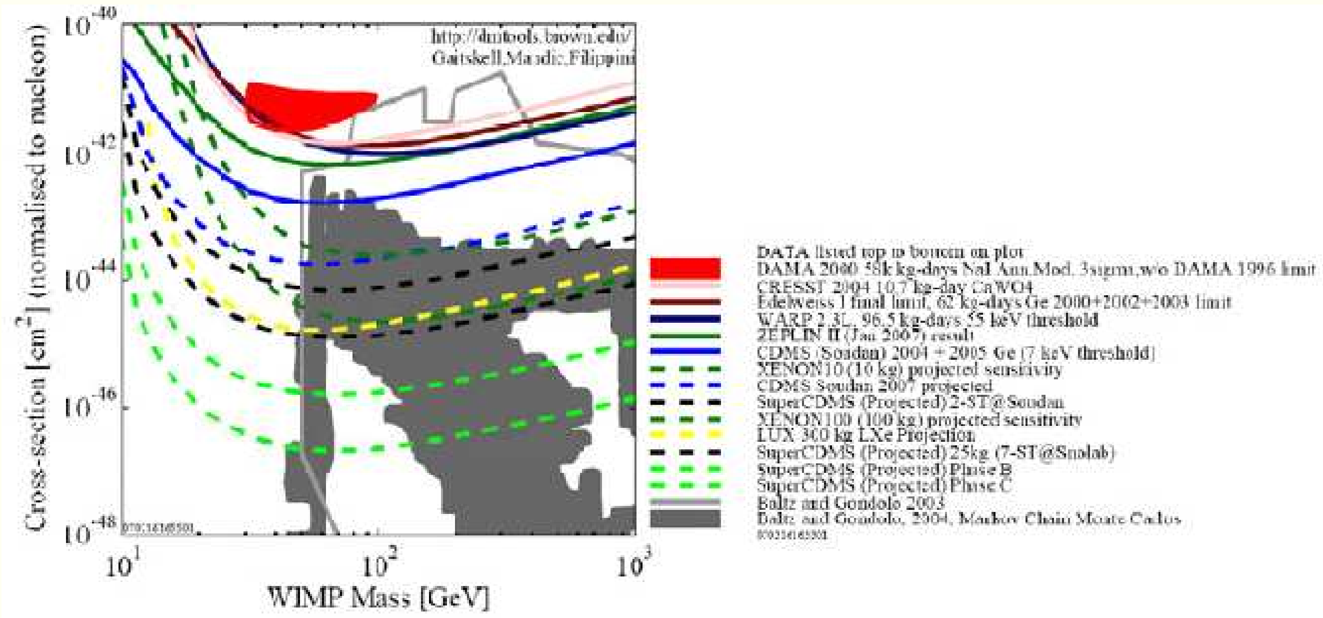
★ Stage 3:

- SuperCDMS, LUX, (mini)CLEAN
- WARP, ArDM

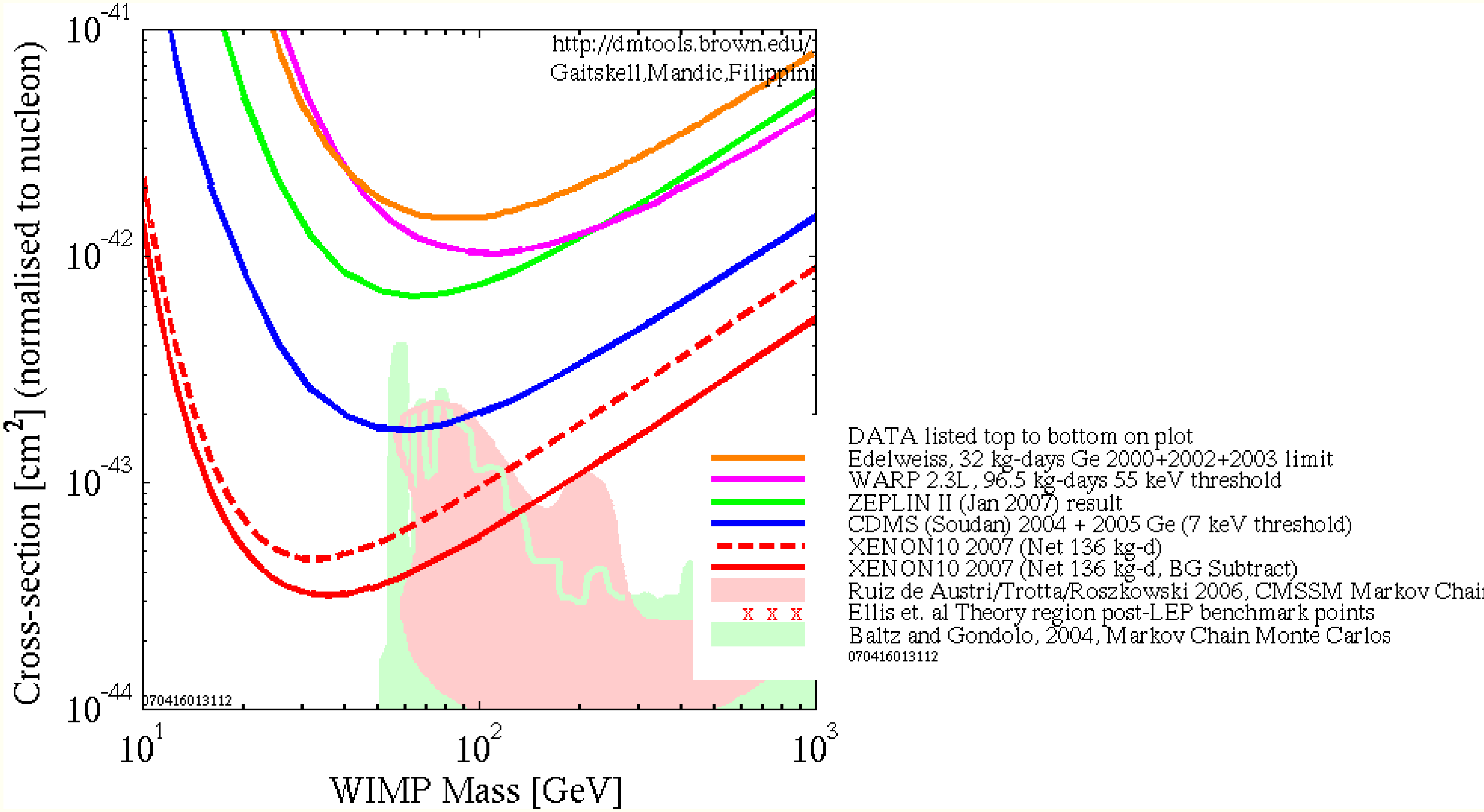


Current limits from direct WIMP searches

- ⋆ DAMA NaI detector: signal via annual modulation?
- ⋆ region of $\sigma_{SI}(\widetilde{Z}_1 p)$ rules it out (e.g. CDMS)
- ⋆ but light WIMP $\sim 5-13$ GeV still allowed via σ_{SD} if σ_{SI} is small (Savage, Freese, Gondolo)

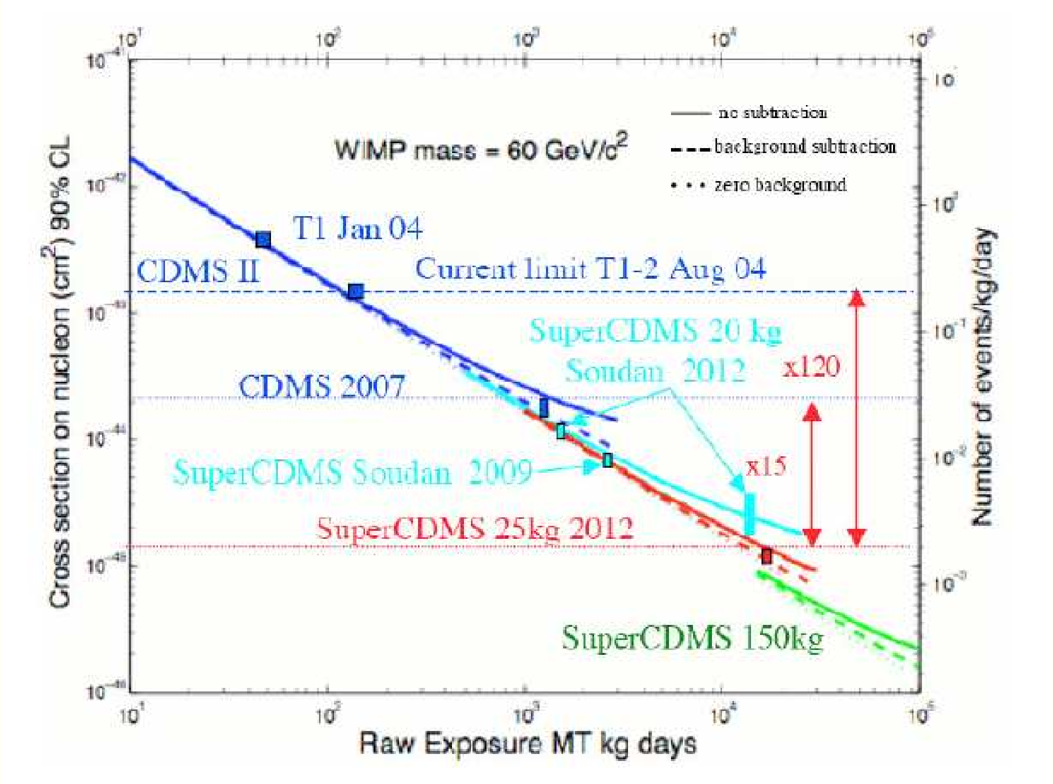


Current best limit: new Xenon-10 result!



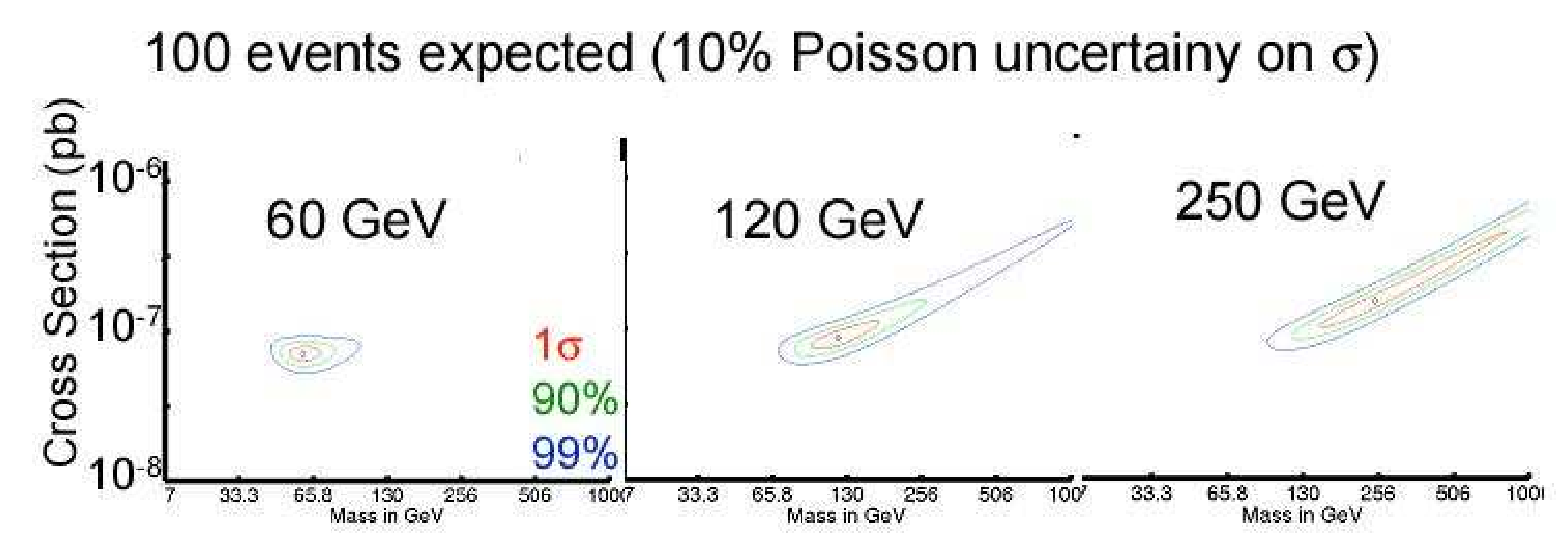
Projected reach of CDMS upgrades

⋆ reach $10^{-9} pb$ by 2012? probe MHDM (HB/FP region)!



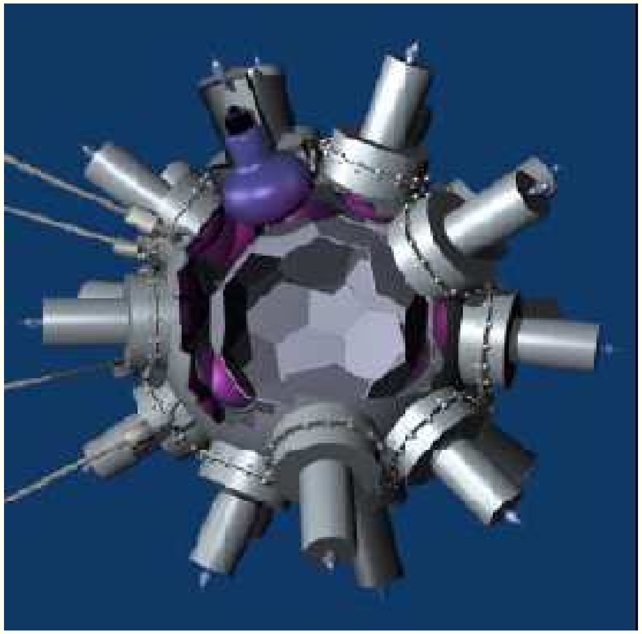
Direct DM detection: mass extraction

★ using high stats; construct recoil E spectrum
(R. Schnee; A.Green)



Towards large noble gas/liquid detectors

- ⋆ Xe: Zeplin; Xenon; LUX
- ⋆ Ar: (mini)CLEAN, DEAP, ArDM
- ⋆ Ne: (mini)CLEAN
  - bigger-the-better: n-rejection via multiple scatter
  - push to ton or more size detector: probe $\sim 10^{-10}$ pb?



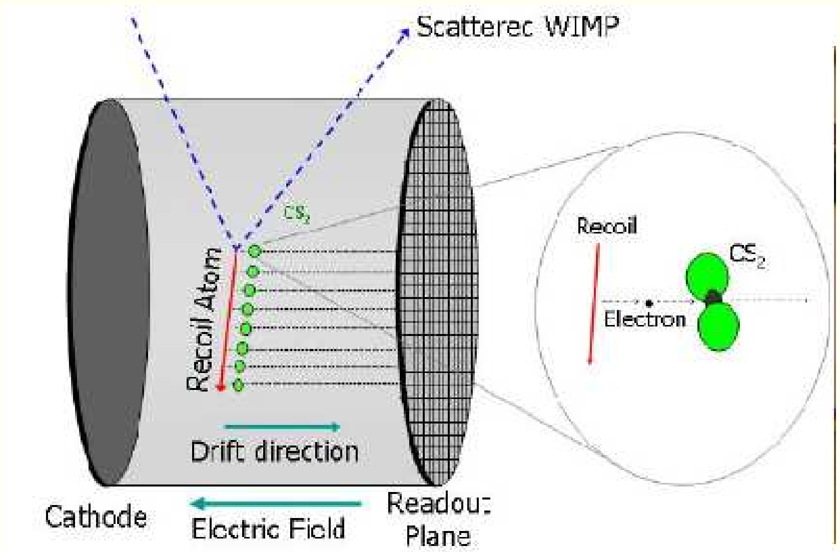
Other intriguing ideas

⋆ COUPP: bubble chamber

- CF_3I target: spin-dep. sensitivity

⋆ Drift2: low pressure gas: directional sensitivity

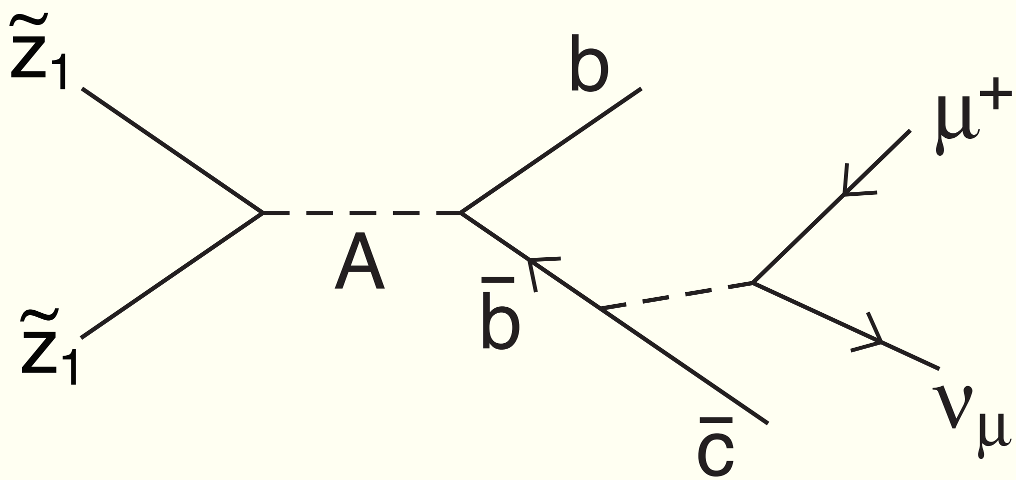
⋆ SIGN/HPGS: high pressure gas



DRIFT set-up

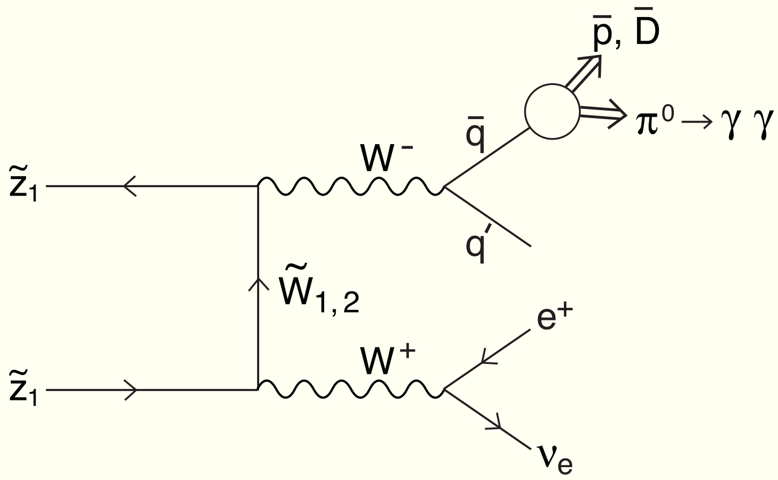
Indirect detection (ID) of SUSY DM: ν-telescopes

- ⋆ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes
- ⋆ flux is largest when $\sigma(\widetilde{Z}_1 p)$ is largest
  - – $e.g.$ low $m_{\tilde{q}}$ or HB/FP region for mSUGRA
  - • experiments: Amanda, Icecube, Antares

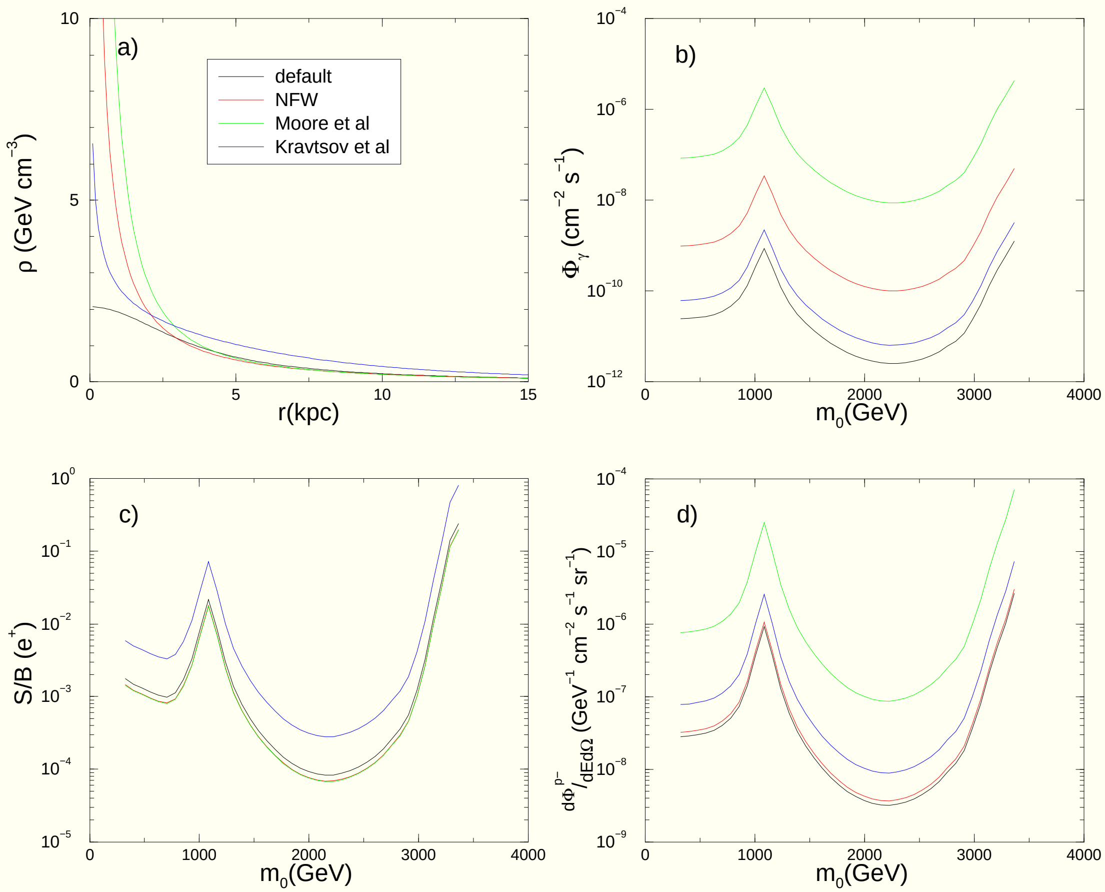


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo

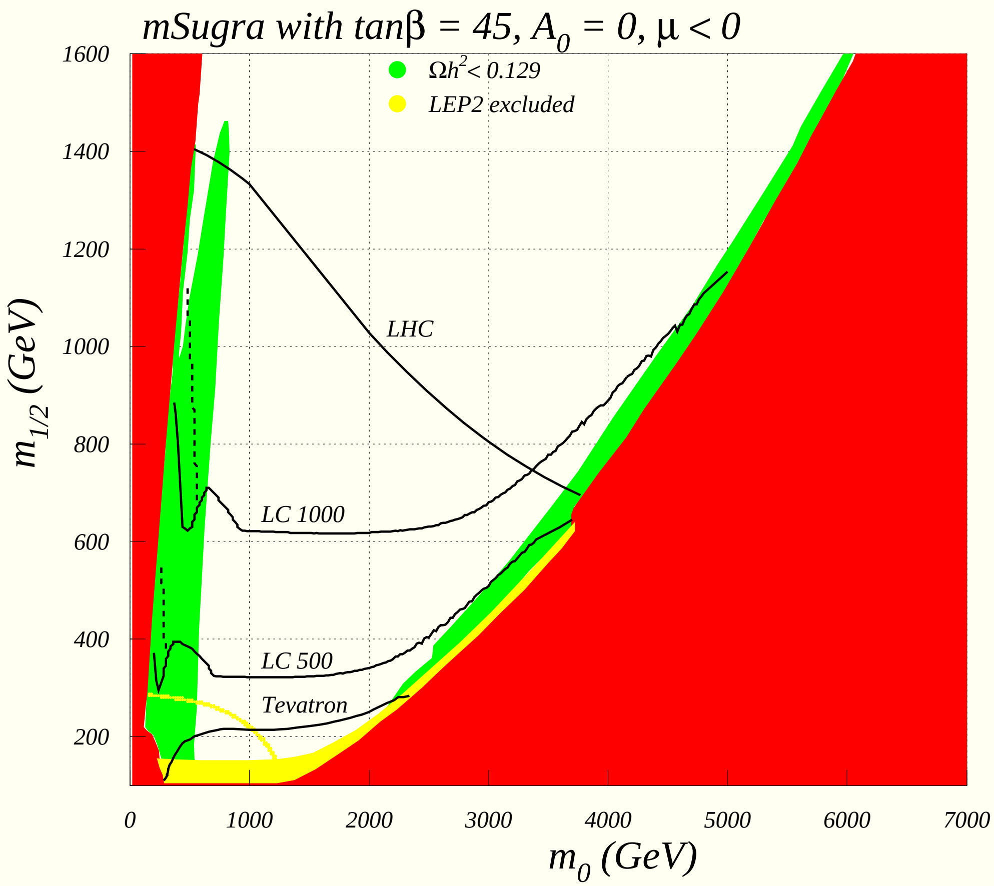


Rates for γs, e^+s, $\bar{p}$s vs. m_0 for fixed $m_{1/2} = 550$ GeV, $\tan\beta = 50$



- rates enhanced in A-funnel and HB/FP region (MHDM)

Sparticle reach of all colliders and relic density

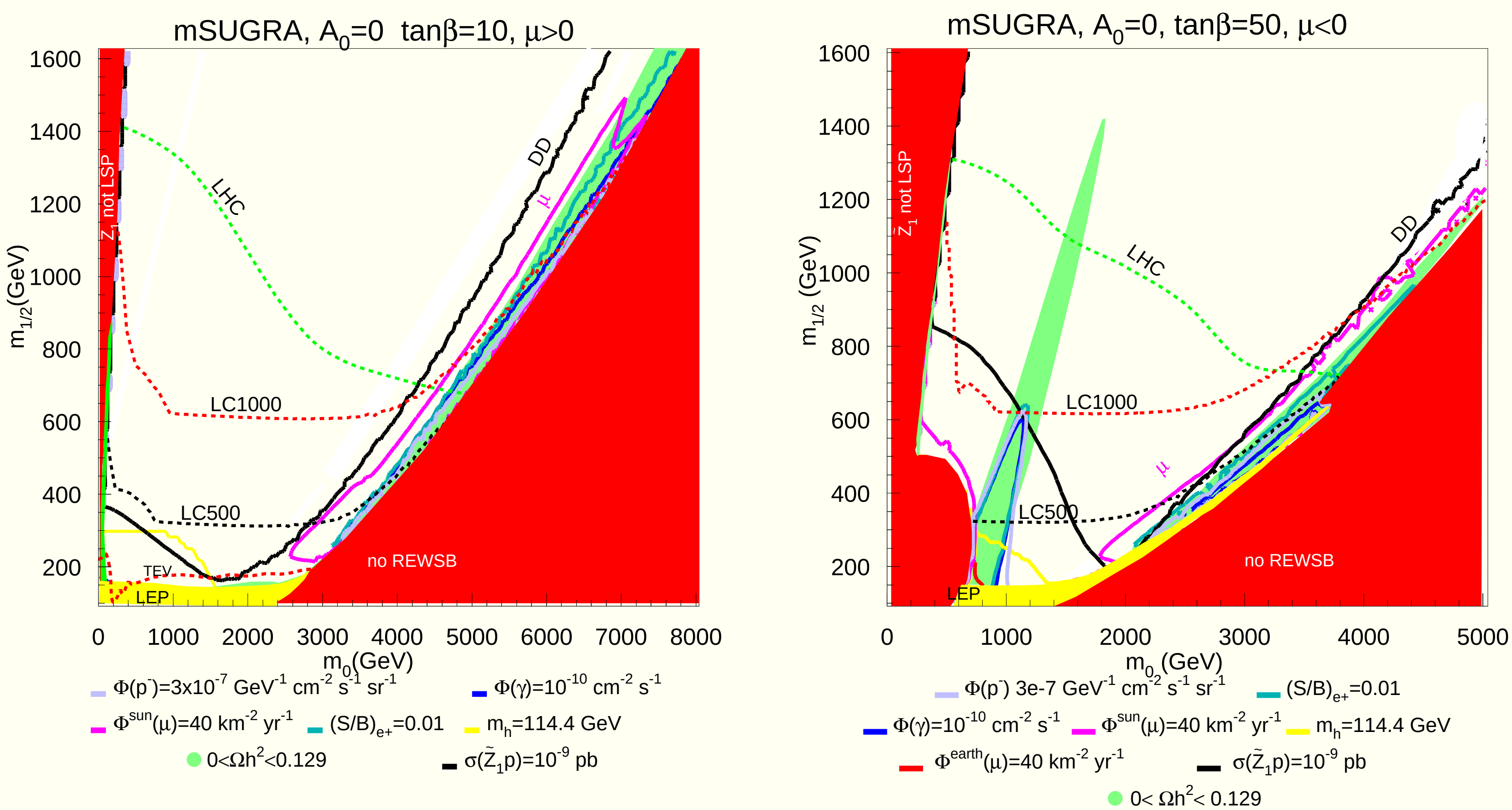


HB, Belyaev, Krupovnickas, Tata

International linear e^+e^- collider (ILC)

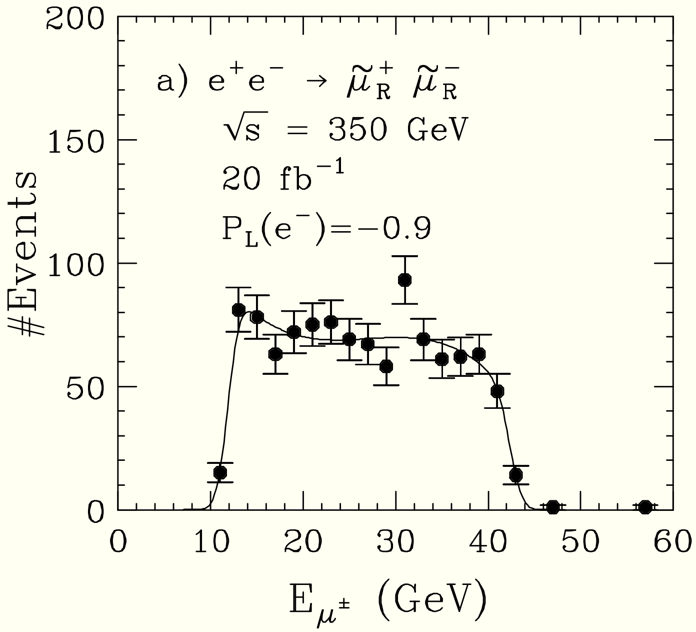
- ⋆ A linear e^+e^- collider with $\sqrt{s} = 0.5 - 1$ TeV is highest priority project for HEP beyond LHC! Why?
  - All beam energy $\Rightarrow$ collision (aside from brem/beamstrahlung losses)
  - beam energy known
  - clean collision environment
  - low (electroweak) background levels
  - adjustable beam energy (threshold scans)
  - e^- and possibly e^+ beam polarization
- ⋆ ILC will be *ideal* machine to perform precision spectroscopy of any new (EW interacting) matter states (provided they are kinematically accessible)!
- ⋆ timeline: decision-2012; ready-2020

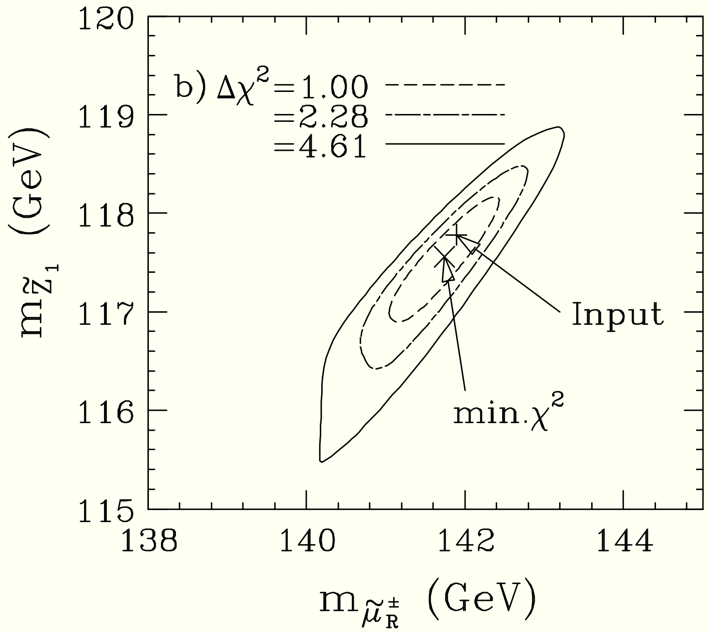
Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

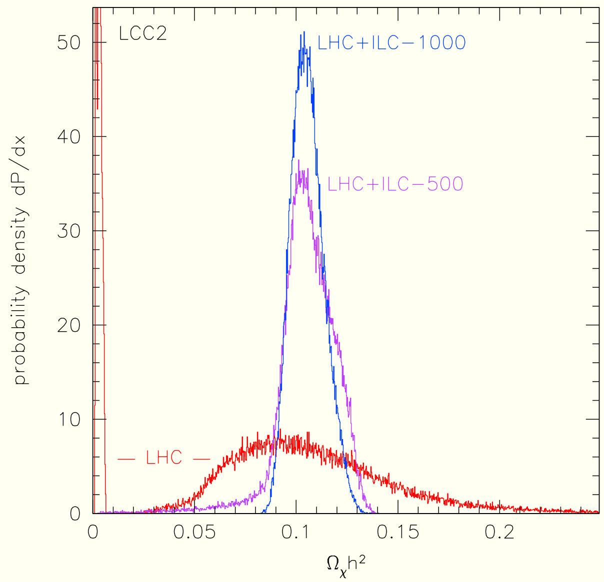
Precision sparticle measurements at a e^+e^- linear collider





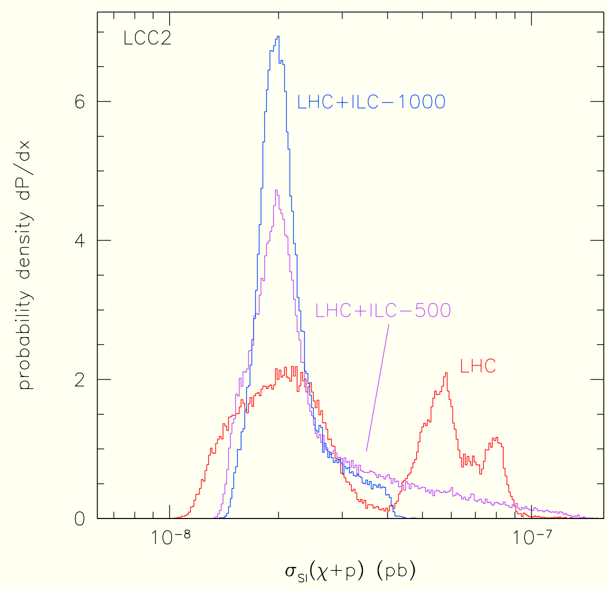
Role of ILC in DM physics

- Baltz, Battaglia, Peskin, Wizansky analysis
- fit all sparticle measurements to determine underlying SUSY parameters
- then plug in to theory to find relic density
- does $\Omega_{\widetilde{Z}_1} h^2$ saturate measured value?
- possible mixed dark matter? superWIMPs?



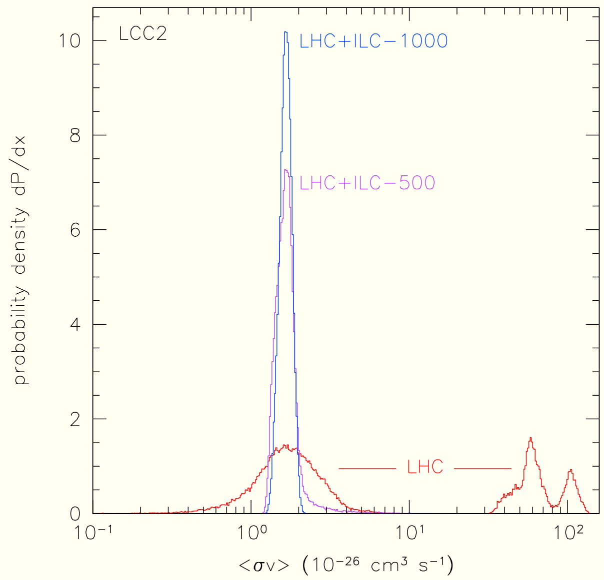
Also determine $\sigma_{SI}(\widetilde{Z}_1 p)$

- use to extract local DM density



Also determine $\langle \sigma v \rangle$

- couple to ID to gain *e.g.* DM halo tomography



SuperWIMPs (e.g. $\tilde{G}$ in SUGRA or G in UED)

⋆ $m_{\tilde{G}} = F/\sqrt{3}M_* \sim$ TeV in Supergravity models

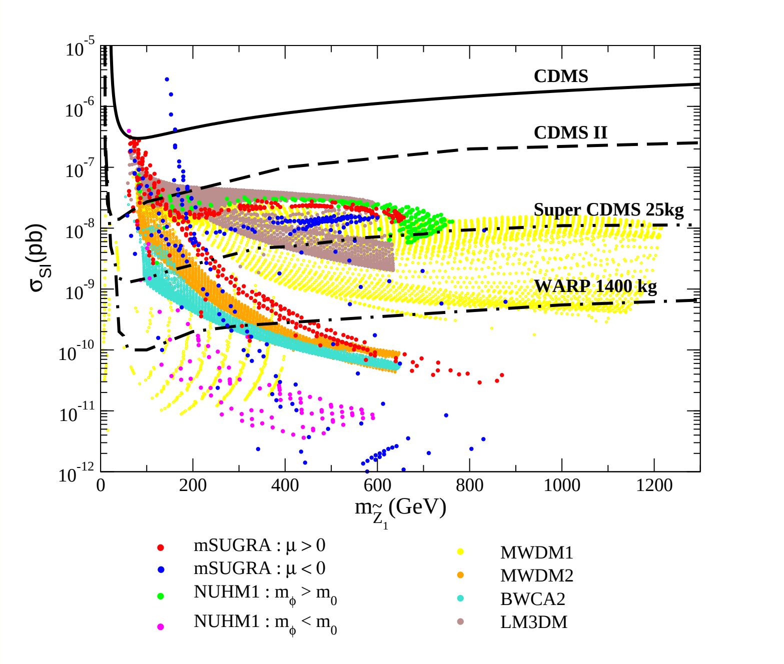
- usually $\tilde{G}$ decouples (but see Moroi et al. for BBN constraints)
- if $\tilde{G}$ is LSP, then calculate NLSP abundance as a thermal relic: $\Omega_{NLSP}h^2$
- $\widetilde{Z}_1 \to h\tilde{G},\ Z\tilde{G},\ \gamma\tilde{G}$ or $\tilde{\tau}_1 \to \tau\tilde{G}$ possible
  - ∗ lifetime $\tau_{NLSP} \sim 10^4 - 10^8$ sec
  - ∗ constraints from BBN, CMB not too severe
  - ∗ DM relic density is then $\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{NLSP}}\Omega_{NLSP}$
  - ∗ Feng, Rajaraman, Su, Takayama; Ellis, Olive, Santoso, Spanos
- $\tilde{G}$ undetectable via direct/indirect DM searches
- unique collider signatures:
  - ∗ $\tilde{\tau}_1$=NLSP: stable charged tracks
  - ∗ can collect NLSPs in e.g. water (slepton trapping)
  - ∗ monitor for $NLSP \to \tilde{G}$ decays

Conclusions

- ⋆ Overwhelming evidence for CDM in the universe: identity unknown
- ⋆ Numerous candidate CDM particles from theory
- ⋆ Axions: searches ongoing (ADMX group)
- ⋆ WIMPs: thermal relic from Big Bang
- ⋆ SUSY is favored WIMP candidate, but many others
- ⋆ Direct detection: push to 10^{-10} pb!
- ⋆ Indirect DM detection prospects
- ⋆ Detection at colliders: Tevatron, LHC, ILC
- ⋆ SuperWIMPs: $\tilde{G}$ in SUSY; G in UED
- ⋆ We are on our way to unveiling the mystery of Dark Matter in next several years!

Direct detection of well-tempered neutralino

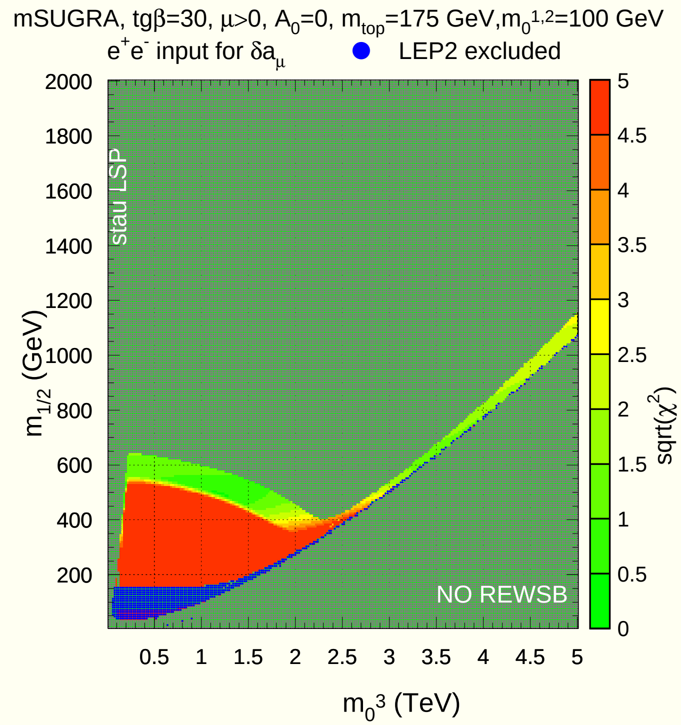
- adjust mixing of $\widetilde{Z}_1$ to get $\Omega_{\widetilde{Z}_1} h^2 \sim 0.11$
- then also get enhanced DD rates
- DD asymptotes around $\sim 10^{-8}$ pb



HB, Mustayaev, Park , Tata

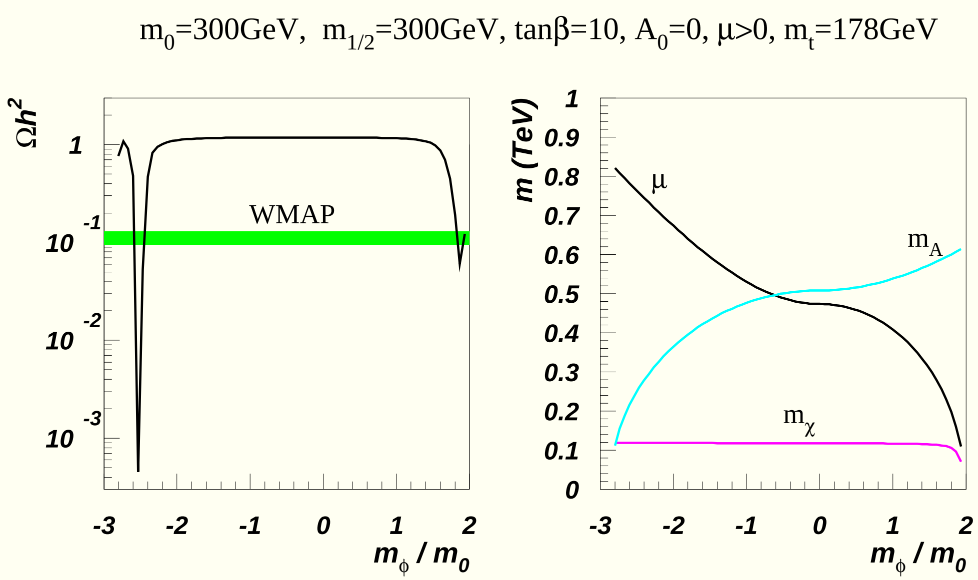
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy NMH: HB, Belyaev, Krupovnickas, Mustafayev
- $m_0(1) \simeq m_0(2) \ll m_0(3)$ (preserve FCNC bounds)
- motivation: reconcile $BF(b \to s\gamma)$ with $(g-2)_\mu$ anomaly



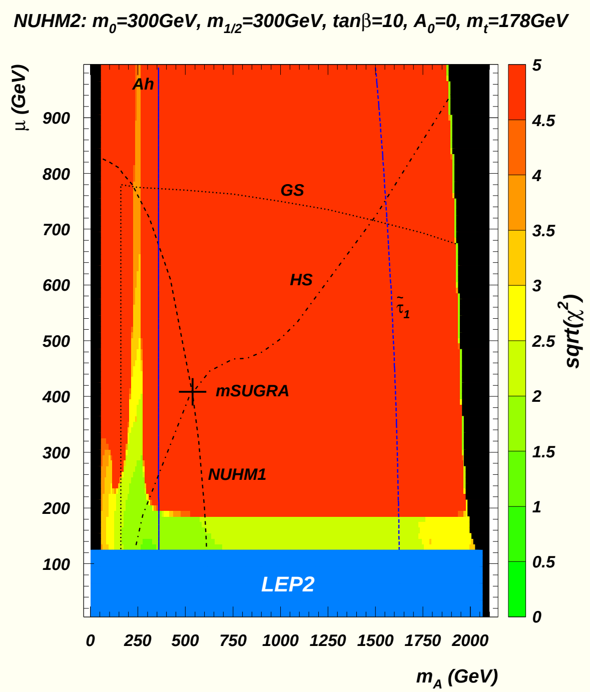
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$
- $m_\phi^2 \gg m_0 \Rightarrow$higgsino DM for any m_0, $m_{1/2}$
- $m_\phi^2 < 0 \Rightarrow$ can have A-funnel for any $\tan\beta$



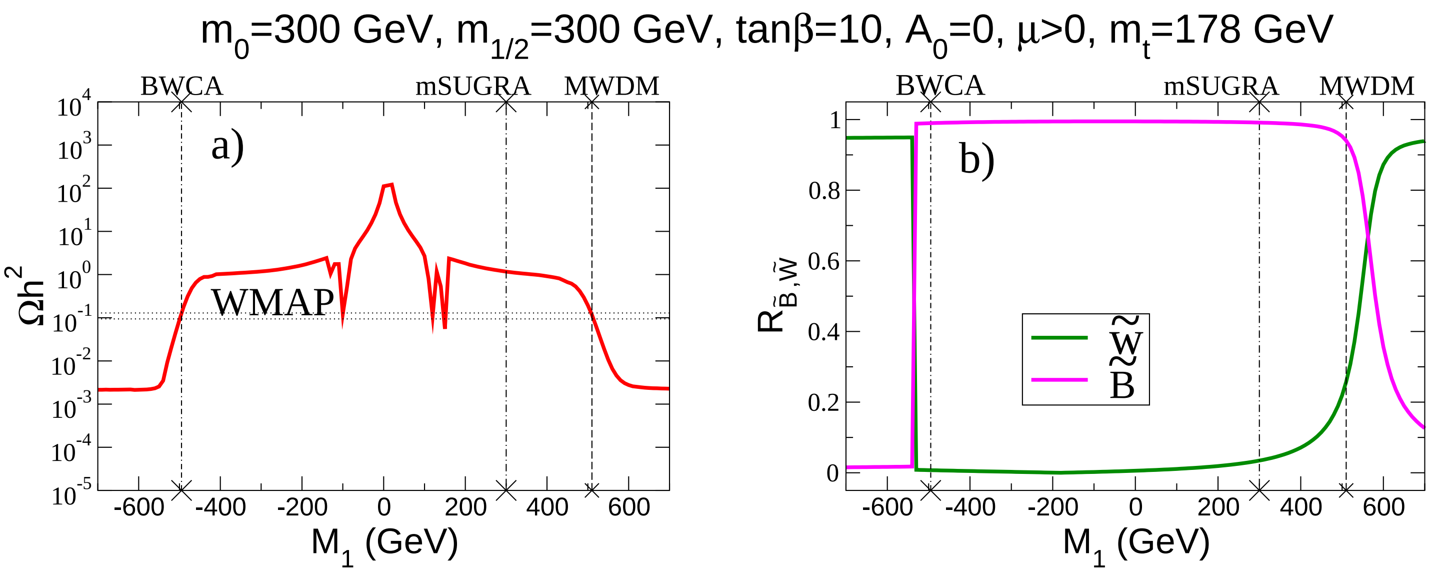
NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SU(5)$ SUSYGUTs where $\hat{H}_u \in \phi(5)$, $\hat{H}_d \in \phi(\bar{5})$
- can re-parametrize $m_{H_u}^2,\ m_{H_d}^2 \leftrightarrow \mu,\ m_A$ (Ellis, Olive, Santoso)
- large S term in RGEs $\Rightarrow$ light $\tilde{u}_R,\ \tilde{c}_R$ squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



Gaugino mass non-universality

- $M_1 \neq M_2 \neq M_3$: HB, TK, AM, EP, SP, XT
- motivation: SUSYGUTs where gauge kinetic function transforms non-trivially
- $M_2 \sim M_1$ at M_{GUT}: mixed wino dark matter (MWDM)
- $M_2 \simeq -M_1$ at M_{GUT}: bino-wino co-annihilation (BWCA)



Gaugino mass non-universality: low M_3 case

- $M_3 < M_1 \sim M_2$: HB, TK, AM, EP, SP, XT
- motivation: mixed-moduli AMSB models
- *lower* $M_3 \rightarrow$ *low* $m_{\tilde{q}} \rightarrow$ *low* $\mu \rightarrow$ *mixed higgsino DM*