Journey to the Dark Side (of the Universe)

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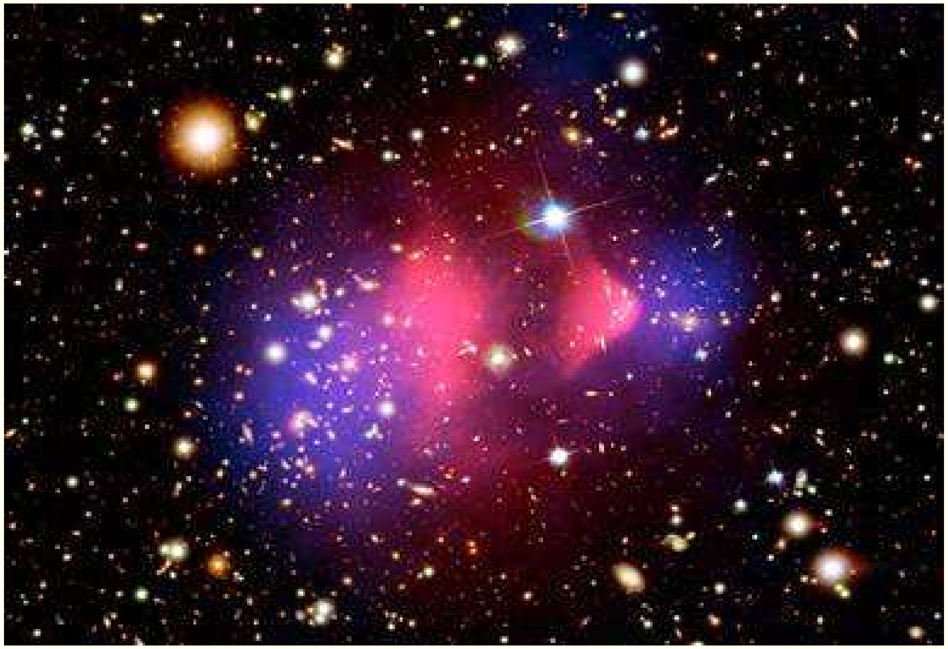
- ⋆ Dark energy
- ⋆ Concordance model
- ⋆ Dark matter
  - • candidates
    - ∗ axions
    - ∗ neutralinos
    - ∗ direct detection
    - ∗ indirect detection
    - ∗ collider detection



Milestones for Dark Energy

- ⋆ 1917: Einstein adds $\Lambda g_{\mu\nu}$ term to field equations to obtain static Universe solution
- ⋆ ~ 1930: Einstein removes CC from field equations in light of Hubble observation of expanding universe
- ⋆ QFT: $\Lambda \sim M_{Pl}^4$? Why so small: finetuning to 10^{120}
- ⋆ 1987: Weinberg anthropic prediction of Λ to factor of 2
- ⋆ 1995: Krauss& Turner suggest $\Lambda \neq 0$
- ⋆ 1999: detection of acceleration of universe via high z type Ia SN
- ⋆ 2003: WMAP CMB probe measures DE: $\Omega_\Lambda \sim 0.7$ with $\Lambda \sim (3\ meV)^4$
- ⋆ 2006: Hubble measurements find DE consistent with Λ at $t = -9B$ years

What is the dark energy?

★ time evolution of expansion of universe:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3} \tag{1}$$

★ various evidence $\Rightarrow \ddot{a} > 0$

★ possibilities:

- universe dominated by particle or field with $w = P/\rho < -1/3$ (quintessence)
- $\Lambda > 0$
- GR is wrong

★ testing DE: measure equation of state parameter $w = P/\rho$ as function of time (redshift z)

- CC: $w = -1$ for all z

Prospects for Dark Energy

⋆ Probes of DE

- type Ia supernovae in distant galaxies: standard candles
- baryon acoustic oscillations: CMB and galaxy density profile
- galaxy cluster counting
- weak gravitational lensing

⋆ testing DE: measure EOS $w(z) = P(z)/\rho(z)$? at different redshifts

⋆ some possible space and land-based projects

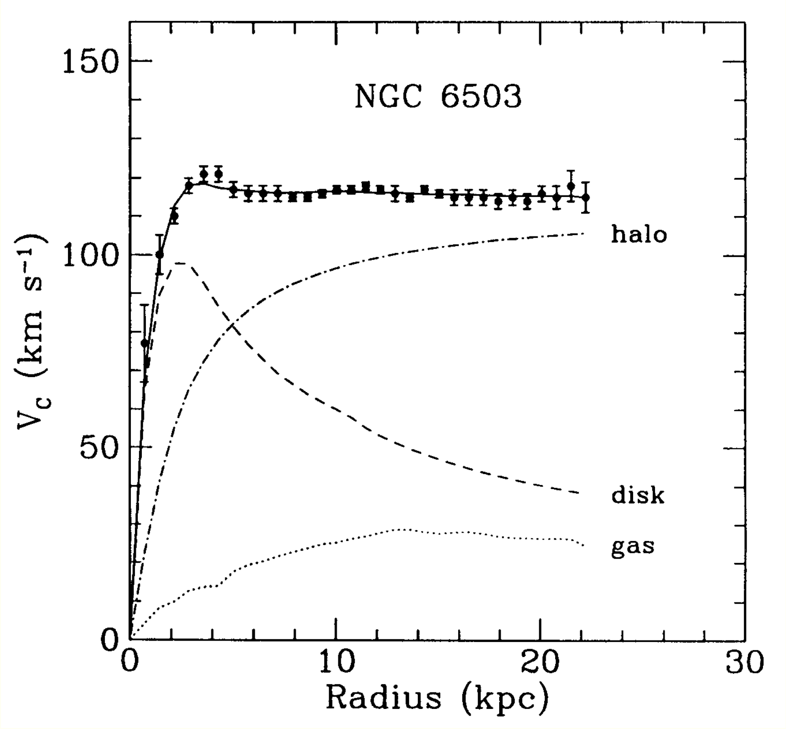
- Dark Energy Survey (DES): land-based
- Supernova Acceleration Probe (SNAP): space-based SN, weak lensing
- Large Synoptic Survey Telescope (LSST): dedicated land-based scope

Current theoretical prejudice about the CC

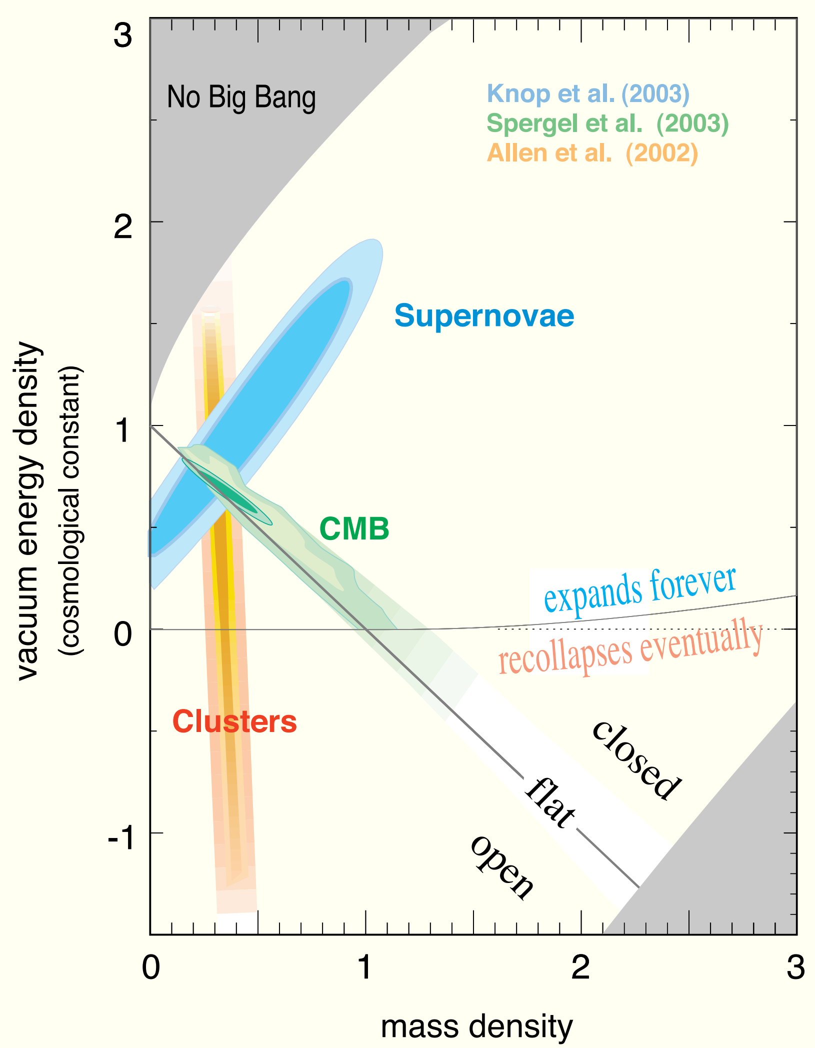
- ⋆ After many years, no compelling solution as to why CC so small
- ⋆ Only known principle to make CC=0: unbroken supersymmetry
  - But SUSY must be broken
- ⋆ the view from string theory: the string landscape!
- ⋆ (motivated by Weinberg 1987 prediction of Λ
  - there exist $\sim 10^{500}$ (?) vacua solutions in string theory
  - each one leads to different physical laws/ universe
  - only in rare cases would a possible universe lead to life (as we know it)
- ⋆ therefore: an anthropic selection of a universe with a small but non-zero CC
- ⋆ perhaps more philosophy than science...

Evidence for Dark Matter

- ⋆ Binding of clusters
- ⋆ Galactic rotation curves
- ⋆ Gravitational lensing
- ⋆ CMB fluctuations
- ⋆ Large scale structure
- ⋆ Standard cosmological model: ΛCDM
  - $\Omega_B h^2 = 0.023 \pm 0.001$
  - $\Omega_\nu h^2 < 0.0076 \;\; 95\% \; CL$
  - $\Omega_\Lambda h^2 \sim 0.35$
  - $\Omega_{CDM} h^2 = 0.113 \pm 0.009$



Dark matter vs. dark energy: concordance (ΛCDM) model



Candidates for Dark Matter

⋆ unseen baryons, e.g. BHs, brown dwarves, stellar remnants

– inconsistent with BBN element abundance calc'n

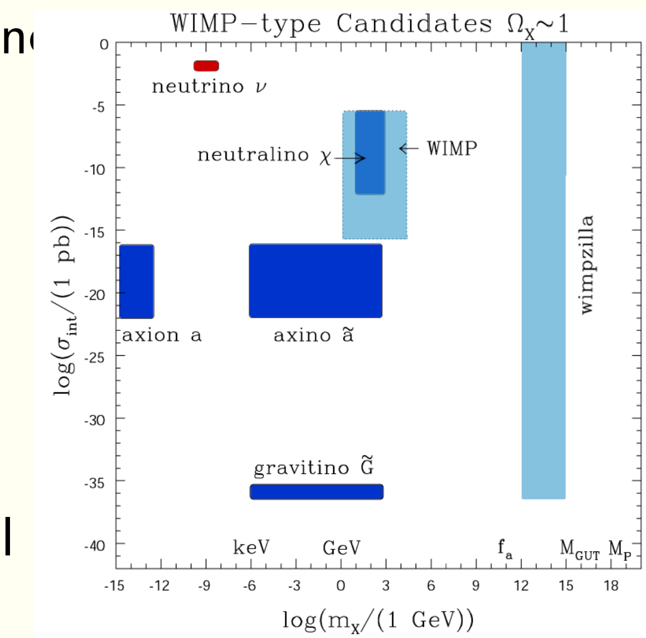
– limits from MACHO, EROS, OGLE

⋆ neutrinos ($= HDM$); structure formation n

⋆ axions

⋆ WIMPS

- RPC supersymmetry: LSP
- UED: lightest KK particle
- Little Higgs models: lightest T-odd ptcl
- Branons (XDDM)
- Wimpzillas?



L. Roszkowski plot

Axions

★ Peccei-Quinn solution to strong CP problem in QCD

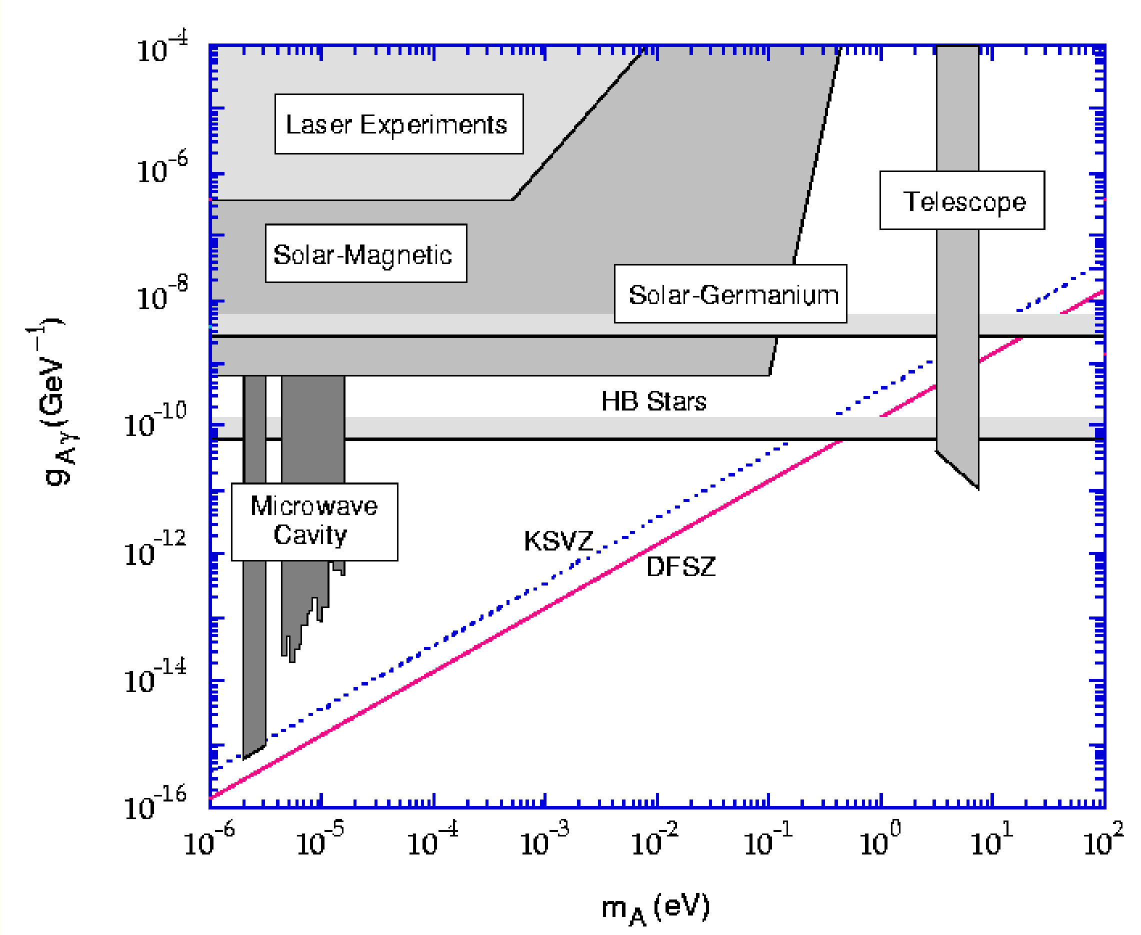
★ pseudo-Goldstone boson from PQ symmetry breaking at scale f_a

★ non-thermally produced via vacuum mis-alignment

- $\Omega_a h^2 = \kappa_a (f_a/10^{12}\ \mathrm{GeV})^{1.175}\theta_i^2$
- $\kappa_a,\ \theta_i \sim 1 \Rightarrow f_a \sim 10^{11}\ \mathrm{GeV}$ needed
- $m_a \sim \Lambda_{QCD}^2/f_a \sim 0.001 - 0.1$meV
- a couples to EM field: $a-\gamma-\gamma$ coupling (Sikivie)
- axion microwave cavity searches
- astrophysical bounds: stellar cooling via a emission

Constraints from axion searches

- ongoing microwave cavity searches: ADMX experiment

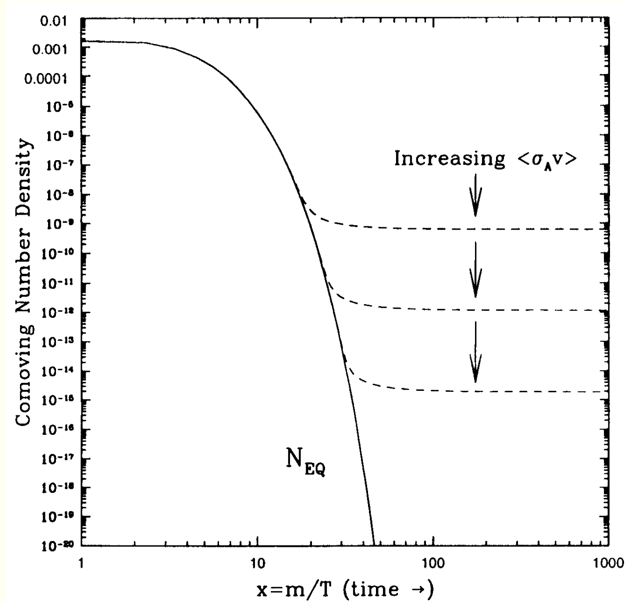


WIMPs: the WIMP miracle!

- 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}!



Physics beyond the SM

- ⋆ extra Higgs multiplets
- ⋆ extra gauge symmetries $U(1)'$
- ⋆ extra matter
- ⋆ remnants of GUTs
- ⋆ supersymmetry
- ⋆ technicolor variations (walking, etc)
- ⋆ large (weak scale) extra dimensions (ADD)
- ⋆ warped extra dimensions (Randall-Sundrum)
- ⋆ little Higgs theories
- ⋆ $\ldots$

SUSY is standard way beyond the SM

"if we consider the main classes of new physics that are currently being contemplated$\cdots$, it is clear that (supersymmetry) is the most directly related to GUTs. SUSY offers a well defined model computable up to the GUT scale and is actually supported by the quantitative success of coupling unification in SUSY GUTs.For the other examples$\cdots$, all contact with GUTs is lost or at least is much more remote. $\cdots$ the SUSY picture$\cdots$ remains the standard way beyond the Standard Model"

G. Altarelli and F. Feruglio, hep-ph/0306265

Some successes of SUSY GUT 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
- ⋆ can give dark energy via CC Λ (but need huge fine-tuning...)
  - SUGRA $=$ low energy limit of superstring?
  - stringy multiverse: anthropic selection of small CC?

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)

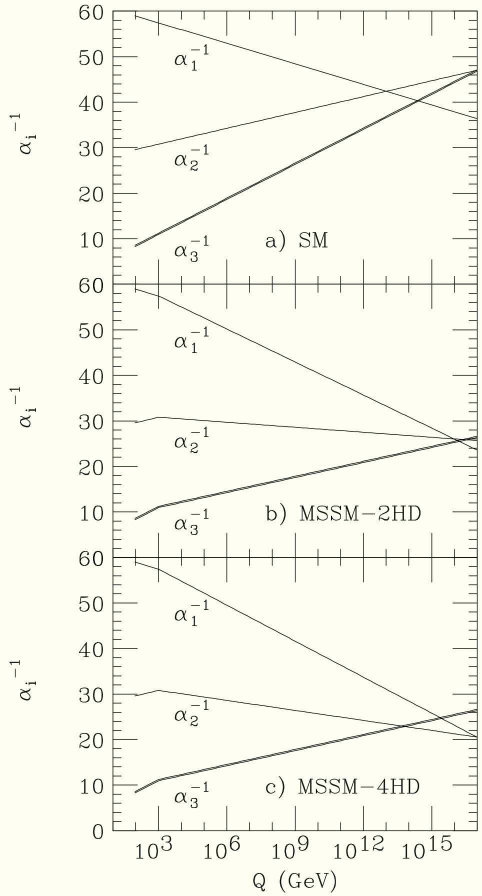
– gravitinos (superWIMPs)

– neutralinos

– GMSB messengers

– hidden sector states

– axino/saxion



Gravity-mediated SUSY breaking models

- ⋆ $m_{3/2} \sim M_s^2/M_{Pl} \sim 10^3$ GeV for $M_s \sim 10^{11}$ GeV
- ⋆ theory below $Q = M_{GUT}$ usually assumed to be MSSM
- ⋆ Soft SUSY breaking boundary conditions usually stipulated at $Q = M_{GUT}$
- ⋆ lots of possibilities depending on SUSY breaking/ GUTs/ compactification $\cdots$ (all unknown physics)
- ⋆ minimal choice: single scalar mass m_0, gaugino mass $m_{1/2}$, trilinear term A_0, bilinear term B
- ⋆ evolve couplings/soft terms to M_{weak} via RG evolution
- ⋆ EWSB radiatively due to large m_t
- ⋆ parameter space: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- ⋆ this is simplest choice and a baseline model, but **many** other possibilities depending on high scale physics

- non-universal scalar masses
- non-universal gaugino masses
- FC soft SUSY breaking terms
- large CP violating phases
- additional fields beyond MSSM below M_{GUT}?
- $\cdots$

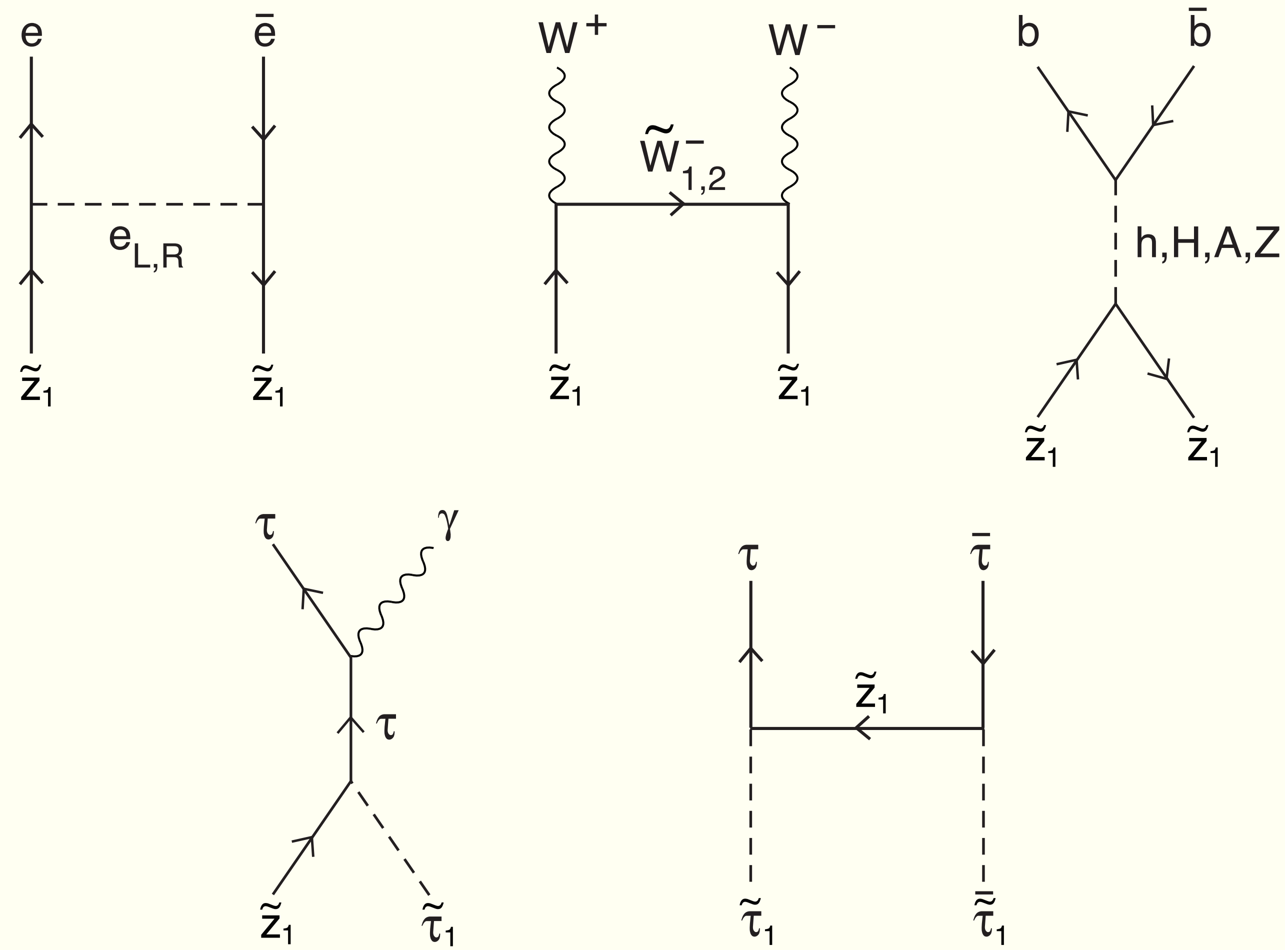
Constraints on SUSY models

- ⋆ LEP2:
  - $m_h > 114.4$ GeV for SM-like h
  - $m_{\widetilde{W}_1} > 103.5$ GeV
  - $m_{\tilde{e}_{L,R}} > 99$ GeV for $m_{\tilde{\ell}} - m_{\widetilde{Z}_1} > 10$ GeV
- ⋆ $BF(b \to s\gamma) = (3.25 \pm 0.54) \times 10^{-4}$
  - SM theory: $BF(b \to s\gamma) \simeq 3.3 - 3.7 \times 10^{-4}$
- ⋆ $a_\mu = (g-2)_\mu/2$
  - $\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (Davier et al. e^+e^-)
  - $\Delta a_\mu^{SUSY} \propto \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$
- ⋆ $BF(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6}$ (CDF)
  - constrains at very large $\tan\beta \gtrsim 50$
- ⋆ WMAP: $\Omega_{CDM} h^2 = 0.113 \pm 0.009$

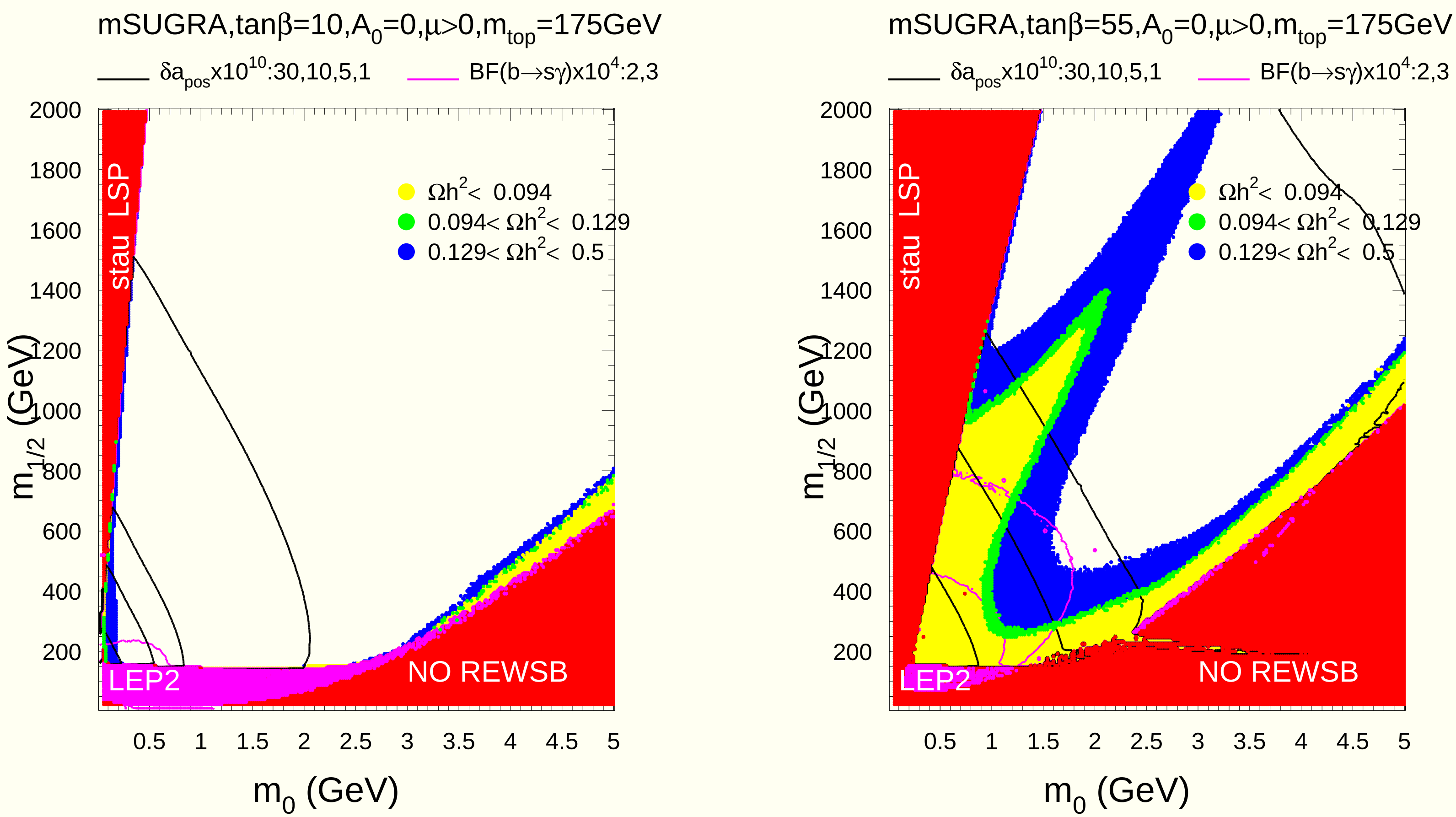
Neutralino dark matter

- ⋆ 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



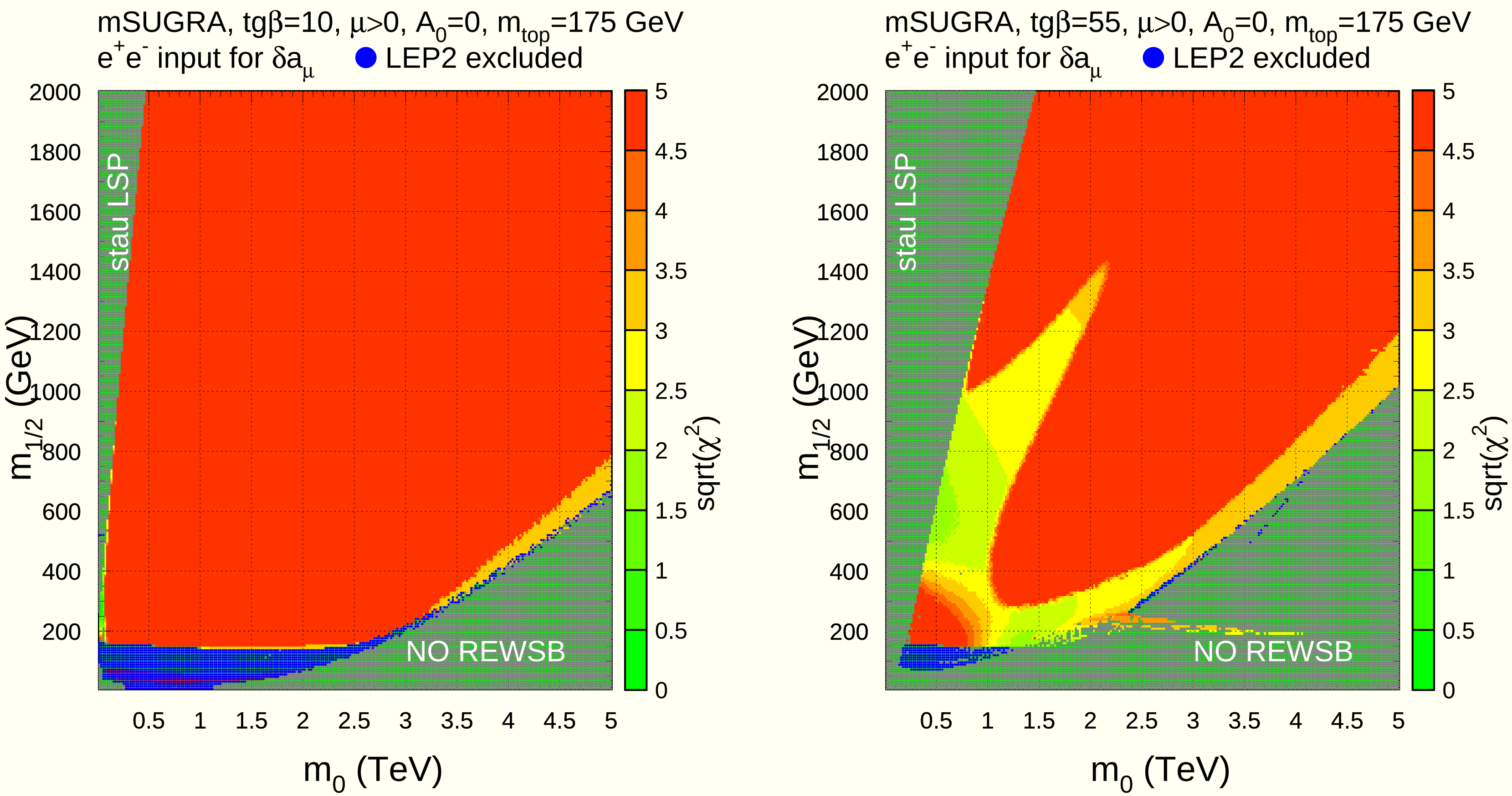
Effect of constraints on mSUGRA model



Main mSUGRA regions consistent with WMAP

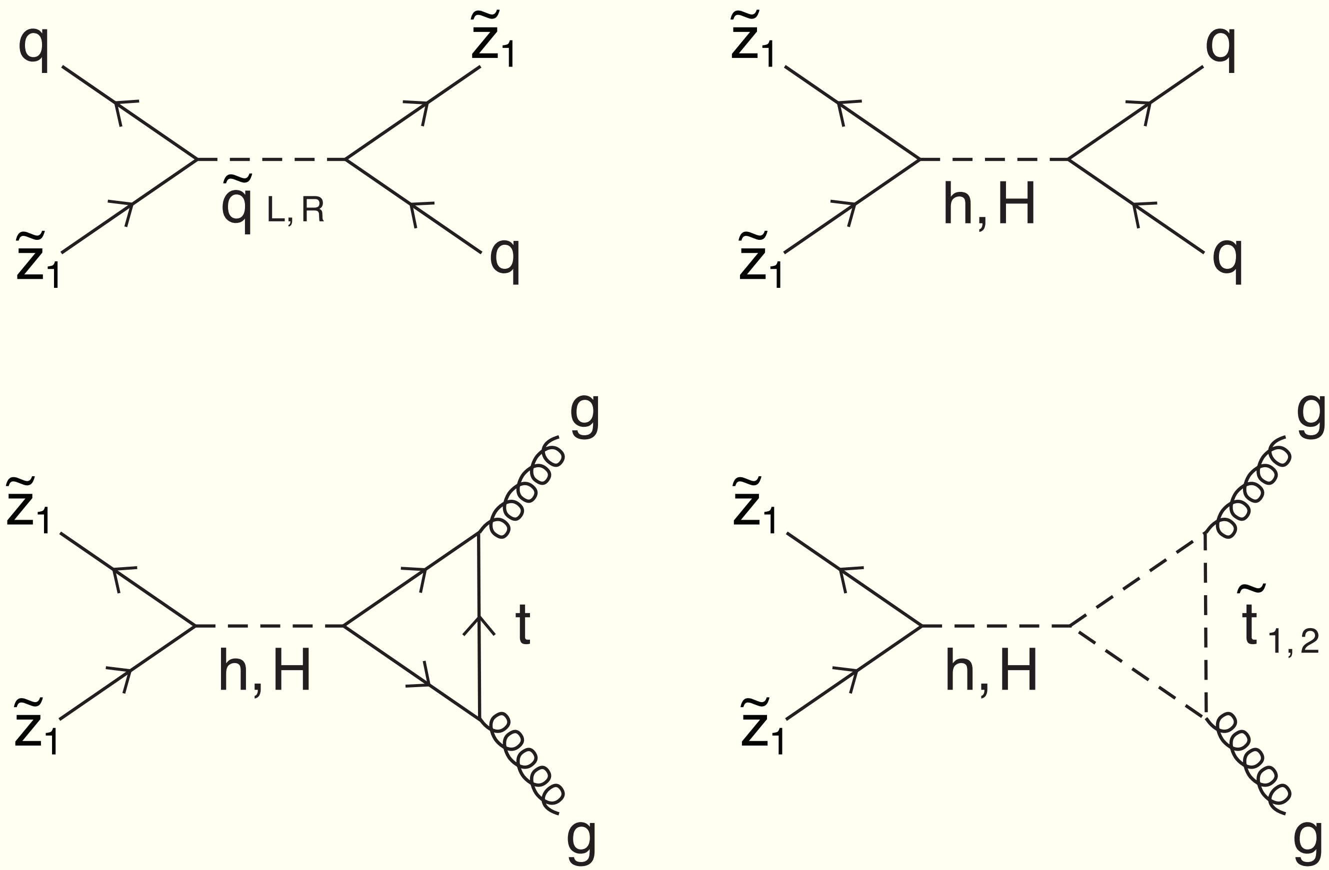
- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \rightarrow small$: Feng, Matchev, Moroi)
- ⋆ A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\widetilde{Z}_1} \simeq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

Constraints as χ^2 on mSUGRA model



Direct detection of SUSY DM

★ Direct search via neutralino-nucleon scattering



Direct detection of SUSY DM

scan over mSUGRA space :

★ Stage 1:

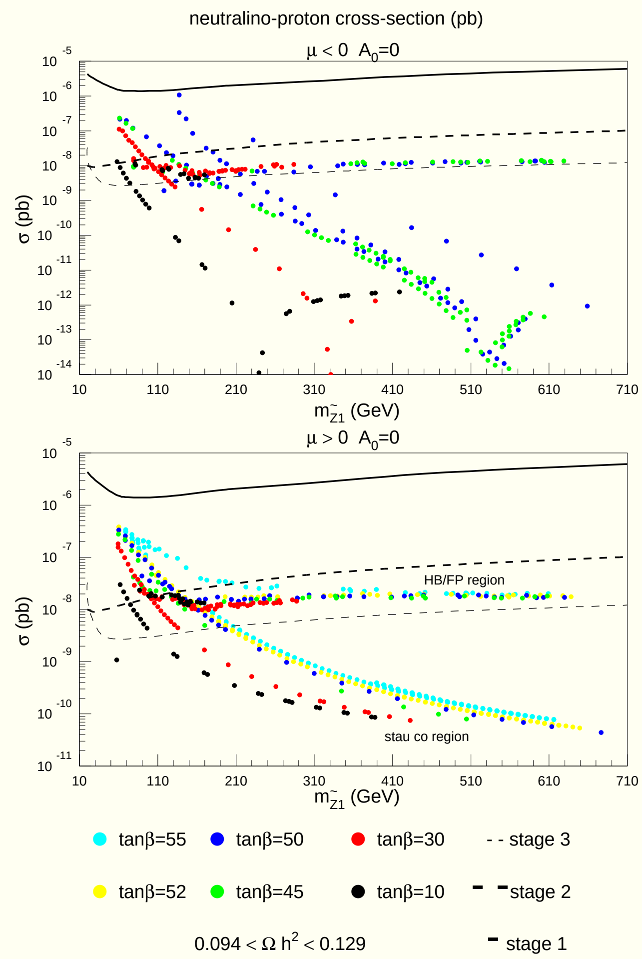
- CDMS1, Edelweiss, Zeplin1

★ Stage 2:

– CDMS2, CRESST2, Zeplin2, Edelweiss2

★ Stage 3:

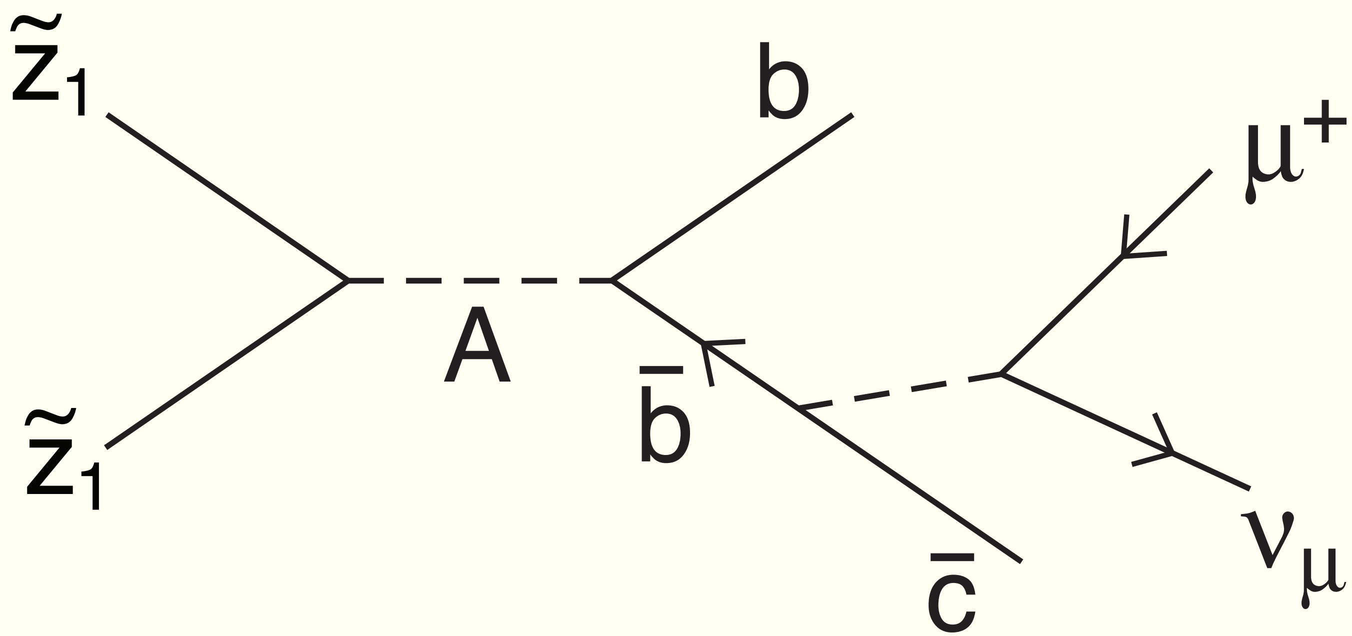
– SuperCDMS, Zeplin4, Xenon, CLEAN



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

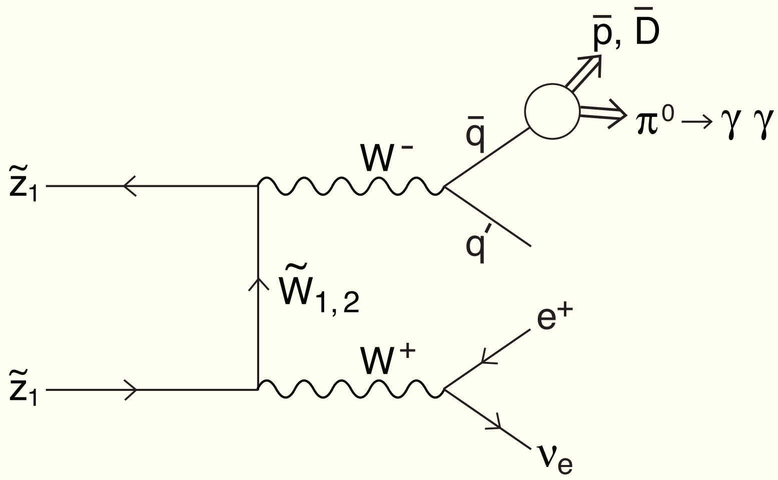
★ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes

- Amanda, Icecube, Antares

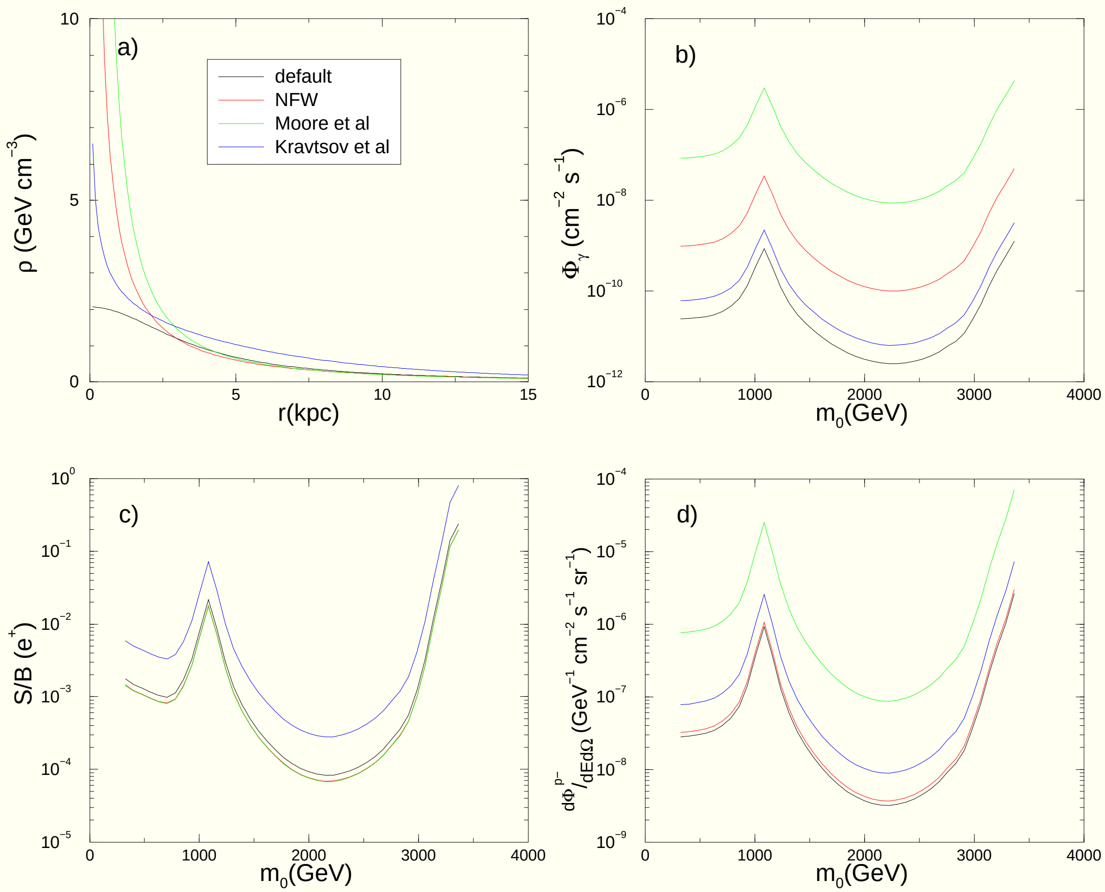


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ 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

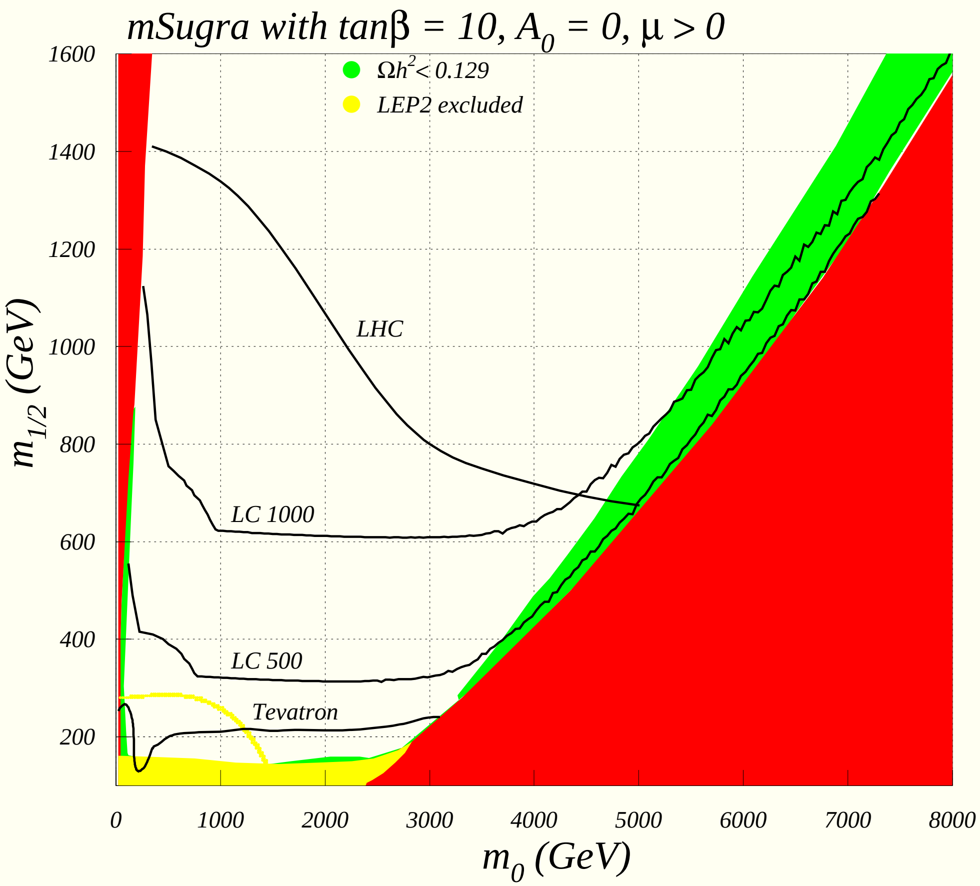


Rates for γs, e^+s, $\bar{p}$s vs. m_0 for fixed $m_{1/2} = 550$ GeV, $\tan\beta = 50$



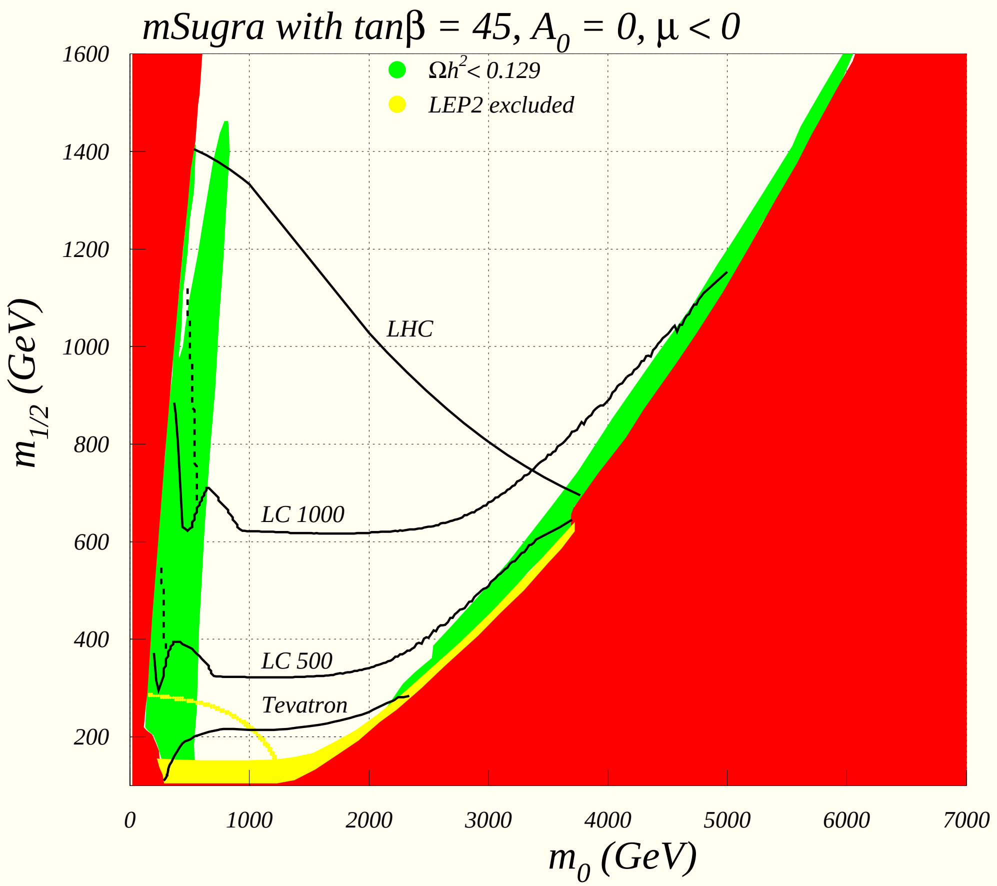
- HB, Belyaev, Krupovnickas and O' Farrill
- rates enhanced in A-funnel and HB/FP region (MHDM)

Sparticle reach of all colliders and relic density



HB, Belyaev, Krupovnickas, Tata

Sparticle reach of all colliders and relic density



HB, Belyaev, Krupovnickas, Tata

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

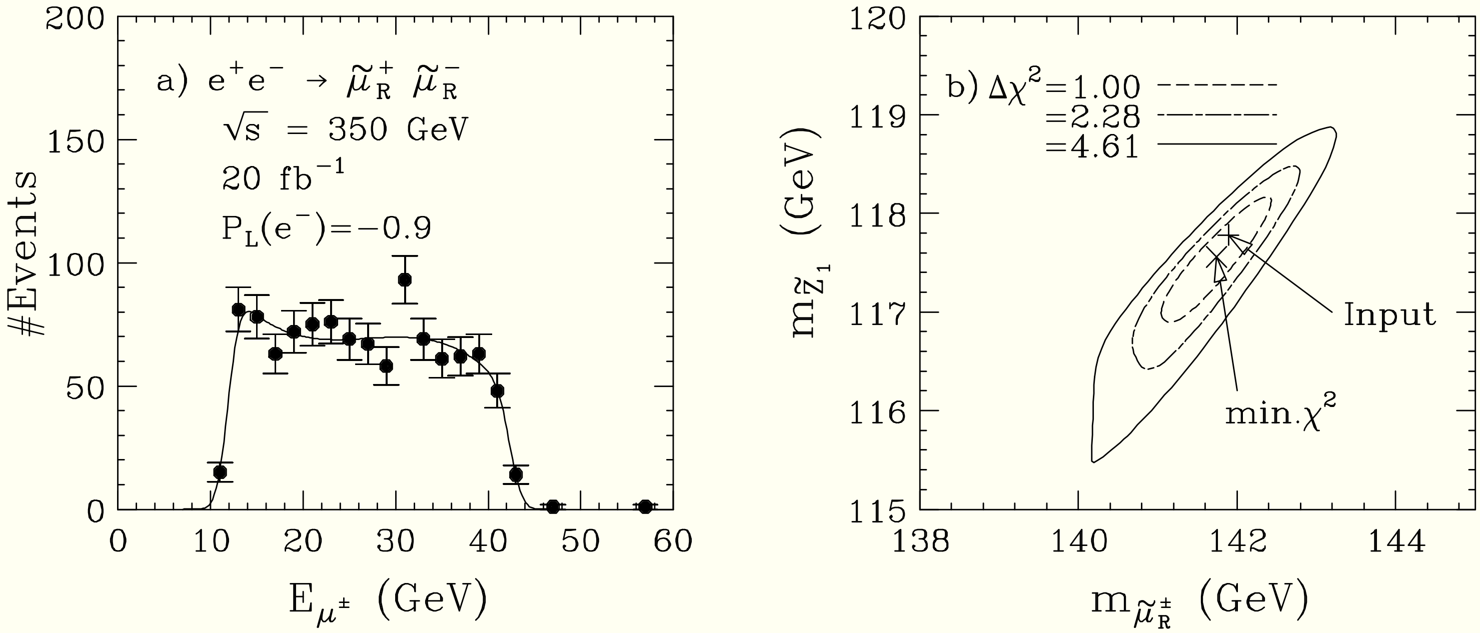
★ A linear e^+e^- collider with $\sqrt{s} = 0.5 - 1$ TeV is highest priority project for HEP beyond LHC! Why?

- 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)!

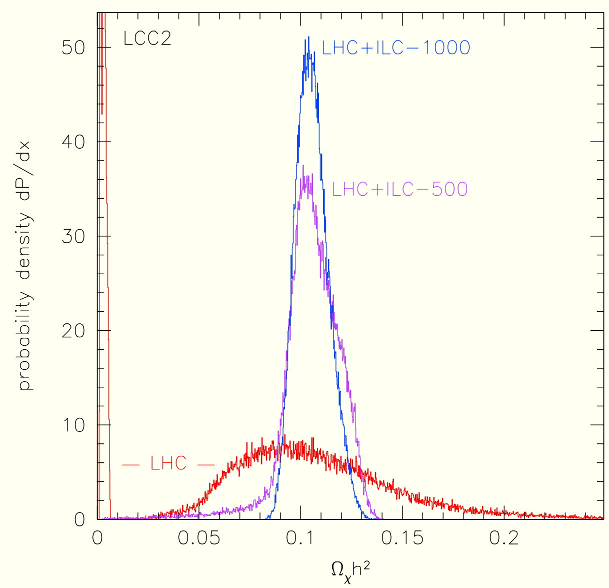
★ timeline: decision-2012; ready-2020

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



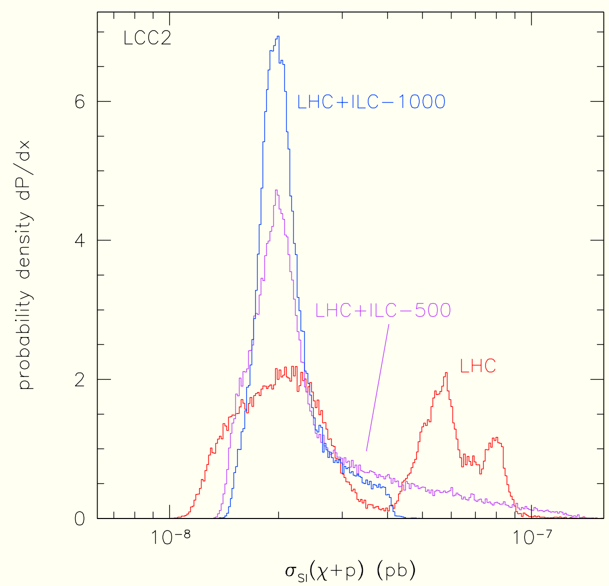
Role of ILC in DM physics

- 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?



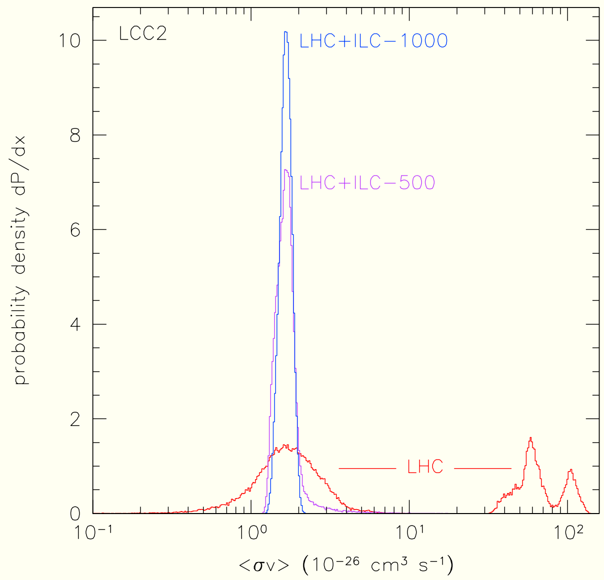
Also determine $\sigma_{SI}(\widetilde{Z}_1 p)$

- use to extract local DM density

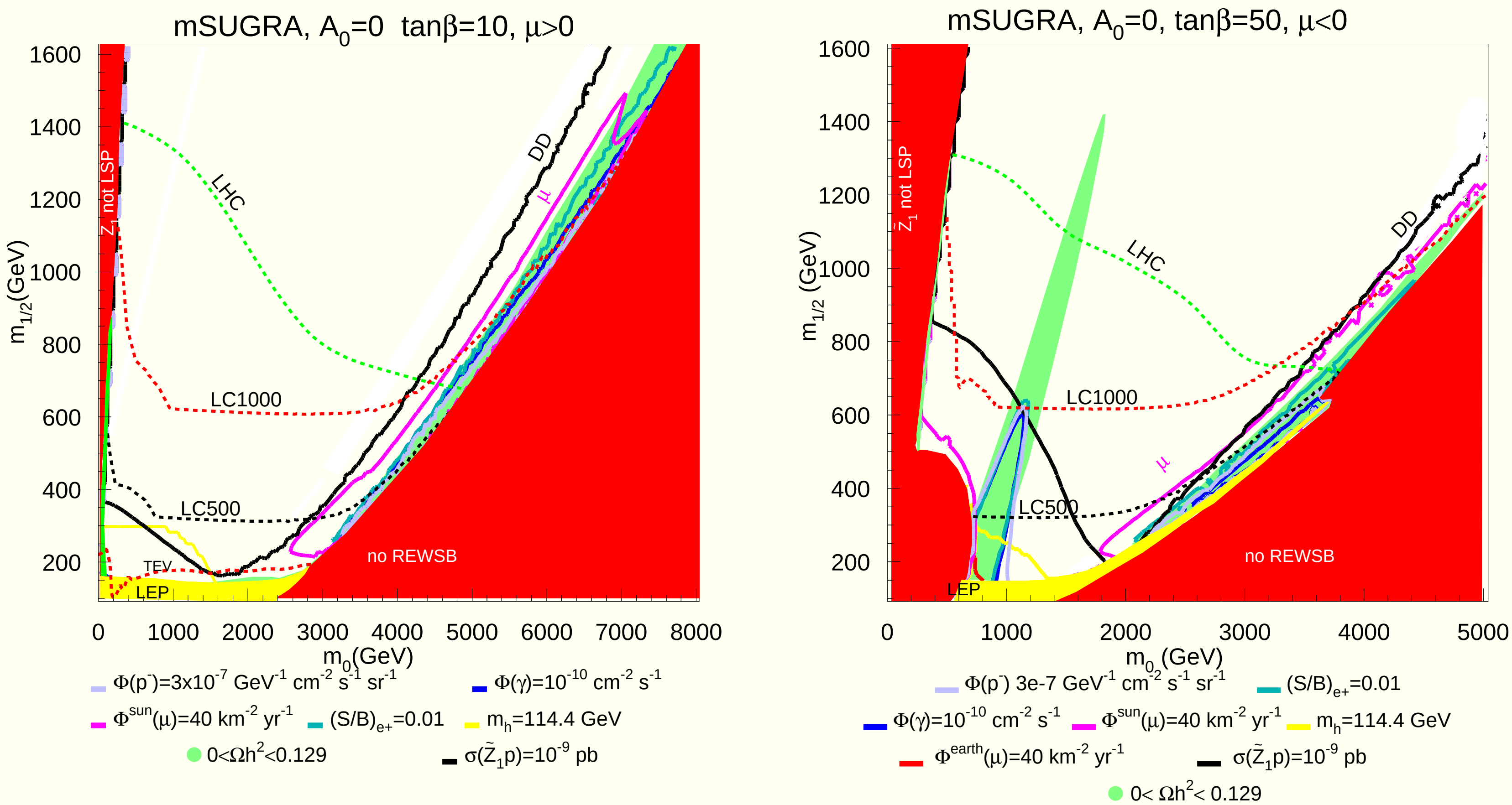


Also determine $\langle\sigma v\rangle$

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



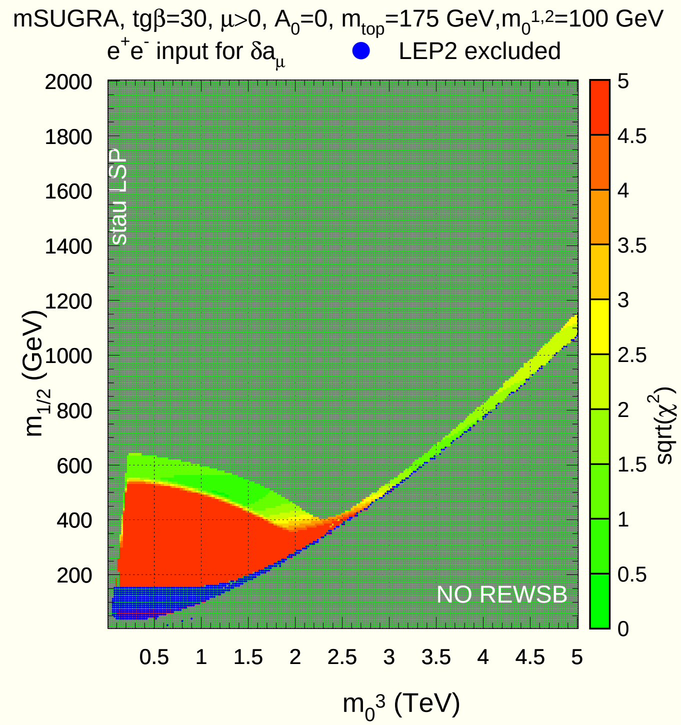
Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

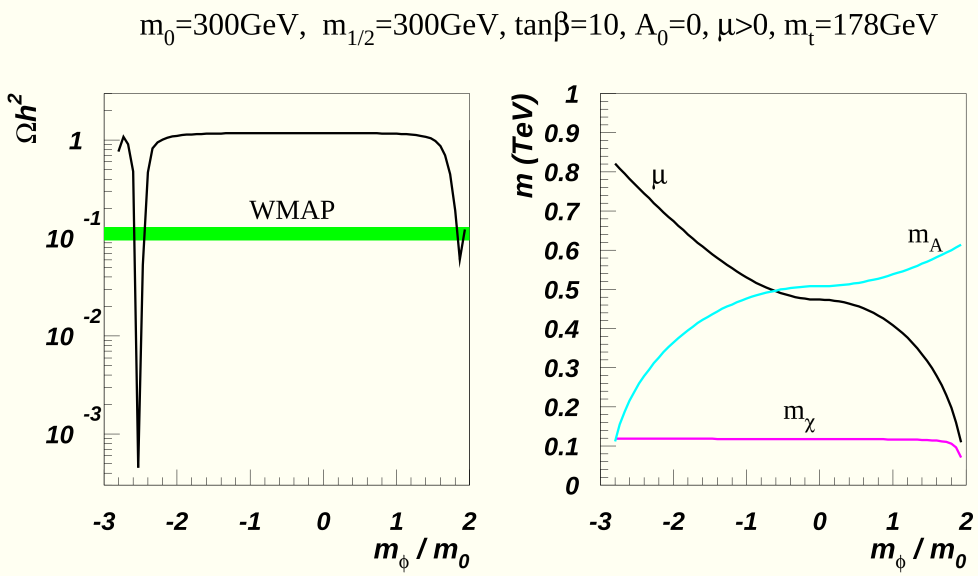
SUGRA models with non-universal scalars

- 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



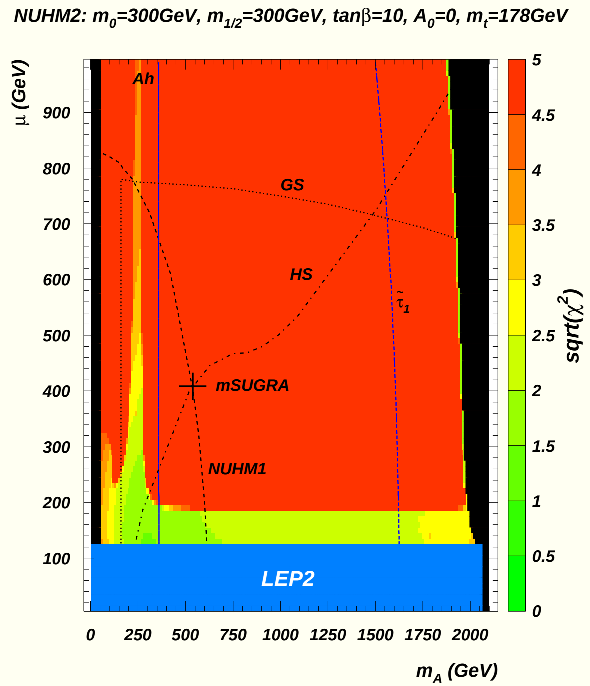
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: 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 $\tan\beta$



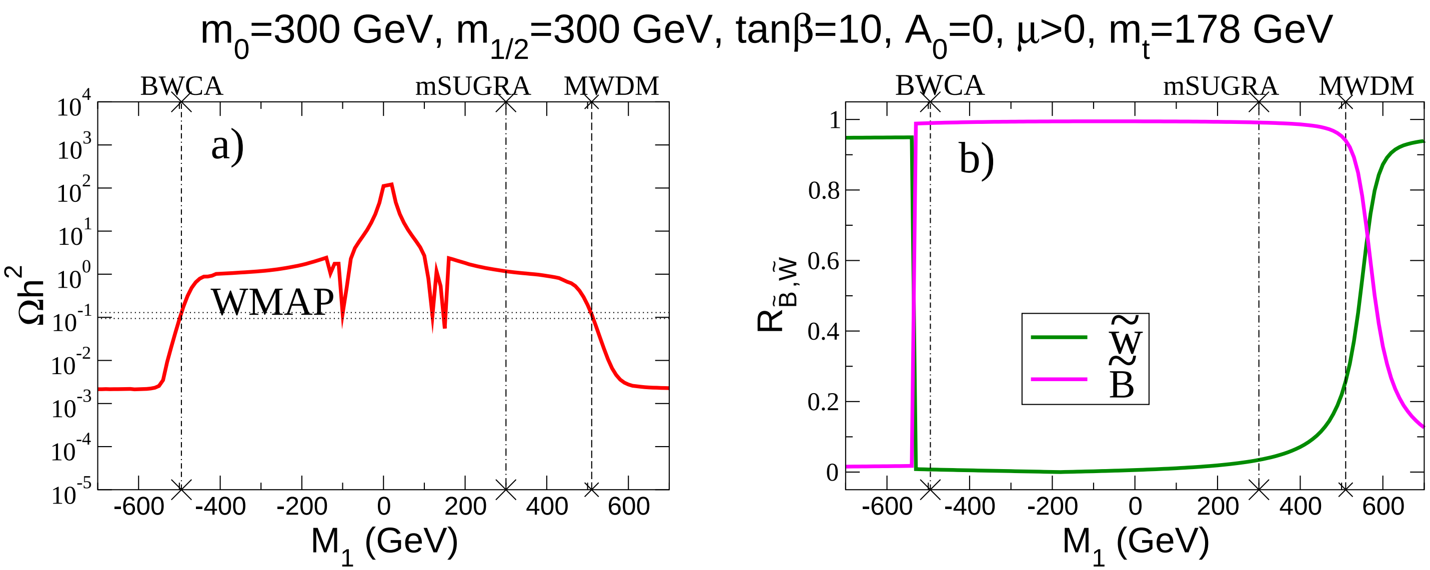
NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: 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, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



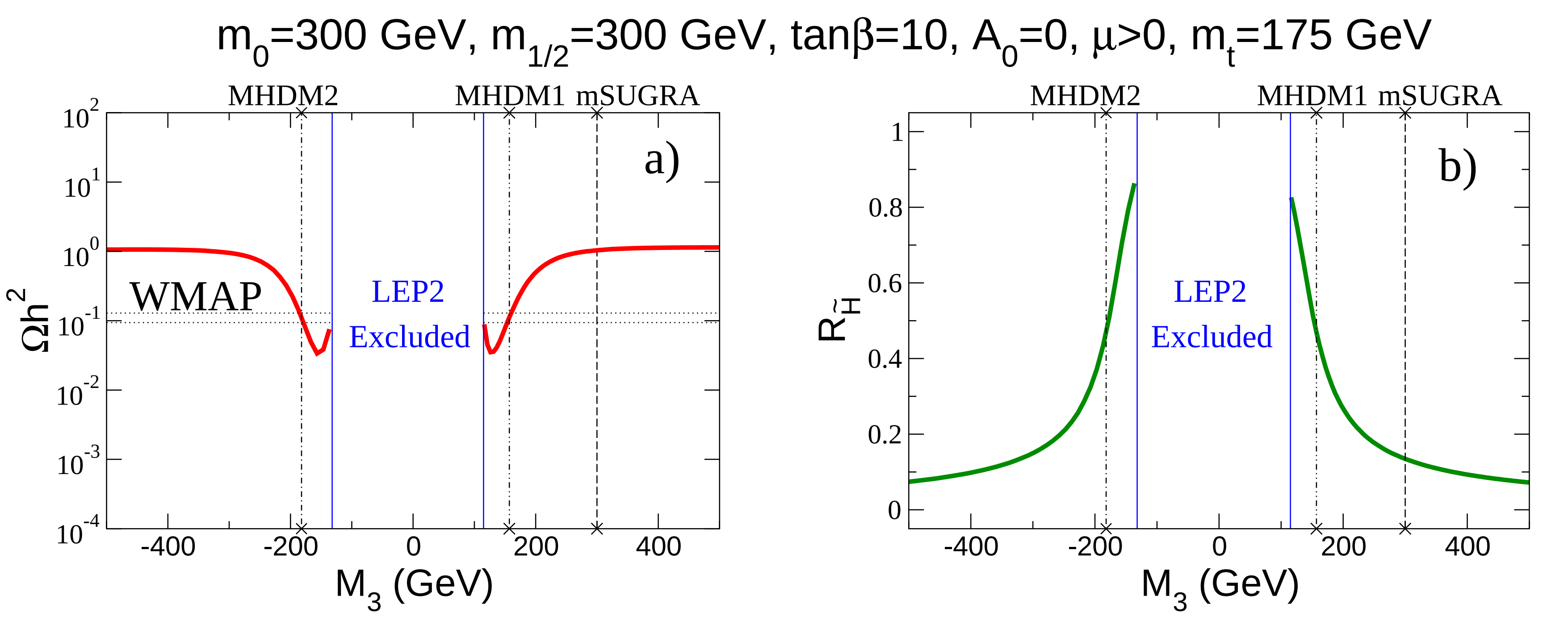
Gaugino mass non-universality

- $M_1 \neq M_2 \neq M_3$: 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)



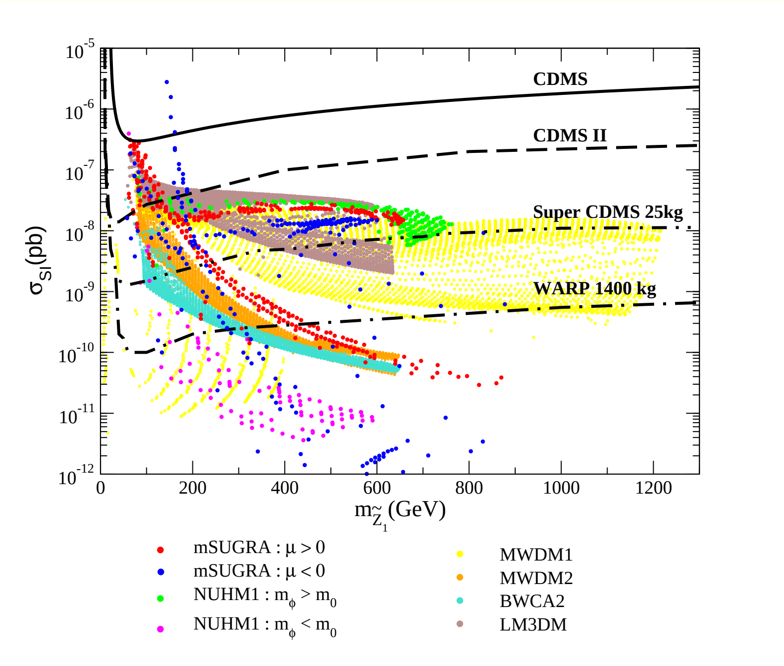
Gaugino mass non-universality: low M_3 case

- $M_3 < M_1 \sim M_2$: 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*



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



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
- ⋆ Numerous candidate CDM particles
  - Axions: searches ongoing (ADMX group)
- ⋆ WIMPs: thermal relic from Big Bang
- ⋆ SUSY is favored WIMP candidate, but must test
- ⋆ Direct/ indirect DM detection prospects
- ⋆ Detection at colliders: Tevatron, LHC, ILC
- ⋆ Beyond mSUGRA:
  - normal mass hierarchy, NUHM1, NUHM2 models
  - gaugino mass non-universality: MWDM, BWCA, low M_3
- ⋆ SuperWIMPs: $\tilde{G}$ in SUSY; G in UED