LHC and the Cosmos

Dark Matter Searches

and

Dark Matter Reconstruction

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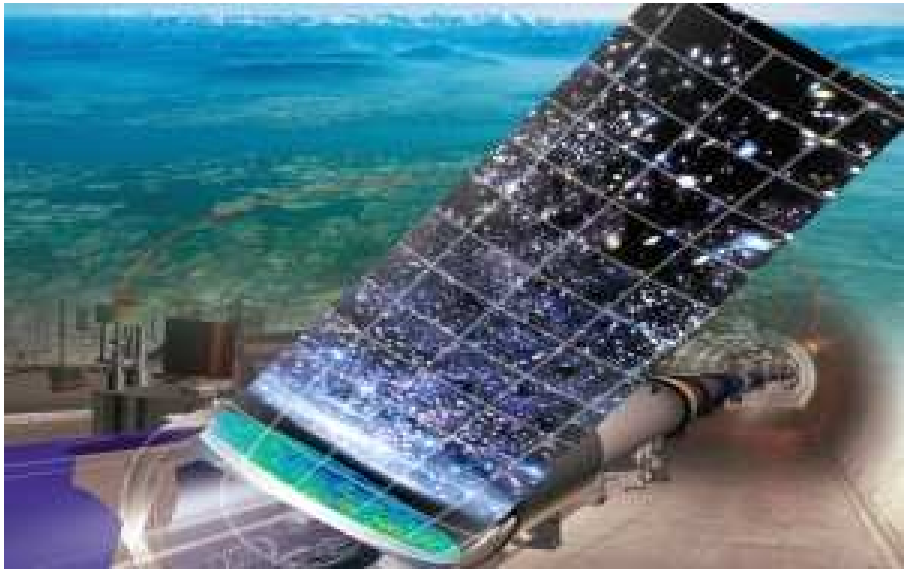
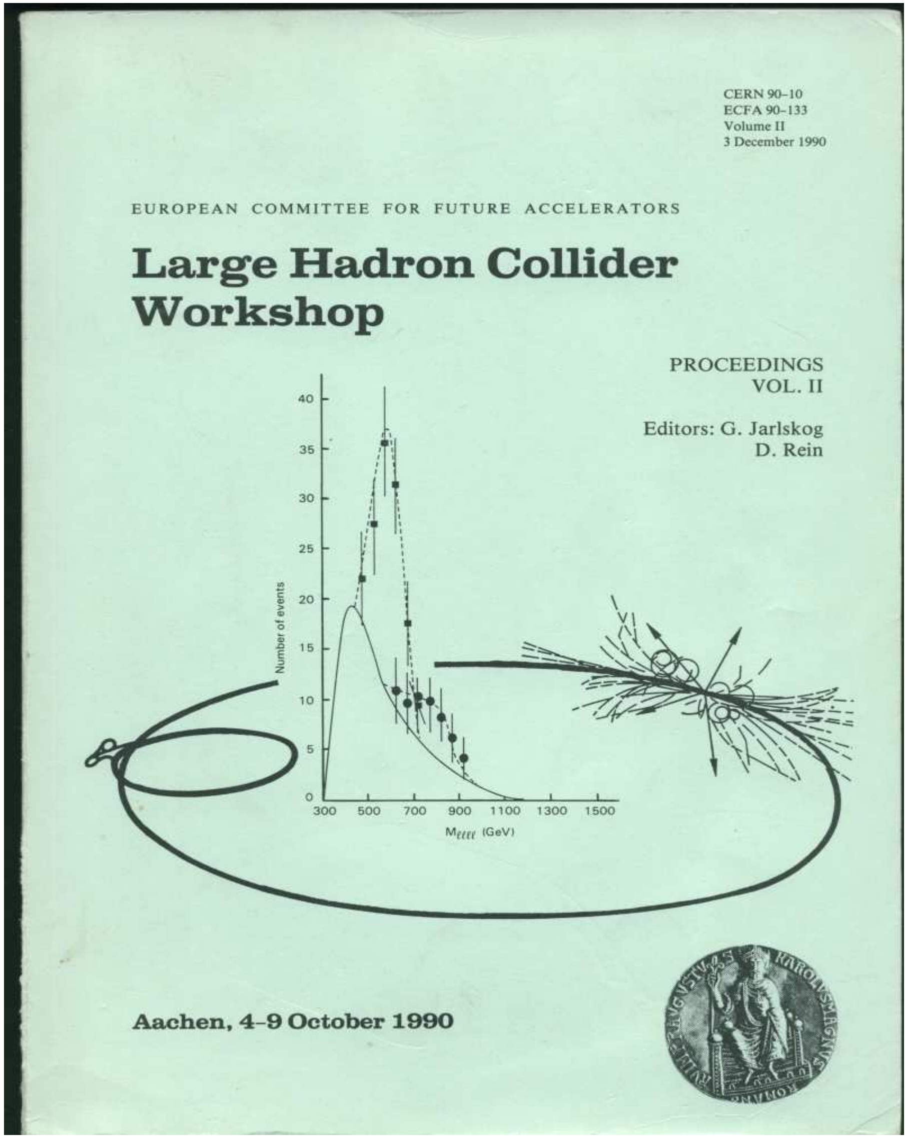
LHC Dark Matter Connection



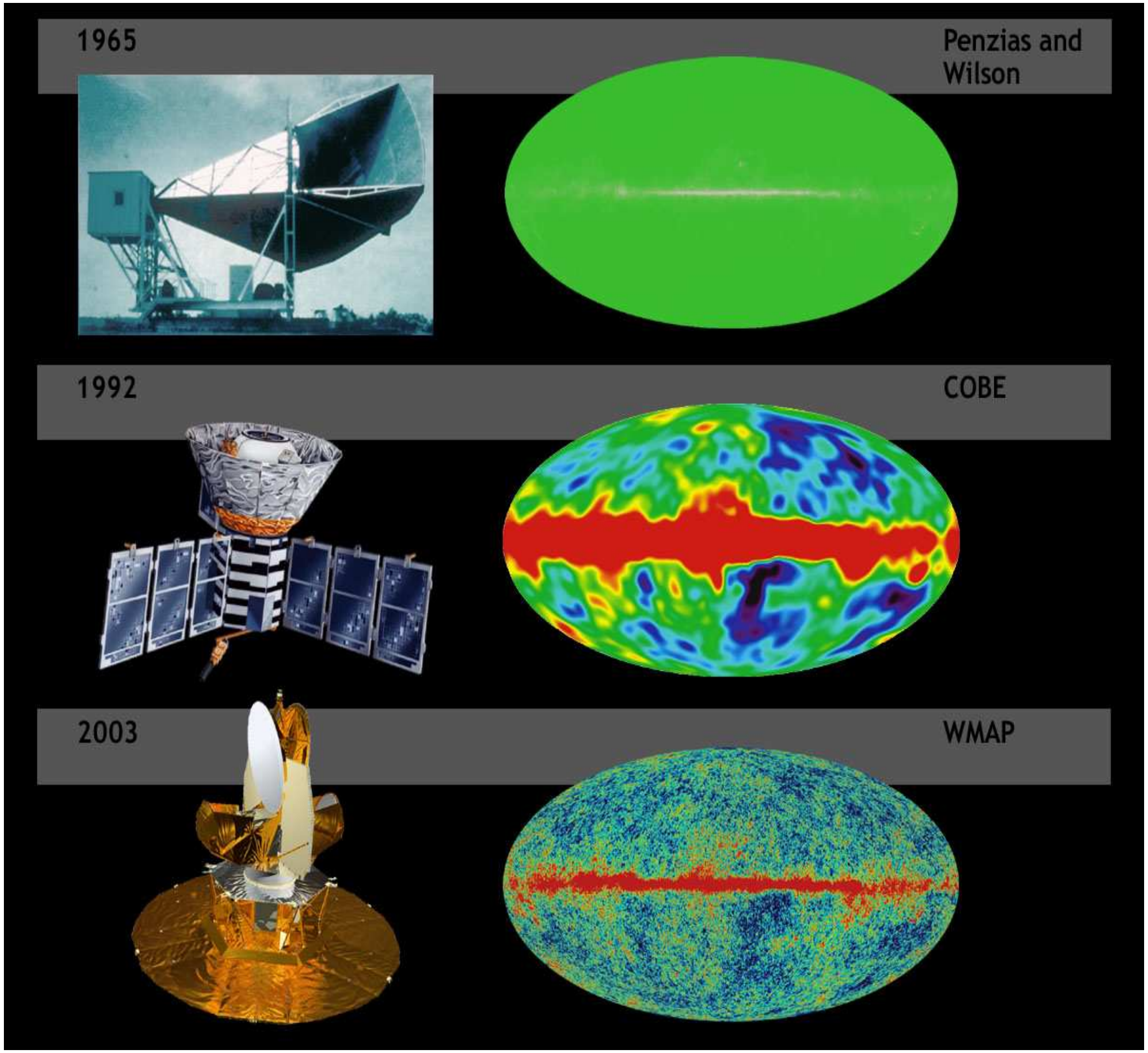


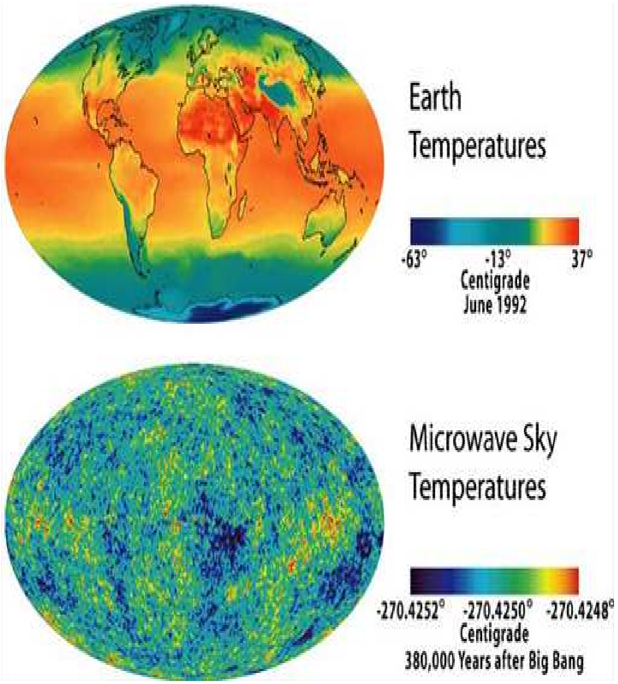
no mention of a connection, despite a SUSY WG

mention of LSP to be stable/neutral because of cosmo reason

LHC: Symmetry breaking and Higgs

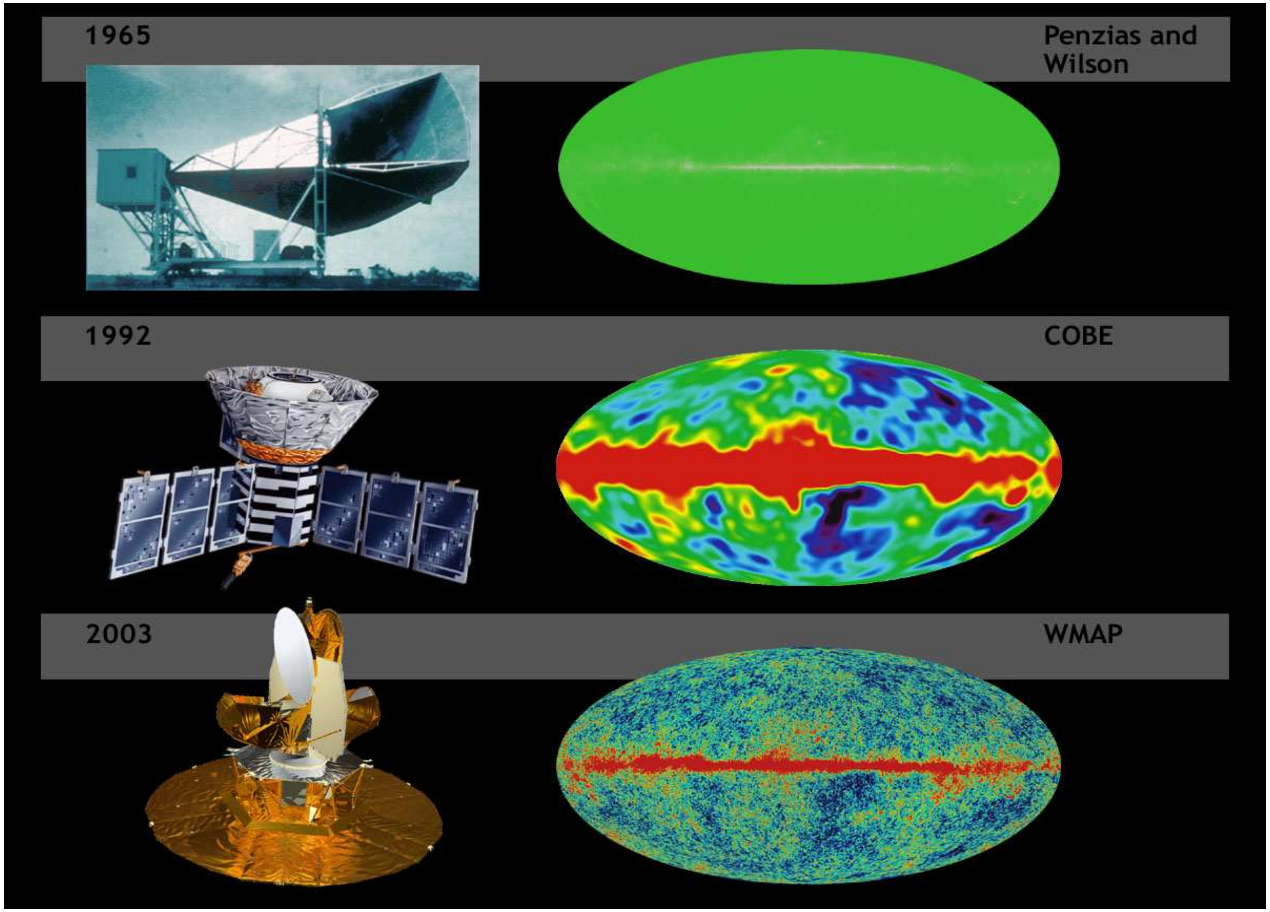
The new paradigm why? Cosmology in the era of precision





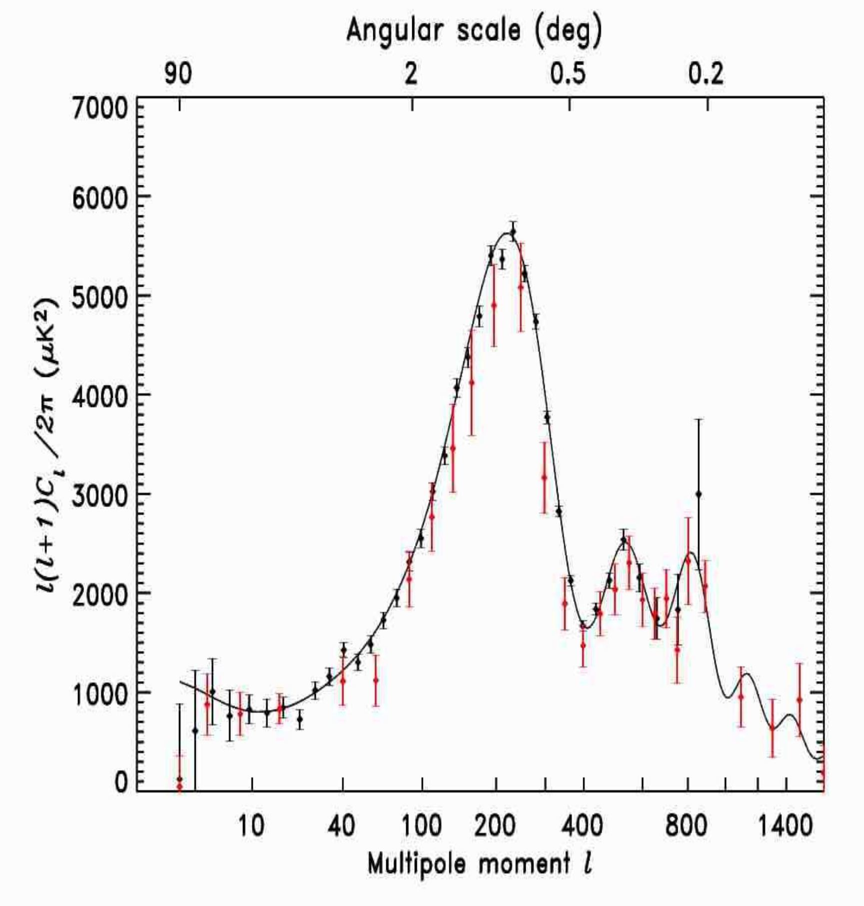
observed temperature anisotropies (related to the density fluctuations at the time of emission) is 10^{-5}

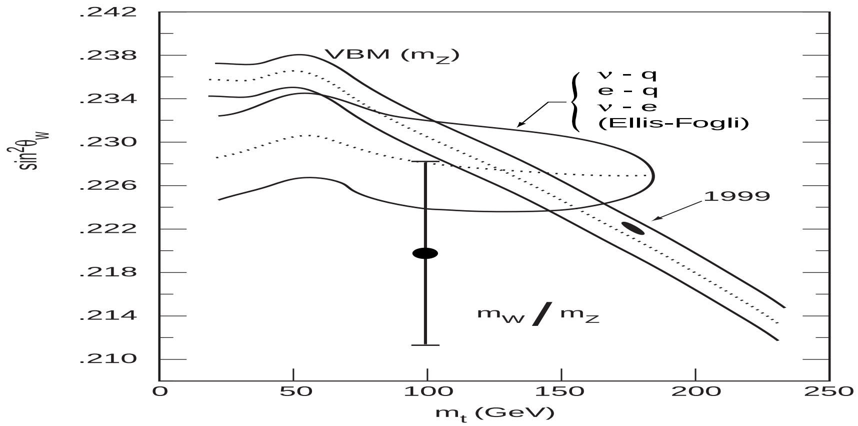
Cosmology in the era of precision measurement 1.

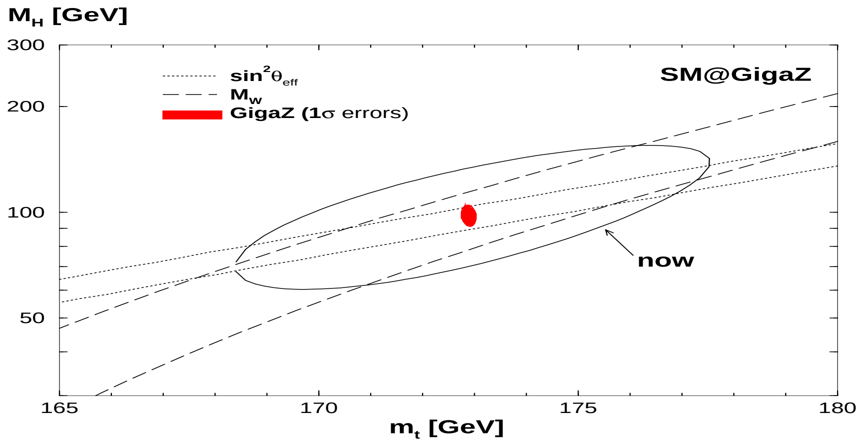


Pre-WMAP and WMAP vs Pre-LEP and LEP

Cosmology in the era of precision measurement 2.





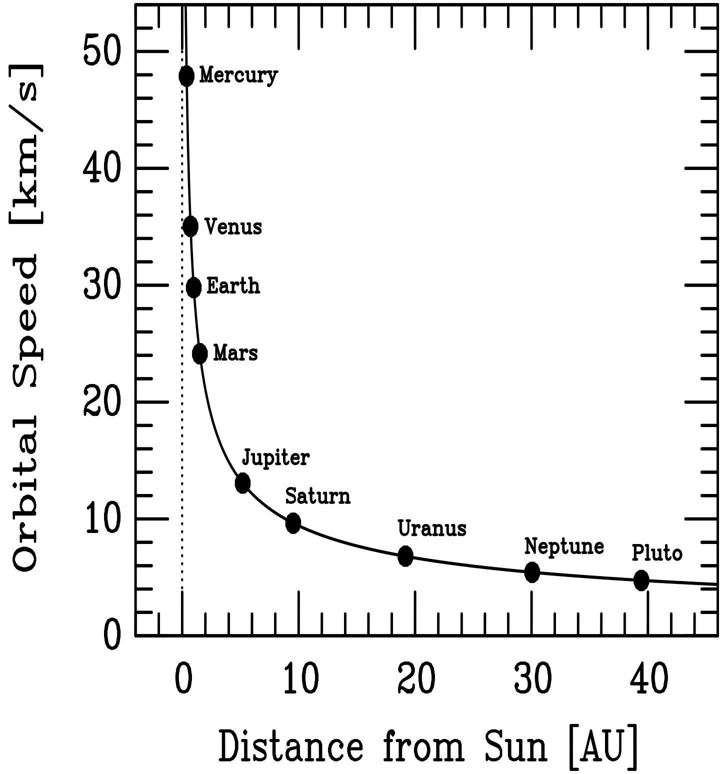


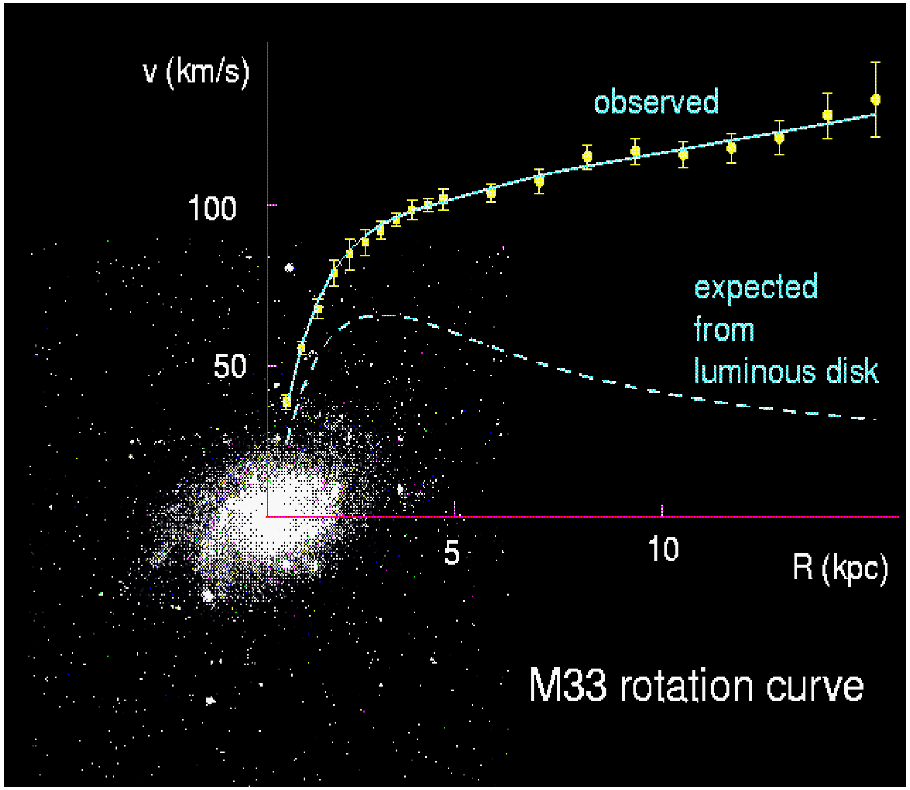
angular power spectrum of the CMB, pre-WMAP and WMAP

Planck+SNAP will do even better (per-cent precision) like from LEP to LHC+LC

The need for Dark Matter

Newton's law $\longrightarrow$ $v^2_{\mathrm{rot.}}/r = G_N M(r)/r^2$ (tracer star at a distance r from centre of mass distribution)



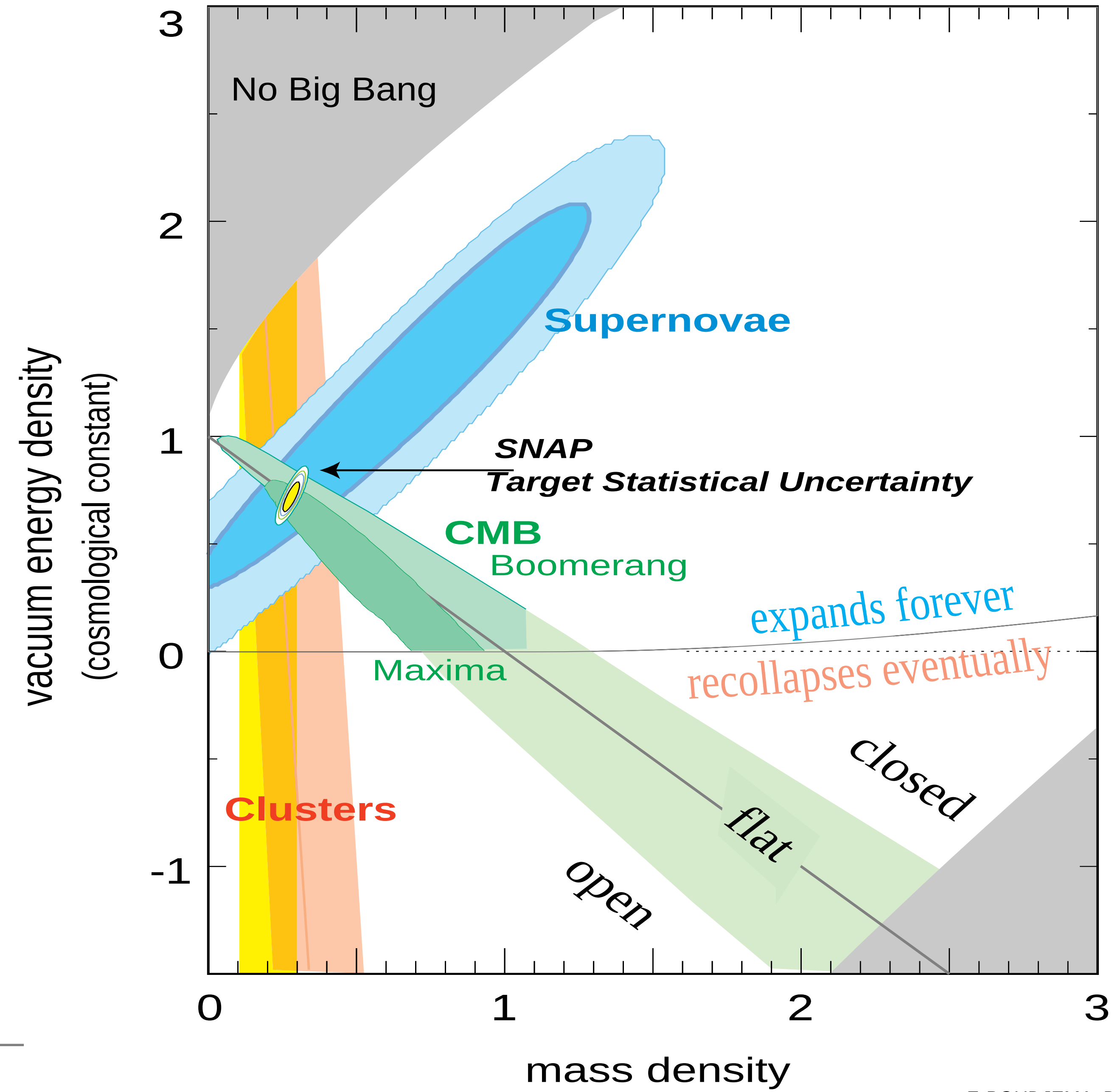


We are not in the centre of the universe

Dark Matter= New Physics

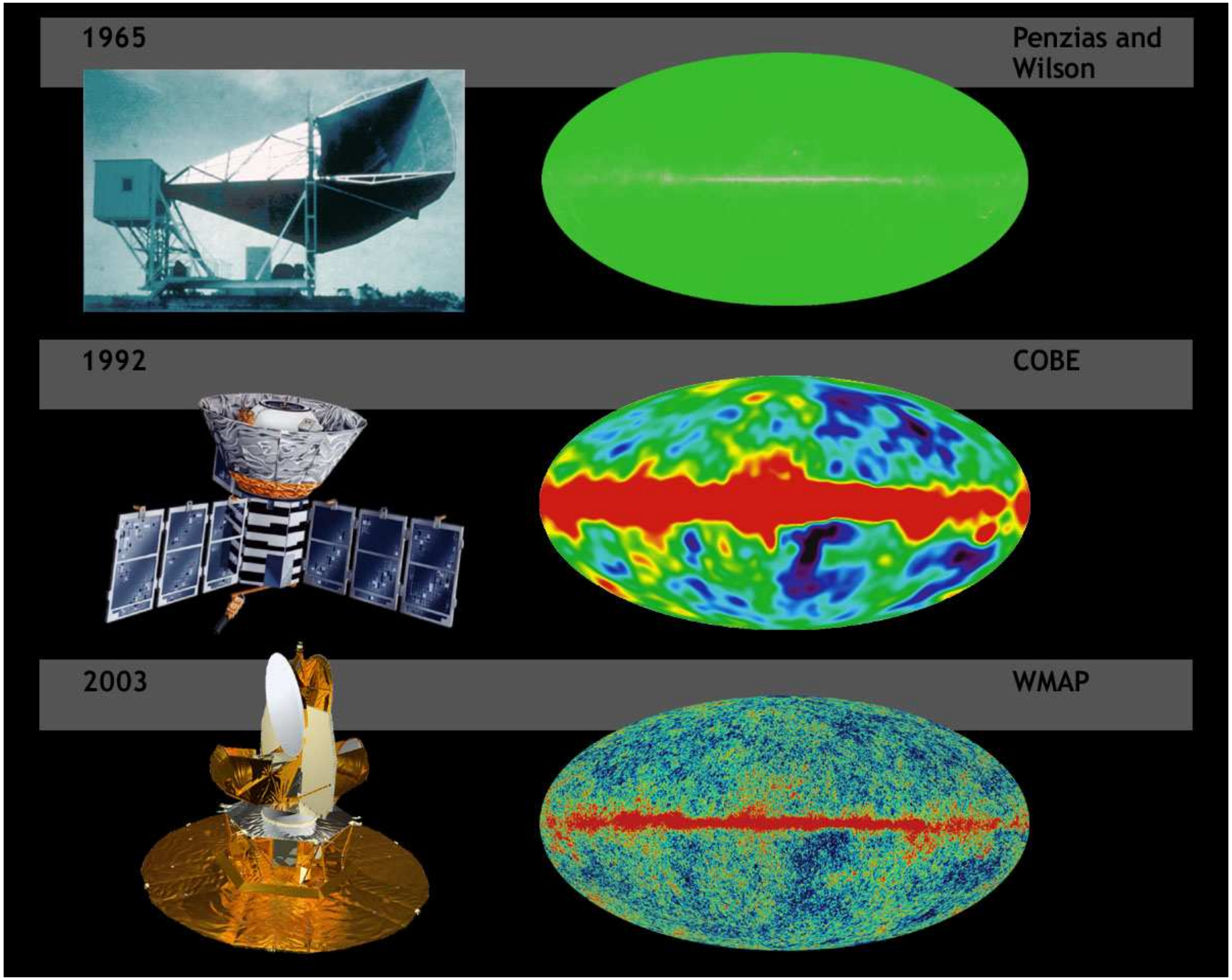
we are not made up of the same stuff as most of our universe

Cosmology in the era of precision measurement I: standard candles



observed luminosity and red-shift exploits the different z dependence of matter/energy density

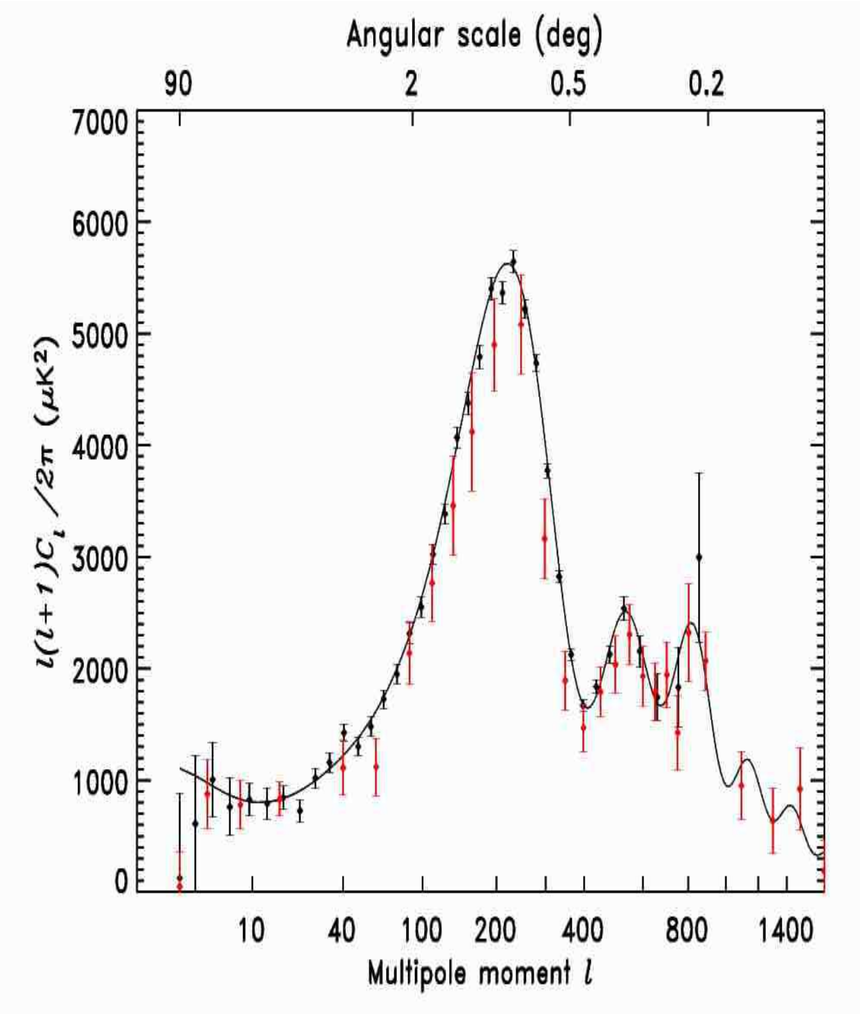
Cosmology in the era of precision measurement II: CMB

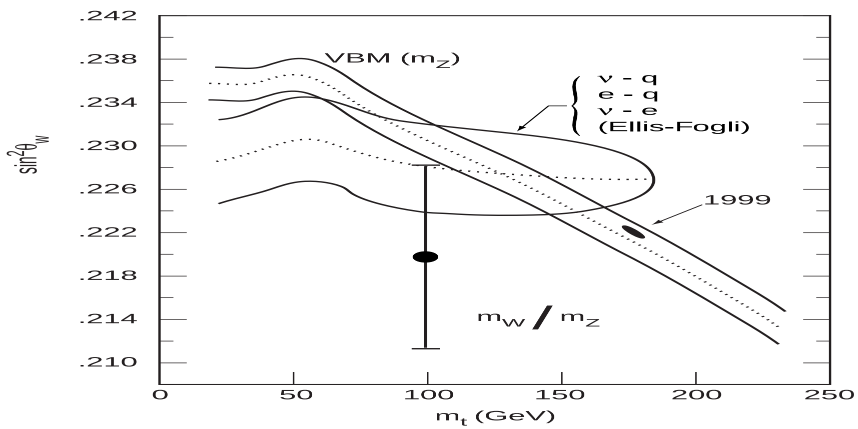


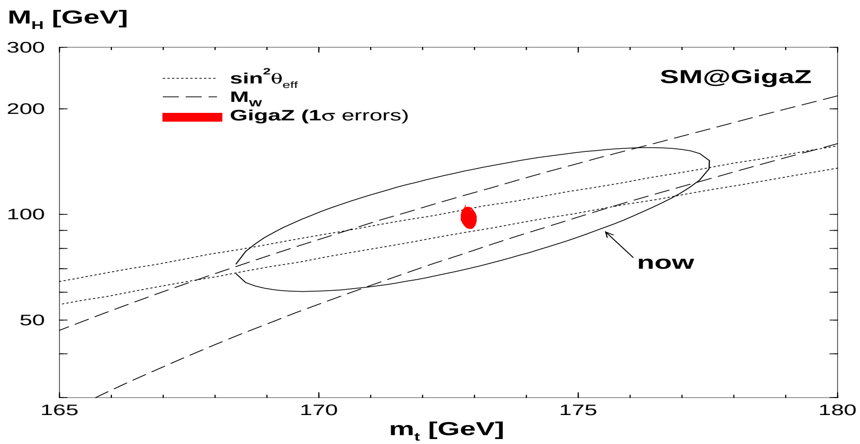
observed temperature anisotropies (related to the density fluctuations at the time of emission) is 10^{-5}

Pre-WMAP and WMAP vs Pre-LEP and LEP

power spectrum of anisotropies, WMAP vs Pre-WMAP



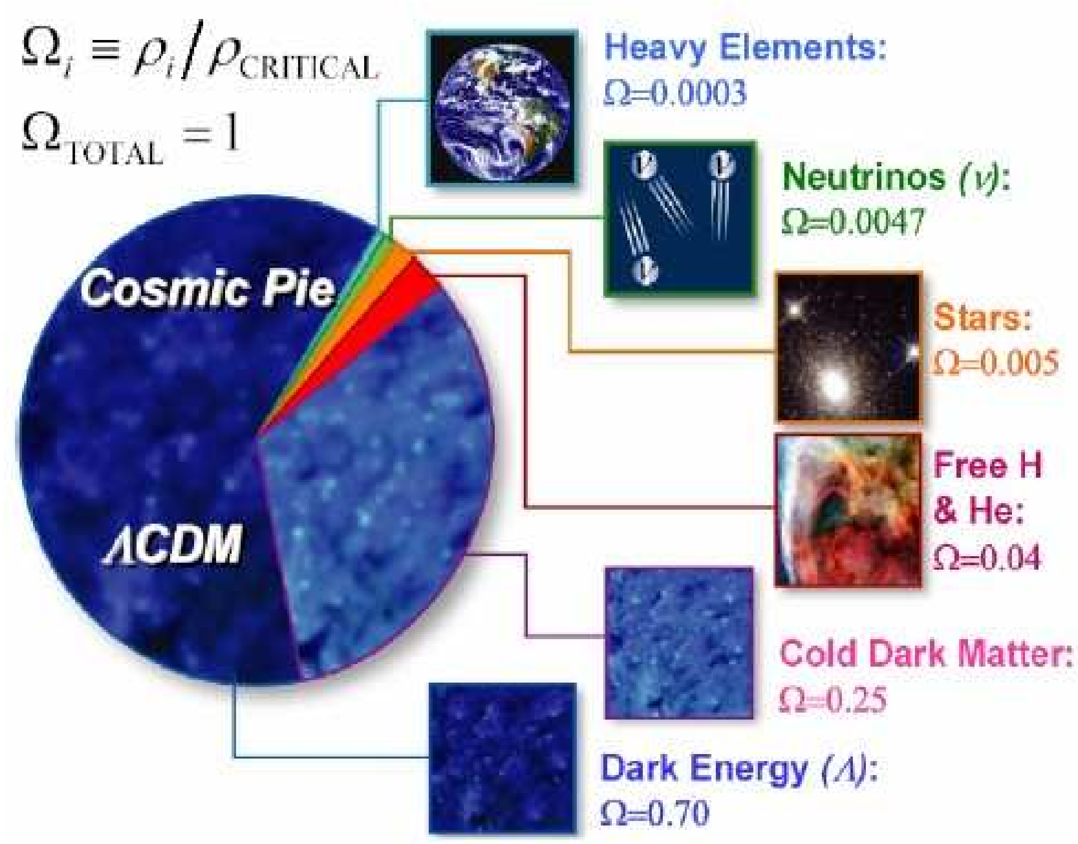




Planck+SNAP will do even better (per-cent precision)

improvement like going from LEP to LHC+ILC

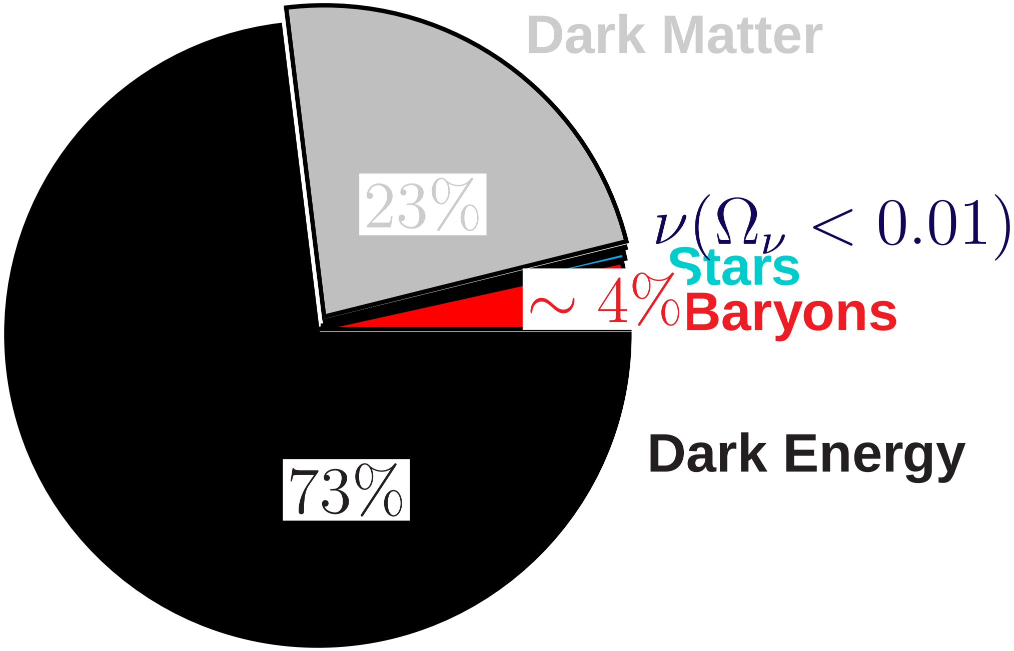
LHC, PLanck ⟶ 2007 ILC,SNAP ⟶ 2015



$\sim 10^{28}$ cm

(Cf. 1998: $\Omega_\Lambda = 0$? $\Omega_{CDM} = 0.2 - 0.6$)

Matter Budget and Precision 2.



$t_0 = 13.7 \pm 0.2$ Gyr (1.5%)	$\alpha^{-1} = 10 t_0 (10^{-7}\%)$
$\Omega_{tot} = 1.02 \pm 0.02 (2\%)$	$\rho = \Omega_{tot} (\sim 0.1\%)$
$\Omega_{DM} = 0.23 \pm 0.04 (17\%)$	$\sin^2\theta_{eff} = \Omega_{DM} (0.08\%)$

We should then be able to match the present WMAP precision!...

once we discover susy dark matter

Matter Budget and Precision 3. Testing the cosmology

Present measurement at 2σ $\boxed{0.0975 < \omega = \Omega_{\rm DM}h^2 < 0.1223}$ **(6%)**

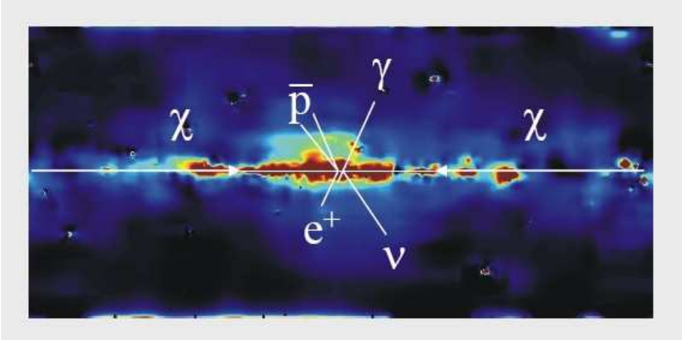
future (SNAP+Planck) $\rightarrow < 1\%$

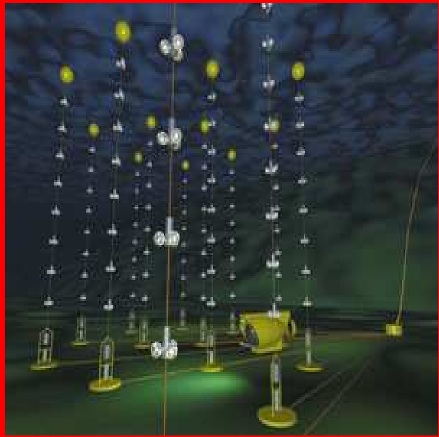
Particle Physics $\leftrightarrow$Cosmology through ω

- is wholly New Physics
- But will LHC, ILC see the "same" New Physics?
- New paradigm and new precision: change in perception about this connection
- ω used to: constrain new physics (choice of LHC susy points, benchmarks)
- Now: if New Physics is found, what precision do we require on colliders and theory to constrain cosmology? (Allanach, Belanger, FB, Pukhov JHEP 2004)

strategy/requirements on theory and collider measurements to match the present/future precision on ω

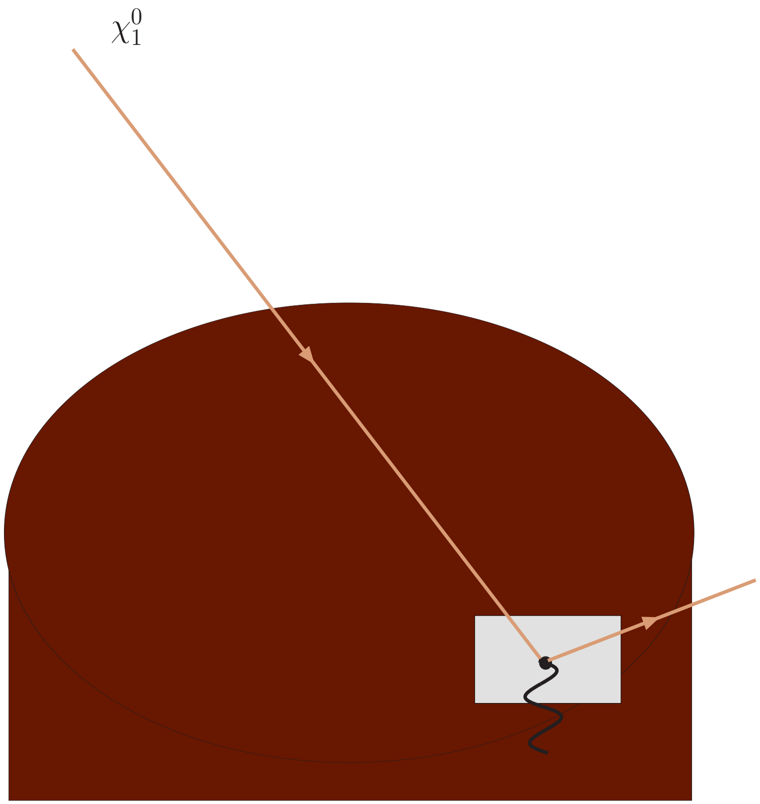
Indirect Detection

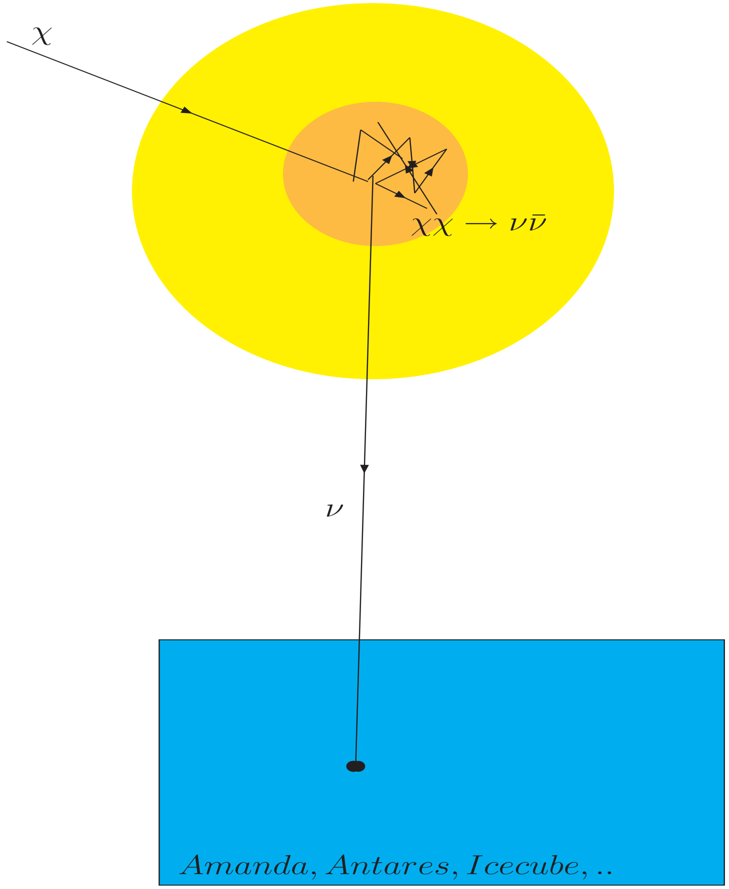




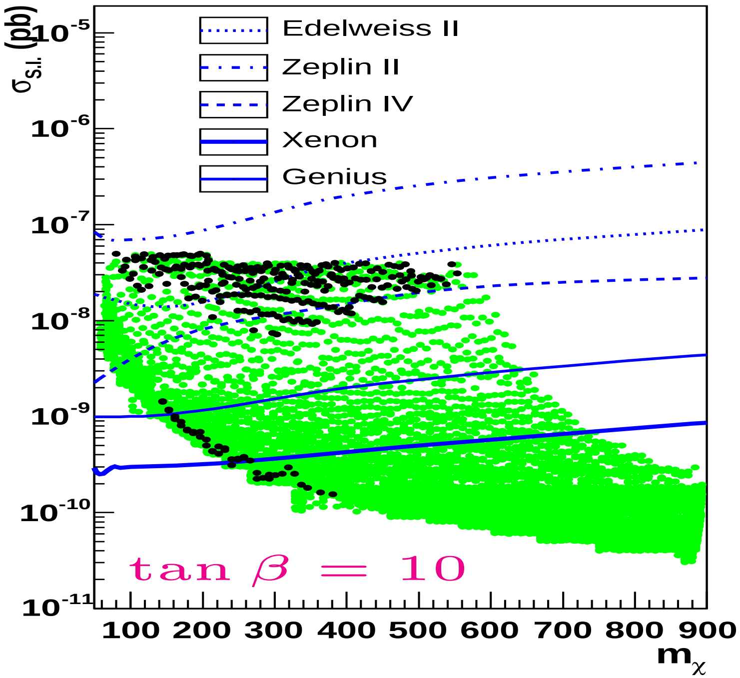
Direct and Indirect Searches

$$\bar{p},\ e^{+},\ \gamma,\ \nu, \ldots$$

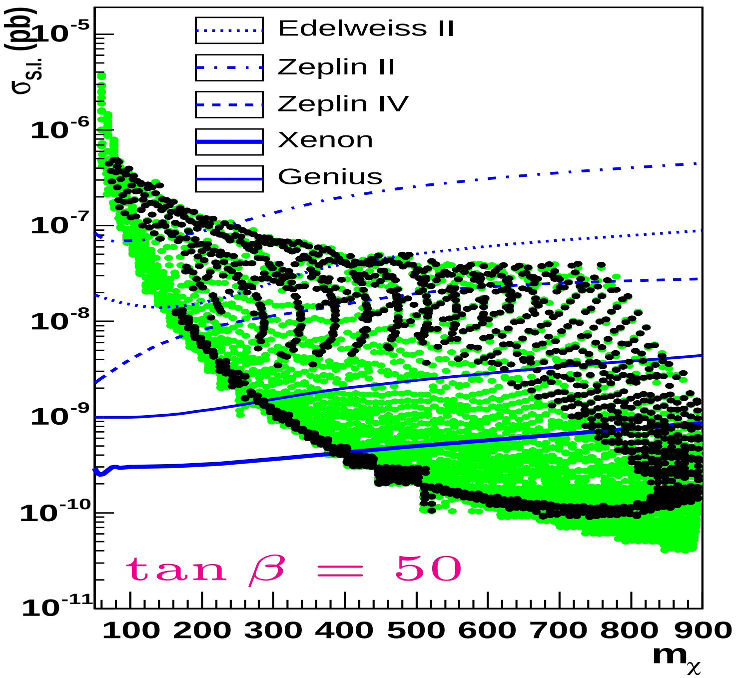




- within WMAP



$\sigma_{S.I.}$ (pb)
Edelweiss II
Zeplin II
Zeplin IV
Xenon
Genius
tan β = 10
m_χ



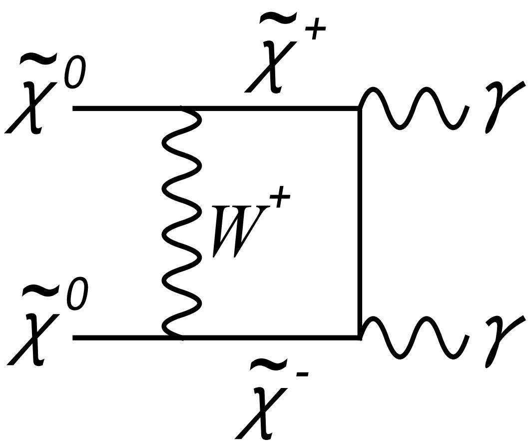
$\sigma_{S.I.}$ (pb)
Edelweiss II
Zeplin II
Zeplin IV
Xenon
Genius
tan β = 50
m_χ

Annihilation into photons

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE_\gamma}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Physique des Particules}} \underbrace{\int \rho^2 dl}_{\text{Astro}}$$

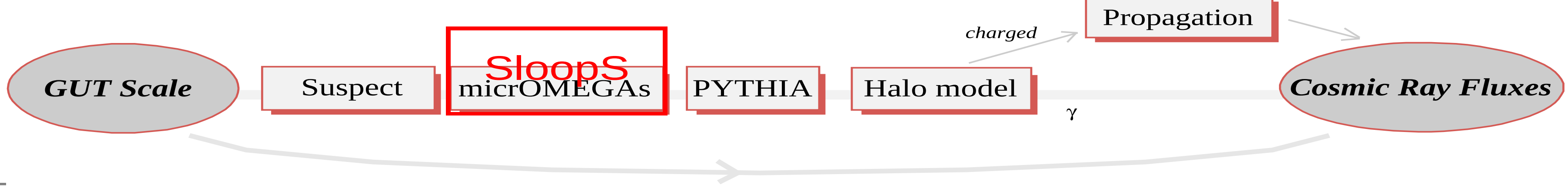
$\gamma's$: Point to the source, independent of propagation model(s)

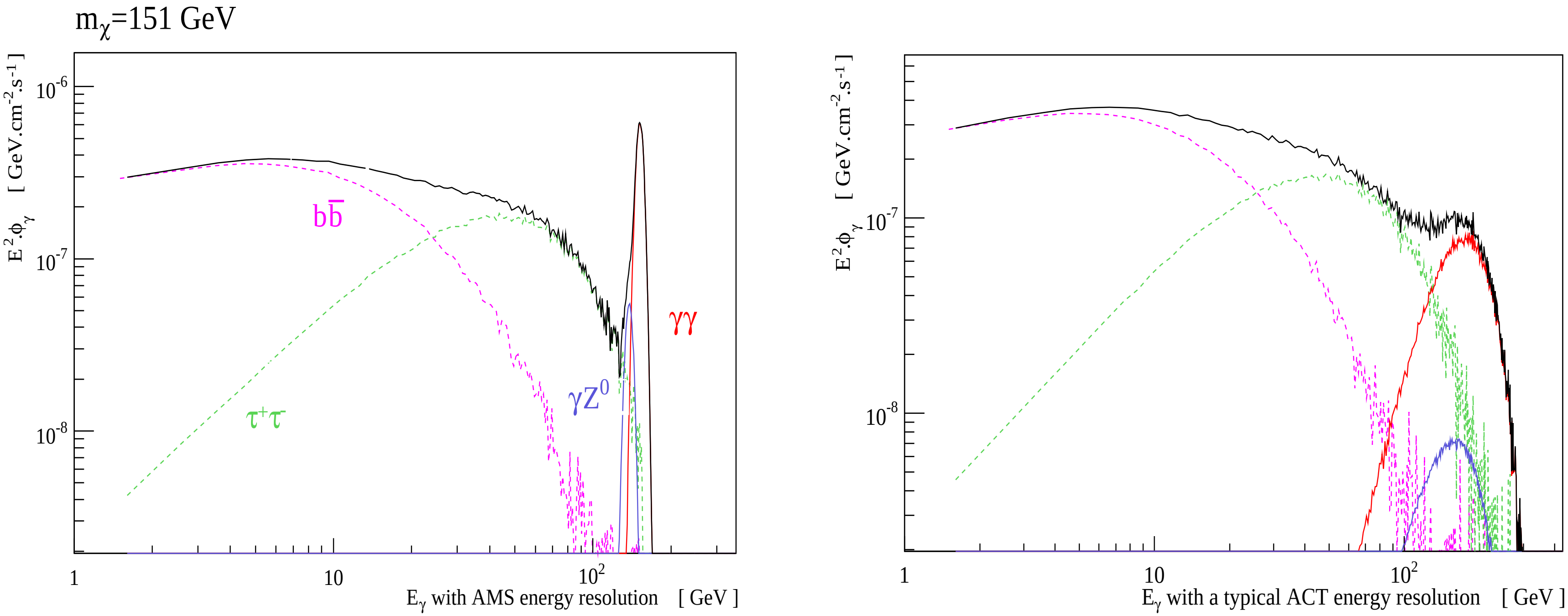
- continuum spectrum from $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow f\bar{f},\ldots,$ hadronisation/fragmentation ($\rightarrow \pi^0 \rightarrow \gamma$) done through isajet/herwig
- Loop induced mono energetic photons,$\gamma\gamma$, $Z\gamma$ final states



<u>ACT</u>: HESS, Magic, VERITAS, Cangoroo, ...

<u>Space-based</u>: AMS, GLAST, Egret,...





SIMULATION:

Parameterising the halo profile:

$(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$kpc. (core radius), $r_0 = 8kpc$ (distance to galactic centre), $\rho_0 = 0.3\,GeV/cm^3$ (DM density), opening angle cone 1^o

SUSY parameterisation

$m_0 = 113$GeV, $m_{1/2} = 375$ GeV, $A = 0$, $\tan\beta = 20$, $\mu > 0$

γ lines could be distinguished from diffuse background

Symmetry breaking and DM

- The SM Higgs naturalness problem has been behind the construction of many models of New Physics: at LHC not enough to see the Higgs need to address electroweak symmetry breaking
- DM is New Physics, most probable that the New Physics of EWSB provides DM candidate, especially that
- All models of NP can be made to have quite easily and naturally a conserved quantum number, Z_2 parity such that all the NP particles have $Z_2 = -1$ (odd) and the SM part. have it even
- Then the lightest New Physics particle is stable. If it is electrically neutral then can be a candidate for DM
- This conserved quantum number is not imposed just to have a DM candidate it has been imposed for the model to survive

Symmetry breaking and DM

- Survival

  evade proton decay

  indirect precision measurements (LEP legacy)

- Examples:

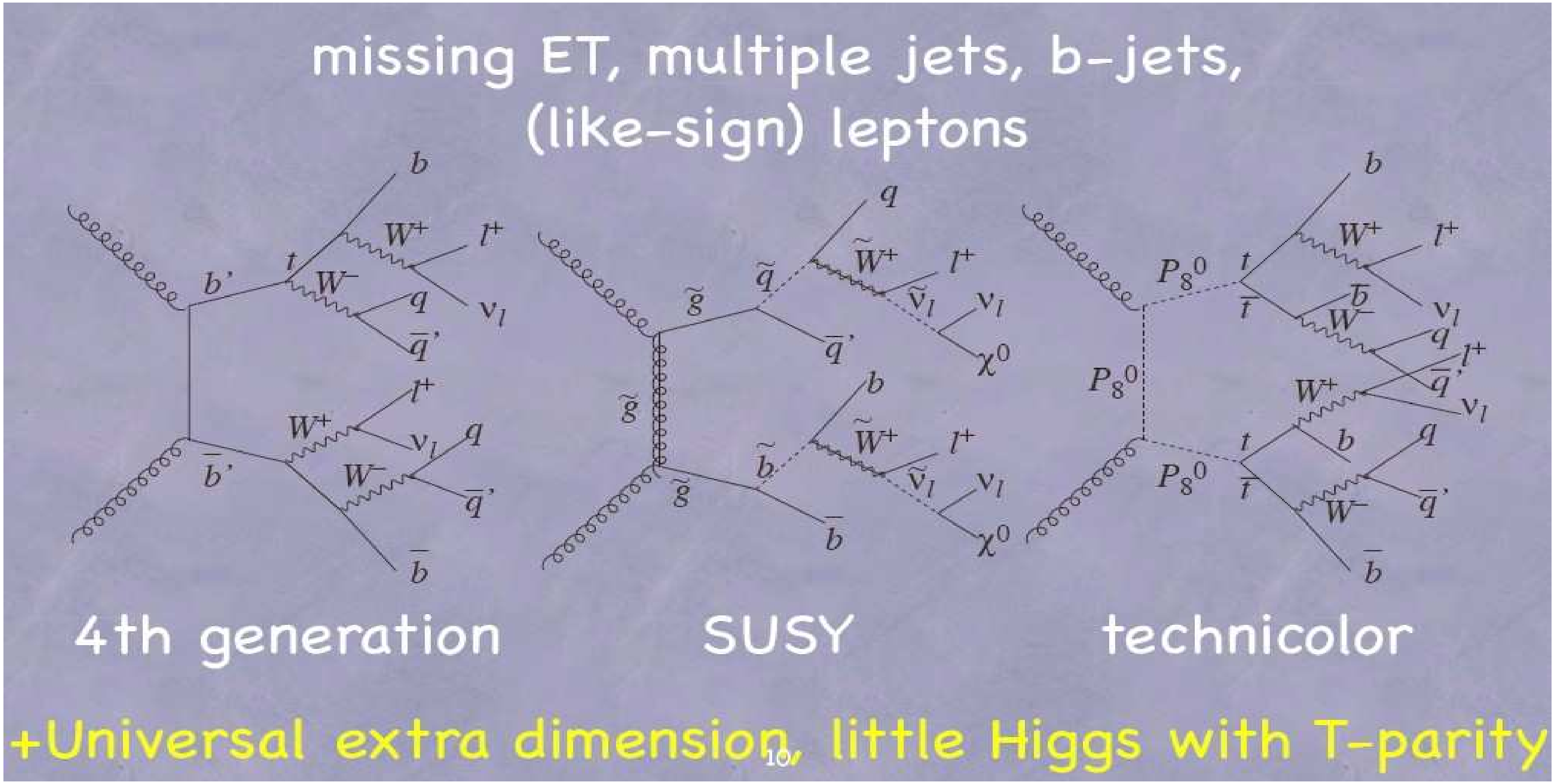
  R-parity and LSP in SUSY (majorana fermion)

  KK parity and the and LKP in UED (gauge boson)

  T-parity in Little Higgs with the LTP (gauge boson)

  LZP (warped GUTs) (actually it's a Z_3 here) (Dirac fermion)

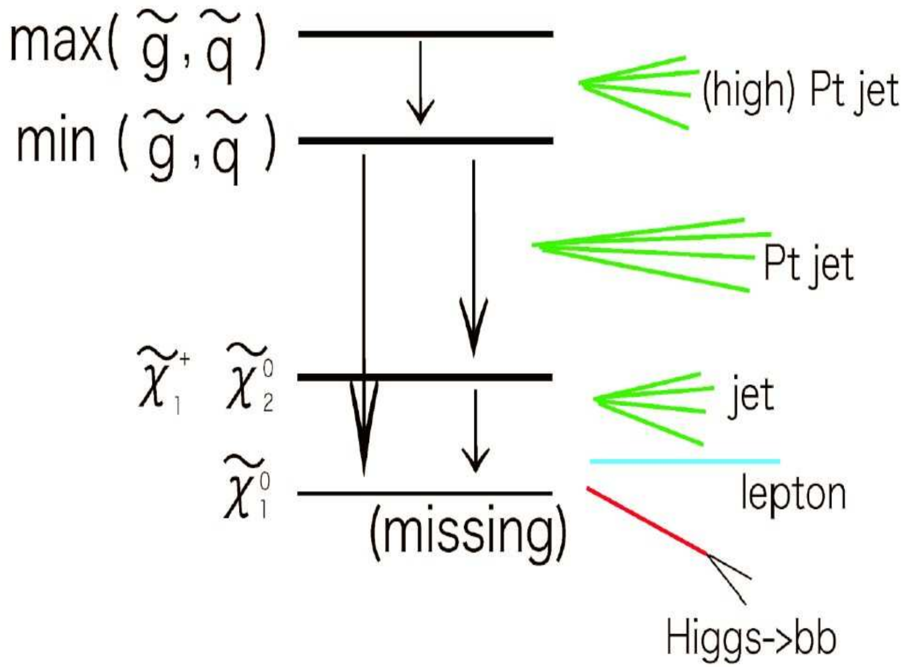
  even modern technicolour has a DM candidate



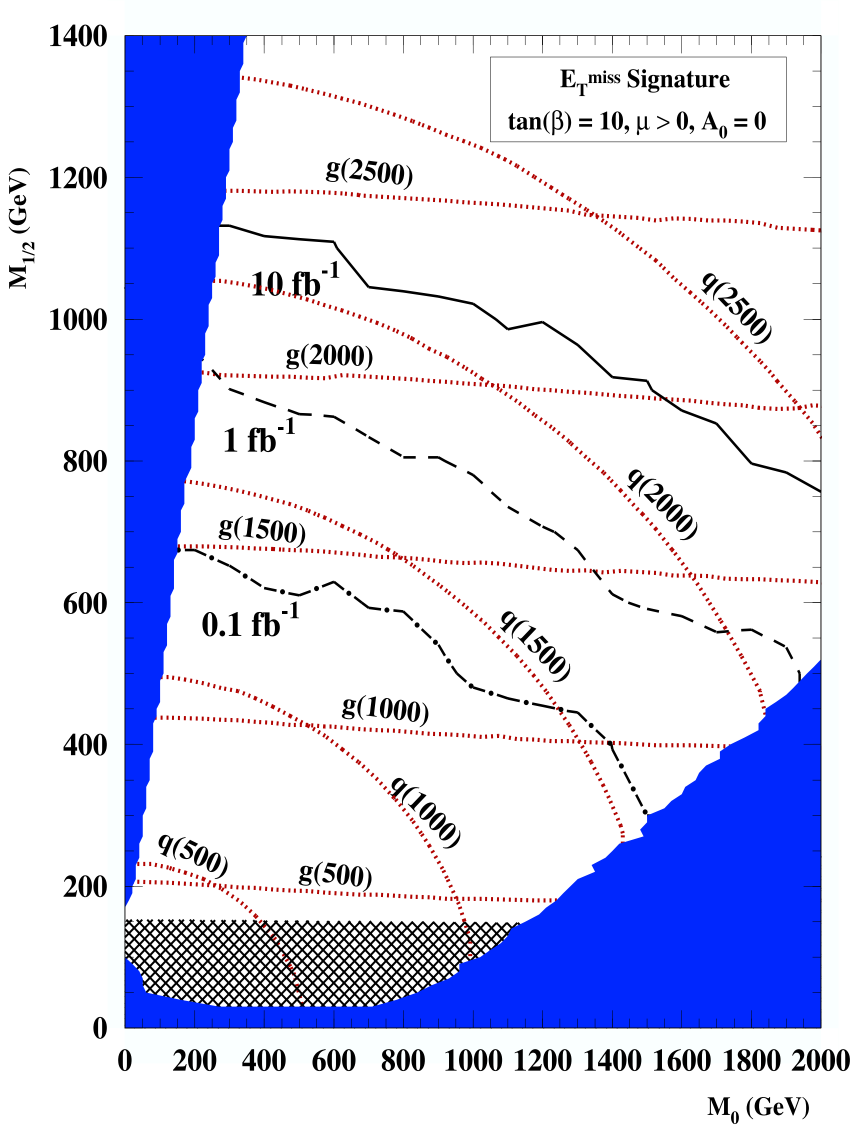
Is it necessarily DM candidate?

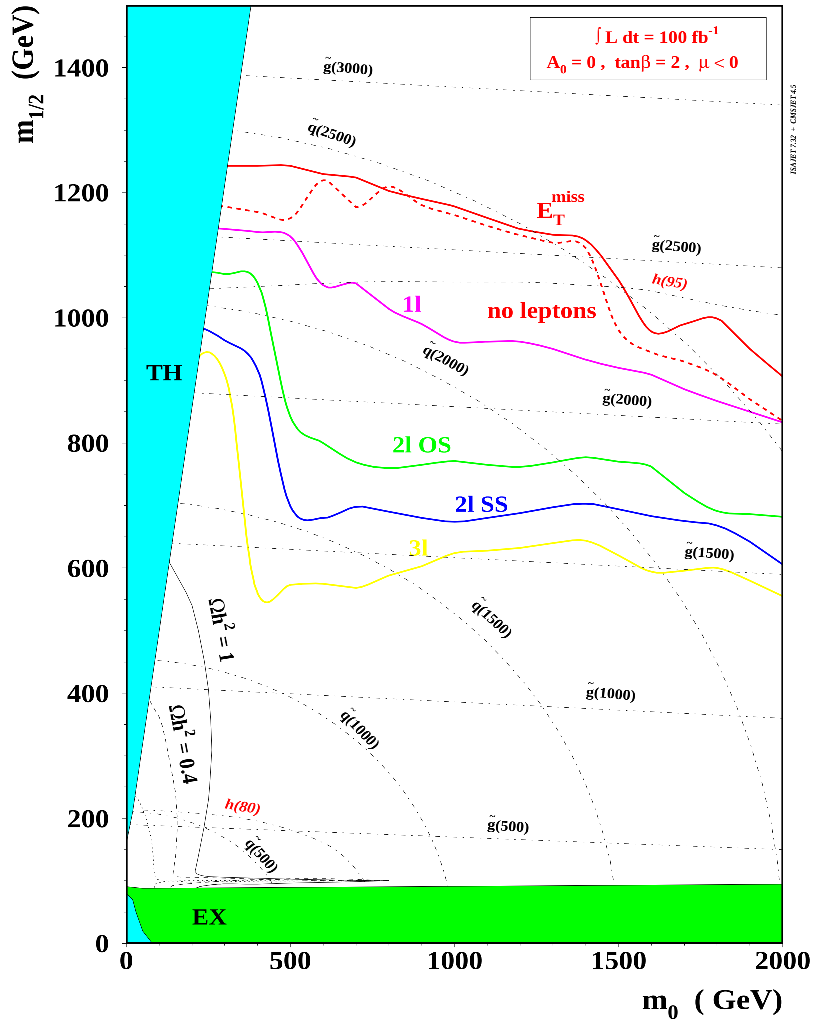
stable at the scale of LHC detectors, 1ms, not age of the Universe....

in 1998 we were told to expect an early SUSY discovery

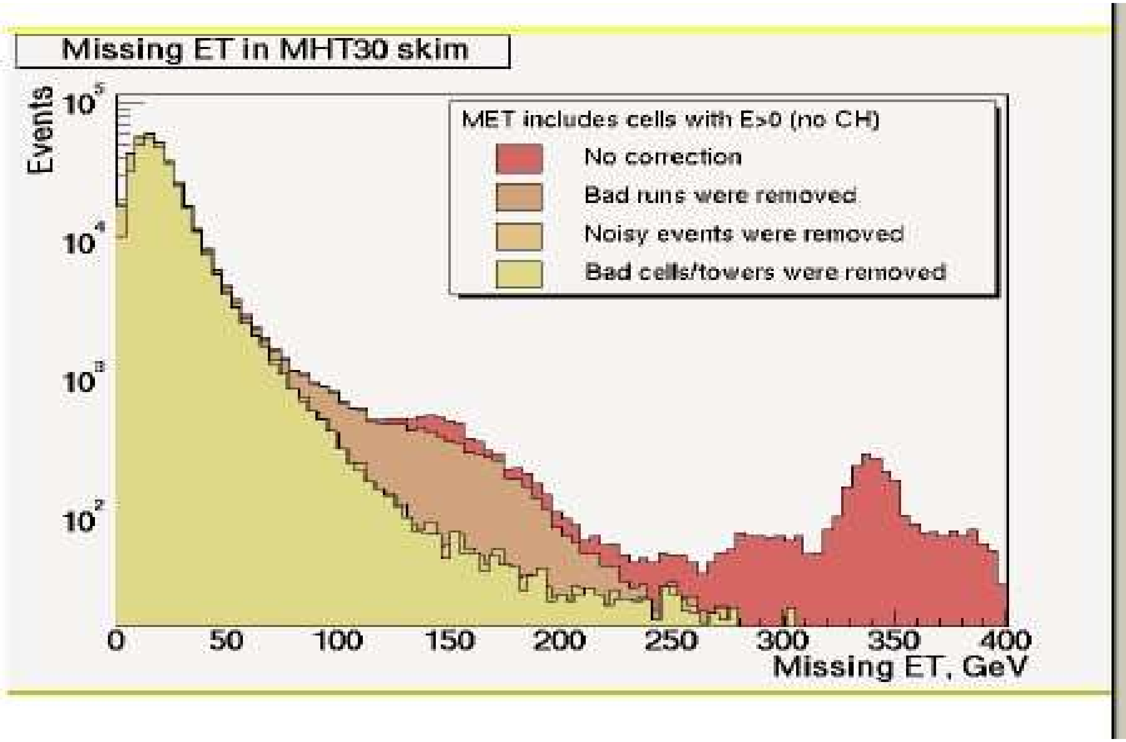


Discovery of miss Et





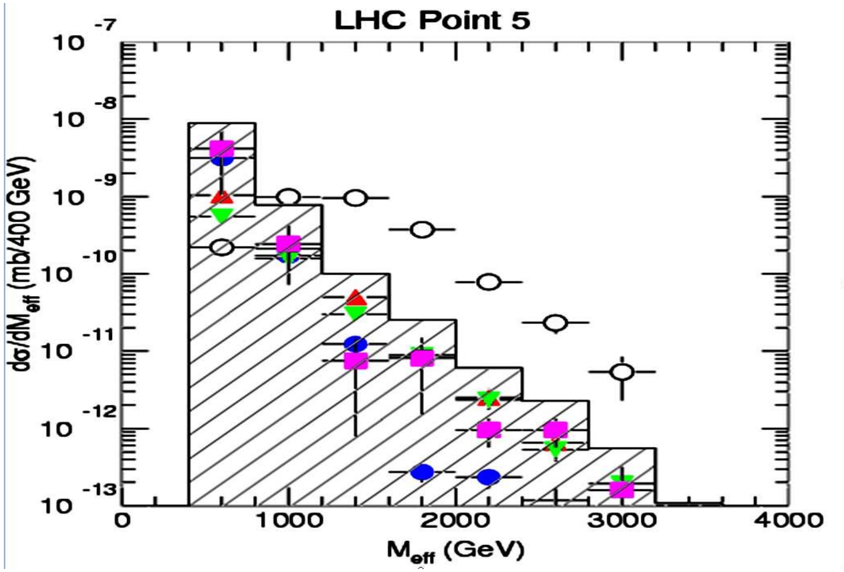
But fake miss Et: Not even SM physics!



Miss Et pointing along jets

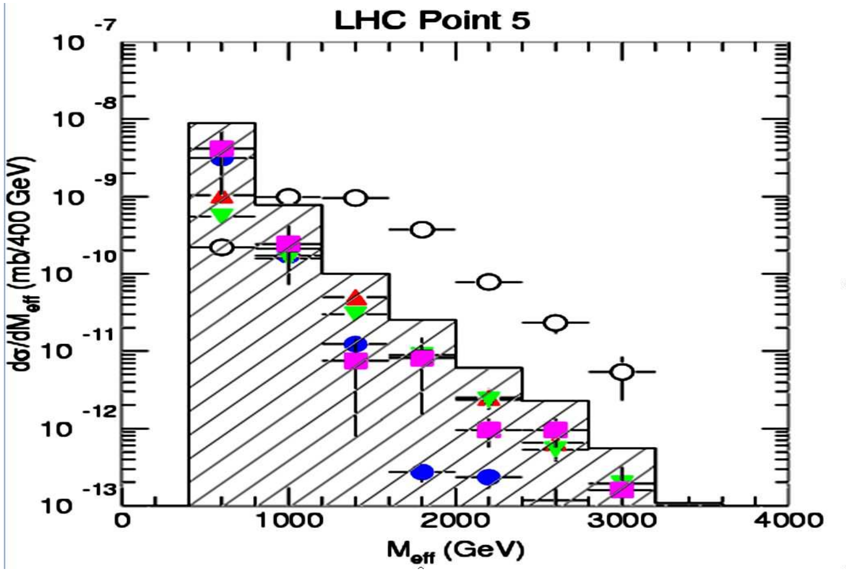
All machine garbage ends up in Et miss trigger

ATLAS TDR (same with CMS)

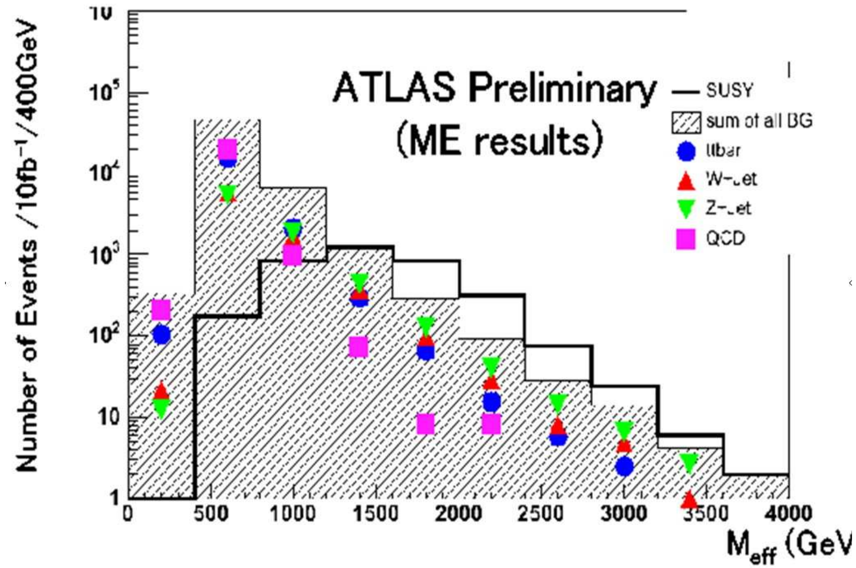


ATLAS TDR 98
(mSUGRA point, PreWMAP)

ATLAS TDR (same with CMS)

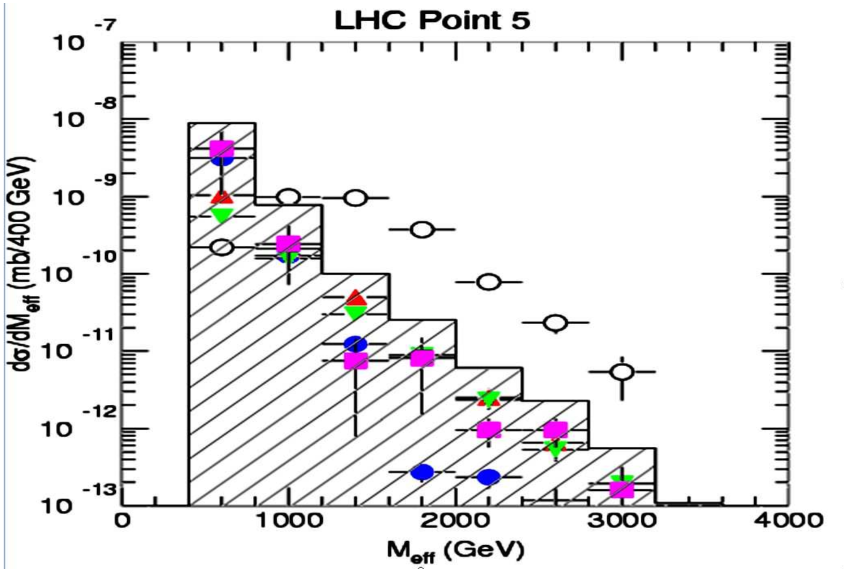


ATLAS TDR 98
(mSUGRA point, PreWMAP)



ATLAS 2006

ATLAS TDR (same with CMS)



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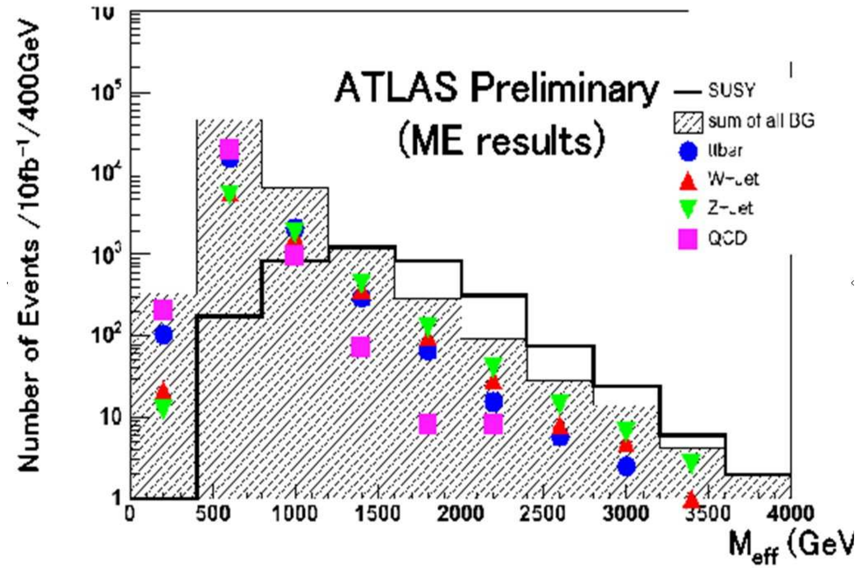
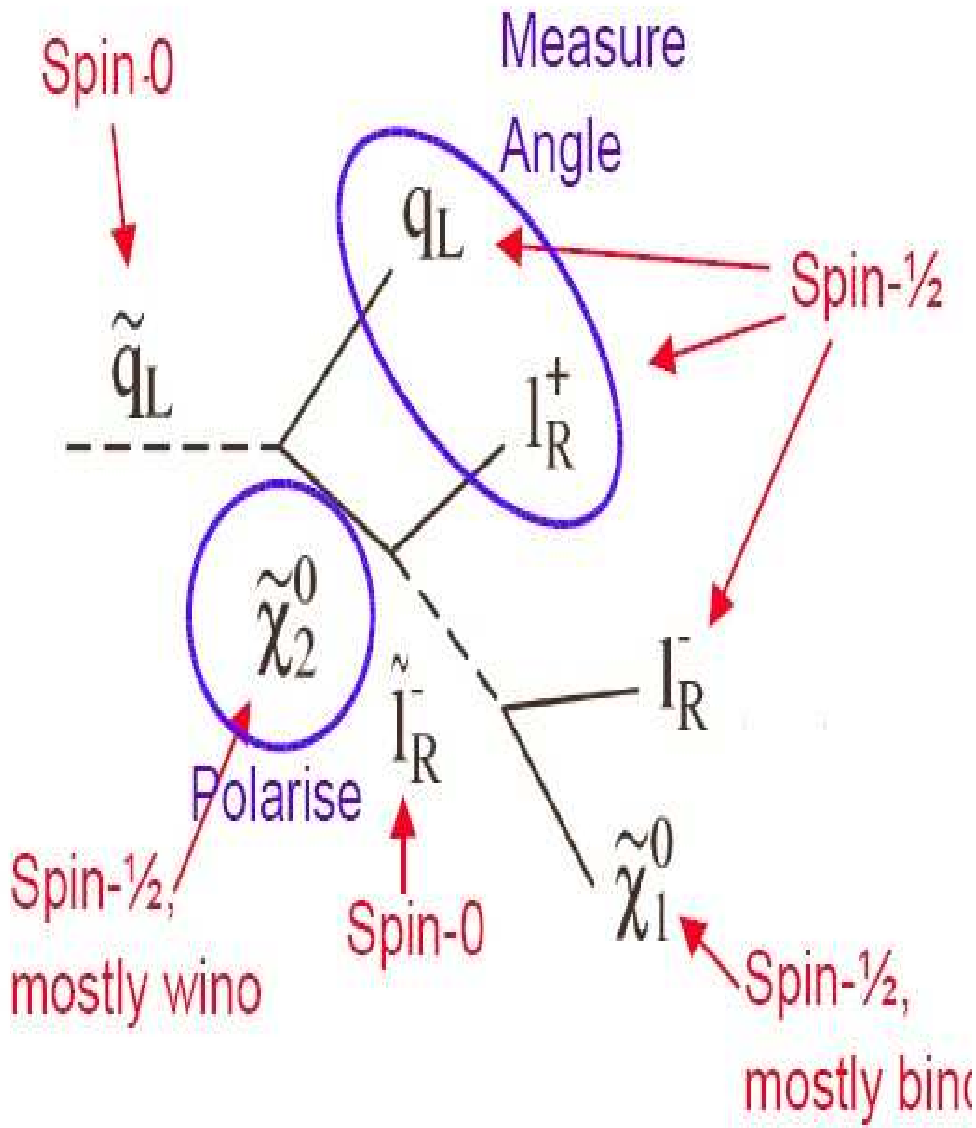


ATLAS 2006

What happened? Real Et miss from neutrinos
Complex multi-body final states: can not rely on MC alone. Need data and MC. Improve NLO multilegs, matching,...

What we hope for!



$$\tilde{q}_L \to \tilde{\chi}_2^0 \quad q$$
$$\hookrightarrow \tilde{\ell}_R^{\pm} \quad \ell^{\mp}$$
$$\hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm}$$

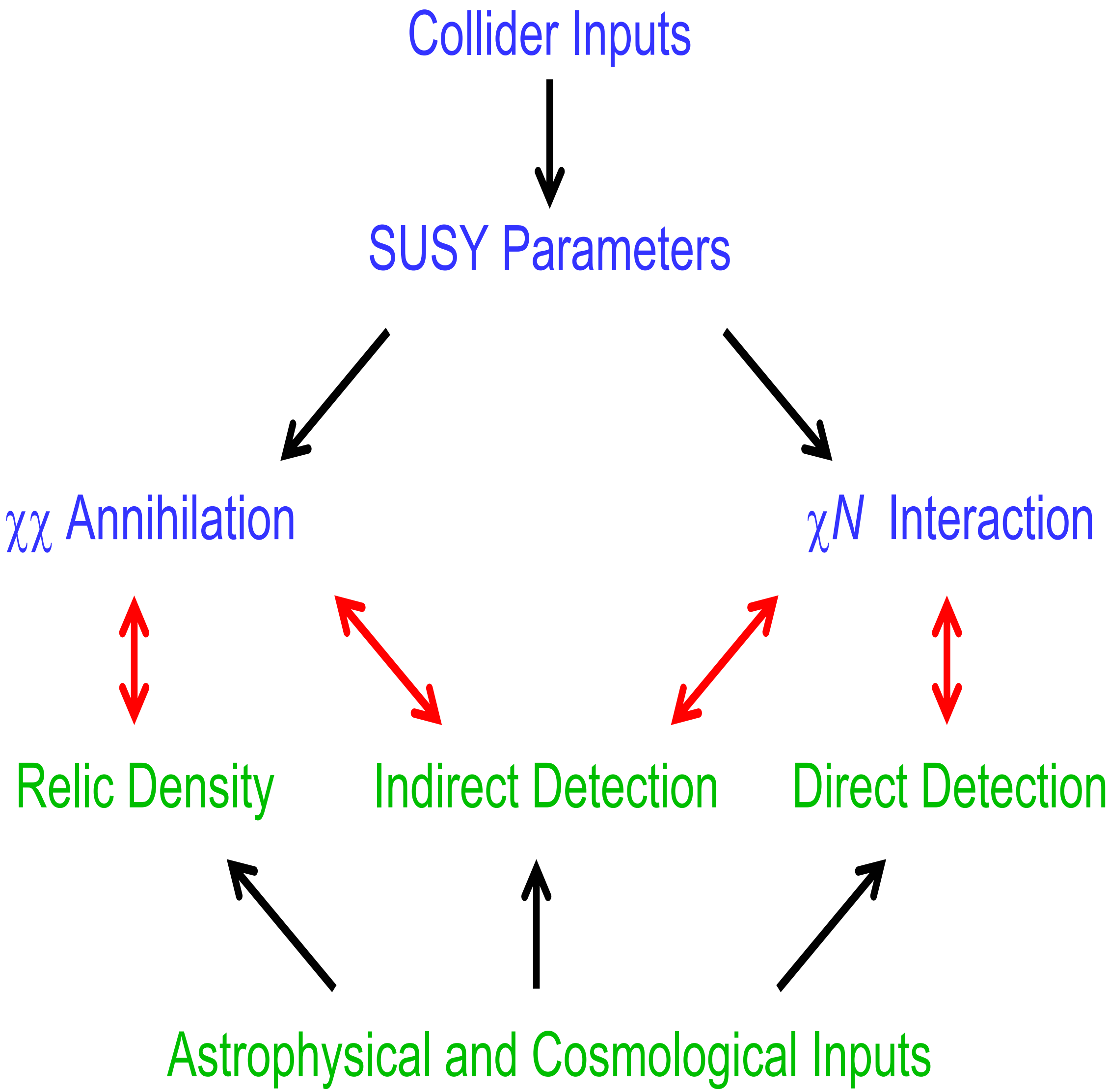
Synergy Collider-Cosmology-Astrophysics

- What does it take to prove it is a DM candidate

  the right relic density

  has to confirm the rate of Dark Matter Direct Detection

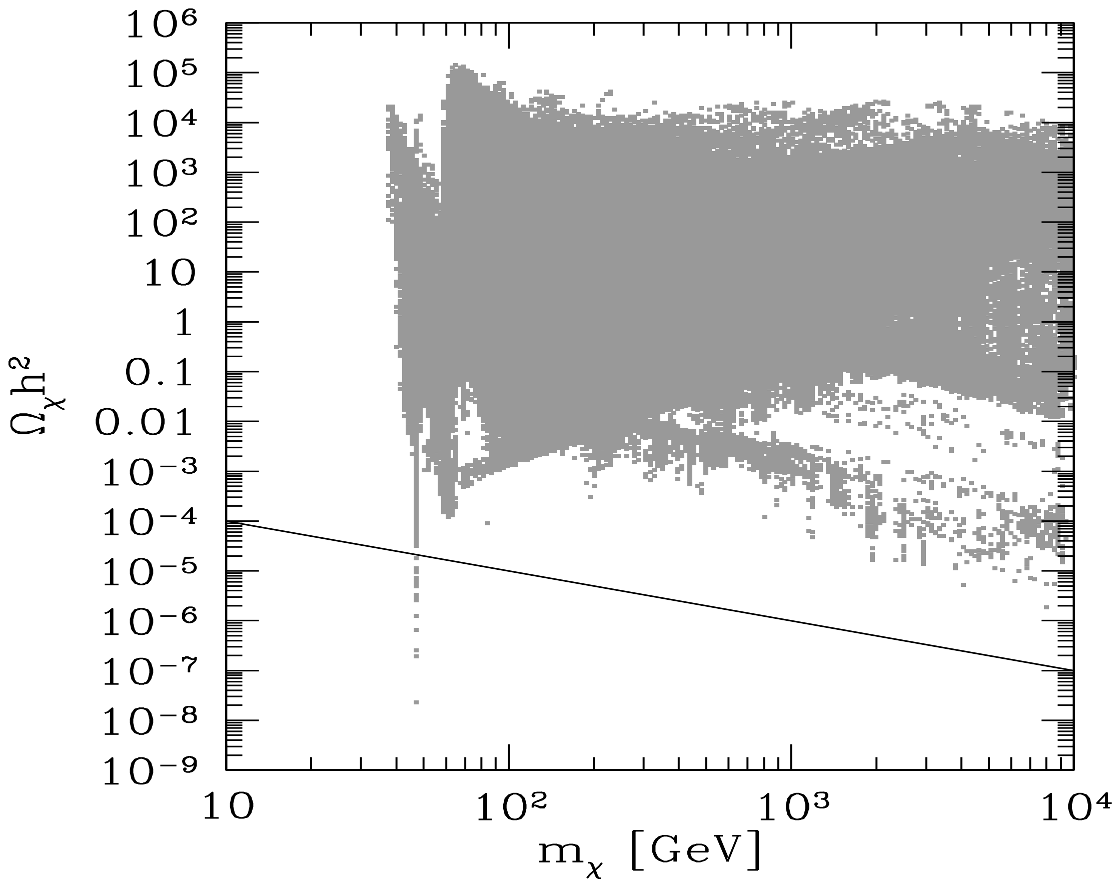
  has to confirm Indirect Detection rates: annihilations into anti-matter, photons, neutrinos
- But all three items carry substantial assumptions or drastic differences in the modelling of astrophysics
- one is assuming detection is assured in DD and Ind. Detection
- Important to extract as precise as possible the microscopic properties of DM, interaction
- constrain the cosmological models
- constrain the astrophysics models: DM distribution, clumping, perhaps propagation
- may even use some hints from astrophysics to input at colliders


Collider Inputs
SUSY Parameters
$\chi\chi$ Annihilation
χN Interaction
Relic Density
Indirect Detection
Direct Detection
Astrophysical and Cosmological Inputs

Example 1: Relic Density

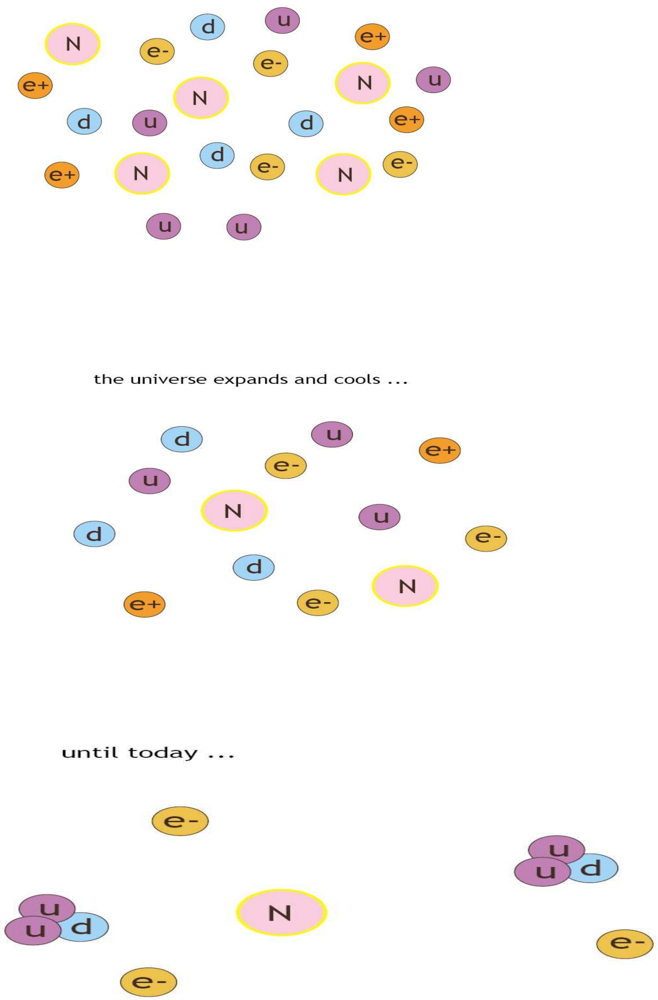
Assuming that R-Parity conserving SUSY is discovered at the LHC, an interesting question will arise regarding the compatibility of that signal with existing relic density constraints (e.g. $0.094 < \Omega_\chi h^2 < 0.129$ at 2σ fr WMAP data [1, 2, 3]), and the implications it has for terrestrial Dark Matter searches.

Constraining relic density parameter space:SUSY unconstrained



Orders of magnitude, DM cross sections orders of magnitude also (same for direct and indirect detection)

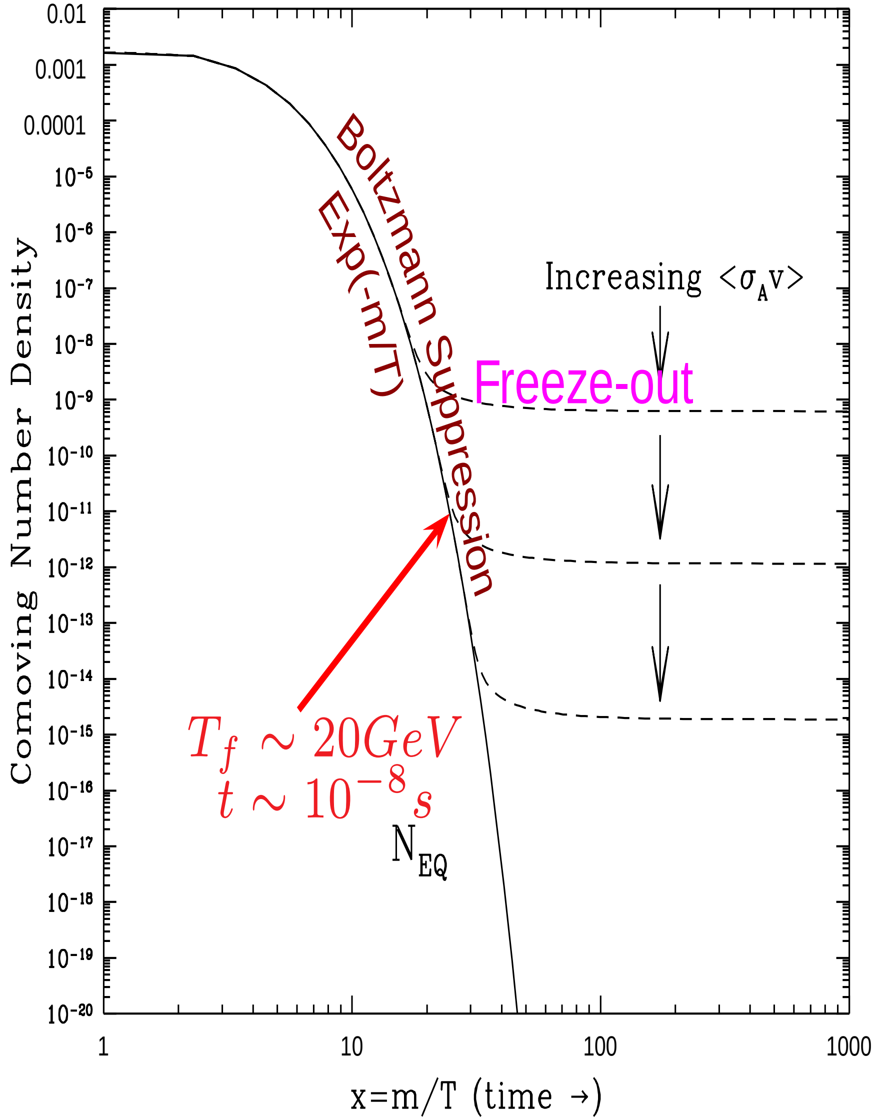
formation of DM: Very basics of decoupling



- At first all particles in thermal equilibrium, frequent collisions and particles are trapped in the cosmic soup
- universe cools and expands: interaction rate too small or not efficient to maintain Equil.
- (stable) particles can not find each other: freeze out and get free and leave the soup, their number density is locked giving the observed relic density
- from then on total number $(n \times a^3) = cste$
- Condition for equilibrium: mean free path smaller than distance traveled: $l_{\rm m.f.p} < vt \quad l_{\rm m.f.p} = 1/n\sigma$ $t \sim 1/H$ or Equilbrium: $\Gamma = n\sigma v > H$

freeze ou/decoupling occurs at $T = T_D = T_F : \Gamma = H$ and $\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$

Relic Density: Boltzman transport equation



based on $\mathcal{L}[f] = \mathcal{C}[f]$

dilution due to expansion

$$dn/dt = -3Hn - <\sigma v> (n^2 - n_{eq}^2)$$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow X$

$X \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- at early times $\Gamma \gg H \rightarrow n \sim n_{eq}$
- $T \sim m$ x not enough energy to give $X \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ n drops and so does Γ

$T_f \simeq m/25$

$$\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$$

All in all...

$$\Omega_{\tilde{\chi}_1^0} h^2 \simeq \frac{10^9}{M_P} \frac{x_f}{\sqrt{g_\star}} \frac{1}{<\sigma_{\tilde{\chi}_1^0} v>}$$

$$\Omega_{\tilde{\chi}_1^0} h^2 \sim 0.1 \rightarrow < \sigma_{\tilde{\chi}_1^0} v > \sim 1pb$$

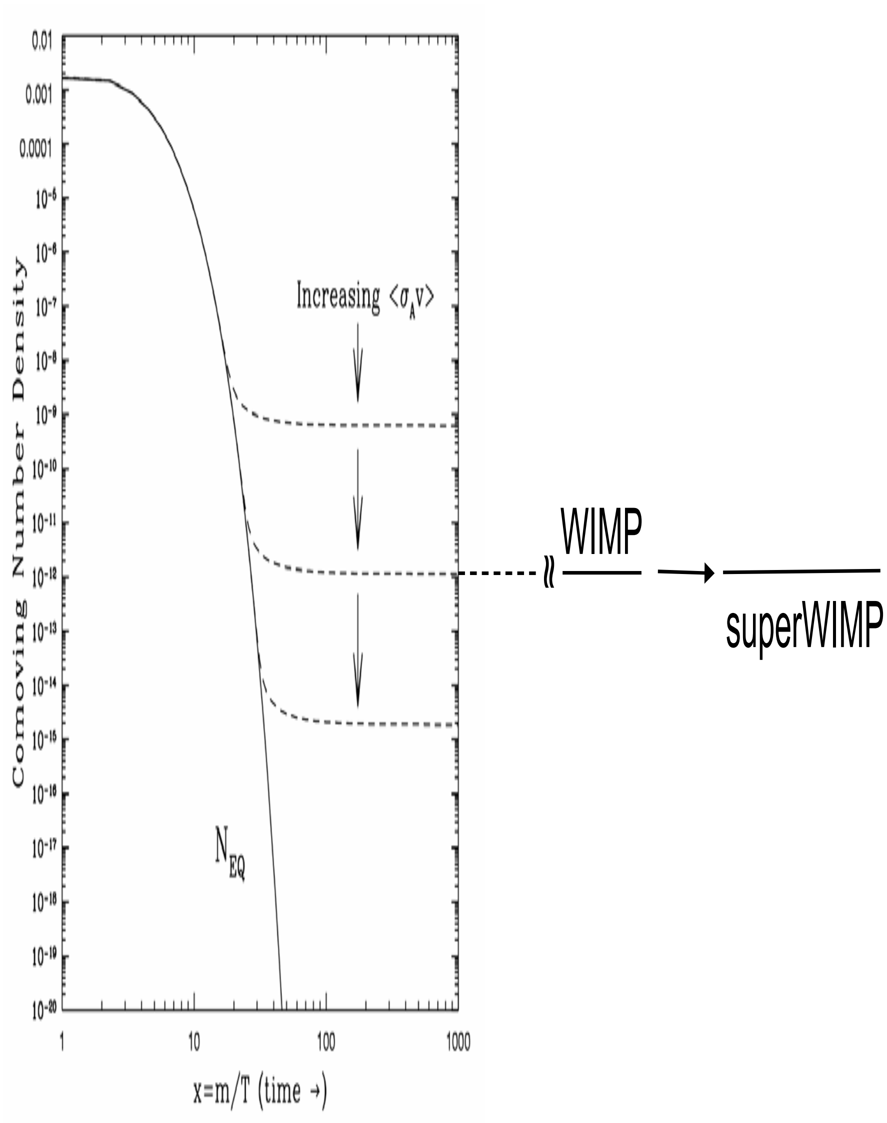
order of magnitude of LHC cross sections

$$< \sigma_{\tilde{\chi}_1^0} v > = \pi \alpha^2 / m^2$$

$$\Omega_{\tilde{\chi}_1^0} h^2 \sim (m/TeV)^2 \rightarrow m \sim G_F^{-1/2} \sim 300\text{GeV}$$

but with the precision on the relic that we have now (6%) and the many possibilities from the particle physics perspectives, need more than orders of magnitudes calculations.

- At early times Universe is radiation dominated: $H(T) \propto T^2$ ◀
- Expansion rate can be enhanced by some scalar field (kination), extra dimension $H^2 = 8\pi G/3\ \rho(1 + \rho/\rho_5)$, anisotropic cosmology,...
- Entropy conservation (entropy increase will reduce the relic abundance
- Wimps (super Wimps) can be produced non thermally, or in addition produced in decays of some field (inflaton,....)

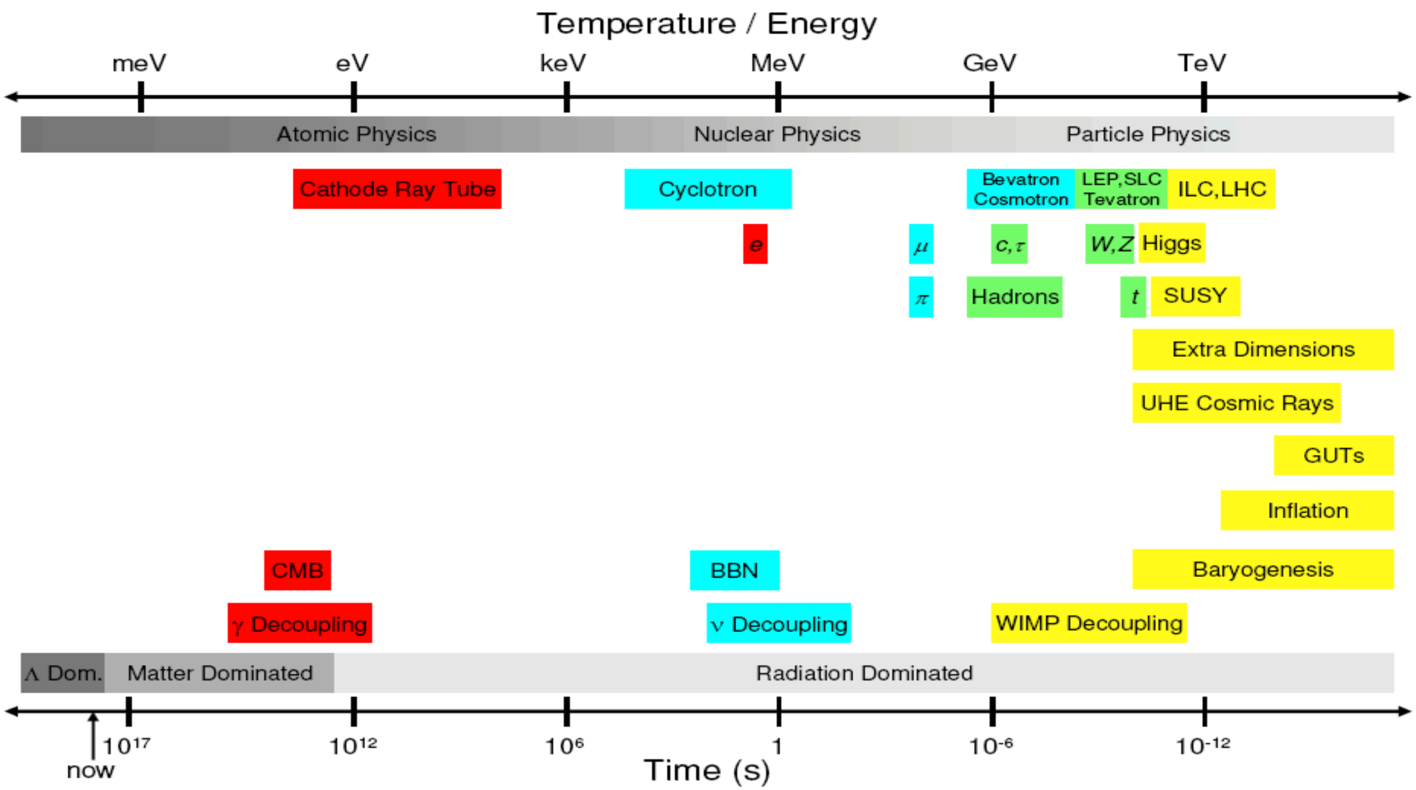


Assuming that each WIMP decay produces one one sWimp, the inherited density is simply

$$\Omega_{sWimp} = \frac{m_{\rm sWimp}}{\rm Wimp}\Omega_{Wimp}$$

beware though: If couplings very weak, decays may be very late and would directly impact on BBN, CMB, diffuse γ flux (energy released in visible decay products serious stopper!)

History of the Universe,



- WIMP density depends on the history of the Universe before BBN (0.8MeV) (abundance of light elements), large time scale between freeze-out and BBN
- for BBN to hold it is enough that the earliest and highest temperature during the radiation era $T_{RH} > 4$MeV

  $T_{RH} >$ is to be understood as the temp. which after a period of rapid inflationary expansion the Universe reheats (defrosts) and the expanding plasma reaches full thermal equilibrium

- Density may decreased by reducing rate of thermal production, possibility to have tiny $T_{RH} < T_{\rm f.o}$ or by production of radiation after freeze-out
- increased by injecting Wimps from decays or/and increasing the expansion rate
- Open up more possibilities, constrain Physics at the Planck scale??

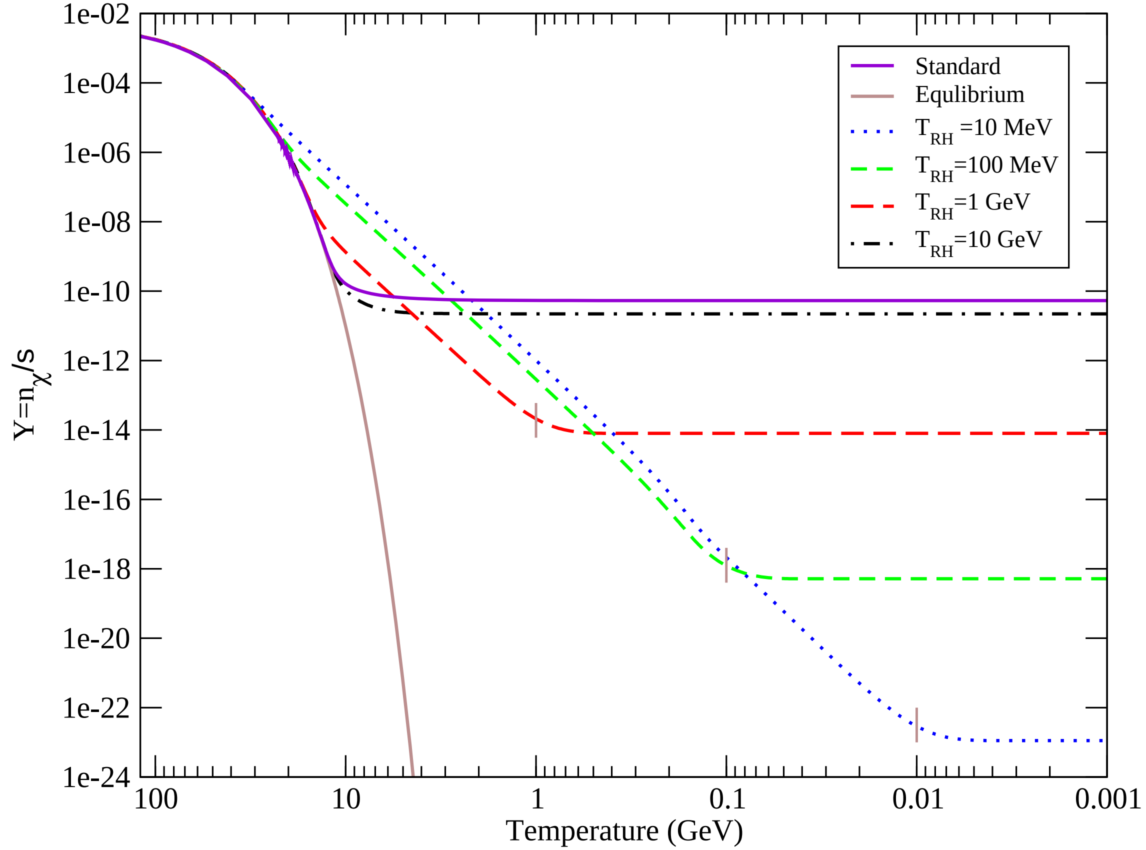
Prototype: A scalar field decaying not long before BBN Giudice, Kolb; Gelmini and Gondolo, ...

$$\begin{aligned}
\frac{d\rho_\phi}{dt} &= -3H\rho_\phi - \Gamma_\phi\rho_\phi \\
\frac{dn}{dt} &= -3Hn - \langle\sigma v\rangle\left(n^2 - n_{eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi \\
\frac{ds}{dt} &= -3Hs + \frac{\Gamma_\phi\rho_\phi}{T}
\end{aligned}$$

where m_ϕ, Γ_ϕ, and ρ_ϕ are respectively the mass, the decay width and the energy density of the scalar field, and b is the average number of neutralinos produced per ϕ decay. Notice that b and m_ϕ enter into these equations only through the ratio b/m_ϕ ($eta = b\,(100TeV/m_\phi)$) and not separately. Finally, the Hubble parameter, H, receives contributions from the scalar field, Standard Model particles, and supersymmetric particles,

$$\begin{aligned}
H^2 &= \frac{8\pi}{3M_P^2}\left(\rho_\phi + \rho_{SM} + \rho_\chi\right). \\
T_{RH} &= 10MeV(m_\phi/100TeV)^{3/2}(M_P/\Lambda) \quad \Gamma_\phi \sim m_\phi^3/\Lambda^2
\end{aligned}$$

Non Standard Cosmo, Figs Gelmini and Gondolo



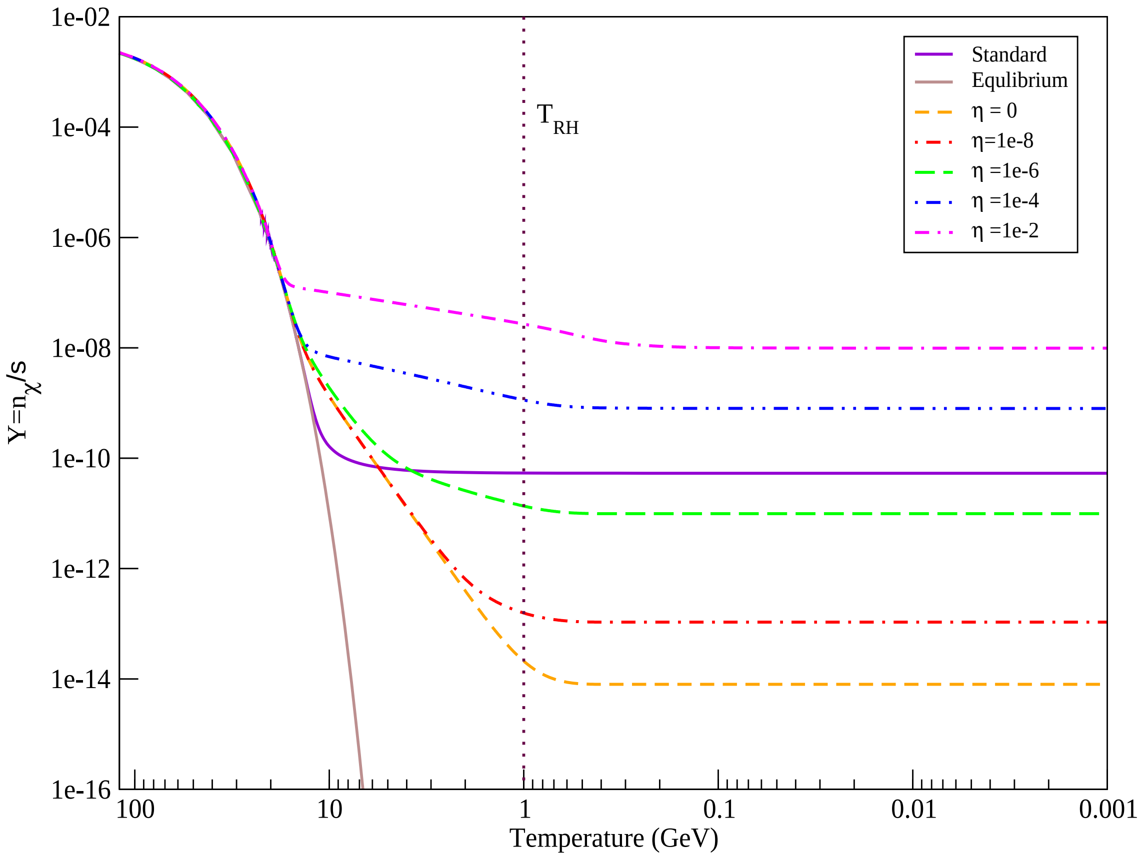
mSUGRA parameters

$M_{1/2} = m_0 = 600\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$,

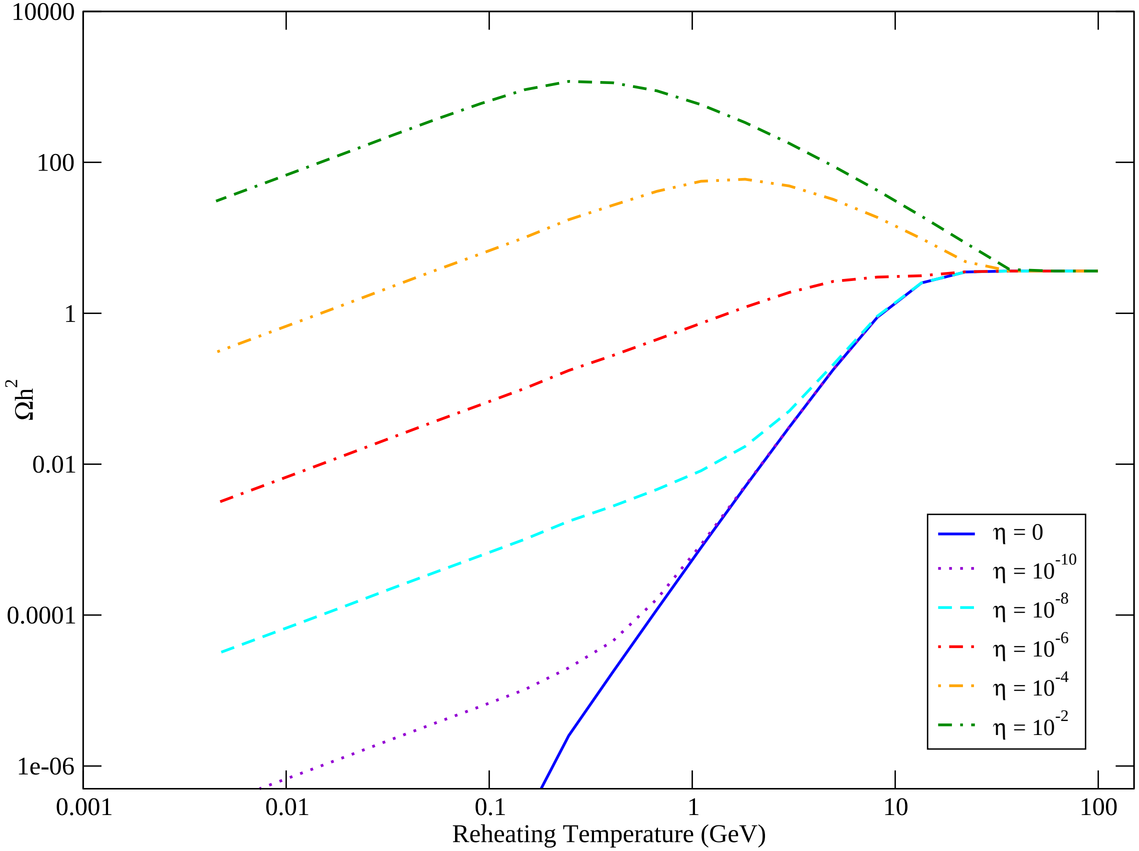
$\rightarrow m_\chi = 246\,\mathrm{GeV} \rightarrow T_{f.o} = 10GeV$. $\Omega_{\mathrm{std}} h^2 \simeq 3.6$

$\eta = 0$

Non Standard Cosmo



Non Standard Cosmo

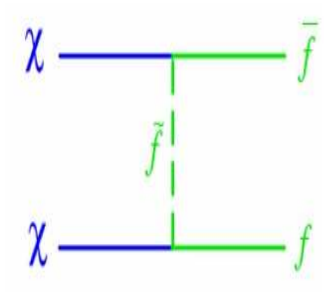


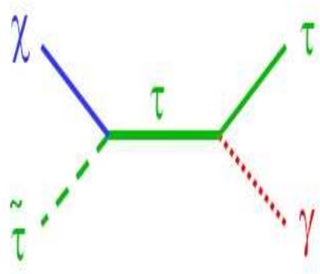
Note that different cosmological models may look standard!

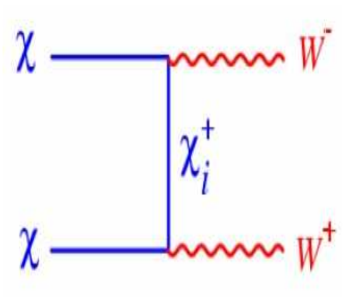
Important Message

The bulk region can be correct, good news for parameter extraction at LHC

Large Wino cross sections that are good for Indirect Detection not ruled out

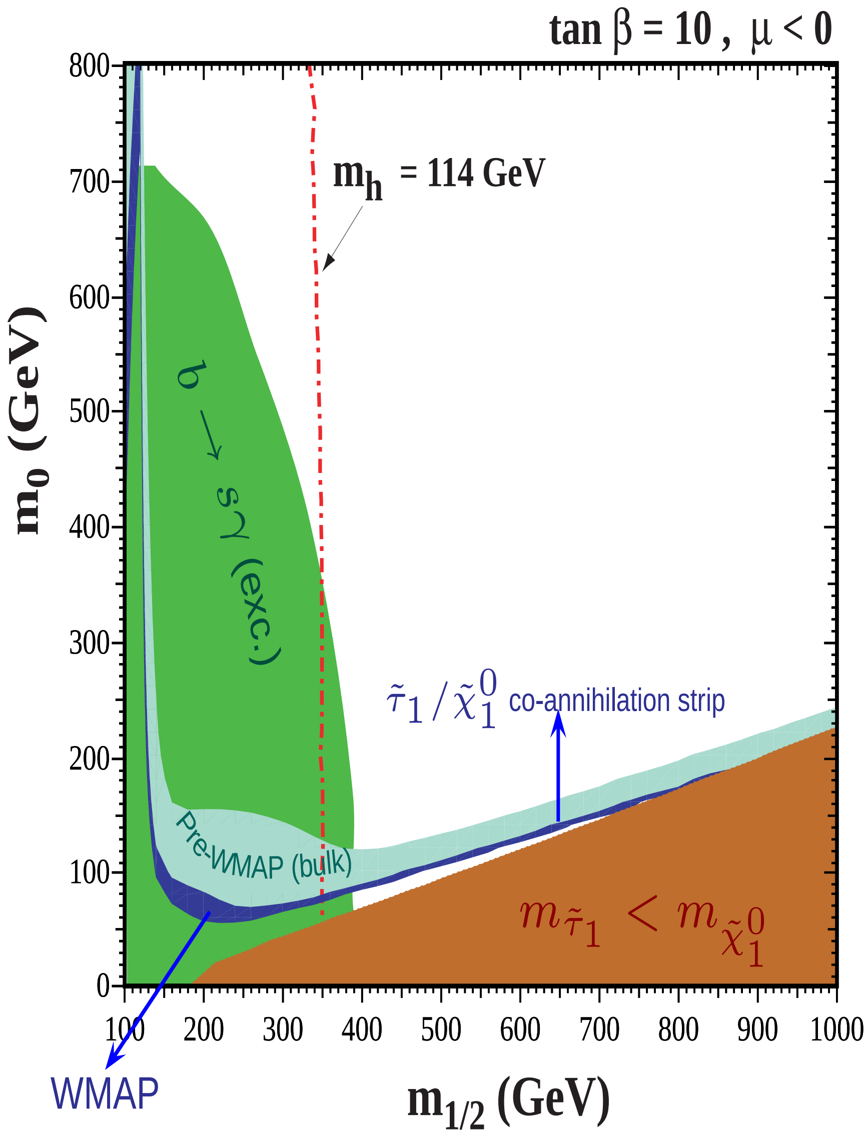






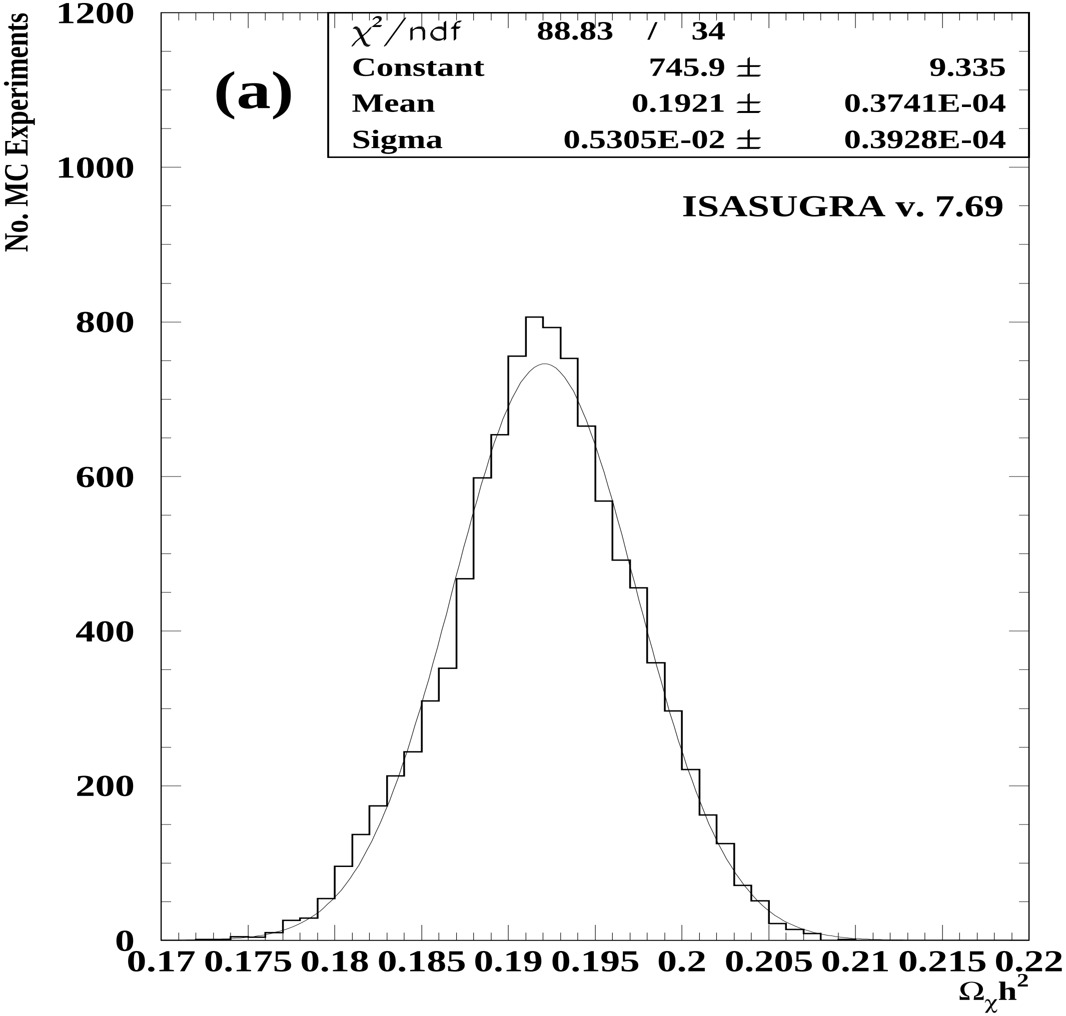
- measure masses and all important relevant couplings (bino/wino/ components,....., mixing) that enter the relic calculation
- Most often this is also what enters the indirect detection
- strive to measure the coupling of the Higgs to the DM

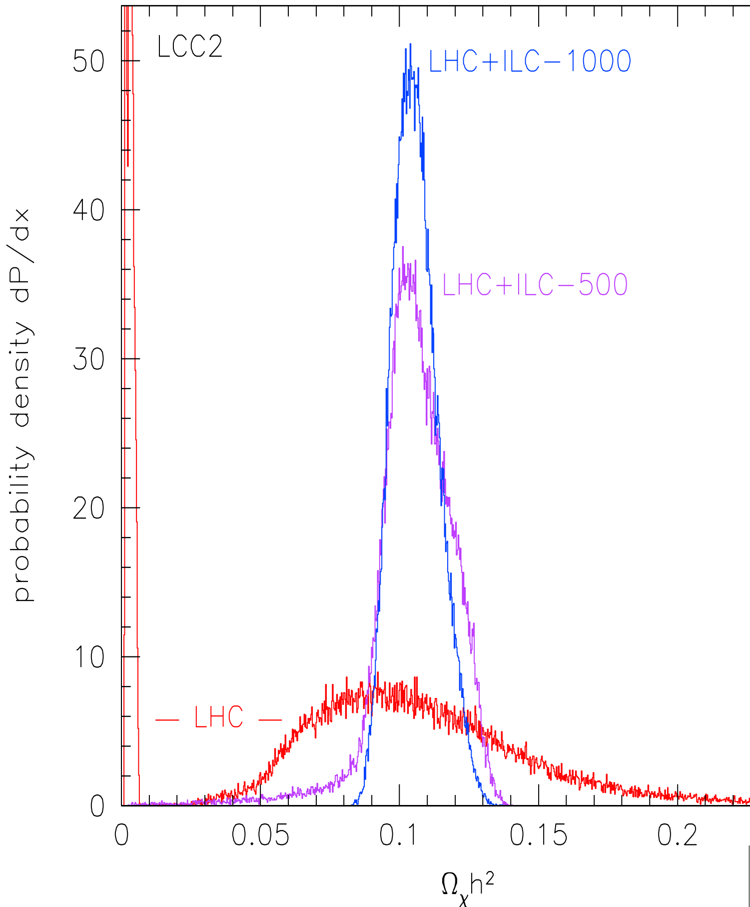
The mSUGRA inspired regions



- Bulk region: bino LSP, $\tilde{l}_R$ exchange, (small $m_0, M_{1/2}$)
- $\tilde{\tau}_1$ co-annihilation: NLSP thermally accessible, ratio of the two populations $exp(-\Delta M/T_f)$ small m_0, $M_{1/2}$: 350 – 900GeV
- Higgs Funnel: Large $\tan\beta$, $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to A \to b\bar{b}, (\tau\bar{\tau})$, $M_{1/2}$: 250 – 1100GeV, m_0 : 450 – 1000GeV
- Focus region: small $\mu \sim M_1$, important higgsino component, requires very large TeV m_0

LHC+ILC

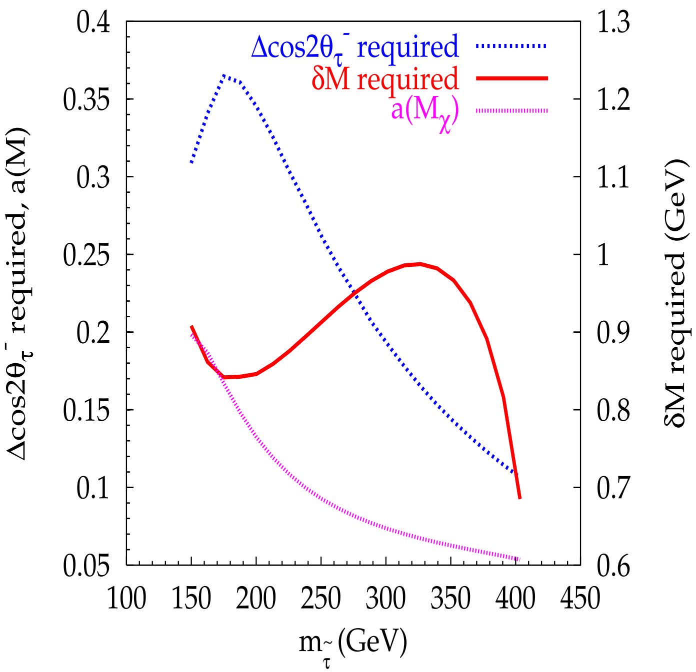




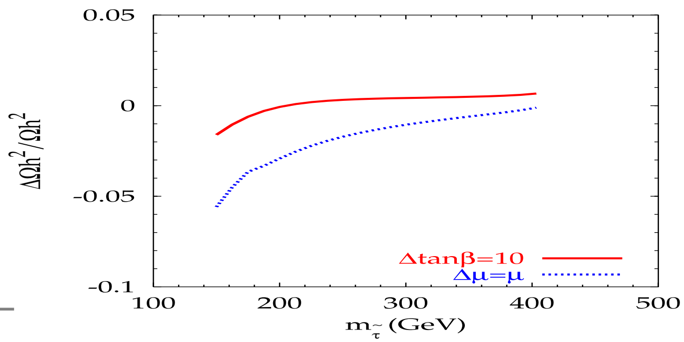
Polesello+Tovey, LHC, bulk

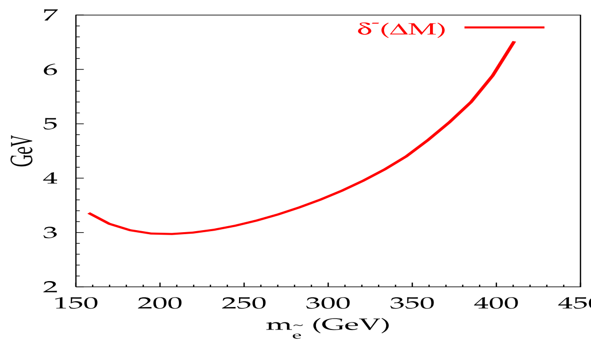
Baltz,Battaglia, Peskin and Wisansky

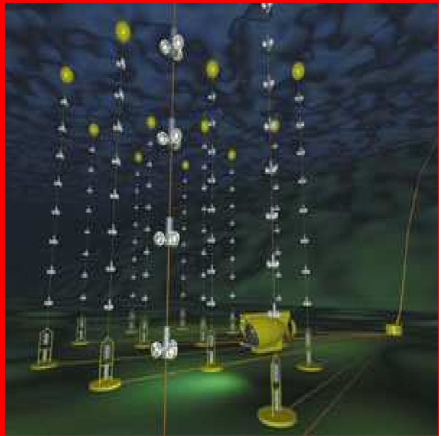
$\tilde{\tau}_1$ co-annihilation region: Model Independent



- ΔM must be measured to less than 1GeV
- mixing angle accuracy should be feasible at ILC
- accuracy on LSP mass not demanding but this is because we have constrained ΔM.
- other slepton masses need also be measured
- in terms of physical parameters residual $\mu \tan\beta$ accuracies not demanding
- Preliminary studies indicate these accuracies will be met for the lowest $m_{\tilde{\chi}_1^0}$

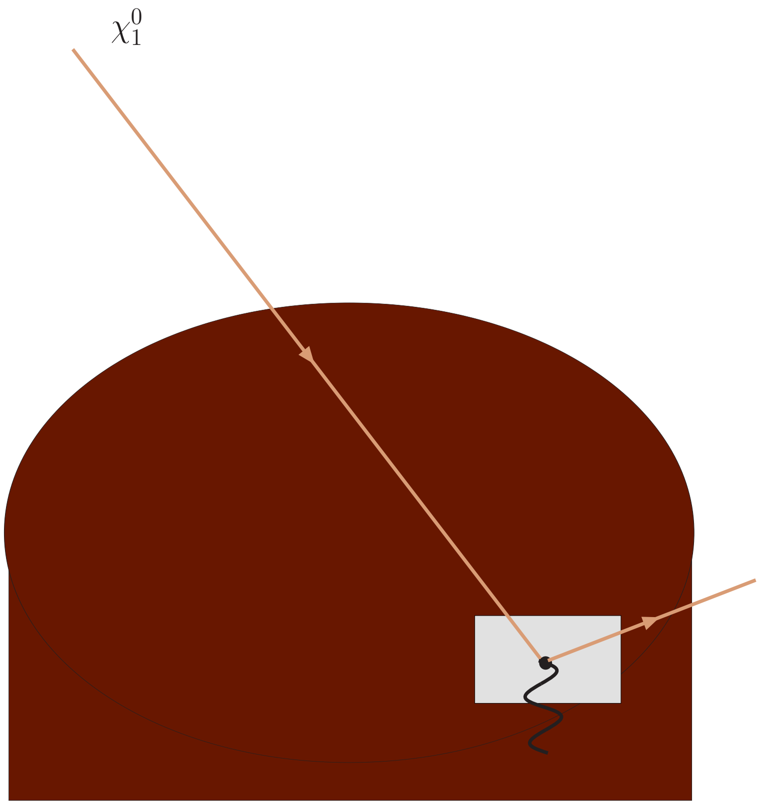




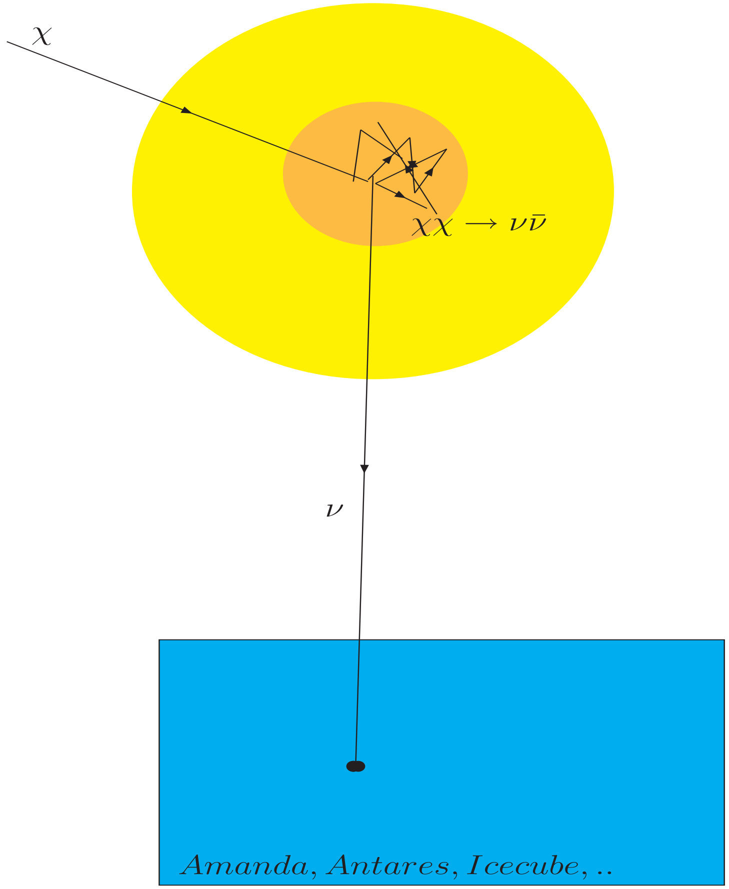


Direct and Indirect Searches

$$\bar{p},\ e^{+},\ \gamma,\ \nu, \ldots$$



$CDMS, Edelweiss, DAMA, Genuis, ..$

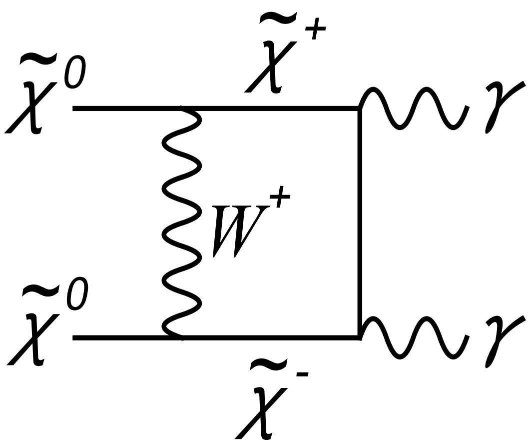


Annihilation into photons

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \sum_i \underbrace{\frac{dN^i_\gamma}{dE_\gamma}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particulephysics}} \underbrace{\int (\rho + \delta\rho)^2 dl}_{\text{Astro}}$$

$\gamma' s$: Point to the source, independent of propagation model(s)

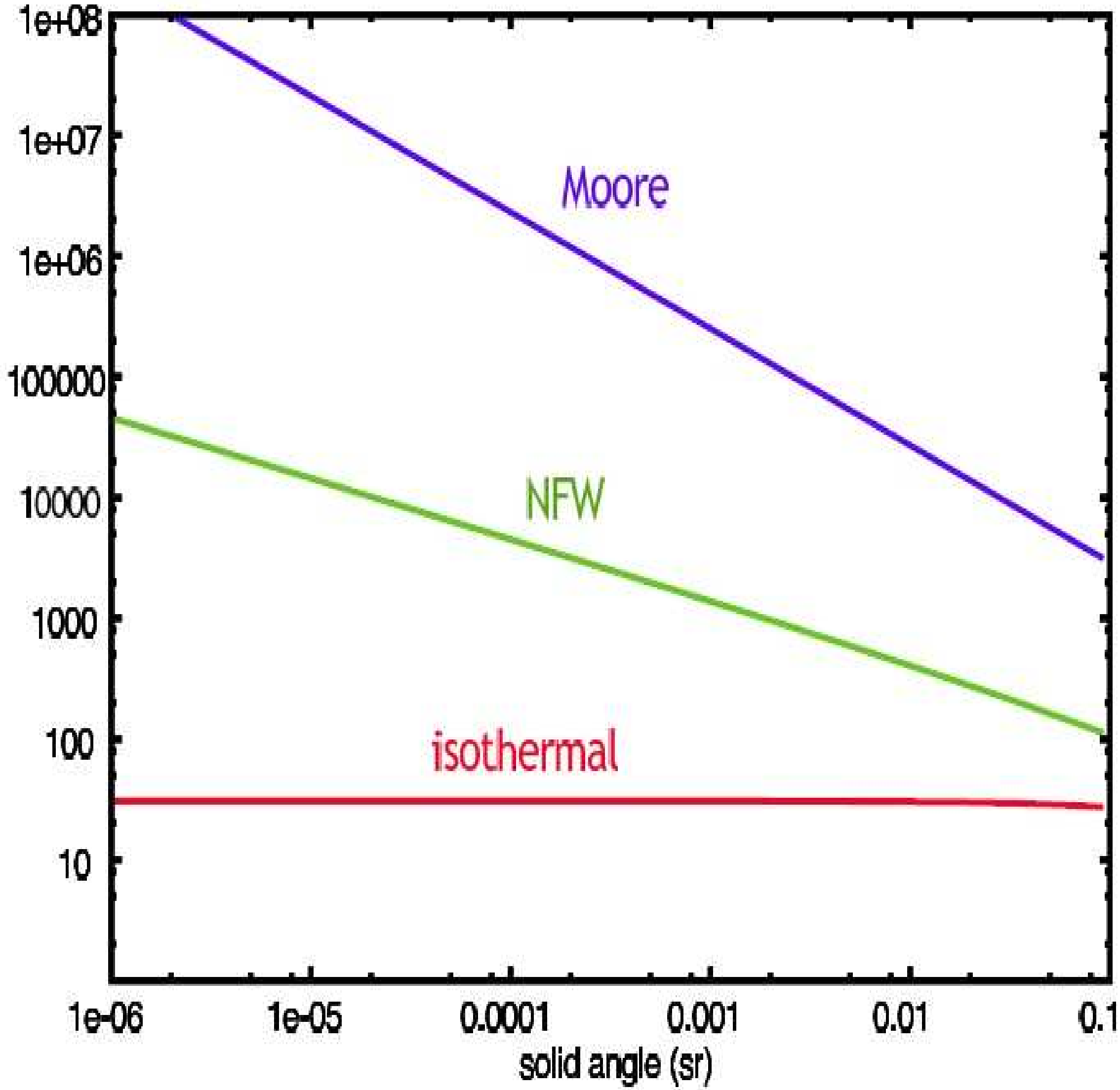
- continuum spectrum from $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow f\bar{f}, \ldots,$ hadronisation/fragmentation ($\rightarrow \pi^0 \rightarrow \gamma$) done through isajet/herwig
- Loop induced mono energetic photons, $\gamma\gamma$, $Z\gamma$ final states

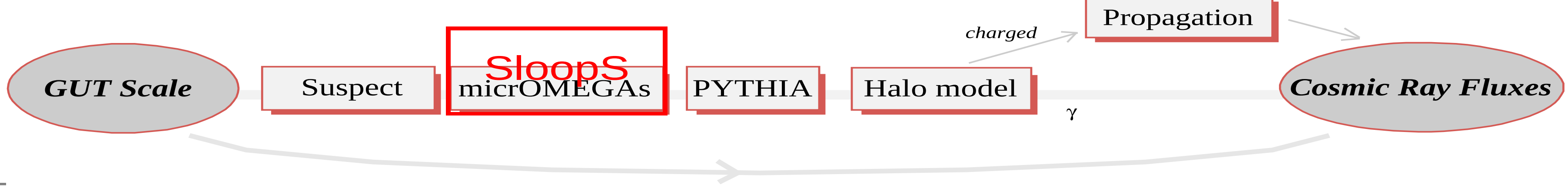


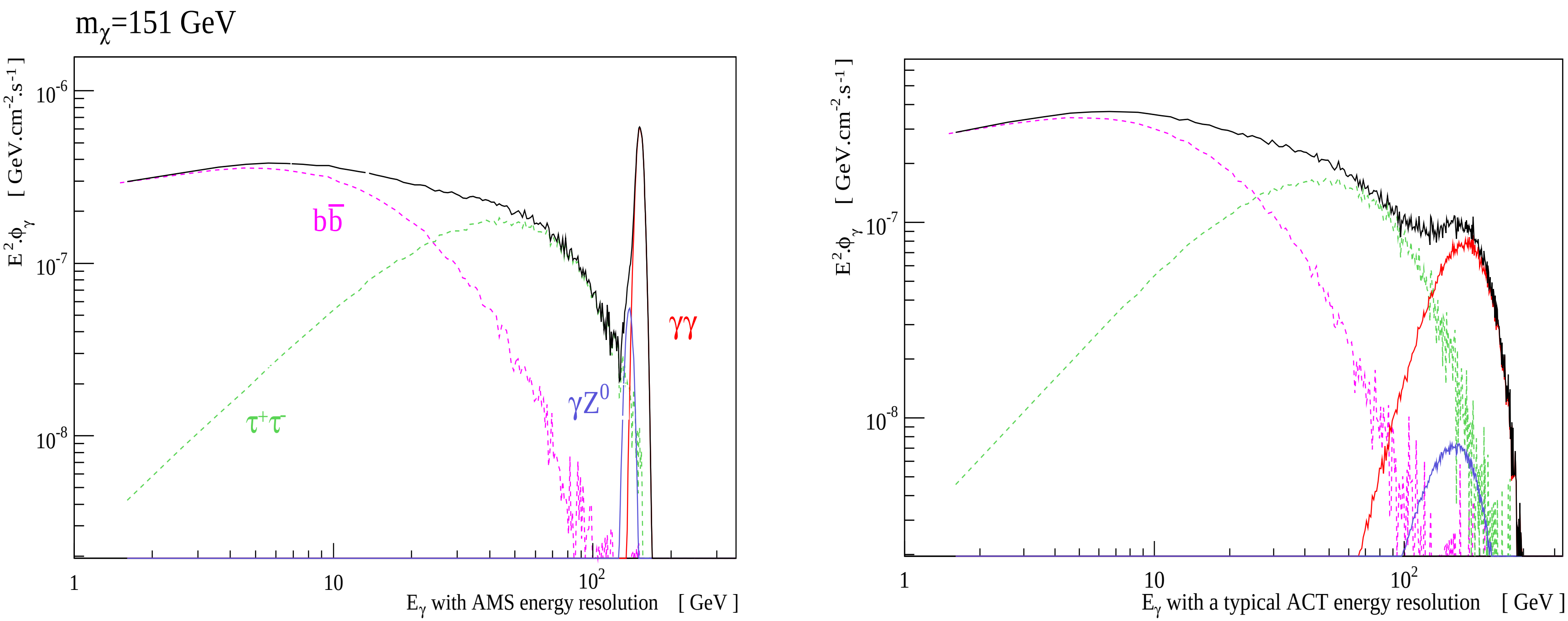
ACT: HESS, Magic, VERITAS, Cangoroo, ...

Space-based: AMS, GLAST, Egret,...

Halo Profile Modelling







SIMULATION:

Parameterising the halo profile:

$(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$kpc. (core radius), $r_0 = 8kpc$ (distance to galactic centre), $\rho_0 = 0.3\, GeV/cm^3$ (DM density), opening angle cone 1^o

SUSY parameterisation

$m_0 = 113$GeV, $m_{1/2} = 375$ GeV, $A = 0$, $\tan\beta = 20$, $\mu > 0$

γ lines could be distinguished from diffuse background

Annihilation into $e^+, \bar{p}, \bar{D}$

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN^i_{\bar{f}}}{dE_{\bar{f}}} \sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particlephysics}} \underbrace{\int (\rho + \delta\rho)^2 P_{prop}}_{\text{Astro}}$$

$\gamma' s$: Model of propagation and background

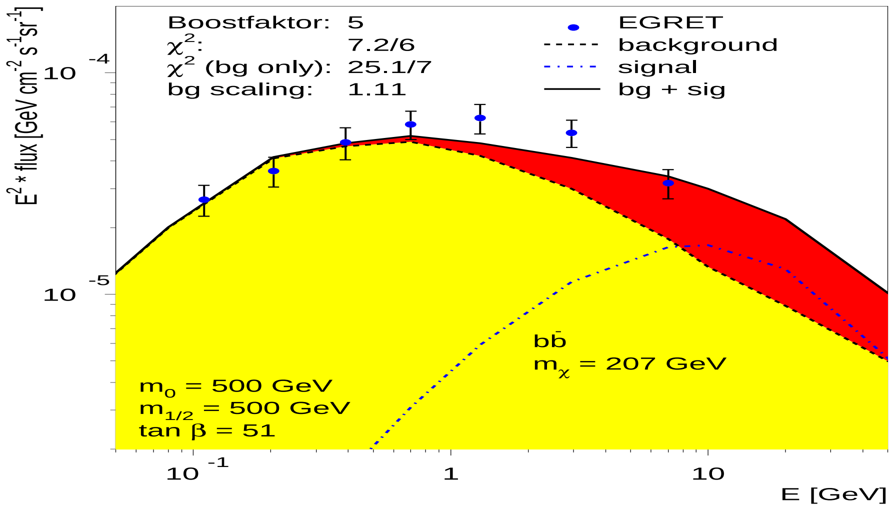
- Halo Profile modeling, clumps, cusps,..boost factors,..

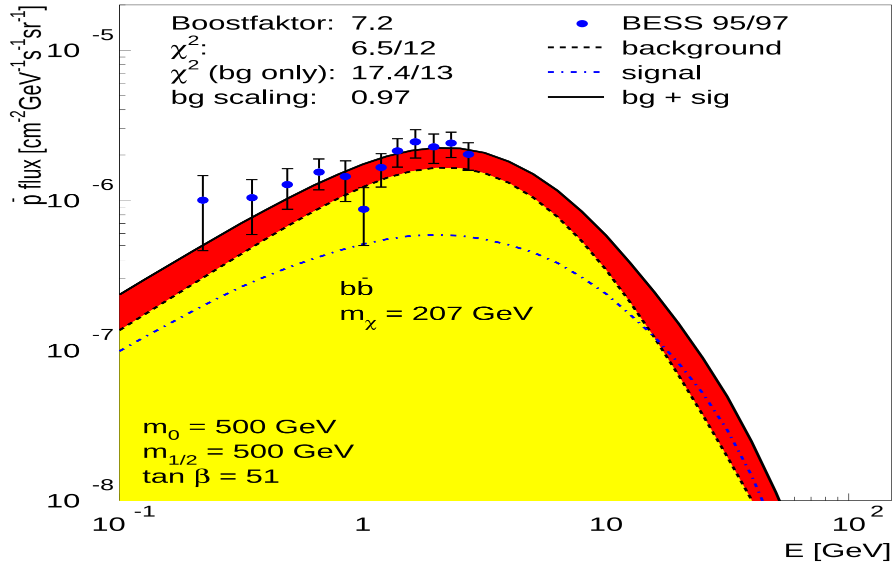
If particle Physics fixed, constrain astrophysics

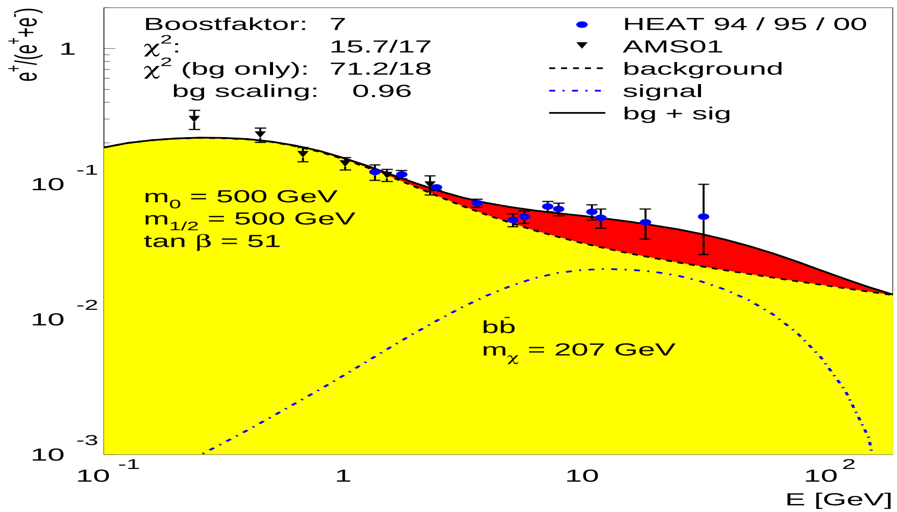
ACT: HESS, Magic, VERITAS, Cangoroo, ...

Space-based: AMS, GLAST, Egret,...

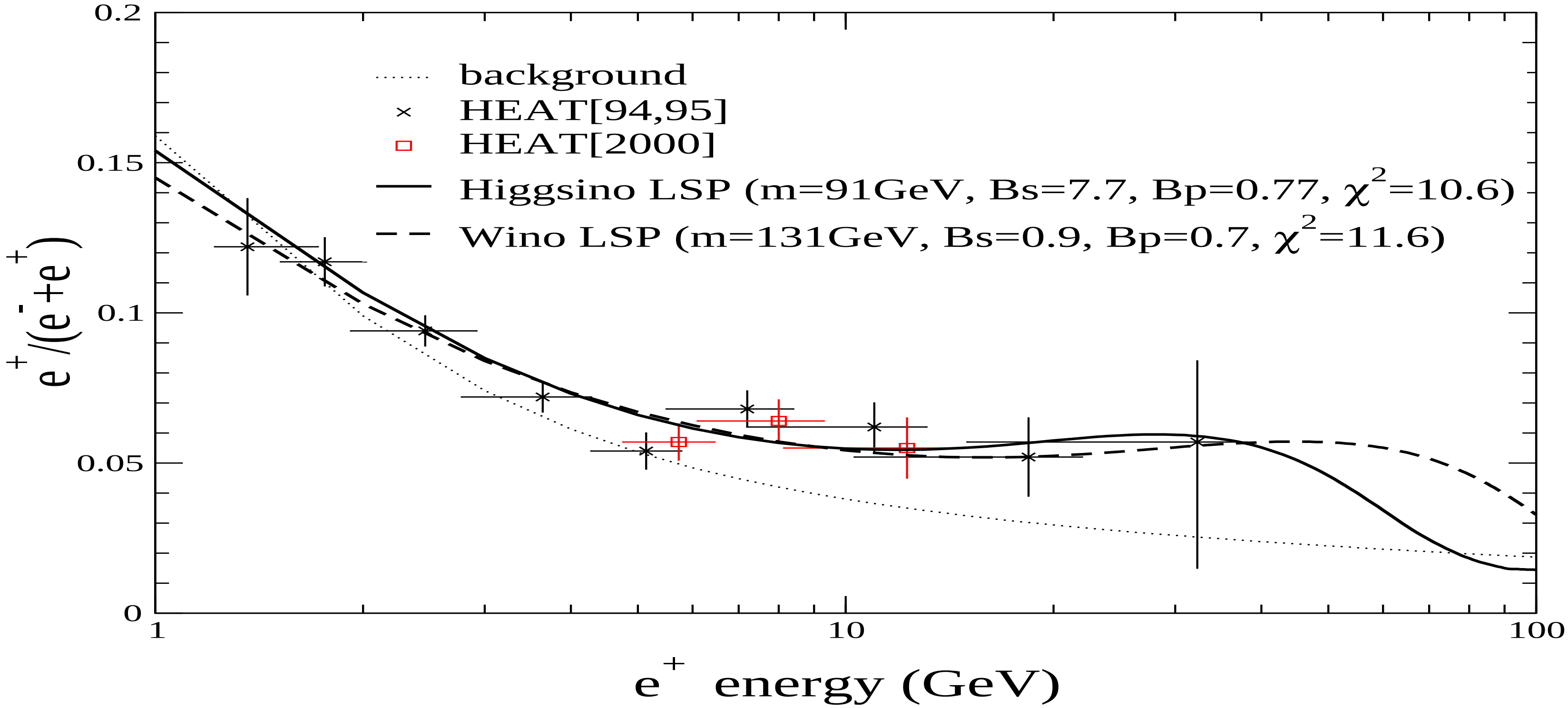
Otherwise tempted to fit with large uncertainties







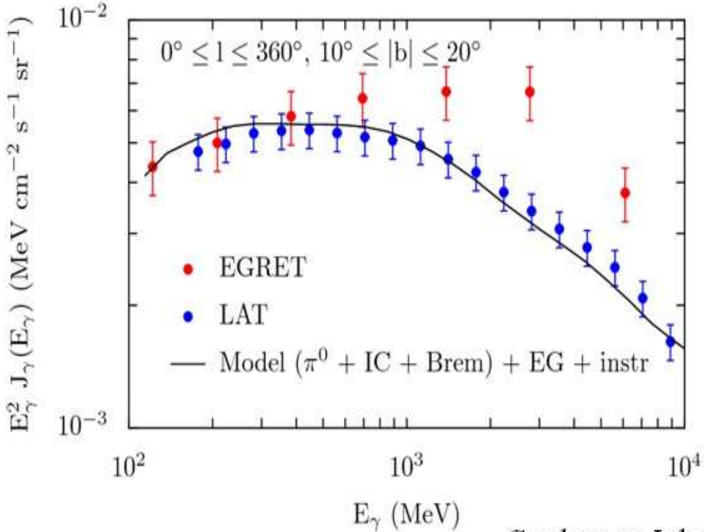
Wim de Boer and Co


background
HEAT[94,95]
HEAT[2000]
Higgsino LSP (m=91GeV, Bs=7.7, Bp=0.77, χ^2=10.6)
Wino LSP (m=131GeV, Bs=0.9, Bp=0.7, χ^2=11.6)
$e^+/(e^-+e^+)$
e^+ energy (GeV)
0.2
0.15
0.1
0.05
0
1
10
100

G. Kane and Co

from a few days back in Moriond..

NO GEV EXCESS IN THE DIFFUSE GBR



Guolaugur Johannesson (Stanford)

➔ The EGRET GeV excess is not seen with the LAT.

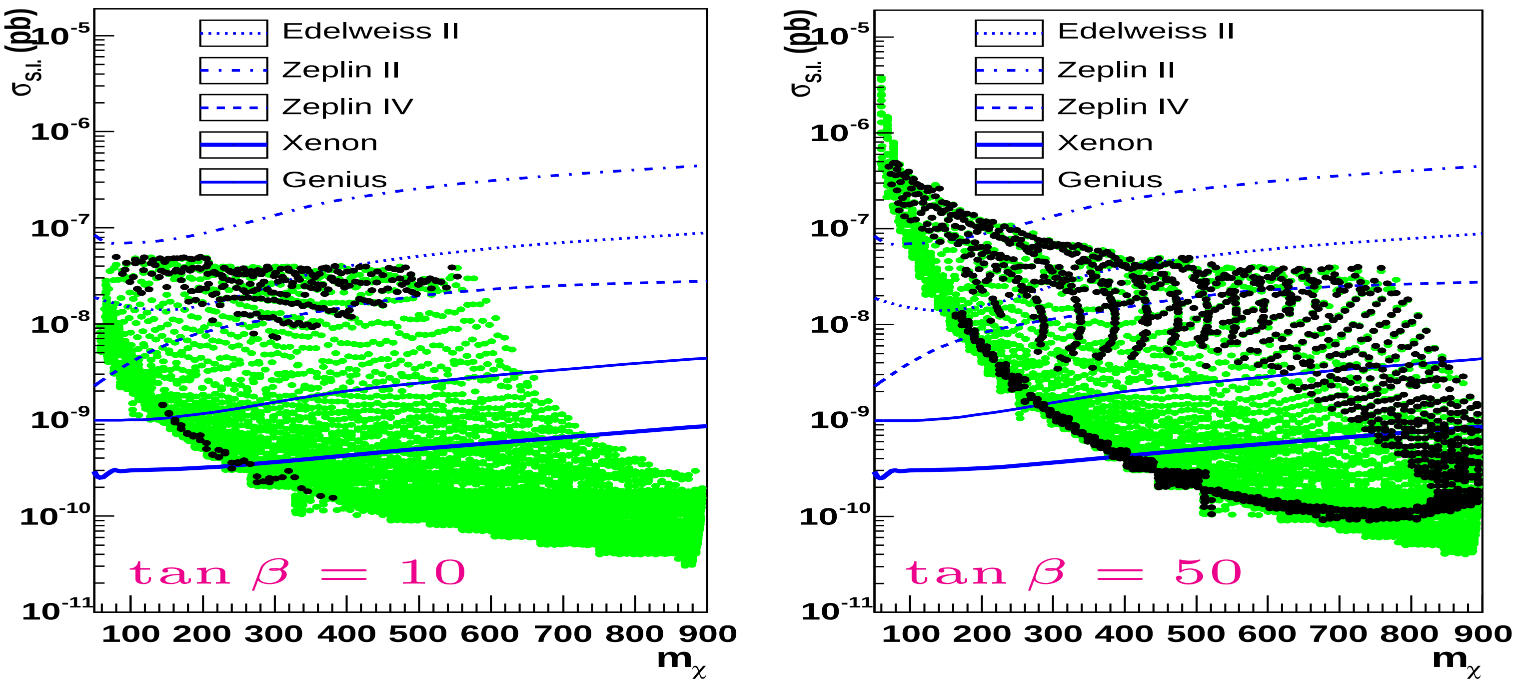
➔The measured intermediate latitude γ-ray spectra can be explained by cosmic ray propagation models based on the locally observed spectrum of cosmic-ray nuclei and electrons.

Moriond Feb 2009

➔ No GeV excess ➔ No evidence for GeV gammas from dark matter anihilation

Uncertainties coming from nuclear form factors (still large, strange component), velocity distribution,...

- within WMAP



Summary

- Cosmology has entered the era of precision measurements. Particle Physics component of DM must be extracted unambiguously. If large clean and understood signals of Etmiss at LHC there is most probably a link with DM
- Strive for as much as possible for a model independent reconstruction of the important relevant parameters of DM
- One may be lucky to be a good region of the New physics parameter space
- Other hints and constraint can come from observables not necessarily with Etmiss, the rest of the NP spectrum even Higgs
- In a first stage one can fit to constrained models
- strategy would also depend on how the astrophysics scene evolves
- in the most lucky situation an extraordinary synergy between collider physics, astrophysics and cosmology, a glimpse on the history of the Universe, remnants of the Planck scale???