Dark Matter

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SILAFAE

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Questions

Some Outstanding Issues

1. Dark Matter content (Ω_{DM} is 27%)

2. Electroweak Scale

3. Baryon Content (Ω_b is 5%)

4. Rapid Expansion of the Early Universe

5. Neutrino Mass

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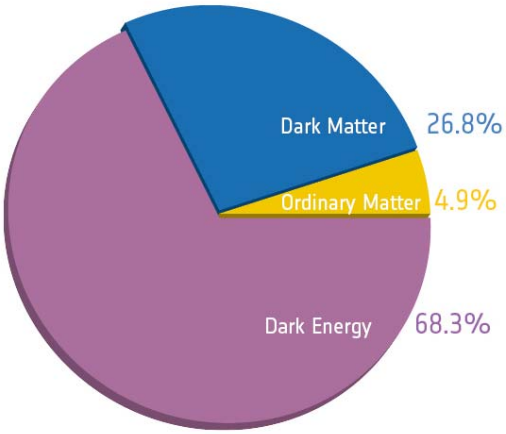
Presentation Outline

What have we learnt so far?

- **LHC, Direct and Indirect Detection Experiments, Planck Data**

Origin of DM

- **Thermal, Non-thermal, Non-standard cosmology**



Expectations

- **Dark Matter at the LHC**

Concluding Insights

LHC

Most models predict: 1-3 TeV (colored particle masses)
So far: No colored particle up to <u>1.6 TeV</u>

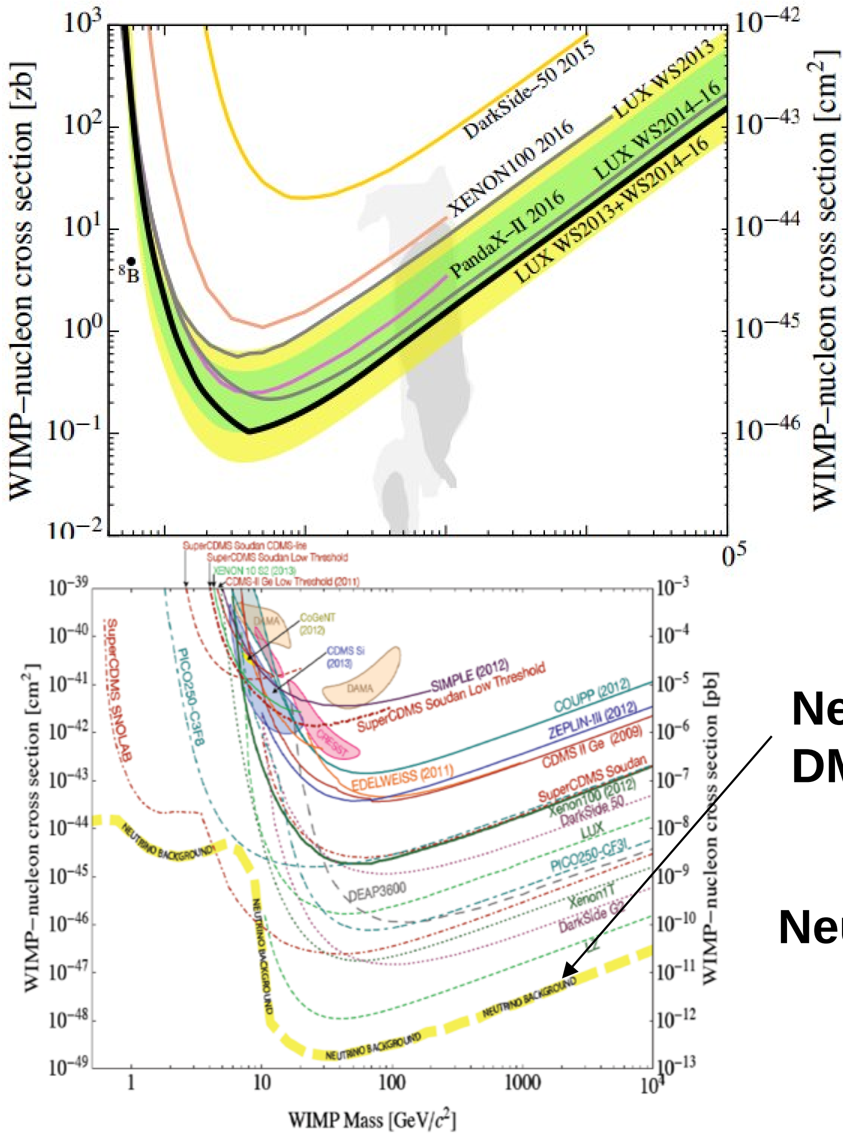
Non-colored SUSY particles: 100 GeV to 1-2 TeV
(Major role in the DM content of the Universe)
<u>Weak LHC bound</u> for non-colored particles➔ hole in searches!

Trouble in Models with very tight correlation between colored and non-colored particles , e.g., minimal SUGRA/CMSSM

LHC + Direct Detection + Indirect Detection+Planck ➔ quite constraining

Direct Detection Experiments

Status of New physics/SUSY in the direct detection experiments:



LUX: No signal for Low or High DM mass

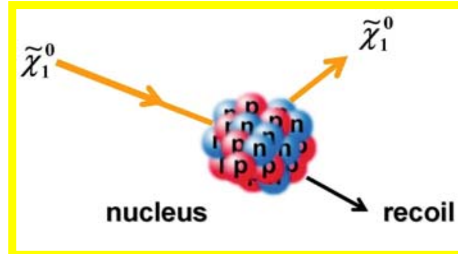
- **Astrophysical and nuclear matrix element uncertainties**
- **No signal: some particle physics models are ruled out**

Neutrino floor: A serious concern for the DM experiments

Neutrinos arise from astrophysical sources

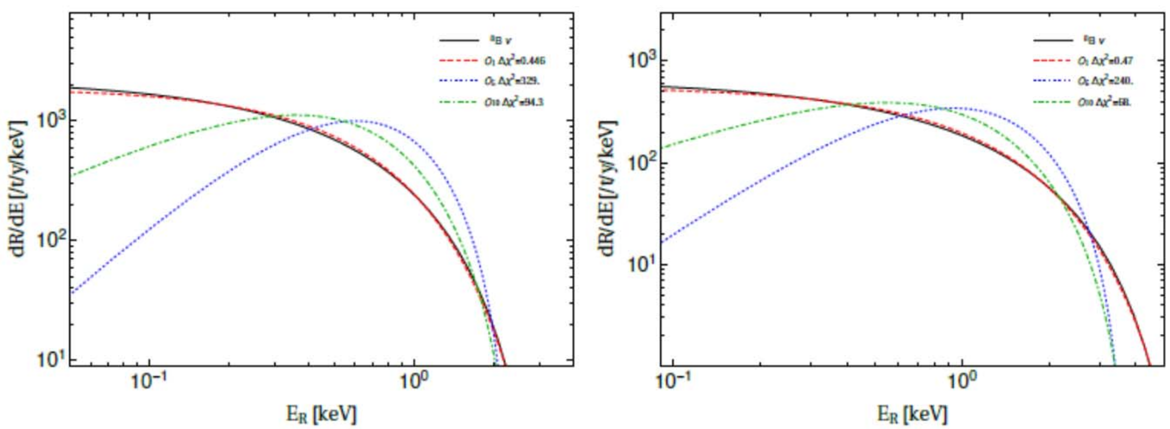
Neutrino Floor

1. Can we cut through it?



Study the nuclear recoil spectra

It is possible to detect some operators quickly compared to the other operators, e.g., $\bar{\chi}\chi\bar{q}q$ *vs* $\bar{\chi}\chi\bar{q}\gamma^5 q$ *vs* $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$



Dent, Dutta, Newstead, Strigari,'16

2. Can we determine the neutrino background from other experiments?

CEνNS experiments: COHERENT, CENNS;
CONNIE (reactor), TEXONO(reactor), MINER (reactor: Texas A&M University) etc.

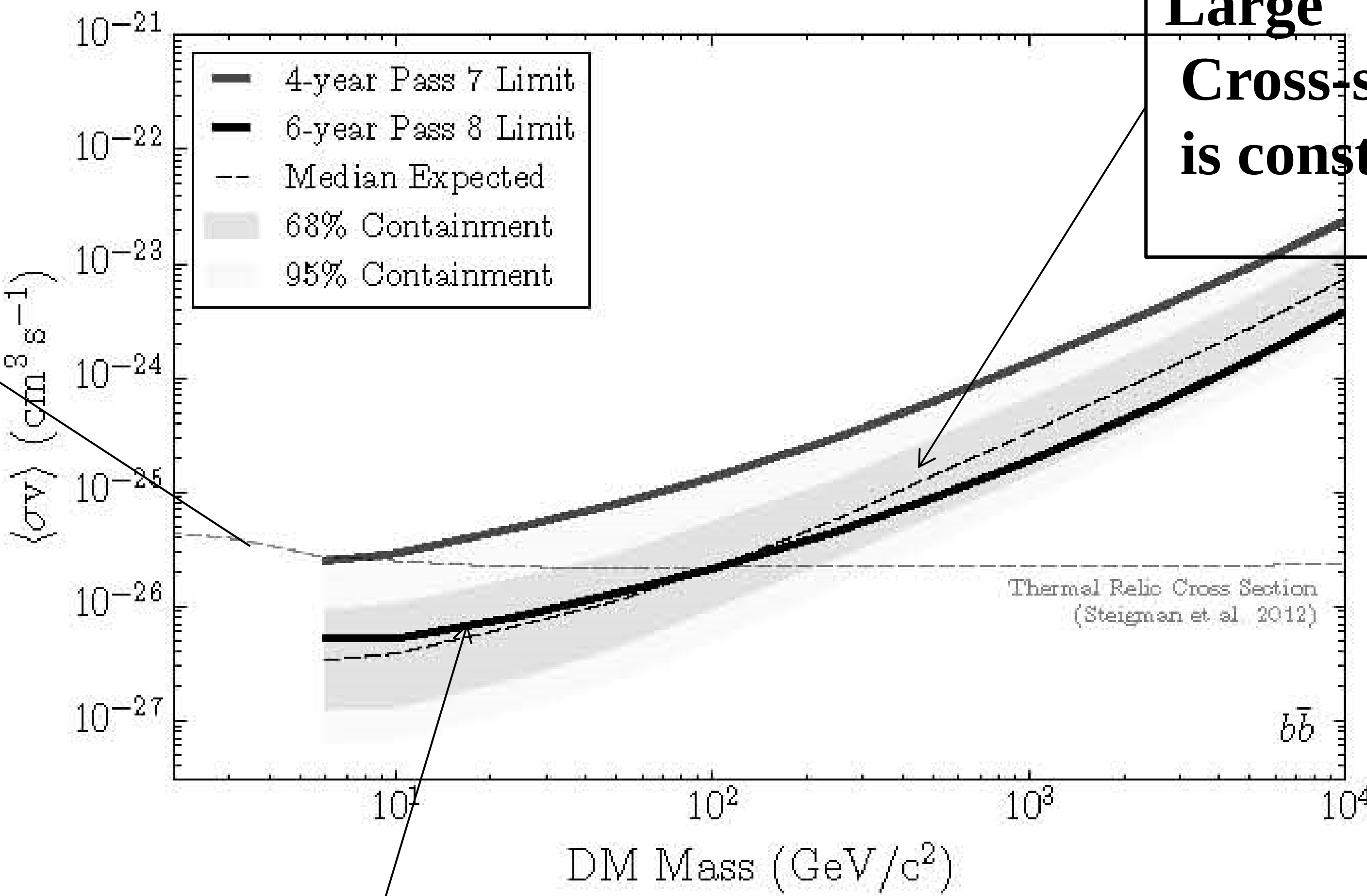
S. Wagner's talk

Indirect Detection: Fermi

Experimental constraints: $<\sigma_{ann} v>$

Large Cross-section is constrained

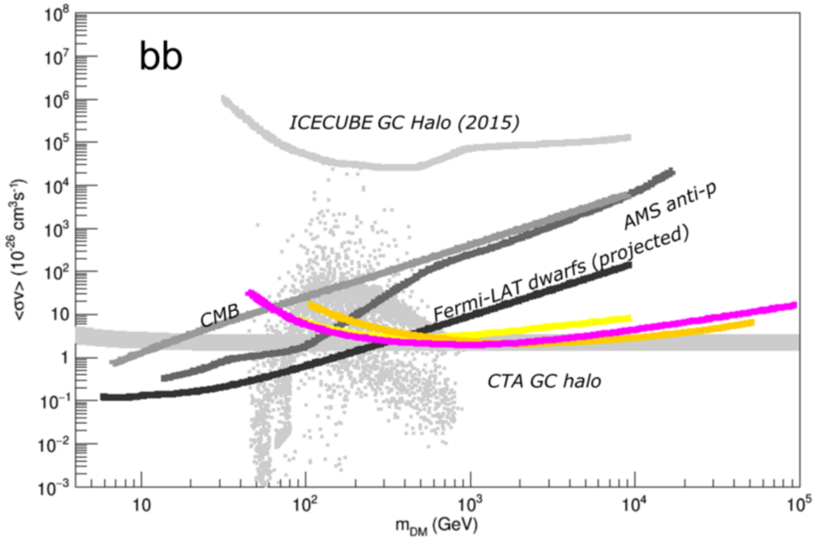
Thermal DM



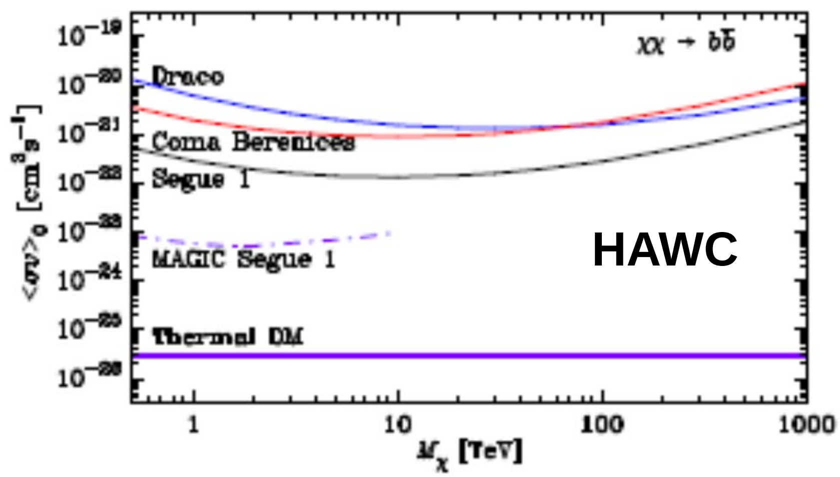
$<\sigma_{ann} v>_o$**: smaller than the thermal value**

Fermi Collaboration: arXiv:1503.02641

γ : Future



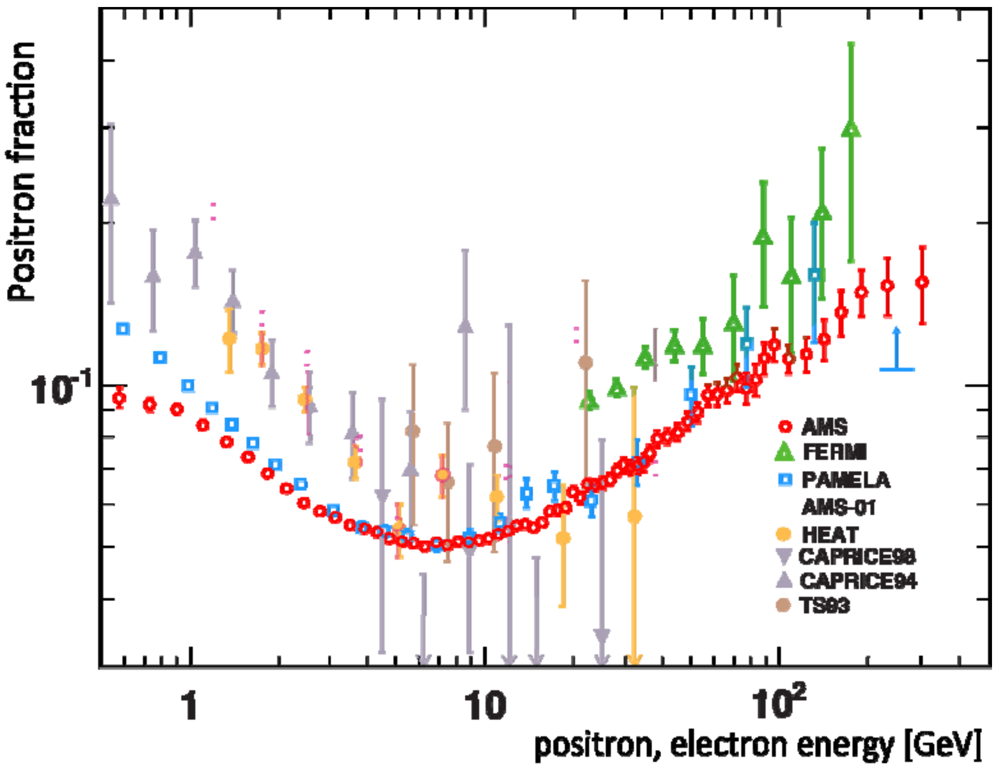
bb
ICECUBE GC Halo (2015)
AMS anti-p
Fermi-LAT dwarfs (projected)
CMB
CTA GC halo
<σv> (10^-26 cm^3s^-1)
m_DM (GeV)



χχ → bb̄
Draco
Coma Berenices
Segue 1
MAGIC Segue 1
Thermal DM
HAWC
<σv>_0 [cm^3s^-1]
M_χ [TeV]

Indirect Detection

Excess of positrons has been found by both AMS, PAMELA and Fermi

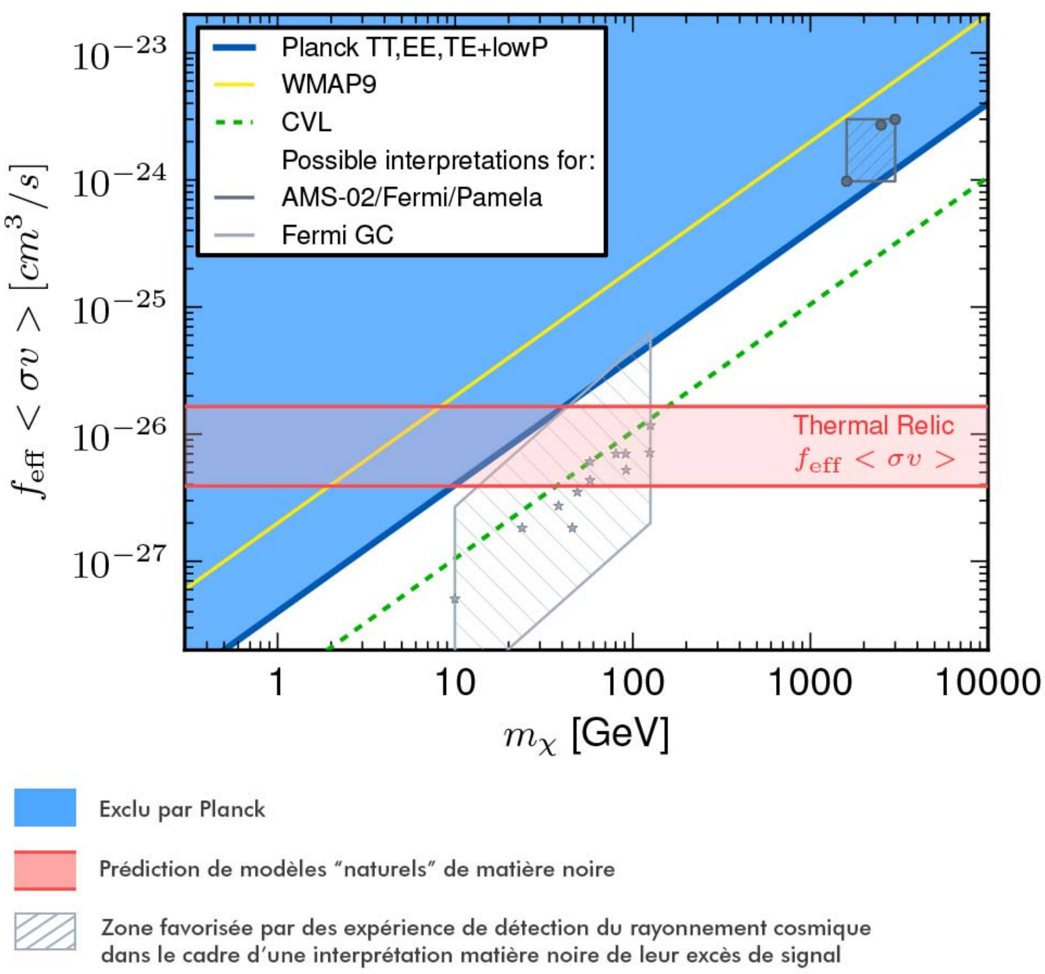


Is this excess due to DM annihilation?

Need Larger Cross-section (larger than the thermal cross-section 3x 10^{-26} cm^3/sec)

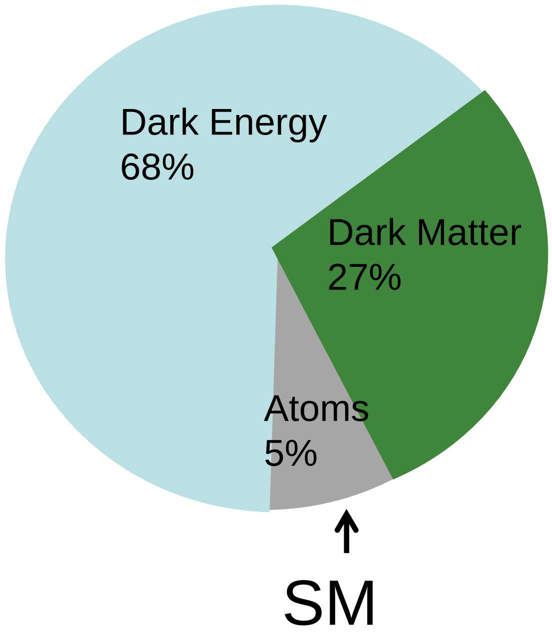
Dark Matter Mass: More than 100 GeV
Theory Models predictions: The excess will fall off
Pulsar can produce this excess

Latest result from Planck



http://public.planck.fr/images/resultats/2014-matiere-noire/plot_constraints_planck2014.jpg

Probing Dark Matter



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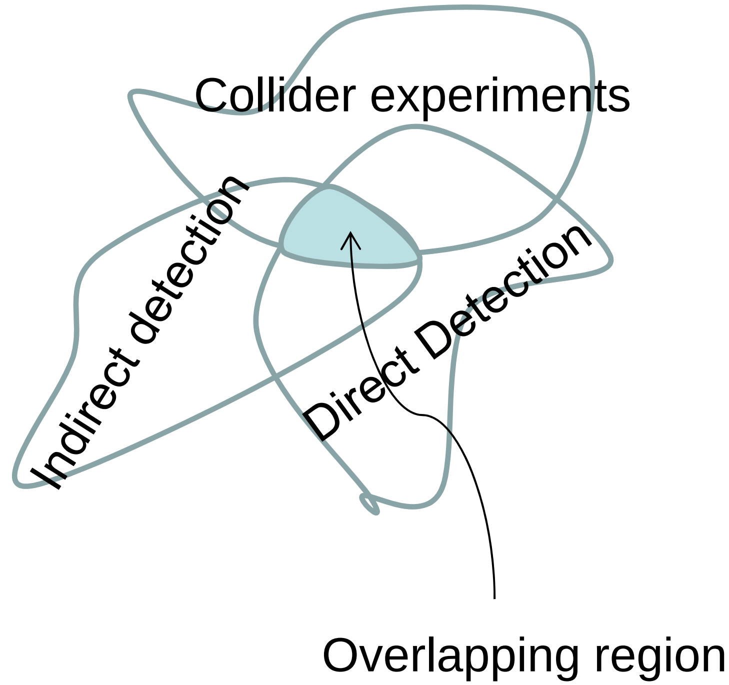


DM content (CMB) + overlapping region:

Thermal history, particle physics models, astrophysics

Dark Matter: Thermal

Production of thermal non-relativistic DM:

$$Y = \frac{n}{s} = \frac{n}{g_{*s}T^3}$$

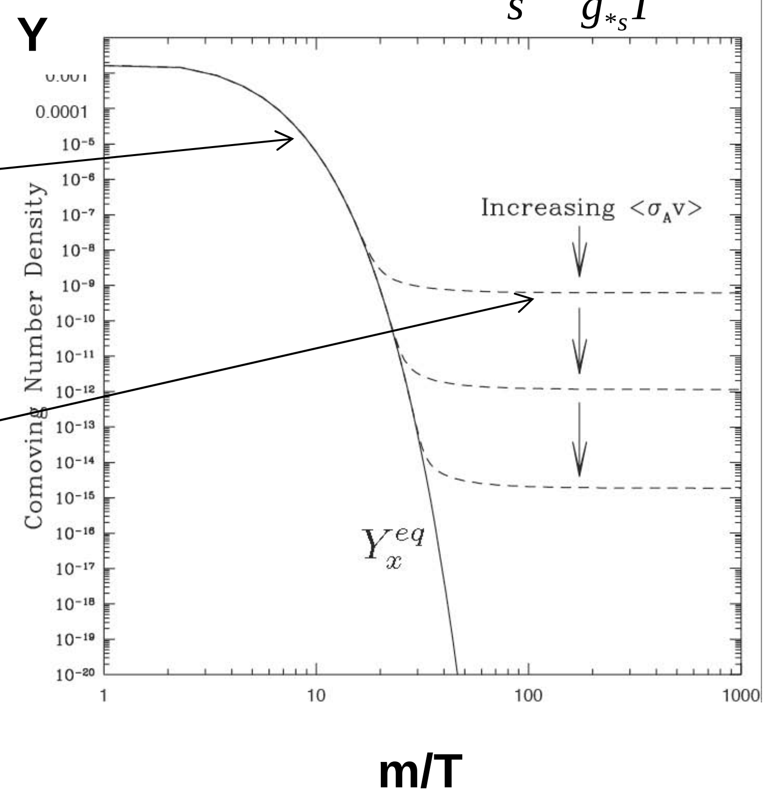
$$DM + DM \Leftrightarrow f + \bar{f}$$

$\downarrow$ **Universe cools (T<m$_{DM}$)**

$$DM + DM \Rightarrow f + \bar{f}$$

$\downarrow$

$$DM + DM \not\Leftrightarrow f + \bar{f}$$



Boltzmann equation

$$\boxed{\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle_{eq} [n_{DM}^2 - n_{DM,eq}^2]}$$

$$\langle \sigma v \rangle_{eq} = \frac{\int \frac{d^3p_1 d^3p_2 \sigma v e^{-(E_1+E_2)/T}}{(2\pi)^6}}{\int \frac{d^3p_1 d^3p_2 e^{-(E_1+E_2)/T}}{(2\pi)^6}}$$

$$n = g \int \frac{d^3 p f(\vec{p}, t)}{(2\pi)^3} \equiv nos./vol$$

Thermal Dark Matter

Boltzmann equation

$$\boxed{\frac{dn_{DM}}{dt} + 3Hn_{DM} = \langle \sigma v \rangle_{eq} [n_{DM}^2 - n_{DM,eq}^2]}$$

$$n_{DM,eq} = g_*(z)\left(\frac{mT}{2\pi}\right)^{3/2} e^{-\frac{m}{T}}$$

$$\Gamma_{eq} = n_{eq} \langle \sigma v \rangle_{eq}$$ **Interaction rate,**

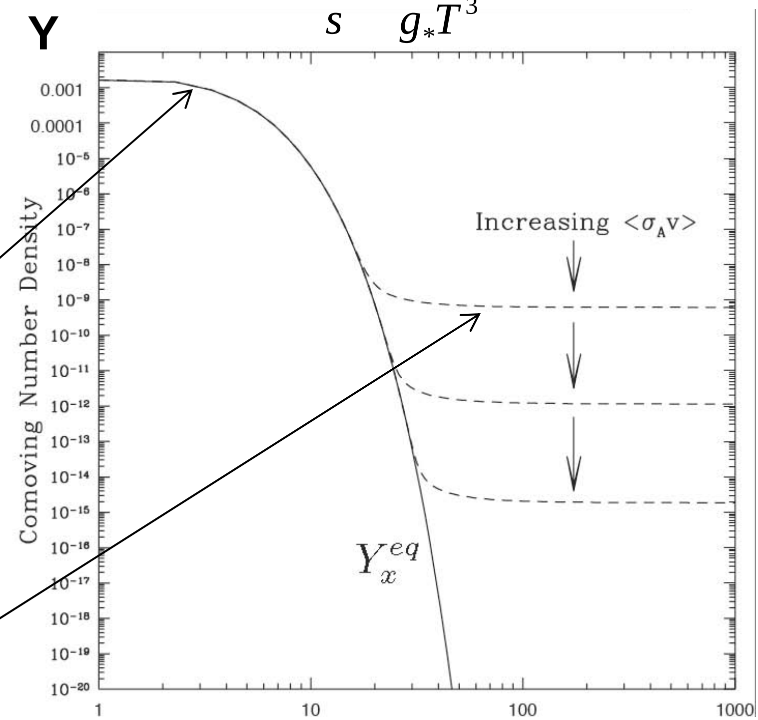
$$\boxed{\frac{x}{Y_{eq}} \frac{dY}{dx} = -\frac{\Gamma_{eq}}{H} \left[\frac{Y^2}{Y_{eq}^2} - 1\right]}$$

$$x = m/T, \quad H = T^2/M_{pl}$$

$$\frac{\Gamma_{eq}}{H} >> 1, \quad Y \rightarrow Y_{eq}$$

$$\frac{\Gamma_{eq}}{H} << 1, \quad Y \rightarrow const$$

$$Y = \frac{n}{s} = \frac{n}{g_* T^3}$$



Solution:

$$n_{DM} \cong \left(\frac{4\pi^3 G_N g_*(z)}{45}\right)^{1/2} \frac{T_0^3 g_{*s}(0)}{m g_{*s}(Z_f)} \frac{1}{\int_0^{Z_f} \langle \sigma v \rangle dz}$$

$$Z_f = \frac{KT_f}{m_{DM}} \qquad T_f = \frac{m_{DM}}{20}:$$ **Freeze-out temp**

Dark Matter: Thermal

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

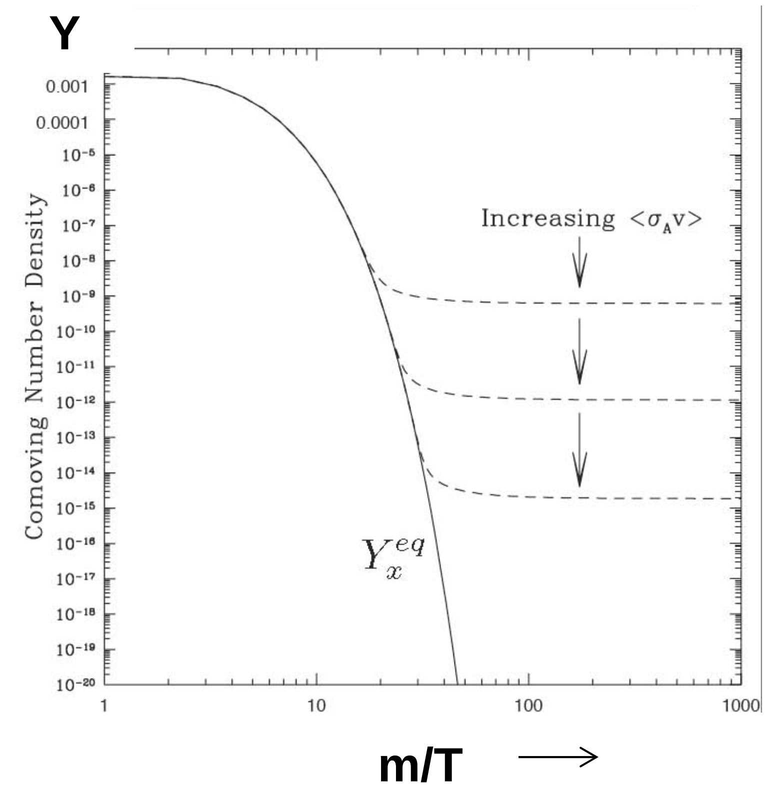
$$\Omega_{\mathrm{DM}} = \frac{m_{DM} n_{DM}}{\rho_c} \sim \frac{1}{\langle \sigma \mathrm{v} \rangle} \qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$

freeze out ➔ $T_f \sim \dfrac{m_{DM}}{20}$

➔ $$\langle \sigma \mathrm{v} \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$$

Assuming : $\langle \sigma \mathrm{v} \rangle_f \sim \dfrac{\alpha_\chi^2}{m_\chi^2}$

α_χ~O(10^{-2}) with m_χ ~ O(100) GeV leads to the correct relic abundance



Y becomes constant for $T>T_f$

Y~10^{-11} for m_χ~100 GeV to satisfy the DM content

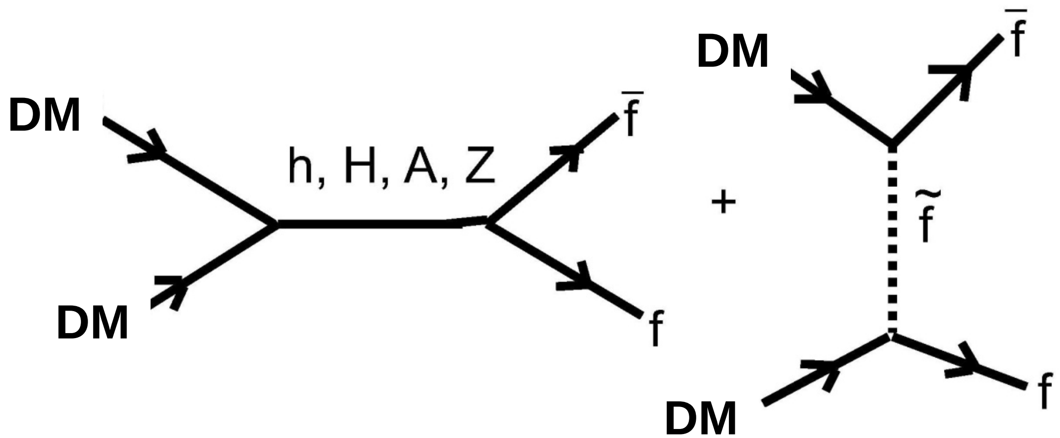
Thermal Dark Matter

DM particle + DM Particle→ SM particles

Annihilation Cross-section Rate: $<\sigma_{ann}v>$

DM Abundance:

$$\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$$



f: SM particles; h, H, A: various Higgs, : $\tilde{f}$ SUSY particle

Note: All the particles in the diagram are colorless

- **We need** $\langle \sigma v \rangle = 3\times 10^{-26}\,\frac{cm^3}{s}$ **to satisfy thermal DM requirement**

Thermal Dark Matter

Suitable DM Candidate:
Weakly Interacting Massive Particle (WIMP)

Typical in Physics beyond the SM (LSP, LKP, …)

Most Common: Neutralino (SUSY Models)

smaller annihilation cross-section

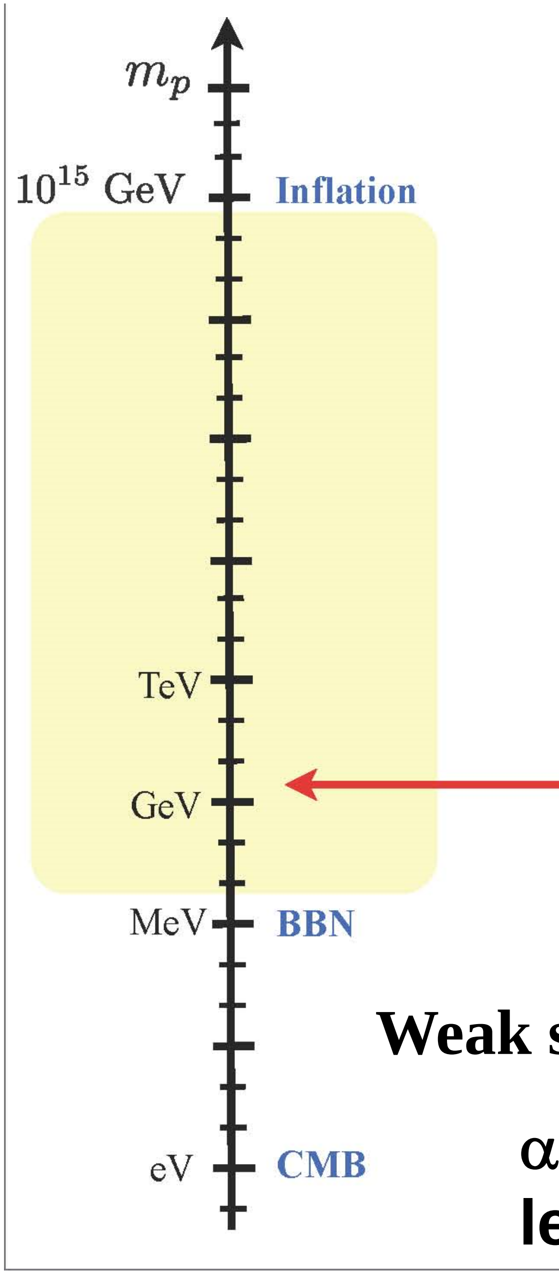
Neutralino: Mixture of Wino, Higgsino and Bino

Larger annihilation cross-section

$$\Omega_{\mathrm{DM}} \sim \frac{1}{\langle \sigma v \rangle}$$

Larger/Smaller Annihilation ➔
non-thermal DM/non-standard cosmology

Thermal Dark Matter

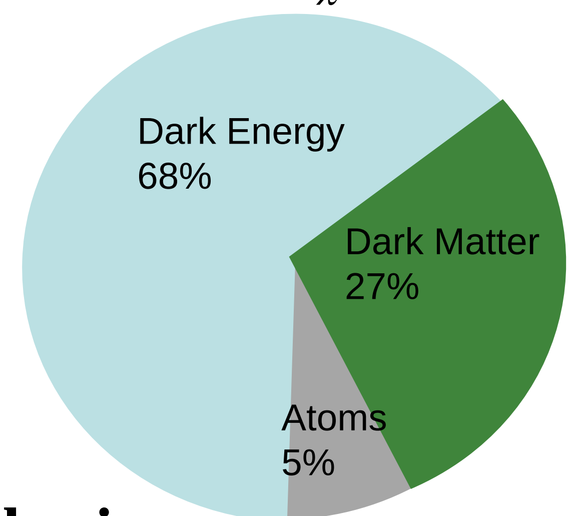


WIMP

Dark Matter content: $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$

$$\langle \sigma v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$$

freeze out ➔ $T_f \sim \frac{m_{DM}}{20}$



➔ $\langle \sigma v \rangle = 3 \times 10^{-26} \, \frac{cm^3}{s}$

Weak scale physics :

$\alpha_\chi \sim O(10^{-2})$ with $m_\chi \sim O(100)$ GeV
leads to the correct relic abundance

Status of Thermal DM

Thermal equilibrium above T_f is an assumption.

History of the Universe between the BBN and inflation is unknown

Non-standard thermal history at is generic in some explicit UV completions of the SM.

Acharya, Kumar, Bobkov, Kane, Shao'08
Acharya, Kane, Watson, Kumar'09
Allahverdi, Cicoli, Dutta, Sinha,'13

DM content will be different in non-standard thermal histories (i.e., if there is entropy production at $T < T_f$).

Barrow'82, Kamionkowski, Turner'90

DM will be a strong probe of the thermal history after it is discovered and a model is established.

Non-Thermal DM

$< \sigma_{ann} v >$: **different from thermal average,** $\Omega_{\rm DM} \sim \frac{1}{\langle \sigma v \rangle}$ **is not 27%**

Non-thermal DM can be a solution

DM from the decay of heavy scalar field, e.g., Moduli decay

Moroi, Randall'99; Acharya, Kane, Watson'08, Randall; Kitano, Murayama, Ratz'08; Dutta, Leblond, Sinha'09; Allahverdi, Cicoli, Dutta, Sinha,'13

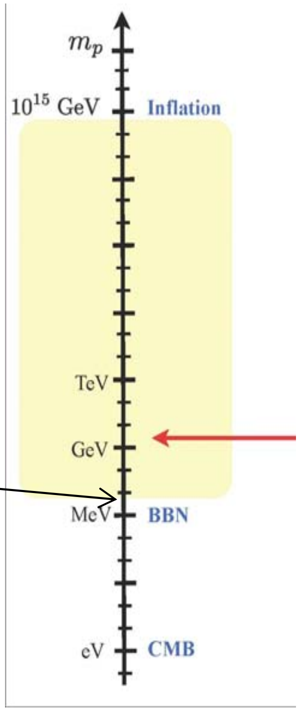
[Moduli : heavy scalar fields gravitationally coupled to matter]

History:

Radiation domination➔Moduli dom. (m_ϕ>H)➔Radiation dom.

Decay of moduli/heavy field occurs at:

$$T_r \sim c^{1/2} \left(\frac{m_\phi}{100\mathrm{TeV}} \right)^{3/2} (5\mathrm{MeV})$$



For T_r<T_f: Non-thermal dark matter

T_r**~ MeV : Not allowed by BBN**

Abundance of decay products (including DM) $Y_\phi \equiv \frac{3T_r}{4m_\phi}$

DM content: also needs to consider the DM annihilation.

Non-Thermal DM

Large entropy dilutes the thermal abundance:

$$\Omega_{th} \approx \Omega \left(\frac{T_r}{T_f}\right)^3$$ ➔ **small unless $\langle\sigma_{ann}v\rangle$ is small..**

Moduli decay into dark matter and the correct dark matter content can arise from the decay products:

1.

$$\Omega = 0.27 \times \left(\frac{3\times 10^{-26}\, cm^3/s}{\langle \sigma v\rangle (\frac{T_f}{T_r})} \right) \Rightarrow \langle \sigma v \rangle = 3\times 10^{-26} (\frac{T_f}{T_r}) cm^3/s$$

➔ **Larger annihilation cross-section is needed since $T_f > T_r$**

2. **Abundance of Decay products (Y_ϕ) is small enough, i.e., annihilation is not important any more**

Benefit of Non-Thermal DM

- **For $T_r < T_f$, larger annihilation cross-section** $\langle \sigma_{ann} v \rangle_f = \langle \sigma_{ann} v \rangle_f^{th} \dfrac{T_f}{T_r}$ **is needed for** $\Omega \to 27\%$

- **For $T_r \ll T_f$, Yield** $Y_\phi \equiv \dfrac{3T_r}{4m_\phi}; \quad Y_{DM} = Y_\phi BR_{\phi \to DM}$ **is small ~10^{-10}**
  DM will be produced without any need of annihilation
  [Note: For m_{DM}~10 GeV, Y_ϕ is needed to be ~10^{-10} to satisfy the DM content]

Outcome:

- **Large and small annihilation cross-section from models are okay**
- **We may not need any annihilation**

Since $\phi \to DM +$ **other particles, abundance (for $T_r \ll T_f$): 10^{-10}**

- **The Baryon and the DM abundance are correlated ~ 10^{-10}**

Allahverdi, Dutta, Sinha'11

DM and Baryon Abundance

$$\frac{\Omega_b}{\Omega_{DM}} = \frac{5}{27}$$

Baryon abundance: $\Omega_b = \frac{m_b n_b}{\rho_c}$

DM abundance: $\Omega_{DM} = \frac{m_{DM} n_{DM}}{\rho_c}$

ρ_c=critical density

n = number density

If m_{DM} ~ few GeV ➔ $n_b \sim n_{DM}$ (since m_b=1 GeV)

Same number densities➔ same origin

Heavy field decay to DM and generate Baryon abundance

(without any annihilation cross-section uncertainty)

➔Solves the coincidence problem

Why baryon and DM abundances are similar?

Predictive model has been constructed

Allahverdi, Dutta, Mohapatra, Sinha, '13

Dark Matter & Baryogenesis from ϕ

$$W_{extra} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha + M_\alpha X_\alpha \overline{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta$$

N : **SM singlet;** $X, \overline{X}$: **Color triplet, hypercharge** $\pm$ **4/3**

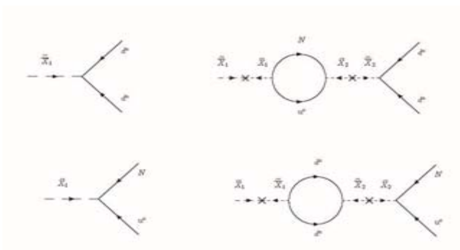
***N* fermions and *X* scalars and their SUSY partners**

➔ R parity conserved

$\tilde{N}$ **: can be the DM candidate (spin 0) with small mass and large spin-independent cross-section**

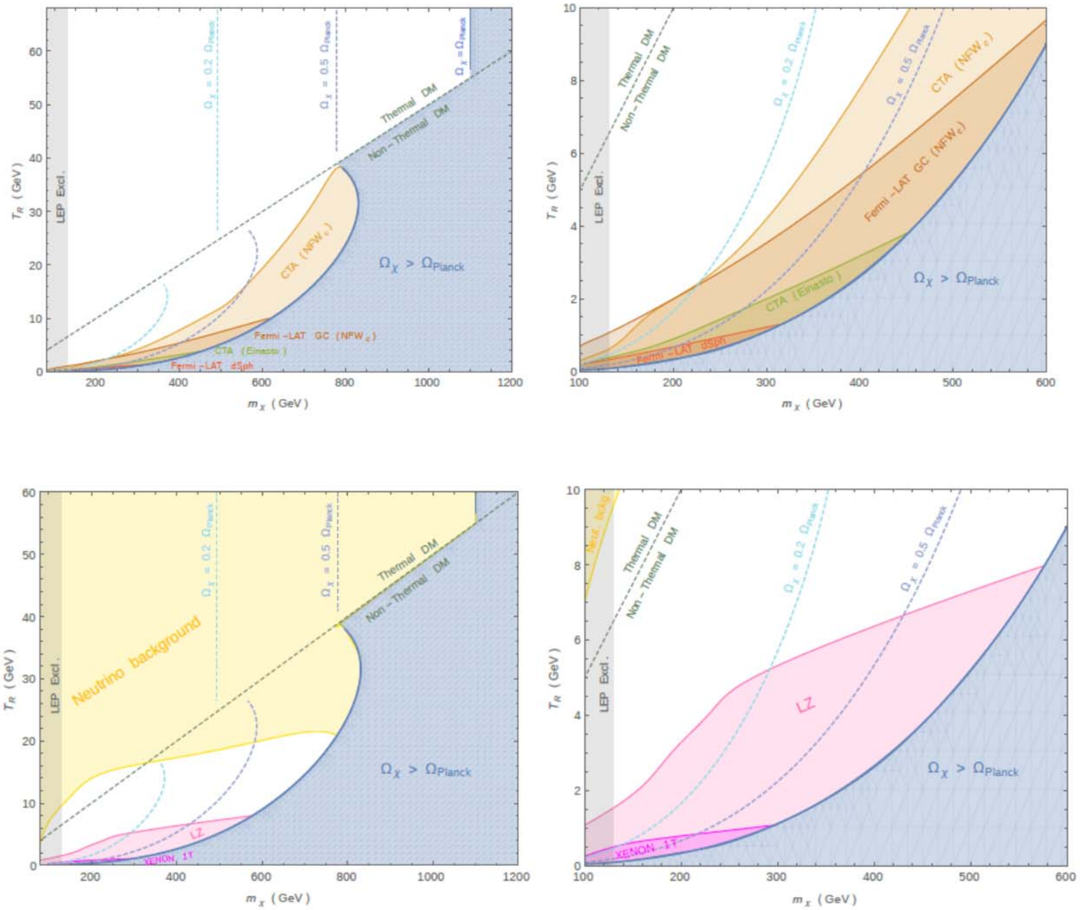
[Allahverdi, Dutta, Mohapatra, Sinha'13]

Baryogenesis from decays of $X, \overline{X}$ **or** N



$$\epsilon_1 \simeq \frac{1}{8\pi} \frac{\sum_{i,j,k} \mathrm{Im}(\lambda_k^{1*} \lambda_k^2 \lambda_{ij}^{\prime 1*} \lambda_{ij}^{\prime 2})}{\sum_{i,j} |\lambda_{ij}^{\prime 1}|^2 + \sum_k |\lambda_k^1|^2} \frac{B_1 B_2 M_1 M_2 m_{\tilde{X}_1}^2}{(m_{\tilde{X}_1}^2 - m_{\tilde{X}_2}^2)^3}.$$

Non-Thermal CMSSM



Aparicio, Cicoli, Dutta, Muia, Quevedo'16

- ❑ **CMSSM/mSUGRA parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$, sign of μ + T_R**
- ❑ **We consider the case with large $<\sigma v>_{ann}$**

This scenario can be realized in the context of LVS

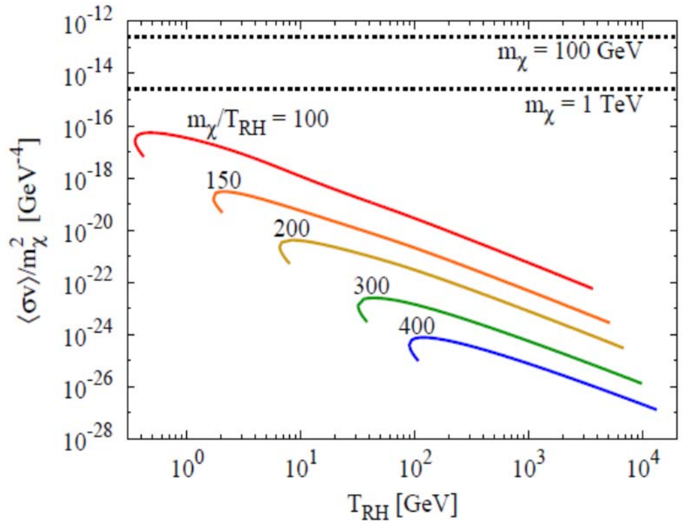
DM from Early Matter domination

DM abundance from early matter domination (moduli)

DM candidate can be Neutralino

Kamionkowski and M. S. Turner,'90; Giudice, Kolb, Riotto,'01; Gelmini,Gondolo'06

$$\Omega_\chi h^2 \simeq 1.6 \times 10^{-4} \frac{\sqrt{g_{*\mathrm{RH}}}}{g_*(T_f)} \left(\frac{m_\chi/T_f}{15}\right)^4 \left(\frac{150}{m_\chi/T_{\mathrm{RH}}}\right)^3 \times \left(\frac{3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle}\right),$$



Small $<\sigma_{ann}v>$ is allowed by the DM content

- ❑ **If the dark matter kinetically decouples prior to reheating**
  ➔ **enhances small-scale perturbations which significantly increase the abundance of microhalos**

Erickcek'15

Erickcek, Sigurdson,'11

- ❑ **The boost to the annihilation rate from the microhalos is sufficient to be observed at Fermi**

Non-Standard Cosmology

Correlation between DM and DE

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,R - \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + V(\phi)\right] - \int d^4x\sqrt{-\tilde{g}}\,\mathcal{L}_{DM}(\tilde{g}_{\mu\nu})$$

$$\tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi\,,$$

Bekenstein'93
Koivisto, Wills, Zavala, '13

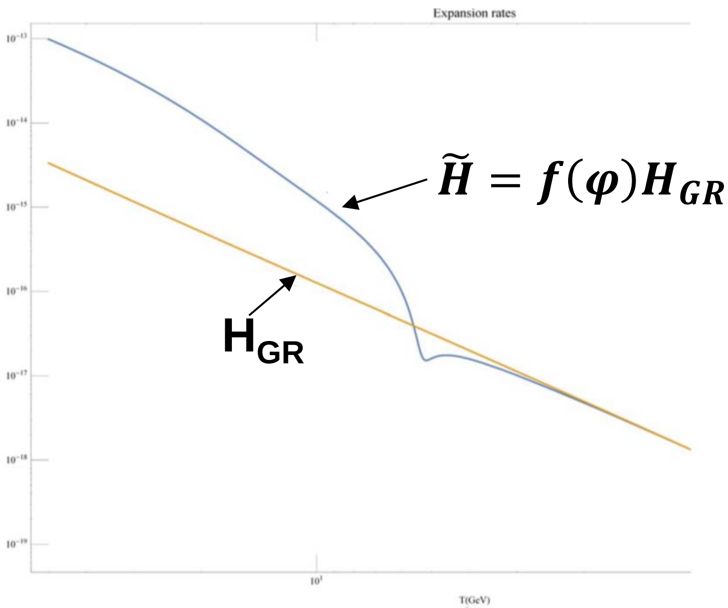
A new H ($\equiv \frac{\dot{a}}{a}$) appears which is different compared to the standard cosmology

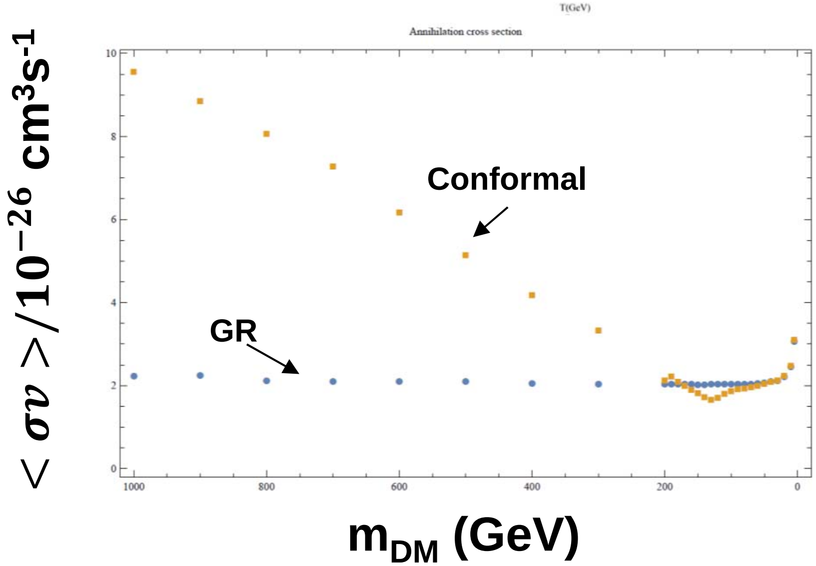
Catena, Fornengo, Masiero, Pietroni, Rosati'04
Lahanas, Nanopoulos, Mavromatos, 06
Meehan, Whittingham, '15

The Boltzmann equation also gets modified

➔ Modify <σ_{ann}v> to satisfy the DM content

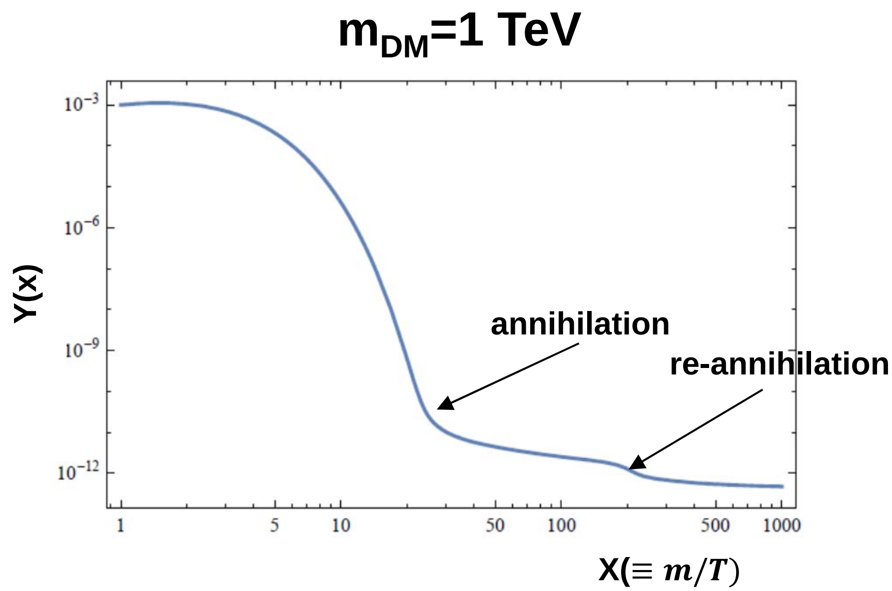
Changing H before BBN





Initial conditions:

$\varphi = 0.2, \varphi' = -1.180$



Dutta, Jiminez, Zavala, to appear

So Far…

Measurement of DM annihilation cross-section is crucial
Large : multicomponent/non-thermal/non-standard cosmology;
Small: Non-thermal/early matter domination/non-standard

- **LHC: Determine the model then calculate** $< \sigma_{ann} v >$

- **DM annihilation from galaxy, extragalactic sources**

    Annihilation into photons: Fermi, CTA, HAWC

    Annihilation into neutrinos: IceCube

Dark Matter at the LHC

Annihilation of lightest neutralinos ➔ quarks, leptons etc.
At the LHC: proton + proton ➔ DM particles

DM Annihilation diagrams: mostly non-colored particles
e.g., sleptons, staus, charginos, neutralinos, etc.

How do we produce these non-colored particles and the DM particle at the LHC? Can we measure the annihilation cross-section $< \sigma_{ann} v >$?

1. **Cascade decays of squarks and gluinos**
2. **Monojet Searches**
3. **Via stop squark**
4. **Vector Boson fusion**

1. Via Cascade decays at the LHC

LHC is very complicated

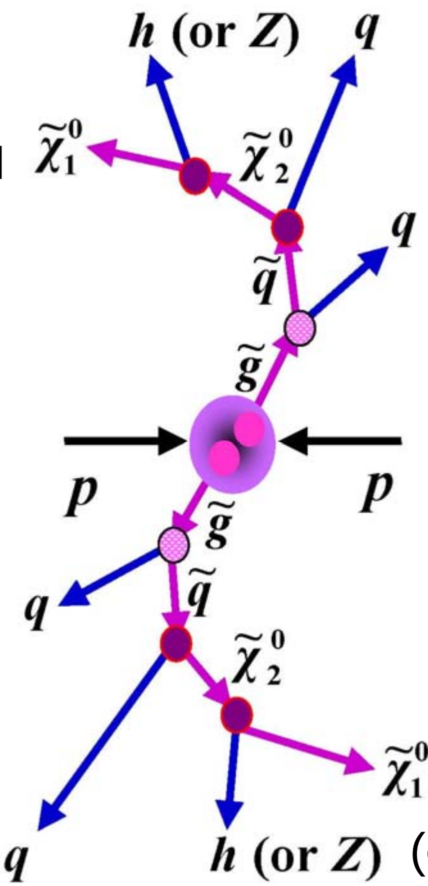
Colored particles are produced and they decay finally into the weakly interacting stable particle

(or l^+l^-, $\tau+\tau-$)

High P_T jet

[mass difference is large]

DM



The p_T of jets and leptons depend on the sparticle masses which are given by models

DM **R-parity conserving**

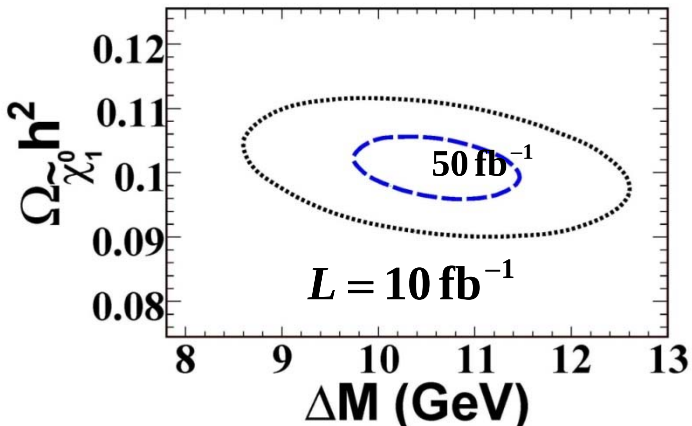
High P_T jet (or l^+l^-, $\tau+\tau-$)

The signal :

jets + leptons+ t's +W's+Z's+H's + missing E_T

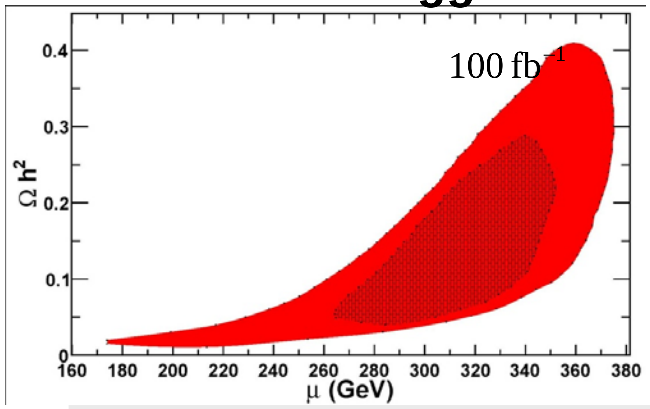
Via Cascade decays at the LHC

mSUGRA



Arnowitt, Dutta, Kamon, Gurrola, Krislock, Toback: PRL 100 (2008) 231802

Non Universal Higgs Model



$\mathcal{L}$ (fb^{-1})	$m_{1/2}$ (GeV)	m_H (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ (GeV)	$\Omega_{\tilde{\chi}_1^0} h^2$
1000	500 ± 3	727 ± 10	366 ± 26	3 ± 34	39.5 ± 3.8	321 ± 25	$0.094^{+0.107}_{-0.038}$
100	500 ± 9	727 ± 13	367 ± 57	0 ± 73	39.5 ± 4.6	331 ± 48	$0.088^{+0.168}_{-0.072}$
Syst.	± 10	± 15	± 56	± 66	± 4.5	± 48	$^{+0.175}_{-0.072}$

Dutta, Gurrola,Kamon, Krislock, Mavromatos, Nanopoulos: Phys.Rev. D79 (2009) 055002

Mirage Mediation Model

Particle	Mass	Stat.
$\tilde{t}$	690	$\pm$ 6
$\tilde{b}$	1002	$\pm$ 126
$\tilde{\tau}$	717	$\pm$ 10
$\tilde{q}$	1133	$-132, +167$

@ 200 fb^{-1}

$$\Omega h^2 = 0.23 \pm 0.13.$$

Dutta, Kamon, Krislock, Sinha, Wang: Phys.Rev. D85 (2012) 115007

Determine DM content at 14 TeV LHC with high luminosity If squarks are produced

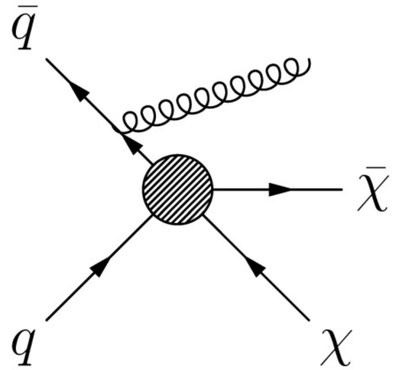
2. Monojet Searches

Dark Matter production ➔missing energy
Jets from a gluon radiated from quarks➔
Monojet plusMET (similarly monophoton+MET)

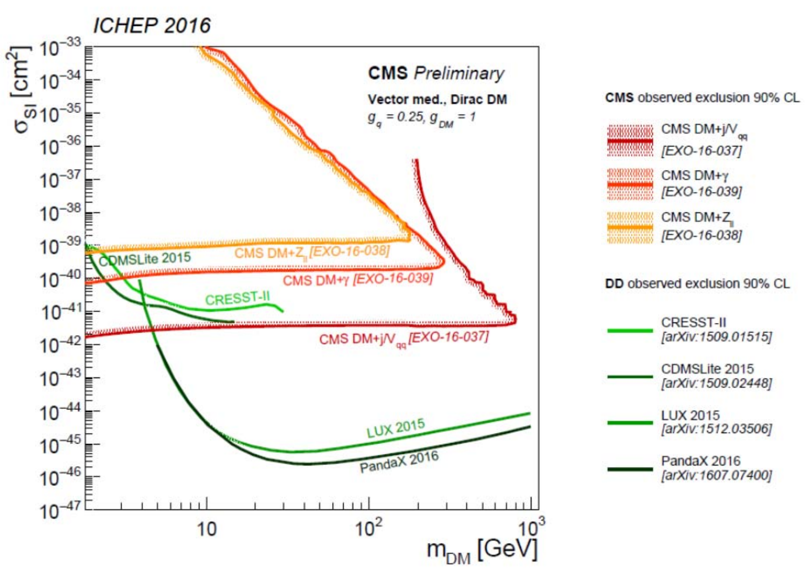
Effective Operators, e.g.,

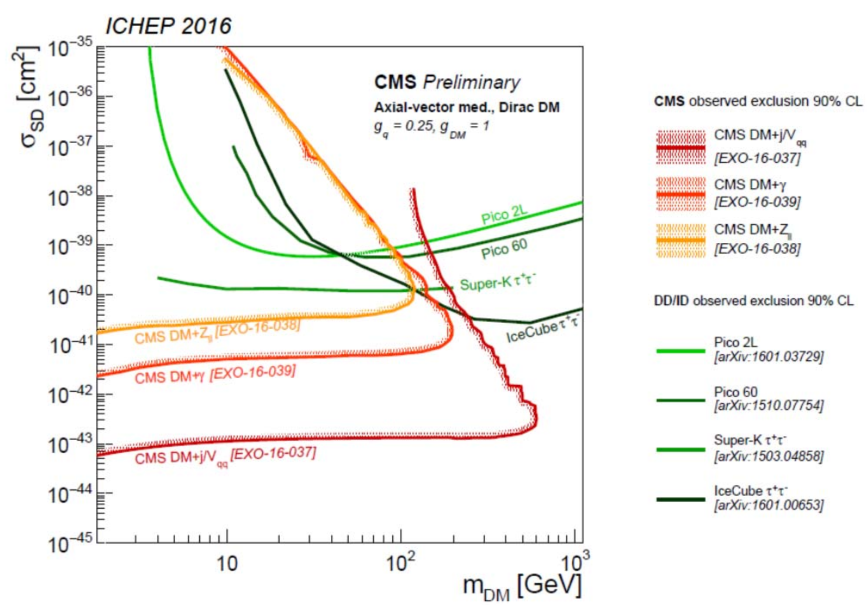
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$



[Bai,Fox and Harnik,JHEP 1012:048 (2010)]; Goodman, Ibe,Rajaraman, Shepherd,Tait,Yu, Phys.Rev.D82:116010 (2010)]





3. DM via Stop at the LHC

Utilize Stop decay modes to search charginos, sleptons, neutralinos

Ex. 1 χ_1^0 **is mostly bino and** χ_2^0 **is wino**

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

Stop can identified via fully hadronic or 1 lepton plus multijet final states

[Bai, Cheng, Gallichio, Gu, '12;Han, Katz, Krohn, Reece, 13;Plehn, Spannowsky, Takeuchi, JHEP '13;Kaplan, Rehermann, Stolarski, JHEP '12; Dutta, Kamon, Kolev, Sinha, Wang,'12]

Ex. 2 $\chi_{1,2}^0$ **are mostly Higgsino**

Topness variable to identify stops

Grasser, Shelton, '13

Ex. 3 χ_1^0 **is mostly Bino-Higgsino**
➔ Correct relic density

For lighter sleptons

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_2^0 \rightarrow t + l + \tilde{l}^* \rightarrow t + l + \bar{l} + \tilde{\chi}_1^0,$$
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm} \rightarrow t + \nu + \tilde{l} \rightarrow t + l + \nu + \tilde{\chi}_1^0$$
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

2 jets+ 2 leptons (OSSF-OSDF) +missing energy

Dutta, Kamon, Kolev,Wang, Wu, '13

➔ Existence and type of DM particle, hard to calculate the DM content

4. DM at the LHC Via VBF

- LHC has a blind spot for productions of non-colored particle

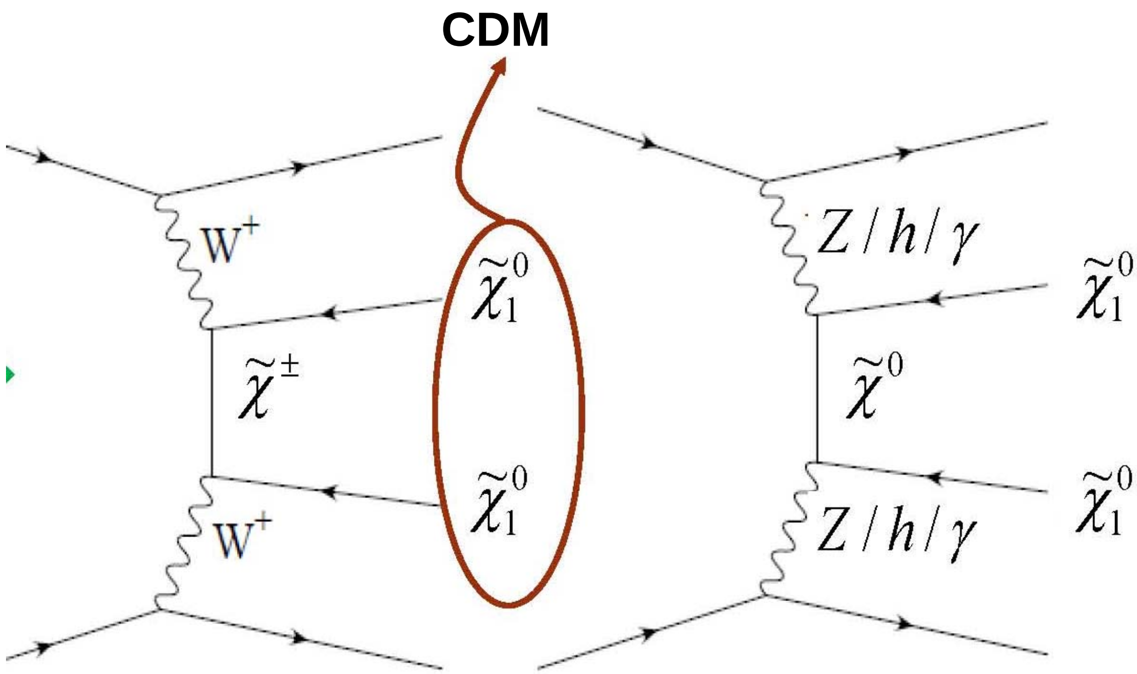
- The W boson (colorless) coming out of high energy protons
  can produce colorless particles➔
  Vector Boson Fusion(VBF)

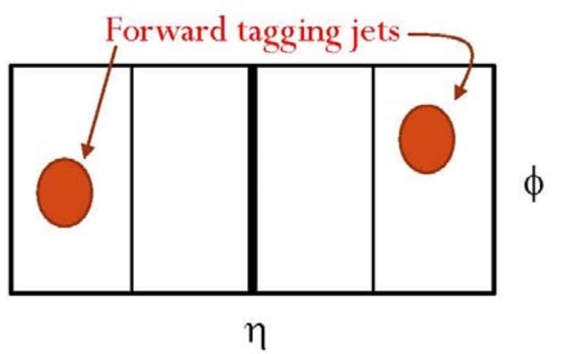
- Special search strategy needed to extract the signal

- New way of understanding DM or new physics
  sector at the LHC

DM Via W at the LHC

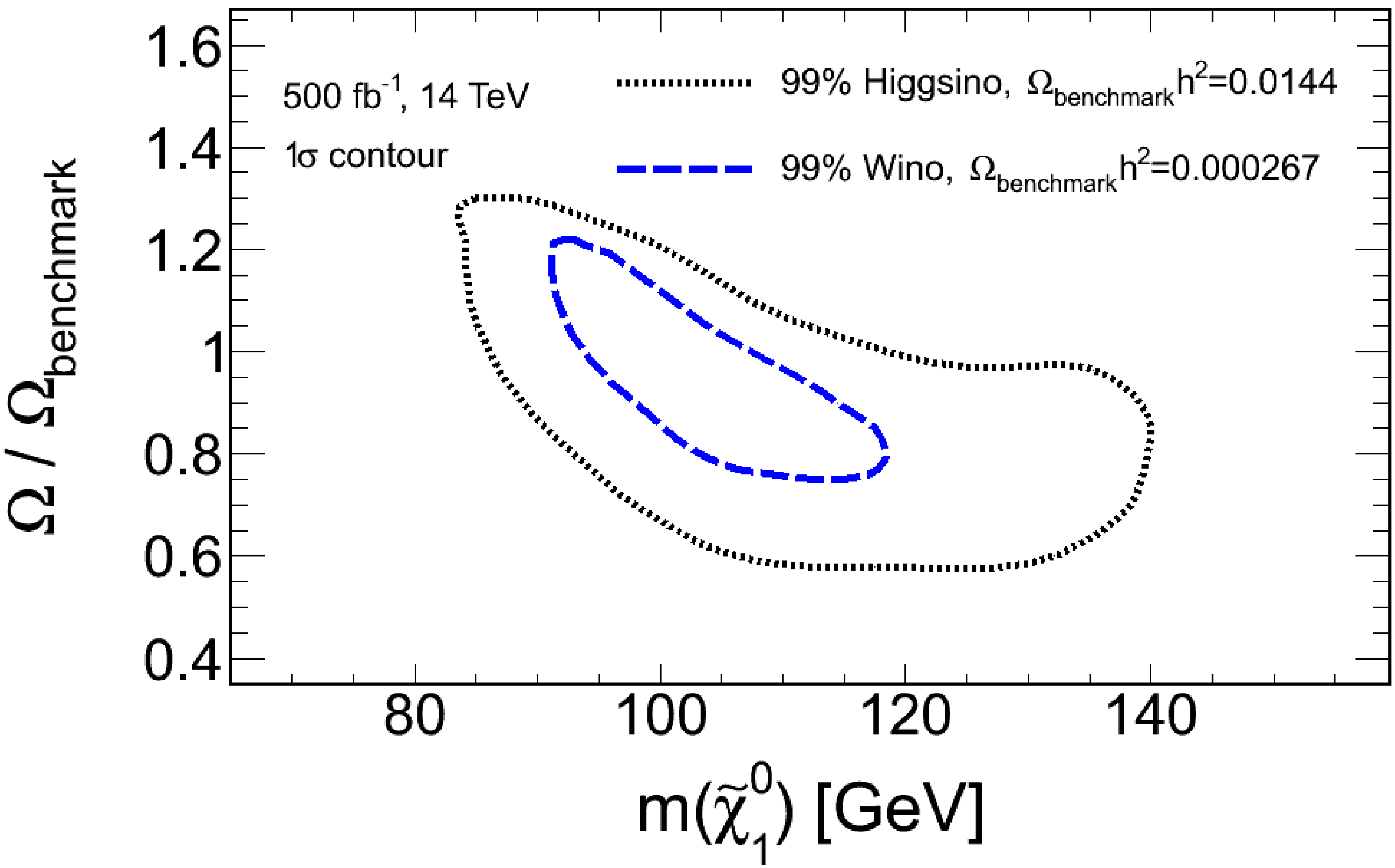
$$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj$$





DM Content via VBF

Simultaneous fit of the observed rate, shape of missing energy distribution:



Conclusion

- **History of the Universe between the BBN and inflation is unknown➔ the origin of the DM content may not be due to thermal and/or standard cosmology.**

- **Non-thermal/non-standard cosmology scenarios can accommodate both large and small annihilation cross-sections and can allow us to understand the baryon-DM coincidence puzzle**

- **DM ideas have constraints from LHC, Planck, direct and indirect detection constraints**

- **Measurements of $\langle\sigma_{ann}v\rangle$ is crucial LHC and Indirect detections ➔ identify DM model**

- **Understanding the Neutrino floor is crucial to utilize the DM direct detection results in the upcoming days**