Scalar Dark Matter and Standard Model with Four Generations

e-Print: arXiv:1004.3464 [hep-ph]

Ho-Chin Tsai
NCKU
In Collaboration with
XG He, SY Ho, J Tandean (NTU)

CYCU May 25, 2010

Outline

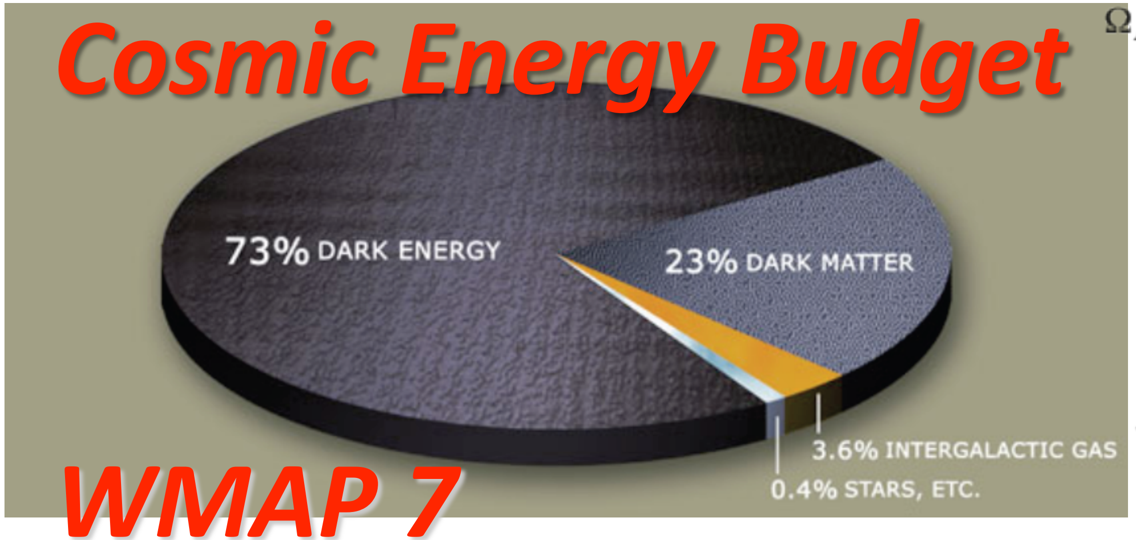
1. Introduction
2. Standard Model + Scalar Dark Matter
3. 4^{th} Generation Fermions added
4. Darkon Effect on Higgs sector
5. Constraint from B decay
6. FCNC decay of Top quark and b′, t′
7. Conclusions

1. Introduction

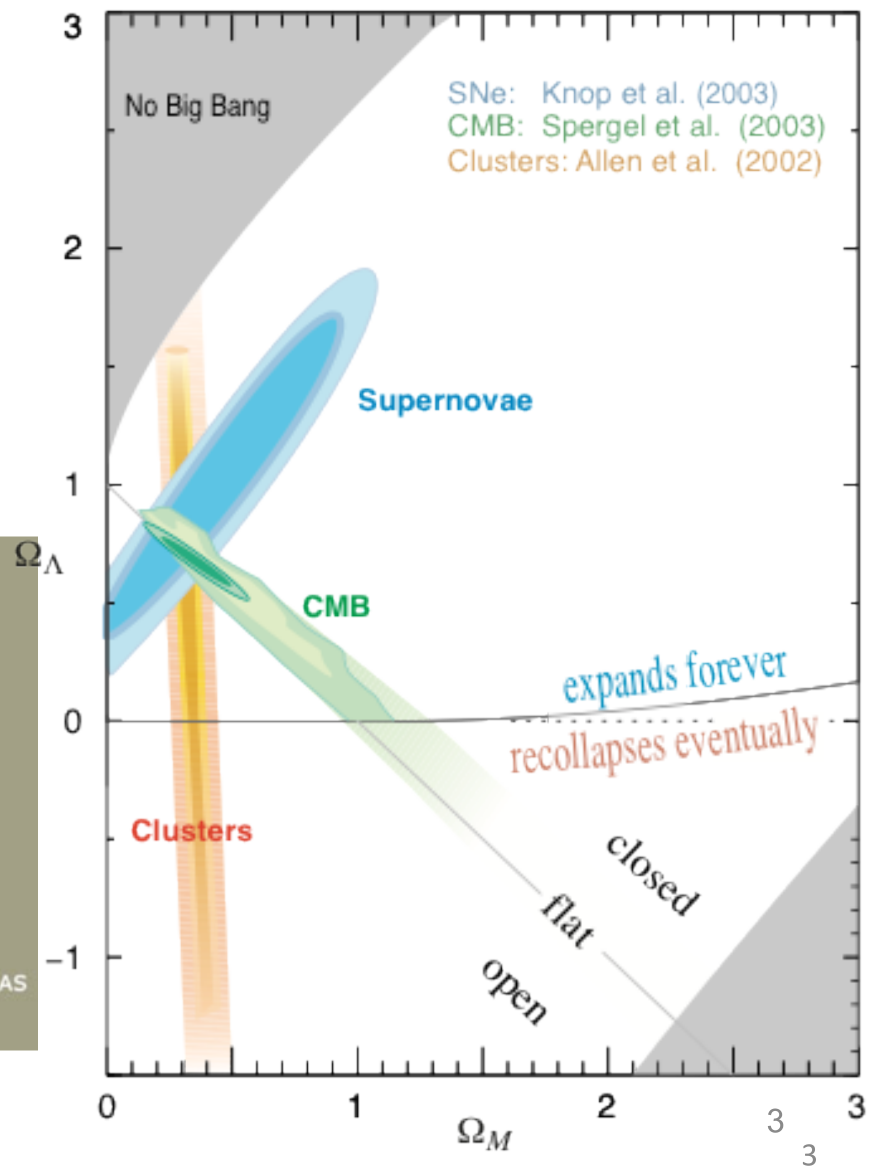
Hot Big-Bang Cosmology
Theoretical Support:
- *GR in FRW metric, particle physics, …*

Experimental support:
- *Hubble's Law, CMB, BBN, …*
- *DM PreBBN ?*

Global fit to various cosmological parameter

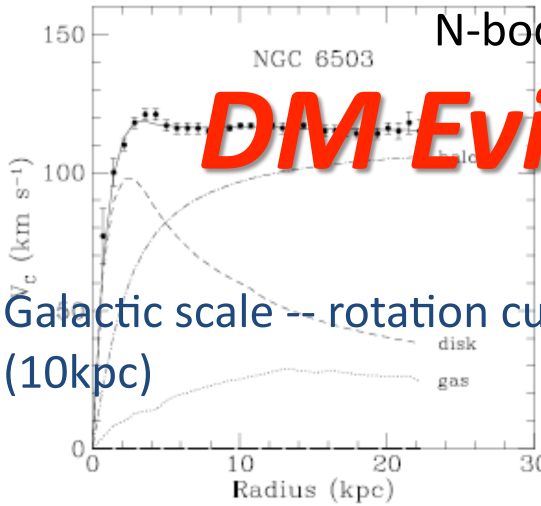


$$\Omega_D h^2 = 0.1123 \pm 0.0035$$



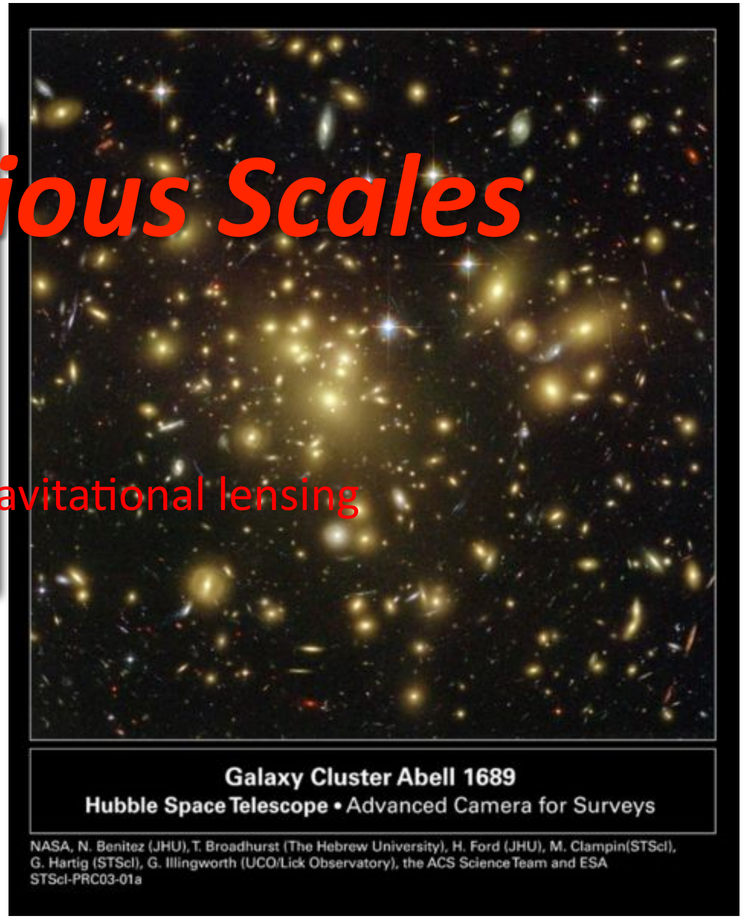
DM Evidences in Various Scales

N-body simulation

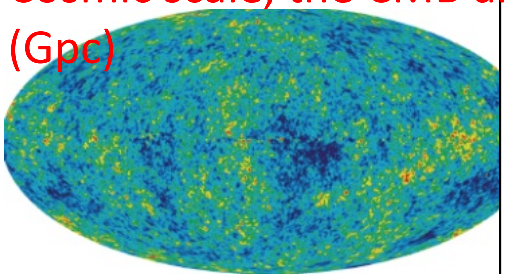


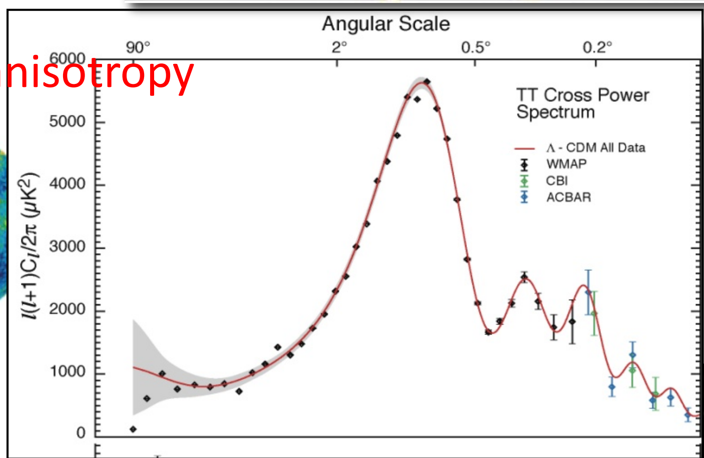
Galactic scale -- rotation curve (10kpc)

Gravitational lensing

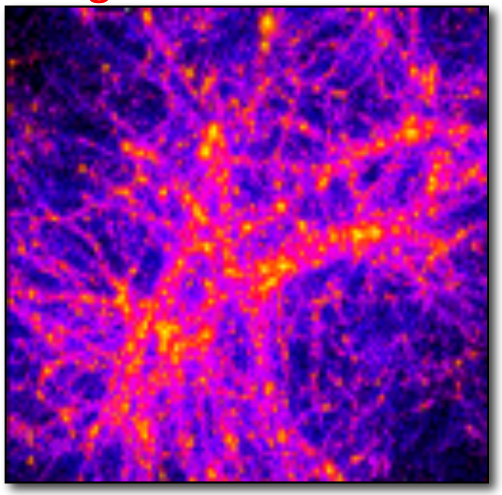


Cosmic scale, the CMB anisotropy (Gpc)

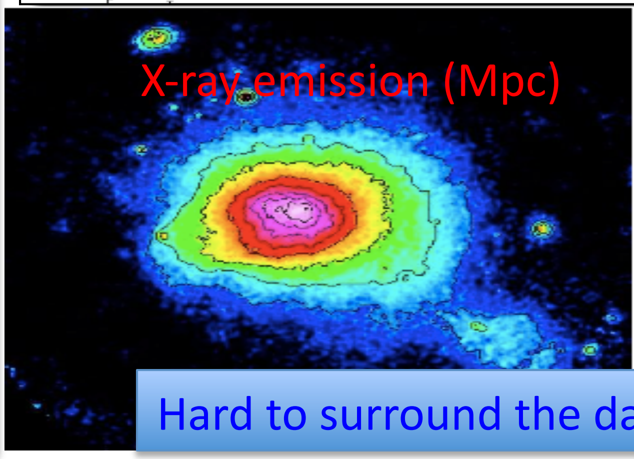




Large scale structure



X-ray emission (Mpc)



Hard to surround the dark matter explanation

Introduction

- The simplest model with a WIMP candidate is SM3+D:
  - the minimal SM with 3 generations of fermions (SM3) — Silveira & Zee, 1985
  - plus a real scalar field *D*, called darkon, as dark matter.
- It's been much studied, and its DM sector is compatible with current experimental data.

- The SM with a 4th sequential generation (SM4) has received lots of attention in recent years.
- Among the reasons are it
  - is not ruled out by electroweak precision tests — Kribs et al., 2007; Chanowitz, 2009
  - offers possible resolutions for some anomalies in flavor-changing processes — Hou et al., . . . ; Soni et al., . . . ; . . . .
  - might solve baryogenesis-related problems. — Hou, 2009

Introduction

- It is then of interest also to consider SM4+D.
  - If a new sequential family exists, SM4+D is the simplest model having a WIMP candidate.

- The darkon in SM4+D can have major implications for the Higgs sector not present in SM3+D

- The extra fermions in SM4+D may lead to darkon-related experimental signatures absent or suppressed in SM3+D

- The LHC, and perhaps also the Tevatron, may be able to produce the new particles and/or detect their effects.

Simplest Model SM+D

Add a real SM gauge singlet, Z2 symmetry

-> stable, weakly interacting

-> couple to Higgs only by renormalization

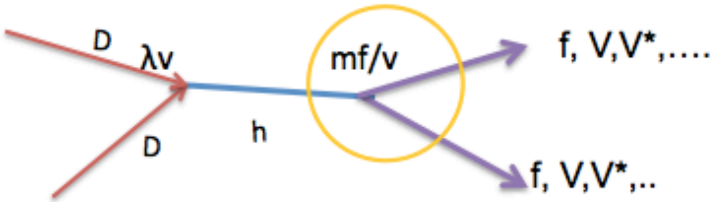
$$L_D = \frac{1}{2}\partial^\mu D \partial_\mu D - \frac{\lambda_D}{4} D^4 - \frac{m_0^2}{2} D^2 - \lambda D^2 H^\dagger H$$

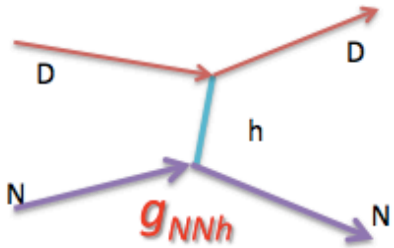
Few parameters

$$L_D = \frac{1}{2}\partial^\mu D \partial_\mu D - \frac{\lambda_D}{4} D^4 - \frac{(m_0^2 + \lambda v^2)}{2} D^2 - \frac{\lambda}{2} D^2 h^2 - \lambda v D^2 h$$

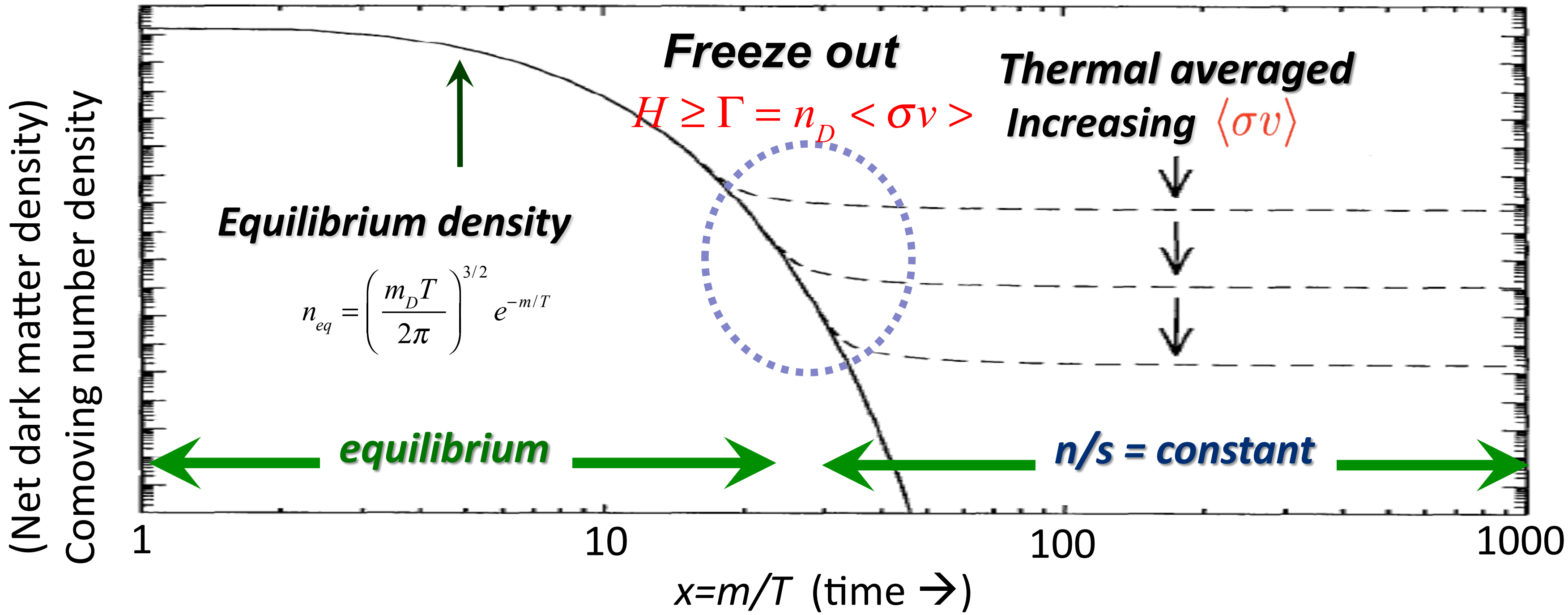
lambda_D

DD to hh





Dark Matter as Thermal Relic



Large cross section reduces relic abundance.

The competing effect of expansion and annihilation are described by the Boltzmann eq

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

$$T \geq m_D : H \propto T^2 \ \& \ n \propto T^3 \rightarrow n = n_{eq}$$

$$T_f \simeq m_D / 20, (x_f \simeq 20)$$

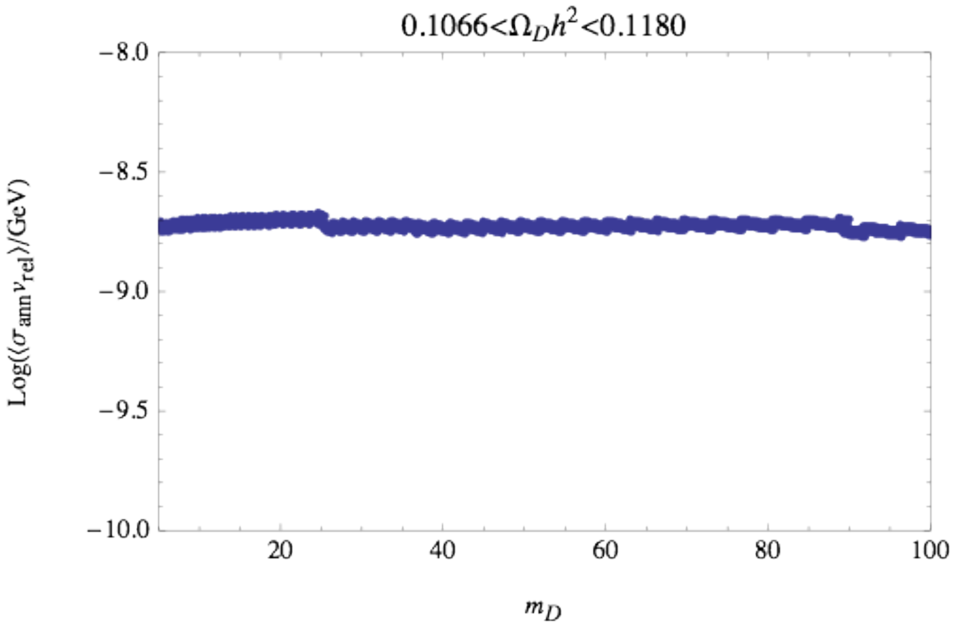
(E.W.Kolb and M.Turner)

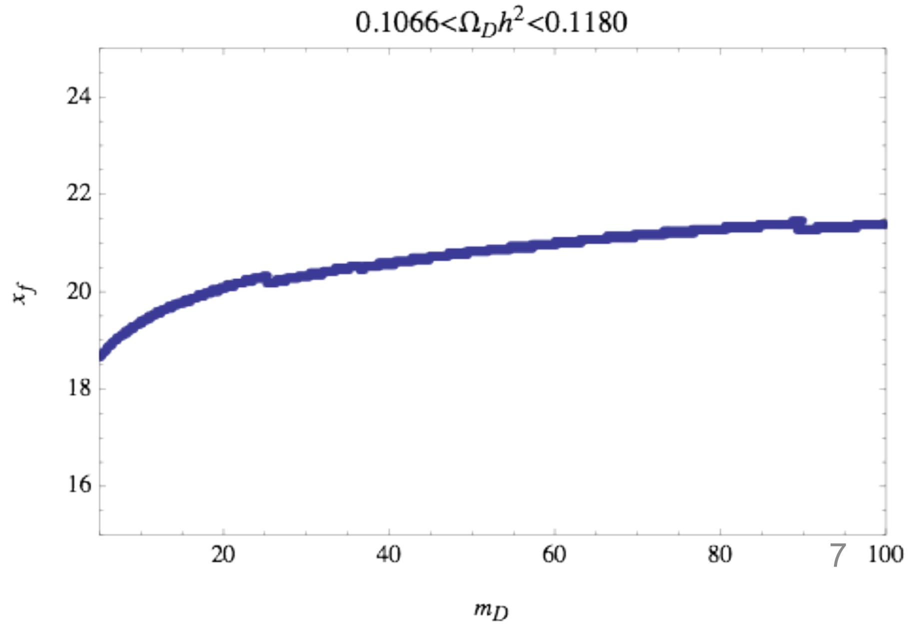
Reproduce DM relic

$$\Omega_D h^2 \simeq \frac{1.07 \times 10^9 \, x_f}{\sqrt{g_*} \, m_{\rm Pl} \, \langle \sigma_{\rm ann} v_{\rm rel} \rangle \, {\rm GeV}} , \qquad x_f \simeq \ln \frac{0.038 \, m_{\rm Pl} \, m_D \, \langle \sigma_{\rm ann} v_{\rm rel} \rangle}{\sqrt{g_* \, x_f}} ,$$

h is the Hubble constant in units of 100 km/(s Mpc)

g_* is the relativistic degrees of freedom with mass less than T_f





Relic density in SM3+D

- The interactions of any WIMP candidate with SM3 particles must satisfy constraints from relic-density data.
- The darkon annihilation rate into SM3 particles is related to its relic density Ω_D by

$$\Omega_D\, h^2 \sim \frac{0.1\ \mathrm{pb}}{\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle}$$

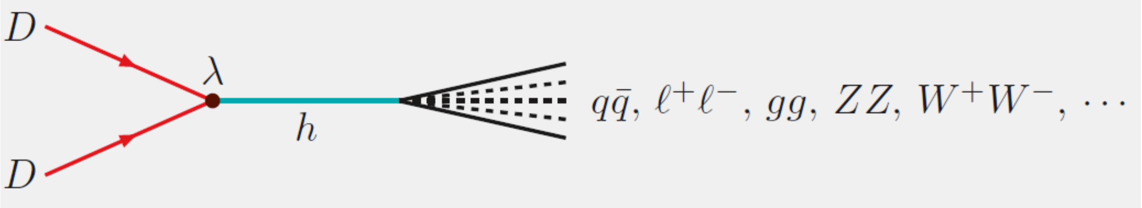
Kolb & Turner, 1990

h is the Hubble constant in units of 100km/(s·Mpc),
σ_{ann} the darkon annihilation cross-section into SM3 particles,
v_{rel} the darkon-pair relative speed in their cm frame.

- WMAP7 & other data yield $\Omega_D h^2 = 0.1123 \pm 0.0035$ Komatsu *et al.*, 2010
- We use the 90%-C.L. range $0.1065 \le \Omega_D h^2 \le 0.1181$

Darkon annihilation rate

- For $m_D \le m_h$ the relic density results from darkon annihilation into SM3 particles via Higgs (h) exchange.



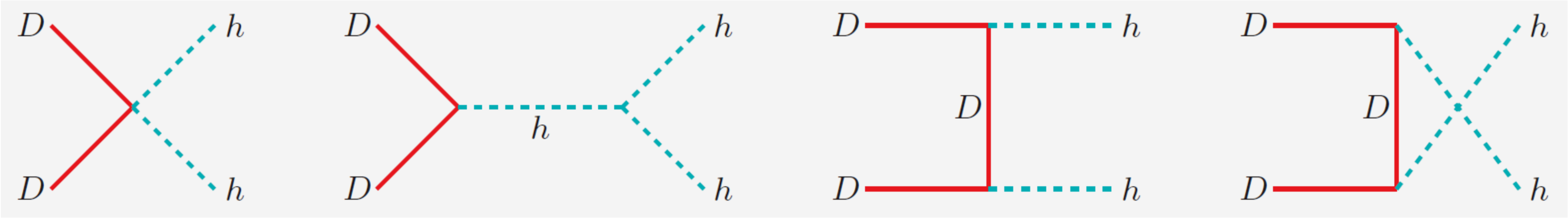
- The h-mediated annihilation cross-section

$$\sigma_{\rm ann}\, v_{\rm rel} \;=\; \frac{8\lambda^2 v^2}{\left(4m_D^2 - m_h^2\right)^2 + \Gamma_h^2\, m_h^2}\; \frac{\sum_i \Gamma\big(\tilde{h} \to X_i\big)}{2m_D}$$

$\tilde{h}$ is a virtual Higgs boson having the same couplings to other states as the physical h of mass $m_h > m_D$, but with invariant mass $\sqrt{s} = 2m_D$, and $\tilde{h} \to X_i$ any possible decay mode of $\tilde{h}$.

Darkon annihilation rate

- For $m_D > m_h$ contributions from $DD \to hh$ need to be included in σ_{ann}.



- For large darkon masses, $m_D >> m_{W,Z,h}$, these dominate, along with $DD \to h^* \to WW, ZZ$

Darkon annihilation rate in SM4+D

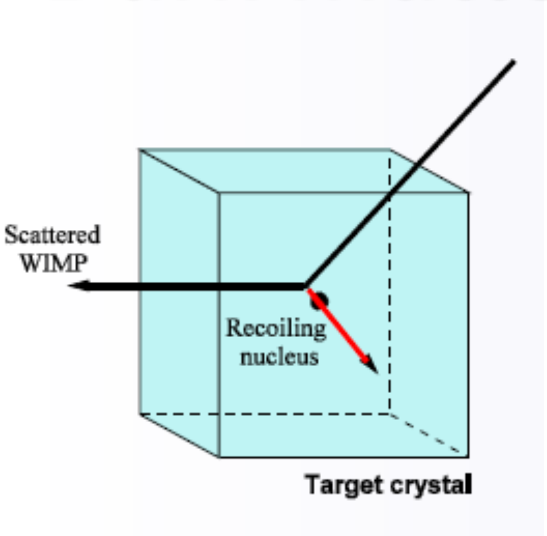
- The new family/generation in SM4 consists of
  - quarks: *t'* and *b'*
  - leptons: *ν'* and *ℓ'*

- Their presence increases the total Higgs width mainly via
  - $h \to$ fermion antifermion (if kinematically allowed)
  - loop effects in $h \to gg$

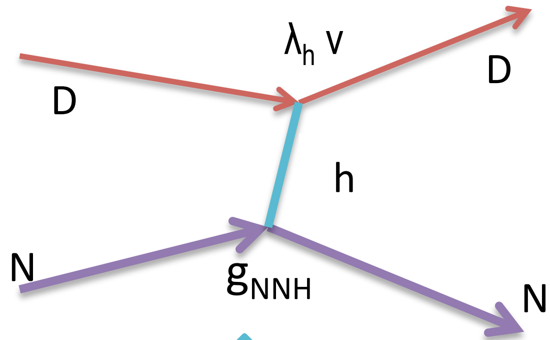
- This modifies the darkon annihilation cross-section $\sigma_{\rm ann}$

$$\sigma_{\rm ann}\, v_{\rm rel} \;=\; \frac{8\lambda^2 v^2}{\left(4m_D^2 - m_h^2\right)^2 + \Gamma_h^2\, m_h^2}\, \frac{\sum_i \Gamma\left(\tilde{h} \to X_i\right)}{2m_D}$$

Dark Matter Direct Search Experiment

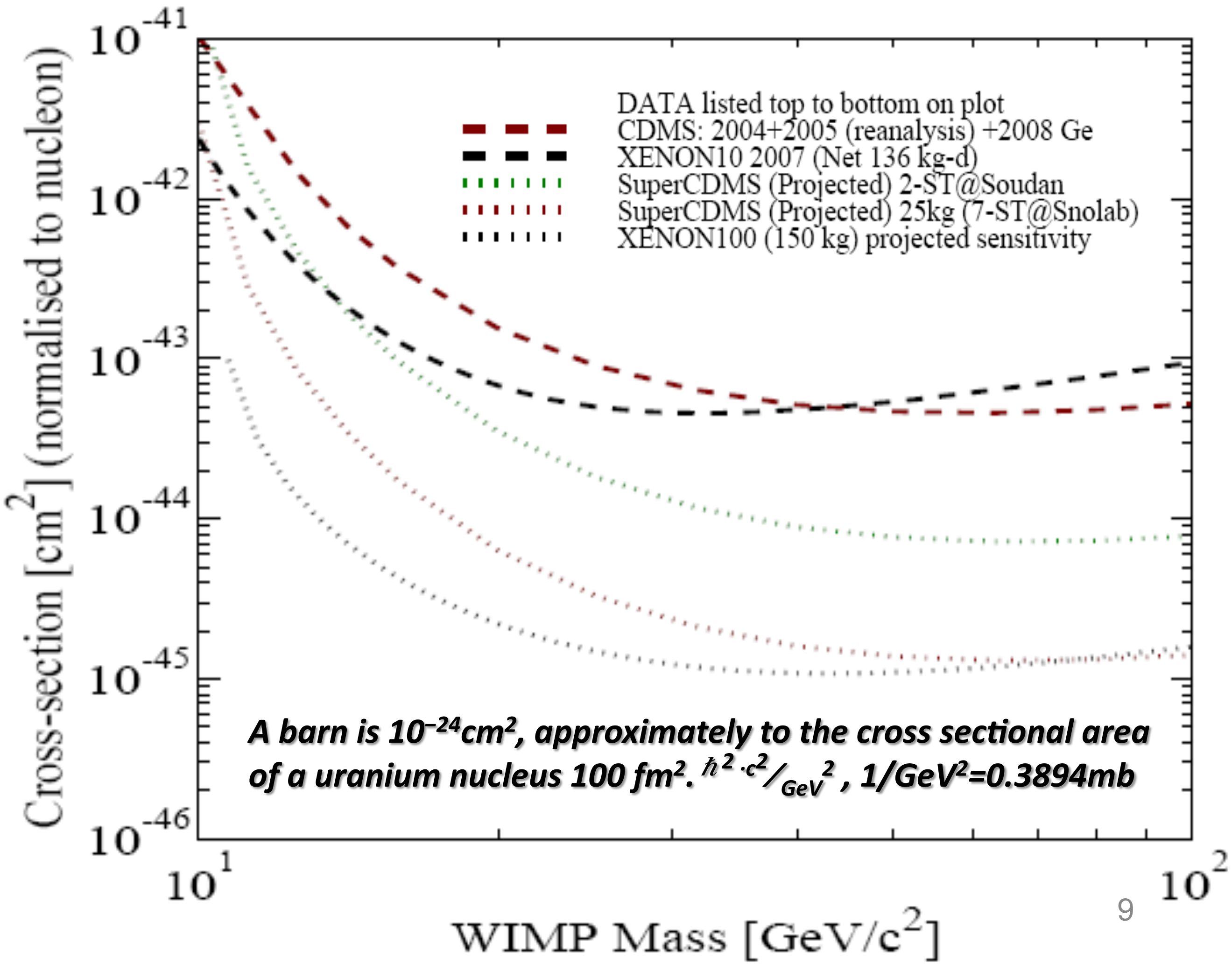


$$\sigma_{el}^{SM} \simeq \frac{\lambda^2 g_{NNh}^2 v^2 m_N^2}{\pi (m_D + m_N)^2 m_h^4}$$



Effective Higgs-nucleon coupling is needed

The current and projected limits for the spin-independent WIMP-nucleon elastic scattering cross-section as a functions of WIMP mass. http://dmtools.berkeley.edu/limitplots



A barn is 10^{-24}cm^2, approximately to the cross sectional area of a uranium nucleus 100 fm^2. $\hbar^2 \cdot c^2 / GeV^2$, 1/GeV^2=0.3894mb

Constraints on masses of new fermions

- From searches at LEP $m_{\ell'} > 100.8\,\mathrm{GeV}$ and $m_{\nu'} > 90.3\,\mathrm{GeV}$
- From searches at Tevatron $m_{t'} > 311\,\mathrm{GeV}$ and $m_{b'} > 338\,\mathrm{GeV}$

CDF, 2008 & 2010

- Electroweak precision data prefer

Kribs et al., 2007

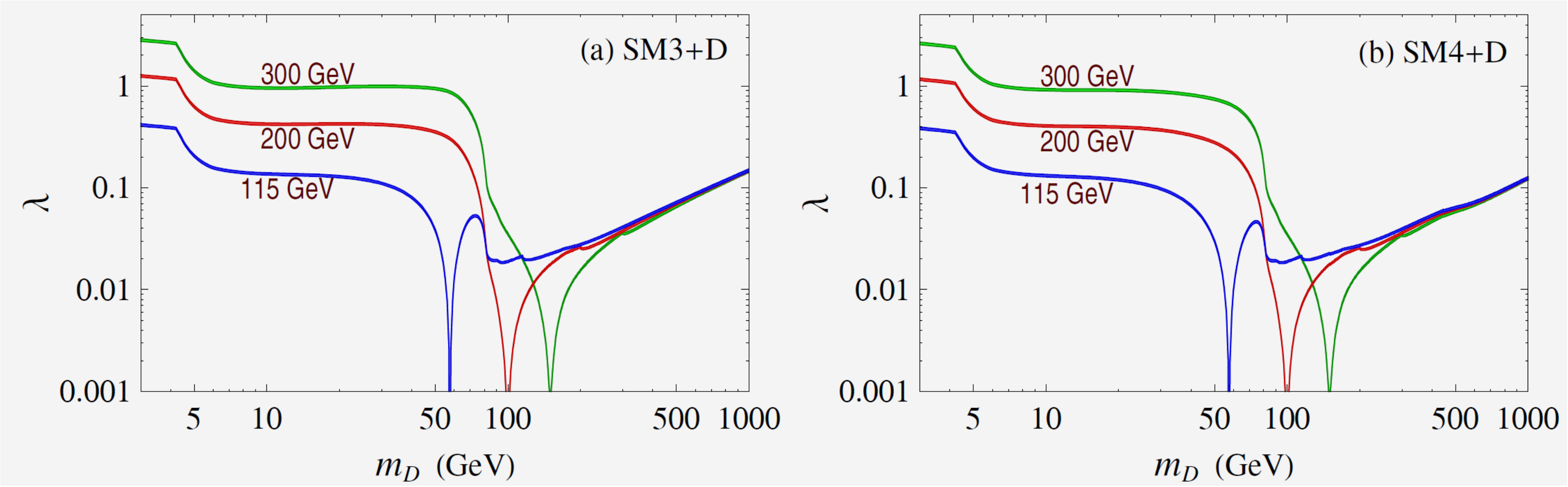
$$m_{t'} - m_{b'} \simeq \left[5 + \ln\left(m_h/115\,\mathrm{GeV}\right)\right] \times 10\,\mathrm{GeV} \text{ and } 30\,\mathrm{GeV} \lesssim m_{\ell'} - m_{\nu'} \lesssim 60\,\mathrm{GeV}$$

- Perturbative unitarity implies $m_{t',b'}$ not exceed ~600 GeV
- For definiteness, we take
  - $m_{t'}$ = 500 GeV and $m_{b'} = m_{t'}$ – 55 GeV
  - $m_{\nu'}$ = 150 GeV and $m_{\ell'}$ = 200 GeV

Darkon-Higgs coupling

- The darkon-Higgs coupling λ for each m_D can be inferred from $\langle\sigma_{\rm ann} v_{\rm rel}\rangle$ range allowed by Ω_D constraint, once m_h is specified.

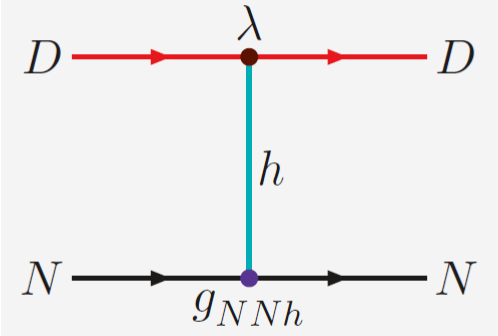
- Allowed ranges of λ vs. m_D for m_h= 115,200,300 GeV in SM3+D and SM4+D with $m_{t'}$ = 500 GeV



- The models comfortably satisfy the relic-density constraint.
- For lower m_D values, λ is not very small.

Darkon-nucleon elastic cross-section

- The direct detection of dark matter is through the recoil of nuclei when a darkon hits a nucleon *N*.
- In SM+D, this occurs via Higgs exchange in the *t*-channel elastic scattering $DN \to DN$.



- Amplitude for $DN \to DN$

$$\mathcal{M}_{\rm el} \simeq \frac{2\lambda\, g_{NNh}\, v}{m_h^2}\, \bar{N} N$$

- Cross section of $DN \to DN$

$$\sigma_{\rm el} \simeq \frac{\lambda^2\, g_{NNh}^2\, v^2\, m_N^2}{\pi\,(m_D + m_N)^2\, m_h^4}$$

Higgs-nucleon couplings

- After relating Higgs-quark couplings to Higgs-nucleon couplings, in SM3 we estimate

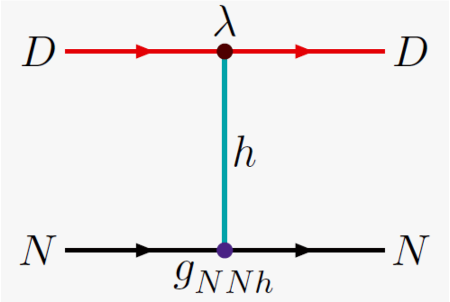
$$g_{NNh} \simeq 1.71 \times 10^{-3}$$

He, Li, Li, JT, Tsai, 2009

- In SM4 the new quarks cause g_{NNh} to increase by ~23%.

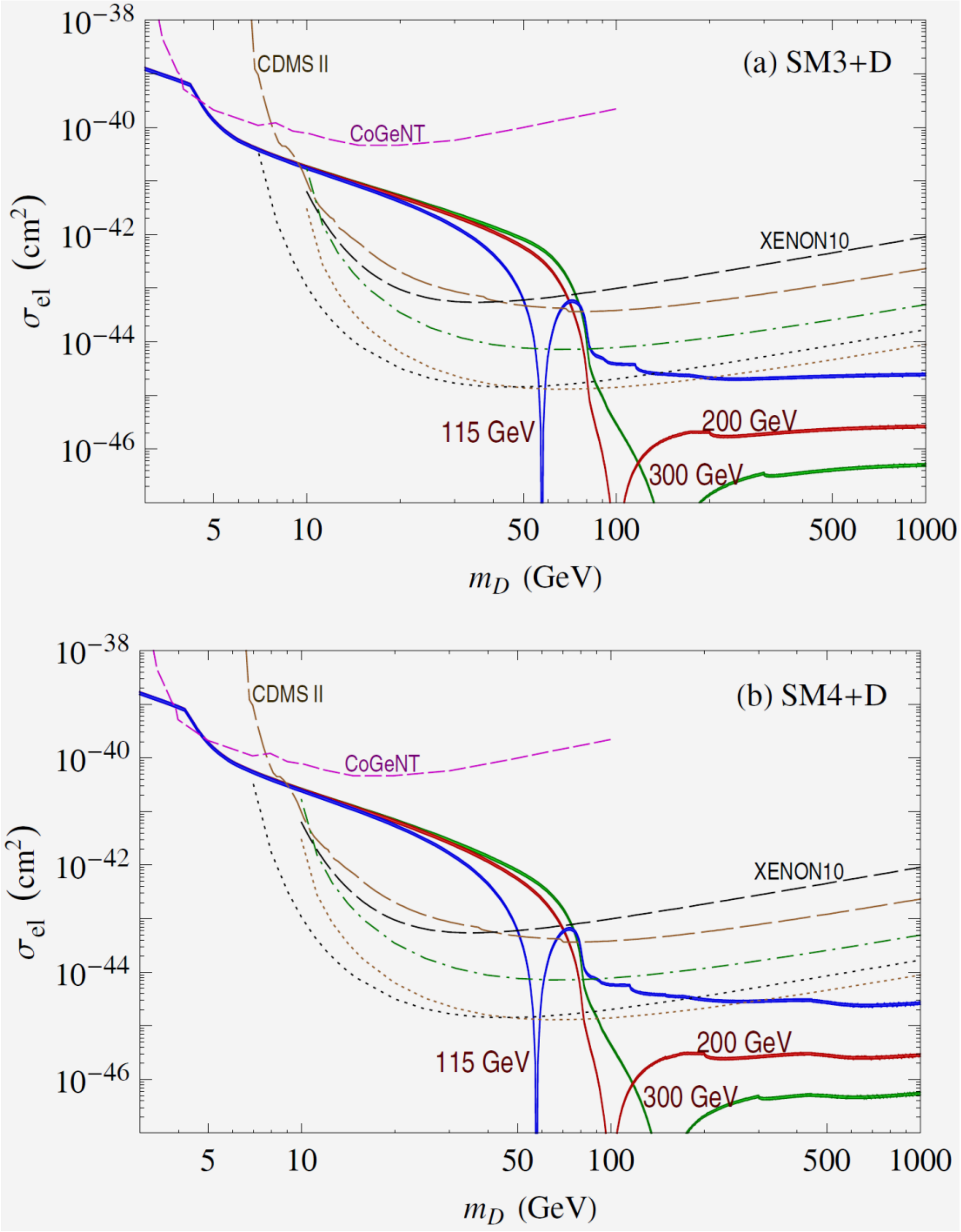
- In both models, estimates of g_{NNh} involve uncertainties within factors of 2.

- With λ and g_{NNh} known, one can predict the darkon-nucleon elastic cross-section σ_{el} for specific m_D and m_h values.



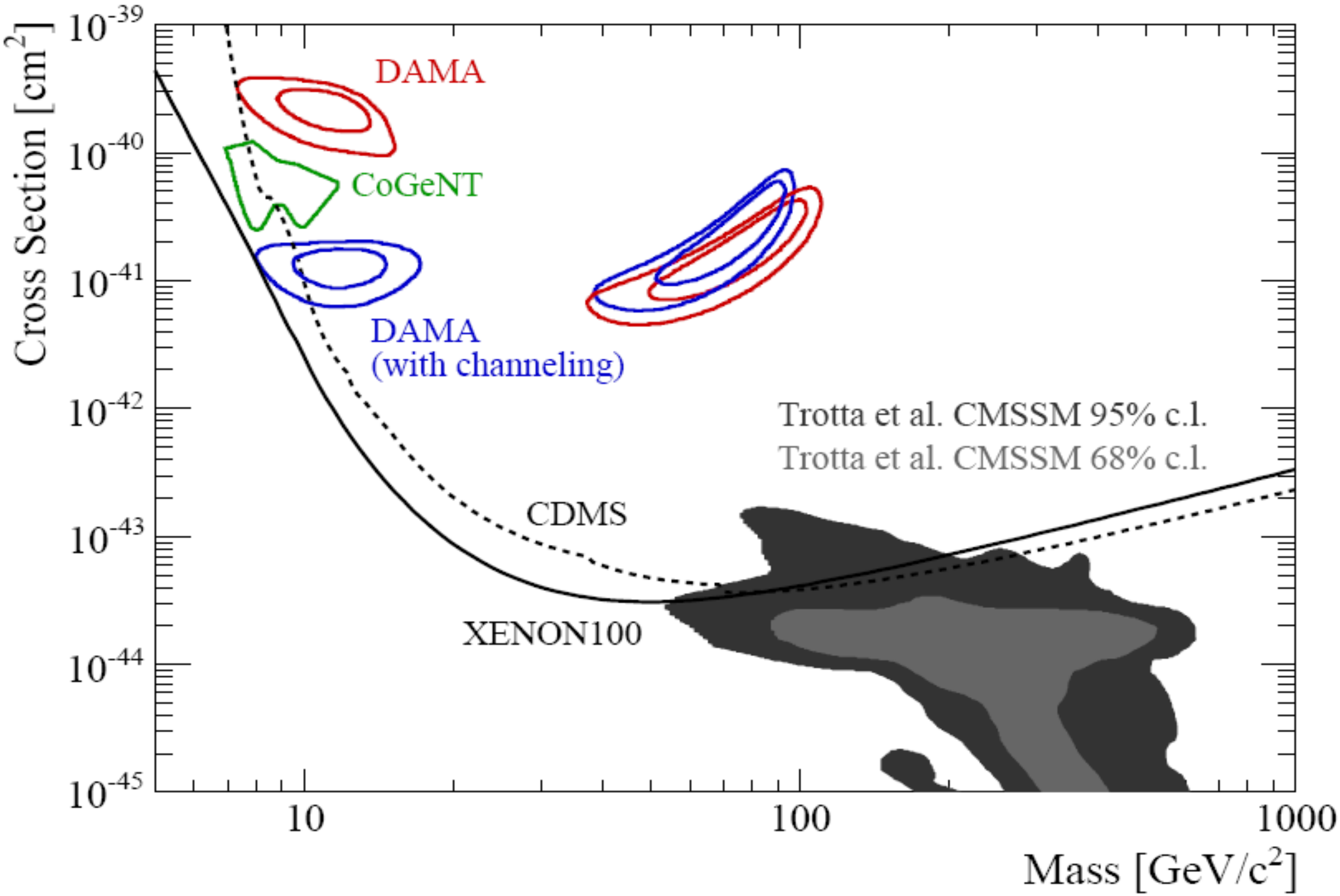
Darkon-nucleon elastic cross-section

- Predicted cross-section in SM3+D & SM4+D for $m_h = 115, 200, 300$ GeV
- Large regions in the parameter space of the two models are consistent with current data, although sizable part of it is now excluded



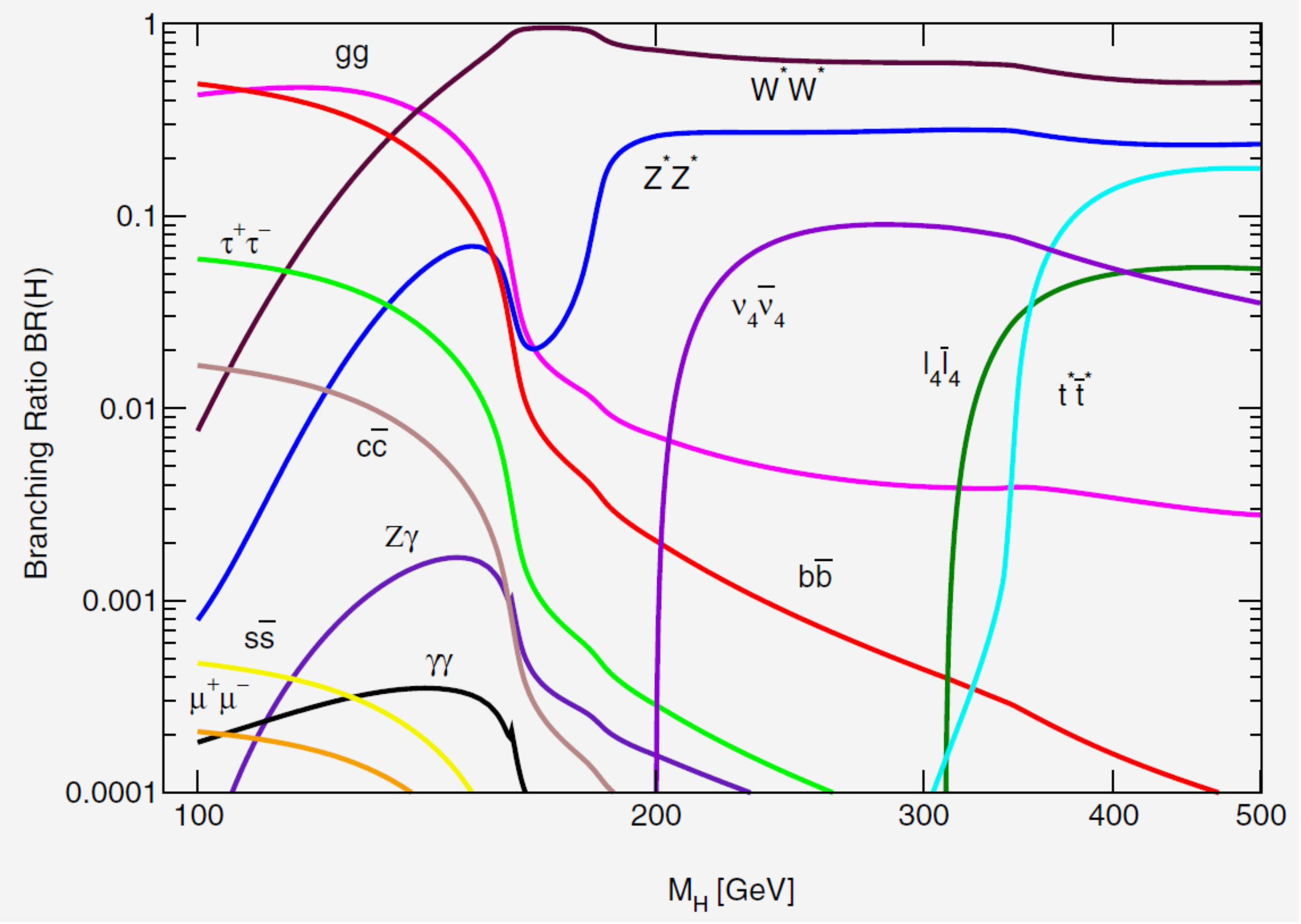
Disputed

XENON100



Higgs branching ratios in SM4

- In the absence of the darkon, $h \to gg$ dominates for m_h from ~ 100 to $\sim 140\,\mathrm{GeV}$



Kribs et al., 2007

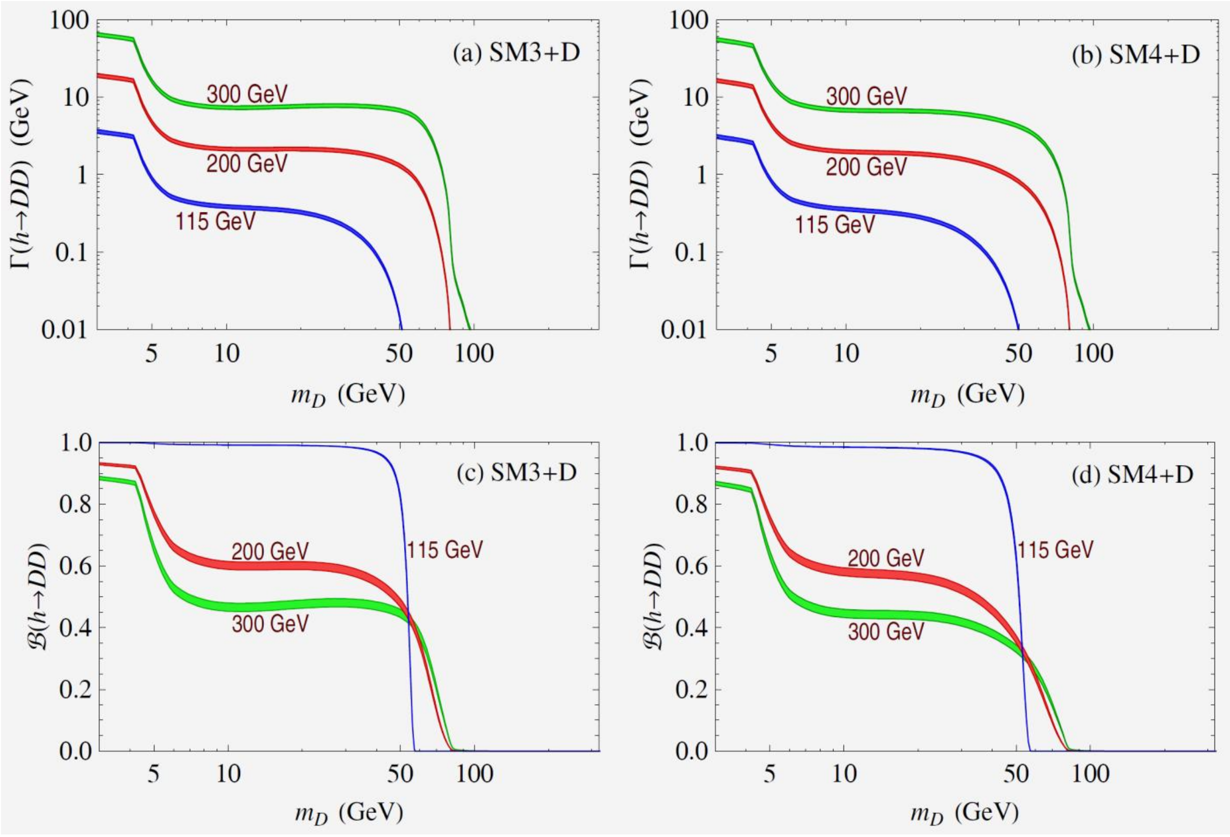
Higgs invisible decay modes

- Since the darkon is stable, $h \to DD$ mode will be invisible.
  - If $m_h > 2m_D$, this new channel is open, increasing $\mathcal{B}(h \to invisible)$
  - If $m_h < 2m_D$, $\mathcal{B}(h \to invisible) = \mathcal{B}(h \to invisible_{SM})$, not affected by the introduction of the darkon.

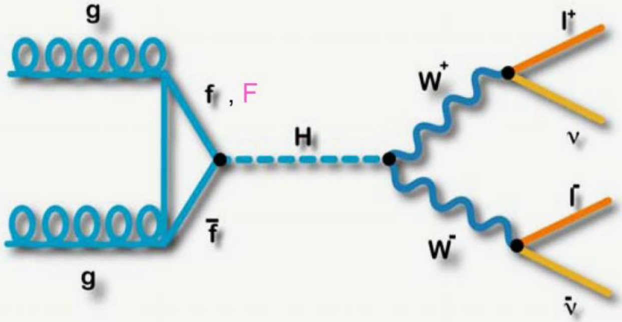
- Darkon presence in both SM3+D and SM4+D can lead to huge enhancement of Higgs' total width via $h \to DD$ if $m_h > 2m_D$.

- This can significantly affect Higgs searches

- Higgs studies at LHC are complementary to DM direct searches in probing darkon properties

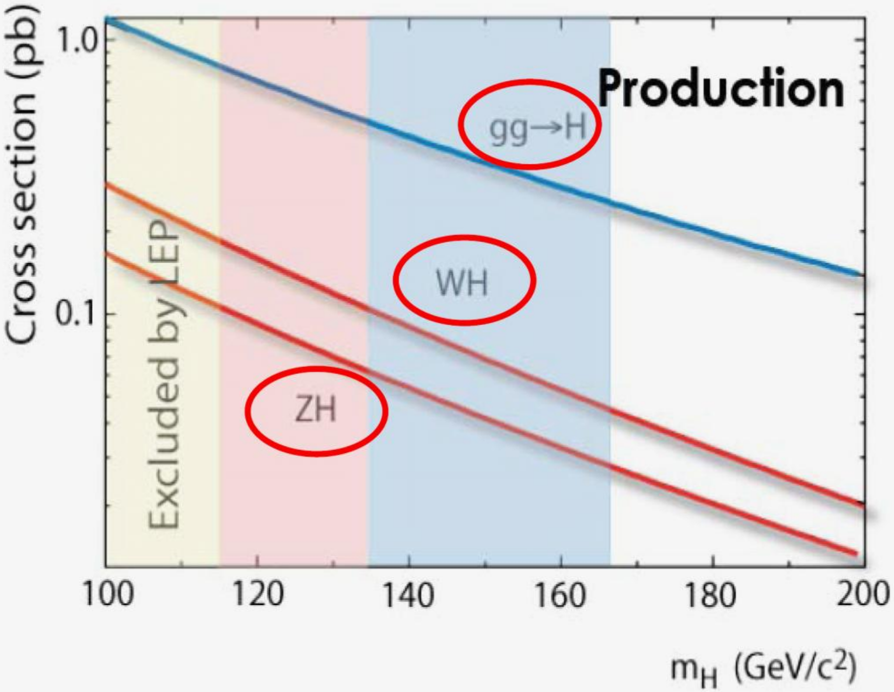


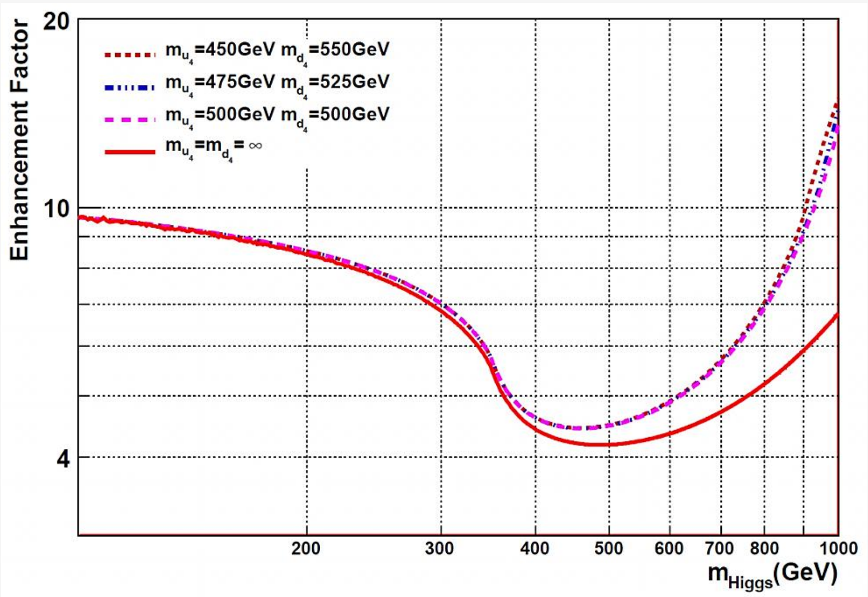
Search for H→WW*



Sensitive to > 3 SM generation since

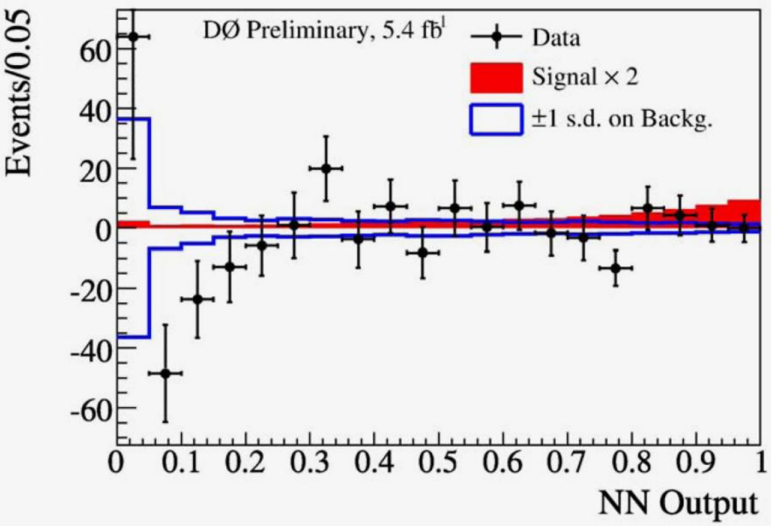
- additional heavy fermion (F) loops in the dominant gg-fusion process enhances ~9 times the Higgs production cross section
- the WW* decay is the best to study the gg-fusion production the bb and gg final states are swamped by the QCD background

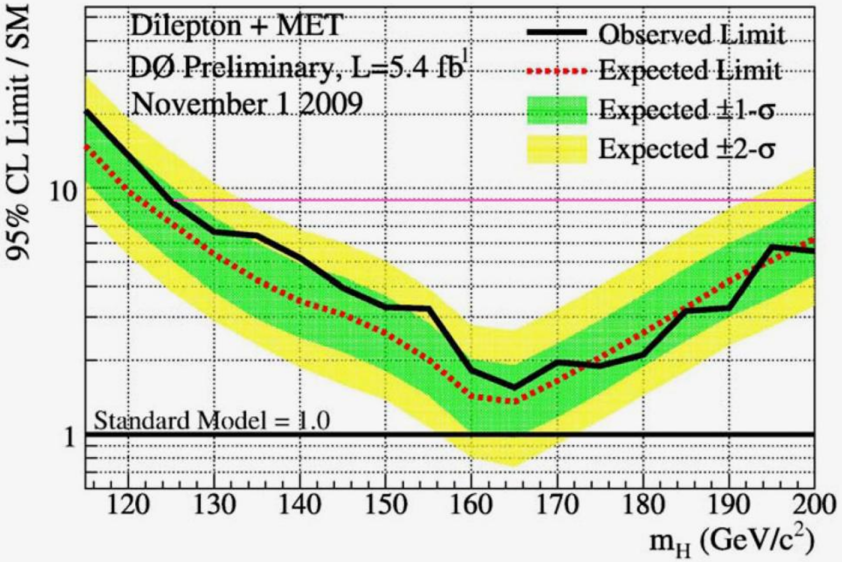




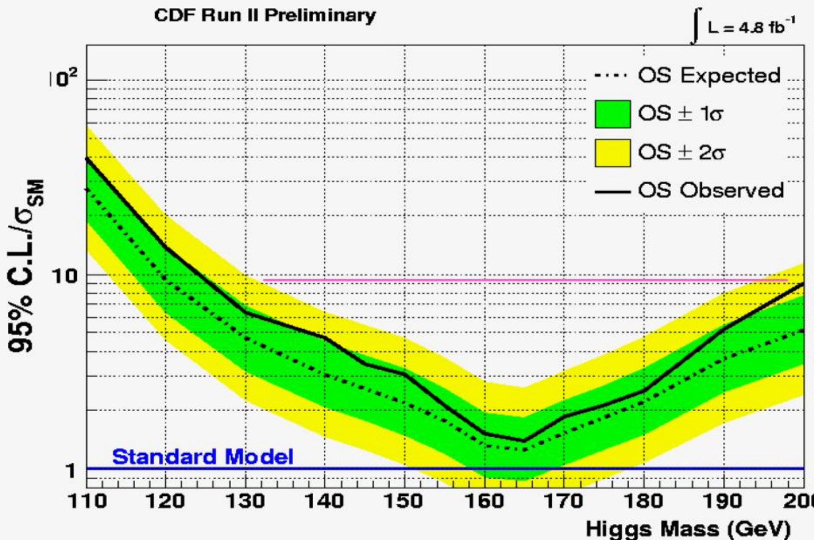
N.Becerici Schmidt et al, arXiv:0908.2653v3

D0 all channels combined





CDF has obtained comparable limit on SM Higgs cross section (4.8 fb^{-1})



Approximate sensitivity for a 4th generation fermion can be obtained by a line at ~9 x SM

Determination of a precise limit on 4th generation fermions in a combined CDF-D0 analysis is underway

18

B3G WS 14-Jan-2010 E. Nagy

Probing lower darkon masses

- Current and near-future direct DM searches are not expected to be sensitive to m_D less than a few GeV.
- Such darkon masses can be probed using decays of mesons containing the *b* quark.

- Strong constraints on low-m_D values can be obtained from the *B*-meson decay $B \to KDD$
  - It contributes to the *B* decay into *K* plus missing energy.
  - This is sensitive to m_D up to ~2.4 GeV
  - Experimental information is available.

- For larger m_D up to ~5 GeV there may also be bounds from future measurements of spin-1 bottomonium decay $\Upsilon \to \gamma DD$.
  - Present experimental limits on $\Upsilon \to \gamma$ + missing E are not yet restrictive enough.

$B \to KDD$

- This arises from the quark decay $b \to sh^* \to sDD$ with the bsh^* vertex generated at one loop.
  - The loop contains up-type quarks and *W* boson.

- The heaviest quarks in the loop dominate the amplitude.

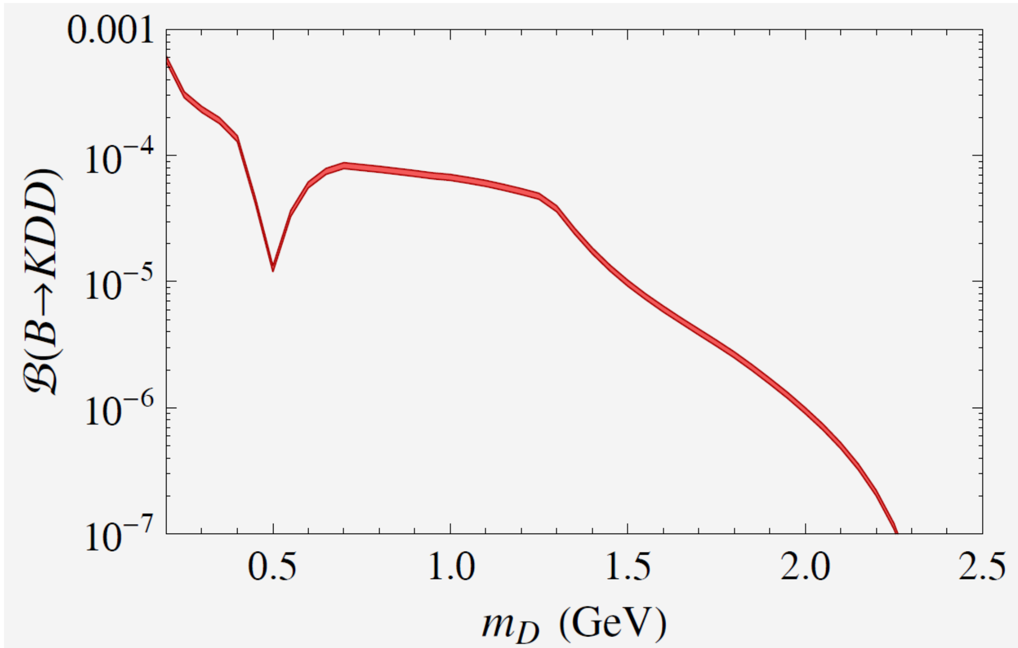
- The darkon-Higgs coupling λ for the *hDD* vertex is found from

$$\sigma_{\rm ann} v_{\rm rel} \simeq \frac{\lambda^2}{m_h^4} \frac{4v^2 \sum_i \Gamma(\tilde{h} \to X_i)}{m_D}$$

- But the Higgs decay rates for low m_h are not precisely known.

Constraints for $B \to KDD$

- From the experimental bound $\mathcal{B}_{\rm exp}(B^+ \to K^+\nu\bar{\nu}) < 14 \times 10^{-6}$
  and the SM3 prediction $\mathcal{B}_{\rm SM3}(B^+ \to K^+\nu\bar{\nu}) \sim 4.5 \times 10^{-6}$
  we infer $\mathcal{B}(B^+ \to K^+DD) < 1 \times 10^{-5}$



- Similar bound in SM4+D.
- Prediction in SM3+D
  - involve significant uncertainties
- SM4+D prediction comparable
- Much of the m_D range below ~1.5 GeV is excluded.
- Improved data from future measurements are needed for more definitive conclusion.

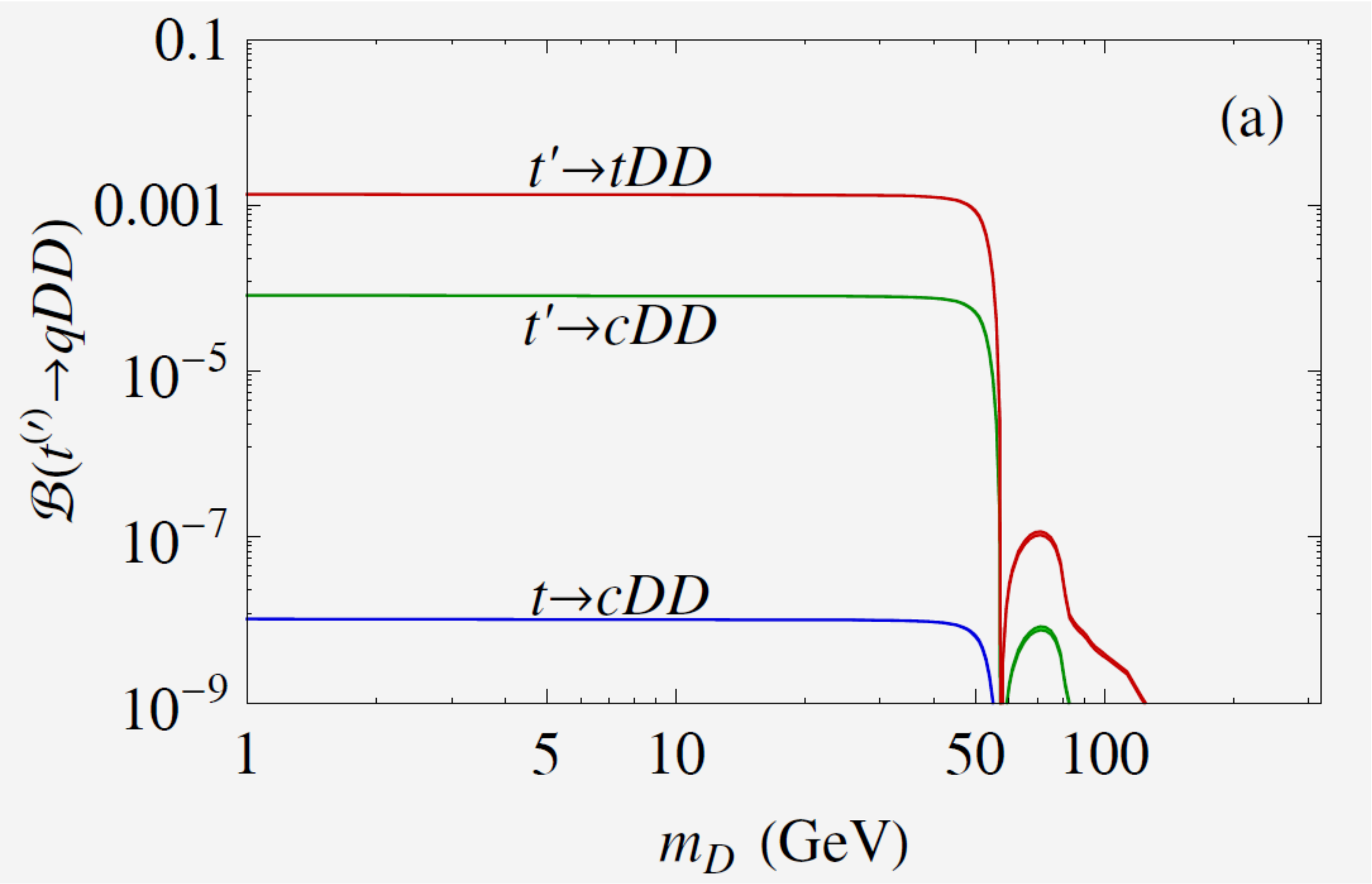
Flavor-changing heavy quark decays

- The new quarks in SM4+D can have important implications for the darkon sector that are lacking or absent in SM3+D.
- For instance
  - In SM3+D the loop-induced top decay $t \to ch^* \to cDD$ is suppressed due to GIM cancelation and has a branching ratio of order 10^{-14}
  - But in SM4+D the heavy *b*'-quark can cause the rate to be enhanced by orders of magnitude.

- Some of the decay modes of *t′* and *b′* are
  - $t' \to (c, t)h^* \to (c, t)DD$
  - $b' \to (s,b)h^* \to (s,b)DD$
- If observed, they can probe m_D from zero to hundreds of GeV.

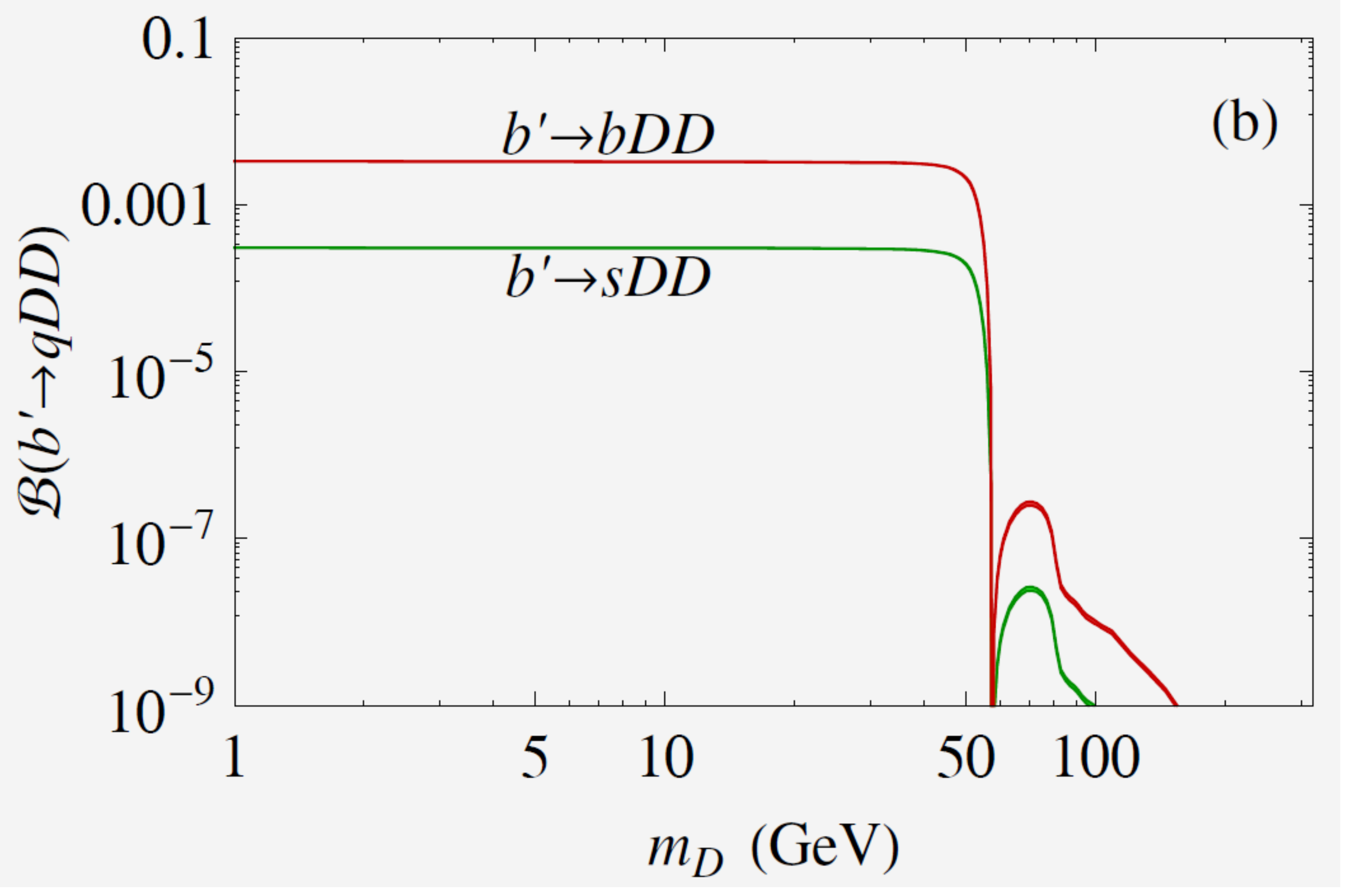
- These decays can have sizable rates and may be detectable at the LHC or even the Tevatron.

$t \to cDD,\ t' \to cDD,\ t' \to tDD,$



- The top decay may be undetectable in the near future, but the *t′* decays are potentially measurable.

$b' \to sDD$, $b' \to bDD$,



- These decays are also expectedly detectable.

Summary

1. *We have explored the simplest WIMP DM model in the presence of 4 sequential generations of quarks and leptons, SM4+D.*
2. *We obtained constraints on the SM4+D from DM direct searches and from B→KDD*

   Most parameter allowed, Similar in SM3+D case.
3. *We considered processes absent or suppressed in SM3+D*

   t'→cDD, tDD and b'→sDD, bDD, t→cDD

   They may be observable at the LHC and help test darkon models
4. *The interplay between direct searches for DM and LHC studies on Higgs boson & new quarks can yield crucial information about darkon properties.*

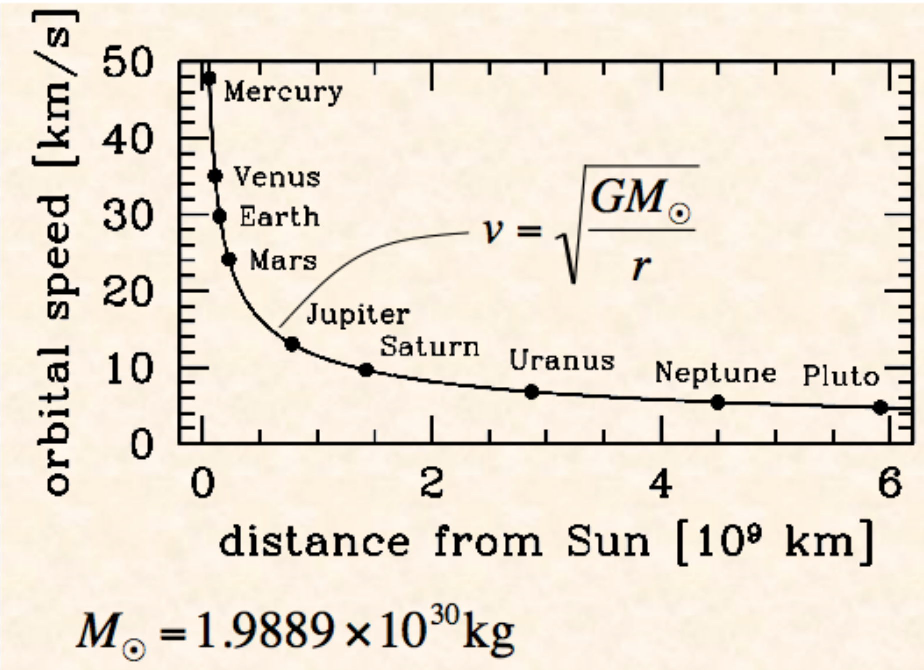
Thanks for Your Attentions!!

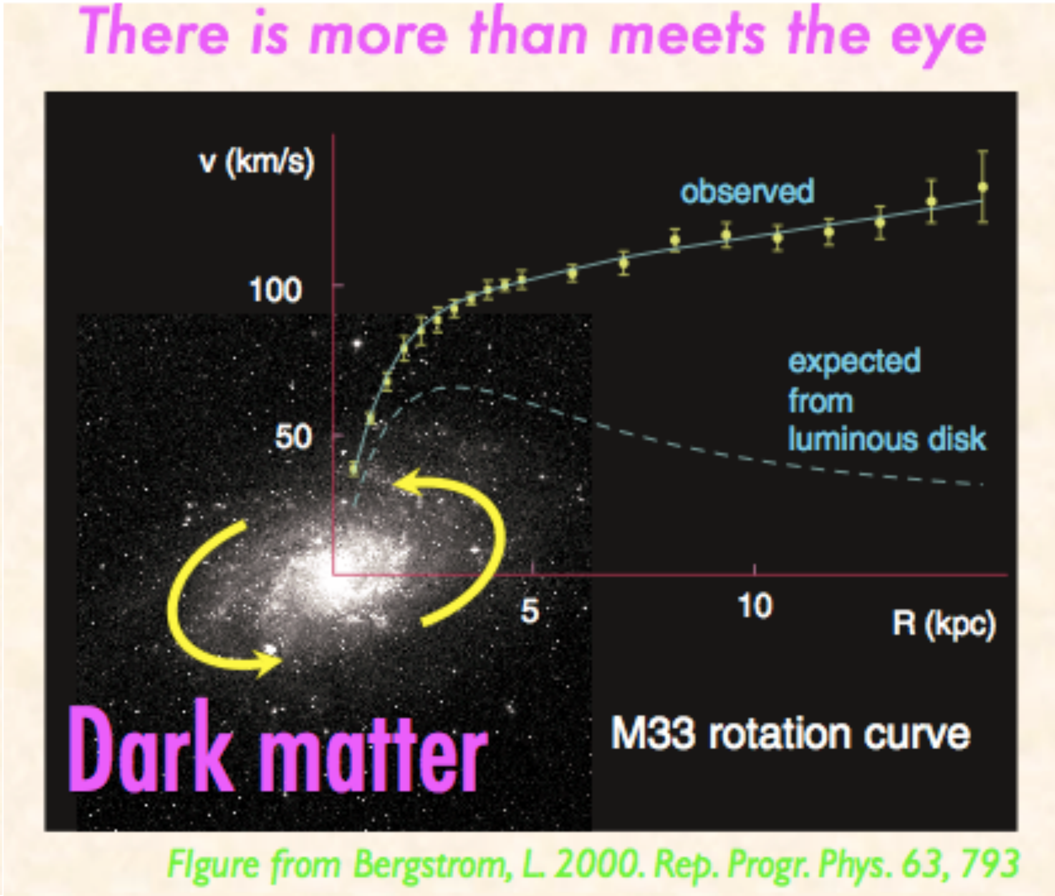
Dark Matter Evidence

Galaxy rotation curves - most concrete evidence

1970' Vera Rubin

$$\frac{M}{M_{\rm vis}} > 4$$

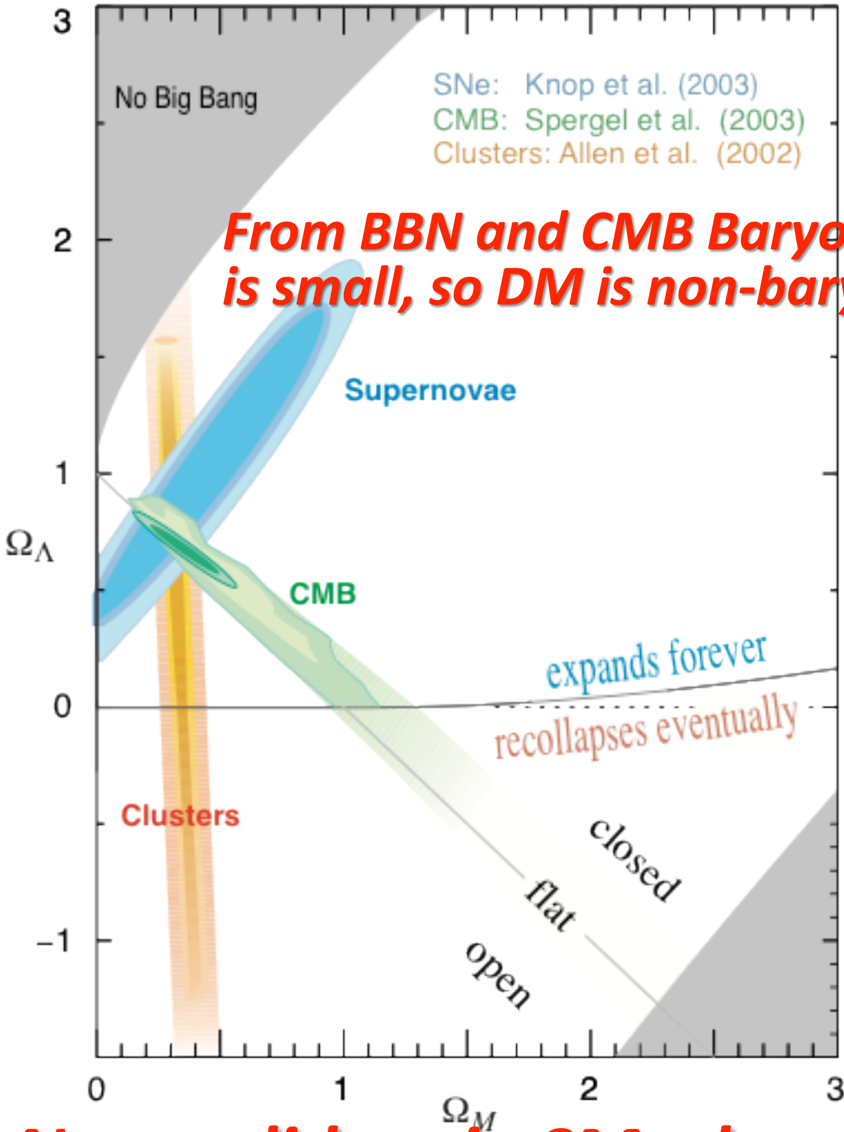




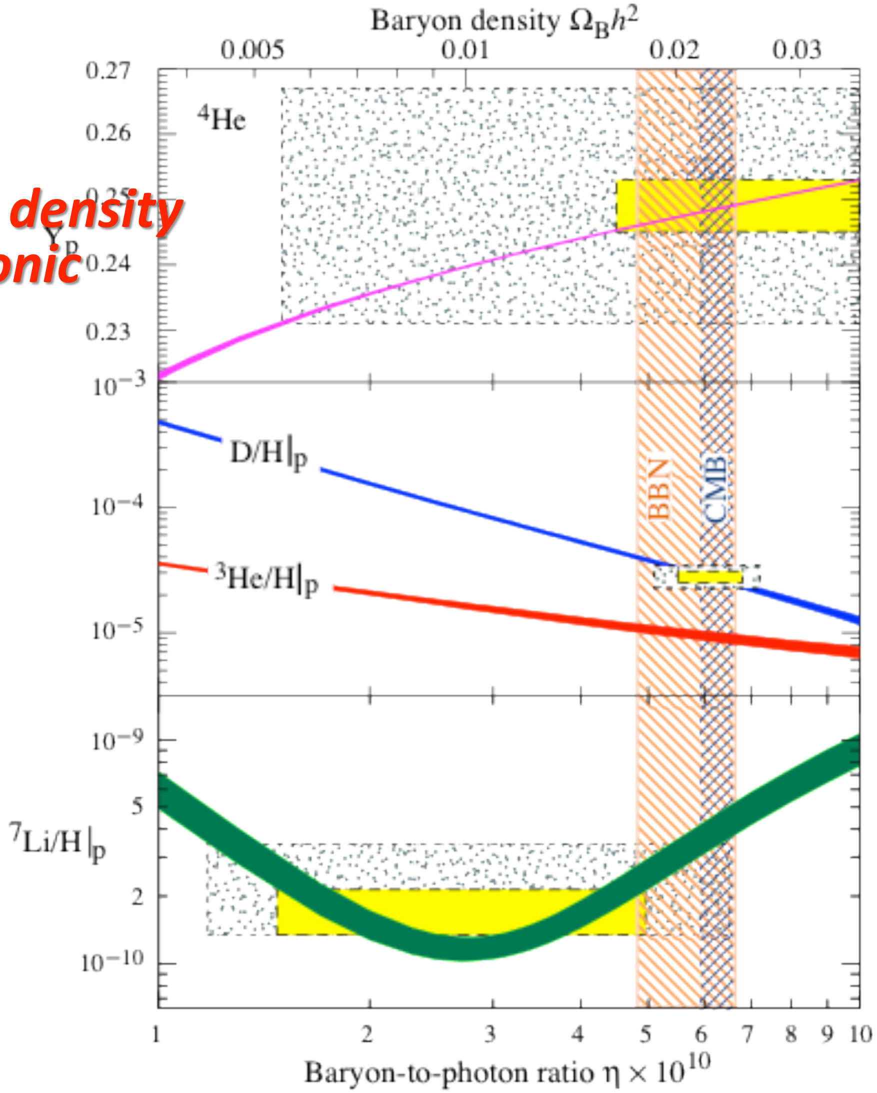
First evidence of DM :Fritz Zwicky in 1933
used viral theorem measure mass to light ratio of galaxy cluster

$$\frac{M}{M_{\rm vis}} \simeq 6$$

Dark Matter and Baryon Density

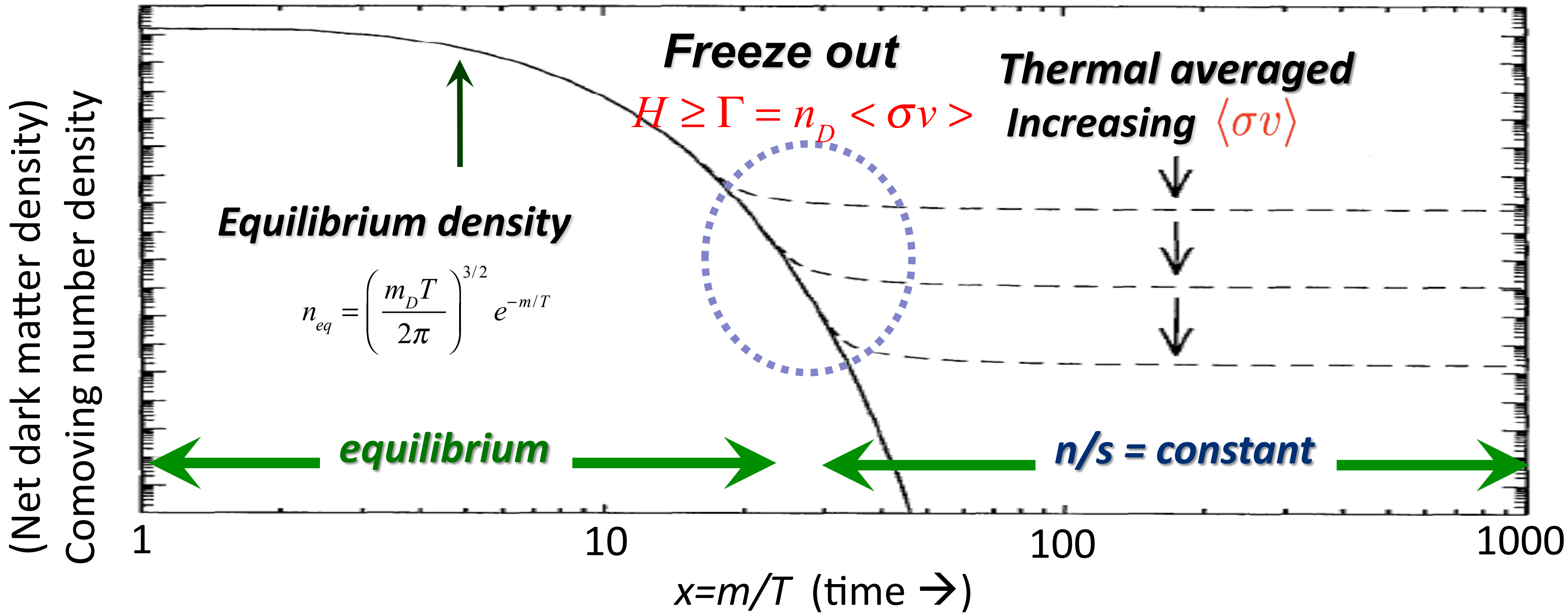


From BBN and CMB Baryon density is small, so DM is non-baryonic



No candidate in SM: chargeless, longlived, weakly interact, Nonrelativistic

Dark Matter as Thermal Relic



Large cross section reduces relic abundance.

The competing effect of expansion and annihilation are described by the Boltzmann eq

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

$$T \geq m_D : H \propto T^2 \ \& \ n \propto T^3 \rightarrow n = n_{eq}$$

$$T_f \simeq m_D / 20, (x_f \simeq 20)$$

Thermal Equilibrium

$T >> m$

$$n_{eq} \simeq \frac{g}{2\pi^2}\int_0^\infty \frac{E^2 dE}{e^{E/T} \mp 1} = \begin{cases} \frac{g}{\pi^2}\zeta(3)T^3 - boson \\ \frac{3}{4}\frac{g}{\pi^2}\zeta(3)T^3 - fermion \end{cases}$$

$$\zeta(s) = \sum_{n=1}^{\infty}\frac{1}{n^s}; \zeta(2) = \frac{\pi^2}{6} \approx 1.645; \zeta(3) = 1.202$$

$$s = \frac{\rho + P}{T} = \frac{2\pi^2}{45} g_{*S} T^3; S = a^3 s = const.$$

$$T \propto 1/a$$

$$\rho \simeq \frac{g}{2\pi}\int_0^\infty \frac{E^3 dE}{e^{E/T} \mp 1} = \begin{cases} \frac{\pi^2}{30} g T^4 - boson \\ \frac{7}{8}\frac{\pi^2}{30} g T^4 - fermion \end{cases}$$

$$H = 1.66 g_*^{1/2} T^2 / m_{pl} \leftarrow H^2 \simeq 4\pi G_N \rho_R$$

$$m_{pl} = 1.22 \times 10^{19} GeV$$

$T << m$

$$n_{eq} \simeq \frac{g}{2\pi^2}\int_0^\infty p^2 e^{-\left(m + \frac{p^2}{2m} - \mu\right)/T} dp = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T}$$

$$\rho \simeq (m + \frac{3}{2}T)n$$

$$RD: a \propto t^{1/2}, T \propto 1/a \propto t^{-1/2}, H = \dot{a}/a = t^{-1}/2 \sim T^2$$

$$MD: a \propto t^{2/3}, T \propto 1/a \propto t^{-2/3}, H = \dot{a}/a = 2t^{-1}/3 \sim T^{3/2}$$

$$MD: a \propto e^{Ht}, T \propto 1/a \propto e^{-Ht}$$

Relic Abundance

$$\Omega_D h^2 = \frac{8.5\times10^{-11} x_f}{\sqrt{g_*} J(x_f) GeV^2}$$

Time of freeze out determined first from H=Γ

$$J(x_f) = \int_{x_f}^{\infty} dx \frac{<\sigma v>}{x^2}$$

Relic today is slightly different from the abundance at freeze out

$$x = m / T$$

$$<\sigma v> = \frac{2x^{3/2}}{\sqrt{\pi}} \int_0^{\infty} (\sigma v) \frac{v^2}{4} e^{-x\frac{v^2}{4}} dv$$

$$\sigma v \simeq \mathrm{A} + Bv^2, (v \ll 1 \leftarrow T_f \simeq m_D / 20 \ll m_D, non-relativistic)$$

$$A : s-wave, B : s, p-wave$$

$$\Omega_D h^2 \sim 0.1 \left(\frac{3\times10^{-26} cm^3 /\sec}{\langle \sigma_{ann} v_{rel} \rangle} \right)$$

WIMP miracle

Weakly Interacting Massive Particles

The WIMP miracle,
for typical gauge coupling and masses of order the electroweak scale we obtain correct relic

$$\Omega_D h^2 \sim 0.1\left(\frac{3\times10^{-26} cm^3/\sec}{\langle\sigma_{ann} v_{rel}\rangle}\right)$$

Many candidates, Axions,

Weakly Interacting Massive Particles (WIMPS),

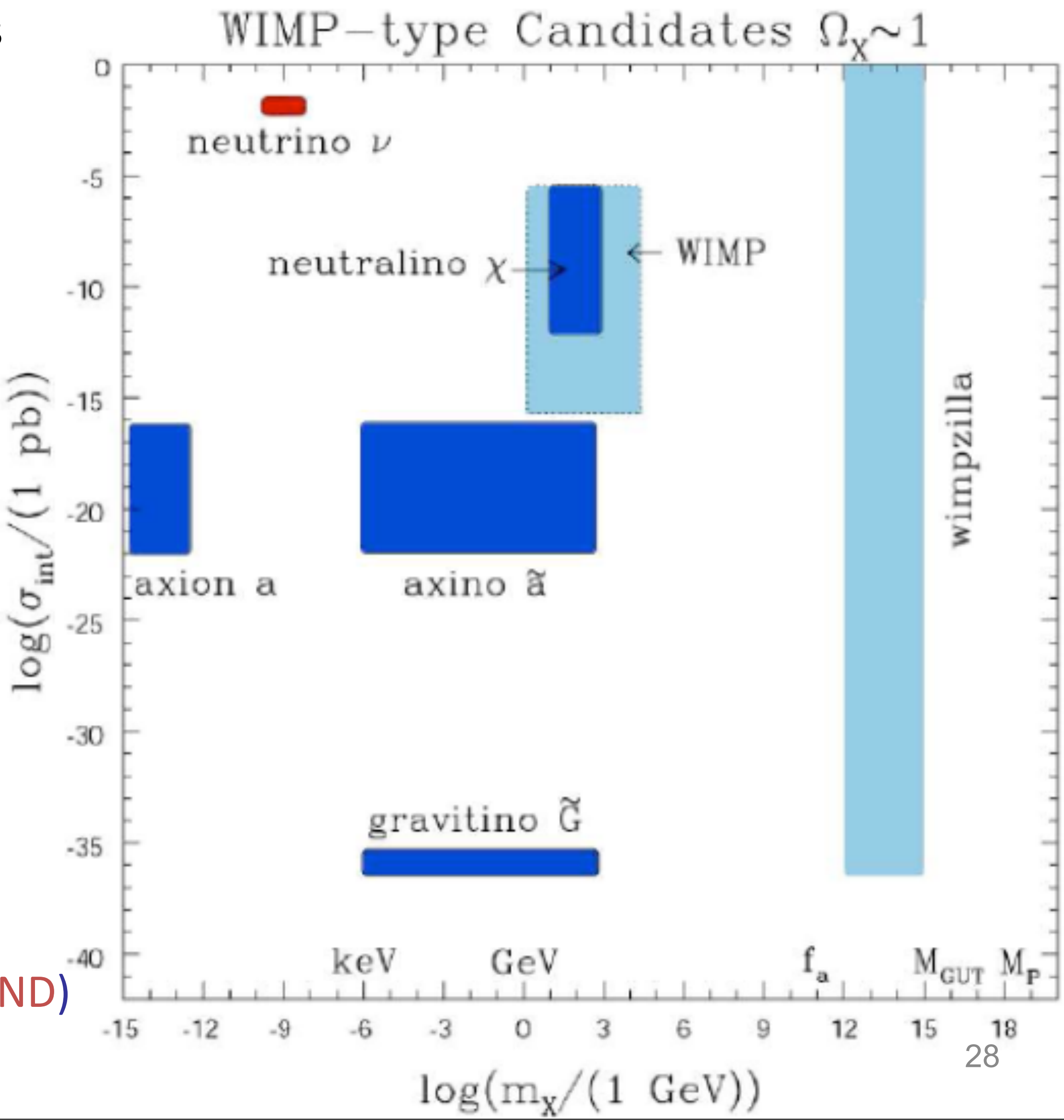
Lightest Supersymmetric Particle,

Lightest Kaluza-Klein Particle,

SIMPs, CHAMPs, SIDM,

WIMPzillas, Scalar DM, Light DM,

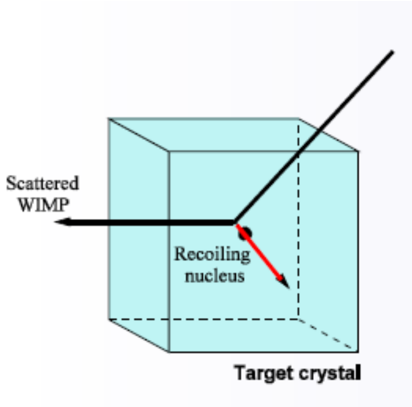
… Modified Newtonian Dynamics (MOND)



Dark Matter Study

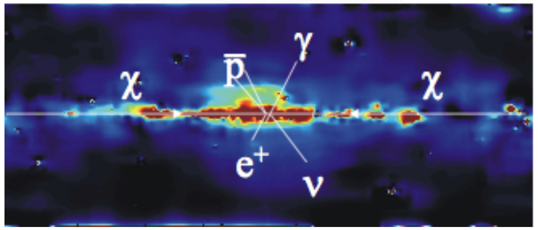
Dark Matter is called <-- relic & halo

Direct Detection



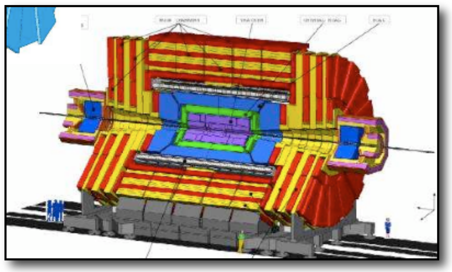
Can not say a signal does is due to WIMP scattering…

Indirect Detection



Too complicated processes involved…

Collider Searches



Hard to produce if heavy…