Dark Matter Direct Detection: New solutions to the annual modulation seen by DAMA

Fu-Sin Ling

LPC, Clermont-Ferrand, 15 mars 2010

T. Hambye, FSL, L. Lopez-Honorez, J. Rocher, arXiv:0903.4010
C. Arina, FSL, M. Tytgat, arXiv:0907.0430
FSL, E. Nezri, E. Athanassoula, R. Teyssier, arXiv:0909.2028
FSL, arXiv:0911.2321
S. Andreas, C. Arina, T. Hambye, FSL, M. Tytgat, arXiv:1003.2595

Service de Physique Théorique
Université Libre de Bruxelles

Outline

DAMA signal @ 8.2 σ C.L.

Null Experiments

Analysis of the compatibility

Particle physics

Scalar candidate

Elastic Scattering

Light WIMP solution ($M_{DM} \sim O(10)$ *GeV*) ?

Inelastic Scattering

Heavy WIMP solution ($M_{DM} \sim O(1\text{-}10)$ *TeV* ?

Astrophysics

N-body simulations

Elastic Scattering

Relevance of dark disc ?

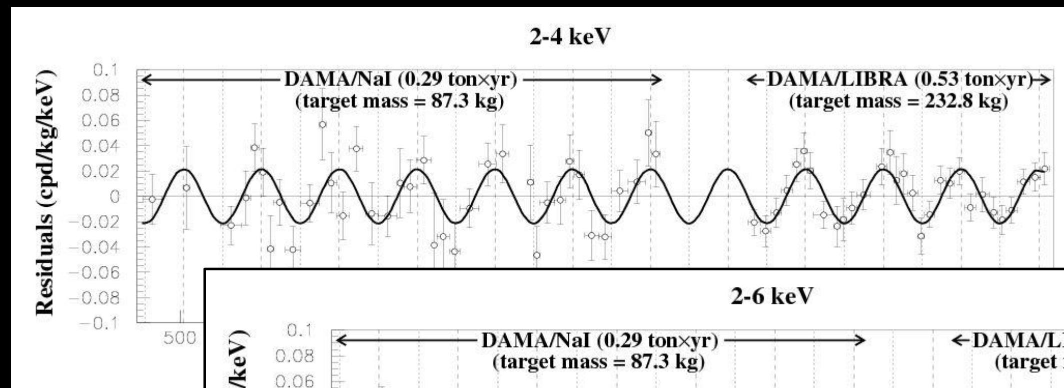
Inelastic Scattering

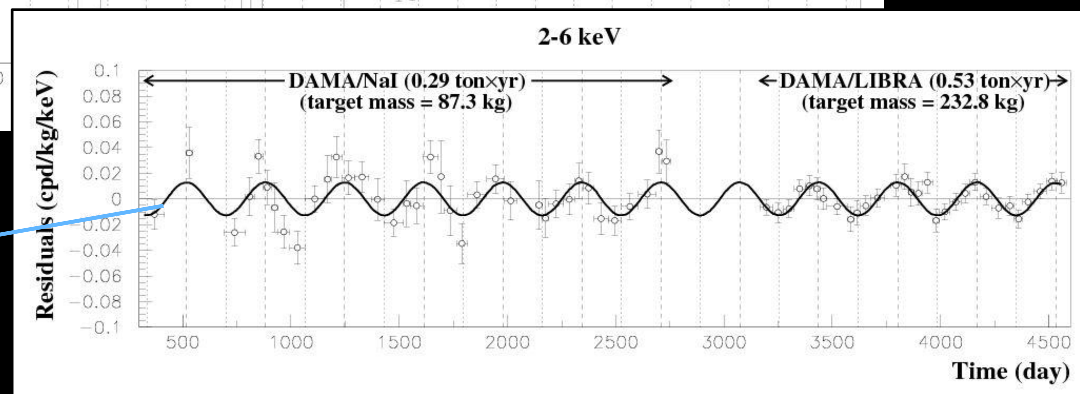
Deviations from Maxwellian distributions ?

DAMA signal

Eur. Phys. J. C56: 333-355(2008) arXiv:0804.274

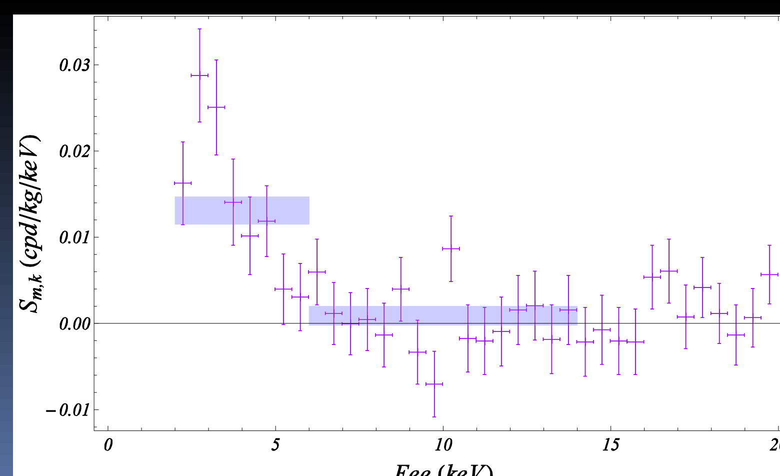
Time residuals



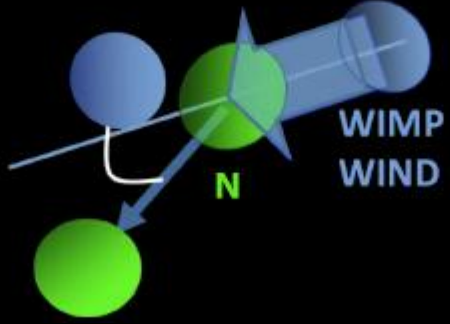


$$t_0 = 144.0 \pm 7.5$$

Modulation spectrum



Direct Detection – Event rate



Differential rate

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{M_{DM}} \frac{d\sigma}{dE_R} \eta(E_R, t)$$

particle and nuclear physics

$$\frac{d\sigma}{dE_R} = \frac{M_N}{2\mu_n^2} \sigma_n^0 \frac{\left(Z\ f_p + (A-Z) f_n\right)^2}{f_n^2} F^2(E_R)$$

astrophysics

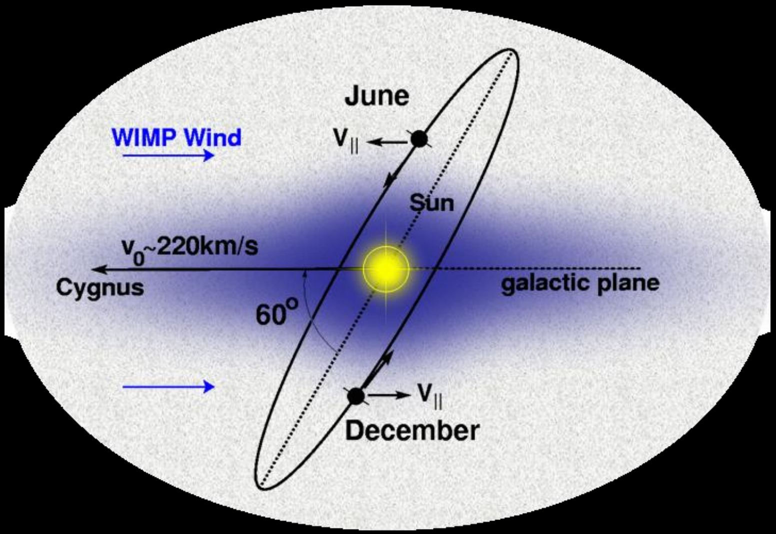
$$\eta = \int d^3\vec{v}\, \frac{f(\vec{v})}{|\vec{v} - \vec{v}_{\oplus,G}|}$$

Total rate

$$R(t) = \int_{E_1}^{E_2} dE_R\, \varepsilon(E_R) \left(\frac{dR}{dE_R} * G(E_R, \sigma(E_R)) \right)$$

detector efficiency and energy resolution

Annual modulation



Modulation of the Earth velocity

$$v_{\oplus,G} = v_S + v_{\oplus,S} \sin\gamma \cos\omega(t - t_0)$$

$$t_0 = t_1 + \frac{\pi}{2\omega} + \frac{1}{\omega}\arctan\frac{\vec{v}_S \cdot \vec{e}_2}{\vec{v}_S \cdot \vec{e}_1} \approx 151.5$$

Modulation of the differential event rate

$$\eta(E_R, t) = \eta_0(E_R) + \eta_1(E_R)\frac{v_{\oplus,S}}{v_S}\sin\gamma\cos\omega(t - t_0)$$

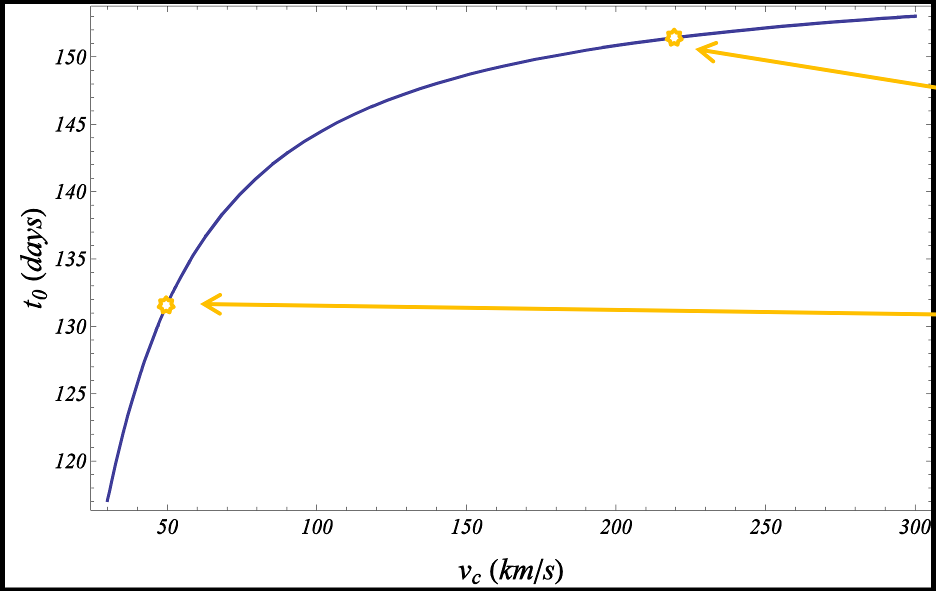
Inverse velocity function

$$\eta(E_R,t) = \int_{w_{min}(E_R)}^{v_{esc}} d^3\vec{v}\, \frac{f(\vec{v})}{|\vec{v}-\vec{v}_{\oplus,G}(t)|}$$

$$w_{min} = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N E_R}{\mu}+\delta\right)$$

- Two scenarios : elastic (δ=0) or inelastic (δ>0)
- Usual assumption : Isotropic Maxwellian distribution for f(v)
- Additional parameter : escape velocity
- The Dark Matter halo is not rotating

Annual modulation



Standard Halo

$t_o = 152.5$ → June 2nd

Fast rotating Dark Disk

$t_o = 131.5$ → May 11th

→ 3 weeks earlier

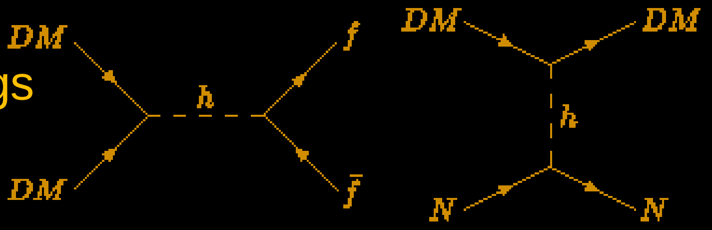
DAMA *(2 < Eee < 6 keV) :* $t_o = 144 \pm 7.5\ (1\sigma)$ → May 24th

Particle Physics

A simple scenario

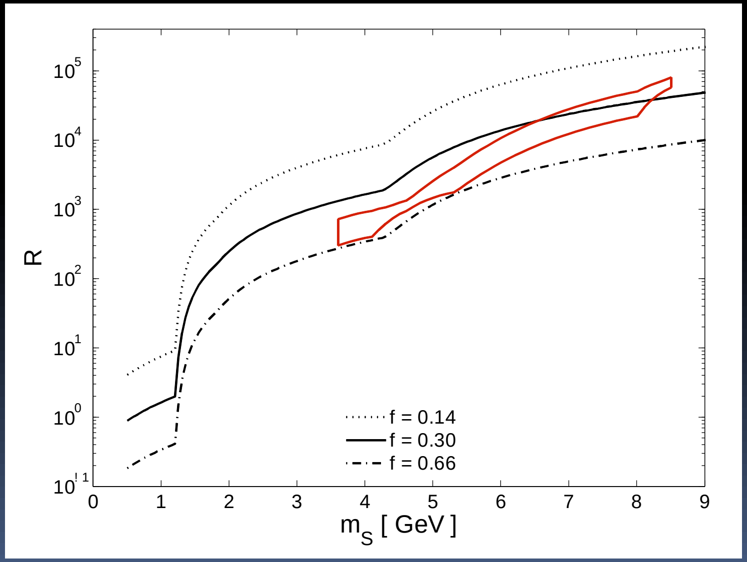
CP. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B619:709 (2001) arXiv:hep-ph/0011335
S. Andreas, T. Hambye, MHG. Tytgat, JCAP 0810:034(2008) arXiv:0808.0255

DM is a Singlet Scalar coupled to SM through Higgs

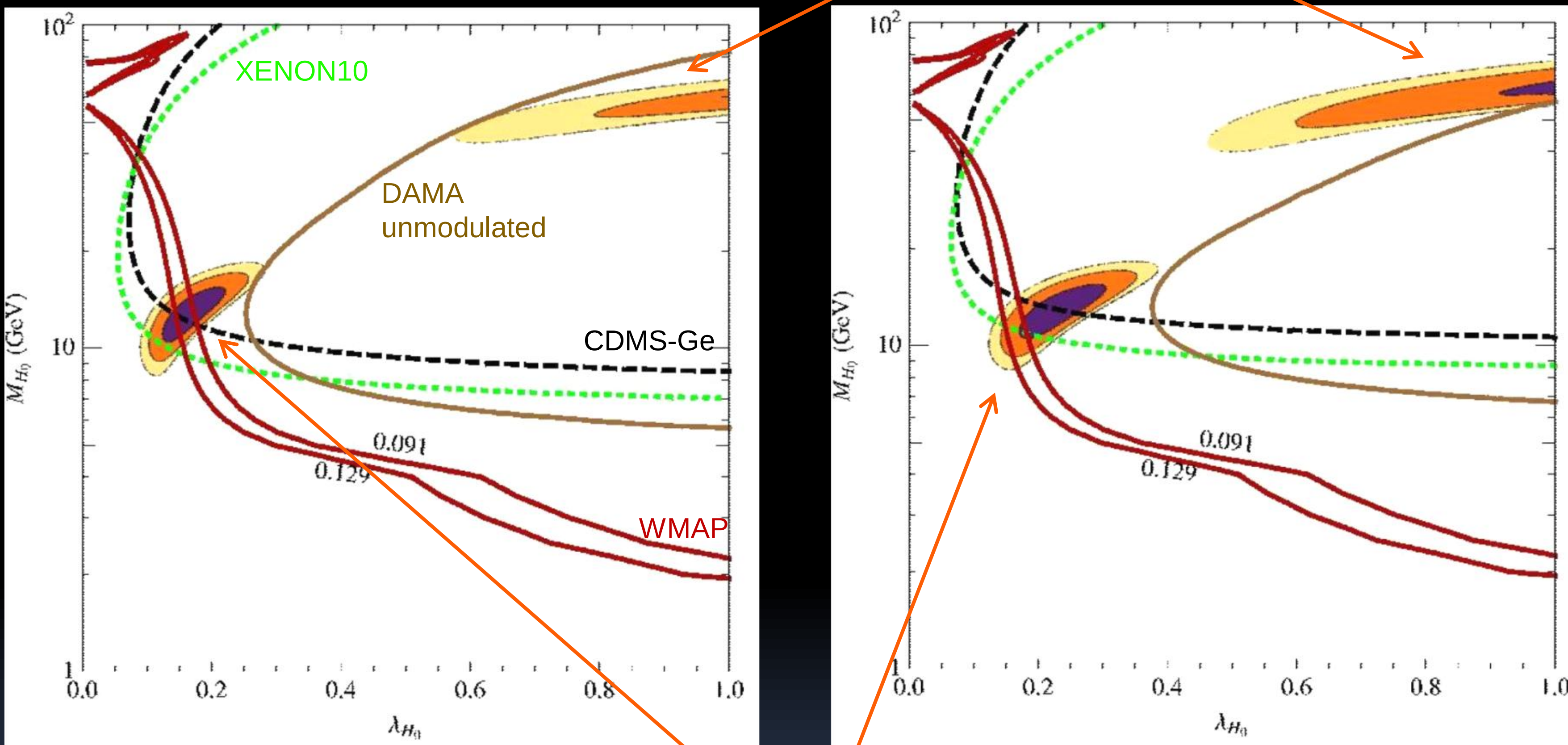


- Scalar field, odd under Z_2 parity
- Standard freeze-out in thermal bath
- Spin-independent
- 2 parameters :

DM mass	M_{DM}
Scalar coupling	λ



Elastic fit



v_{esc} = 600 km/s

v_{esc} = 450 km/s

Uncertainties

Nuclear physics

- Form factor (Helm) 10-20%

$$F(q) = 3e^{-q^2 s^2/2} \frac{J_1(qr)}{qr}$$

- Effective coupling to nucleon

$f = 0.3$ $\quad$ $0.15 \le f \le 0.6$

- Quenching factors, channeling effects

$q_I = 0.09$ $\quad$ $q_I \approx 1$

(R. Bernabei et al., Eur.Phys. J., C53:205213 (2008),
arXiv:0710.288)

Astrophysics

- Local DM density

$$\rho_{DM} = 0.3 \; GeV / cm^3$$

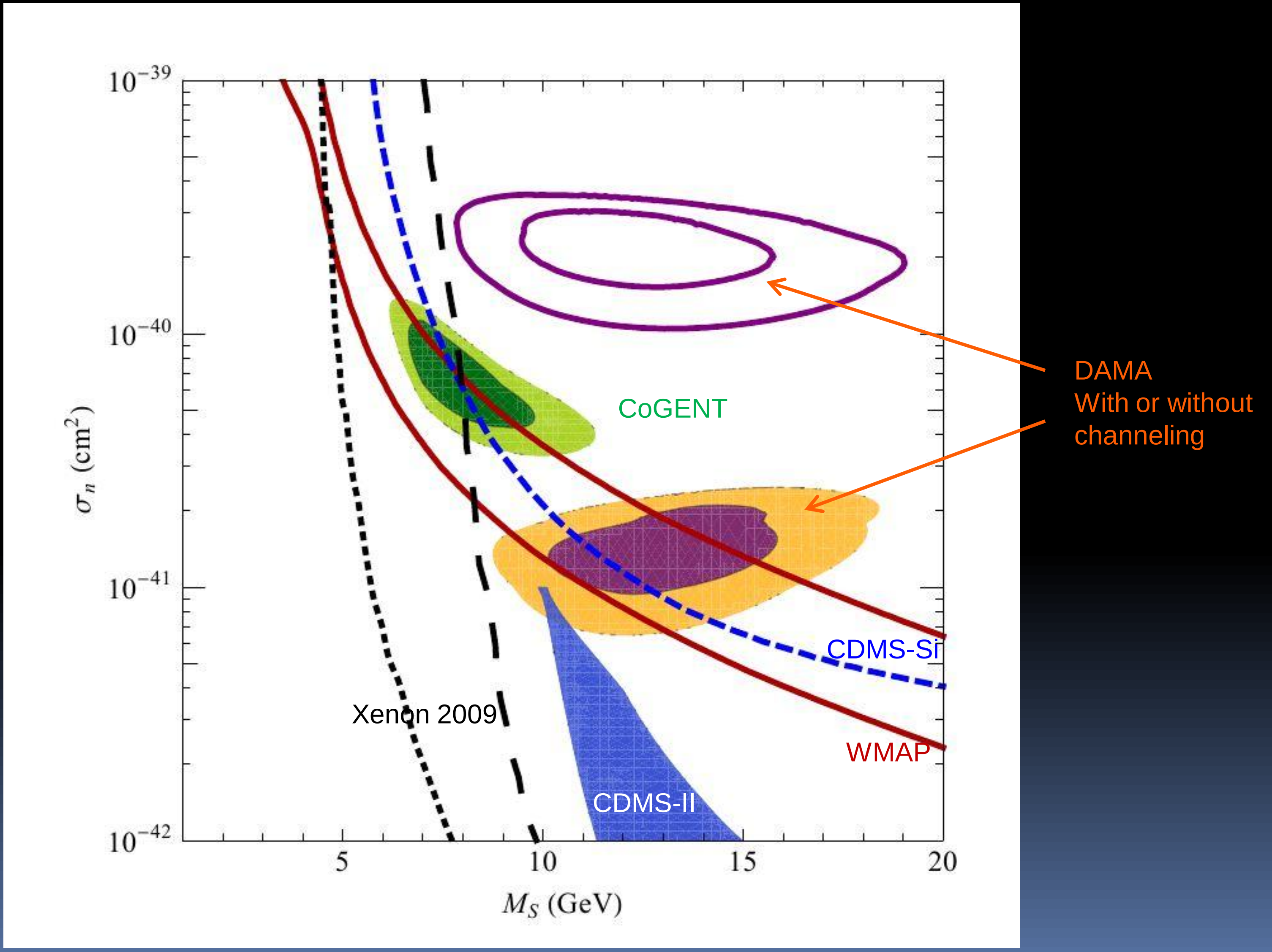
- Velocity distribution: isotropic M-B

$$f(\vec{v}) \propto e^{-v^2/v_0^2}$$

- Escape velocity
- Anisotropies ??
- Deviations from M-B ??
- Clumps ??
- Rotating Dark Disk component ??

Update 2010

S. Andreas, C. Arina, T. Hambye, FSL, M. Tytgat, arXiv:1003.2595



Summary I

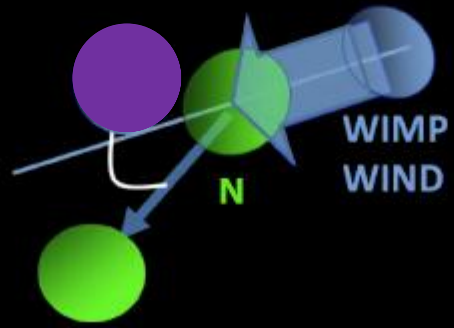
- A singlet scalar DM candidate enables to have both the correct relic density and a fit of DAMA.

- The channeling region of DAMA is only marginally consistent with null experiments, but some freedom is permitted by nuclear and astrophysical uncertainties.

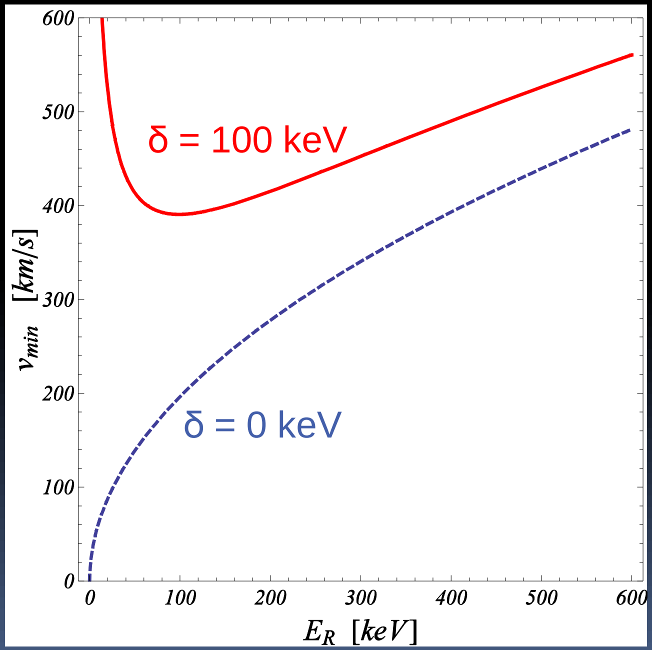
Can we do better ?

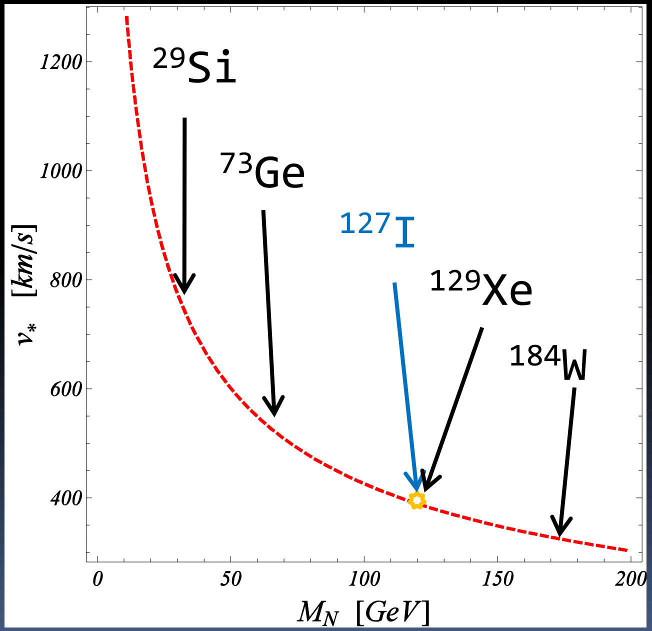
Inelastic Dark Matter

D. Tucker-Smith and N. Weiner, Phys. Rev. D64, 043502(2001), arXiv:hep-ph/0101138.



$$v_{min} = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N E_R}{\mu} + \delta\right)$$





M_{DM} = 10 TeV

Q: Can we realize the Inelastic scenario with scalar DM ?

A: Yes, the simplest possibility is to take an Inert Scalar Doublet

Inert Doublet Model

Deshpande & Ma '78

- Minimal extension of the Standard Model:
  usual Higgs doublet H_1 + additional inert doublet H_2 , odd under Z_2

- Z_2 symmetry → If lightest odd particle is neutral → candidate for DM
  → no FCNC

- Langrangian and Potential

Gauge interactions

$$L = (D_\mu H_2)^+ (D^\mu H_2) - V(H_1, H_2)$$

$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^+ H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^+ H_2)^2 + h.c. \right]$$

Scalar interactions

- $\langle H_2 \rangle = 0$: Z_2 unbroken

- Mass spectrum at tree level

$$H_1 = \begin{pmatrix} 0 \\ (v_0 + h)/\sqrt{2} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

$Y_{H2} = 1$

DM candidate

$$M_{H_0}^2 = \mu_2^2 + \lambda_{H_0} v_0^2$$
$$M_{A_0}^2 = \mu_2^2 + \lambda_{A_0} v_0^2$$
$$M_{H_c}^2 = \mu_2^2 + \lambda_{H_c} v_0^2$$

$$\lambda_{H_0} = (\lambda_3 + \lambda_4 + \lambda_5)/2$$
$$\lambda_{A_0} = (\lambda_3 + \lambda_4 - \lambda_5)/2$$
$$\lambda_{H_c} = \lambda_3/2$$

- Quartic Scalar interactions with Higgs

$$V_{H-h} = \frac{1}{2}\left(\lambda_{H_0} H_0^2 + \lambda_{A_0} A_0^2 + 2\lambda_{H_c} H_+ H_-\right)\left(2v_0 h + h^2\right)$$

- If λ5 = 0 , there is a Peccei-Quinn symmetry

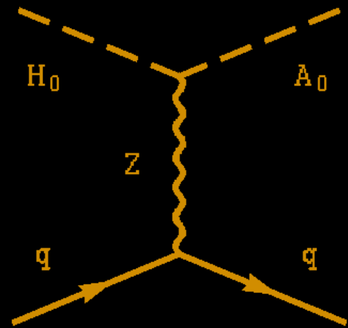
→ $\delta = M_{A0} - M_{H0}$ is protected against radiative corrections

- Perturbativity & Vacuum stability conditions

Low mass regime >< High mass regime

Direct detection ?

- At tree level :

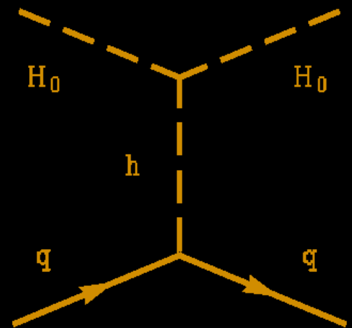


× $\delta = 0$:

Excluded by null experiments

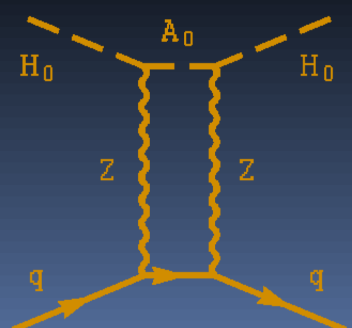
√ $\delta \sim 100$ *keV :*

Inelastic DM



Subdominant if *Z* exchange present

- At 1-loop level :

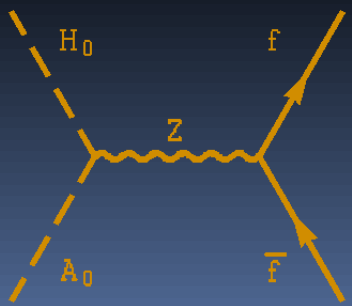


Minimal Elastic cross section

→ IDM can be tested by future DD experimen

Low mass regime & DAMA

- Either $M_{A0}, M_{Hc} >> M_{H0} \sim 10\ GeV$, A_0 , H_c decouple → back to singlet
  - √ Z width constraint
  - √ Relic abundance set by WMAP
- Either $\delta = M_{A0} - M_{H0} \sim 100\ keV$ & $M_{Hc} > M_{H0}$
  - √ Z width constraint → OK if $M_Z < 2\ M_{H0}$
  - × Relic abundance set by WMAP : too fast coannihilation



Asymmetry ?

High mass regime & DAMA

- Annihilation into pairs of gauge bosons open

  → Mass threshold set by WMAP $M_{H_0} \geq 535\ GeV$

- Small mass splittings → coannihilations non negligible

- Three independent scalar quartic couplings λ_{H0}, λ_{A0}, λ_{Hc}

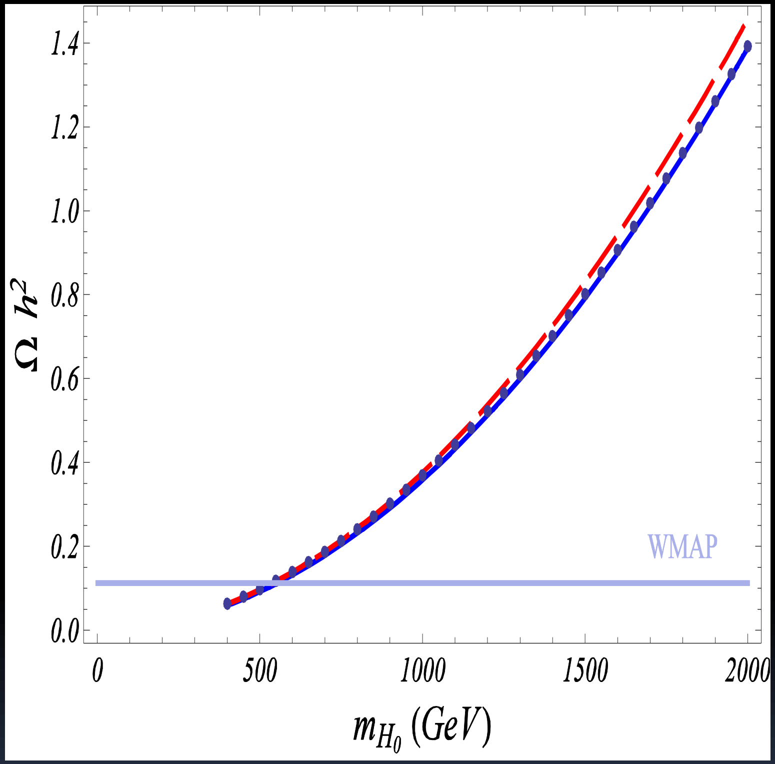
  √ $\delta = M_{A0} - M_{H0} \sim 100\ keV$

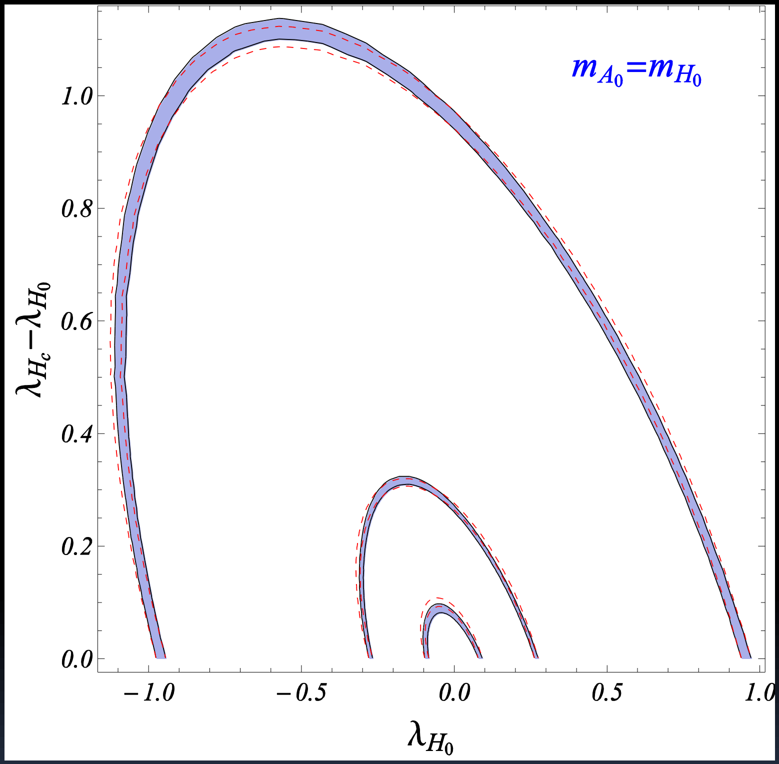
$$\lambda_5 = 3.3 \cdot 10^{-7} \left(\frac{M_{H_0}}{100\ GeV} \right) \left(\frac{\delta}{100\ keV} \right)$$

  √ Relic abundance set by WMAP

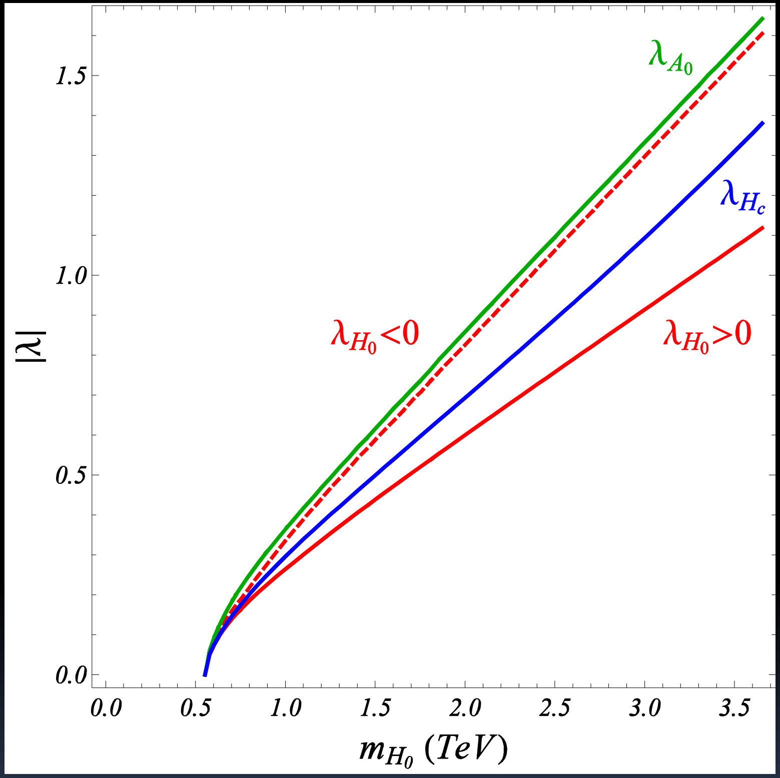
Pure gauge limit

With scalar quartic couplings

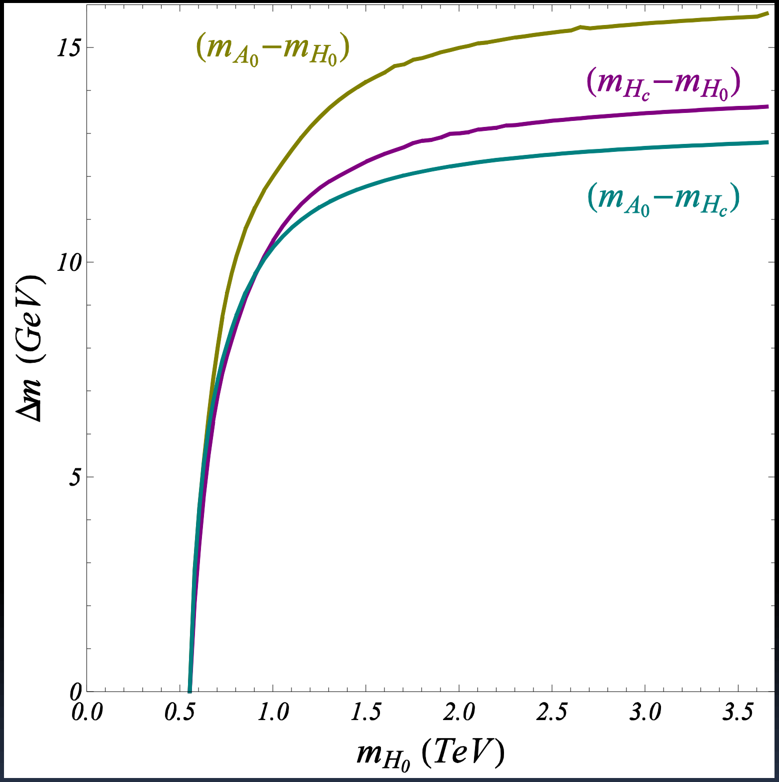




Scalar quartic couplings

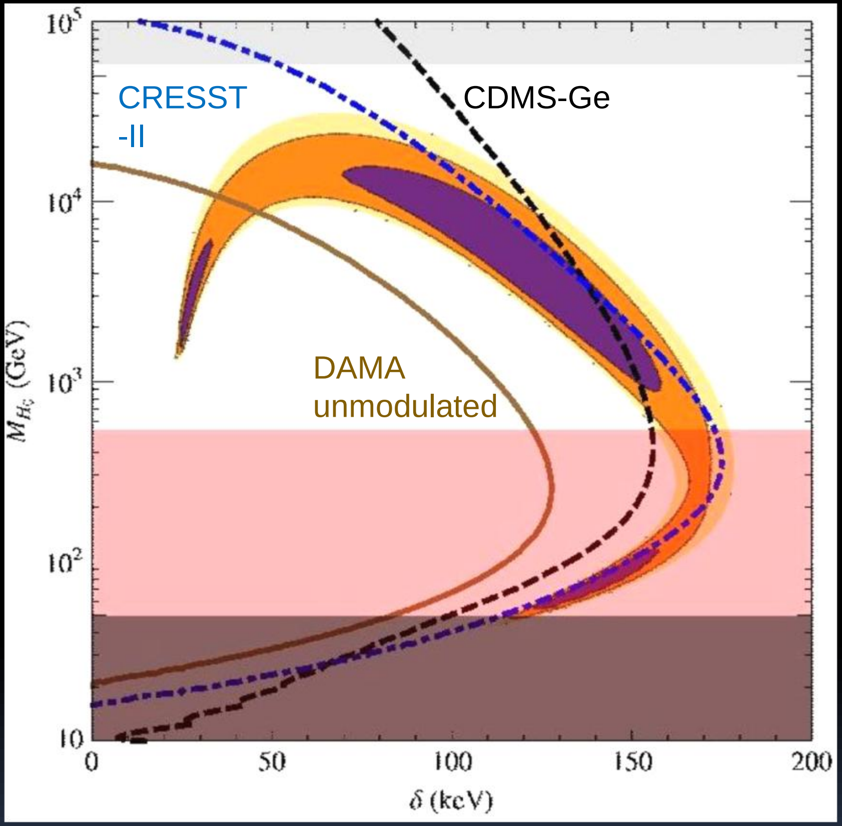


Mass splitting

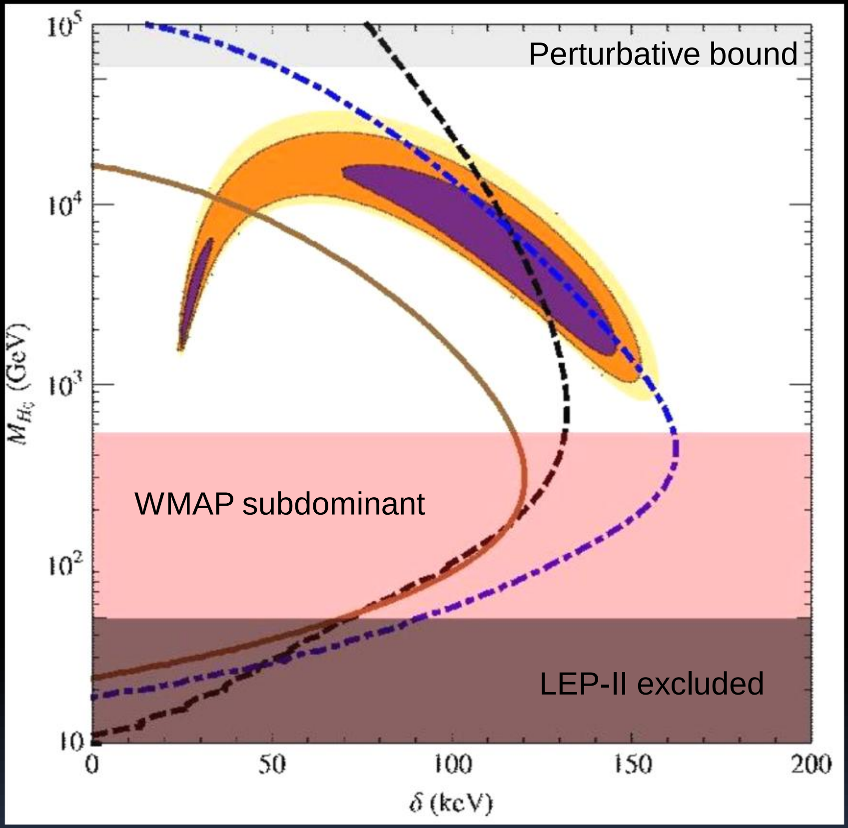


So what do we get ?

Inelastic fit



v_{esc} = 650 km/s



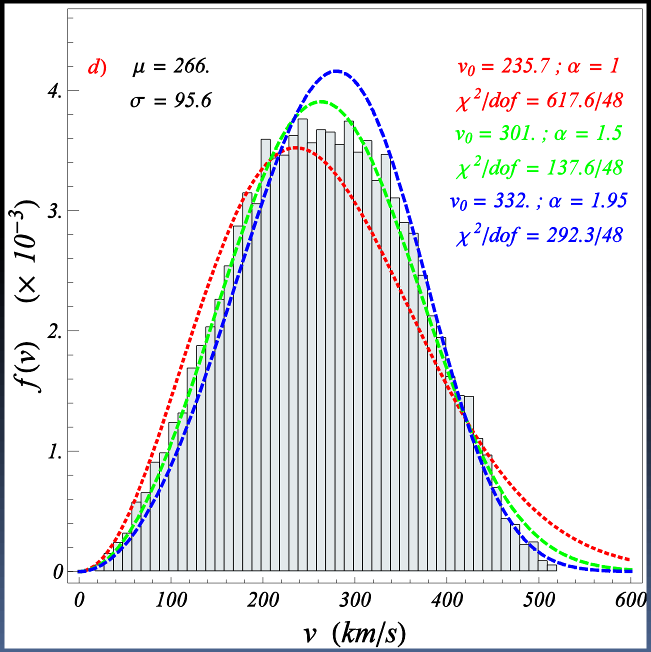
v_{esc} = 450 km/s

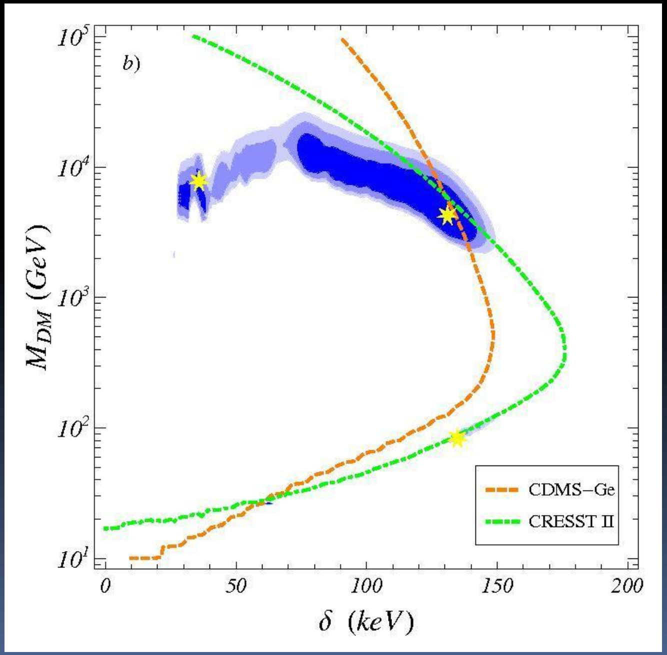
Candidates for iDM

- M_{DM} ~ *few TeV* , δ ~ *30 keV* → Excluded by DAMA itself
- M_{DM} ~ *few TeV* , δ ~ *130 keV*

→ Improved goodness-of-fit with a realistic halo

Here : fit with the DM halo from a N-body simulation with stars and gas





- M_{DM} ~ 50-100 GeV , δ ~ 130 keV

  1. Subdominant relic density
  2. Charge asymmetry

$$\lambda_5 = 3.3 \cdot 10^{-7} \left(\frac{M_{H_0}}{100\ GeV} \right) \left(\frac{\delta}{100\ keV} \right)$$

In the limit $\lambda_5 \to 0$, exact PQ symmetry

$$H_n = (H_0 + iA_0)/\sqrt{2}$$

PQ = +1

Charge asymmetry only broken by processes controlled by λ_5

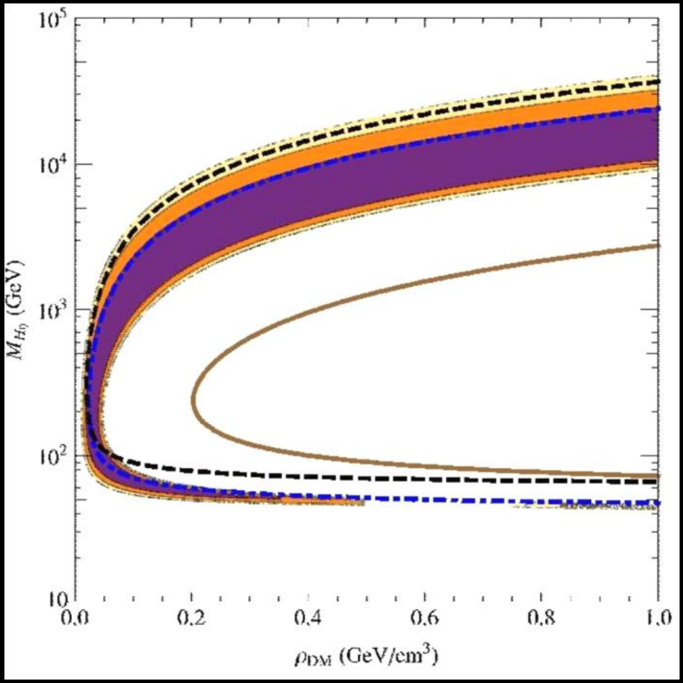
$$H_n\ H_n \to (h) \to f\ \bar{f}$$
$$H_n\ H_n \to h\ h$$
$$H_n\ h \to H_n^*\ h$$

Annihilation through Higgs neglected

Simplified Boltzmann equation to get an upper bound. We find

$$\lambda_5 < 10^{-7} g_*^{1/4} \sqrt{\frac{T}{10\ GeV}}$$

→ out-of equilibrium for M_{DM} < *O(100) GeV*



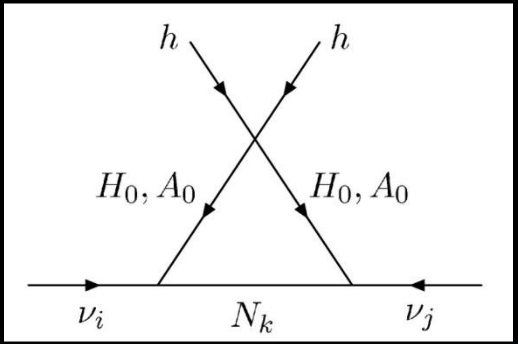
Neutrino masses & Leptogenesis

- Add right-handed neutrinos. If they are odd under Z_2 , the most general lagrangi

$$L = L_{IDM} + i\bar{N}_i \partial N_i - \bar{N}_i Y_{Nij} \tilde{H}_2^+ L_j - \frac{1}{2} m_{Ni} N_i N_i$$

- Radiative see-saw neutrino masses

$$(m_\nu)_{ij} = -\frac{\lambda_5 v_0^2}{16\pi^2} \sum_k \frac{Y_{Nki} Y_{Nkj}}{m_{Nk}} \left[\log \frac{m_{H_0}^2}{m_{Nk}^2} + 1 \right]$$



Compare with standard see-saw

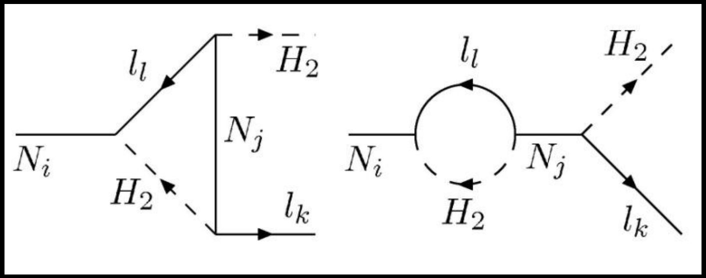
$$(m_\nu)_{ij} = -\frac{v_0^2}{2} \sum_k \frac{Y_{Nki} Y_{Nkj}}{m_{Nk}}$$

Extra suppression allows for lower right-handed neutrino masses

- Leptogenesis

  CP asymmetry essentially unchanged

$$\varepsilon_{N1} = -\sum_{j=2,3} \frac{3}{16\pi} \frac{m_{N1}}{m_{Nj}} \frac{\sum_i \mathrm{Im}\left[\left(Y_{N1i} Y^{+}_{Nij}\right)^2\right]}{\sum_i \left|Y_{N1i}\right|^2}$$



$$m_{N1} \geq \frac{\lambda_5}{8\pi^2} 6 \cdot 10^8 \ GeV$$

$$\lambda_5 \leq 1.5 \cdot 10^{-4} \left(\frac{m_{N1}}{1\, TeV} \right)$$

  → Bound on N_1 mass lowered to TeV scale !

- Yukawa couplings

  Out-of-equilibrium decay of N_1 → $\left|Y_{N1j}\right|^2 < 4 \cdot 10^{-14} \left(\frac{m_{N1}}{1\, TeV} \right)$

  Hierarchical pattern to obtain observed neutrino Δm^2 → $Y_{Nji} \geq 1 \cdot 10^{-3} \left(\frac{m_{Nj}}{m_{N1}} \right)^{1/2} \quad (j = 2 \text{ or } 3)$

- Washout conditions OK!

Summary II

- The Inert Doublet Model naturally provides candidates for inelastic DM.
- Heavy candidates with a mass M_{DM} ~ *few TeV* are consistent with WMAP. A simple extension with odd right-handed neutrinos at the TeV scale enables to have radiative neutrino masses & leptogenesis at the TeV scale.
- Lighter candidates with a mass M_{DM} ~ *50-100 GeV* have a subdominant relic abundance, unless protected by an asymmetry in the Dark sector.
- If *Z* exchange is negligible, scalar interations will hopefully be probed by future ton-sized direct detection experiments.

Astrophysics

Aims

Use of N-body simulations to derive more realistic velocity distributions & discuss in particular :

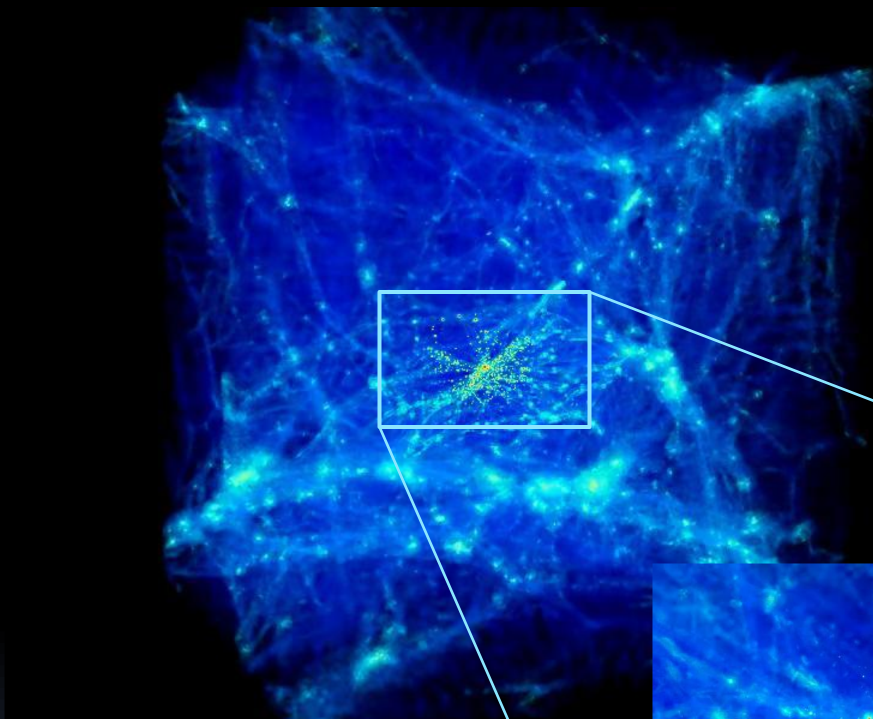
- Local Dark Matter density value

- Deviations from Maxwell-Boltzmann distributions

- Any kind of anisotropy, in particular the rotation of the halo

- Existence of a dark disc

Description of the simulation



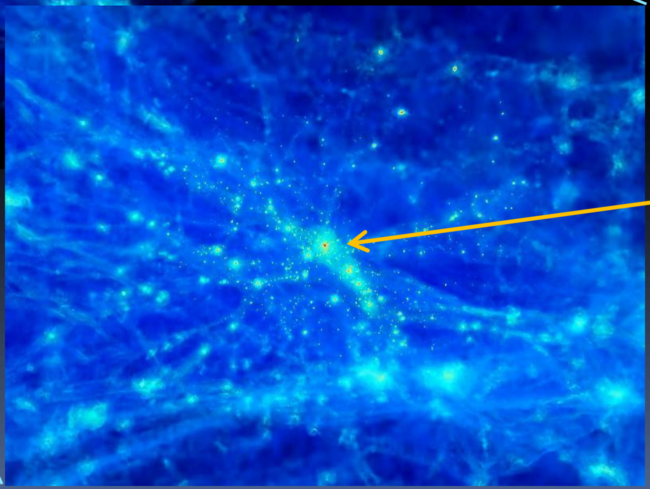
Cosmological parameters :

$\Omega_b = 4.5\ \%\ ;\ \Omega_m = 30\ \%\ ;\ \Omega_\Lambda = 70\ \%$

Includes DM, stars & gas. Full hydro with :

- gas radiative cooling
- star formation
- SN feedback
- chemistry

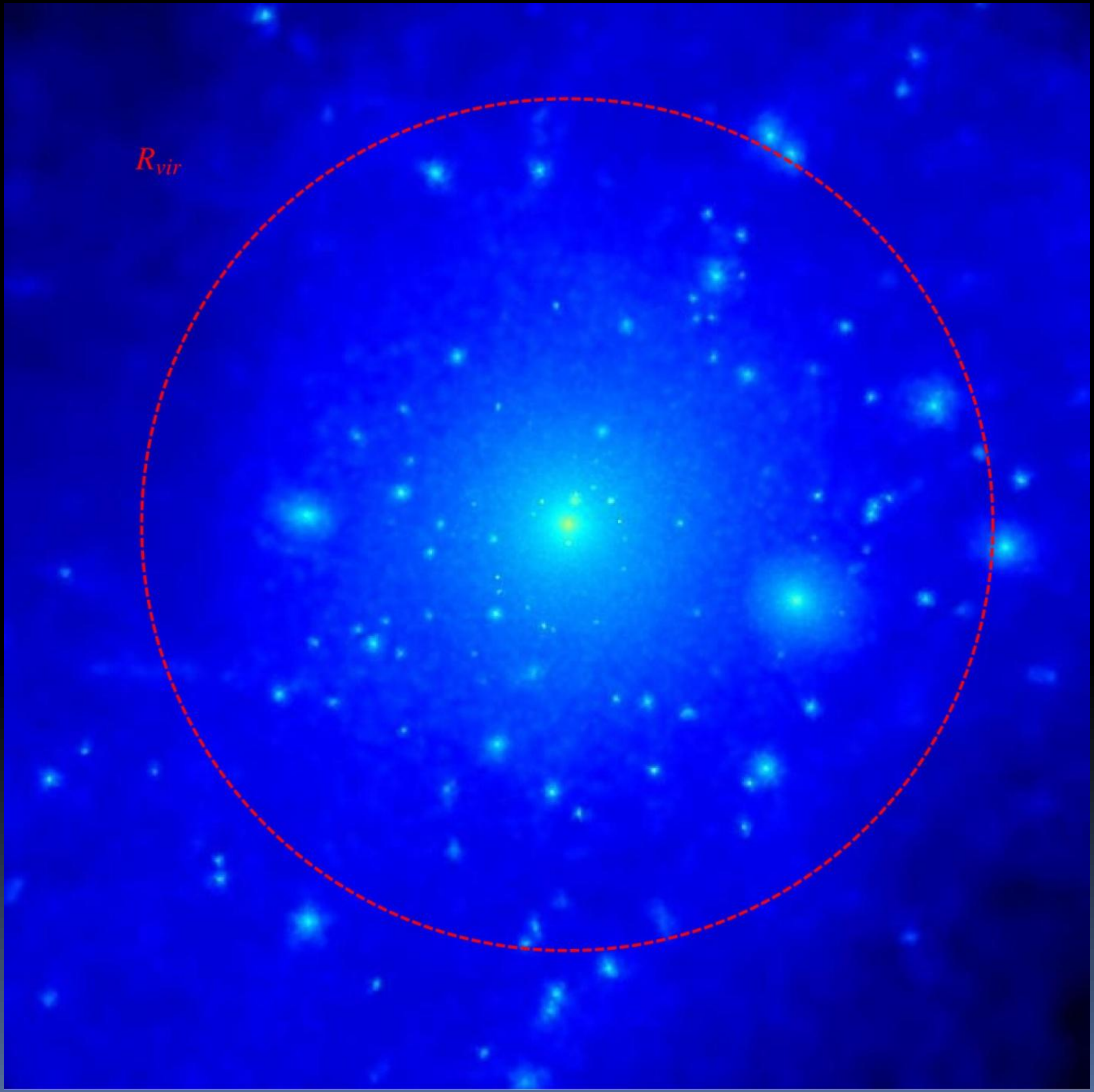
code : AMR Ramses (R. Teyssier)



$L_{box} = 20\ Mpc/h$

$N = 1024^3$ *elements*

Galactic DM halo



R_{vir} = 264 kpc

N_{DM} = 843 000

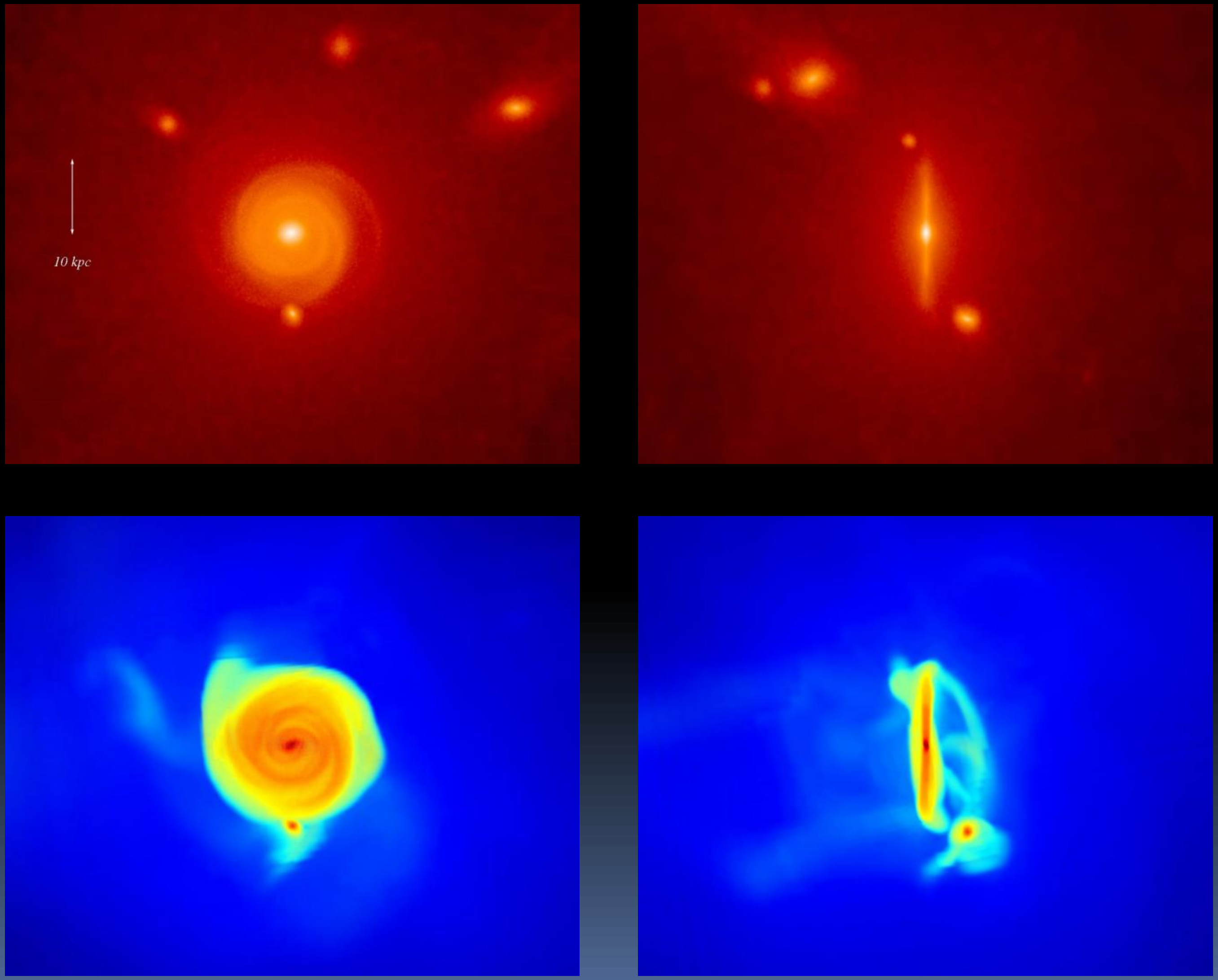
$M_{vir} = 6.3 \times 10^{11} M_{sun}$

δl = 200 pc

Galactic disc and bulge

Stars

Gas



Comparison with Milky Way

	Milky Way	Simu
DM halo mass	$2.35 \times 10^{12}\ M_{sun}$	$6.3 \times 10^{11}\ M_{sun}$
Bulge mass	$1.8 \times 10^{10}\ M_{sun}$	$4.0 \times 10^{10}\ M_{sun}$
Disc mass	$6.5 \times 10^{10}\ M_{sun}$	$4.0 \times 10^{10}\ M_{sun}$
Disc scale radius	$3.5\ kpc$	$1.9\ kpc$

↓

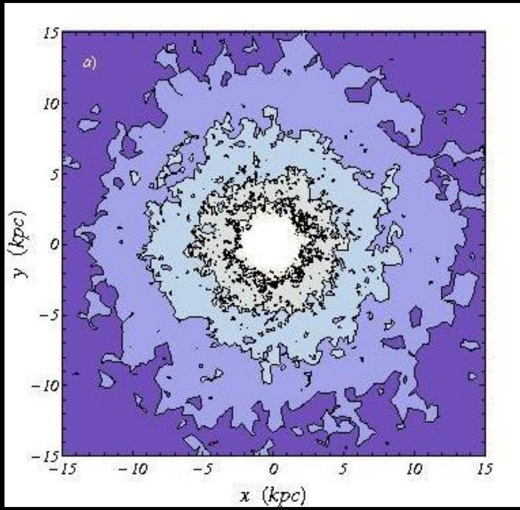
Sofue, Honma, Omodaka 2008, arXiv:0811.0859

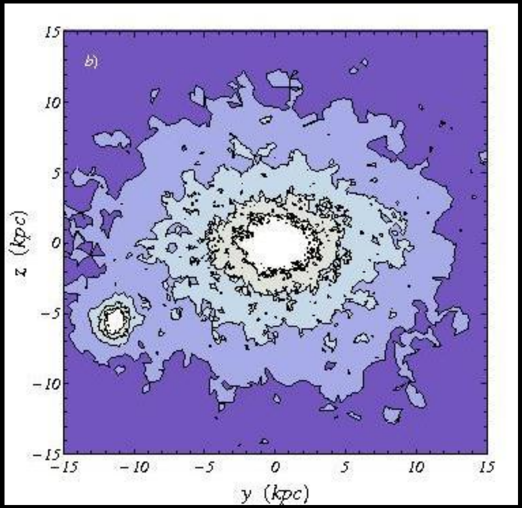
- Low mass halo
- Bulge too fat
- Disc too small

→ generic problems of simulations with baryons

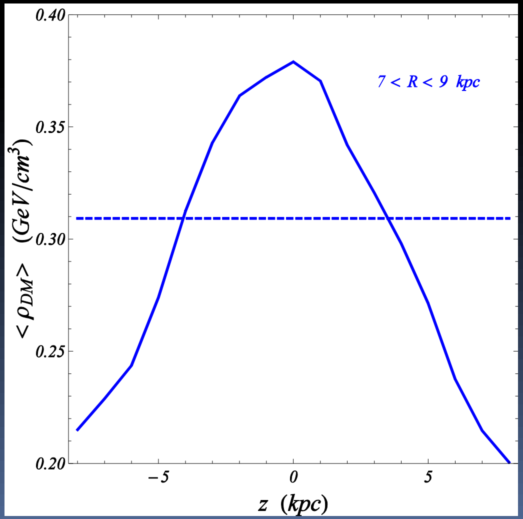
Dark Matter density

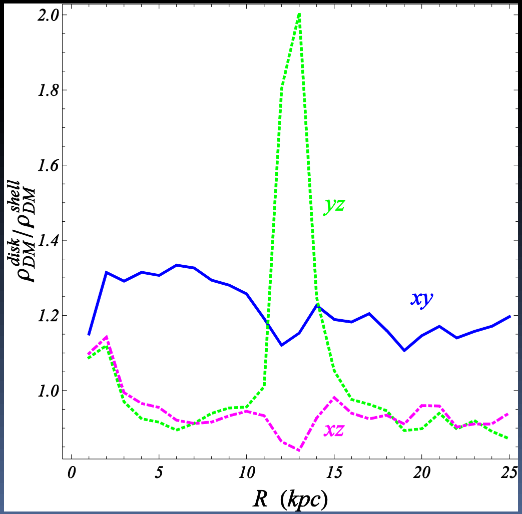
Pxy
(galactic plane)





Pyz

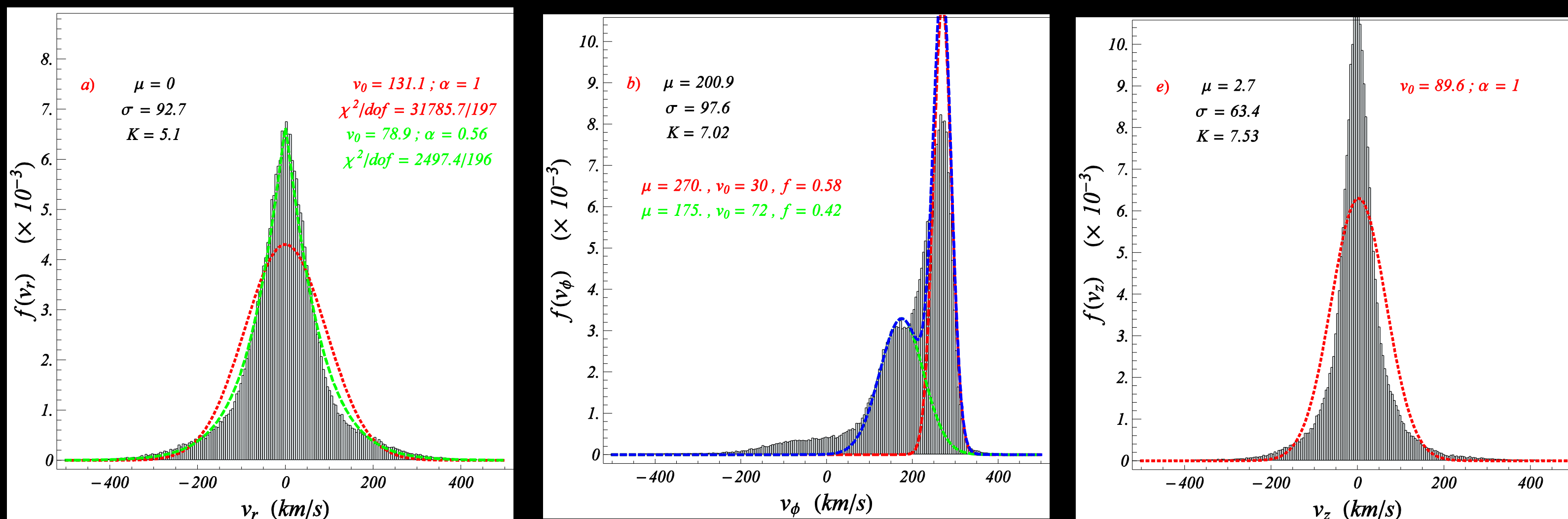




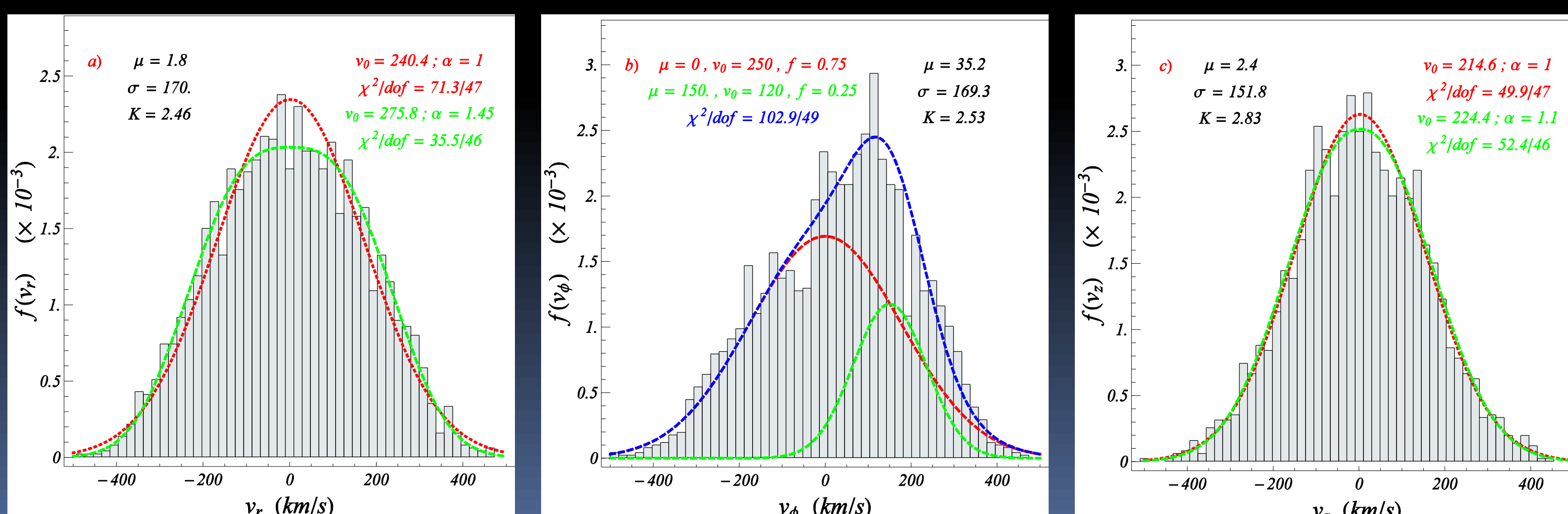
Velocity distributions

$N_{ring} = 2\ 650$

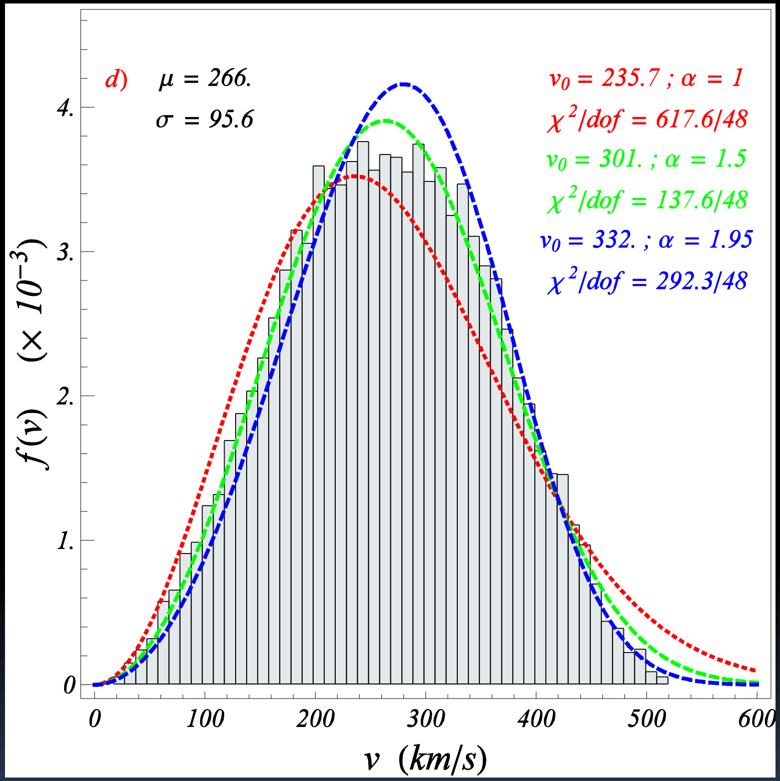
Stars



DM



Velocity wrt galactic center



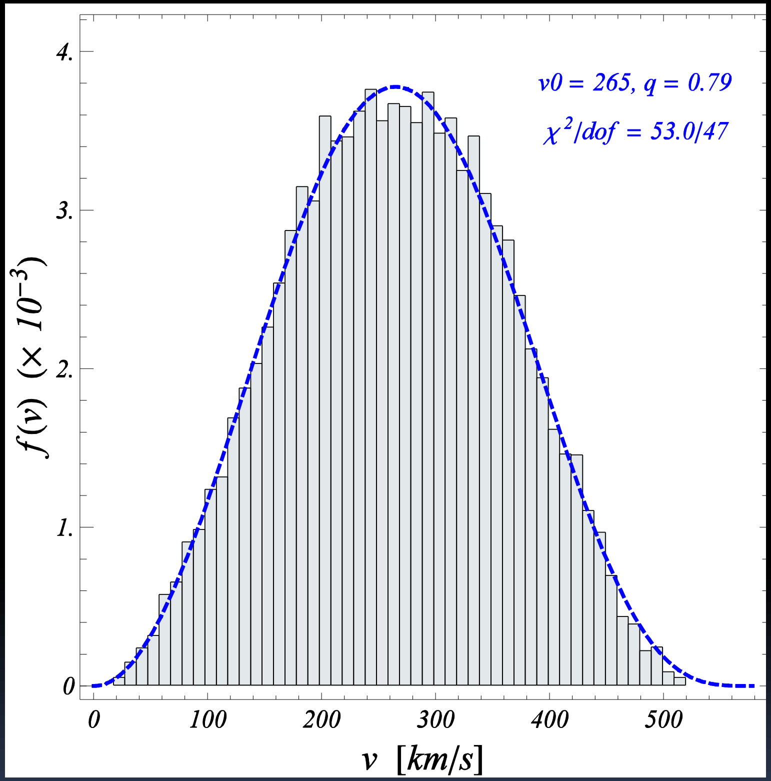
N_{shell} = 16 500

Generalized Gaussian and Maxwellian distributions

$$f(\vec{v}) \sim e^{-((v-\mu)^2/v_0^2)^\alpha}$$

$$f(\vec{v}) \sim v^2 e^{-((v-\mu)^2/v_0^2)^\alpha}$$

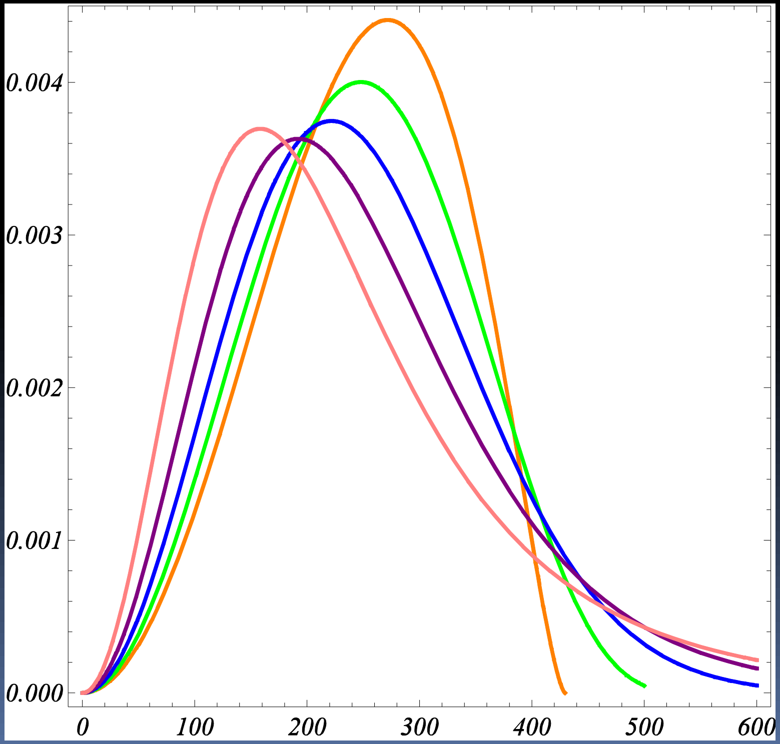
Velocity wrt galactic center



N_{shell} = 16 500

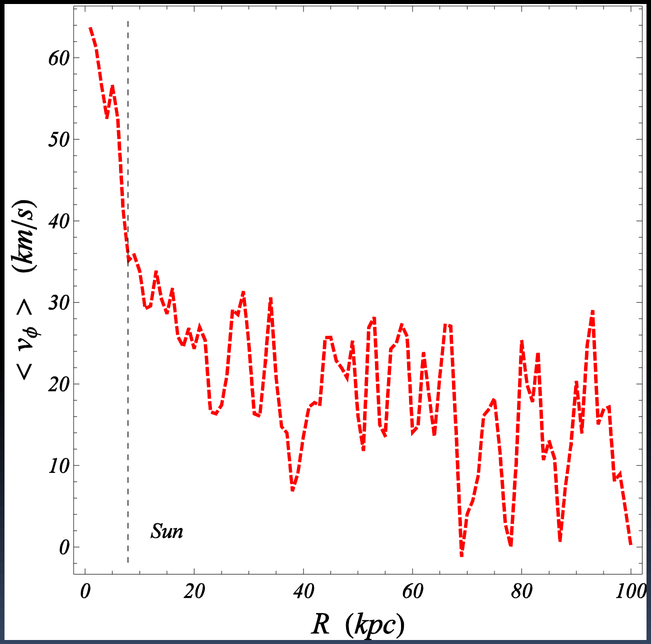
Tsallis distribution

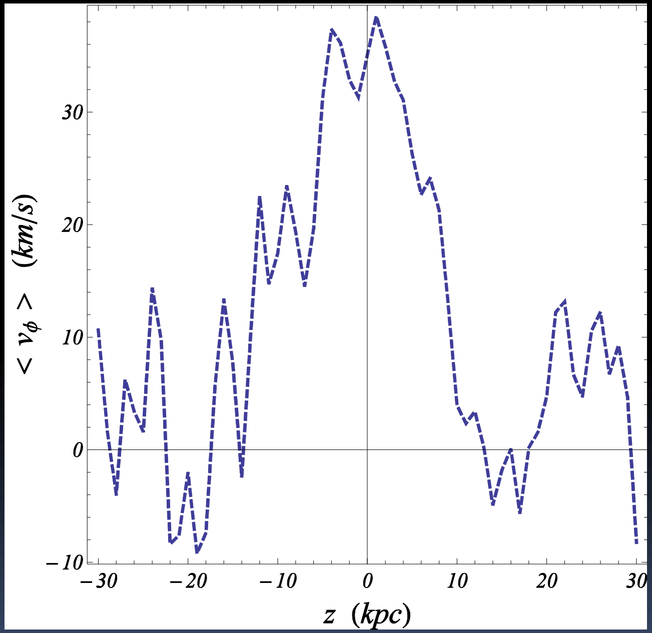
$$f(\vec{v}) \sim v^2 \left(1-(1-q)\frac{v^2}{v_0^2}\right)^{\frac{q}{1-q}}$$



Dark Disk

- New DM component found (?) in cosmological N-body simulations : thick disk of DM co-rotating with the galactic disc of stars





Dark Disk

- New DM component found (?) in cosmological N-body simulations :
  thick disk of DM co-rotating with the galactic disc of stars

- Origin of dark disc and rotation :
  Accreted DM from mergers, preferential drag towards galactic plane

- Characteristics depend on merger history and correlate with those of accreted stars

  $\rho_{DD} = 0.25 \ldots 1.5\ \rho_H$

  $v_{lag} = 0 \ldots 150$ *km/s*

- Velocity dispersion :
  - small in controlled simulations $\sigma \sim 50$ *km/s*
  - large in full hydro simulations $\sigma > 100$ *km/s*

Implications for searches

- Direct detection : - Enhanced signal @ low energy recoil

  - Enhanced annual modulation

  - Modulation phase : maximum occurs earlier

- Indirect detection : - Enhanced capture in the Sun

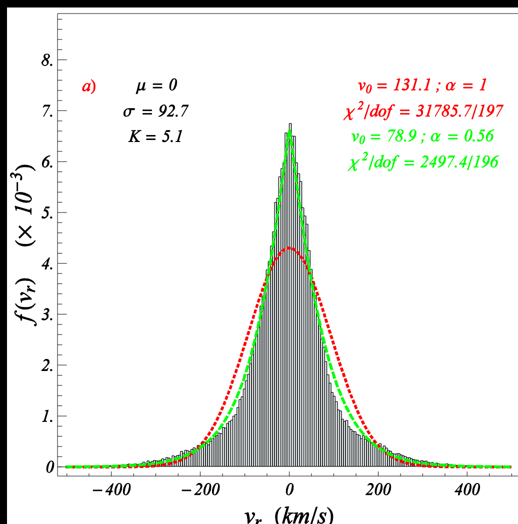
  - Enhanced capture in the Earth

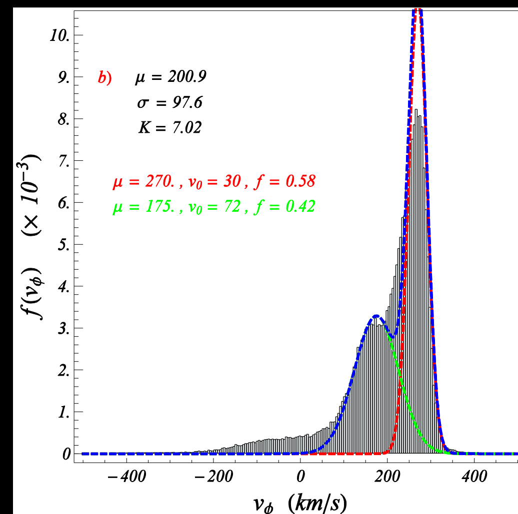
  → Larger muon neutrino flux

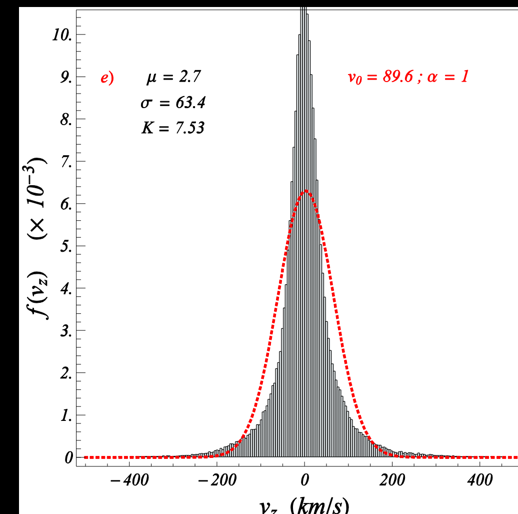
Velocity distributions

$N_{ring} = 2\ 650$

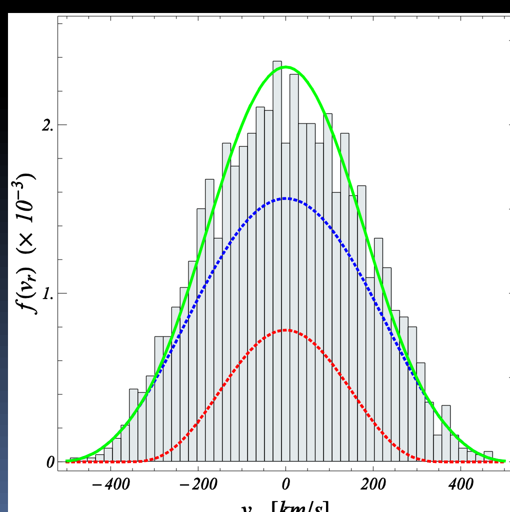
Stars

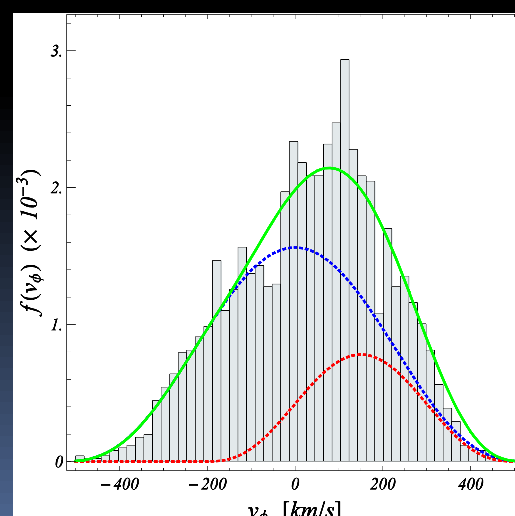


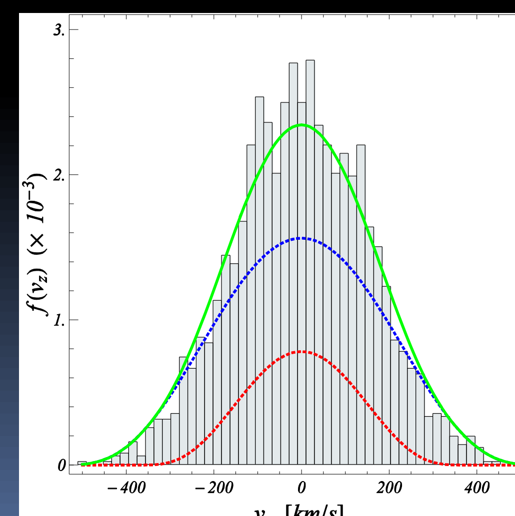




DM







Is there a Dark Disk ?

- Resolution is not sufficient to clearly disentangle a rotating dark disk from a static halo
- Velocity distributions compatible with mild dark disc

$$\rho_{DD} = 0.25\,(\rho_H + \rho_{DD})$$

$$v_{lag} = 70\ km/s$$

- Velocity dispersion : $\sigma \sim 120\ km/s$

but platykurtic (K < 3) distributions in *r* and *z* !!

Velocity wrt the Sun

Standard Maxwellian Halo :

$v_{oH} = 220$ km/s
→ $\sigma_H = 155$ km/s

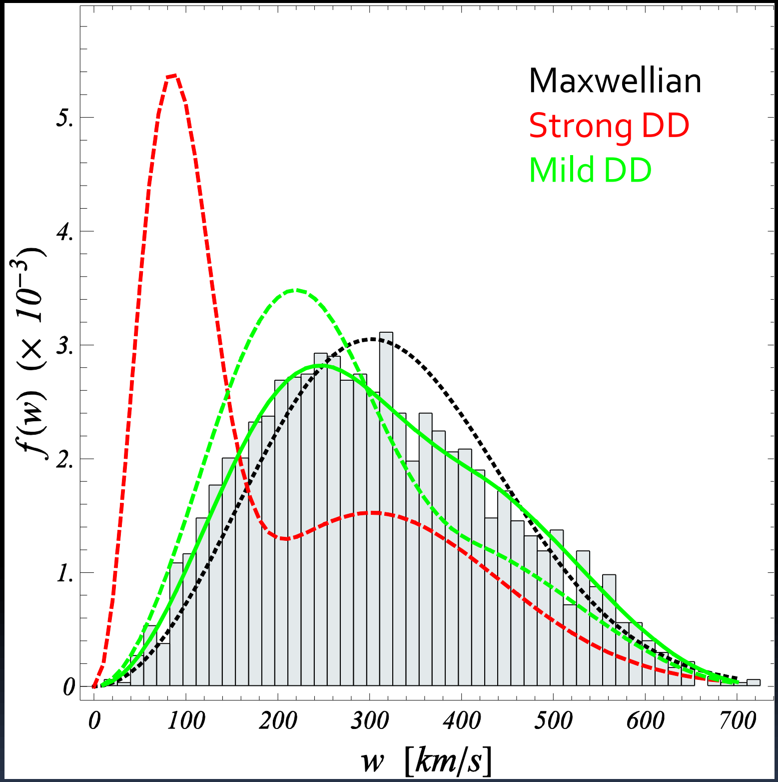
SH + Strong Dark Disk (Maxwellian):

$v_{oD} = 70$ km/s
→ $\sigma_D = 50$ km/s
$v_{lag} = 50$ km/s
$\rho_D/\rho_H = 1/1$

Mild Dark Disk (Tsallis):

$v_{oH} = 300$ km/s ; $q_H = 0.7$
→ $\sigma_H = 176$ km/s

$v_{oD} = 200$ km/s ; $q_D = 0.7$
→ $\sigma_D = 117$ km/s
$v_{lag} = 70$ km/s
$\rho_D/\rho_H = (1/3, 1/1)$



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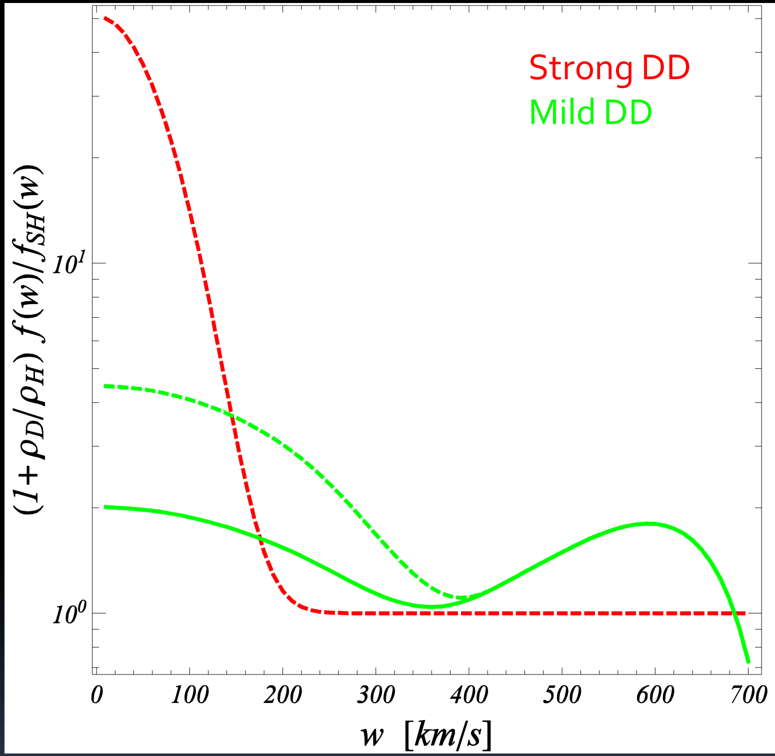
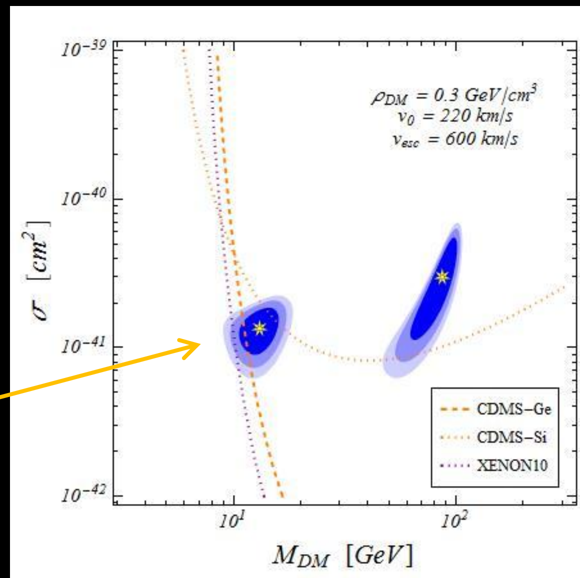
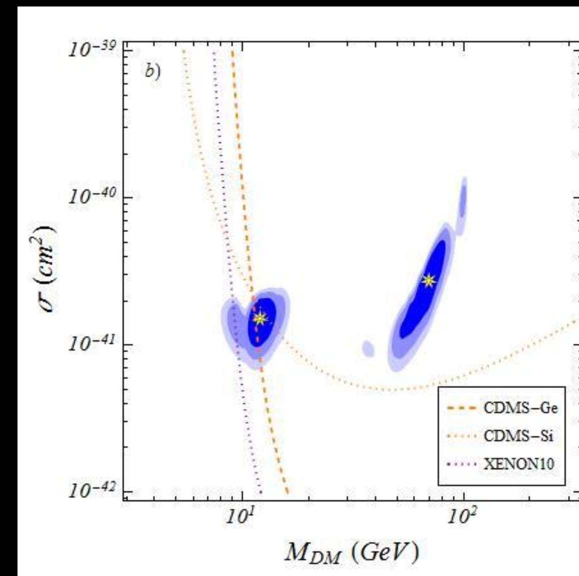


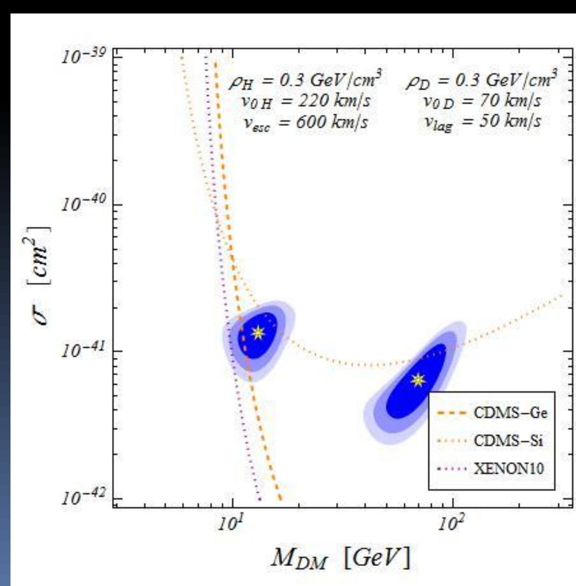
DAMA vs. Null experiments

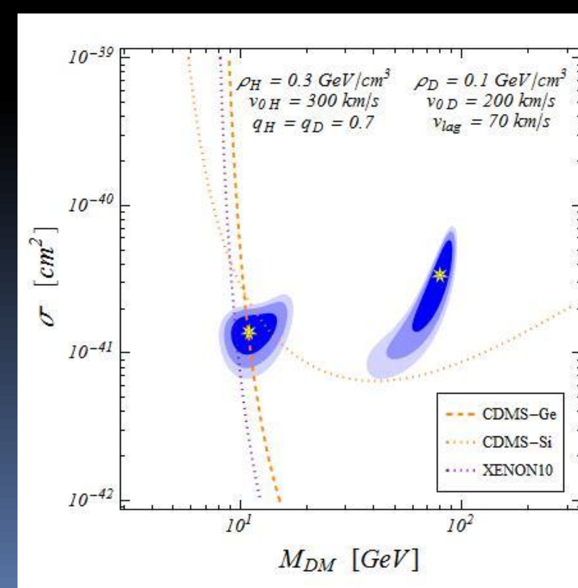
<u>Elastic scenario</u>





Channeling region little affected by Dark Disk



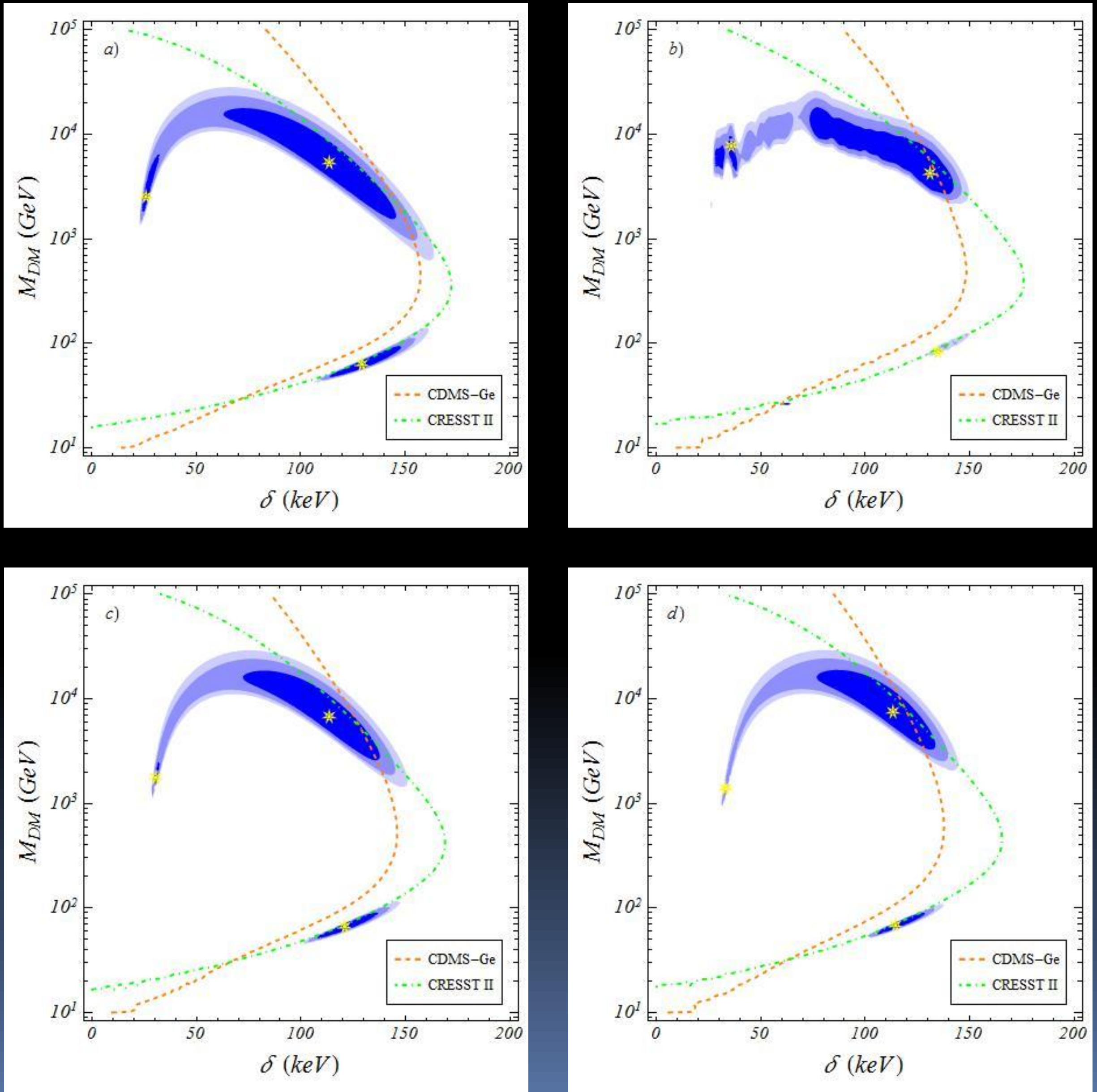


DAMA vs. other
→ improvement
in compatibility
with a Tsallis Dark Disk

DAMA vs. Null experiments

Inelastic scenario

$\sigma = \sigma_Z$

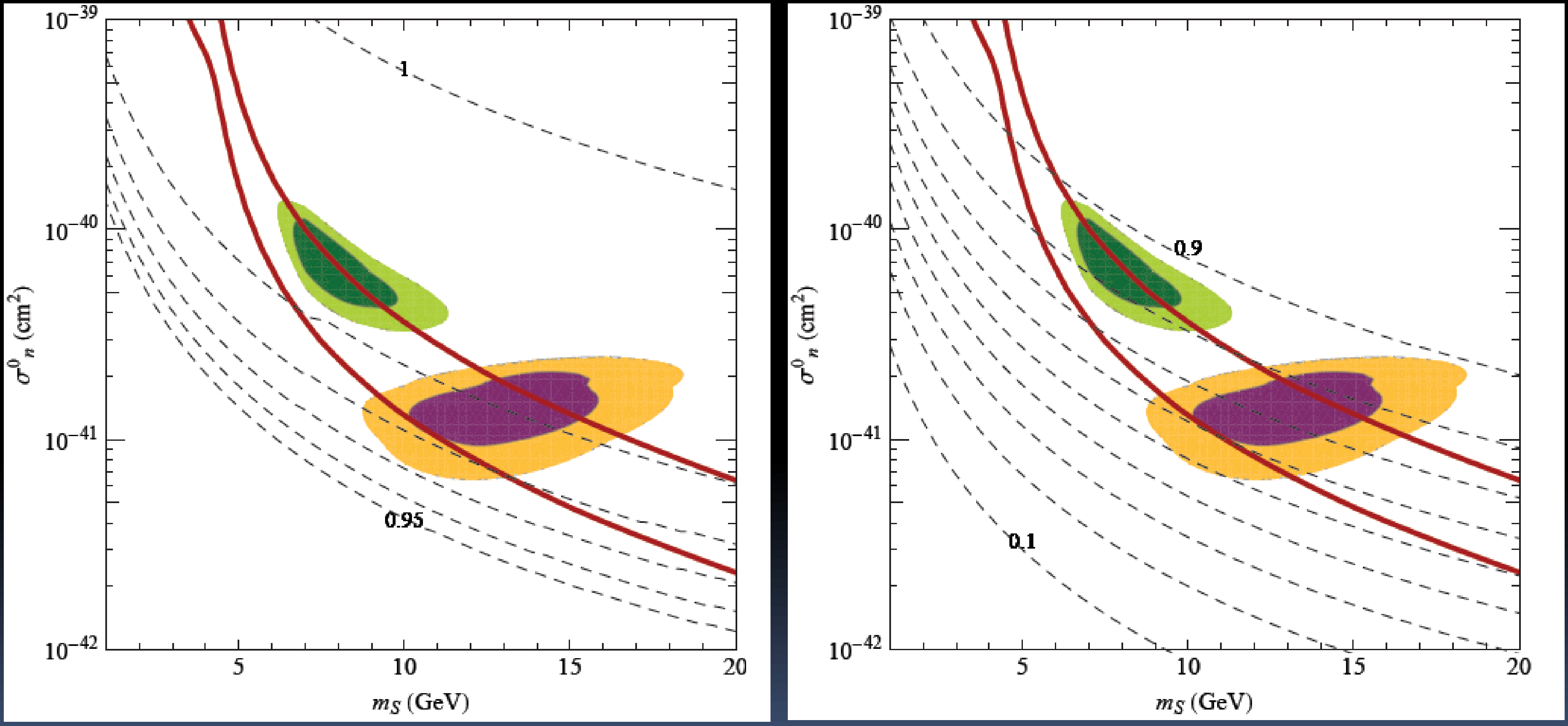


Summary III

- N-body simulations can be used to discuss astrophysical uncertainties in the calculation of direct detection rates, such as the
  - DM local density,
  - velocity distributions & deviations from M-B
  - anisotropies & rotation
  - influence of a dark disc component
- Recent N-body simulation with baryons :
  - most deviations from standard picture are mild
  - non-gaussianities are significant
  - resolution is too poor to disentangle the possible dark disk component
  - boost effect from dark disc mild
  - improvement of compatibility between DAMA and null experiments in both elastic and inelastic scenarios

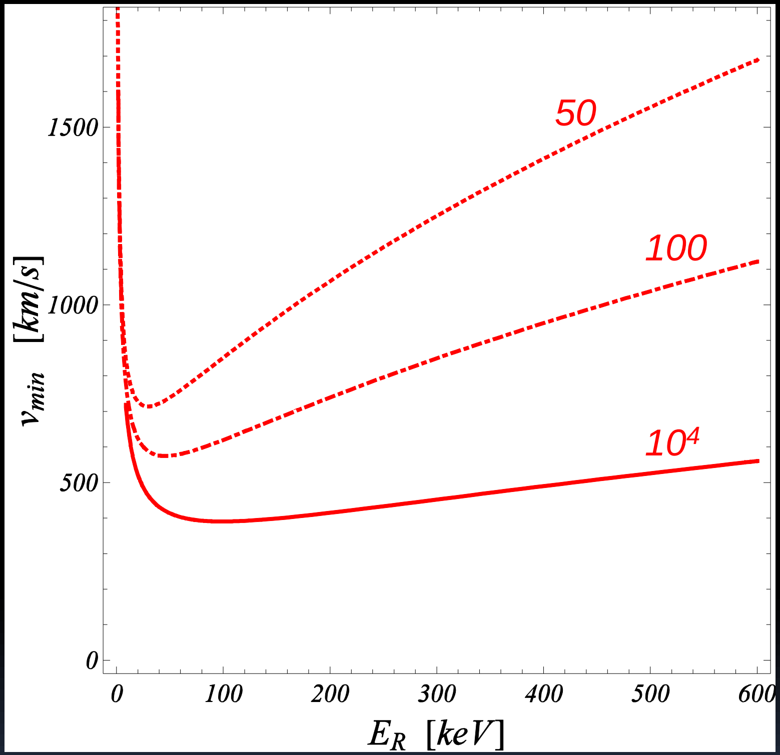
More slides

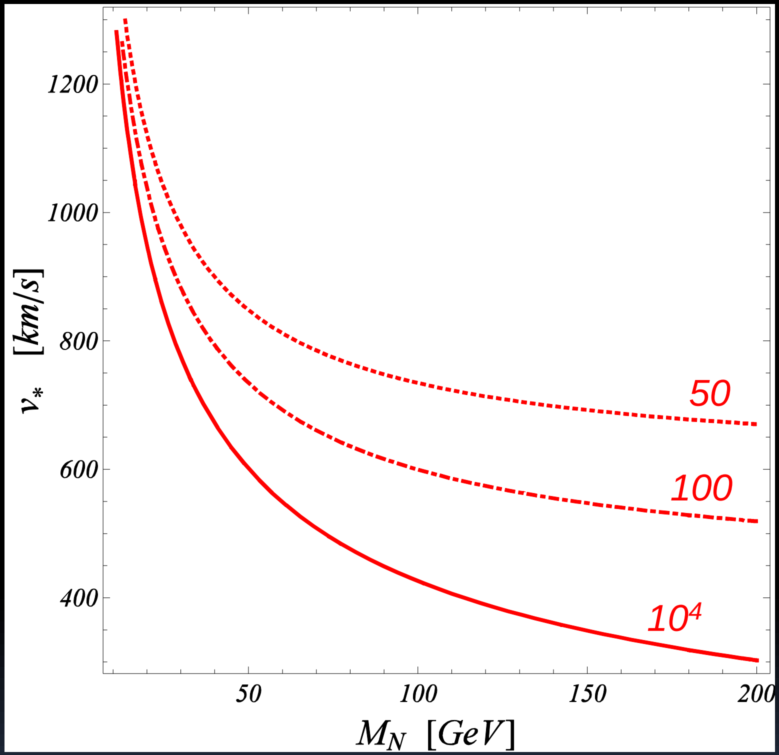
Branching ratio H → DM DM



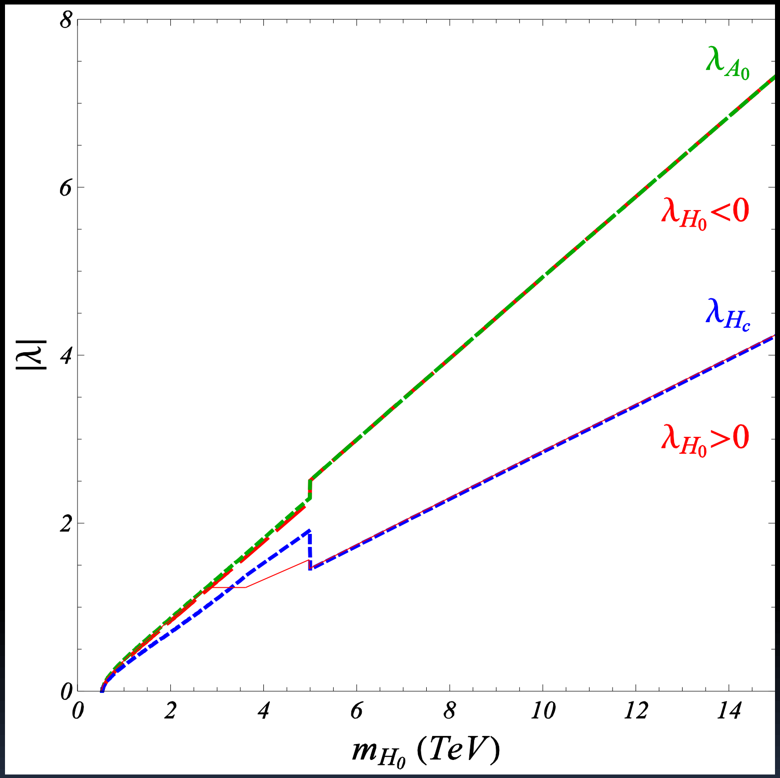
S. Andreas, C. Arina, T. Hambye, FSL, M. Tytgat, arXiv:1003.2595

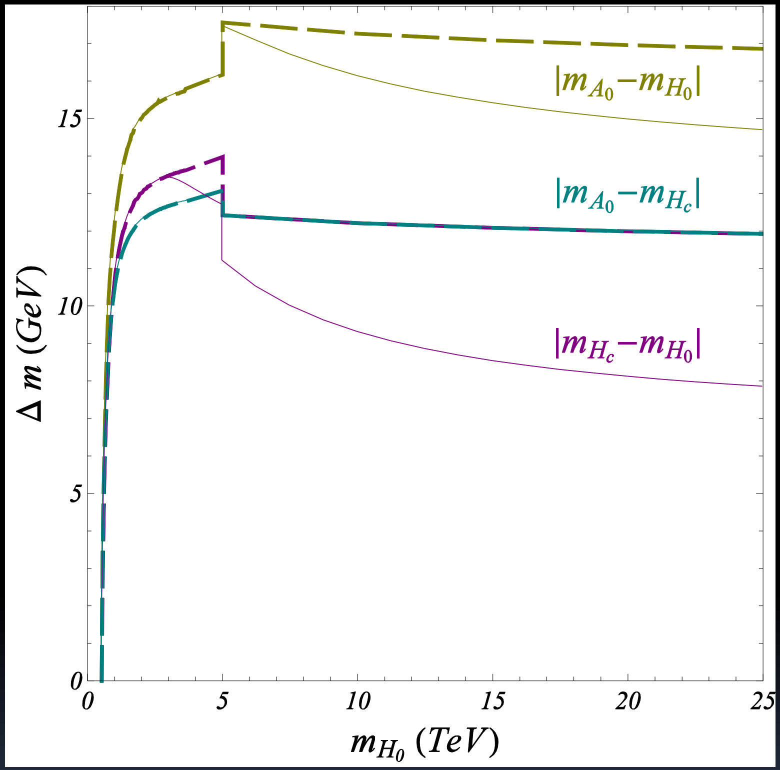
M_{DM} = 50 Gev, 100 GeV, 10 TeV





If we try to take EW phase transition and vacuum stability conditions into account …..





If $\delta >> 100\ keV$ ...