An Introduction to Dark Matter

A Particle Theorist's Perspective

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Two Universes

Two Universes

shining Universe

Two Universes

shining Universe

Two Universes

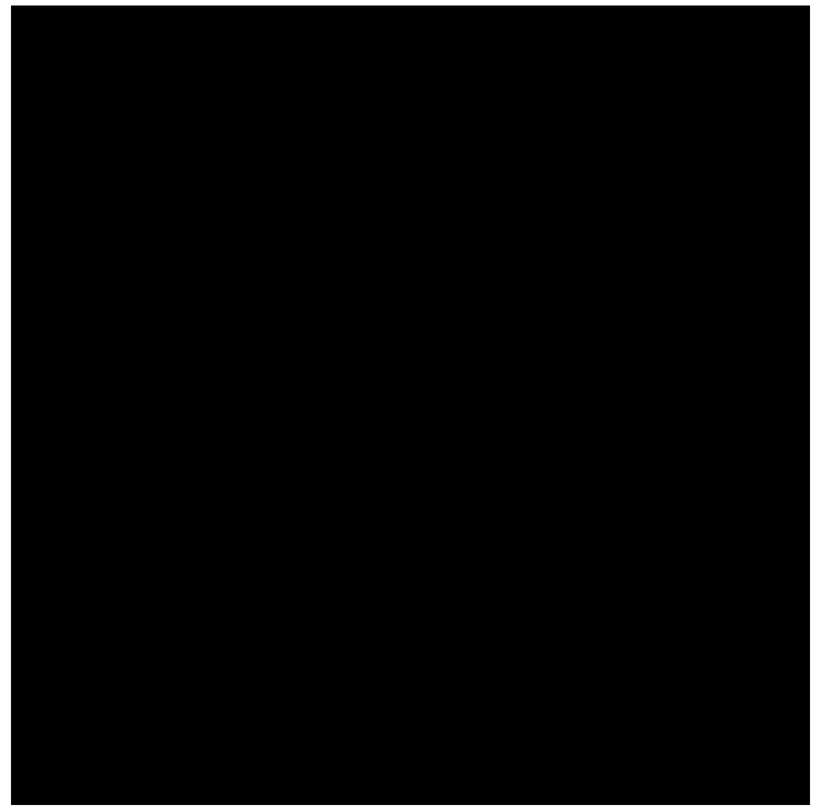
shining Universe

dark Universe

Two Universes

shining Universe

dark Universe



Outline

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  - Fermi/GLAST
  - (LHC)

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- summary

Dark Matter - Evidence

among the oldest puzzles in cosmology

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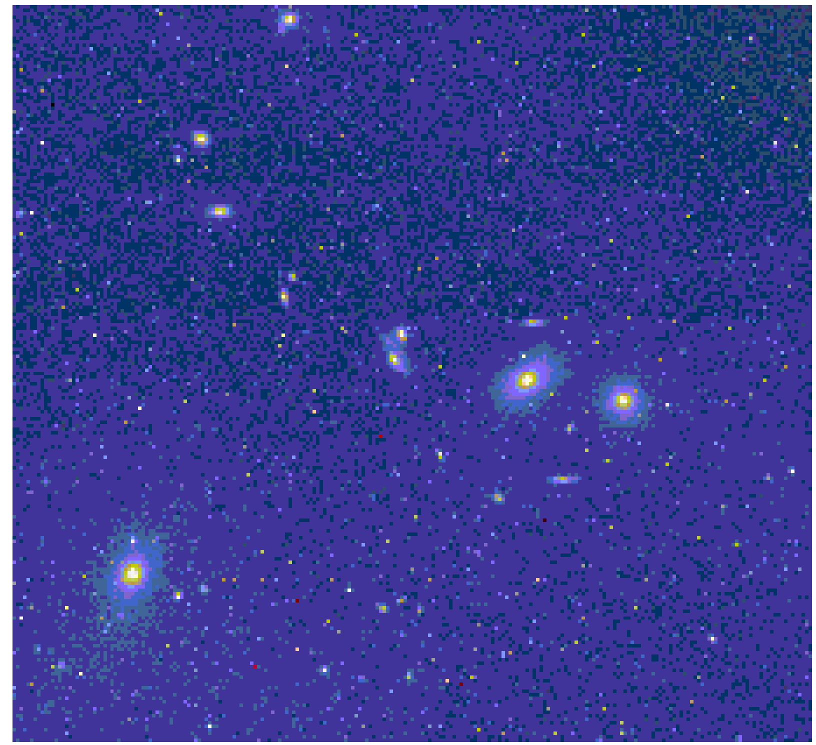
- Zwicky ('33): Coma cluster

visible mass not enough to bound it



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flat rotation curves

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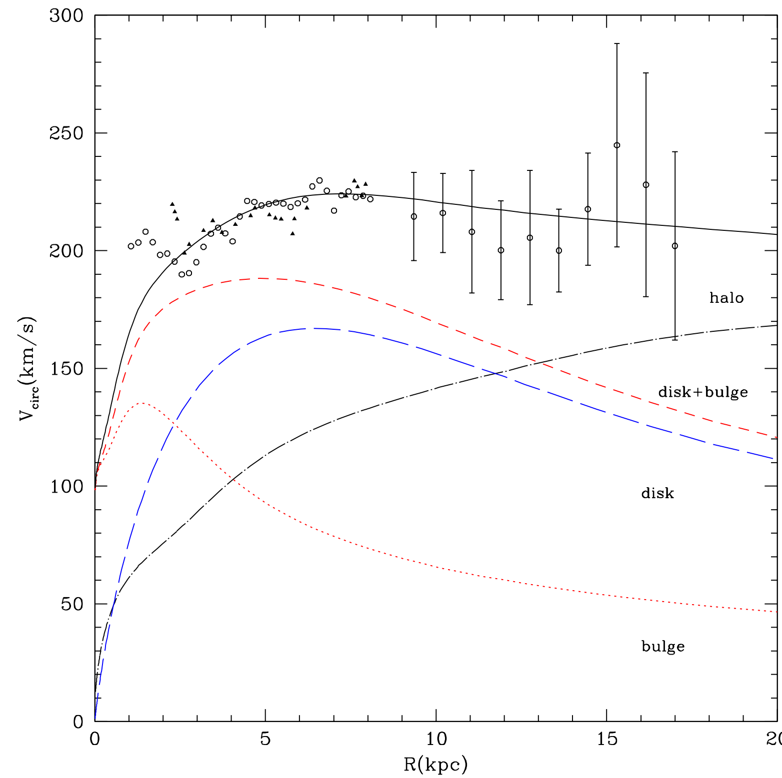
$$\frac{mv^2}{r} = \frac{GMm}{r^2} \Rightarrow \boxed{v = \sqrt{G\frac{M}{r}}}$$

Milky Way (Klypin, et al.)



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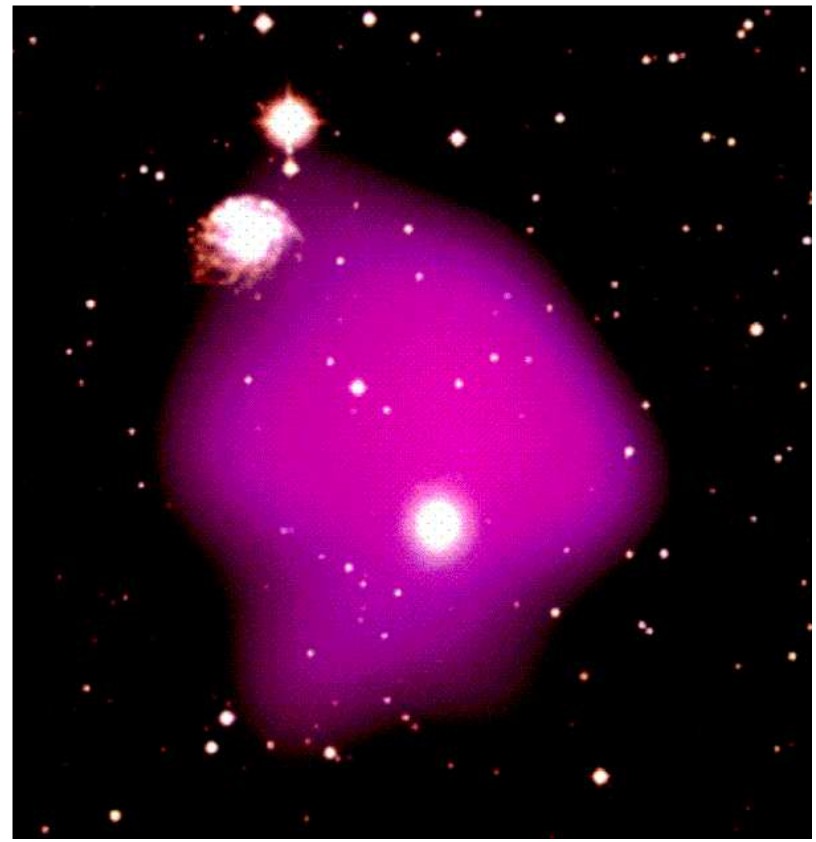
- clusters of galaxies

hot gas, $\sim 10^8$ K



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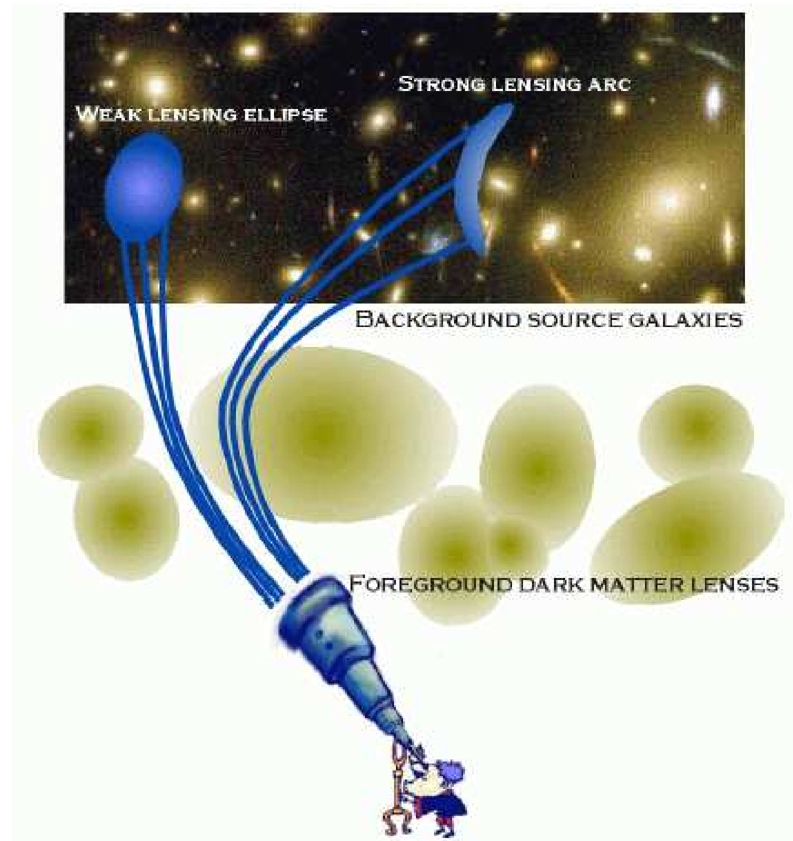
images of distant objects



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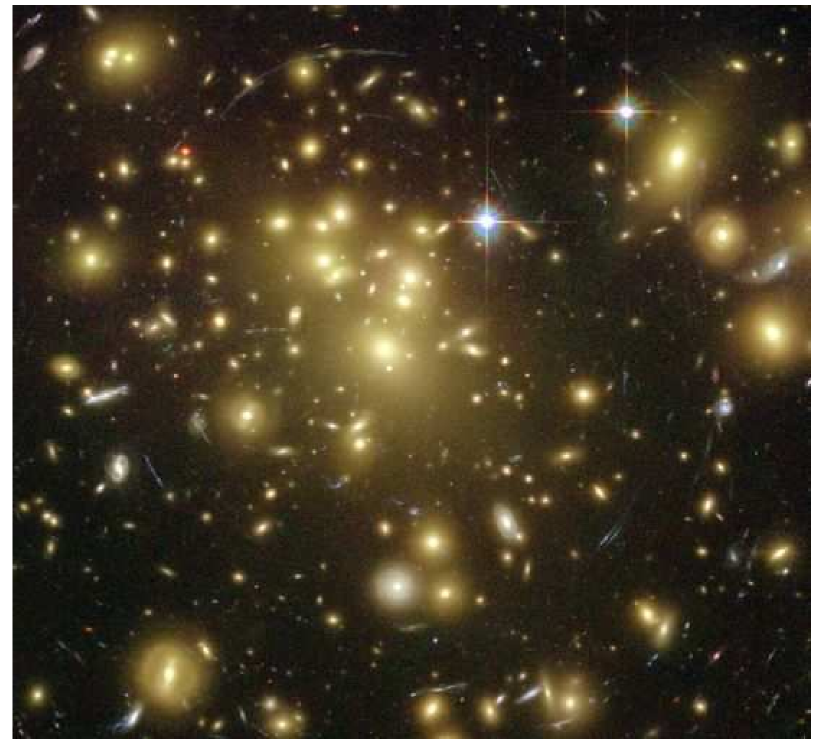
arc images of distant quasars



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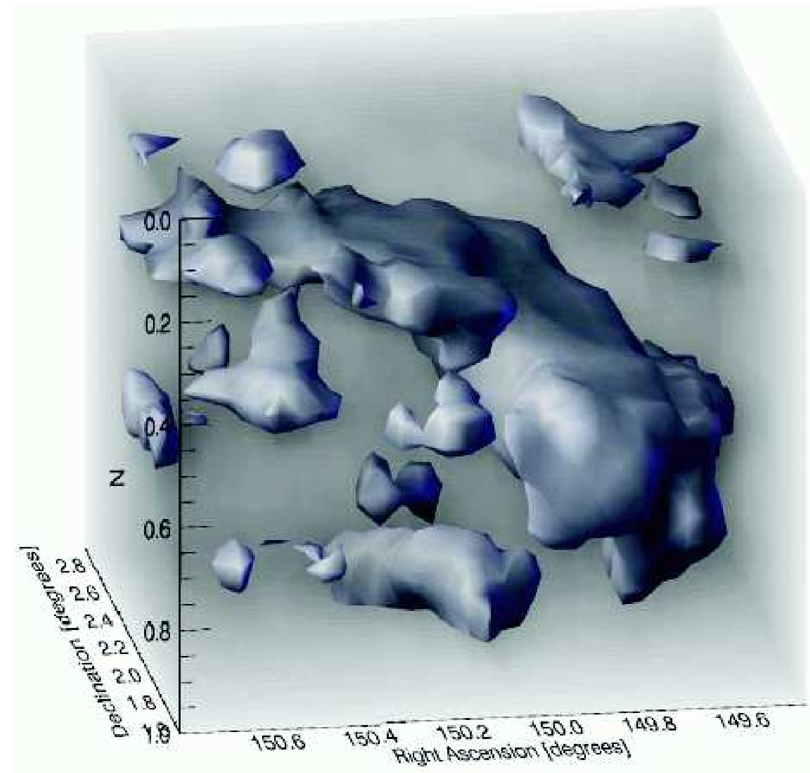
3dim DM distribution, (Massey, et al, '07)



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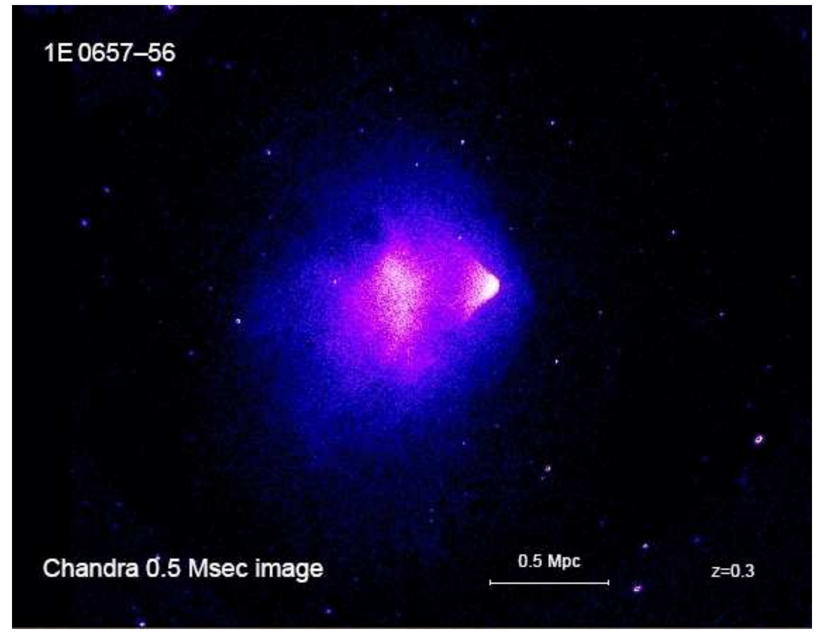
Bullet cluster, 2006



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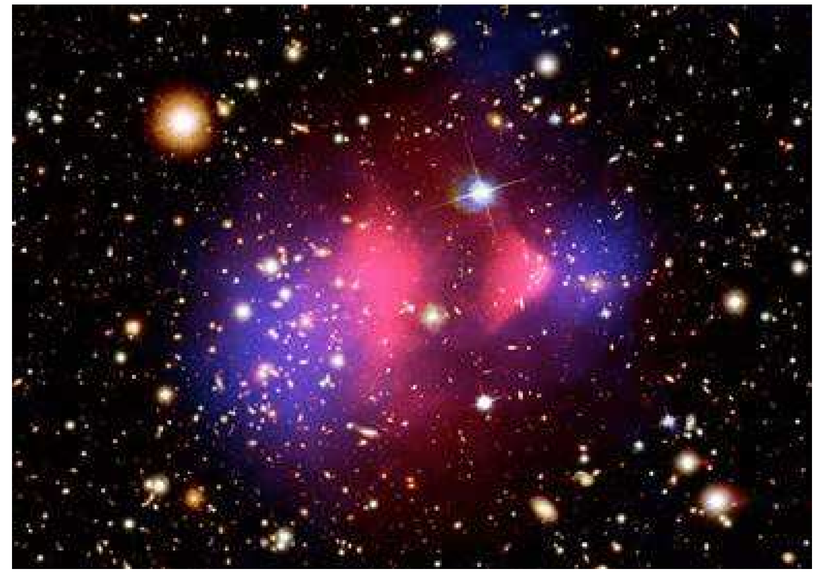
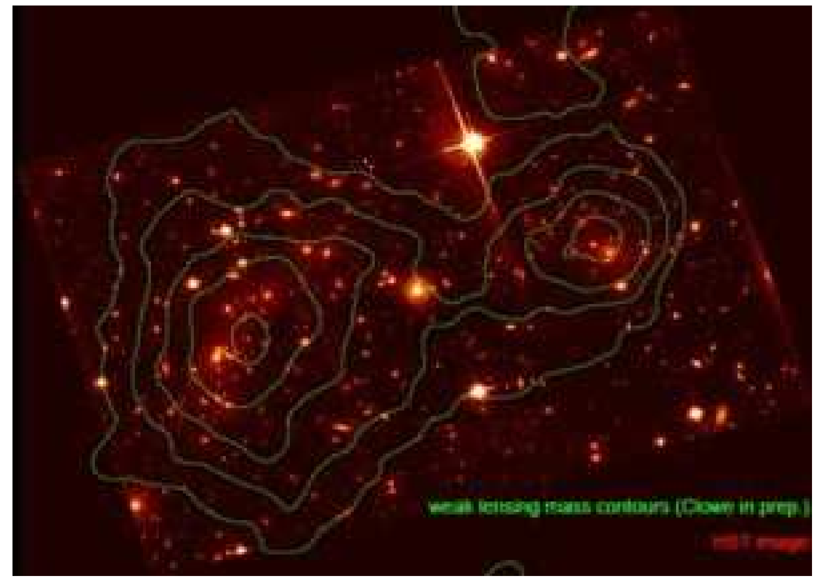
inferred DM distribution



Dark Matter - Evidence

among the oldest puzzles in cosmology

DM separated from baryons



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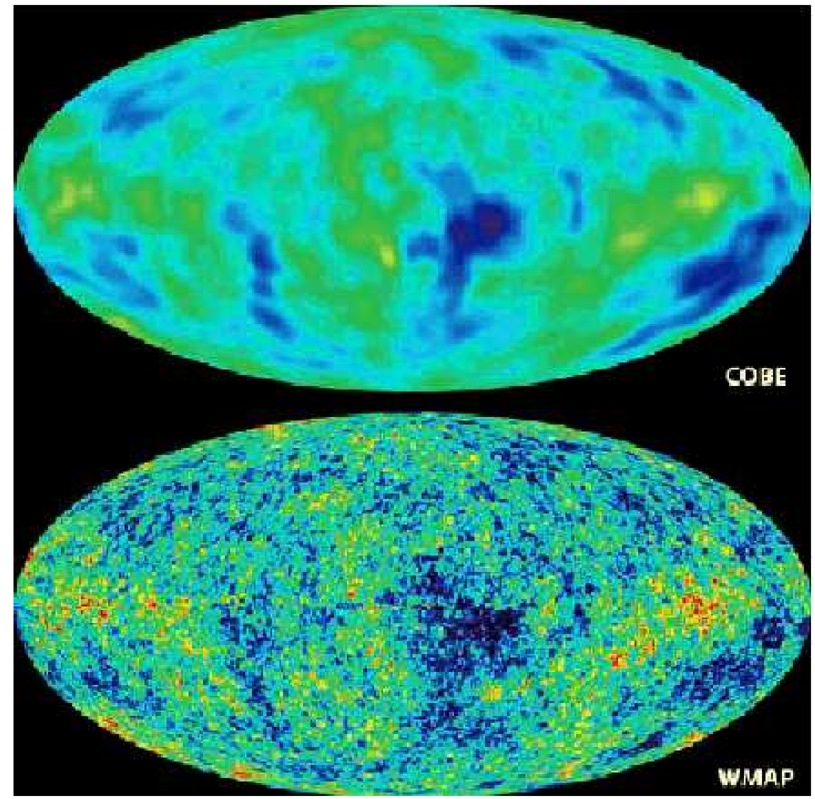
- CMB: precision measurements



Cosmology After WMAP...

Post WMAP-5yr (April 08) ...+ACBAR+CBI+SN+LSS+... $\Omega_i = \rho_i / \rho_{crit}$

Hubble $H_0 = 100\, h$ km/ s/ Mpc

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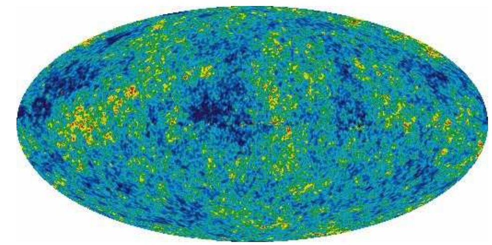
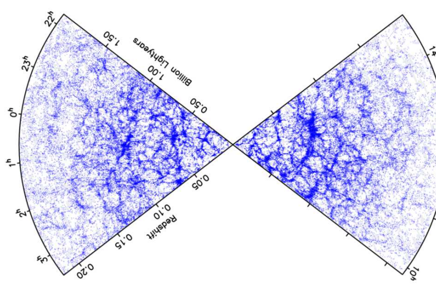
CMB (WMAP, ACBAR, CBI,...)



assume simplest ΛCDM model

- matter $\Omega_{\rm m} h^2 = 0.1378 \pm 0.0043$
- baryons $\Omega_{\rm b} h^2 = 0.02263 \pm 0.00060$
- $\Rightarrow$ $\boxed{\Omega_{\rm CDM} h^2 = 0.1152 \pm 0.0042}$
- $h = 0.696 \pm 0.017$
- $\Omega_\Lambda = 0.715 \pm 0.20 \ldots$

LSS (2dF, SDSS, Lyman-α)



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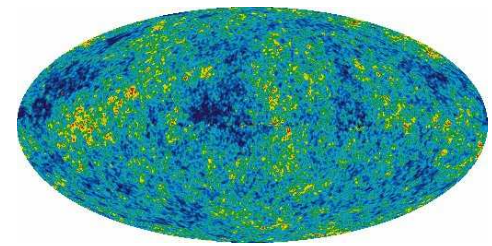

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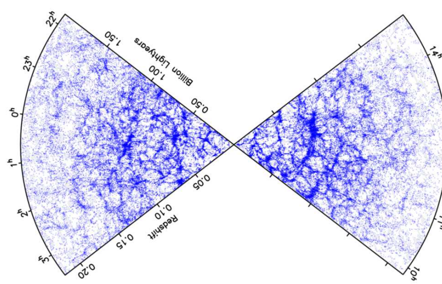
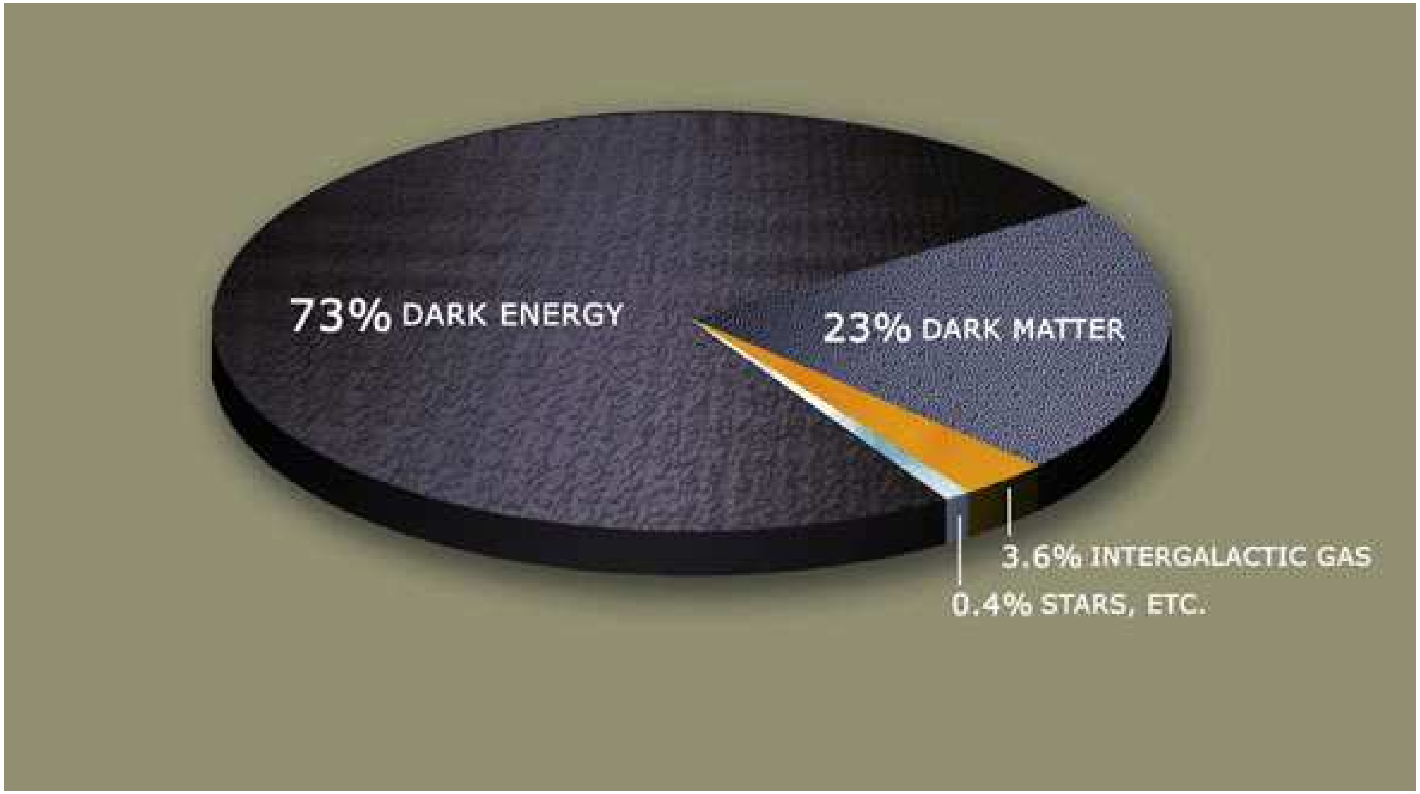


- concordance model works well
- main components: dark energy and dark matter

factor of 4-10 improvement expected from Planck

Cosmic Pie



73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

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  Some anomalies and hints – DM origin of 'signal' not convincing.

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$\Rightarrow$ most matter non–baryonic (DM problem)

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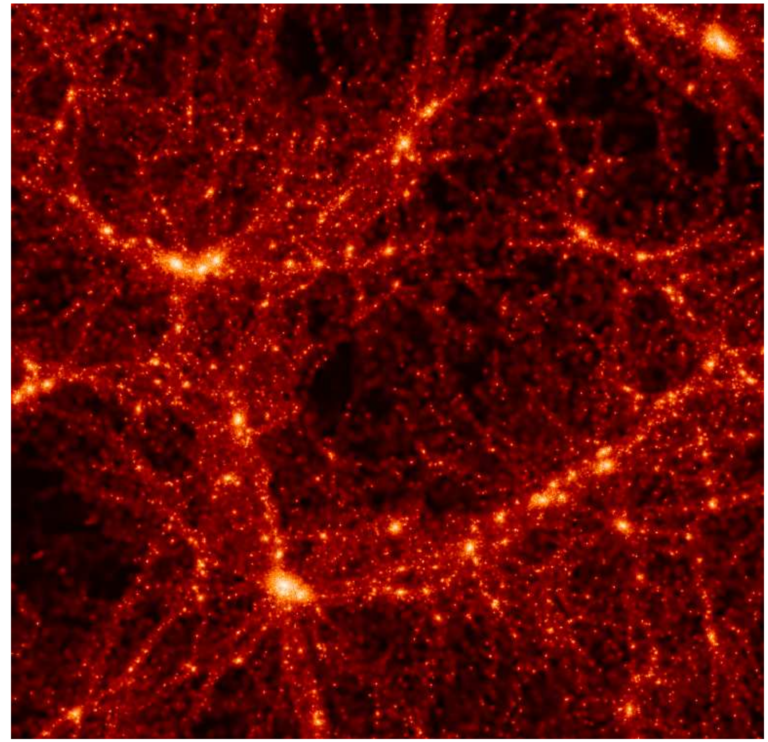
⇒ most matter non–baryonic

(DM problem)

⇒ DM is cold (CDM)

or possibly (?) warmish

numerical simulations of LSS



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plausible choice ⇒ WIMP

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...How weak can weak be?

A simple, persuasive argument:

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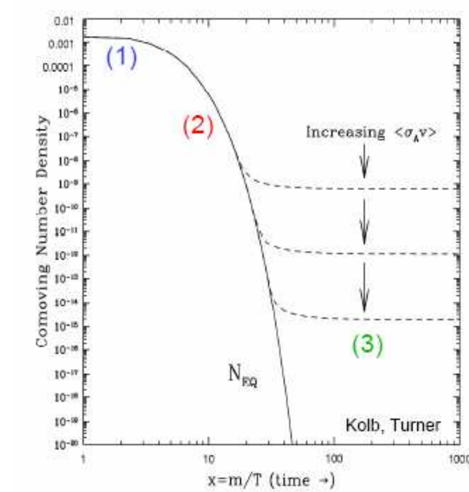
- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



$$x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

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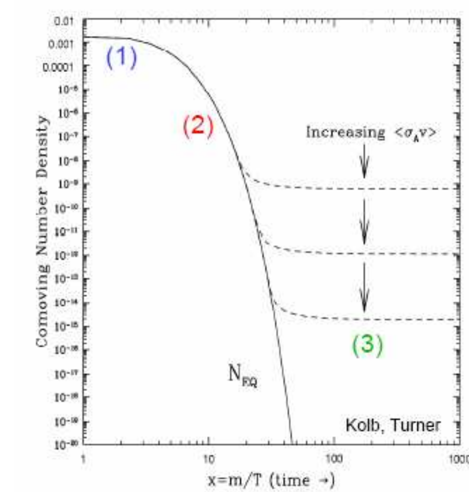

WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{ann}}{10^{-38}\mathrm{cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle} \qquad x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

σ_{ann} – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

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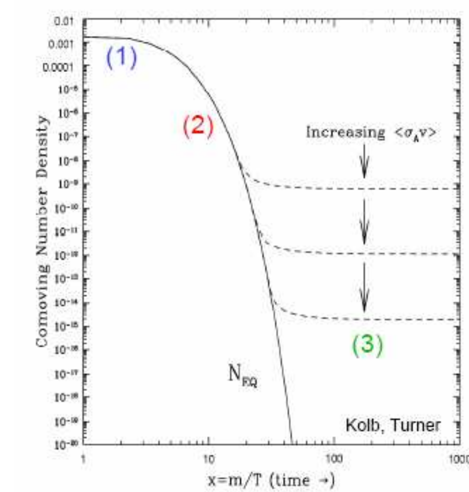

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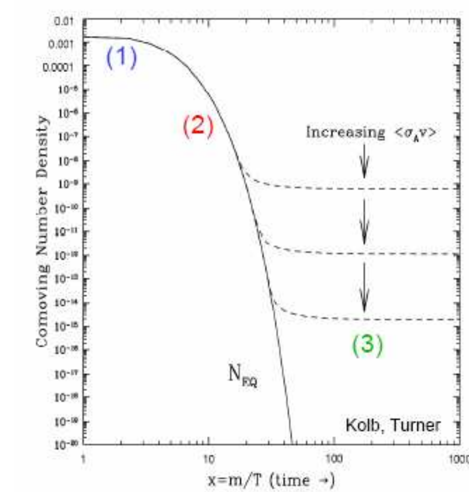

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A hint? Possibly, but...

The Big Picture

L.R. (2000), hep-ph/0404052

well–motivated particle candidates s.t. $\Omega_{\rm DM} \sim 1$

The Big Picture

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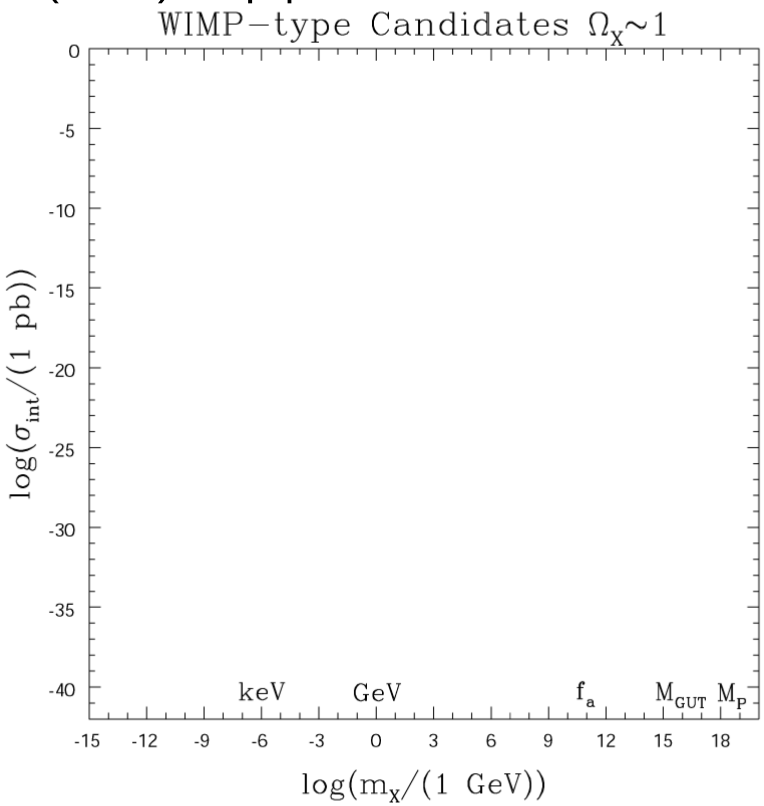

The Big Picture

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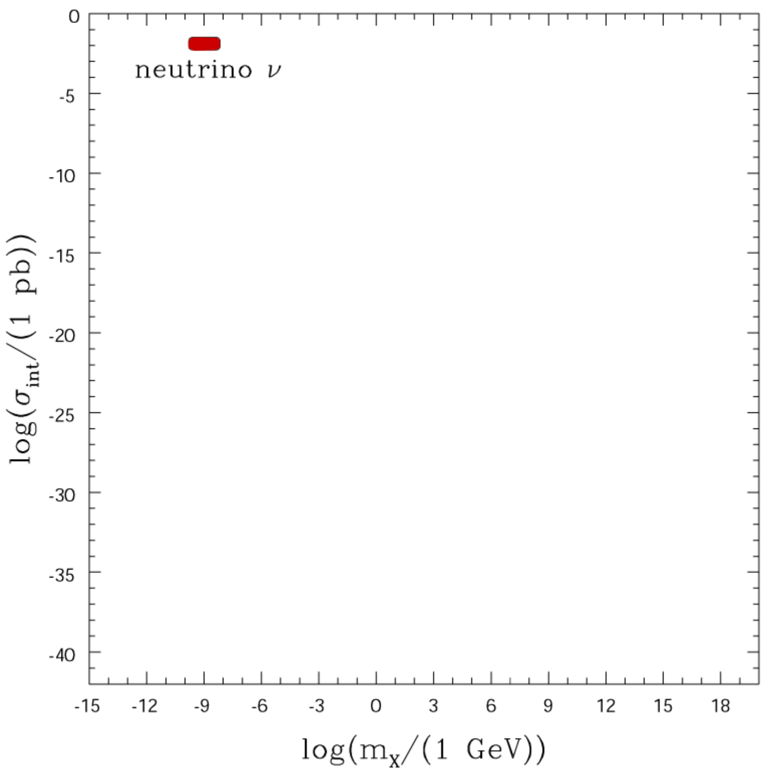

- neutrino ν – hot DM

$$\mathcal{O}(0.01\,\mathrm{eV}) \lesssim m_\nu \lesssim \mathrm{few\,eV}, \quad \sigma \sim \sigma_{weak}$$

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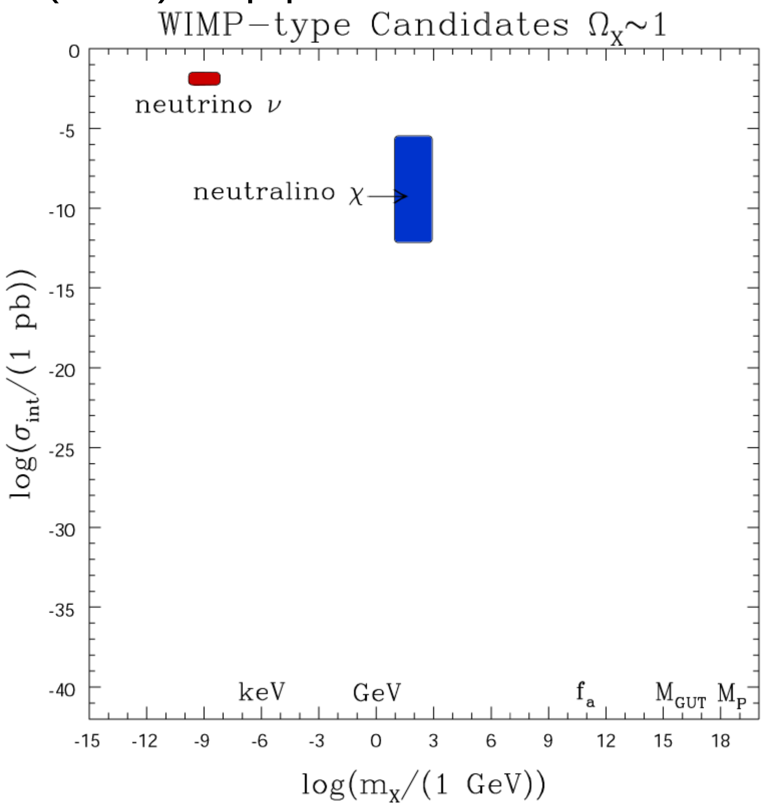

- neutrino ν – hot DM
- neutralino χ

(LEP) $\mathcal{O}(100\,\mathrm{GeV}) \lesssim m_\chi \lesssim \mathcal{O}(1\,\mathrm{TeV})$, 10^{-5} pb $\gtrsim \sigma \gtrsim 10^{-12}$ pb, or less

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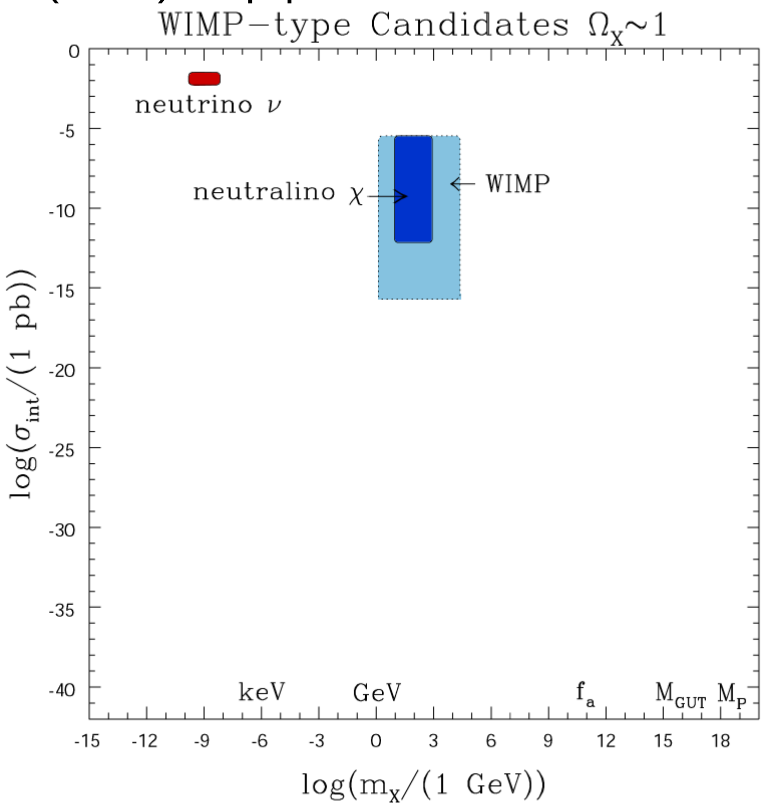

- neutrino ν – hot DM
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- “generic” WIMP

(“LW bound”) $\mathcal{O}(1\,\mathbf{GeV}) \lesssim m \lesssim \mathcal{O}(300\,\mathbf{TeV})$ (unitarity), 10^{-5} pb $\gtrsim \sigma \gtrsim ????$

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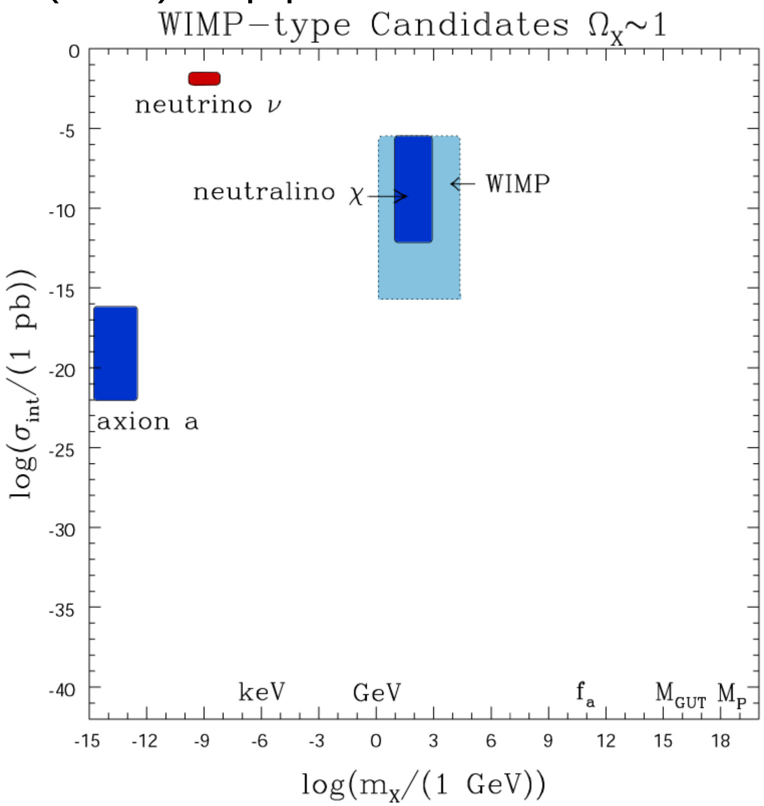

- neutrino ν – hot DM
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$$m_a \sim \mathcal{O}(10^{-5}\,\mathrm{eV}), \quad \sigma \sim (m_W/f_a)^2\,\sigma_{weak} \sim 10^{-16} - 10^{-22}\,\mathrm{pb}$$

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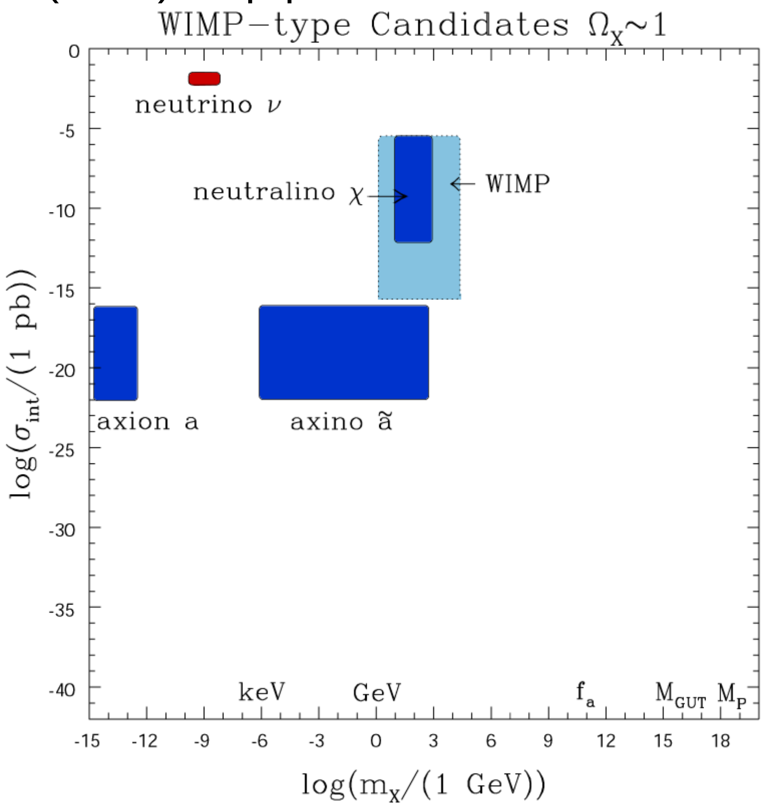

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- axino $\widetilde{a}$

$$\mathcal{O}(1\,\mathrm{keV}) \lesssim m_{\widetilde{a}} \lesssim \mathcal{O}(1\,\mathrm{TeV}), \quad \sigma \sim (m_W/f_a)^2\, \sigma_{weak} \sim 10^{-16} - 10^{-22}\,\mathrm{pb}$$

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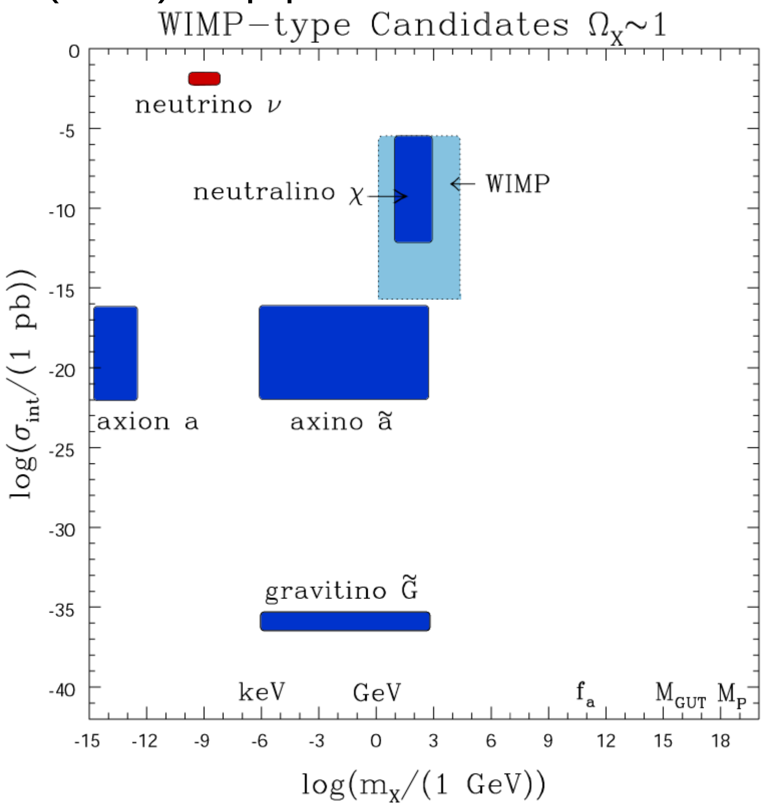

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- gravitino $\widetilde{G}$

$\mathcal{O}(1)\,\mathrm{keV} \lesssim m_{\widetilde{G}} \lesssim \mathcal{O}(1)\,\mathrm{TeV},\ (M_{\mathrm{SUSY}}),\quad \sigma \sim (m_W/M_{\mathrm{P}})^2\,\sigma_{weak} \sim 10^{-36}$ pb

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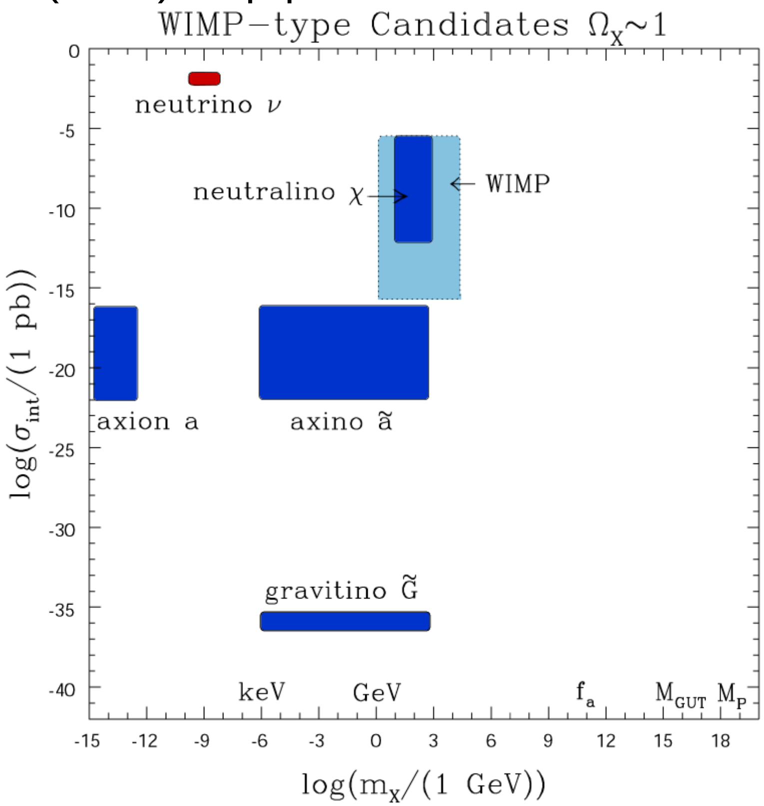

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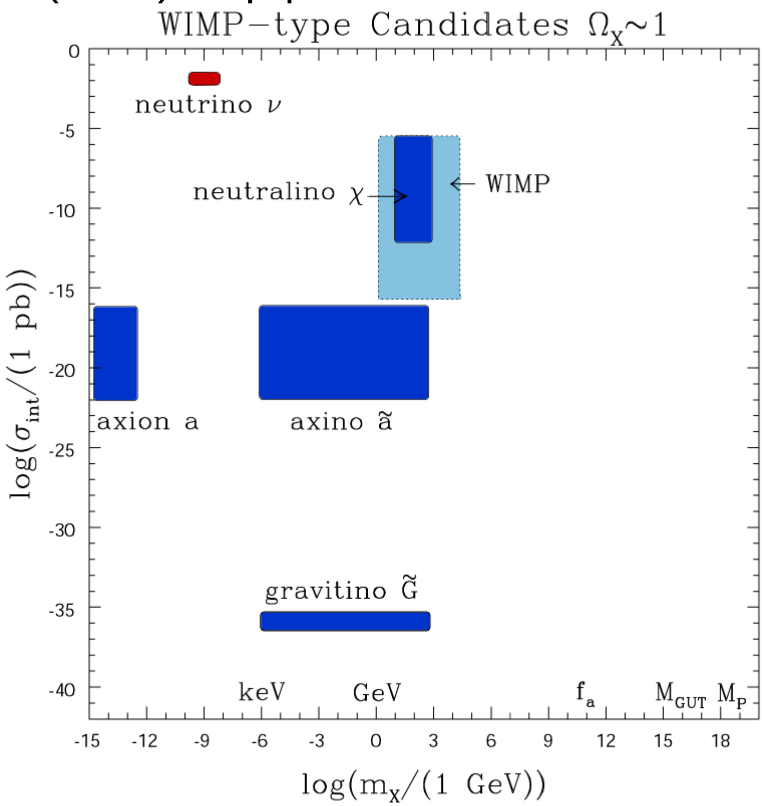

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...sterile (RH) neutrino or sneutrino?, lightest Kałuża-Klein (KK) particle?, etc, etc

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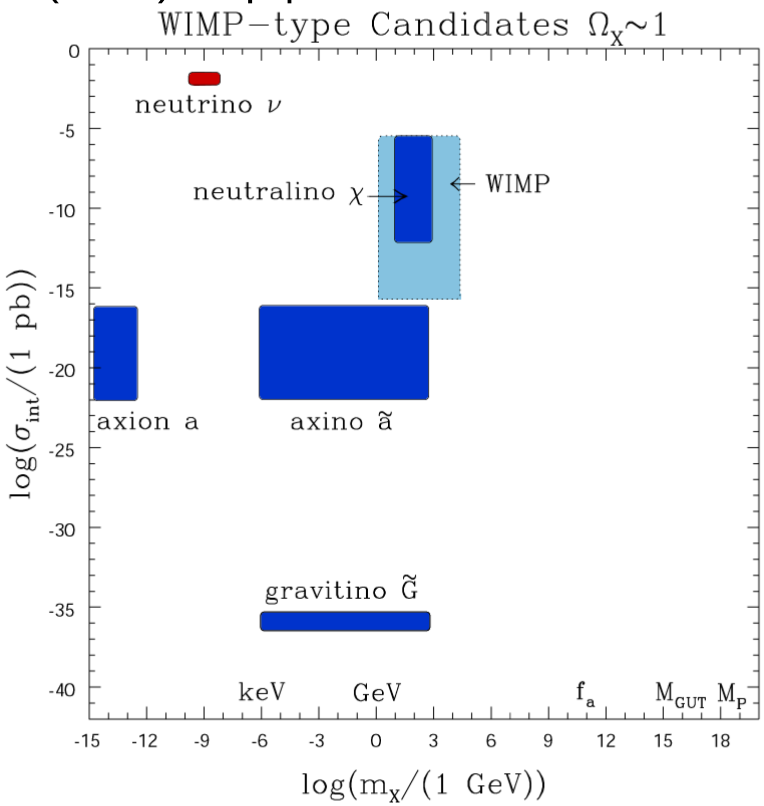

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vastly different ranges of mass and σ, all give $\Omega \sim 1$

reason: different production mechanisms after the BB

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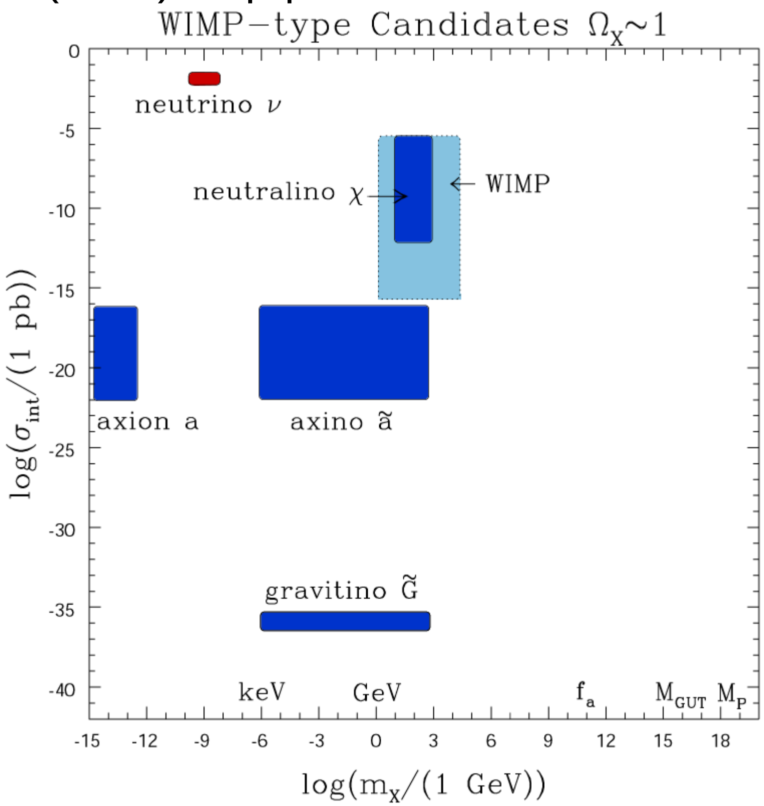

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solution of DM: must go beyond SM!

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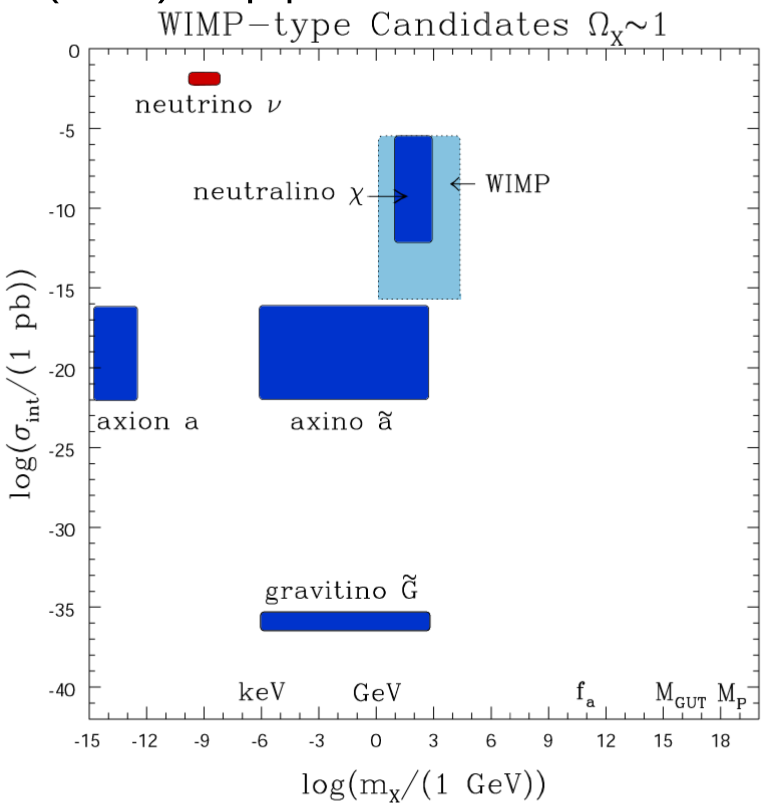

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WIMP DM testable at present/near future

$\widetilde{a}$, $\widetilde{G}$ EWIMPs not directly testable, but hints from LHC (?)

Some WIMP candidates for Cold DM

No shortage of ideas...

...but few good ones, ...and even fewer longer-lasting

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- lightest neutralino χ of supersymmetry

  $m_\chi \sim M_{\mathrm{SUSY}}$ ($\sim 0.1 - 1\,\mathrm{TeV}$), interactions sub-weak ($\lesssim 10^{-4}\sigma_{weak}$)

Some WIMP candidates for Cold DM

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- lightest neutralino χ of supersymmetry

  $m_\chi \sim M_{\rm SUSY}$ $(\sim 0.1 - 1\,{\rm TeV})$, interactions sub-weak ($\lesssim 10^{-4}\sigma_{weak}$)

- lightest Kałuża-Klein (KK) state from warped/universal extra dimensions

  $m_{\rm KK} \sim 0.4 - 1\,{\rm TeV}$, interactions $\lesssim$ those of χ, testable

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several other interesting candidates: well-tempered neutralino, multiple (UPT) DM, little Higgs DM, mirror DM, shadow DM, sequestered DM, secluded DM, flaxino DM, Higgs portal DM, inflation and DM, modulus DM, etc etc. – no nonsense but not superior either

It is fairly easy to invent a DM relic

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it is much (!) harder to invent a (lasting) model of ‘new physics’

WIMP Detection

Where to find the WIMP?

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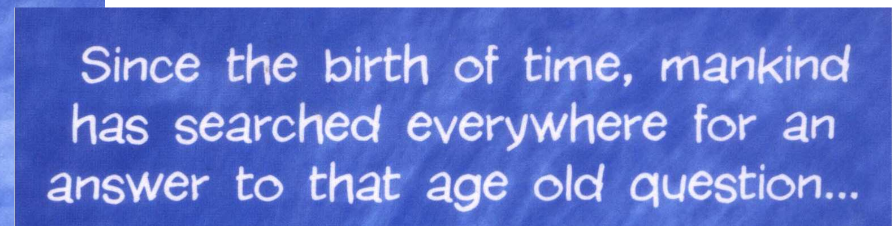
Since the birth of time, mankind has searched everywhere for an answer to that age old question...

Where to find the WIMP?



...go underground!

Strategies for WIMP Detection

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- direct detection (DD): measure WIMPs scattering off a target

go underground to beat cosmic ray bgnd

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- (the LHC)

Go underground/–ice/–water

... or to space

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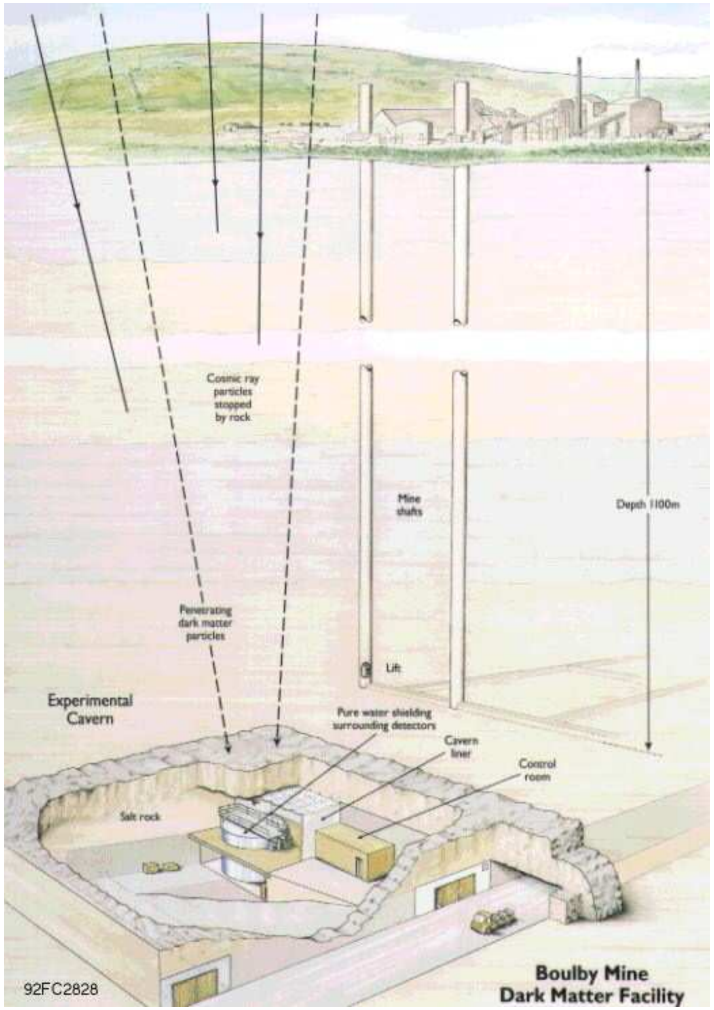

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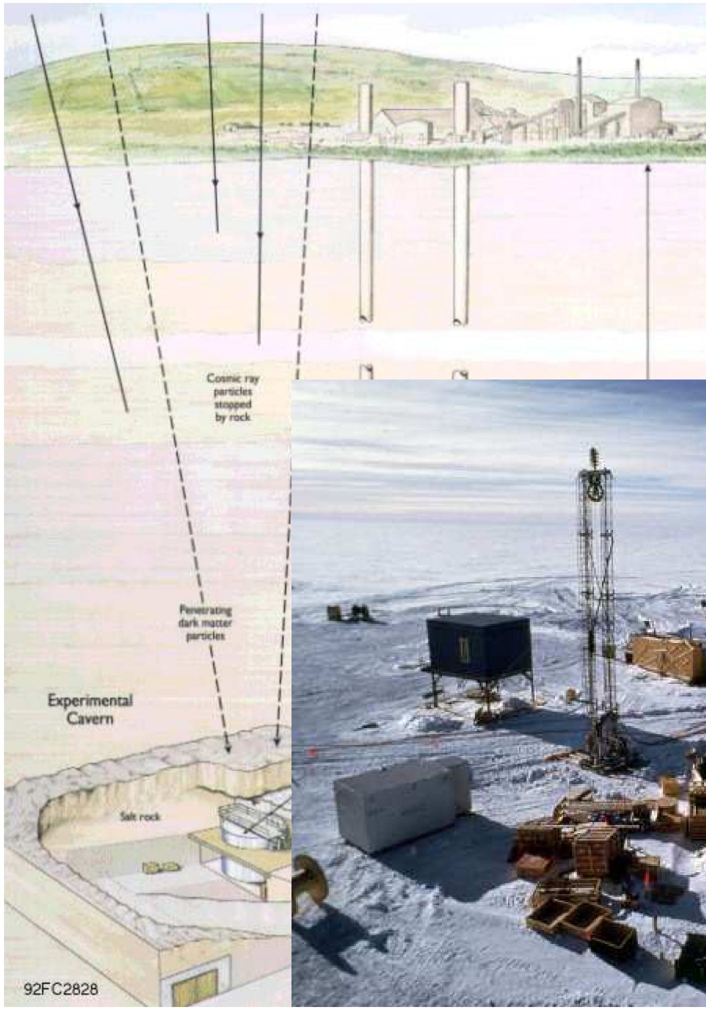

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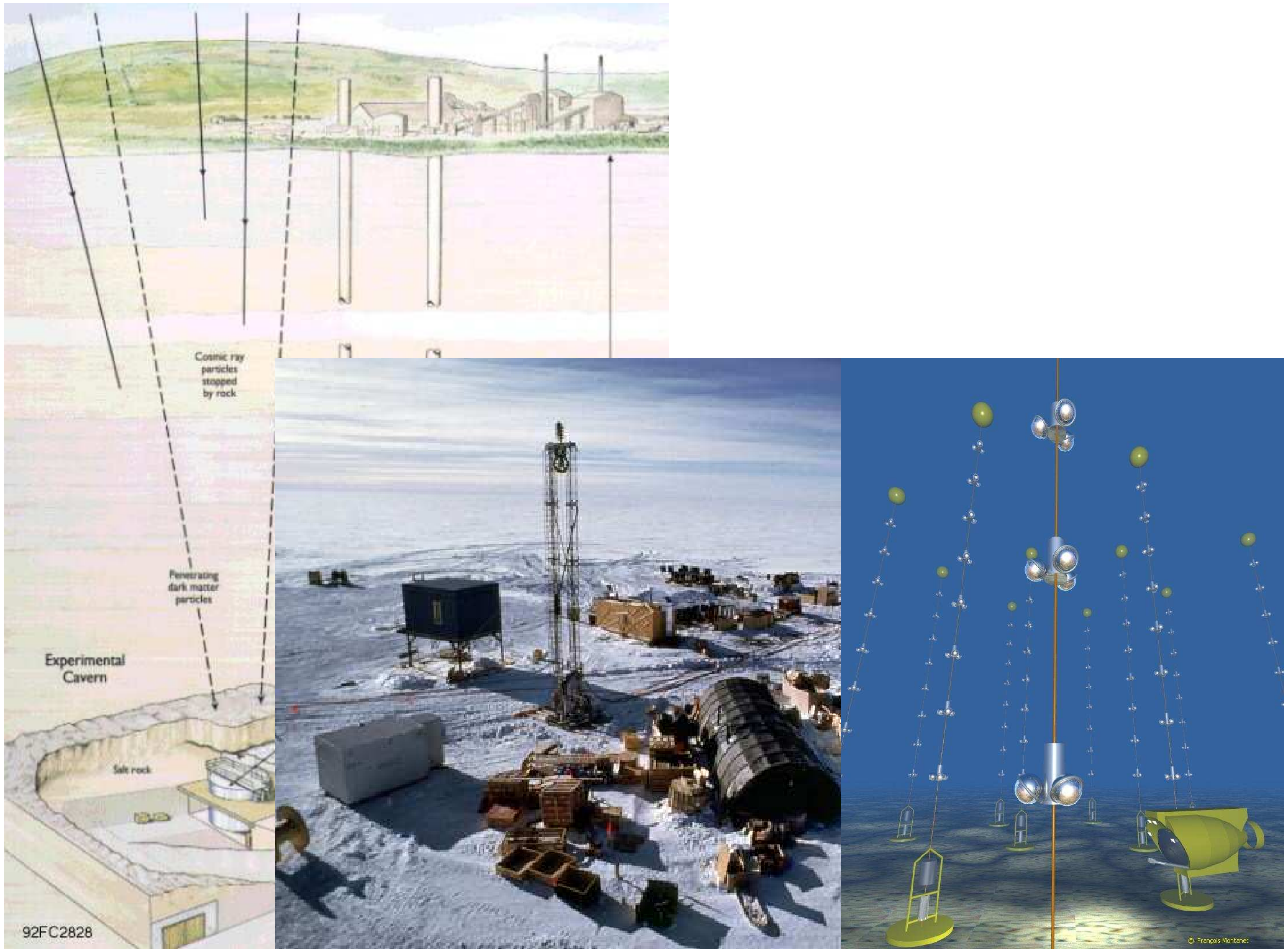

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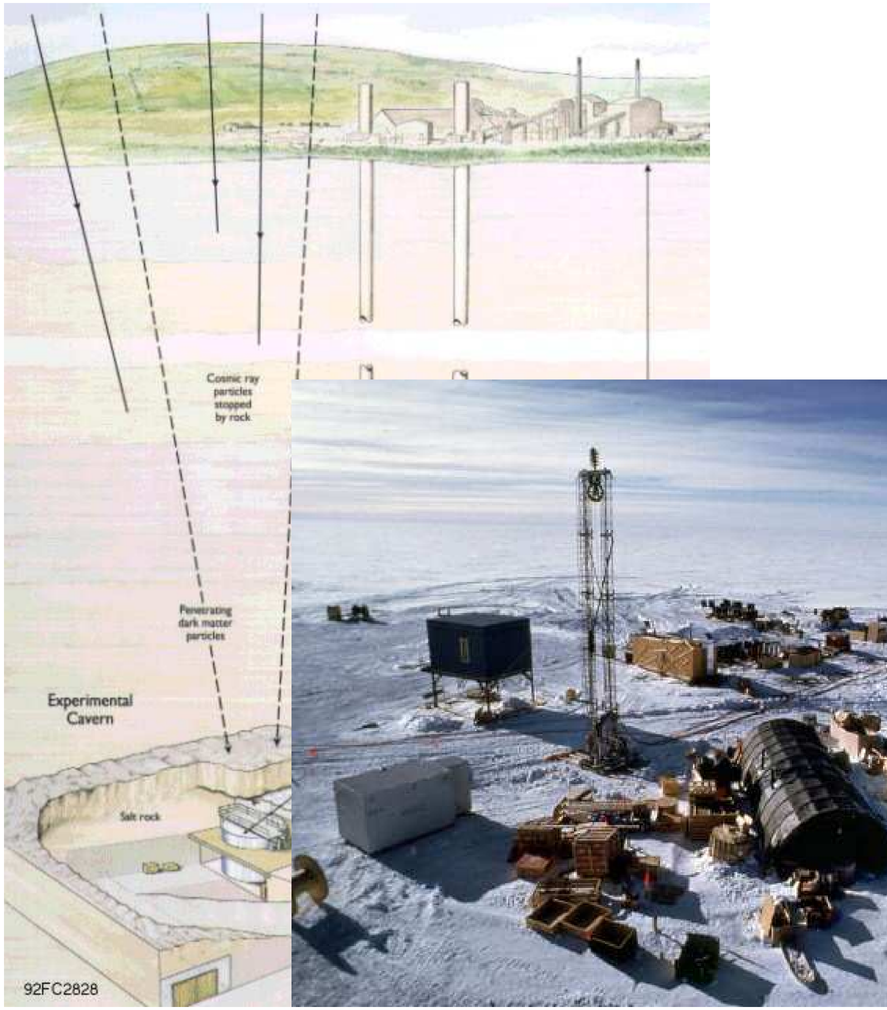

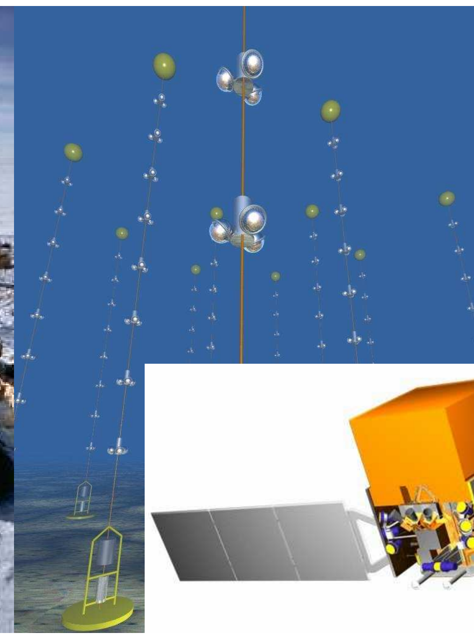

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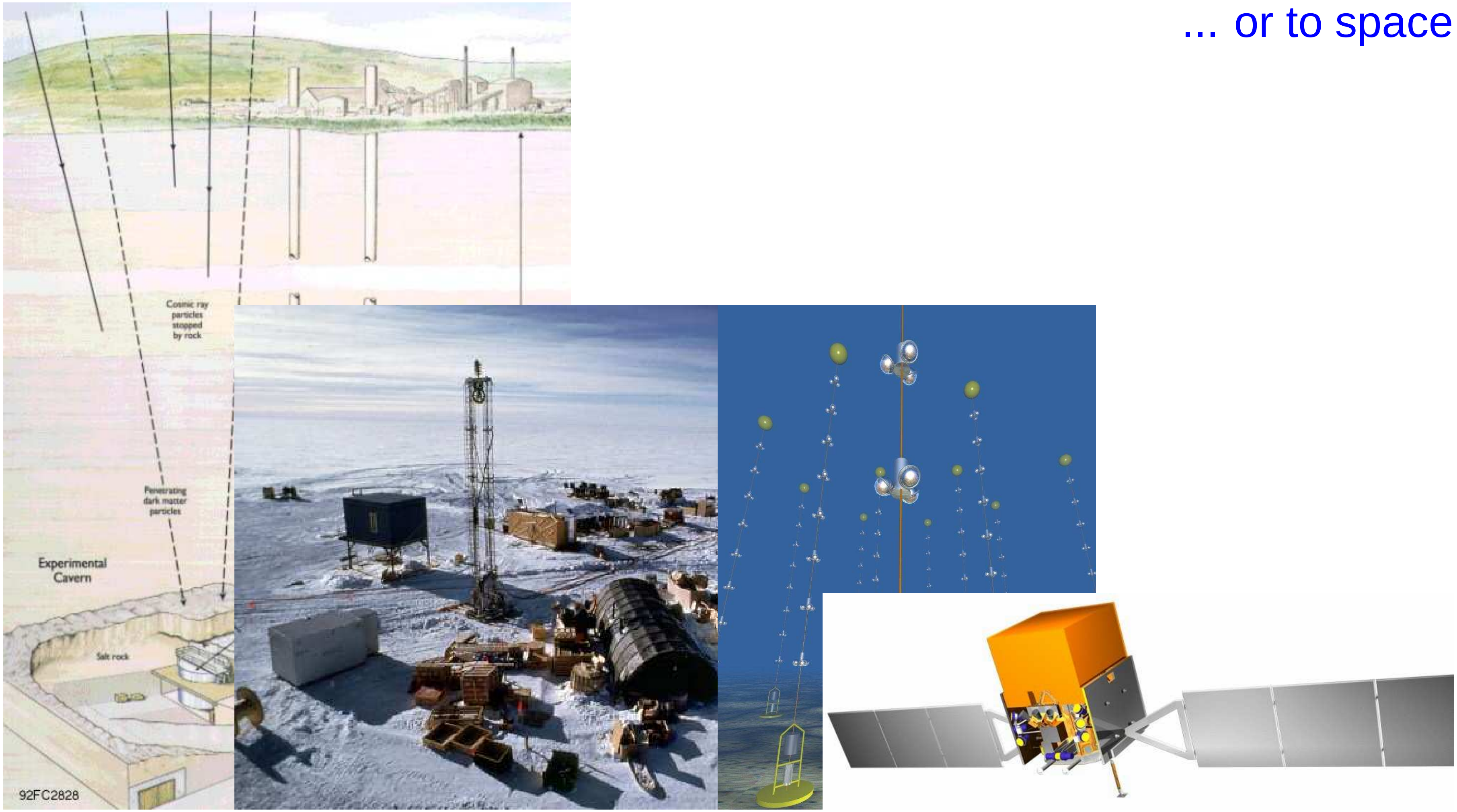
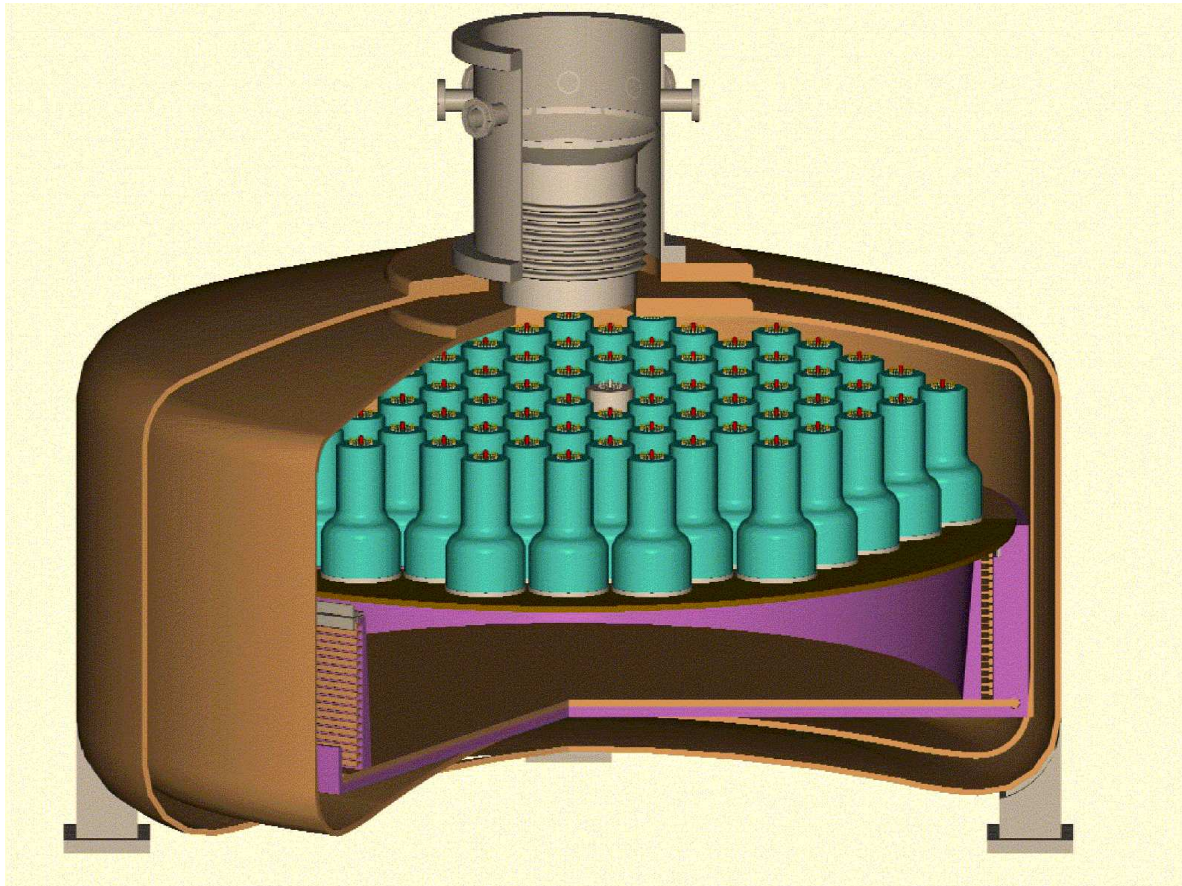


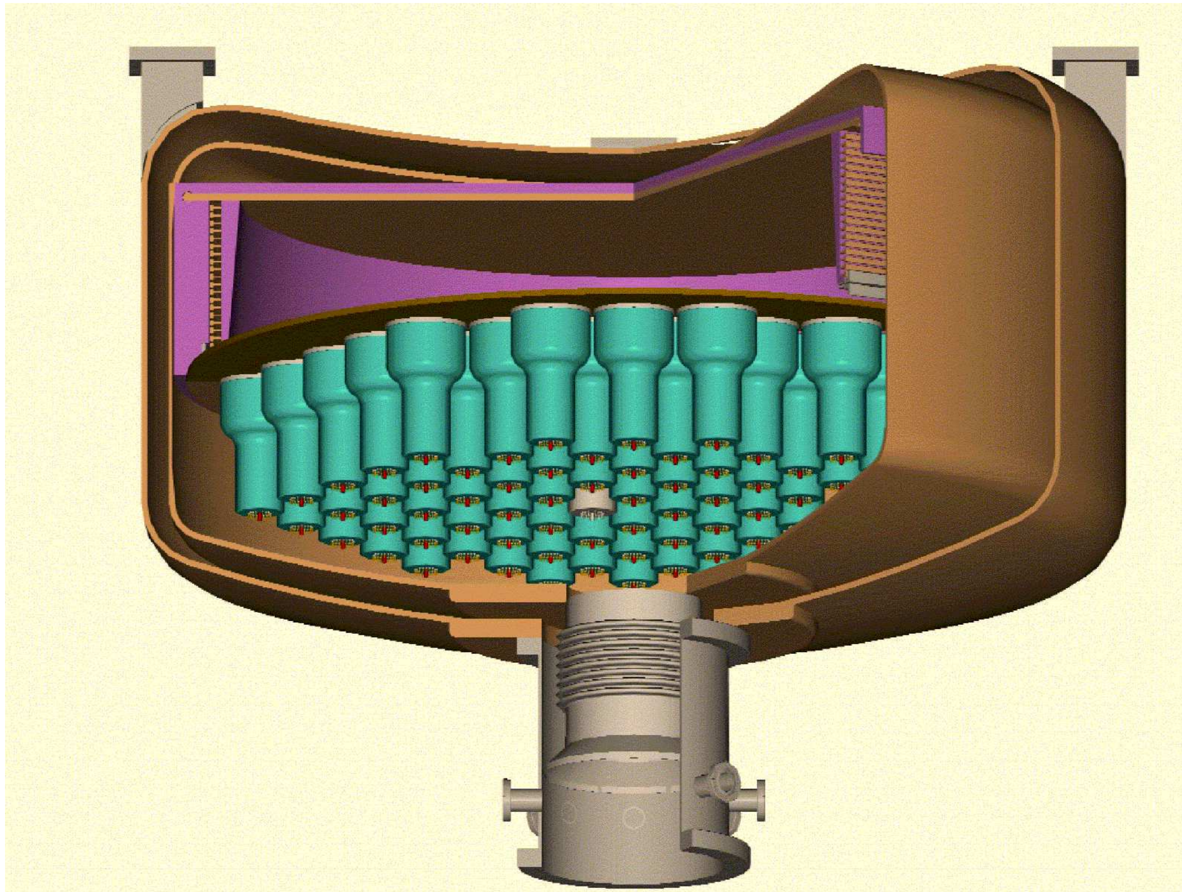
impressive experimental effort

Zeplin Detector



can this thing detect most mass in the Universe???

• • •

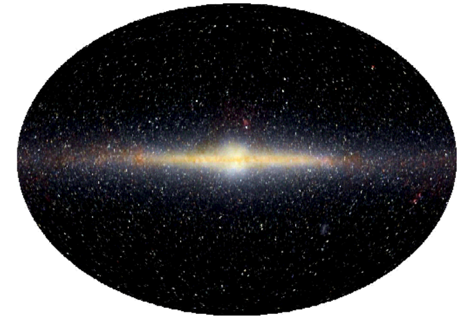


... or at least milk a cow???

Direct detection

Direct detection

MW is immersed in a halo of WIMPs



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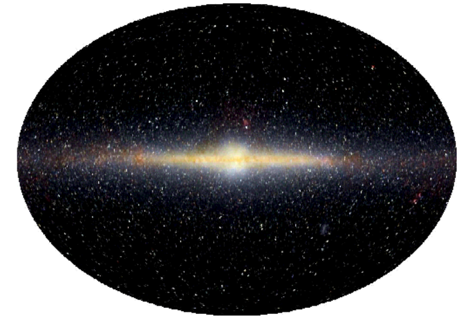

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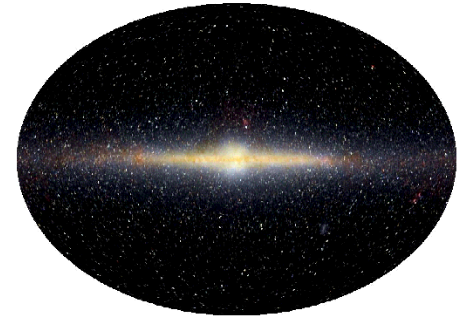

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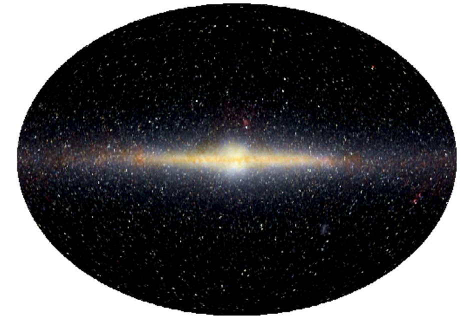

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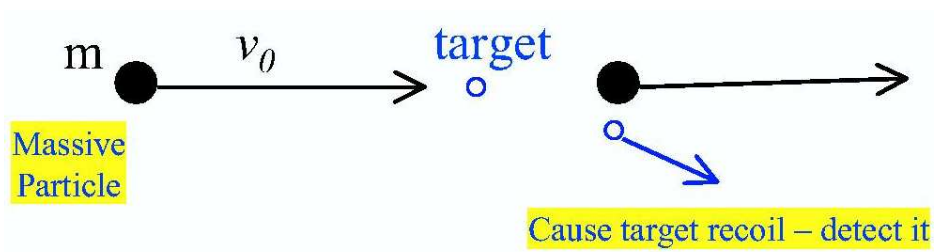

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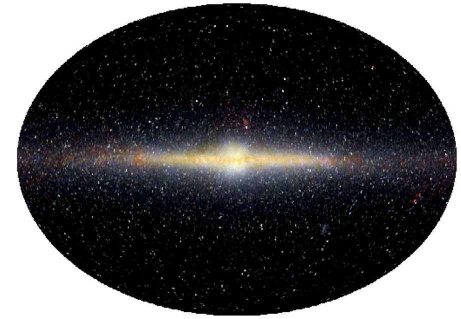

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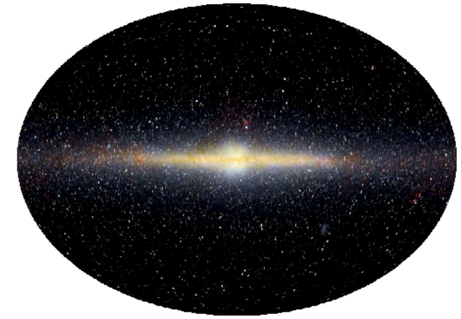

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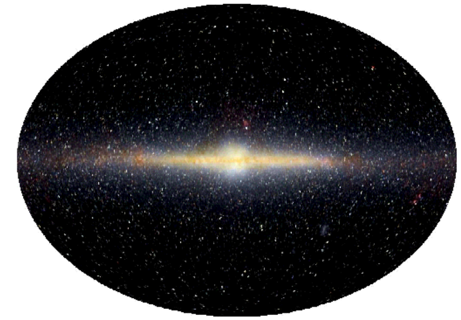

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target: nucleus X_Z^A, $f_n \simeq f_p \longleftarrow$ input from PP

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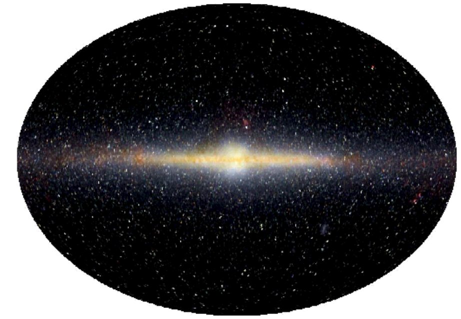

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New results from CDMS

CDMS, 0912.3592v1 (18 Dec '09)

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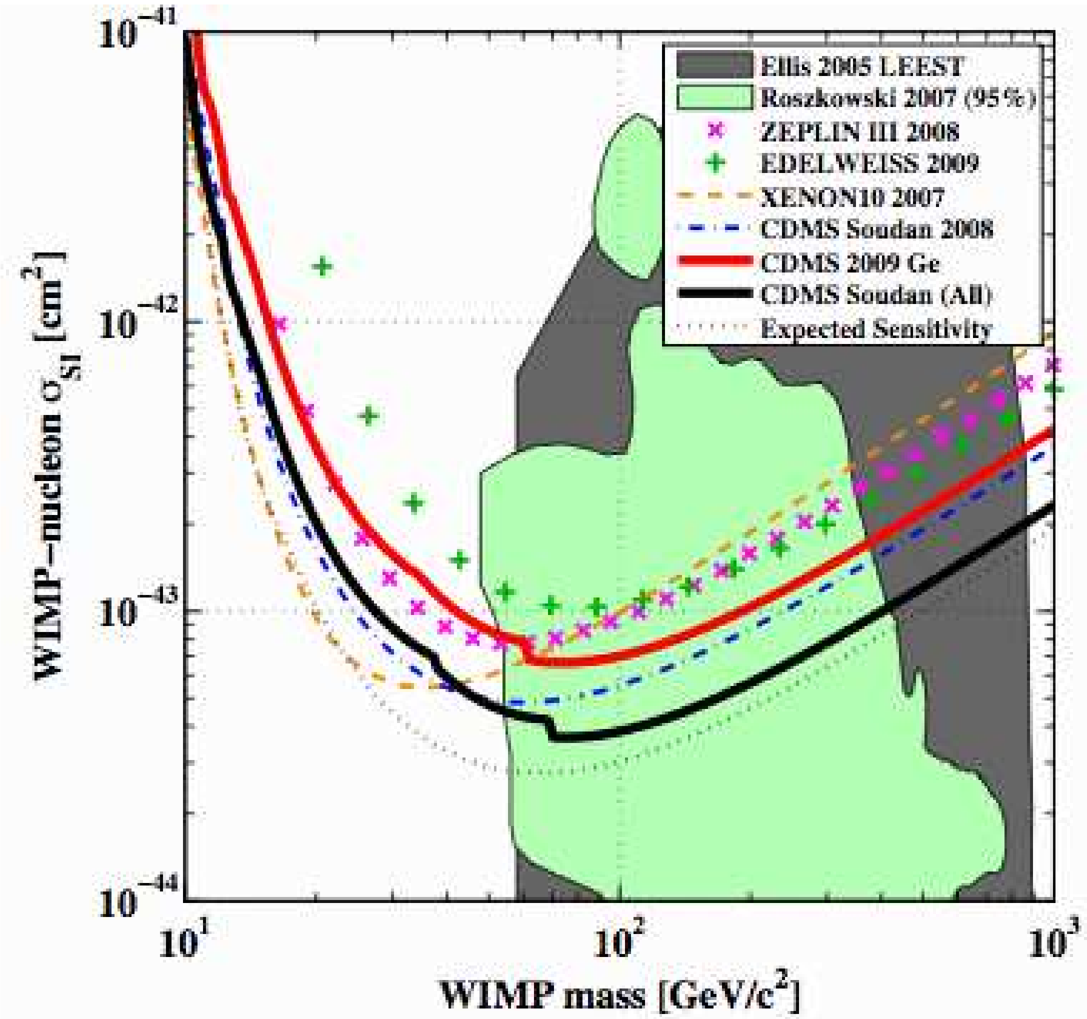
CDMS, 0912.3592v1 (18 Dec '09)

CDMS-II final run, 612 kg·days of data

currently best limit (slightly better than in Feb '08)



elastic

spin-independent

(scalar) c.s.

90% CL limits

$(10^{-40}\mathrm{cm}^2 = 10^{-4}$ pb)

CDMS – Possible DM signal?

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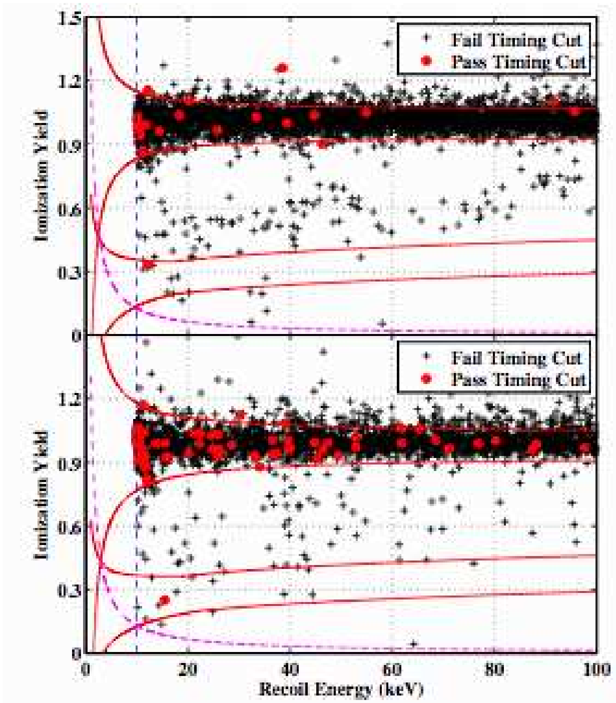

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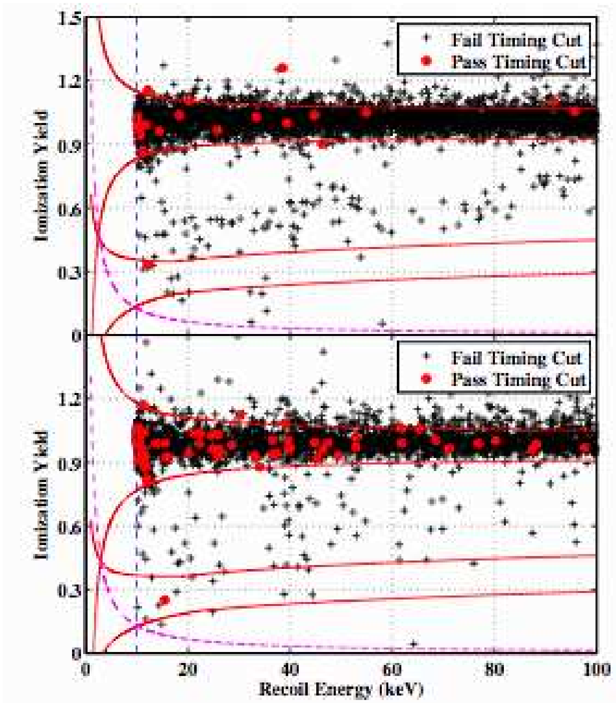

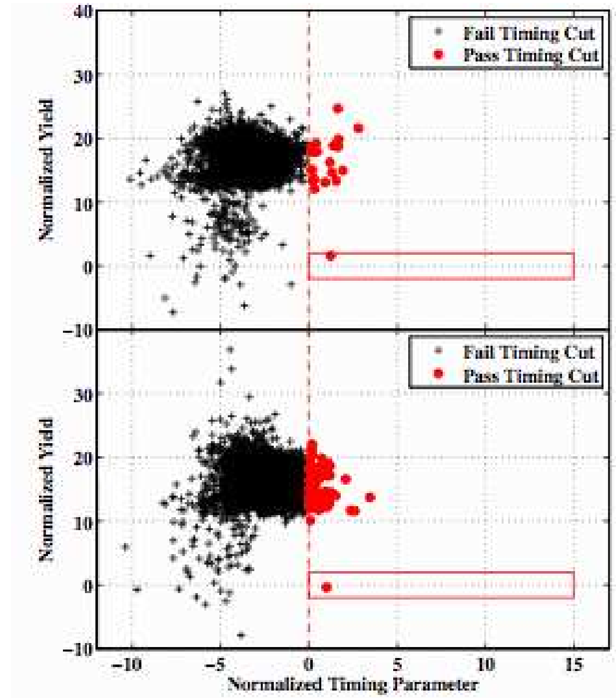

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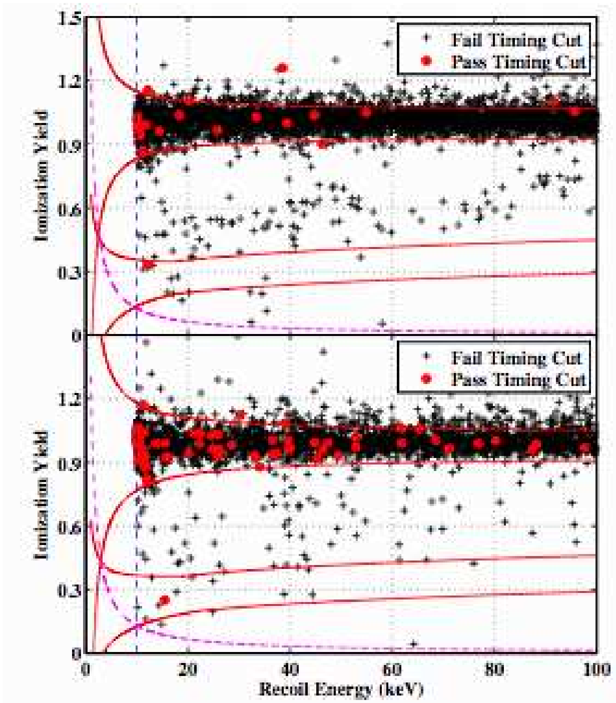

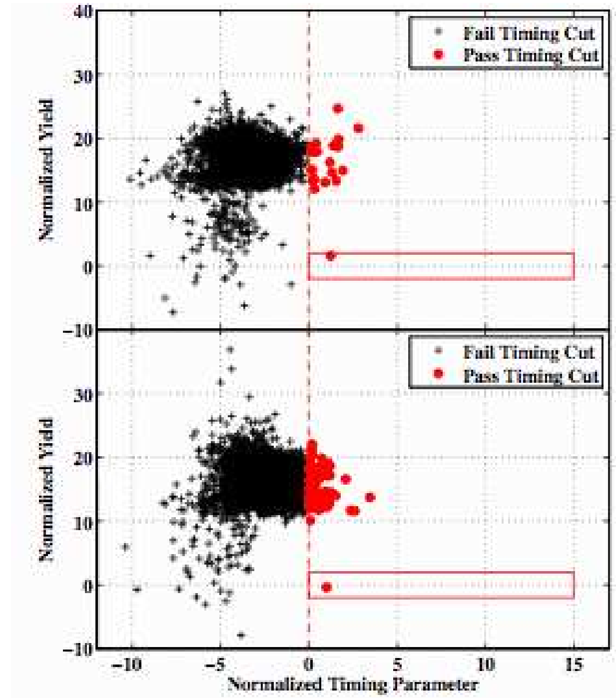

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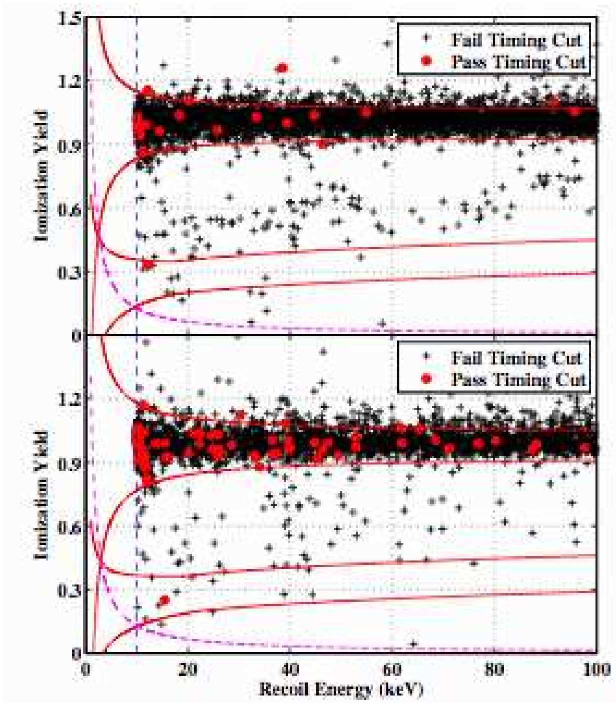

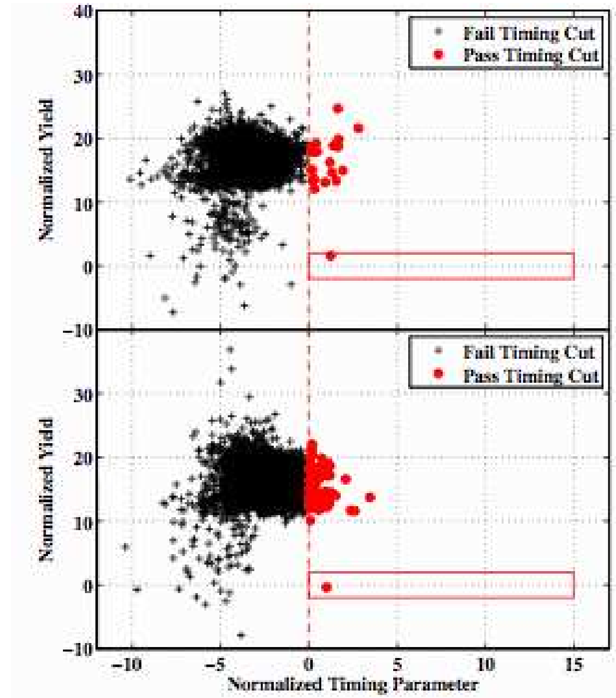

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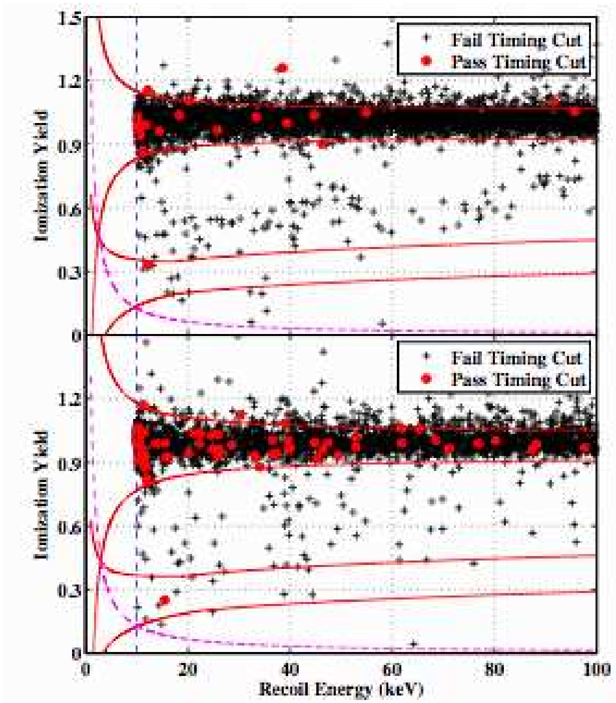

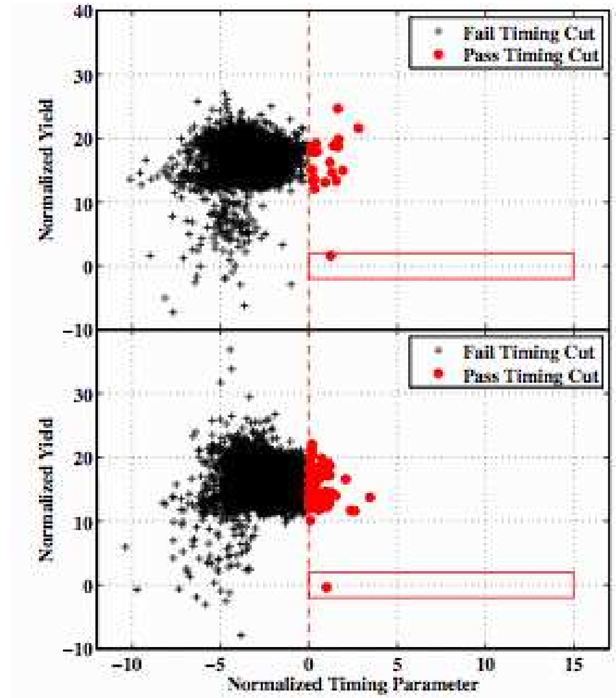

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CDMS events as WIMP signal?

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already many papers out

Assume spin independent interactions:

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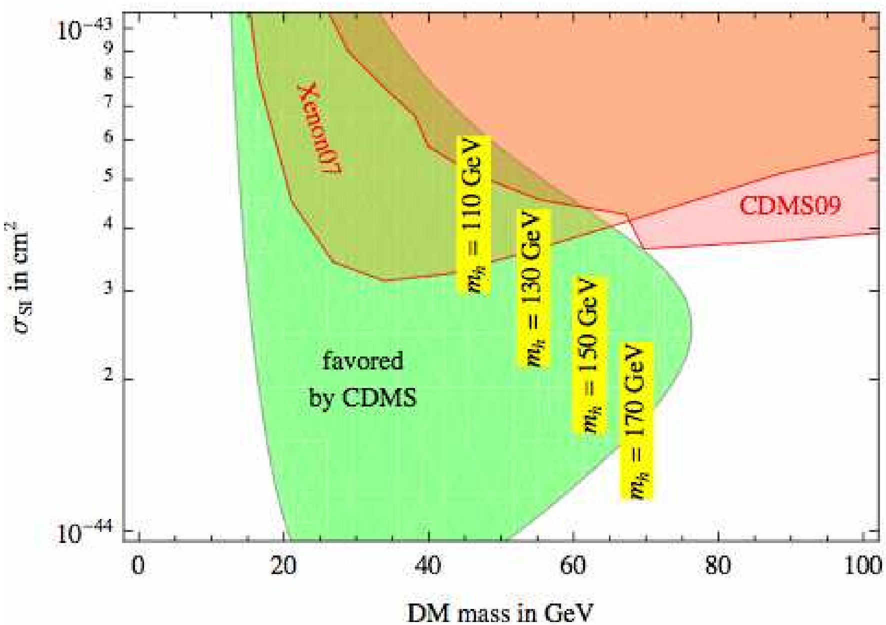
al. et Strumia, 0912.5038



(78% CL)

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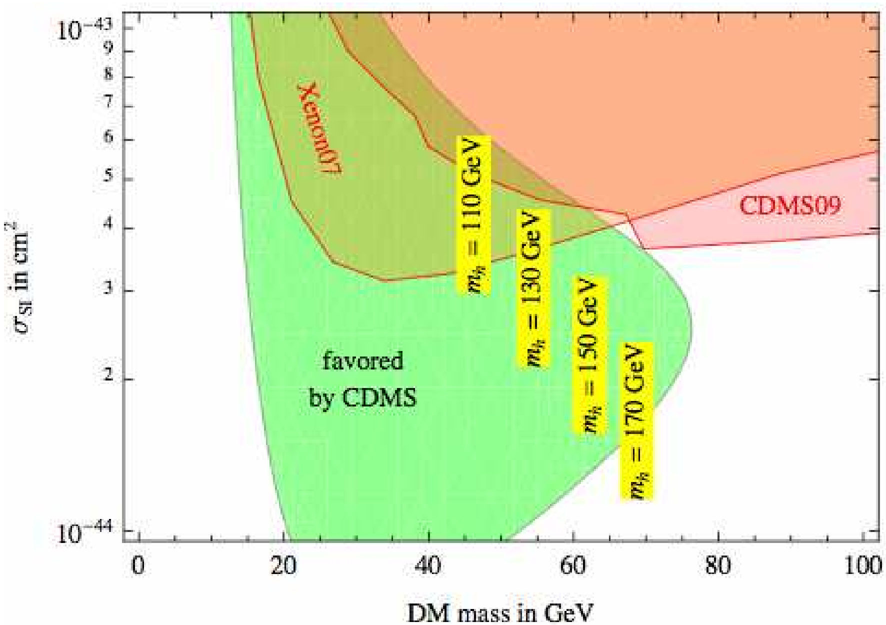

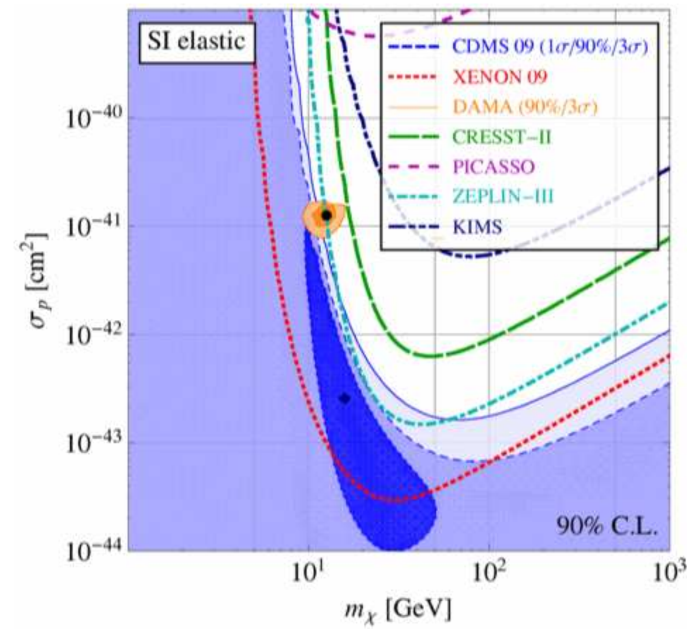

(78% CL)

(1σ)

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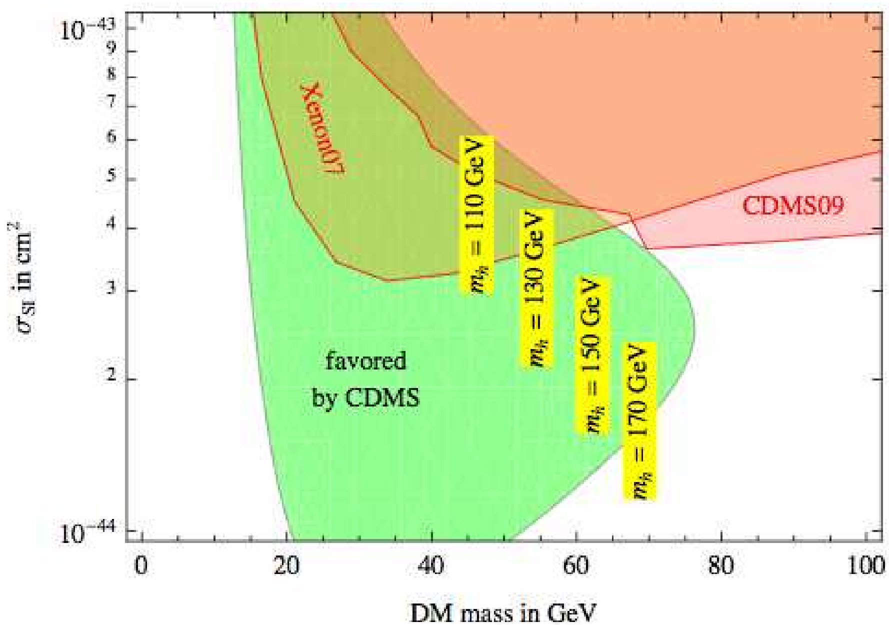

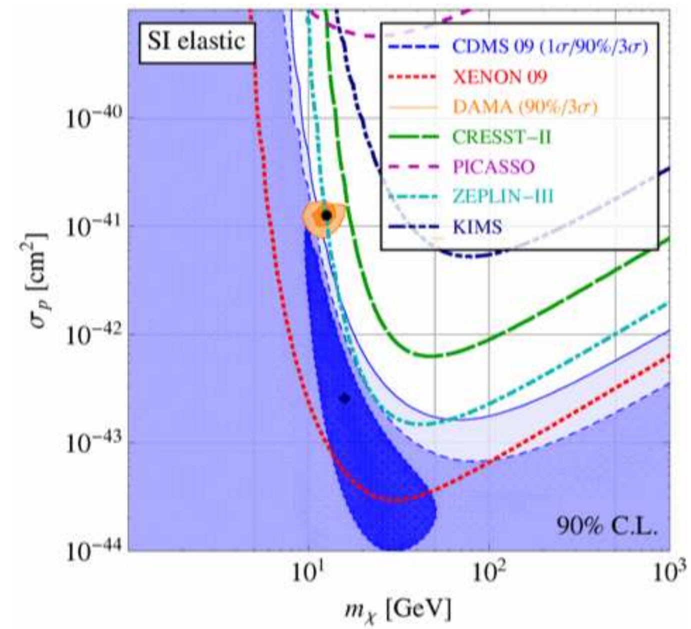

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(1σ)

Rough implications:

- $m_{\rm WIMP} \sim 10 - 100\,{\rm GeV}$

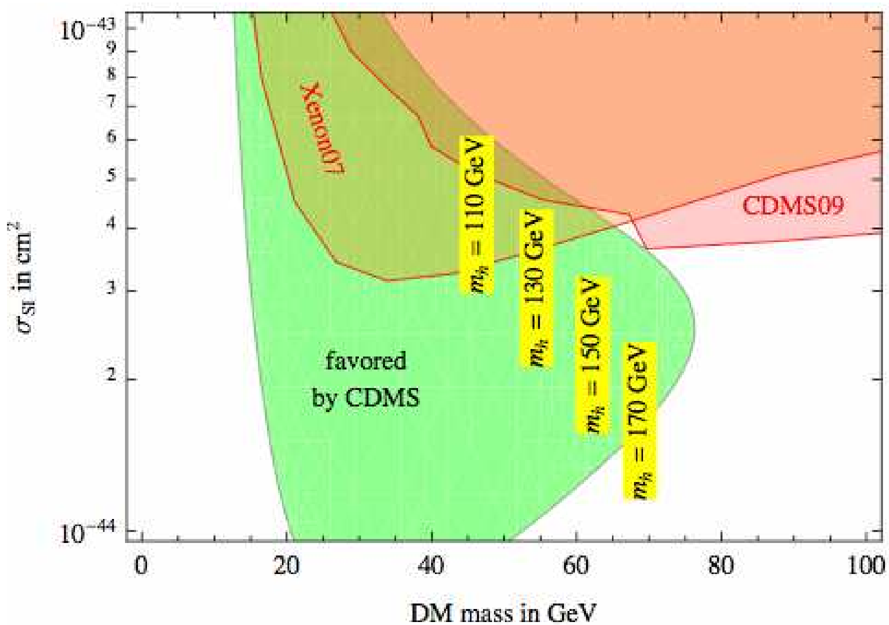
CDMS events as WIMP signal?

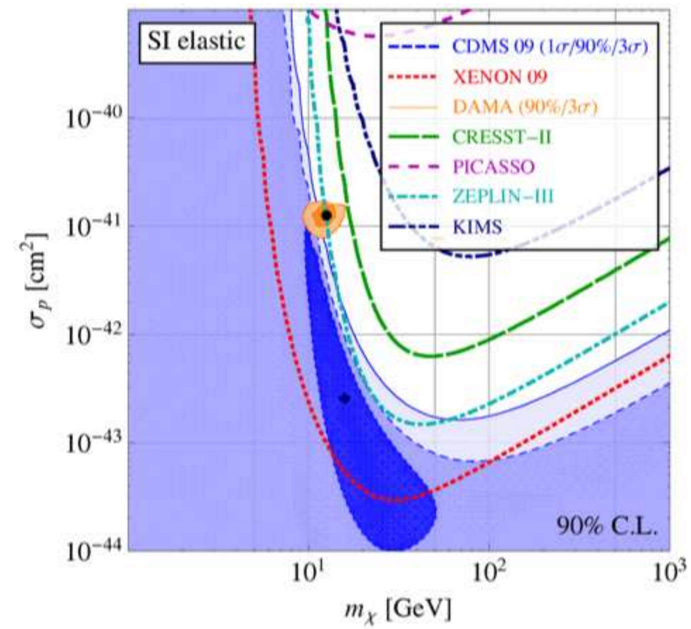
already many papers out

Assume spin independent interactions:

al. et Strumia, 0912.5038

Kopp, Schwetz and Zupan, 0912.4264





(78% CL)

(1σ)

Rough implications:

- $m_{\mathrm{WIMP}} \sim 10 - 100\,\mathrm{GeV}$
- $\sigma_p^{\mathrm{SI}} \sim 10^{-5} - 10^{-8}$ pb

Remember: only 2 events!

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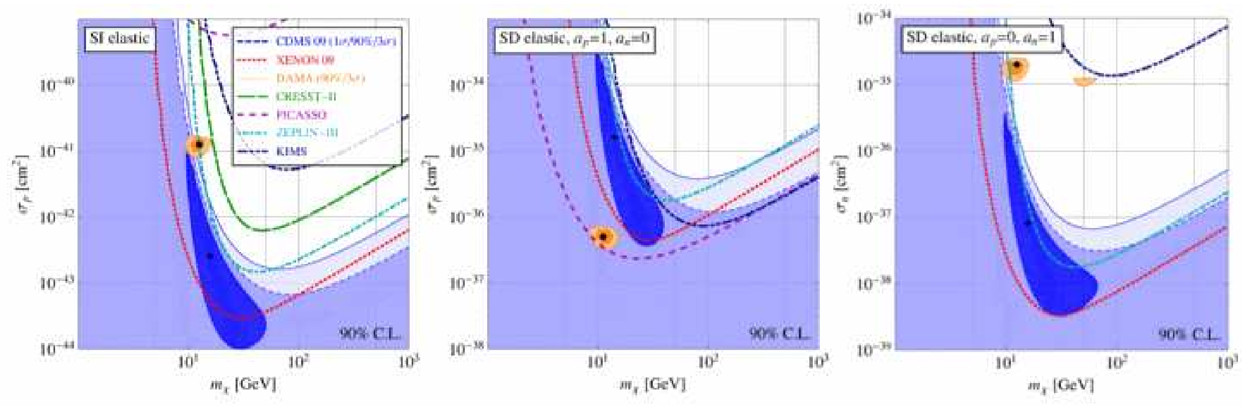

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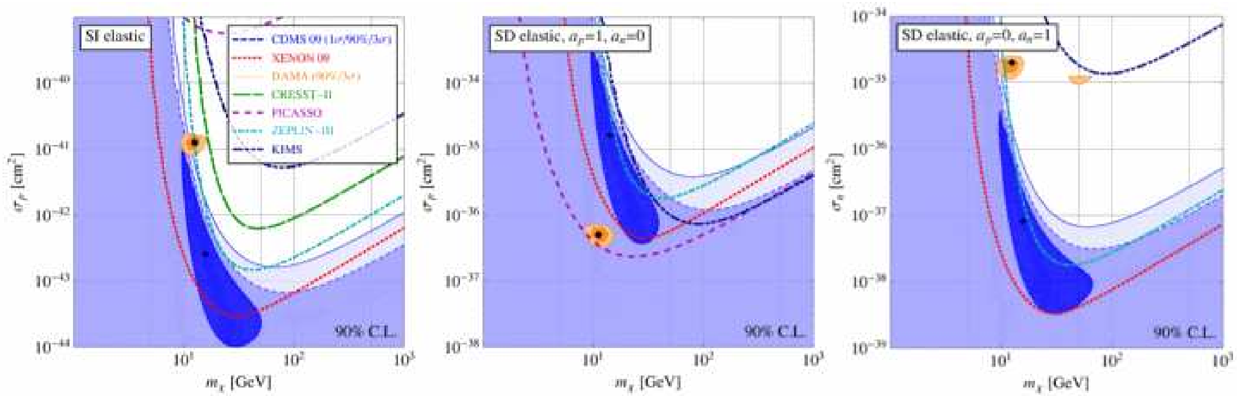

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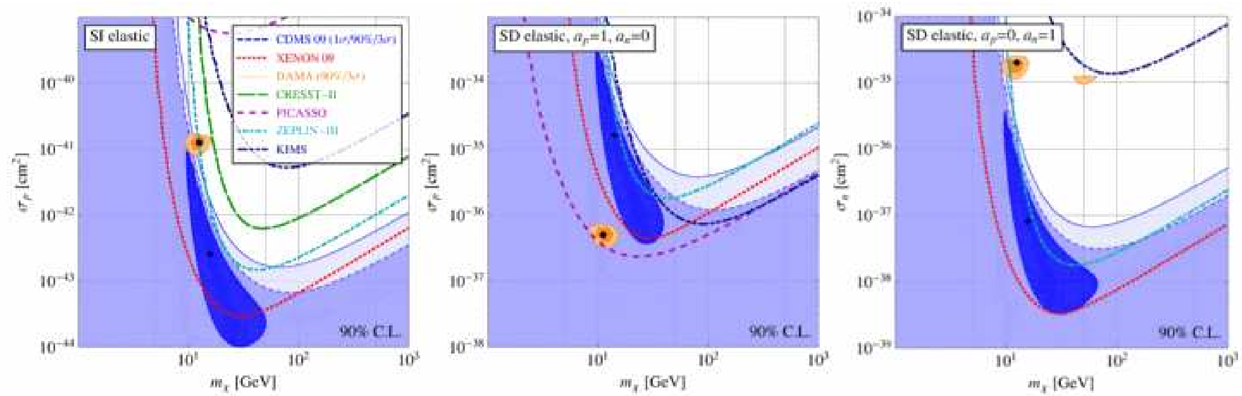

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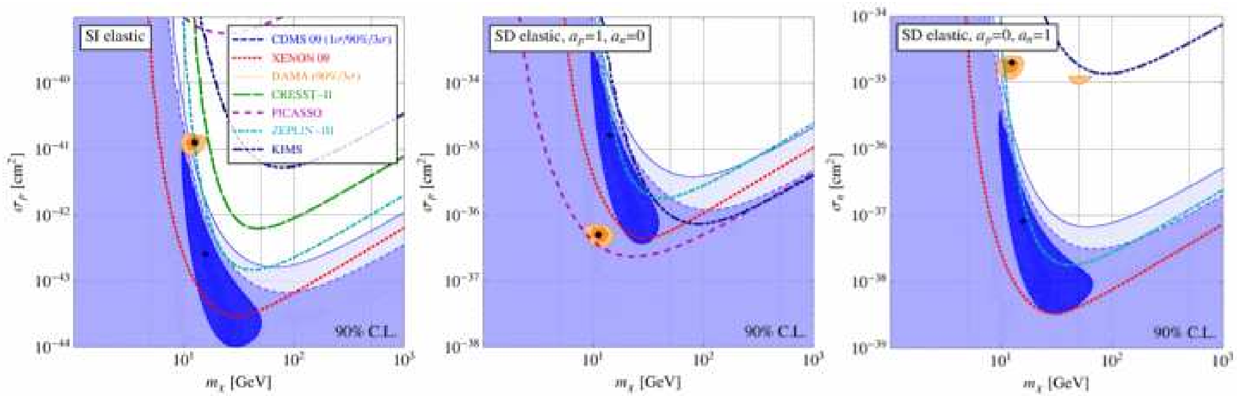

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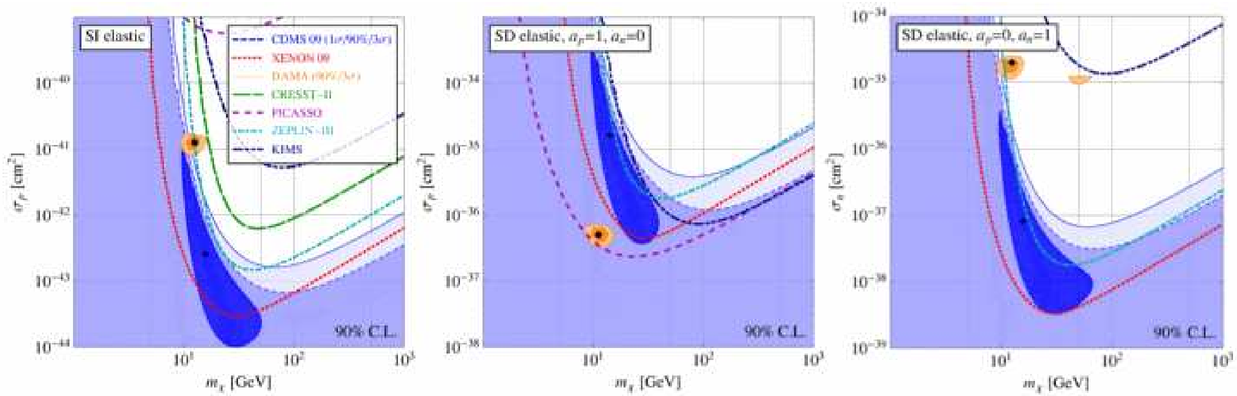

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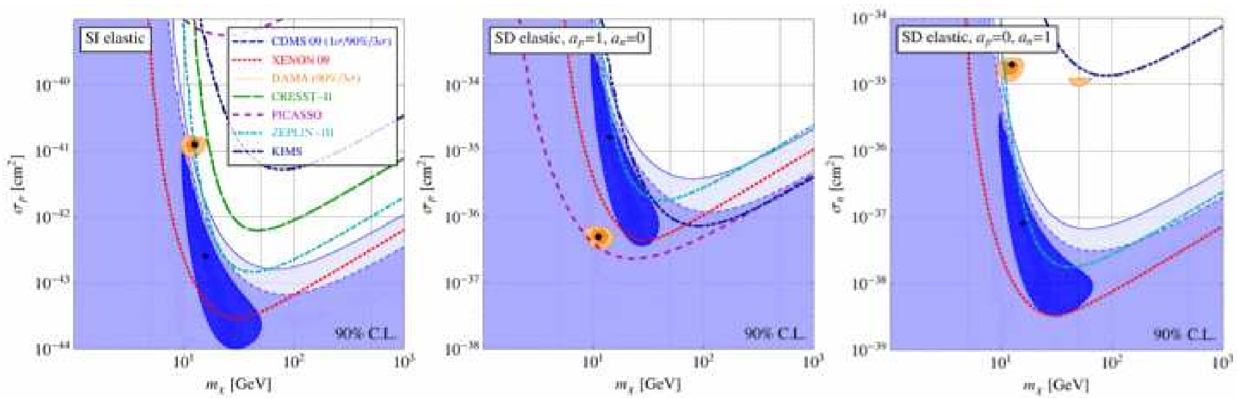

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$\Rightarrow$ CDMS events: unlikely to be due to DM signal

Next: XENON

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XENON-100: comparable in sensitivity to CDMS

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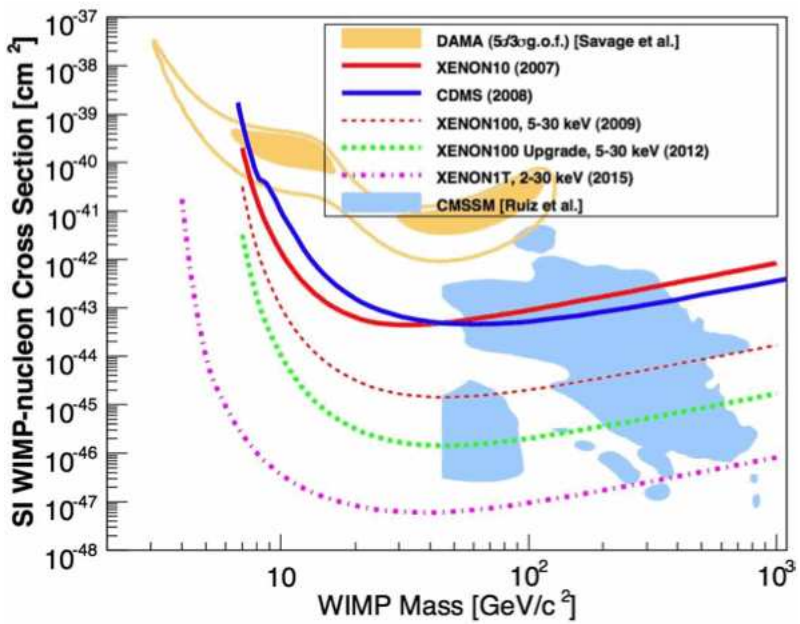
Aprile and Baudis, 0902.4253

spin independent



- XENON-100: expected to reach down to $\boldsymbol{\sigma_p^{\mathrm{SI}} \sim \mathbf{a\ few} \times 10^{-9}}$ pb!
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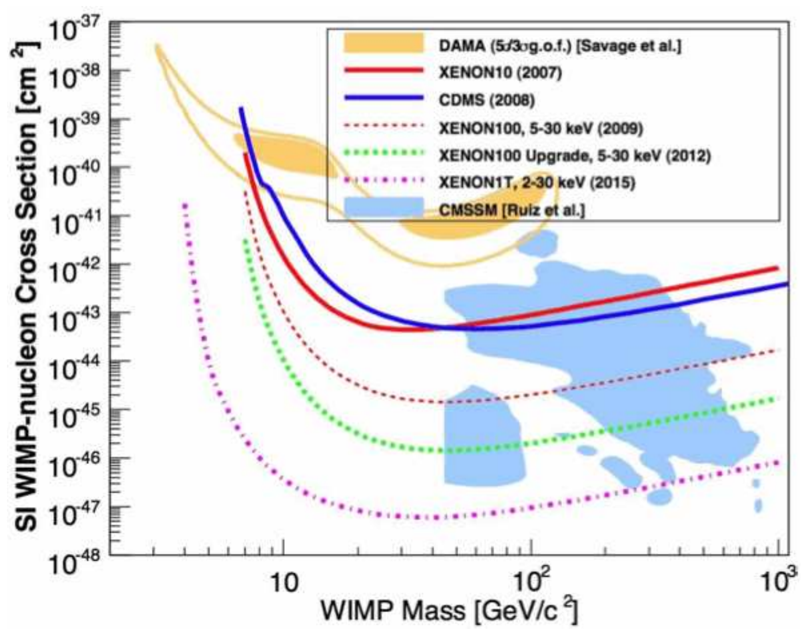

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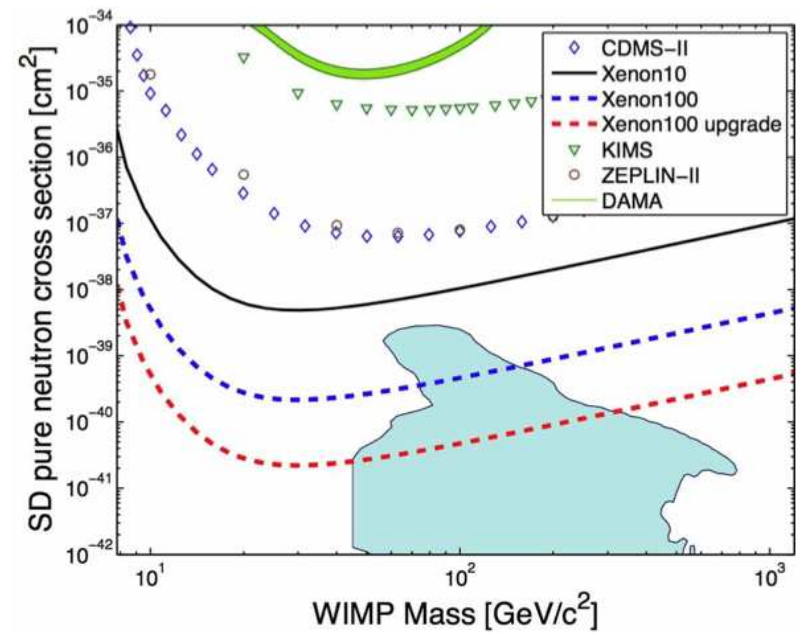

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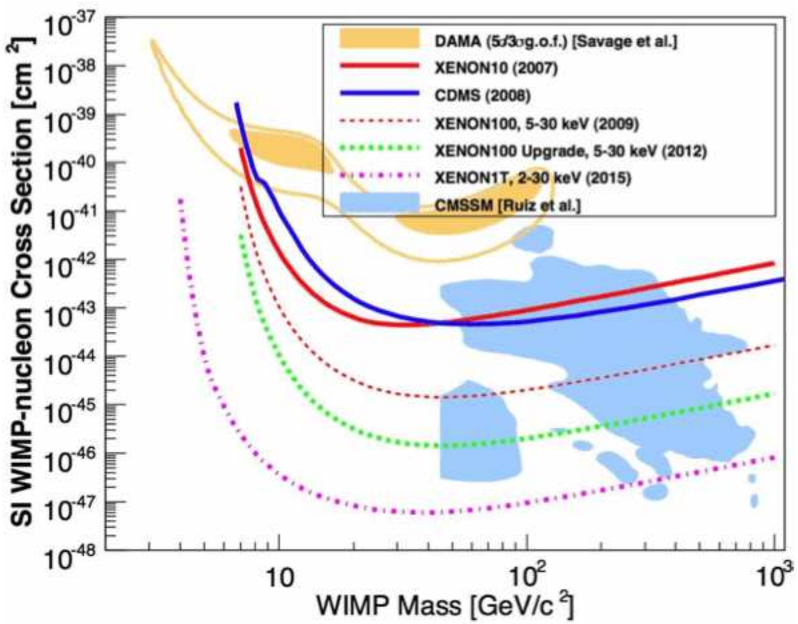

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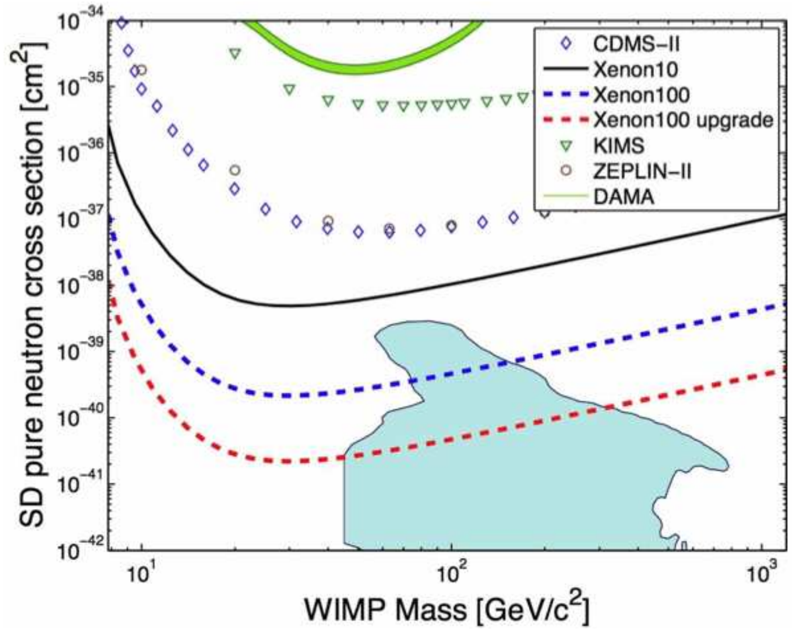

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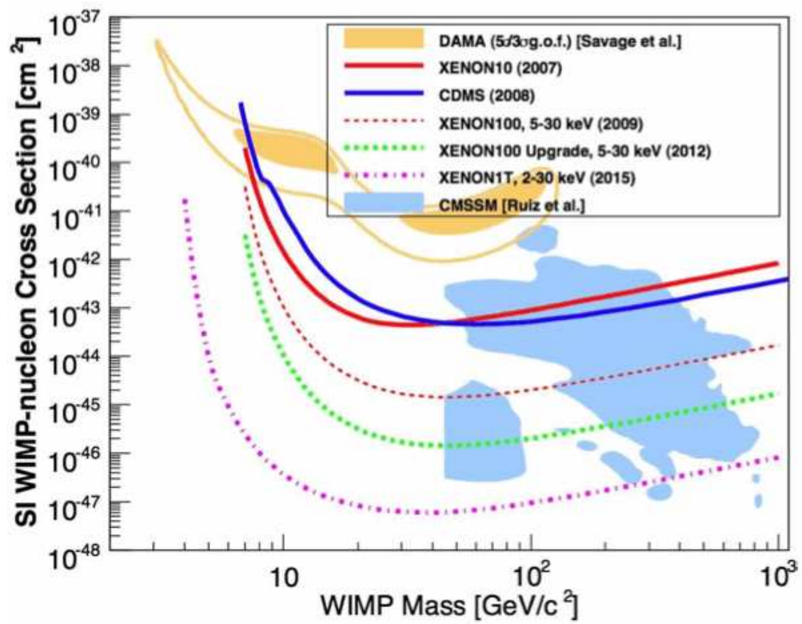

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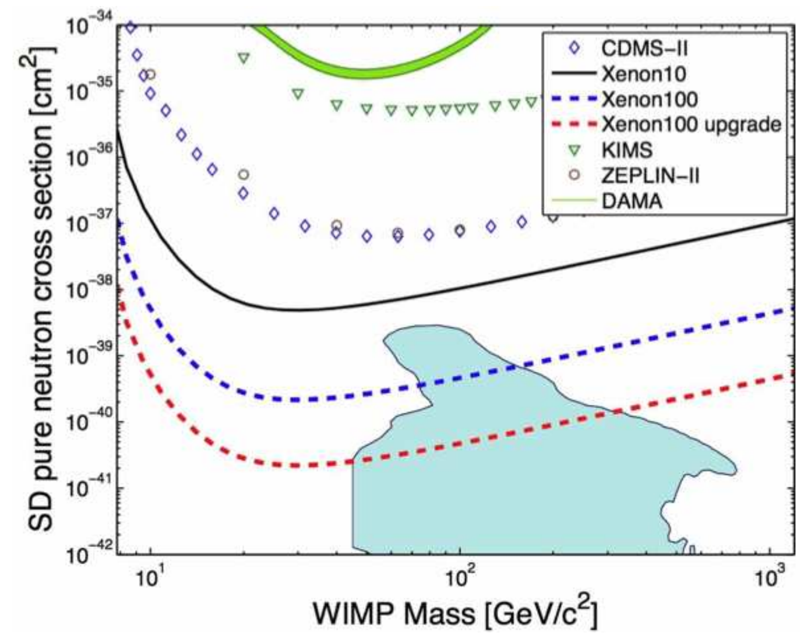

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CDMS and inelastic SI and SD

DM of $\sim \mathbf{100\,GeV}$ with a tiny mass split $\boldsymbol{\delta} \sim \mathbf{keV}$ $\Rightarrow$ inelastic DM

suggested to reconcile DAMA with other expts (Tucker-Smith and Weiner, 2001)

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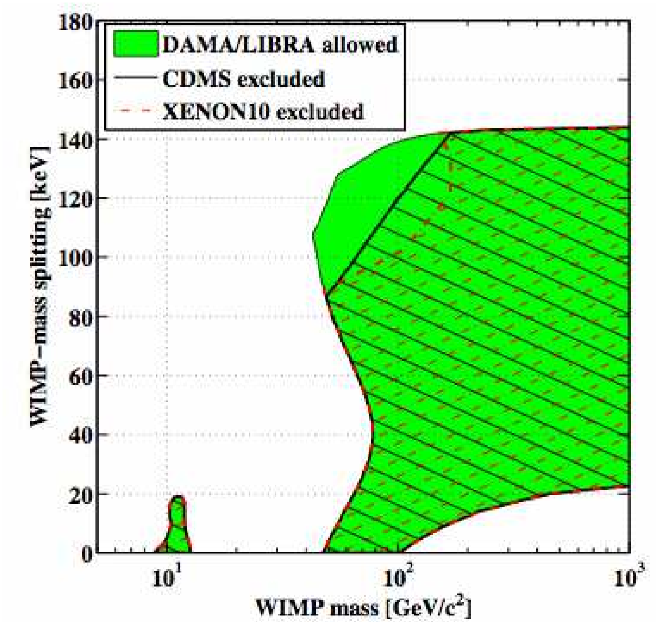
CDMS, 0912.3592



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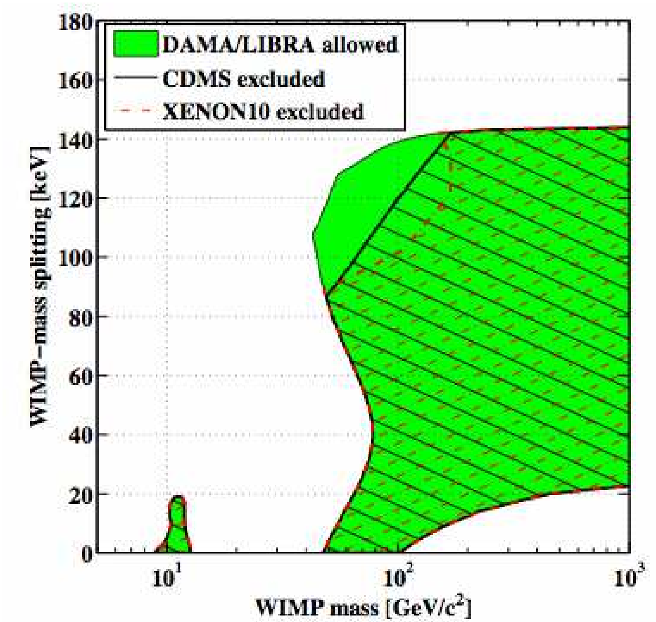

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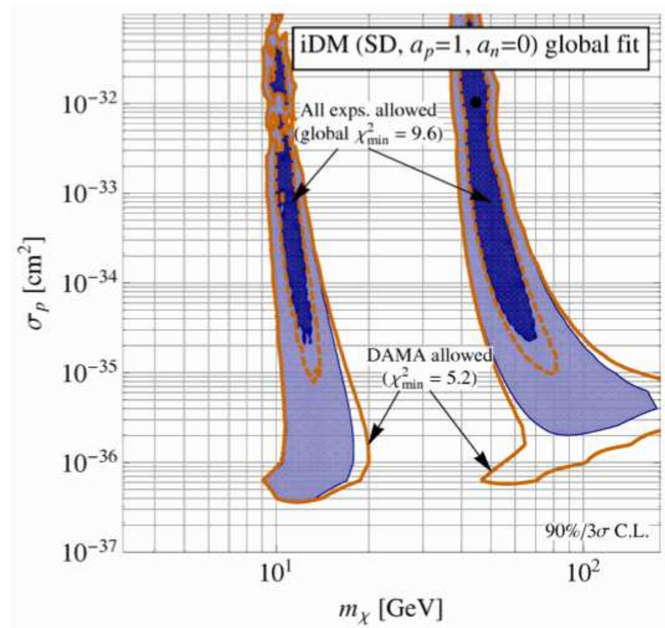

- two tiny regions allowed

but much fine-tuning...

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- more to come, stay tuned