DARK MATTER @ PNHE

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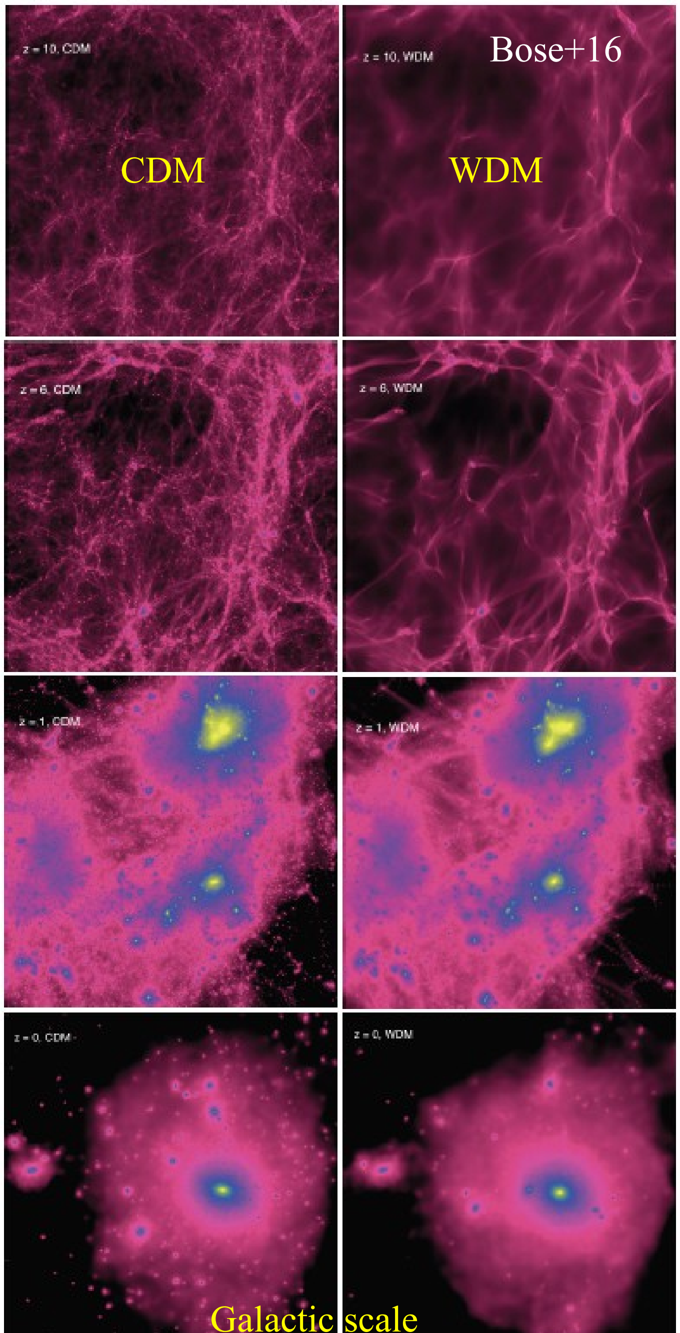
Journées du PNHE
APC, Paris, 30-31 March 2016

* DM: The broad picture
* Some candidates + searches
* The French DM community
* Near future and expected PNHE support

Dark matter: successes and issues



<u>So far, only gravitational evidence for DM</u>
(cosmological structures+CMB)

<u>CDM successes:</u>

- CMB peaks
- Successful structure formation (from CMB perturbations)

=> CDM seeds galaxies, galaxies embedded in DM halos

- Lensing in clusters + rotation curves of galaxies
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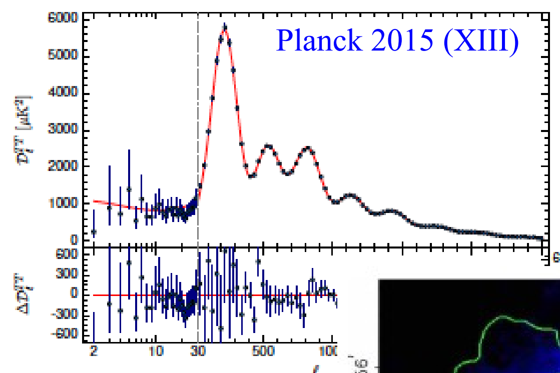
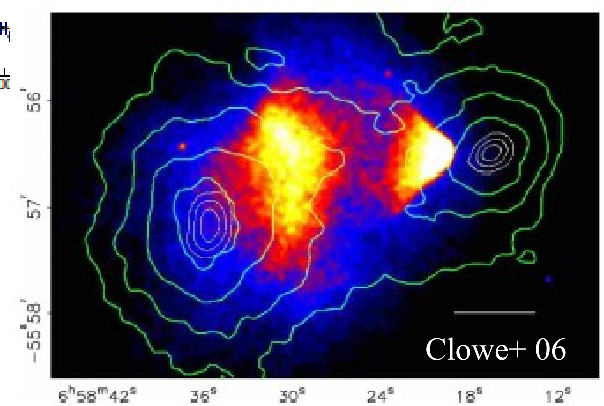
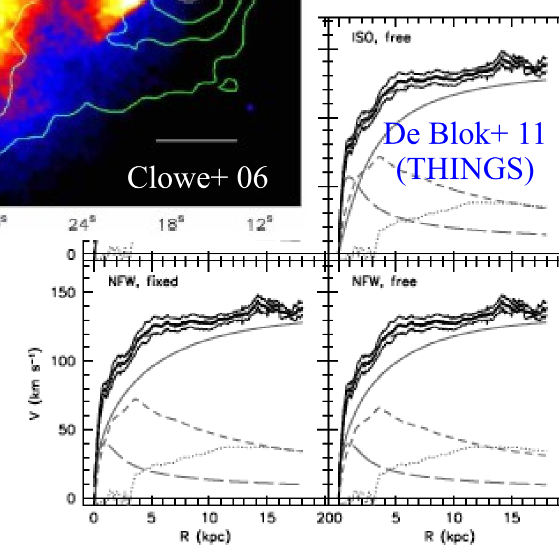


PNCG AREA





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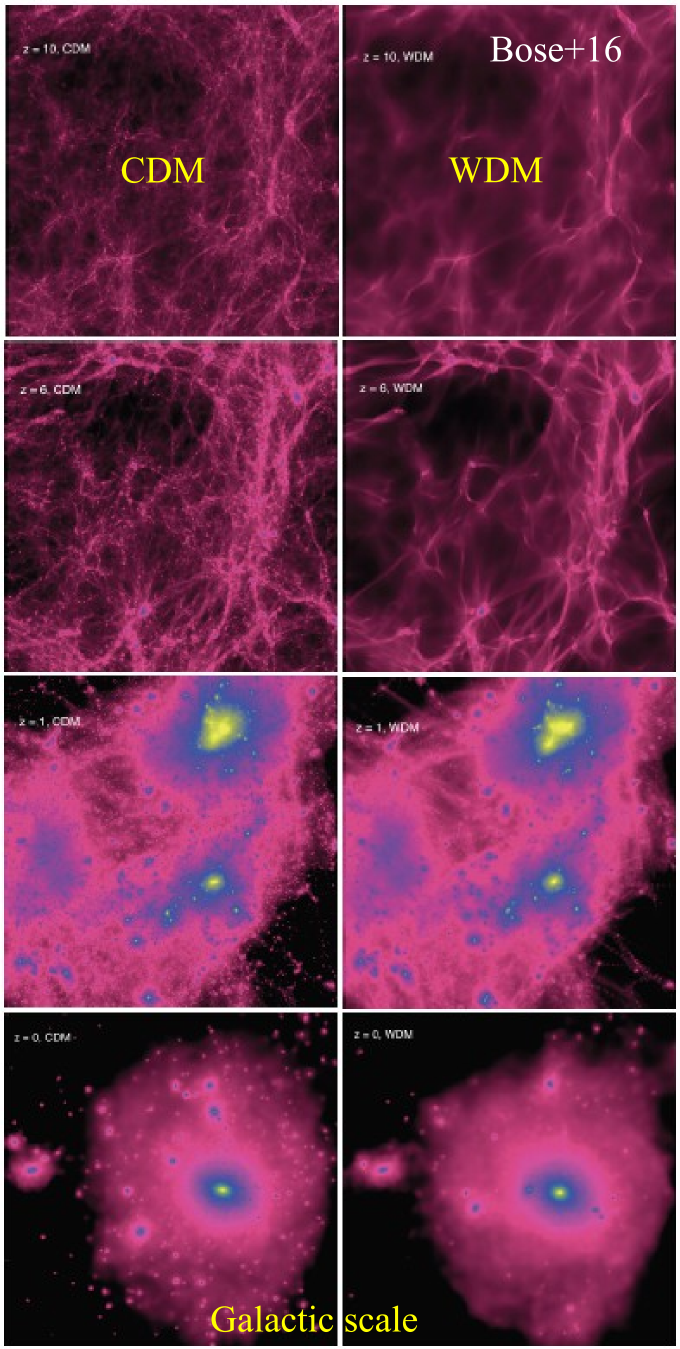

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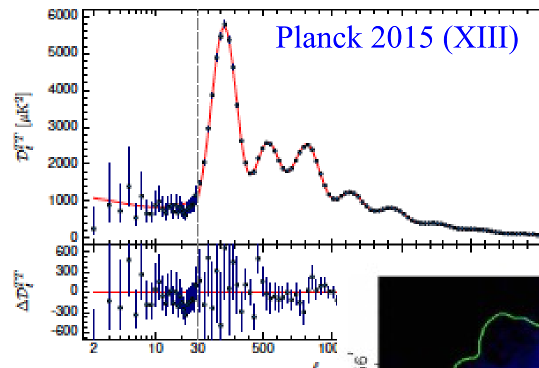

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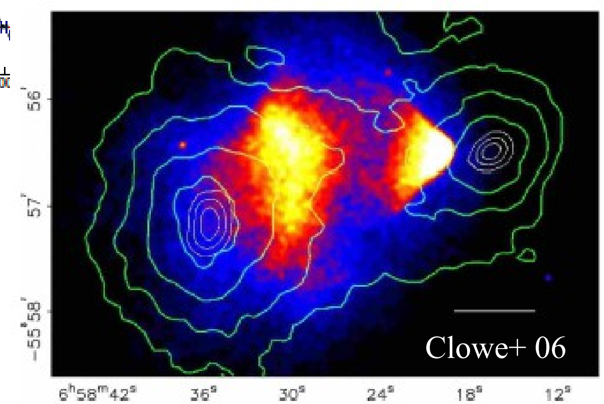
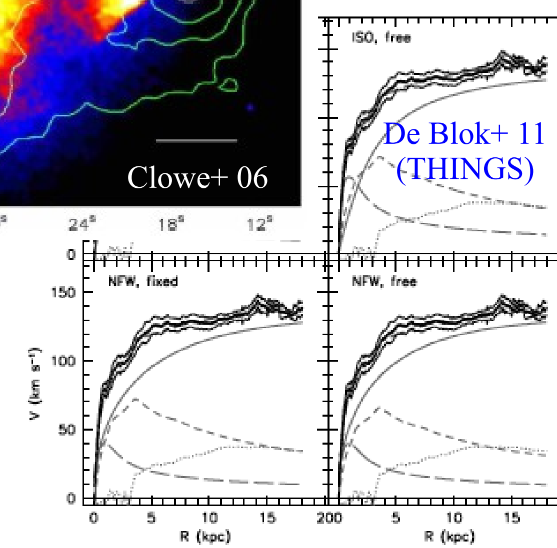
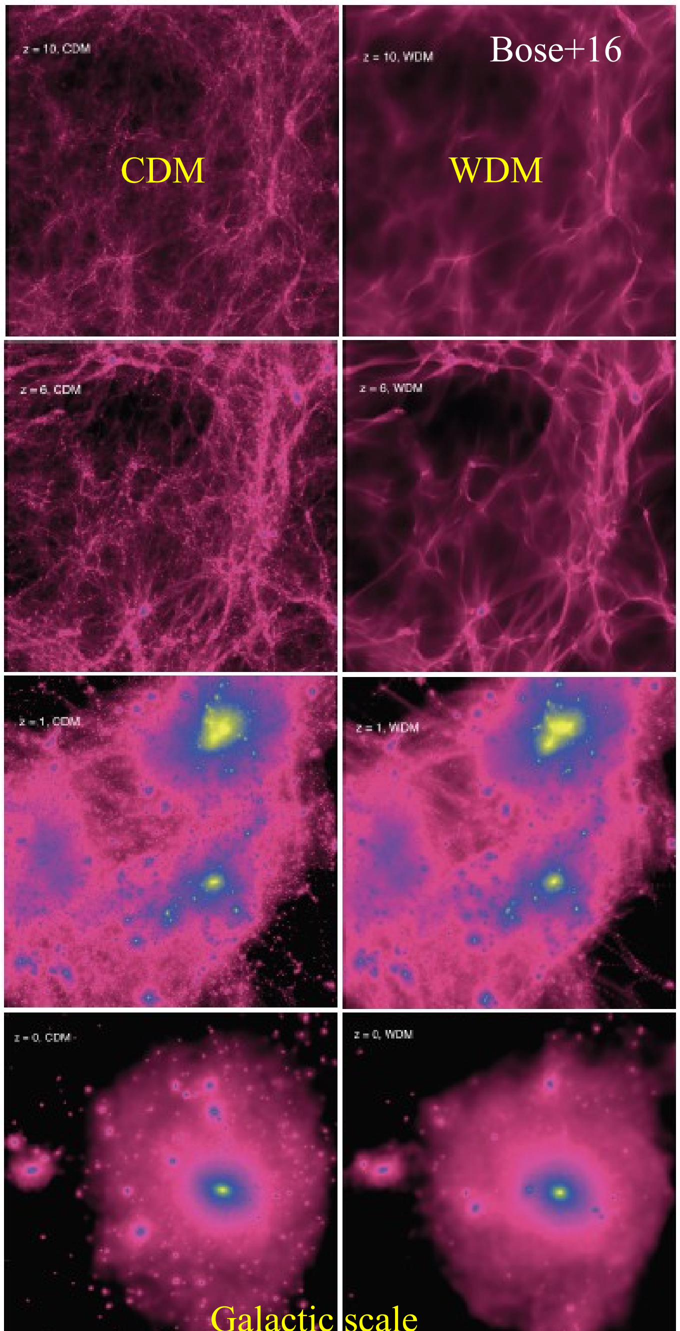




CMB + structure formation
=> Severe issues for modified gravity
=> Additional DM fields required

Dark matter: successes and issues



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<u>How cold?</u>

<u>Cold enough to form Dwarf Galaxies:</u>

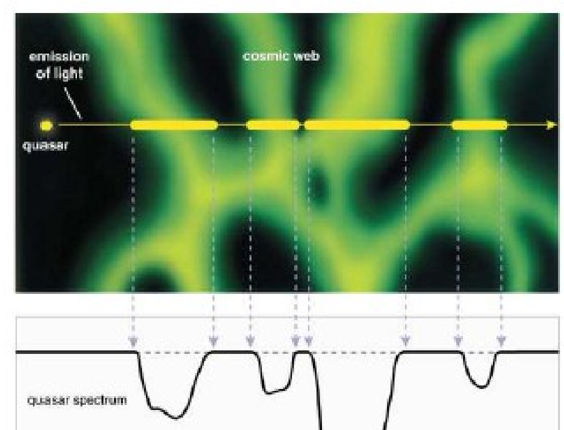
* Tremaine & Gunn 79, Boyarsky+ 06: **m > 1 keV**

PNCG AREA

<u>Cold enough to be consistent with Lyman-alpha forest</u>

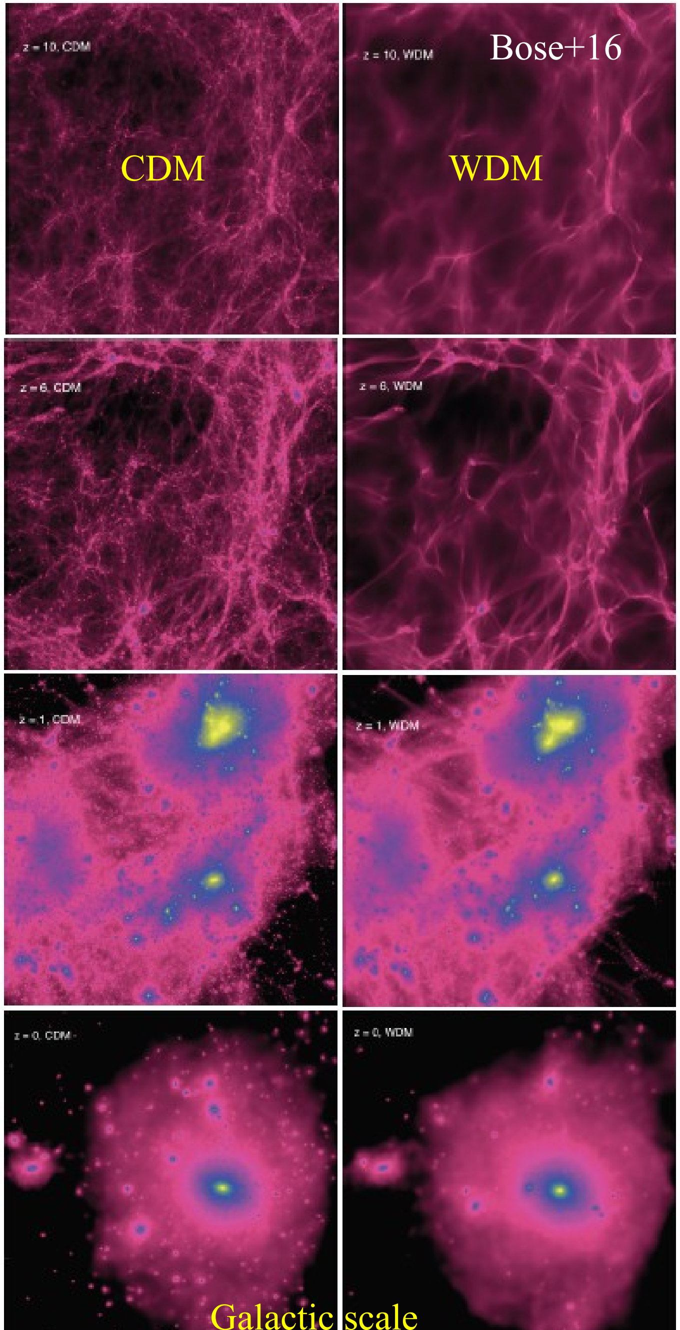
* Boyarsky+ 08 => **m > 5 keV** (thermal)

=> WDM and/or CDM allowed, but then **WDM is almost CDM**.



Courtesy O. Ruchayskiy

Dark matter: successes and issues



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NOT DEVOID OF ISSUES:

*** NOT DISCOVERED YET**
*** SMALL SCALE ISSUES:**
1) The core-cusp pb
Some galaxies better fitted with DM cores than with predicted cusps (e.g. NFW profile).
2) The too-big-to-fail pb (=missing satellite pb)
CDM predicts more satellite galaxies than observed.

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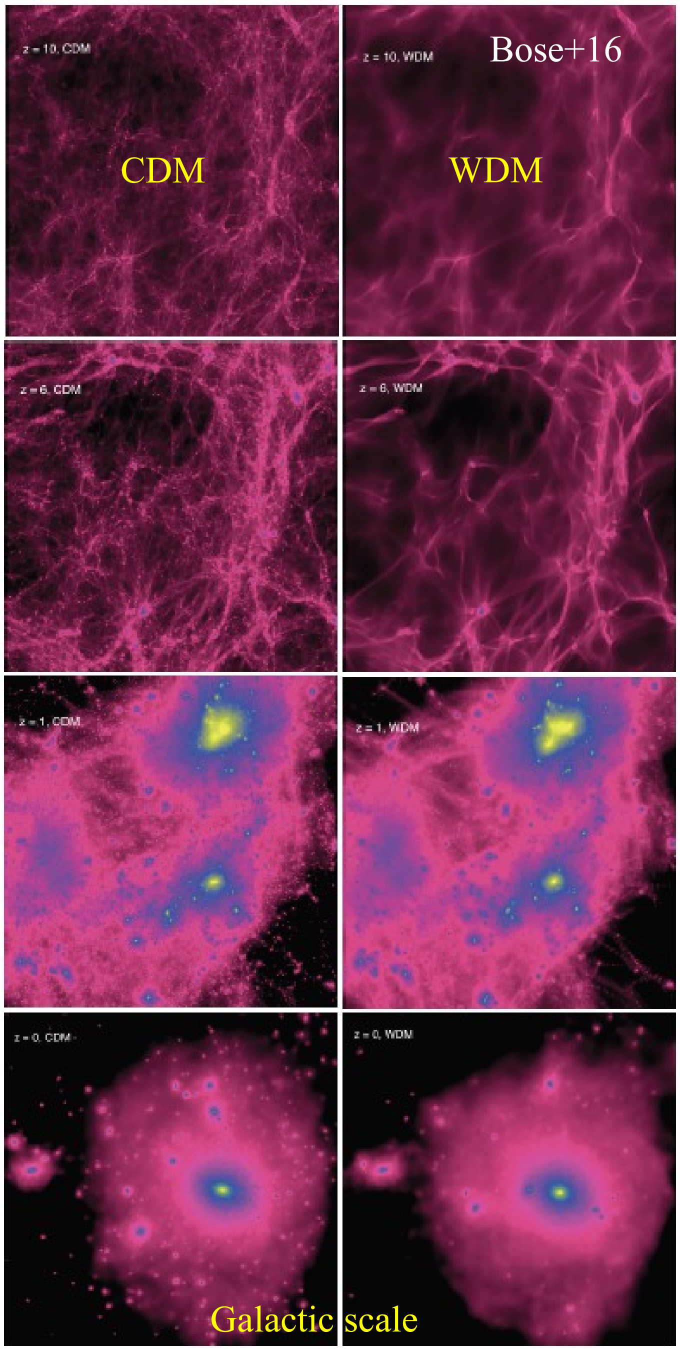

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POTENTIAL SOLUTIONS:
1) Baryon physics rules the halo centers (stellar + SN feedback)
→ how controlled? (ongoing works) – **must be included anyway**
2) Pure DM solution: Self-Interacting DM (SIDM).

Particle candidates

Focus on (non-exhaustive, but representative)

* **Sterile neutrinos**

* **WISPs**: (very) weakly interacting slim particles
→ axions, axion-like particles (ALPs), hidden/dark photons (HP/DP)

* **WIMPs**: weakly interacting massive particles

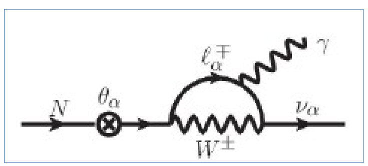
(will not discuss: SIDM, XDM, etc.)

Sterile neutrino (W)DM

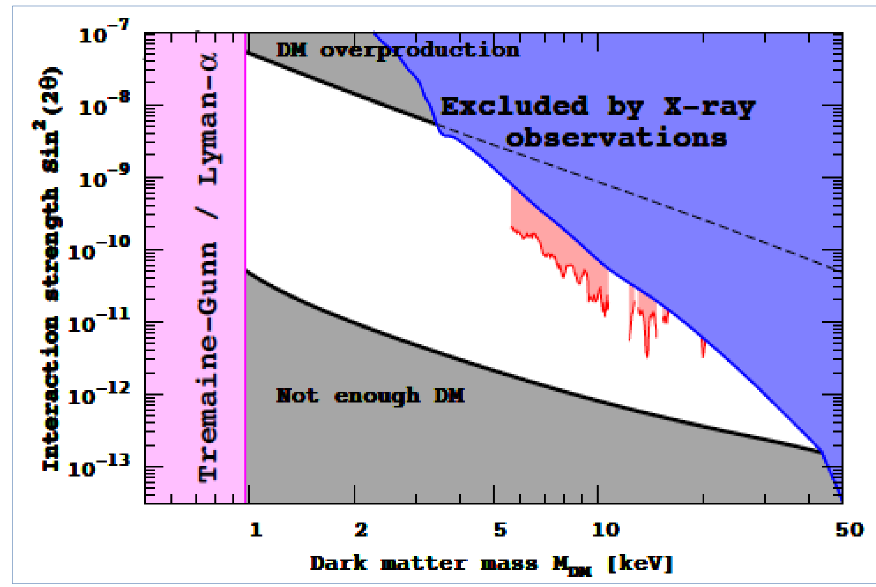
Sterile neutrino DM
e.g. Dodelson & Widrow 94,
Shi & Fuller 99,
Shaposhnikov+06

→ **Neutrino masses (see-saw)**
→ **Leptogenesis**
→ **DM candidates (more or less warm)**
→ **keV mass range (!= thermal mass)**

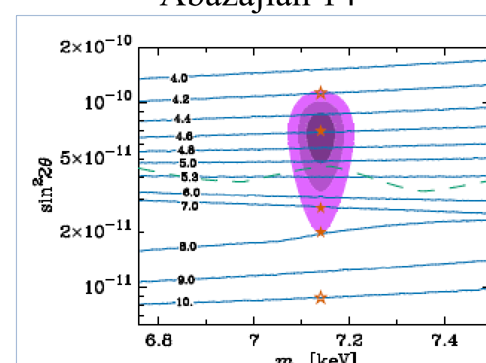
$$\mathcal{L} \supset \mu \left[\frac{\phi}{v}\right] \bar{\nu}_l \, \nu_r + M \, \nu_r \, \nu_r + \text{h.c.}$$



Boyarsky+ 13



Abazajian 14



Aspects relevant to cosmology:
* suppress power on small scales
(free-streaming scale larger than CDM)
→ viable? (e.g. Schneider 15)
* current limits on thermal masses > 1.7 keV

Detection (main):
* neutrino experiments (double ß decay)
* decays to X-ray line: hints @ 3.5 keV (Bulbul+14, Boyarsky+14)
→ 7 keV consistent with thermal mass of 2 keV(e.g. Abazajian 14)
→ hot debate, could be systematics (cf. Jeltema & Profumo)

Sterile neutrino DM in France

NB: French GDR Neutrino
(sterile neutrino DM not discussed much)

* **IN2P3:**

Exp-obs:

→ neutrino experiments (double ß, etc.)

→ cosmology experiments

Th/pheno/mod:

→ astrophysical impact: APC-Paris

→ leptogenesis: IPNL-Lyon

→ LFV: LPC-Clermont

* **INSU** (Exp-obs):

→ X-ray astronomy (nobody involved in sterile neutrino physics to my knowledge)

* **INP** (Th/pheno/mod):

→ leptogenesis/LFV: LPT-Orsay

→ mass matrix: L2C-Montpellier

* **CEA**:

Exp-obs (IRFU):

→ neutrino experiments (double ß, etc.)

→ X-ray astronomy

Th/pheno/mod (IPhT):

→ leptogenesis

=> X-ray community (PNHE integrated) might want to discuss with French experts in the future

Axions

(+ axion-like particles + dark/hidden photons = WISPs)

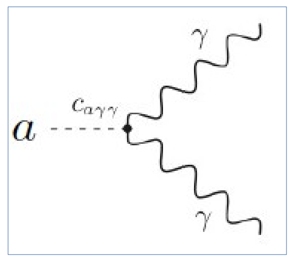
Peccei-Quinn, Wilczek, Weinberg, Kim, Shifman, Vainshtein, Zakharov, Dine, Fishler, Srednicki, Sikivie – 70'-80'

(Very) weakly interacting slim particles
→ solves the strong CP problem (BSM physics required)
→ CDM candidate (not necessarily DM!)
→ μeV-meV mass range

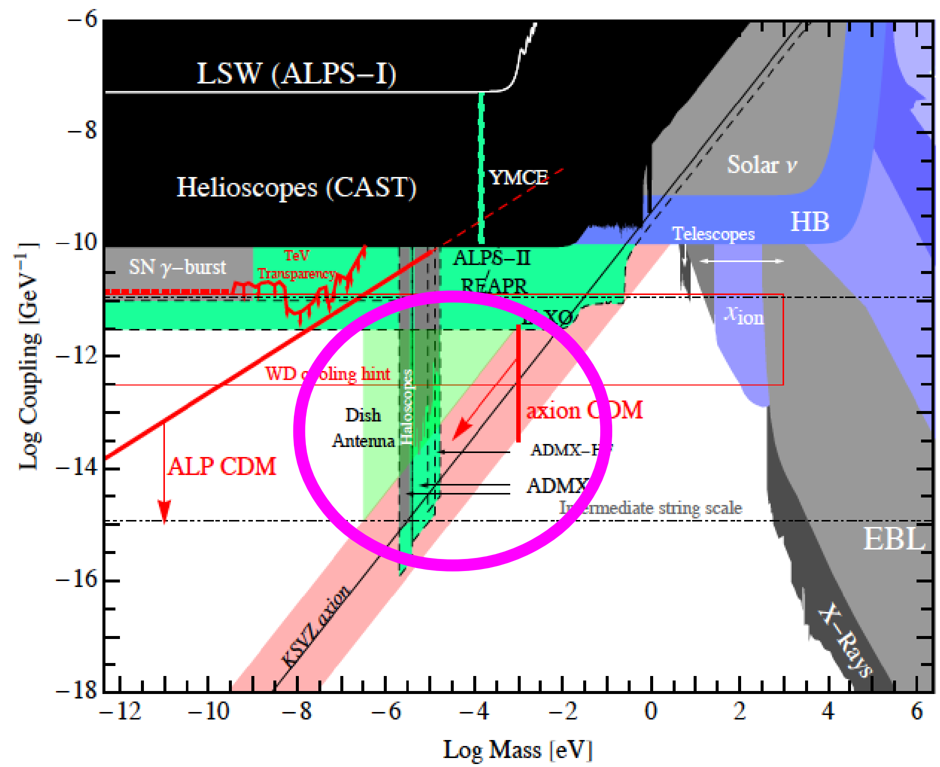
$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

$$m_a \approx 0.6 \text{ meV} \times \left[\frac{10^{10} \text{ GeV}}{f_a}\right]$$

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} \left\{ g_{a\gamma} \equiv \frac{\alpha_s}{2\pi f_a} C_{a\gamma} \right\} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Essig+12



Aspects relevant to cosmology:
* non-thermal remnants => expected ultra-cold DM
→ minimal mass scale ~ 10^{-12} Msun subhalos
→ detailed structure formation under study

Detection (main):
* from interactions with photons: conversion
→ e.g. ADMX (ongoing): conversion of DM axions into photons

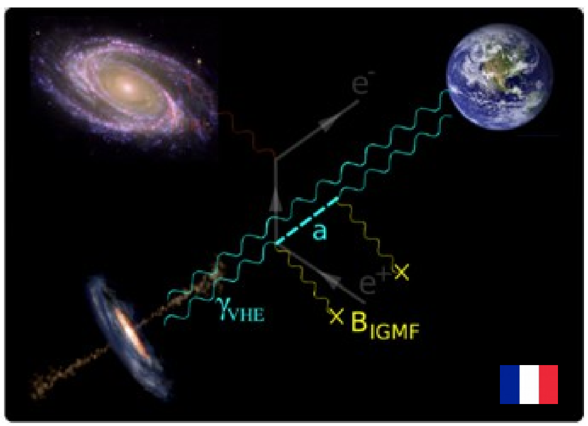
Extra:
* Axion-like particles (ALPs), arising in string-inspired theories => relaxed axion mass range
* Hidden photons: kinetic mixing with photons from broken U(1) in some BSM extensions =>

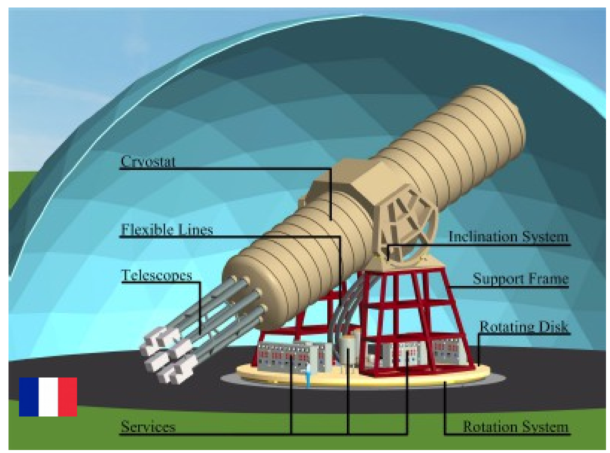
Axion searches

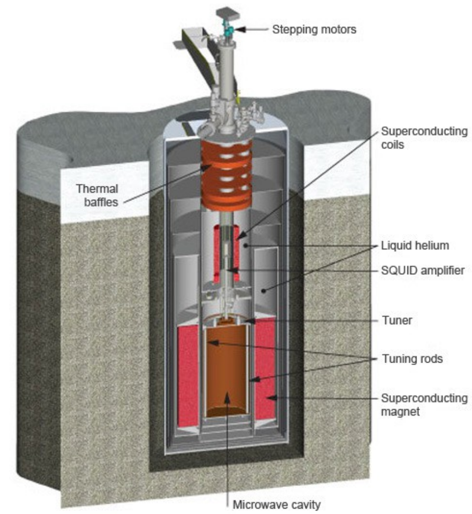
NB: B-field for axions or ALPs, not for HPs

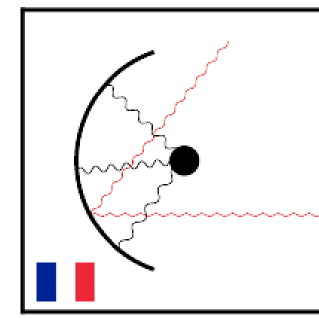
= French contrib.

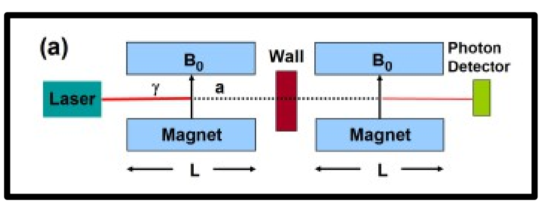
TeV blazar gamma-ray conversion to axions
e.g. HESS-CTA
=> PNHE related











"Light shining through a wall"
(laser + B-field + wall)
e.g. ALPS@DESY

Helioscopes
CAST + IAXO @ CERN
B-field + micromegas

Haloscopes
Microwave cavities / dish antennae
B-field + detector (~GHz)

Not sensitive to DM

Sensitive to DM axions (irrespective of local DM density)

Needs that local DM density is made of axions

DM ALPs/HP in France

Obs-exp mostly at CEA-IRFU:

* TeV blazar spectra (HESS-CTA) → not sensitive to DM axions
* IAXO → all axions (including DM)
* Dish antennae → DM axions only

Th/pheno/mod. (not core research):

* gravitational systems of axions: IPNL-Lyon (IN2P3), LPT-Toulouse (INP)
* dark photons in early universe: LUPM-Montpellier (IN2P3)
* astrophysical searches: LAPTh-Annecy (INP), IRFU
* model building (HP, ALPs): LPTHE-Paris (INP), LPT-Orsay (INP) + fluctuating/irregular places

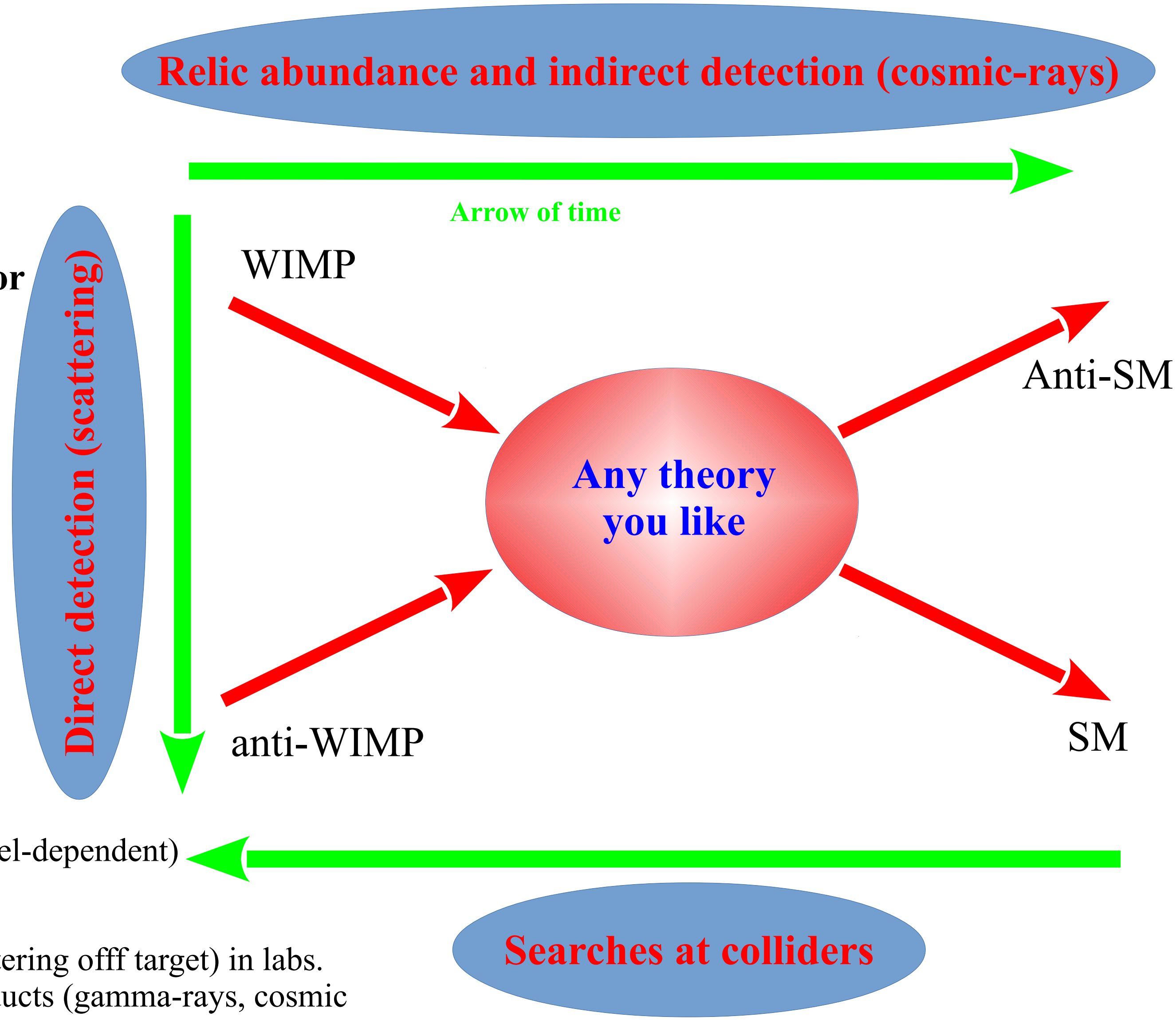
=> Axion/ALP/HP not at the core of PNHE activities
=> Should not be excluded if funding resources allow
=> Case by case / favor complementarity with other activities / help foster new ideas/collabs. in initial stages

WIMPs

Weakly interacting massive particles

→ Stability + origin of the Higgs sector
→ susy / extra-dim / composite
(+ proton stability)
→ GeV-TeV masse range

Popular ex: neutralino



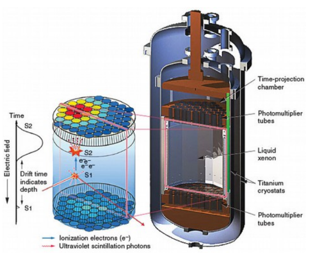
Aspects relevant to cosmology:
* Pure CDM
→ min mass scale ~ 10^{-6} Msun subhalos (model-dependent)

Detection:
*colliders (production) + direct searches (scattering offf target) in labs.
* indirect searches for annihilation/decay products (gamma-rays, cosmic rays, neutrinos).
→ Many experiments currently running (e.g. LHC, Fermi, AMS, LUX).

Astro/particle complementarity

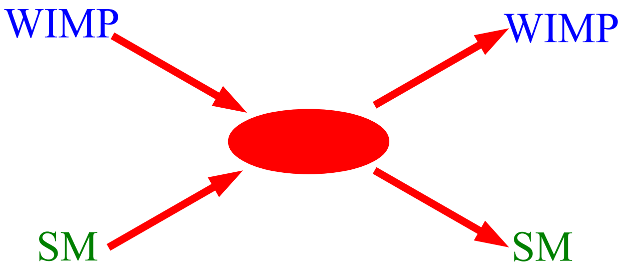
Direct detection rate – WIMP-matter scattering

$$\frac{d\Gamma_{\chi-\mathrm{N}}}{dE_r}(E_r,t) = \frac{\sigma_{\chi-\mathrm{N}}\,F^2(E_r)}{2\,\mu_r^2}\,\frac{\rho_\odot}{m_\chi}\int_{v>v_{\min}} d^3\vec{v}\,\frac{f(\vec{v},t)}{v}$$



Scattering

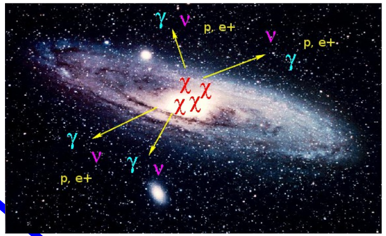
(→ kinetic decoupling in early universe)



$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

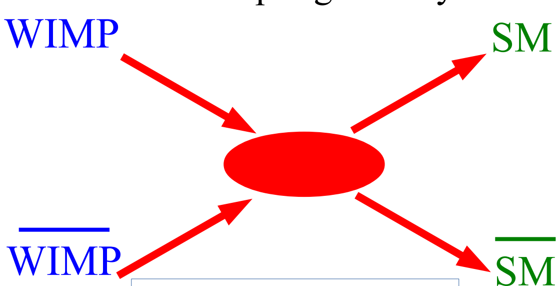
Annihilation vs. scattering
=> constraints from cosmological abundance
+ minimal scale for DM structures (subhalos)

Dark matter profile + phase space
(+ cosmic-ray transport)
=> constrained by Milky Way-mass model
(full gravitational potential DM + baryons)



Annihilation

(→ chemical decoupling in early universe)



$$\Gamma_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}}\, v\rangle\, n_\chi$$

Indirect detection rate (e.g. gamma rays)
– WIMP annihilation

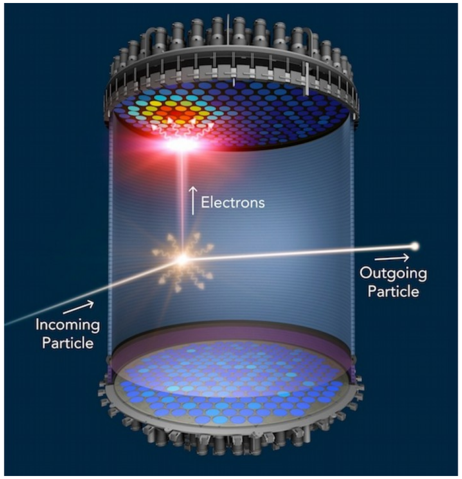
$$\frac{d\phi_\gamma^{\mathrm{ann.}}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\mathrm{res.}} d\Omega\int_{\mathrm{l.o.s}} dl\left[\frac{\rho(r)}{m_\chi}\right]^2$$

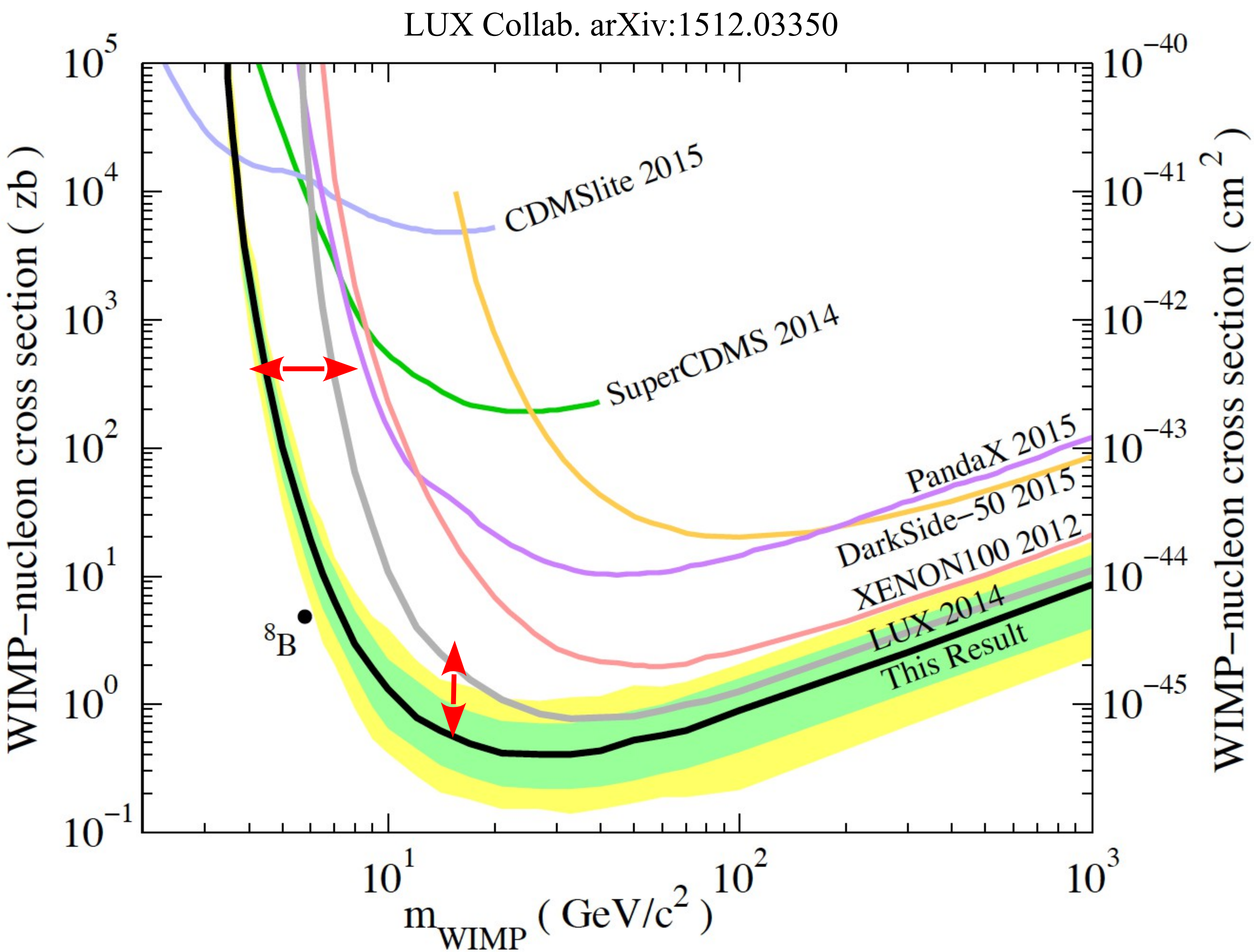
Direct DM searches: recent results

Latest LUX results:
(same data as 2014,
improved analysis)

* Dual-phase xenon (S1,S2)
* 1.4x10^4 kg.day
* improved calibration
* improved efficiency
* increased fiducial volume
* threshold 3 → 1.1 keV!

=> the sub-zepto-barn era!





Direct DM searches: recent results

Latest CRESST results:
(same data as 2012, improved analysis)

* Ca(20)W(74)O(8)
* 52 kg.day
* threshold 0.6 → 0.3 keV!

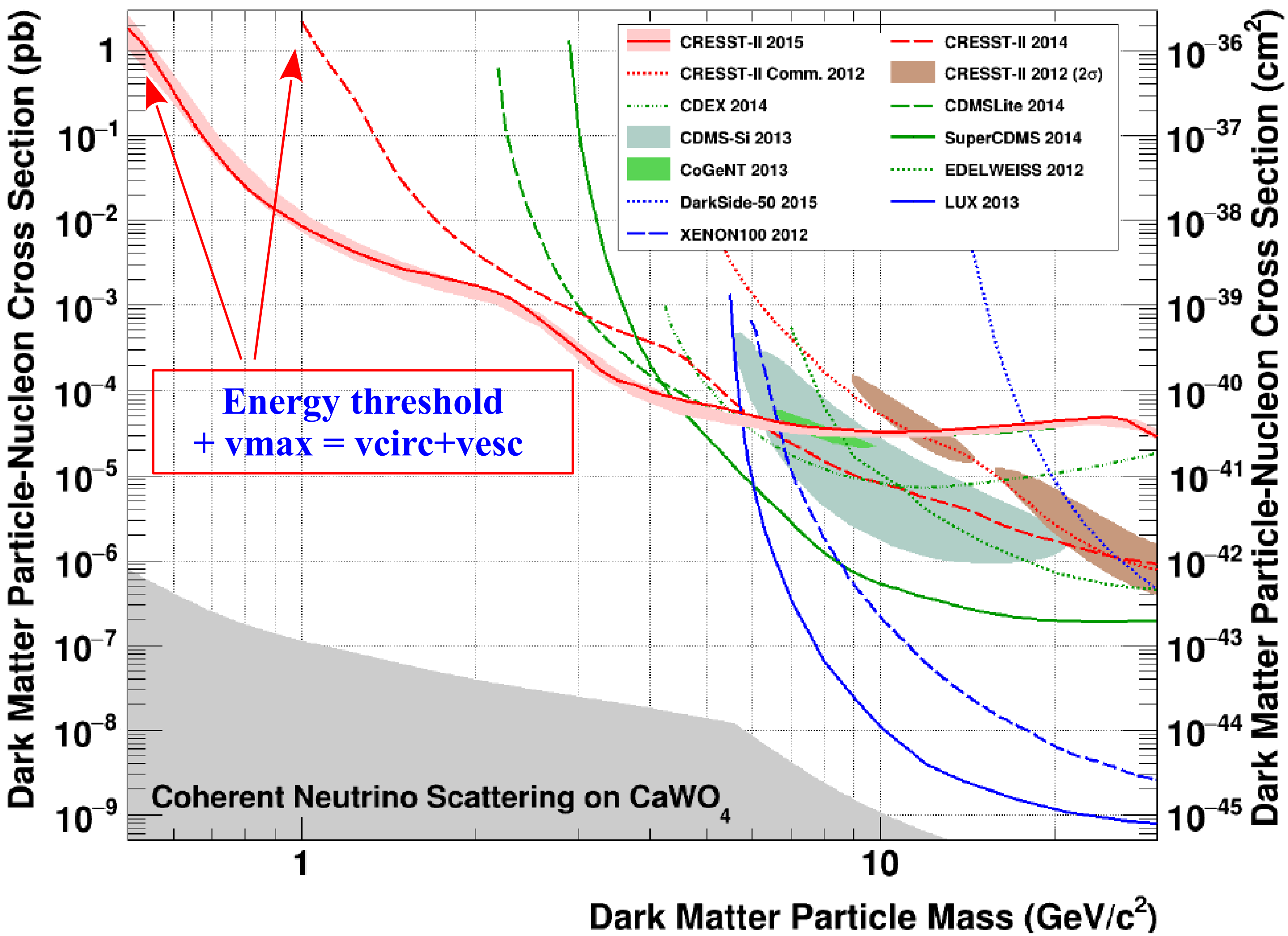
=> the sub-GeV era!

Limits assume “standard halo model” (**SHM**):

* local DM of 0.3 GeV/cm3
* v_{sun} = 220 km/s
* v_{esc} = 544 km/s
* truncated Maxwellian f(v)

→ indicative limits
(to be taken with care)

CRESST-II Collab. arXiv:1509.01515



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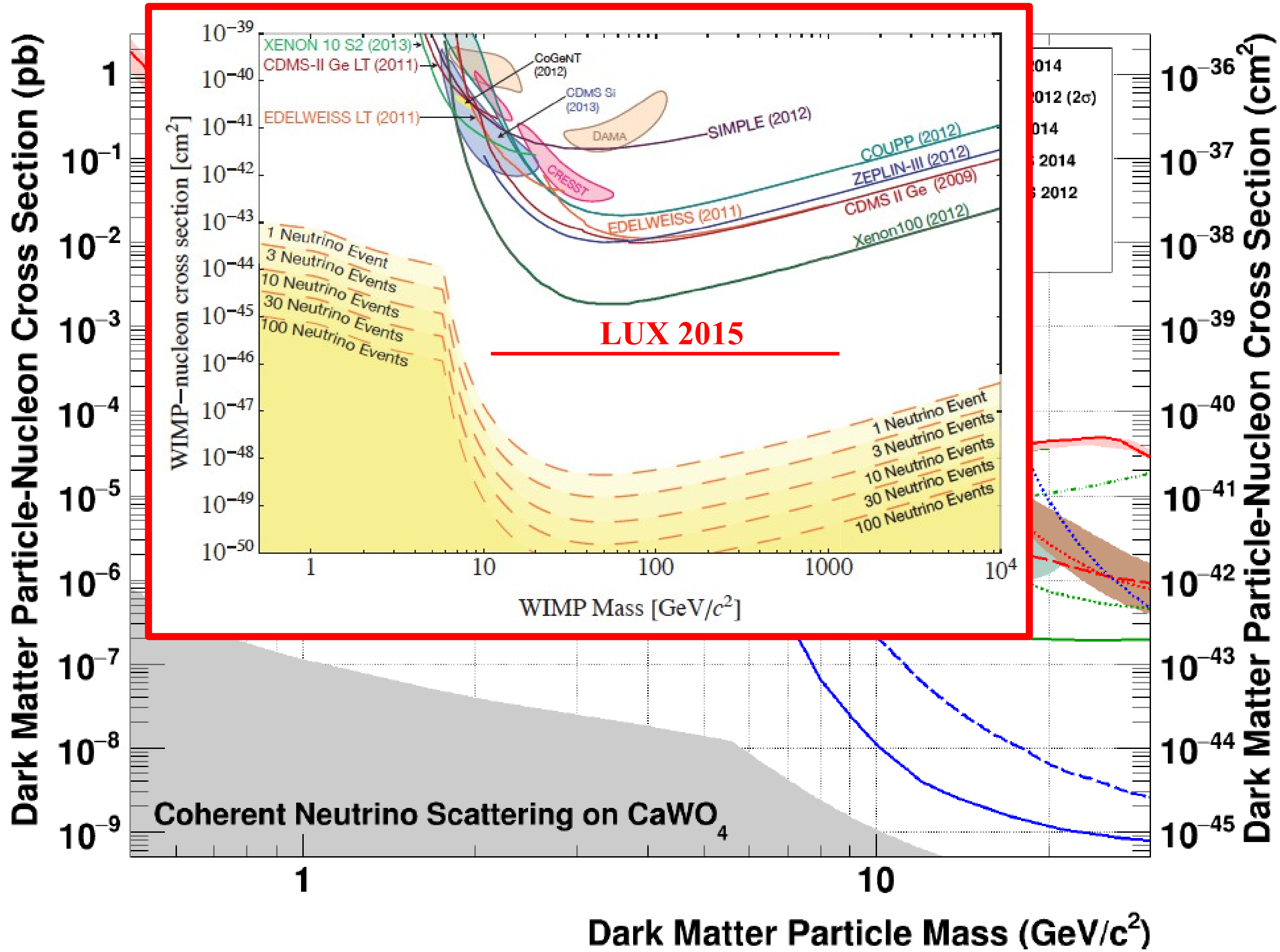
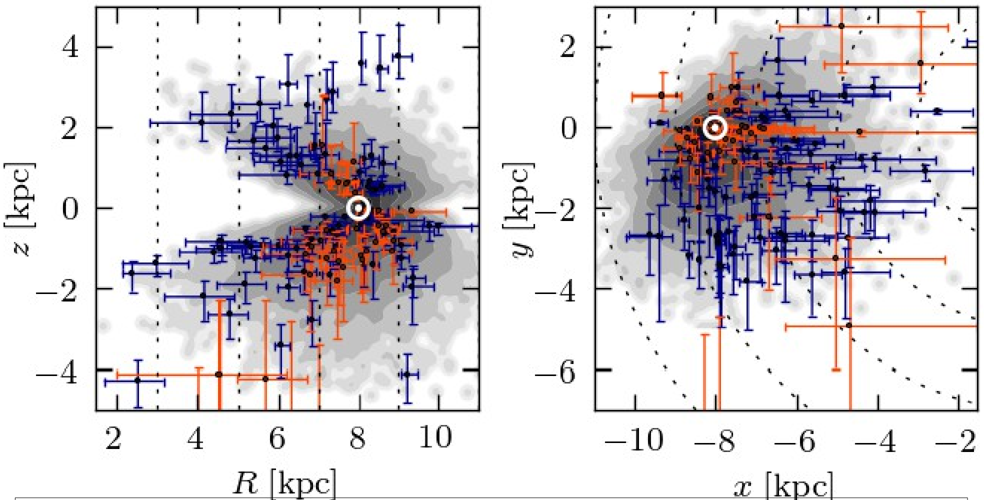
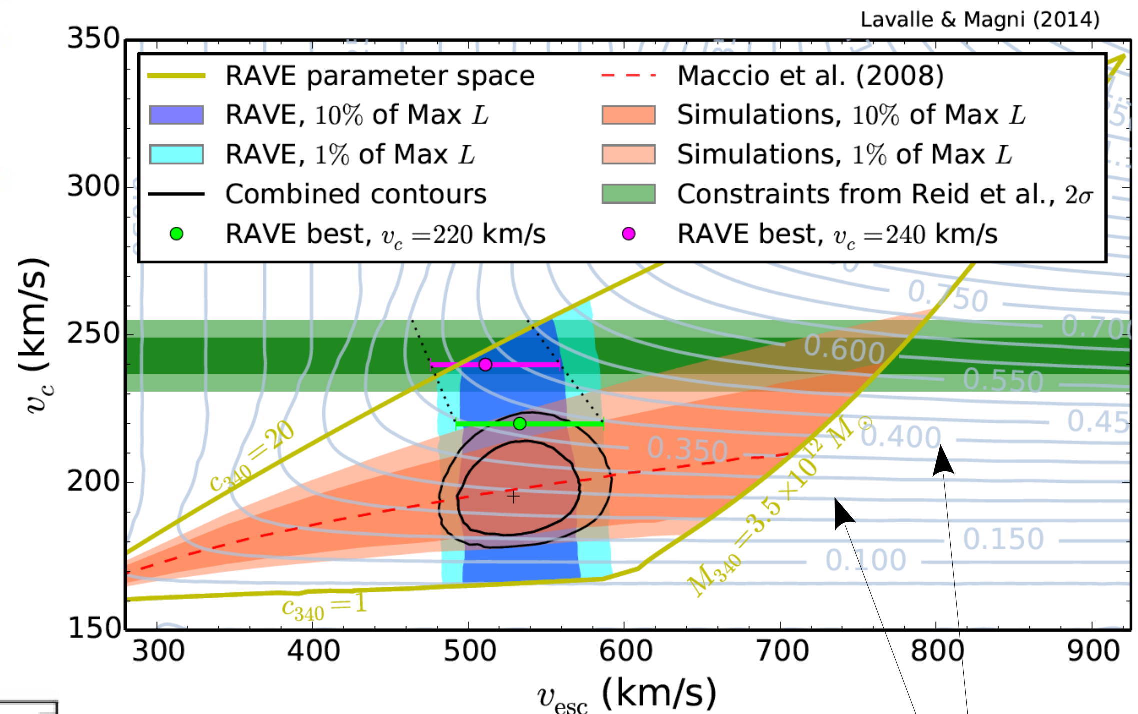
Billard+ 13



Beware astrophysical assumptions!

Piffl+14





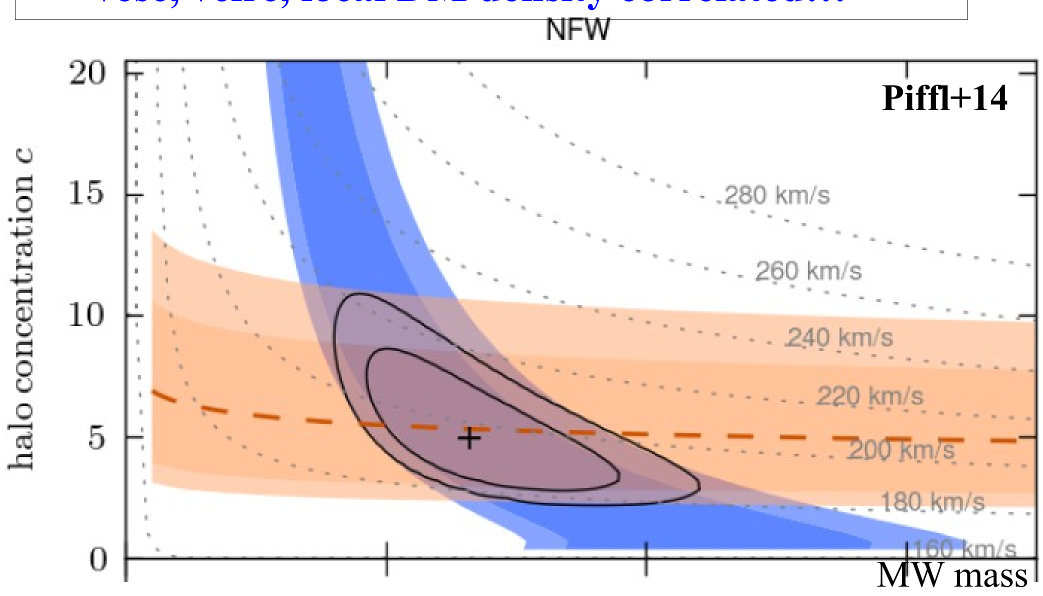
Quoted **escape speeds are from RAVE** survey (Smith+07, Piffl+14)

* v-tail of non-corotating stars (not in the disk)

* Galactic mass model assumed to "relocate" at solar position

=> vesc, vcirc, local DM density correlated!!!

Iso-density curves



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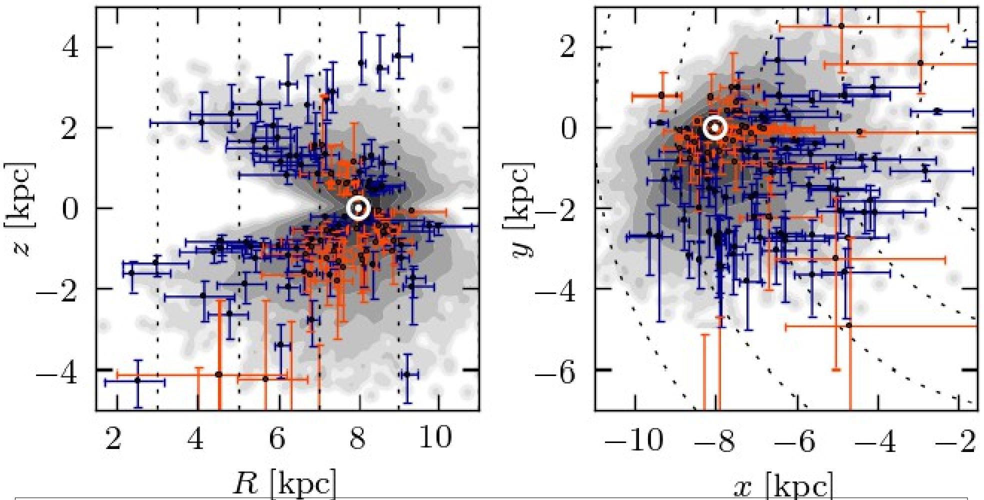

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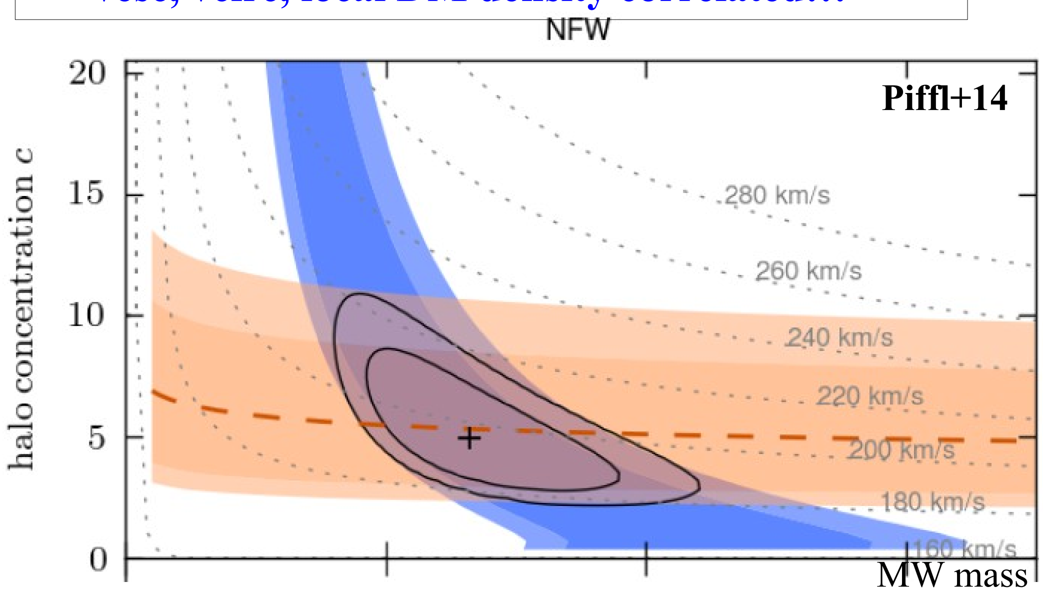
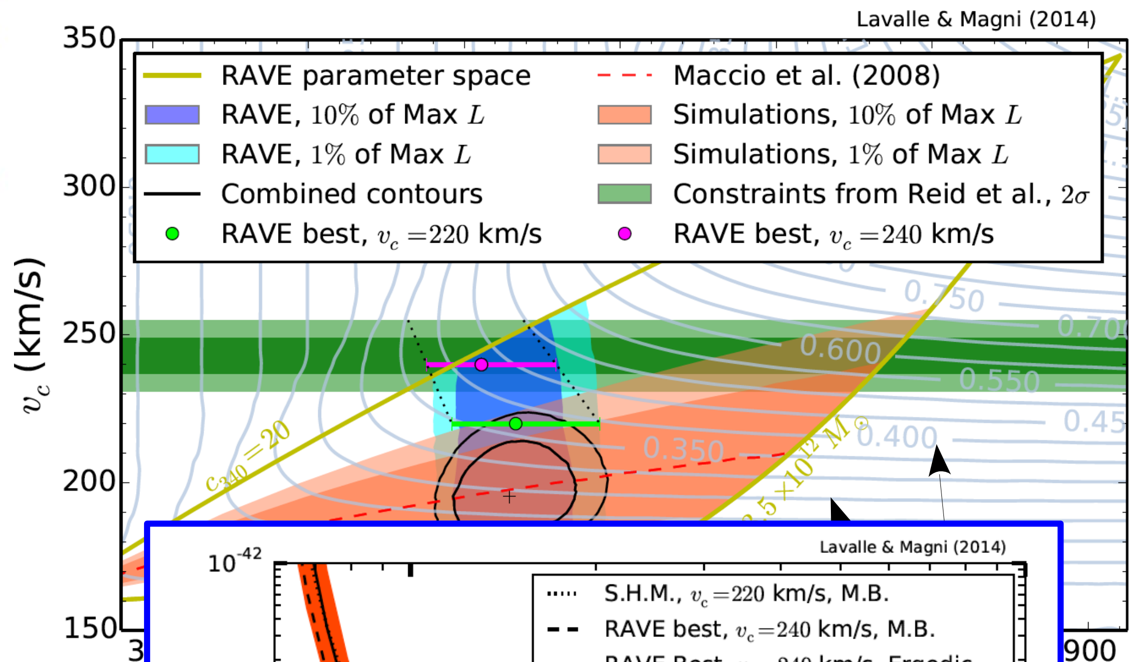
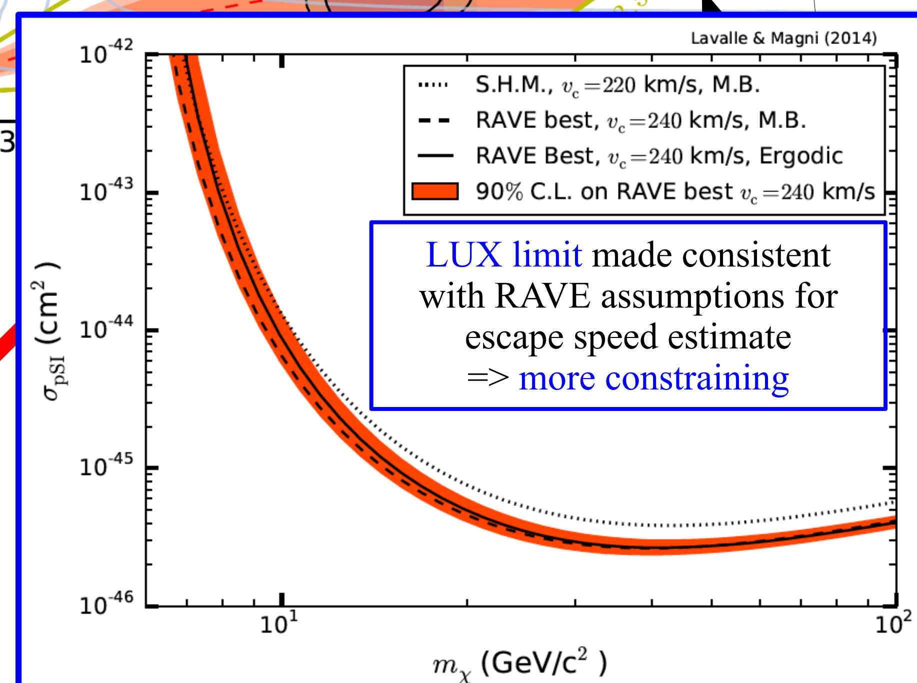
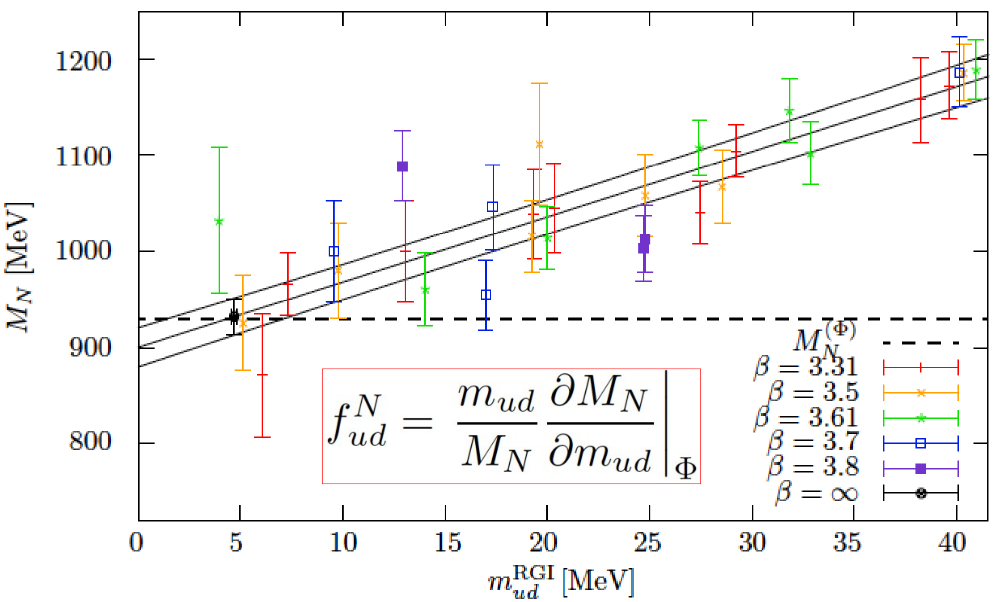
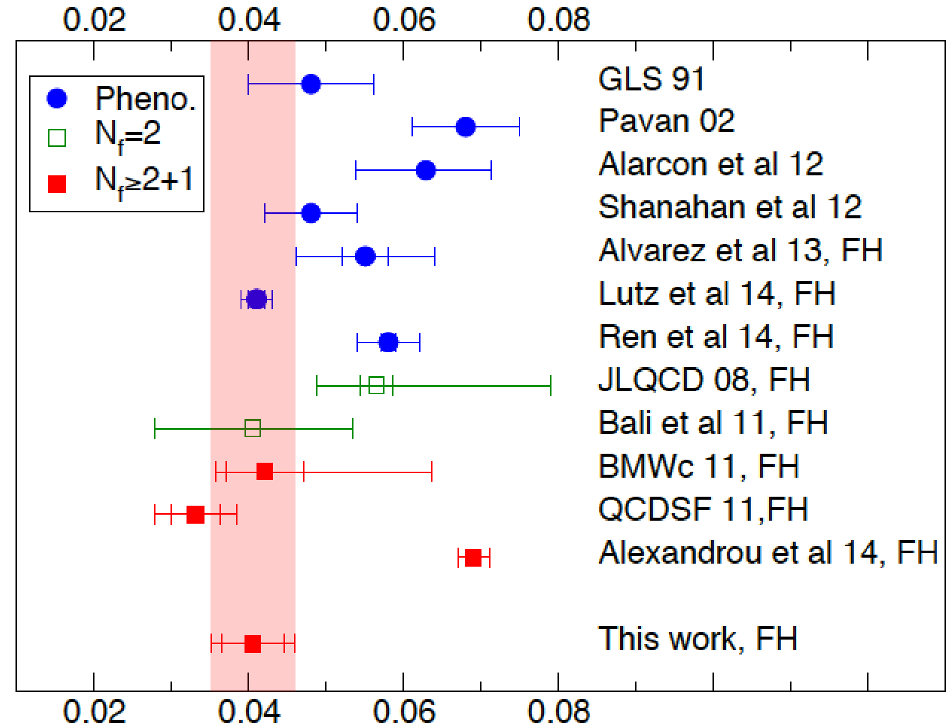




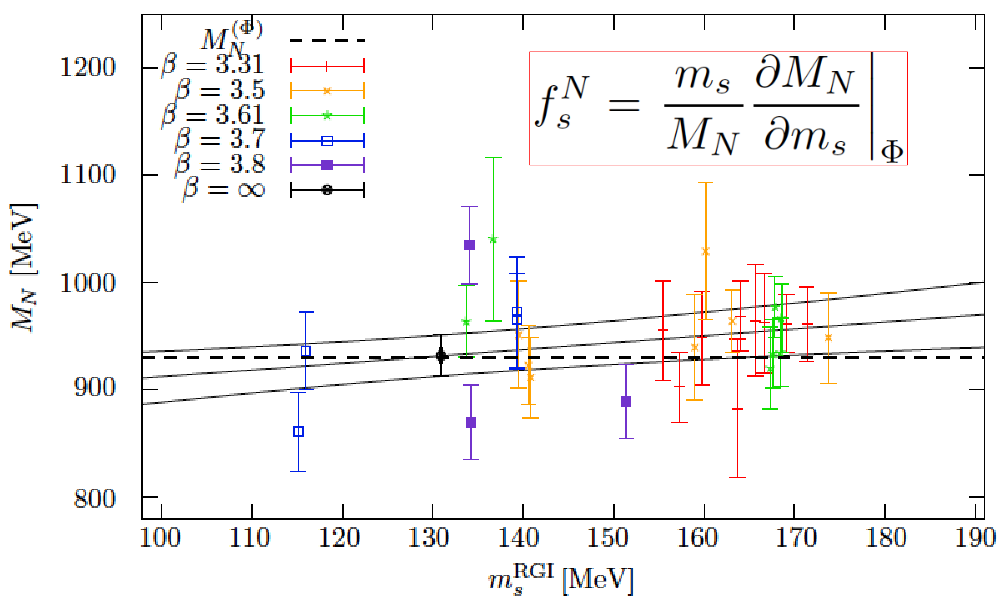


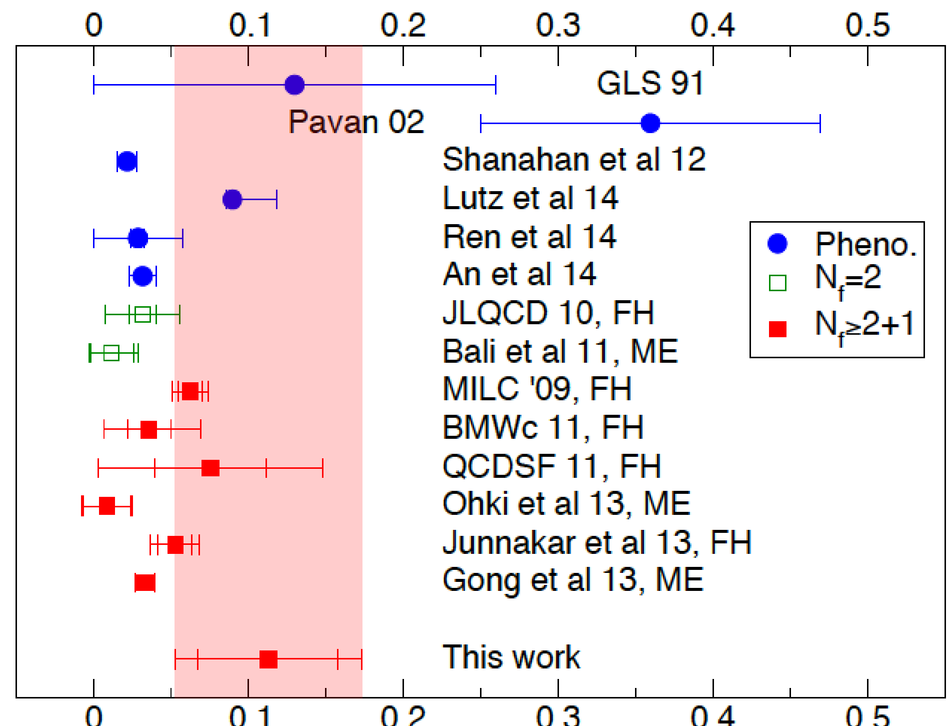
Direct detection on the Lattice: sigma term



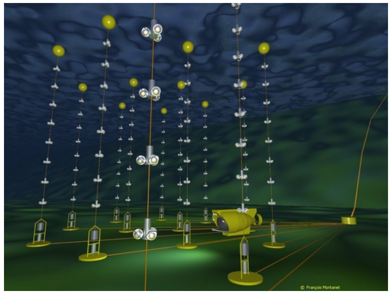


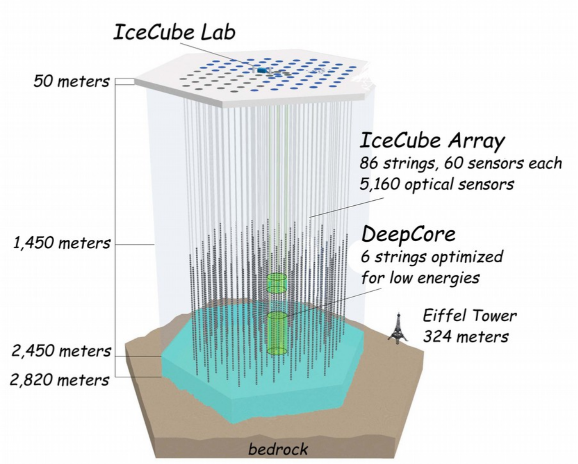
BMW collaboration arXiv:1510.08013
(incl. L. Lellouch & C. Torrero, CPT-Marseille)



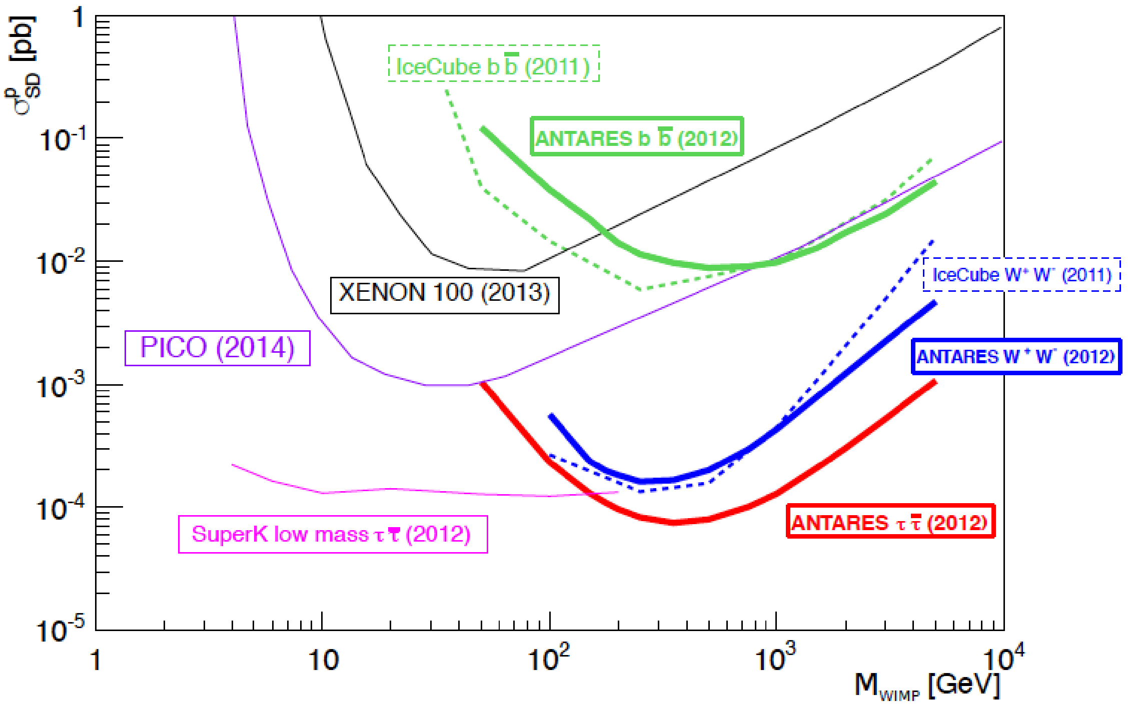


Complementary to direct detection: neutrinos from the Sun

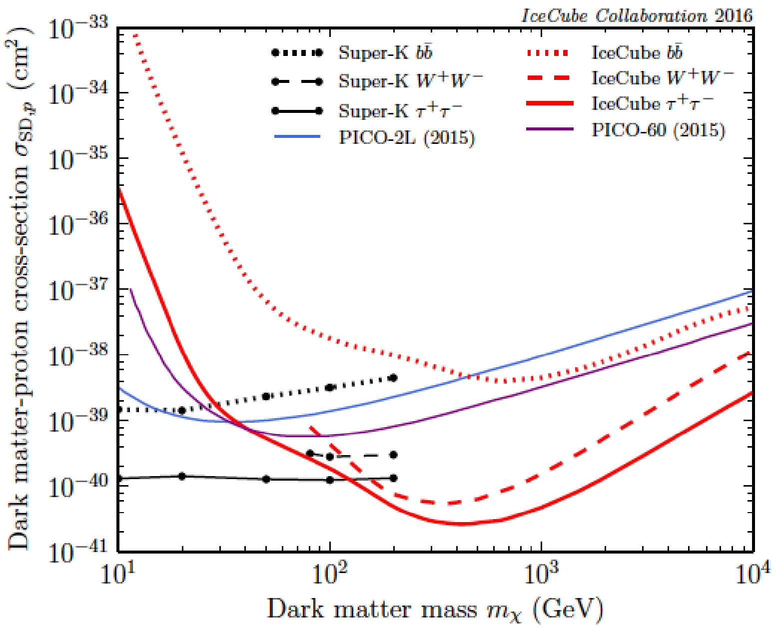




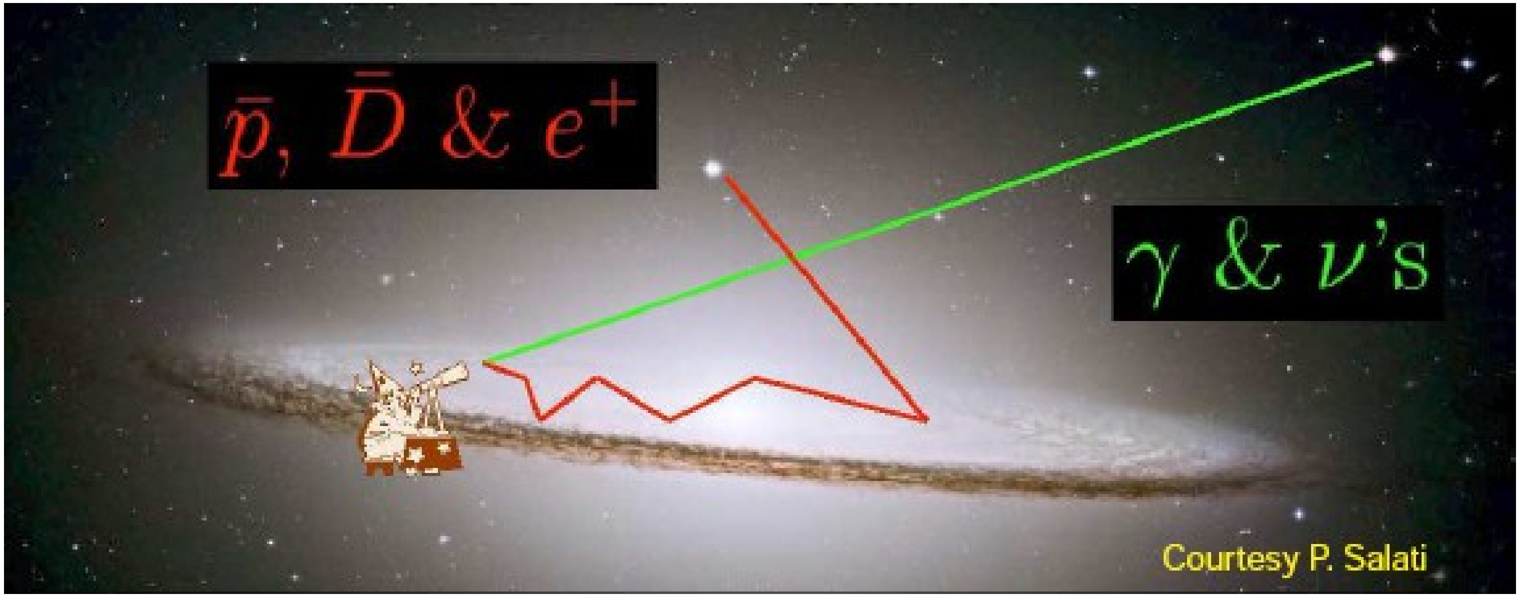
Antares Collab. 2015



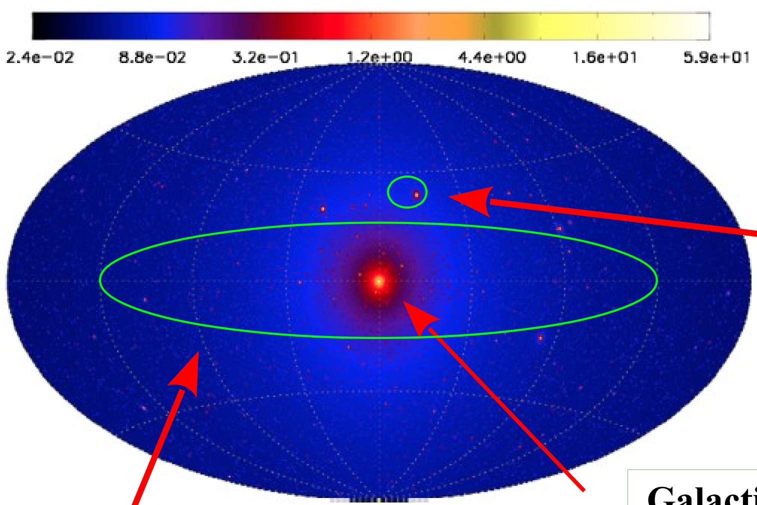
Icecube Collab. 2016



Up to the skies!



Pieri, JL+ 11



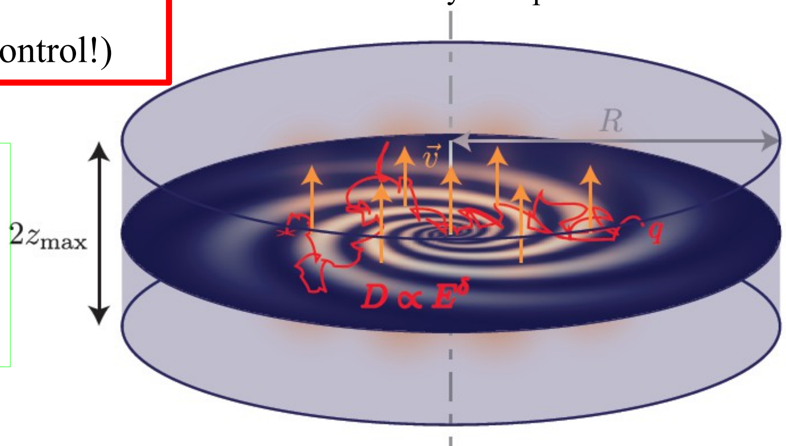
Best cases:
* clean spectral signature (e.g. lines)
* large S/B (and B under control!)

Big DM subhalos
* known **Dwarf Spheroidal Galaxies** (~20) – no other HE astrophysical processes expected there.

Galactic Center
* Closest/Largest expected annihilation rate
* **Large theoretical uncertainties (background not controlled)**

Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

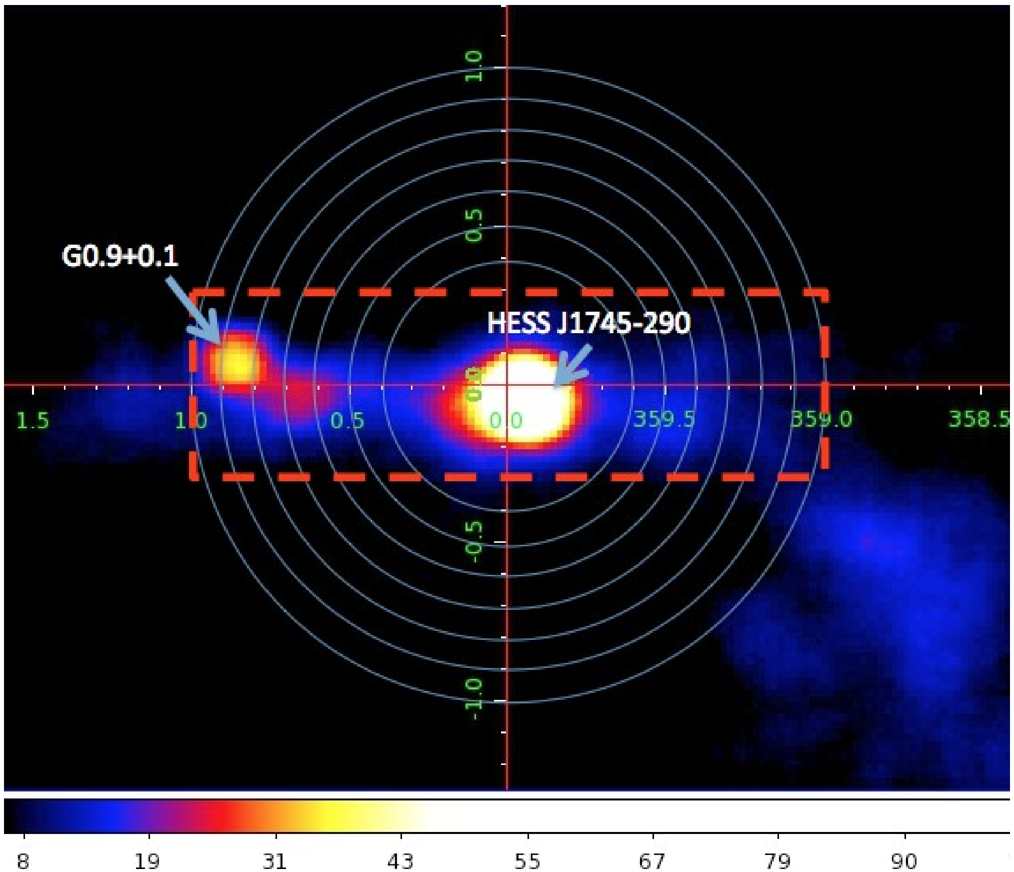
Cosmic-ray transport

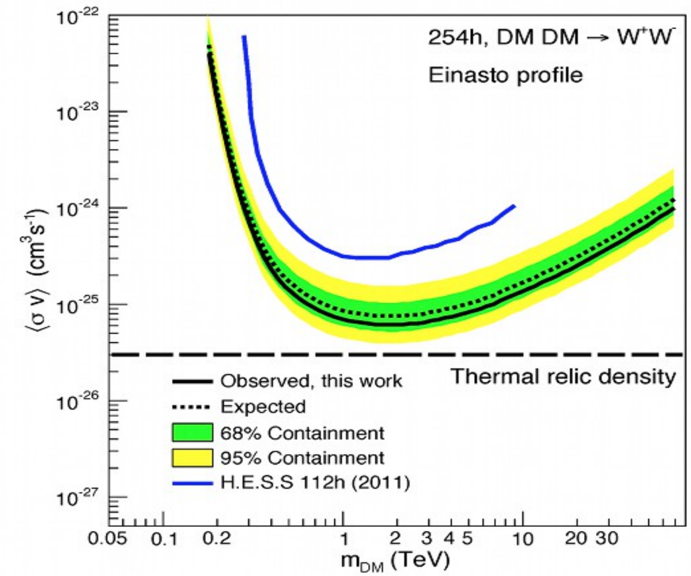


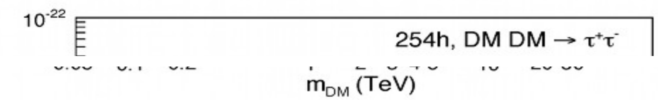
Mertsch PhD thesis 10

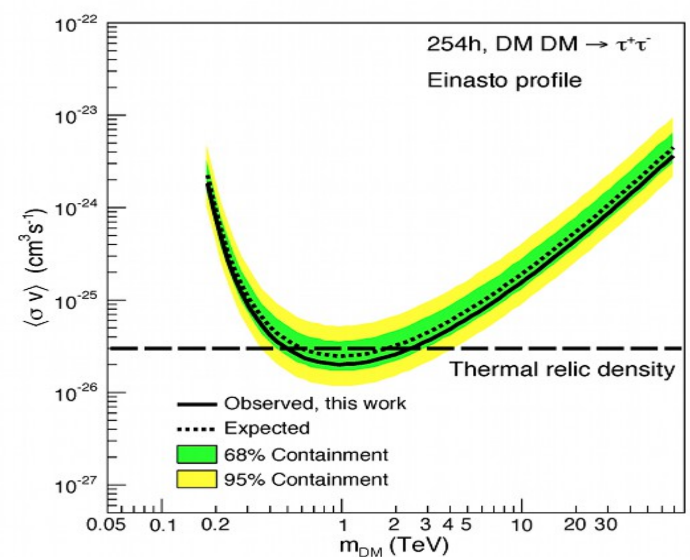
HESS

HESS Collab. to appear



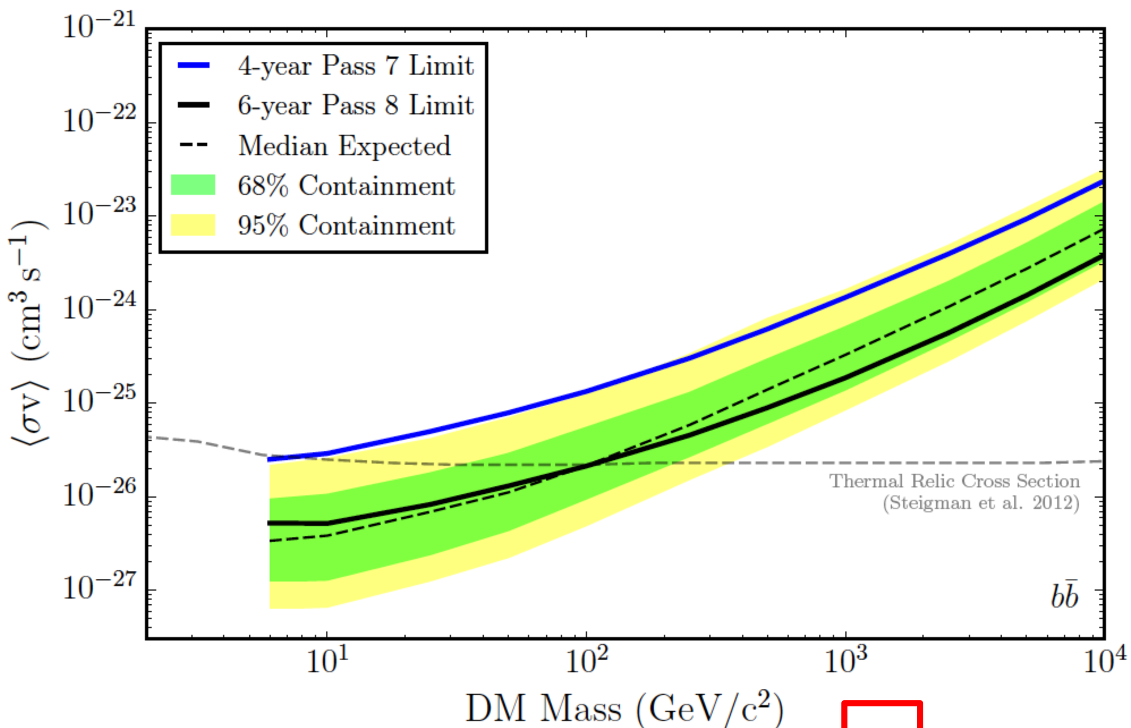






=> CTA instrumental in the TeV mass scale in the future

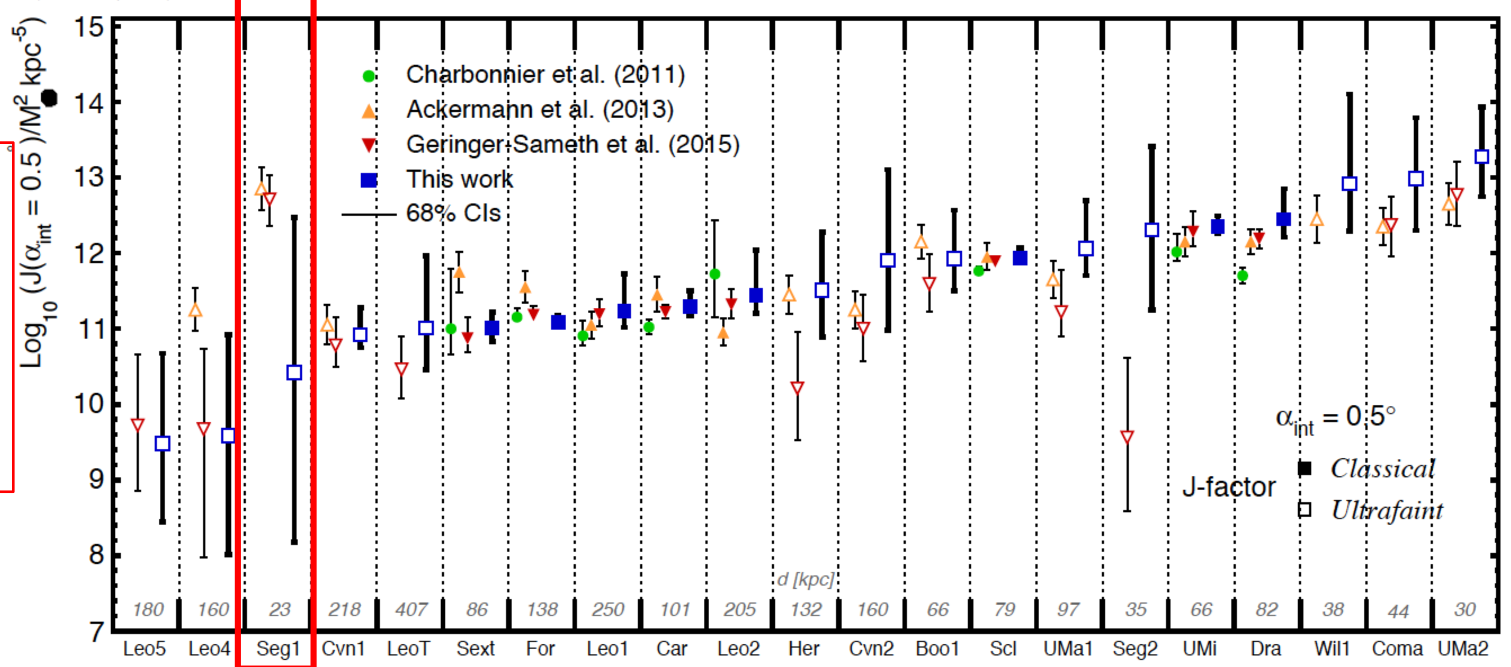
Satellite dwarf galaxies with Fermi



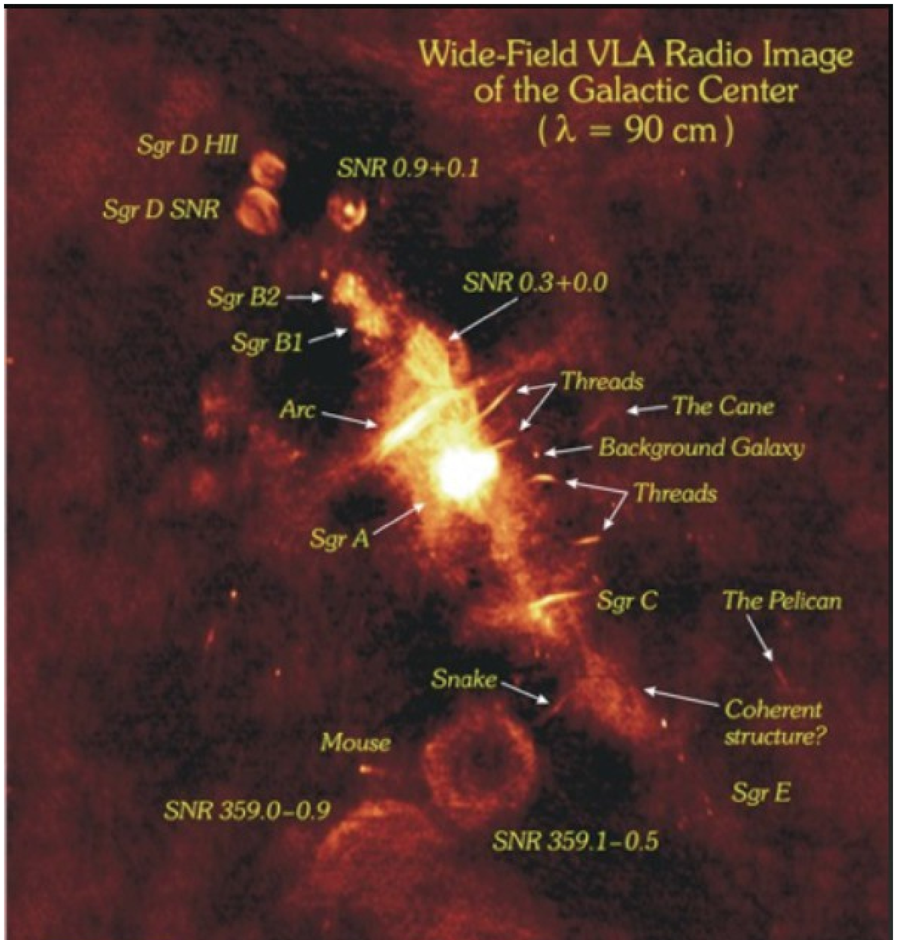
Fermi Collab. 15:
* 15 satellite DSphG – stacked
* 6 yrs of data, PASS8 reconstruction
=> improved limit
=> start probing 100 GeV mass range!
=> DSphG population not complete (more with DES, LSST, etc.)

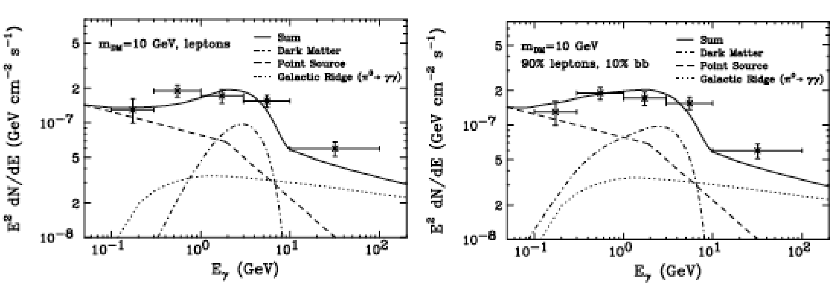
New kinematic study, including non-spherical halo + updated limits in Hayashi+ 16 (not shown here)

Bonnivard+15
→ Individual J-factors+errors:
* Careful Jeans analysis from velocity dispersion measures
* Systematics from mock data
=> Segue I overestimated
=> Fermi limit likely affected



Galactic Center anomaly? (not the 511 keV)





Hooper, Linden+12-15

GC = very complicated region
→ star formation, molecular clouds, etc.

Is background under control? NO
→ Excess wrt what? → very sensitive to change in bg!!!

→ CR modeling too limited (steady state)
→ source distribution unknown (MSPs + other CR sources)
→ gas distribution very partially known

It should not come as a surprise that standard astrophysics plays a significant role there.

e.g. Carlson & Profumo 15: H2 + sources tracking H2
+ Carlson, Linden+, e.g. 1510.04698

Appears that we may have been premature in arguing that cosmic-ray emission can't spectrally reproduce the excess.

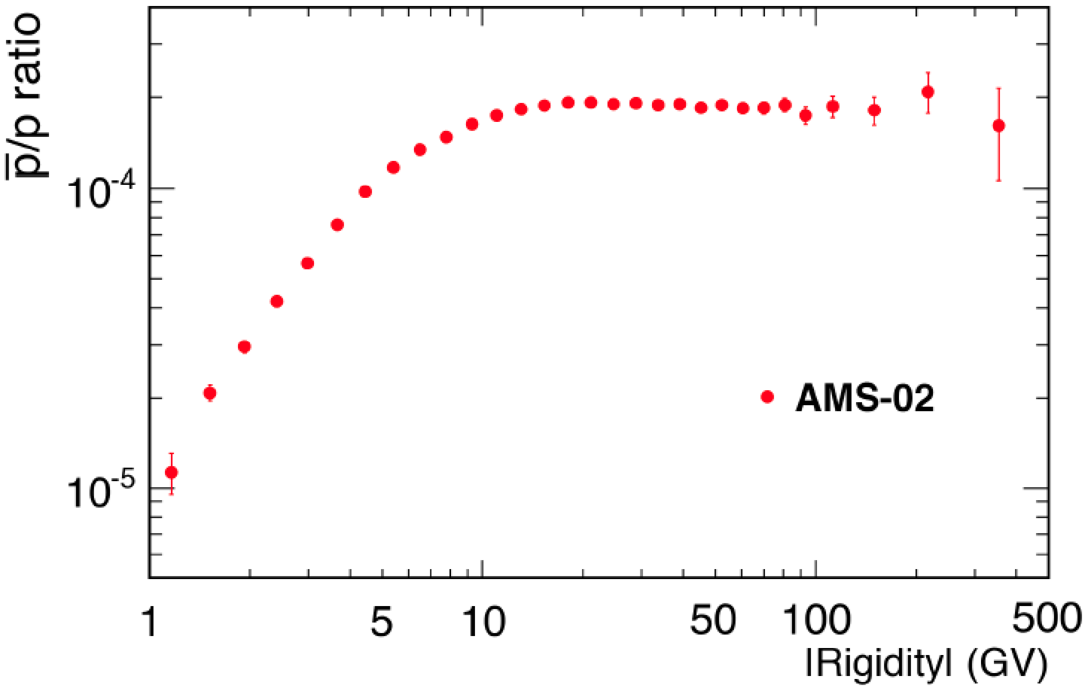
Tim Linden @ Gamma rays and dark matter (Austria), 12/2015

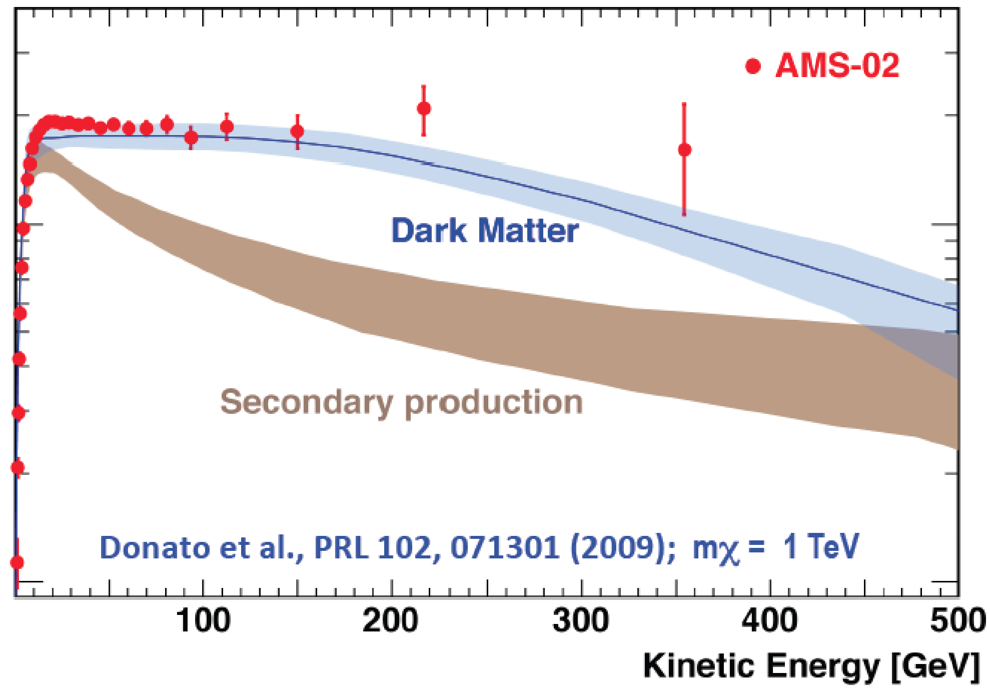
The Cosmic-Ray Saga

Standard astrophysical phenomena can explain these data

Don't underestimate the power of the dark sector

Antiprotons by AMS-02

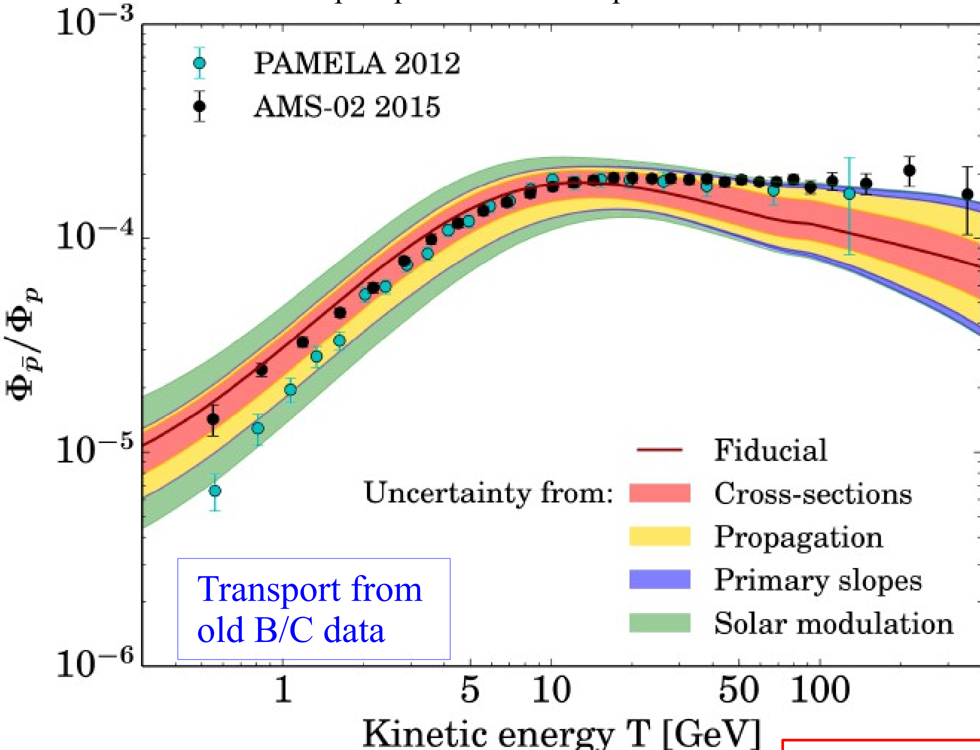




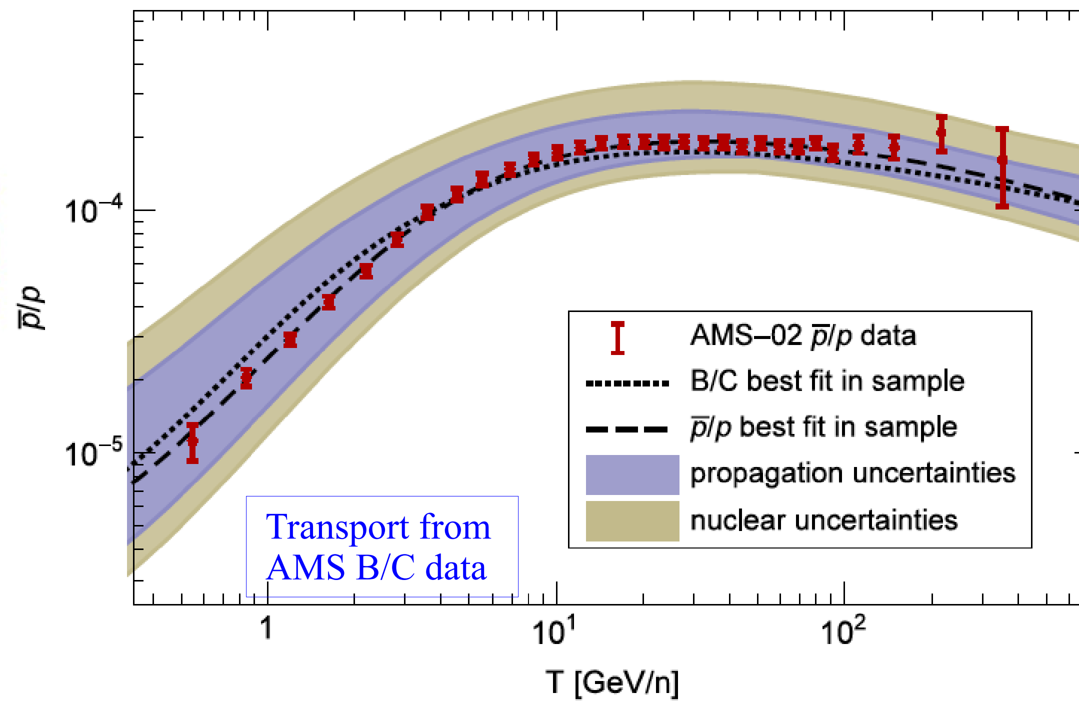
AMS-02: Kounine @ AMS days, CERN, 04/2015

Predictions for secondaries?

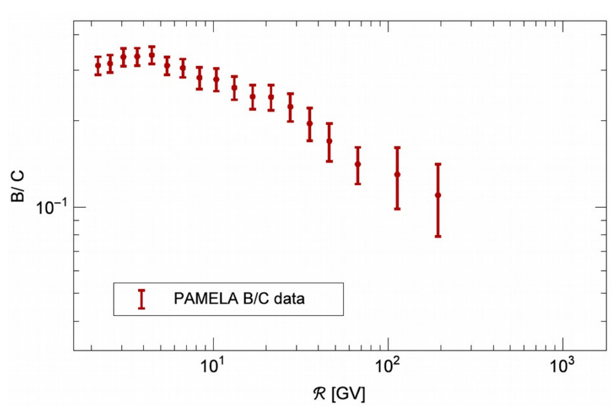
Giesen, Boudaud+15 (USINE)
Transport parameters from pre-AMS02 B/C data

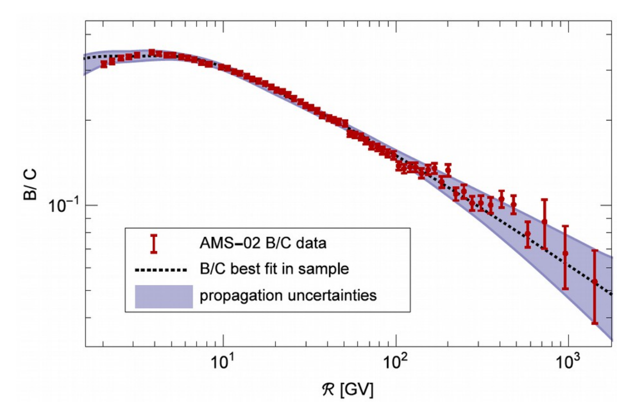


Kappl, Reinert & Winkler 15
Transport parameters from prelim. B/C AMS-02



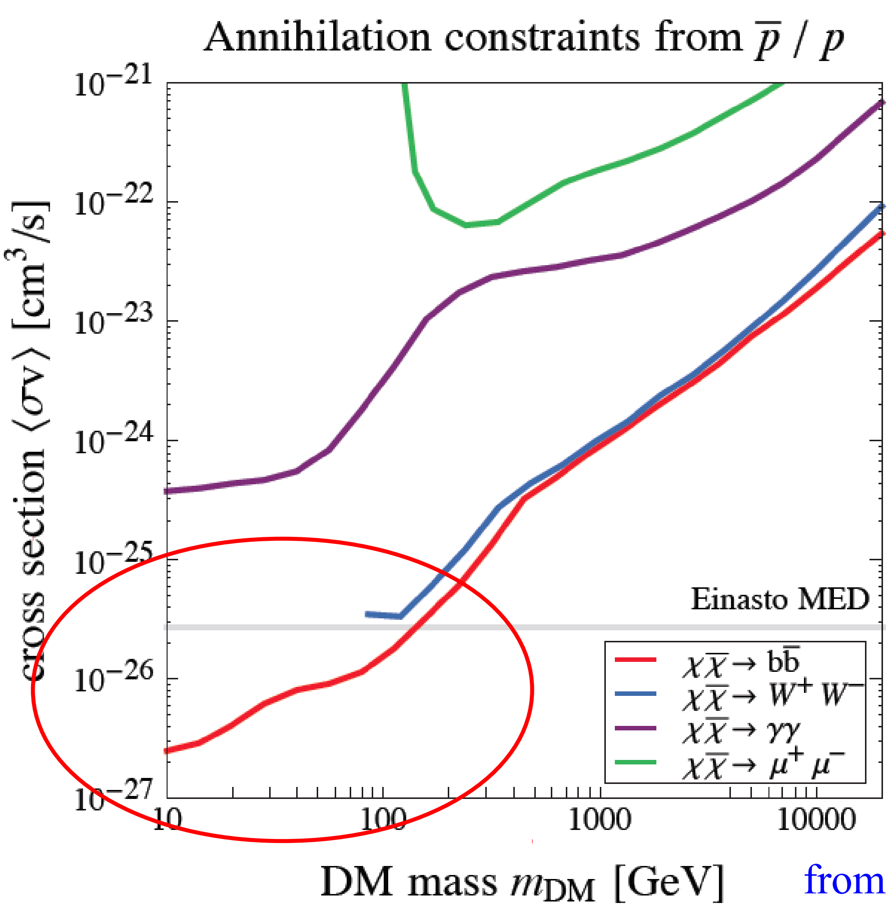
Consistent with secondary antiprotons

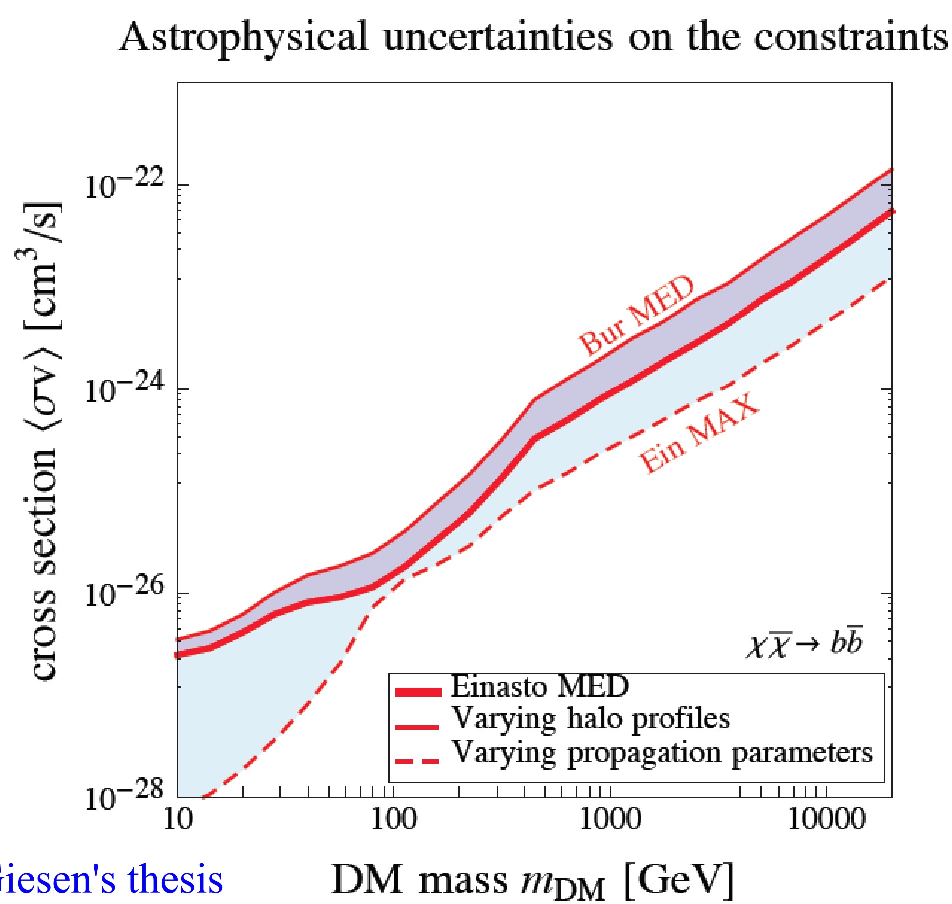




Antiproton constraints on WIMPs

M. Boudaud, G. Giesen+15

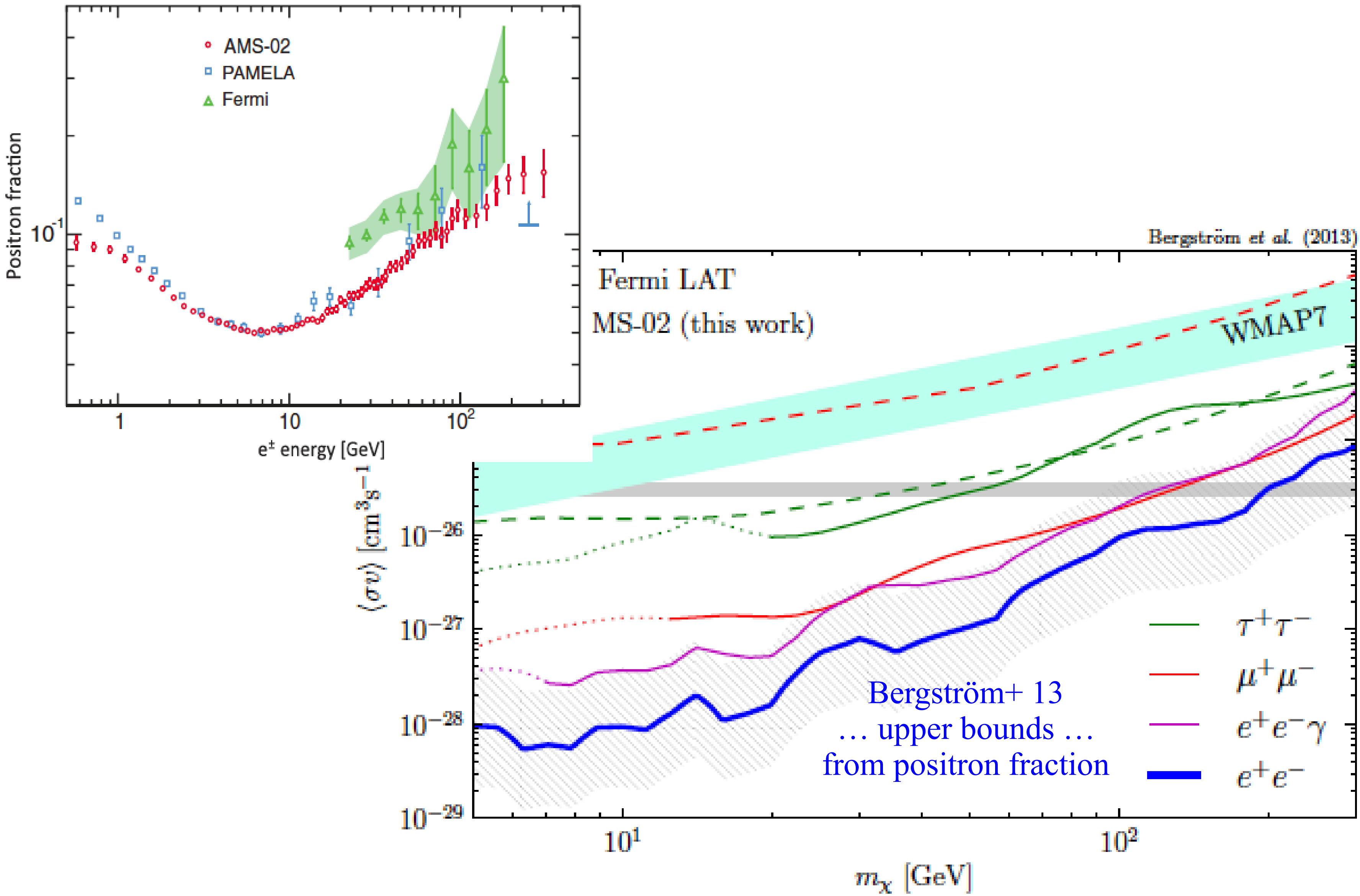




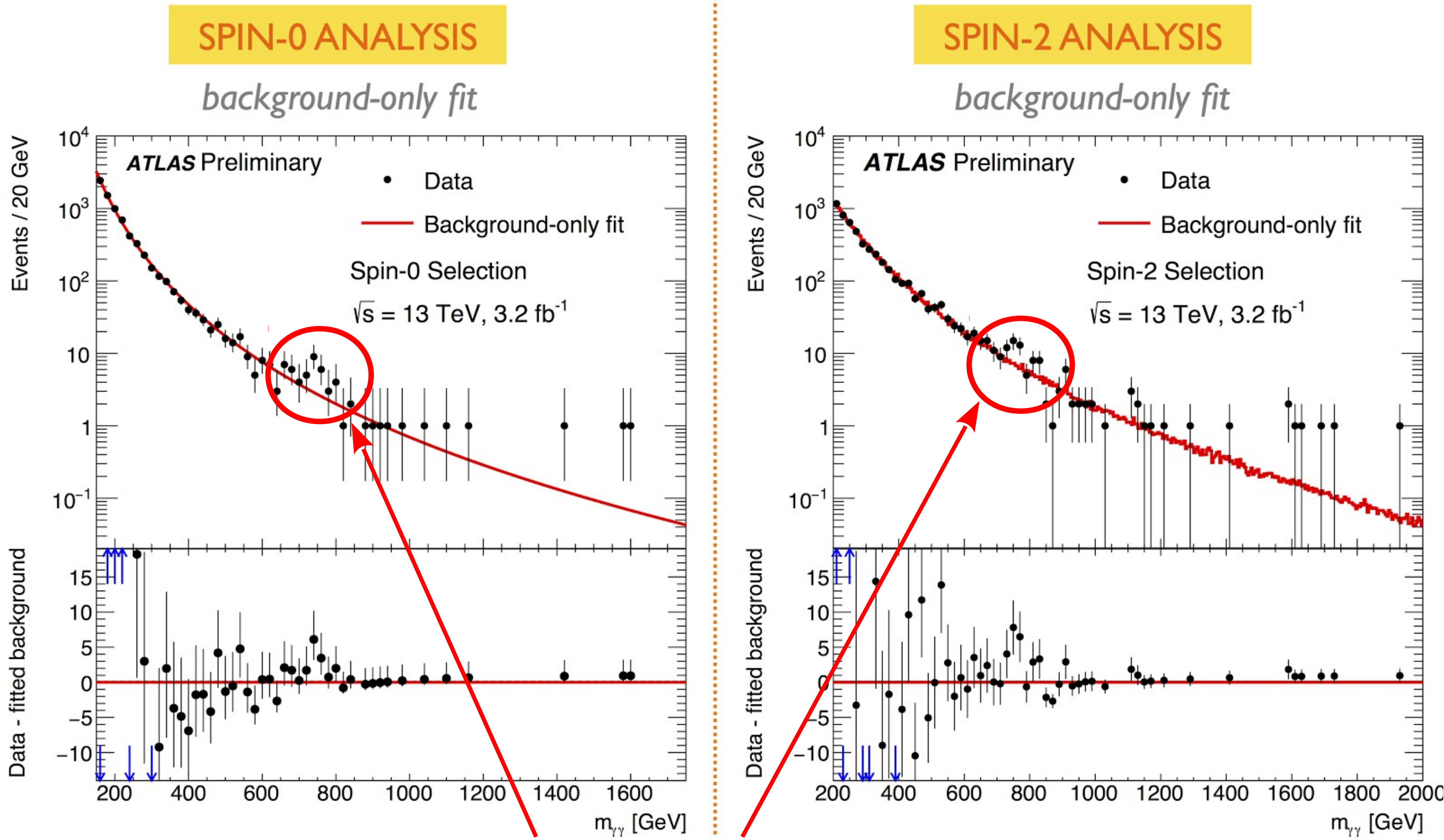
from G. Giesen's thesis

No much room left to play with CR transport parameters:
→ diffusion halo size > 3 kpc (see A. Putze)
+ moderate effect of halo shape

Positron constraints on WIMPs

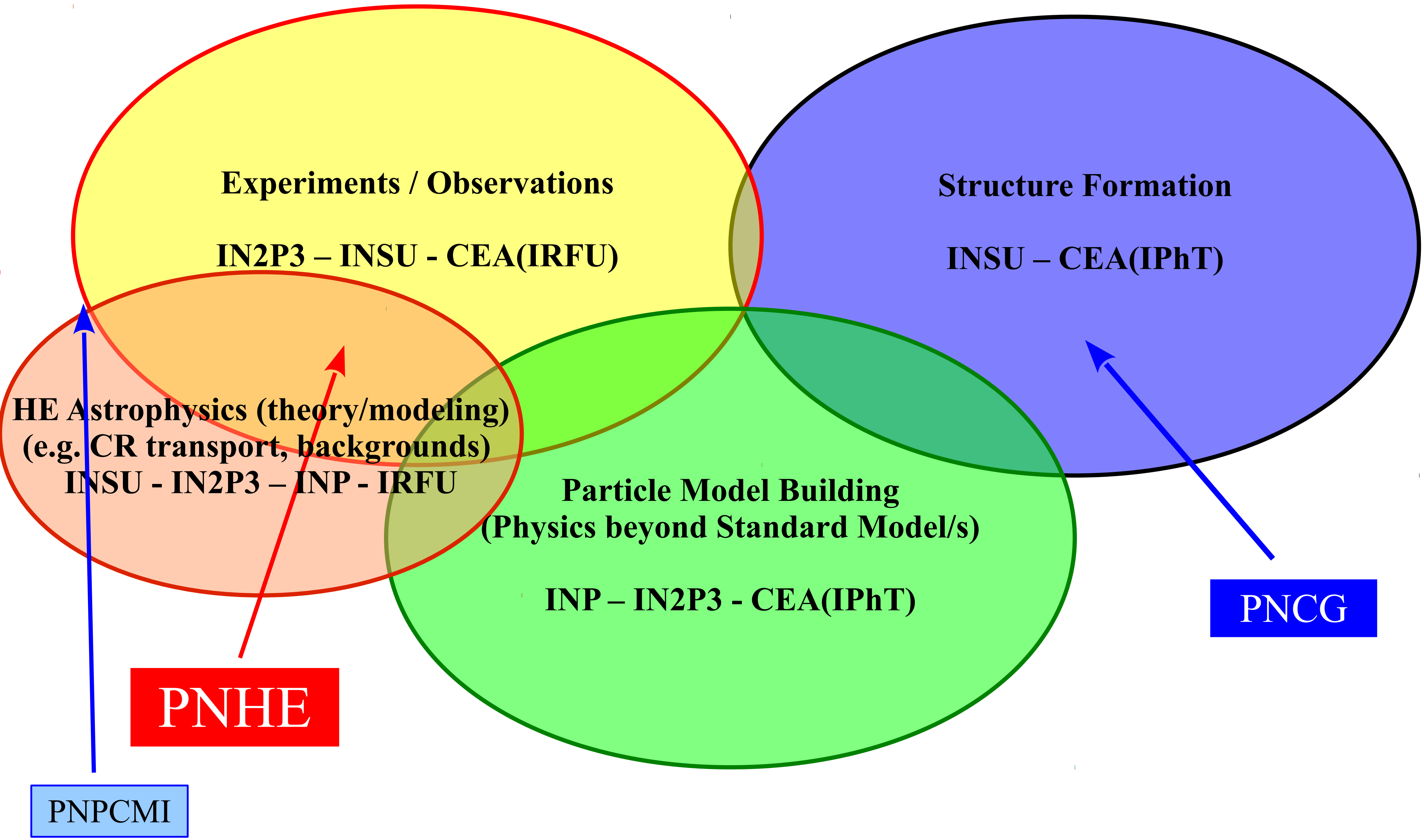


In the meantime at LHC



A new **resonance** at **750 GeV**??? (also seen in CMS)
→ First big hint of new physics??? (answer by summer 2016)

Organization of tasks in France (the broad picture)



Census

(people working on DM with potential links with PNHE)

IN2P3:

* Th/pheno/mod.: LPC-Clermont, LPSC-Grenoble, LUPM-Montpellier, IPNL-Lyon
* Obs-exp: CPPM-Marseille, LAPP-Annecy, LPC-Clermont, LPNHE-Paris, LPSC-Grenoble, LUPM-Montpellier

→ AMS-02, Antares-km3, Fermi-LAT, HESS-CTA

* Exp. direct detection: APC-Paris, CSNSM-Orsay, IPNL-Lyon, LPSC-Grenoble, Subatech-Nantes

→ Edelweiss, Xenon, DarkSide + projects

INP:

* (Th/pheno/mod.): LAPTh-Annecy, L2C-Montpellier, LPTHE-Paris, LPT-Orsay
* Exp. direct detection: Néel Institute Grenoble, LPN-Marcoussis

→ Edelweiss, Super-CDMS

INSU:

* (Th/pheno/mod.): CRAL-Lyon, IAP-Paris, LAM-Marseille
* Obs-exp: IRAP

→ Fermi-LAT, (Integral)

* Exp. direct detection: LSBB-Apt

→ SIMPLE

CEA:

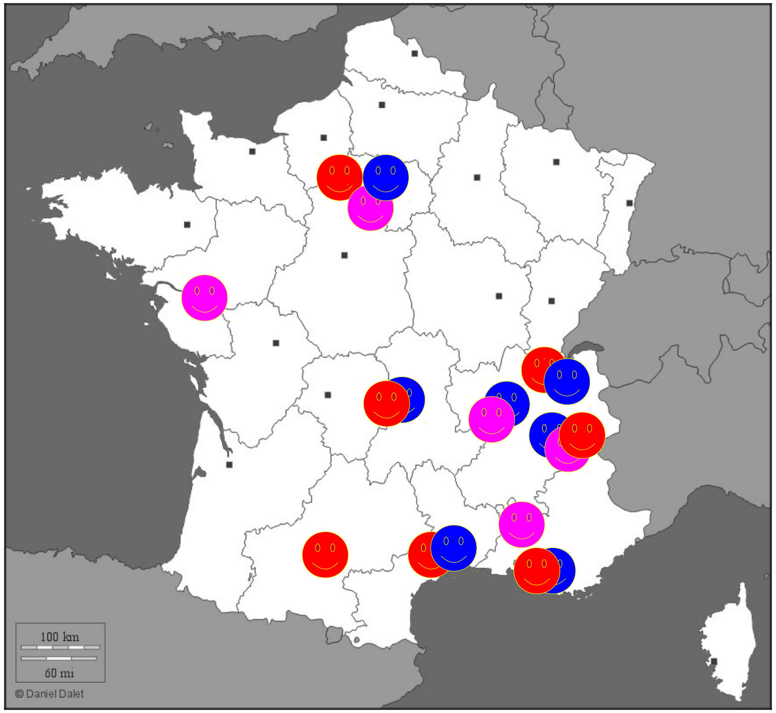
* Th/pheno/mod.: IPhT (main group has moved to LPTHE)
* Obs-exp: IRFU

→ HESS-CTA, IAXO

* Exp. direct detection: IRFU

→ Edelweiss + projects

NB: most requests to PNHE related to DM have come from
→ Annecy/Grenoble/Marseille/Montpellier/Paris (~ 15 people)



Near future + role of PNHE

Prospects:

*** **Experiments!**

* **WIMPs: (now or not)**

→ Follow up of AMS-02, Fermi-LAT (dwarf galaxies) + HESS2 (GC), waiting for CTA (GC + lines).

→ 2016-2017 **LHC results will be crucial for BSM physics at the TeV scale** (WIMPs concerned)

→ Direct detection: XENON 1t in commissioning phase (start operation in 2016)

* **Sterile neutrinos:**

→ 3.5 keV line under scrutiny: next X-ray satellite? (Astro-H dead?)

* **Axion-like particles or dark photons**

→ Indirect from TeV emission from blazars on-going (DM parameter space out of reach)

→ Dedicated searches: cavities + dish antennae (local DM); helioscopes (any axions including DM); etc.

*** Pheno todo list (except for new ideas + not exhaustive)

→ Constrain the (phase-space) distribution of DM in the MW (and satellites): dynamical studies (e.g. from Gaia data) + structure formation, impact of substructures => links with PNCG

→ Astrophysical backgrounds (diffuse emission, CR transport, astro source distribution, etc.) => related to core of PNHE activities, not necessarily involving DM scientists.

→ multi-messengers + complementarity indirect/direct/colliders/others + complementarity PNHE/PNCG

PNHE resources until 2016:

* workshops/meetings/conferences (not necessarily only focused on DM)

* small collaborations (a few people)

* cheap R&D (e.g. axion searches)

Pros and cons (from the DM scientist viewpoint):

+++ yearly call: allows for anticipation

+++ success rate rather high

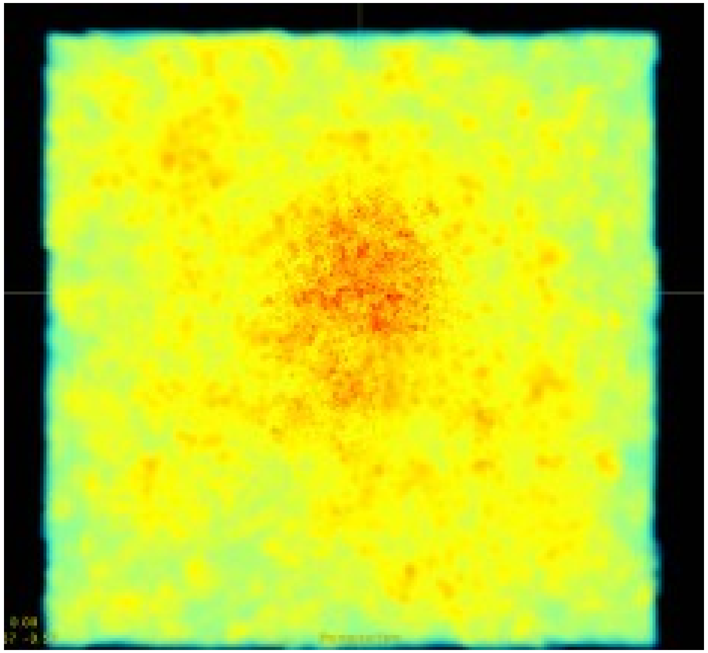
--- Moderate amount of money wrt to form content / competition with labexes

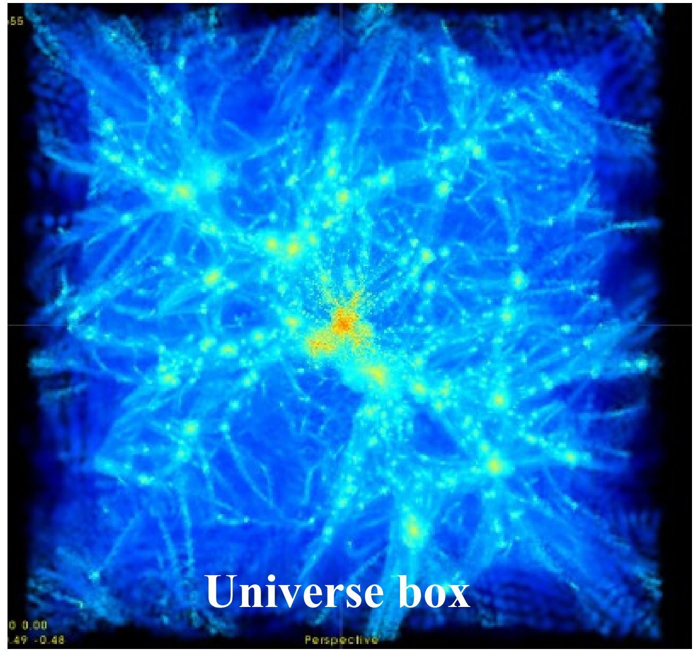
--- French DM community rather small and spread => a very few proposals

=> PNHE can play a role in structuring the HE-astro-connected community at the national level

BACKUP

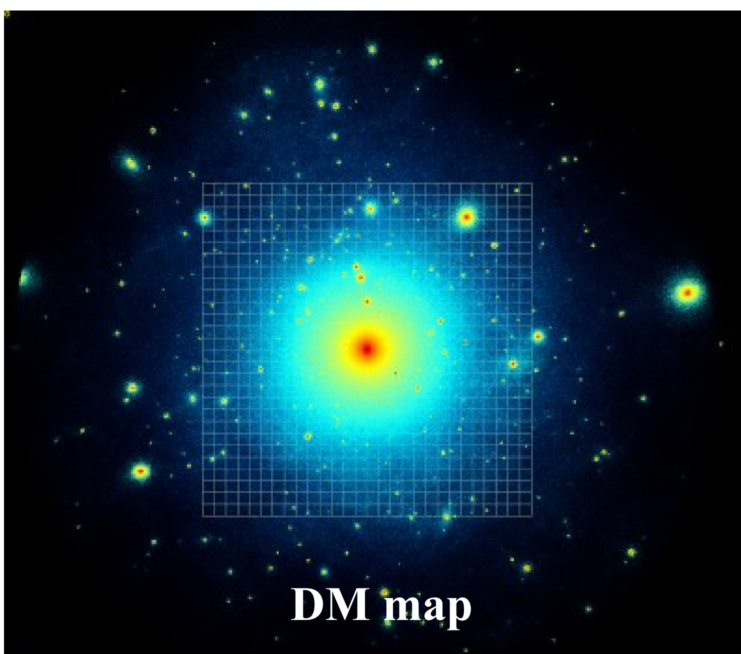
DM studies from cosmological simulations

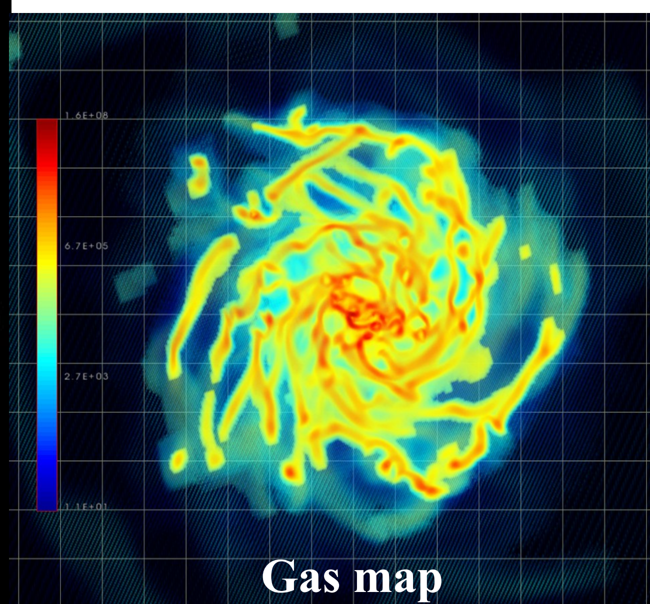


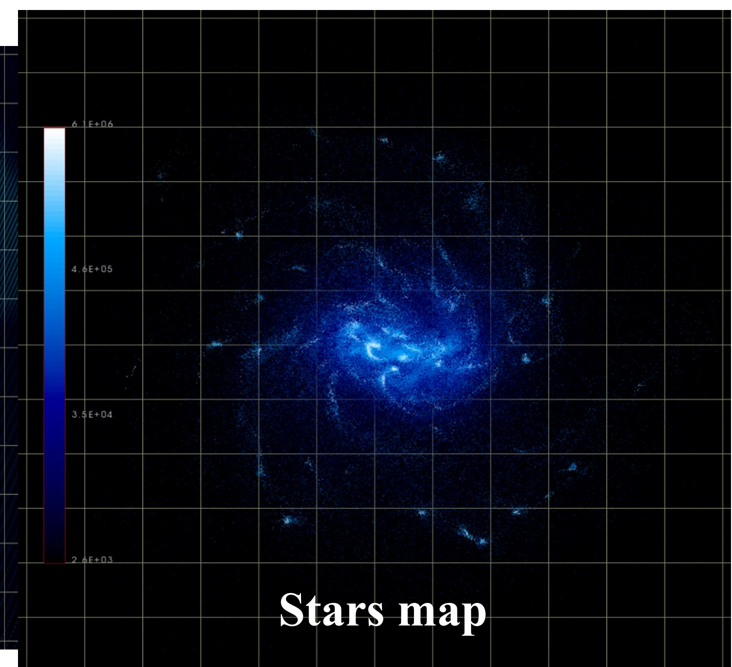


Mollitor et al (MNRAS, 2015)
→ 3 MW-like galaxies
→ among the best resolutions achieved so far (150 pc)

→ being analyzed for DM searches

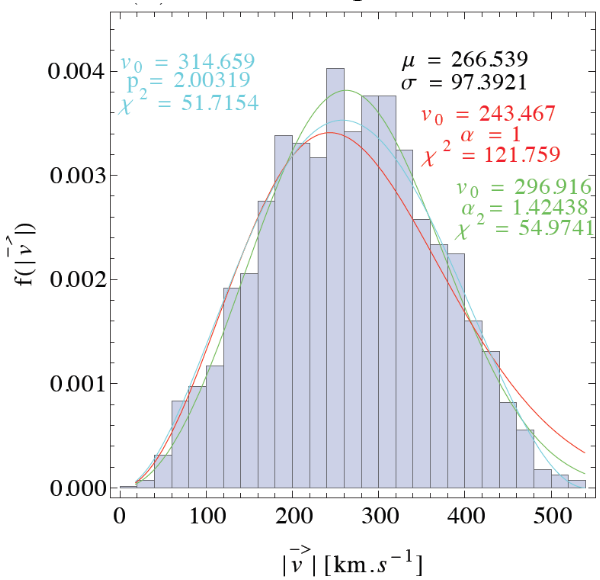






DM Phase space from cosmological simulations

DM speed



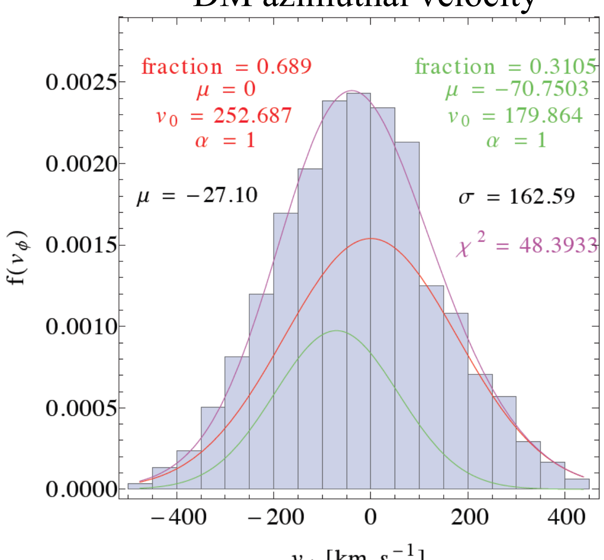
Direct DM detection studies:

* Study/understand DM velocity distribution
* Study/understand DM density evolution inside disk

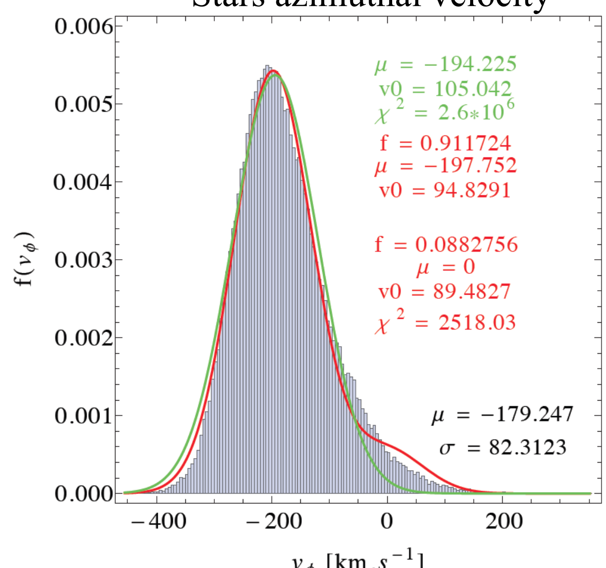
→ issue of dark disk

Ling+10, Nezri, Teyssier+14
JL, Nezri, Teyssier in prep

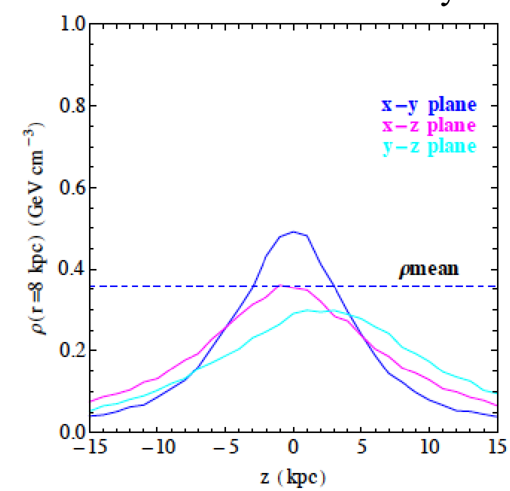
DM azimuthal velocity



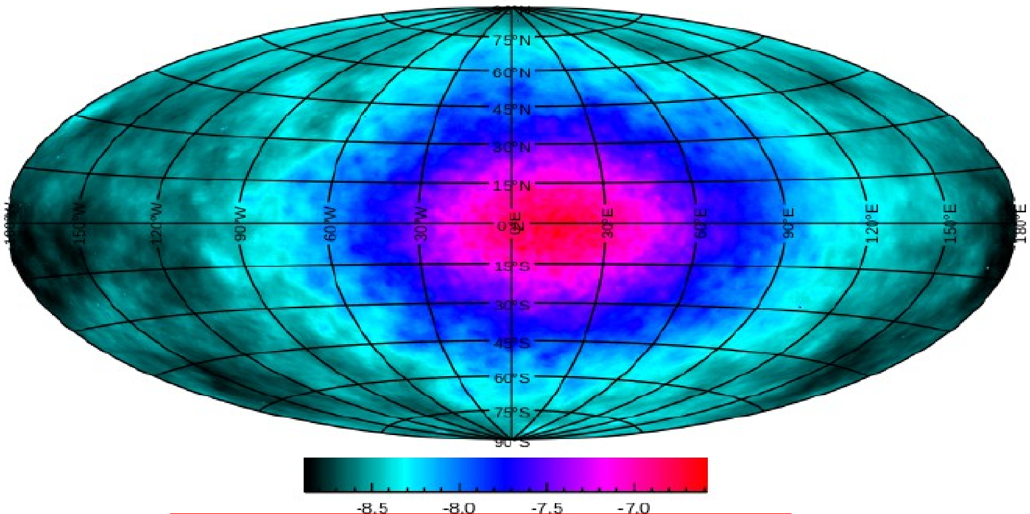
Stars azimuthal velocity



Dark disk overdensity



HE astrophysics in a virtual galaxy

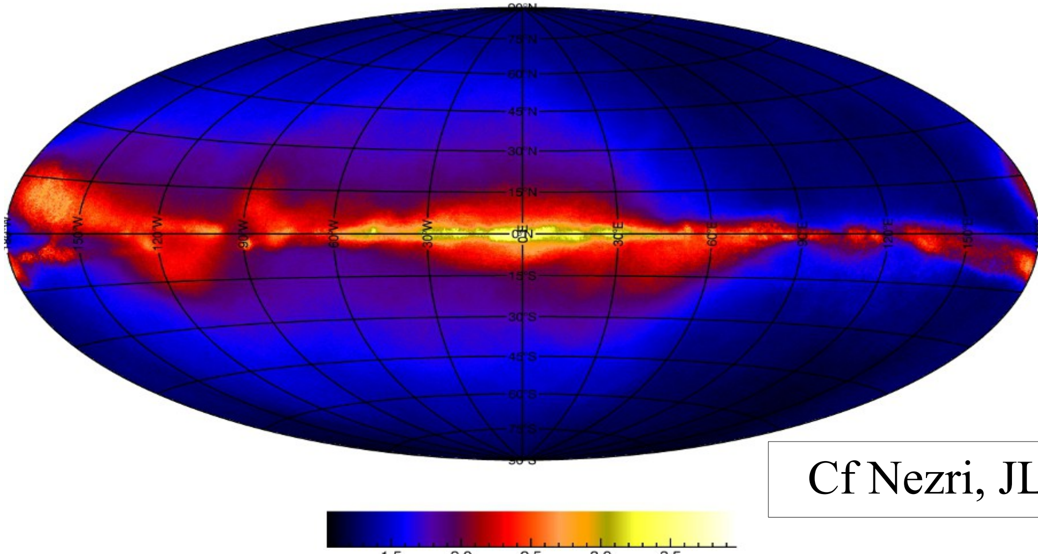


DM annihilation map (**sim**)

Indirect DM search studies (gamma rays):

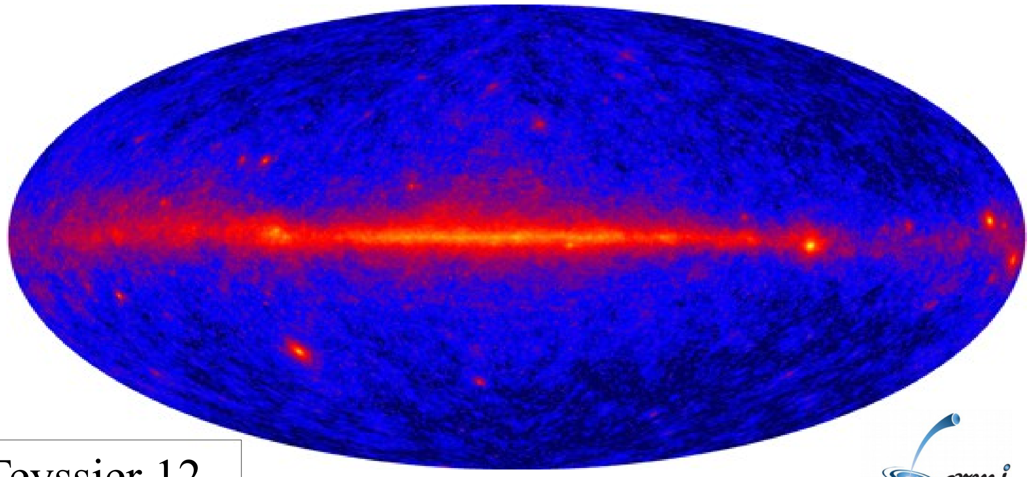
* develop/plug in cosmic-ray production + transport (supernovae + DM)
* focus on diffuse emission + galactic center

→ differences with real data (baryonic physics at the galactic center)
→ but check consistency of methodology used for real data analysis (e.g. background modeling from gas + CRs)



Diffuse gamma rays (**sim**)
(cosmic rays x baryonic gas)

Cf Nezri, JL, Teyssier 12



Fermi Gamma-ray Space Telescope

Diffuse gamma rays from Fermi observations (**real**)

Integrating astrophysics out?

Fox+11, Frandsen+12, Gondolo+12, Herrero-Garcia+12, etc.

* Event rate (for all DD experiments) proportional to

$$\tilde{\eta}(v_{\min}) = \sigma_p(\rho/m)\eta(v_{\min})$$

which contains all the astrophysics

* For a given DM particle mass, one can trade the recoil energy for the min speed

$$v_{\min} = \sqrt{\frac{m_{A,Z}E}{2\mu^2_{A,Z}}}$$

$$dE = (4\mu^2_{A,Z}/m_{A,Z})v_{\min}\,dv_{\min}$$

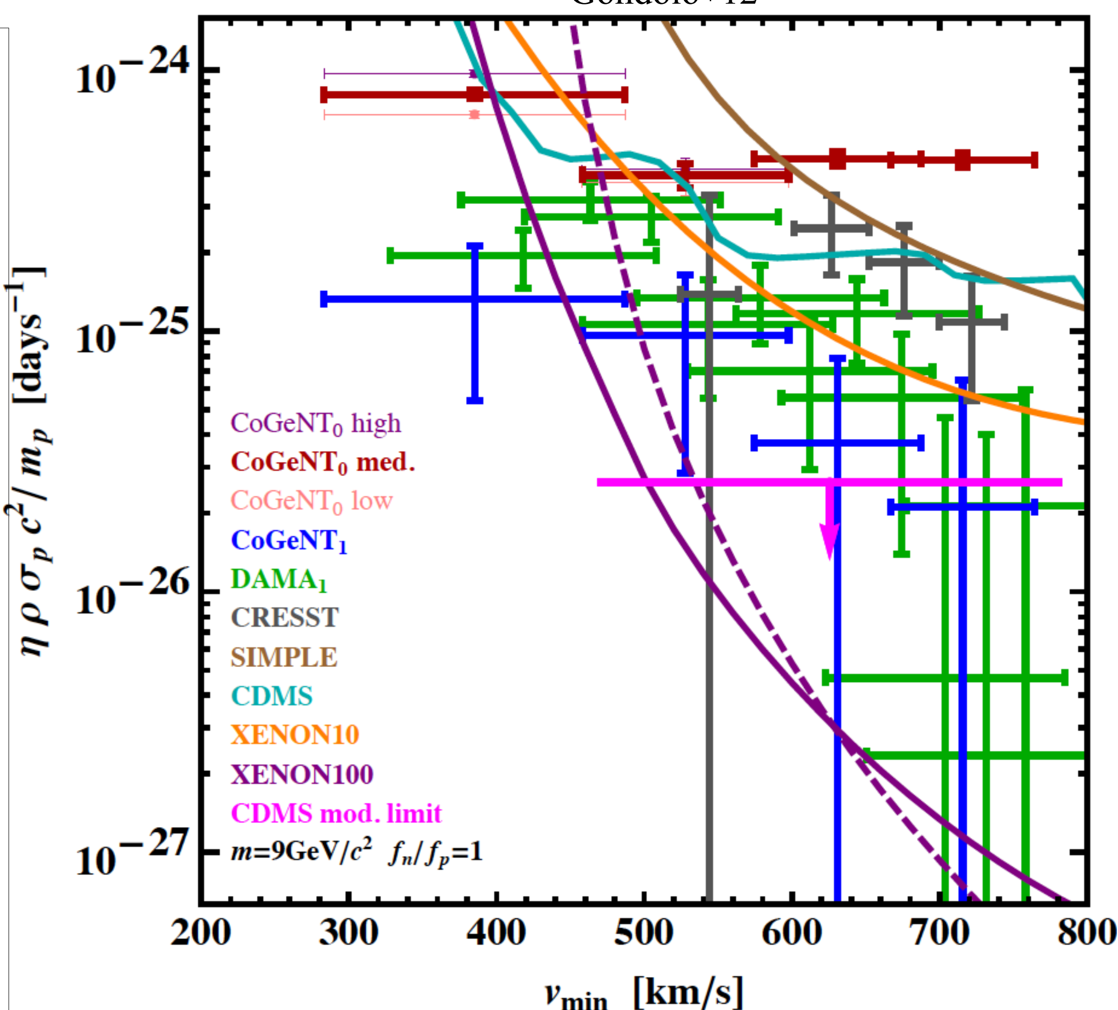
* The event rate in a bin can be recast as

$$R_{[E'_1,E'_2]} = \int_0^\infty dv_{\min}\,\mathcal{R}^{SI}_{[E'_1,E'_2]}(v_{\min})\,\tilde{\eta}(v_{\min})$$

=> For a given target nucleus, one can match an energy bin to a bin in min speed:

$$[E'_1, E'_2] \longrightarrow [v_{\min,1}, v_{\min,2}]$$

Gondolo+12



Check positive signals against limits for a given WIMP mass.
BUT ONLY FOR A GIVEN WIMP MASS

Integrating astrophysics out?

Ferrer, Ibarra, Wild – arXiv:150603386

*** Based on complementarity between DD and neutrino telescopes (WIMP capture in the Sun)

=> **Annihilating WIMPs only!!!**

* Expand f(v) over infinite set of DM streams

$$f(\vec{v}) = \int_{|\vec{v}_0| \le v_{\max}} d^3 v_0 \, \delta^{(3)}(\vec{v} - \vec{v}_0) f(\vec{v}_0)$$

$$R = \int_{|\vec{v}_0| \le v_{\max}} d^3 v_0 \, f(\vec{v}_0) \, R_{\vec{v}_0}$$

$$C = \int_{|\vec{v}_0| \le v_{\max}} d^3 v_0 \, f(\vec{v}_0) \, C_{\vec{v}_0}$$

* Each stream rate is bounded by experimental limit => max cross section (as a function of m) for each stream:

$$\sigma^{DD}_{\max}(v_0)$$

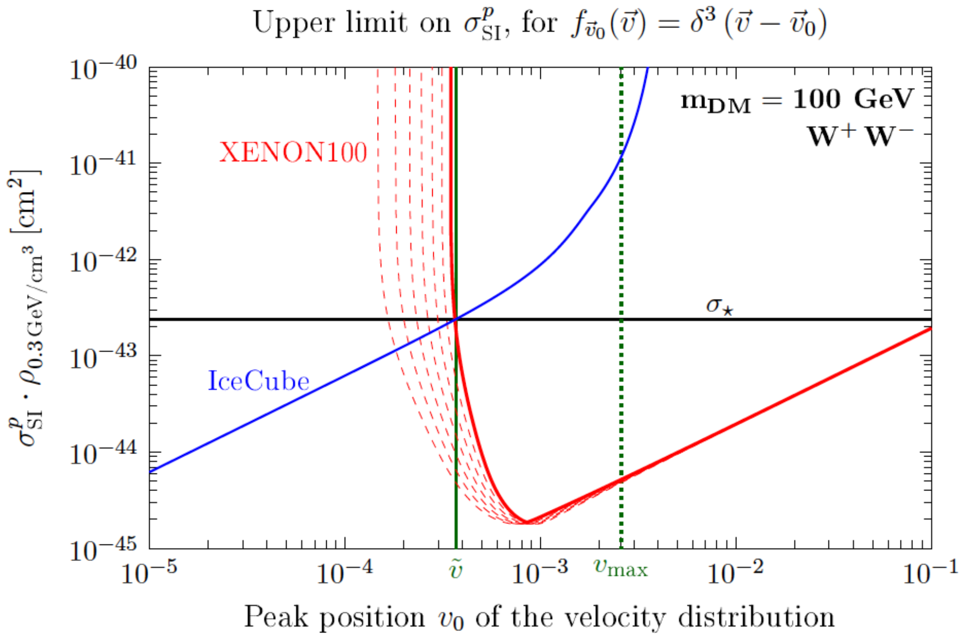
$$R_{\vec{v}_0}(\sigma) \ge R_{\max} \text{ for } \sigma \ge \sigma^{DD}_{\max}(v_0)$$

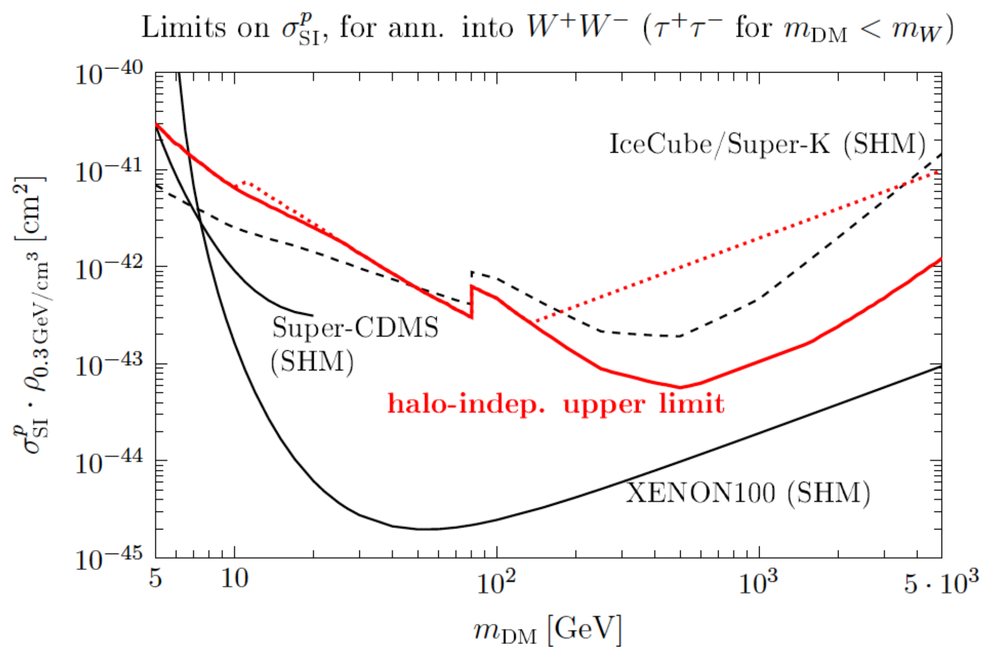
* After some algebra

$$\sigma \le \left[\int_{|\vec{v}_0| \le v_{\max}} d^3 v_0 \frac{f(\vec{v}_0)}{\sigma^{DD}_{\max}(v_0)} \right]^{-1}$$

$$\sigma \le 2\sigma_*$$

** Still depends on local DM density





Nuclear Uncertainties

Courtesy Rolf Kappl