On Dark Matter searches

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Outline

* The Cold Dark Matter paradigm: successes and issues

* Dark matter as particles: some candidates

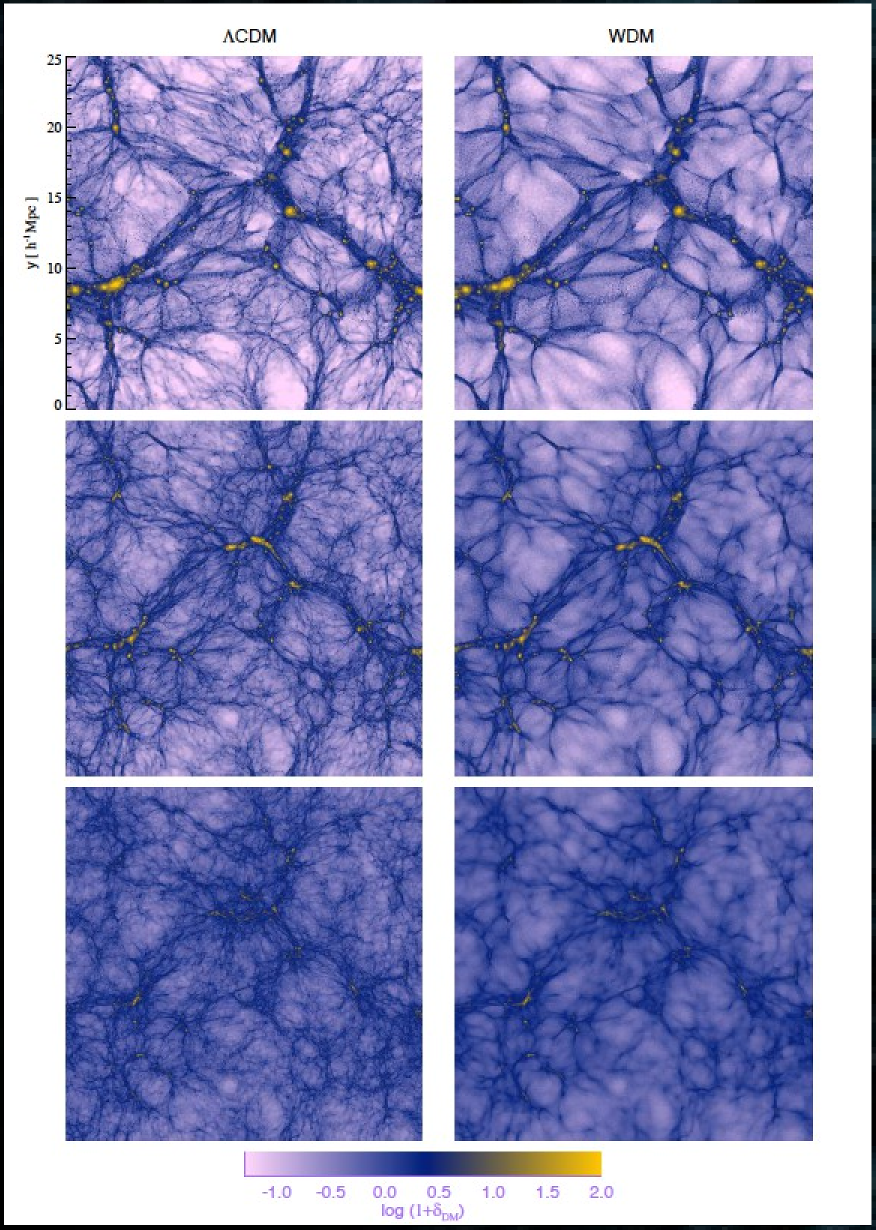
* The WIMP paradigm: production and freeze out in the early universe

* WIMP searches:
    - indirect searches
    - direct searches
    - searches at colliders

* Perspectives

CDM: successes and issues

Viel++ (11)



<u>Indirect proofs for DM:</u>

Observed (gravitational effects) from sub-galactic to cosmological scales

<u>CDM successes:</u>

- Successful theory of structure formation (from CMB perturbations)

=> CDM seeds galaxies, galaxies embedded in DM halos

- Non-linear collapse probed with cosmological N-body simulations
- Including baryons is an ongoing (difficult) task but seems promising
- Most of observed properties (CMB / clusters / galaxies) reproduced from theory

<u>Alternatives to DM: Modified gravity ????</u>

- Interesting and difficult theoretical direction
- Fails in forming galaxies without DM (eg large CMB multipoles)

=> (hot/warm) DM required even in modified gravity models => not minimal!!!!

<u>Free-streaming scale must at least allow for Dwarf Galaxies:</u>

Fermionic DM => Tremaine & Gunn 79, Boyarsky+ 06: m > 1 keV
=> WDM and/or CDM allowed

<u>Small scale issues for CDM (too much power on small scales):</u>

So-called "Cusp-core problem"
=> CDM predicts cusps + concentrated centers, observations cores
(e.g. Navarro-Frenk-White profile)

More subhalos than observed (≲ dwarf galaxy mass)
*** more have been detected recently (SDSS)
*** inefficient star formation, feedback effects (UV pressure, SN)

CDM: successes and issues

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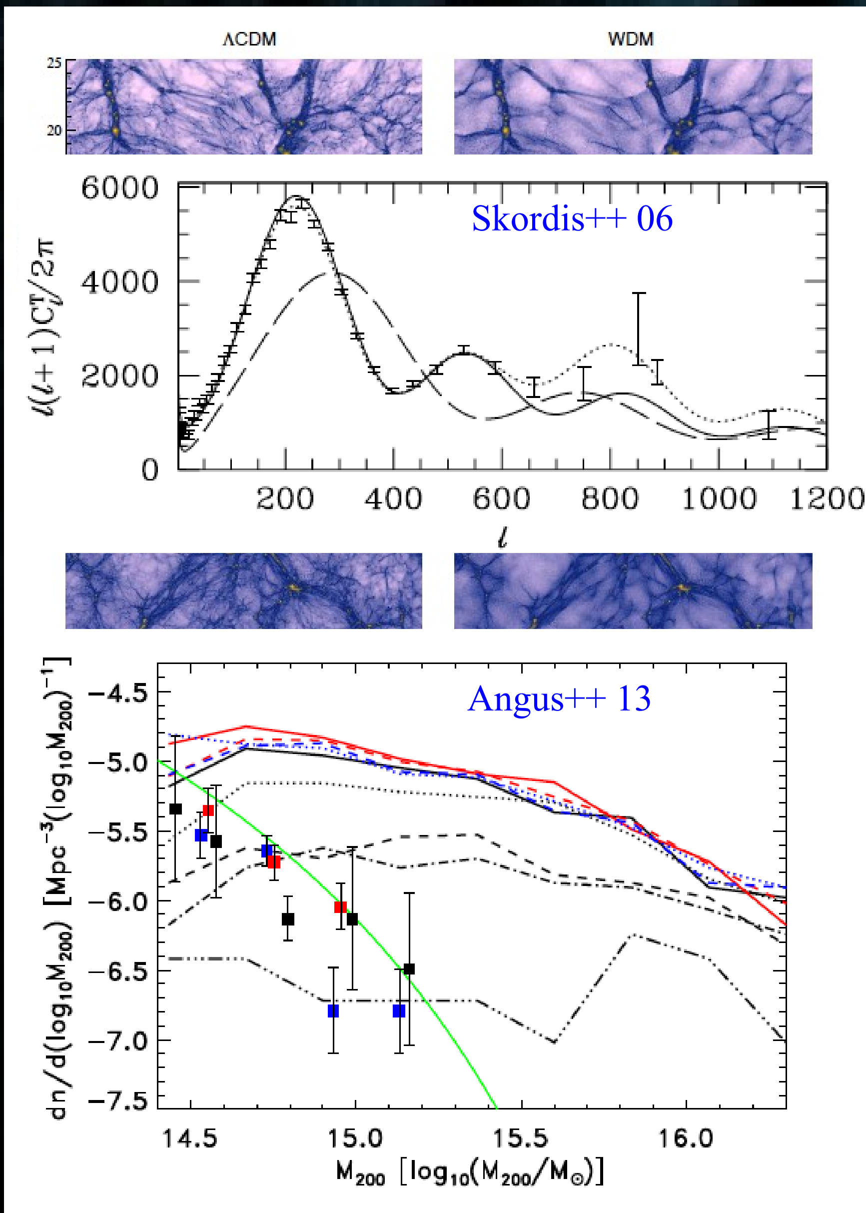

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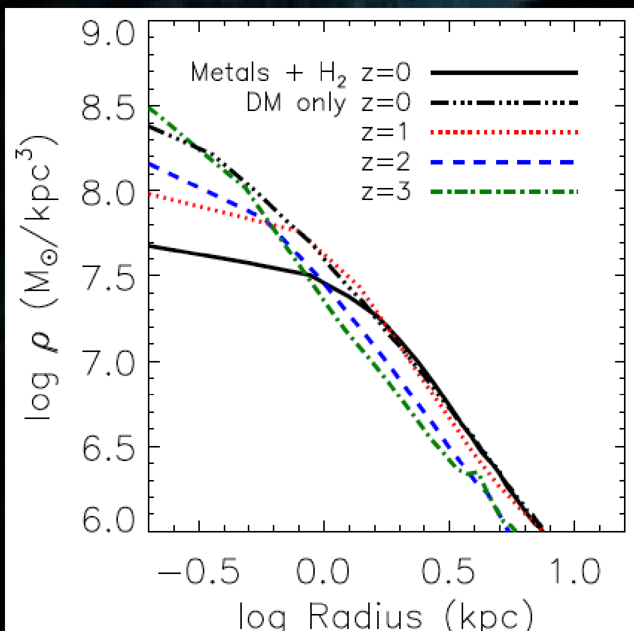
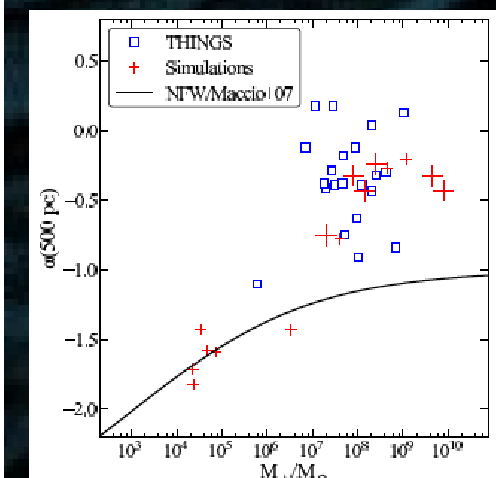
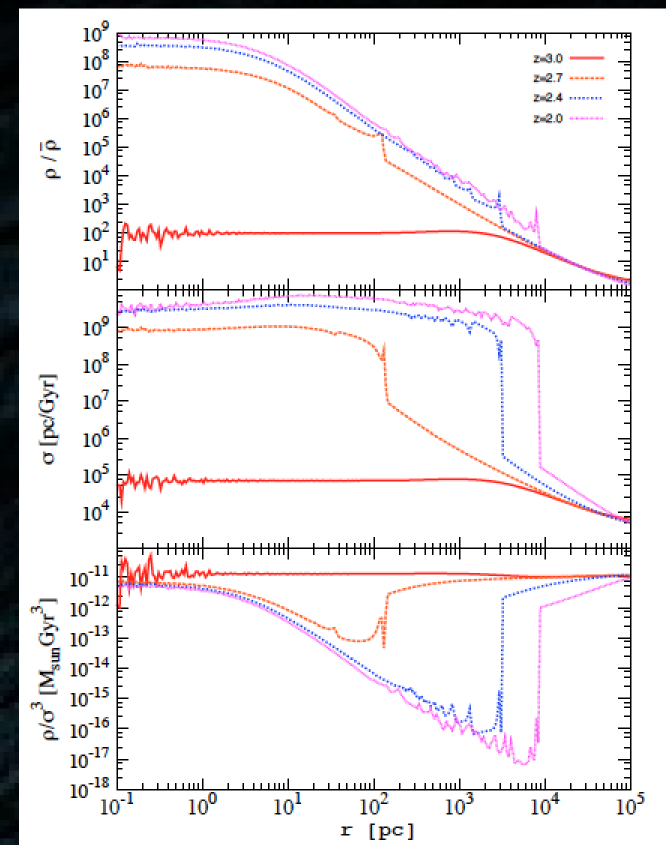
The core-cusp problem
(mostly in late-type LSB galaxies, e.g. de Blok 10)

Governato++ (12)
CDM + more realistic physics for baryons => cusps are flattened
(star formation: radiative feedback from massive star + SN feedback)

Villaescuela-Navarro & Dalal (10)
WDM does not prevent cusp formation
(Core radius / virial radius < 0.001)





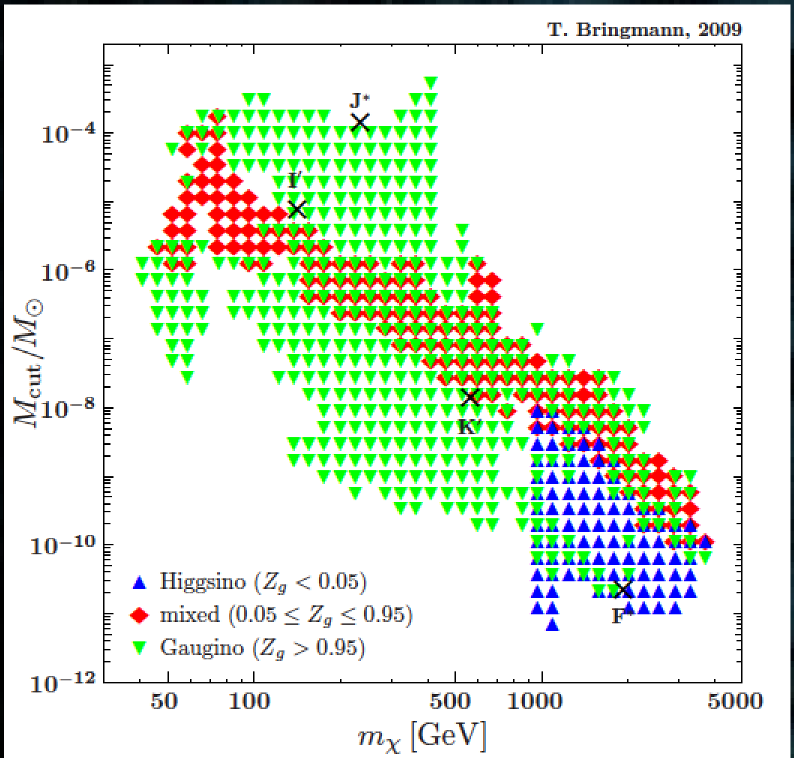


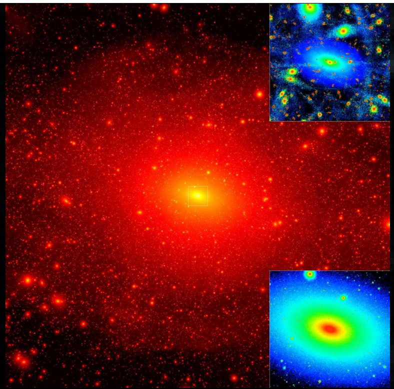
Conclusions:
→ WDM alone does not solve the issue:
* must be close to CDM to form DSphs (> 1-10 keV)
* then core radii are way too small wrt observations

→ CDM in better shape when baryons are included
(still some debate)

The subhalo problem: too many, too concentrated?

Bringmann (09):
The minimal proto-halo scales for SUSY WIMPs





Via Lactea II simulation (MW-like galaxy)
Diemand++ (08) – CDM only
=> > 20,000 subhalos with M >$10^{6\text{-}7}$ Msun

Too big to fail? The puzzling darkness of massive Milky Way subhaloes

Michael Boylan-Kolchin*†, James S. Bullock, and Manoj Kaplinghat
Center for Cosmology, Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697, USA

<u>"Too big to fail":</u>
* CDM => massive, concentrated subhalos => should form stars, but not observed (ultra-faint SDSS DSphs not enough)
BUT: very sensitive to cosmological parameters

Solutions may come from baryonic effects:
* feedback (Governato ++12)
* H2-regulated star formation (Kuhlen++ 12-13)

Other solutions from particle physics:
* Self-interacting DM (Spergel & Steinhard 00)

=> Sometimes viewed as a big issue for CDM
=> Investigate baryonic effects in detail

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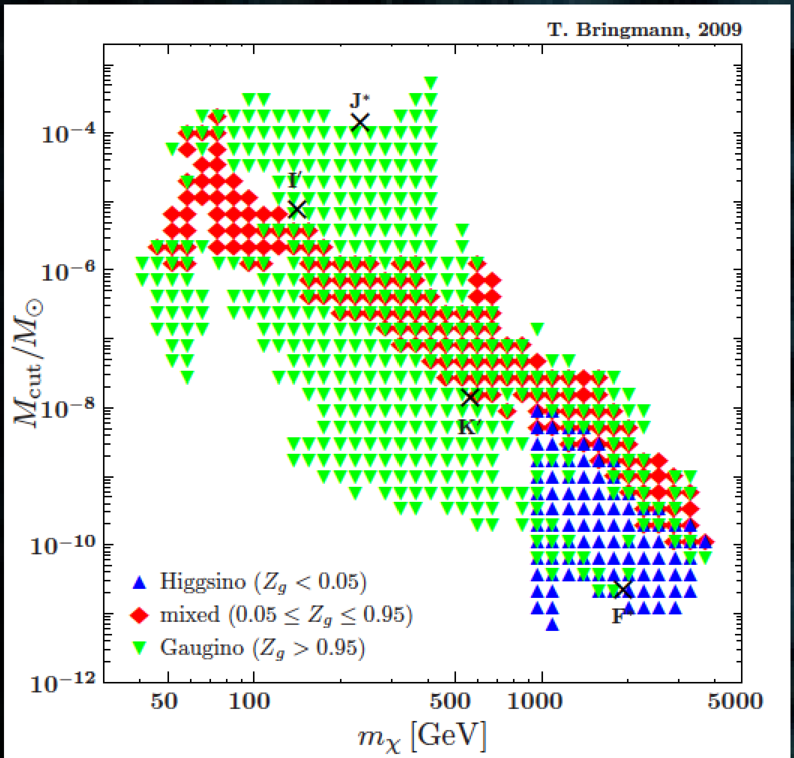

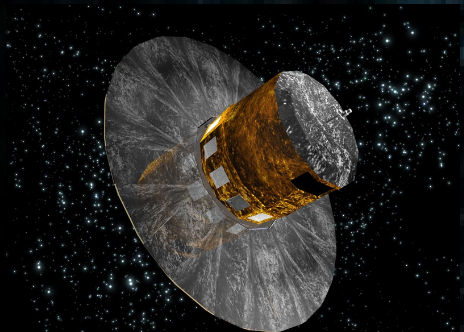

Gaia (launch Dec. 19) will probe Galactic dynamics to unprecedented accuracy.

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DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

R. G. Carlberg[1]

Gaps in star streams: NW (M31), Pal 5, Orphan, EBS (MW)
=> ~ 10^5 subhalos with M > 10^5 Msun (but large systematic errors)

Detecting Dark Matter Substructures around the Milky Way

Robert Feldmann,[1,**] and Douglas Spolyar[2,*]
[1]*Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[2]*Institut d'astrophysique de Paris, Paris, 75014, France*

Subhalos pull stars when crossing disk: could be observed with Gaia.

++ See also reionization + Ly-alpha studies.

Dark Matter candidates

Different mass/energy scale depending on
inherent theoretical motivations

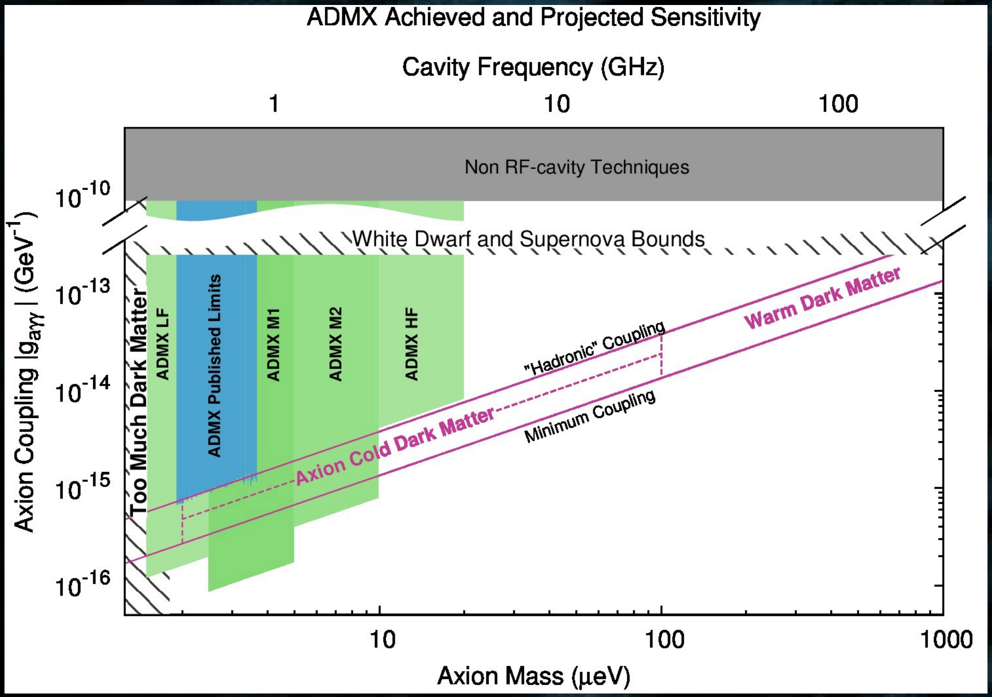
What does particle physics tell us about DM ?

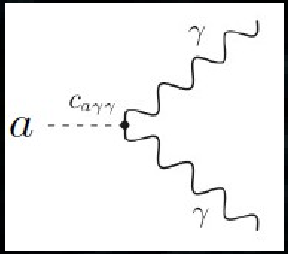
Motivations	**Strong CP problem in QCD [sub-eV]**	**Neutrino masses [keV]**	**Origin, stability and naturalness of the Higgs sector (EWSB) [GeV-TeV]**	**Dark matter [GeV-TeV]** **++ Neutral scalar, Fermion, or vector ++**
Framework & Candidate(s)	**Peccei-Quinn** **++ axion ++** **or axion-like (ALPs)** **(string-inspired)**	**RH-neutrinos + seesaw** **++ sterile neutrino ++** **++ Asymmetric DM ++**	**SUSY, Xdim, IDM, Composite, etc.** **++ LWP ++** **(lightest whatever particle)**	
Additional benefits		**Leptogenesis**	**e.g.: GUT, inflation**	**GUT**

Axions and sterile neutrinos

Peccei-Quinn, Wilczek,
Weinberg, Kim, Shifman,
Vainshtein, Zakharov

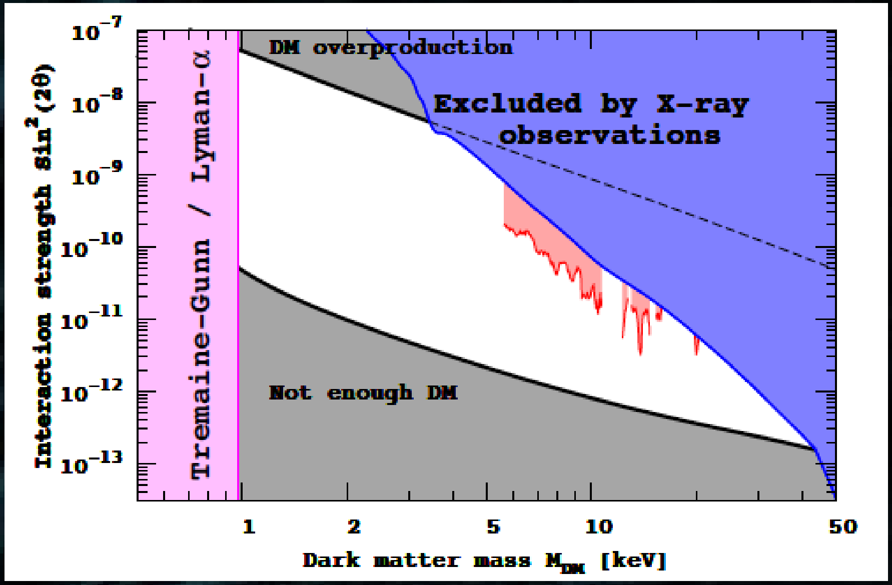
ADMX collab.

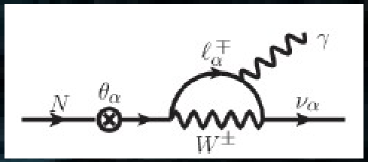




Dodelson, Widrow

Boyarsky++ 13





WIMP production and freeze out

* $T > m$ and $\Gamma_{ann} > H$ (and $\Gamma_{scat} > H$):
Chemical equilibrium, n/s = cst

* $T < m$ and $\Gamma_{ann} > H$ (and $\Gamma_{scat} > H$):
Chemical equilibrium, n/s ∝ exp(-m/T)
(Boltzmann suppression)

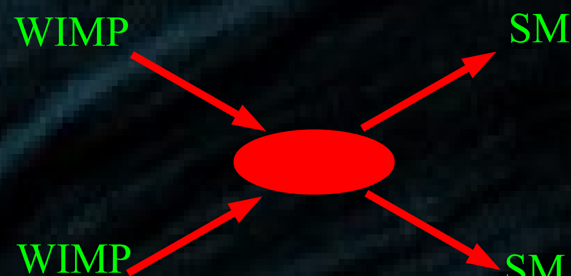
* $T < m$ and $\Gamma_{ann} < H$ (and $\Gamma_{scat} > H$):
Chemical decoupling (freeze out)

See e.g.Lee & Weinberg 77, Srednicki++ 88, Gondolo & Gelmini 91

* $T < m$ and $\Gamma_{scat} < H$:
Kinetic decoupling
=> free-streaming scale
=> minimal mass scale for structure formation
(modulo extra-damping from acoustic oscillations)

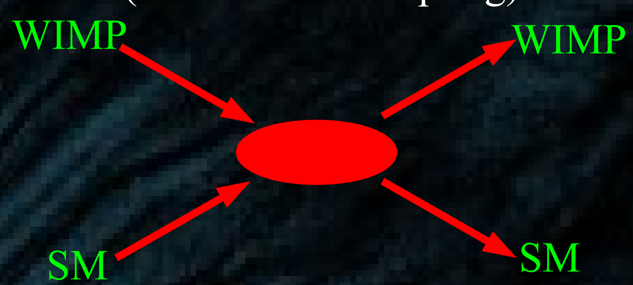
See e.g. Schmid++ 99, Boehm++ 00, Chen++ 01, Hofmann++ 01, Berezinsky++ 03, Green++ 04-05, Loeb++ 05.
For susy, see review in Bringmann 09.

Annihilation
(→ chemical decoupling)



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

Scattering
(→ kinetic decoupling)



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

Freeze out

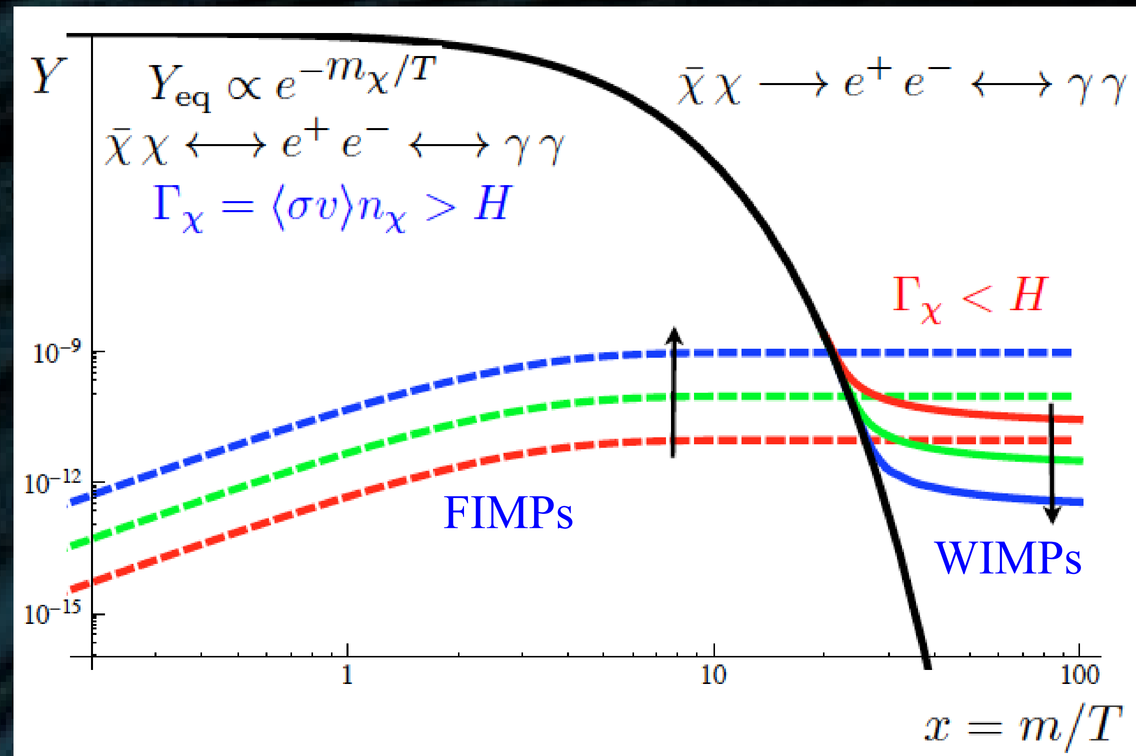
Production:

- Coupling to matter fields => thermal production in pairs if $T > m_{wimp}$ (NB: implicit assumption about reheating).
- Weak couplings => thermal/chemical equilibrium quickly reached (WIMPs) <=> production/annihilation rates >> expansion rate.
- Feeble (weaker) couplings => equilibrium never reached <=> slow production (large density of plasma), annihilation inefficient (low density of DM particles).

Decoupling:

- Occurs when expansion rate >> annihilation rate (equilibrium before, e.g. WIMPs), or when T < m (e.g. FIMPs).

→ see e.g. Gondolo & Gelimini 91, Gondolo & Edsjo 97



Hall++ (10)

In practice:

- Solve the Boltzmann equation

$$\frac{dn_\chi}{dt} = -3\,H\,n - \langle\sigma v\rangle\,\{n_\chi^2 - n_{\rm eq}^2\}$$

$$Y_\chi \equiv \frac{n_\chi}{s}$$

$$\frac{dY_\chi}{dt} = -s(T)\,\langle\sigma v\rangle\,\{Y_\chi^2 - Y_{\rm eq}^2\}$$

$$x \equiv m_\chi/T \propto m_\chi/v^2$$

$$\frac{dY_\chi}{dx} \propto -\frac{g_\star^{1/2}(x)}{x^2}\,\langle\sigma v\rangle\,\{Y_\chi^2 - Y_{\rm eq}^2\}$$

General conclusions for WIMPs:

- Cosmological abundance fixes annihilation cross section.
- Canonical value for ~100 GeV WIMPs

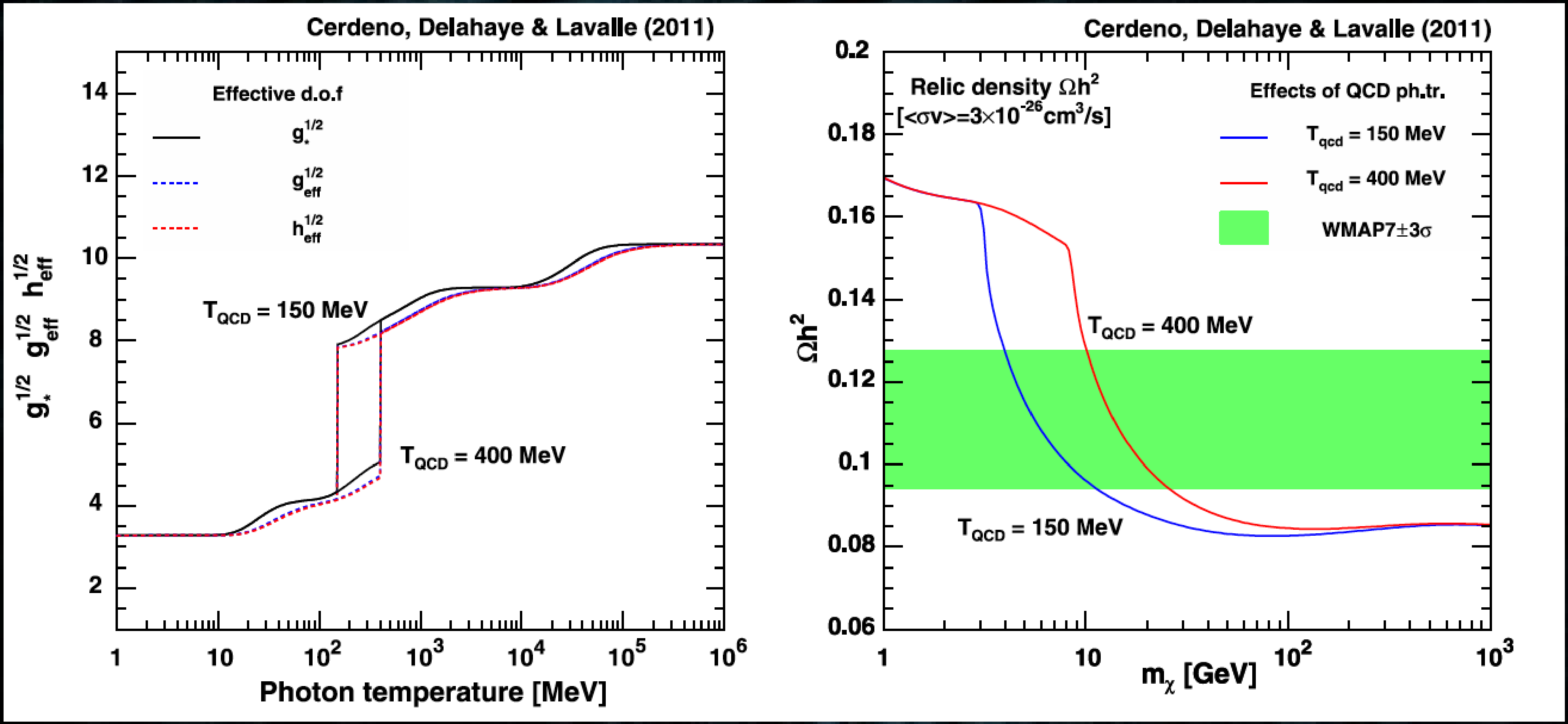
$$x_{\rm dec} \approx 20$$

$$\Omega_\chi \propto 1/\langle\sigma v\rangle$$

$$\langle\sigma v\rangle \approx 3 \times 10^{-26}\,{\rm cm^3/s}$$

Freeze out

How accurate is the canonical cross-section value $<\sigma v> = 3.10^{-26}$ cm^3/s ?

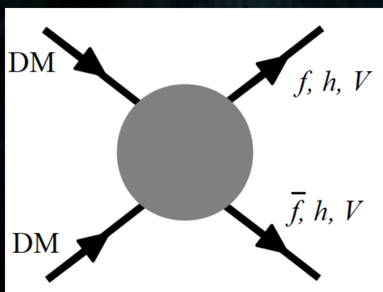


<u>**Advice: beware of standard lores (unless clearly understood):**</u>
=> The canonical value is not accurate!
*** QCD phase transition effect! Relativistic degrees of freedom strongly reduced (factor of 4) when quarks get confined into hadrons.
=> < σv> larger by factor of 1.5 below 10 GeV
=> < σv> smaller by factor of 1.3 below 10 GeV

$$\Omega_\chi \tilde{\propto} \frac{1}{g_\star^{1/2}(x_{\rm dec})\,\langle \sigma v\rangle}$$

Annihilation at freeze out vs. in galaxies

Exception: Sommerfeld effect (mediator mass << WIMP mass)
<=> long-range attractive force in some cases



$$\langle \sigma v \rangle \approx \underbrace{\overbrace{a}^{\text{in galaxies}} + b/x + \mathcal{O}(x^{-2})}_{\text{relic density}}$$

$$x_{\rm dec} \approx 20 \quad \Longleftrightarrow \quad x_{\rm MW} = \frac{3}{\beta^2_{\rm MW}} \approx 10^6$$

=> P-wave contribution (dependent on v) is suppressed in Galaxies by 5 orders of magnitude wrt early universe
=> In general, indirect searches only relevant to models with dominant S-wave contributions.

** Focus on S-wave
=> Annihilation at rest implies a few additional features, if one looks at a pair of WIMPs more closely
=> Majorana fermion pair at rest: C=1; S-wave => L=0 => S=0 => CP=-1 => process selection!

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S} \qquad C(\text{Majorana pair}) = 1$$

$$CP = (-1)^{2L+S+1} = (-1)^{S+1}$$

$$\begin{aligned} J^{PC}(\lambda) &= 0^{++} \\ J^{PC}(i\,\lambda\,\gamma_5) &= 0^{-+} \\ J^{PC}(\lambda\,\gamma^\mu) &= 1^{--} \\ J^{PC}(\lambda\,\gamma^\mu\,\gamma_5) &= 1^{++} \end{aligned}$$

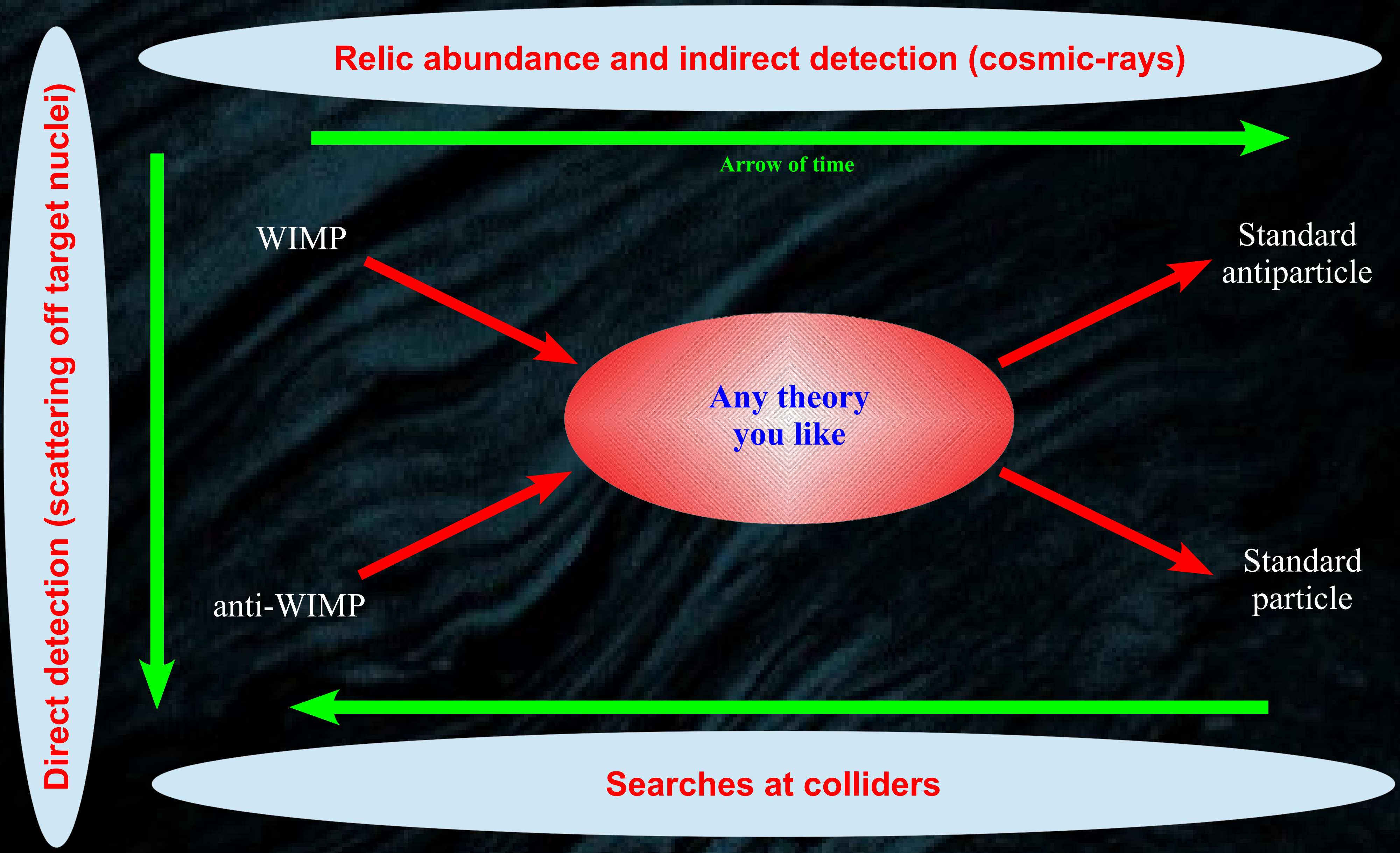
=> important for complementarity with direct searches!

++ Helicity suppression

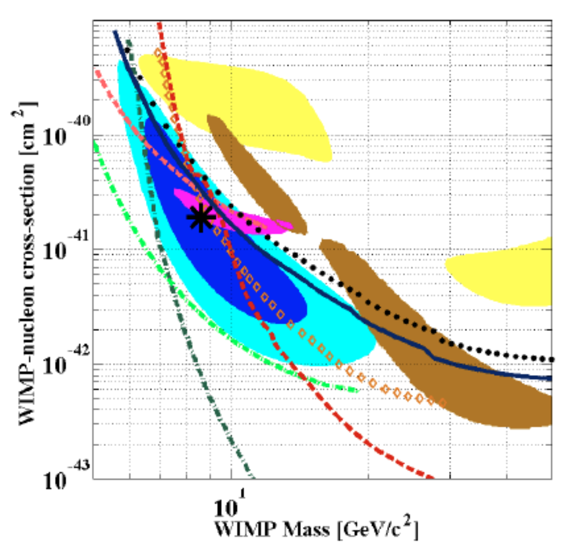
$$\langle \sigma v \rangle \propto m_f^2$$

Exception: Sommerfeld effect

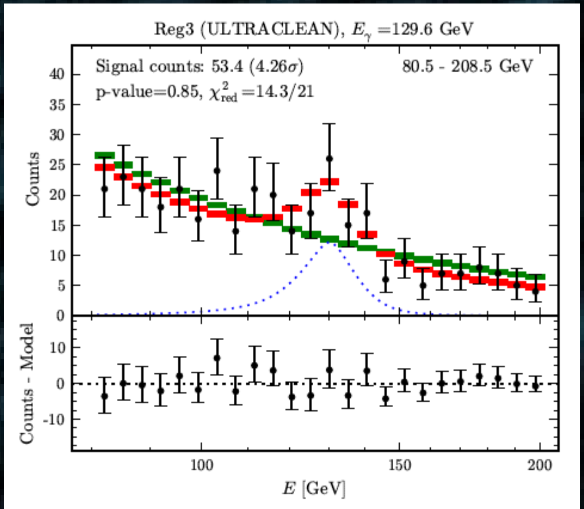
WIMPs: detection methods



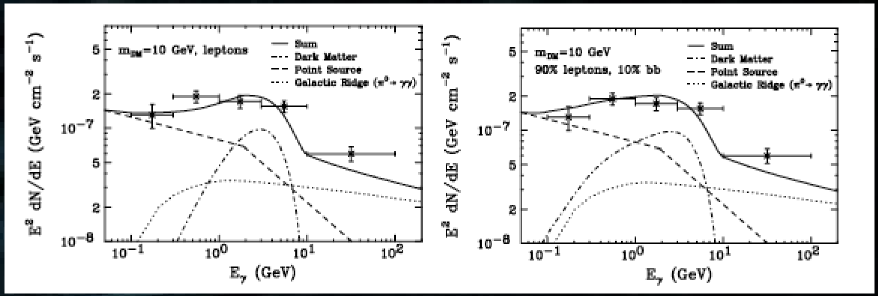
Dark matter has long been discovered !



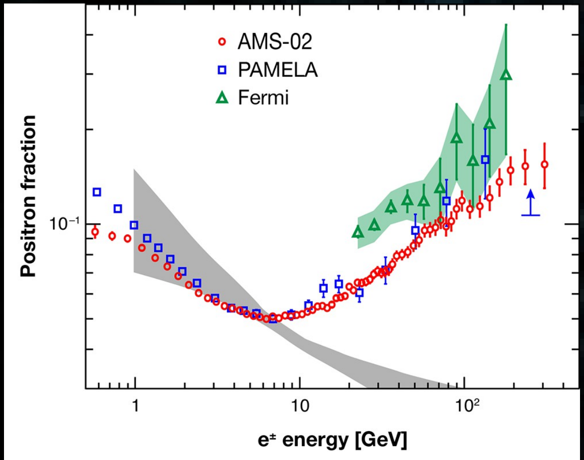
Agnese++ 13
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
→ DM around 10 GeV

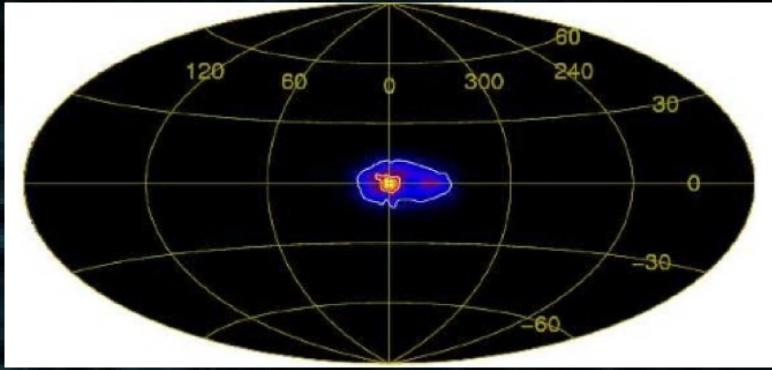


Around the GC
Weniger++, Finkbeiner++ 12
→ DM around 130 GeV



Hooper++ 12: gamma-rays + radio at GC
→ DM around 10 GeV





511 keV, Knödlséder/Weidenspointner++ 05 - 08
Boehm, Hooper++ 04 → DM around 1 MeV

HEAT/PAMELA/AMS positron excess
Bergström++, Cirelli++ 08 → DM around 300-1000 GeV

Indirect searches

Indirect dark matter detection in the Milky Way

THE ASTROPHYSICAL JOURNAL, 223:1015–1031, 1978 August 1

SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

J. E. GUNN*
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Received 1977 December 1; accepted 1978 February 14

VOLUME 53, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1984

Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

Joseph Silk
Astronomy Department, University of California, Berkeley, California 94720, and Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
and
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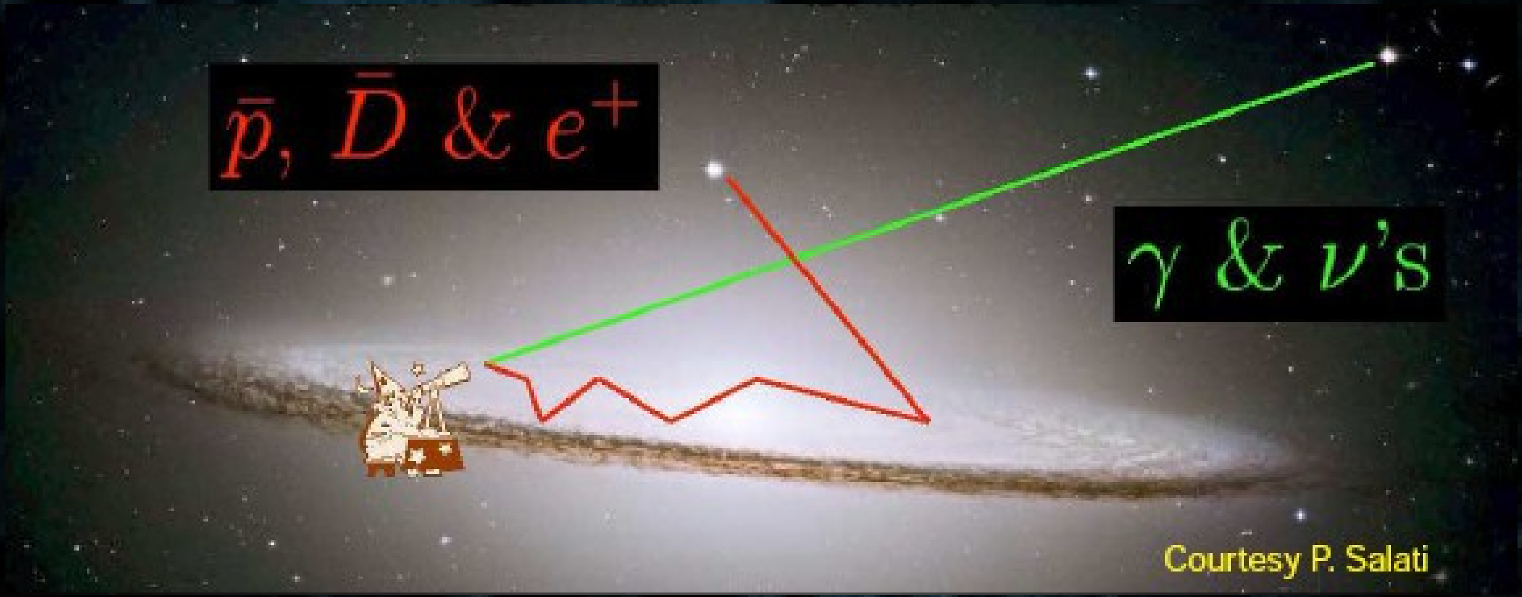

Main arguments:
- Annihilation final states lead to: gamma-rays + antimatter
- γ-rays : lines, spatial + spectral distribution of signals vs bg
- Antimatter cosmic rays: secondary origin of astro contrib, therefore low bckgd (in principle)
- Neutrinos: Sun most promising target

But:
- Do we control backgrounds?
- Specific spectral differences in signals vs backgrounds?
- Careful estimates of theoretical errors for signals and backgrounds very important (difficult exercise in practice)

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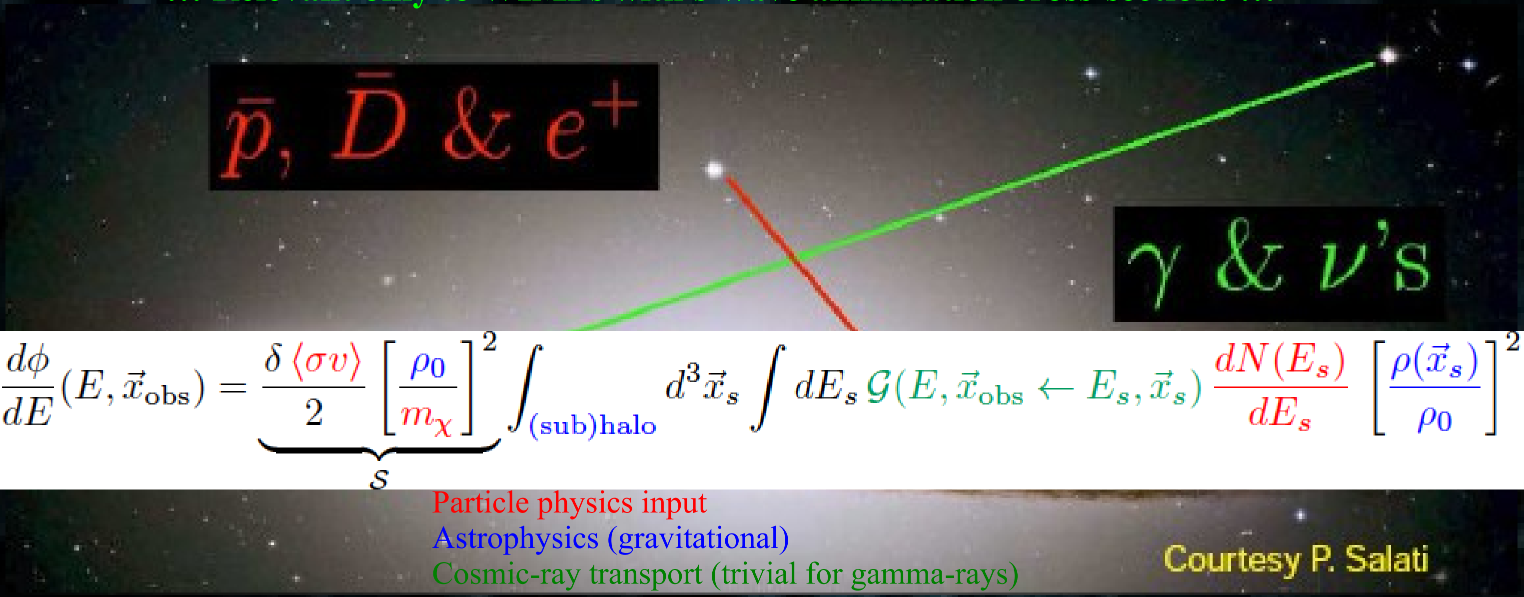
!!! Relevant only to WIMPs with s-wave annihilation cross-sections !!!



$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \underbrace{\frac{\delta\,\langle\sigma v\rangle}{2}\left[\frac{\rho_0}{m_\chi}\right]^2}_{S}\int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\, \mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}\left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

Particle physics input
Astrophysics (gravitational)
Cosmic-ray transport (trivial for gamma-rays)

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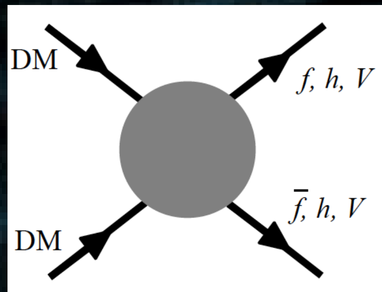
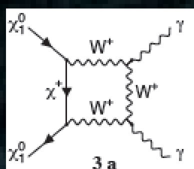
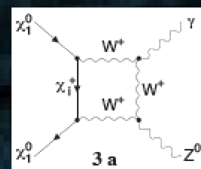
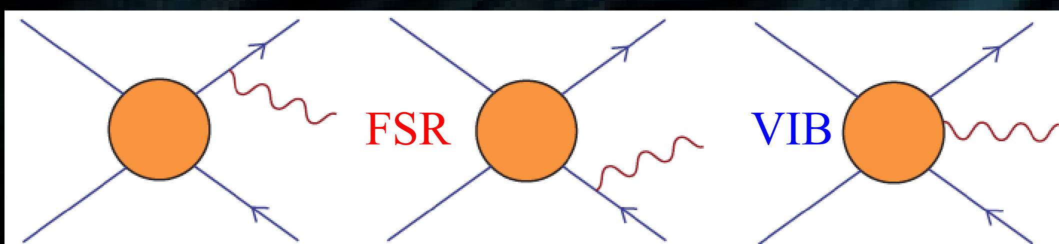
Gamma-ray signals: spectral signatures

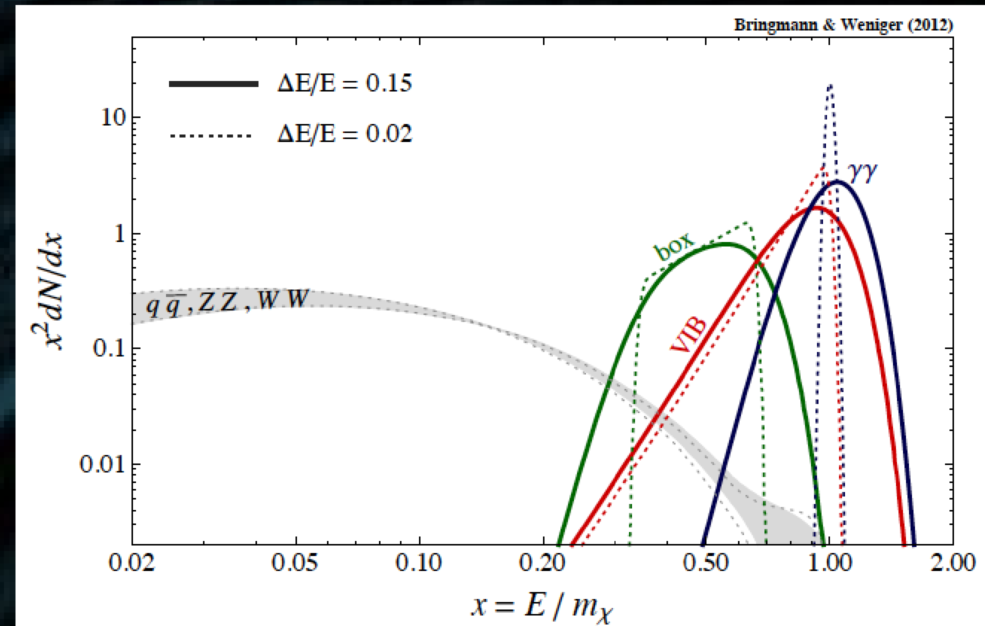








Bringmann++ 09



Bringmann & Weniger 12

DM signals depend on annihilation final states:

1) Gamma-ray lines/boxes: the cleanest signatures! (but loop suppressed)

=>eg: γγ, γX, ϕϕ → 4γ

2) quarks, massive bosons => typical hadronization spectra (pion production/decay)

=> continuous spectrum, close to E^{-2}, with exponential cut-off => rather soft spectrum

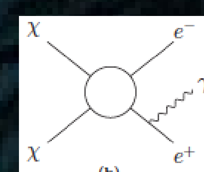
3) Virtual internal Bremsstrahlung (VIB) may be significant if final states are bosons and mediator mass degenerate with WIMP mass (strongly model-dependent)

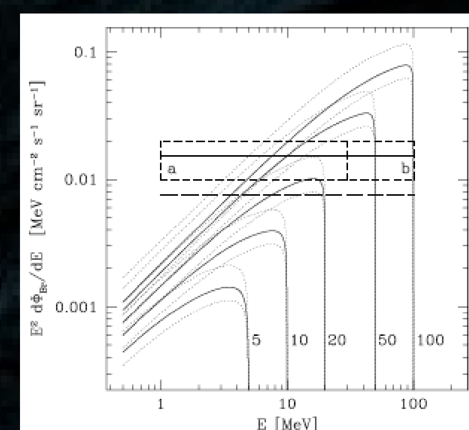
=> hard spectrum

…

x) (mostly for non-susy): FSR for annihilation into charged leptons

=> hard spectrum.

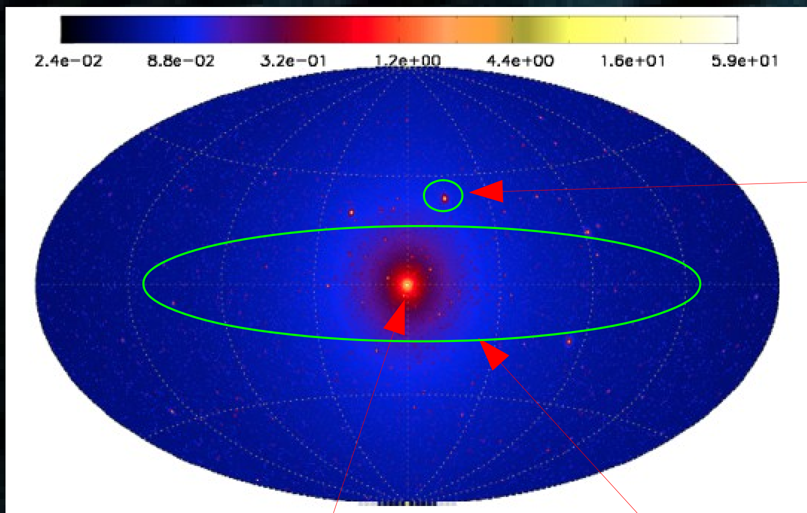




Beacom++ 05

Gamma-ray targets

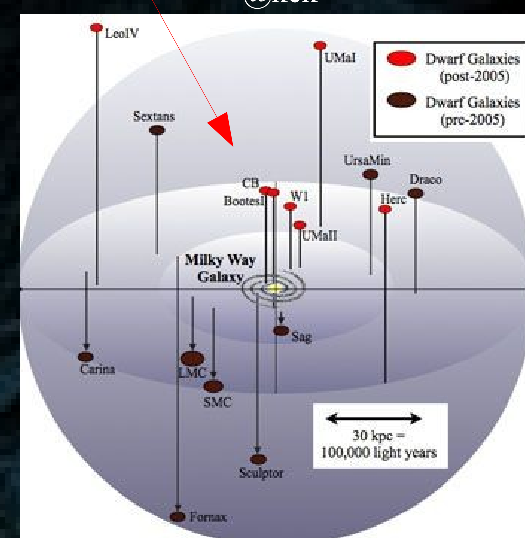
Pieri, JL++ 11



Big DM subhalos
* unknown objects if star formation inefficient
=> potential unidentified gamma-ray sources.
* known Dwarf Spheroidal Galaxies (~20) – no other HE astrophysical processes expected there.

If no line observed elsewhere, DSphs are the most secure for a discovery.

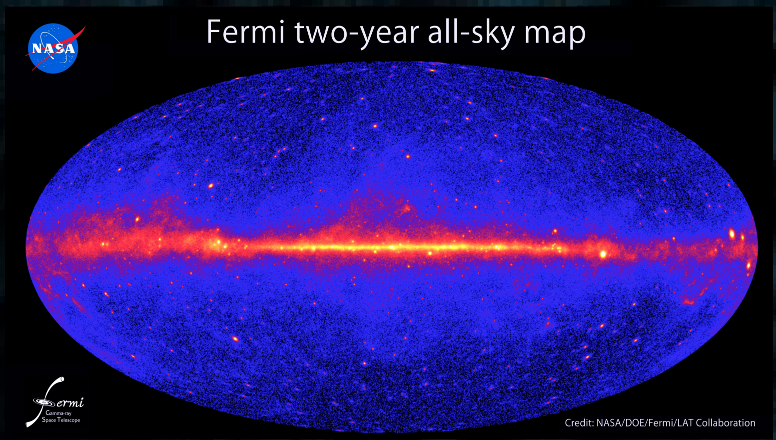
@kek



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

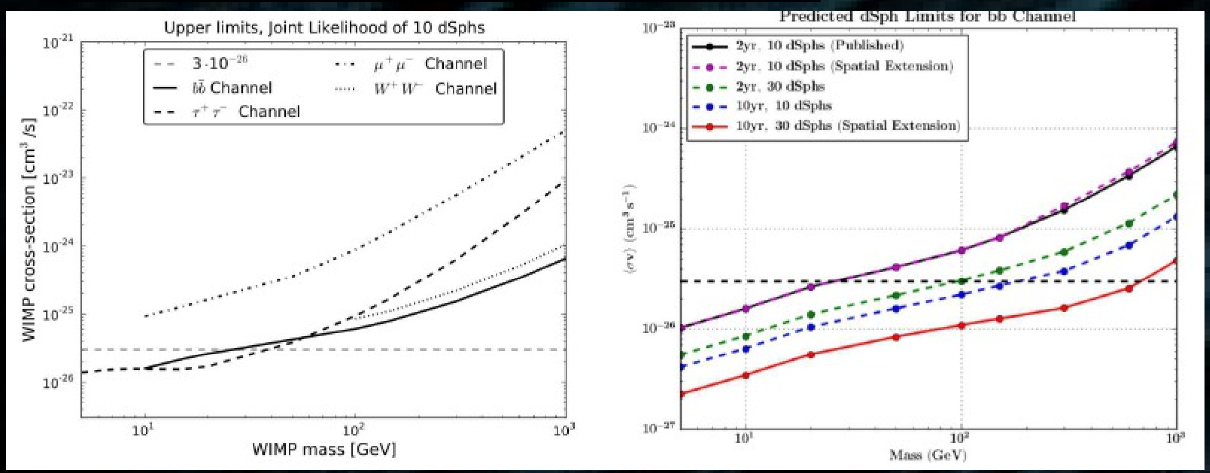
Galactic Center
* Closest/Largest expected annihilation rate
* Large theoretical uncertainties (signal and background)

Indirect detection with gamma rays

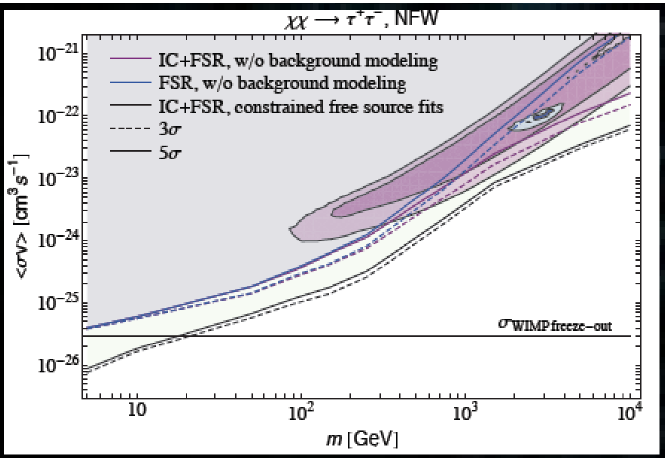


Gamma-ray targets/features:
- Dwarf Spheroidal Galaxies: DM-dominated
- Galactic center
- Diffuse gamma-ray sky (high latitudes)
- Gamma-ray lines (all targets)

Best running experiment is Fermi (ACTs like HESS have larger energy thresholds and limited fields of view).



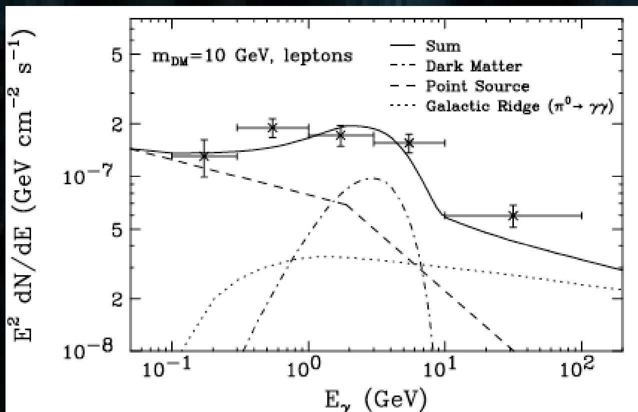
Constraints from DSphs:
- Geringer-Sameth & Koushiappas (11), Fermi collab. (11)
- Constraints on WIMP masses < 20-30 GeV (DM $\rightarrow$ tau leptons, quarks)
- Start probing WIMP parameter space
- Sensitivity will have increased by factor of 3 in 2018 => 100 GeV mass range within reach



Fermi Collab (11-13)

Constraints from Diffuse emission (high-latitude constraints):
- Fermi collab. (12), Abazadjan++ (11-12), etc.
- Constraints on the so-called PAMELA region

Galactic center observed in gamma rays



Hooper++ (10-13)

10 GeV excess???:

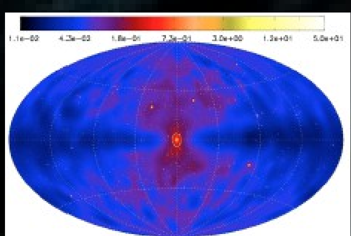
- Hooper++ (10-13) claim for an excess around 10 GeV
- Could be fit with DM annihilation into massive charged leptons
- Can be achieved in some DM models (NMSSM, extra-dim, etc.)
- Debate on systematics:
  - * contamination of unresolved sources
  - * region dominated by baryons: bkgd estimate not controlled
  - * DM profile uncertain in GC => affects cross-section estimate

NB: HESS detected TeV gamma-rays consistent with CR acceleration

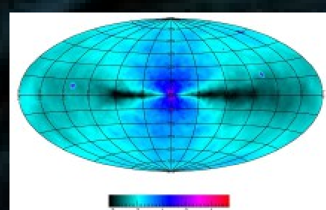
111-130 GeV gamma-ray line(s)???:

- Found by Bringmann++(11), Weniger (12), Su & Finkbeiner++(12), etc.
- Smoking gun signal for DM annihilation!
- Model-building difficult, but points toward generic resonant (loop) processes
- Debate on systematics:
  - * Fermi collab. revised significance down to 2 sigma
  - * Earth-limb events cast doubt

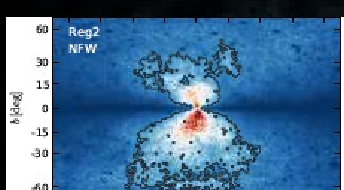
→ Have to wait for HESS-2 and more Fermi data



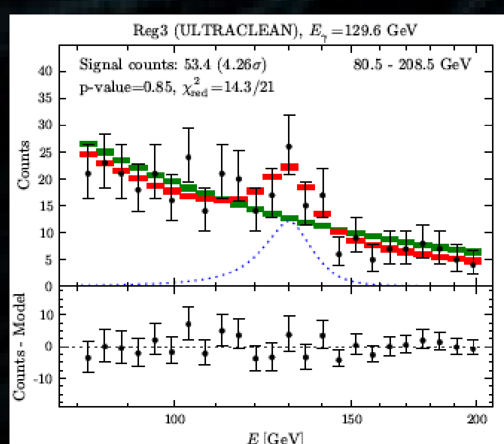
DM/bg semi-analytic
Pieri, JL, Bertone, Branchini (11)

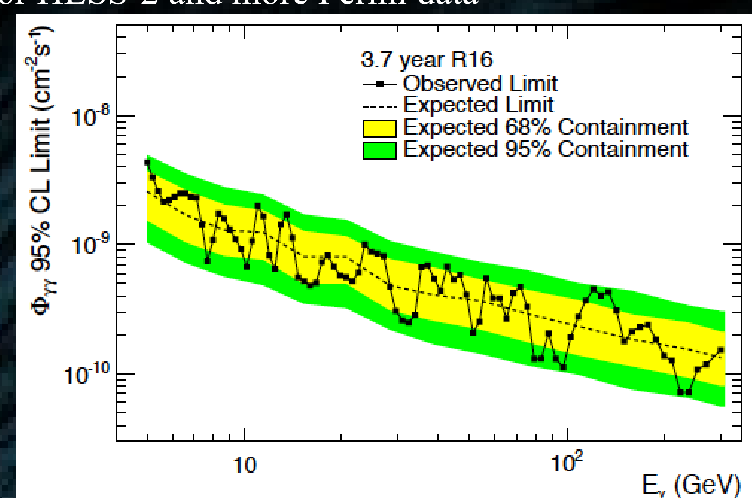


DM/bg Nbody CDM+baryons
Nezri, JL, Teyssier (12)



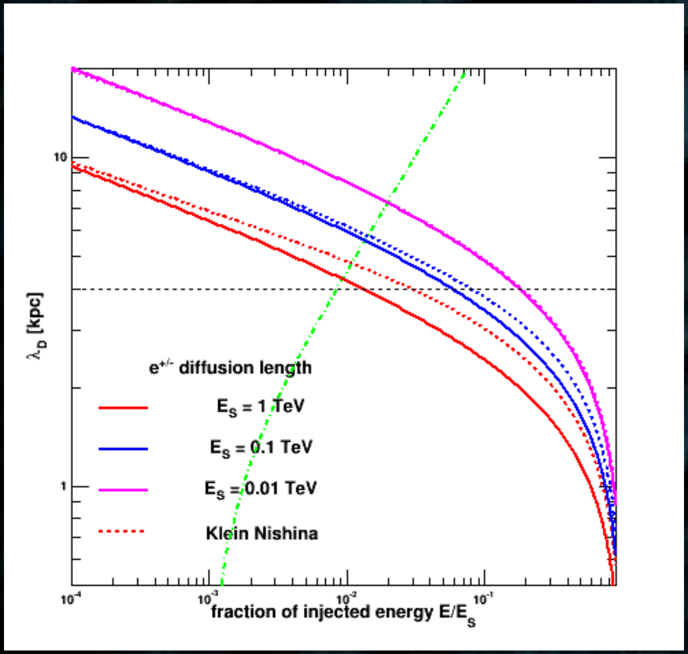
Weniger (12)





Fermi Collab. (13)

Indirect detection with antimatter CRs



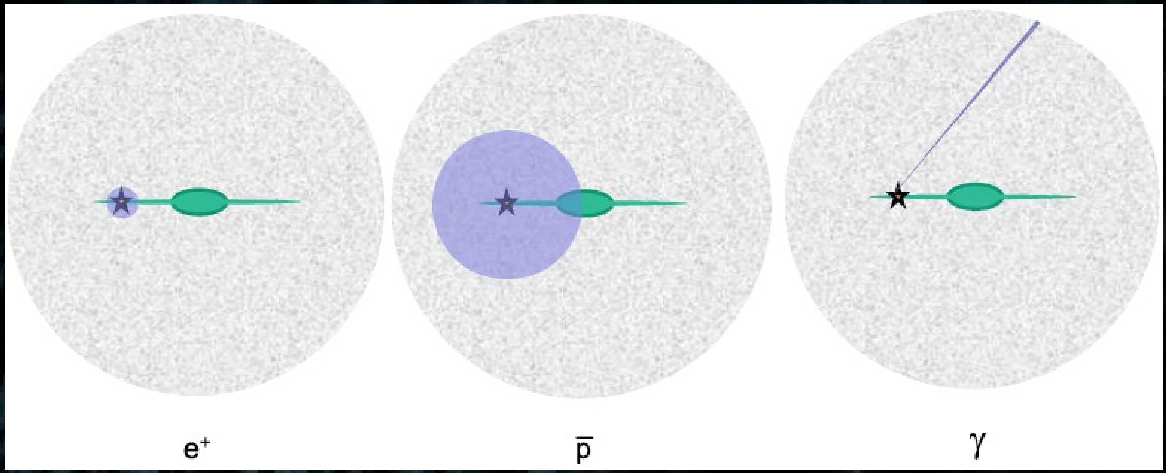
JL++ 08

2 types of messenger:
* "antinuclei": antiproton / antideuteron
* positrons
=> different propagation properties.

Antinuclei: spatial diffusion + spallation + convection
Positrons: spatial diffusion + energy losses

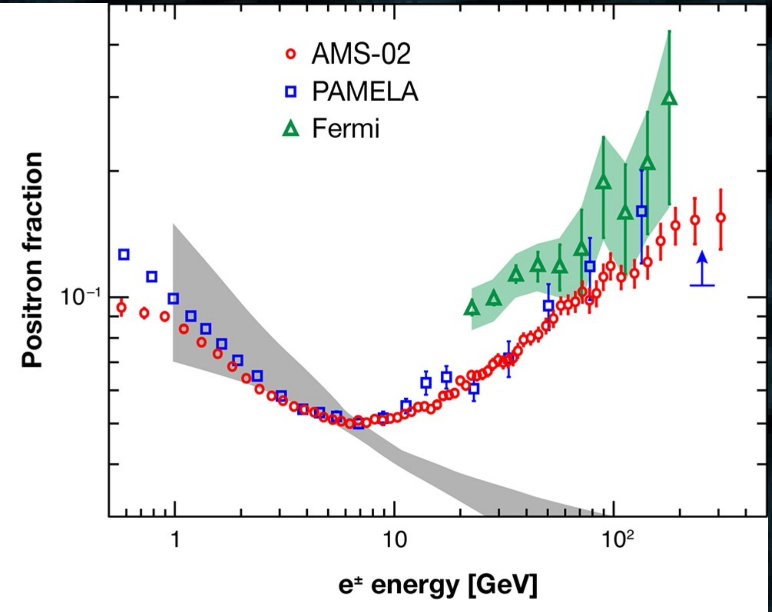
=> different propagation scales!
=> probe different parts of the MW
=> less sensitive to halo shape
NB: boundary effects when l>L or/and l>R

Bergström 09

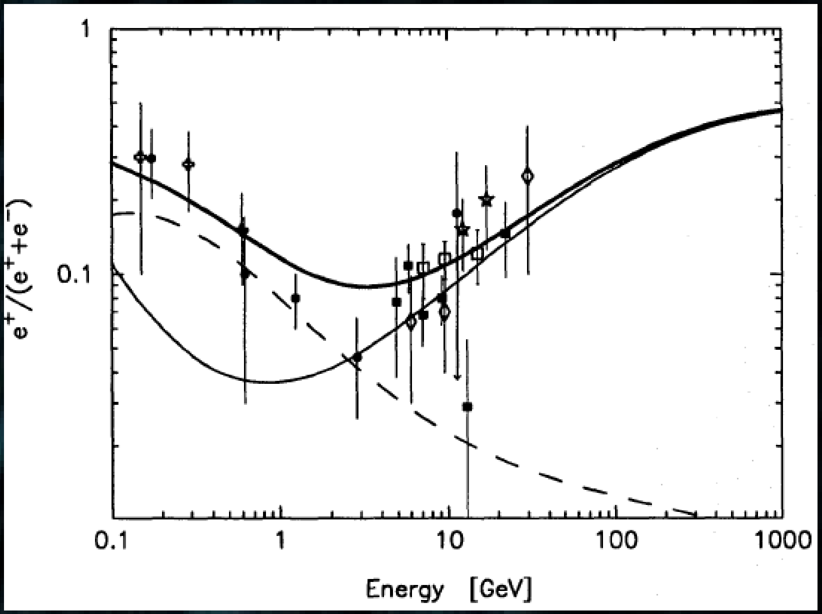


Antimatter: the positron fraction

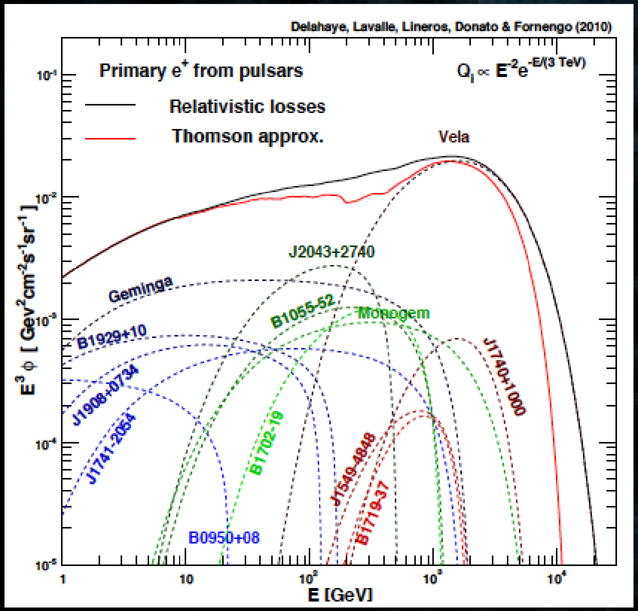
AMS result: nothing really new but impressive precision



AMS Collab (2013)



Aharonian+ (1995)



Pulsars efficiently produce e+/- pairs.
Realistic modeling is complicated (eg Delahaye et al 10).
=> separate distant/local sources, and accommodate the full data (e-, e+, e+e-, e+/e+e-) …

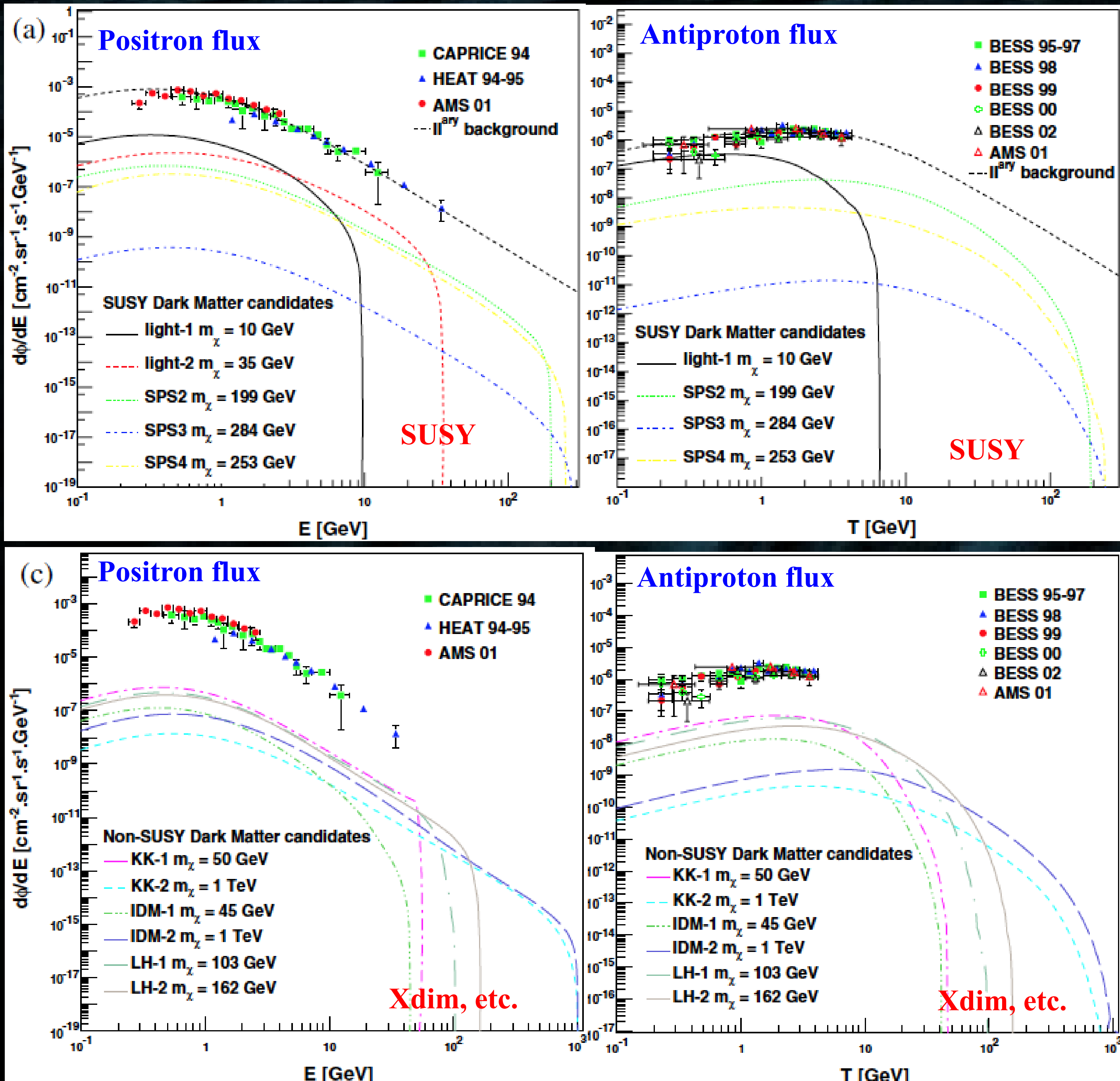
=> Pulsar wind nebulae (PWNe) as HE positron/electron sources
=> SNRs as HE electron sources (each PWN is paired with an SNR)

=> you may fit amplitudes / spectral indices … then what?

** Observational constraints!

=> use pulsar period, multiwavelength data for all observed sources … but … not that simple.

"Usual" DM candidates do not fit the positron data



Lavalle++ 08

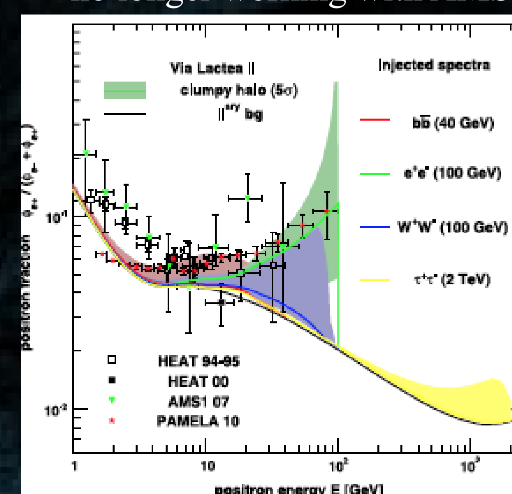
Main generic points:

* Annihilation cross section too small

* Associated antiproton flux prevents large positron flux

=> boost annihilation rate
=> suppress antiprotons < 100GeV

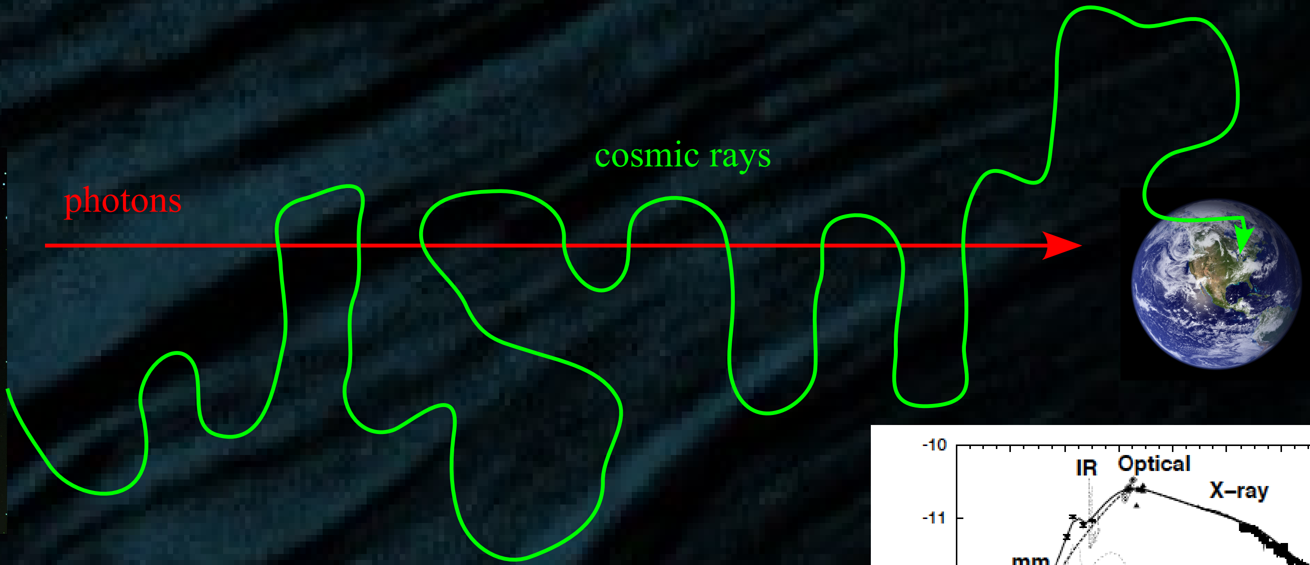
Example: could fit PAMELA data with 100 GeV DM → e+e- (small boost from DM subhalos).
*** no longer working with AMS



Pieri, JL++ 11

Modeling the electron/positron sources?

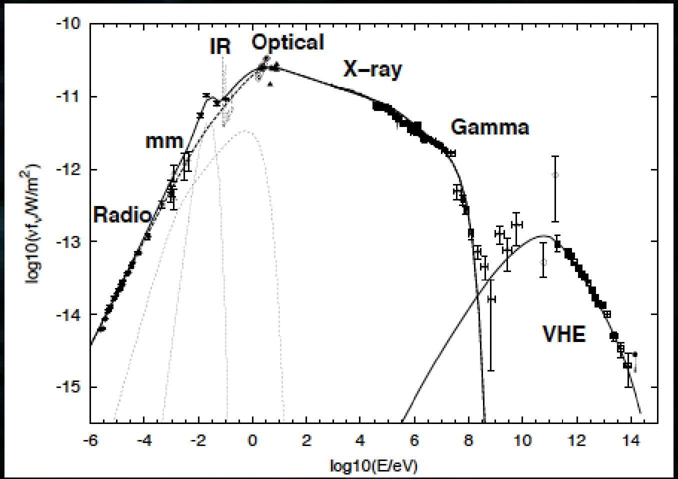
Crab nebula (ESA)
(just for illustration,
not relevant for e+/e-)



$$\text{photon obs. time} = \frac{d}{c} \approx 300\,\text{yr}\left[\frac{d}{100\,\text{pc}}\right]$$

$$\text{transport time} \approx \frac{d^2}{K(E)} \approx 30\,\text{kyr}\left[\frac{E}{1\,\text{TeV}}\right]^{-1/2}\left[\frac{d}{100\,\text{pc}}\right]^2$$

$$\text{E-loss time} = \int_E^{E_s} dE'\, b(E') \approx 300\,\text{kyr @ 1 TeV}$$



Horns & Aharonian (04)
Crab SED

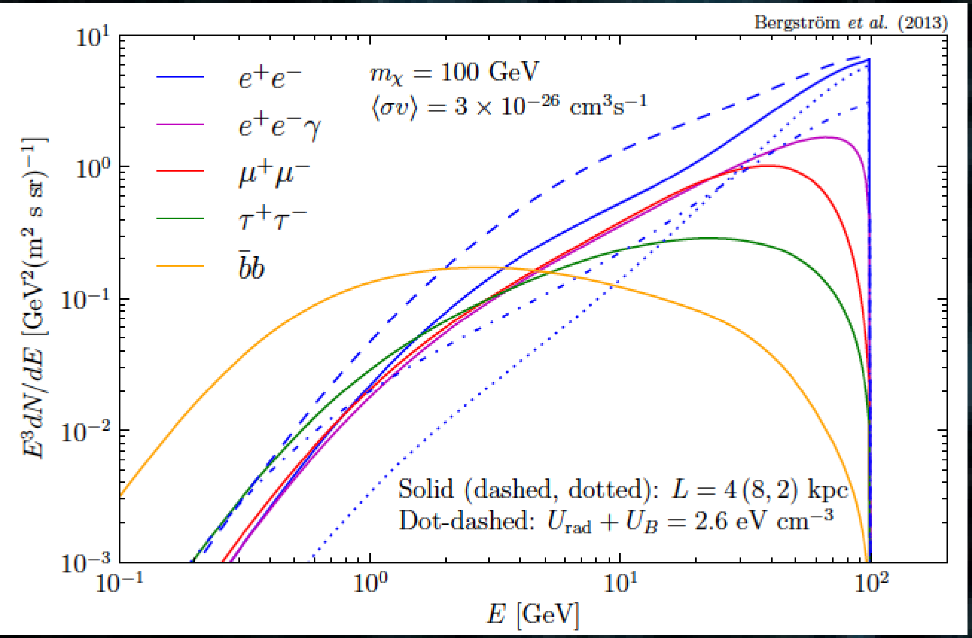
Different timescales:
1) E-loss time > source age > transport time
2) transport time >> photon time
=> cannot directly use photon data
=> requires dynamical models for sources (time evolution)

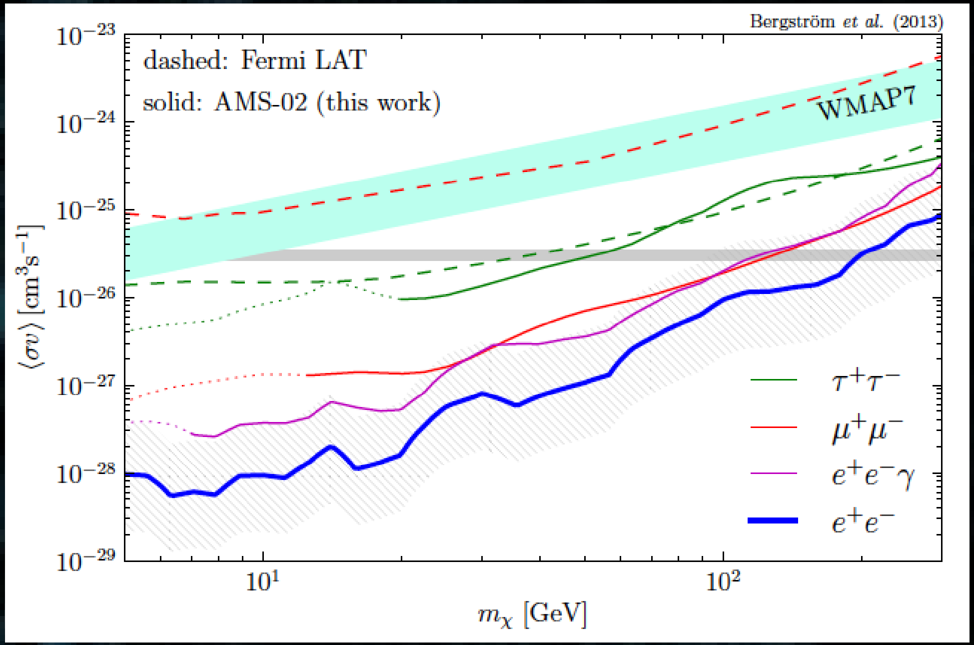
Very complicated problem:
1) photon data: CRs which are mostly still confined in sources (escape issue)
2) coupled evolution of magnetic fields and CR density

Some attempts at the source level (eg Ohira+ 10-11), but much more work necessary.

Upside down approach to positron data: the proper way to use them

Bergström++ 13





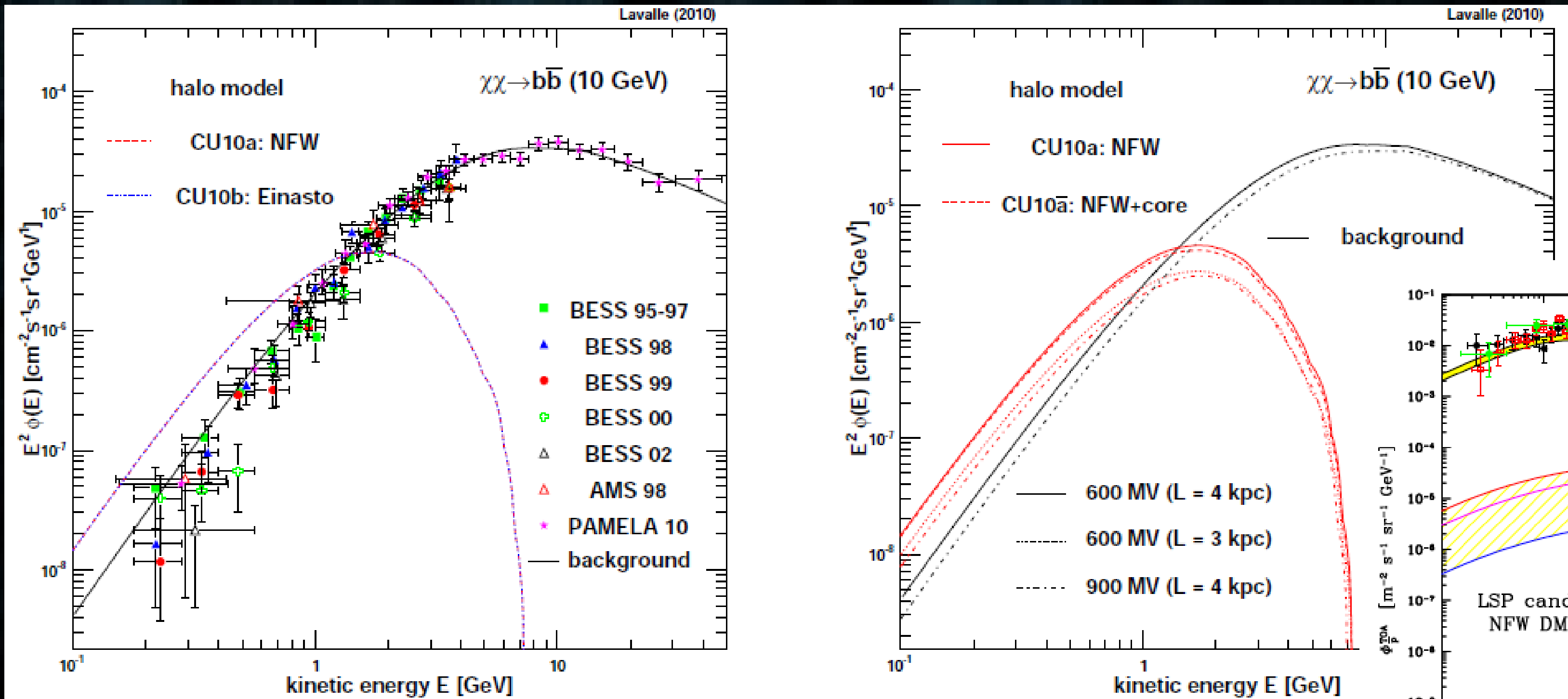
=> very competitive constraints on leptophilic models!

NB1: formally impossible to exclude DM contribution … BUT we know pulsars do exist (with the relevant properties) … you bet?

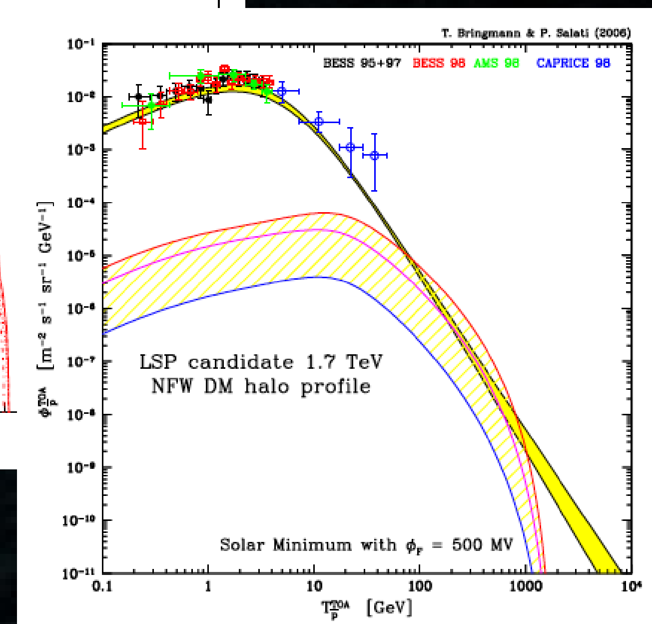
NB2: the answer will be clear sooner or later (the role of scientific research); still an interesting research line: any new contribution is encouraged!

Antimatter: antiprotons, antideuterons

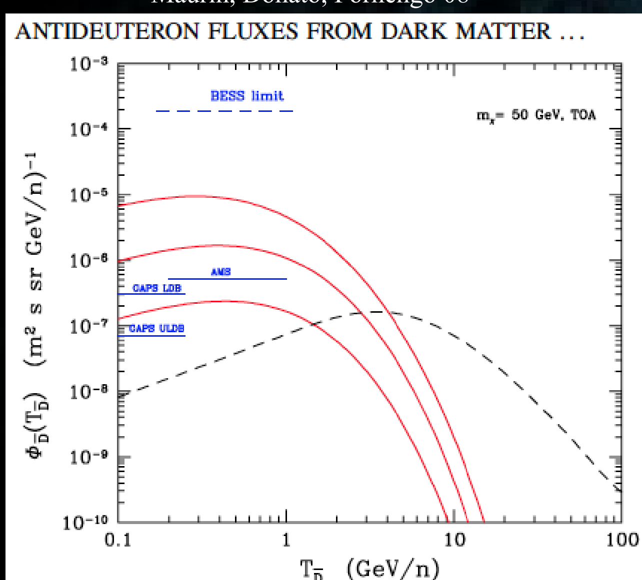
Lavalle 10



Bringmann & Salati 07



Maurin, Donato, Fornengo 08



Antiprotons:

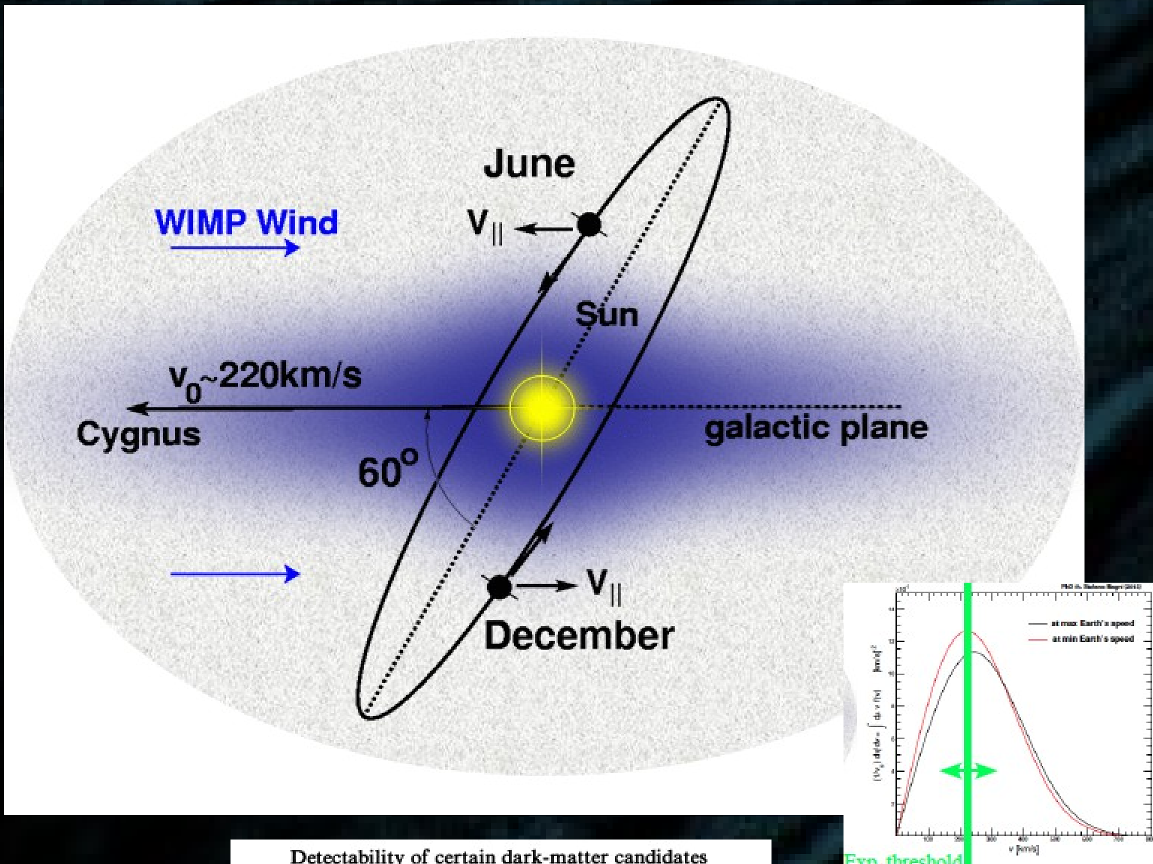
* constraints on WIMPs annihilating into quarks/heavy bosons
* Thermal WIMPs with masses < 20-30 GeV excluded
* Waiting for AMS-02 > 100 GeV
* Beware of possible astro contamination (secondaries created/accelerated at SNR shocks)!

Antideuterons:

* Interesting DM/bg ratio
* Correlated to antiproton signal
* Experimentally challenging (antiproton rejection)
* GAPS and AMS-02

Direct detection

Direct detection of DM



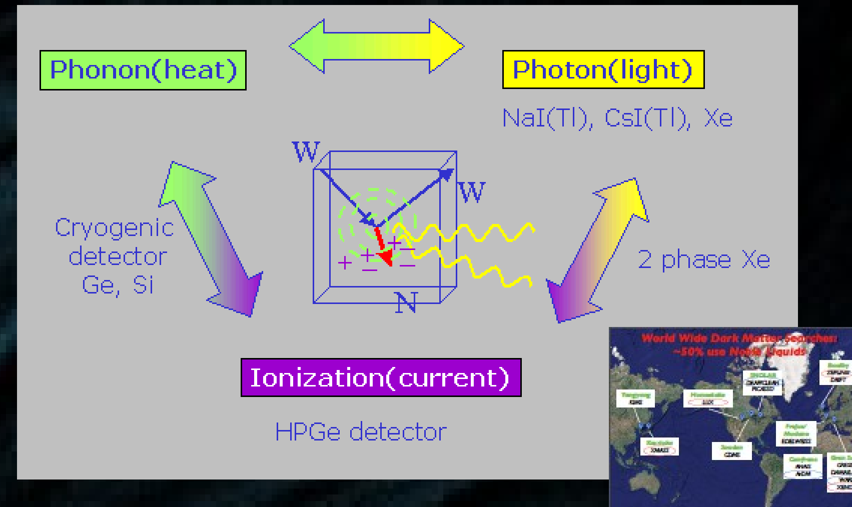
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

Direct detection (Goodman & Witten 85, Drukier++ 86)

Backgrounds: Cosmic-rays, radioactivity
=> deep underground shielded detectors

Smoking-gun signal: annual modulation (a few % of evt rate)
Drukier++ (86), Freese++ (88)
+ Cygnus direction



Different detection methods, different systematics:
Scintillation: DAMA, CRESST, XENON
Ionization : CDMS
Phonon (Ge): CDMS
=> discriminate electronic/nuclear recoils

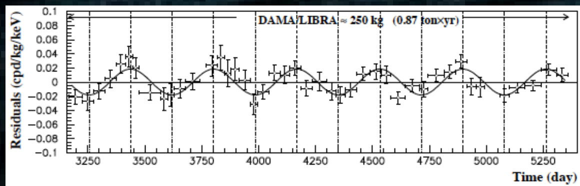
$$\sigma_{\chi-\mathrm{N}} \propto \begin{cases} \underbrace{\alpha_{\rm v}\,\bar\chi\,\gamma_\mu\,\chi\,\bar q\,\gamma^\mu\,q}_{\text{non-Majorana WIMPs}} + \alpha_{\rm scal.}\,\bar\chi\,\chi\,\bar q\,q & \propto A^2 \;\text{(spin-independent)} \\ \alpha_{\rm a-v}\,\bar\chi\,\gamma_\mu\,\gamma_5\,\chi\,\bar q\,\gamma^\mu\,\gamma_5\,q & \propto (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2 \;\text{(spin-dependent)} \end{cases}$$

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

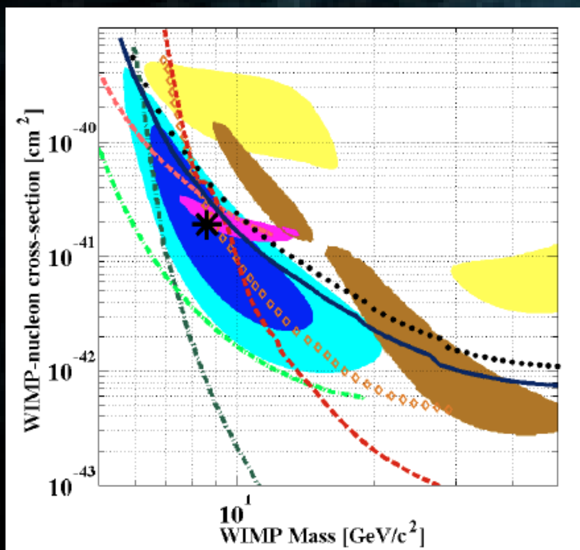
Local DD rate depends on local DM phase-space
(number density, velocity distribution)

Typical WIMP-nucleon cross section << 10^{-4} pb !!!!

Direct detection of DM: dazed hints

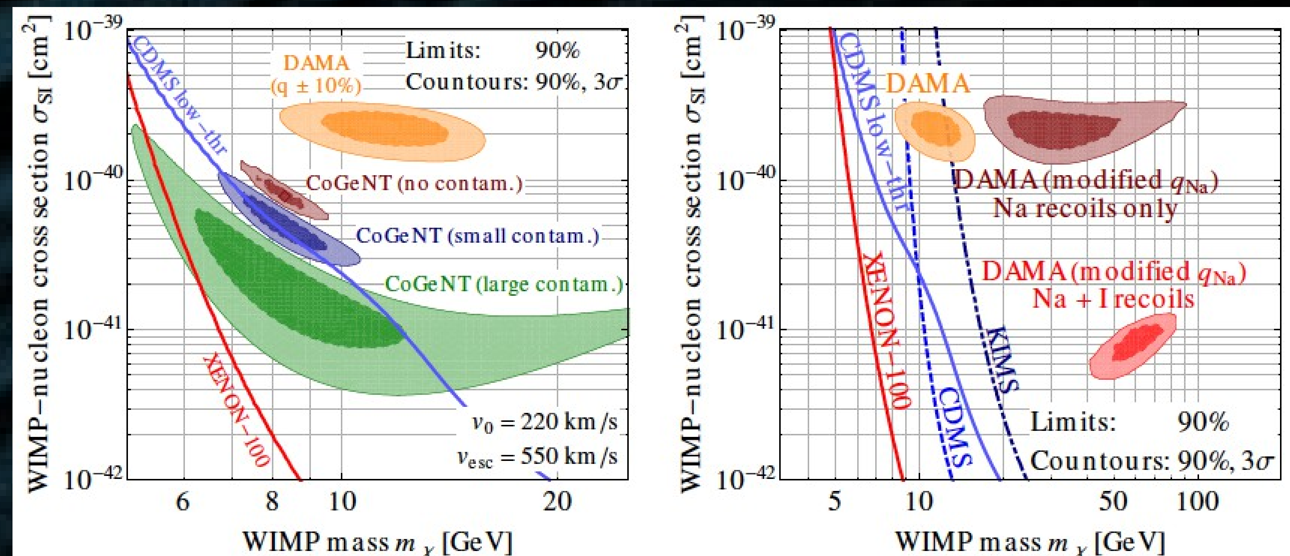


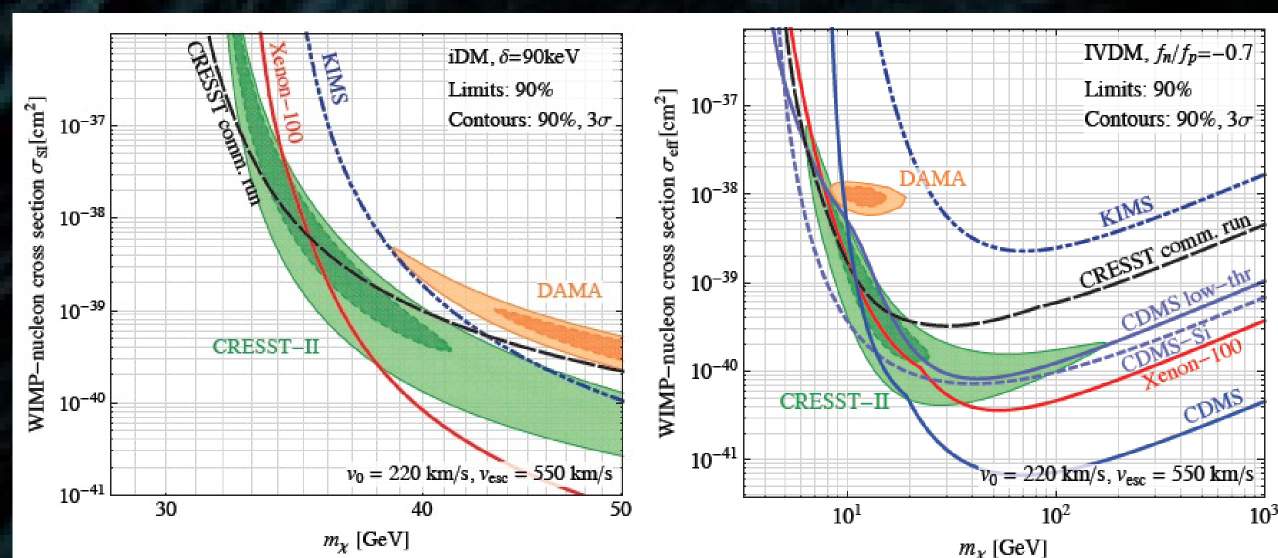
Annual modulation *detected* by DAMA
Bernabei++(98-13)



CDMS/Si (Agnese++ 13)
=> 3 evts / 0.41 +-0.2 +- 0.25 expected
=> 2-3 sigma “excess”

Kopp++ (11) – spin-independent analysis



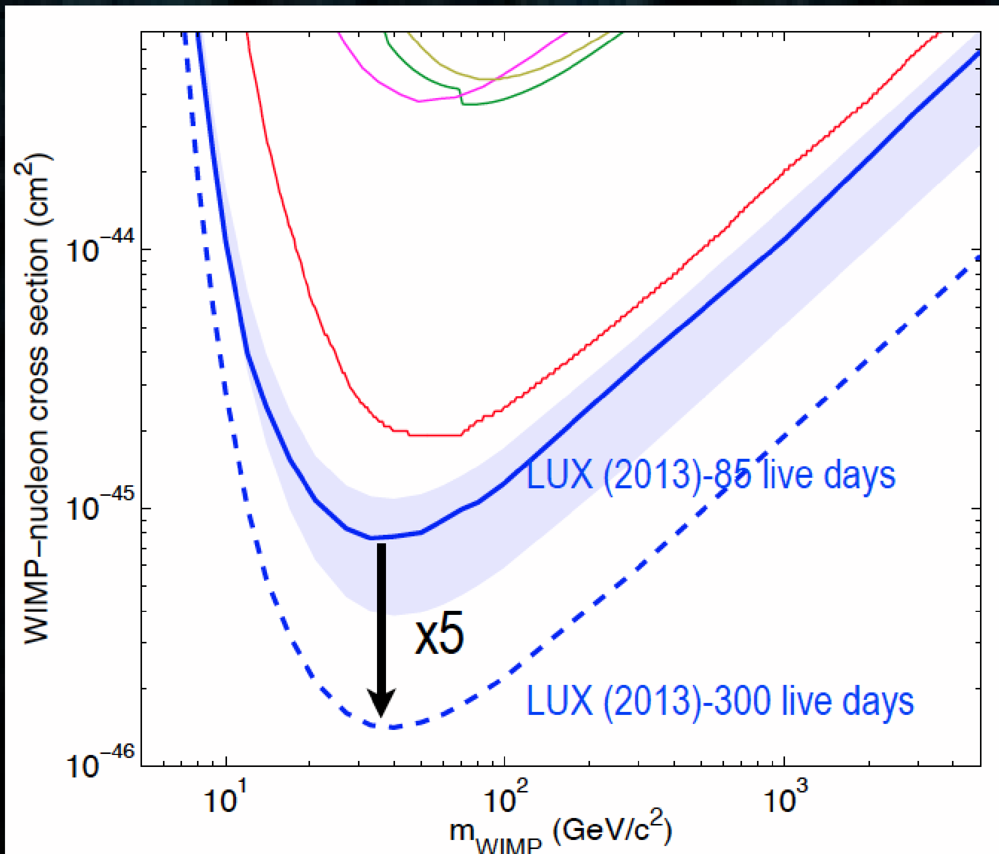


Two types of hints:

* Annual modulation:
Detection by DAMA, not confirmed
*Excess events: (low significance < 3 sigma)
CoGeNT, CRESST, CDMS/Si
**** But constraints by XENON-10/100
=> hard to reconcile/interpret

=> Exciting! (model-building not standard)
=> Close to threshold: large systematics
=> need more data!

Direct detection of DM: dazed hints

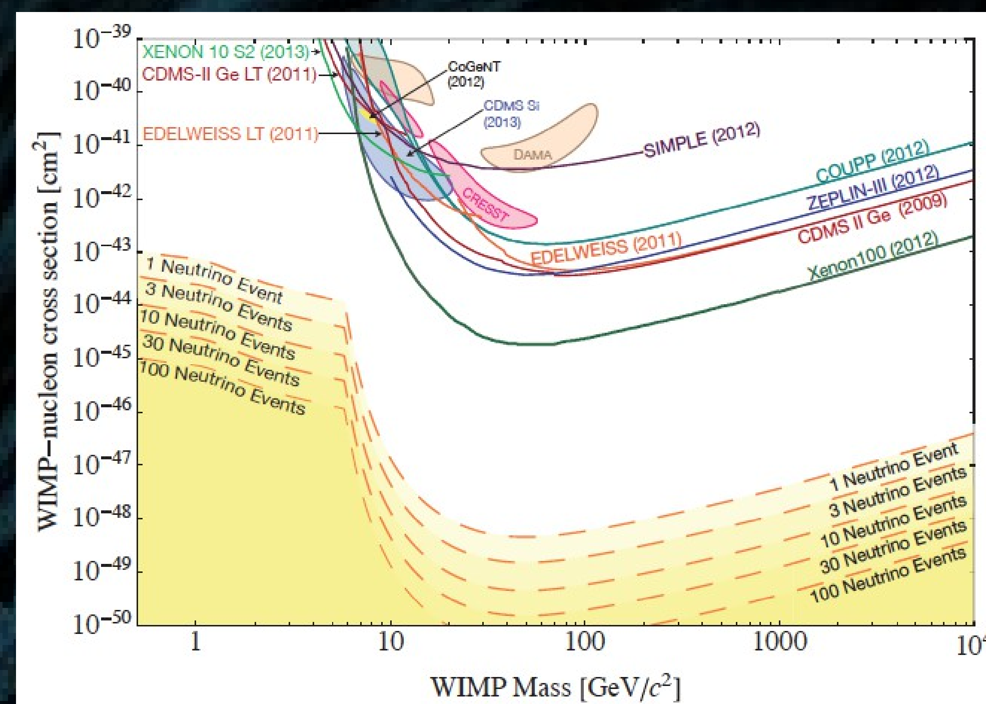


LUX collab.

Impressive sensitivity reached by LUX.
=> rules out DAMA/CoGeNT/CDMS-Si regions
=> … but regions close to threshold

XENON 1t is coming soon

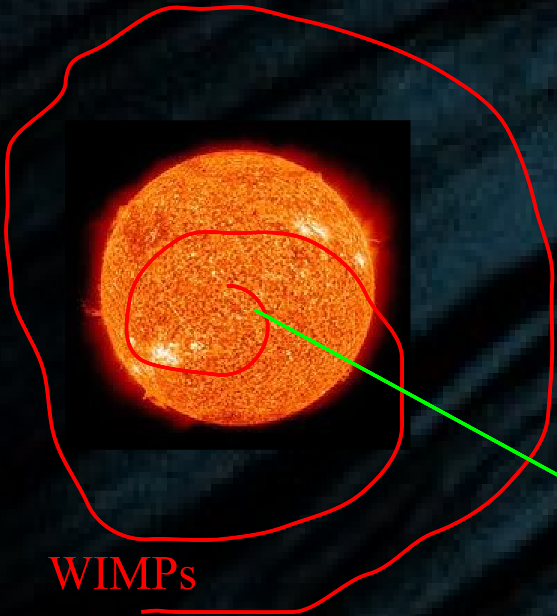
Billard++ 13



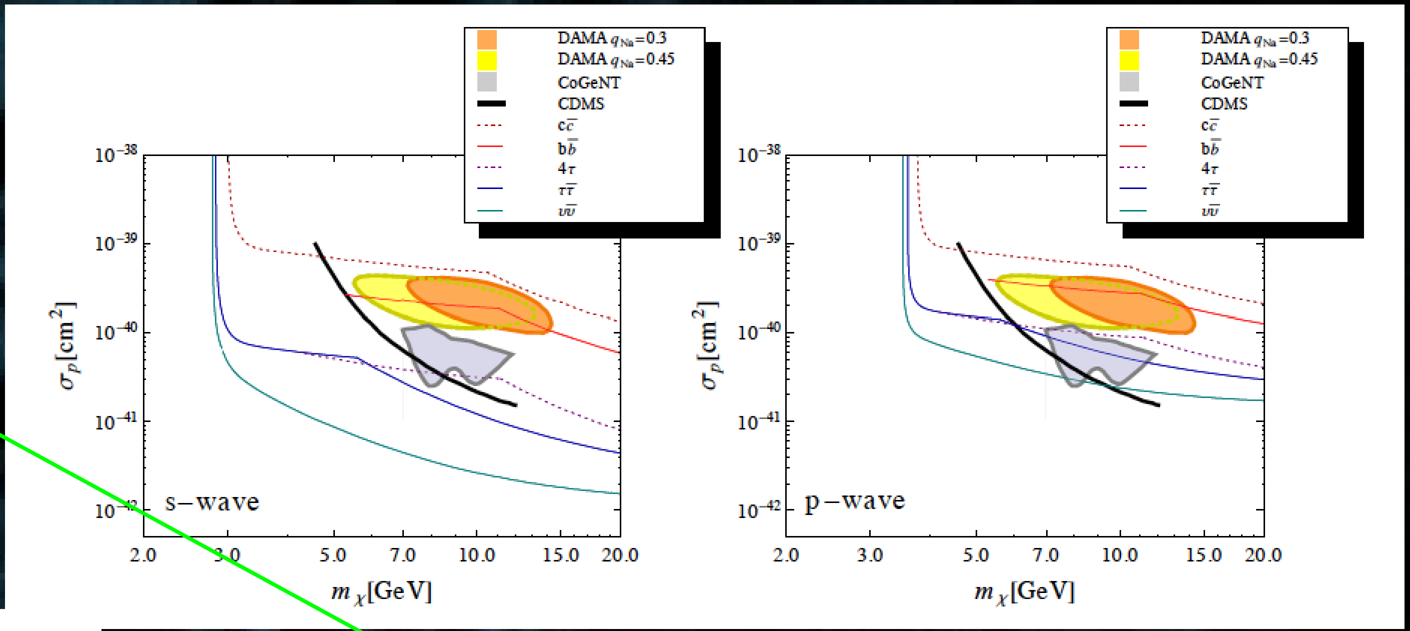
Recall that there are other WIP (not WIMPs): neutrinos!

=> irreducible background for direct detection

Neutrinos from the Sun (clean DM signature)



Kappl & Winkler 11



$$\frac{dC_{\odot,i}}{dV} = \frac{\rho_\chi\, \rho_{\odot,i}(r)}{2m_\chi \mu_i^2}\, \sigma_i \int_0^\infty du\, \frac{f(u)}{u} \int_{E_{R,\min}}^{E_{R,\max}} dE_R\, |F(E_R)|^2$$

$$\dot{N} = C_\odot - A_\odot N^2 - E_\odot N$$

$$N = \sqrt{\frac{C_\odot}{A_\odot}} \tanh(\sqrt{C_\odot A_\odot}\, t)$$

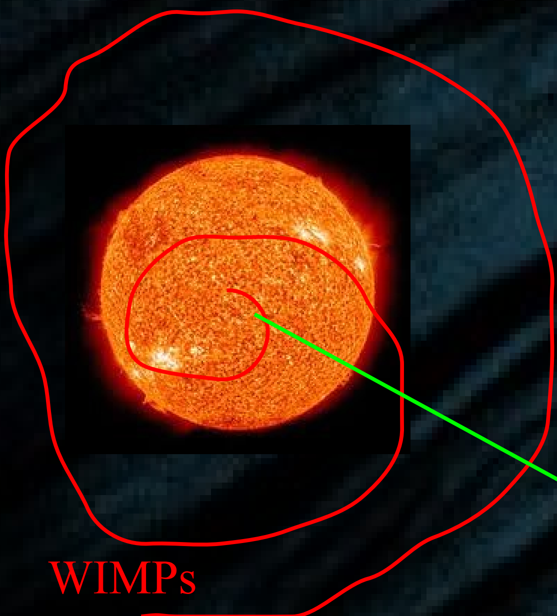
$$\Gamma_\odot = \frac{1}{2} A_\odot N^2 = \frac{1}{2} C_\odot \tanh^2\left(\sqrt{C_\odot A_\odot}\, t_\odot\right)$$

WIMPs captured in the Sun
(gravitation + elastic scattering off material)
=> can annihilate
=> at equilibrium: annihilation = capture rate

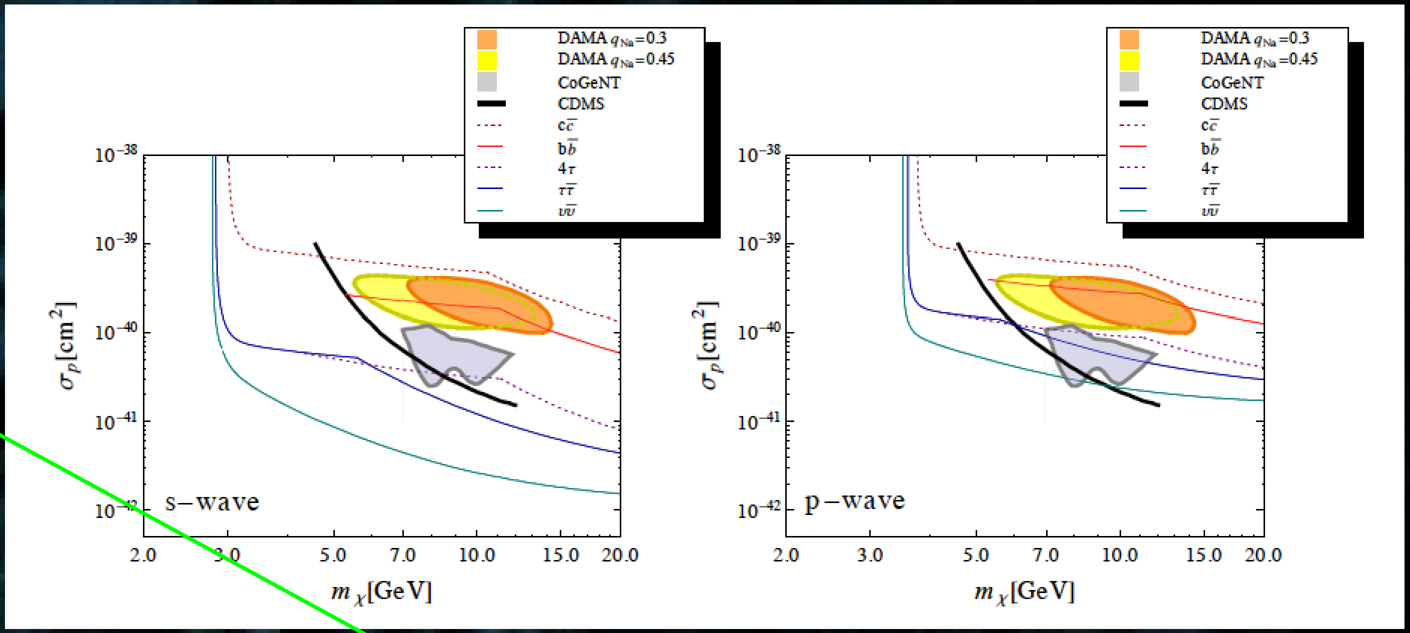
Super-Kamikande very powerful for GeV particles
Amanda/Icecube and Antares/Km3 only for WIMP masses > 50 GeV

→ Leptophilic WIMPs strongly constrained
→ Quarkophilic WIMPs survive

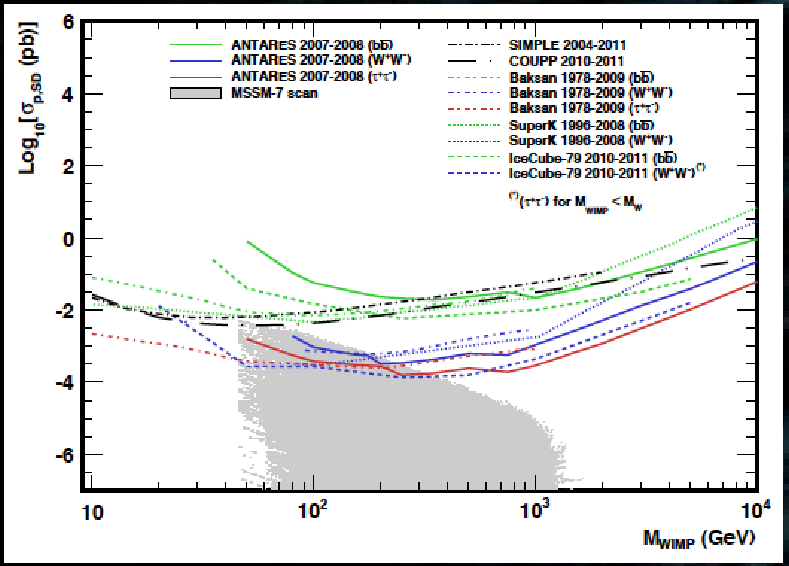
Neutrinos from the Sun (clean DM signature)



Kappl & Winkler 11



Antares collab. 13

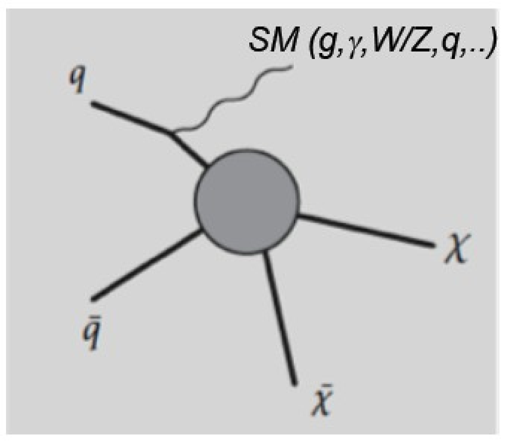


WIMPs captured in the Sun
(gravitation + elastic scattering off material)
=> can annihilate
=> at equilibrium: annihilation = capture rate

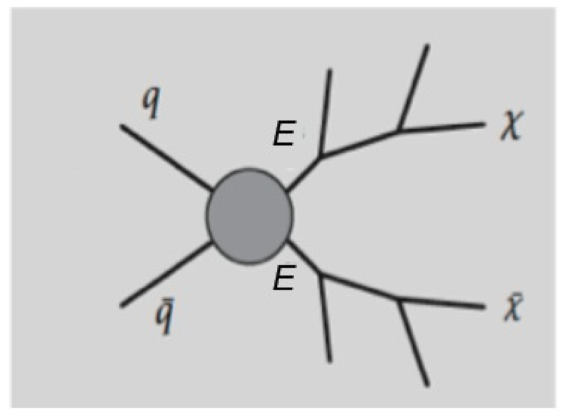
Limits on SD cross-section by Icecube and Antares.

Searches at colliders

Searches at colliders



More model independent



More model dependent

+ Searches for mediators
+ many others (e.g. invisible H decay, etc.)

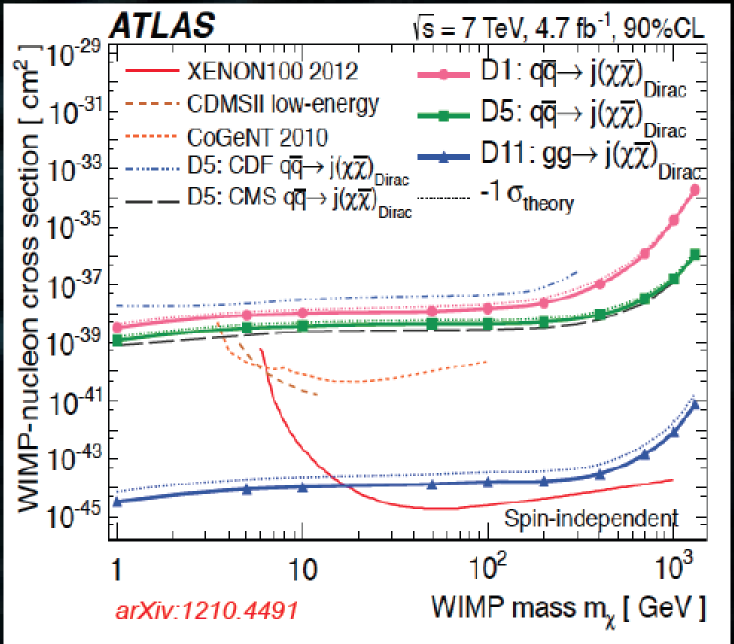
Searches at colliders

PRD 82, 116010 (2010)

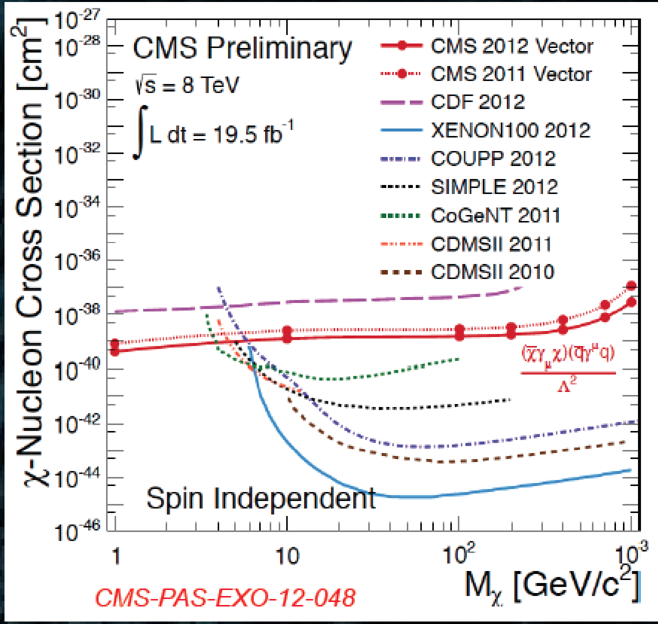
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Spin independent

Spin dependent



arXiv:1210.4491

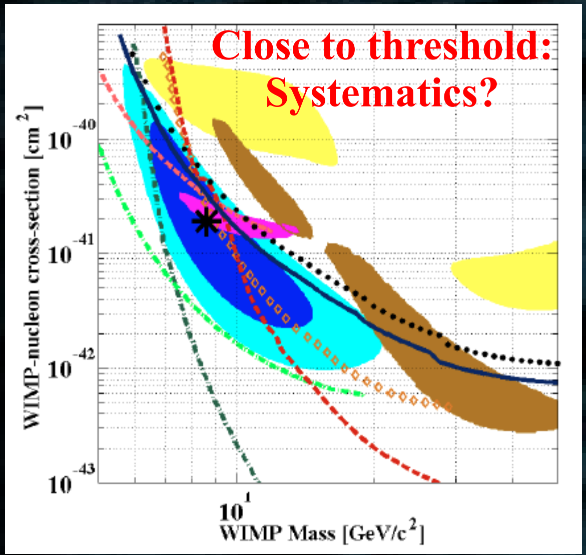


CMS-PAS-EXO-12-048

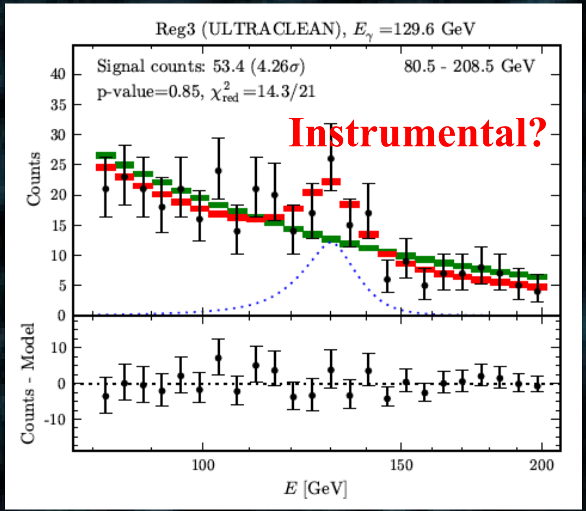
WARNING: contact operator assumption relies on mediator mass M>>E
=> ATLAS/CMS constraints on D1 not relevant for most DM models

More to come from 2015

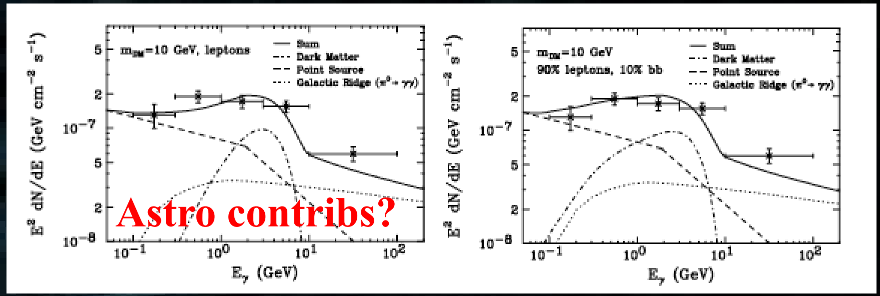
Has dark matter been discovered?



Agnese++ 13
DAMA, CoGenT, CRESST … + CDMSII(SI)
versus XENON-10, XENON-100
→ DM around 10 GeV



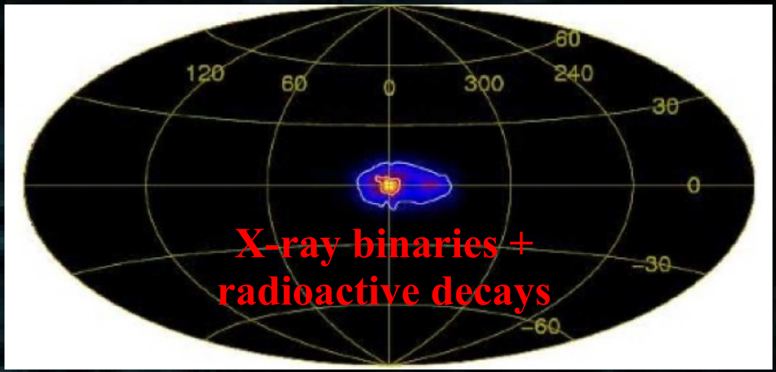
Around the GC
Weniger++, Finkbeiner++ 12
→ DM around 130 GeV



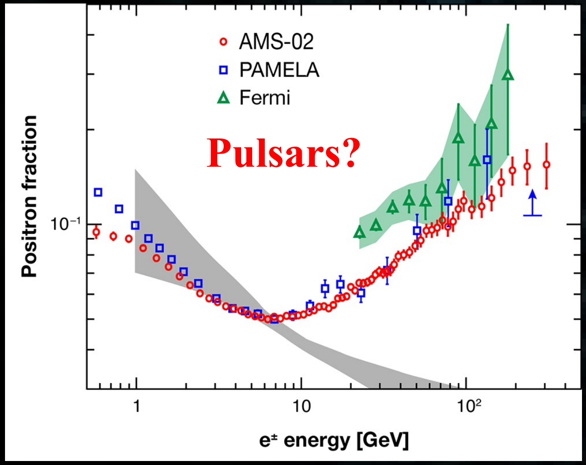
Hooper++ 12: gamma-rays + radio at GC
→ DM around 10 GeV

All point toward different mass scales :
1 MeV / 10 GeV / 130 GeV / 500 GeV

Hard to explain with a single DM candidate
(except maybe for XDM,
Weiner++ 04-12, Cline +, etc.)



511 keV, Knödlsëder/Weidenspointner++ 05 - 08
Boehm, Hooper++ 04 → DM around 1 MeV



HEAT/PAMELA/AMS positron excess
Bergström++, Cirelli++ 08 → DM around 300-1000 GeV

Summary

* Strong observational/theoretical motivations for the existence of DM particles.

* Potential hints from indirect searches, but large uncertainties.

* Hints from direct detection in the 10 GeV mass range (close to exp. thresholds!) to be checked by current future experiments. Strong constraints from LUX => very good detection prospects.

* LHC provides constraints on SUSY neutralino in MSSM (constrained or not) => MSSM can still provide 50 GeV WIMPs. Typically, neutralinos > *O* (100 GeV).

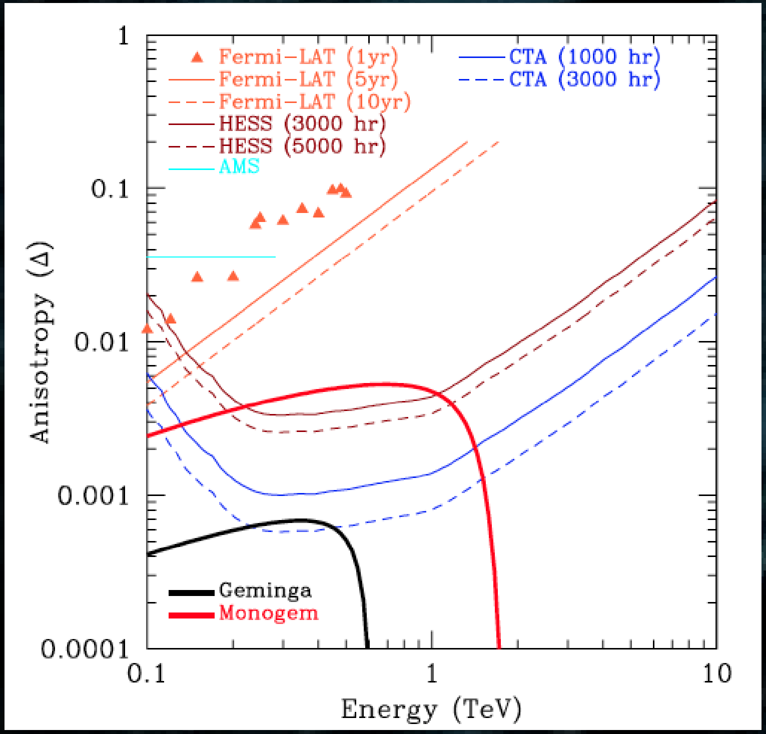
* Other theoretically motivated scenarios exist (lighter DM allowed): singlet+SUSY (e.g. NMSSM, sneutrino, excited DM, etc.

***** Complementarity of detection methods (indirect/direct/LHC) very important/efficient in probing WIMP parameter space.**

***** Many experiments in the race:**
*** Colliders: LHC (run 2 starting 2015 → 13 TeV)**
*** Indirect searches: Fermi, AMS-02, HESS-2 ++ CTA (+ radio, X-rays, etc.).**
*** Direct searches: many are already running, sensitivity will increase by 2 o.m. in 5 yrs.**

***** WIMP scenario likely discovered/excluded by 2020.**

Anisotropy as a test?



Linden & Profumo (2013)

Caveats:

* model-dependent (diffusion halo size again!)
* contributions of other sources (eg dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole
* multipole analysis necessary

Still:

* physically meaningful information
* should be provided for all CR species separately (eg positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS and CTA may reach the necessary sensitivity

Diffuse emission: a top bottom approach

Cosmological simulation:
self-consistent modeling of a galaxy (DM, gas, stars)

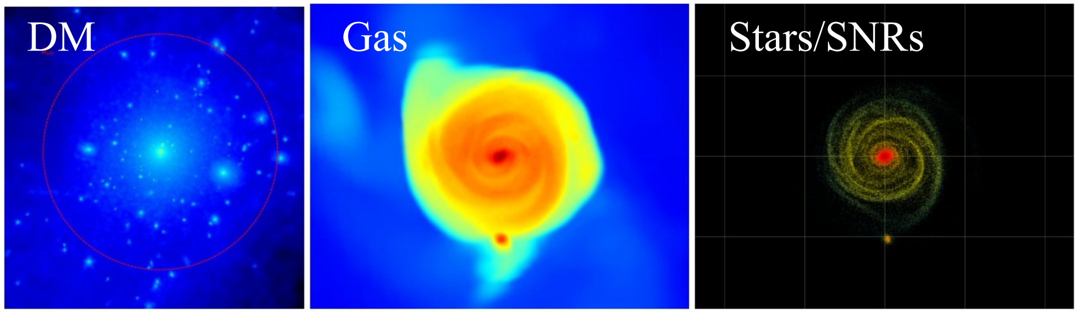


FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

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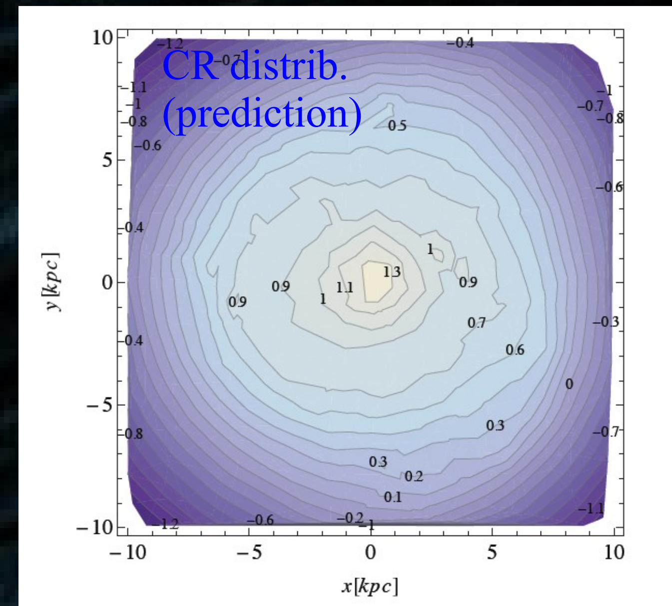
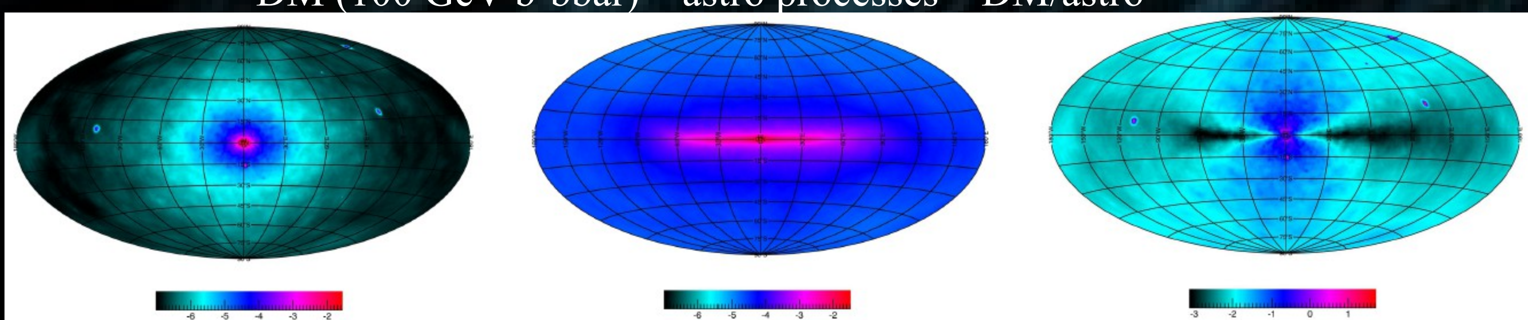


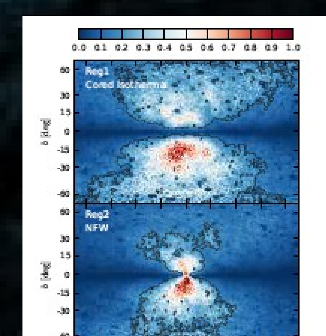
Skymaps:
DM (100 GeV b-bbar) – astro processes – DM/astro



Advantages:
* all ingredients are identified and localized (sources and gas)
* check the relevance of current assumptions

Limits: spatial resolution

=> preliminary results encouraging, work in progress



Compare e.g. with Weniger 12
(optimized region for 130 GeV line)