Dark matter round table discussion

Why a *table ronde*?

To create a space for informal discussion, in which

· We exchange ideas and debate interesting questions in DM physics.

· We discuss our ideas with other colleagues and get a second (or even first!) opinion about potential projects.

· We develop collaborations with other colleagues possessing complementary expertise.

The plan

For this first edition of the round table

· Seven colleagues will briefly present a topic of their choice and initiate a conversation.

· You are all encouraged to participate in the discussion!

Looking forward to your valuable feedback for future sessions!

Outline

- **Bradley Kavanagh** (LPTHE – Paris): Direct detection (TH)
- **Julien Billard** (IPNL – Lyon): Direct detection (EXP)
- **Geneviève Bélanger** (LAPTh – Annecy): Dark matter candidates (TH)
- **Marc Besançon** (IRFU – Saclay): Dark matter at the LHC (EXP)
- **Francesca Calore** (LAPTh – Annecy): Indirect detection – low-energy gamma-rays (TH)
- **Julien Lavalle** (LUPM – Annecy): Indirect detection – astrophysical aspects (TH)
- **Emmanuel Moulin** (IRFU – Saclay): Indirect detection – high-energy gamma-rays (EXP)

Bradley Kavanagh

LPTHE – Paris

Direct detection (TH)

Coming up with a *standard* for Direct Detection results/data…

…to aid *recasting* & *re-use* in the pheno community

Preliminary discussion and tools at:

https://github.com/bradkav/DirectDetectionStandard/wiki

or if you don't like typing:

tinyurl.com/terascale

Bradley J. Kavanagh (LPTHE), in collaboration with Jayden L. Newstead (ASU)

Julien Billard

IPNL – Lyon

Direct detection (EXP)

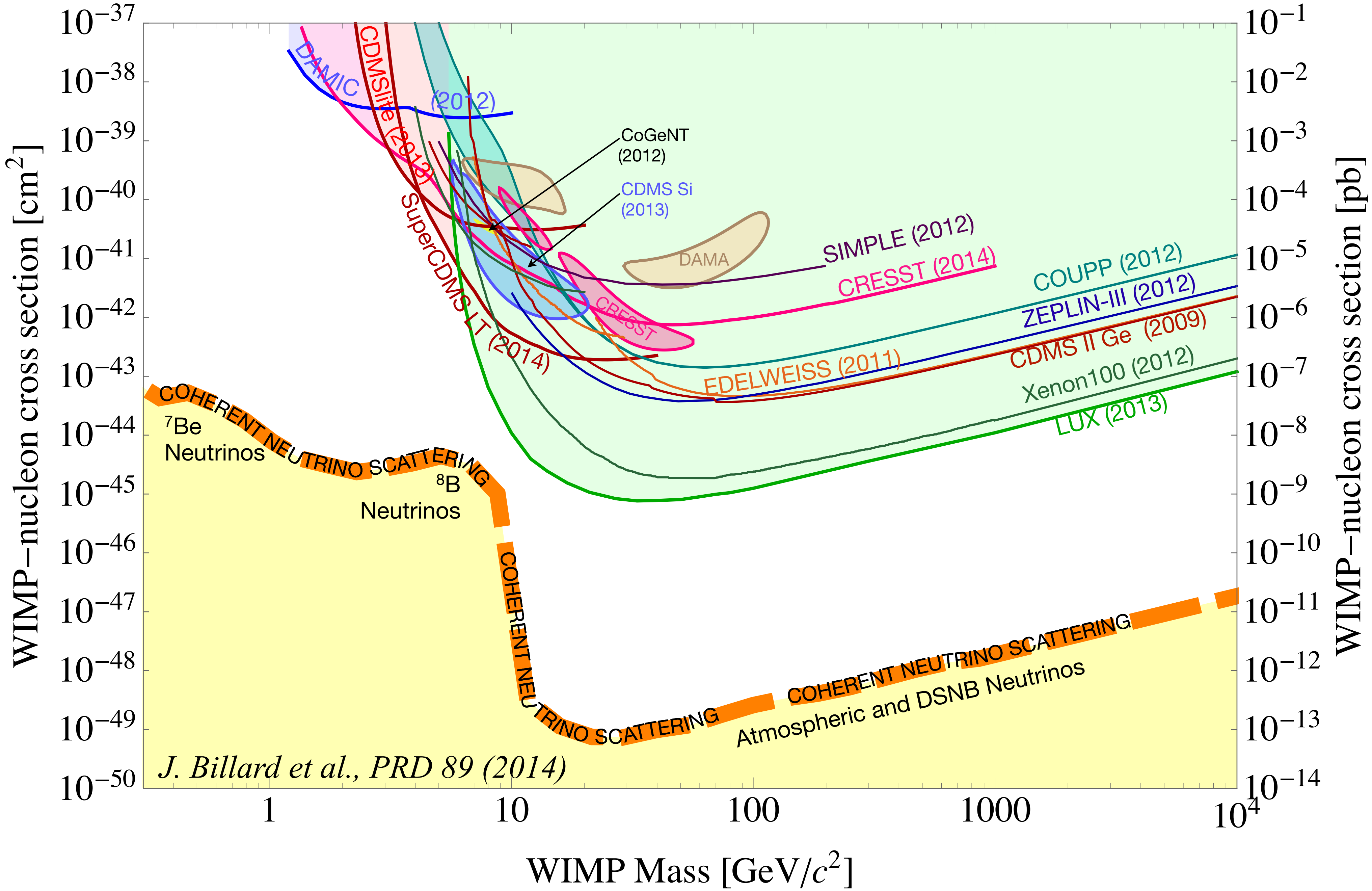
Round Table discussion: Low Mass Dark Matter

Julien Billard
Institut de Physique Nucléaire de Lyon / CNRS / Université Lyon 1

Based on: Dark Sector 2016 Workshop - arXiv:1608.08632

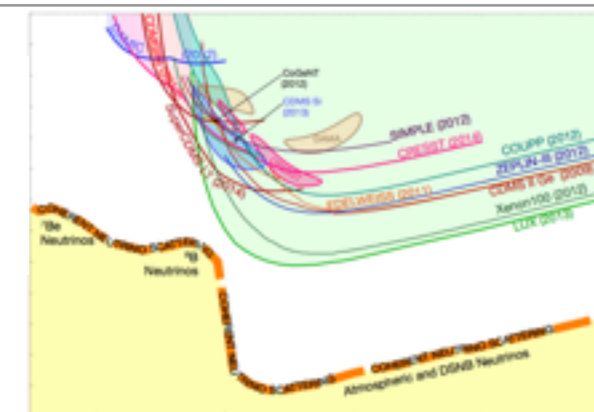
GDR Terascale
July 3rd, 2017

State of the art: standard WIMP searches



So far most of the efforts have been focusing on the standard GeV - TeV SUSY motivated WIMP, but nothing promising so far…

Beyond the ***Nuclear Recoil*** signature

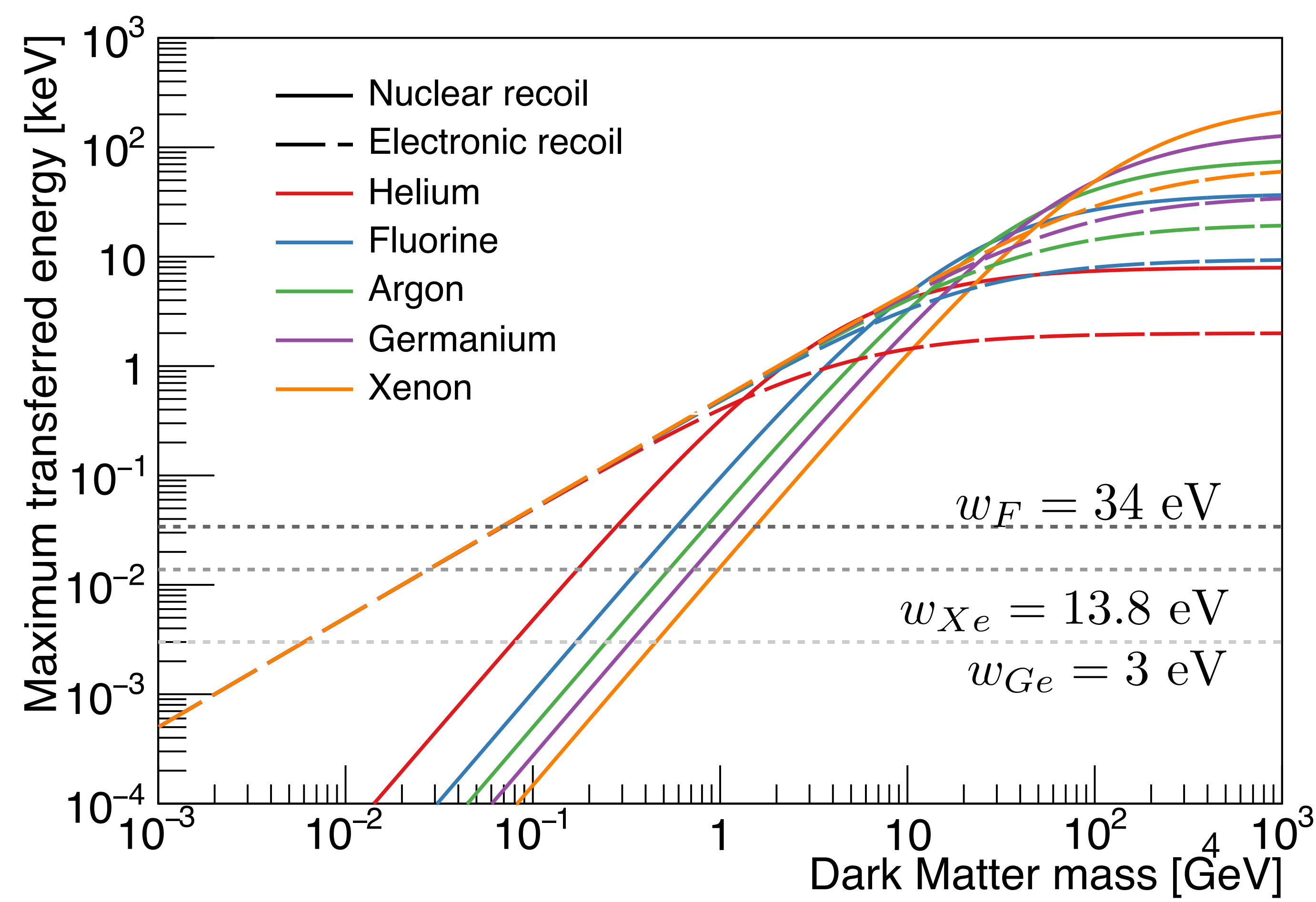


1 keV — 1 MeV — 1 GeV — 100 TeV

Electronic Recoils | **Nuclear Recoils**

For Light DM kinematics favors ER:

- Maximum NR energy: $E_r^{\max} \to 2v^2 \dfrac{m_\chi^2}{m_N}$
- Maximum ER energy: $\Delta E_e^{\max} = \dfrac{1}{2}\mu_{\chi N} v^2$
- Limited by electron binding energy (*threshold*)
    - Gas (~30's of eV)
    - Liquid (~10's eV)
    - Semiconductor (~ few eV)
    - Supraconducting metals (~ few meV)



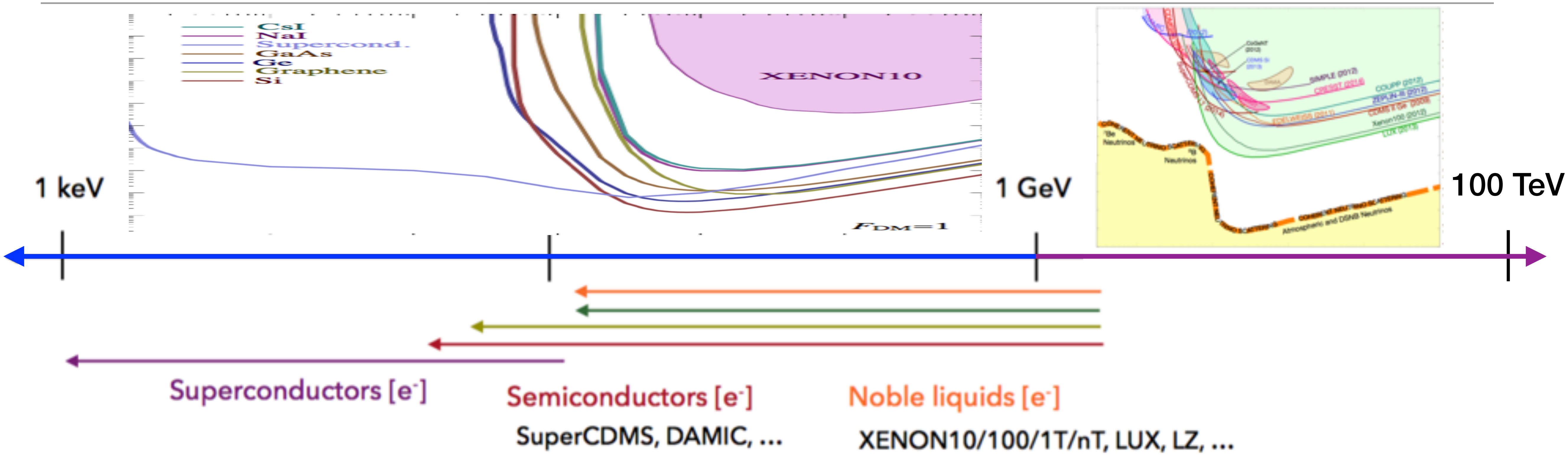
Julien Billard (IPNL)

Beyond the ***WIMP*** paradigm

The WIMP candidate only covers a small fraction of the possible phase space !

- Cosmological constraints motivate searching for DM as light as keV (structure formation)
- Requires new dark sectors with the existence of new light bosons connecting the dark (hidden) sector to the Standard Model
- Excellent probe for new physics beyond the Standard Model (and outside SUSY)

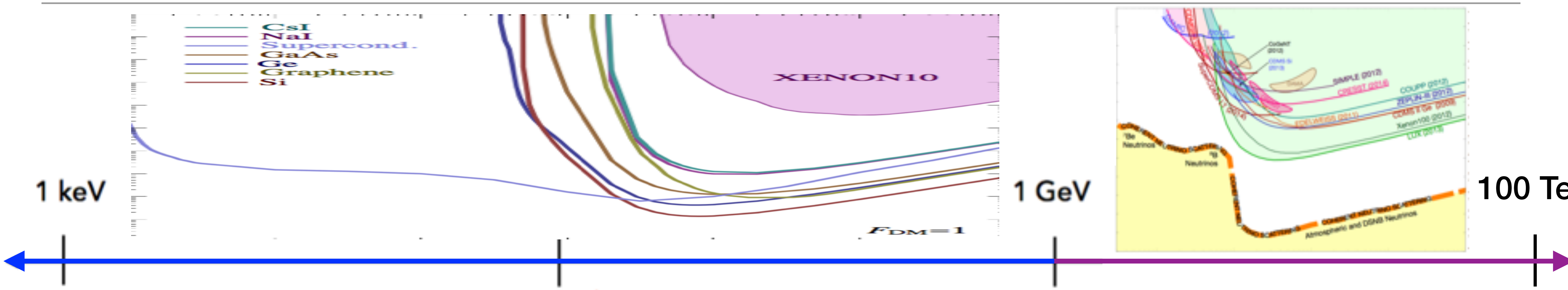
Few experimental examples



- **Noble liquids (14 eV):** sensitivity to single electron from S2 only analysis demonstrated (first experimental limit on these new searches)
- **Semiconductors (~3 eV):**
  - ionization only in Si (DAMIC/SENSEI): sub-single electron demonstrated
  - ionization + heat in Ge (SCDMS and EDELWEISS): yet to be demonstrated
- **Supraconductors (~meV)**: R&D has yet to be started (at least for that specific purpose)

For all of these techniques: unknown backgrounds and calibration challenges ahead !!!

Toward new possible ways to collaborate…



- **From the theory side:**
  - Are these new searches useful / meaningless ?
  - Do we have candidates that can be reachable, not only threshold wise, but from their cross-section and expected interaction rates ?
  - Where should we focus our effort on (parameters scans, new « focus point ») ?
- **From the experimental side:**
  - In France most existing DD technology are represented, can we collaborate more on common issues: **low** background, **low** noise electronics and readout techniques and **low** energy calibration methods ?
  - All existing technologies have *pros’* and *cons’*, could we think of a new alternative technology dedicated to these searches ?

Geneviève Bélanger

LAPTh – Annecy

DM candidates (TH)

Dark matter models and light particles

- Much emphasis on 100GeV Wimps for astroparticle/collider studies
- But candidates with mass below GeV scale are also possible, light wimps or light FIMPs …
- Moreover many models propose light mediators

- Project : investigate new dark matter models with GeV scale new particles and their phenomenology : relic density, direct detection, high intensity frontier, cosmology, colliders

Freeze-in

- DM particles are NOT in thermal equilibrium with SM
- Recall

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left((n_\chi)^2 - (n_\chi^{eq})^2\right)$$

Depletion of χ due to annihilation

Creation of χ from inverse process

- Initial number of DM particles is very small

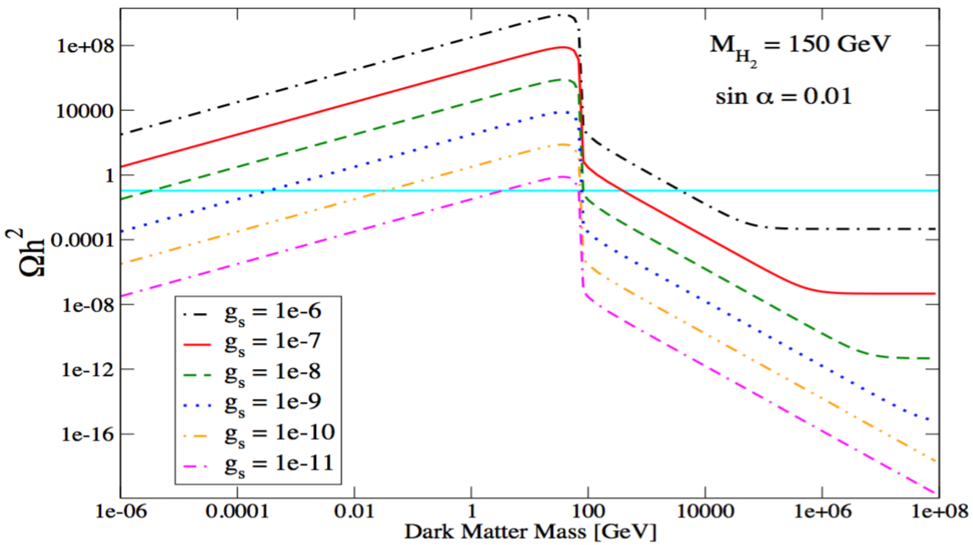
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}(T) n_{eq}^2(T) + n_{eq}(T)\Gamma_{Y\to\chi\chi}(T)$$

annihilation

Decay
(X,Y in Th.eq. With SM)

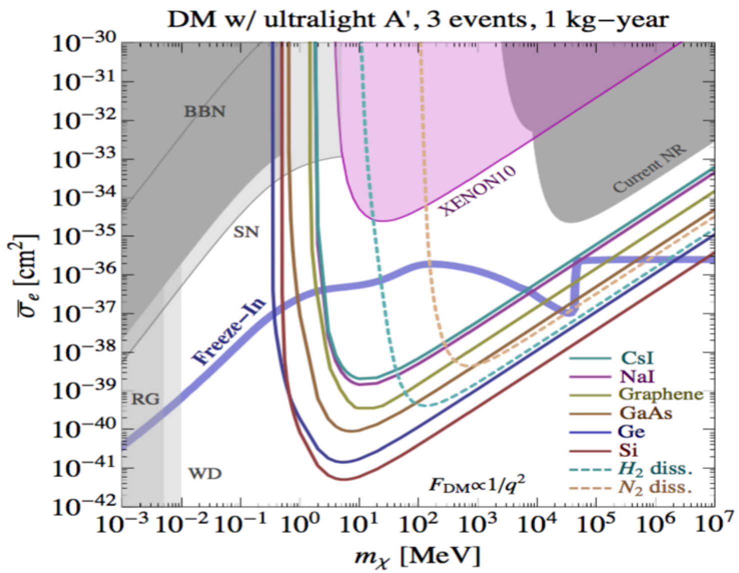
A simple example

- Simplified FIMP model : SM+ majorana fermion (DM) + real scalar + Z_2 symmetry (Klasen, Yaguna, 1309.2777



- Light wimp (30 MeV) affect CMB - number of equivalent neutrinos- and BBN - Nollett, Steigman 1312.5725
- Other cosmological constraints : dark sector sensitive to primordial initial conditions in freeze-in
- Direct detection : new projects to search for very light DM with new materials e.g. semiconductor, superconductors, exploit DM-e- scattering others DM -nucleus

Alexander et al, 1608.08632



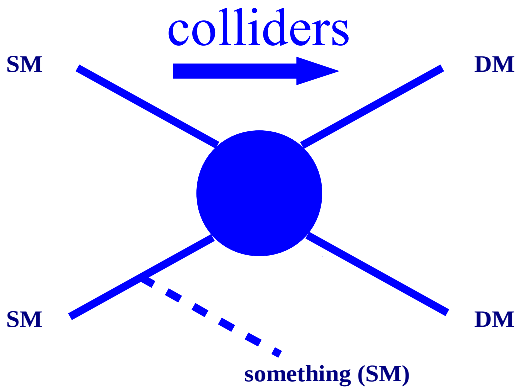
Marc Besançon

IRFU – Saclay

Dark matter at the LHC (EXP)

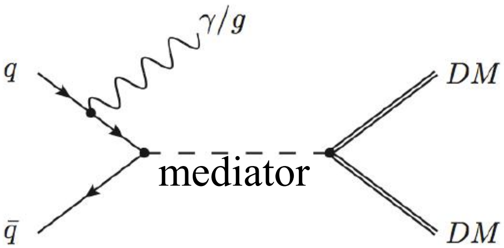
Dark Matter round table

DM searches at the LHC



- **MET + X searches**

- **invisible Higgs boson decay**



- **interpretation in terms of simplified models**

  4 parameters : DM mass , mediator mass ,
  mediator coupling to SM, to DM

- **direct search for mediator (dijet)**

- **comparison with Direct and Indirect Detection (DD, ID)**

Marc Besançon

Dark Matter round table

DM searches at the LHC

- MET + X , mediator direct search and invisible Higgs searches to continue at the LHC at Run2, Run 3 … as well as interpretation within simplified models

improving on many items e.g. :

- reducing syst. uncertainties (e.g. Z+jet,/W+jet ratio in monojet)
- backgrounds (NLO V+jets)
- mediator width
- comparison with DD (ID) e.g. running coupling from LHC to DD scales
- "conventional" simplified model interpretations

  model buiding with DM, mediator and interactions (SM gauge charge for DM and mediator)

  and spin of DM (0, 1/2 , 1 , 3/2) , spin of mediator (0, 1/2 , 1 , 2), interaction of mediator to DM/SM
- ……

- "conventional" simplified DM models → non conventional simplified models ?
  - e.g. Dark gauge symmetry (dark U(1), SU(N)) ? Thermal DM ? Hidden valley via Higgs portal ? others ?
  - additional signatures to search for DM at the LHC (displaced vertices/jets, emerging jets) ?
  - comparison with DD, ID ?

- continue searches in the context of more specific ("complete") models

Francesca Calore

LAPTh – Annecy

Indirect detection – low-energy gamma-rays (TH)

IRN Terascale@Montpellier

Dark matter round table

3rd July 2017

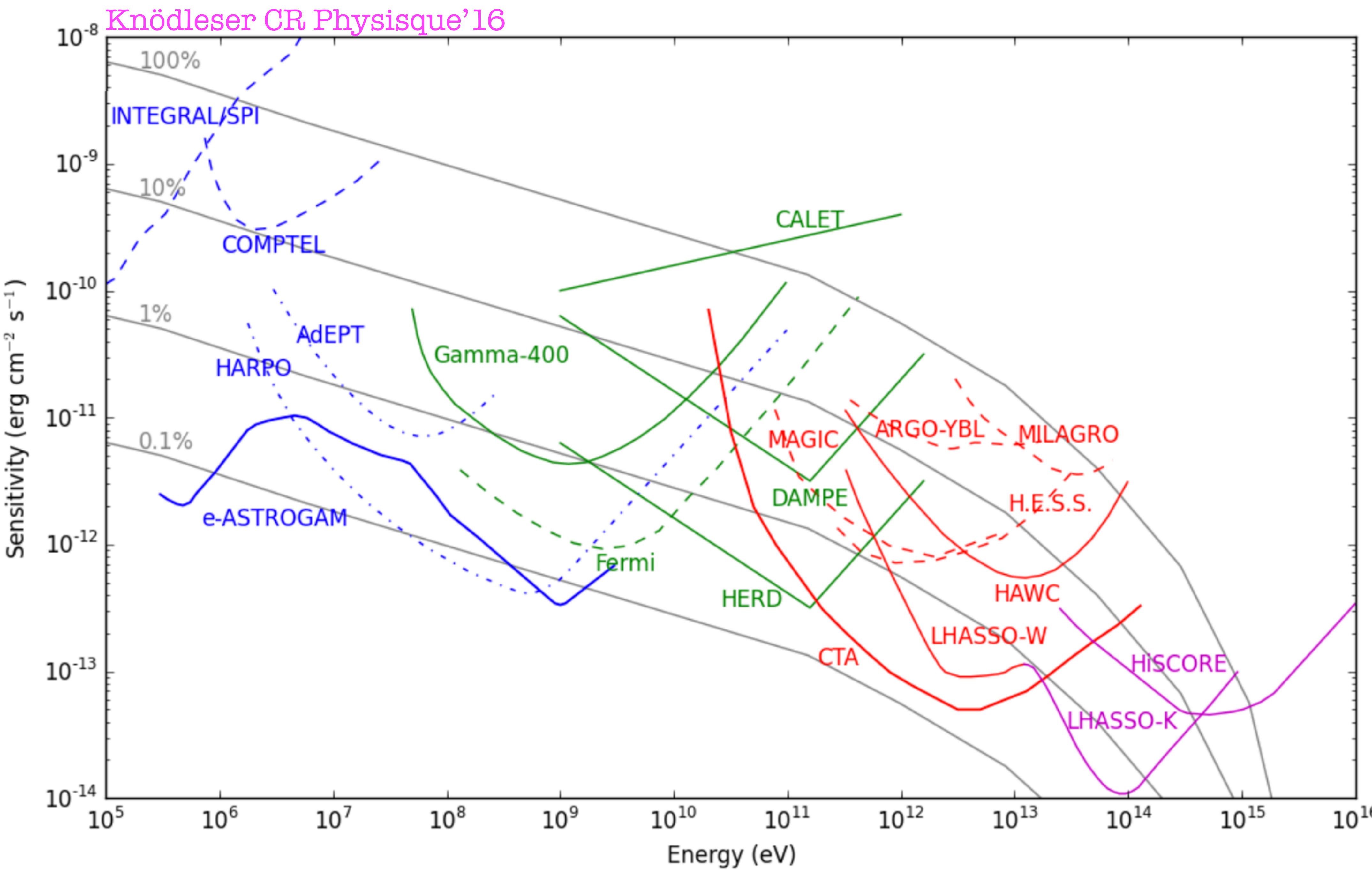
Dark matter searches with sub-GeV gamma rays

Francesca Calore — calore@lapth.cnrs.fr

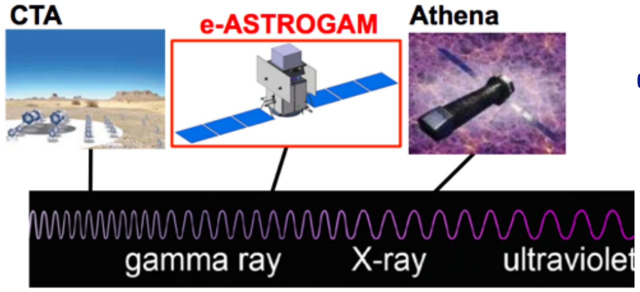
Laboratoire d'Annecy-le-Vieux de Physique Théorique

Université Savoie-Mont Blanc

The future of gamma-ray astronomy



Differential 5σ point source sensitivities of future gamma-ray instruments (for different observing times)

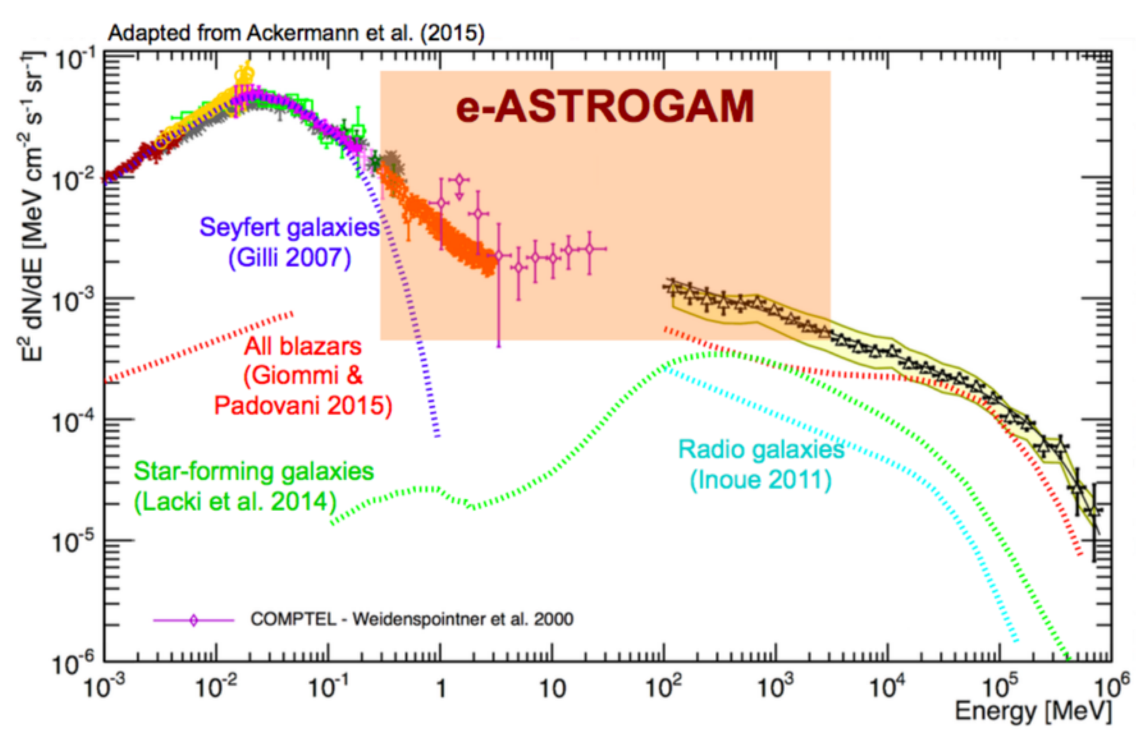


The sub-GeV gamma rays

	Compton domain		
	e-ASTROGAM	COMPAIR	ADEPT
Energy range [MeV]	0.3–10	0.2 – 10	–
$\Delta E/E$	1.3%	2%–5%	–
A_{eff} [cm^2]	50–560	50 – 250	–
FoV [sr]	2.9	3	–
	Pair-conversion domain		
	e-ASTROGAM	COMPAIR	ADEPT
Energy range [MeV]	10–3000	10–500	5–200
$\Delta E/E$	20–30%	12%	30%
A_{eff} [cm^2]	215–1810	20–1200	50–700
FoV [sr]	2.5	3	3

Energy range: 0.2 MeV — few GeV
O(10) improved energy and angular resolution
Large field of view (2.5 sr)
Able to detect photon polarisations for both transient and steady-state sources

[**AMEGO** mission, proposed for NASA]



sub-GeV dark matter gamma rays

Prompt photons

$$\chi\chi \to \gamma\gamma$$

gamma-ray line @ $E_\gamma = m_\chi$

$$\chi\chi \to \pi^0\gamma$$

$$\chi\chi \to \pi^0\pi^0$$

gamma-ray box

Boddy & Kumar, Phys. Rev. D92, 023533 (2015);
Boddy+ Phys. Rev. D94, 095027 (2016)

Radiative emission

$$\chi\chi \to \pi^+\pi^-$$

$$\chi\chi \to \ell^+\ell^- \quad \ell = e, \mu$$

$$\chi\chi \to \phi\phi \quad \phi \to e^+e^-$$

E.m. radiative corrections, in-flight annihilation, bremsstrahlung, inverse Compton

Bartels+, JCAP 05 (2017) 001

Other **spectral features** from:

- Quarkonium (monochromatic photons)

  Srednicki+ PRL 56, 263 (1986); Rudaz PRL 56, 2128 (1986)
- 4th generation quarks decay in s + photon (step-like)

  Bergström, Nucl. Phys. B325, 647 (1989)
- De-excitation of mesons (D,B) from bb, cc DM

  Bringmann+ PRD 95, 043002 (2017)

Constraints on MeV dark matter from CMB (s-wave) and BBN

Some open issues

Dark matter MeV/sub-GeV models

- Viable DM models @ MeV masses? [BBN, CMB, diffuse photons constraints]
- Other annihilation channels [e.g. relevance of EW corrections?]
- ALPs/photon coupling oscillations at low energies?

Radiative emission modelling

- Understanding low-energy CR propagation [almost no constraints from current data]

Astrophysical background and dark matter

- Resolving most of Fermi-LAT unassociated sources (spectrum E^{-2}) => Sensitivity to DM subhalos? [angular resolution]
- Discriminating nuclear gamma-ray lines from low energy CR vs DM spectral lines [angular resolution; spatial analysis]
- Discriminating origin of GeV excess (DM vs MSPs) based on spectral analysis [angular resolution]

Julien Lavalle

LUPM – Annecy

Indirect detection –
astrophysical aspects (TH)

Emmanuel Moulin

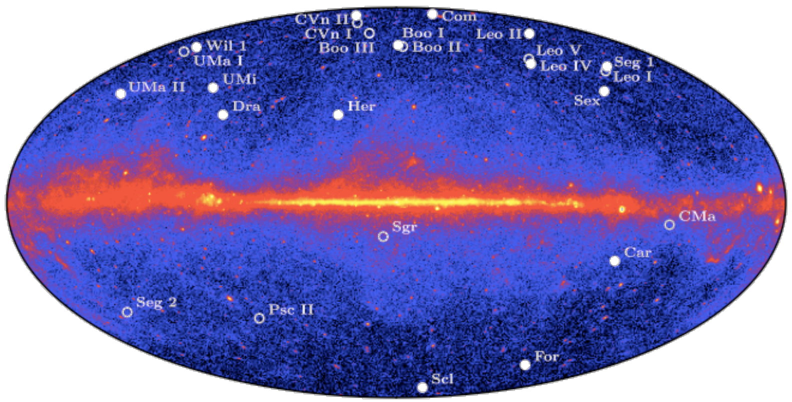
IRFU – Saclay

Indirect detection – high-energy gamma-rays (EXP)

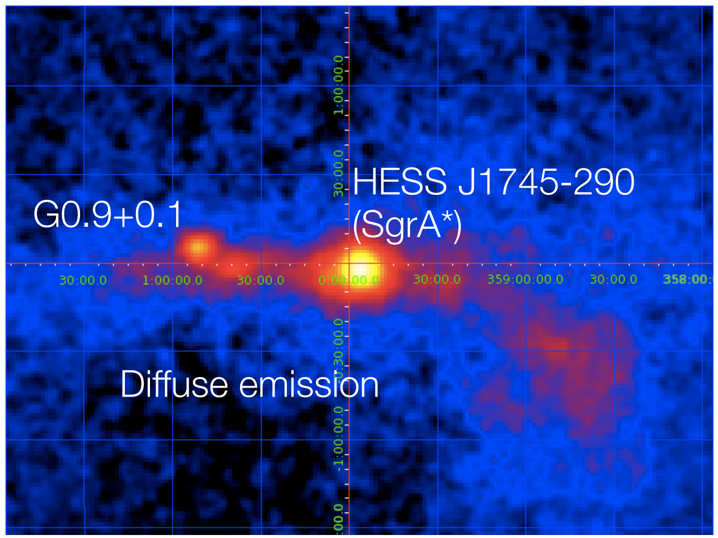
CEA - Saclay

Dark matter round table : Indirect detection with HE/VHE gamma-rays

Observations of nearby dwarf galaxies with Fermi-LAT



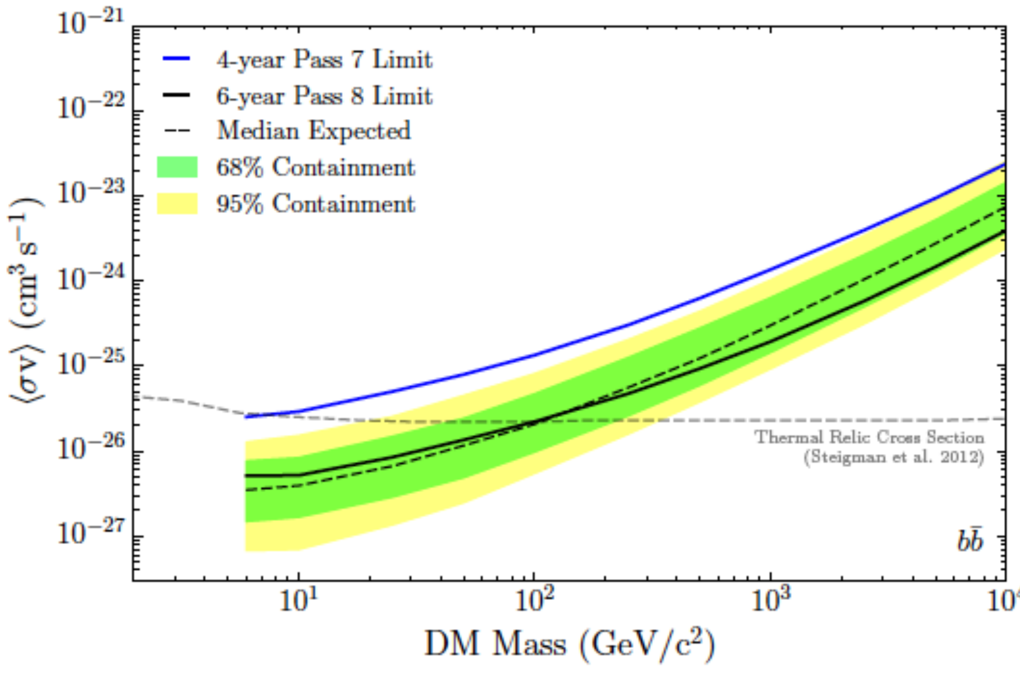
Inner Galactic halo observations with H.E.S.S.



- Dwarf galaxies: modest signal, potentially low background
- Inner Galactic halo : large signal, large background
    - Two complementary targets
- Strongest gamma-ray limits on annihilating dark matter

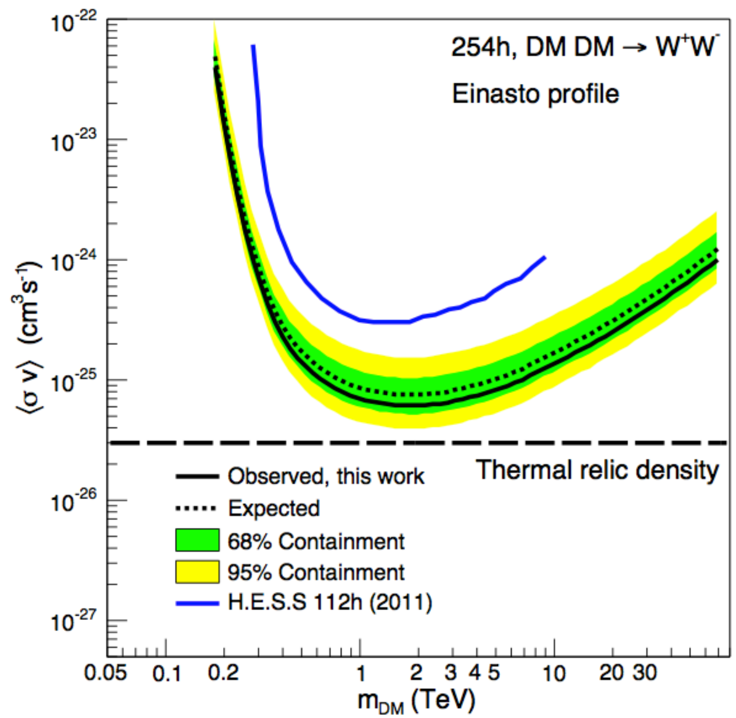
Dark matter round table :
Indirect detection with HE/VHE gamma-rays

Observations of nearby dwarf galaxies with Fermi-LAT



Fermi-LAT coll. PRL 115, 231301 (2015)

Inner Galactic halo observations with H.E.S.S.



H.E.S.S. Coll., PRL. 117, 111301 (2016)

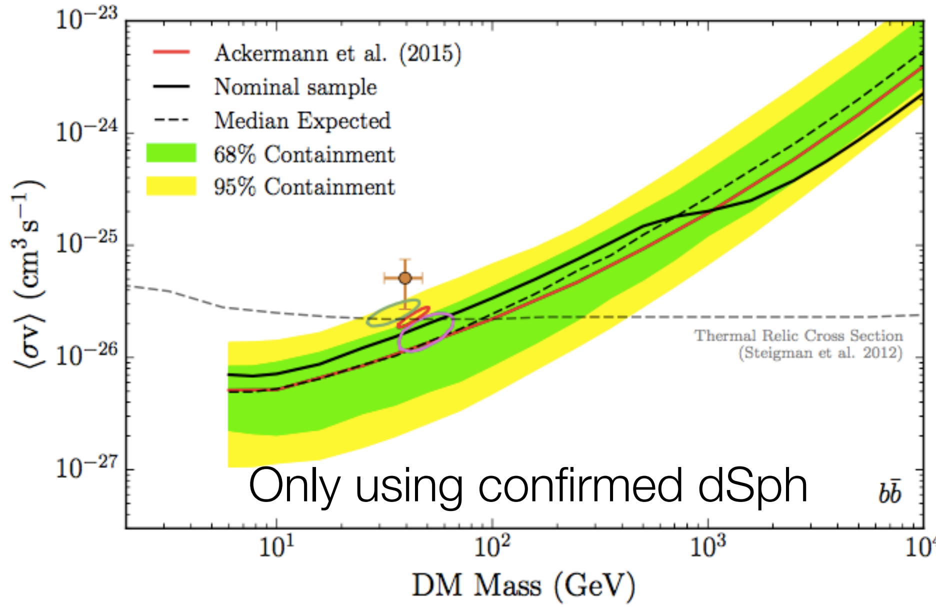
- Strongest gamma-ray limits on annihilating dark matter

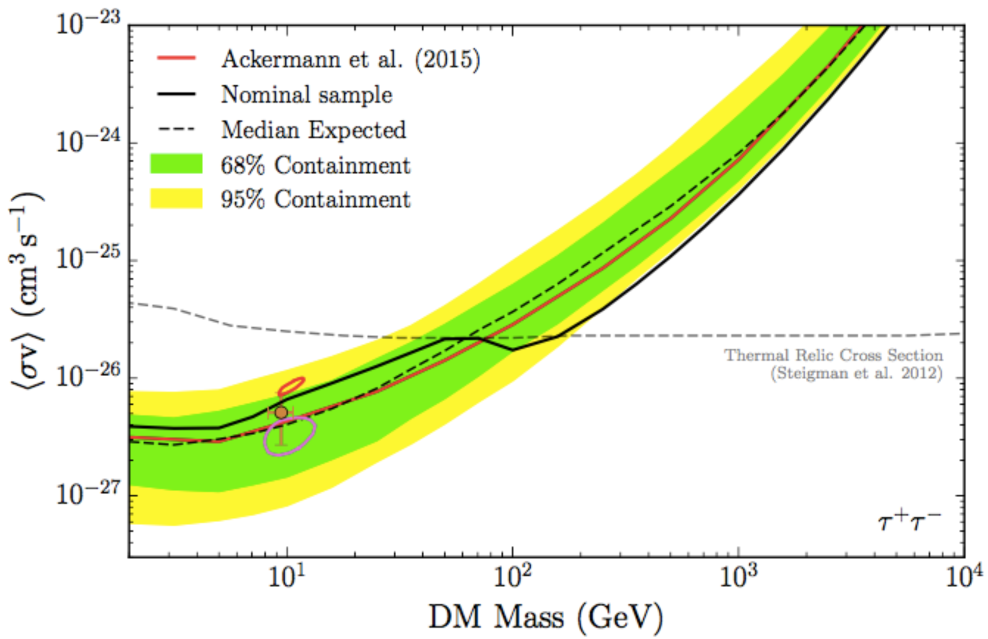
Dwarf Milky Way satellites

- New surveys ongoing
  - 45 stellar systems :
    28 confirmed dSphs and 17 newly discovered candidates by DES

Table 1
Confirmed and Candidate Dwarf Galaxies

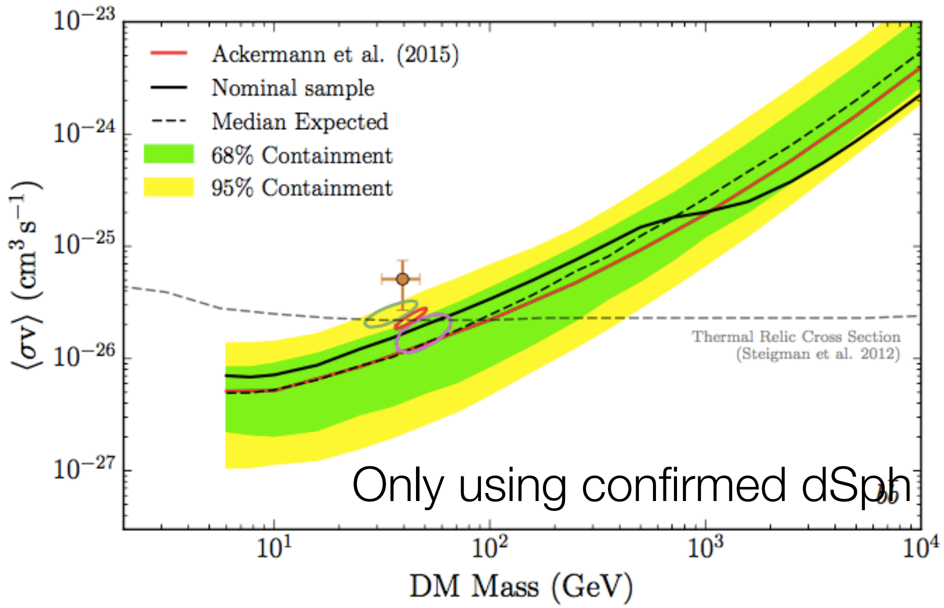
(1) Name	(2) l, b (deg, deg)	(3) Distance (kpc)	(4) $r_{1/2}$ (pc)	(5) M_V (mag)	(6) $\log_{10}(J_{meas})$ $\log_{10}(\mathrm{GeV^2\,cm^{-5}})$	(7) $\log_{10}(J_{pred})$ $\log_{10}(\mathrm{GeV^2\,cm^{-5}})$	(8) Sample
Kinematically Confirmed Galaxies							
Boötes I*	358.08, 69.62	66	189	-6.3	18.2 ± 0.4	18.5	I,N,C
Boötes II	353.69, 68.87	42	46	-2.7	...	18.9	I,N,C
Boötes III	35.41, 75.35	47	...	-5.8	...	18.8	I,N
Canes Venatici I	74.31, 79.82	218	441	-8.6	17.4 ± 0.3	17.4	I,N,C
Canes Venatici II*	113.58, 82.70	160	52	-4.9	17.6 ± 0.4	17.7	I,N,C
Carina*	260.11, -22.22	105	205	-9.1	17.9 ± 0.1	18.1	I,N,C
Coma Berenices*	241.89, 83.61	44	60	-4.1	19.0 ± 0.4	18.8	I,N,C
Draco*	86.37, 34.72	76	184	-8.8	18.8 ± 0.1	18.3	I,N,C
Draco II	98.29, 42.88	24	16	-2.9	...	19.3	I,N,C
Fornax*	237.10, -65.65	147	594	-13.4	17.8 ± 0.1	17.8	I,N,C
Hercules*	28.73, 36.87	132	187	-6.6	16.9 ± 0.7	17.9	I,N,C
Horologium I	271.38, -54.74	87	61	-3.5	...	18.2	I,N,C
Hydra II	295.62, 30.46	134	66	-4.8	...	17.8	I,N,C
Leo I	225.99, 49.11	254	223	-12.0	17.8 ± 0.2	17.3	I,N,C
Leo II*	220.17, 67.23	233	164	-9.8	18.0 ± 0.2	17.4	I,N,C
Leo IV*	265.44, 56.51	154	147	-5.8	16.3 ± 1.4	17.7	I,N,C
Leo V	261.86, 58.54	178	95	-5.2	16.4 ± 0.9	17.6	I,N,C
Pisces II	79.21, -47.11	182	45	-5.0	...	17.6	I,N,C
Reticulum II	266.30, -49.74	32	35	-3.6	18.9 ± 0.6	19.1	I,N,C
Sculptor*	287.53, -83.16	86	233	-11.1	18.5 ± 0.1	18.2	I,N,C
Segue 1*	220.48, 50.43	23	21	-1.5	19.4 ± 0.3	19.4	I,N,C
Sextans*	243.50, 42.27	86	561	-9.3	17.5 ± 0.2	18.2	I,N,C
Triangulum II	140.90, -23.82	30	30	-1.8	...	19.1	I,N,C
Tucana II	328.04, -52.35	58	120	-3.9	...	18.6	I,N,C
Ursa Major I	159.43, 54.41	97	143	-5.5	17.9 ± 0.5	18.1	I,N,C
Ursa Major II*	152.46, 37.44	32	91	-4.2	19.4 ± 0.4	19.1	I,N,C
Ursa Minor*	104.97, 44.80	76	120	-8.8	18.9 ± 0.2	18.3	I,N,C
Willman 1*	158.58, 56.78	38	19	-2.7	...	18.9	I,N
Likely Galaxies							
Columba I	231.62, -28.88	182	101	-4.5	...	17.6	I,N,C
Eridanus II	249.78, -51.65	331	156	-7.4	...	17.1	I,N,C
Grus I	338.68, -58.25	120	60	-3.4	...	17.9	I,N,C
Grus II	351.14, -51.94	53	93	-3.9	...	18.7	I,N,C
Horologium II	262.48, -54.14	78	33	-2.6	...	18.3	I,N,C
Indus II	354.00, -37.40	214	181	-4.3	...	17.4	I,N,C
Pegasus III	69.85, -41.81	205	57	-4.1	...	17.5	I,N,C
Phoenix II	323.69, -59.74	96	33	-3.7	...	18.1	I,N,C
Pictor I	257.29, -40.64	126	44	-3.7	...	17.9	I,N,C
Reticulum III	273.88, -45.65	92	64	-3.3	...	18.2	I,N,C
Sagittarius II	18.94, -22.90	67	34	-5.2	...	18.4	I,N,C
Tucana III	315.38, -56.18	25	44	-2.4	...	19.3	I,N
Tucana IV	313.29, -55.29	48	128	-3.5	...	18.7	I,N,C
Ambiguous Systems							
Cetus II	156.47, -78.53	30	17	0.0	...	19.1	I
Eridanus III	274.95, -59.60	96	12	-2.4	...	18.1	I
Kim 2	347.16, -42.07	105	12	-1.5	...	18.1	I
Tucana V	316.31, -51.89	55	16	-1.6	...	18.6	I

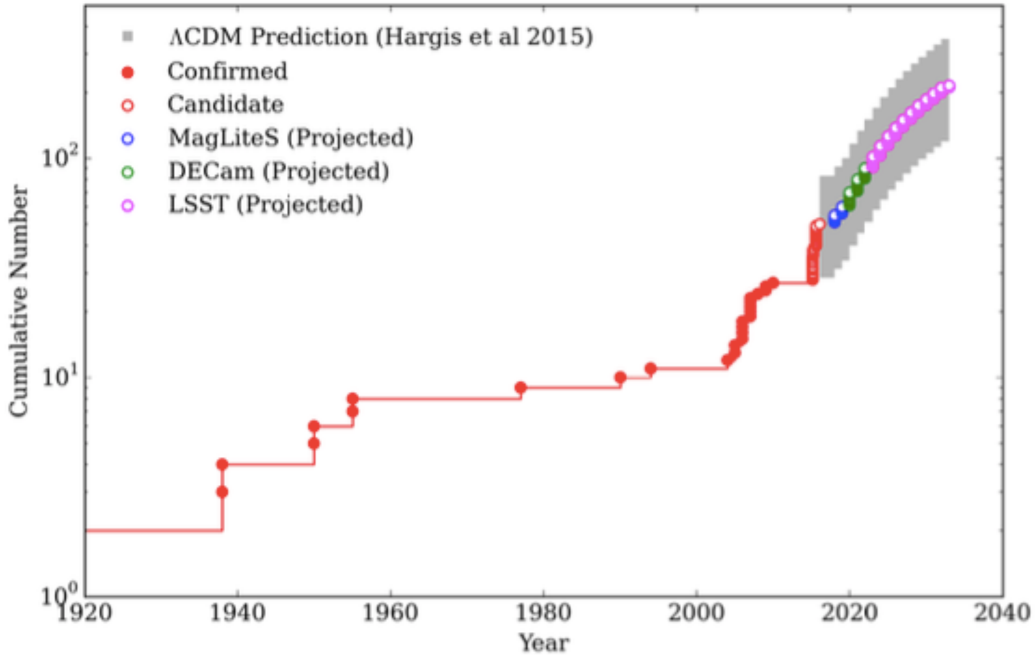




Dwarf Milky Way satellites

- New surveys ongoing
  - 45 stellar systems :
    28 confirmed dSphs and 17 newly discovered candidates by DES



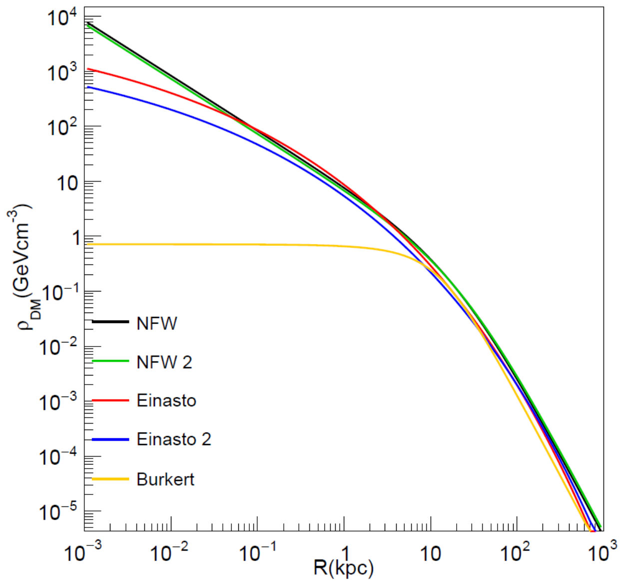


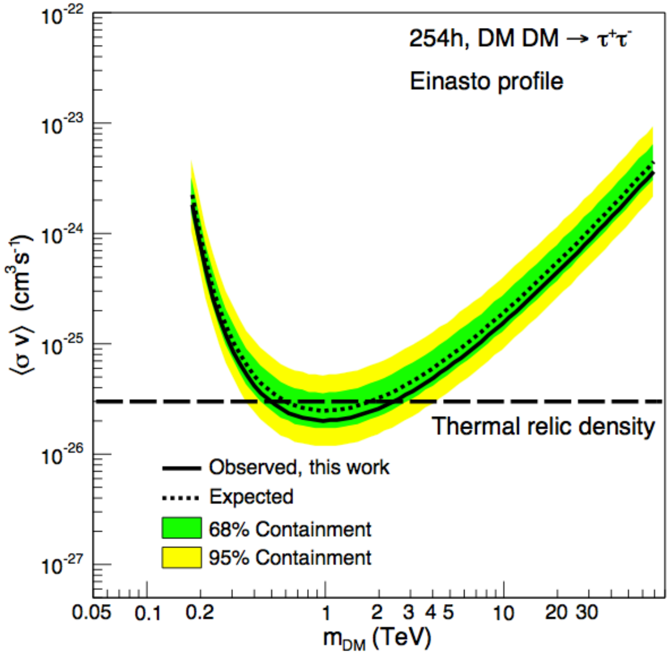
- The next generation of surveys (i.e., LSST) should complete our census of the ultra-faint dwarfs out to the virial radius of the Milky Way
- Fermi-LAT will continue to observe any new discoveries
- All IACTs have programs to observe new ultra-faint dwarf galaxies

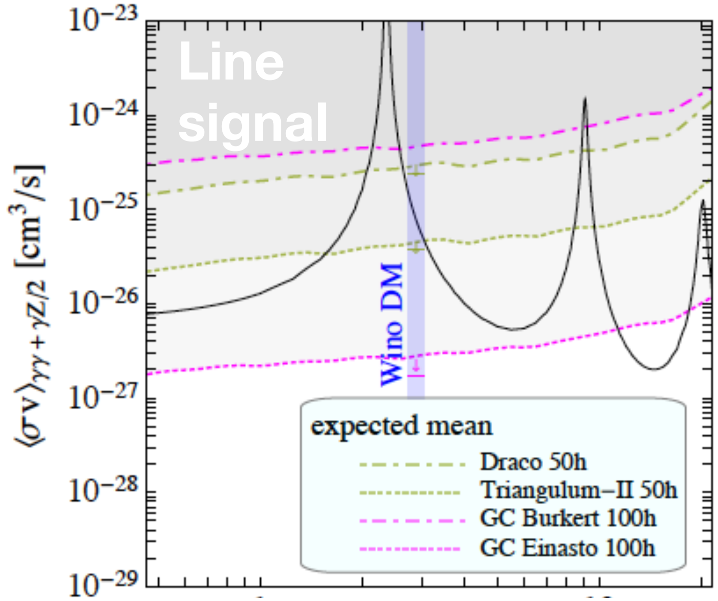
- Significant recent works on the modelling of DM distribution in dwarf galaxies
  - in particular, systematics from Jeans modelling framework

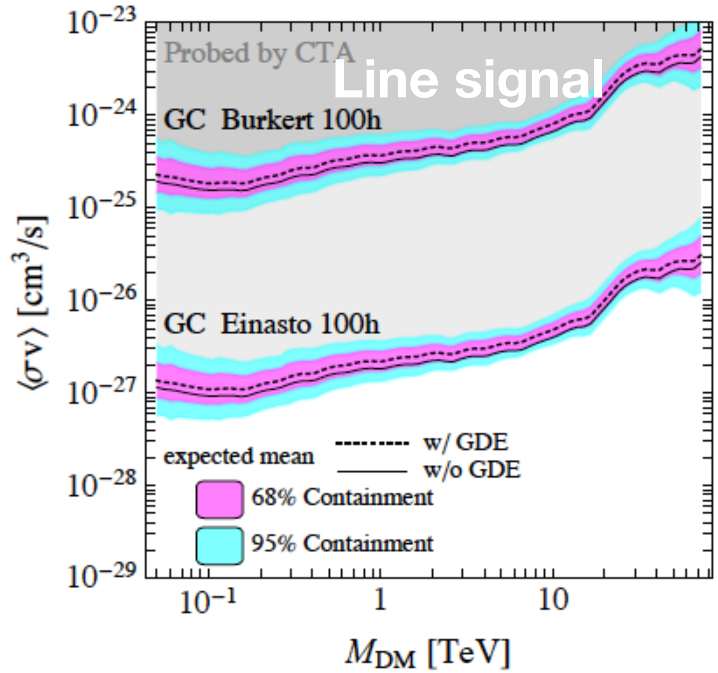
Inner Galactic halo

- **MW dark matter density distribution models**







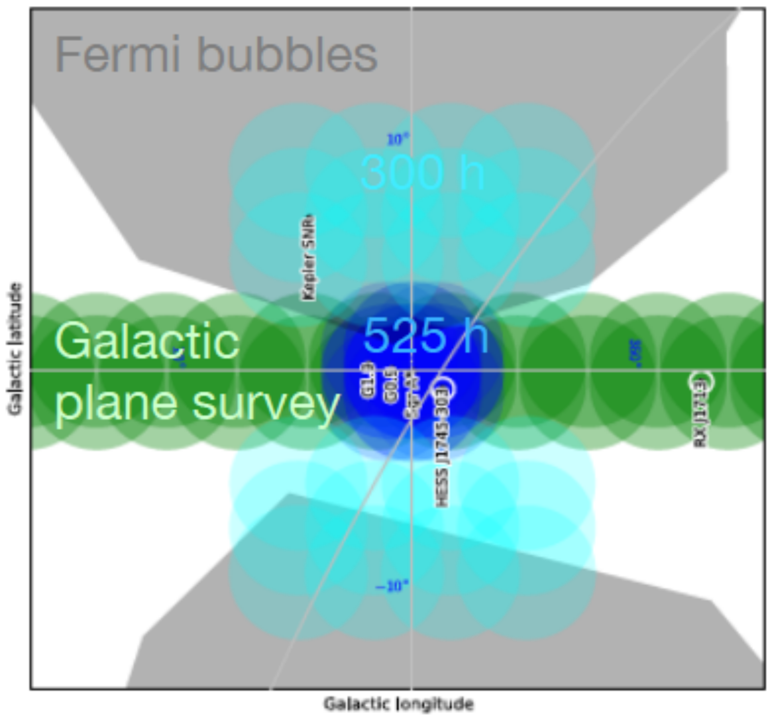


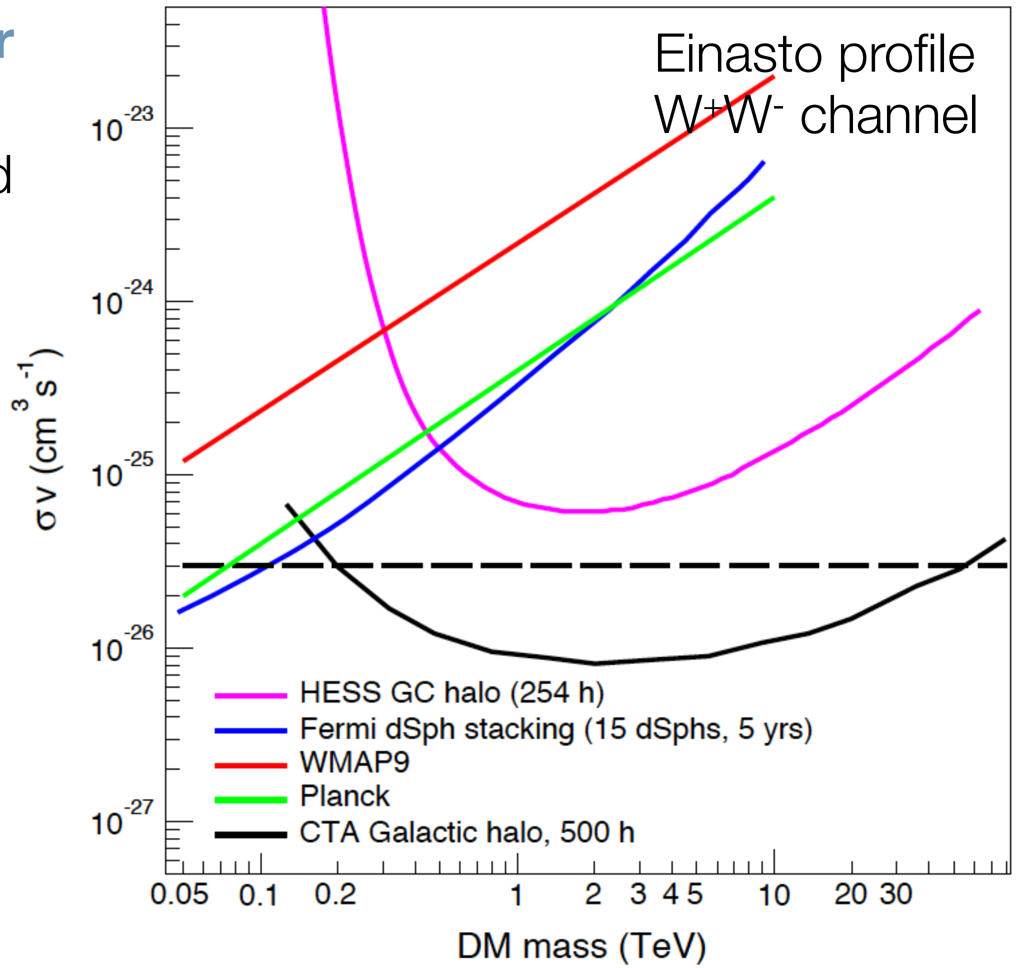
- H.E.S.S. is leading since 2015 a large observation program of the inner 5 degrees of the inner Galactic halo

- Dark matter distribution is not well not known
  - Dynamics is dominated by stars and gas
  - in the inner kpc of the MW

Near future: Cherenkov Telescope Array

- **Priority target in the CTA Dark Matter programme**
  - Fair balance between brightness and robustness





- **Fermi/CTA will be able to probe thermal WIMPs from a few GeV up to a few tens of TeV**
- **Thermal WIMPs strongly constraints in the next few years**

Observation strategy in gamma-rays

- **Ground-based telescope experiments i.e. IACTs**
  - The inner region of the Milky Way halo harbors a large amount of dark matter:
    → Given its proximity, it is one of the most promising targets to detect for DM
  - The Galactic Centre is a very complex region in HE/VHE gamma-rays

- **Satellite experiments i.e. Fermi-LAT**
  - Stacking analyses of dwarf galaxy satellites of the Millky Way provide the strongest constraints up to a few 100 GeV

- **Fermi/CTA will be able to probe thermal WIMPs from a few GeV up to a few tens of TeV**
  → Thermal WIMPs strongly constraints within the next few years

- **What next ?**
  - New TeV models
  - Non-thermally produced dark matter models
  - PeV dark matter …