Dark Matter
and
Signatures in Multimessenger Astronomy

Julien Lavalle
CNRS – LUPM – Montpellier

Journées du PNHE – en ligne – September 16th, 2021

Outline

- Transdisciplinary context
- Candidates
- Multimessenger signatures and recent progresses

Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

But increasing observational precision has led to tensions btw diff probes:
- Tensions on large scales
- Tensions on small scales

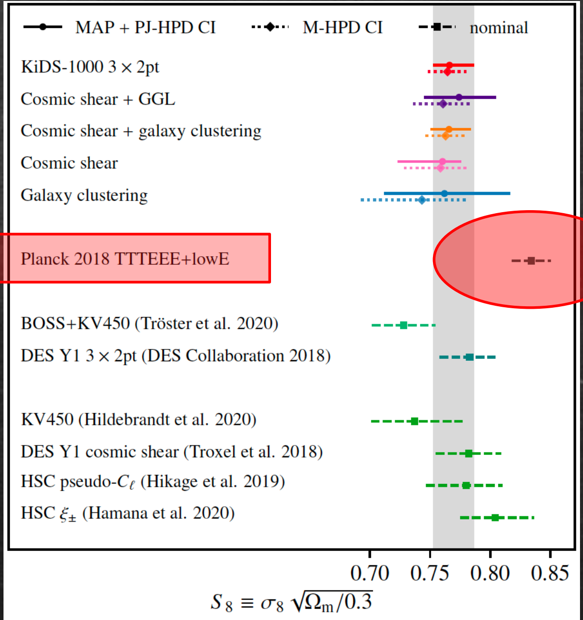
Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

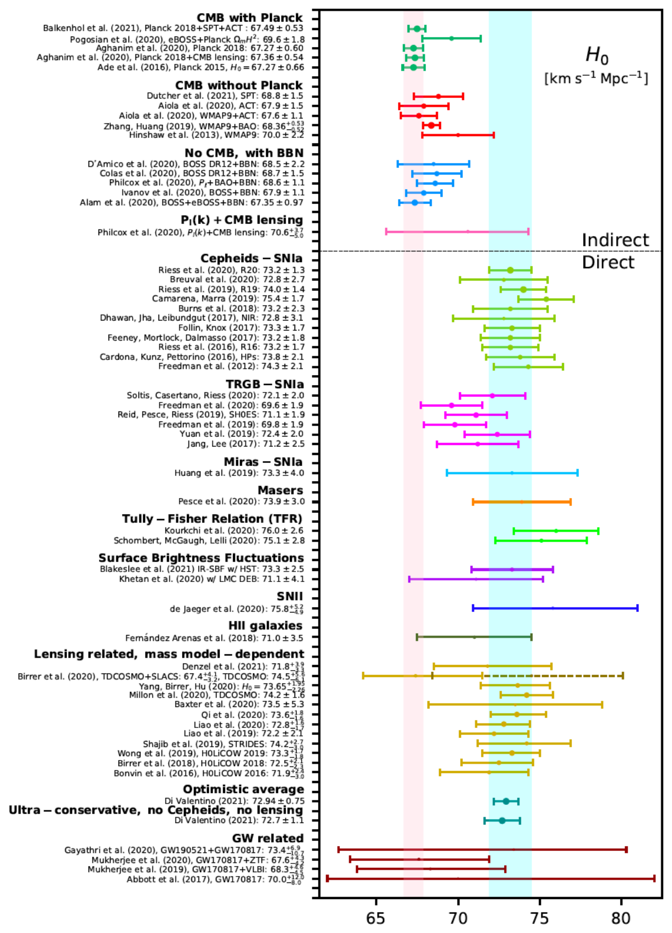
But increasing observational precision has led to tensions btw diff probes:
- **Tensions on large scales**
- Tensions on small scales

The ***H_0* tension**
(distant vs. local probes)

The ***S_8* tension**
(discrep. amplitude of matter power spectrum on large scales)



Heymans+'20



Di Valentino+'21 / Visinelli (github)

Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

But increasing observational precision has led to tensions btw diff probes:
- **Tensions on large scales**
- Tensions on small scales

Keep in mind (large scales):

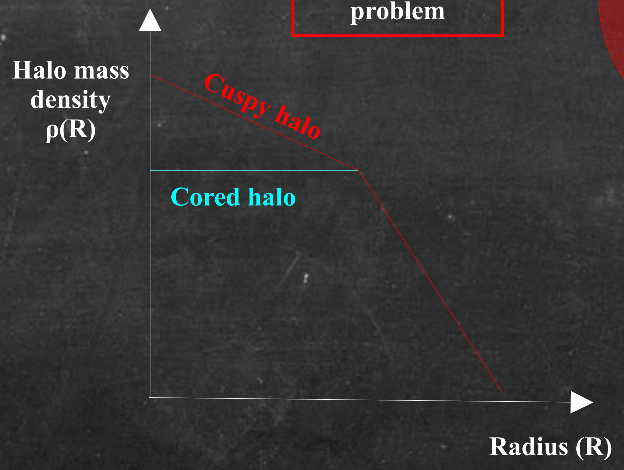
- LCDM not secured yet (+ dark components unknown)
- Tensions might have implications on properties of DM (the S_8 tension mostly)

Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

But increasing observational precision has led to tensions btw diff probes:
- Tensions on large scales
- **Tensions on small scales**

The core-cusp problem



Mass density profiles of galactic halos:

- predicted cuspy down to very inner parts (NFW, Einsato)
- halo mass fixes all parameters

… but found cored in significant fraction of galaxies (not always).

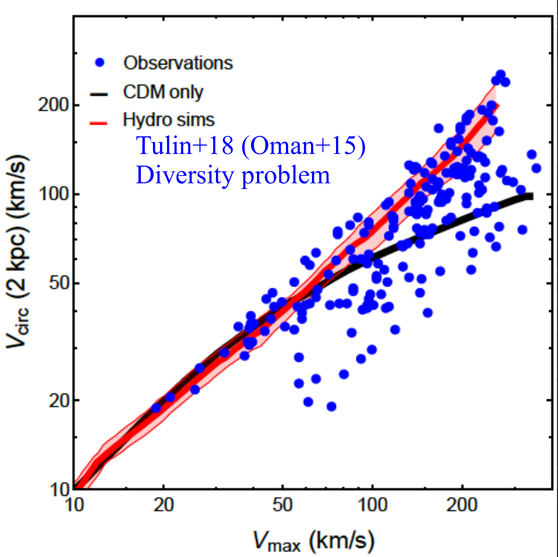
Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

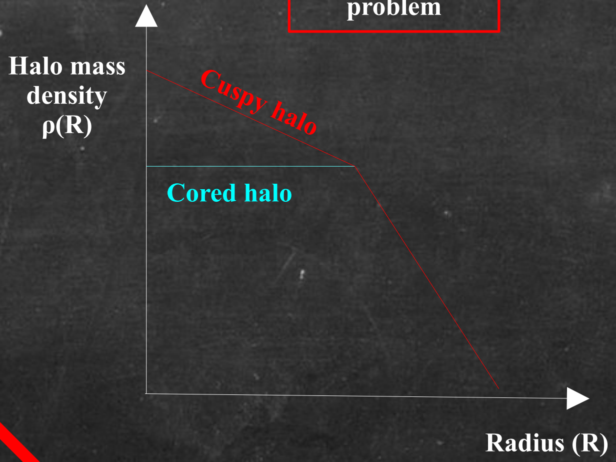
But increasing observational precision has led to tensions btw diff probes:
- Tensions on large scales
- **Tensions on small scales**

Diversity problem

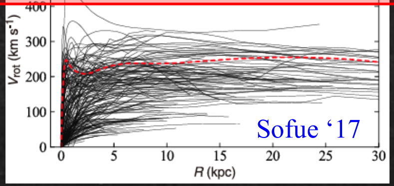
Halos of similar masses (V_{max}) have a large scatter in central properties (V_{circ})



The core-cusp problem



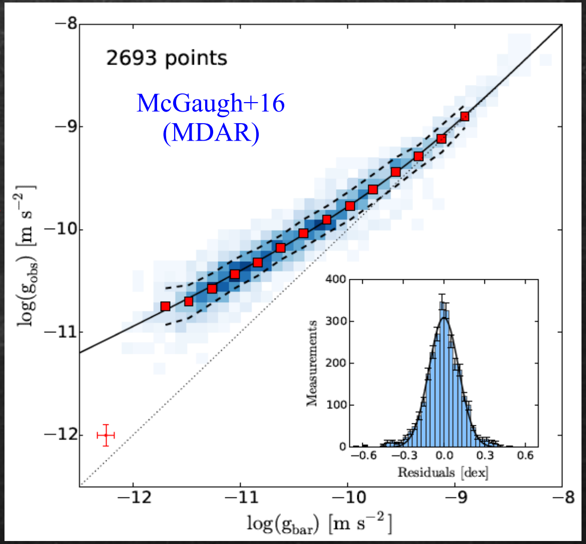
Recast galaxy rotation curves



Regularity problem

Total acceleration tightly correlated with baryonic acceleration (Mass Discrepancy Acceleration Relation).

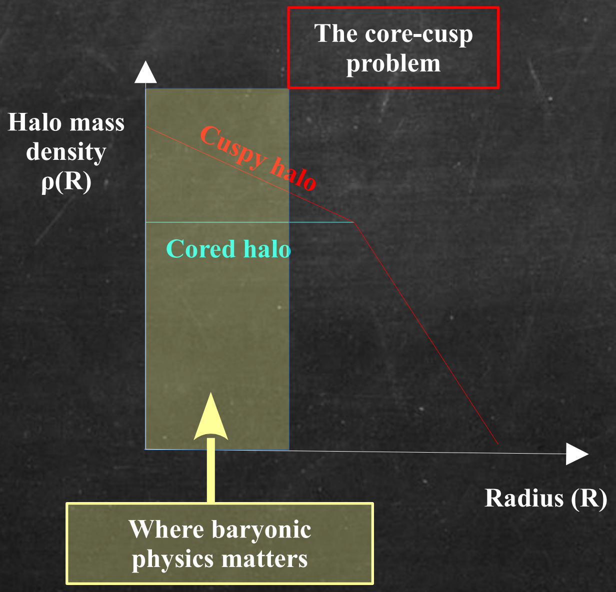
(NB: predicted by MOND)



Context (1): Cosmology

LCDM impressively successful so far (Nobel prize to J. Peebles):
- compelling interpretation of CMB, BBN, LSS, structure formation, etc.

But increasing observational precision has led to tensions btw diff probes:
- Tensions on large scales
- **Tensions on small scales**



Keep in mind (small scales)

- Cusp/core puzzle (structure formation)
↔ diversity vs. regularity

- Alleviated by baryonic physics (how much?)
- Could point to specific DM properties:
    - Self-interactions (SIDM)?
    - Ultra-light bosons?
    - Superfluid DM?

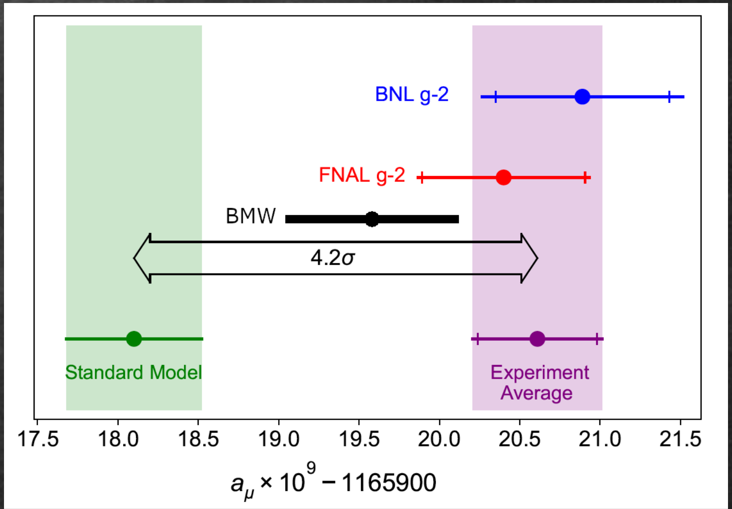
Context (2): Particle Physics

LHC did not find (yet) new physics at TeV:

→ “EW hierarchy pb” strongly affected as a theoretical research program
→ Latest surviving exp. “anomaly” is g_μ-2: very fragile (see LQCD results)
=> Popular WIMP no longer a top-down prediction
=> Top-down survivors (gained popularity):
- axions (strong QCD pb)
- sterile neutrinos (leptogenesis)

→ Bottom-up approaches flourish (DM a goal, not a by-product)
=> Game is: production mechanisms in early universe vs. interaction properties
=> Based on more or less complex dark sectors
=> Comprise WIMP-like, FIMP-like, axions-like (ALPs), etc. particles.

→ Many energy scales motivated [e.g. axions, neutrinos, WIMPs, etc.]
=> Multimessenger + multiwavelength + multitechnique searches.
=> HE astro + astro + cosmo + laboratory probes/signatures

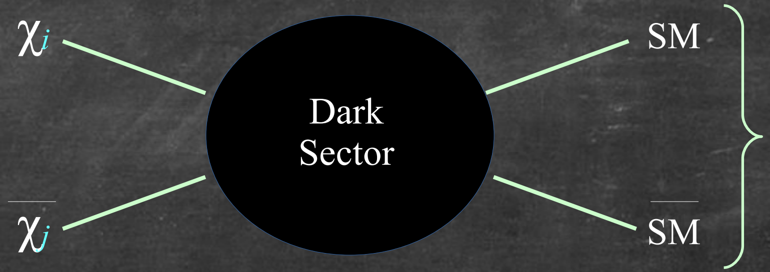


Courtesy L. Lellouch
[FNAL’21 + BMW’20]

Typical candidates and (PNHE) signatures

Thermal (non-neutrino) DM
[1 keV – 100 TeV]

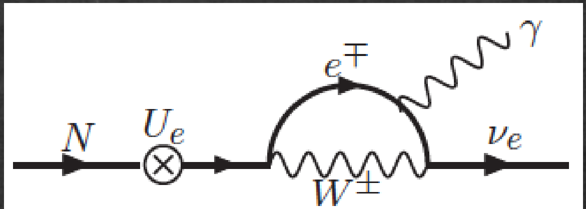
WIMPs, FIMPs, asymmetric, etc.



- photons (MeV-TeVs)
- neutrinos (keV-TeVs)
- matter+antimatter CRs
- secondary radio+X-rays

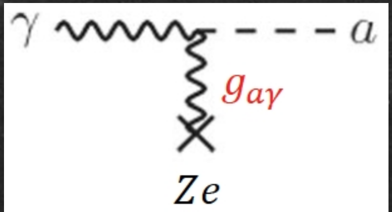
Sterile neutrinos
[1 – 50 keV]

(production from mixing only)



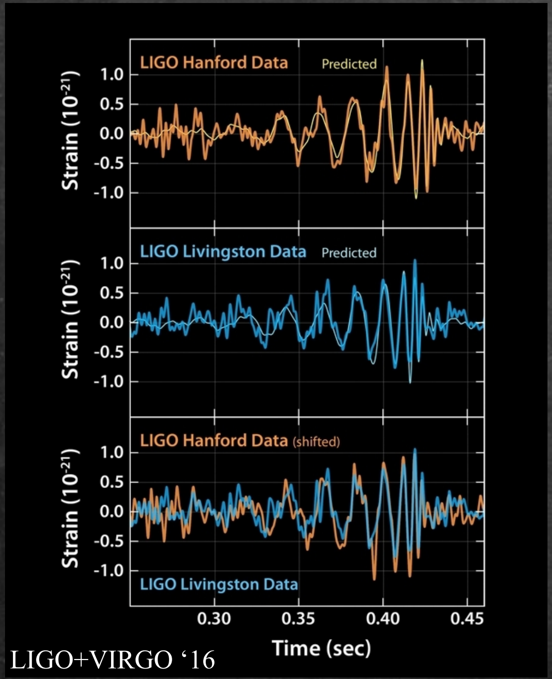
- X-ray line (1-50 keV)

Axions
[1μeV – 1 meV]
[← → for ALPs beyond QCD-axion]



- axion←→gamma-ray conversion
in B fields
(e.g. from blazars or CCSN)
e.g. Calore+'20-'21

An elephant in the room



LIGO+VIRGO '16

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

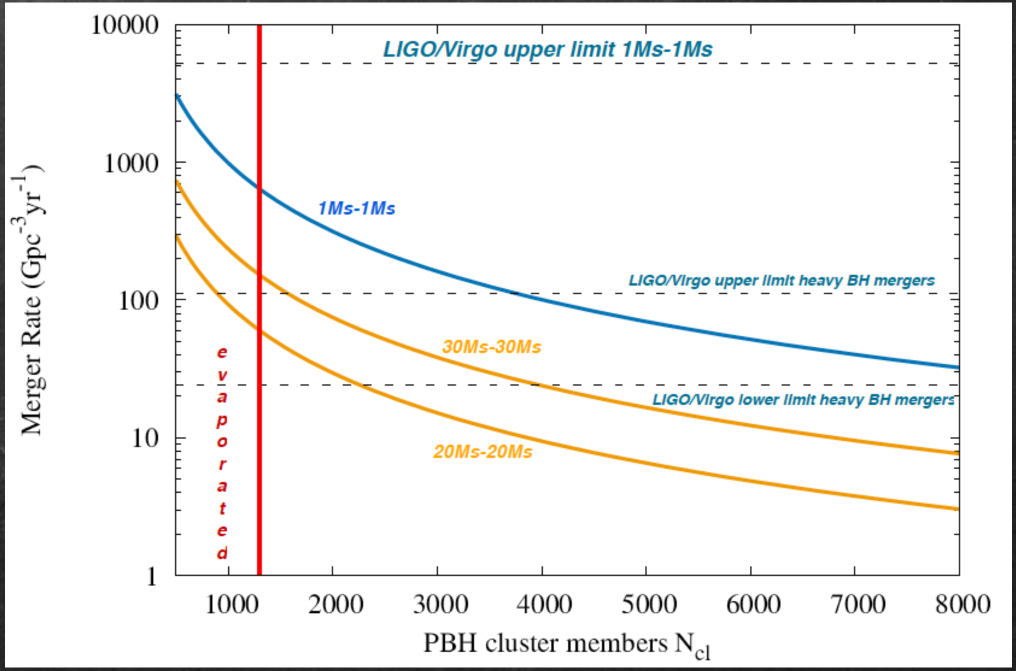
arXiv:1603.00464 (PRL)

arXiv:2007.03565 (PRL)

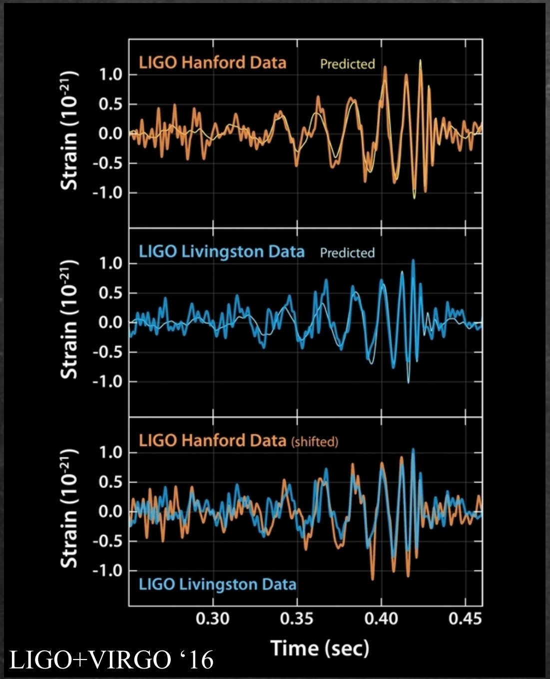
Evidence for primordial black hole dark matter from LIGO/Virgo merger rates

Karsten Jedamzik[1]

[1] *Laboratoire de Univers et Particules de Montpellier, UMR5299-CNRS, Universite de Montpellier, 34095 Montpellier, France*



An elephant in the room



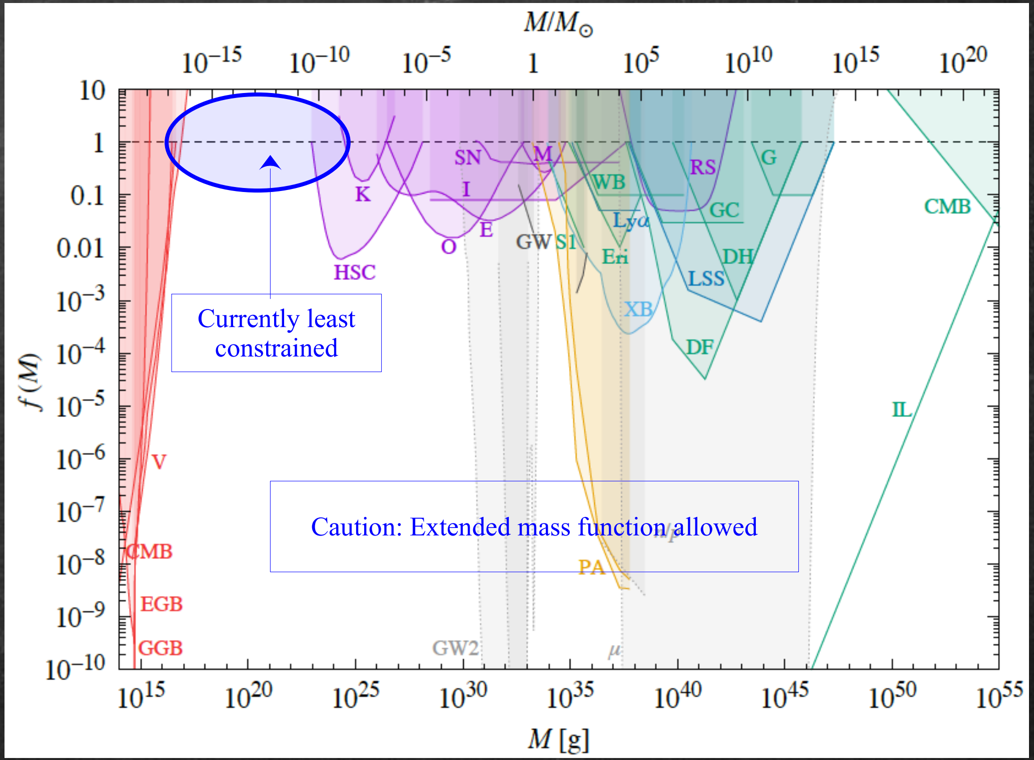
Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

arXiv:1603.00464 (PRL)

Carr+'20
(see also Green+'21)



Many constraints but PBH DM a strong science case.
Relies on non-minimal inflation, but rather generic

Predicting (PNHE) signals

Signals = DM Particle Fundamental Properties x DM phase-space properties x Astro "transfer function"

- DM particle mass
- annihilation/decay cross section (incl. v-dependencies)
- branching ratios
- spectra of final states

- Spatial distribution of DM
- Inhomogeneities (subhalos)
- Velocity distribution of DM

=> recent developments here

- From injection to observer

→ propagation for CRs

→ oscillations for neutrinos

→ e.g. absorption for photons

Predicting (PNHE) signals

Signals = DM Particle Fundamental Properties x DM phase-space properties x Astro "transfer function"

- DM particle mass
- annihilation/decay cross section (incl. v-dependencies)
- branching ratios
- spectra of final states

- Spatial distribution of DM
- Inhomogeneities (subhalos)
- Velocity distribution of DM

=> recent developments here

- From injection to observer

→ propagation for CRs
→ oscillations for neutrinos
→ e.g. absorption for photons

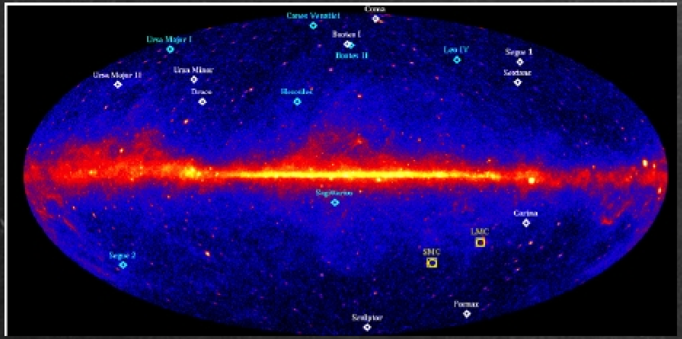
Upper limits (so far) derived by:
- Exp. collabs when theory settled (e.g. gamma-rays through s-wave ann.)
- Th./ph. groups otherwise

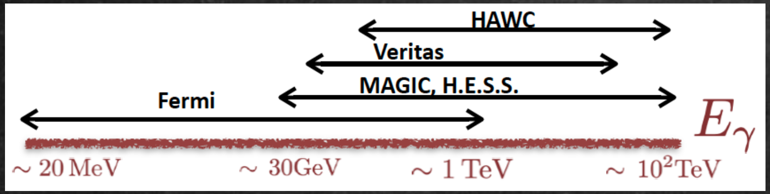
Active theoretical dev.
+ Gaia data to constrain PSDF and granularity of Galactic halo.

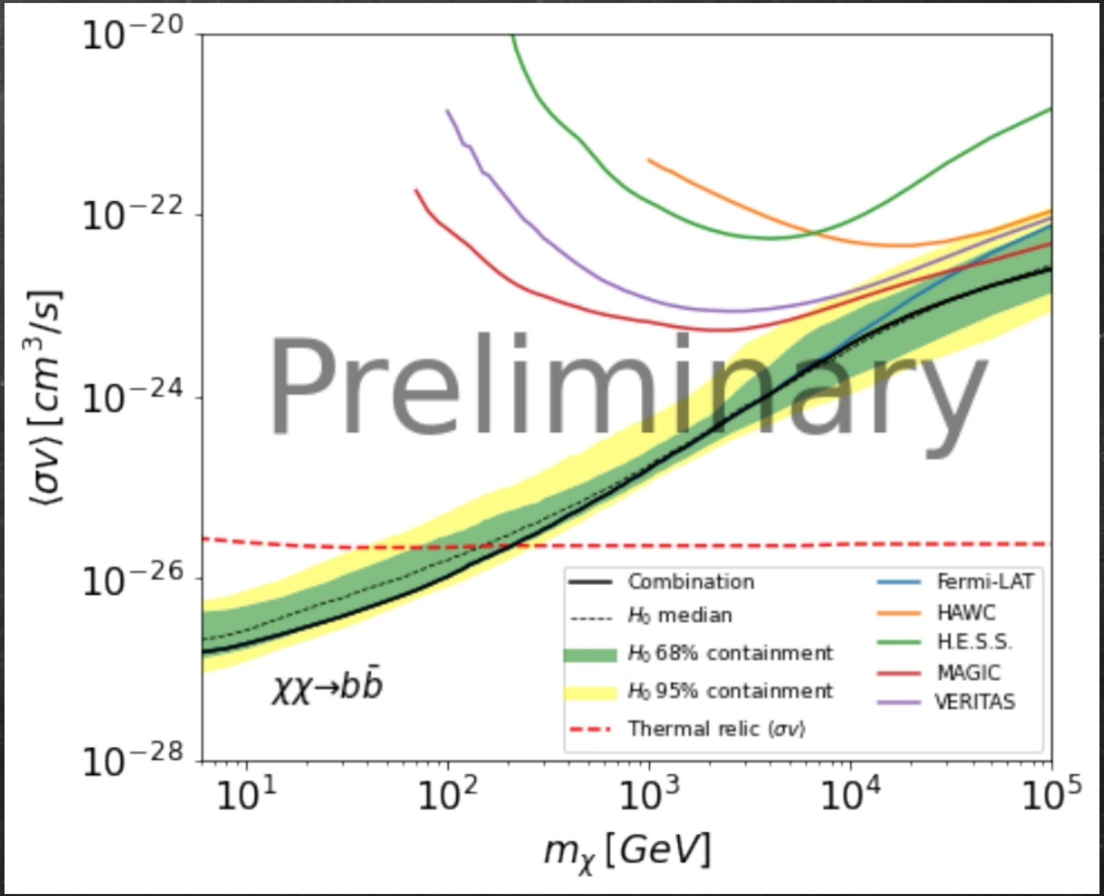
Active th/pheno dev.
+ AMS02 data to constrain CR propagation models + multimess. astro backgrounds

Gamma-ray searches

Point your telescopes to Dwarf Galaxy Satellites (DGSs)
(free of other HE processes – only Galactic foreground)



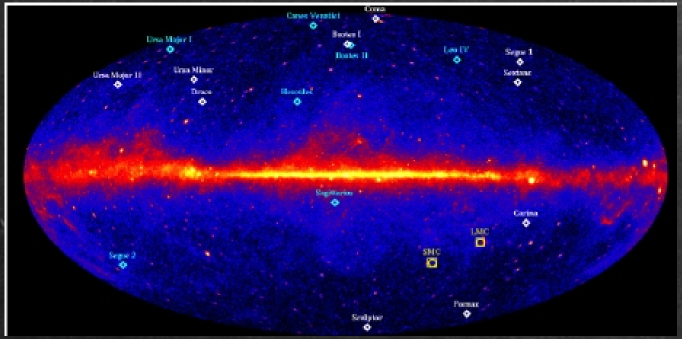


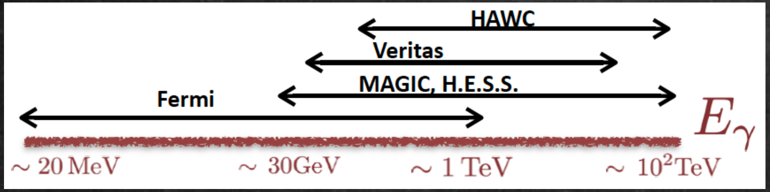


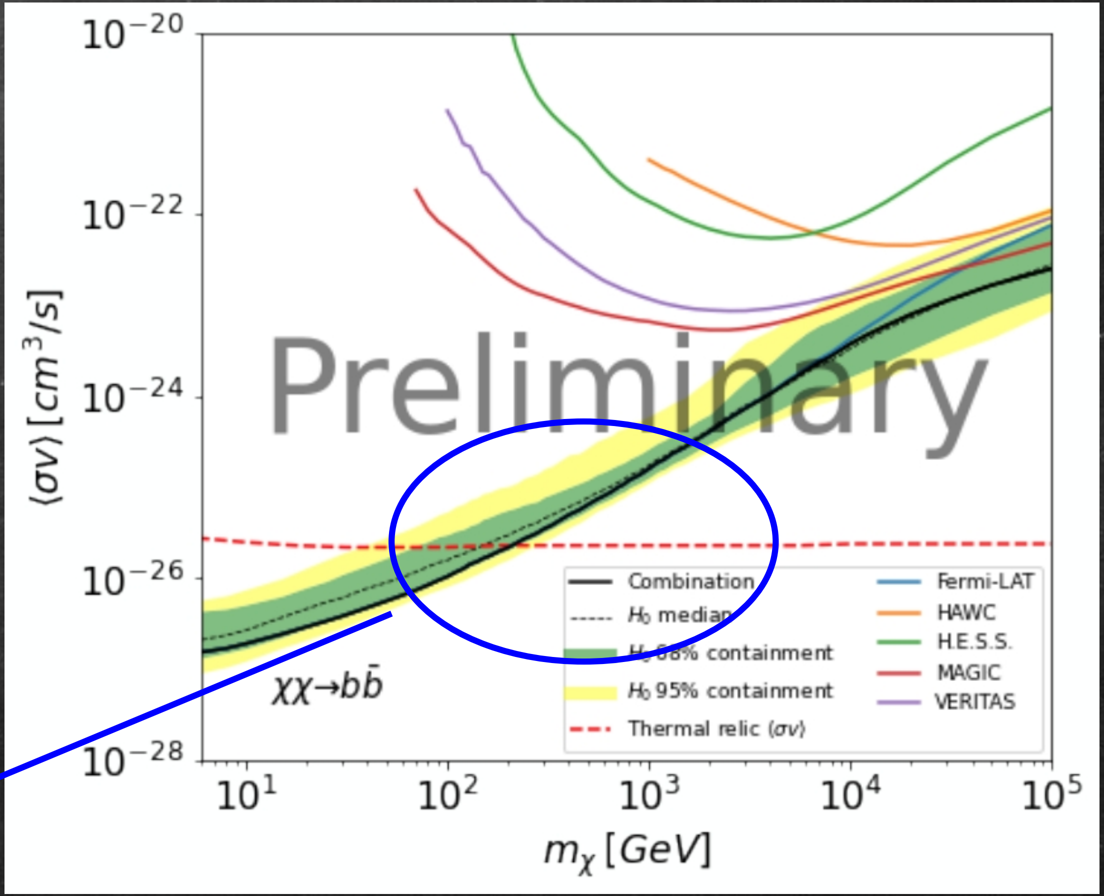
Armand+'21 (@ICRC-21)

Gamma-ray searches

Point your telescopes to Dwarf Galaxy Satellites (DGSs)
(free of other HE processes – only Galactic foreground)





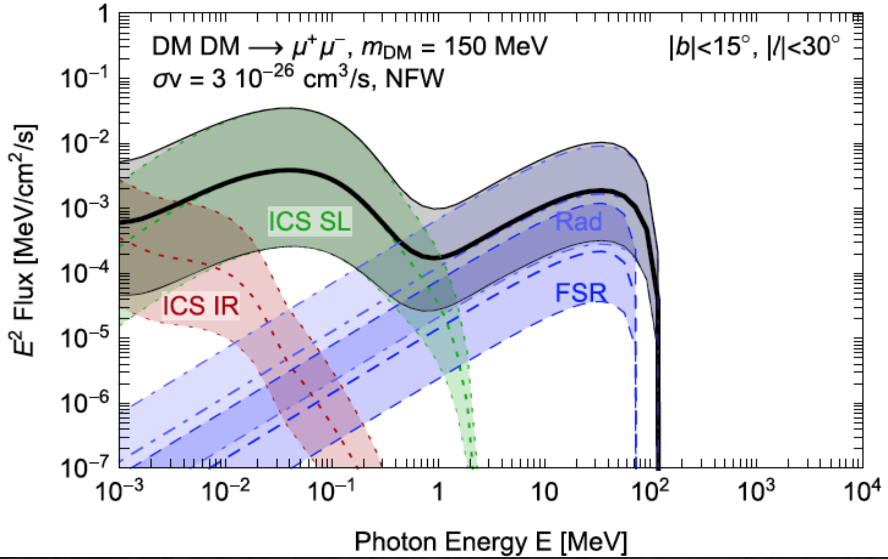


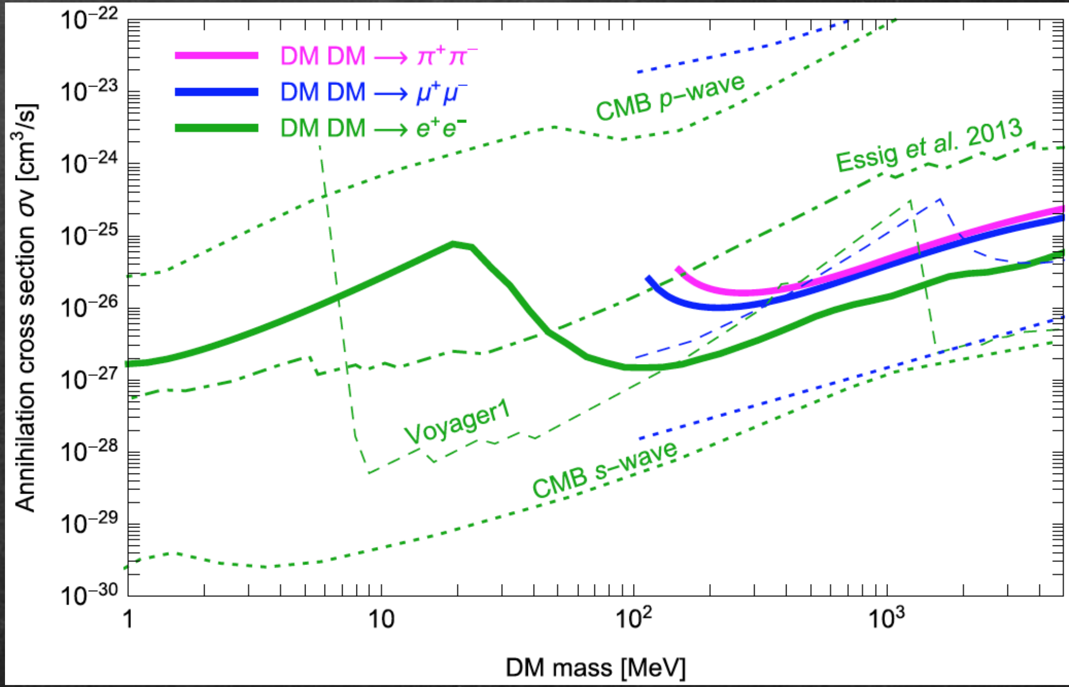
Where CTA will improve
(DGS modeling should also improve)

Armand+'21 (@ICRC-21)

X→ Gamma-ray searches

Diffuse Galactic emission
INTEGRAL data (0.02-2 MeV) and |l|<30° |b|<15°





Cirelli+’21

Recent developments in gamma-rays

Accounting for DM subhalos in v-dependent signals
→ typical of Sommerfeld enhancement $\sim 1/v^n$
←→ Compton length << interaction length
(similar to gravitational cross section)

↓

Relies on:
- Dynamically constrained subhalo population model
- Velocity DF predictions in (sub)halos of all masses
- Many intricate effects … but very strong impact!

IN PREPARATION

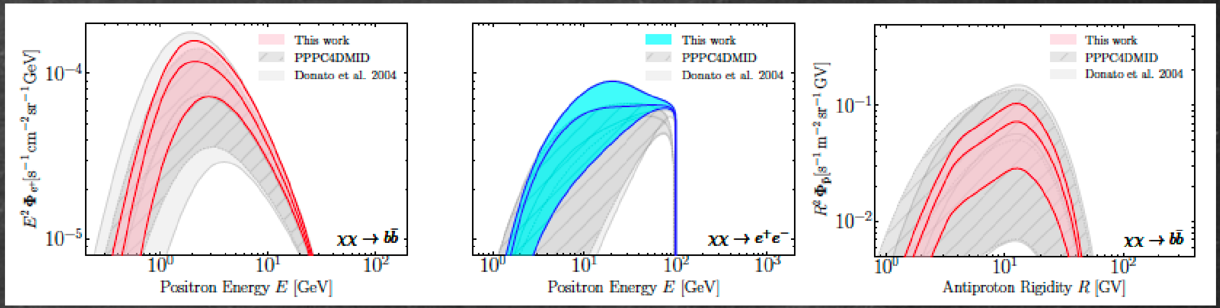
Lacroix+ (in prep)

A word on the GC gamma-ray emission

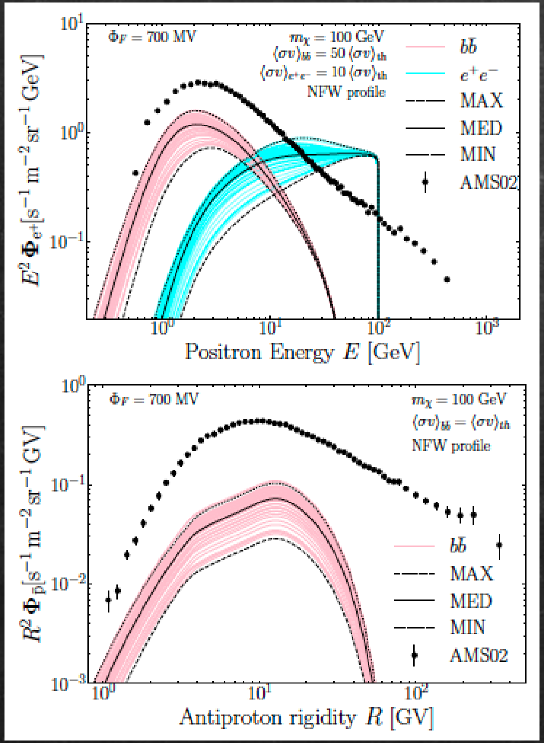
- Intense extended emission seen in Fermi data
- Template fitting not well suited for physical interpretation: CR properties, propagation, magnetic + radiation fields not well controlled.
  => Theoretical uncertainties >> inferred "effective" excess
- Hard astrophysical modeling work (while quite easy DM signal)
- Good candidates: milli-second pulsars + other diffuse component
  => Very likely emission of astrophysical origin
  => GCE OK to derive limit on DM, harder for signals (except gamma-ray lines)
- See e.g. recent work by Calore+'15-'21

Antimatter cosmic rays

New benchmark propagation models to bracket theoretical uncertainties: MIN-MED-MEX
(old ones by Donato+'04)
=> prediction uncertainties reduced by a factor of ~5

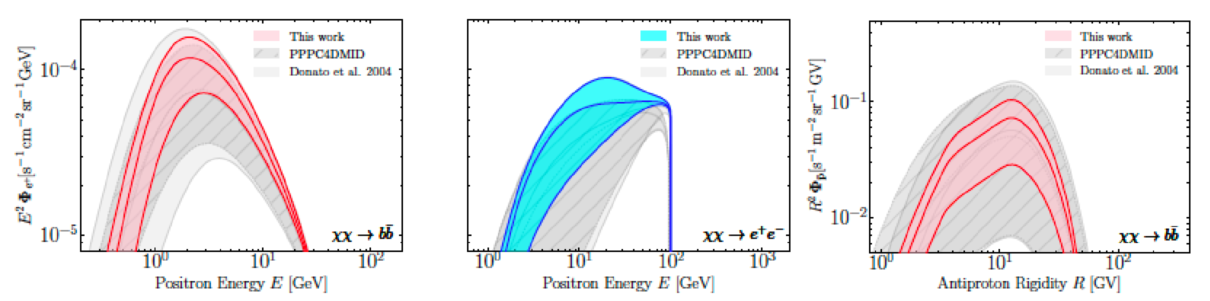


Génolini+'21

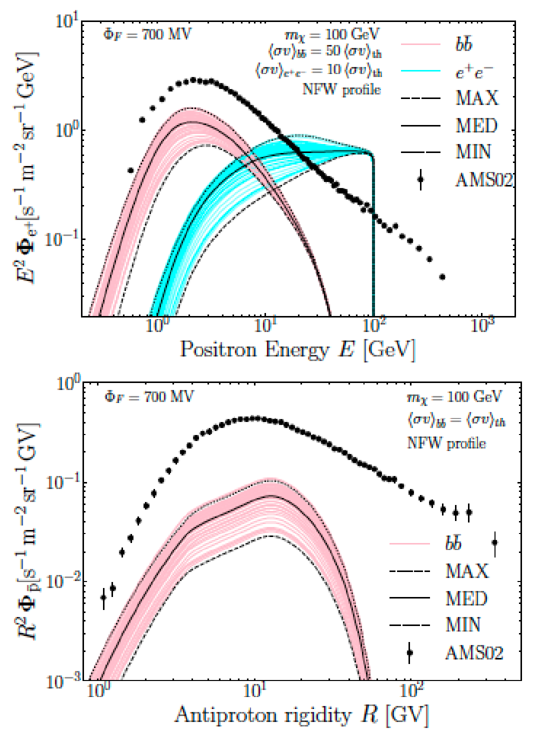


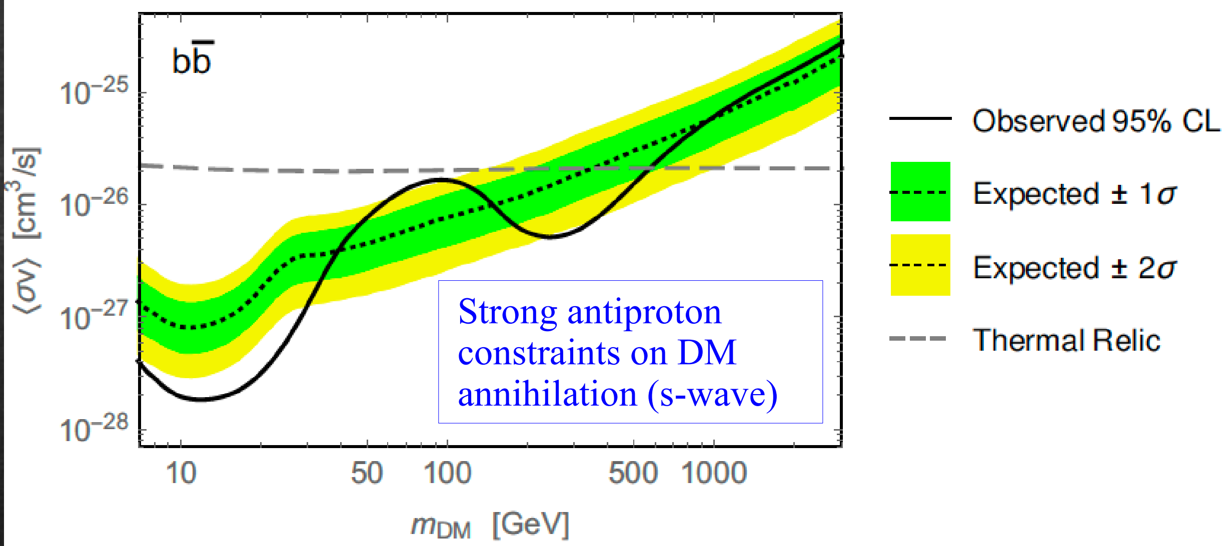
Antimatter cosmic rays

New benchmark propagation models to bracket theoretical uncertainties: MIN-MED-MEX
(old ones by Donato+'04)
=> prediction uncertainties reduced by a factor of ~5



Génolini+'21





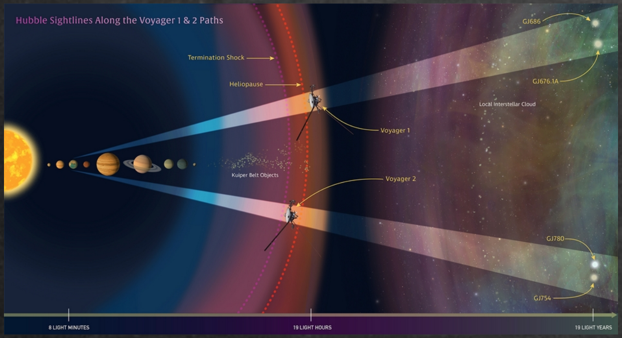
Reinert & Winkler'17
(Full analysis from Génolini+ expected soon)

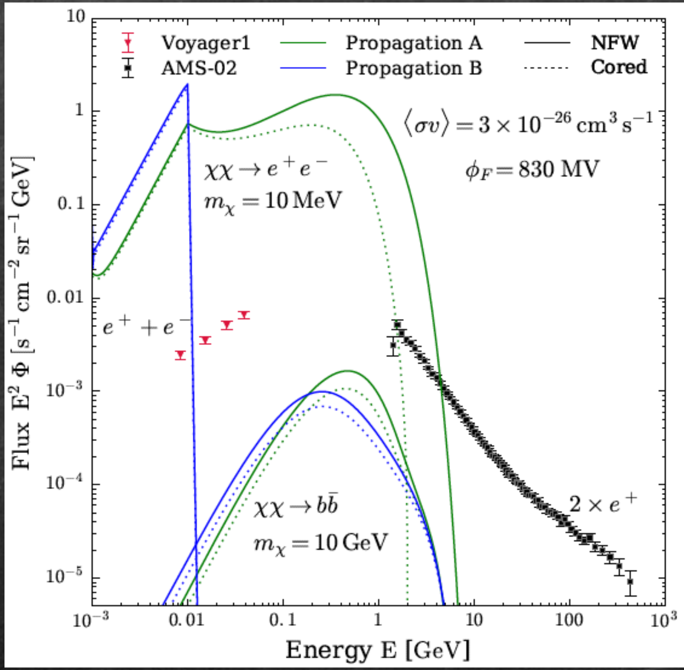
Antimatter cosmic rays in the MeV domain

Old stuff matters!!!
Voyager spacecraft missions (1977)

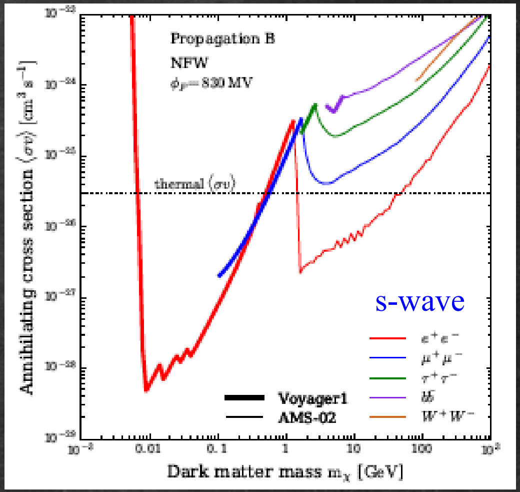
→ a probe of solar modulation and interstellar CRs

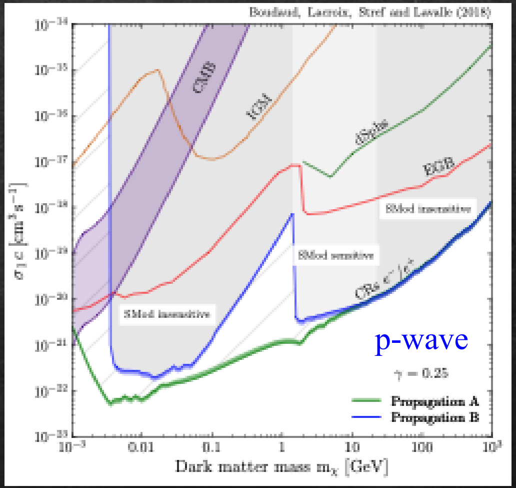
**** For DM: e+e- measurements at ~10 MeV ****





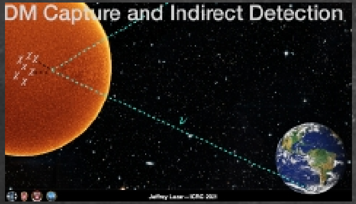
Boudaud+'17-'18



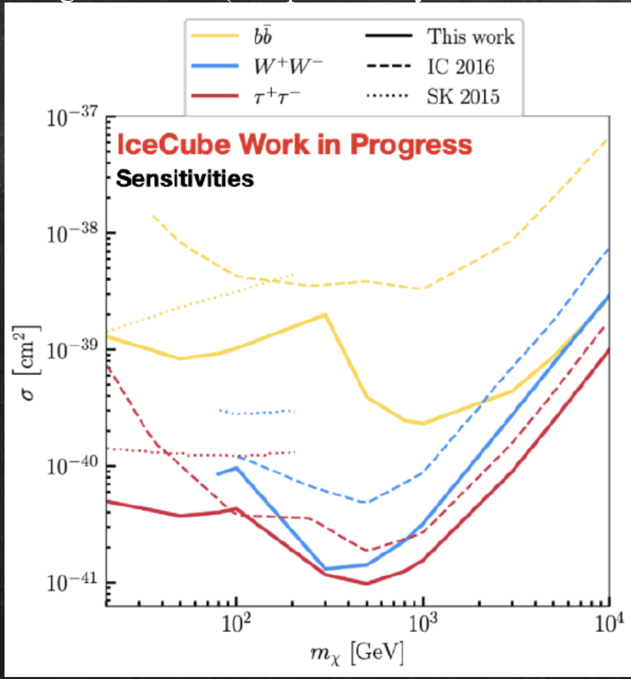


→ Very powerful probe of DM annihilation
(bg free + **insensitive to DM halo profile, local DM only**)

Neutrinos

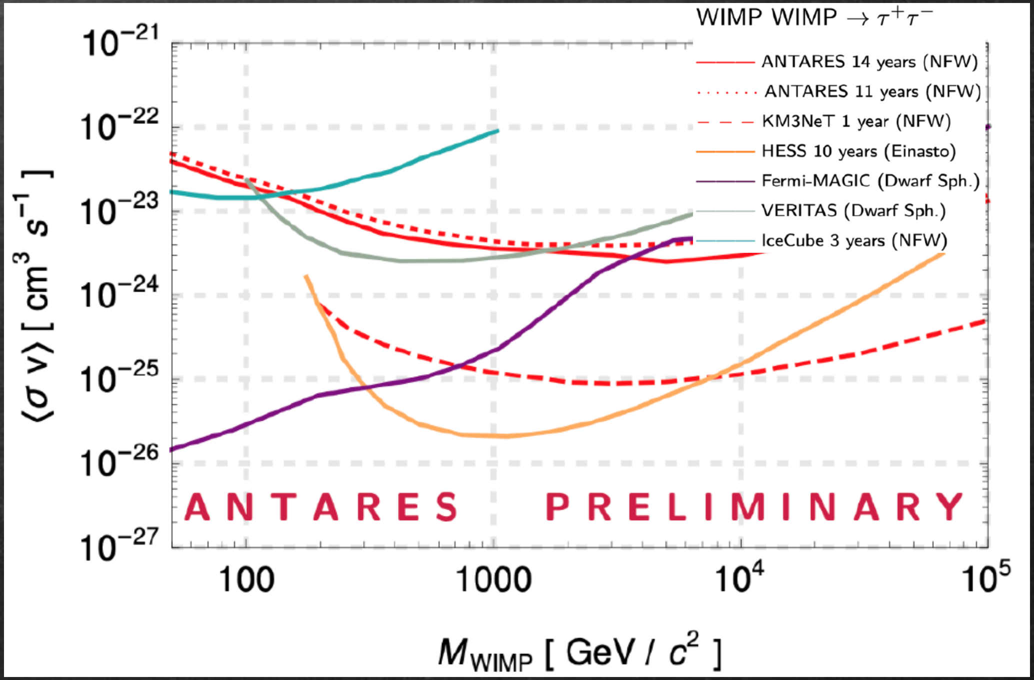


Pointing to the Sun (complementary to direct searches)



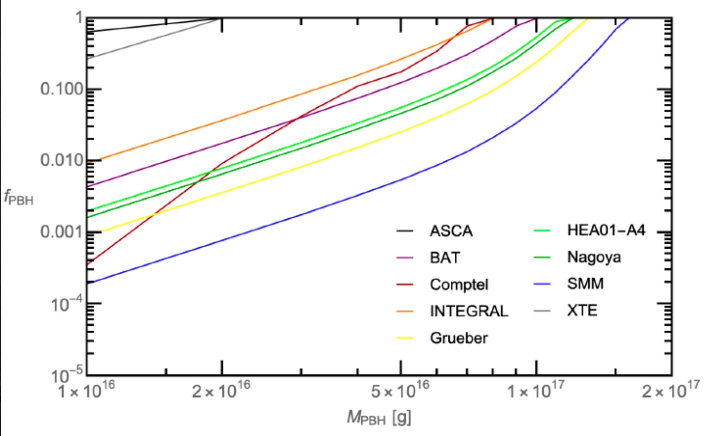
Lazar+@ICRC-21

Pointing to the GC (complementary to gamma-ray searches)



Gozzini+@ICRC-21

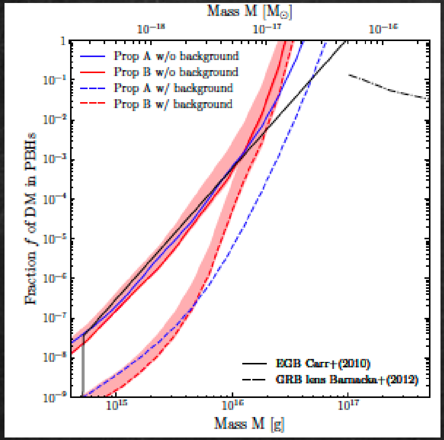
Primordial black holes



Iguaz+'21
(X→ soft gamma-rays)

1-10 M_{sun} PBHs
accrete and heat gas
=> X-rays

(No) limits from X-rays
(gas is turbulent)

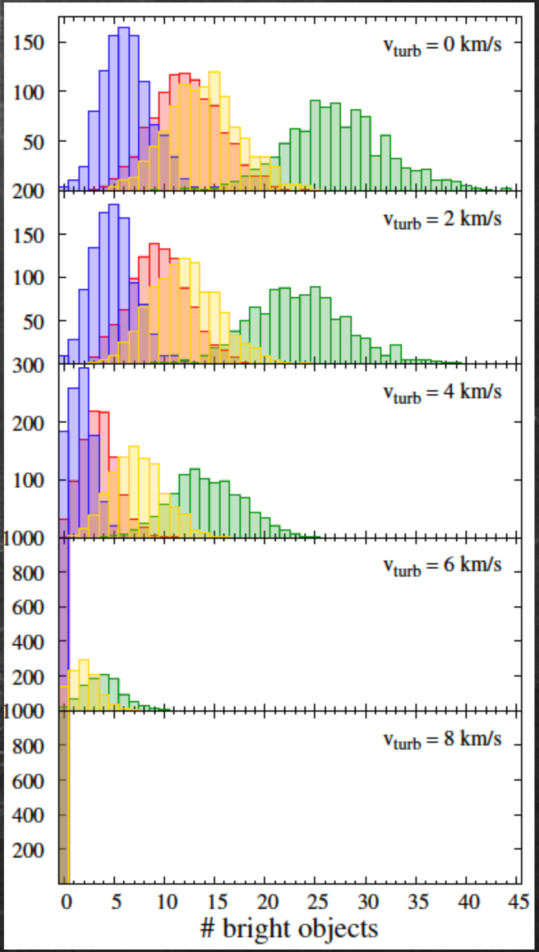


Boudaud+'18
(Voyager e+e-)

Light PBHs decay through
Hawking radiation.

T ~ 1 GeV * (10^{13}g/m)

Lifetime ~ 10 min (m/10^{10}g)^3



Hektor+'18 (NuSTAR)
(NB: contradicts Gaggero+'17)

A tiny fraction of PBHs kills s-wave DM annihilation

IN

PREPARATION

Lacroix+ (preliminary)
See also Eroschenko'16, Boucenna+'18,Carr+'21, Boudaud+'21

Conclusions

- LCDM not secured yet: implication/s for DM nature or properties?

- Structure formation plagued with issues on small scales: baryons? DM properties? (SIDM?)

- DM candidates: axions and rh neutrinos from top-down arguments; WIMPs (and declensions) motivated by simple thermal production mechanism/s in early universe.

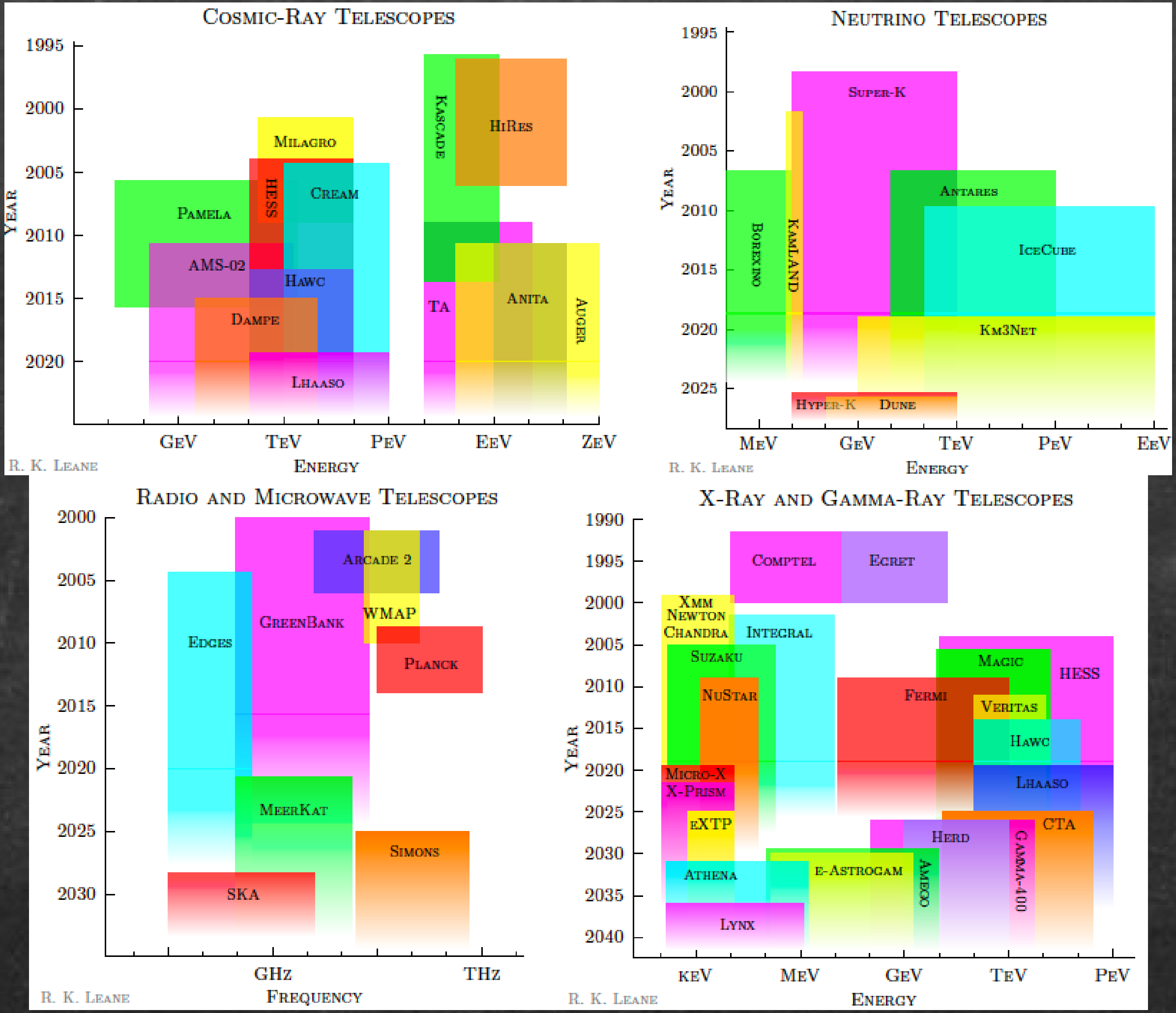
- Multimessenger astronomy:
  - powerful probe/s of thermal DM + heavy decaying DM (sensitivity entering the ballpark)
  - sub-GeV and multi-TeV to explore further (MeV astro + CTA)
  - v-dependencies of signals + impact of subhalos

- PBHs: elephants in the room:
  - Even a tiny fraction of PBH DM kills s-wave annihilating DM
  - Strong science case for the coming years (GWs and X-rays).

- DM theory / searches: transdisciplinary approaches necessary
  => Strong French groups + PNHE plays an important role

Backup

Experimental landscape



DM candidates' mass range

Lower mass bounds

Upper mass bounds

Thermal particle DM (boson/fermion)
~ keV
[Ly-alpha, dwarf galaxies]

Thermal particle DM (boson/fermion)
~ 100 TeV
[Unitarity]

Fermionic particle DM (single species):
~ 0.1 keV
[Dwarf galaxies as degenerate Fermi gas systems]
[aka Tremaine-Gunn limit]

(Non-thermal) **Macroscopic** DM:
e.g. primordial black holes ~ 1-10 M_{sun}

Bosonic particle DM:
~ 10^{-22} eV
[de Broglie wavelength ~ size of dwarf galaxies]

Summary

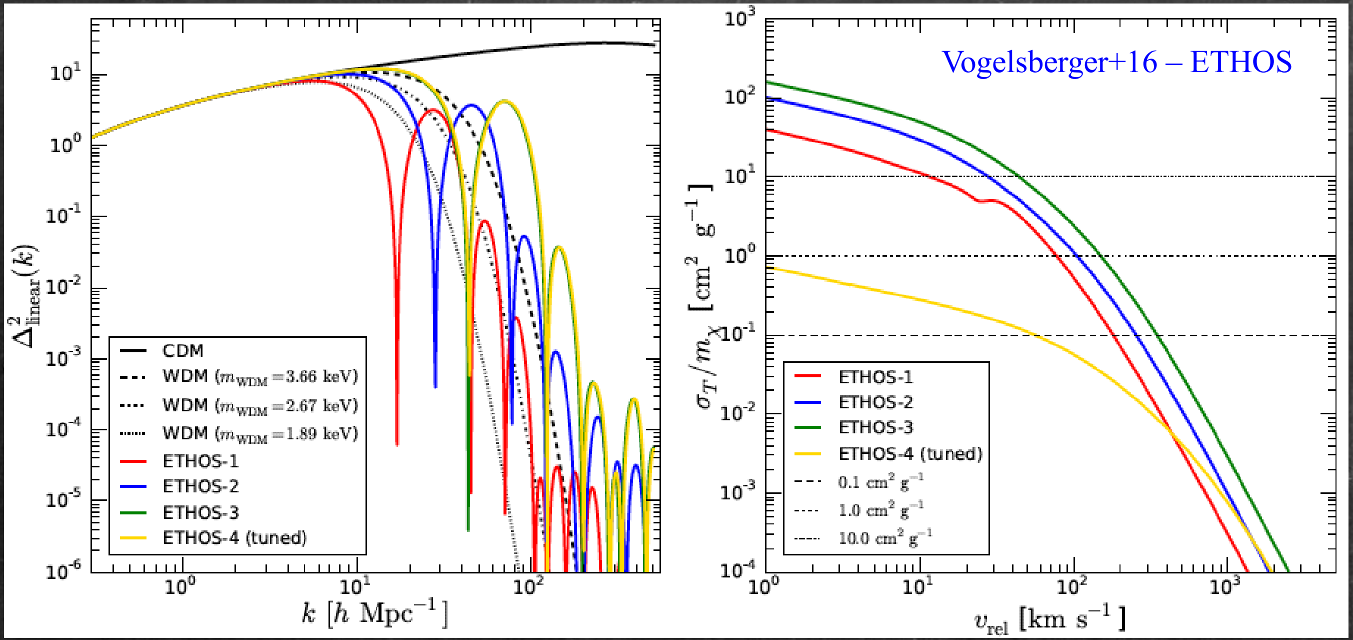
Thermal DM particles in range ~1 keV - 100 TeV

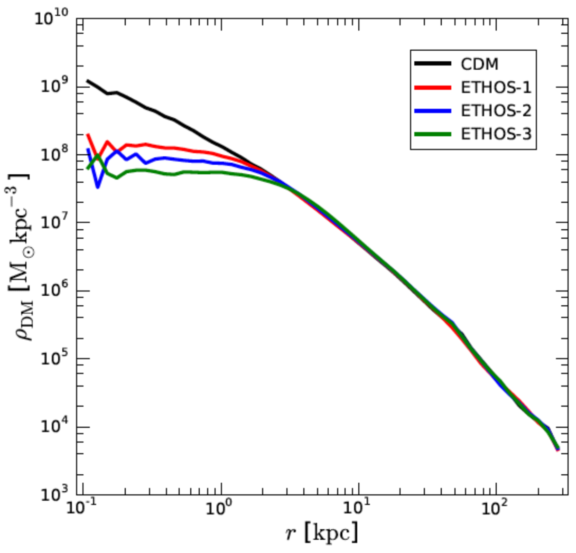
Non-thermal DM:

- > 10^{-22} eV (bosons)
- > 0.1 keV (fermions)

Macro DM: < 10 Msun

Core-cusp solution through (self-) interactions





Collisional damping vs. WDM vs. SIDM: [e.g. ETHOS – Vogelsberger+'16]

Scattering with light SM species suppresses power spectrum on small scales

→ suppression similar to WDM [Boehm+'01-'15, etc.]

+ self-scattering (SIDM) => density-dependent setting of cores in halos

Typically constrained by Ly-alpha [e.g. Dvorkin+'20]

N_{eff} from BBN and CMB

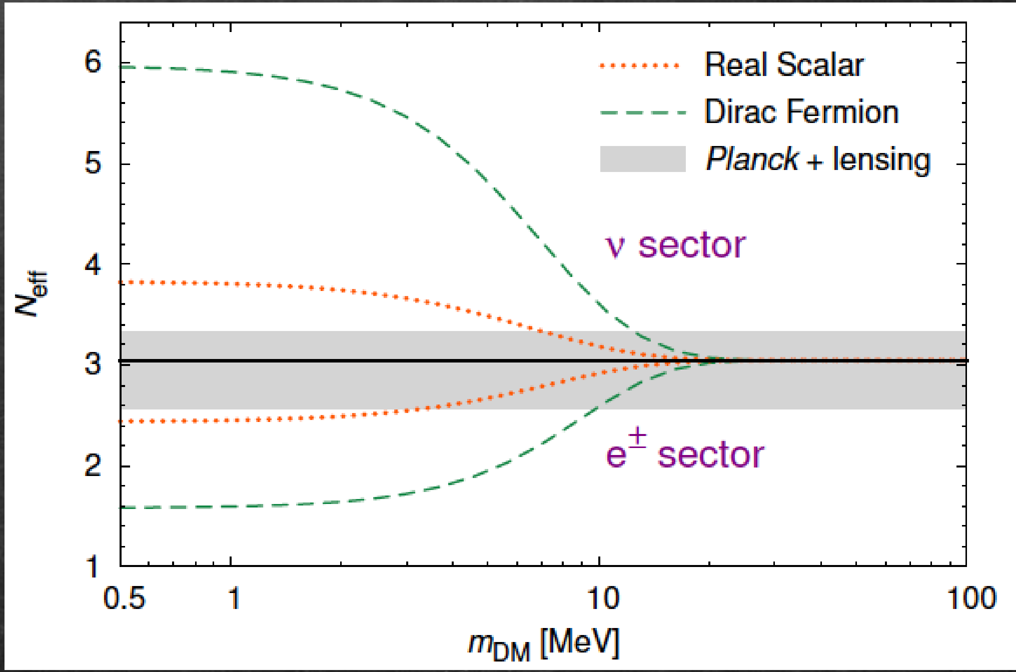
[Assume tuning to 511 keV signal + couplings to e’s and nu’s only]

MeV DM can freeze out after ν decoupling

DM dominant coupling to ν’s (s-wave):
→ contributes additional ν’s: N_{eff}
→ increases expansion rate during BBN and recombination
→ n/p freezes out earlier ↔ Y_p & D/H
→ DM-ν scattering prevents ν’s to free stream

DM dominant coupling to e^+e^- (p-wave):
→ transfers entropy to visible sector
→ fixed photon density today => decreases N_{eff}

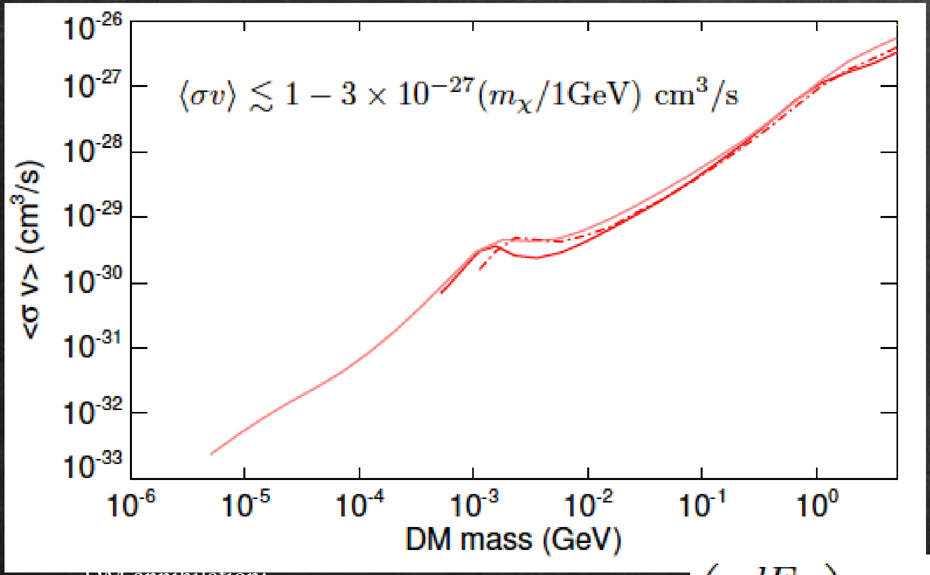
Wilkinson, Boehm+’16



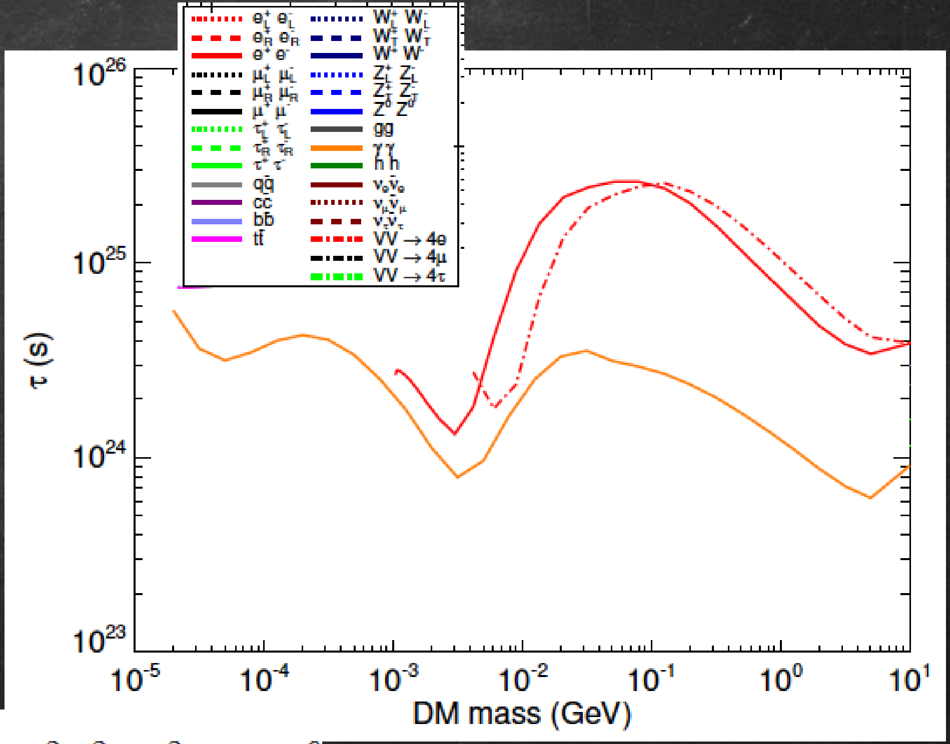
CMB Constraints

Studied since early 2000's
[e.g. Finkbeiner+, Slatyer+, Galli+, etc.]

DM annihilation/decay products inject energy that contributes ionization at recombination and after.



DM annihilation:
Slatyer '16



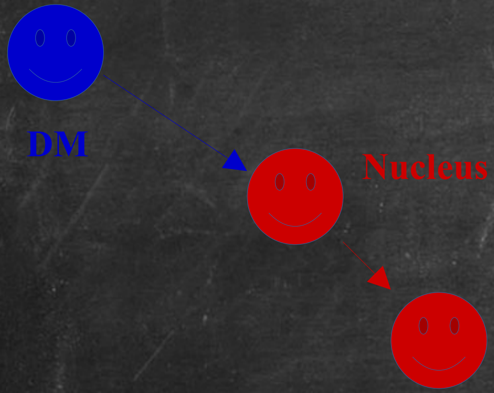
DM decay:
Slatyer & Wu '19

$$\left(\frac{dE}{dt\,dV}\right)_{\text{ann}} = p_{\text{ann}}(z) c^2 \Omega_{\text{DM}}^2 \rho_c^2 (1+z)^6$$

$$p_{ann} \equiv f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

Direct searches

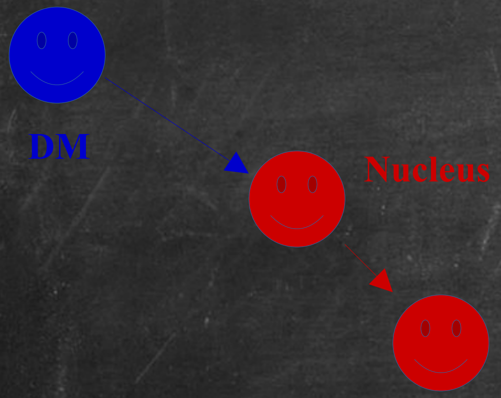
Classical WIMP searches:
Scattering off target **nuclei**
=> **nuclear recoils**

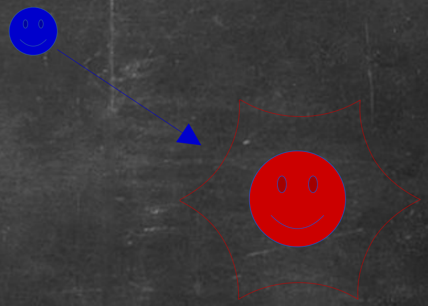


Astrophysical input important:
- local DM abundance + inhomogeneities
- local phase-space distribution of DM
[high tail of v-distribution gives largest kinetic energy]
→ Gaia data + theory dev.

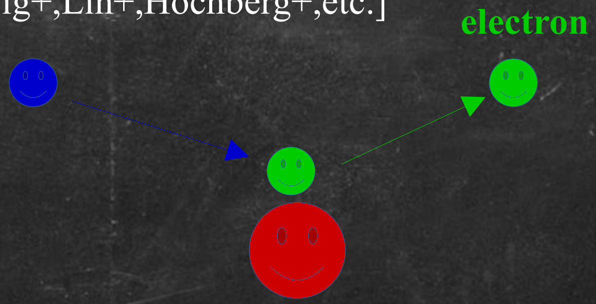
Direct searches

Classical WIMP searches:
Scattering off target **nuclei**
=> **nuclear recoils**



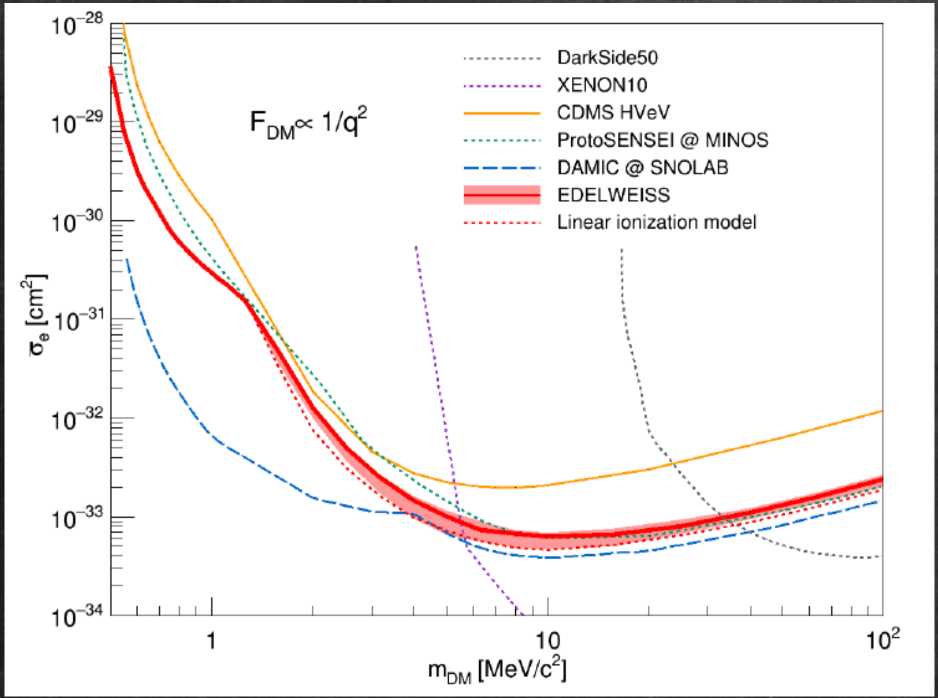


Light WIMP searches:
Short in kinetic energy
=> nuclear excitation/ionization
(e.g. Ibe+’17, Kouvaris+’17)
=> Scattering off **electrons/phonons**
=> **Electronic recoils/heat**
[Intense theoretical effort: Essig+,Lin+,Hochberg+,etc.]

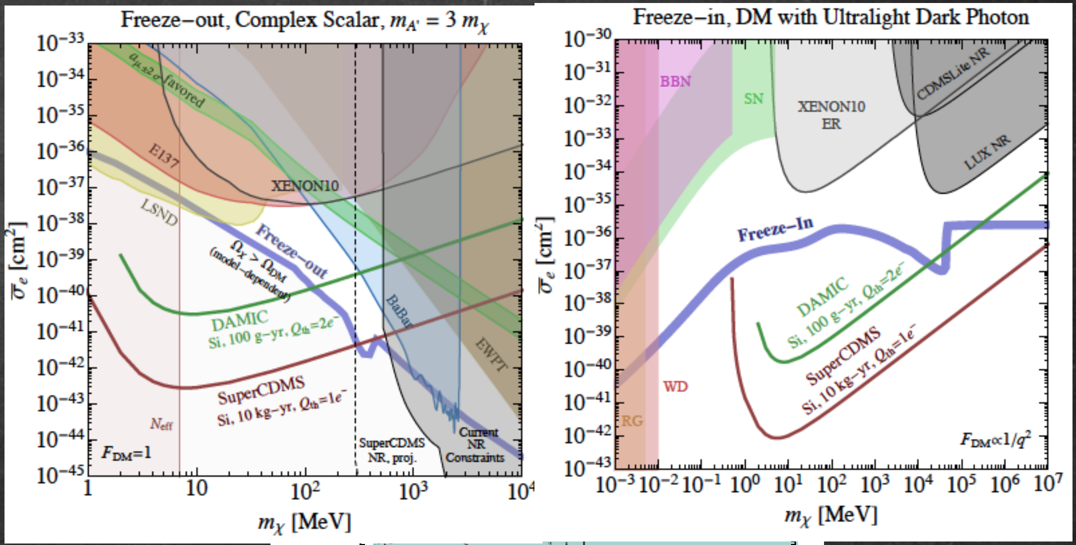


Energetics:	m	keV	MeV	GeV
Recoil ~ kinetic E ~ mv^2	T	meV	eV	keV

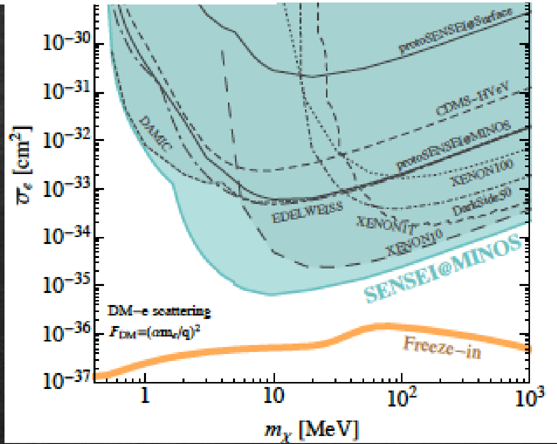
Direct searches



EDELWEISS+'20 [Ge]
Scattering off electrons
Semiconductors better than noble gas
[lower band gap energy]



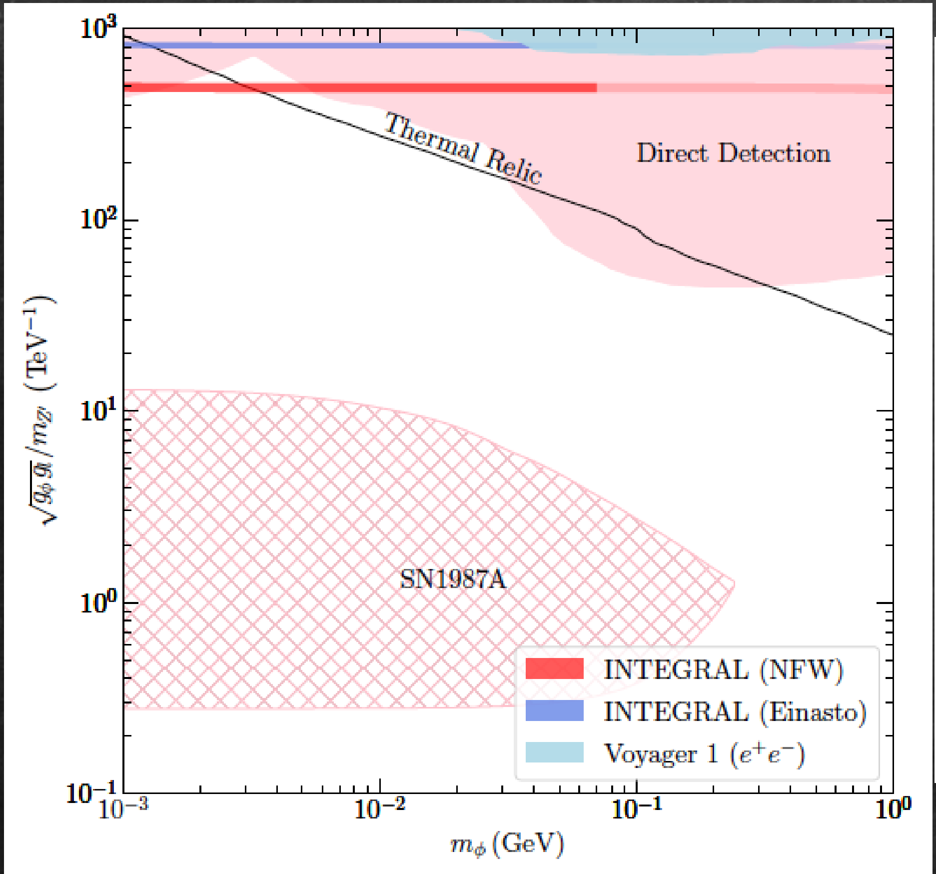
Essig+'16



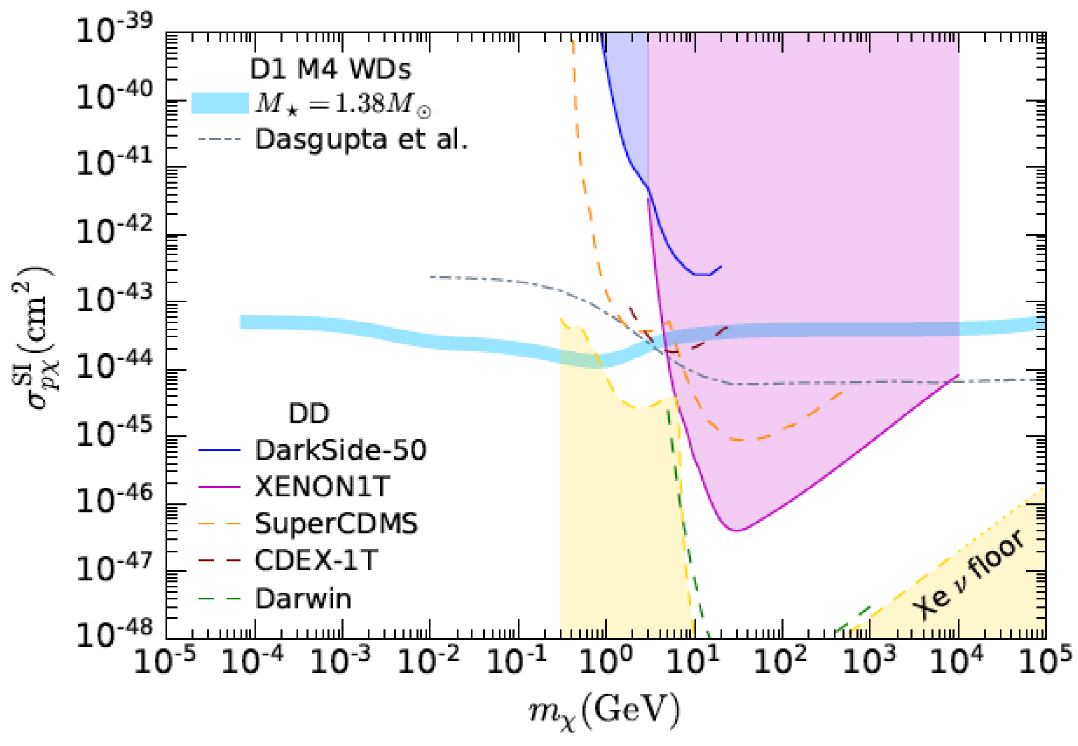
SENSEI+'20

Huge theoretical + experimental activity ongoing

Stars

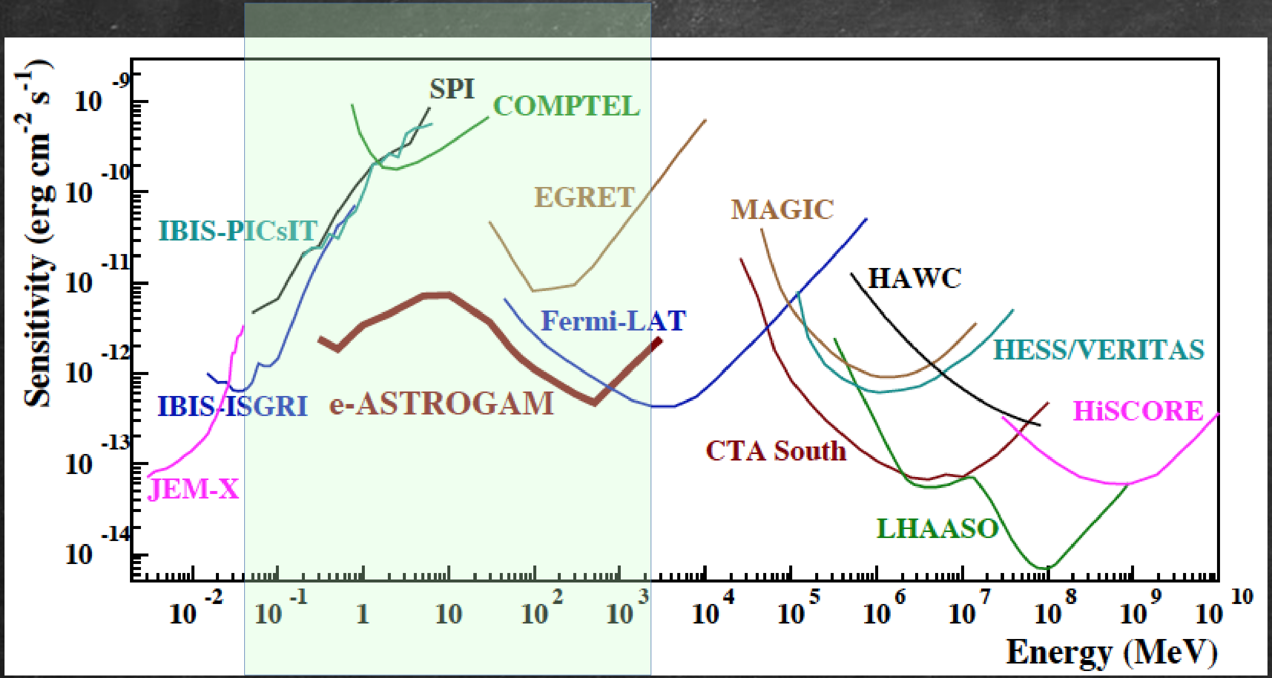


Boehm+'21
SN1987A cooling by DM production
[Raffelt+]



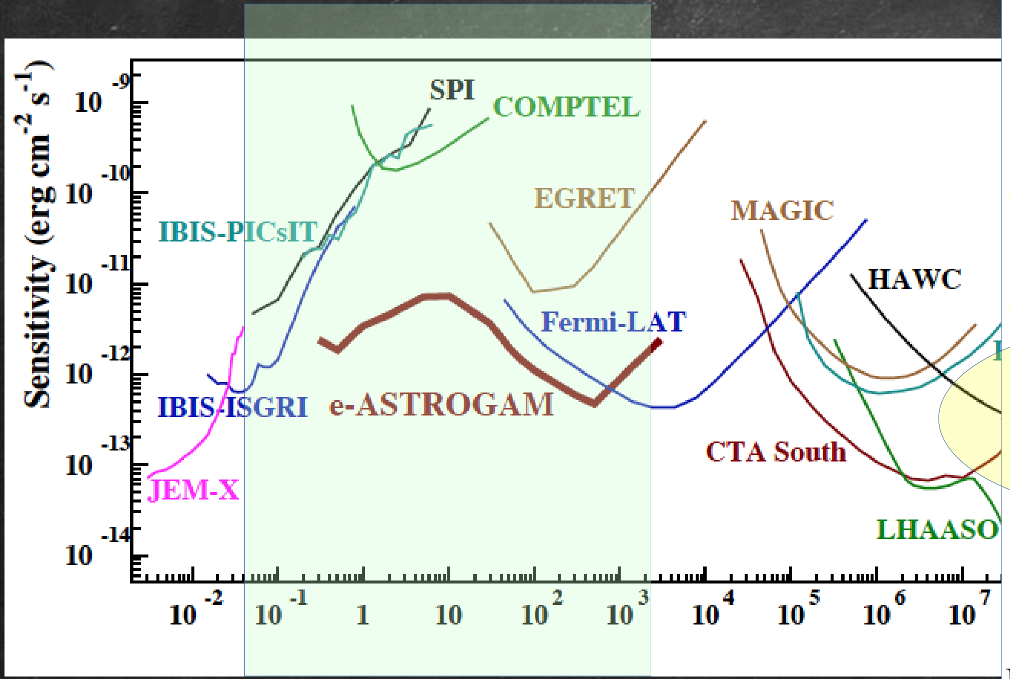
Bell+'21
Heating of white dwarfs (bw assumptions)
[also Bertone, Fairbairn'08-'10]

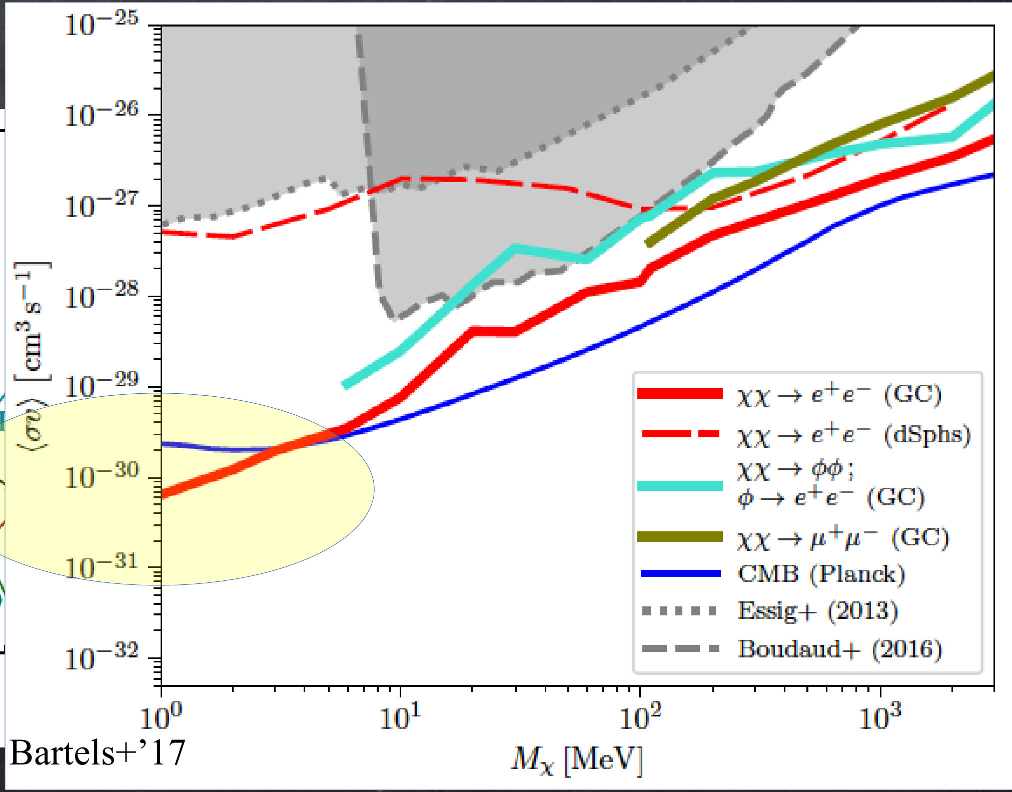
Gammas & positrons



e-Astrogam proposal
De Angelis, Tatischeff+'18

Gammas & positrons

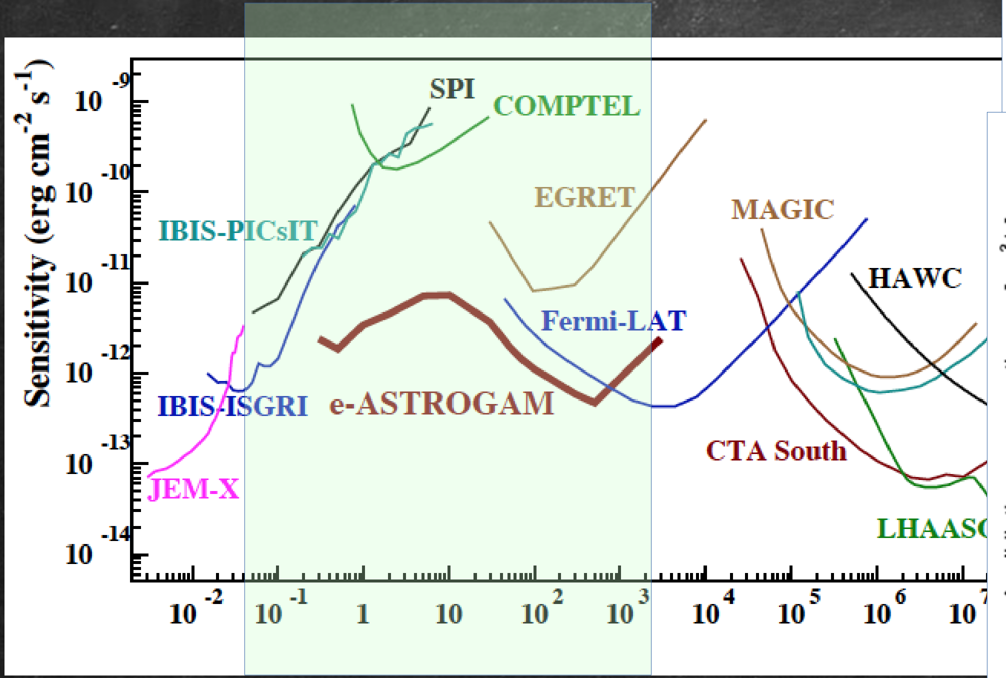


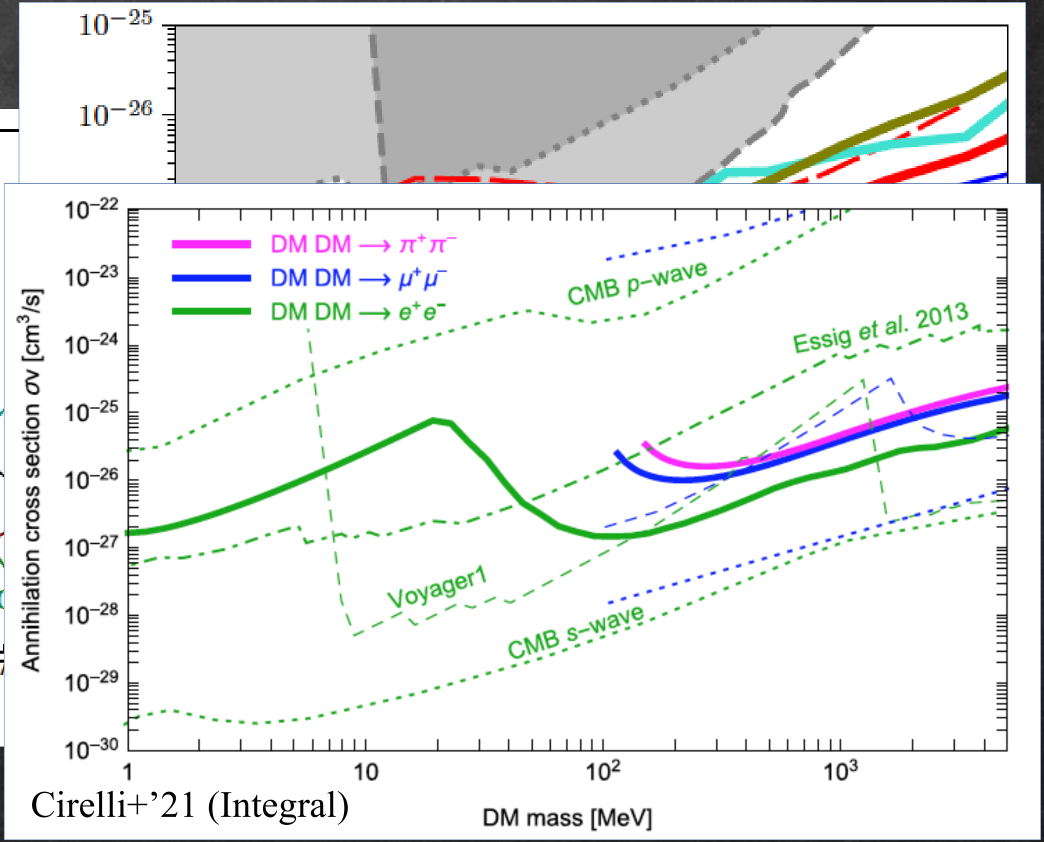


Bartels+'17

e-Astrogam proposal
De Angelis, Tatischeff+'18

Gammas & positrons

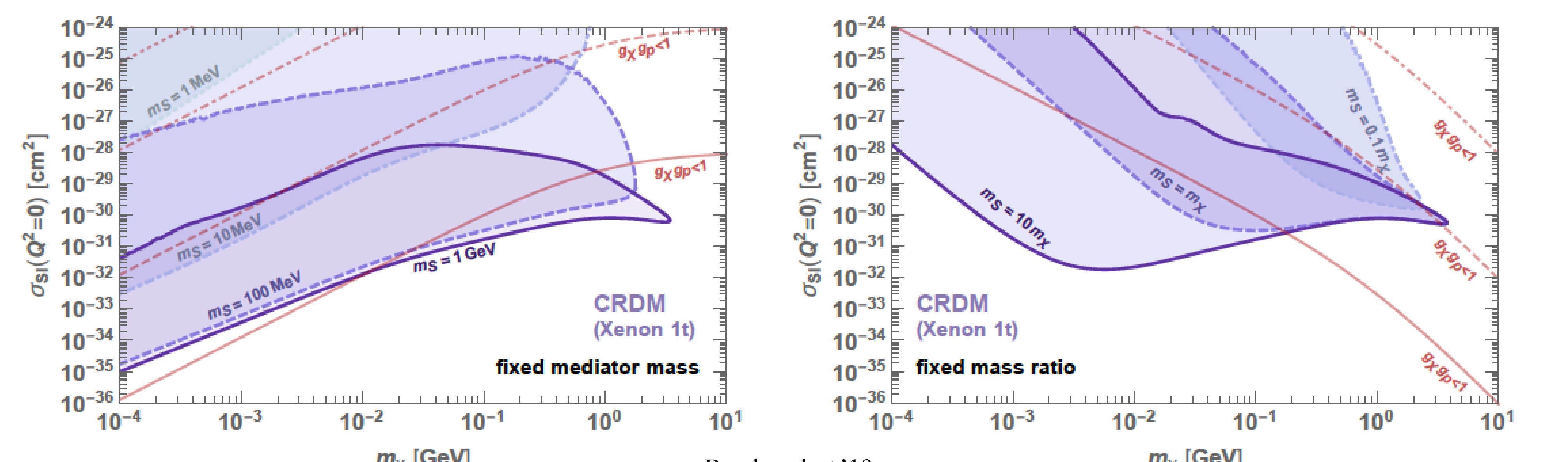




Cirelli+’21 (Integral)

e-Astrogam proposal
De Angelis, Tatischeff+’18

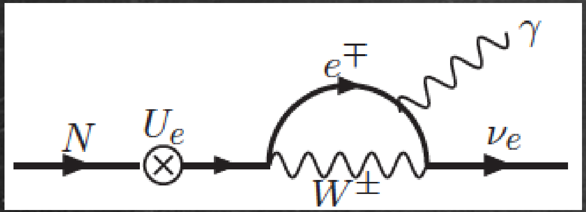
Scattering with cosmic rays

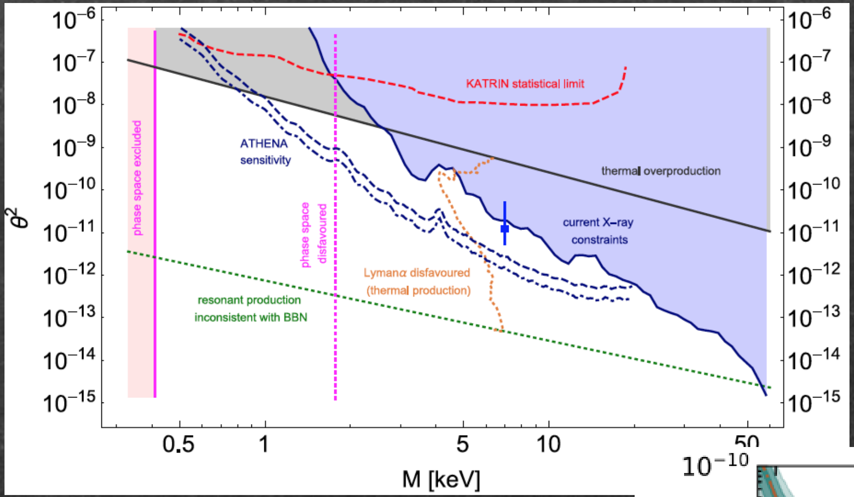


Bondarenko+'19

Scattering of cosmic rays with DM kicks up the latter to high velocities
=> induced DM cosmic rays (large kinetic energy) [e.g. Bringmann+'18]
=> can be probed at direct detection experiments

Sterile neutrinos from X-rays

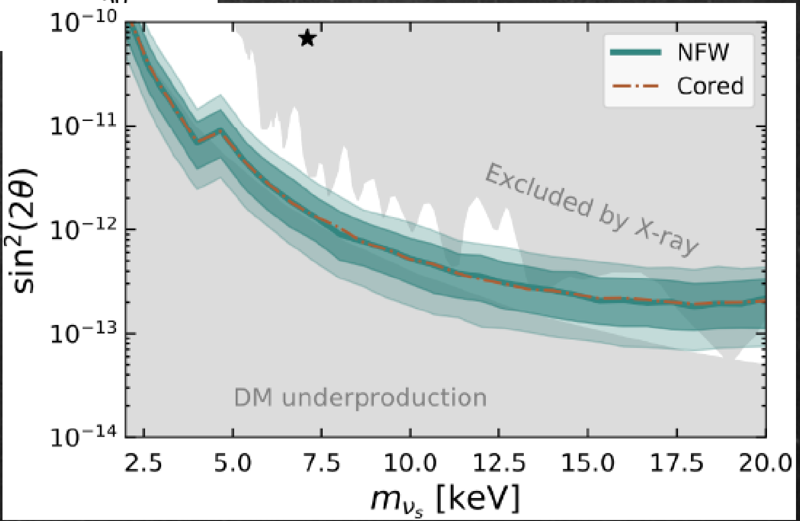




Boyarsky+'19

Main constraints:

- Matter power spectrum (Ly-alpha)
- Subhalo/dwarf galaxy counts
- X-ray observations



Dekker+'21
(@ICRC)
e-ROSITA sensitivity