WIN2019 - THE 27TH INTERNATIONAL WORKSHOP ON WEAK INTERACTIONS AND NEUTRINOS
BARI, JUNE 3-8, 2019

ASTROPARTICLE EXPERIMENTS

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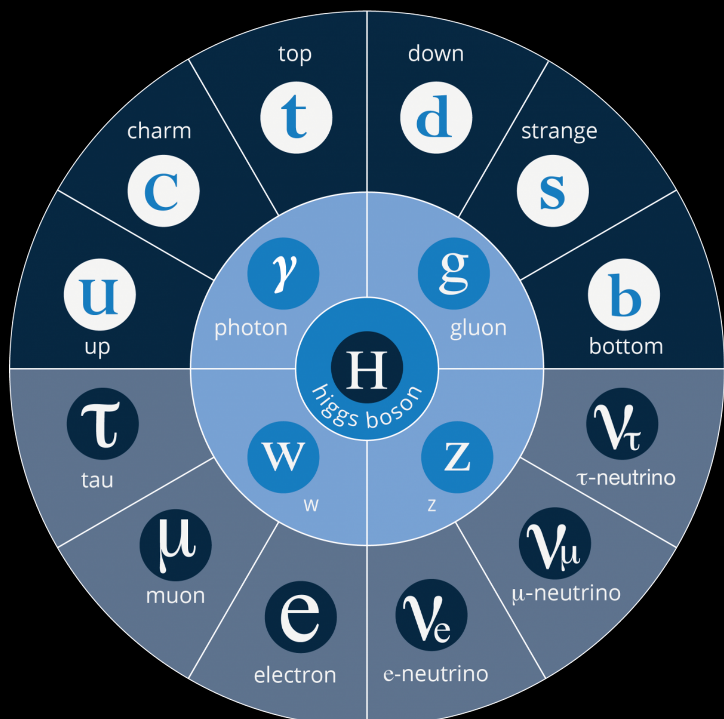
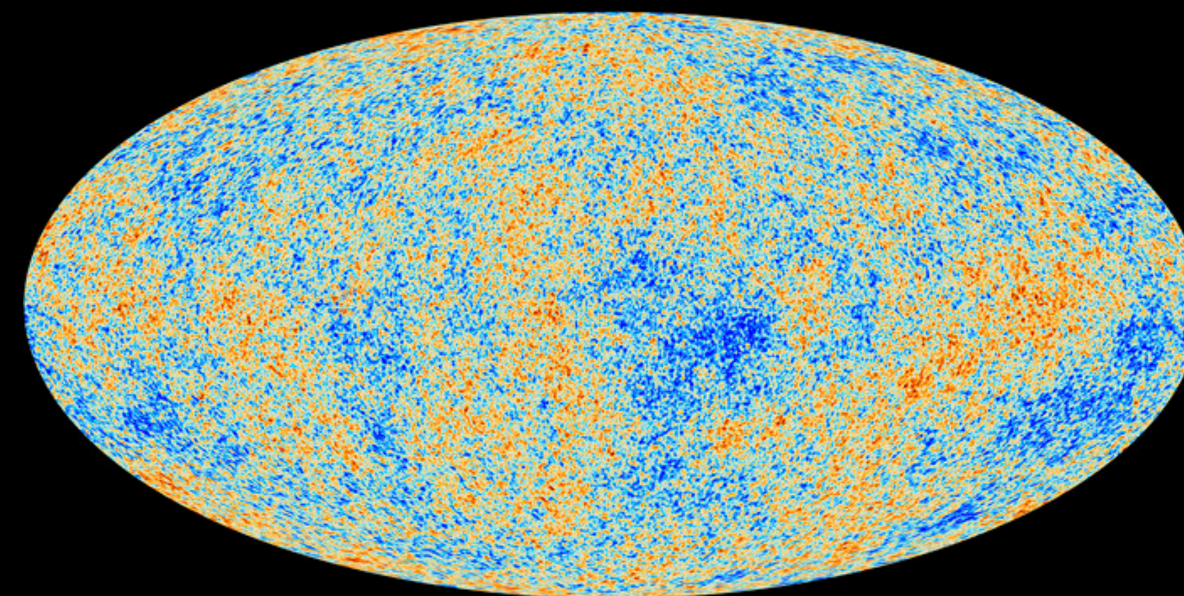
UNIVERSITÀ DEGLI STUDI DI NAPOLI "FEDERICO II" & INFN

ASTROPARTICLE PHYSICS

A bridge between the Standard Models



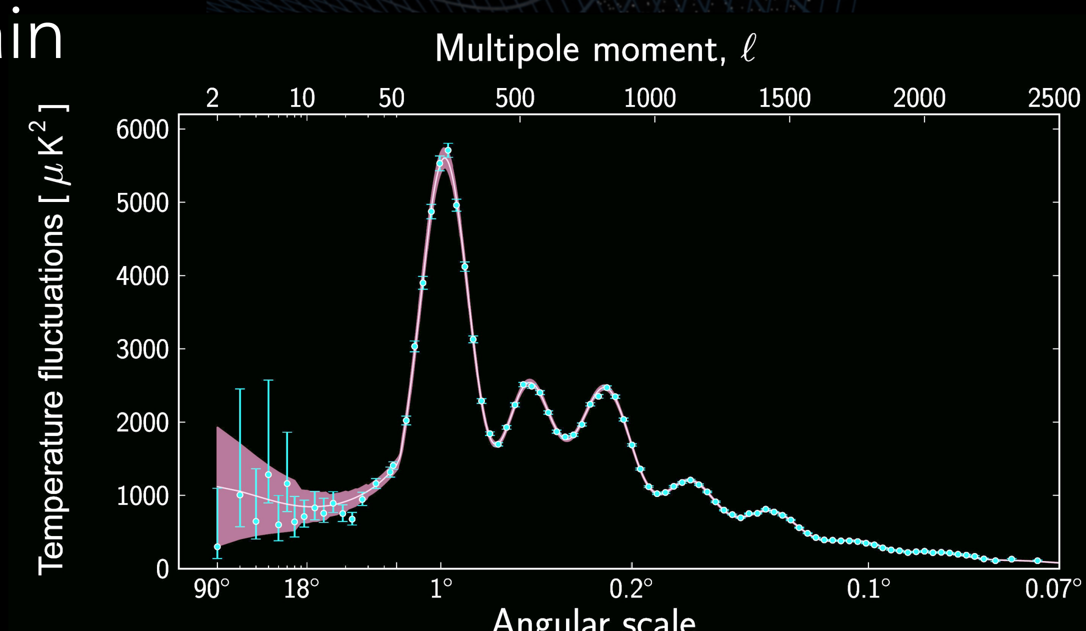
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

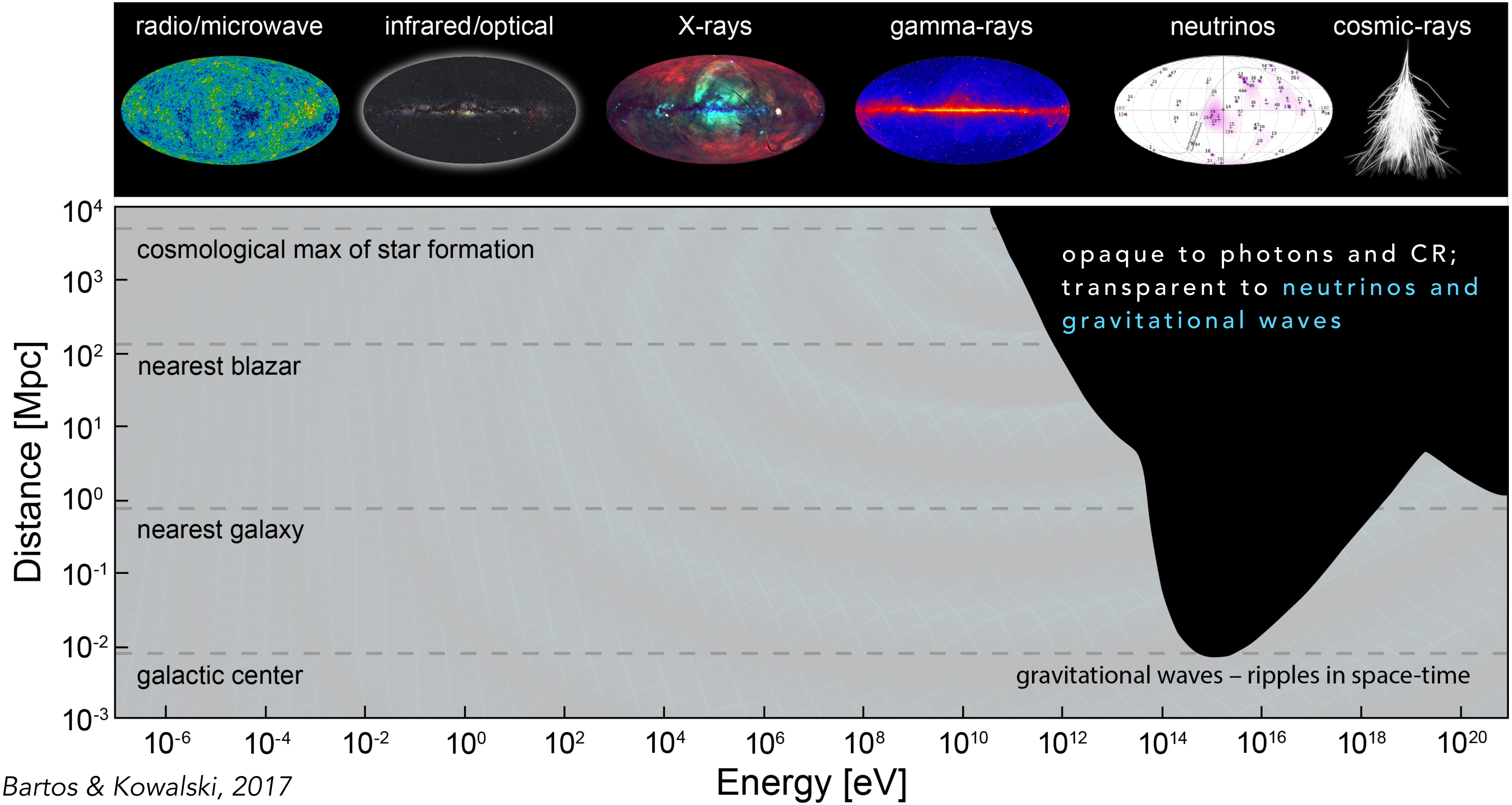
Things that the Standard Models cannot explain

- ❖ Neutrino masses and mixing
- ❖ DM and DE
- ❖ Matter-antimatter asymmetry
- ❖ Inflation
- ❖ Quantum Gravity



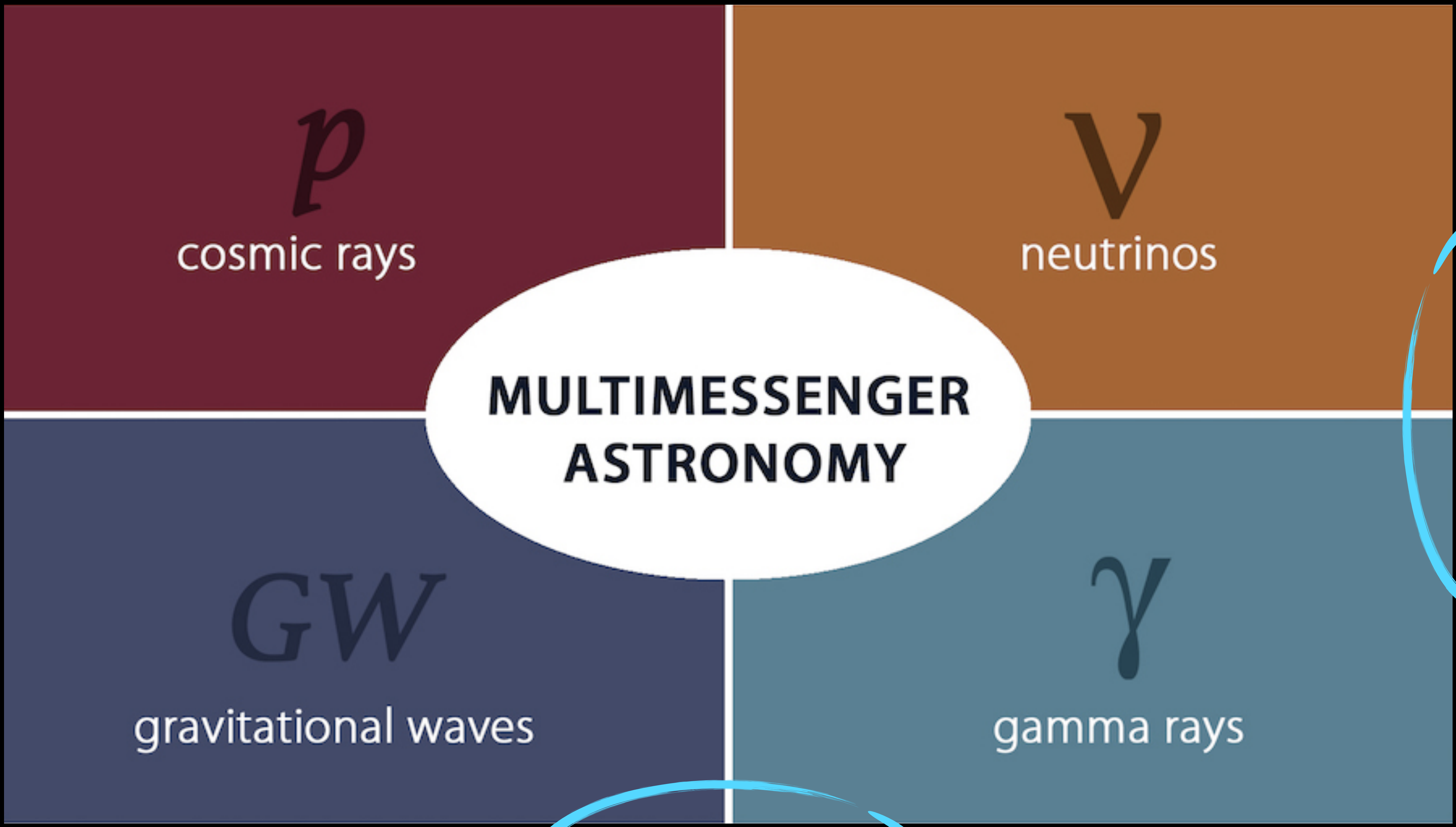
COSMIC MESSENGERS

Distance horizon at which the Universe becomes optically thick to electromagnetic radiation



Bartos & Kowalski, 2017

A MULTI-MESSENGER APPROACH

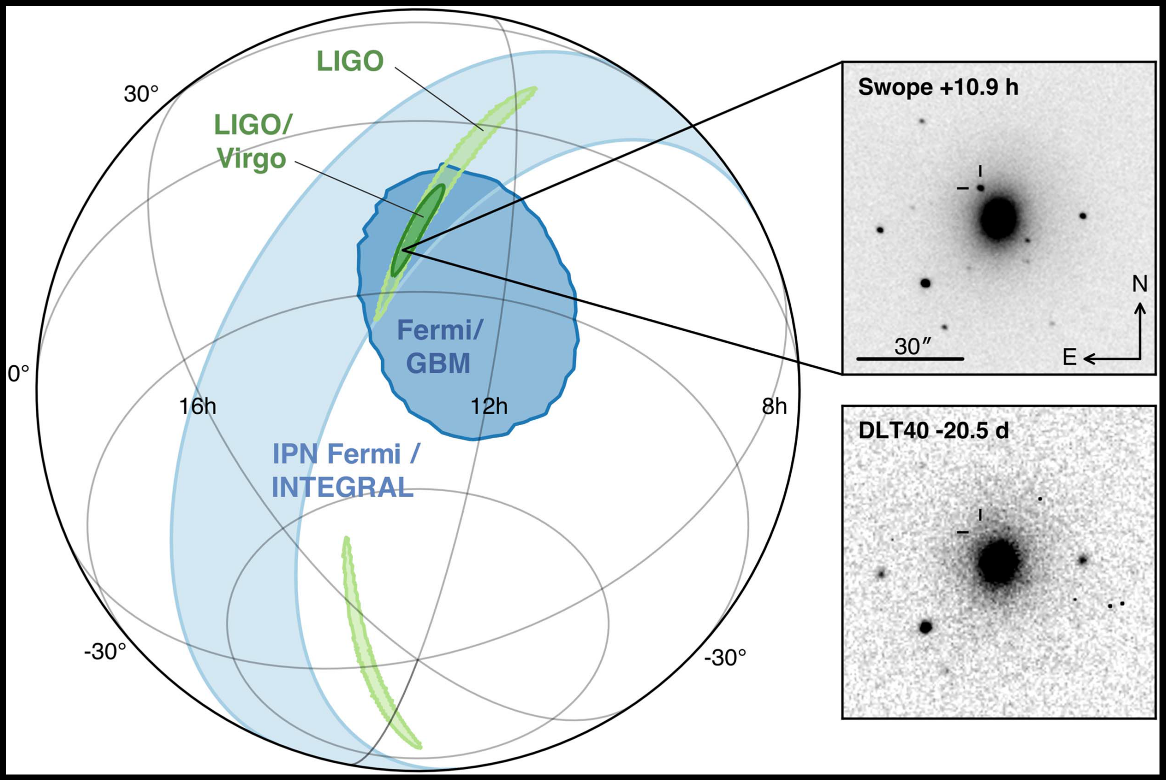


TXS 0506+056

GW170817

Kowalski, ESPP, Granada 2019

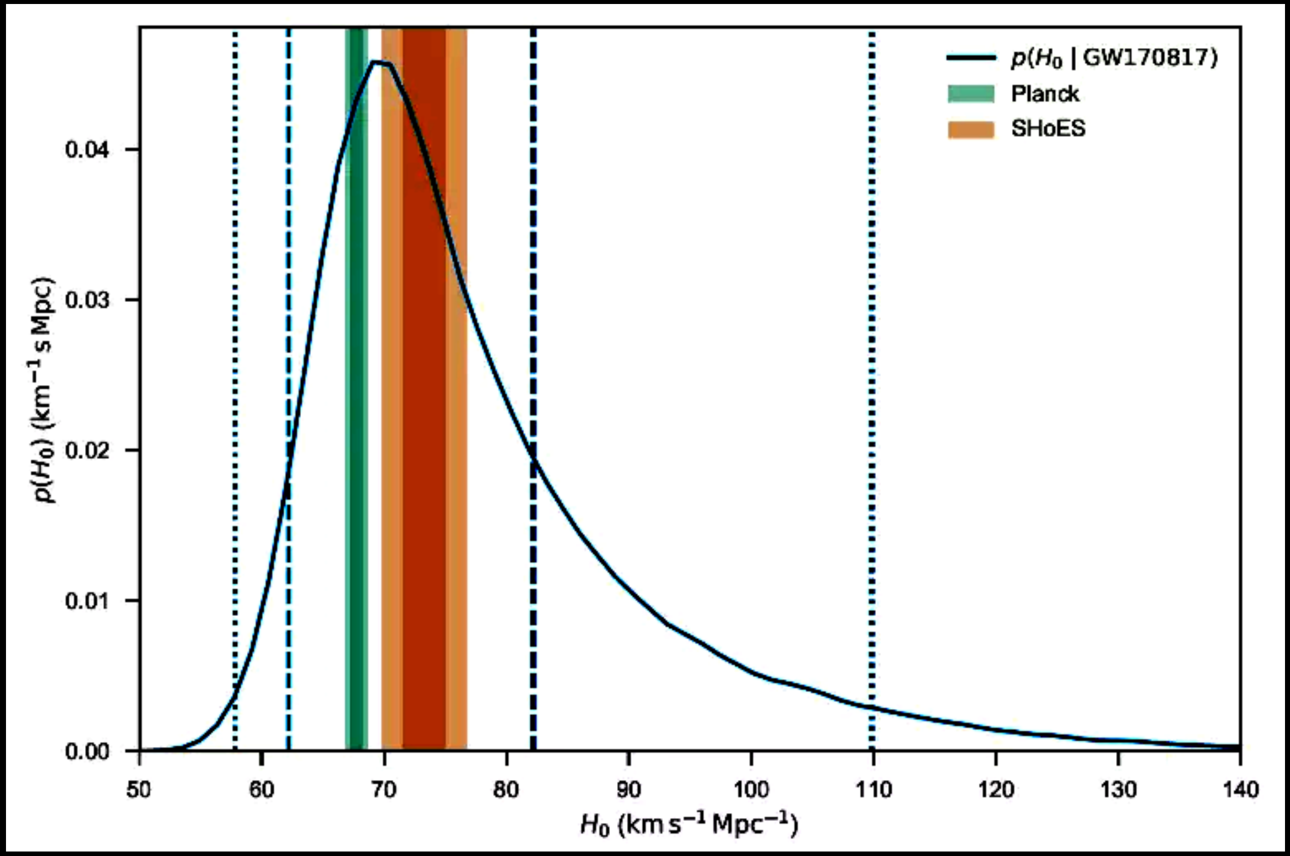
PHOTONS AND GW: STANDARD SIREN COSMOLOGY



merger of a binary neutron-star system
GW170817 + GRB 170817A

$$H_0 = \text{velocity}/\text{distance}$$
$$= 70^{+12}_{-8}\ \text{km s}^{-1}\text{Mpc}^{-1}$$

Tension in H_0 measurement from CMB and SHoES
evidence of new/missing physics?



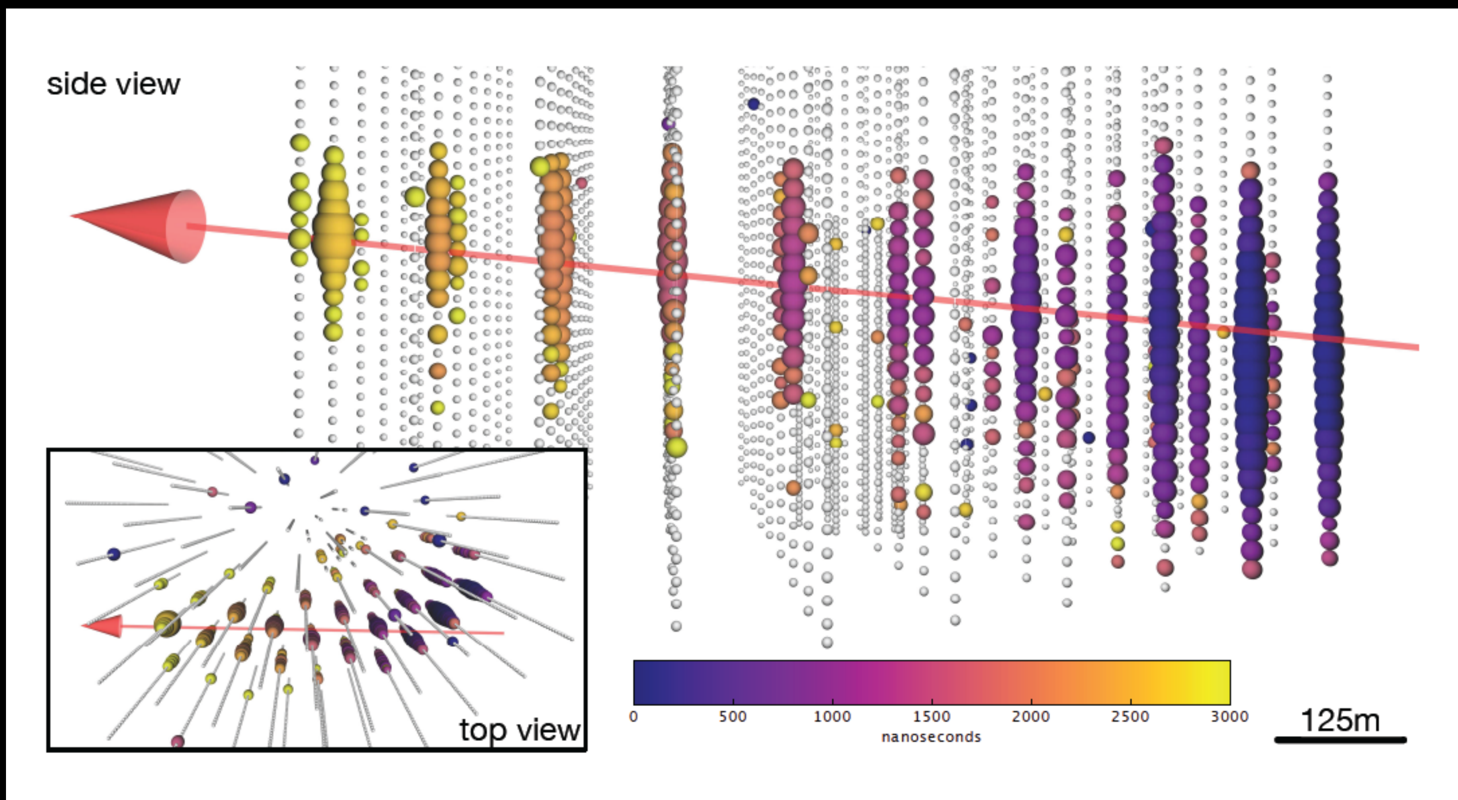
Abbott+, Nature (2017)

3G network will detect millions of mergers,
calibrate nearby supernovae,
determine dark energy equation of state and its variation with redshift

Sathyaprakash @ ESPP, Granada 2019

HE NEUTRINOS AND GAMMA RAYS

Science, 361 (2018) *IC170922A*



- High-energy cosmic neutrino in coincidence with the TXS 0506+056 Blazar emitting gamma rays beyond 100 GeV energies
- Compelling evidence for neutrino emission from the Blazar $\Longrightarrow$ identification of a cosmic hadron accelerator with >PeV energies!
- Stringent constraints on Lorentz violation in the propagation of neutrinos

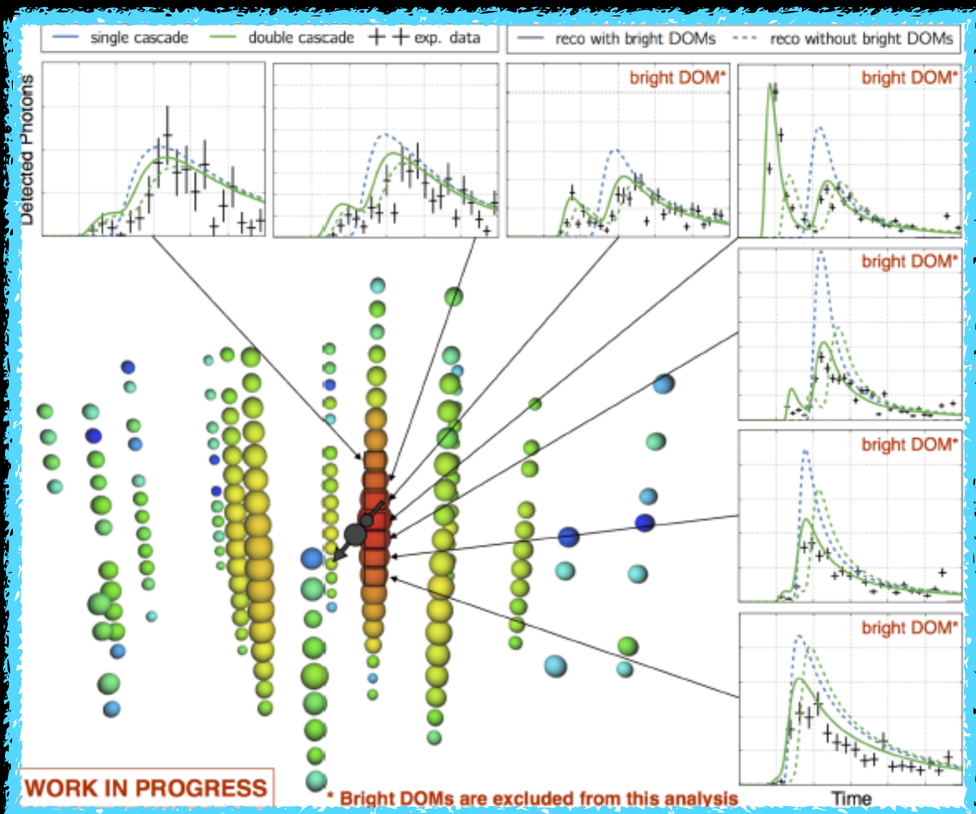
$E_\nu > 200$ TeV; d= 4×10^9 ly; $\Delta T_{\nu\gamma} \sim 10$ days
$\Longrightarrow -\Delta v_{\nu\gamma} = E_\nu / M_1 \geq 3 \times 10^{16}$ GeV
6 orders of magnitude stronger than the limit obtained from SN1987A

"…the advent of multimessenger neutrino/photon astronomy has not only launched a new era in the study of the origins of high-energy cosmic rays, but also made possible a breakthrough in the exploration of Lorentz symmetry using neutrinos."

J. Ellis et al., Phys.Lett. B789 (2019)

COSMIC NEUTRINOS

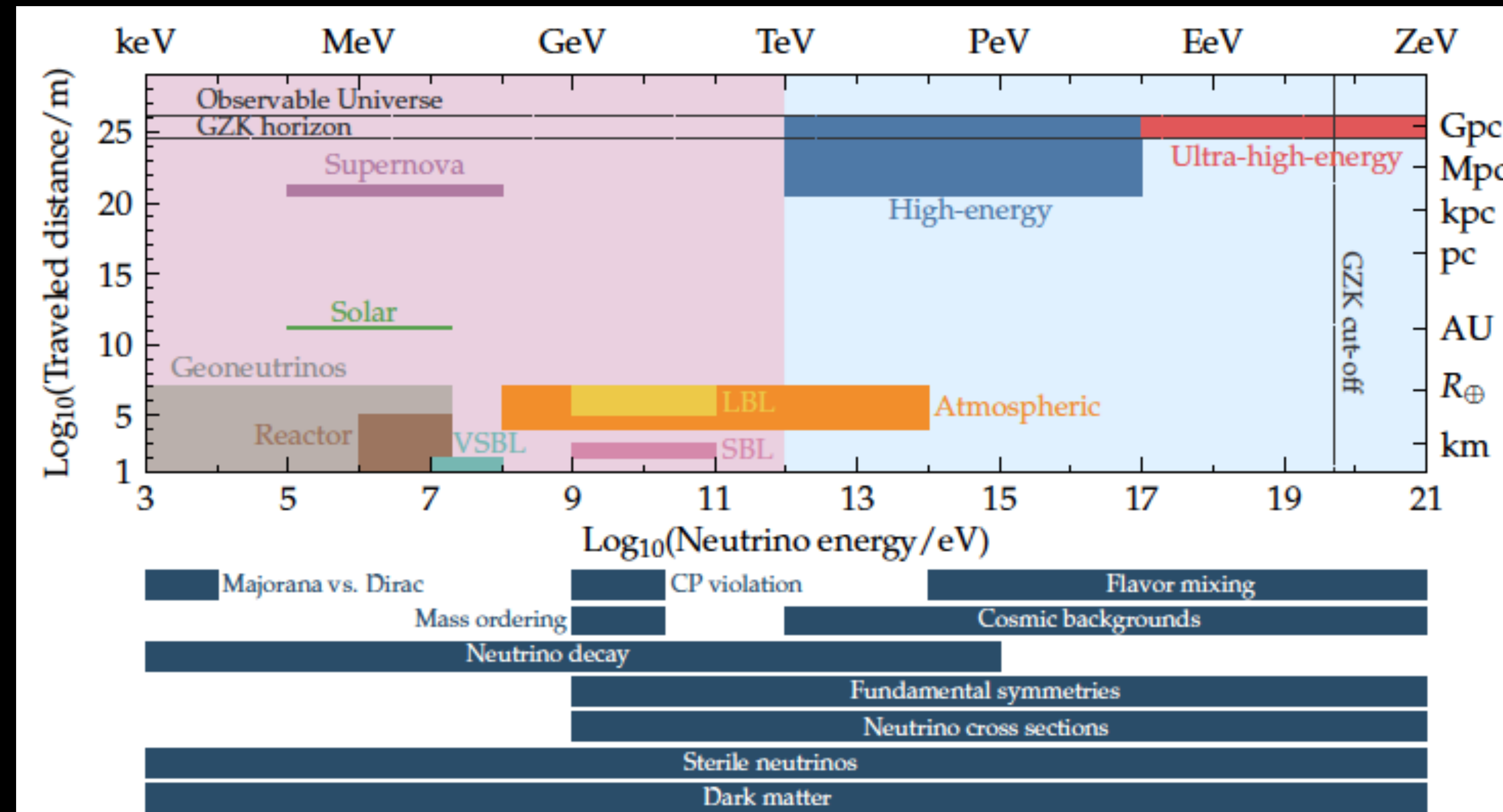
Astro2020 Science White Paper, arXiv:1903.04333v1

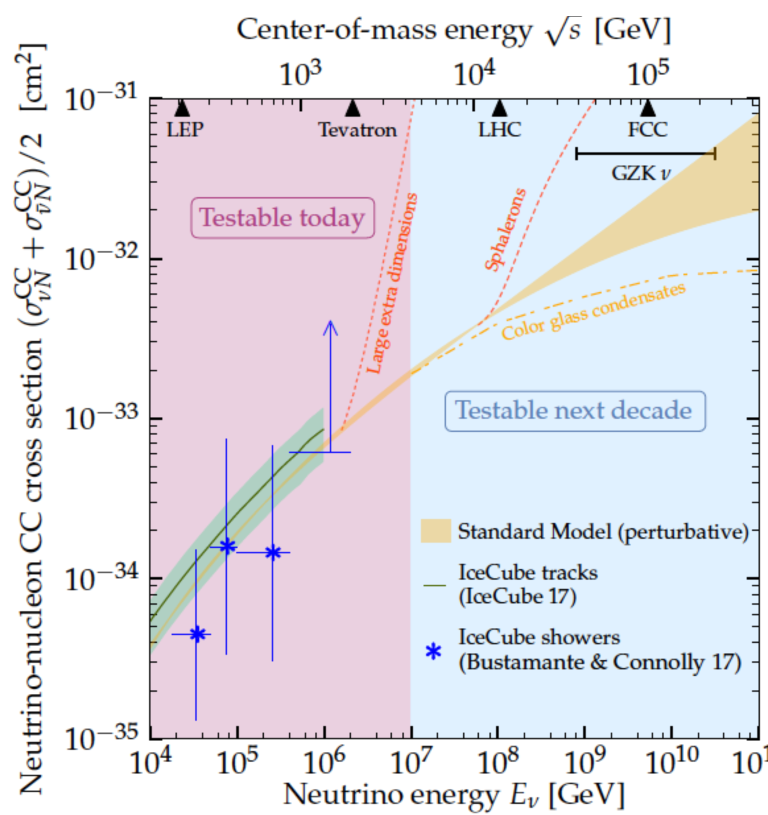


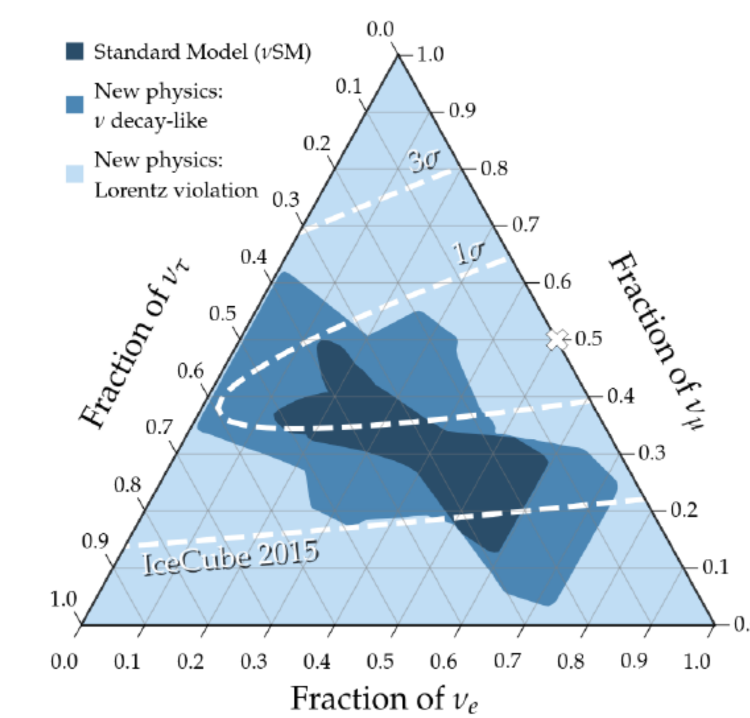
Halzen, Granada 2019

first (cosmic) tau neutrino candidate in 7.5 yrs of IceCube data

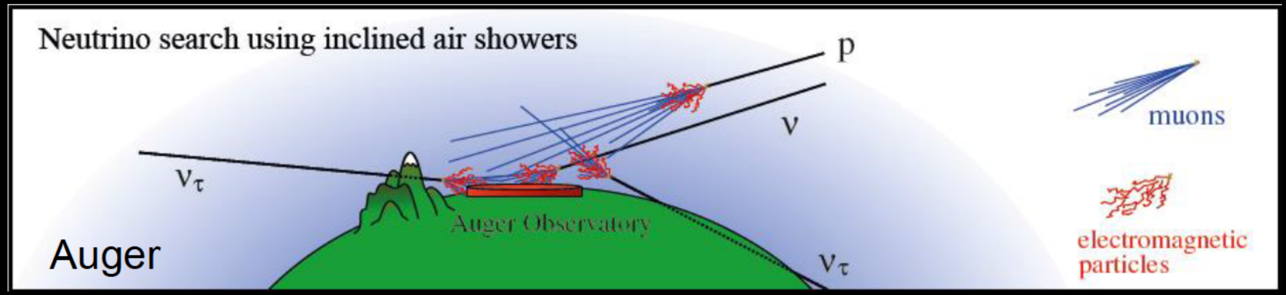
- Test of fundamental physics BSM
- Cross-section and (cosmic) neutrino mixing studies

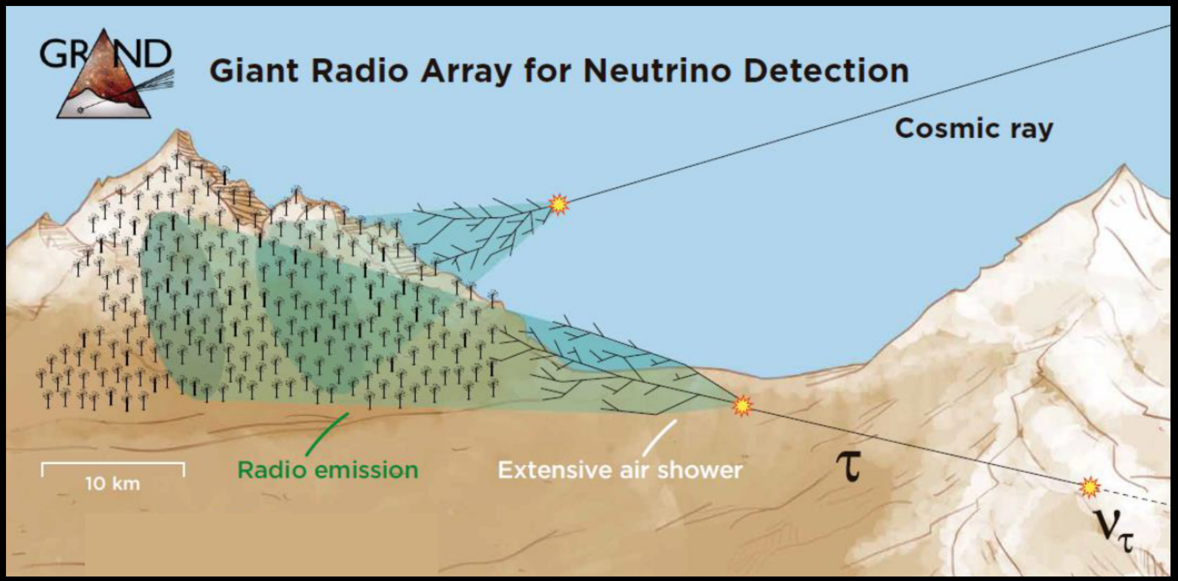


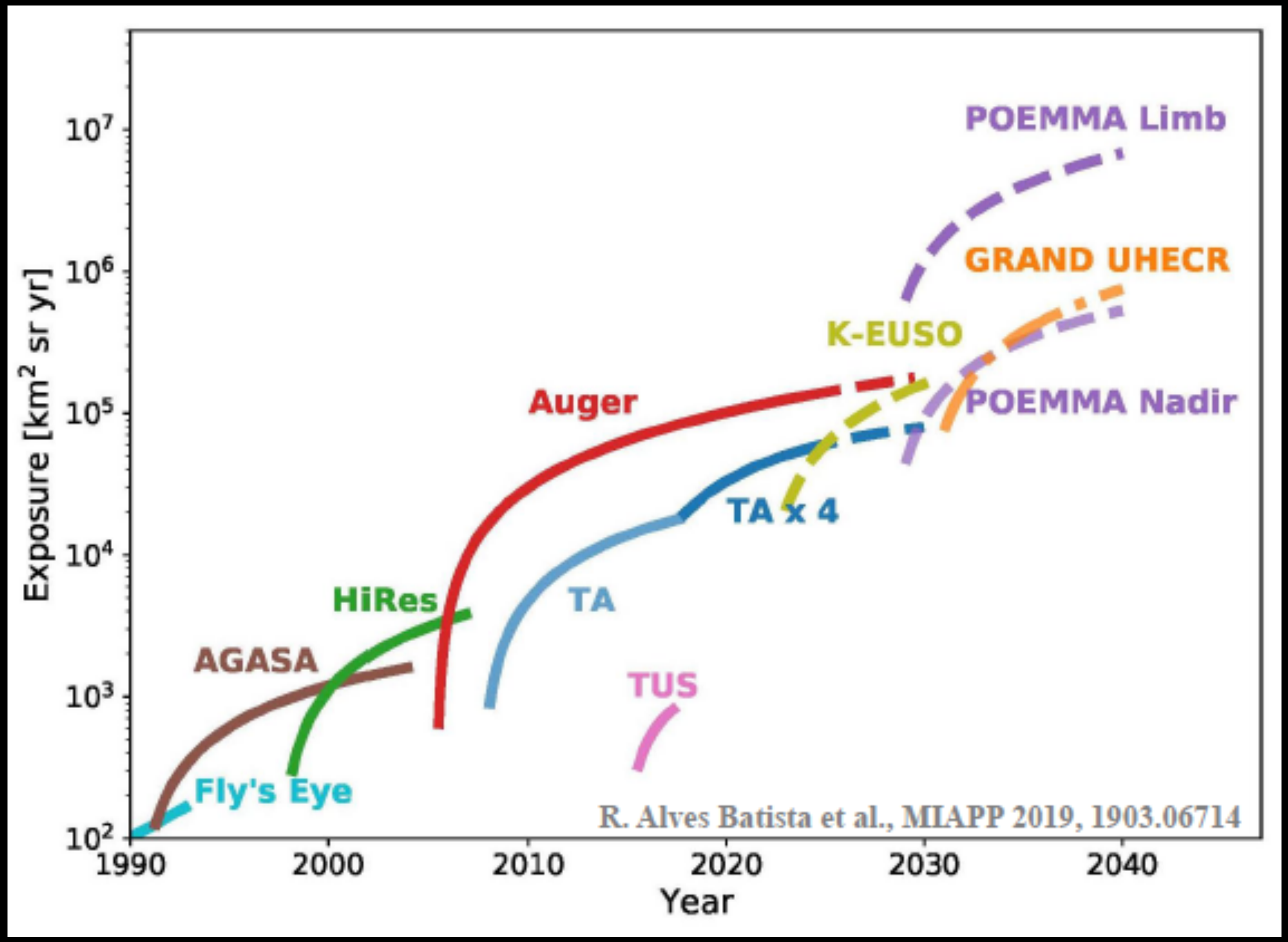


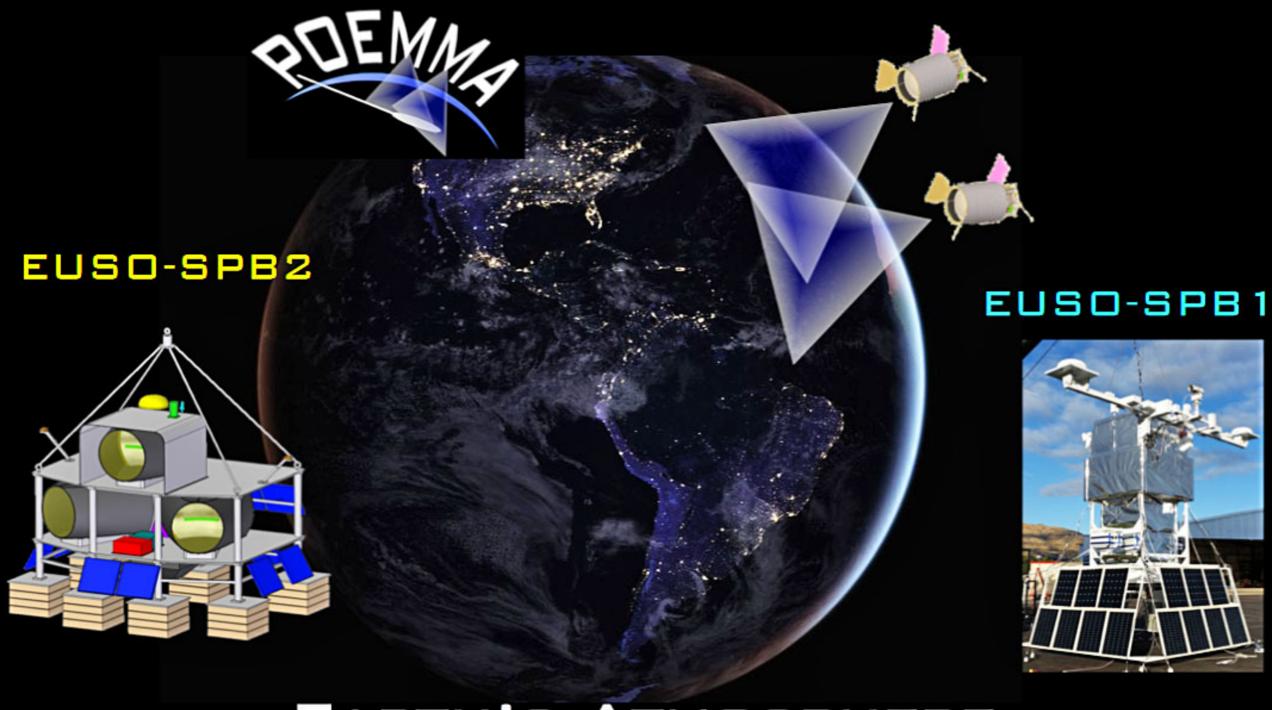


EXTREME MULTI-MESSENGER ASTROPHYSICS: CR AND NEUTRINOS







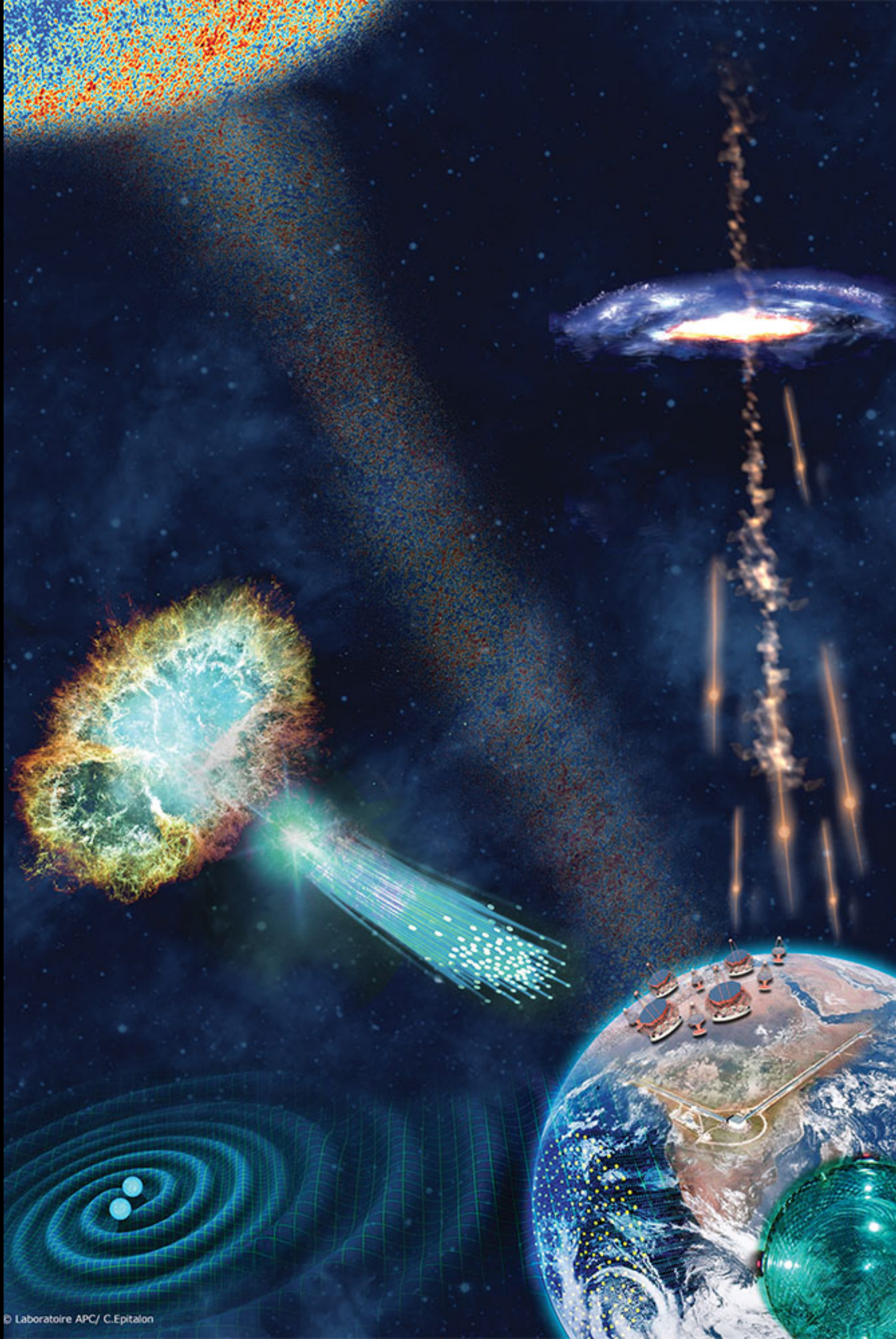


Earth's Atmosphere as an Extreme Particles Observatory

Prospects for UHECR: higher statistics!

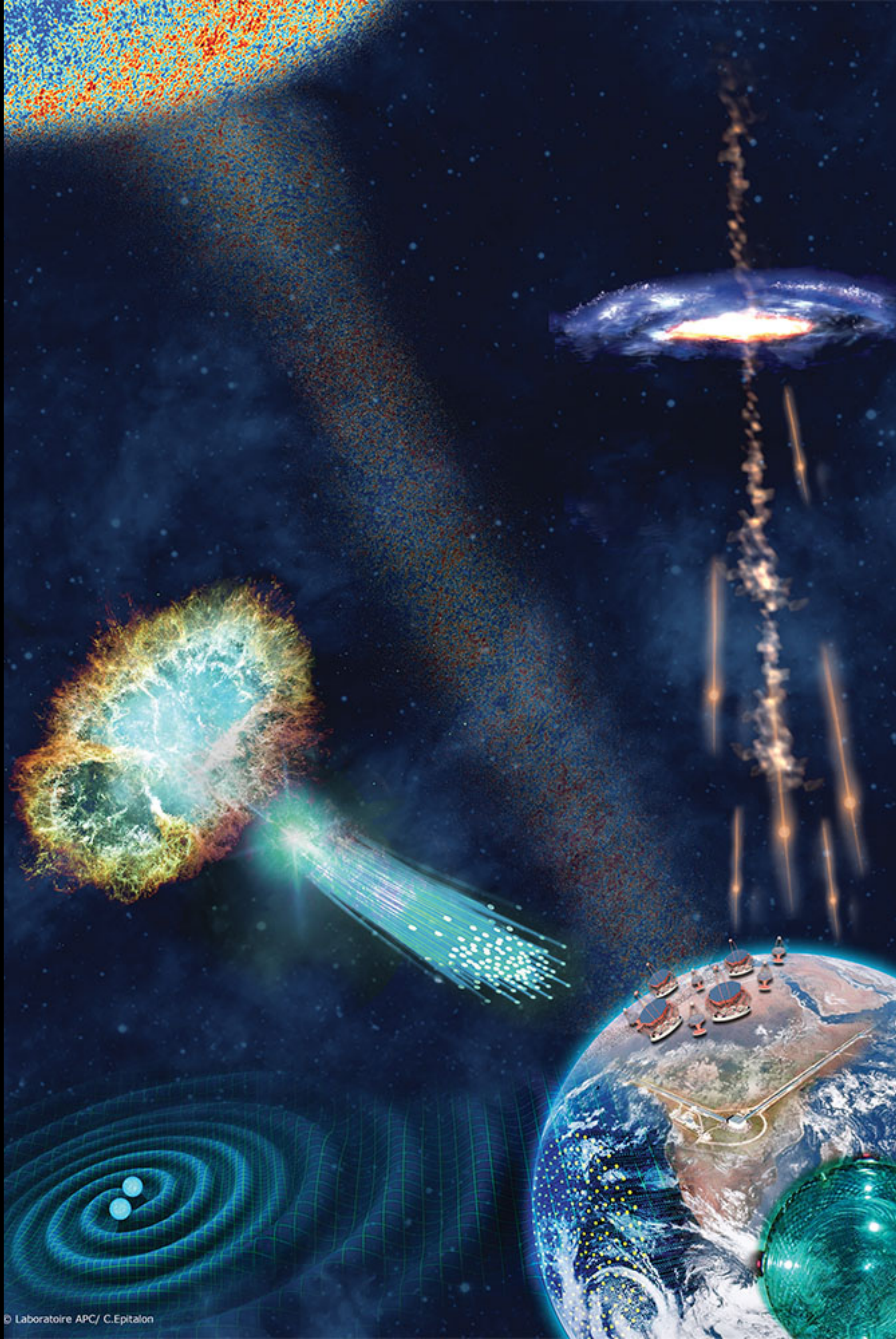
ASTROPARTICLE PHYSICS AND COSMOLOGY: TOPICS COVERED AT WIN2019

- Dark Matter
- Cosmic Rays, Gamma Rays, Neutrinos
- Gravitational Waves
- Cosmological Observations



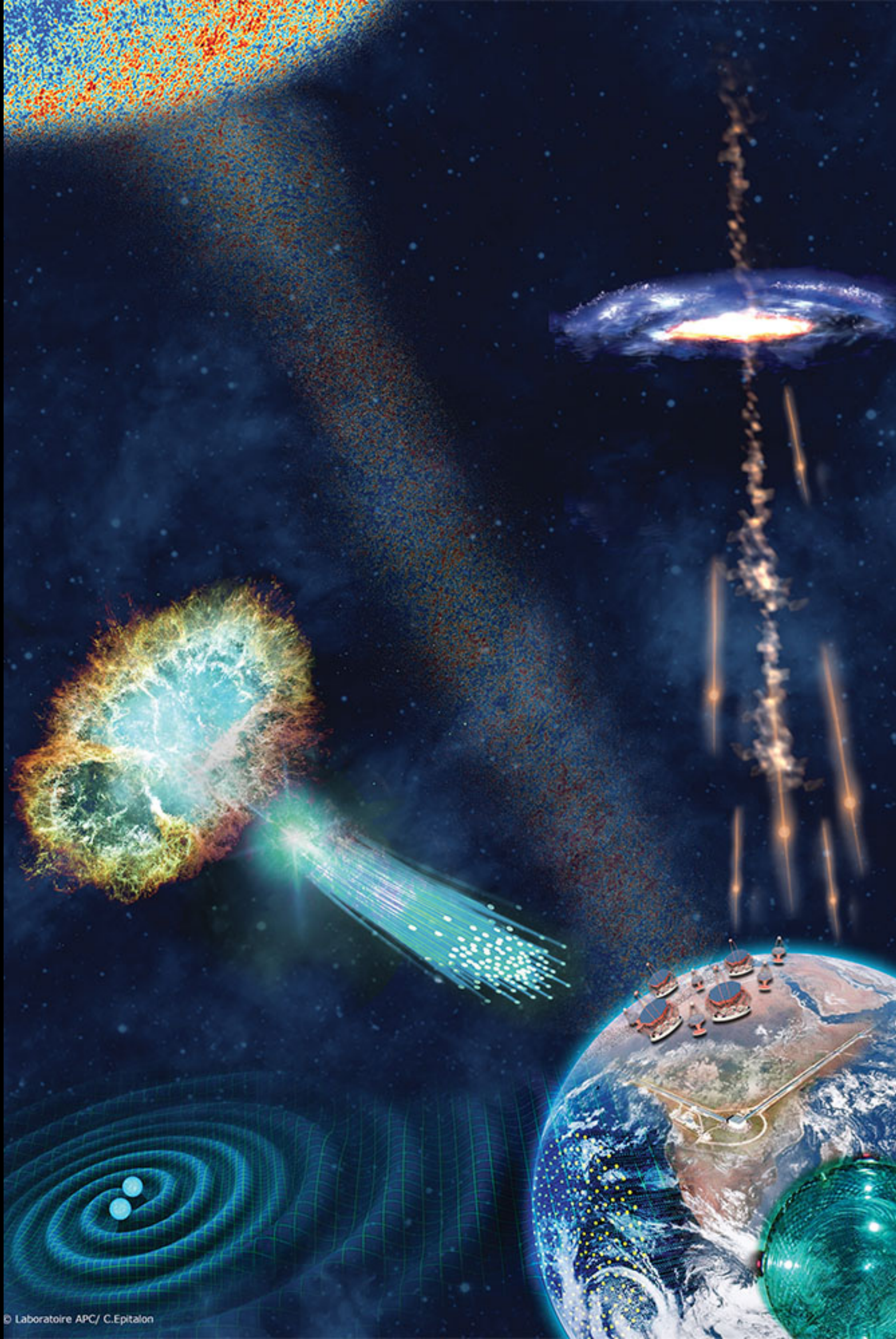
ASTROPARTICLE PHYSICS AND COSMOLOGY: TOPICS COVERED IN THE HIGHLIGHTS

- Dark Matter
- Cosmic Rays, Gamma Rays, Neutrinos
  - → *Markus Ahlers Thu 6/6*
- Gravitational Waves
  - → *Fulvio Ricci Wed 5/6*
- Cosmological Observations
  - → *Paolo De Bernardis Thu 6/6*



THE REST OF THIS TALK

- Dark Matter
  - WIMPs
  - Direct searches
  - Indirects searches
    - Neutrinos
    - Gamma
    - CR antimatter



WHAT DO WE KNOW OF DARK MATTER?

- Mostly “negative” information:
    - No colour charge
    - No electric charge
    - No strong self-interaction
- Stable, or very long-lived
- Cold

CMB EVIDENCE THAT IT IS NON-BARYONIC
PLANCK: $\Omega_C \approx 5\ \Omega_B$

DM ACCOUNTS FOR ALMOST 85% OF TOTAL MATTER IN UNIVERSE

Nature 445, 286 (2007)

dark matter forms a loose network of filaments, growing over time, which intersect in massive structures at the locations of clusters of galaxies

WHAT IS DARK MATTER?

The Minimal WIMP Model Basic Assumptions:

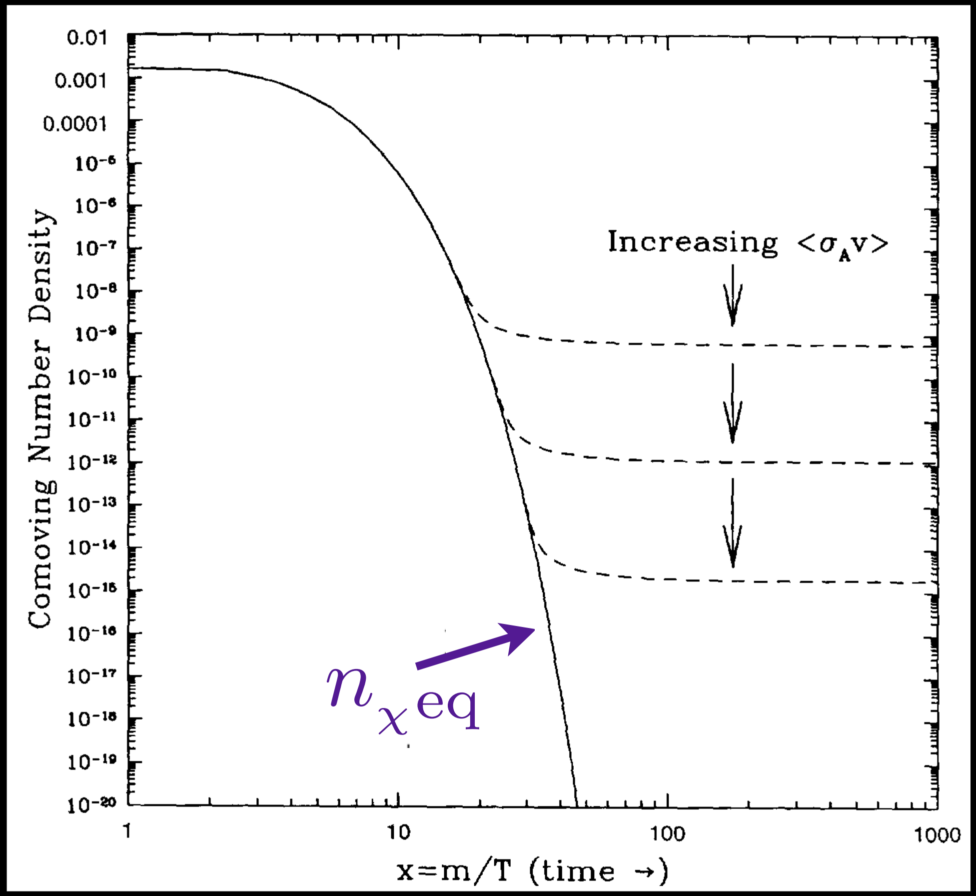
- Single particle that does not interact with itself
- Interacts weakly with Standard Model
- 2→2 annihilations primarily in s-wave
- Annihilations set thermal abundance today

THE WIMP MIRACLE

WIMP number density in the early universe:

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

$$\langle\sigma v\rangle : \chi\chi \to \text{SM SM (thermal average)}$$



"Freeze-out" when annihilation rate falls behind expansion rate (→ $a^3 n_\chi \sim$ const.)

Relic density (today) for weak scale interaction

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\text{cm}^3/\text{s}}{\langle\sigma v\rangle}$$

$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

Planck 2018 results

$$\Omega_\chi h^2 = 0.120 \pm 0.001$$

"weak" coupling
"weak" mass scale → correct abundance

PARTICLE DM: PARADIGM SHIFT DRIVING SOCIAL CHANGE

Murayama @ ESPP, Granada, 2019

We used to think

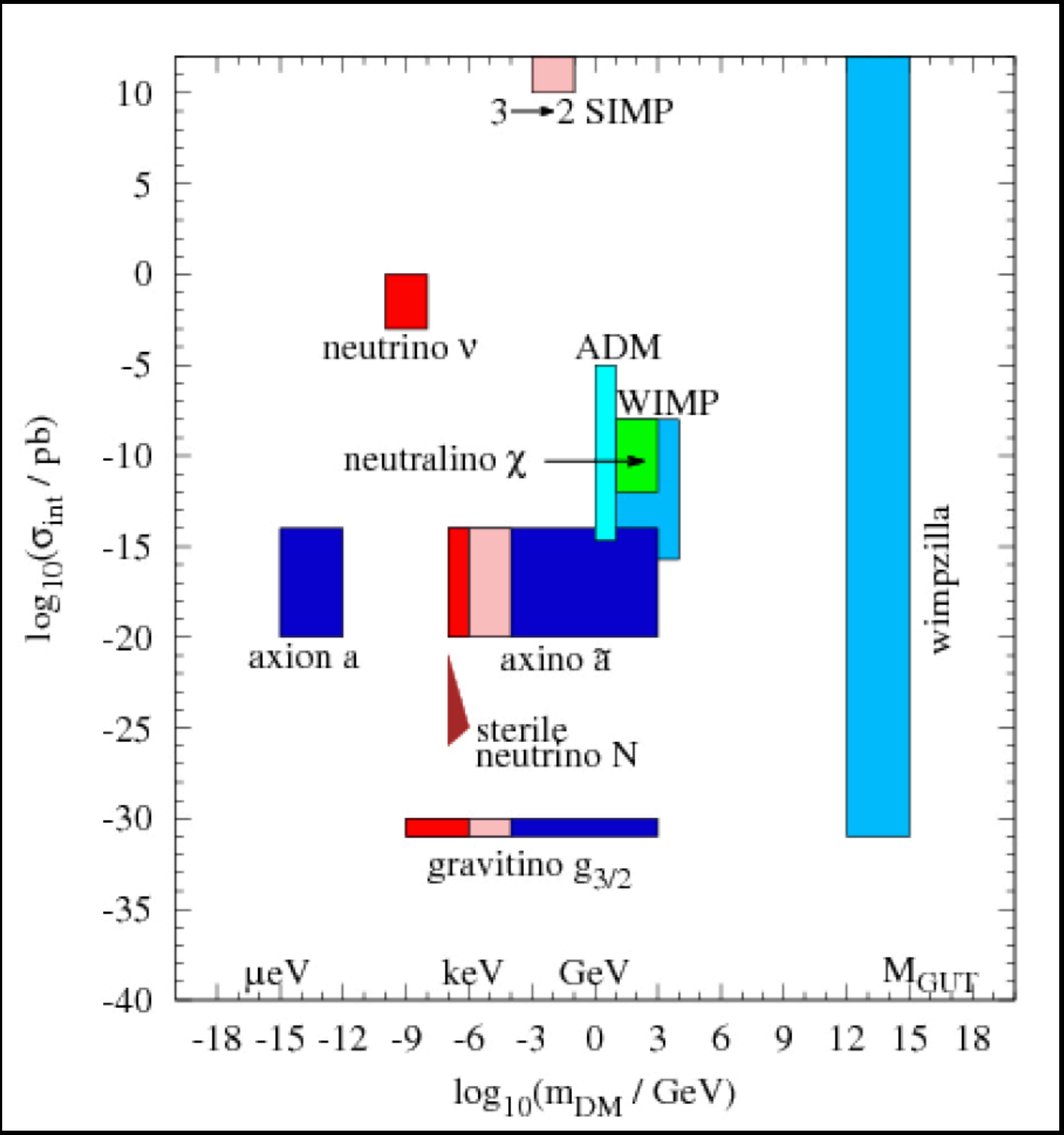
- need to solve problems with the SM of Particle Physics (hierarchy problem, strong CP, etc)
- great if new theory (supersymmetry, extra dim) also gives a DM candidate as a byproduct

$$\Downarrow$$

Now we think

- need to explain DM on its own
- great if the DM solution also helps to elucidate important issues with the SM
- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV
  - or rather lighter and weaker coupling? e.g., ALPs

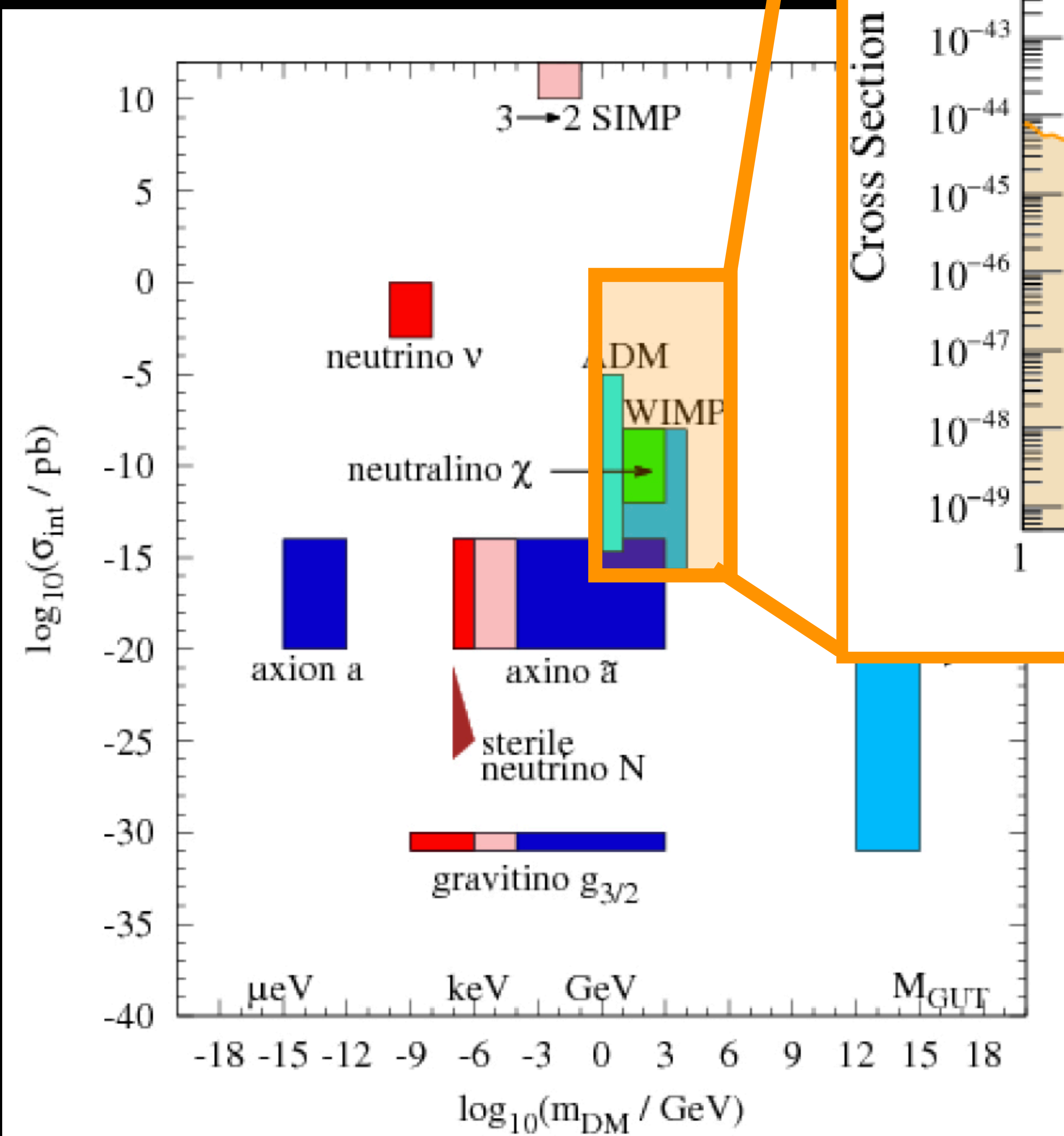
DARK MATTER CANDIDATES



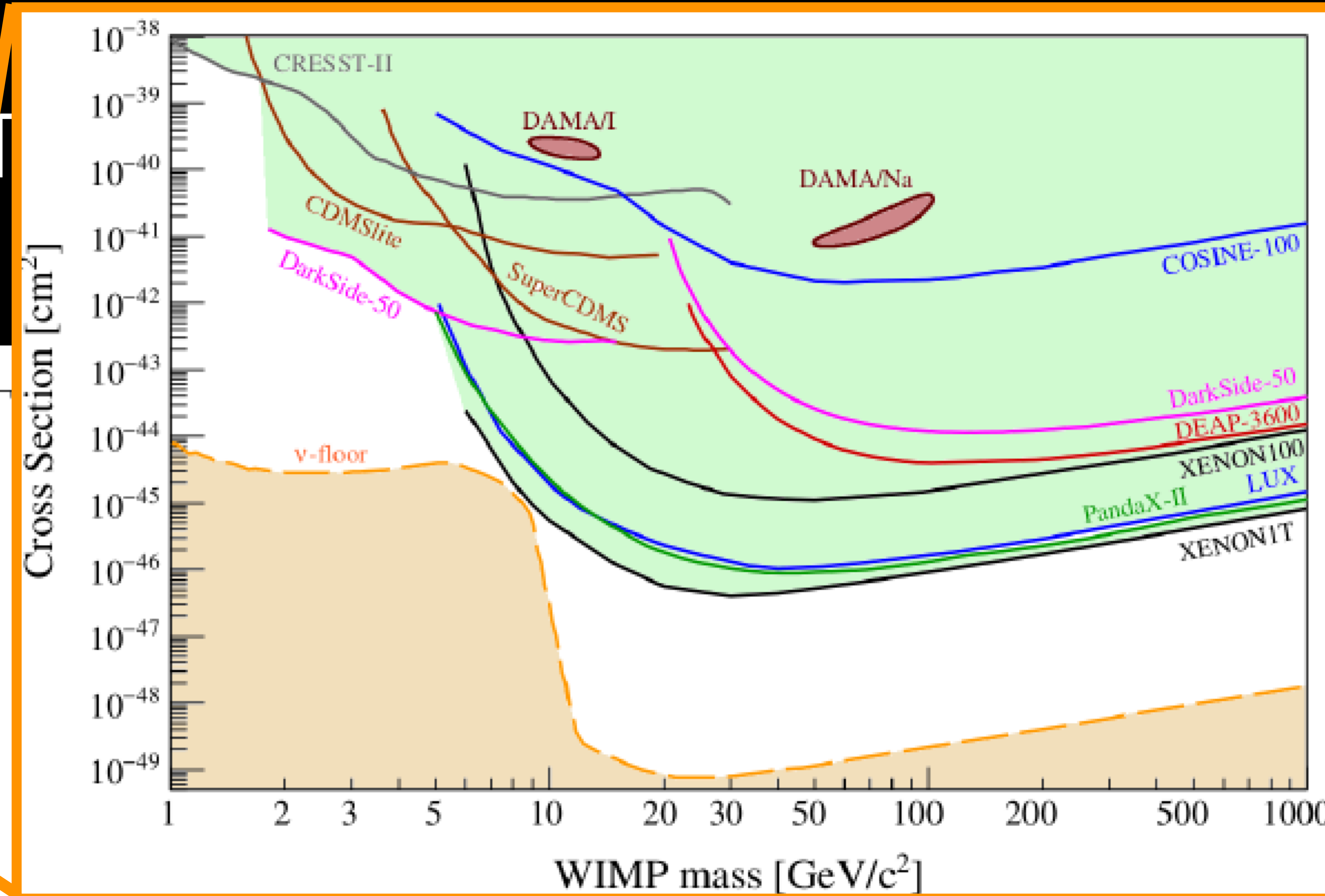
Baer et al., arXiv:1407.0017

- Thermal relics:
  - WIMP: generic weakly interacting massive particle
  - ADM: asymmetric dark matter
  - SIMP: strongly interacting massive particle
  - …
- Non- thermal relics
  - Axion: very light mass (10^{-5} eV), CDM because produced at rest in the early Universe. Its interaction strength is strongly suppressed relative to the weak strength by a factor $(m_W/f_a)^2$, where $f_a \sim 10^{11}$ GeV is the PQ breaking scale
  - … and many more

DARK MATT



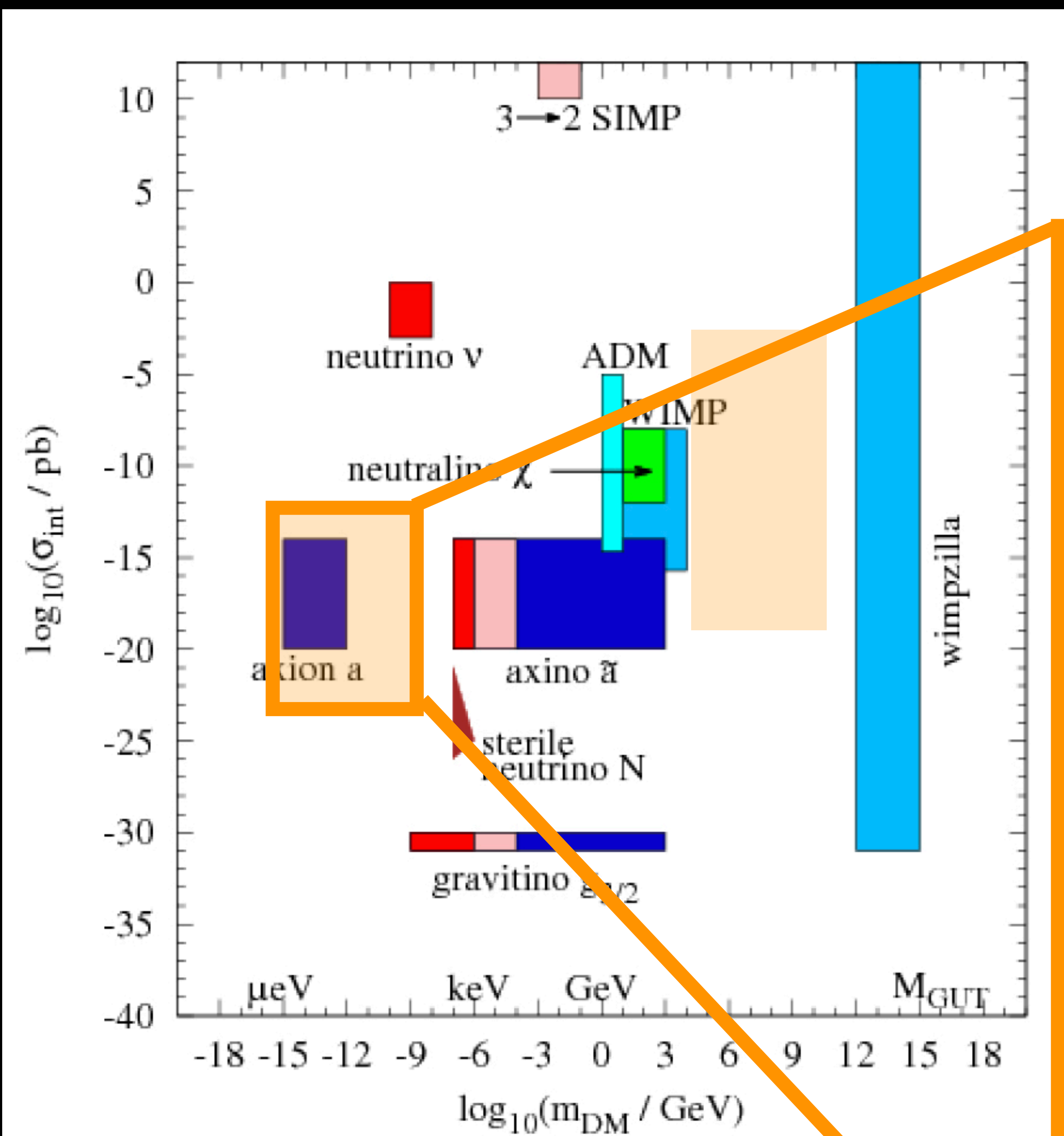
Baer et al., arXiv:1407.0017



Schumann, arXiv:1903.03026

Direct searches generally optimised for WIMP sensitivity…

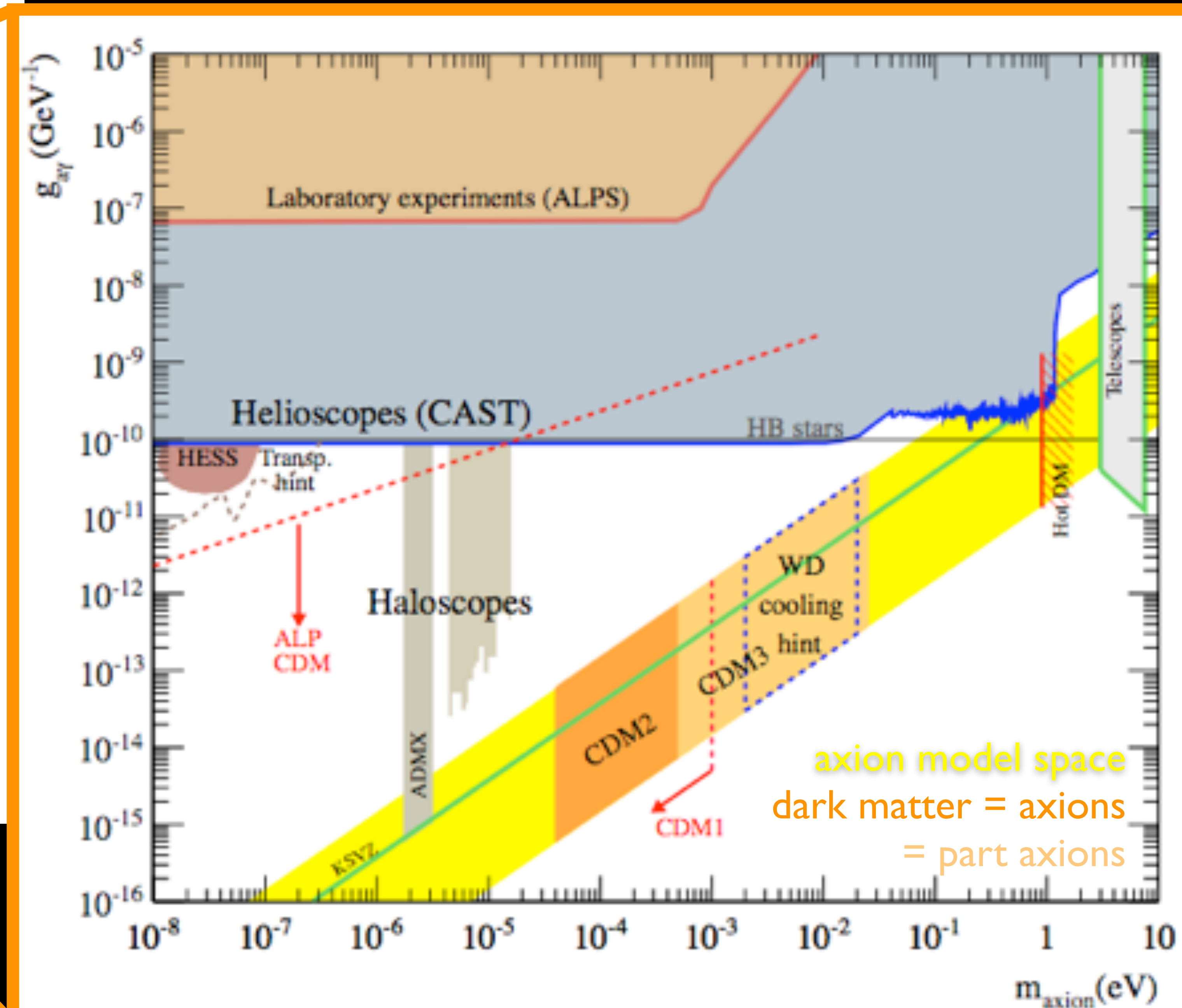
DARK MATTER CANDIDATES



Baer et al., arXiv:1407.0017

… starting to look for axions/ALPs too!

(but no time to cover these here)



WIMP DIRECT DETECTION

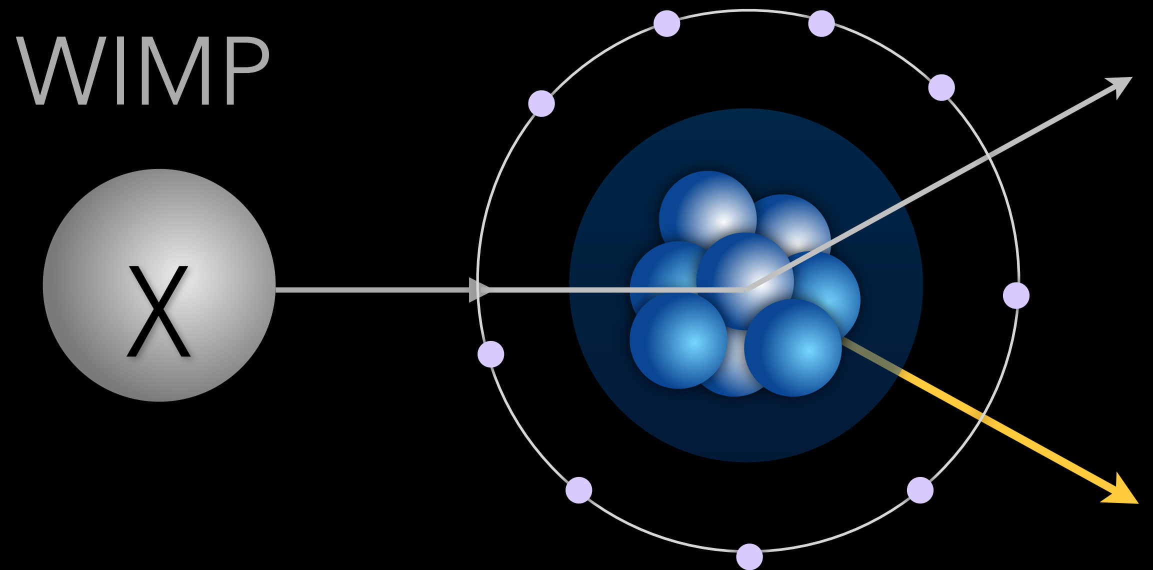
- Goodman & Witten (1985): "Detectability of certain dark matter candidates"

  coherent scattering off nuclei

$\chi N \to \chi N$

elastic scattering off nuclei

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int d\mathrm{v}\, f(\mathrm{v})\, \mathrm{v} \frac{d\sigma_\chi}{dE_R}$$

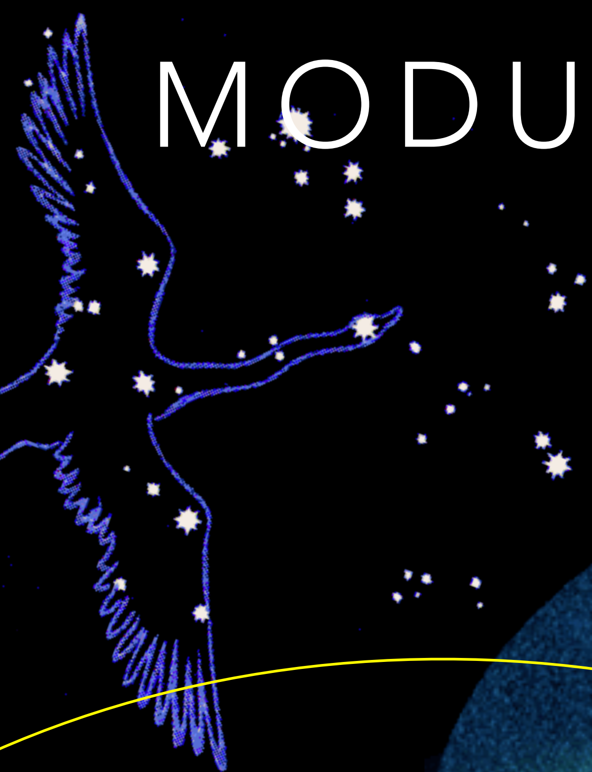


- Large detector mass, long exposure
- Low energy threshold
- Ultra-low radioactive bg
- Good bg discrimination

Nuclear recoil energy

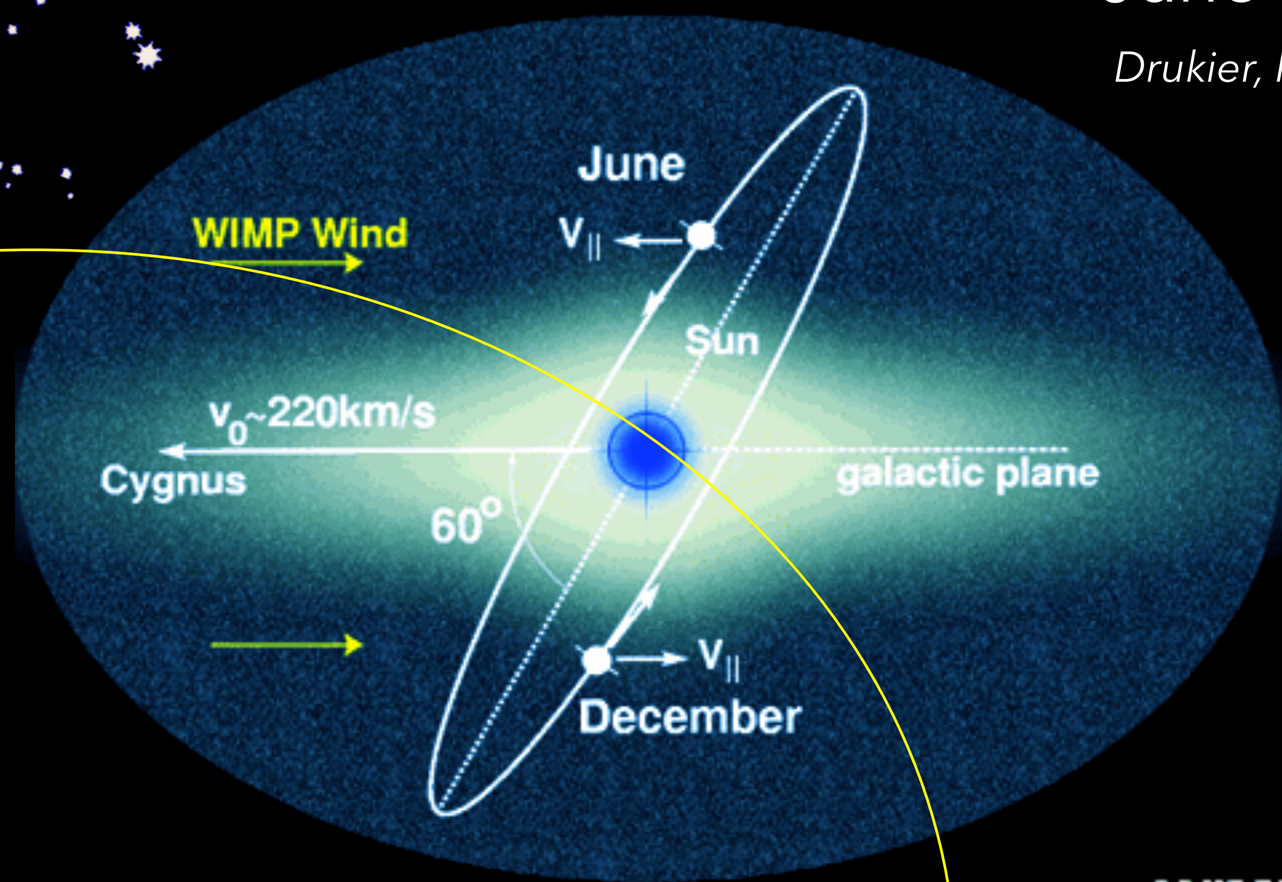
≈ 1÷100 keV

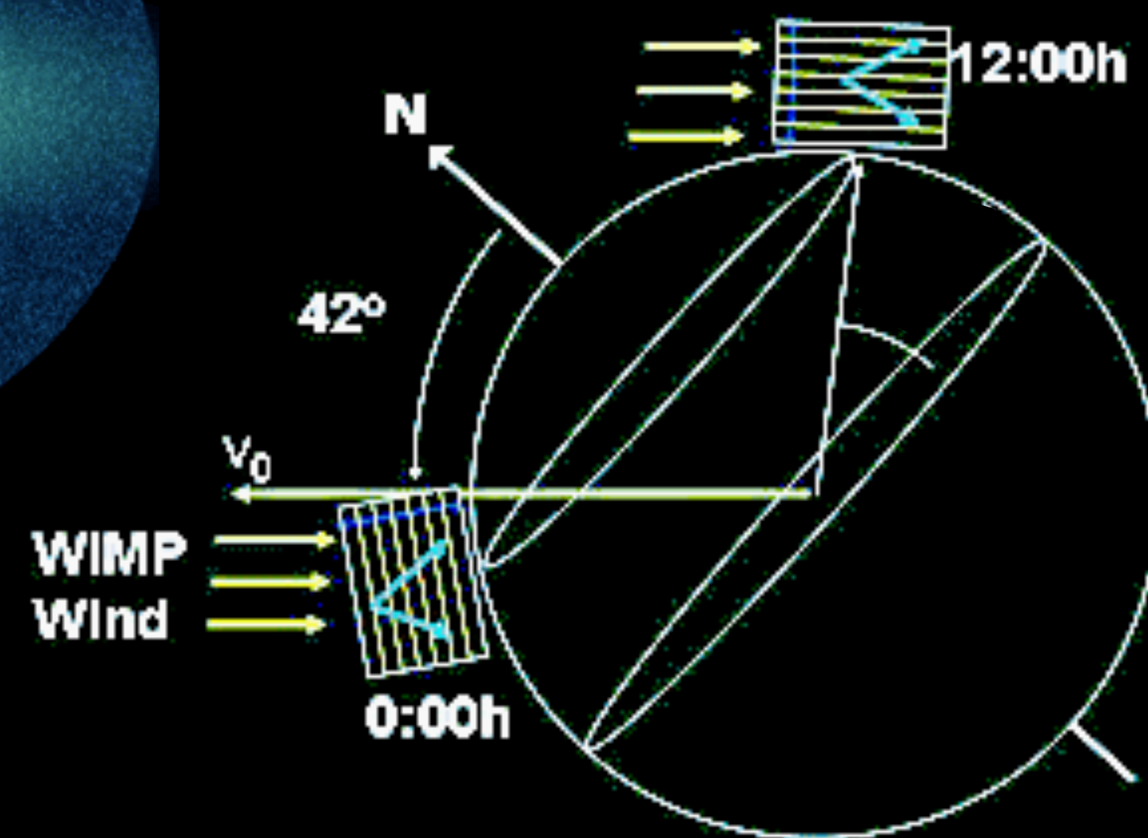
MODULATION SIGNATURES



Annual event rate modulation:
June-December asymmetry ~2-10%

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate

Spergel, Phys. Rev. D36:1353 (1988)

×3 rate variation of parallel vs
perpendicular directions

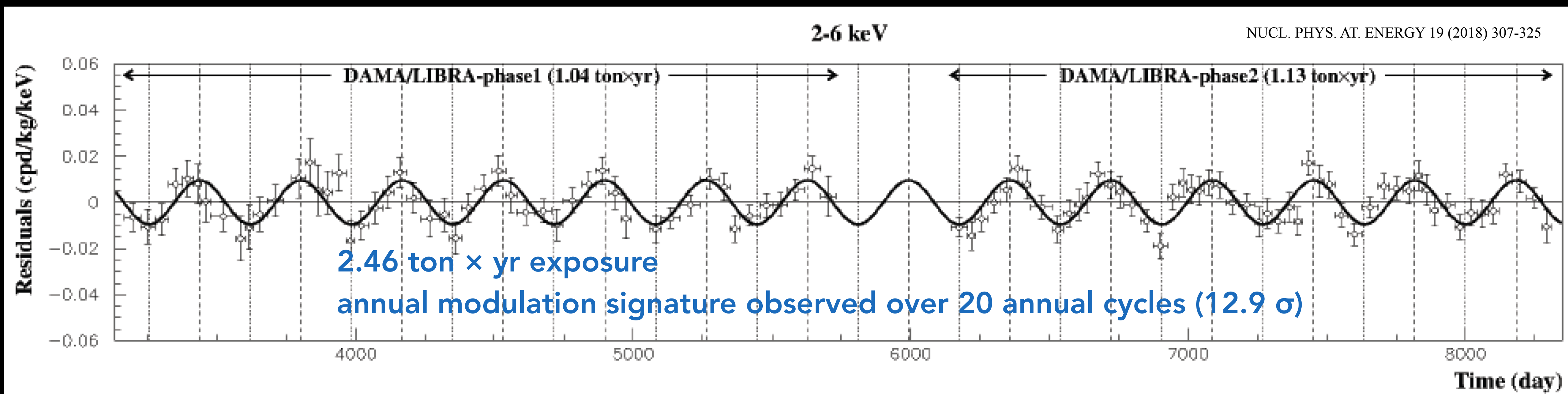
Credits Jocelyn Monroe

MODULATION RECENT RESULTS

Standard Halo Model predicted modulation A~0.02-0.1, t_0=152.5 days

DAMA/NaI + DAMA/LIBRA-phase1 + phase2:

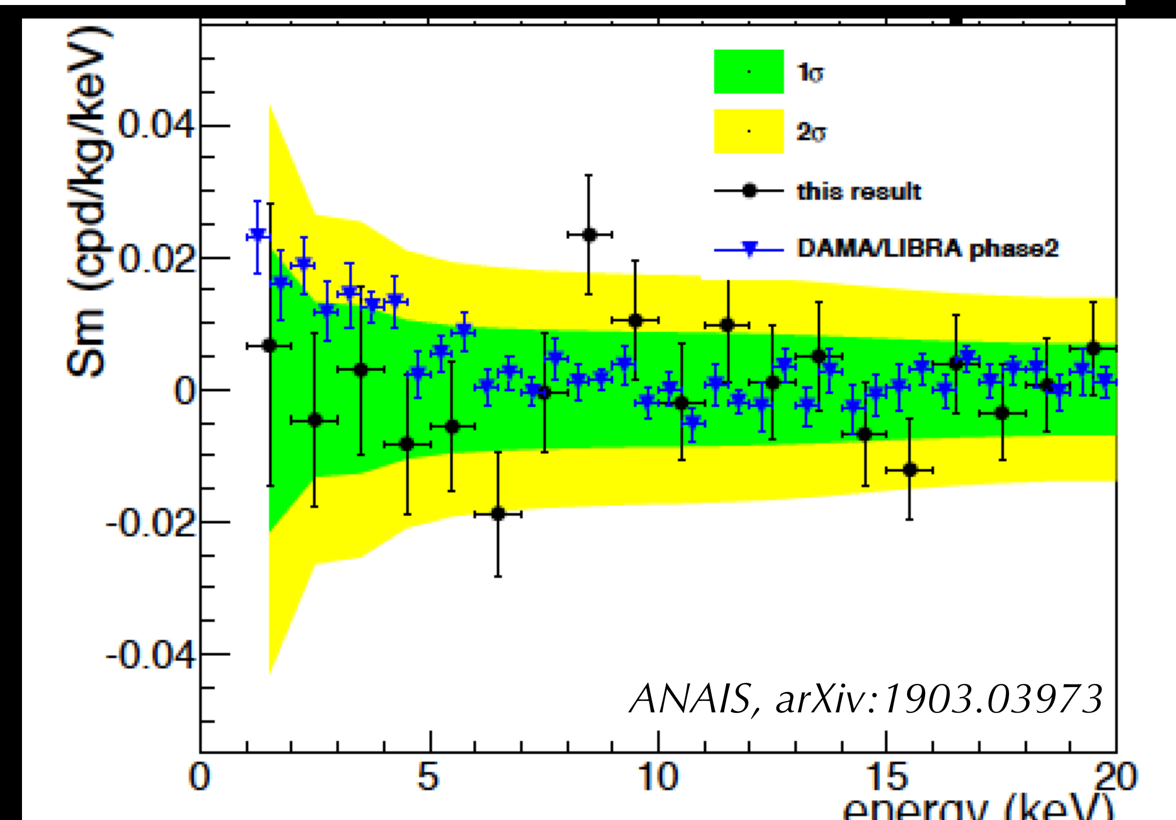
A= (0.0103 ± 0.0008) cpd/kg/keV, t_0 = (145±5) d in 2.46 t-yr (2 - 6 keV)



many other searches, on Ge, CsI, Xe, etc. observe no evidence of modulation

In the same underground laboratory:
XENON100: Xe, 5.7σ exclusion of DAMA, dark matter electron interactions via axial vector coupling *PRL118,101101 (2017)*

Using the same target (NaI):
ANAIS (LSC), **COSINE-100** (Y2L)
~consistent at 1σ, project 3σ test in 5 years



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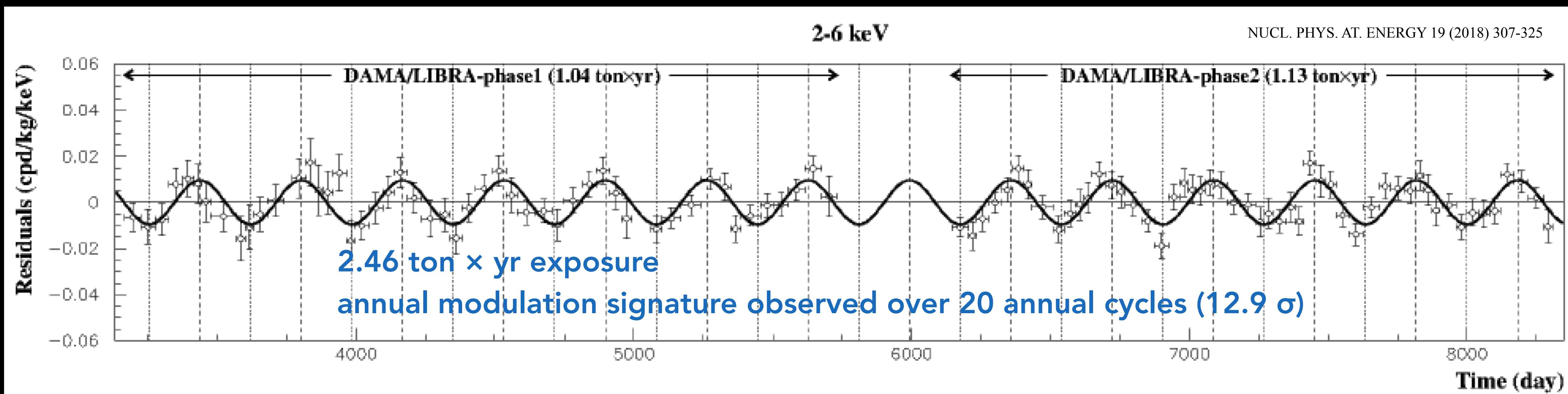

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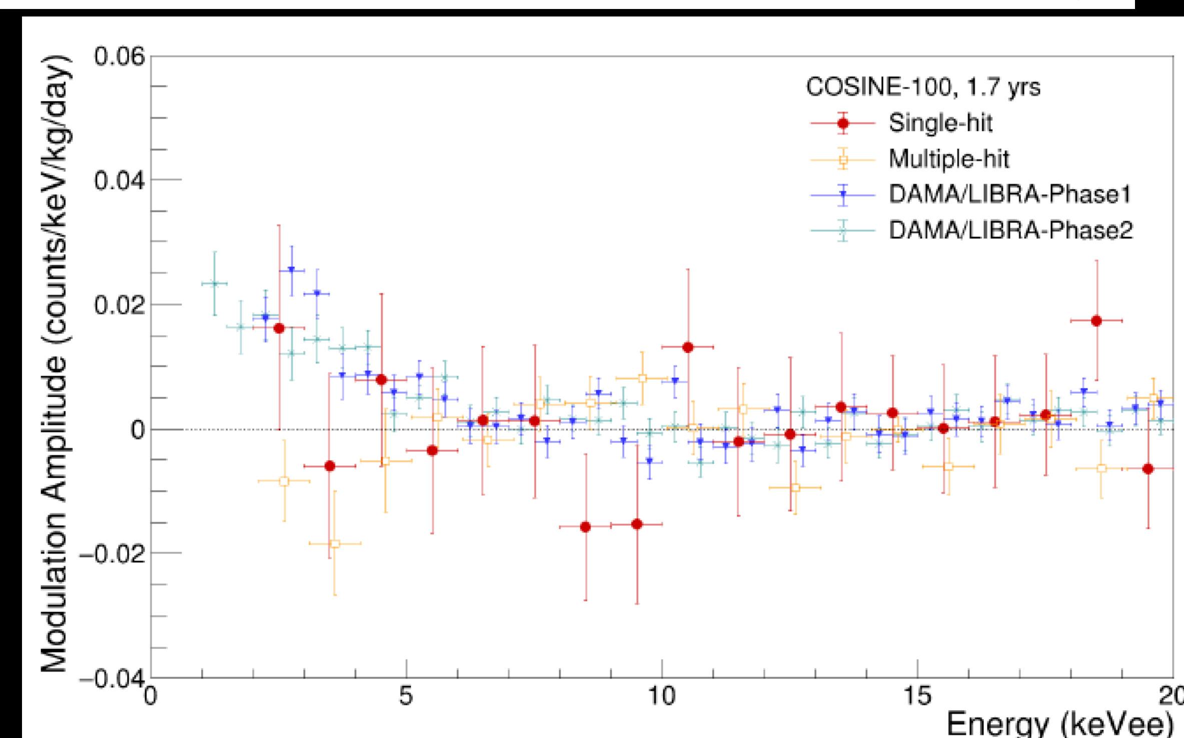
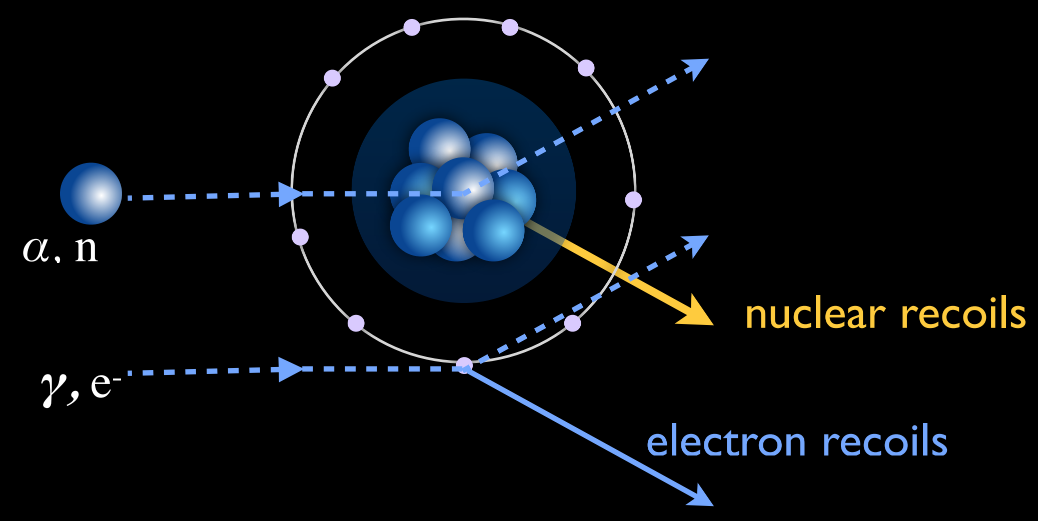


COSINE-100, arXiv:1903.10098

DISCRIMINATING BACKGROUNDS



from natural radioactivity:

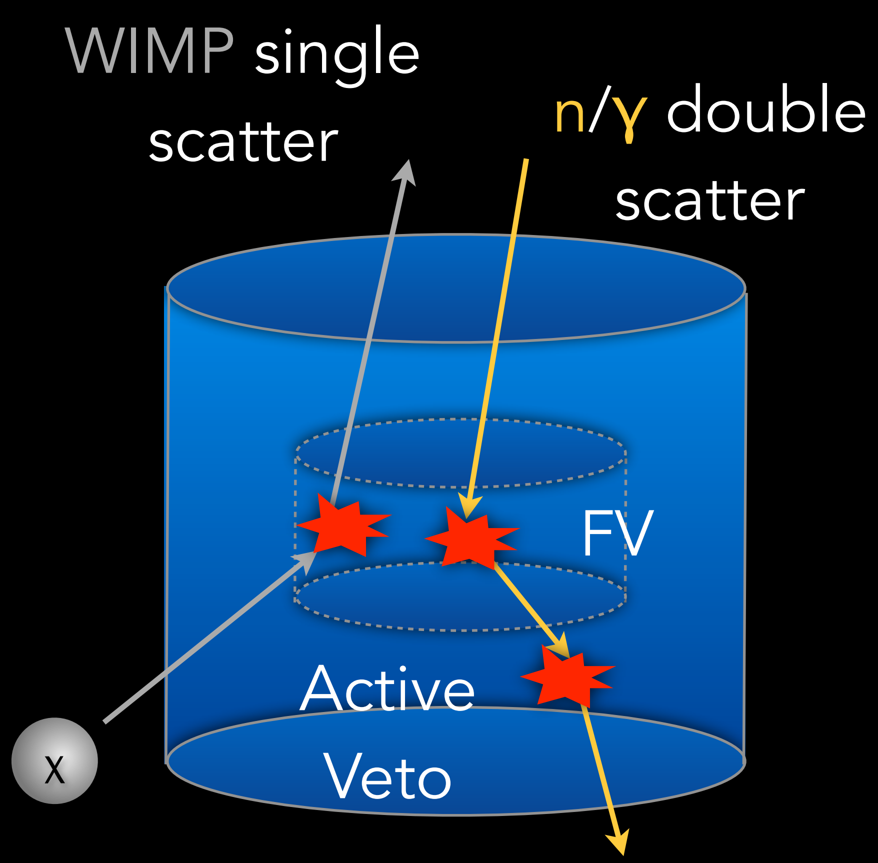
γ e⁻ → γ e⁻

nN → nN

N → N′ + α, β

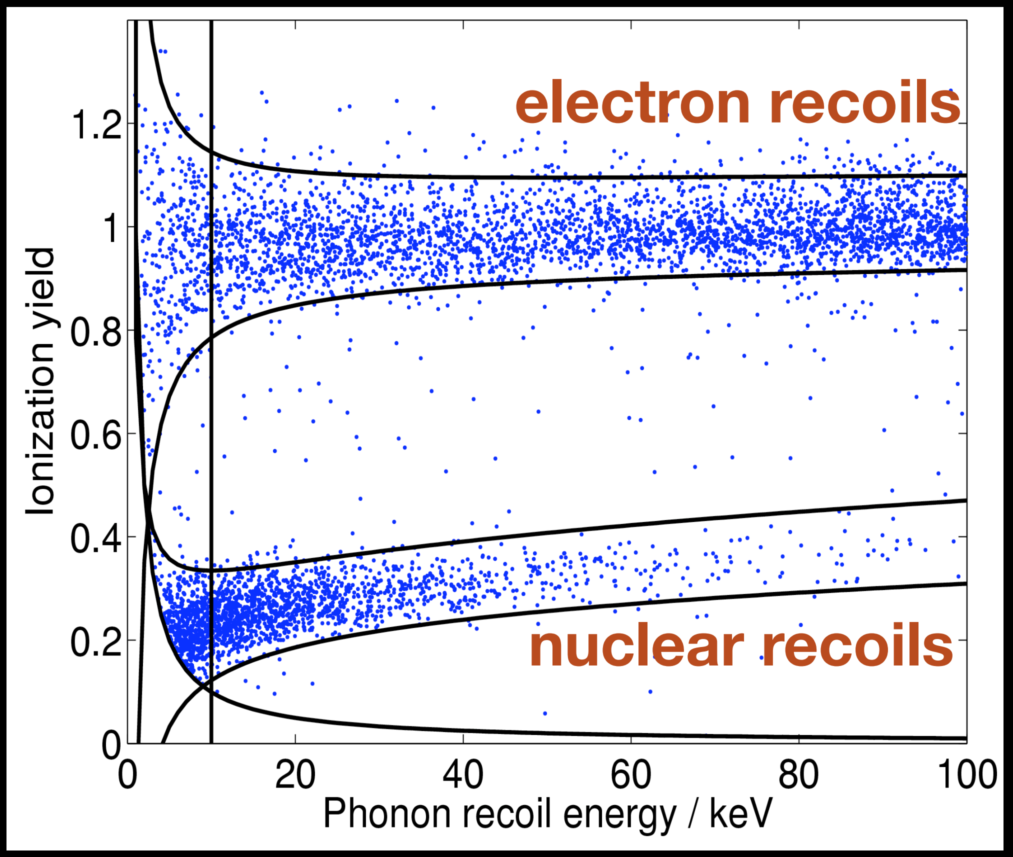
Active veto shield and fiducialization
→ identification of neutron recoils

Signal split in two components which respond differently to NR/ER
→ separation of S and B



Background region

Expected signal region



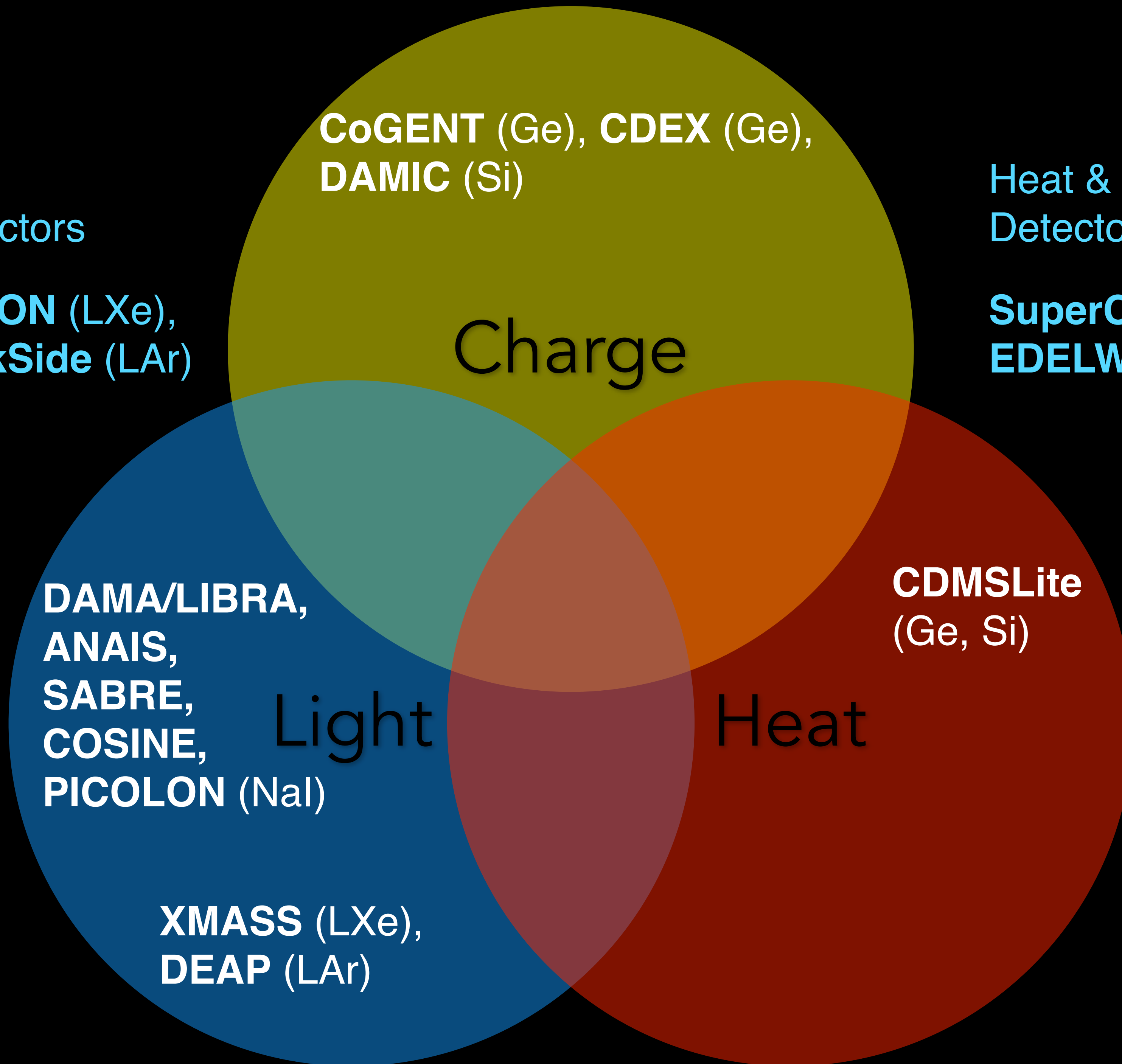
DETECTOR TECHNOLOGIES

Light & Charge Detectors

PandaX (LXe), **XENON** (LXe), **LUX/LZ** (LXe), **DarkSide** (LAr)

Heat & Charge Cryogenic Detectors

SuperCDMS (Ge, Si), **EDELWEISS** (Ge)



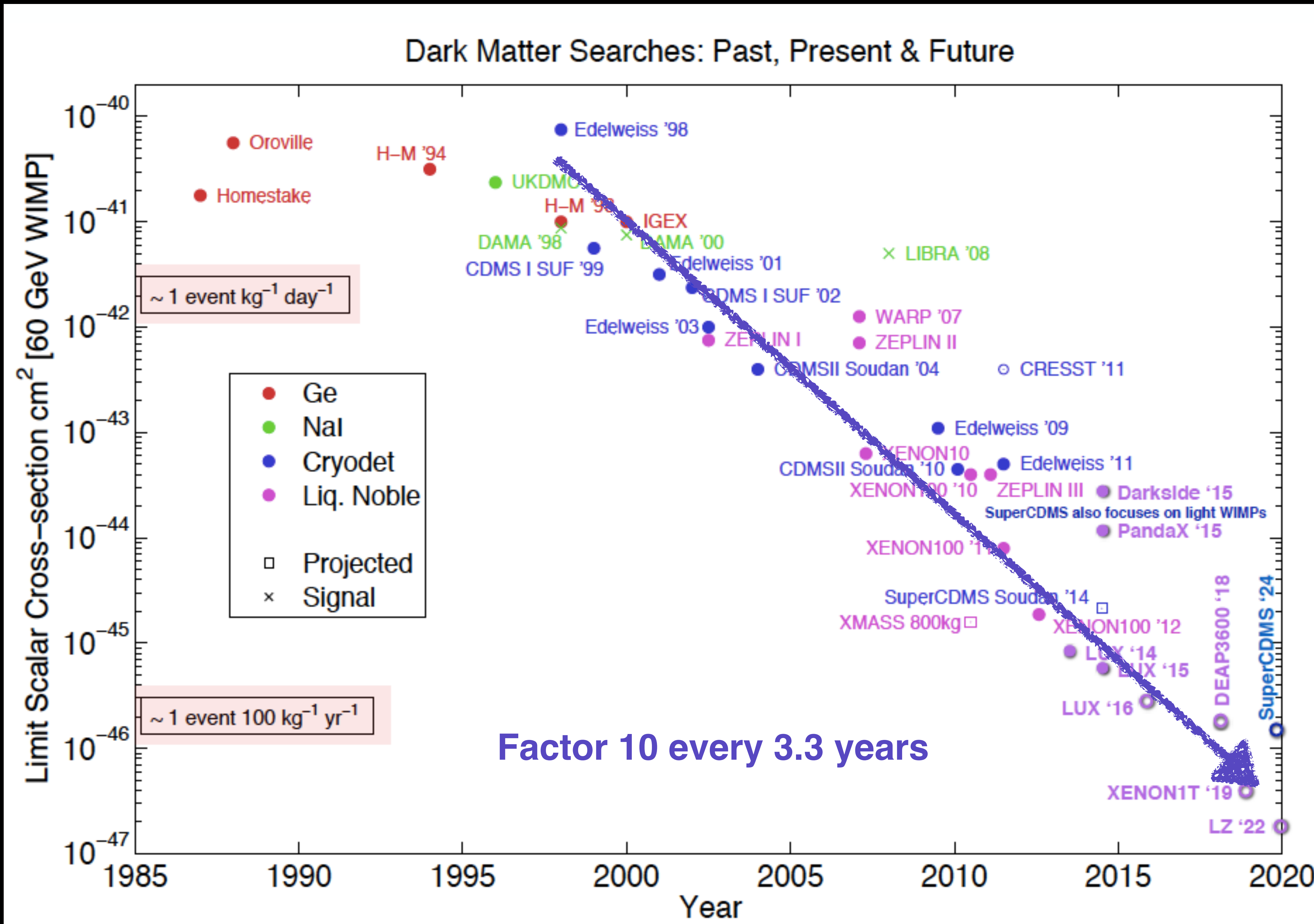
PICO (C_3F_8, CF_3I)

Light & Heat Cryogenic Detectors

CRESST ($CaWO_4$), **COSINUS** (NaI)

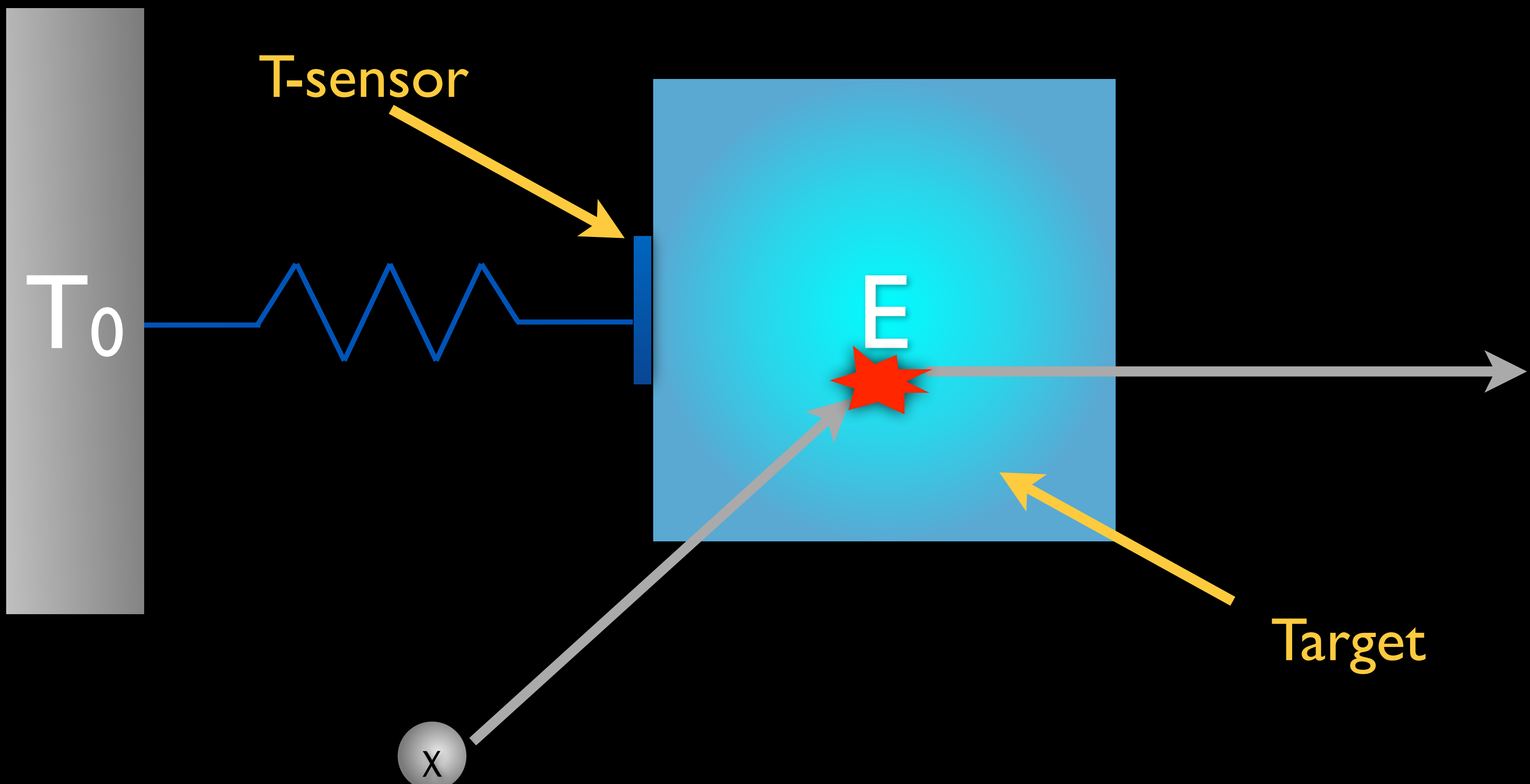
Too many experiments: only a selection here

WIMP SEARCH SENSITIVITY IMPROVEMENT IN BOTH DIRECTIONS: HIGH AND LOW MASSES



R. Gaitskell IDM2016

CRYOGENIC CRYSTALS

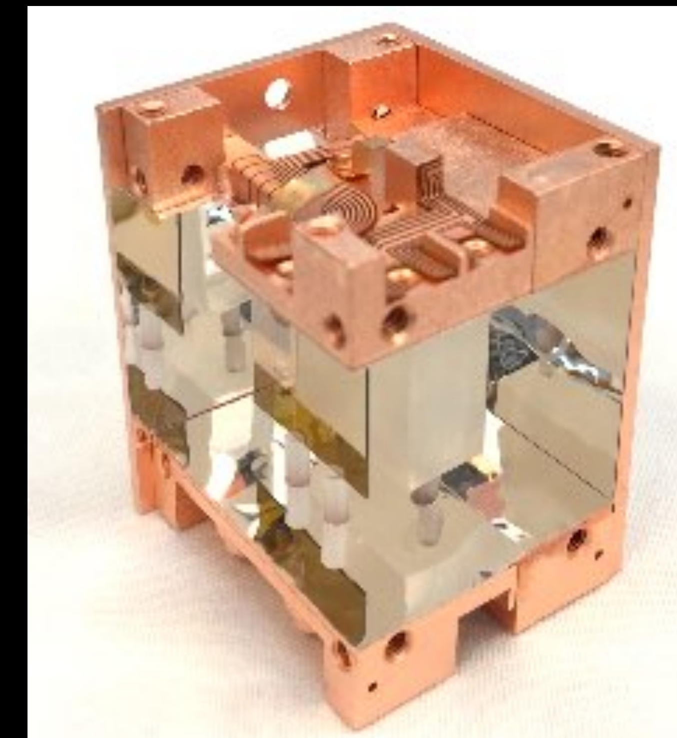


CHARGE & PHONONS:	SUPERCDMS
	CDMSLITE
	EDELWEISS
LIGHT & PHONONS:	CRESST

E deposition → temperature rise $\Delta T \sim \mu K$ → requires detectors at mK

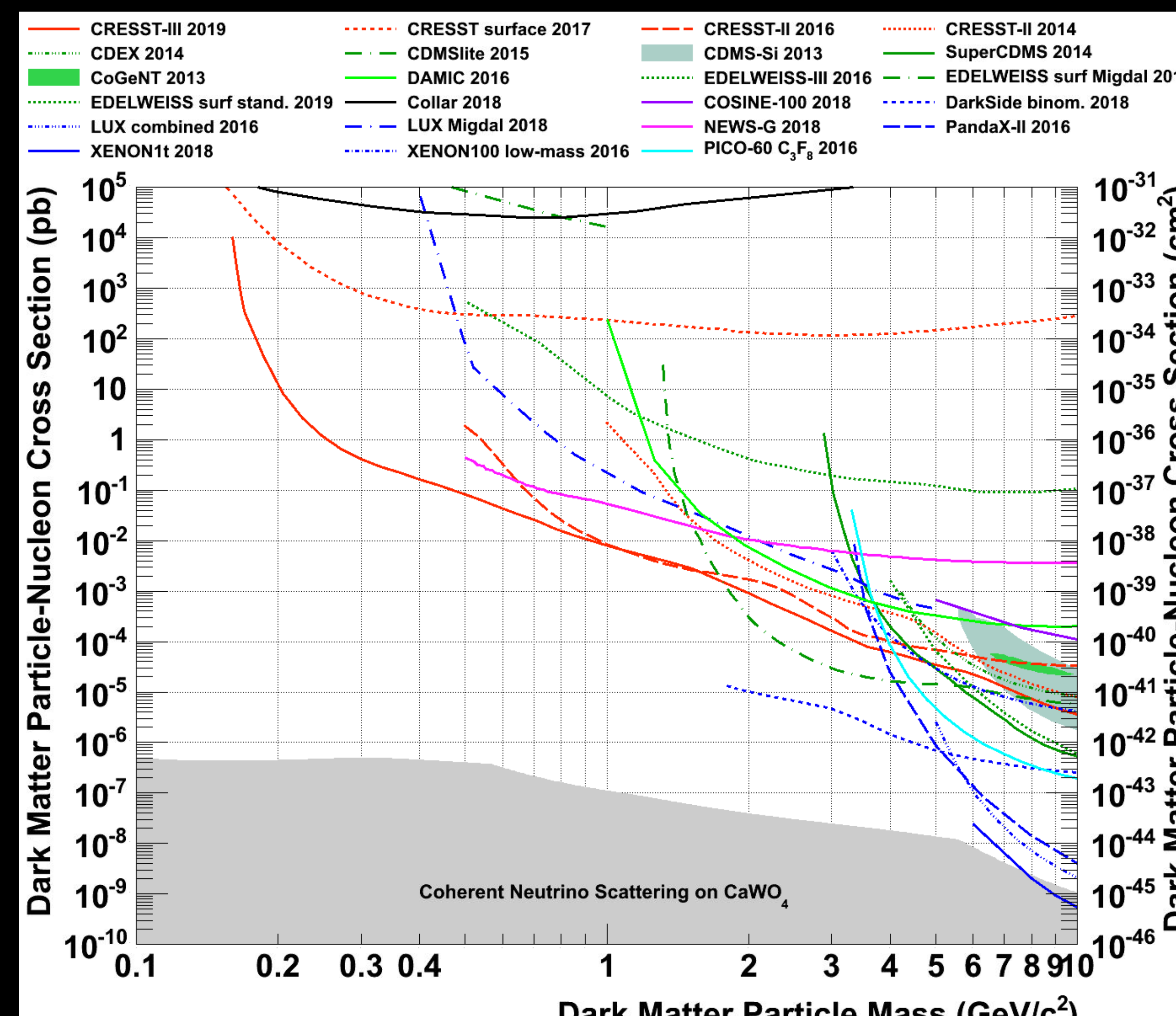
- Crystals: Ge, Si, $CaWO_4$, NaI
- T-sensors:
  - superconductor thermistors (highly doped superconductor): NTD Ge → EDELWEISS
  - superconducting transition sensors (thin films of SC biased near middle of normal/SC transition): TES → CDMS, CRESST

LOW THRESHOLD: CRESST



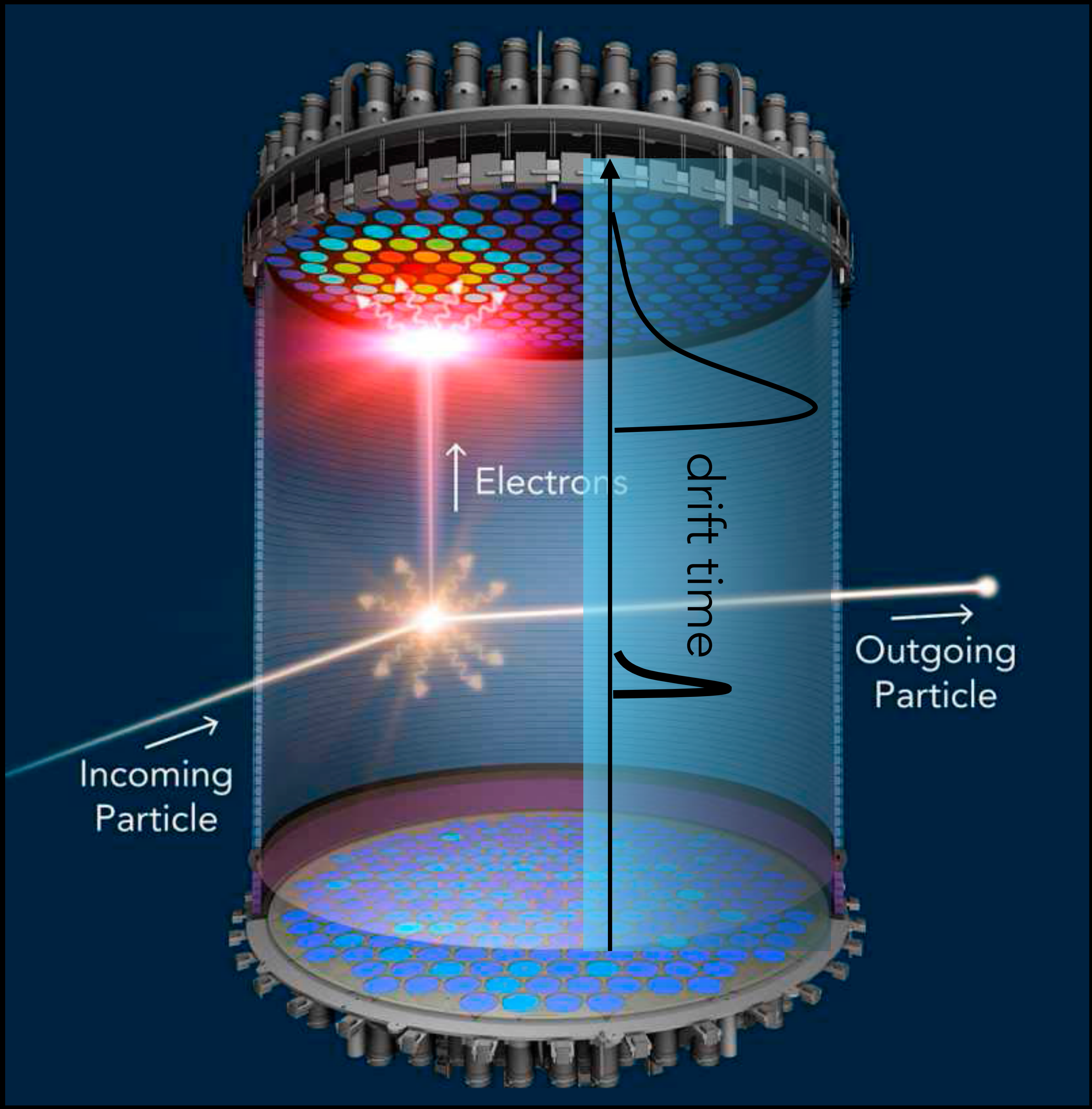
- First CRESST-III run 07/2016 - 02/2018
- Unprecedented low nuclear recoil thresholds of 30 eV
- Leading sensitivity over one order of magnitude:
  - 160 MeV/c² →1.8 GeV/c²
- CRESST-III phase 2 will push further the threshold (10 eV), exposure (1tonne*day with 1000 CRESST modules) and background (improving a factor of ~100) to approach the neutrino floor.

arXiv:1904.00498v1



LARGE MASS: NOBLE LIQUIDS

- dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets
- read out primary scintillation: "S1" + proportional gas scintillation from drifted electrons: "S2"
- 3D position reconstruction:
  - time difference between S1 and S2 gives Z position (few mm resolution)
  - pattern of S2 light gives XY position (~1cm resolution)
- background identification + passive suppression
- zeptobarn (10^{-45} cm^2) to yoctobarn (10^{-48} cm^2) sensitivity to dark matter



XENON DETECTORS

XENON 10 (LNGS)

10 kg

ZEPLIN II (Boulby)

ZEPLIN III (Boulby)

2010

XENON 100 (LNGS)

100 kg

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

1000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

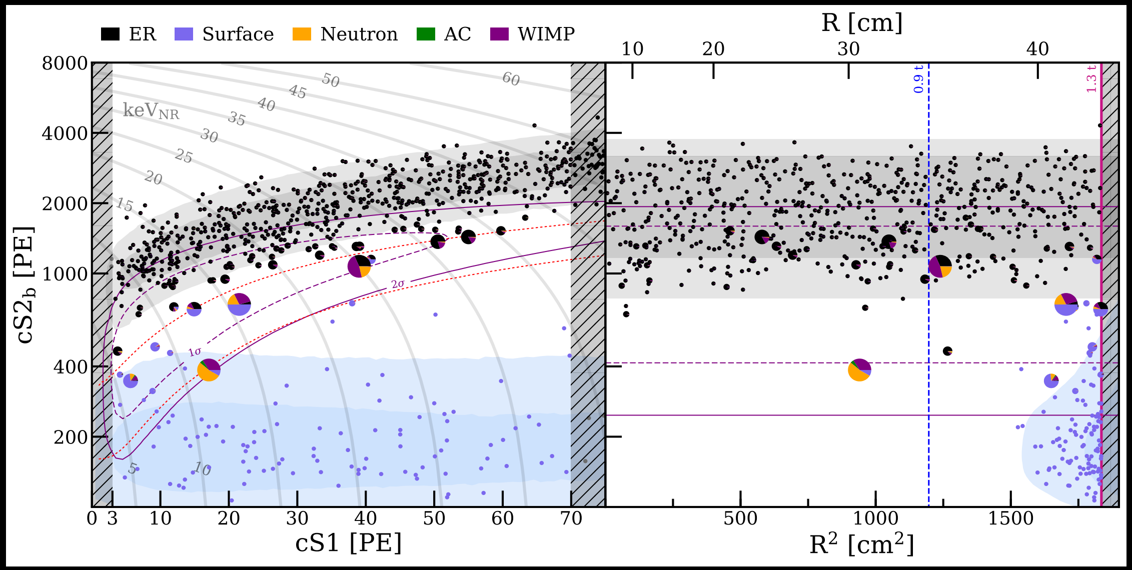
LZ: (7t, SURF)

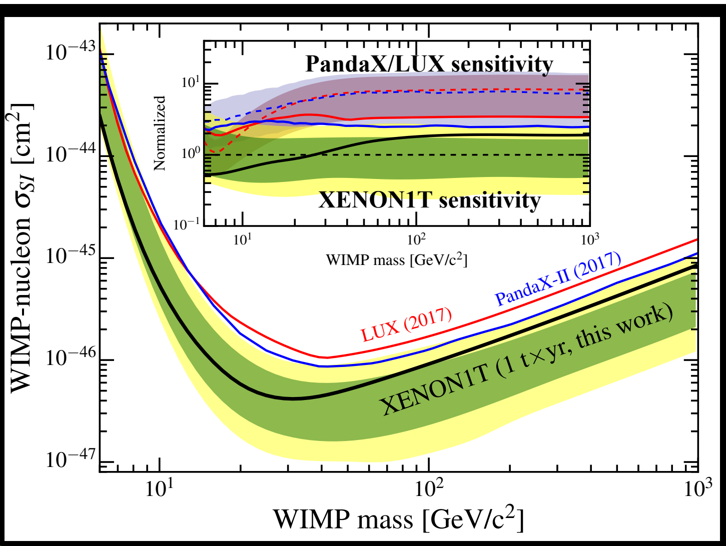
2020

10000 kg

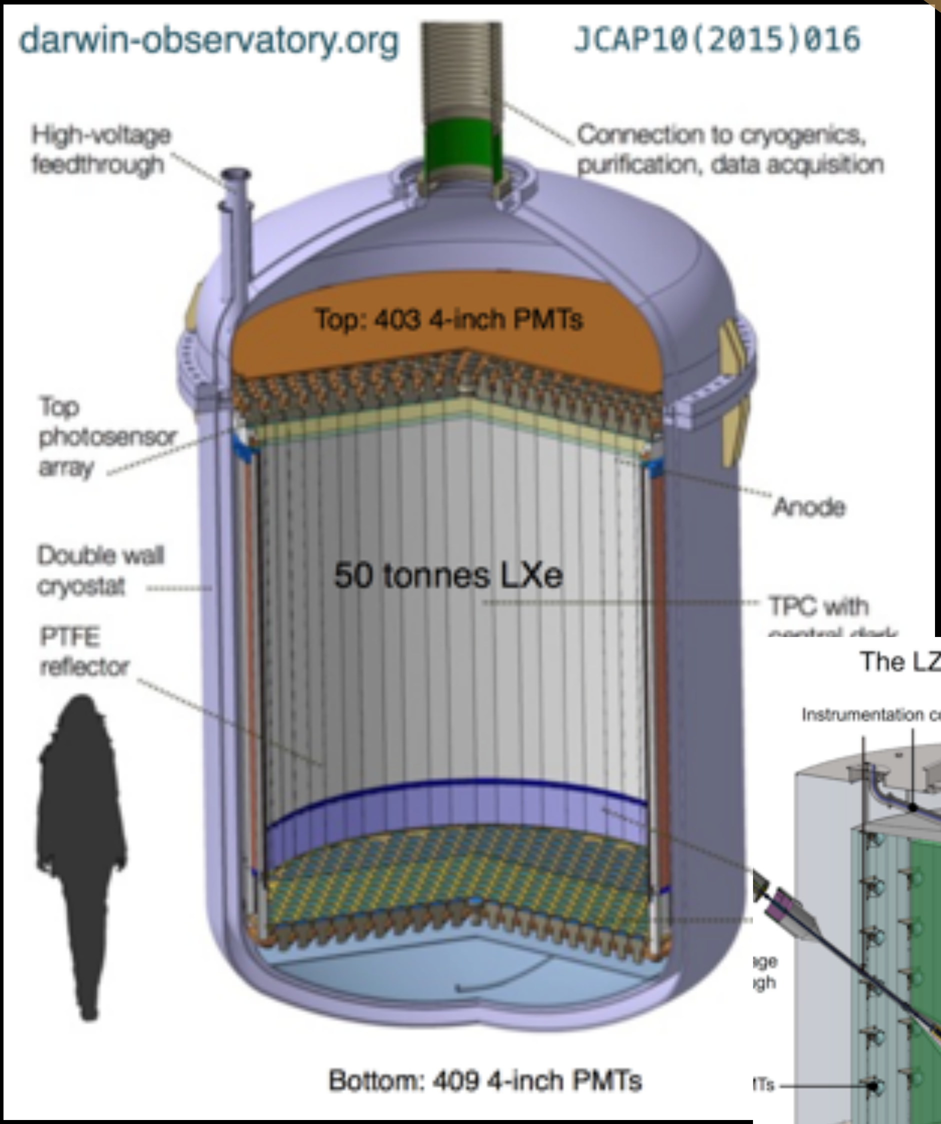
DARWIN: 50 t, ESPPU Document #62

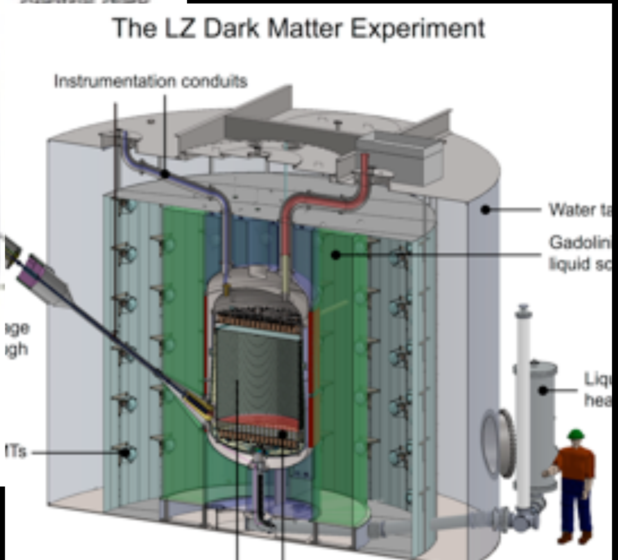
XENON1T: best limit for high WIMP masses





Aprile et al, Phys. Rev. Lett. 121, 111302 (2018)





Jocelyn Monroe, ESPP, Granada 2019

ARGON DETECTORS

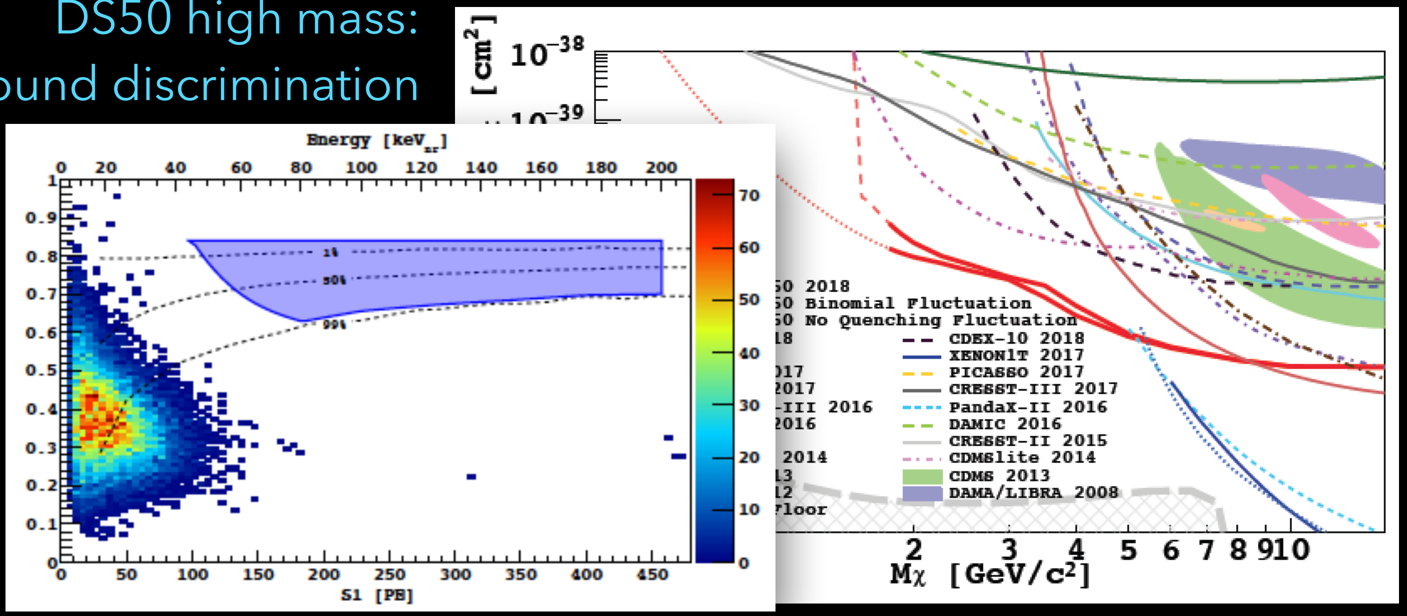
10 kg

2010

DarkSide-50
(50 kg, LNGS)

DS50 low mass: leading SI limit at 1-5 GeV/c²

DS50 high mass:
background discrimination



Phys. Rev. D 98, 102006 (2018)

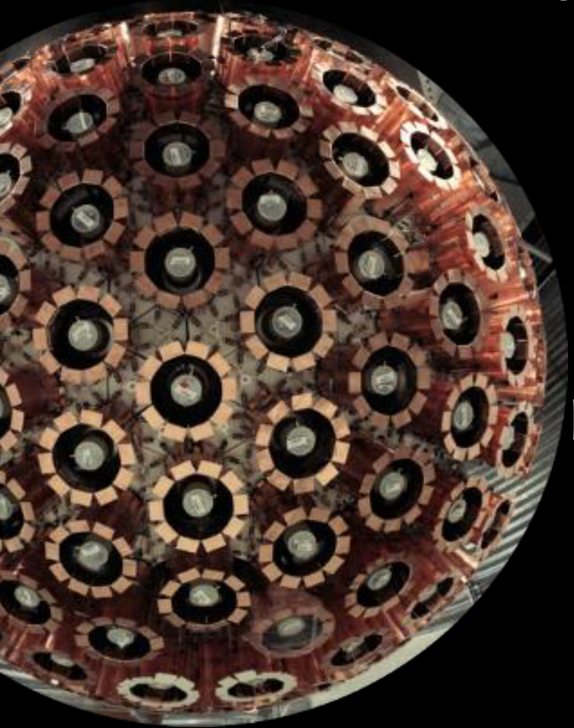
Phys. Rev. Lett.121.081307 (2018)

ArDM
(1t, LSC)

100 kg

1000 kg

2015



DEAP-3600 (3.6t, SNOLAB)

10000 kg

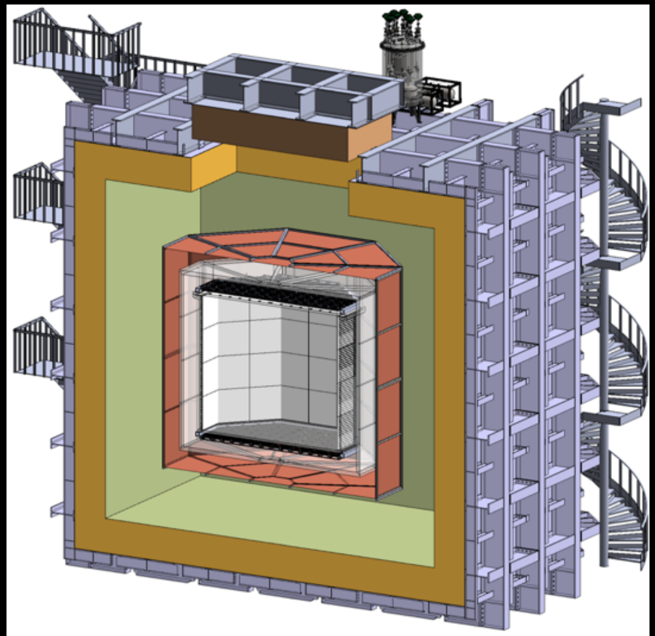
Global Argon Dark Matter Collaboration formed:

2020

DarkSide-20k
(50t, LNGS)

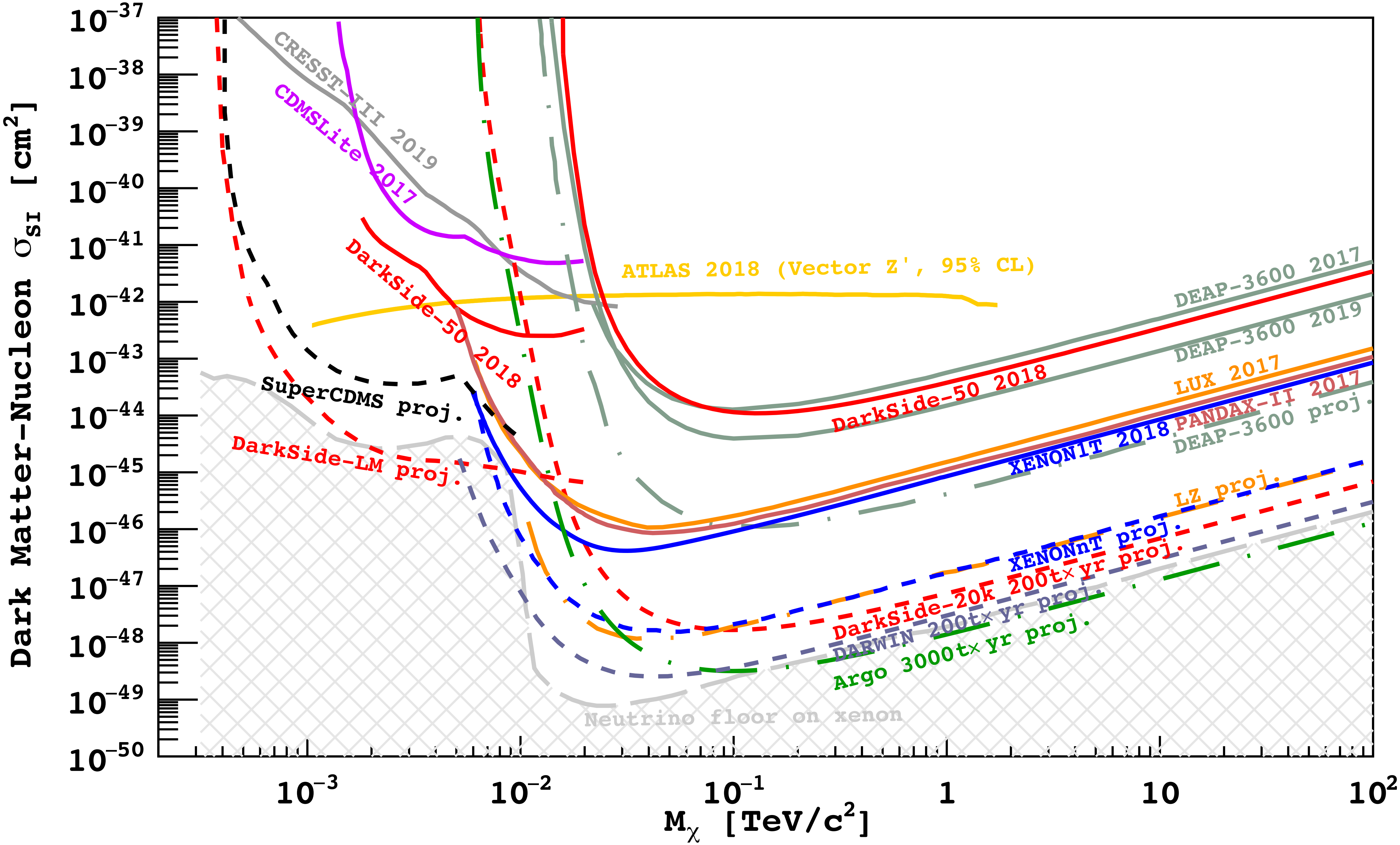
100000 kg

ARGO: 400 t,
ESPPU Document #97



Jocelyn Monroe, ESPP, Granada 2019

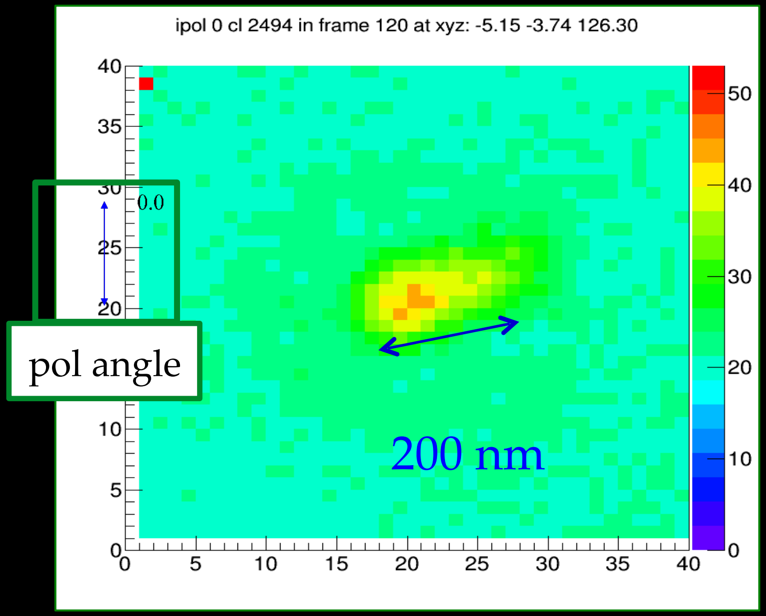
DIRECT DETECTION STATUS AND PROSPECTS



DIRECTIONAL DETECTION: BEYOND THE NEUTRINO FLOOR

- Mature technology: gaseous TPC (DRIFT, MIMAC, DMTPC, NEWAGE, D3, CYGNO)

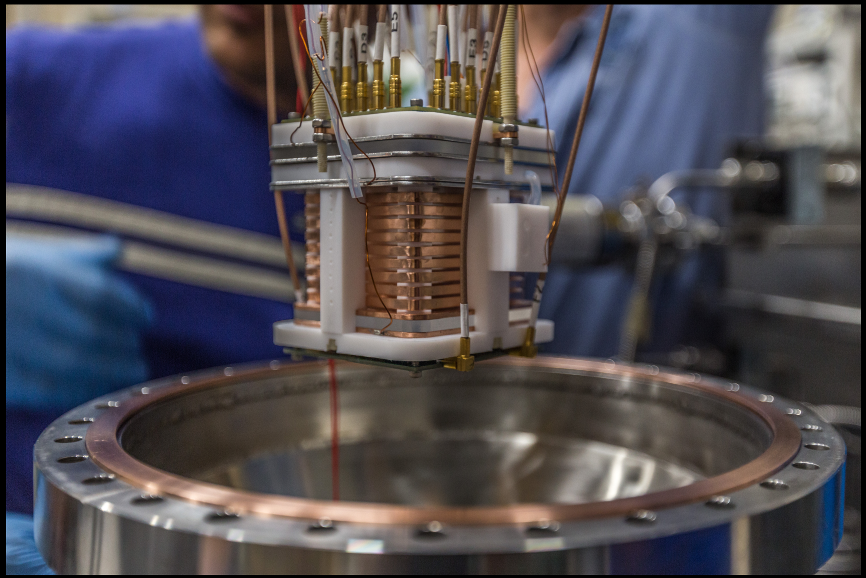
- R&D on several other techniques:



Barycenter shift (100keV C ion)

- **NEWS**
  - Nanometric track direction measurement in nuclear emulsions
  - Exploit resonant light scattering using polarised light
  - Measurement of track slope and length beyond the optical resolution
  - Unprecedented accuracy of 6 nm achieved on both coordinates

- **RED**
  - Columnar Recombination in liquid argon TPC
- **PTOLEMY**
  - Graphene target (nanoribbon or nanotubes)

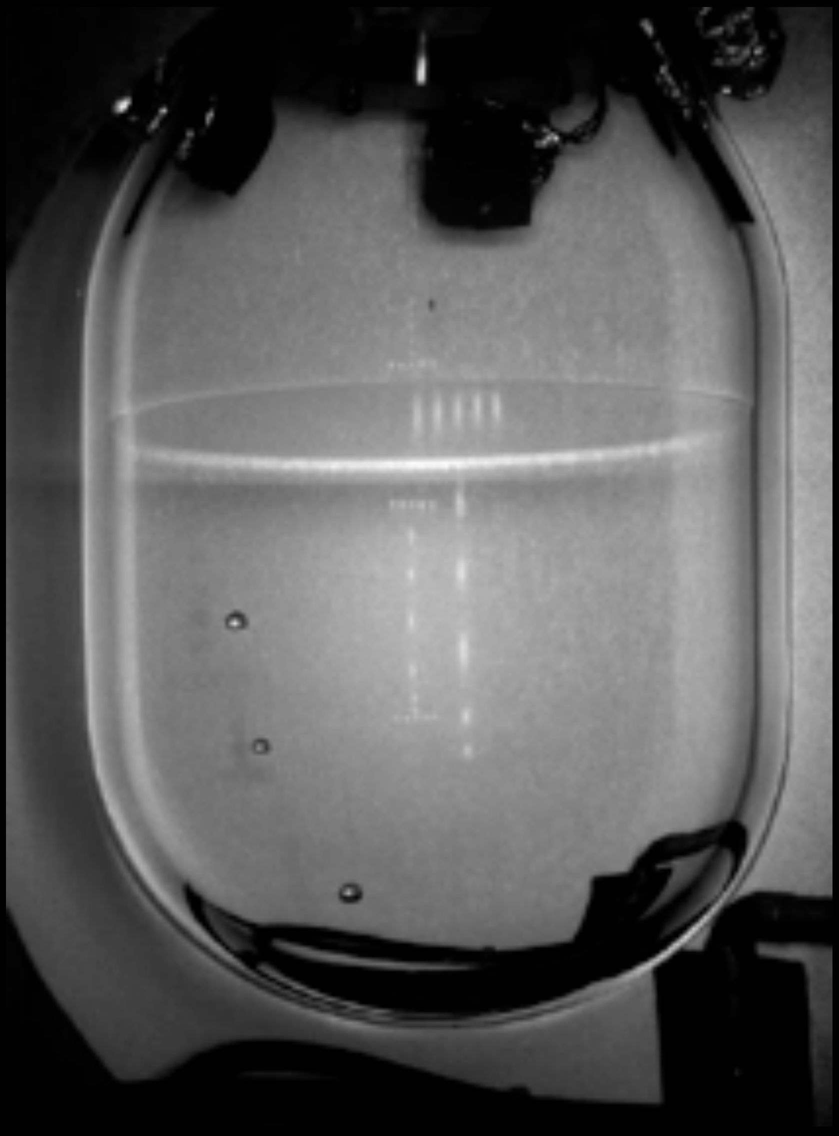


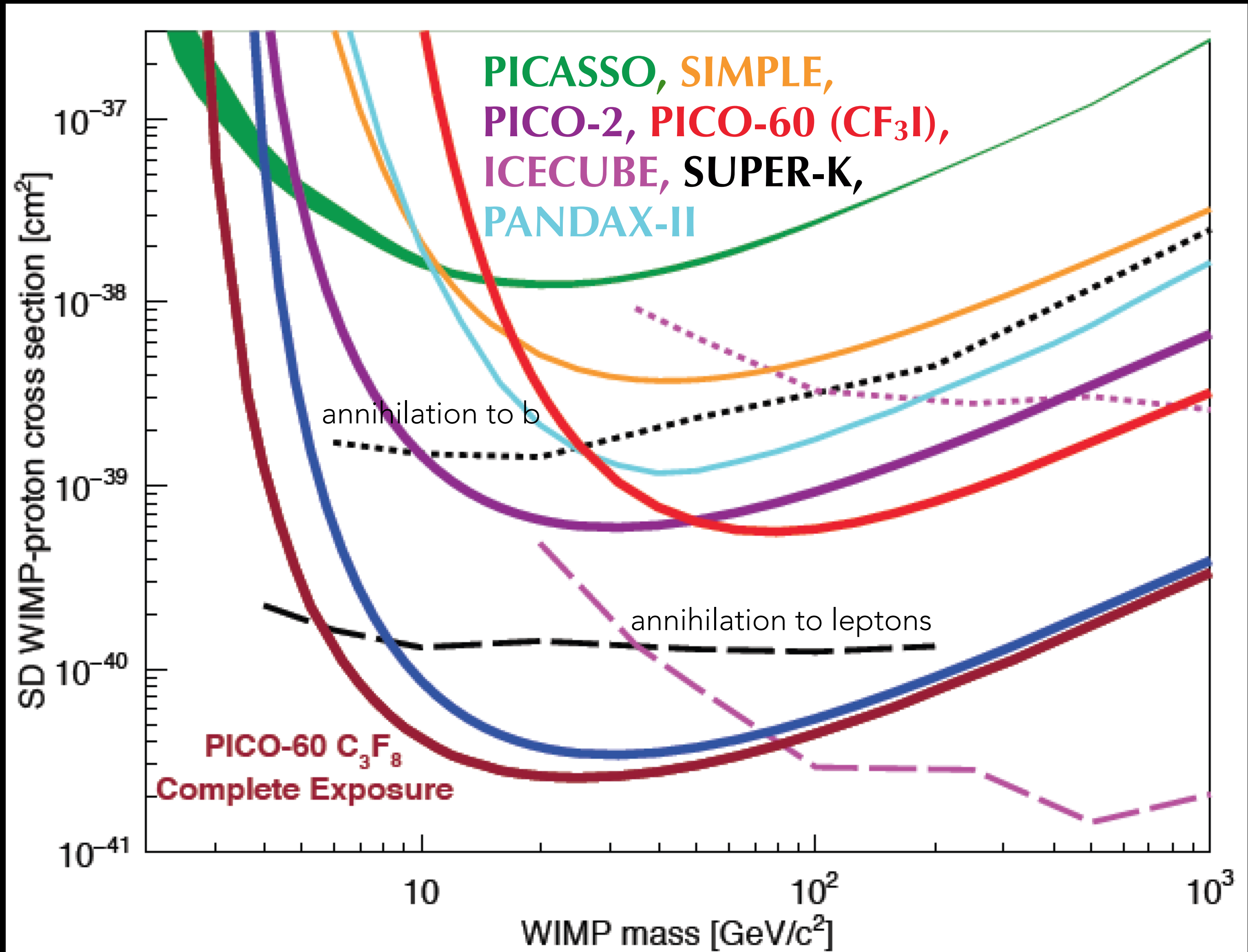
SPIN-DEPENDENT INTERACTIONS

superheated target ($C_N F_M$), camera + acoustic readout, background rejection based on topology $O(10^{-2})$, measure counts above threshold when dE/dx > nucleation,
SIMPLE (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)

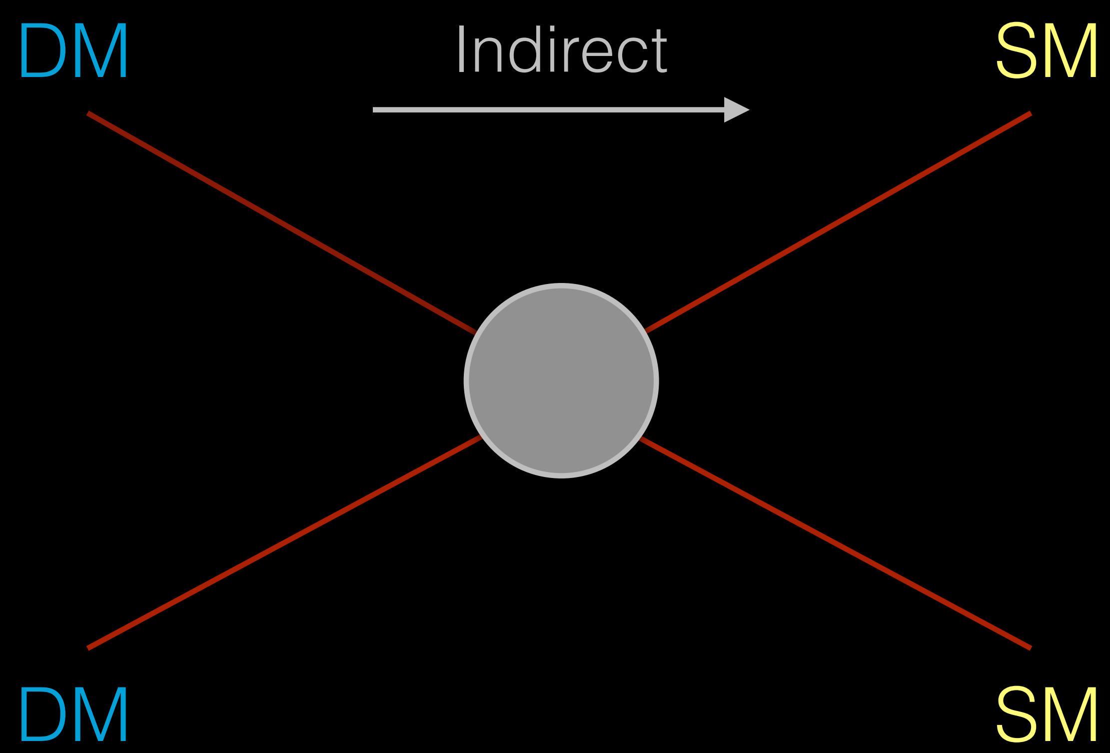
PICO-60: leading WIMP-p limit, C_4F_8 target (60 kg), 500 kg planned
competitive limits from neutrino telescopes (IceCube, Antares, SuperK)
leading WIMP-n limits from Xe 2-phase TPCs

arXiv:1902.04031v1





WIMP INDIRECT DETECTION



Annihilation in overdense regions of the Universe: source of gamma rays, neutrinos and cosmic rays

Targets: Dwarf satellite galaxies & Galactic Center, Sun or Earth in case of neutrinos

Relevant particle physics properties:

- Annihilation cross section (the key quantity that feeds into relic abundance calculation)
- Mass of the DM particle
- BR in the different final states

Differential flux

energy spectrum

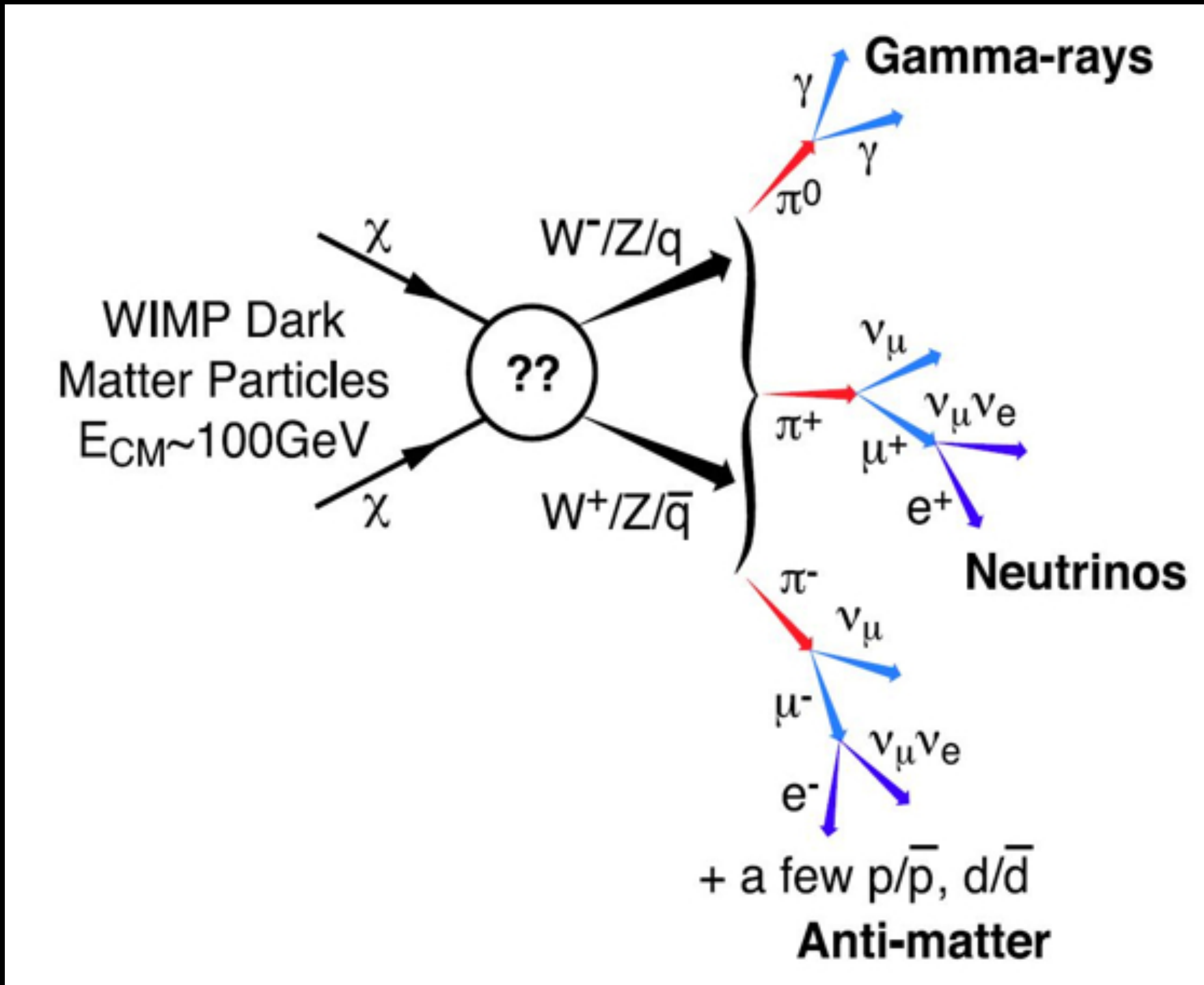
$$\frac{d\Phi}{d\Omega dE} = \frac{\sigma v}{8\pi m_\chi^2} \times \frac{dN}{dE} \times \int_{l.o.s.} ds\, \rho^2(\vec{r}(s,\Omega))$$

dark matter distribution

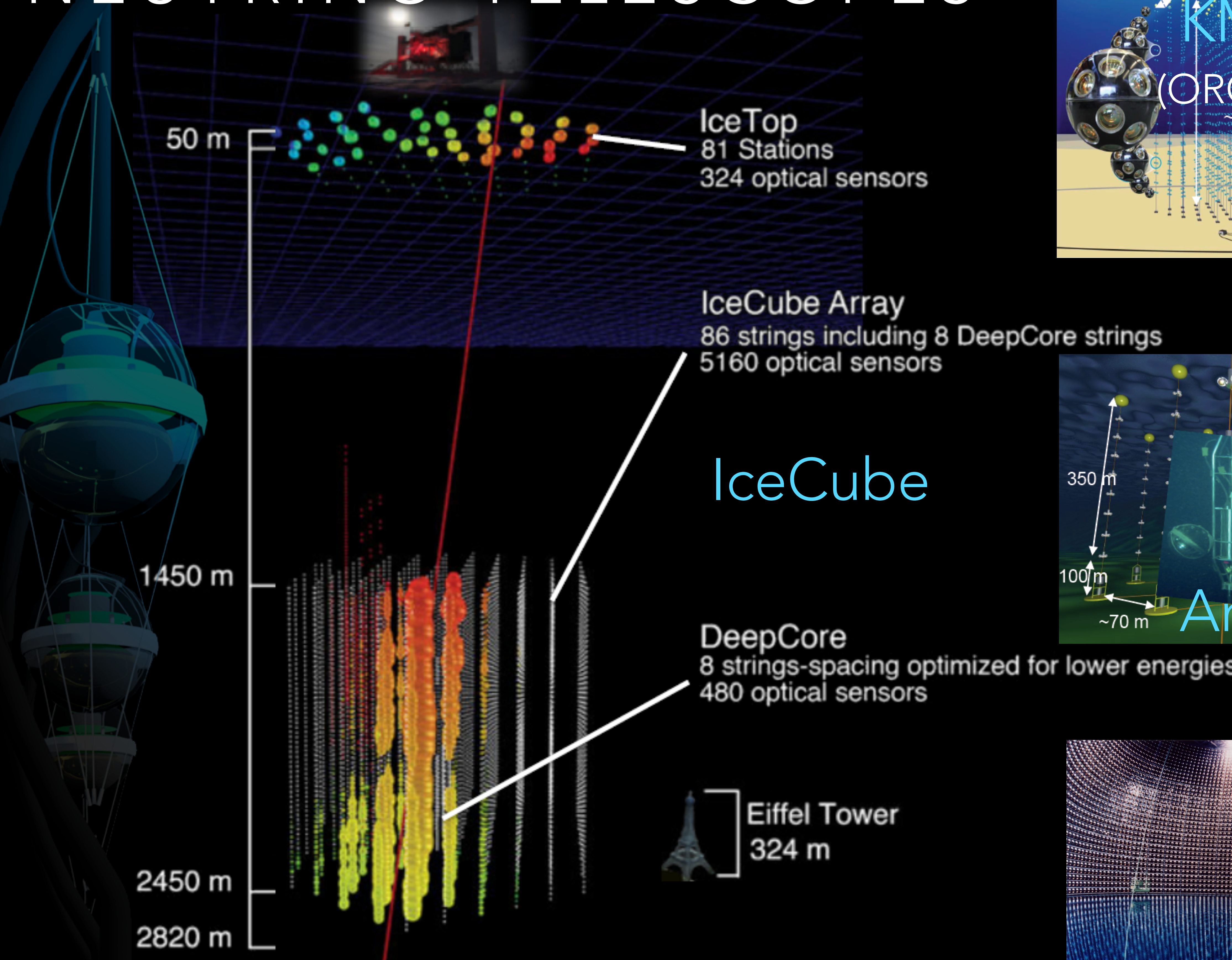
annihilation cross section

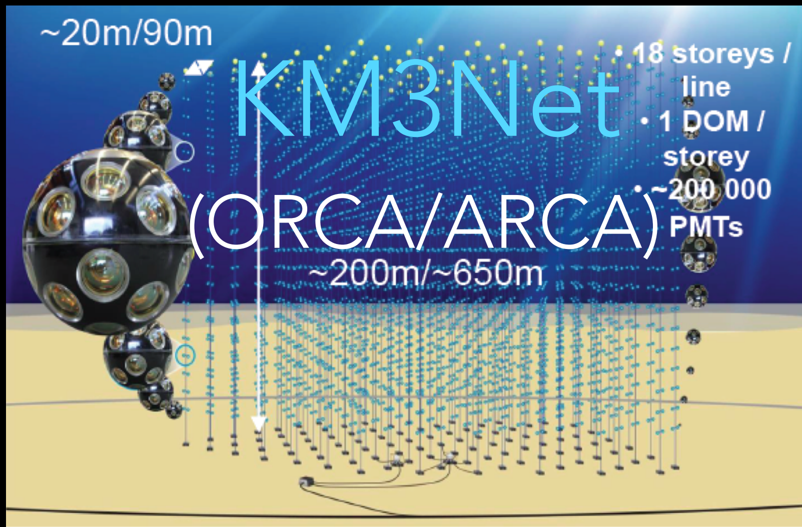
A MULTI-MESSENGER APPROACH

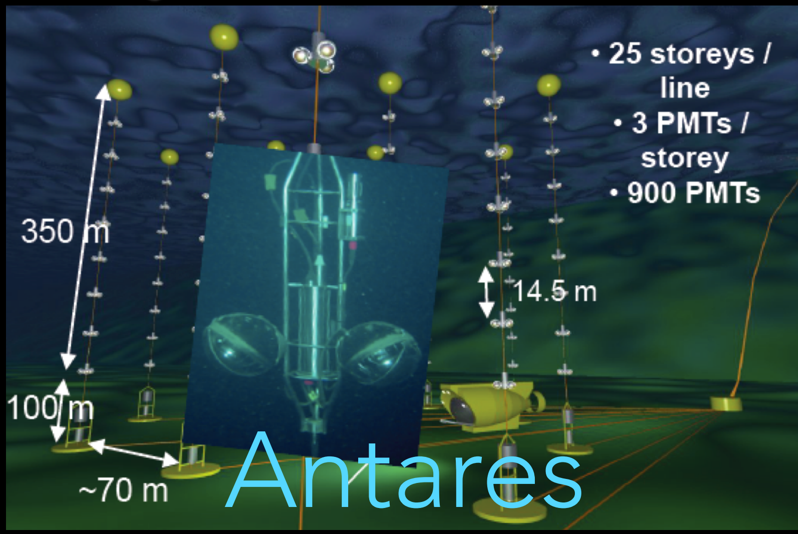
- neutrinos from DM annihilation in the Sun
- neutrinos and gammas from Galactic Center and Dwarf Spheroidal Galaxies
- anomalies in CR antiparticle spectra



NEUTRINO TELESCOPES



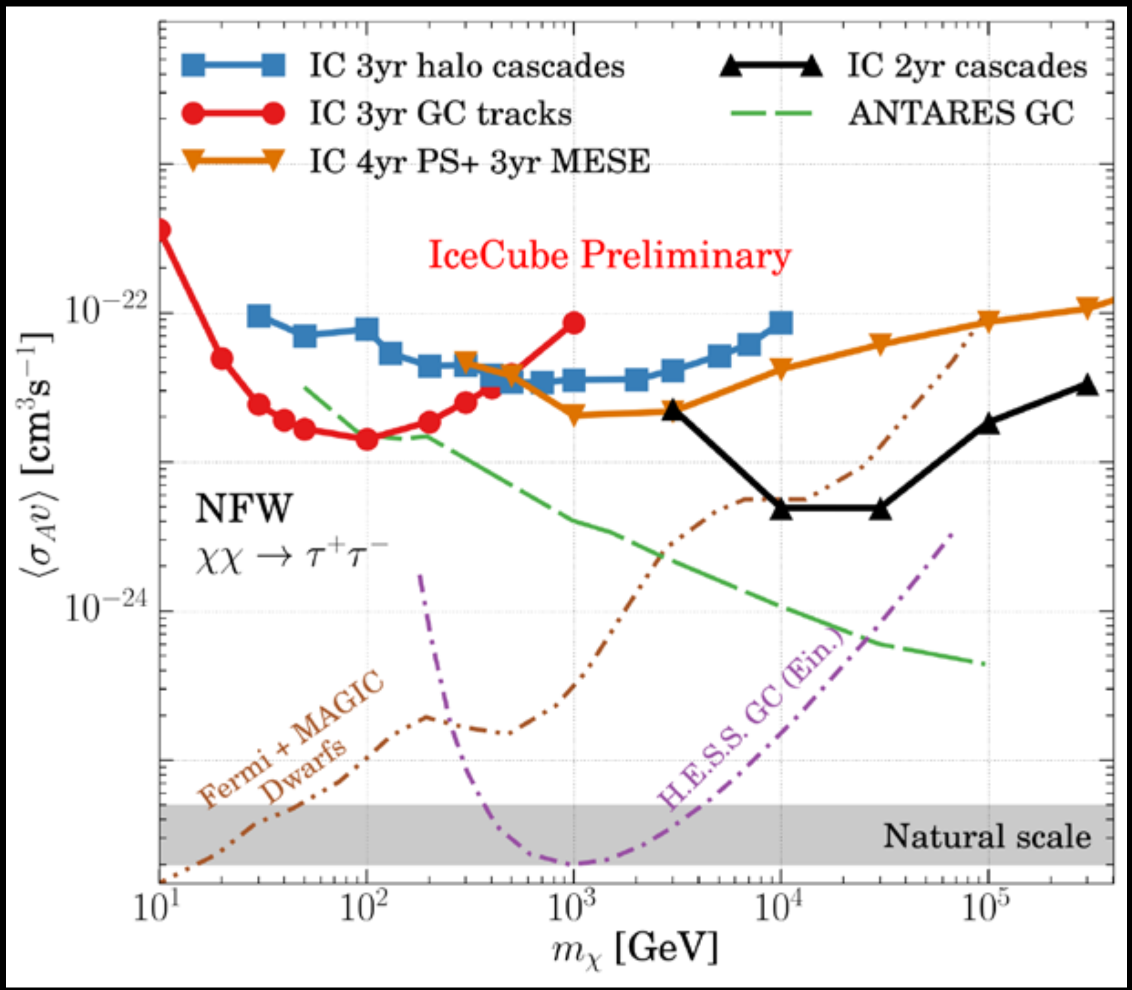


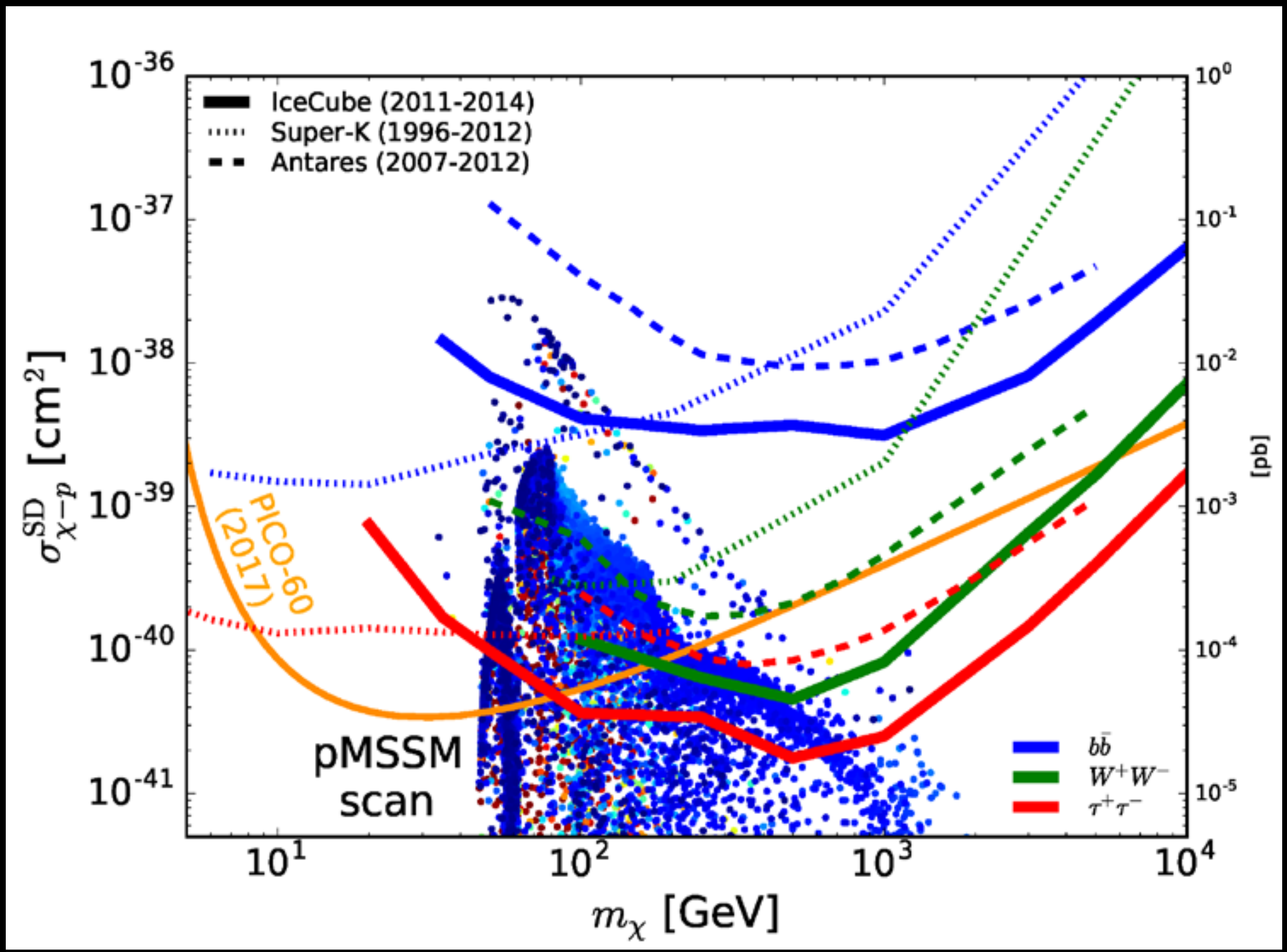


DM SEARCHES WITH COSMIC NEUTRINOS

DM annihilation of WIMPs captured in the Sun
Flux depends on WIMP-proton scattering
(in equilibrium)

EPJ Web of Conferences 207, 04006 (2019)





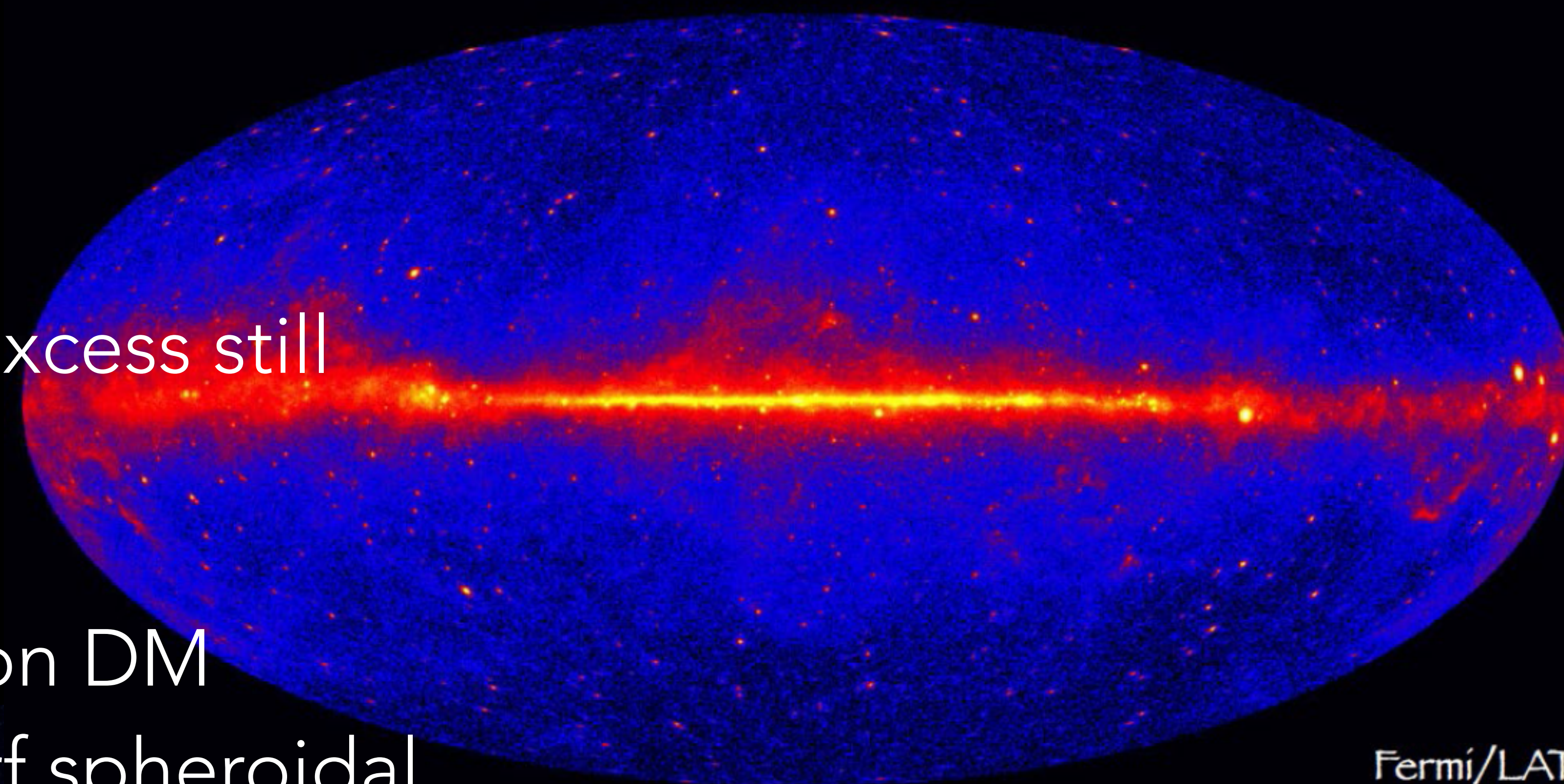
Aguilar Sánchez, VLVnT-2018

Situation

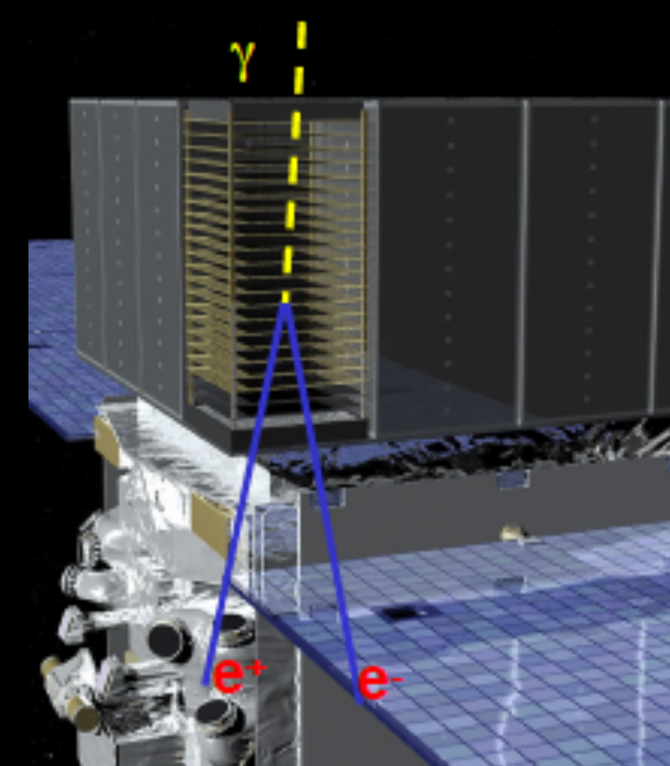
- Most stringent bounds on spin-dependent scattering cross-section in the 100 GeV to multiple TeV range come from neutrino telescopes
- However, searches for signal from GC not very competitive with gamma ray telescopes

GAMMA RAYS

- Fermi
  - Galactic Center GeV excess still debated
  - strongest constraints on DM annihilation from dwarf spheroidal galaxies
- Cherenkov telescopes
  - strongest constraints in the TeV DM mass range



Fermi/LAT



GAMMA RAYS

- Fermi
  - Galactic Center GeV excess still debated
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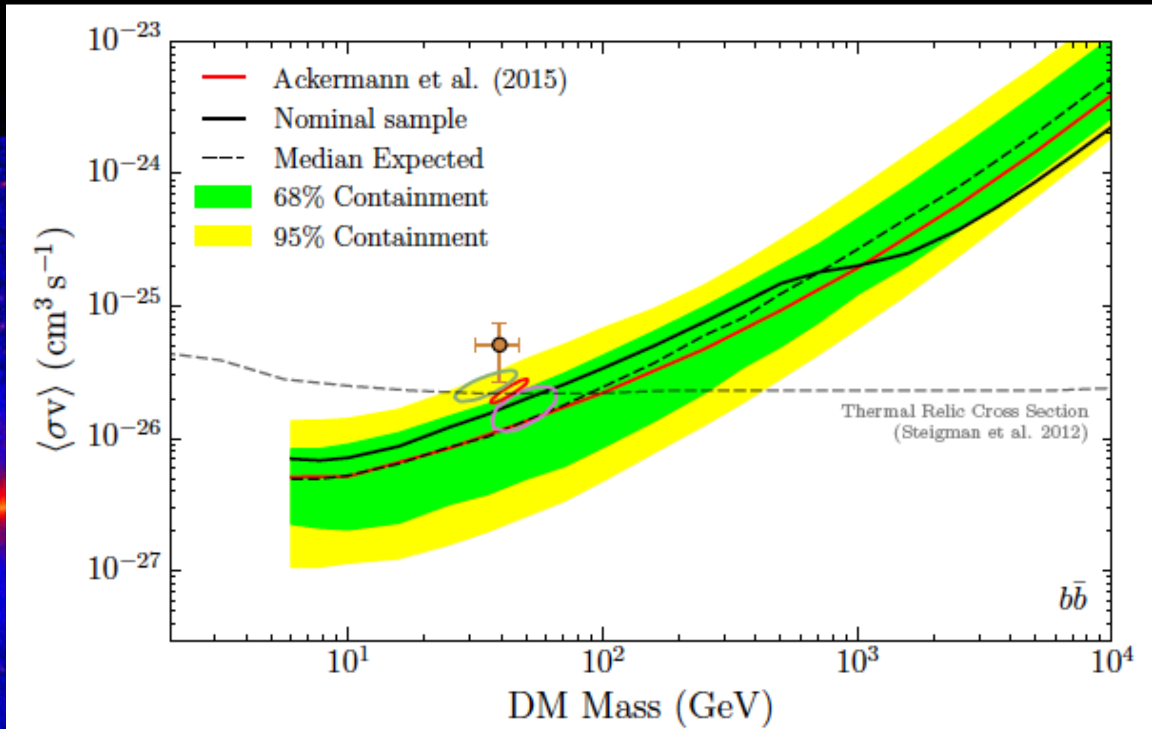
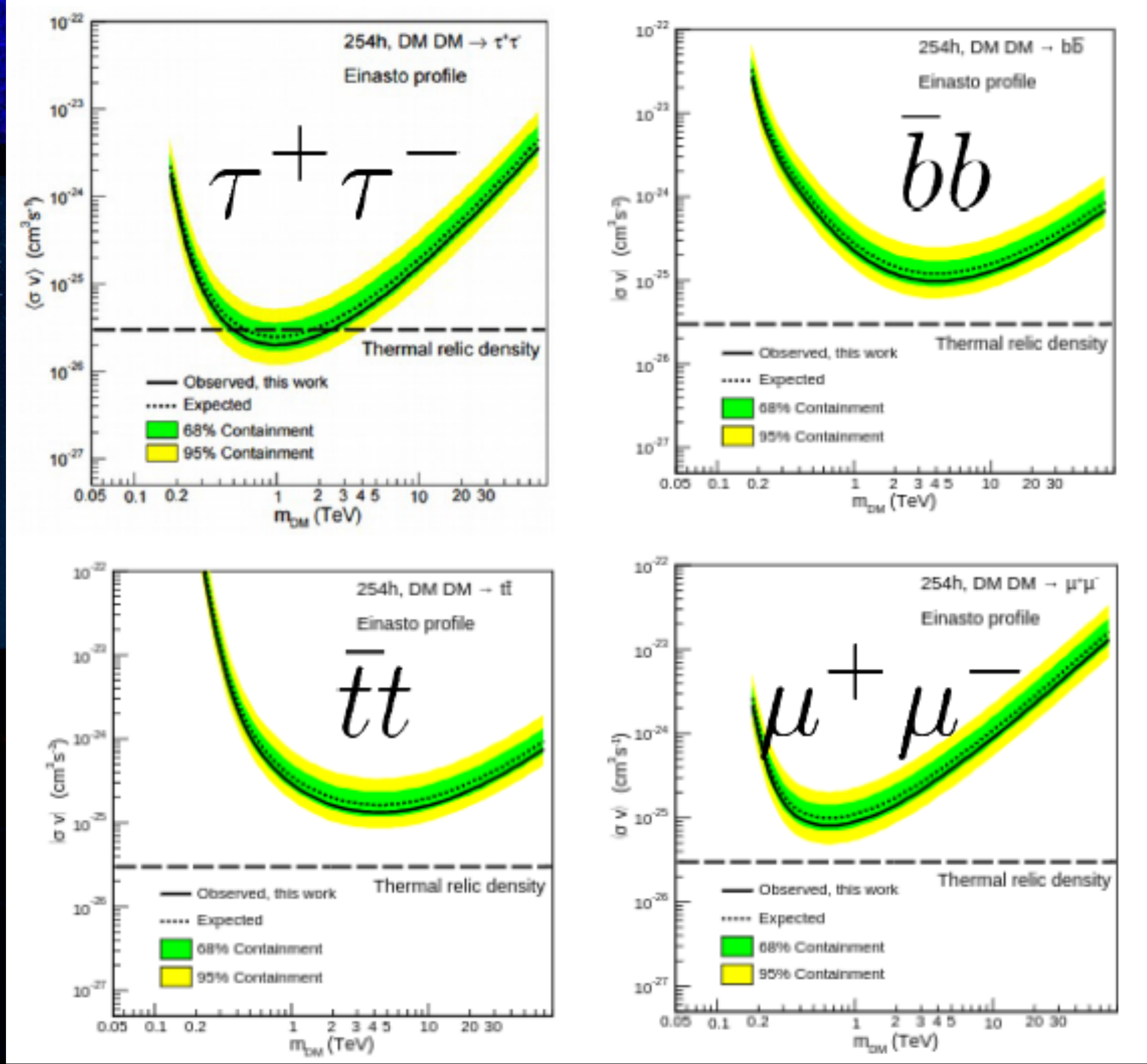
FERMI, arXiv: 1611.03184v1

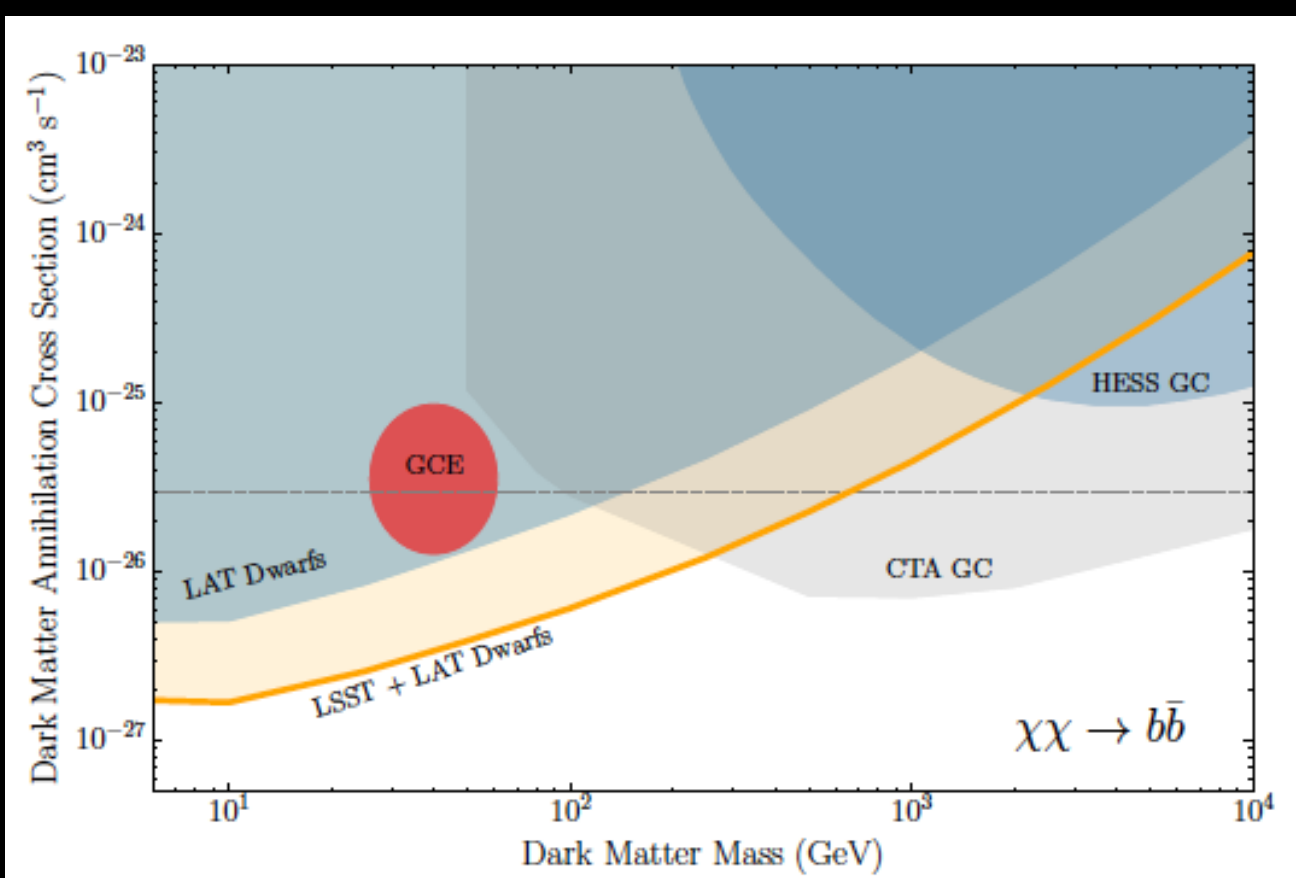




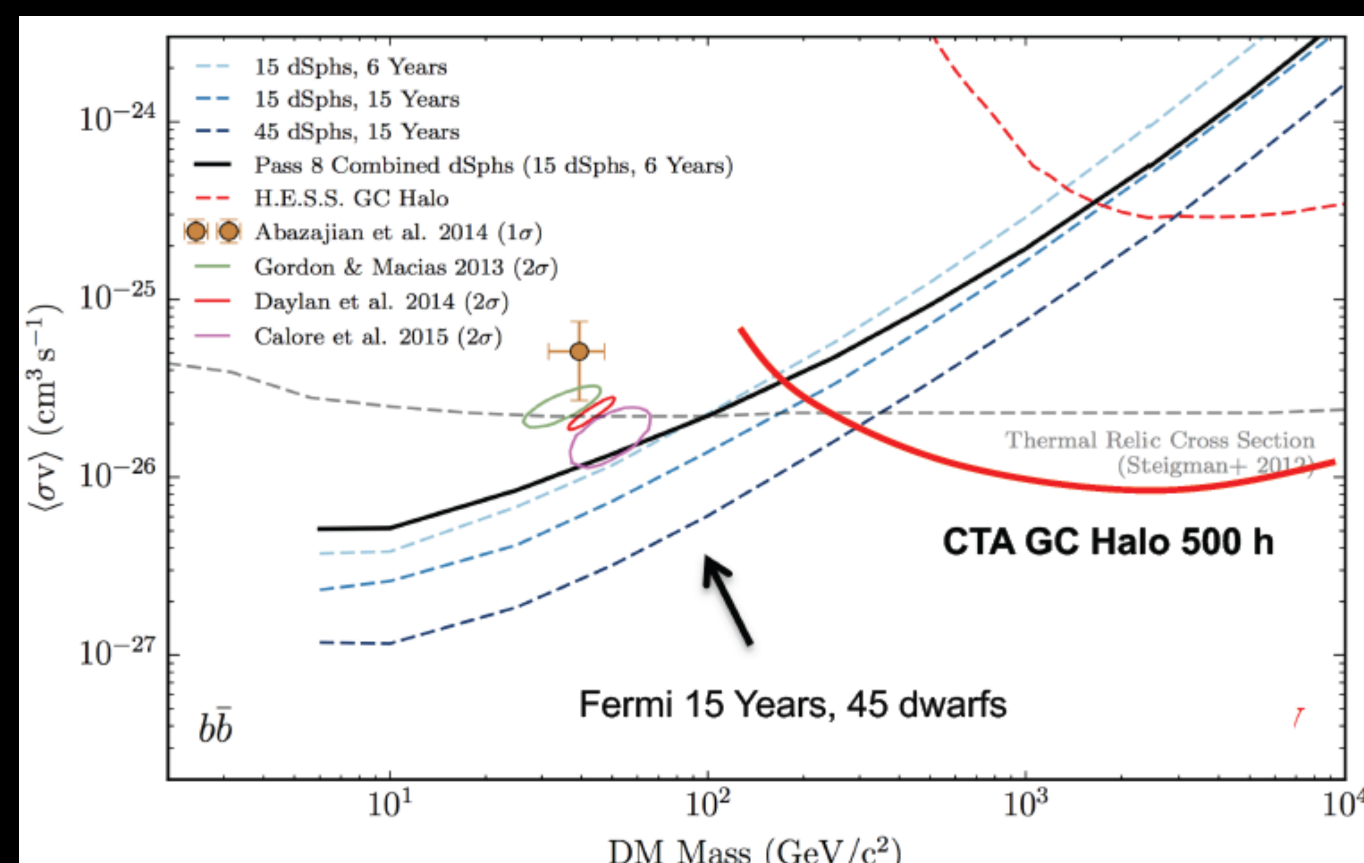
H.E.S.S., PRL 117, 111301 (2016)

OUTLOOK ON HIGH-ENERGY GAMMA RAYS

- Fermi observations of dSph rule out the simple relic benchmark annihilation cross section for masses up to 60 GeV (for the case of annihilations to b)
- Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section



LSST DM Group, arXiv:1902.01055v2



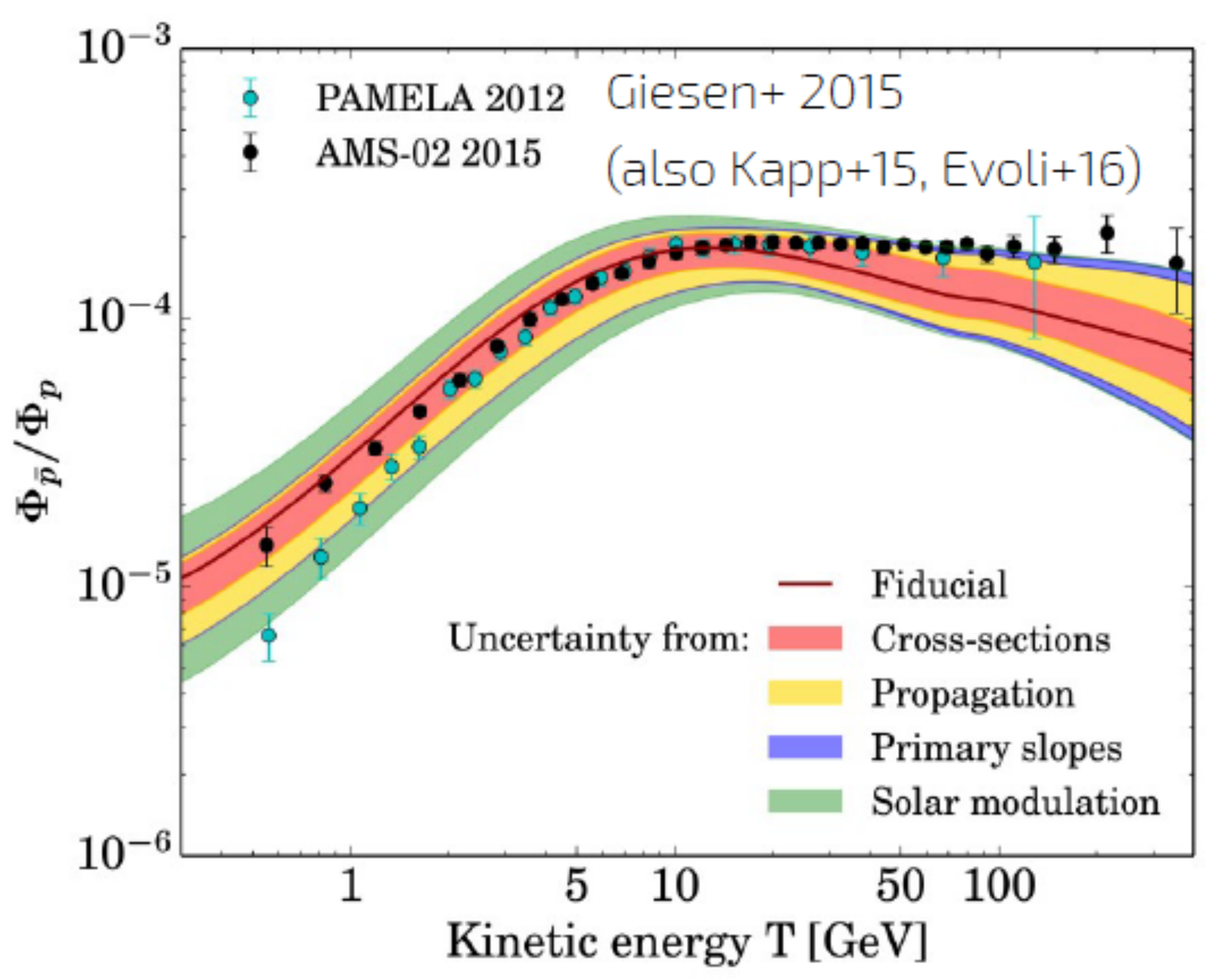
A. Morselli, MAGIC Dark Matter Workshop, 2019

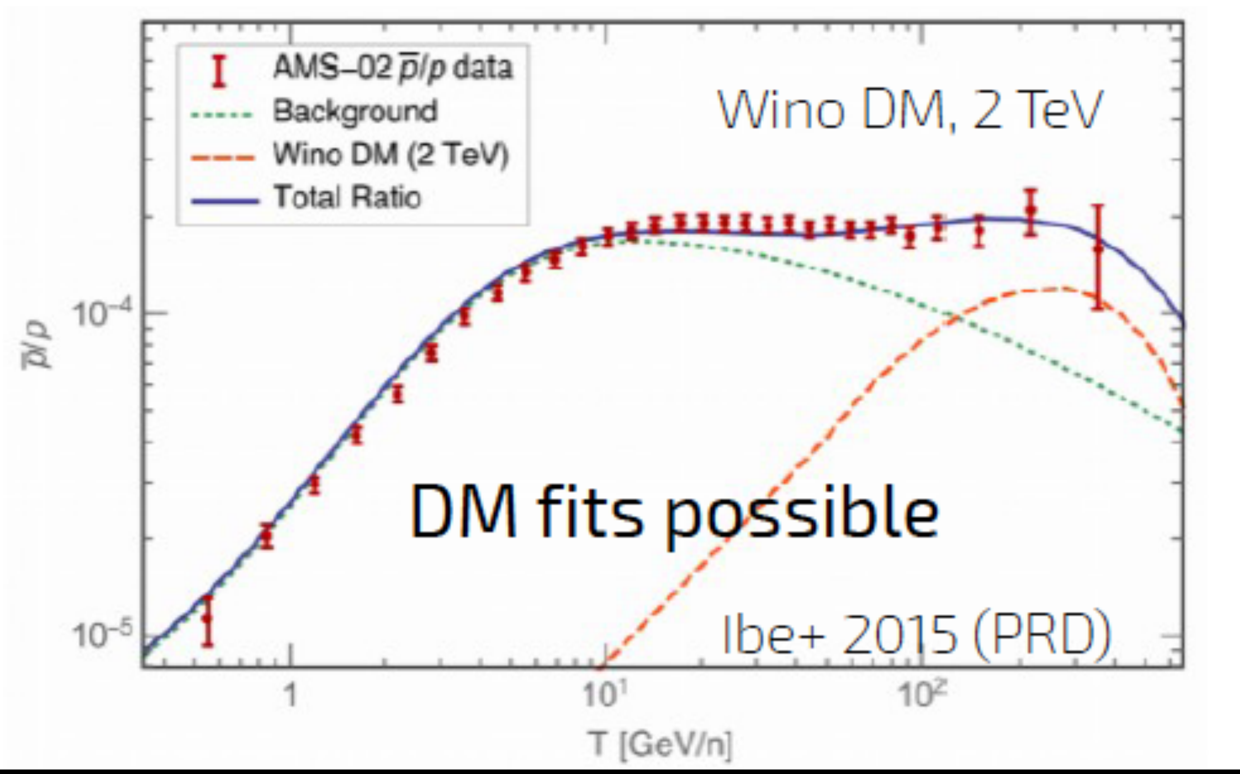
ANTIPROTONS

- Background of secondary anti-protons can be predicted within factor of a few
- AMS-02 measurements marginally consistent with secondary background
- Hard to exclude astro explanation for excesses above secondaries (e.g. nearby SNR, non-universal diffusion, etc)

Systematics:

1. Cosmic-ray injection and transport in the ISM
2. The antiproton production cross section
3. The impact of the solar wind (solar modulation)





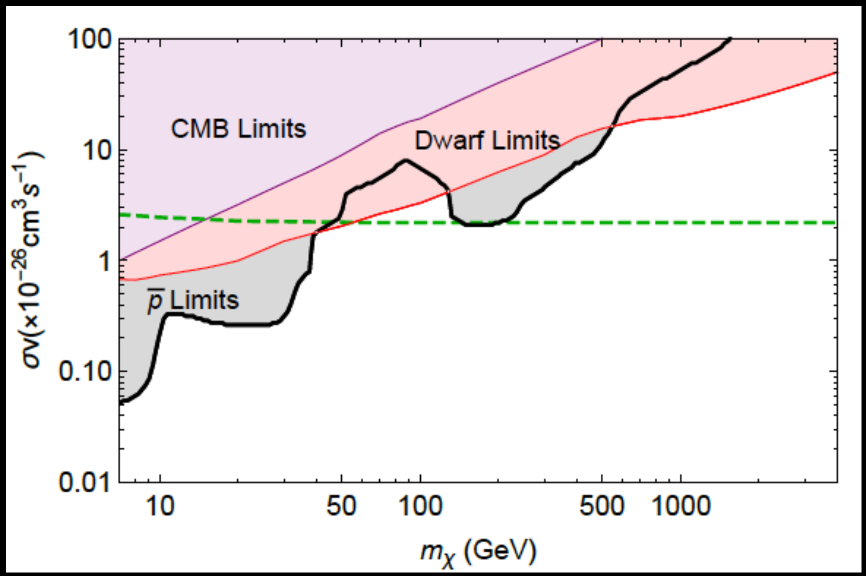
ANTIPROTON EXCESS

Cuoco+ 2019

- First identified in Cuoco+ 2017, with ~4 sigma significance
- After new systematic checks, still at few sigma level
  - Marginalizing over pbar production cross section reduces significance
  - Correlated instrumental systematics are important, of same order as excess, but correlation structure is now publicly available

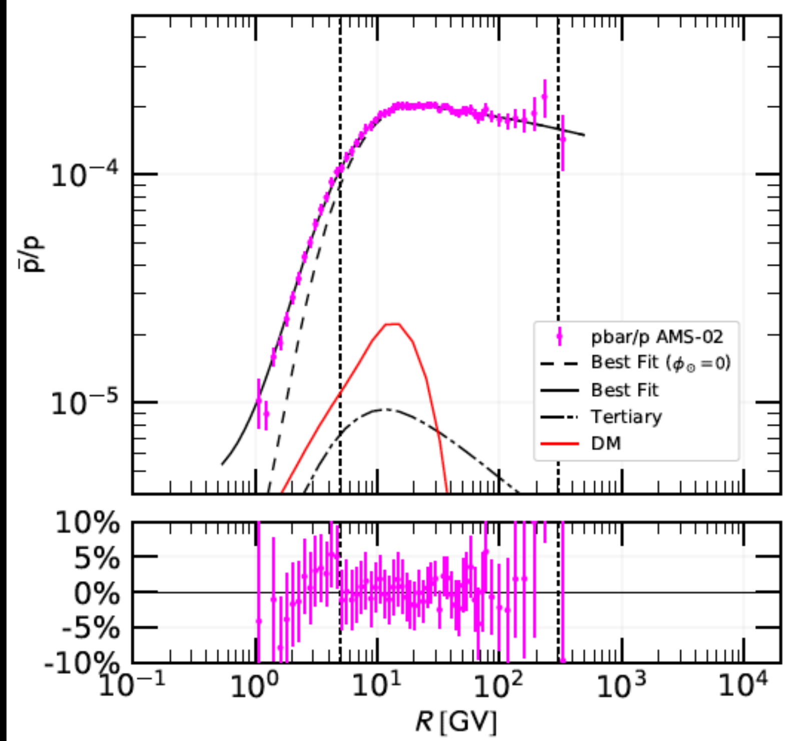
Cholis+ 2019

- Marginalizing over all parameters in fit, WIMP DM:
  - m~46-94 GeV
  - **σ**v ~(0.7-5.2)x10^{-26} cm^3/s (for annihilations to bb)
- can account for both the gamma-ray excess and the antiproton excess

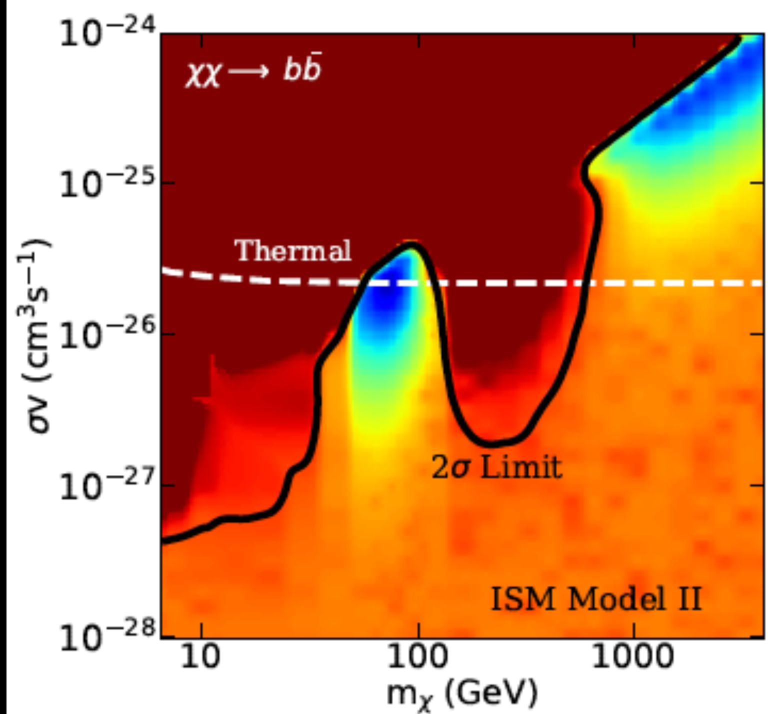


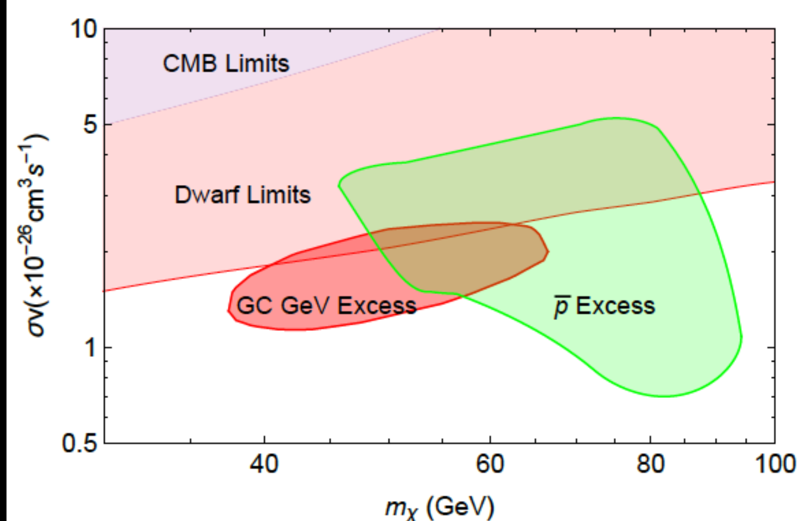
arXiv:1903.02549

Aside from excess, data place stringent limits on the DM annihilation cross section



Cuoco et al., arXiv:1903.01472

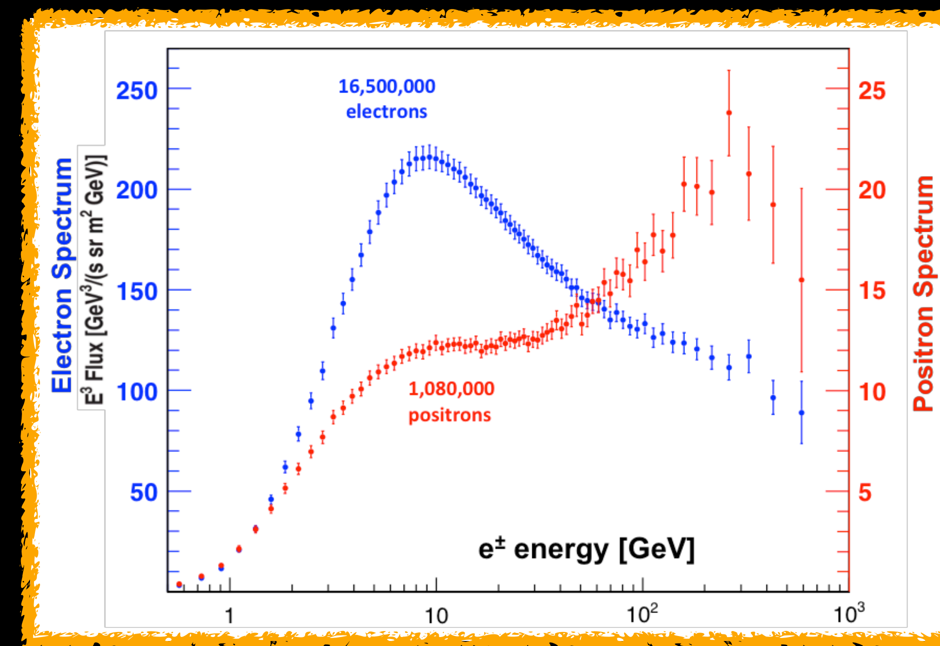


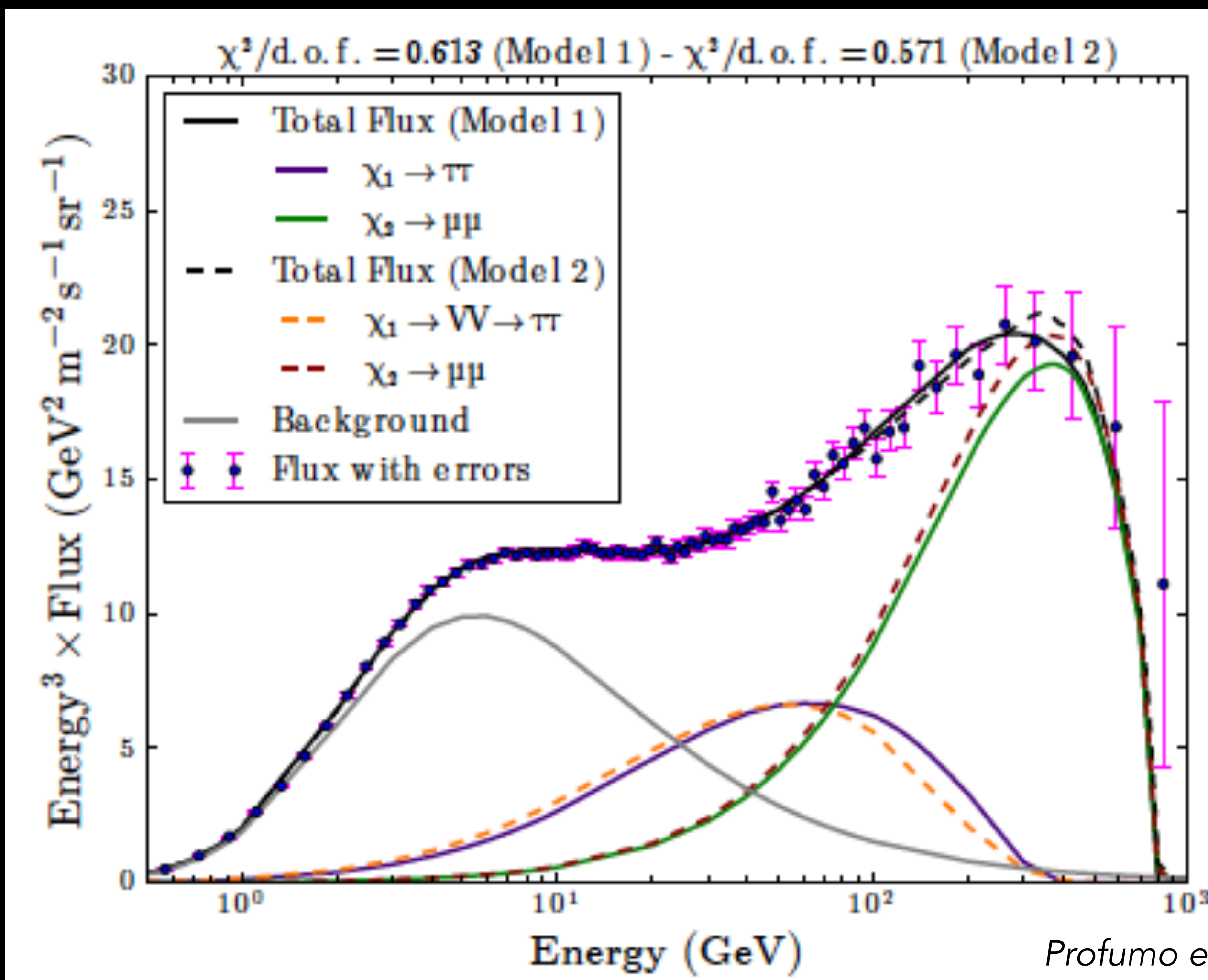


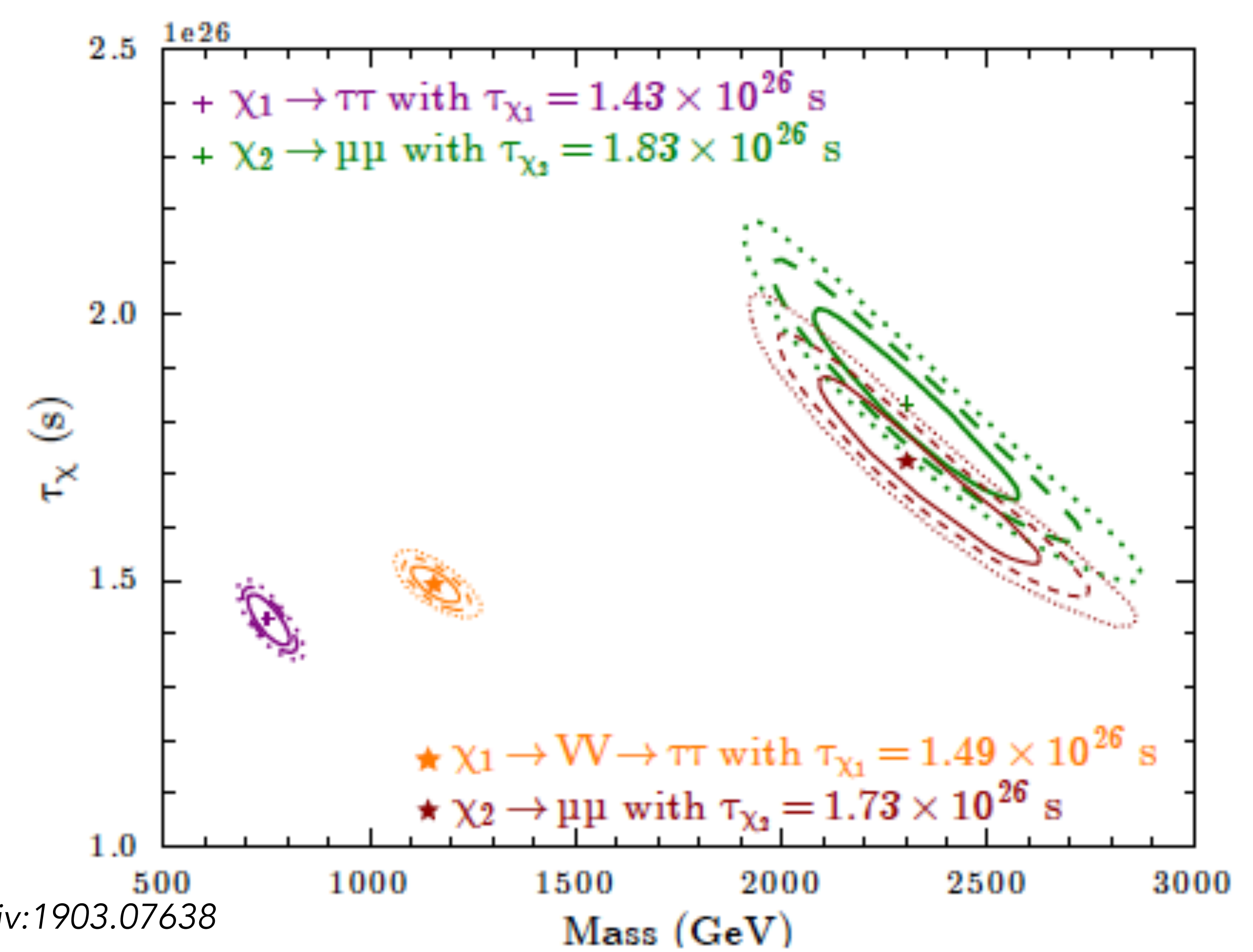
Cholis et al., arXiv:1903.02549

UNEXPECTED FEATURES IN THE POSITRON SPECTRUM

- The most recent AMS-02 data exhibit a bump at an energy around 300 GeV followed by a drop around 800 GeV
- Not understood in terms of astrophysics
- Can be fit with two dark matter particle species contributing equally to the global cosmological DM density







Profumo et al., arXiv:1903.07638

SUMMARY & CONCLUSIONS

- Astroparticle experiments bridging the gap between Particle Physics, Astrophysics and Cosmology
- Newborn multimessenger approach providing exciting opportunities to astronomy and fundamental physics
- Dark Matter an essential building block of the Standard Model of Cosmology awaiting discovery
  - WIMP still main paradigm → reach ν floor
  - *… + many new ideas on lighter dark matter not covered here*

more to come in highlight and parallel talks