Indirect dark matter searches

from PNHE to TUG, and back

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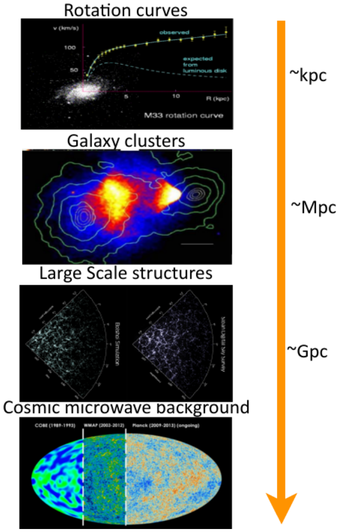
(LAPTh, Annecy, France)

November 6, 2024

Journées Théorie de la communauté Hautes Énergies, APC, Paris

A dark, matter component of the Universe



1parsec=3.3 ly, 1Mpc= 10^{22} m

Required to explain *observed* distribution and amount of structures in the Universe

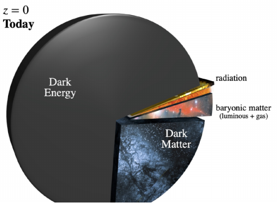
- Most striking evidences come from biggest structures and cosmological timescales
- Galaxies embedded in dark matter halo $\rho(r) \propto r^{-2}$, also Milky Way
- Mostly probe *gravitational coupling*: total mass, spatial distribution

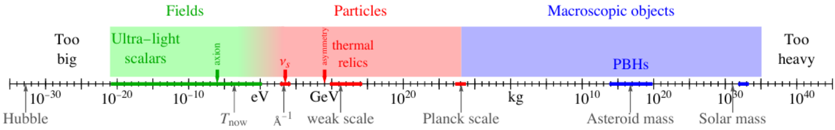
[Recent reviews and lecture notes: 2410.23454, 2406.01705, 2303.02169, 2109.02696]

Dark matter: knows and unknows

From astrophysical and cosmological observations:

- **Massive**: behavior in cosmological evolution
- **Cold**: non-relativistic, allows structure formation
- **Non-interacting**: (or feebly) weak enough
- **Dissipation-less**: cannot easily dissipate energy
- **Stable**: from early Universe until now
- **Smoothly distributed** on cosmo scales



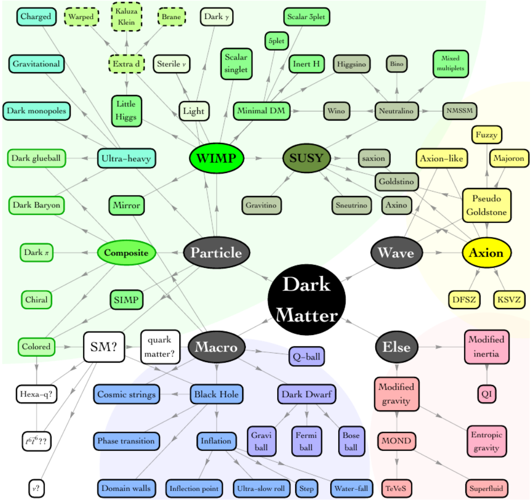


[arXiv:2406.01705]

Too 'big': De Broglie wavelength must be smaller than smallest structures, < kpc
Too heavy: mass must be smaller than smallest observed galaxy, $< 10^5 M_\odot$

understand dark matter nature = understand interactions with barionic matter

Theory landscape



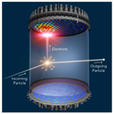
[arXiv:2406.01705]

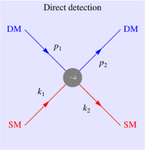
Well-motivated: predictive, prototypical /solve other issues, simple/ elegant

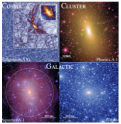
Indirect searches

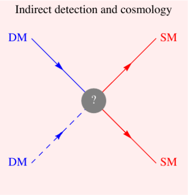
Search for signals of dark matter through:

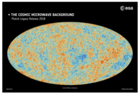
- *Nature-made experimental setups* at different redshifts
- Standard model (astro) particles or subsequent effects (heating, ionization, ...)

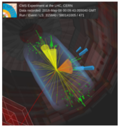


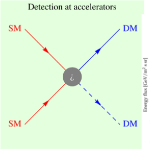


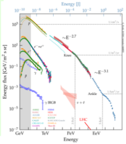


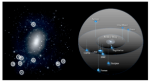










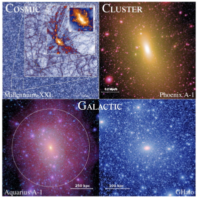


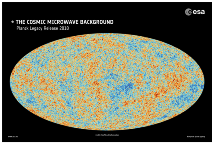
The universe as laboratory: share detectors with high energy astrophysics

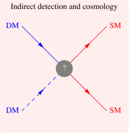
The (barionic) universe as background: share objectives with high energy astrophysics

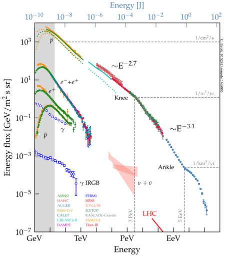
[image credits: SLAC; CMS, CERN; arXiv:2406.01705v2; ESA; arXiv: 1209.5745; C.Evoli; arXiv:1310.6746]

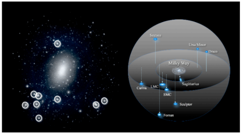
Indirect searches strategies











- Integrate large masses: center of Galaxies / clusters
- Integrate large distances and timescales: cosmological probes
  A.Moradinezhad, M.Cagliari talks [TUG]
- Exploit precision: high energy particles and photons
- Signal to background: dark matter dominated objects, e.g. dwarf satellite galaxies

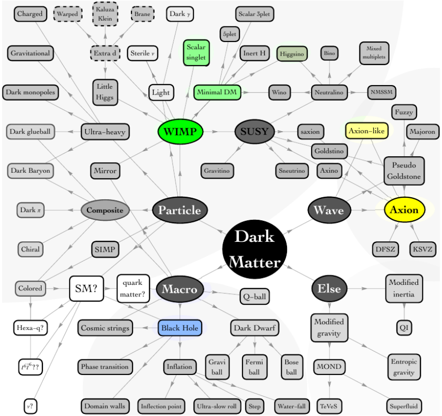
Give me priorities

Theory bias: predictive, prototypical

Observational bias: testability, we have data

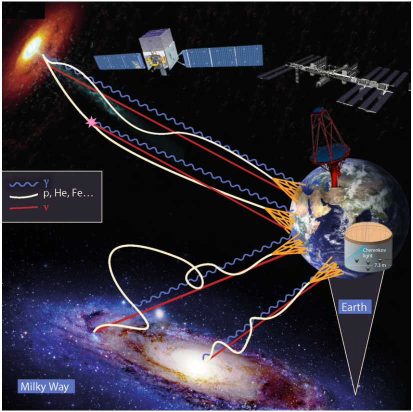
→Motivated candidates testable with high energy observations

→High energy observations available now and in the future



- Thermal relics
- Axion-like particles
- Primordial black holes

High energy messengers: X-ray to TeV, GeV charged



[adapted from DOI:10.22323/1.358.0284]

Satellite: X-ray (XMM-Newton), γ ray GeV (Fermi-LAT), cosmic rays GeV (AMS-02)

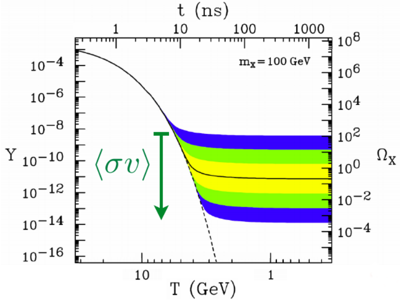
Ground: γ ray TeV (Hess, Veritas, HAWC, LHAASO, ...)

Next generation: γ ray TeV (Cherenkov Telescope Array, CTAO, SWGO)

[2203.06894, 2203.07360, http://tevcat.uchicago.edu/reviews.html,https://inspirehep.net/literature/2151652]

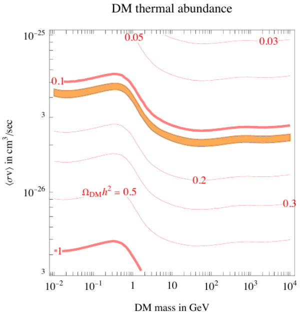
Thermal relics

Massive, stable particles χ directly coupled to primordial plasma $\chi\chi \leftrightarrow \mathrm{SM\,SM}$



Comoving number density $Y = n_i/a^3$

Freeze-out at $\Gamma(T_f) \simeq H(T_f)$



[arXiv:2406.01705v2]

$$\Omega_\chi h^2 \simeq 0.1 \frac{3 \cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{ann} v\rangle}$$

Weakly-interacting massive particle

Production mechanism viable down to 1-10 MeV, new mediators needed for $m_{\rm DM} < 2$ GeV; unitarity limits $m_{\rm DM} < 100$ TeV

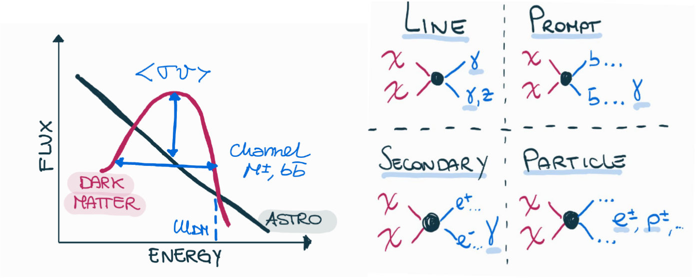
G.Belanger talk [TUG]

Indirect signatures of thermal relics

Dark matter decay, annihilation produces extra flux of astro particles

$$\chi + \chi \to q\bar{q}, \tau^+\tau^-, ... \to \gamma, e^\pm, \bar{p}, p, \nu, ...$$

Messengers: photons, charged particles, neutrinos

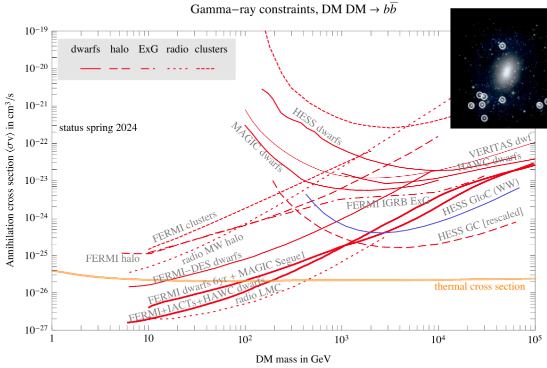


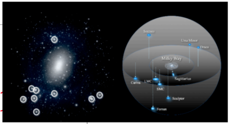
$$\Phi_{\text{messenger}} \propto \frac{\text{interaction strength}}{\text{dark matter mass}} \cdot \frac{dN_{\chi\chi\to\text{messenger}}}{dE} \cdot \int \text{dark matter density}$$

Simple, powerful for model-independent constraints + specific model realization

GeV-TeV candidates: gamma ray constraints

Strong, complementary constraints to 10-100 GeV thermal relics





[arXiv:2406.01705]

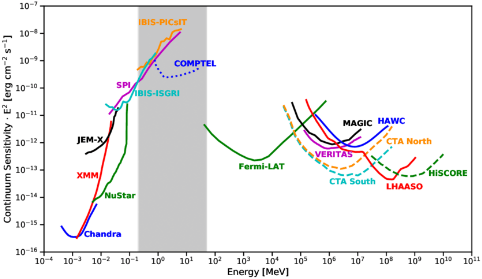
Ideal labs: Dwarfs galaxies: very large mass to light ratios, quiet(er) astro environments

Current main datasets: GeV: Fermi-LAT, TeV: HESS, VERITAS, HAWC
TeV window of opportunity for CTA [1305.0302, 2007.16129, 2008.00692, 2403.04857]

Uncertainties: background modeling (e.g. stellar pop, gas) + dark matter density
D.Kantzas talk on jets [PNHE]

sub-GeV candidates: MeV gap and X-ray patch

Similar signatures and targets, but sensitivity gap 100 keV - 100 MeV, production mechanisms can go beyond thermal freezout



[Lucchetta+2022]

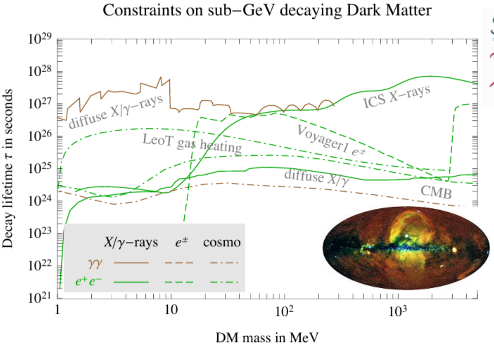
Many ideas and some plan:

- GECCO, AMEGO-X [2112.07190,2208.04990,2203.07360]
- COSI: wide-field, 0.2-5 MeV, scheduled 2027 [1908.04334]

[For status of global fits see 2405.17548; Theory review 2406.01705; INTEGRAL constraints 2401.03795; COSI and GECCO prospects for dark matter 2210.09310,2101.10370,2411.00087; 3.5 keV line 2309.03254]

sub-GeV candidates: MeV gap and X-ray patch

Secondary emissions: annihilation/decay channels with $e^{\pm}$ will produce inverse Compton X-ray photons [2303.08854]



[arXiv:2406.01705, SRG/eRosita]

Current: XMM-Newton; *Future*: newAthena (ESA), AXIS (NASA) [2110.15677,2311.00780]

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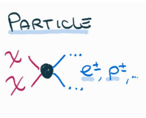
Cosmic ray antimatter

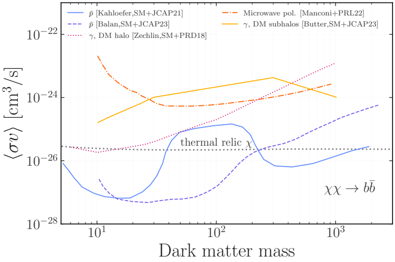


Interactions in the Galactic halo can contribute to local cosmic ray fluxes

Antimatter: lower background, lower flux: sensitive to smaller couplings

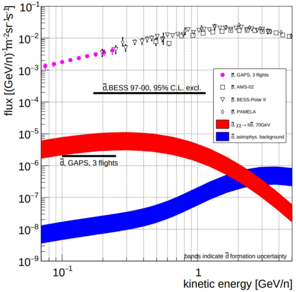
AMS-02 on ISS: **game changer**, data with % precision allow precise tests

Antiprotons



AMS-02 measurents at GeV:
Current best antiparticle to derive constraints, competitive to γ ray dwarfs

Antinuclei: $\bar{d}$



[GAPS coll at ICRC2023]

Below a few GeV/n secondaries suppressed

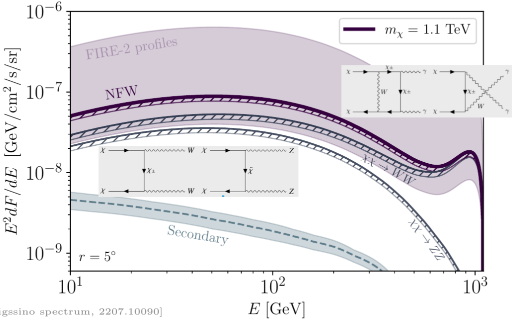
Forthcoming: GAPS ballon antartic flight (late 2024) $\bar{D}, \bar{p}$ optimized for 0.25 GeV/n

Required accurate background models, cross sections *D.Maurin talk [PNHE]*

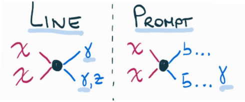
Minimal dark matter: Higgsino

Minimal multiplets: adding new $SU(2)_L$ to Standard Model, abundance set by thermal freezout, fixed mass $\sim$ TeV: γ ray indirect signals most striking [hep-ph/0512090]

Wino (triplet): disfavoured by TeV γ rays [HESS, 1307.4082]



[Higgsino spectrum, 2207.10090]

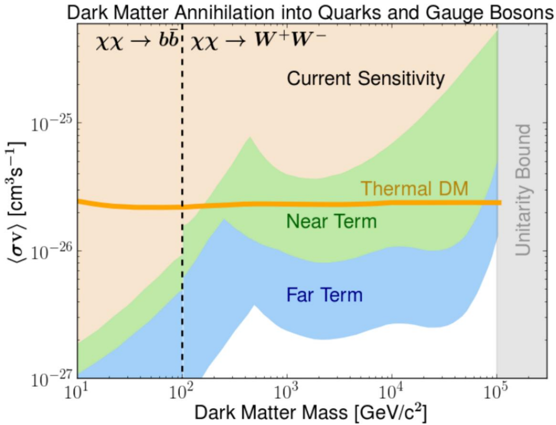


Higgsino (doublet): testable with GeV to TeV γ rays: Fermi-LAT (continuum), CTA (line)

Theory predictions recently refined for all minimal dark matter representations, promising constrain/discovery prospects

[Predictions: 1808.08956,2309.11562; constraints and forecasts: 2207.10090,2405.13104]

Thermal relics: summary and prospects



[2209.07426]

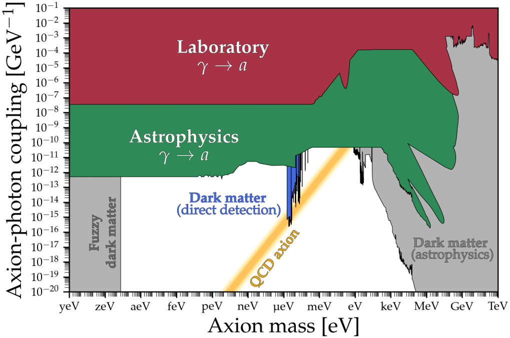
Next 10 years: test thermal relics (annihilations and decay) up to multi TeV
[1805.10305,2209.07426]

With precision data, a number of notable excesses: [2203.06859]
hints of thermal relics or astrophysics? e.g. GeV Galactic Center Excess, 3.5 keV line, ...

Ultra-light dark matter: axion-like particles

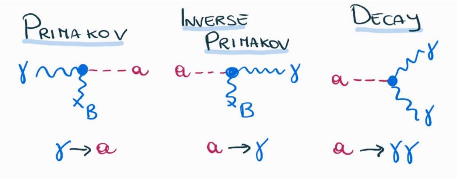
- **Axion** field a as new boson to solve strong Charge-Parity problem in QCD
- **Axion-like**: extremely light $m << 1$ eV and feebly-coupled, arising in many extensions of the Standard Model
- Can be cosmologically relevant as all (or some) dark matter

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}\, a$$



[https://cajohare.github.io/AxionLimits]

Phenomenology set by couplings with photons $g_{a\gamma}$
A.Hees talk [TUG]



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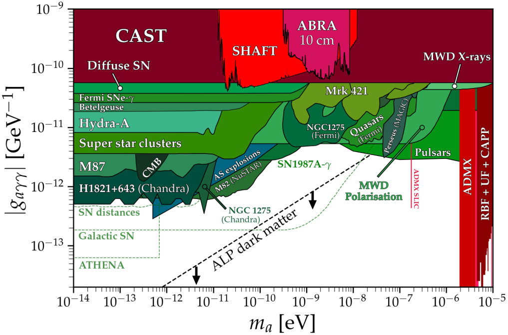

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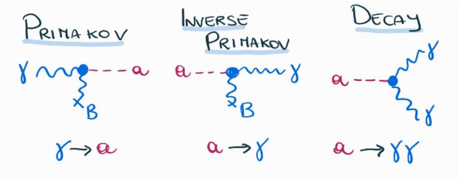
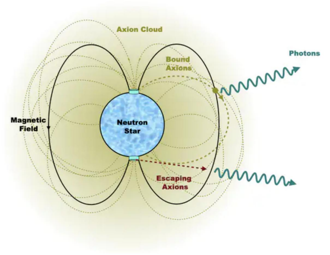


Axion-like particles and high energy astrophysics

Neutron stars as axion laboratories:
large magnetic fields, dilute plasma



[IoP,UvA]

Effects on pulsar/neutron star electrodynamics

[Reviews: 2105.01406,2203.14923,2203.14923,2205.00940,2403.17697,2411.02492]

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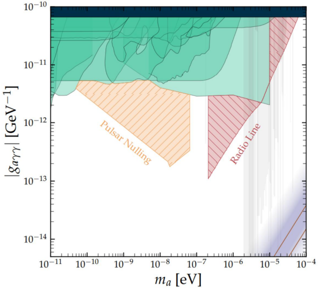

[2311.14795]

Escaping axions, axion clouds signatures:

- Radio spectra lines/broadband
- Transient radio events
- Pulsar nulling

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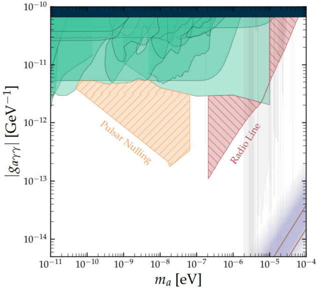

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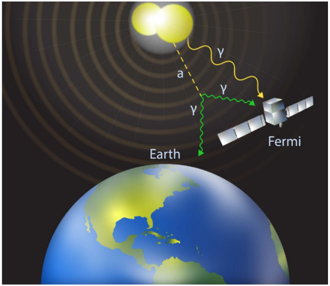
Wiggles in γ ray spectra

- Production of photons in astro source (leptonic or adronic)
- ALPs conversion in intergalactic and/or Milky Way B
- Wiggles: energy-dependent deviations from smooth GeV-TeV spectrum



[2305.01002]

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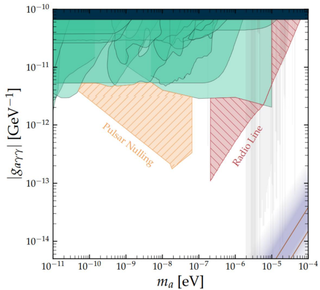

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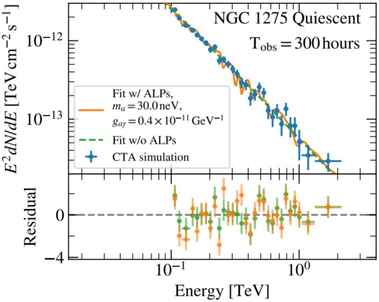

[2010.01349]

Escaping axions, axion clouds signatures:

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Current: Fermi-LAT; Future: CTA
Progress in understanding of B,
unmodulated source spectra, feature finding

[Reviews: 2105.01406,2203.14923,2203.14923,2205.00940,2403.17697,2411.02492]

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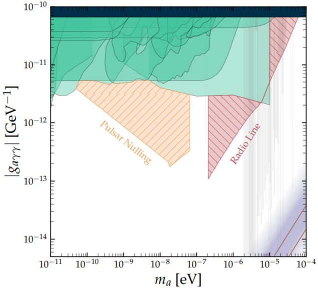

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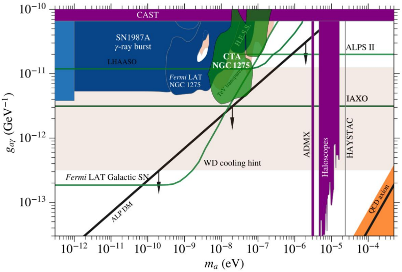

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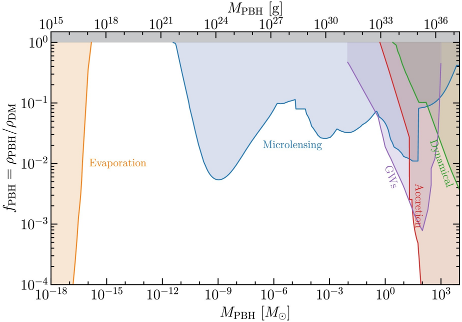
Primordial blak holes

Massive, barionic macroscopic objects, such as black holes

Primordial: collapse of overdensities in the early universe, could be $< 3M_\odot$, exist at $z > 8$ (before first stars) + halo spatial distribution

Evaporation: Hawking radiation, photons and charged cosmic rays at $\sim$ MeV

age > universe: $\gtrsim 2.5 \times 10^{-19} M_\odot$



[credits: PBHbounds, https://zenodo.org/records/3538999]

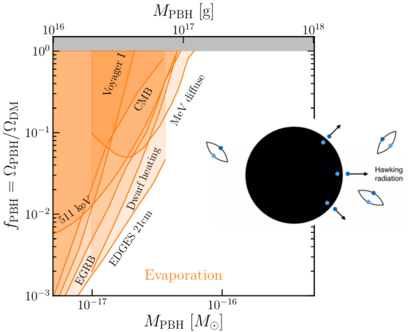
Primordial blak holes

Massive, barionic macroscopic objects, such as black holes

Primordial: collapse of overdensities in the early universe, could be $< 3M_\odot$, exist at $z > 8$ (before first stars) + halo spatial distribution

Evaporation: Hawking radiation, photons and charged cosmic rays at $\sim$ MeV

age > universe:
$\gtrsim 2.5 \times 10^{-19} M_\odot$



[credits: PBHbounds, https://zenodo.org/records/3538999, D. Baumann]

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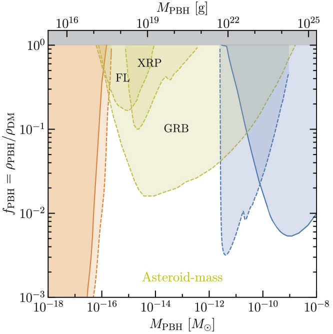


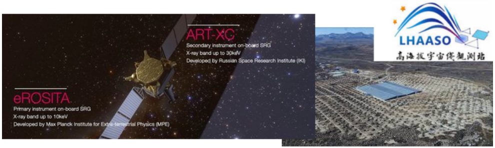
[credits: PBHbounds, https://zenodo.org/records/3538999]

- Limits depend on mass function, usually assumed monochromatic
- Future MeV gamma-ray telescopes will tighten evaporation constraints
- New techniques required to probe asteroid mass window, see e.g. microlensing with gamma-ray bursts or X-ray pulsars

[Reviews: 2007.10722, 2403.03839]

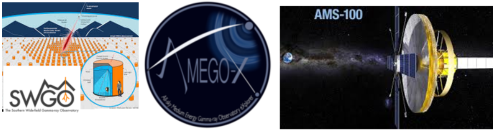
Outlook: high energy observations

Current: SRG/eRosita (x-ray), LHAASO (TeV)



Forthcoming: Athena (x-ray), COSI (MeV), CTA (TeV), GAPS (antimatter)

Dream: SWGO (TeV), Amego-X (MeV), AMS-100/Aladino (antimatter)



Conclusions

Some theory challenges:

- *Particle acceleration & propagation, non thermal emissions*: refine current, phenomenological models to reduce background uncertanties
- *Overwhelming uncertainties*: when astro/theoretical uncertainties cannot be improved, consistently include them in the inference
- *Keep exploring*: new signatures might be accessible using universe's labs

Indirect searches with high energy observations will continue to corner main dark matter candidates offering unique sensitivity and complementarity

Near-future:

- *Thermal relics*: up to TeV masses, explore antimatter clean(er) targets
- *Axion-like particles*: test relevant parameter space for dark matter
- *Primordial black holes*: MeV + theory/searches refinements crucial

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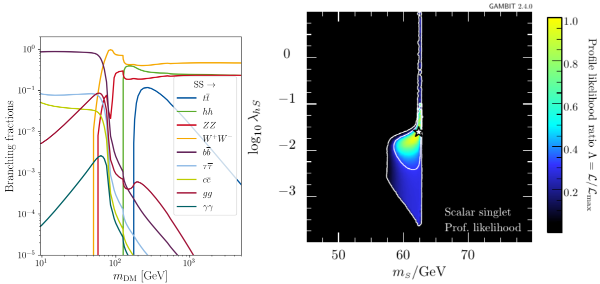
I acknowledge the European Union's Horizon Europe research and innovation programme for support under the Marie Skłodowska-Curie Action PF2021, grant agreement No.10106280, project VerSi.

Cornering Singlet Scalar dark matter

Minimal new degrees of freedom: SM + gauge-singlet real scalar boson S stable $\mathbb{Z}_2$ global symmetry [McDonald,PRD'94,Burgess+NPB'01,Cline+PRD'13]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_{S,0}^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS}\, S^2 H^\dagger H$$

$m_{\rm DM} = m_S = \left[m_{S,0}^2 + \lambda_{hS}\, v^2/2\right]^{1/2}$; λ_{HS}: coupling with Higgs



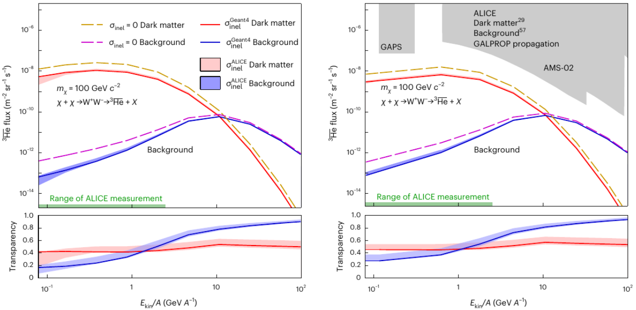
[left: branching fractions; right: constraints from Kahlhoefer,SM+JCAP'21, Balan,SM+JCAP'23 2107.12395, 2303.07362, see also 2305.11937]

State-of-the-art constraints (direct, indirect, LHC searches as in Gambit coll, EJPC'17 + new CMS,ATLAS Higgs invisible width + LZ + PandaX-4T) leave resonance region ($m_s \sim m_h/2$), to be further tested with direct and indirect searches

Antihelium

Similar background-free signature at low energy

AMS-02: *unconfirmed events* (reported at conferences, e.g. Cospar22) from 0 to 10 GeV with charge Z = -2 and rigidity R < 50 GV, with masses in the 3He/4He

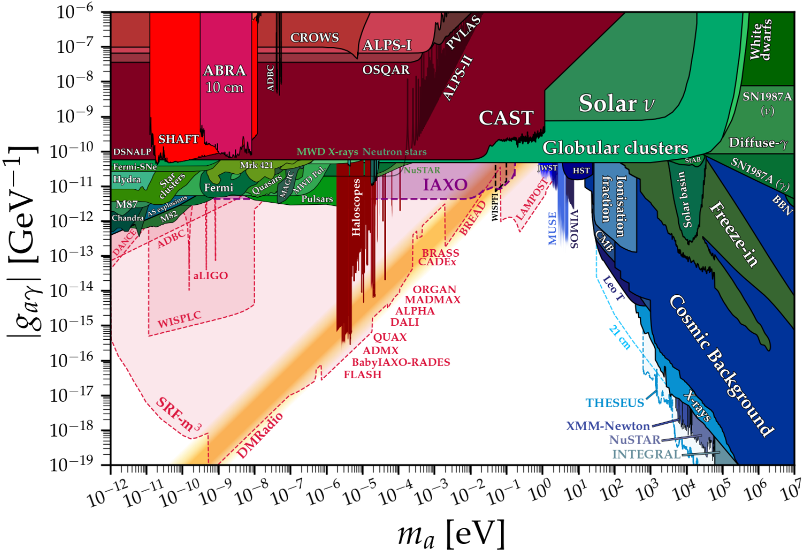


Alice coll,Nat.Ph.'22

Secondary and dark matter 3He is expected to be well below AMS-02 sensitivity

Room for speculation: Antistars? [Poulin+PRD'18]

Enhanced dark matter signal through $\bar{\Lambda}_b$ decays [Winkler+PRL'21,Kachelriess+21] recently excluded by LHCb [LHCb-CONF-2024-005]



[https://cajohare.github.io/AxionLimits]