Dark matter: prospects

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Dark Tools

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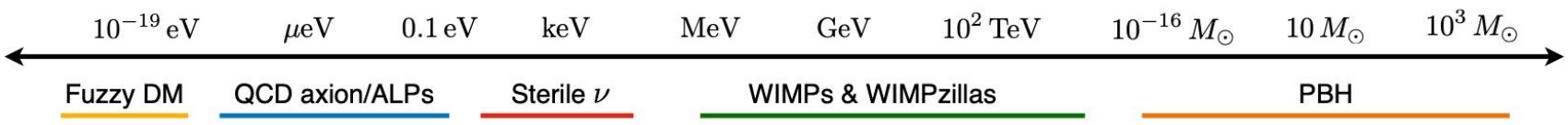
Fundamental Facts and Questions

- Overwhelming evidence that majority of pressurless matter in the Universe is non-baryonic
- Gravitational inference clear, fundamental nature still a mistery
- What is Dark Matter?
  - A particle or a manifestation that we do not understand gravity?
  - If a particle, what are key parameters: mass, spin, interaction types and strengths

What is (sort of) known

- Cosmic density about ¼ of the Universe total budget
  - CMB anisotropies, LSS
- Local density: 0.3-0.4 GeV cm^{-3} = 10^5 average density
  - Local stellar motions
- Local velocity dispersion: (200-300) km s^{-1}
  - Local stellar motions
- No preferred length scale
  - Galaxy clustering and evolution
- Behaves as non-relativistic and pressurless (cold or cold-enough)
  - Structure formation
  - Excludes lightest neutrinos, implication for light scalars
- Early appearance: gravitational influence way before CMB release
  - Galaxy clustering
  - For light bosons, this sets the latest epoch of particle creation
- No significant interaction with ordinary matter or self-interaction
  - Darkness, Bullet cluster

What is unknown



Bosonic
Fluid
"Quantum"

Bosonic
(Thermal)
Non-thermal
Cold DM

Non-thermal
Warm-ish DM

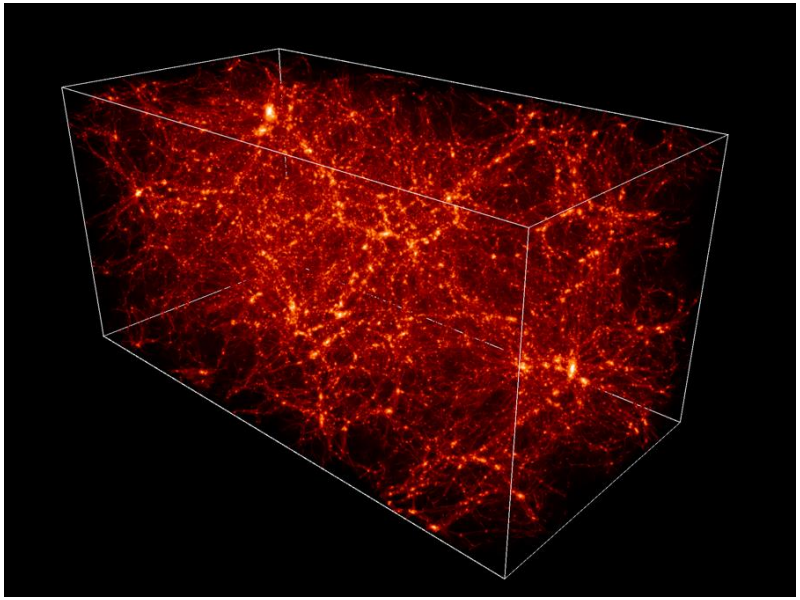
Thermal
Non-thermal
Cold DM

Primordial

Interactions strength

Single vs multi component

Tools at hand



Cosmic surveys

- CMB probes
- Galaxy surveys
- Galaxy clusters surveys
- Filaments?
- Voids surveys
- Weak lensing surveys
- Ly-alpha
- Neutral Hydrogen intensity mapping surveys

- Allow to test DM on different scales and at different times
- Probe coldness, collisionless and pressurless hypotheses, interactions with visible sector, possibly single vs multi-component
- Probe DM clustering (non-linear scales) and growth of structures
- Probe of early DM injected energy: CMB distortion, ionization

Tools at hand

Cosmic laboratories

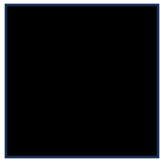
- Sun, other stars
  - Can capture WIMPy DM and produce neutrino fluxes
  - DM can alter their inner structure and energy transport (both for WIMP and axions), thus affecting stellar properties and evolution
  - DM rich environment can affect stellar formation rates and stellar evolution

- Supernovae
  - MeV DM production can affect cooling

- Neutron stars
  - WIMPy DM capture can modify NS temperature (kinetic heating)
  - DM accreted around NS or inside the NS core can affect BH inspirals
  - ALP conversion in magnetosphere

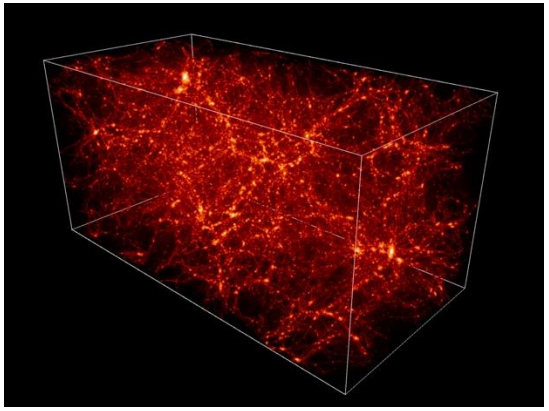
- Black Holes
  - DM accreted around BH can affect BH physics
    - Formation of DM mini-spikes
    - Superradiance for light bosonic DM (ALPs) [effective also for NS]
    - Local DM environment affecting the inspiral signal of compact objects (backreaction on the metric, dynamical friction): extreme mass-ratio inspirals more affected
  - Gravitational waves from PBH merging

- Stocastic GW backgrounds
  - PBH formed from collapse of large fluctuations
  - Non-perturbative production of DM



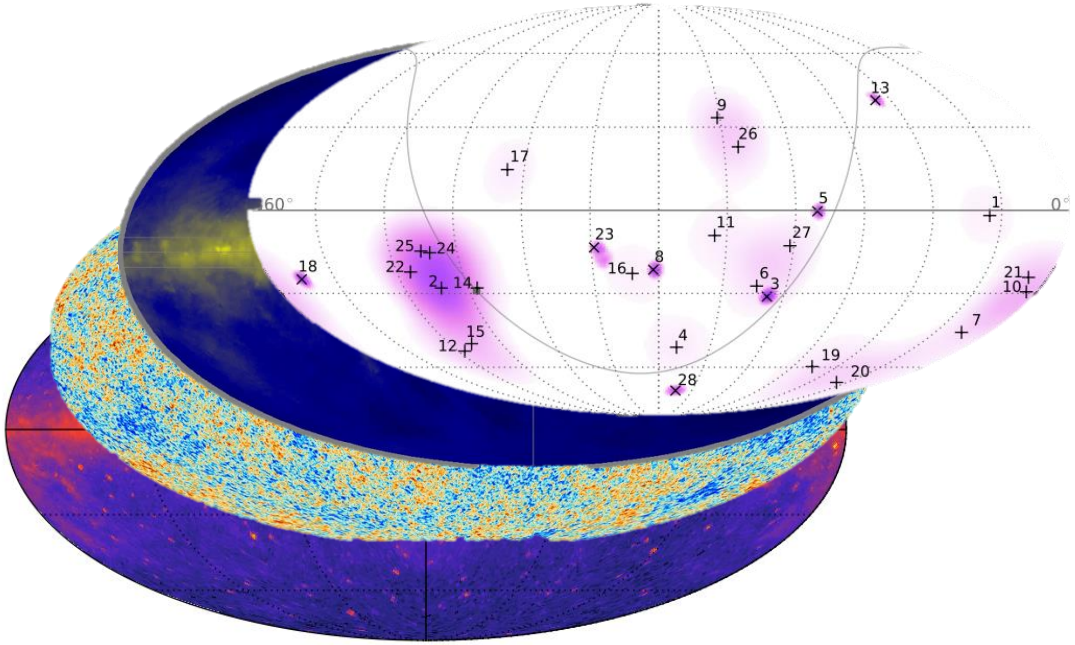
- DM compact objects ?

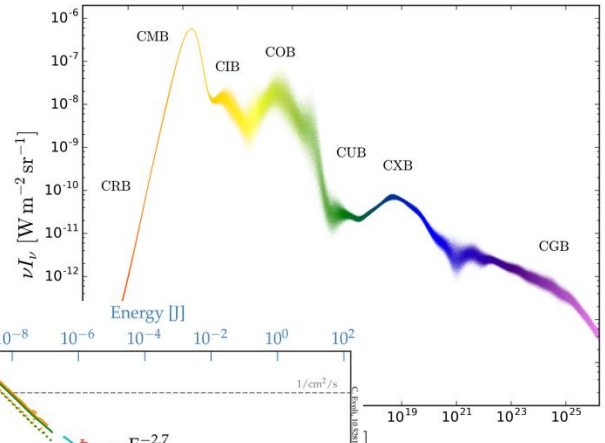
Tools at hand

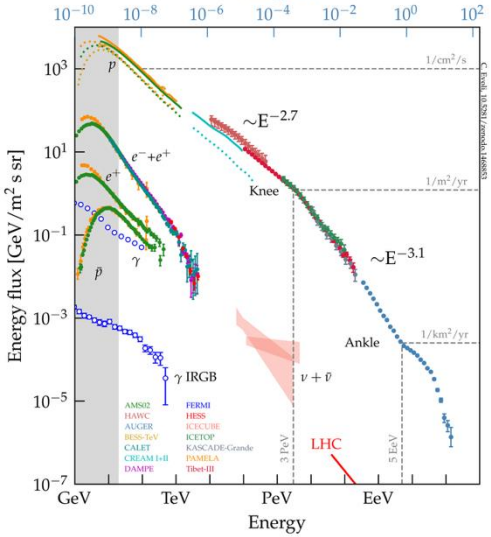


Cosmic messengers

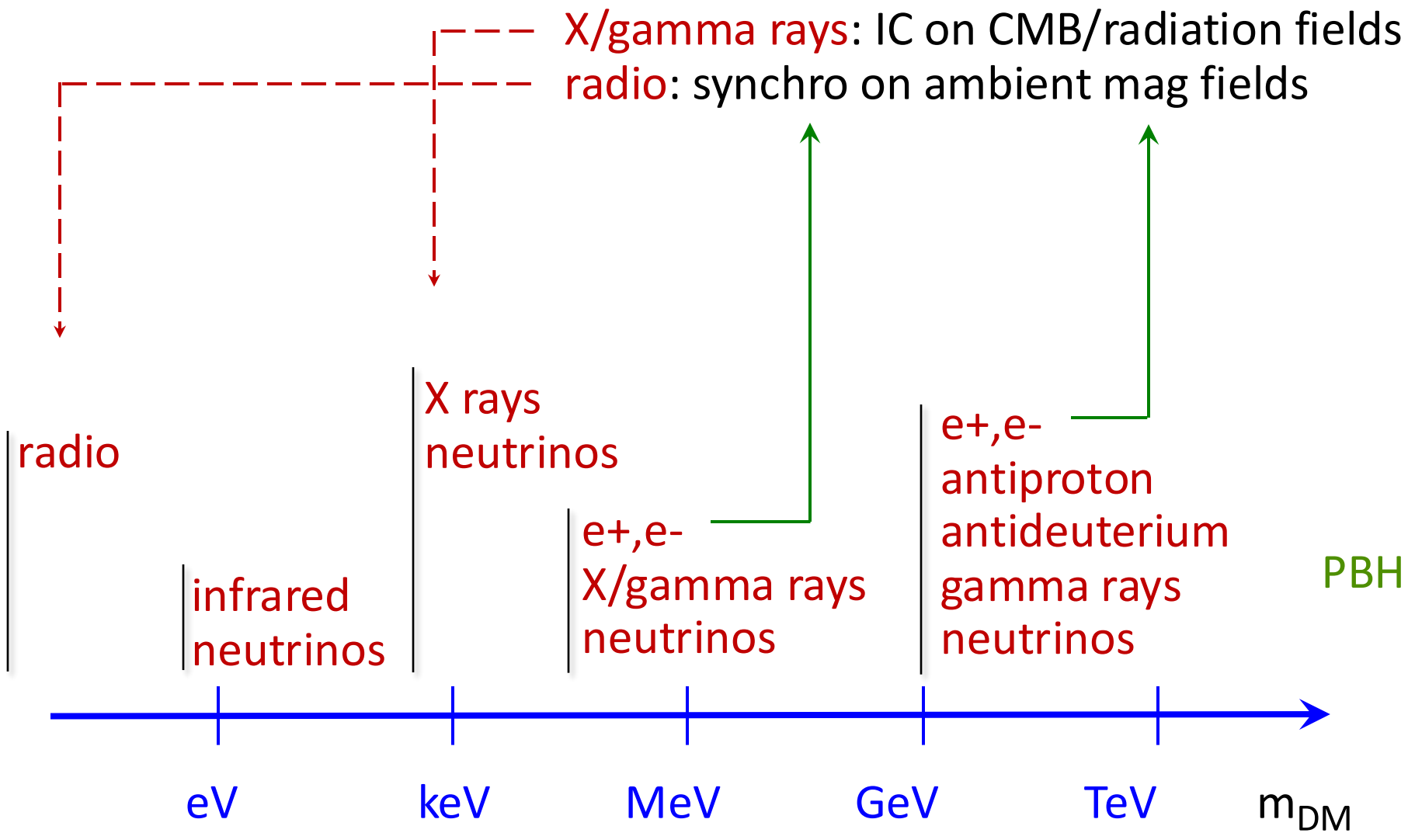
- DM can inject high/low-energy particles (messengers) into cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids):
  - Decay | annihilation | conversion if a particle
  - Evaporation or accretion if a PBH







The Multimessenger Landscape



Tools at hand

Cosmic messengers

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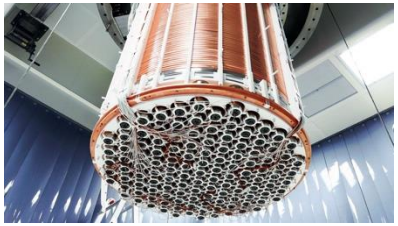
- Messengers might be reprocessed during their travel to us
- Dark matter itself can be the origin of “cosmic messengers reprocessing” (e.g.: ALP birefringence, gamma-ray hardening through ALPs)
- Complex system of signals
- Typically dominant astrophysical backgrounds
- Probe DM interactions with itself and visible sector
- Multi-messenger and –wavelength correlations
- Correlations with cosmological surveys

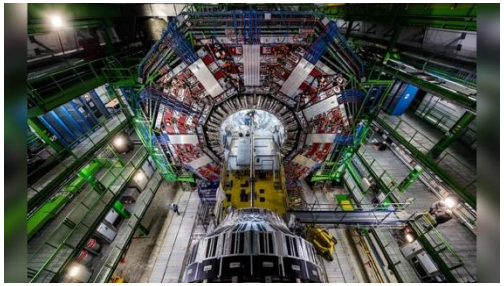
Tools at hand

Experiments in the Lab

- Passive but directly probe DM: direct detection, haloscopes, helioscopes



- Active but indirect: production at high energy accelerators | high intensity beams | axion lab experiments



Connection to particle physics models

- Axion-like, wave (scalar, pseudo-scalar)
  - String theory?
  - Inflationary models?
  - Ad hoc?
- QCD axion (pseudo-scalar)
  - Strong CP-problem
- Sterile neutrinos
  - Very light, KeV, Heavy
  - Neutrino mass models, leptogenesys models
- Dark photons
  - Gauge group extensions: U(1)', SU(2)'
- Heavy (pseudo) scalars
  - Scalar sector extensions: singlets, 2HDM, triplets
- WIMPs
  - Supersymmetry
  - Extra dimensions
  - Minimal DM models
  - Leptogenesys models
- Very heavy particles
  - GUT
  - Leptogenesys

All of them require that DM "cosmological stability" is ensured (accidentally, through a symmetry)

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String theory models often have many scalar field, which could either induce inflation or give a motivation for ALPs

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In principle, well motivated

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Well motivated extension (neutrinos need a mass) although different realizations possible and link to DM might or might not be present (would be a great economical option, especially if leptogenesys is part of the solution)

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Might be the DM or be part of a hidden sector which contains a DM particle (in which case work as new force mediators and might be mixed with ordinary photons)

Introduce long-range forces if very light

Not too different from WIMPs if heavier

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Scalar field sector of the SM might be larger
Many NP extensions require/predict more scalars

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Very strong and predictive symmetry, but needs to be broken

SUSY breaking not understood: induces many frameworks, very large # of free parameters, loosing predictability

Accelerator bounds progressively increase, pushing SUSY scale at higher energies: naturalness in jeopardy, but technically not a short-stopper (SUSY is needed e.g. for string theory or preferred for gauge-coupling unification)

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Contrary to SUSY, it's possible to contain the # of free parameters (e.g. the compactification scale)

Accelerator bounds progressively increase the scale at higher energies

Extra-dim are needed for string theory, but the scale can be close to Planck scale (no need to be accelerator reachable, in principle)

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Ad hoc, but very predictive: e.g. MDM has just one free parameter (DM mass) and SM gauge couplings, successful MDM requires M_{DM} = several TeV, predicts a bunch of associated (almost degenerate in mass with DM) charged fermions

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In principle, well motivated since matter/antimatter asymmetry has to be generated

Often, this is achieved by providing also mass to neutrinos

It would be an excellent solution: hit 3 birds with a stone (disclaimer: no bird has been harmed in building these models)

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Compelling or not? Theoretically intriguing, although protons are so stubborn not to have shown to decay (yet)

Assessing the nature of DM?

- Unfortunately, there is no compelling theoretical direction to follow (although there are some guiding principles)
- "Aestetic" motivations like naturalness for supersymmetry are declining (susy scale progressively pushed up by accelerators searches)
- Even if a new particle is found in a lab experiment, a key challenge will be to confirm that it is the DM particle (caveat: DM might not be a particle, see PBH or wavy DM – or even modified gravity)
- A single technique is currently insufficient to probe the vast landscape of viable DM candidates, and this will not change anytime soon
- Instead of concentrating on specific new physics realizations, I would rather go for classes of signals, looking for general features and avoiding duplications: once something is found, model specifications will follow
- Many (although not all) DM scenarios have many complementary signals available: this should be exploited

A few questions naturally arise

- Do we have compelling candidates | particle physics models? How relevant is to have compelling models to progress in the study of DM?

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  - Direct detections: annual/diurnal modulation | directionality
  - Indirect searches:
    Photon lines (axion, WIMPs) in all bands (radio, IR, UV, X, gamma)
    Low-energy AntiD, antiHe
    Other?

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- Spectral | morphological distortions | excesses are enough?
    Antiproton few GeV excess (spectral)
    Gamma-ray galactic center excess (morphological)
    ARCADE radio excess (size)
    Positron “excess” (spectral – likely pulsars)
    CMB, Ly-alpha, ionization history

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- The question of all questions in 2025: Machine learning can really help?