Charting the Dark Sector
Theoretical Perspectives on Dark Matter

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Fundamental Facts and Questions

- Overwhelming evidence that majority of pressurless, clustered matter in the Universe is non-baryonic
- Gravitational inference clear, fundamental nature still a mistery

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- Overwhelming evidence that majority of pressurless, clustered 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
  - If not a particle, what modification of gravity or spacetime dynamics could reproduce what we call DM across all scales (galaxies, clusters, gravitational lensing, cosmology) ?

What is known

Relevant for the particle cosmological behaviour, production mechanism, mass and interactions

- Cosmic density about 25% of the Universe total budget

    CMB anisotropies, LSS

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- Local density: 0.3-0.4 GeV cm^{-3} = 10^5 average density

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  Local stellar motions

Relevant for direct detection,
Earth/Sun nenutrino flux

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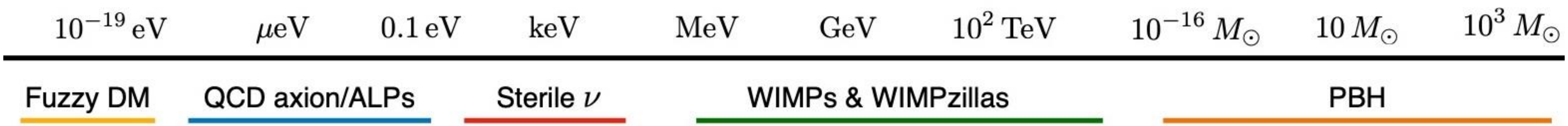
- Local density: 0.3-0.4 GeV cm^{-3} = 10^5 average density
  Local stellar motions
- Local velocity dispersion: (200-300) km s^{-1}
  Local stellar motions
- No preferred length scale
  Galaxy clustering and evolution
- Behaves as non-relativistic and pressurless (cold or cold-enough)
  Structure formation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

Relevant for the particle cosmological behaviour, production mechanism, mass, interactions, direct and indirect detection

Charting the unknown– Mass scale



Fuzzy DM	QCD axion/ALPs	Sterile ν	WIMPs & WIMPzillas	PBH
Bosonic	Boson	Boson Fermion	Boson Fermion	Non particle
Quantum fluid	Thermal Non-thermal	Non-thermal	Thermal Non-thermal	Primordial
Cold	Cold	Warm-ish	Cold	Cold

Charting the unknown – Interaction

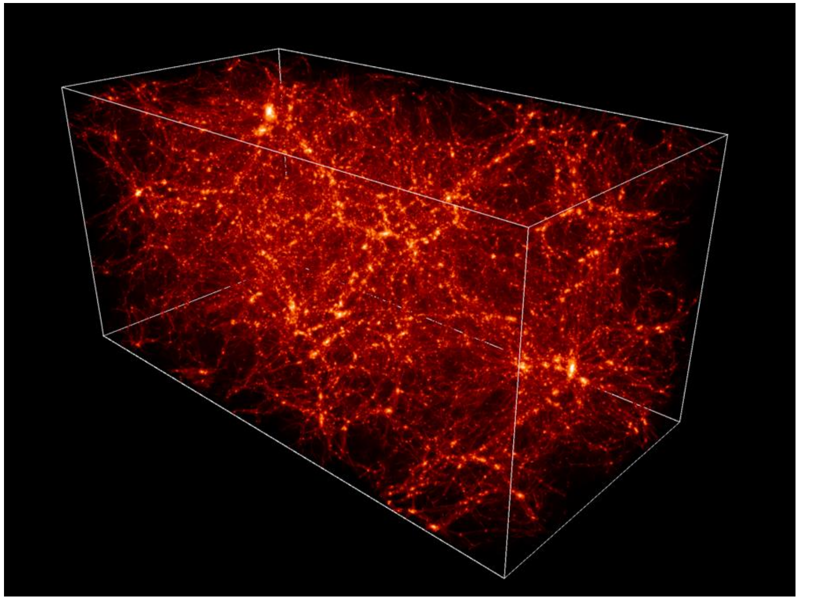
Gravitational only	No detectable non-gravitational coupling	Primordial black holes, compact dark objects
Feeble SM coupling	Never thermalizes with SM; tiny portal couplings	FIMPs / freeze-in DM, sterile-neutrino DM, very weak hidden sectors
Axion-like / Anomaly couplings	Very light bosons with suppressed couplings to photons, gluons, fermions	QCD axion, ALPs, wave-like DM
Portal-mediated hidden sector	DM couples to SM through a mediator	Dark photon / vector portal, Higgs portal, neutrino portal, scalar portal, pseudoscalar portal
Weak-scale interactions	Relic abundance may arise from freeze-out; sizeable annihilation/scattering	WIMPs, SUSY neutralino-like DM, electroweak multiplets, some Higgs-portal or Z′ models
Self-interacting dark sector	DM-DM scattering is important, SM coupling may be tiny	SIDM, light dark mediators, atomic DM, mirror/dark plasma models
Strong/composite dark sector	Confined or composite dark states	Dark baryons, dark mesons, SIMP-like models, asymmetric composite DM

Charting the unknown – Production

Thermal freeze-out	DM was initially in thermal equilibrium and later decoupled when annihilations became inefficient	WIMPs, secluded WIMPs, some SIMPs
Freeze-in	DM was never in equilibrium; produced gradually from rare interactions	FIMPs, sterile neutrinos, some axions
Misalignment mechanism	A classical field stores energy in the early Universe and later oscillates as cold DM	QCD axions, axion-like particles, ultralight scalars
Gravitational production	Produced purely by the expansion of spacetime or inflationary dynamics	Superheavy DM, some primordial relics
Asymmetric production	DM abundance generated by a particle–antiparticle asymmetry analogous to baryogenesis	Asymmetric DM
Dark-sector freeze-out	Freeze-out occurs within a hidden sector, not directly with the Standard Model	Secluded DM, dark photons, hidden-sector DM
'Cannibalization' / SIMP mechanisms	Number-changing self-interactions determine abundance	SIMPs, ELDERs
Non-thermal decay production	Produced from decays of heavier particles after decoupling	Moduli decay, inflaton decay, gravitino decay
Primordial relics	Produced through gravitational collapse or phase transitions	Primordial black holes

Tools at hand

Cosmic surveys

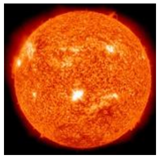


- CMB probes
- Galaxy surveys
- Galaxy clusters surveys
- Weak lensing surveys
- Ly-alpha
- Neutral Hydrogen intensity mapping surveys
- Voids surveys
- Filaments

- 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

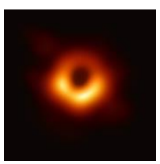
Cosmic laboratories



- 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

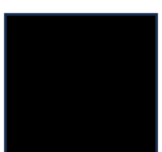
- Supernovae
  - MeV DM production can affect cooling

- Neutron stars
  - WIMPy DM capture can modify NS temperature (kinetic heating) – very effective for sub-sub-GeV DM
  - 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

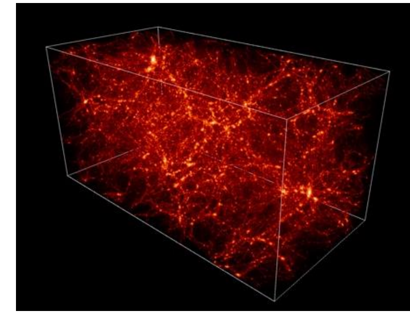
- Stocastic GW backgrounds
  - PBH formed from collapse of large fluctuations
  - Non-perturbative production of DM



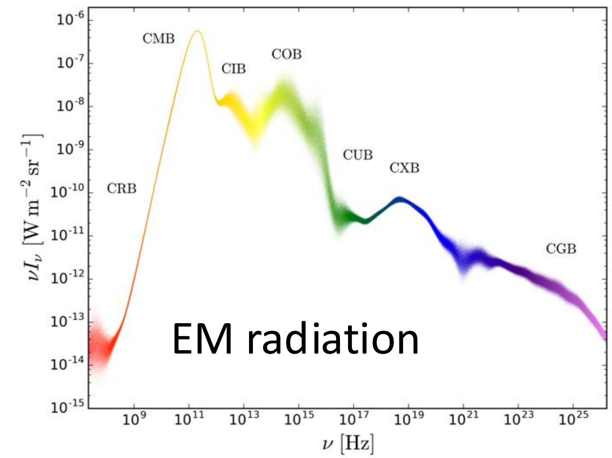
- DM compact objects

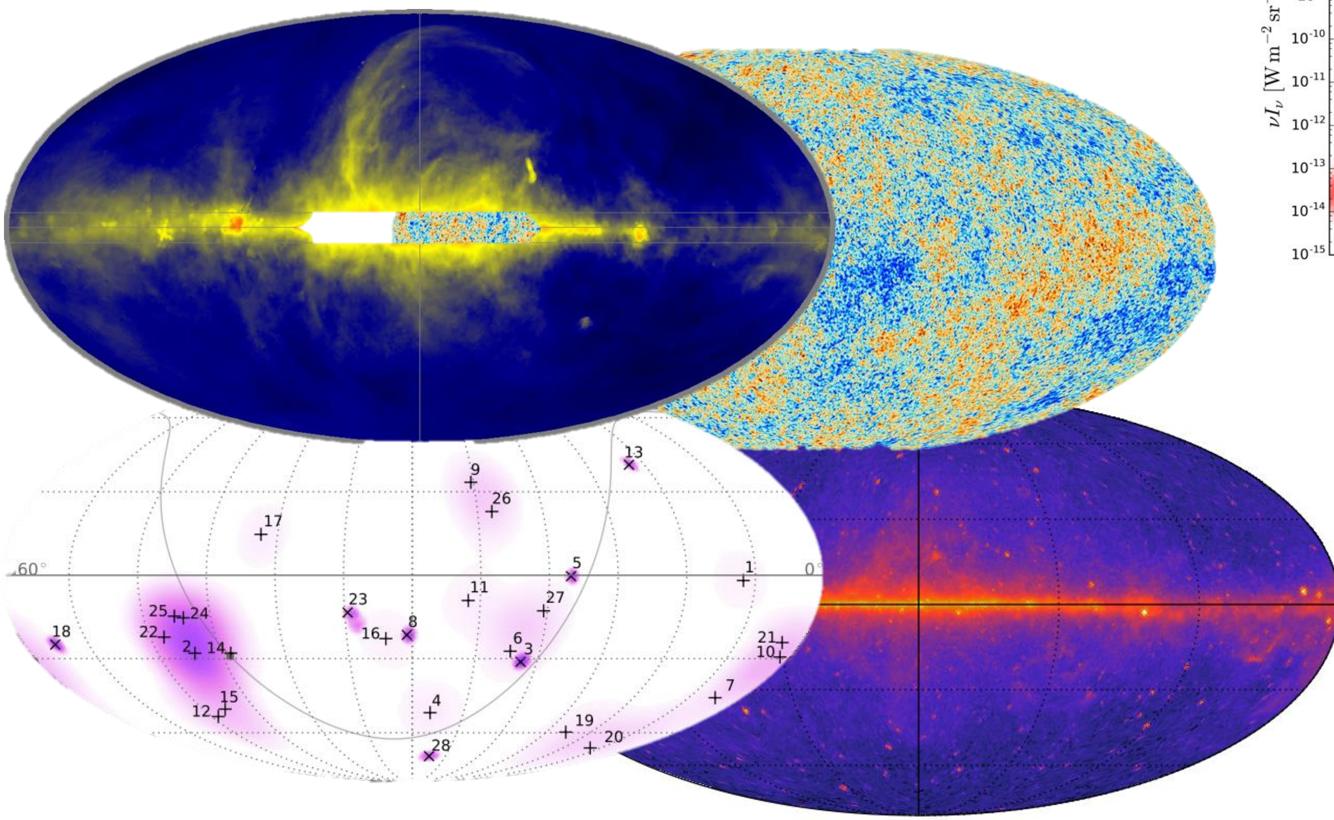
Tools at hand

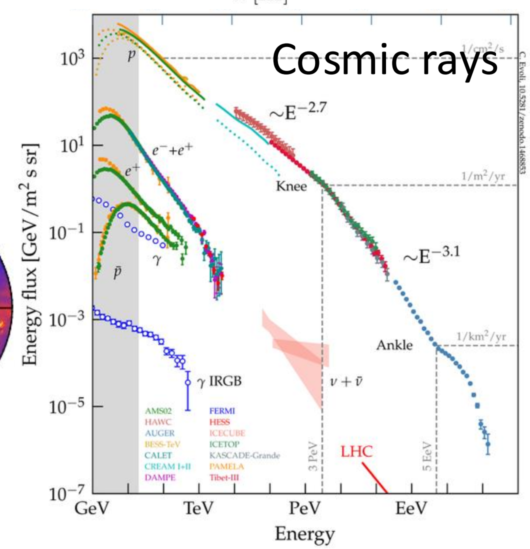
Cosmic messengers



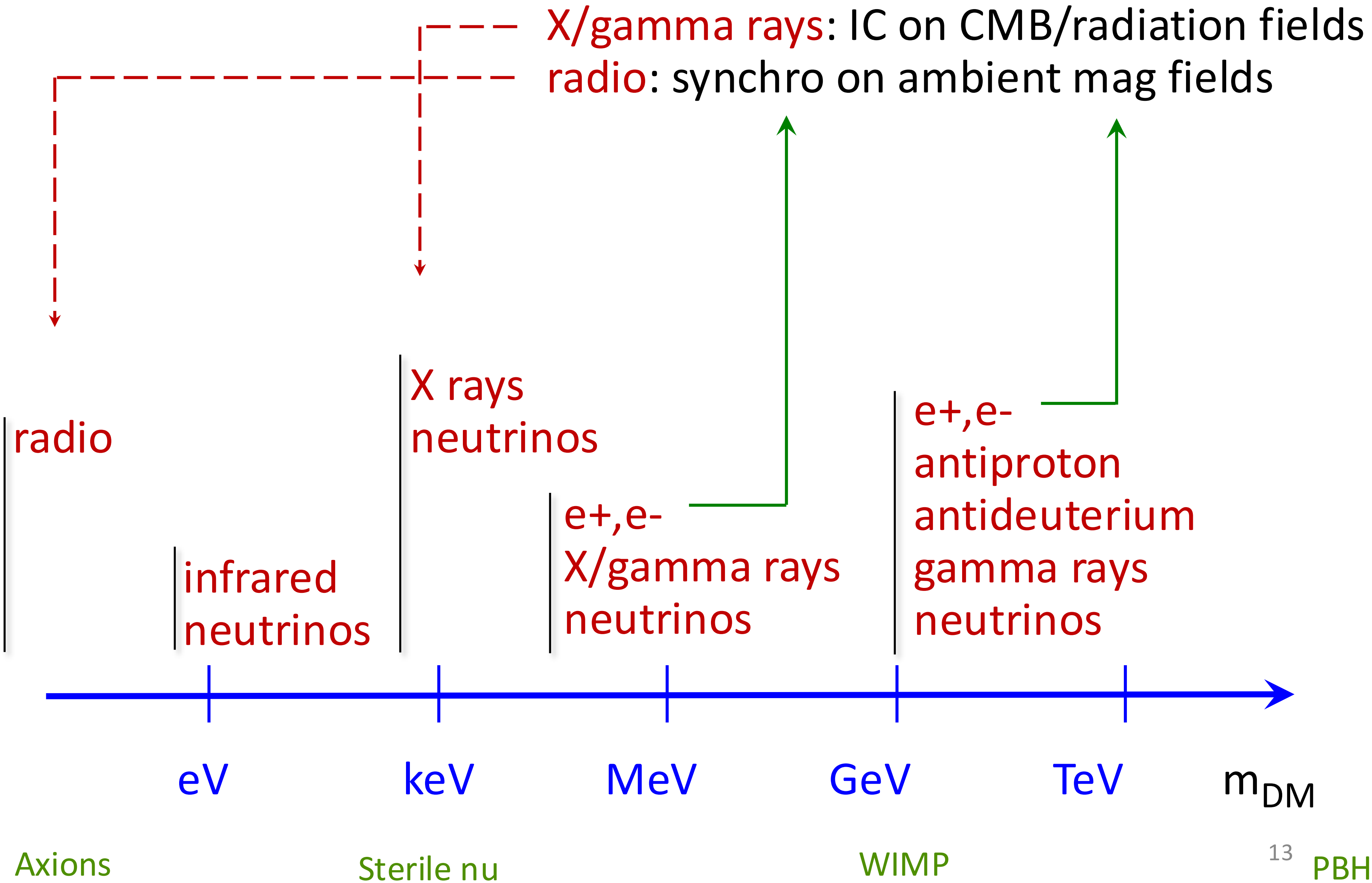
- DM can inject high/low-energy particles (messengers) into cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids):
  - Decay | annihilation | conversion if a particle
  - Evaporation or accretion if a PBH



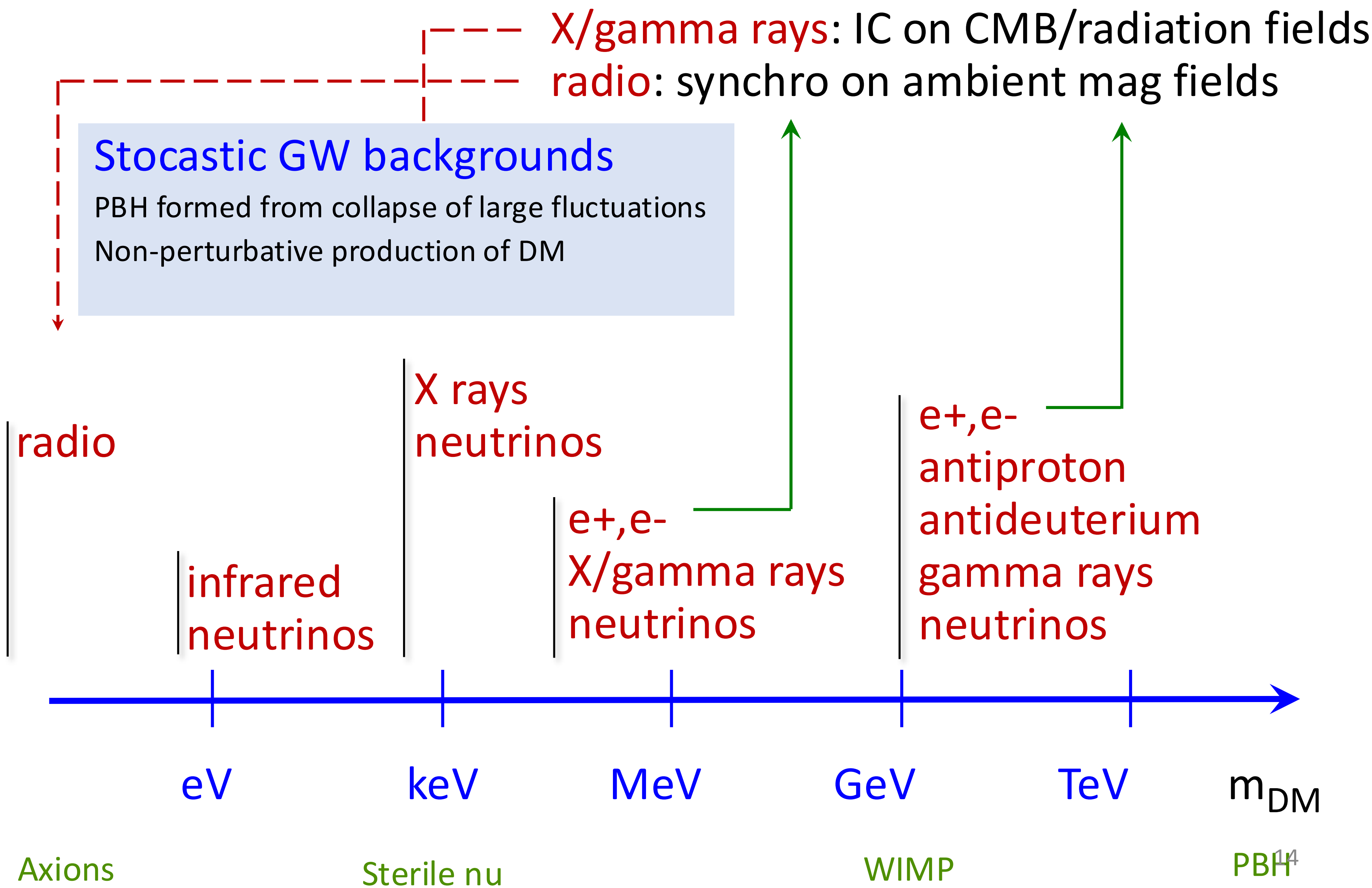




The Multimessenger Landscape



The Complete Multimessenger Landscape



Tools at hand

Cosmic messengers

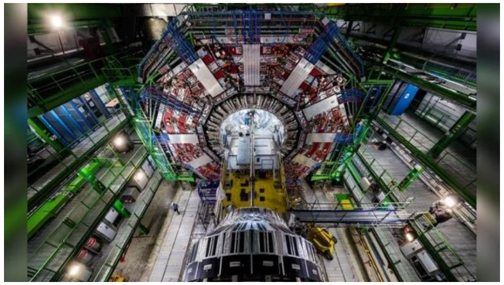
- DM can inject high/low-energy particles (messengers) into cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids):
  - Decay | annihilation | conversion if a particle
  - Evaporation or accretion if a PBH
- Messengers might be reprocessed during their travel to us
- Dark 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 multi–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
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All of them require that DM “cosmological stability” is ensured

(accidentally | through a symmetry | ad hoc | just leave enough)

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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

ALP extension worth to be explored

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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 (but require "millicharge")

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

- WIMPs
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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 somehow predictability (not always)

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 single and clear 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 – maybe it's not even desirable
- Looking for general features of classes of dark sectors (theoretically) and classes of signals (phenomenologically and observationally) migh be particularly effective: once something is found, more specific model specifications will follow
- Many (although not all) DM scenarios have many complementary signals available: this is very captivating and need to be exploited

Opportunities

- Do we have clear signatures for astrophysical | lab signals? How clear are them?
  - 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 with spectral info)
  ARCADE radio excess (size)
  Positron "excess" (spectral – likely pulsars)
  CMB, ionization history

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- How to better control astrophysical backgrounds | foregrounds?

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- Are there windows that are still not properly exploited (e.g. MeV gap)? Gravitational waves are a new window of opportunity for DM?
- How relevant is to exploit statistical correlations among signals? Not just redundance, explicit correlations (radiation fields) x (gravitational probes)

(full multi-wavelength/messenger) x (LSS, voids, lensing)

Inconclusive conclusions

The astroparticle physics community has come a long way since the first IDM Conference 30 years ago

We have made tremendous progress in deepening our understanding of dark matter, extending ideas in many, sometimes unexpected, directions and more are steadily coming

Although a solution to the dark matter problem has not yet been found, we have an ambitious and exciting program ahead for the next 30 years!