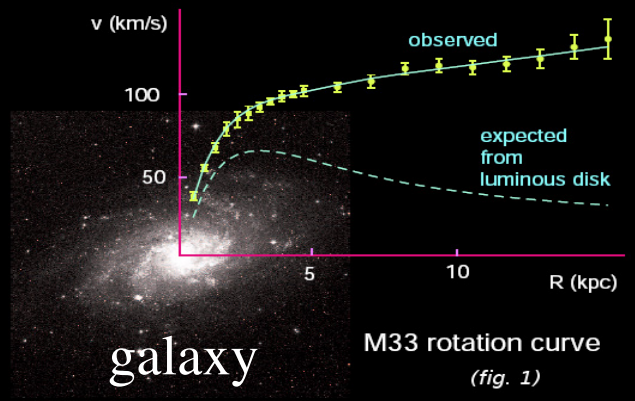
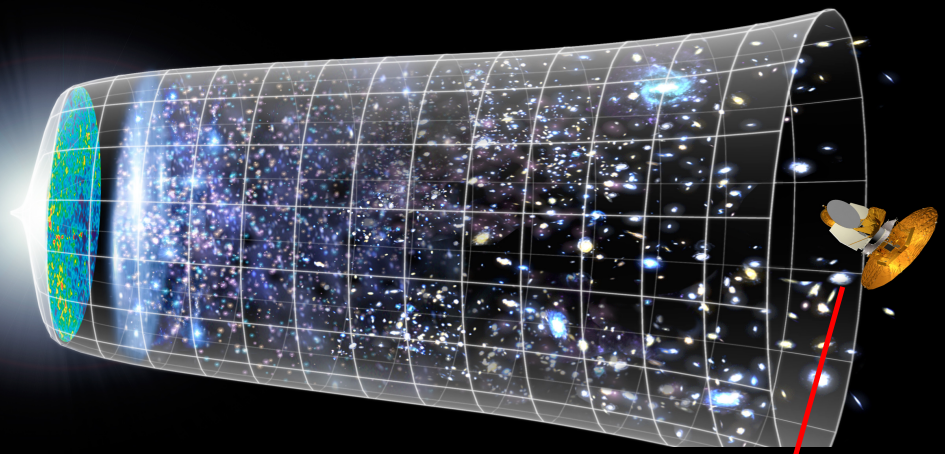
Dark Matter Theory

Laura Lopez Honorez

EPS-HEP, Marseille, 7-11/07/2025



The Quest to determine the Composition of our Universe



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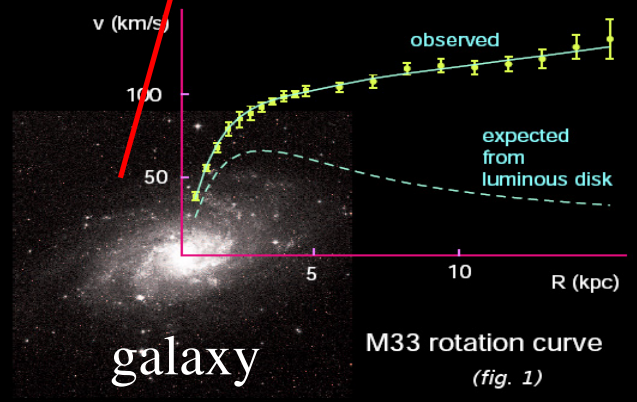

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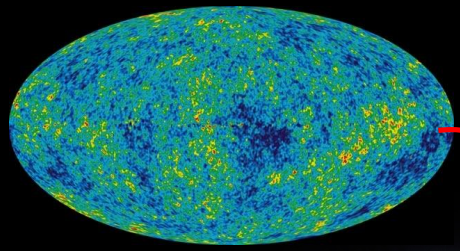
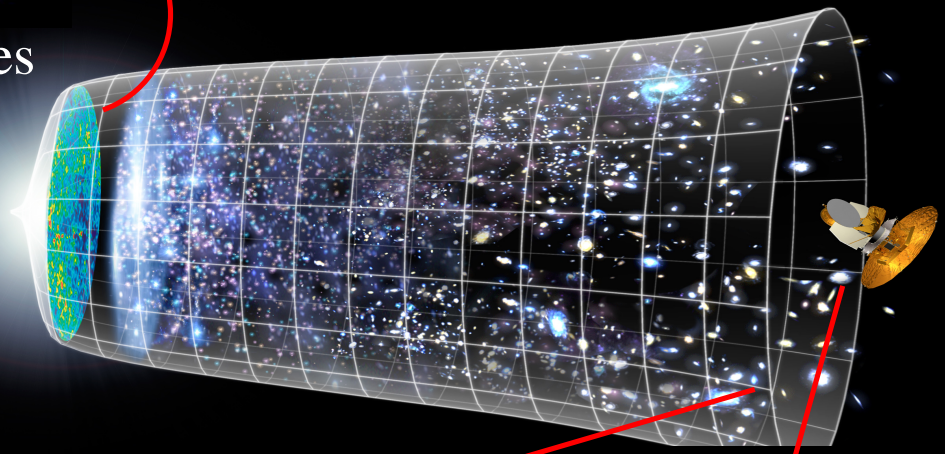


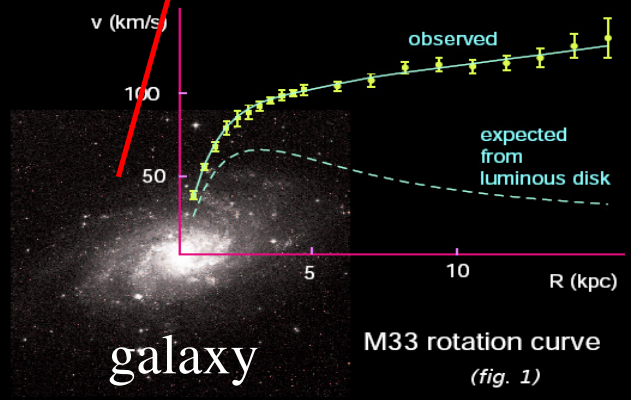
CMB anisotropies



Large Scale Structures (LSS)

SDSS galaxy map

Dark matter



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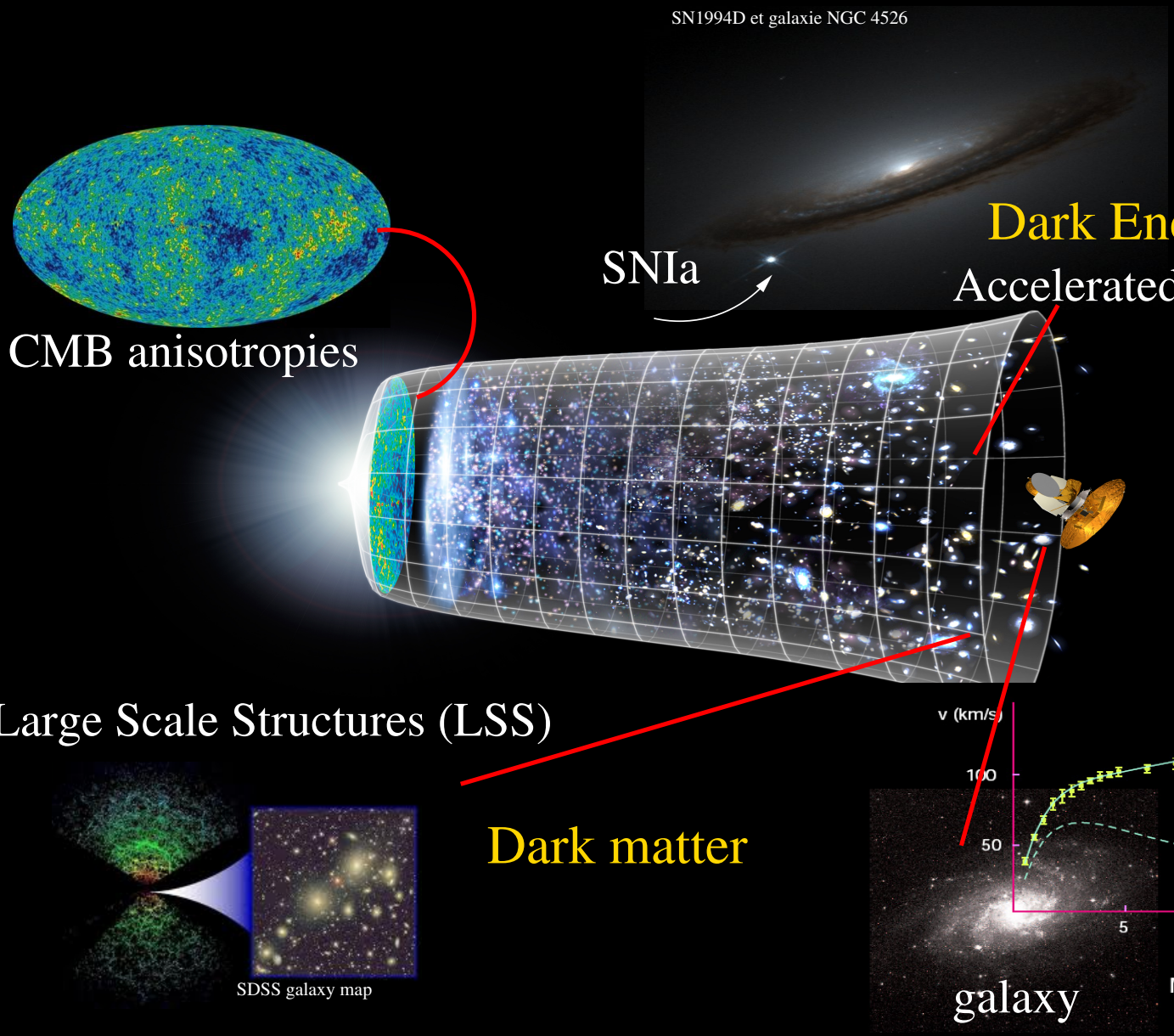

The Quest to determine the Composition of our Universe

84% of the matter content is made of Dark Matter

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- Dark matter interacts gravitationally -has a mass.
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  [see also talks of Juan Salvador Tafoya Vargas: MiliQan, FORMOSALHC for millicharged DM]
- Cold dark matter seeds structure formation:
  DM could still behave as non Cold or self-interacting

  [see e.g. non standard features in talks of Raquel Galazo (ULDM self-interacting), Cristina Benso (keV neutrino)]

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  Connection to other BSM/Cosmo puzzels?
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  Not a comprehensive overview!
- Can we detect observable signatures?
  Make use of cosmology, astrophysics and particle physics complementarity to determine the nature of Dark Matter.

Wide range of mass

Some benchmarks:

- Bosonic DM: $m_{\rm DM} > 10^{-22}$ eV for $\lambda_{\rm DB} <$ kpc

  in addition: $m_{\rm DM} <$few tens of eV wave-like behaviour $\lambda_{\rm DB} > n_{\rm DM}^{-1/3}$

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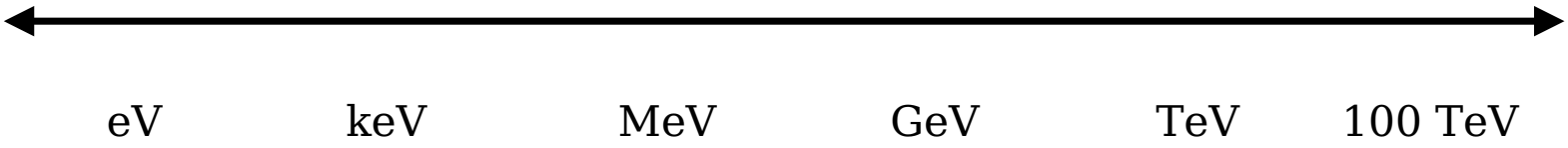
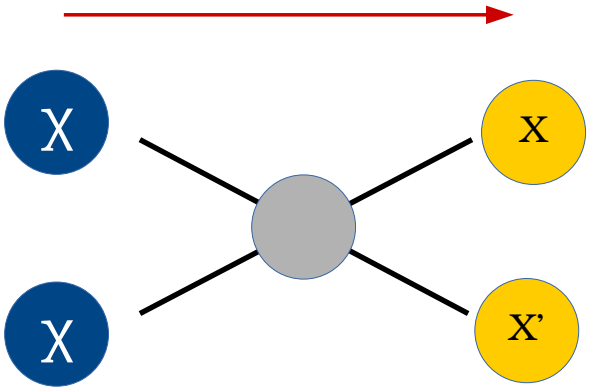
In the talk we focus on *some* particle DM candidates (bosons or fermions)
with masses > few tens of eV from BSM theories
giving rise to distinguishible signatures in (astro-)particle physics probes.

Wide range of mass



Large mass range: WIMP (testable!?) Paradigm

WIMP paradigm
Non-relativistic thermal
DM Freeze-out



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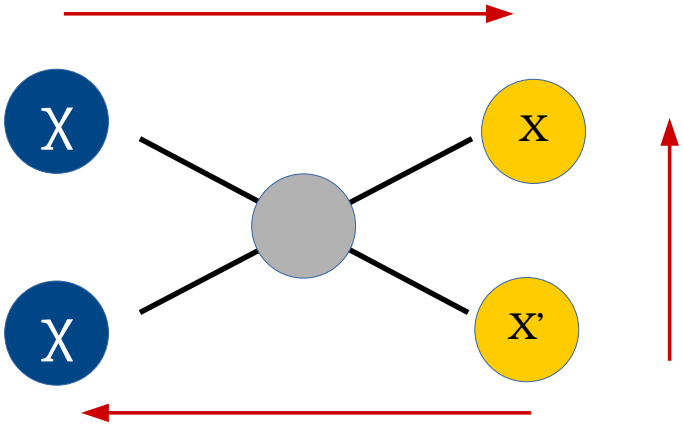


WIMP paradigm
Non-relativistic thermal
DM Freeze-out

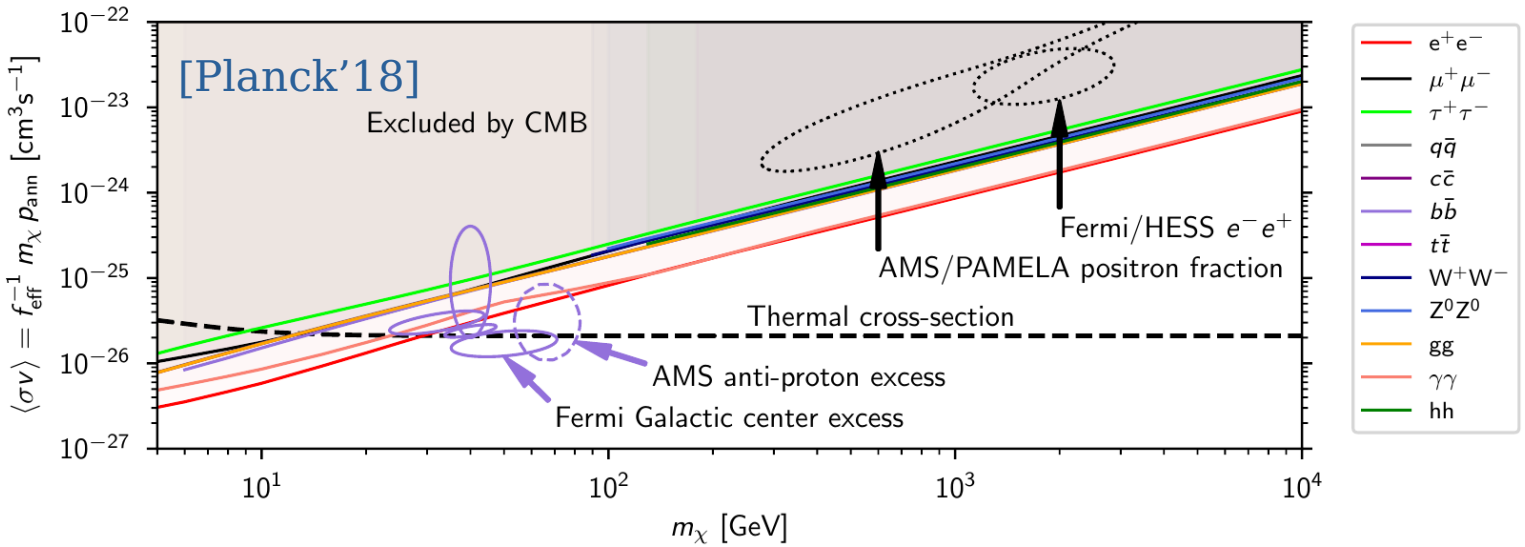
Particle phys DM searches :
Indirect : DM annihilates to SM
Direct : strong threat
Colliders : prompt searches

Cosmology
DM energy injection:
CMB, Ly-alpha, 21cm probes

Large mass range: WIMP (testable!?) Paradigm

eV keV MeV GeV TeV 100 TeV

WIMP window
Non-relativ. thermal



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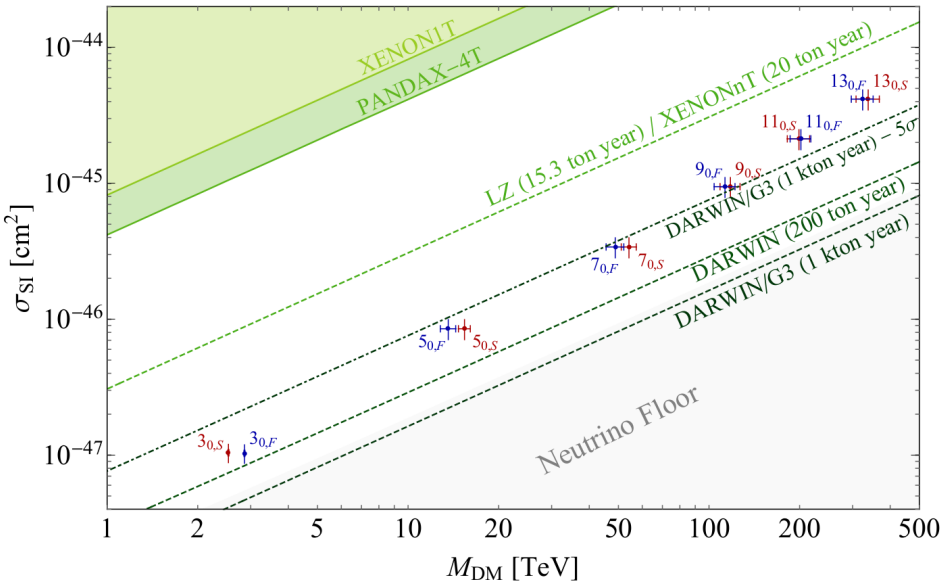
Predictive WIMP benchmark: Minimal DM [Cirelli'05]

DM = EW multiplet $n > 1$, including $\chi_{Q=0}$
& need Z_2 stabilizing symmetry for $n \neq 5$

- Very predictive: $SU(2)_L$ interactions
- Connecting dots? H-portal between n and $n+1$ [Oncala'21,LLH'17]



[Bottaro'22]

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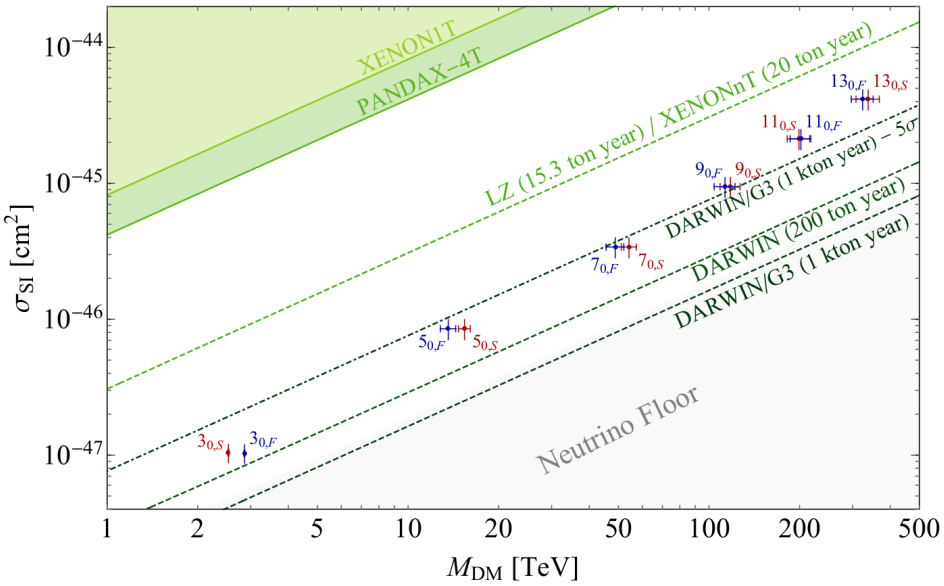
- **Theory Challenge**
  Accurate DM relic and Indirect signatures (γ lines)
  needs Sommerfeld, bound state treatment [Oncala'21,Beacom'19, Mitridate'17]
- **Exp. Challenge**
  Direct Detection (go deeper)
  [see e.g. Zoe Balmforth, Amy Cottle talks]
  Indirect detection (lower ann. cross-section at multi TeV, detect lines, etc)



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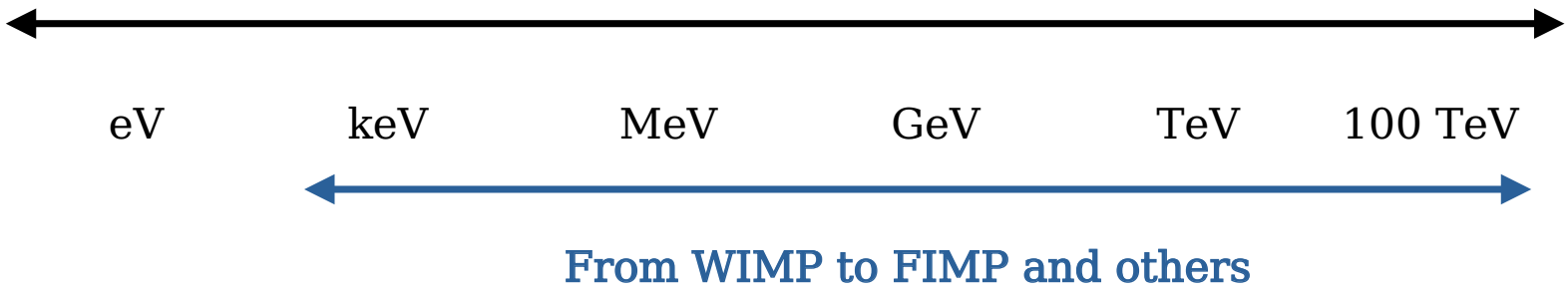
From WIMP to FIMP: thermal and non-thermal candidates



From WIMP to FIMP: thermal and non-thermal candidates

From WIMP to FIMP and others

Thermal to non thermal DM production :
Mediator annihilation/Conversion/Semi-annihilation driven Freeze-out ; Freeze-in – Super-WIMP ; +
+SIMPs ; asymmetric DM ; etc

Particle physics searches :
Direct DM searches: sub-GeV challenge
Colliders : Displaced vertex searches
Beam-dump experiments

Cosmology :
BBN (~MeV), Lyman-alpha (non-cold), ΔNeff, energy injection

From WIMP to FIMP: t-channel as illustrative framework

t-channel models requiere 2 dark sector particles $X =$ DM, $Y =$ mediator

$\mathcal{L} = \lambda\, X\, Y\, SM + h.c.$ & X and Y are Z_2 odd.

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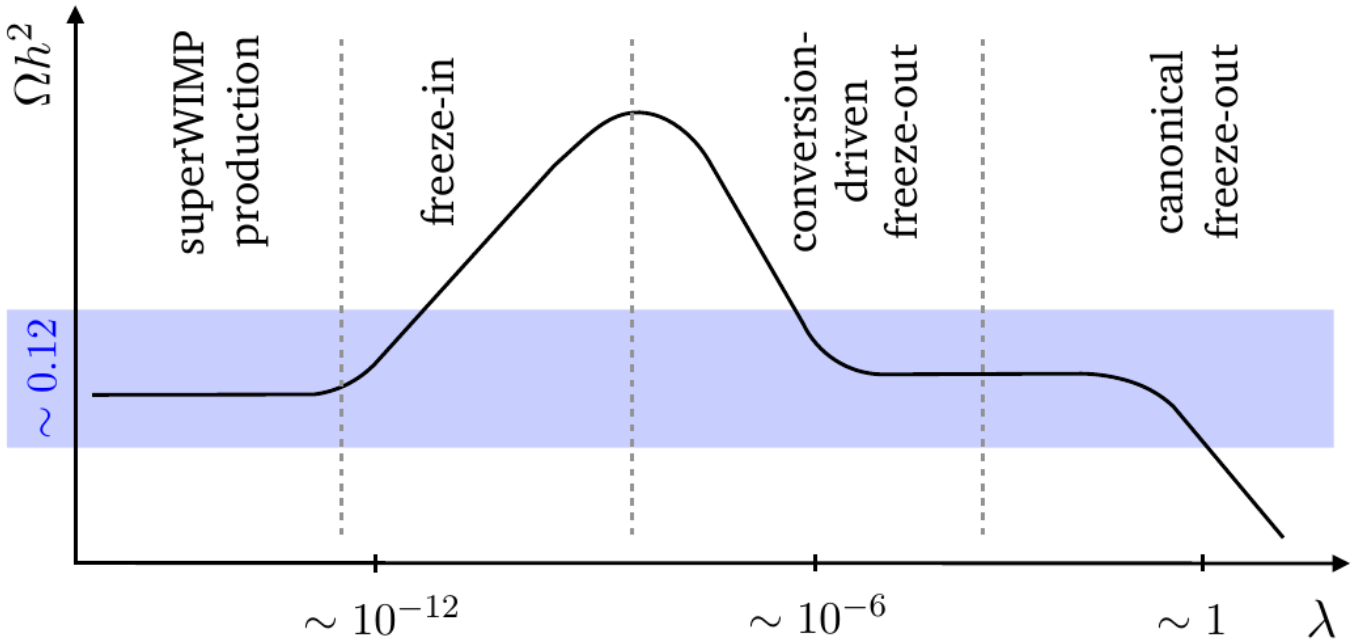
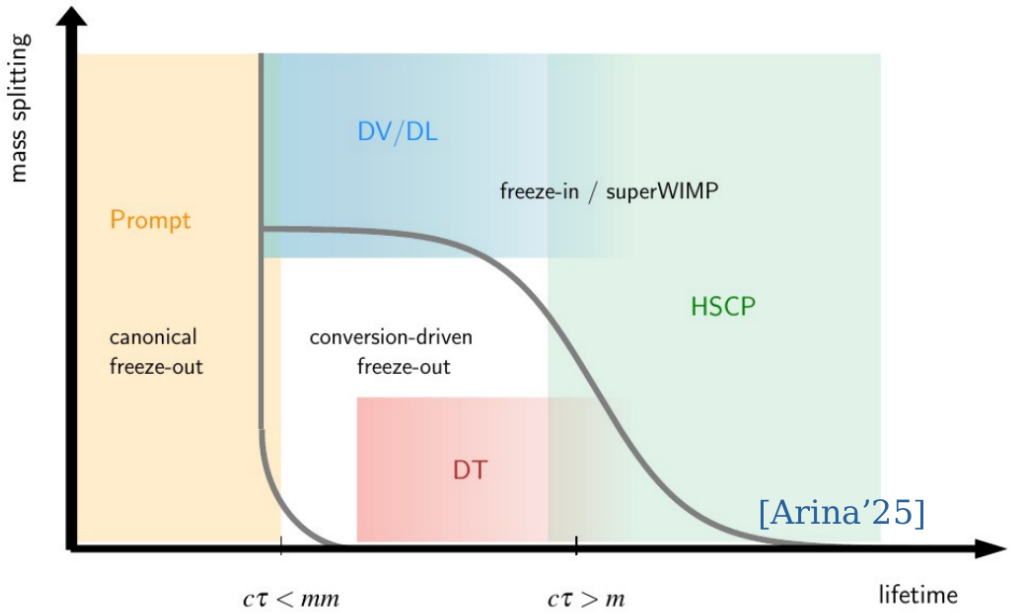


[Arina'25], see [Junius'19] for a concrete example

Can continuously go (for $\Delta m_{XY}/m_Y \ll 1$) from thermal relics,
from DM annihilation freeze-out ($XX \to$ SMSM) & coscaterings ($Y \to X$),
to non-thermal relics from Freeze-in and super-WIMP (set by $Y \to X$)
by decreasing the coupling λ.

From WIMP to FIMP: t-channel as illustrative framework



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Challenge: Large parts of the parameter space are still to be reached

need complementary Astro-Particle-Cosmo exp. efforts to constrain or validate key signatures.

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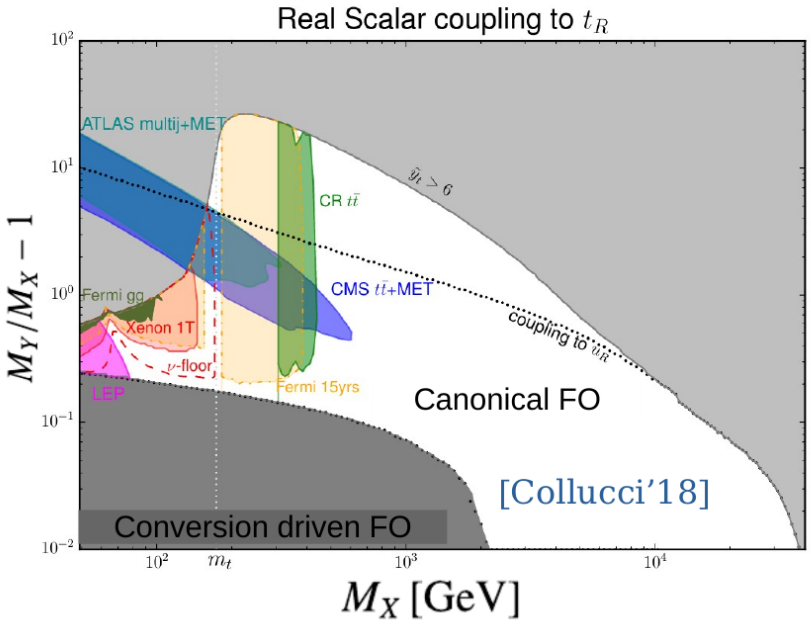

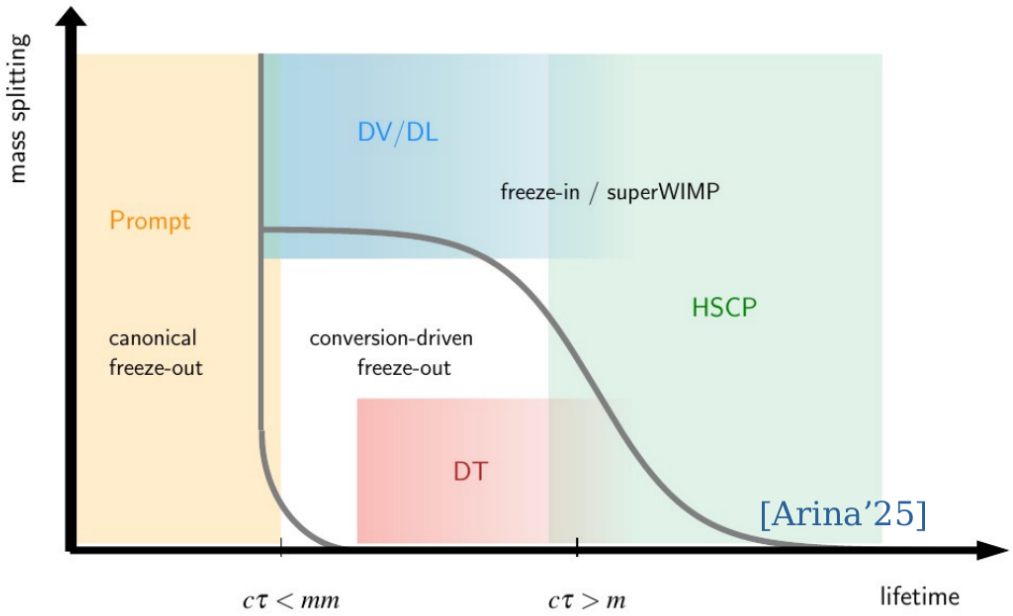

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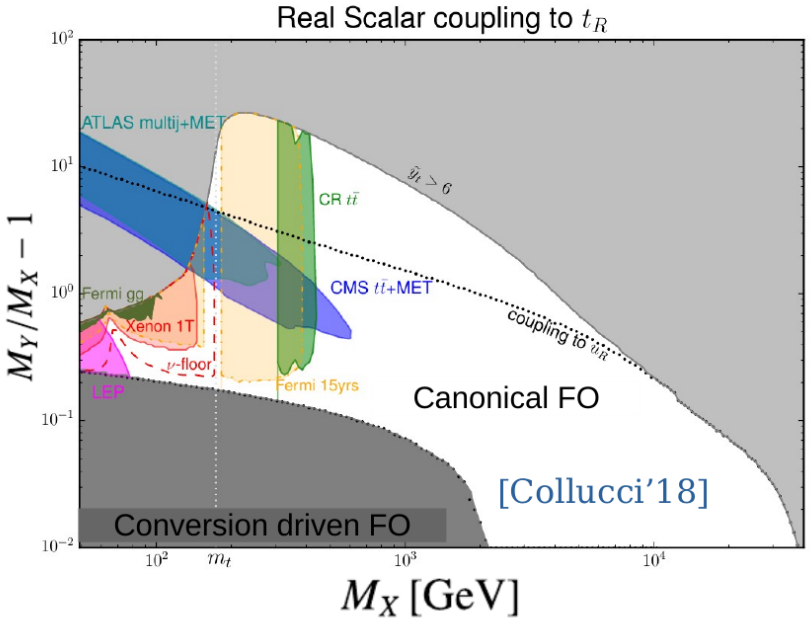

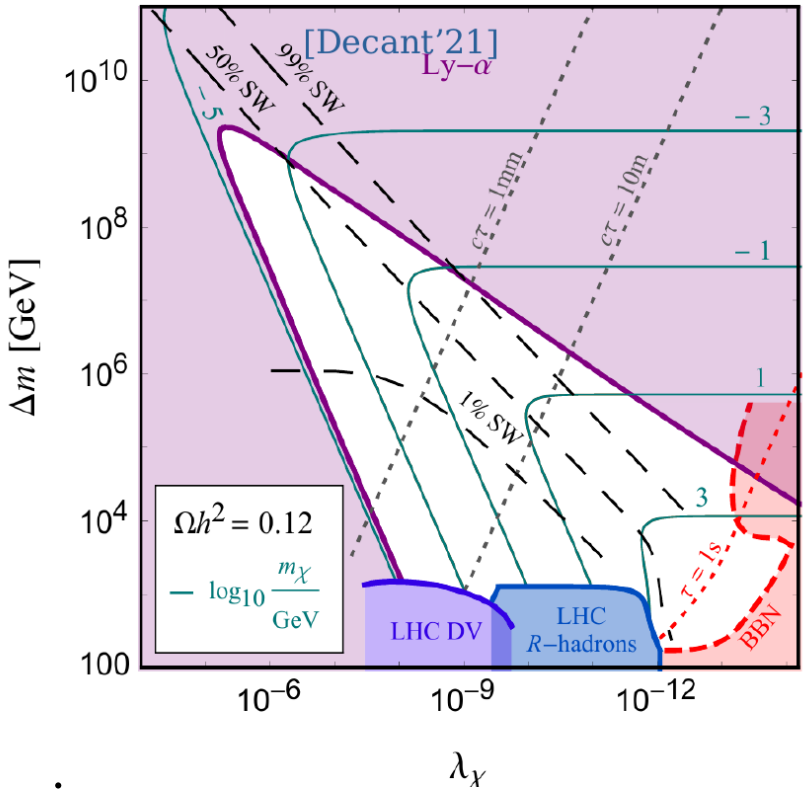

- Colliders may help to probe each regimes
- Complementarity with direct& indirect searches for WIMPs
  see also [Jayita Lahiri] for 2HDM+S talk today.
- Complementarity with Cosmo probes for FIMPs (Ly-α, BBBN, etc)

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Intermediate mass-range: Hidden sectors

Hidden sector: new particles and new forces

$\rightsquigarrow$ allows to populate wider mass range with multiple mechanisms (freeze-in, freeze-out, SIMP, asymmetric, DM etc). Example dark vector portal A'_μ.

Challenge: Experiments to look for
those new forces
$\rightsquigarrow$ viable DM in sub-GeV range.

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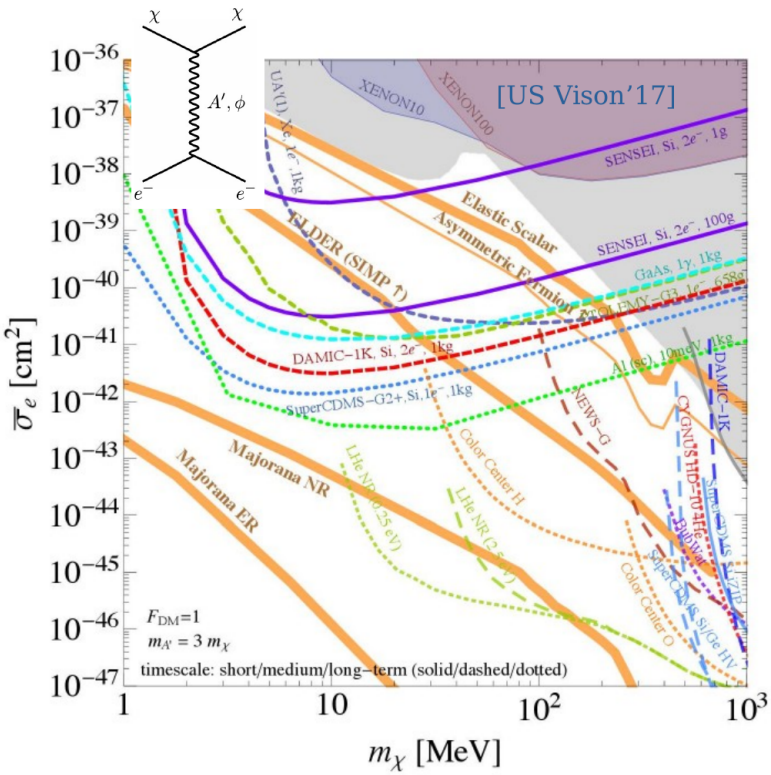
- Direct detection experiments: with electrons scatterings/excitations, making use of different materials (ferromagnets, superfluid He, etc) .
  $\rightsquigarrow$ Diversity of new proposed experiments for low momentum transfer

[see talks Tue& Thu, see also blazar boosted DM of Laura Manenti.]



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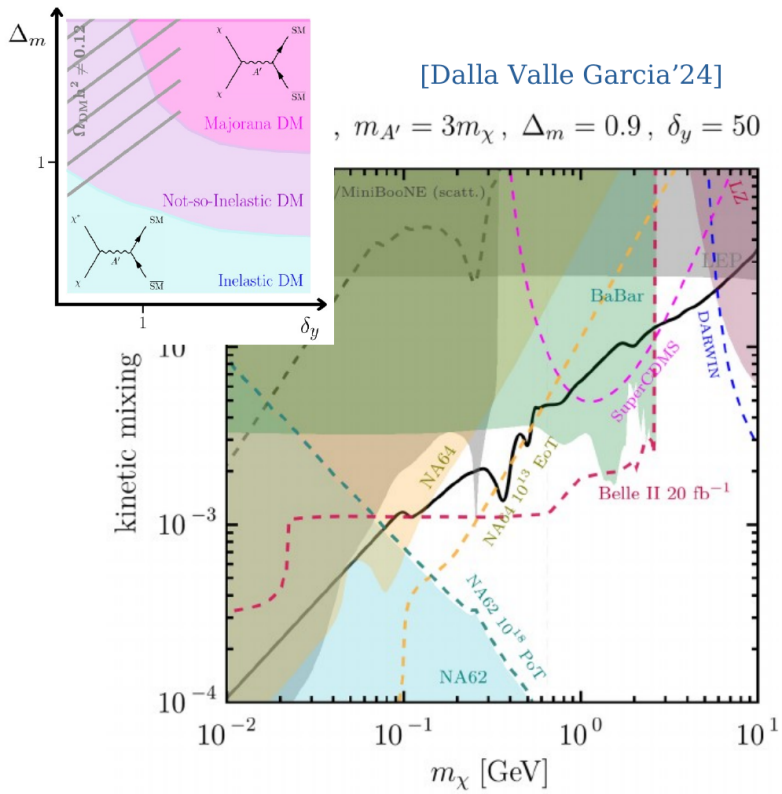
- beam dump exp. & LLP detectors:
  - Inelastic DM or not so: gives displaced decays $A' \to \chi\chi^* \to \chi\chi\bar{l}l$

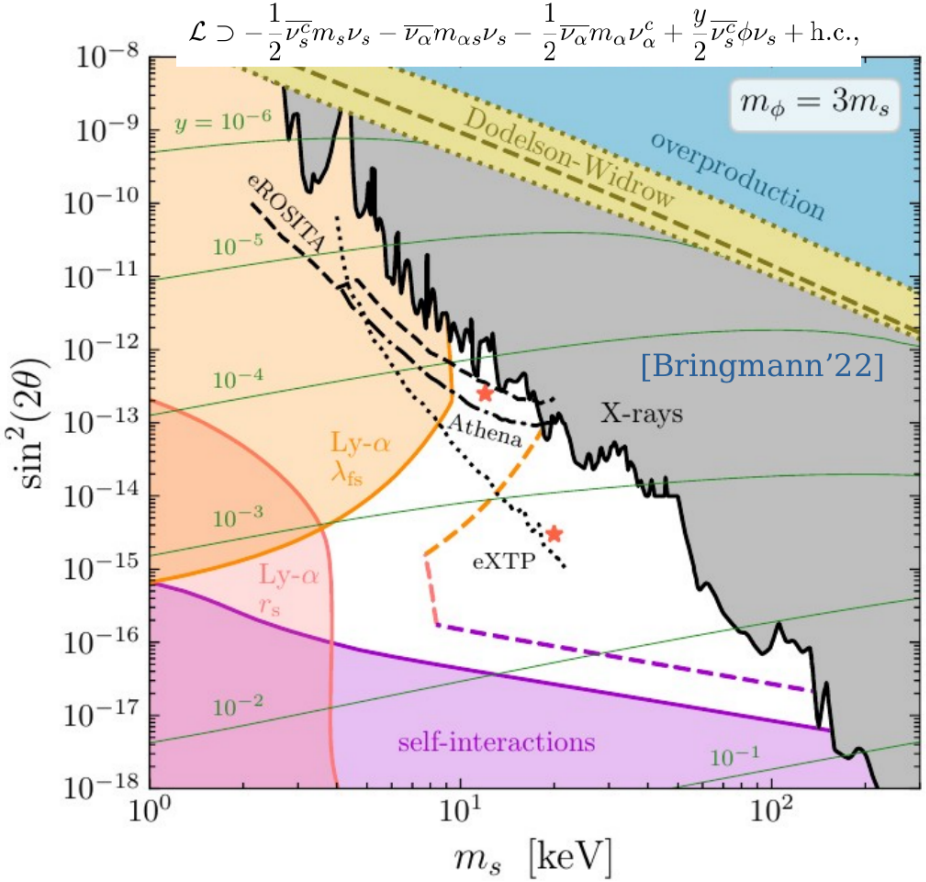
    [G. Dalla Valle Garcia talk]
  - SIMP: Dark pion from confined dark sectors: $3\pi_D \to \pi_D\rho_D$ populates $m > 100$ MeVlong lived ρ_D can give rise to DV at Beam dump exp. [N. Hemme talk]



Intermediate mass-range: Sterile Neutrino

Connection between SM neutrinos and keV DM

- Minimal sterile neutrino DM: Majorana ν_s mixing with SM ν and light scalar ϕ.
  Challenge: strong constraints from X-rays and Ly-α and self interactions.
  [e.g. Bringmann'22]



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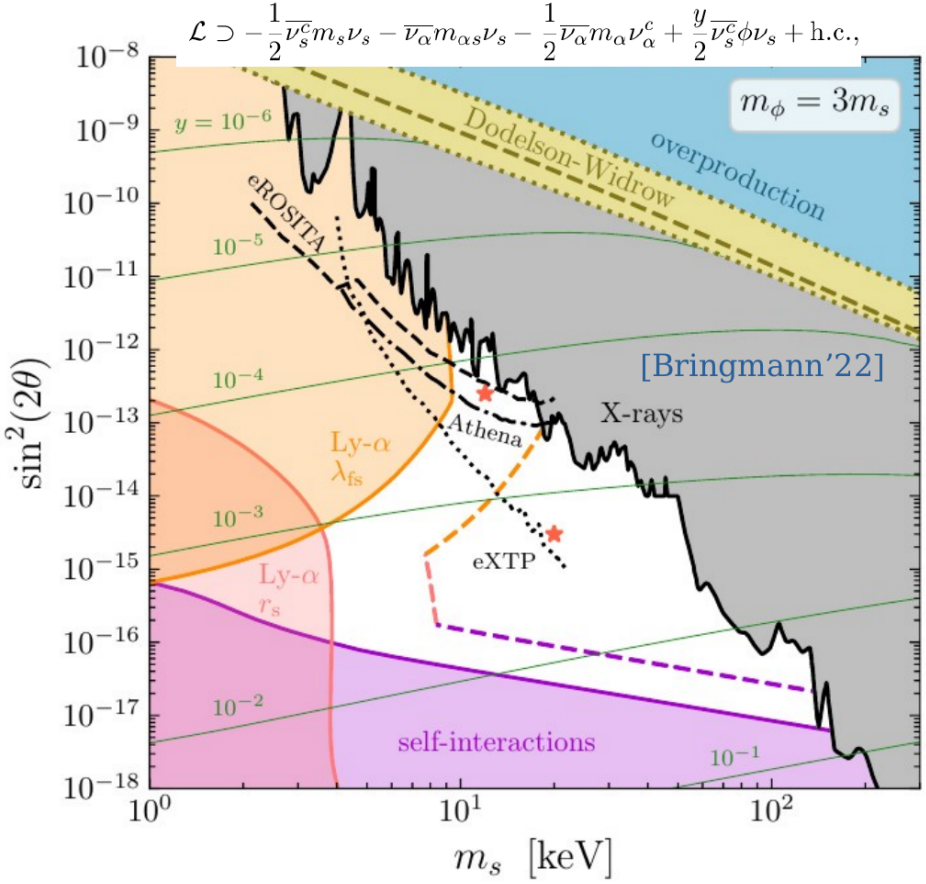
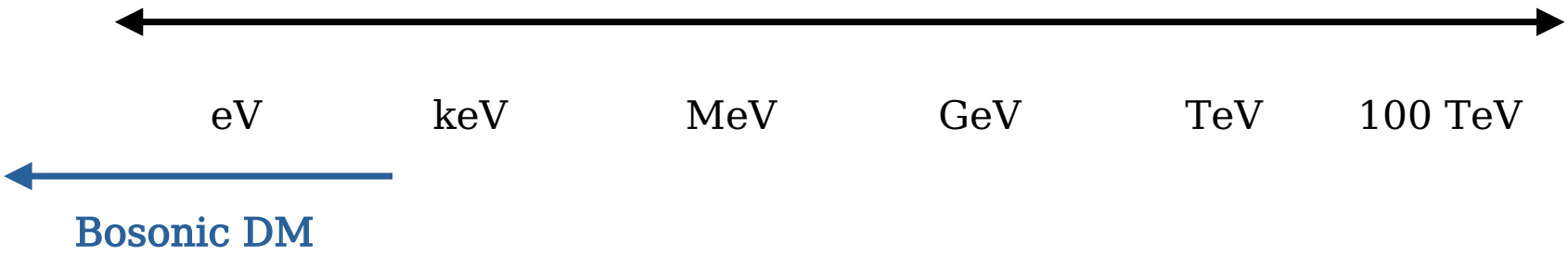
- Adding gauge interactions Z'_μ and light dark fermions χ, Ψ with Ψ =DM:
  Evade X-ray constraints and relax tension between neutrino mass from Cosmo and particle phys.
  [see talk Cristina Benso]



Lower mass-range: Bosonic DM



Lower mass-range: Bosonic DM

Typically non-thermal :
Axions, ALP, Dark photon

Cosmology :
Lyman-alpha (ULDM),
ΔNeff, energy injection.

Lower mass-range: Bosonic DM

eV keV MeV GeV TeV 100 TeV

Bosonic DM

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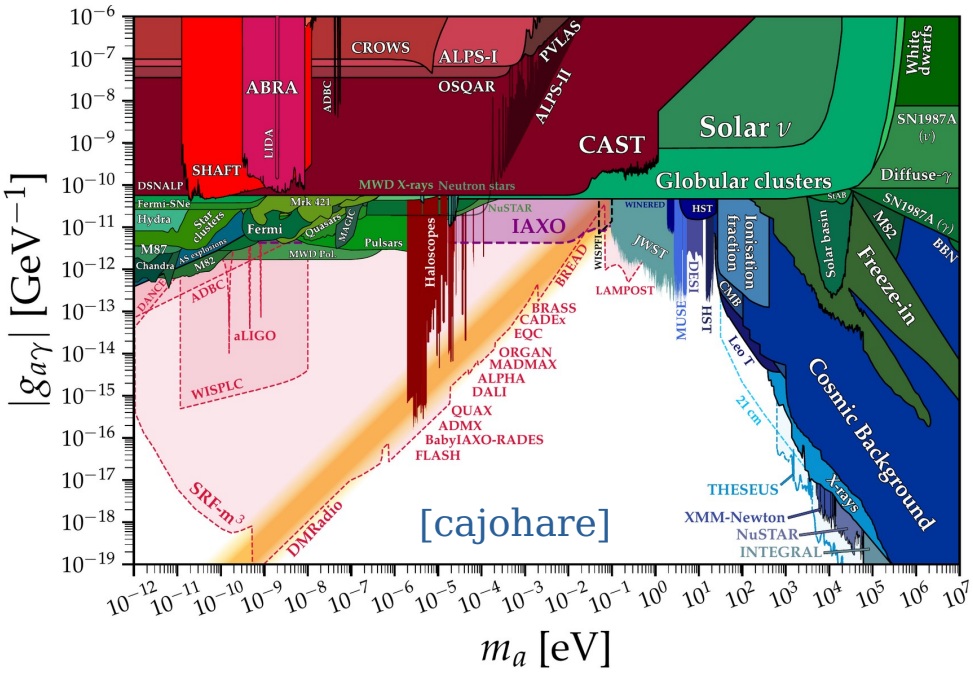

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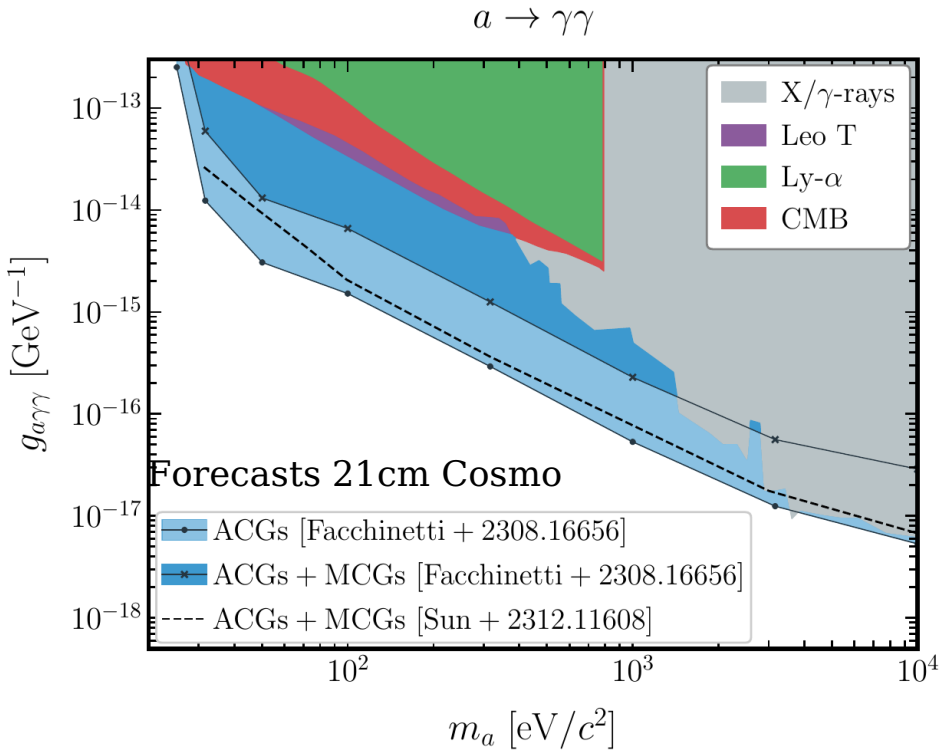


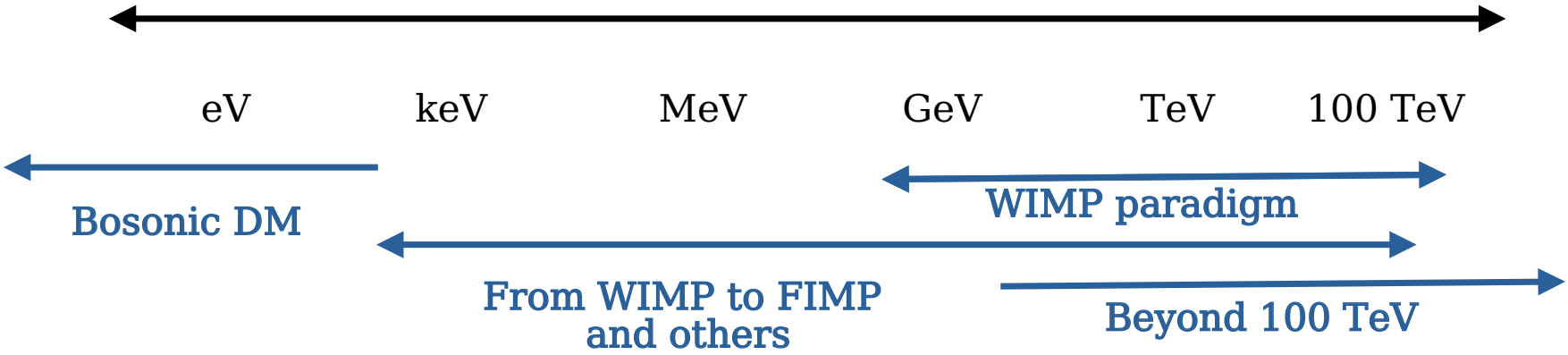
Take home message

- Not one theory of Dark matter but wide range of possibilities to be explored.
- If we detect new signal, the challenge will be to use all probes to charaterize DM.
- Diversity of candidates implies diversity of detection techniques.
  some scenarios/detection avenues I could not mention: asymmetric DM, mesogenesis, astrophysics boosting/probing DM etc
- Complementarity between astro-cosmo-particle is an asset.

Thank you for the invitation
and for your attention!!

Backup

Wide range of possible dark matter mass



Unitary imposes σv too small
(σv+fBS<4Π/(m^{2}v)):
***Non Thermal DM :** e.g. WIMPZilla [Kolb'98], M~HInfl
***Modified Cosmology :** phase trans, energy inj, etc [eg Asadi'21]
***etc**

This is really the end