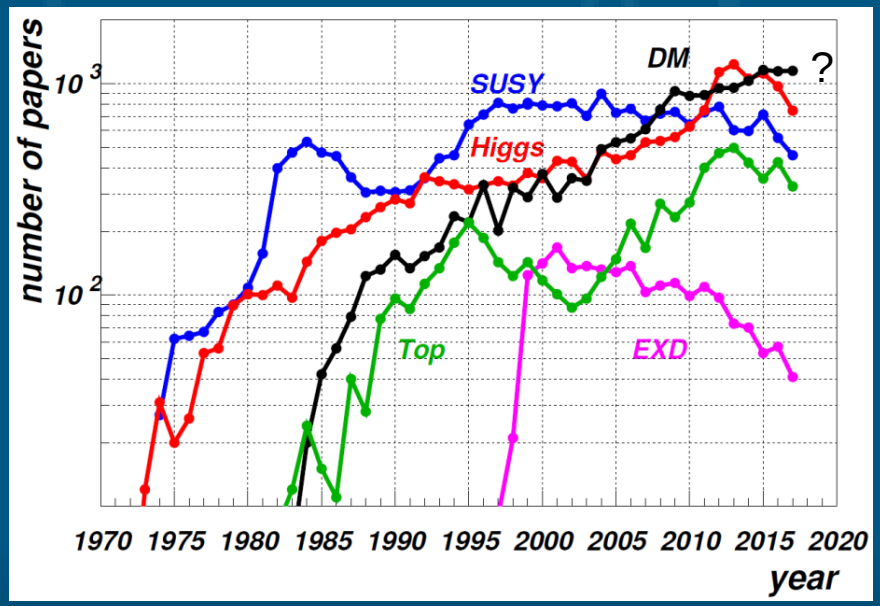
Dark Matter et al.

Richard Jacobsson



A. Belyaev, Southhampton University & RAL

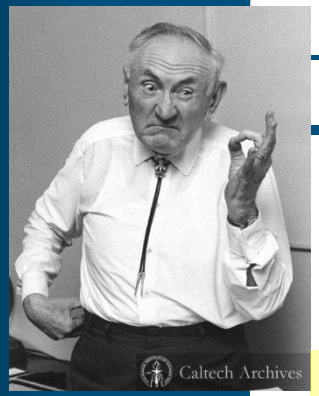
13.7 billion years ago in a far gone place

We have also Dark Matter to thank for our existence!

Our dawn on Dark Matter

- Observation of cluster of “nebulae”: F. Zwicky (1933)

Helvetica Physica Acta, 6, 110, 1933



Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

The Redshift of extragalactic Nebulae

5. Comments on the velocity dispersion in the Coma cluster of Nebulae

In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter [A. Einstein and W. De Sitter, Proc. of the Nat. Acad. Sci. Vol. 18, S.213, 1932]. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

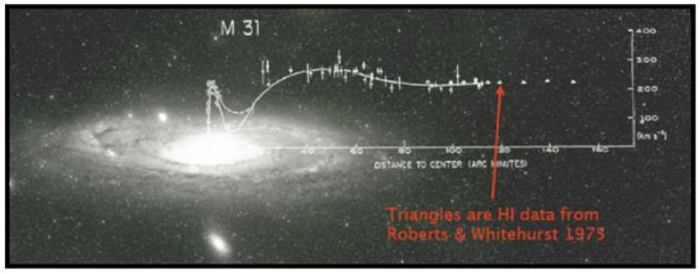
- Galaxy rotation curves: V. Rubin (1970)

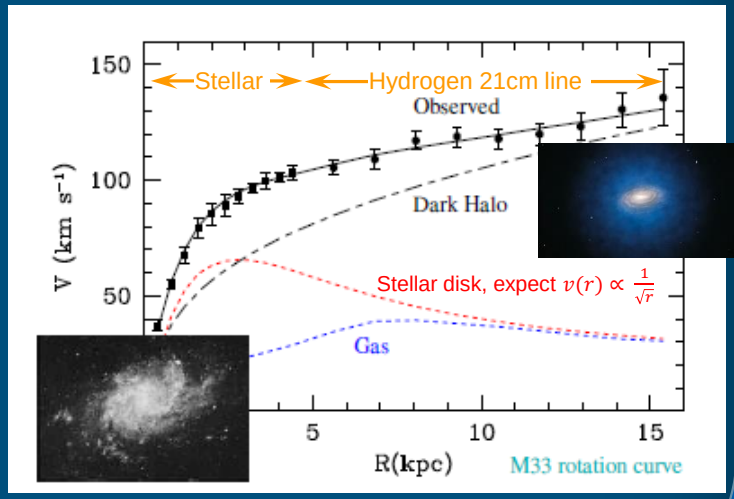
ApJ 159, 379, 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡



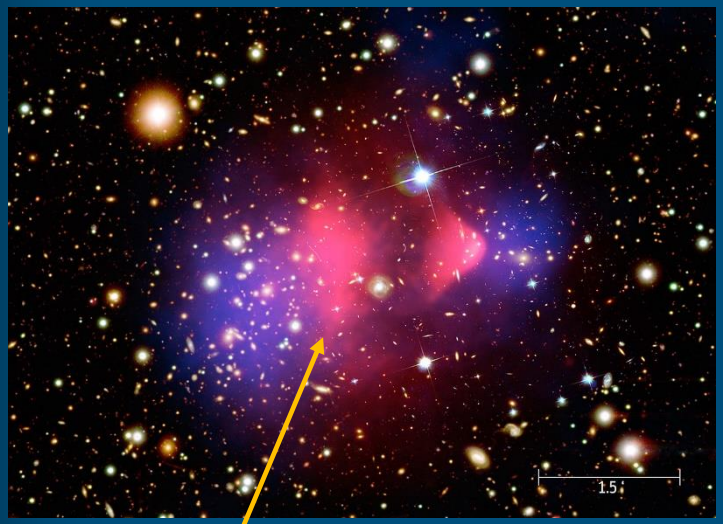


- Dark Matter is non-interacting!

Establishing Dark Matter – direct observation

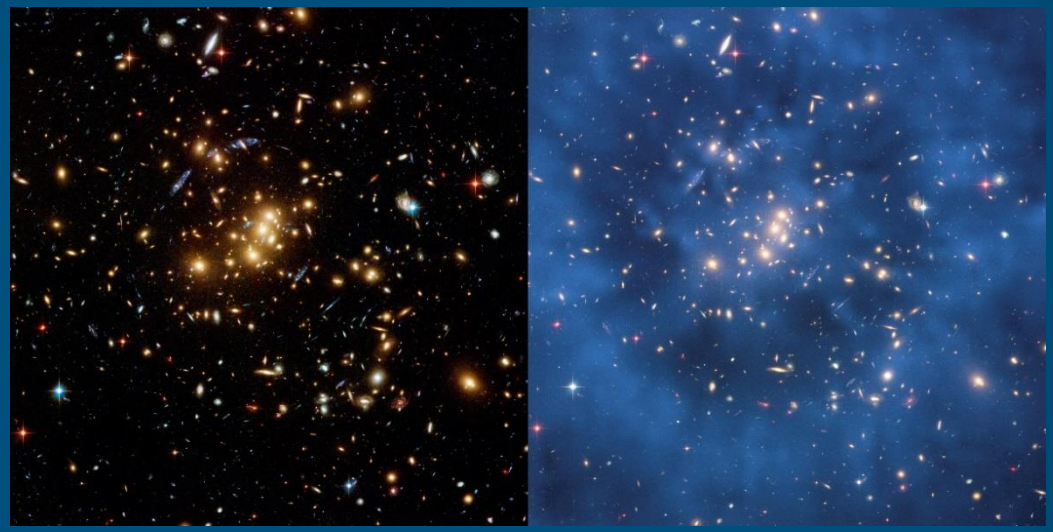
- Tracing DM: Gravitational lensing confirms previous observations (2003)

Bullet galaxy clusters (2003)



https://arxiv.org/abs/astro-ph/0608407

Galaxy cluster Cl 0024+17 (ZwCl 0024+1652)



Credits: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

Collision between two galaxy clusters

- In red, X-ray emitting plasma = dominant baryonic mass (5-15%)
- In blue, reconstruction of total mass distribution from lensing

Dark Matter remains around galaxy clusters (1-2% of mass) undisturbed

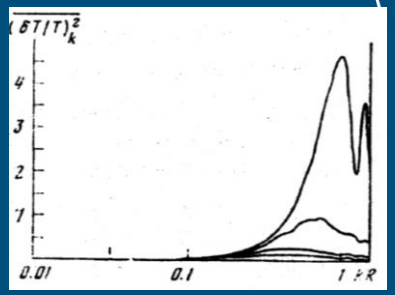
➔ Almost collisionless

➔ Very different density profile and dynamics from ordinary matter!
Why does it form a halo?

➔ Independent limits on Dark Matter self-interaction, and interaction with ordinary matter

Structure formation in the Universe

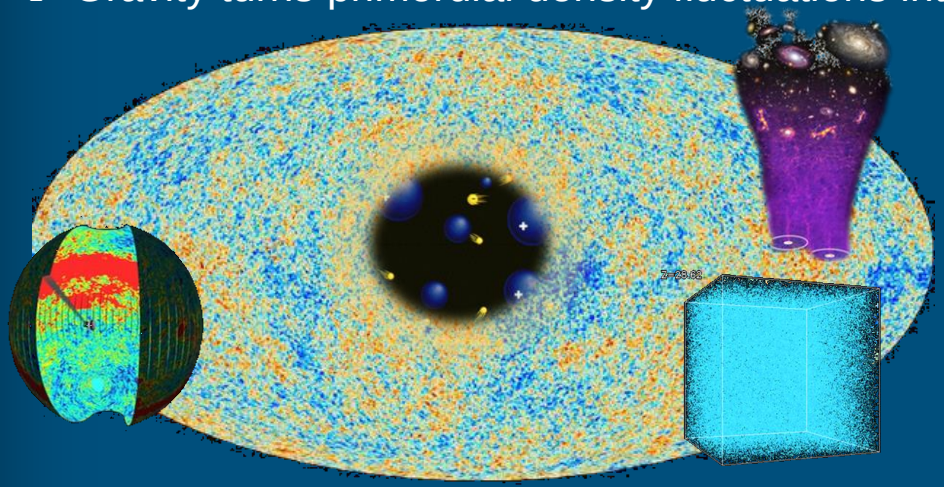
DM evidence from Cosmic Microwave Background (CMB) (2003)

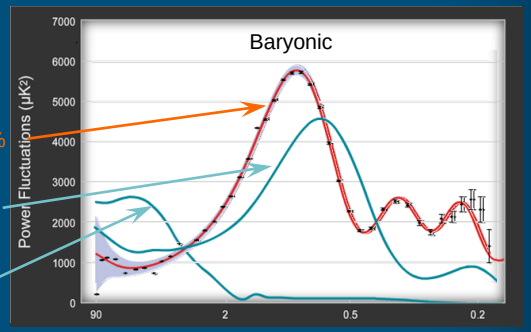


Soviet Astronomy, Vol. 22, p.523, 1978

- Thermal photons decouple from matter at ~T=3000 K at an age of 380 000 years
  - ➔ Universe gets transparent to light
  - ➔ The CMB carries a snapshot of the seeds to structure formation ("acoustic peaks")

➔ Gravity turns primordial density fluctuations into structures



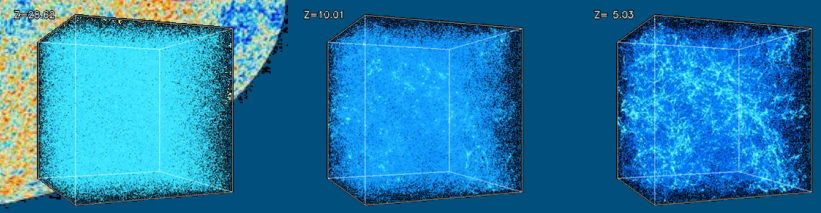


SM:DM:DE=4%:22%:74%

SM:DM:DE=30%:70%:0

SM:DM:DE=100%:0:0

NASA education CMB analyzer



- Distance scale over which mass collapse and form structures ("Jeans' instability")

$$[Distance\ scale] \propto \frac{[temperature]}{[particle\ mass]} \times [matter\ density] \quad \text{(for ordinary matter)}$$

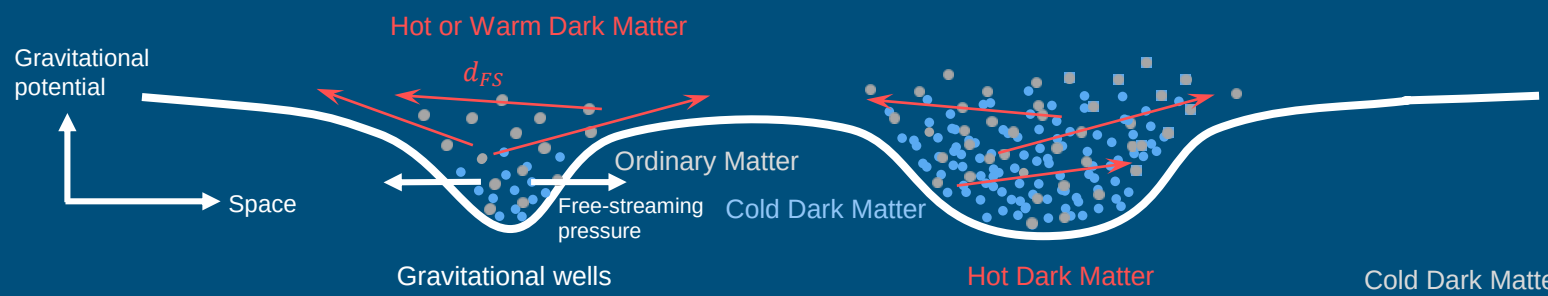
- Gravity and electromagnetism collaborate to form gas clouds, stars and galaxies
- With no self-coupling there is no energy transfer or "sticking" between DM particles

➔ DM distribution becomes "halo-like"

Structure formation and Dark Matter

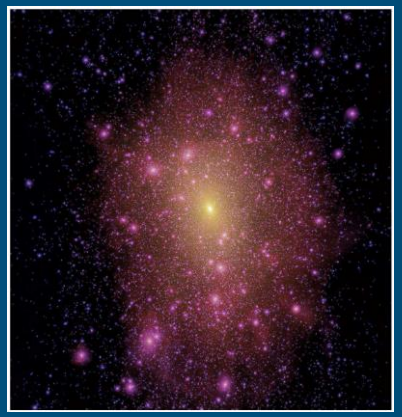
- DM can contribute in two ways:
  - Increasing mass density (increasing Jeans' scale for gravitational collapse)
  - Damping clustering of (too) small structures due to free-streaming $d_{FS} \propto [velocity]/\sqrt{[mass\ density]}$

    ➔ Depends on "velocity" (relativistic=radiation/non-relativistic)



Hot Dark Matter

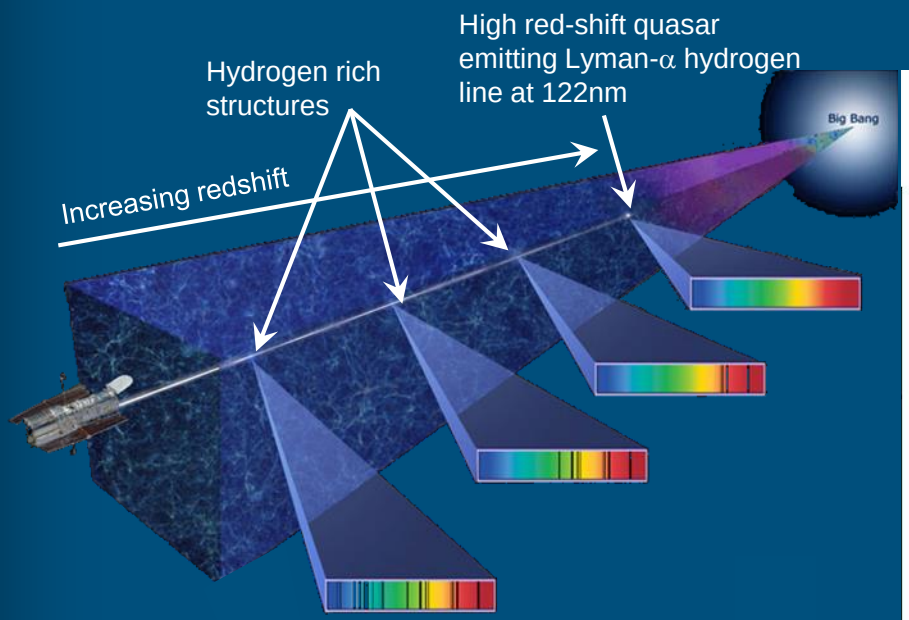
Cold Dark Matter

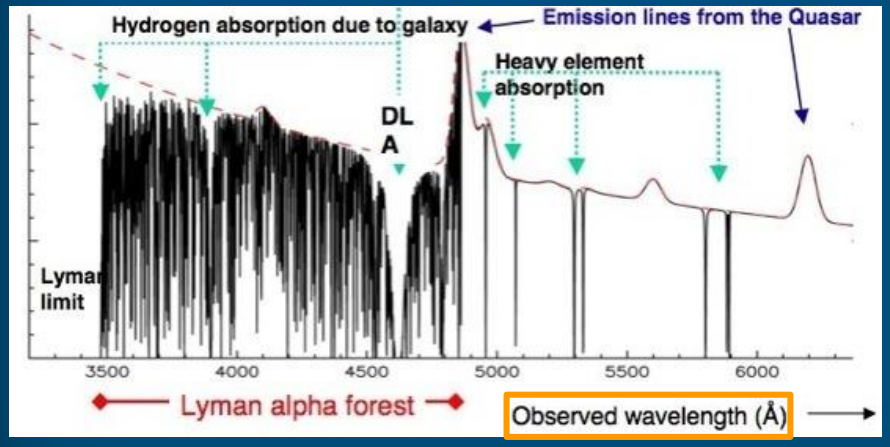


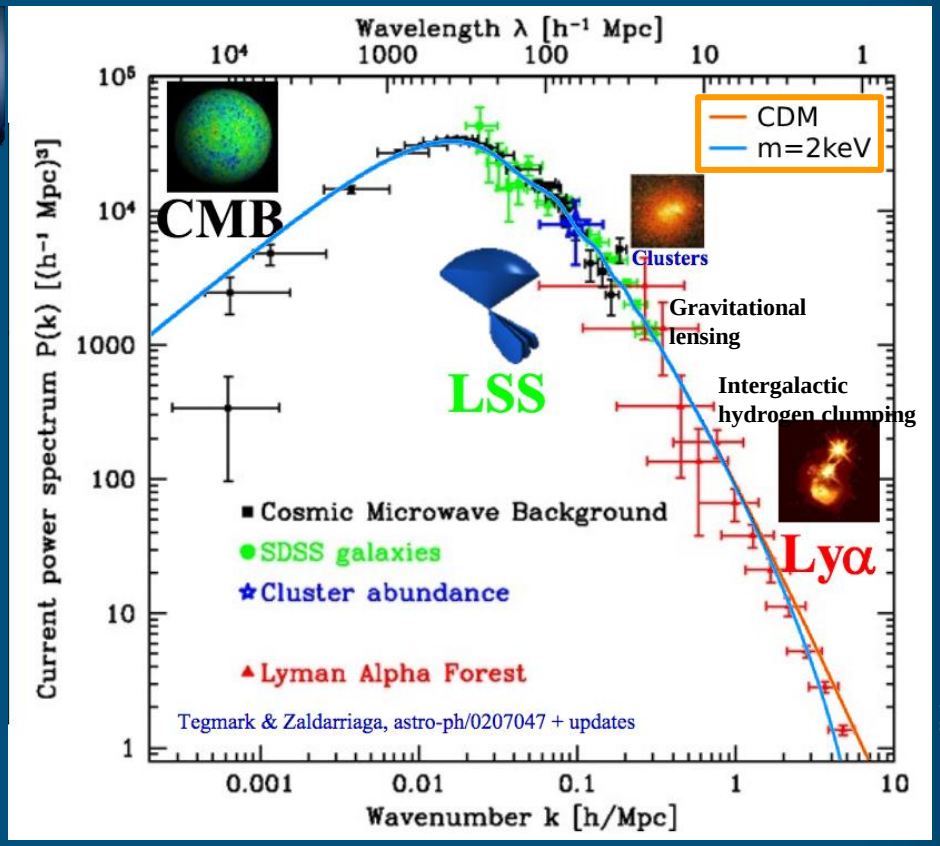
- DM could produce a drop-off in the power spectrum of structures as a function of the scale
  - Wash out of structures with sizes in the range 10^6 – 10^8 solar masses
  - How to measure?
    - Structures of $<10^8$ solar masses are very unlikely to have formed stars!

Current matter power spectrum

1. Gravitational lensing sensitive sub-structures $\mathcal{O}(10^7)$ solar masses
2. "Lyman-α forest" measured by spectroscopic telescopes – intergalactic hydrogen clumping







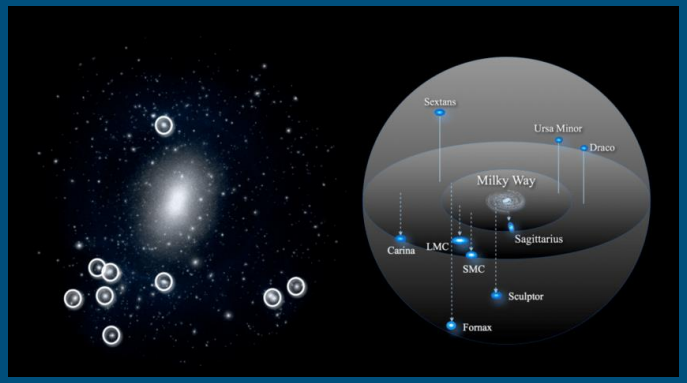
A. Magalich

Large scales ← → Small scales

Open issues

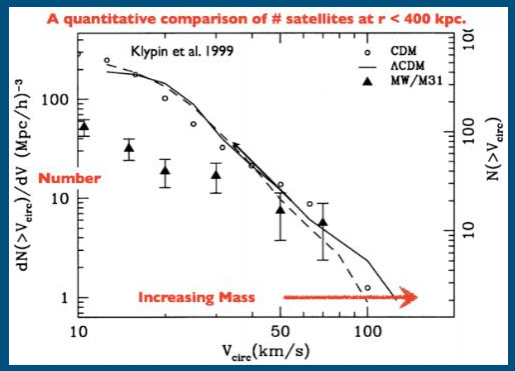
Not everything is singing and dancing:

"Missing satellite" or "too-big-to-fail problem"

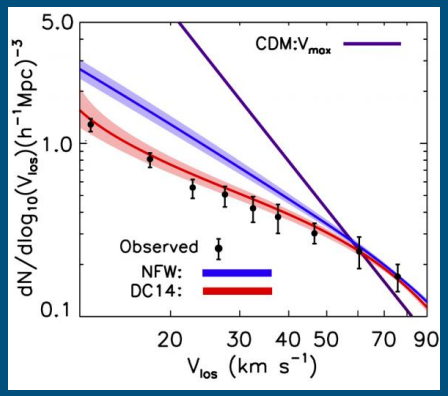


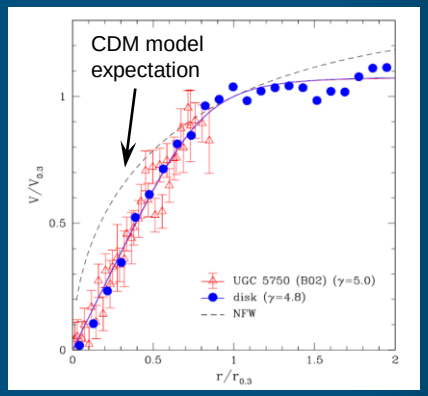
Weinberg et al., arXiv:1306.0913

- Simulated halos retain many DM substructures from initial collapse ("sub-halos")
- Only ~10 satellites strongly visible around Milky Way



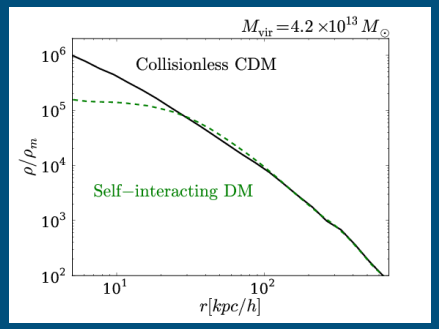
"Core-cusp problem"





arXiv:1506.01019

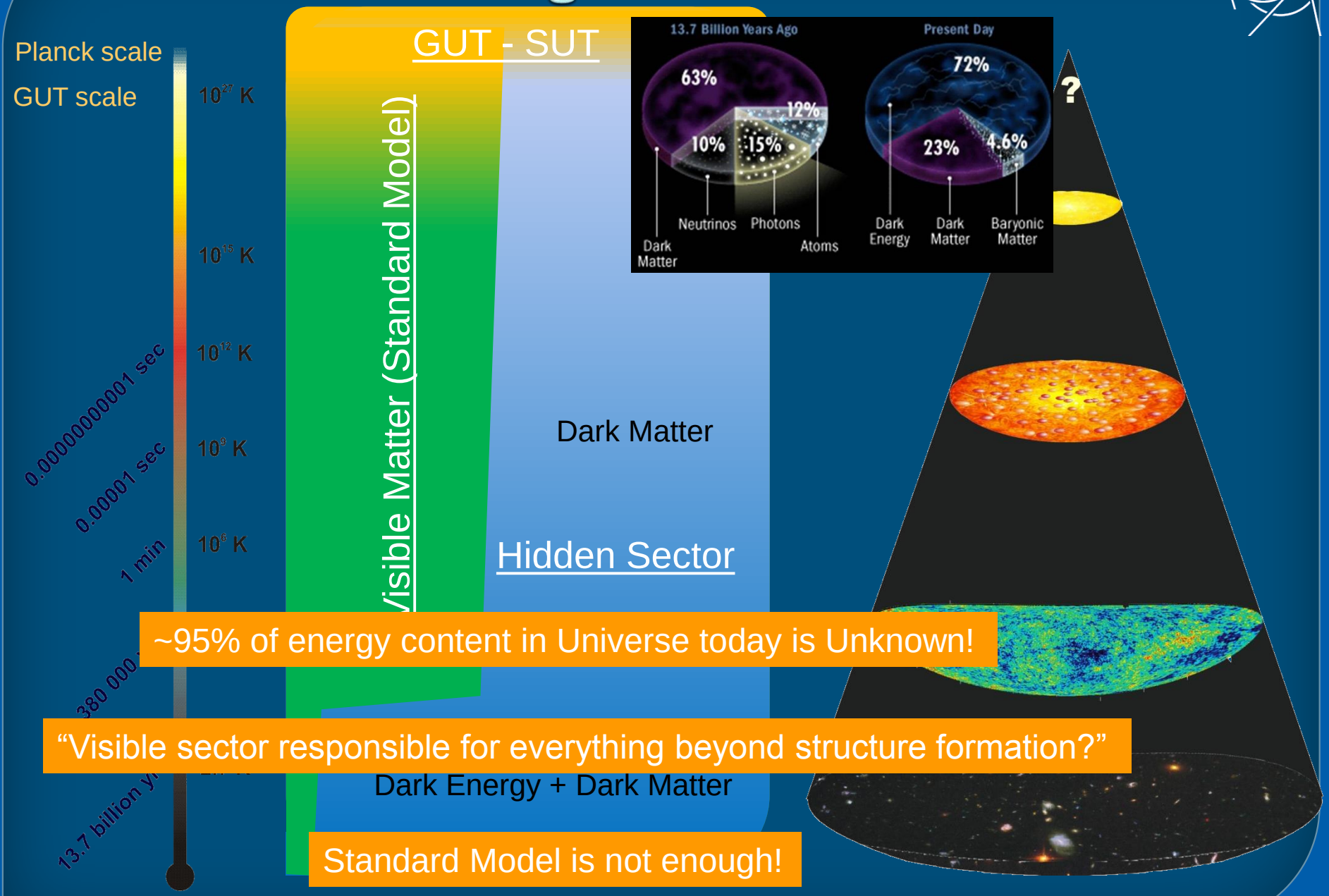
- Central density profile: $\rho(r) \propto r^{-\alpha}$
  - Simulation with CDM: $\alpha = 1 - 1.5$ ("Cuspy")
  - Observed profile closer to : $\alpha \sim 0$ ("Core")
- Supernovae outflows drive flattening of DM profile?



arXiv:1306.0913

- Jury is still out on this
  - An option is self-interacting Dark Matter (SIDM), non-gravitational "Dark Interaction"?
    - How was Dark Matter created, how was the abundance regulated?
    - Is there some dynamics, DM stable/decay? ➔ particle physics questions!

The Big Picture - ΛCDM

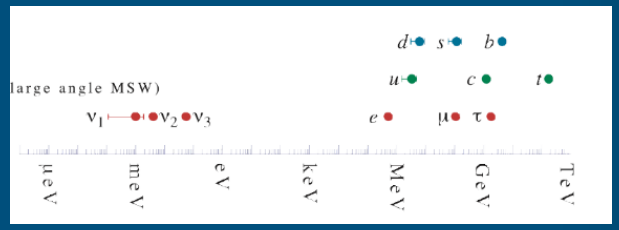


~95% of energy content in Universe today is Unknown!

"Visible sector responsible for everything beyond structure formation?"

Standard Model is not enough!

Fundamental questions = Evidence for "New Physics"



Two types of evidence for New Physics:

Experimental evidence for New Physics

1. Neutrino masses and oscillations
2. Matter/antimatter asymmetry of the Universe, BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim 6 \times 10^{-10}$
3. Dark Matter
4. Dark Energy

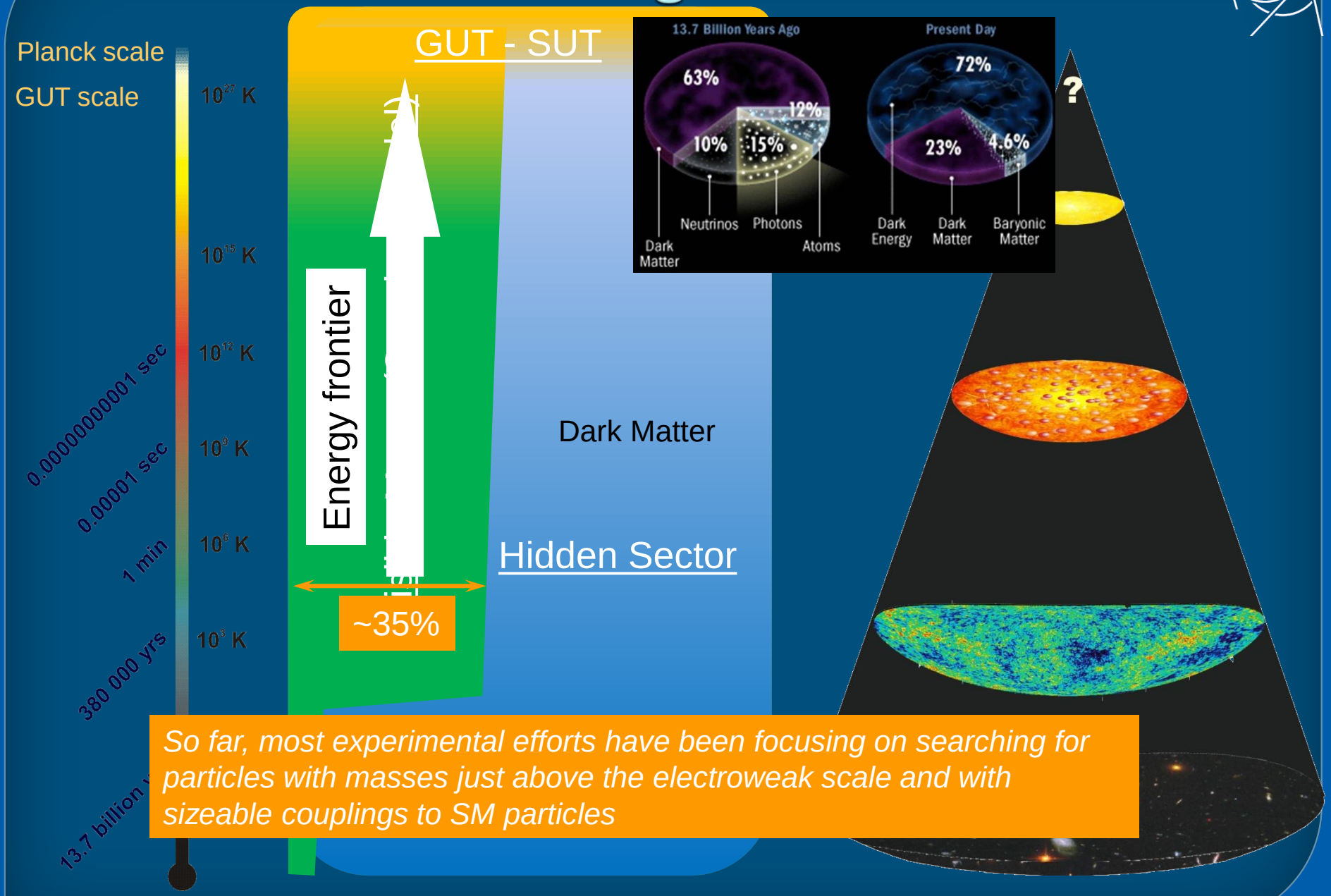
➔ *No prejudice on mass/energy scale of the "new physics" required to solve these!*

Theoretical "evidence" for New Physics – "prejudice"

1. Hierarchy problem and stability of Higgs mass – Naturalness/Fine-tuning
2. Flavour structure of Standard Model
3. Strong CP problem (why CP violation is suppressed in strong interactions?)
4. Unification of interactions
5. Gravity
6. Inflation
7. ….

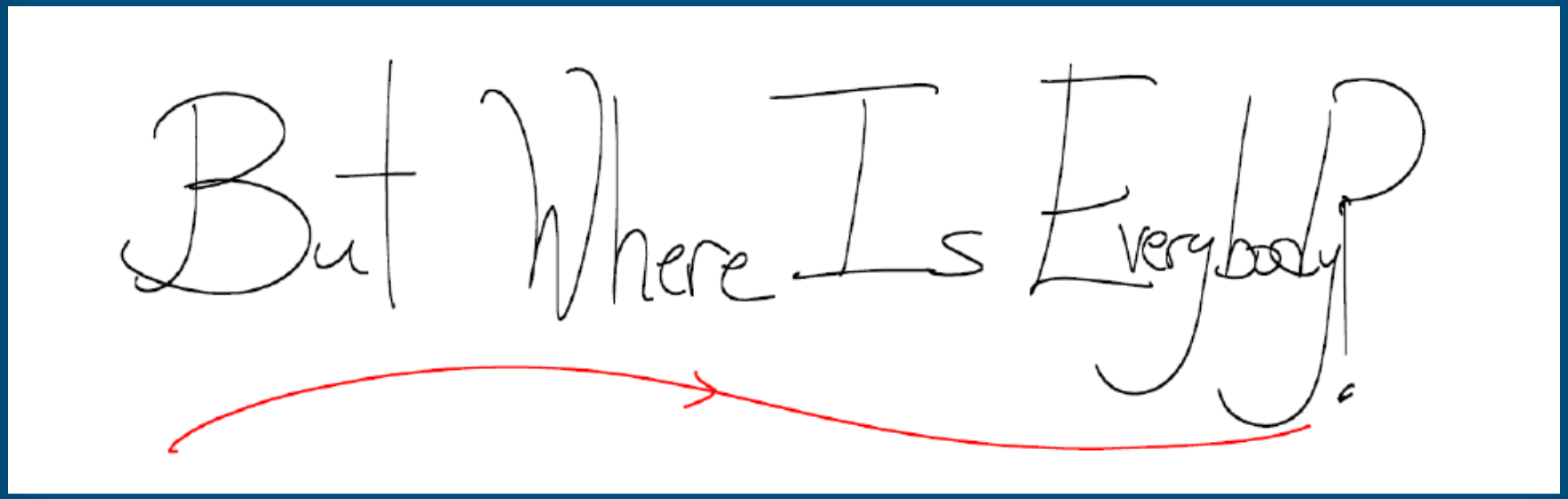
➔ *Preference for high mass/energy scales….*

The Big Picture



So far, most experimental efforts have been focusing on searching for particles with masses just above the electroweak scale and with sizeable couplings to SM particles

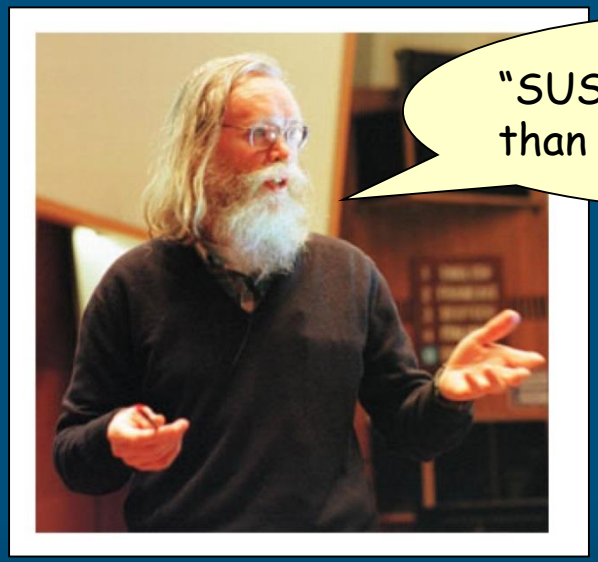
??



Nima Arkani-Hamed

Why still SUSY searches in 2040++ ?

Indeed, even if fine-tuned,
it makes our universe more likely

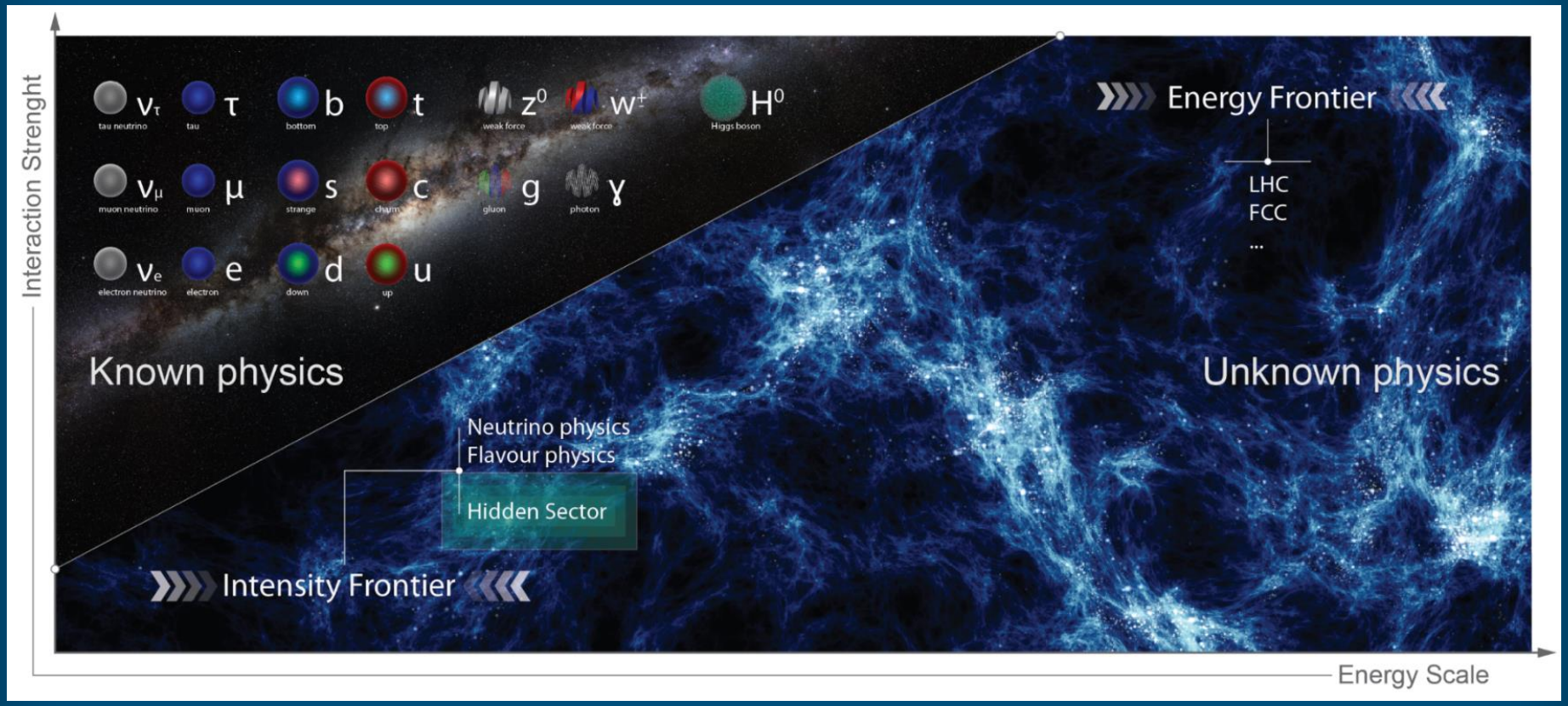


J. Ellis

Mass scale vs coupling scale

- What are the alternatives? "New particles" can hide in two ways:

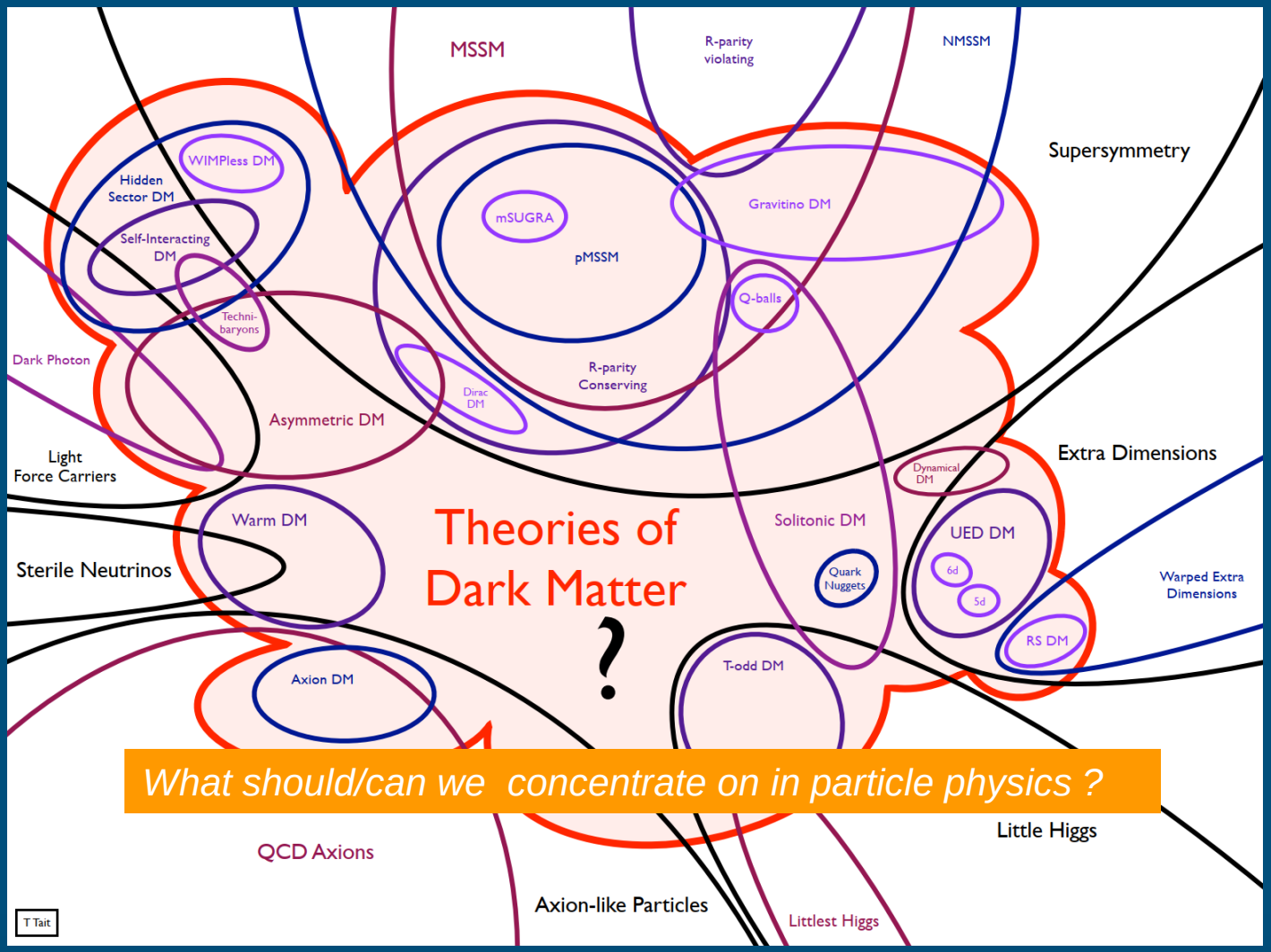
Very massive OR very weakly coupled



- DM tells us there could be a "very weakly interacting" scale

Dark Matter options

W. Pauli (1930) about the neutrino: *"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."*



Tim M.P. Tait, University of California

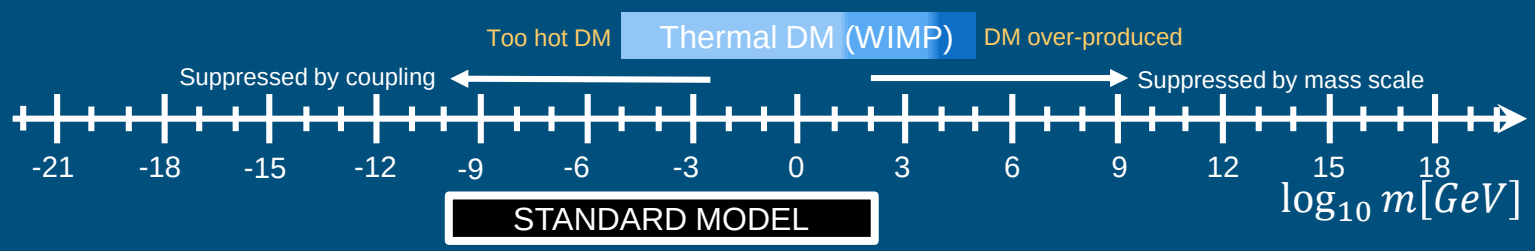
Mass scales for New Physics...

Particles required for baryogenesis

QCD axion

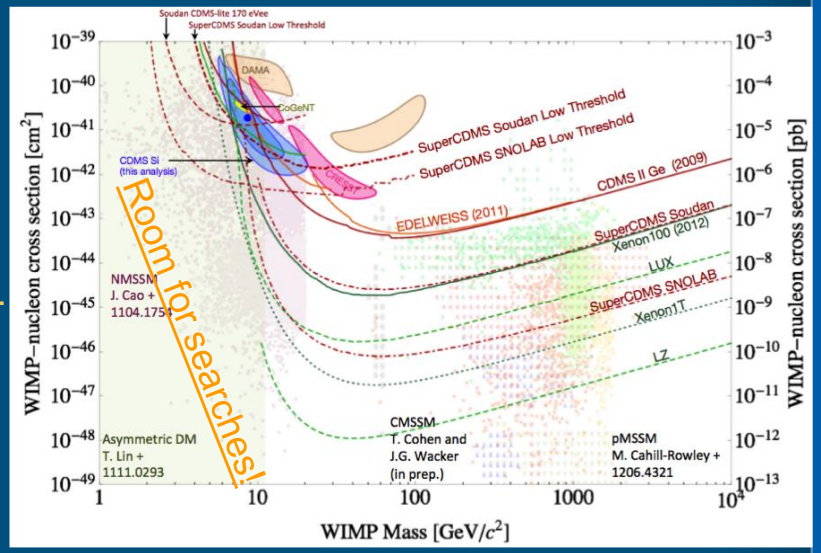
Particles required for Higgs mass stability

Right Handed Neutrinos



- Room for searches below 10 GeV/c^2
- Many reasons MeV – GeV region is particularly interesting…
  1. We know this mass scale exists !...
  2. Absence of hints for new particles at higher energies
  3. Cosmologically interesting
  4. Largely unexplored territory
  5. And because we can!

     (…test many very reasonable and far-reaching theoretical models!)



Space for heavy WIMPs closing

Building a dynamic model of Hidden Sector

- Another “prejudice”: SM not only successful, we discovered everything it predicted
- Extending SM with a “Hidden Sector” using the same successful formalism
  - Lagrangian equation of motion + wave function + relativity + quantization + symmetries ↔ conservation + renormalizability, …
  - Lagrangian $\mathcal{L} \equiv [Kinetic\ terms] - [Potential\ energy] \overset{SM}{\Longrightarrow} [Freemoving\ particles] - [Interactions]$
- Toy example

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- Toy example

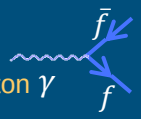
$$\mathcal{L}_{\substack{U(1)\\U'(1)}} = \boxed{i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi} - \boxed{m\bar{\psi}\psi} - \boxed{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} - \boxed{ie\bar{\psi}\gamma^{\mu}A_{\mu}\psi}$$

Free fermion

Fermion mass

Free photon

Interaction fermion-photon



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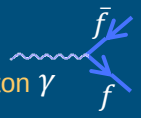
- Toy example (Higgs in the "…")

$$\mathcal{L}_{\substack{U(1)\\U'(1)}} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - ie\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

Free fermion — Fermion mass — Free photon — Interaction fermion-photon



$$+ i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m\bar{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - i\epsilon\bar{\chi}\gamma^{\mu}A'_{\mu}\chi \ldots$$

Free DM — DM mass — Free dark photon — Interaction dark fermion – dark photon DM self-interaction… — Dark electric charge Coupling extremely weak

Building a dynamic model of Hidden Sector

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- Toy example

$$\mathcal{L}_{\substack{U(1)\\U'(1)}} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - ie\bar{\psi}\gamma^{\mu}A_{\mu}\psi - \boxed{\frac{1}{4}\varepsilon F_{\mu\nu}V^{\mu\nu}} + i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m\bar{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - i\epsilon\bar{\chi}\gamma^{\mu}A'_{\mu}\chi \ldots$$

One more fully valid term possible!

Kinetic mixing between ordinary photon and dark photon (can be massive) !
"Vector portal"
→ Coupling extremely week

A weak "interaction" between the visible sector and the dark sector, and a dark matter self-interaction!

Building a dynamic model of Hidden Sector

- Another "prejudice": SM not only successful, we discovered everything it predicted, so…
- Extending SM with a "Hidden Sector" using the same successful formalism
  - Lagrangian equation of motion + wave function + relativity + quantization + symmetries ↔ conservation + renormalizability, …
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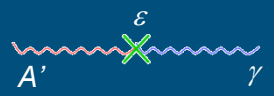
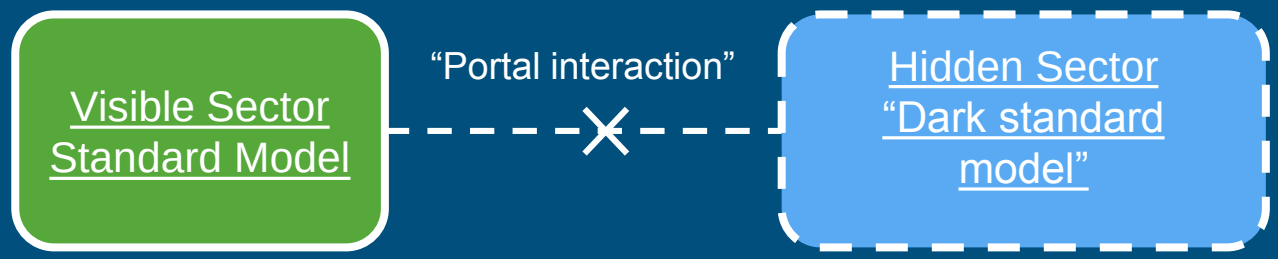


Dark versions can be considered for all (neutral) SM features!

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)}\mathcal{O}_{SM}^{(l)}}{\Lambda^{n}}$$

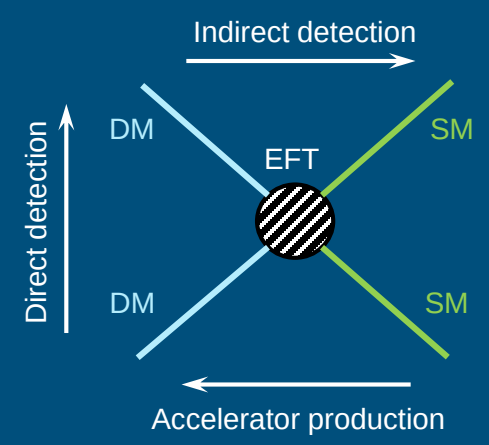
Hidden Sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



➔ Dynamics of Hidden Sector may drive dynamics of Visible Sector!

- Dark Matter (trivial!) – fermionic or scalar
- Neutrino oscillations
- Baryon asymmetry
- Higgs mass
- Dark Energy
- Inflaton
- ……

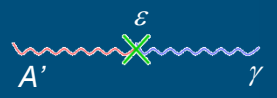


Simple extension and no new energy scale!

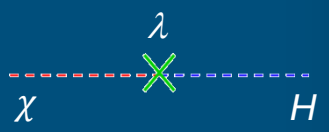
Hidden Sector options (1)

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$

- Composite operators as "portals":
- **Vector portal (γ/Z^0) (aka "Dark photons")**
  - ➔ Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter, g-2 anomaly, …



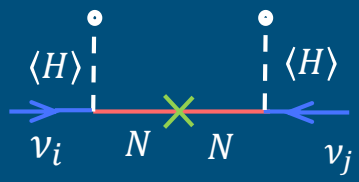
- **Scalar portal (H^0) (aka "Dark Higgses")**
  - Mass mixing with dark singlet scalar χ : $(g\chi + \lambda\chi^2)H^\dagger H$
  - ➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…



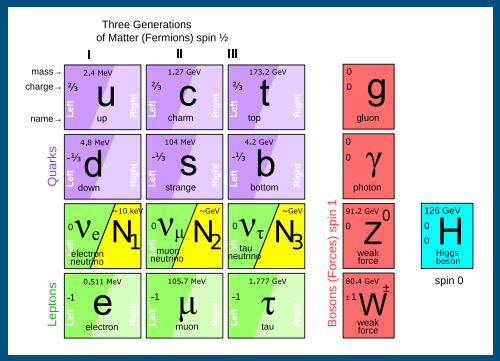
Hidden Sector options (2)

- **“Neutrino portal” (aka “sterile neutrinos”)**
  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^{\dagger} \overline{N}_I L_\ell$

  ➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

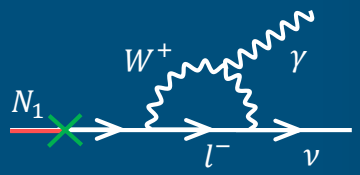


E.g. νMSM (Shaposhnikov et al.)



N_1: O(keV/c^2) mass HNL as decaying dark matter

$N_{2,3}$: Mass in range 100 MeVc^2 – 100 GeV/c^2, origin of neutrino oscillations/mass and baryon asymmetry

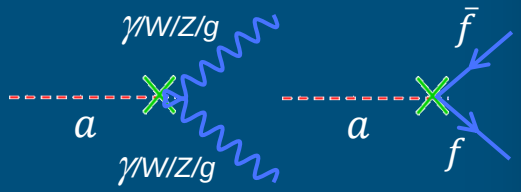


$$E_\gamma = \frac{M_N c^2}{2}$$

- **“Axion portal” (not strong CP axion) (aka axion-like particles ALPs)**
  - Mixing with Axion Like Particles, pseudo-scalars pNGB : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

  ➔ Arise in spontaneous breaking of approximate symmetries at a high mass scale F

  ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…



➔ Or combinations thereof!!

Hidden Sector options (2)

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  - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^{\dagger} \overline{N}_I L_\ell$
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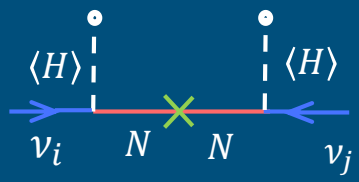

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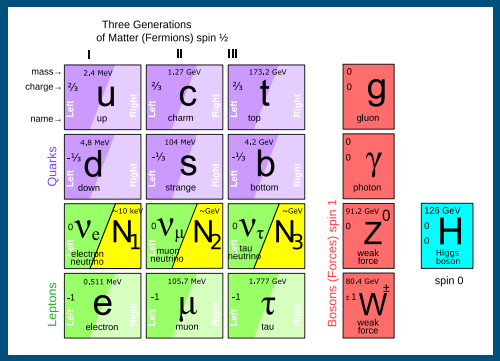

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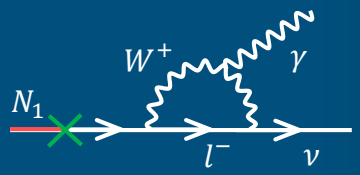

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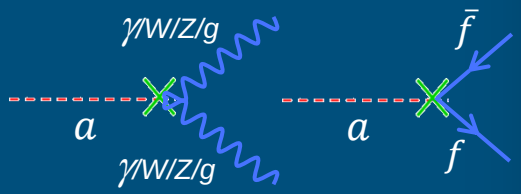


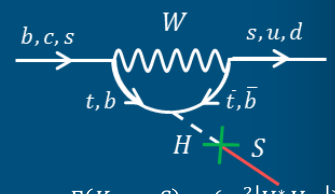
➔ Or combinations thereof!!

Rich variety and phenomenology requires generic and complementary search!

Production and principal sources

- Dark vectors ("Dark Photons")
  - Loads of photons! – Bremsstrahlung, light neutral meson decays, quark annihilation
  - Sources: electron fixed target beams, electron colliders, proton fixed heavy target

E.g. Dark scalar

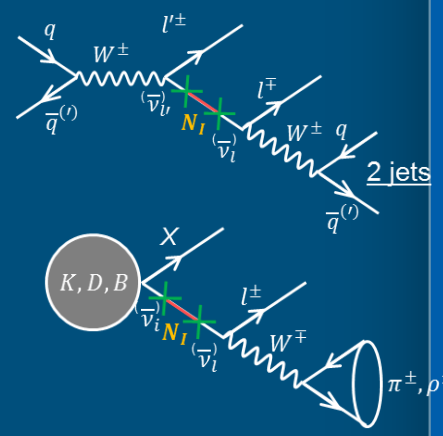


$\Gamma(K \to \pi S) \propto (m_t^2 |V_{ts}^* V_{td}|)^2$
$\Gamma(D \to \pi S) \propto (m_b^2 |V_{cb}^* V_{ub}|)^2$
$\Gamma(B \to \pi S) \propto (m_t^2 |V_{tb}^* V_{ts}|)^2$

- Dark scalars ("Dark Higgses")
  - Loads of Higgses (real) or in Penguin decays of K, D, B mesons
  - Proton colliders, proton fixed heavy target, electron colliders(H factory)

- Heavy neutral leptons ("sterile neutrinos")
  - Loads of weak decays of hadrons, W, Z
  - Sources: proton fixed heavy target, proton colliders, electron colliders (W, Z)

E.g. Heavy Neutral Lepton



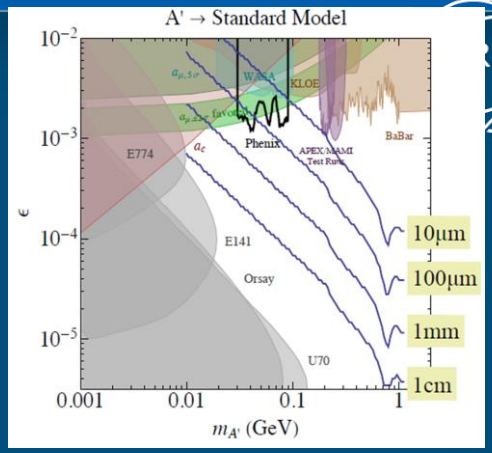
- Axion-like particles ("ALPs")
  - Possible couplings to photons, gluons and fermions, loads of interactions!
  - Proton colliders, proton heavy fixed target, space

- (Light) Dark Matter direct detection ("νWIMPs")
  - Through one of the portals or Space!

- Fixed target luminosities not to be ignored
  - "Primary" SPS FT luminosity for a long target (e.g. 1m++ Mo, ρ_N nucleon density)
    - ➔ SPS $\mathcal{L}_{int}[year^{-1}] = 10^6 s \times \int_0^{"\infty"} \Phi_0 \times \rho_N \times e^{-l/\lambda} dl = \Phi_0 \times \rho_N \times \lambda$ = 3.6 x 10^{45} cm^{-2} (cascades not incl.)
    - ➔ HL-LHC luminosity: $\mathcal{L}_{int}[year^{-1}] = 10^7 s \times 10^{35}$ $s^{-1}cm^{-2}$ = 10^{42} cm^{-2}

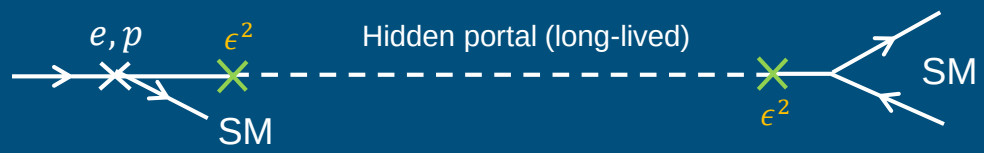
Detection

- Weak couplings and light masses make HS particles "long-lived"
  - Four generic cases for detection ($\epsilon \ll 1$) :

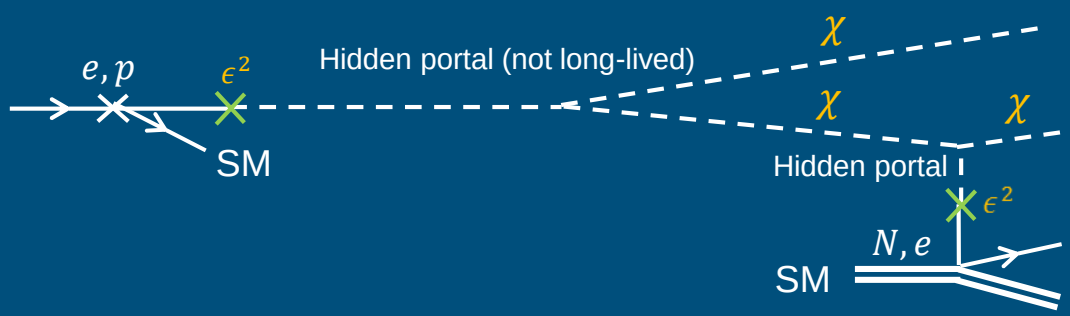


Production | Detection

Direct

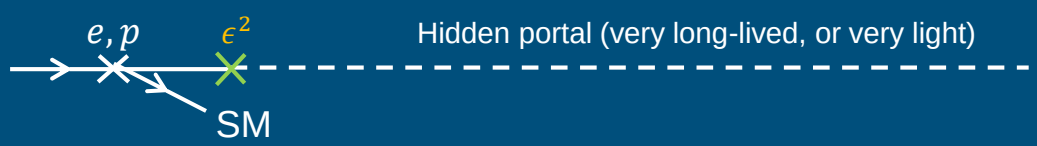


Decay signature ("displaced vertex)
Allow identification of model
Probability ∝ ϵ^4



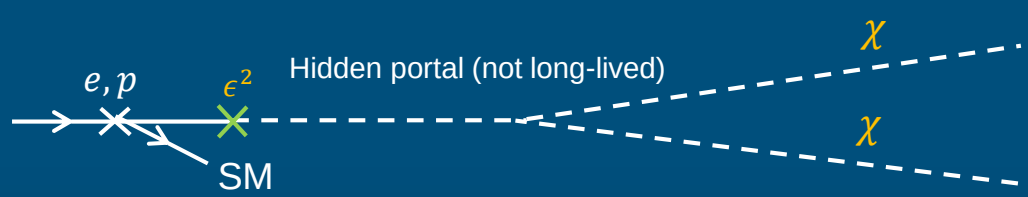
Dark matter scattering
Recoil against electron or nuclei
Probability ∝ ϵ^4

Indirect



Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

Cannot be distinguished



If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass
Probability ∝ ϵ^2

Detection

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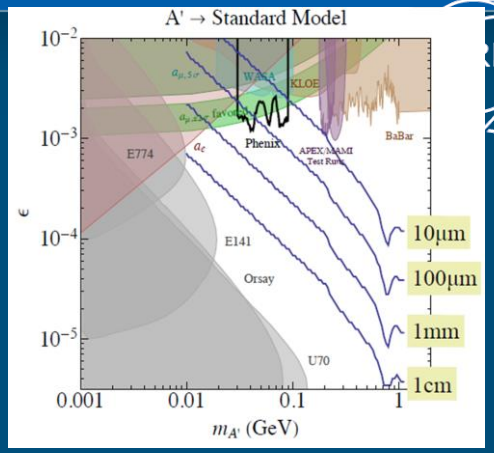
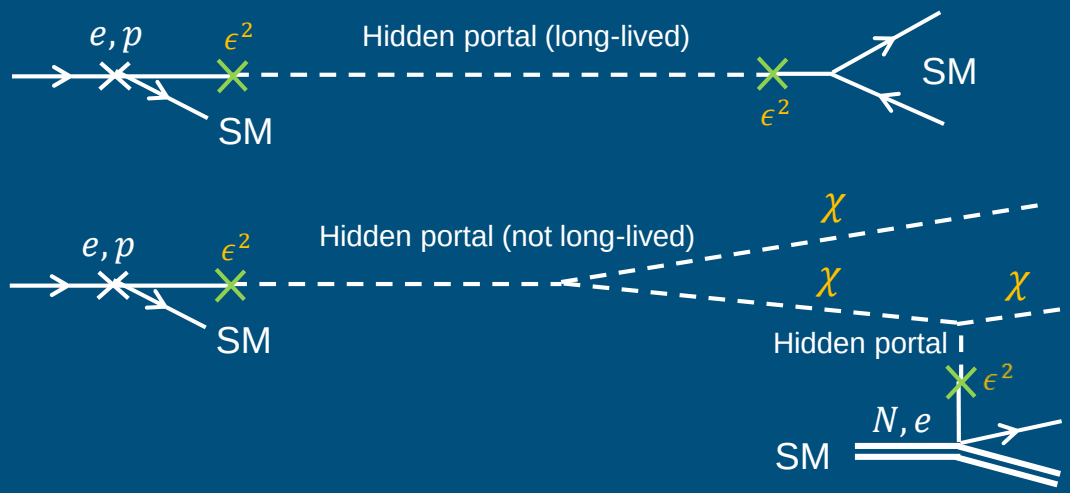


Production | Detection

Direct



Decay signature ("displaced vertex)
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Dark matter scattering
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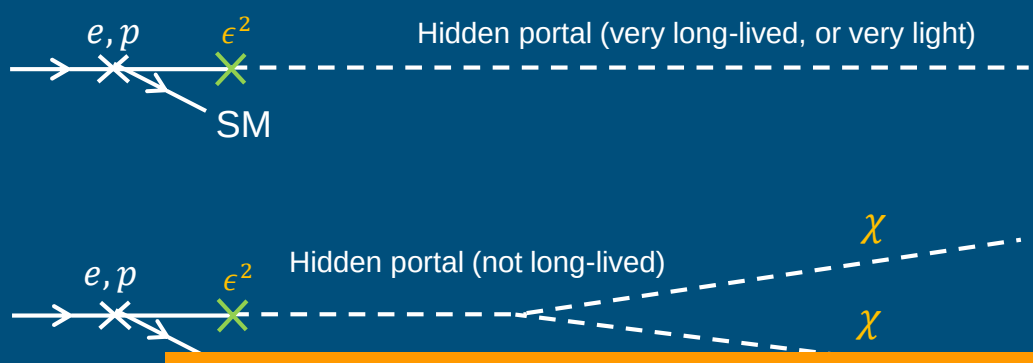

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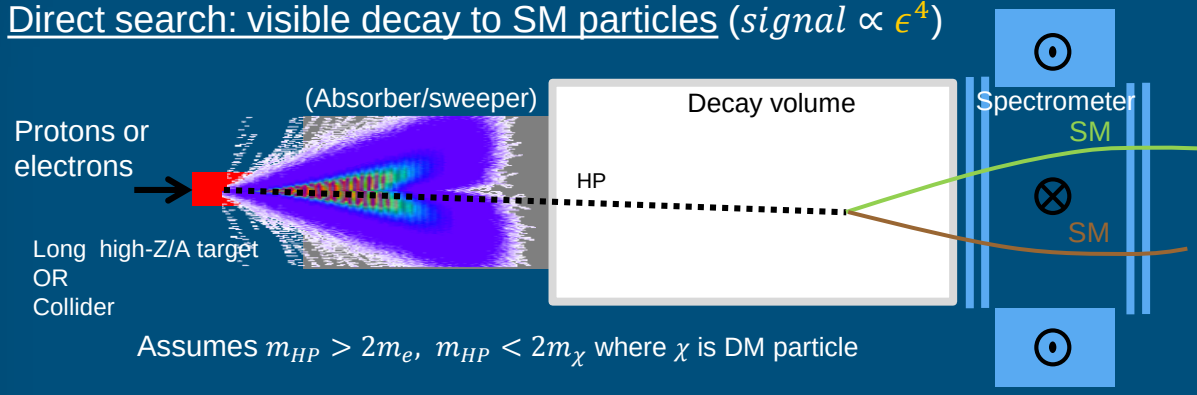
If $m_{HP} > 2m_{DM}$
Escape detector
Missing energy/momentum/mass

Experimental challenge ➔ Intensity Frontier

Experimental techniques

- Direct search: visible decay to SM particles ($signal \propto \epsilon^4$)



Assumes $m_{HP} > 2m_e,\ m_{HP} < 2m_\chi$ where χ is DM particle

"Fixed target mode setups":
NA62++@CERN (p@400, 10^{18})
HPS, APEX, DarkLight@JLAB (e@1-10)
SHiP@CERN (p@400, 2×10^{20}),
SeaQuest@FNAL (p@120, 10^{18}–10^{20})
(LBNF@FNAL)

"Collider mode setups":
ATLAS, CMS, LHCb @LHC (no absorbers)
BELLE2@sKEKB (no absorber)
FASER@LHC
MATHUSLA@LHC (no spectrometer)

Experimental techniques

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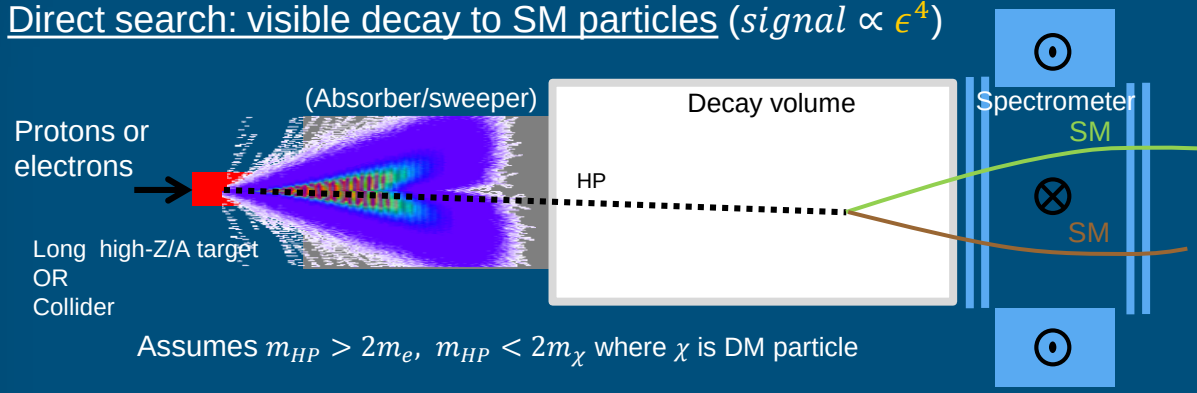

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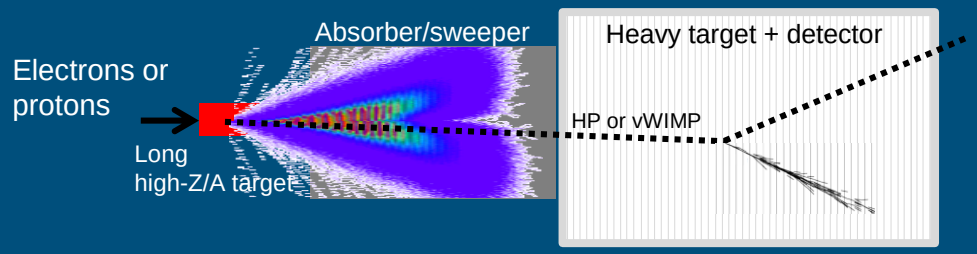
- Direct search: Scattering off atomic electrons and nuclei ($signal \propto \epsilon^4$)



"Fixed target mode setups":
BDX@JLAB (e@11, 10^{22}),
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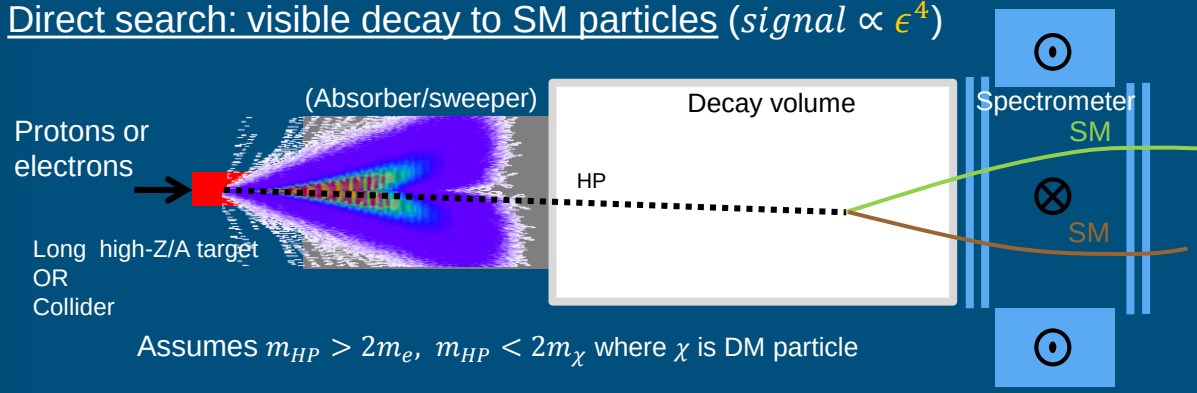
SHiP@CERN (p@400, 2×10^{20})
(interest for BDX-like
experiments at
LNF, Mainz (MESA),
SLAC, Cornell…)

Experimental techniques

- Direct search: visible decay to SM particles ($signal \propto \epsilon^4$)



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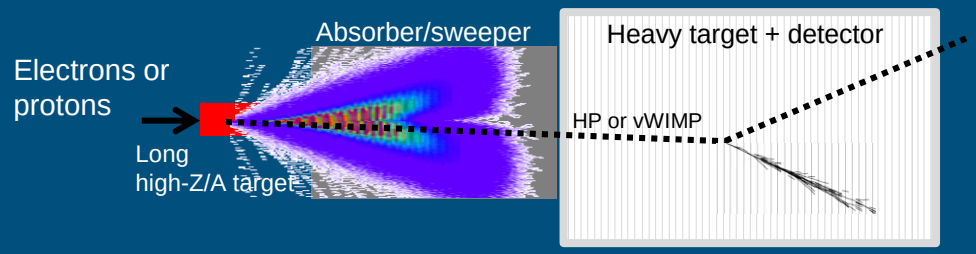

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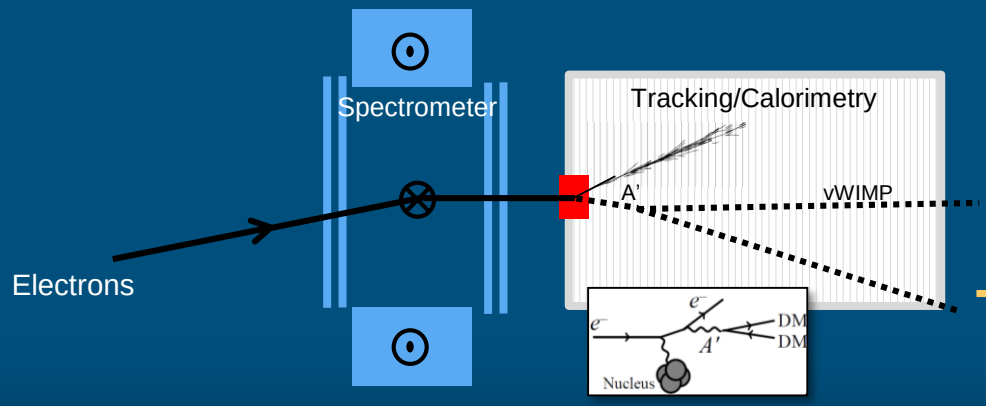
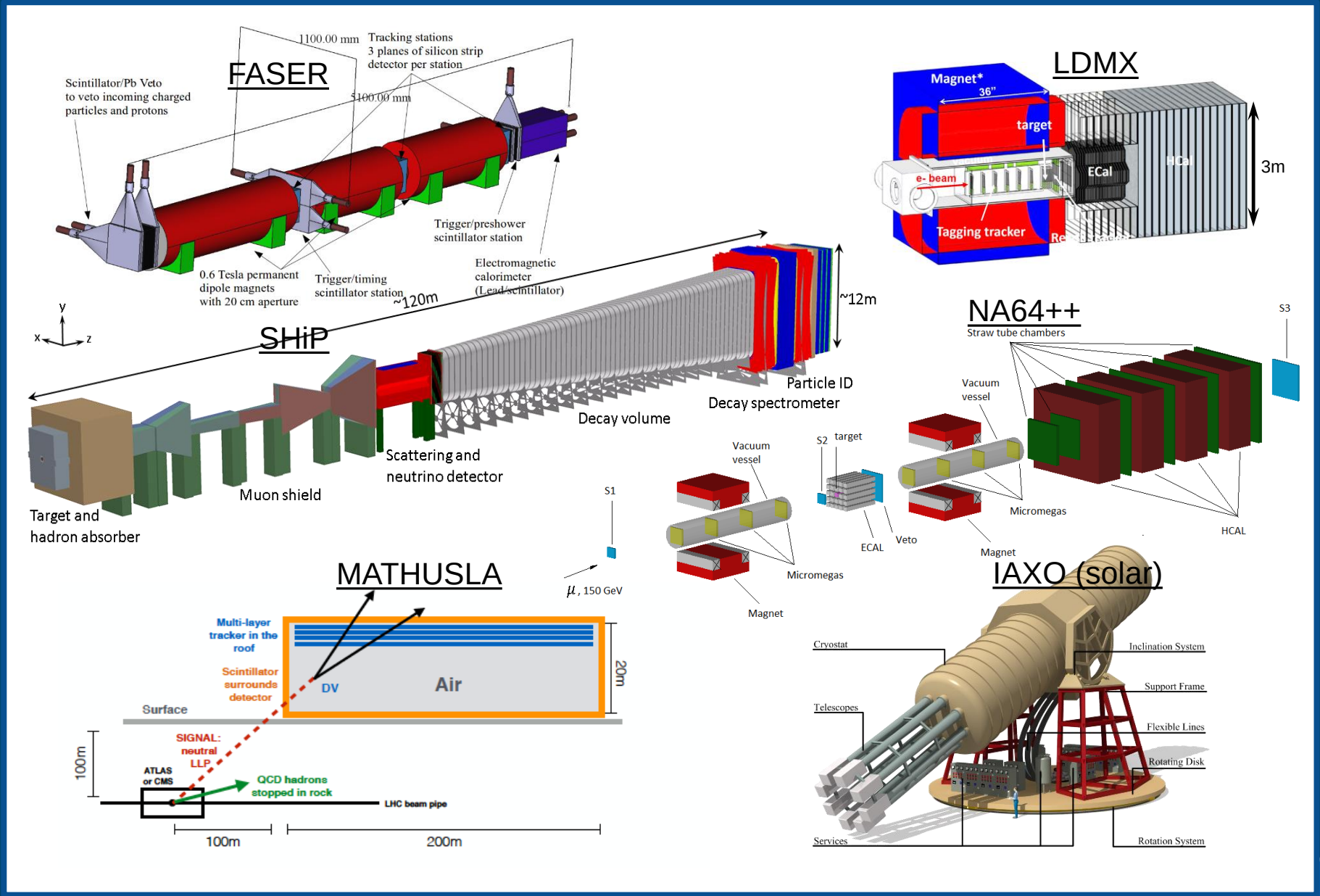
- Indirect search: Missing energy/momentum/mass ($signal \propto \epsilon^2$)



NA64/NA64++@CERN (e@100, 10^{12})
LDMX@SLAC/CERN (e@8-16, 10^{16})

➔ *Operating with electrons (production/detection) assumes vector portal*

Some new options for CERN



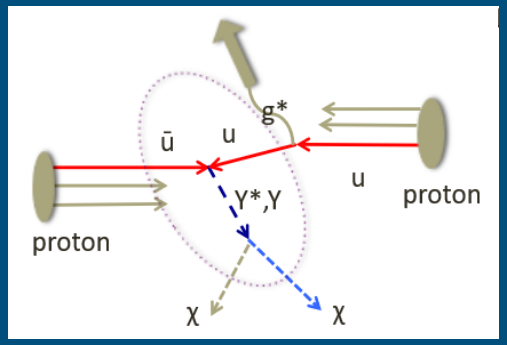
Opportunities for CERN

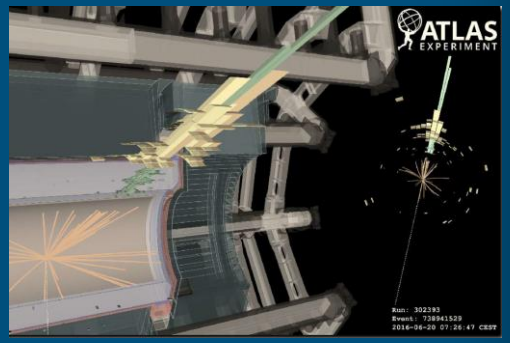
- Summary of the Physics Beyond Collider working group:

Proposal	Main Physics Cases	Beam Line	Beam Type	Beam Yield
sub-eV mass range:				
IAXO	axions/ALPs (photon coupling)	–	axions from sun	–
JURA	axions/ALPs (photon coupling)	laboratory	LSW	–
CPEDM	p, d oEDMs	EDM ring	p, d	–
	axions/ALPs (gluon coupling)		p, d	–
LHC-FT	charmed hadrons oEDMs	LHCb IP	7 TeV p	–
MeV-GeV mass range:				
SHiP	ALPs, Dark Photons, Dark Scalars LDM, HNLs, lepto-phobic DM, ..	BDF, SPS	400 GeV p	$2 \cdot 10^{20}$/5 years
NA62^{++}	ALPs, Dark Photons, Dark Scalars, HNLs	K12, SPS	400 GeV p	up to $3 \cdot 10^{18}$/year
NA64^{++}	ALPs, Dark Photons, Dark Scalars, LDM	H4, SPS	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	$+ L_\mu - L_\tau$	M2, SPS	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	~ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
AWAKE/NA64	Dark Photon	AWAKE beam	30-50 GeV e^-	10^{16} eot/year
RedTop	Dark Photon, Dark scalar, ALPs	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA200	Weak-scale LLPs, Dark Scalar, Dark Photon, ALPs, HNLs	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs, HNLs, $B - L$ gauge bosons	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
CODEX-b	Dark Scalar, HNLs, ALPs, LDM, Higgs decays	LHCb IP	14 TeV p	300 fb^{-1}

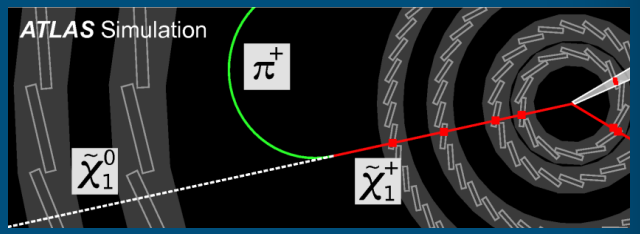
Searches for Long-Lived Particles at LHC

- Access to higher masses
  - ➔ Includes also Dark Matter candidates from SUSY and Extra Dimensions models: Neutralino, sgoldstino, axino, saxion,…)
- Signatures:
  - Mono-jet + missing transverse energy

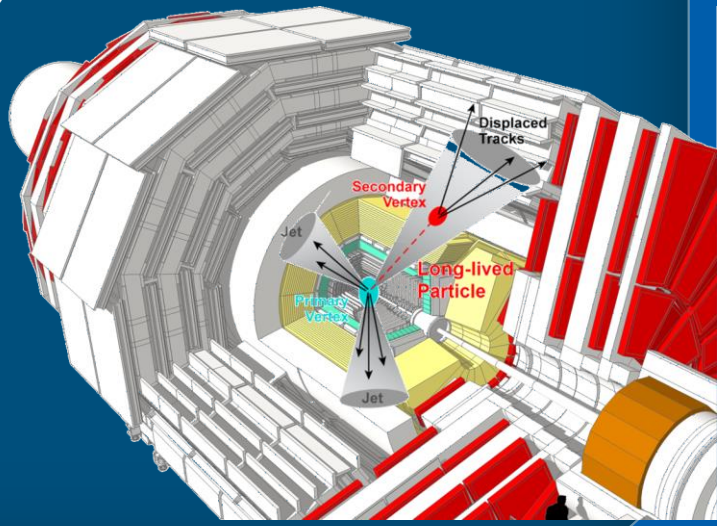




  - Disappearing tracks



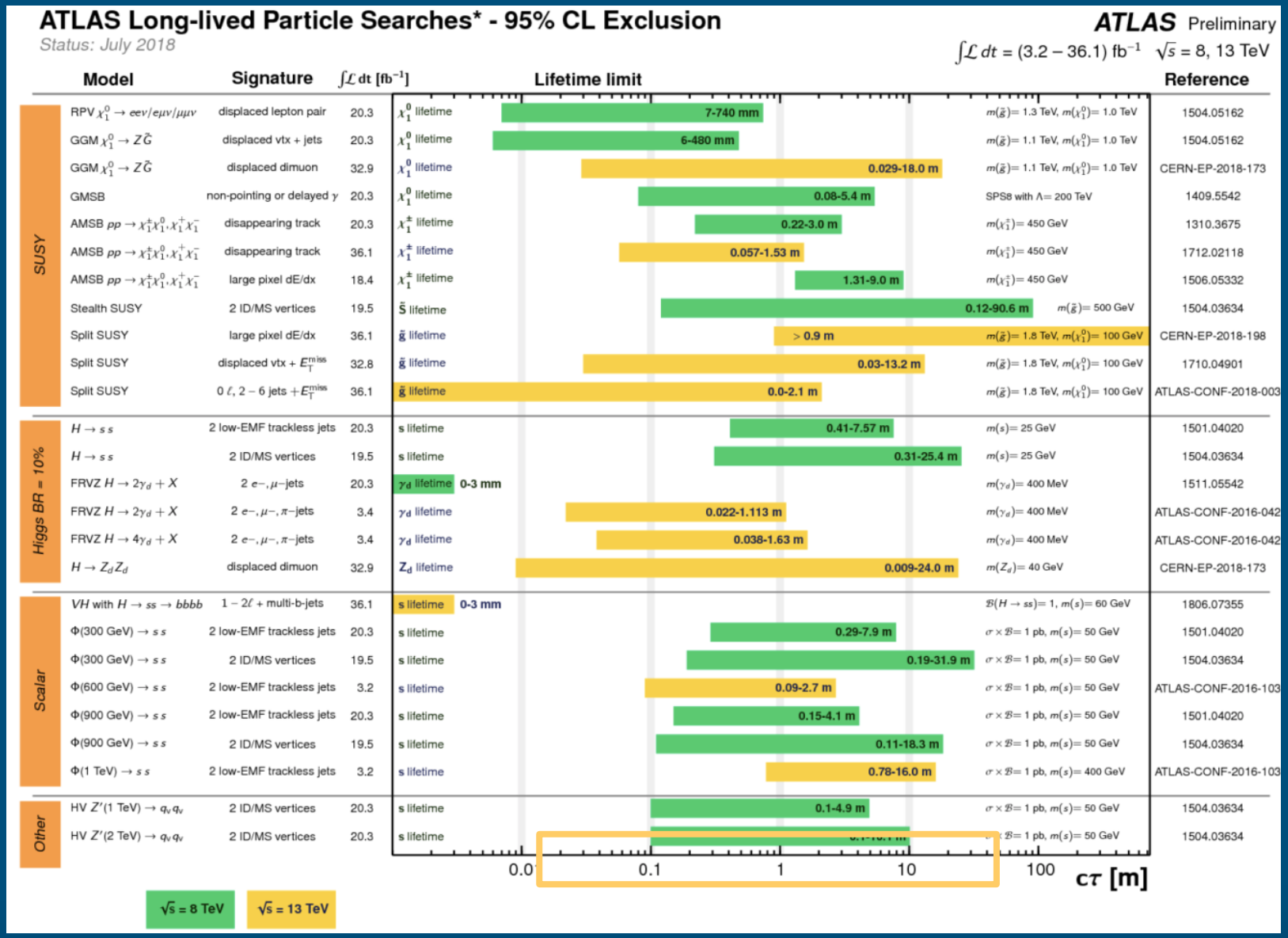
  - Long-lived particle search with displaced vertices (leptons/jets)



  - Invisible Higgs decays $pp \rightarrow Z(\rightarrow ll)H(\rightarrow invisble)$

➔ Very challenging with the increased pileup in the future

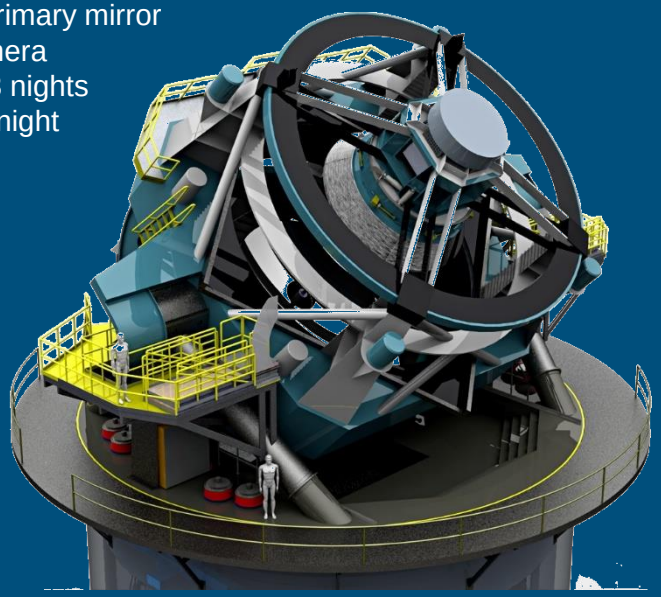
Searches for Long-Lived Particles at LHC

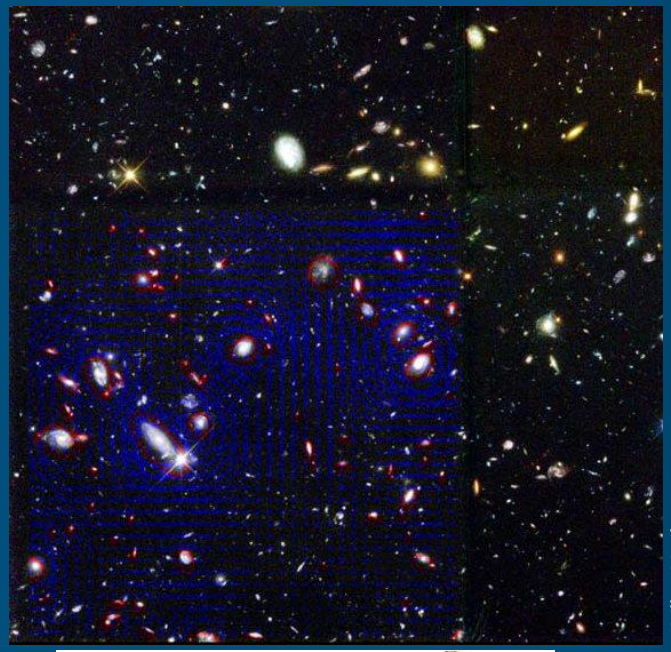


Space prospects - Indirect detection

- Weak gravitational lensing to identify and characterize DM structures – Wide area sky surveys
  - Ongoing: Dark Energy Survey (DES), Kilo-Degree Survey, Hyper Suprime-Cam, Pan-STARRS,
  - Future: Large Synoptic Survey Telescope (LSST), start 2022

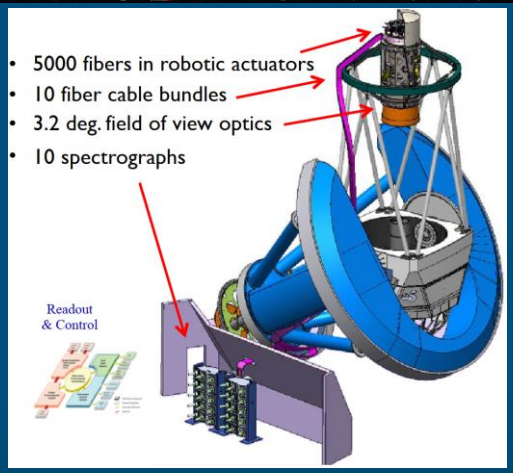
Survey of 30 billion objects expected in 10 years
- 8.4 m diameter primary mirror
- 3.2 gigapixel camera
- Full-sky scan in 3 nights
- 15 terabyte data/night





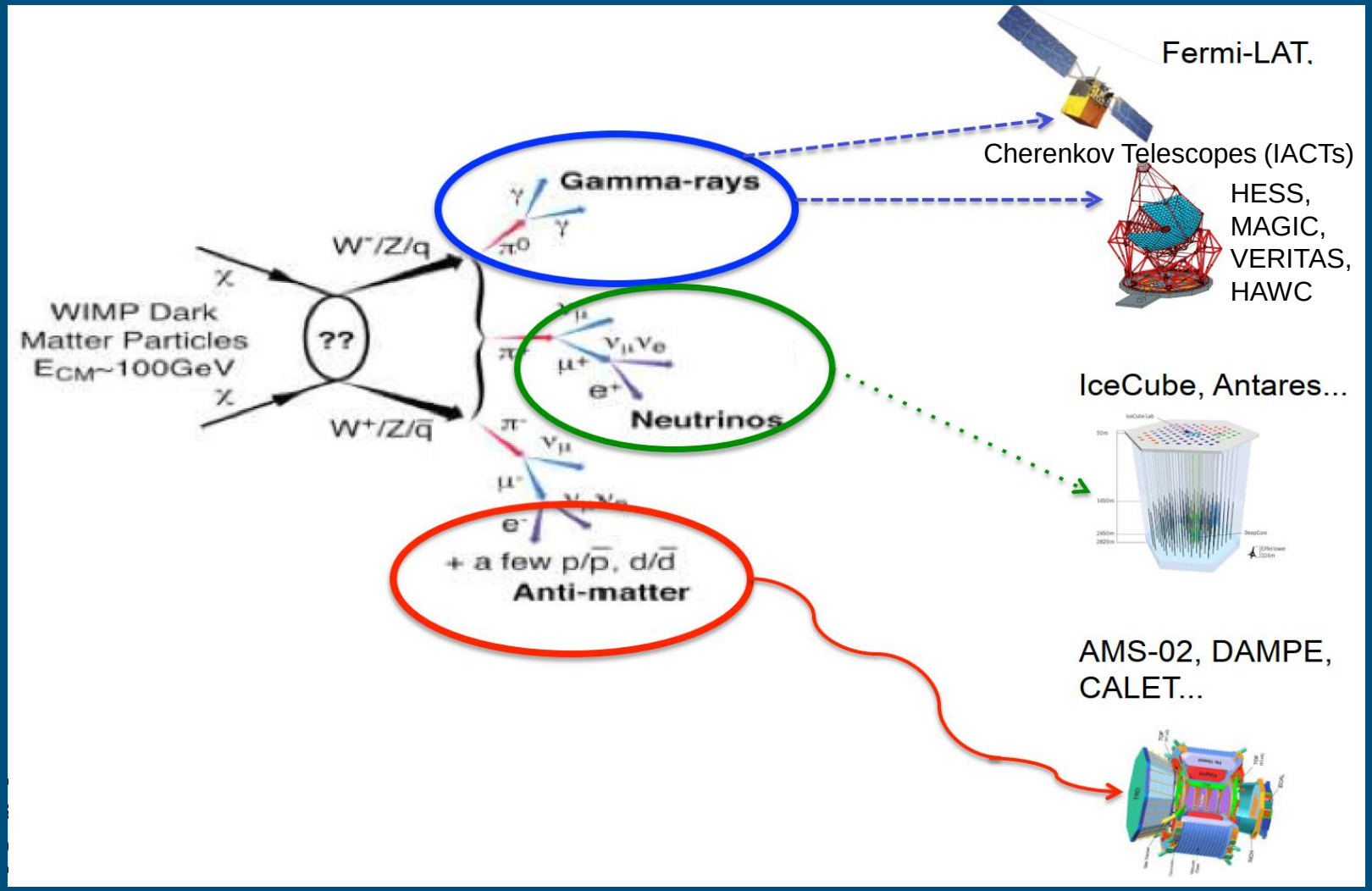
Mike Hudson

- Small scale clustering at large redshift ("Lyman-α forest")
  - Dark Energy Spectroscopic Instrument (DESI), start 2019



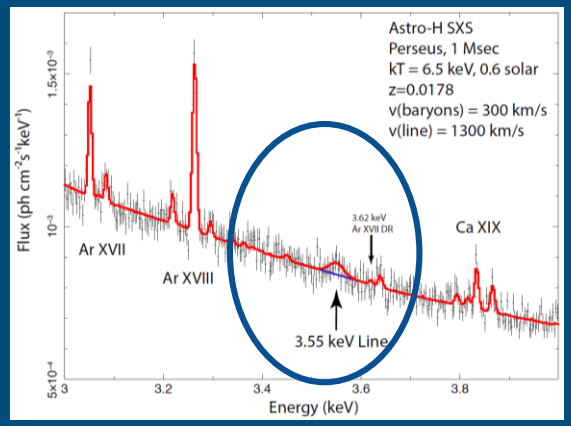
Space prospects - indirect detection

- Observation of decay/annihilation or decay products of cosmological WIMPs



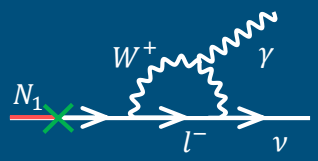
Indirect detection – interesting hints?

- Hint of decaying Dark Matter?



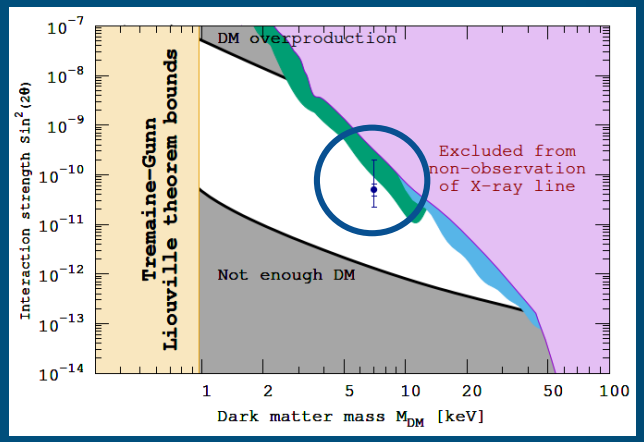
ApJ (2014) [1402.2301]
PRL (2014) [1402.4119]

E.g. 7 keV sterile neutrino



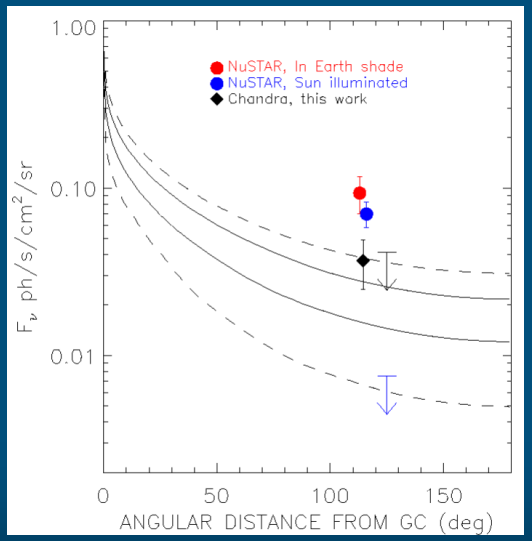
$$E_\gamma = \frac{M_N c^2}{2}$$

$$\tau \sim 10^{28}\ years$$



- More data to confirm/reject was expected from Astro-H/Hitomi X-ray telescope which was lost few weeks after launch on February 17, 2016

- Waiting for a new high-resolution telescope, observation has been substantiated with data from NuSTAR (11σ) and Chandra (3σ)



Cappelluti+'17

What next?
- ➔ New telescope from JAXA?
- ➔ Large ESA X-ray Athena+ mission 2028
- ➔ Or discovery of HNLs at accelerators!...

Space prospects – direct detection (WIMP)

- *Observation of cosmological Dark Matter by WIMP-nucleus/electron collision*

Crystals (NaI, Ge, Si)
Cryogenic Detectors
Liquid Noble Gases

Tracking:
DRIFT, DMTPC
MIMAC, NEWS
NEWAGE

Superheated Liquids:
PICO
SIMPLE

CUORE

Phonons

SuperCDMS
EDELWEISS

CRESST
COSINUS

Charge

Light

CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

XENON, LUX/LZ
ArDM, ***Panda-X***
DarkSide, DARWIN

DEAP-3600*, CLEAN*
DAMA*, KIMS*
XMASS*, COSINE*
ANAIS, ***SABRE***

M. Schumann (Freiburh)

+ Axion searches (IAXO, JURA)

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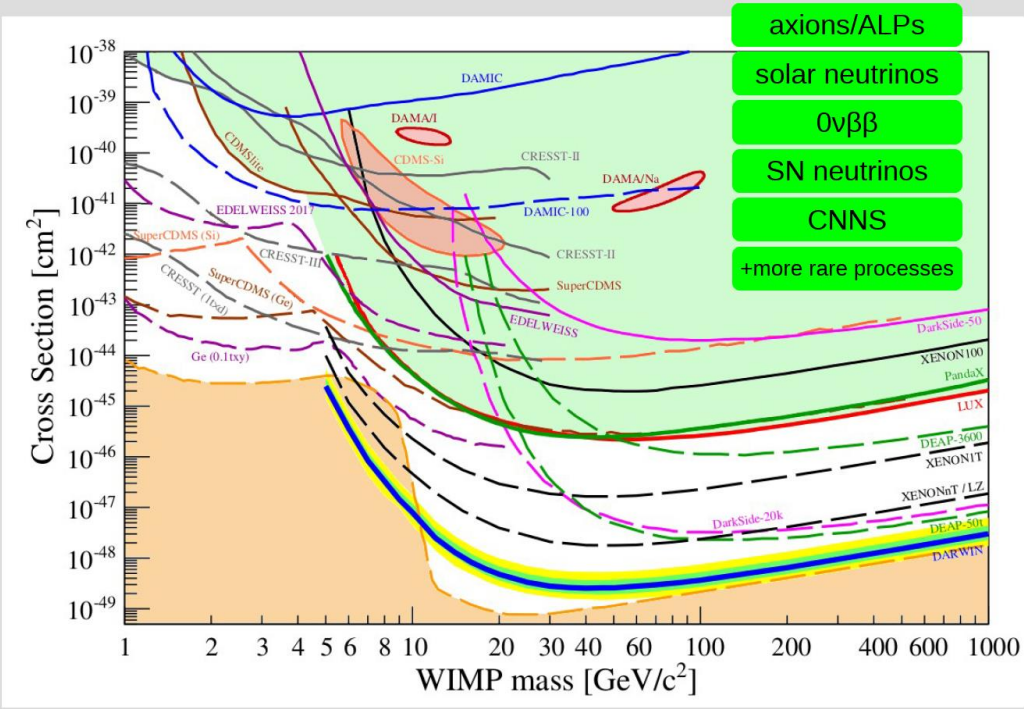

CoGeNT
CDEX
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NEWS (gas)

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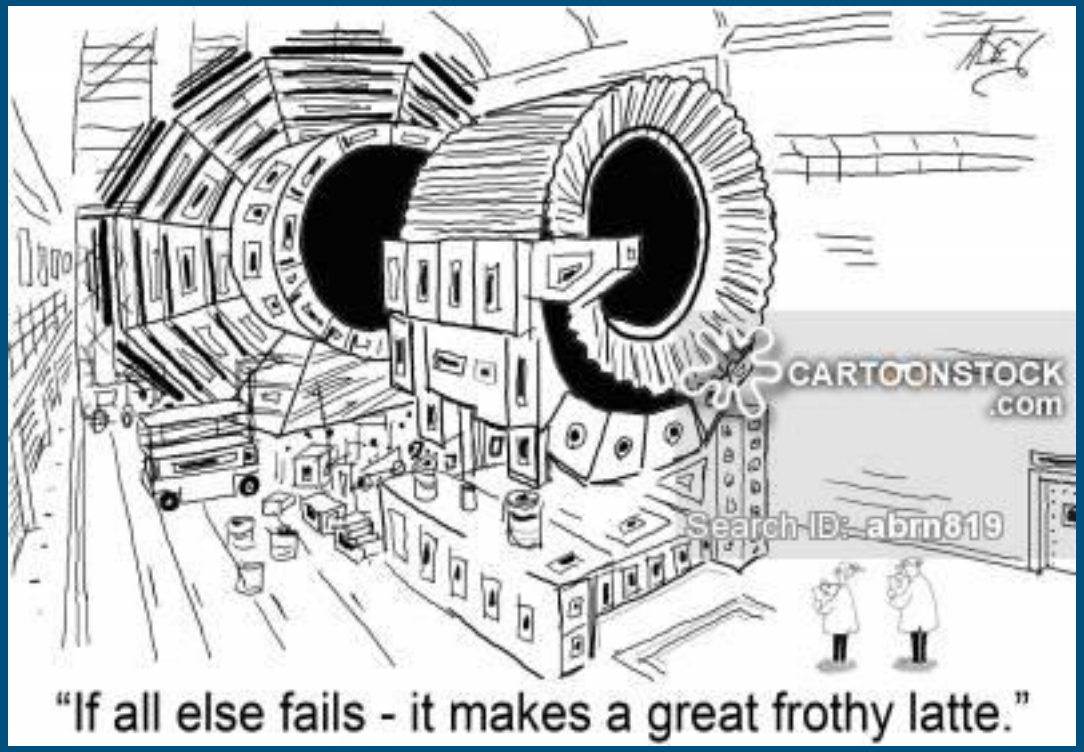
Back to Earth again!

Experimenting with Dark Sector



Any resemblance to actual experiment, living or dead, is purely coincidental

Conclusions

We worried/y about finding just a Standard Model Higgs….

Courtesy: Keyhole Nebula

Conclusions

We worried/y about finding just a Standard Model Higgs….

…but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

Courtesy: Keyhole Nebula

In addition to searches at the high energy frontier,
future lies in a wide and complementary physics program of precision measurements and models with very weak couplings:

- W, Z, Higgs, top precision measurements
- Flavour physics
- Dark Matter and complex Hidden Sectors searches
- Neutrino physics

➔ Intensity Frontier

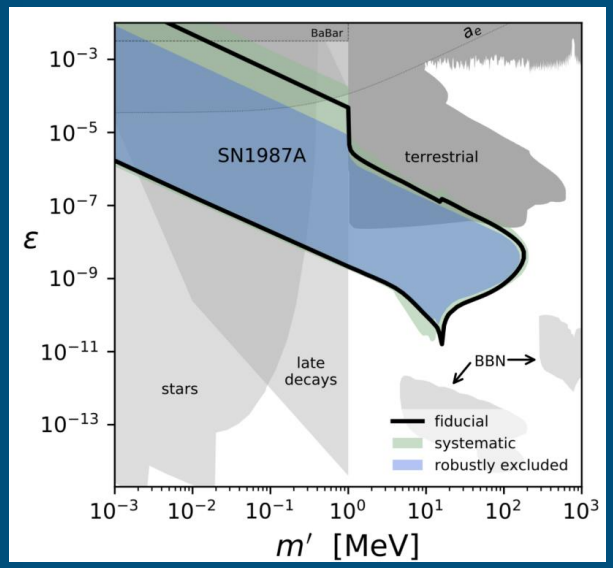
➔ Interest and effort in HS physics has been increasing rapidly in the last few years!

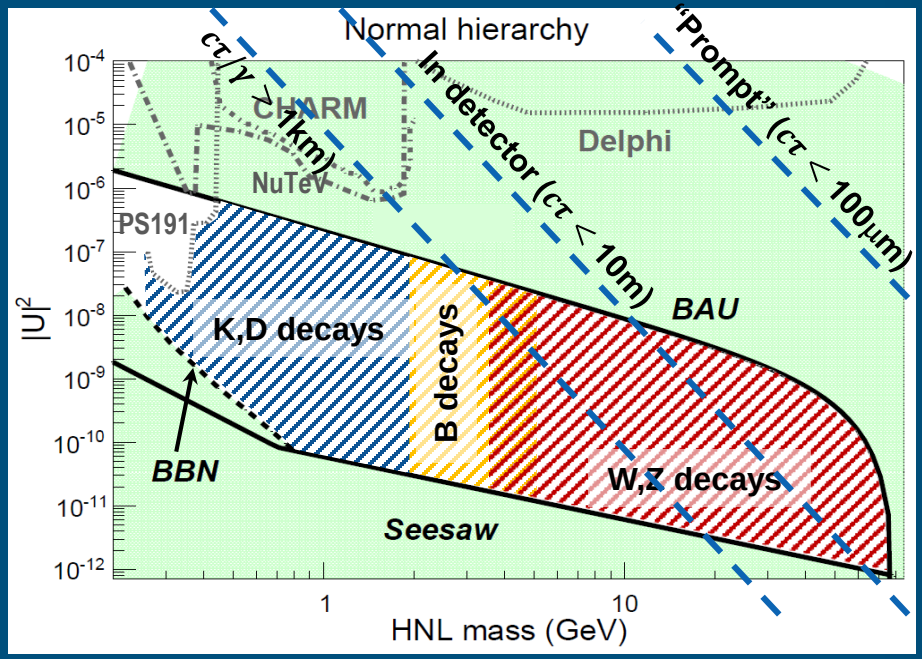
The implications of a discovery is very difficult to overestimate….

<u>Thanks to the superb operation of the accelerators, and collaboration with all departments on developing the future in this domain!</u>

Dinner time!

"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."


BaBar
∂e
SN1987A
terrestrial
stars
late decays
BBN
fiducial
systematic
robustly excluded
ε
m′ [MeV]


Normal hierarchy
cτ/γ > 1km)
In detector (cτ < 10m)
"Prompt" (cτ < 100μm)
CHARM
NuTeV
Delphi
PS191
K,D decays
B decays
BAU
BBN
W,Z decays
Seesaw
|U|²
HNL mass (GeV)
1411.5230v2