Low mass DM in SUSY?

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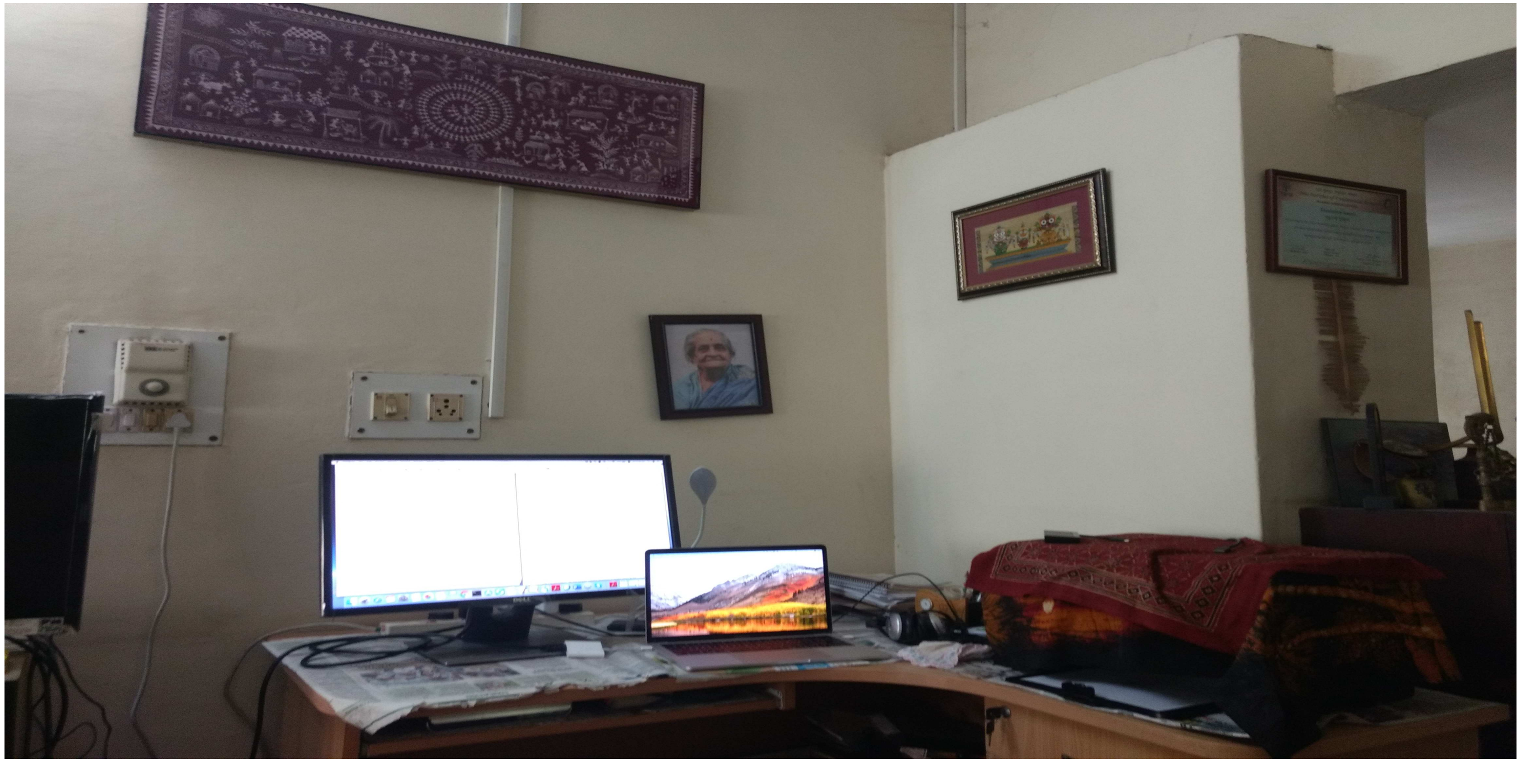


My environment: Effect of the pandemic!

- Current frontiers of exploration in HEP

- DM and questions it asks us.

- How light can it be in SUSY?

1 $\tilde{\chi}_1^0$ LSP: pMSSM, NMSSM

2 $\tilde{\nu}_R$: cMSSM,pMSSM,NMSSM

Based on:

1)R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838;

2)R. K. Barman, G. ,Belanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata,2006.07854;

3)R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Invited Review for EJPC (to be uploaded on the arXive),

4)R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbolelight DM in pMSSM at the HL and HE LHC: thermal and nonthermal case; In preparation.

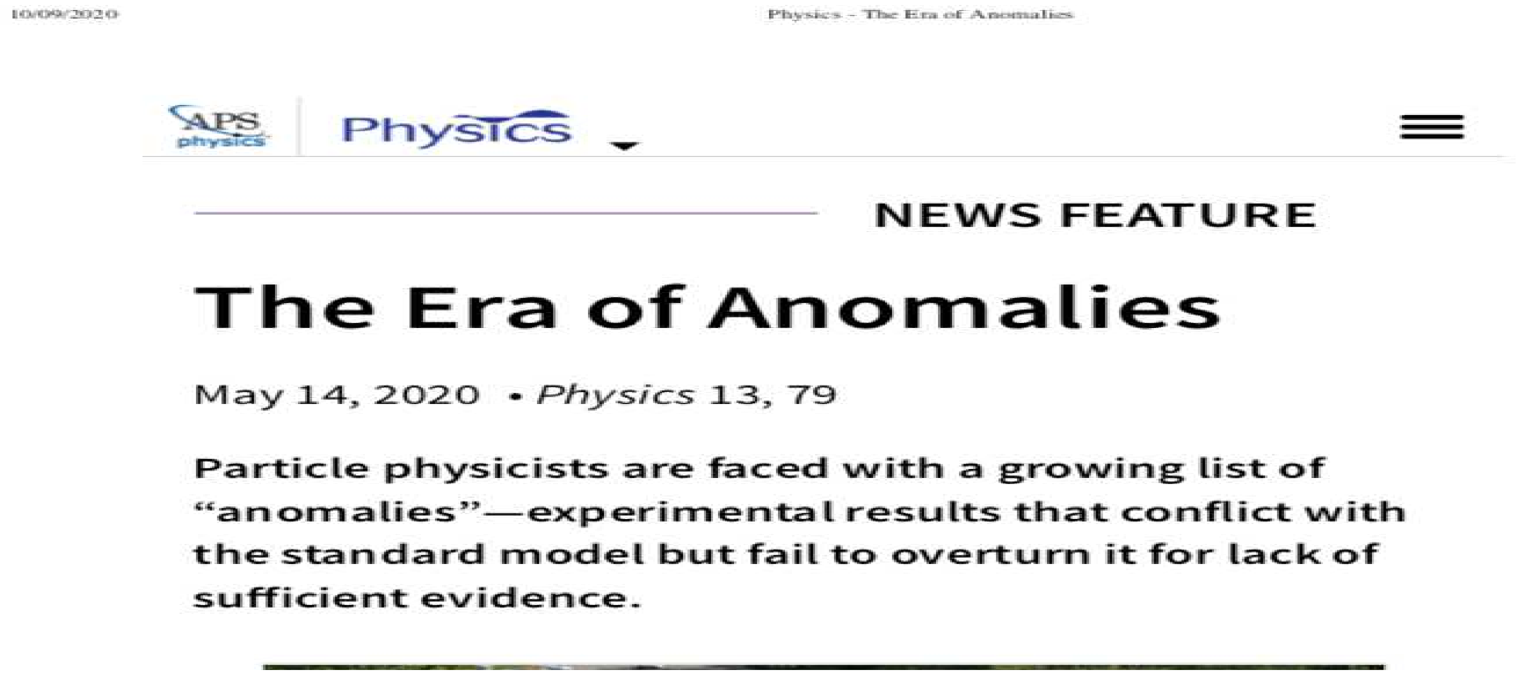
Particle physics finds itself in a very peculiar place.

To steal from 'A tale of two cities': (Apologies to Charles Dickens!)

It is the best of times , it is the worst of times

We have found the SM Higgs, proved the SM, we have no glimmer of BSM that the Higgs properties promise!

A decade after the Higgs discovery now we are looking for BSM through whatever footprints it might leave, in the form of deviations from the SM! Indeed that is the focus of this conference!



10/09/2020 Physics - The Era of Anomalies

NEWS FEATURE

The Era of Anomalies

May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of "anomalies"—experimental results that conflict with the standard model but fail to overturn it for lack of sufficient evidence.

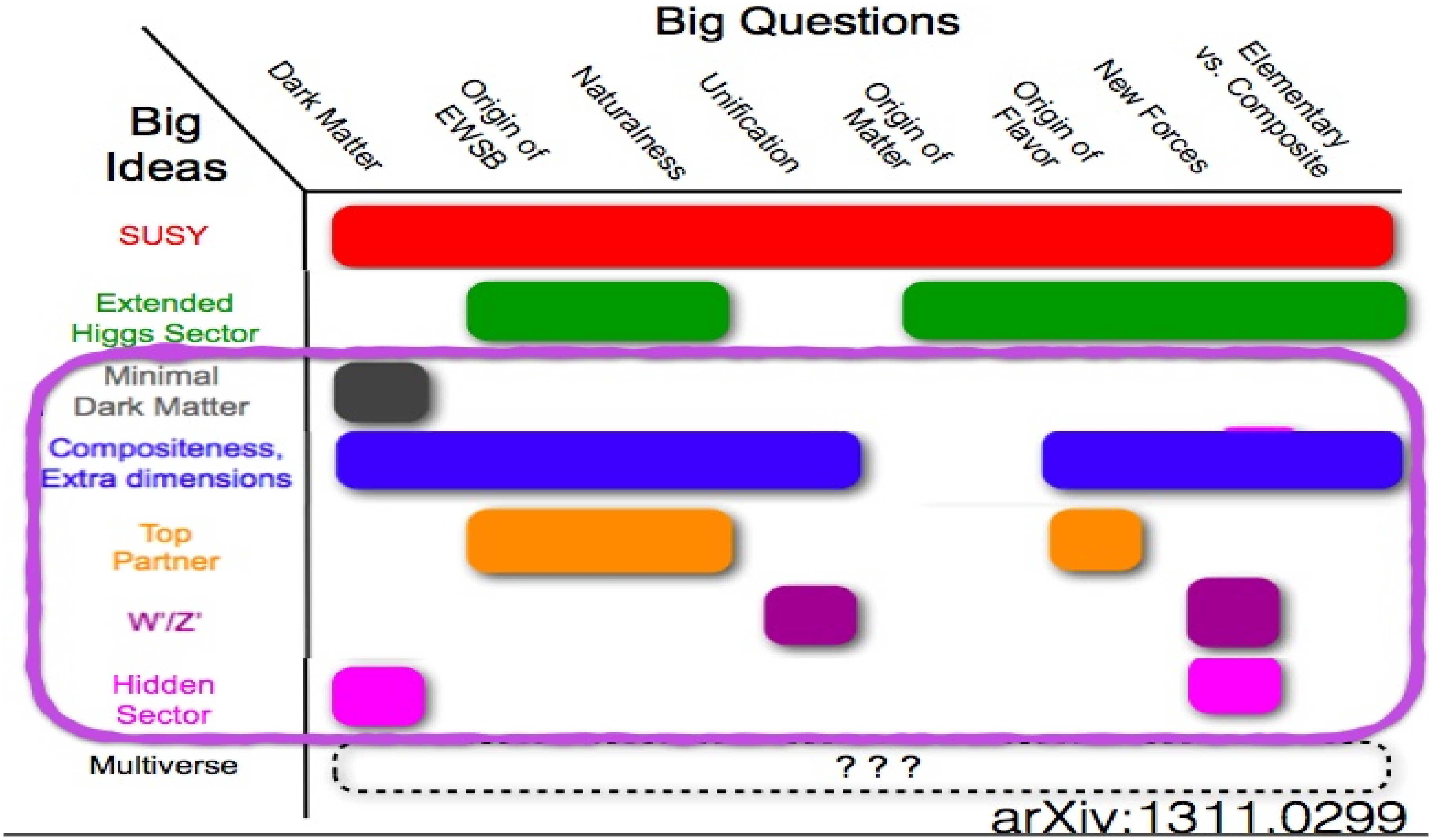
Data driven path of BSM! This is most probably the future!

- **Dark Matter makes up 27% of the Universe.!**
- ~~We have direct evidence for the nonzero ν masses~~
- ~~Need to understand why matter dominates the Universe:~~

~~Matter-Antimatter Asymmetry in the Universe!~~

- **We have found a light Higgs boson at the LHC!**
- ~~We feel the force of gravity but do NOT have a QUANTUM description!~~
- ~~Cosmic Acceleration.~~

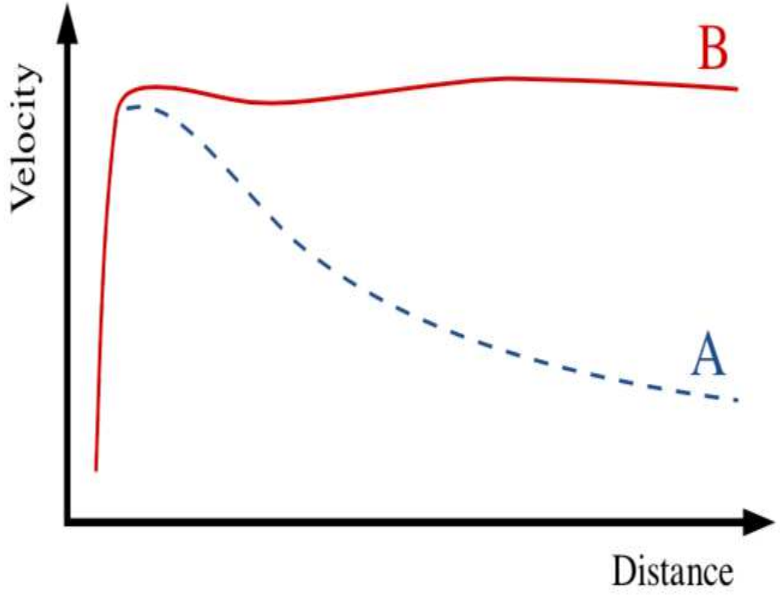
My talk will deal with implications of only two of these.



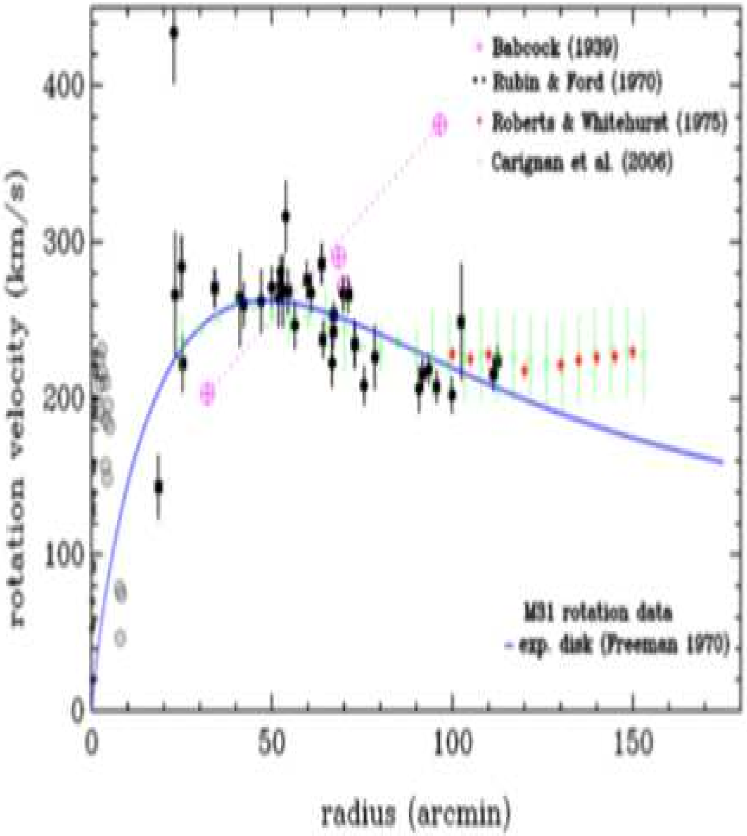
arXiv:1311.0299

For a nice historical review: G. Bertone and D. Hooper, Rev. Mod. Phys. 90 (2018) no.4, 045002 arXiv:1605.04909

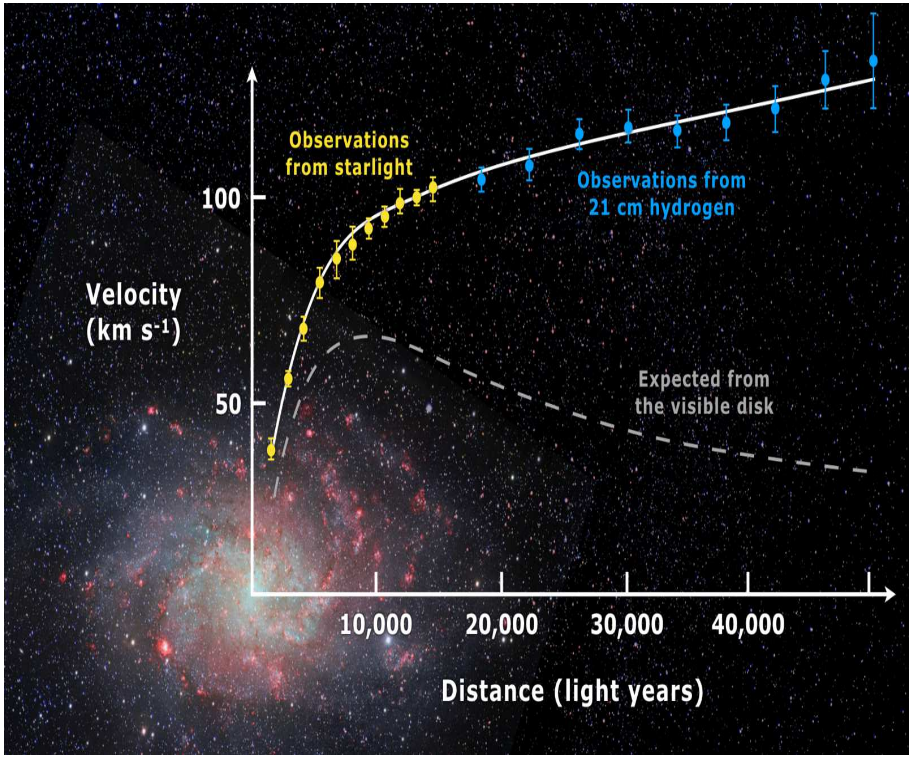
Astrophysical evidence started from Lord Kelvin, but for most people from Zwicki who tried to measure mass of the galaxy from dynamics of galaxy clusters. Was really put firmly in pace by Vera Rubin.



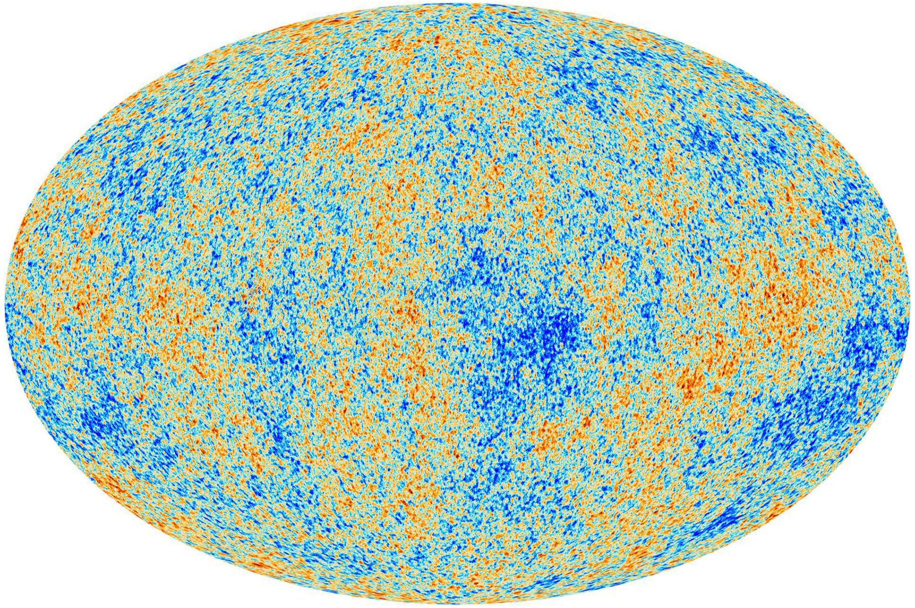
tiny Data



1970: Galaxy M31



Galaxy M33



Bullet Cluster

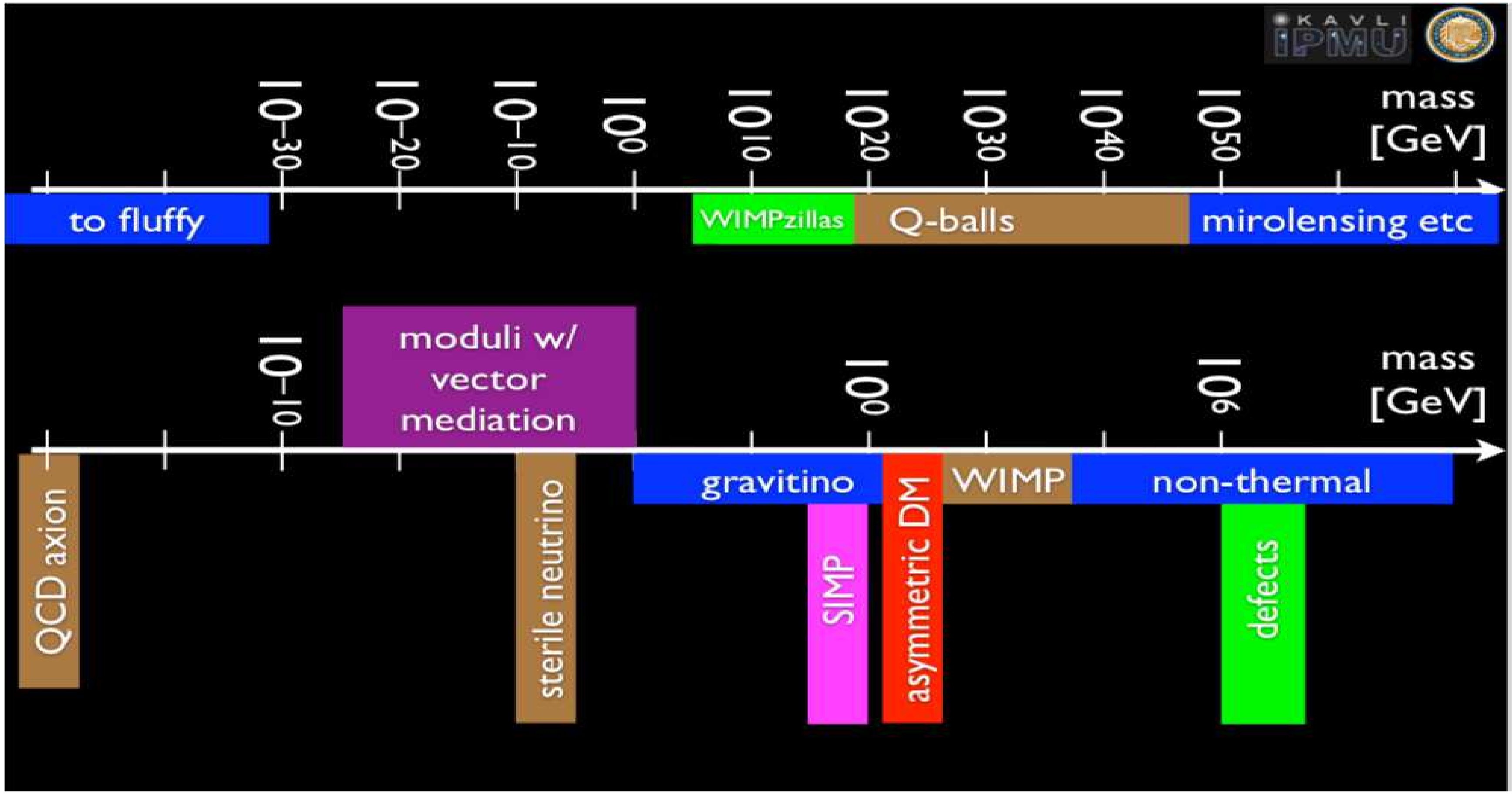
Planck CMB anisotropy.

1)Astrophysical evidence is strong. These are relics left over from the early universe.

2)The expected relic density predictions are determined by the theoretical understanding of early universe and particle content of the particles in the early universe and their interactions. **Truly astro-particle physics object!**

3)Strictly speaking we do not have any observational information which will constrain its mass.

4)Has implications for structure formation in the Universe and hence is constrained by that. What is 'liked' is a particle which would fall out of thermal equilibrium with radiation in the early universe when it is non relativistic. 'Cold Dark Matter' : CDM . The weakly interacting massive particle (WIMP) paradigm ruled for a long time. But it is under tension!


mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
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10^{20}
10^{30}
10^{40}
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to fluffy
WIMPzillas
Q-balls
mirolensing etc
mass [GeV]
10^{-10}
10^{0}
10^{6}
moduli w/ vector mediation
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

BSM Candidates?

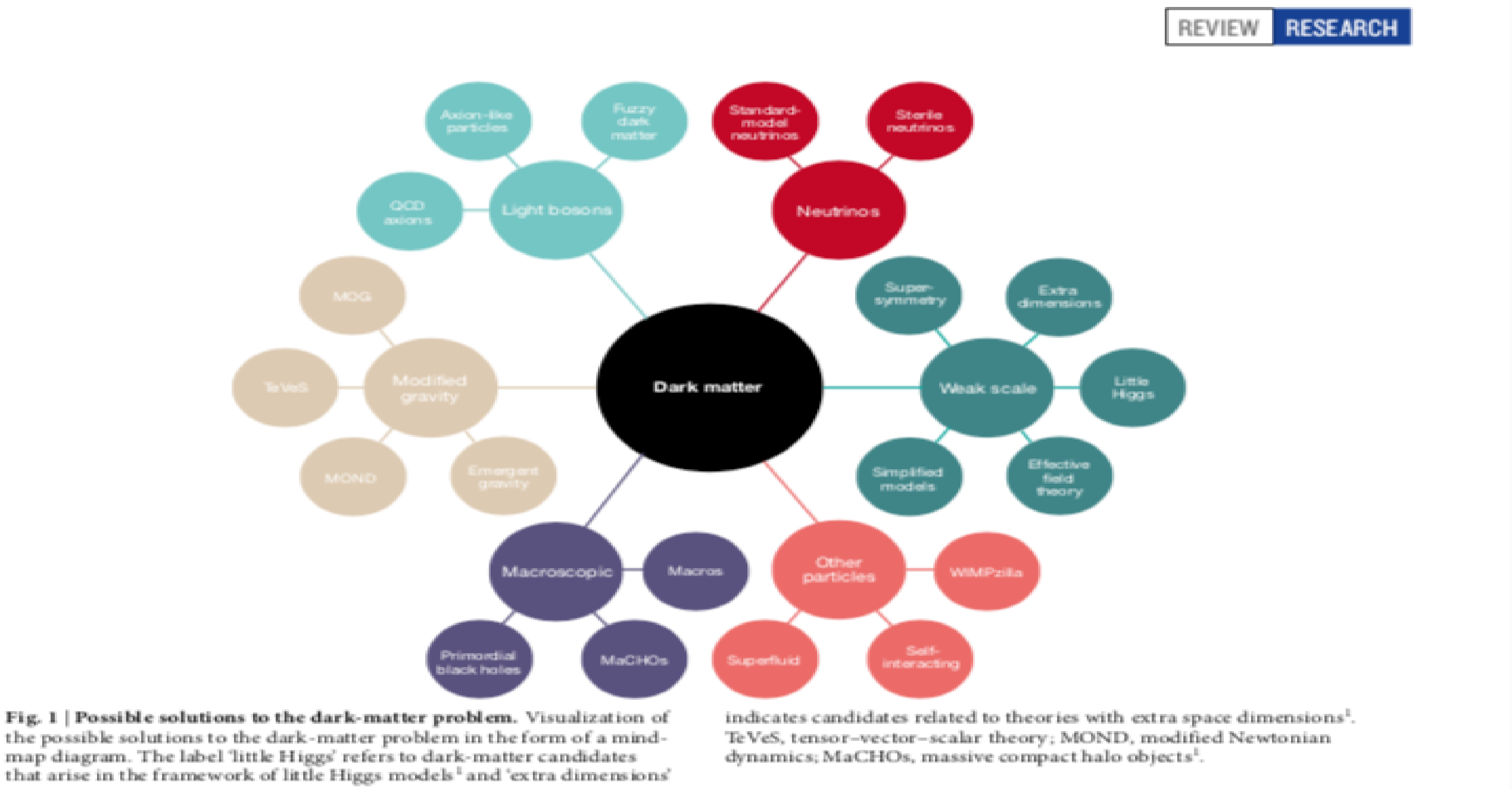


Fig. 1 | Possible solutions to the dark-matter problem. Visualization of the possible solutions to the dark-matter problem in the form of a mind-map diagram. The label 'little Higgs' refers to dark-matter candidates that arise in the framework of little Higgs models[1] and 'extra dimensions' indicates candidates related to theories with extra space dimensions[1]. TeVeS, tensor–vector–scalar theory; MOND, modified Newtonian dynamics; MaCHOs, massive compact halo objects[1].

G. Bertone and T. Tait, M.P., Nature 562 (2018) no.7725, 51-56, arXiv:1810.01668

Planck measurements and the anisotropies tell us

$$\Omega_{DM}h^2 = 0.120 \pm 0.001$$

In a model the predicted relic :

$$\Omega_{\tilde{\chi}}h^2 = \frac{m_{\tilde{\chi}} n_{\tilde{\chi}}}{\rho_c} \simeq \frac{3 \times 10^{-27} \mathrm{c}m^2 s^{-1}}{\langle \sigma_{ann} v \rangle},$$

The couplings of the DM particle which decides σ_{ann} will then decide relic density which in turn will depend on the model. Combinations of $g_{\tilde{\chi}}$ and $m_{\tilde{\chi}}$ will produce the right relic.

This expression above is for thermal relic, ie. the species abundance is decided by the temperature at which it falls out of thermal equilibrium, ie. freezes out.

In the usual scenario one assumes that the expansion of the Universe is adiabatic. If there is an entropy injection, for example decay of a heavier particle (like a heavy modulus), this can then dilute the relic density of a species.

One can thus think of various possibilities which will then give a relic different than predicted from the Ω^{FO} that I wrote above.

These are options of getting the right relic even if the thermal relic is higher or lower than allowed by the Planck data.

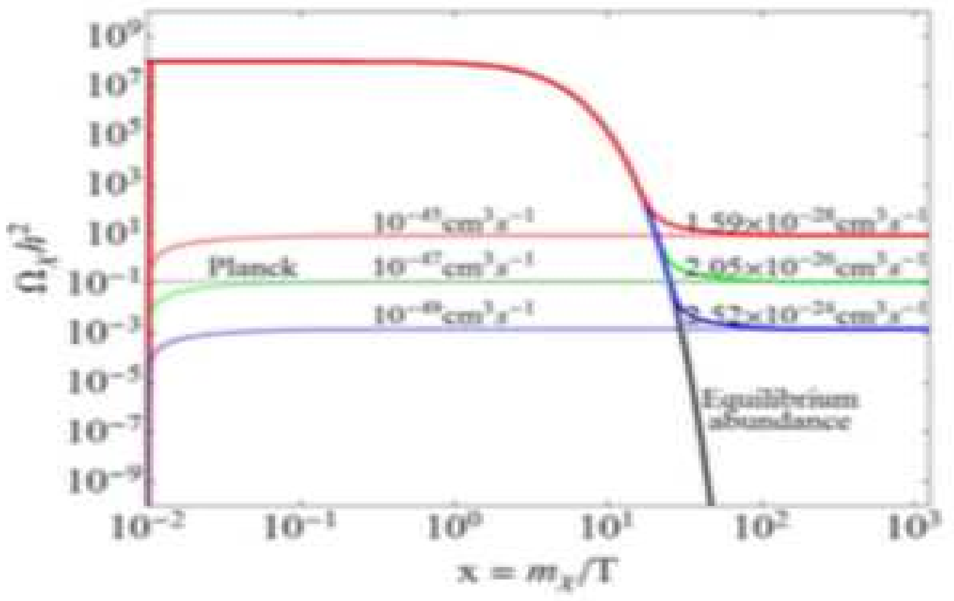


FIGURE 1 | The illustration of freeze-out and freeze-in scenarios in the evolution of thermal DM abundance as a function of $x = m_\chi/T$ for different annihilation rates. Here we have chosen $m_\chi = 100$ GeV and for the initial conditions, $m_\phi = 10^{13}$ GeV, $T_R = 10$ TeV, $B_\chi = 10^{-15}$. The horizontal band gives the observed relic density from Planck data [2].

P. S. Bhupal Dev, A. Mazumdar and S. Qutub, Front. in Phys. **2** (2014), 26, arXiv:1311.5297.

Freeze in:

$$\Omega_{\tilde{\chi}}^{FI}h^2 \simeq \frac{1.09 \times 10^{-27}}{g^{*3/2}} m_{\tilde{\chi}} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

where g^* is the average number of the effective degrees of freedom contributing to the thermal bath and g_i, Γ_i and m_i are the degrees of freedom, the decay width and the mass of the i^{th} BSM particle.

Out of Equlibrium decay of NLSP:

Another possibility is that the NLSP($\tilde{\chi}_1$) decays on a long time scale, either due to compressed spectra or small couplings, into a final state containing the LSP. In that case this 'out of equilibrium' decay of the NLSP will contribute to the relic density of the LSP.

$$\Omega_{\tilde{\chi}}^{FO}h^2 = \frac{m_{\tilde{\chi}}}{m_{\tilde{\chi}_1}} \Omega_{\tilde{\chi}_1} h^2$$

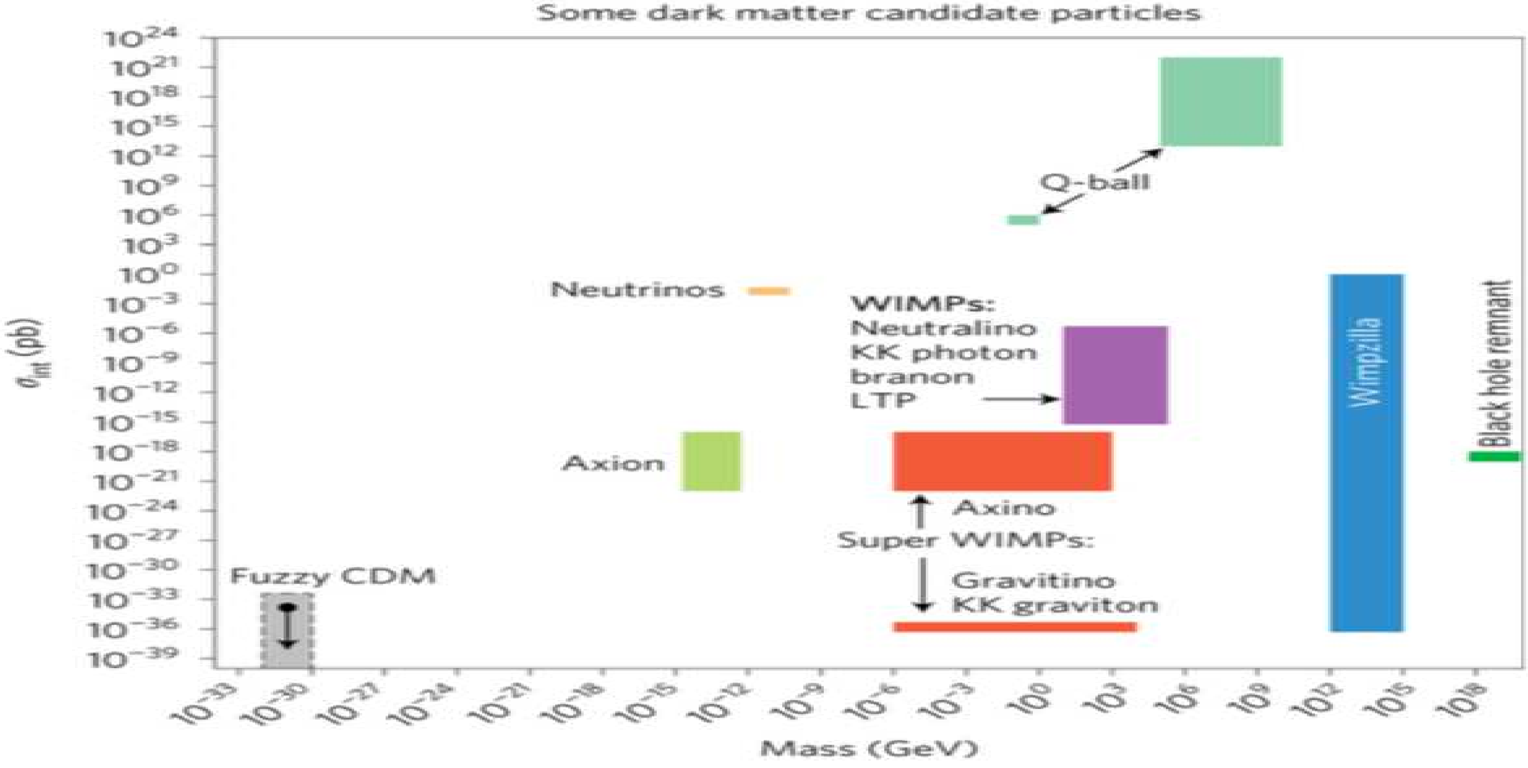
where $\Omega_{\tilde{\chi}_1}$ is the freeze-out relic density of the quasi-stable NLSP.

1) Direct detection in the deep underground experiments

2)Indirect detection via DM annihilation in areas where the DM local density is large: centre of galaxies, centre of the dwarf Spheroidal (dSph) galaxies.

3)Note that when annihilation happens in the early universe and now in galaxies for indirect detection, the velocities of the DM candidate can be different hence $< \sigma_{ann} v >$ at FO and at the present epoch can be different. Depends on the velocity dependence of the annihilation cross-section. story complicated when annihilation happens through a resonance.

4)Direct detection cross-section for pseudoscalar mediator suppressed compared to a scalar of the same interaction strength



Conrad & Reimer, Nature Physics 13 (2017) 224-231

Co-GenT, CRESST, CDMS-SI, DAMA/LIBRA:

C.E. Aalseth et al. Phys. Rev. Lett., 106:131301, 2011. arXiv: 1002.4703. G. Angloher et al. Eur. Phys. J. C, 72:1971, 2012. arXiv: 1109.0702. Z. Ahmed et al. Science, 327:1619–1621, 2010. arXiv: 0912.3592. R. Agnese et al. Phys. Rev. Lett., 111(25):251301, 2013. arXiv: 1304.4279.

R. Bernabei et al. Eur. Phys. J. C, 67:39–49, 2010. arXiv: 1002.1028; R. Bernabei et al. Eur. Phys. J. C, 74(3):2827, 2014. arXiv: 1403.4733.

The DD reports are ruled out by Xenon, LUX

The indirect detection (Fermi-LAT) reports are 'clouded' by astrophysical uncertainties.

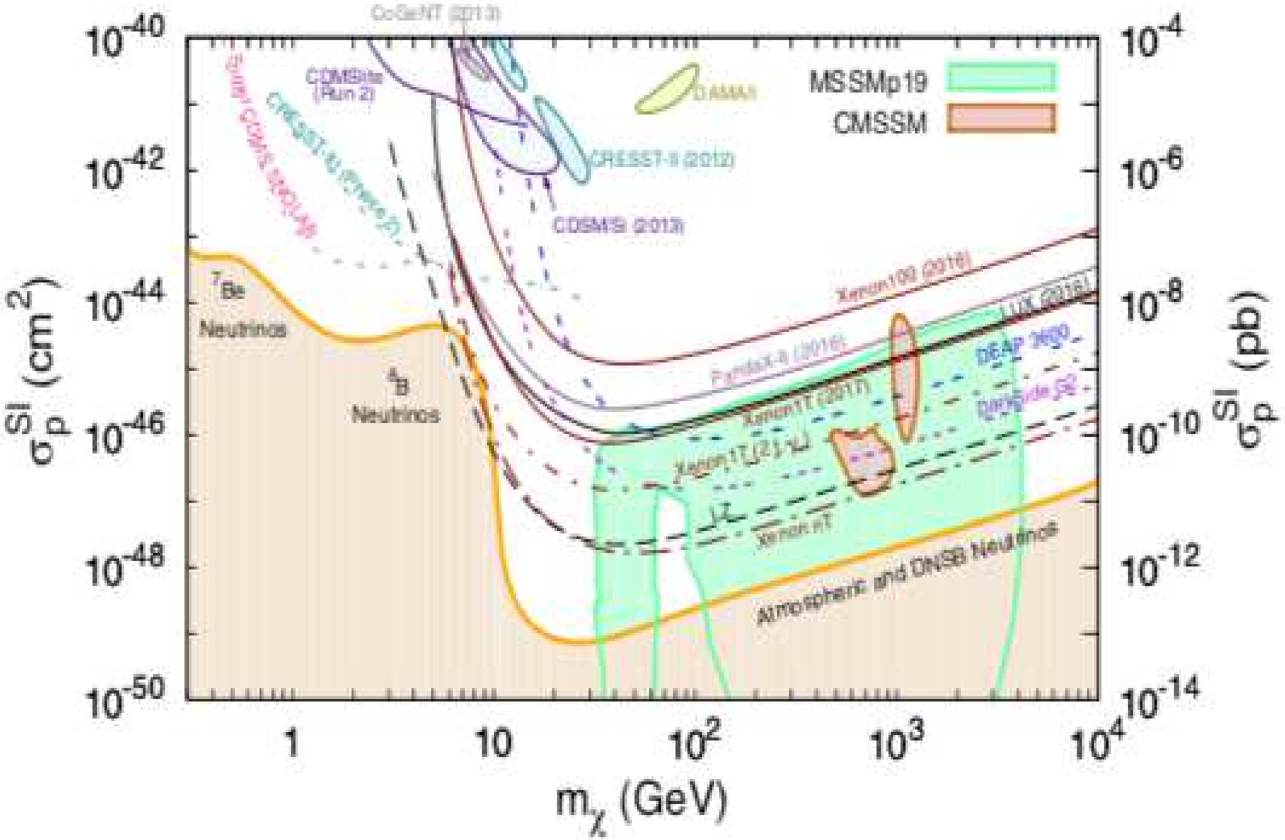
L. Goodenough et al. arXiv: 0910.2998. D. Hooper et al. Phys. Lett. B, 697:412–428, 2011. arXiv: 1010.2752, D. Hooper et al. Phys. Rev. D, 84:123005, 2011. aeXiv: 1110.0006, T. Daylan et al. Phys. Dark Univ., 12:1–23, 2016.

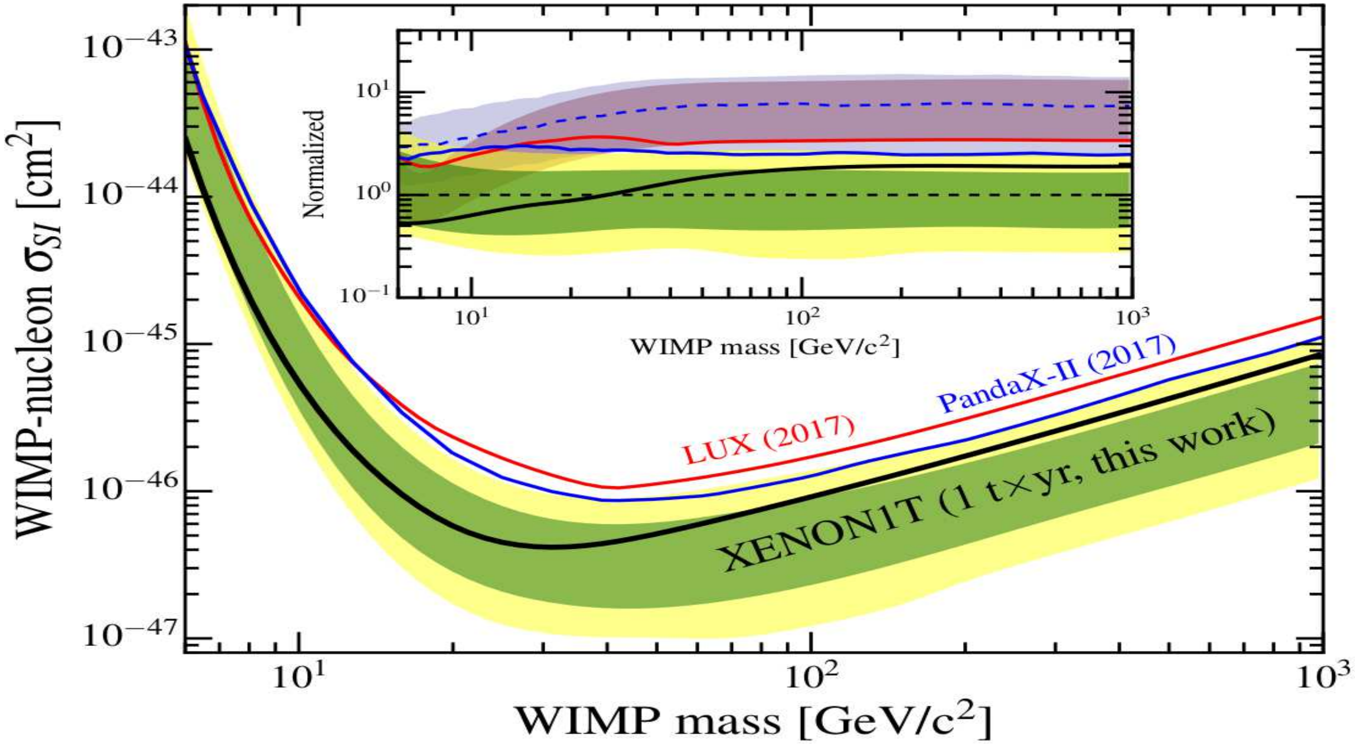
Is there a cosmological limit on how light a CDM particle can be?

C. Boehm et al. J. Phys. G, 30:279–286, 2004. arXiv: astro-ph/0208458; C. Boehm, T.A. Ensslin, and J. Silk, J. Phys. G, 30:279–286, 2004, C. Boehm et al. JCAP, 08:041, 2013. arXiv: 1303.6270

Using PLANCK limit on N_{eff} ; effective number of ν species: masses for CDM as small as $\sim$ MeV and less than a few GeV $\tilde{\chi}_1^0$ (neutralino in SUSY) can be allowed.

Present a summary from L. Roszkowski, E. M. Sessolo and S. Trojanowski,Rept. Prog. Phys. **81** (2018) no.6, 066201 1707.06277 which shows the regions of different reported detections.



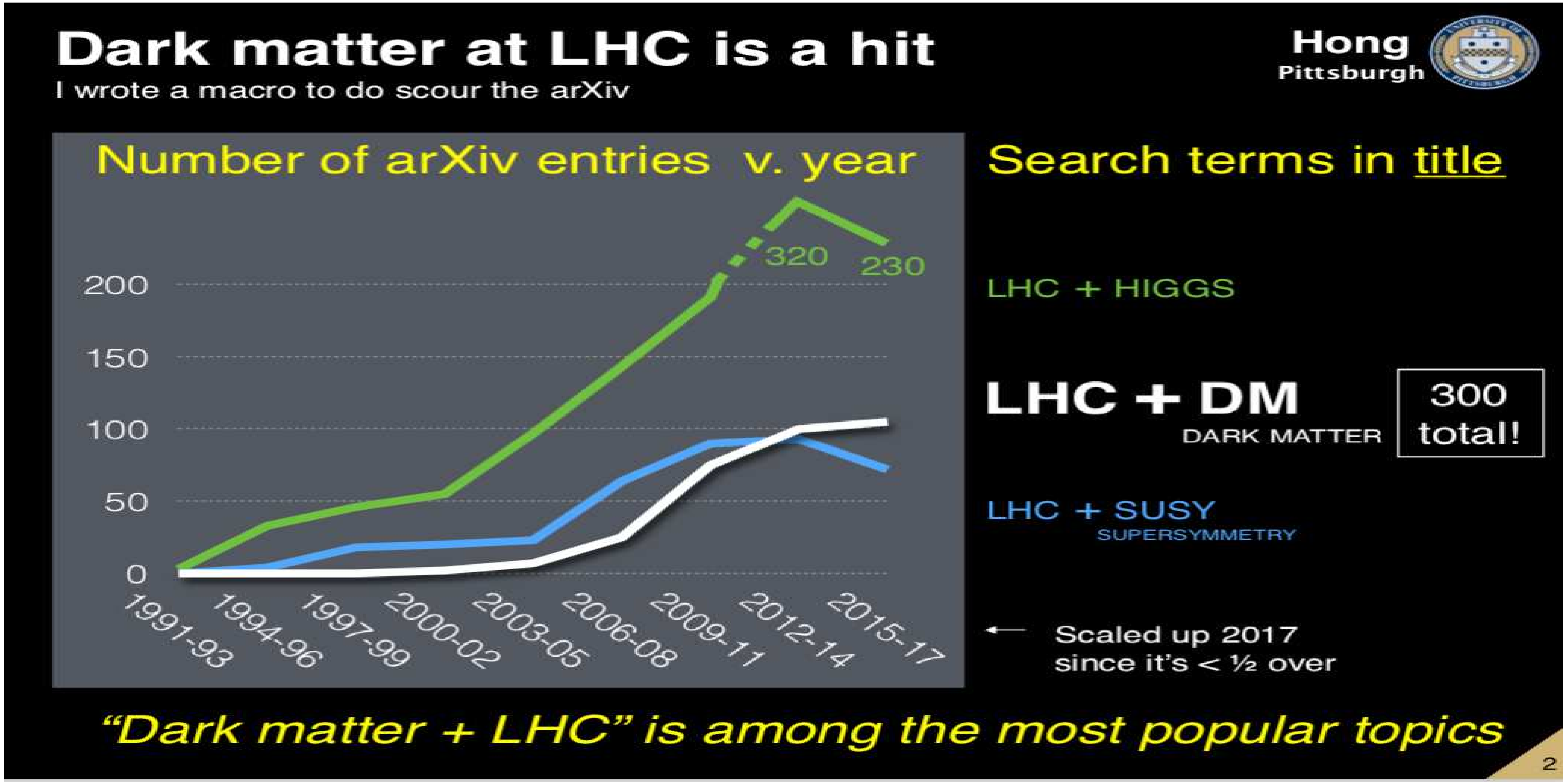


Current situation:

The reported low mass LSP Direct Detection was either due to experimental fluctuations OR not DM. Indirect detection: Lack of clarity due to uncertainties with astrophysics.

Can models and observed relic support a light DM particle if reported in either Direct or Indirect detection experiment?

If yes what can the LHC (current,HL/LHC and HE/LHC) say about it?



Dark matter at LHC is a hit

I wrote a macro to do scour the arXiv

Hong
Pittsburgh

Search terms in <u>title</u>

LHC + HIGGS

LHC + DM
DARK MATTER

300 total!

LHC + SUSY
SUPERSYMMETRY

← Scaled up 2017
since it's < ½ over

"Dark matter + LHC" is among the most popular topics

Current studies are done in a model independent way.

I will mainly discuss in the context of a model: Supersymmetry: phenomenological minimal supersymmetric SM (pMSSM) and next to minimal supersymmetric SM (NMSSM).

Advantage:

Predictions for relic density, Direct/Indirect detection and LHC phenomenology alll decided by the same parameters.

So one can study the model through its implications for all the four issues.

Produce the DM at the colliders. DM particles do not leave tracks in the detector. So their production is indicated by an imbalance of momentum. Produce events with a momentum imbalance: missing transverse energy

a)In the cascade decays of strongly interacting supersymmetric particles: Events with missing $\not{E}_T$. There are only constraints on this! Expts did not find anything here. Looking at compressed spectra. (ref. Ipsita's talk)

b)Direct production of electro weakinos and their decays: signals in the trilpeton + MET channel.

OR

c)in association with other SM particles: famous 'mono'events: mono W/Z/jets...

Example: for $m_{DM} < m_{h125}$:

$$pp \rightarrow hZ \rightarrow Z(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0),$$

$$pp \rightarrow hW \rightarrow W(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

$$pp \rightarrow h + jet \rightarrow jet + (h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

Mono Z/W and mono-jets.

So in the current situation two possibilities to look for light DM in SUSY:

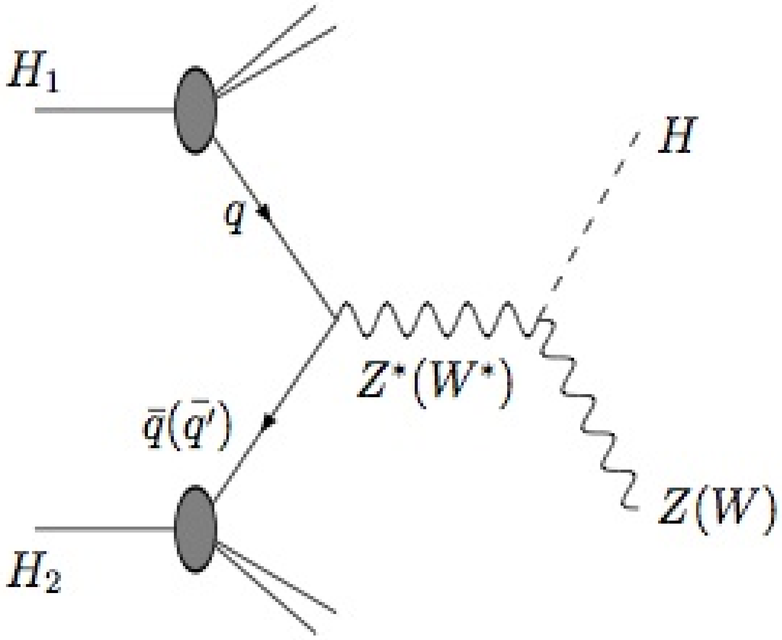
1)look for invisibly decaying Higgs

2)Direct Electroweakino production and their decays.

Even before 'mono' events became a range we had worked on how to look for an invisible Higgs:

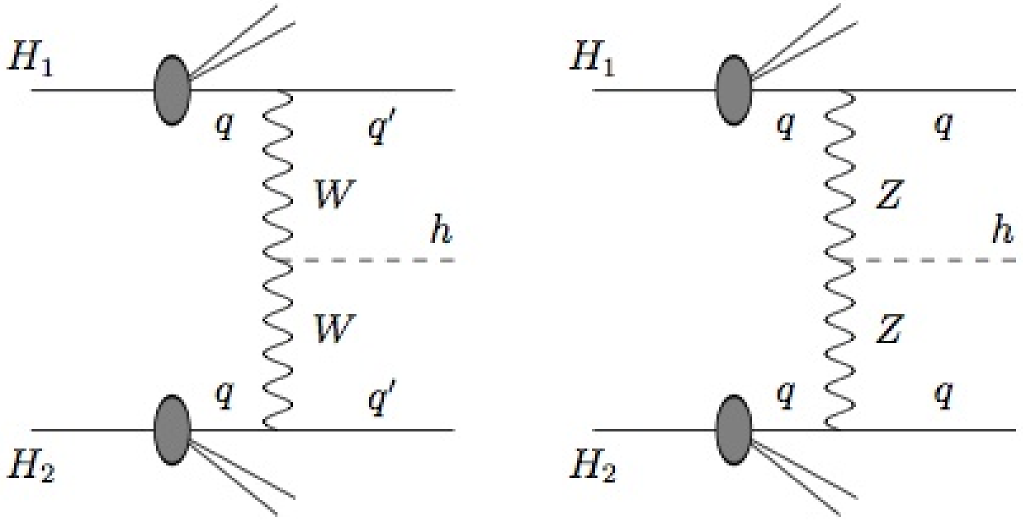
A) How to look for Dark Matter at the colliders through the Higgs portal? Looking for invisible Higgs at the LHC: R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003) "Search for 'invisible' Higgs signals at LHC via associated production with gauge bosons," *Phys. Lett. B* ***571****, pp. 184-192*

D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, (2013) "Looking for an Invisible Higgs Signal at the LHC," Phys. Lett. B 725, arXiv:1211.7015 [hep-ph]

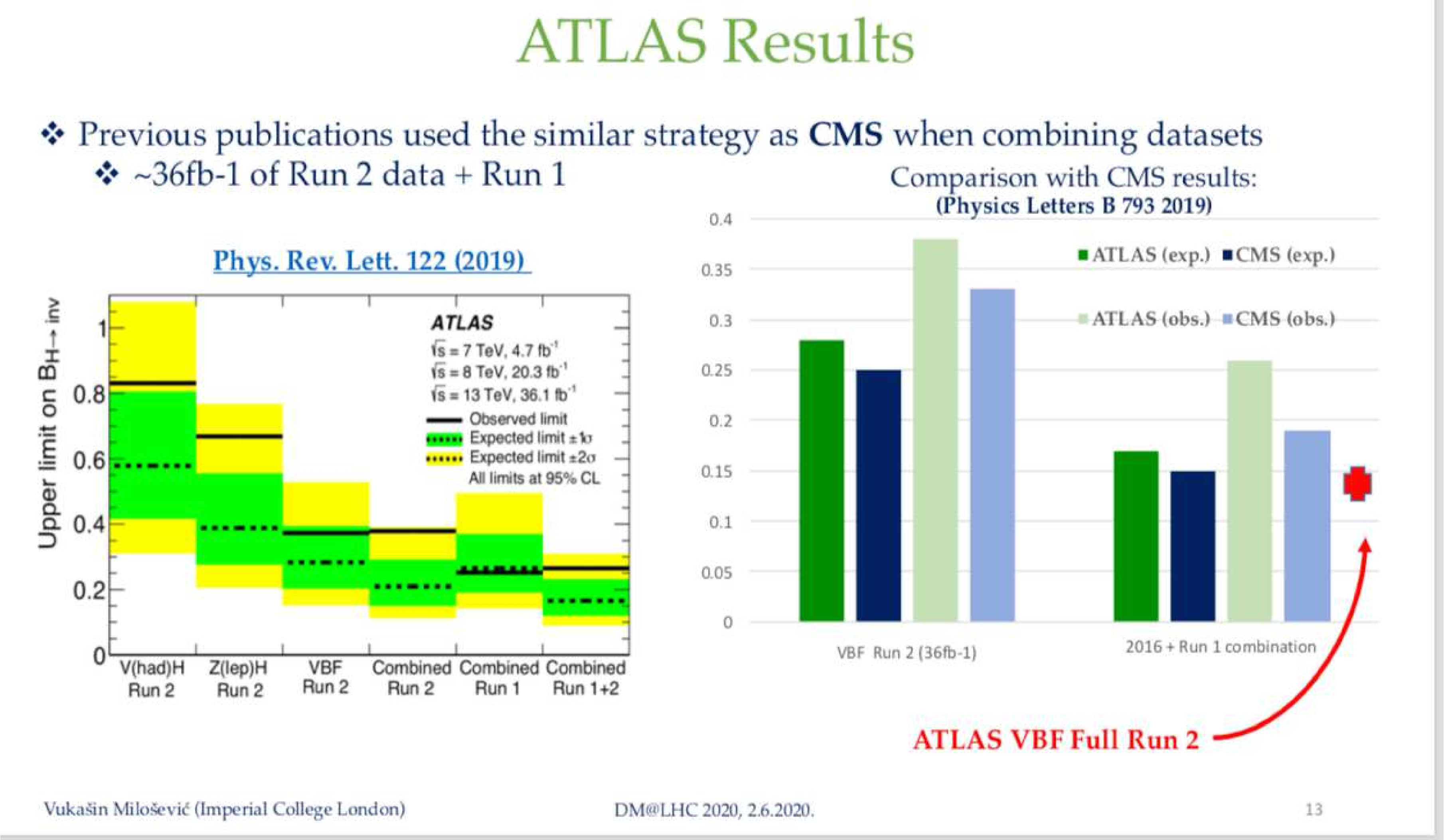


R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003) "Search for 'invisible' Higgs signals at LHC via associated production with gauge bosons," *Phys. Lett. B* **571**, *pp. 184-192*

After the Higgs was discovered, we revisited the analysis, Included other processes as well.



D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, (2013) "Looking for an Invisible Higgs Signal at the LHC," Phys. Lett. B 725, arXiv:1211.7015 [hep-ph]



ATLAS Results

- Previous publications used the similar strategy as **CMS** when combining datasets
  - ~36fb-1 of Run 2 data + Run 1

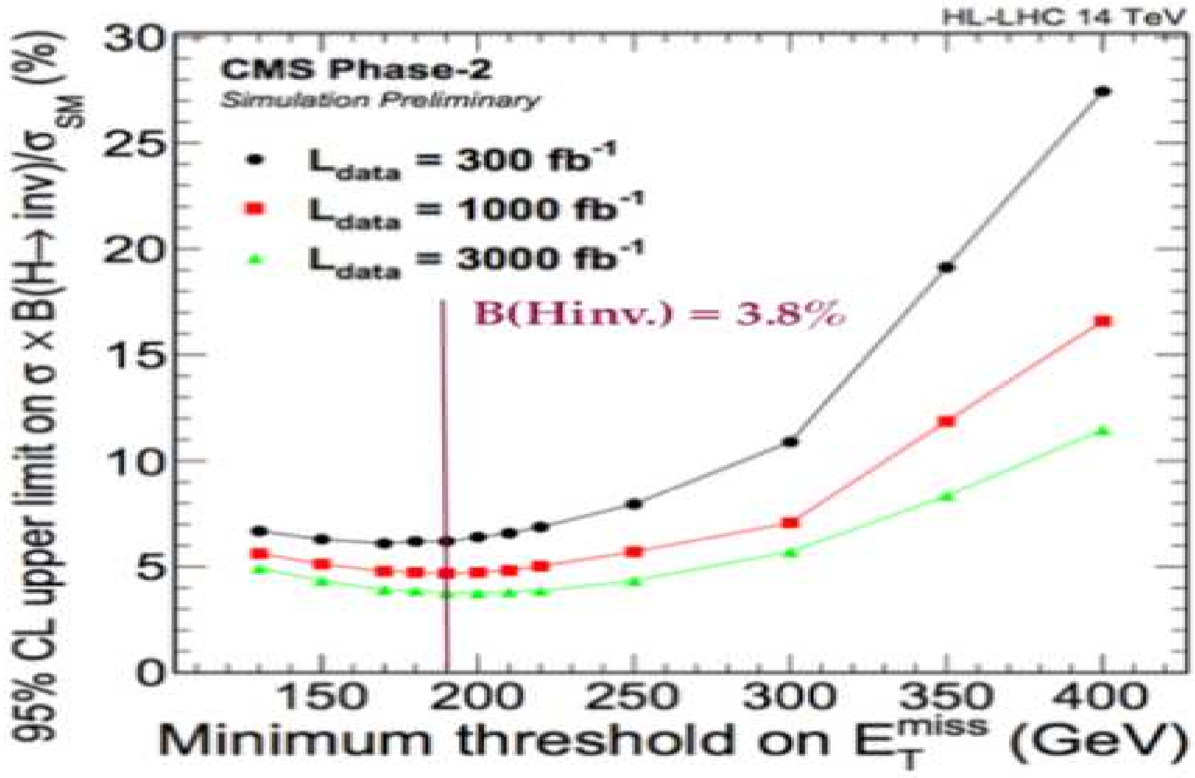
Phys. Rev. Lett. 122 (2019)

Comparison with CMS results:
(Physics Letters B 793 2019)

ATLAS VBF Full Run 2

Vukašin Milošević (Imperial College London) DM@LHC 2020, 2.6.2020. 13

CERN-LPCC-2018-04



$\tilde{\nu}_L$ can never be LSP. Two small relic as the annihilation cross-sections high and also ruled out by direct detection experiments.

Light $\tilde{\nu}_R$ can be LSP. Avoid DD constraints by small Yukawa couplings of the $\tilde{\nu}_R$ (pMMSM,cMSSM). Have an NLSP $\tilde{\tau}_1$. Correct relic by a freeze in mechanism or Decay of long lived $\tilde{\tau}_1$. Interesting phenomenology at the LHC. $\tilde{\nu}_R \sim 30 - 40$ GeV.

S. Banerjee et al. JHEP, 07:095, 2016. arXiv: 1603.08834, S. Banerjee et al. JHEP, 09:143, 2018. arXiv: 1806.04488.

Light $\tilde{\nu}_R$ can be LSP in NMSSM. Interactions of $\tilde{\nu}_R$ with SM particles through additional Higgses:

D. G. Cerdeno et al. Phys. Rev. D, 79:023510, 2009. arXiv: 0807.3029, D.G. Cerdeo et al. JCAP, 08:005, 2014. arXiv: 1404.2572, D.G. Cerdeno et al. Phys. Rev. D, 91(12):123530, 2015. arXiv: 1501.01296.

No recent analysis of this scenario is available. The invisible width measurement of the Higgs can constrain this picture.

In the framework of a model how to look for other manifestations of a 'light' $\tilde{\chi}_1^0$ DM at the collider: pMSSM, NMSSM:

pMSSM: Light $\tilde{\chi}_1^0$: pure Bino, will over close the universe.

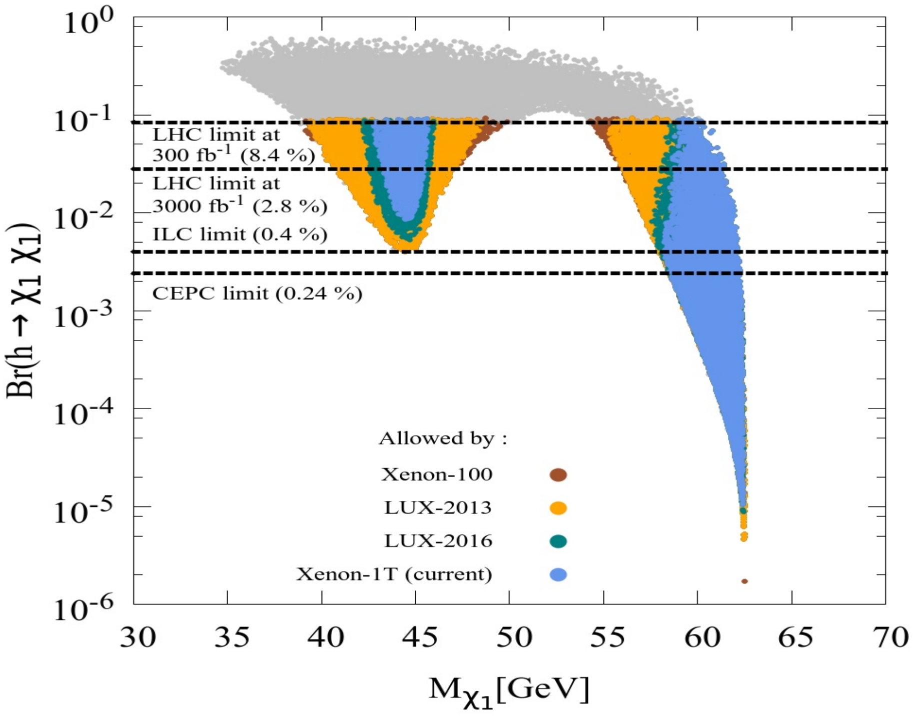
Mixed bino-higgsino efficient annihilation via Z or h_{125}.

Consider parameter range consistent with $m_h \simeq 125$ GeV and no SUSY observation:

$$\begin{aligned}
1 \text{ GeV} < M_1 < 100 \text{ GeV},\ 90 \text{ GeV} < M_2 < 3 \text{ TeV}, \\
1 < \tan\beta < 55,\ 70 \text{ GeV} < \mu <\ 3 \text{ TeV}, \\
800 \text{ GeV} < M_{\tilde{Q}_{3l}} < 10 \text{ TeV}, 800 \text{ GeV} < M_{\tilde{t}_R} < 10 \text{ TeV}, \\
800 \text{ GeV} < M_{\tilde{b}_R} < 10 \text{ TeV}, \\
2 \text{ TeV} < M_3 < 5 \text{ TeV}, -10 \text{ TeV} < A_t < 10 \text{ TeV}
\end{aligned} \tag{1}$$

Light DM in SUSY!

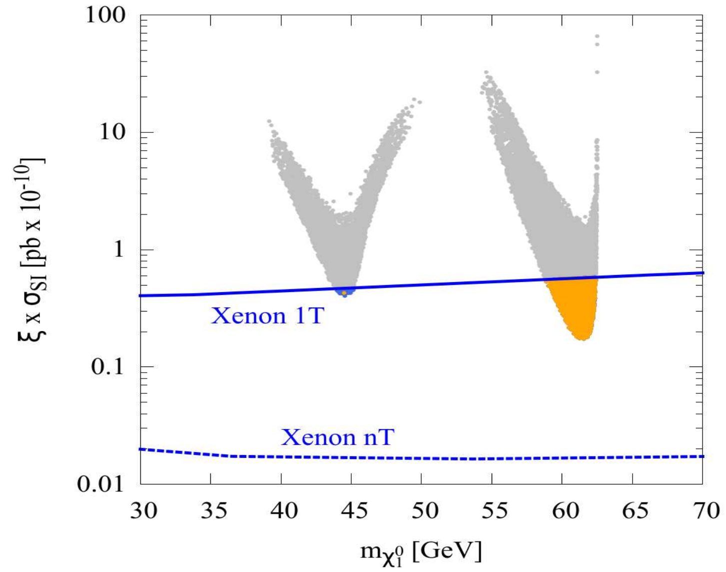
$\tilde{\nu}$



R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838 Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:

300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

Since then LHC run-II data became available and Xenon 1T came up with its result.



Xenon-1T all but rules out now the Z-funnel region. Points still allowed by current LHC Electroweakino searches.

WZ mediated 3l + MET or dilpeton + MET searches and WH_{125} mediated 1l + 2b + MET searches:

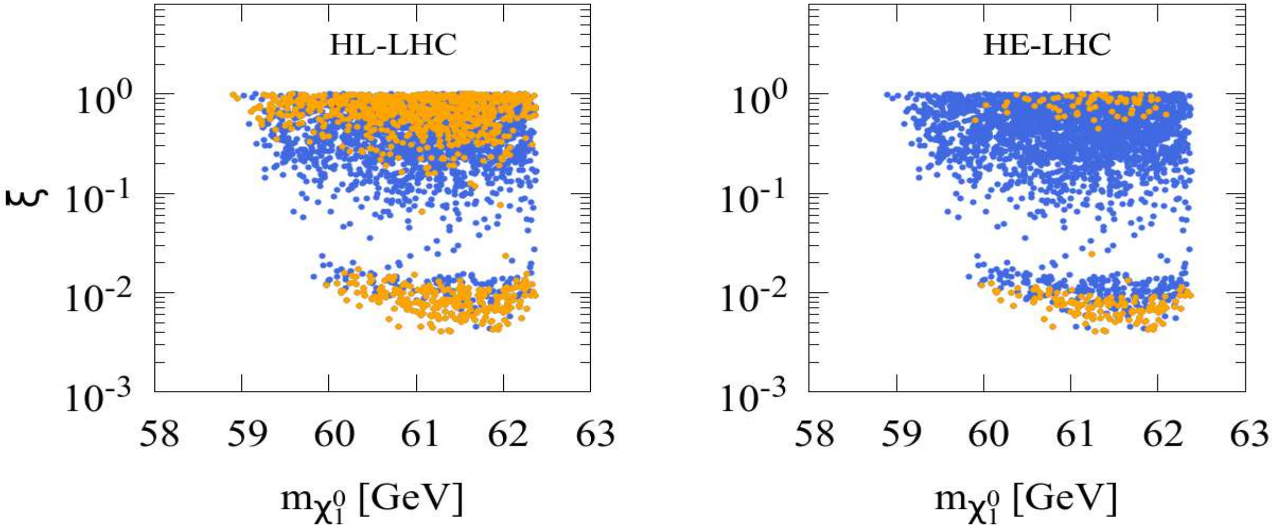
Run-II data 35fb^{-1} . Higgsino upto 390 GeV ruled out. G. Pozzo et al. Phys. Lett. B, 789:582–591, 2019. arXiv: 1807.01476 :

Pure Wino upto 650 GeV ruled out (CMS data).

Translated this to our parameter region.

Exclude points where $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}$ and $m_{\tilde{\chi}_1^\pm}$ is $\leq$ 390 GeV and all three, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_1^\pm$, have a higgsino composition $\geq$ 90%. We also exclude points where $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^\pm}$ are $\leq$ 650 GeV and both $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ have wino composition $\geq$ 90%

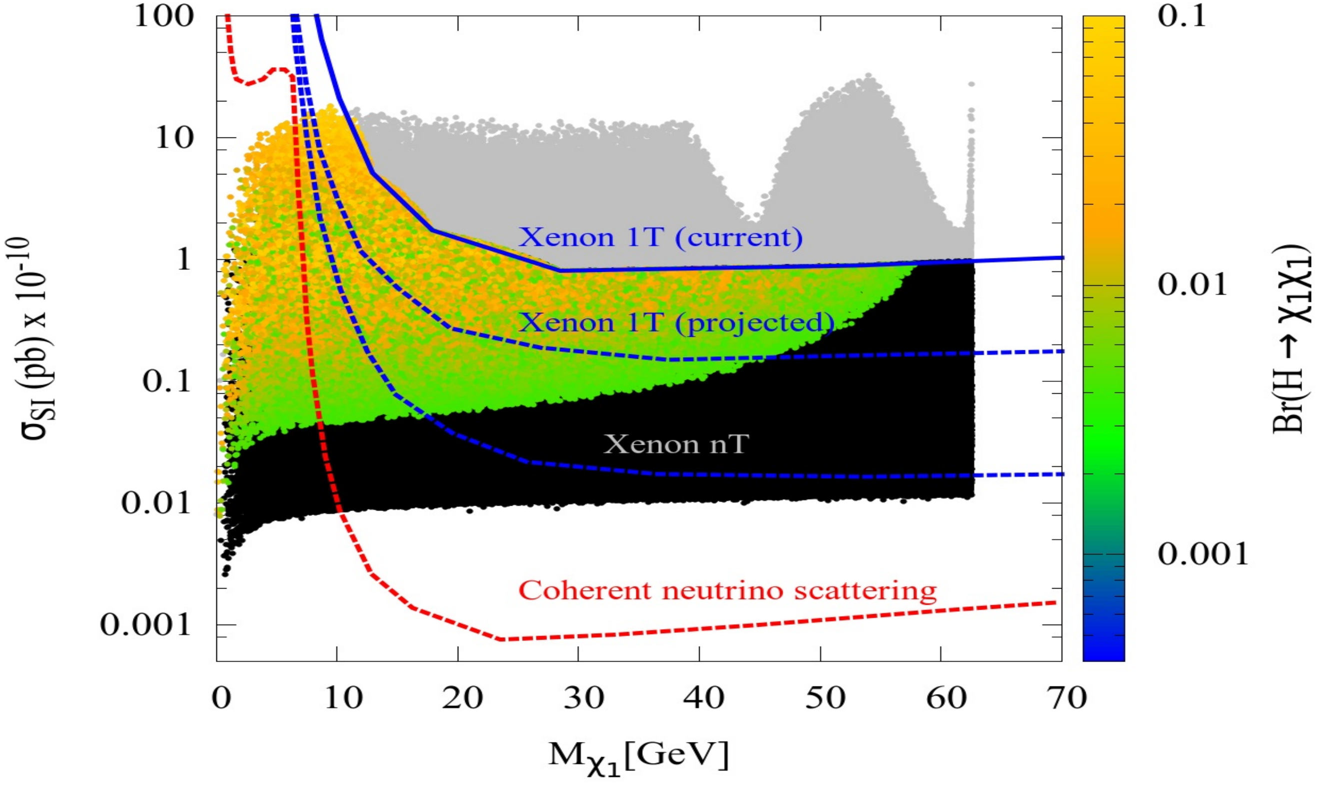
Light DM in SUSY!

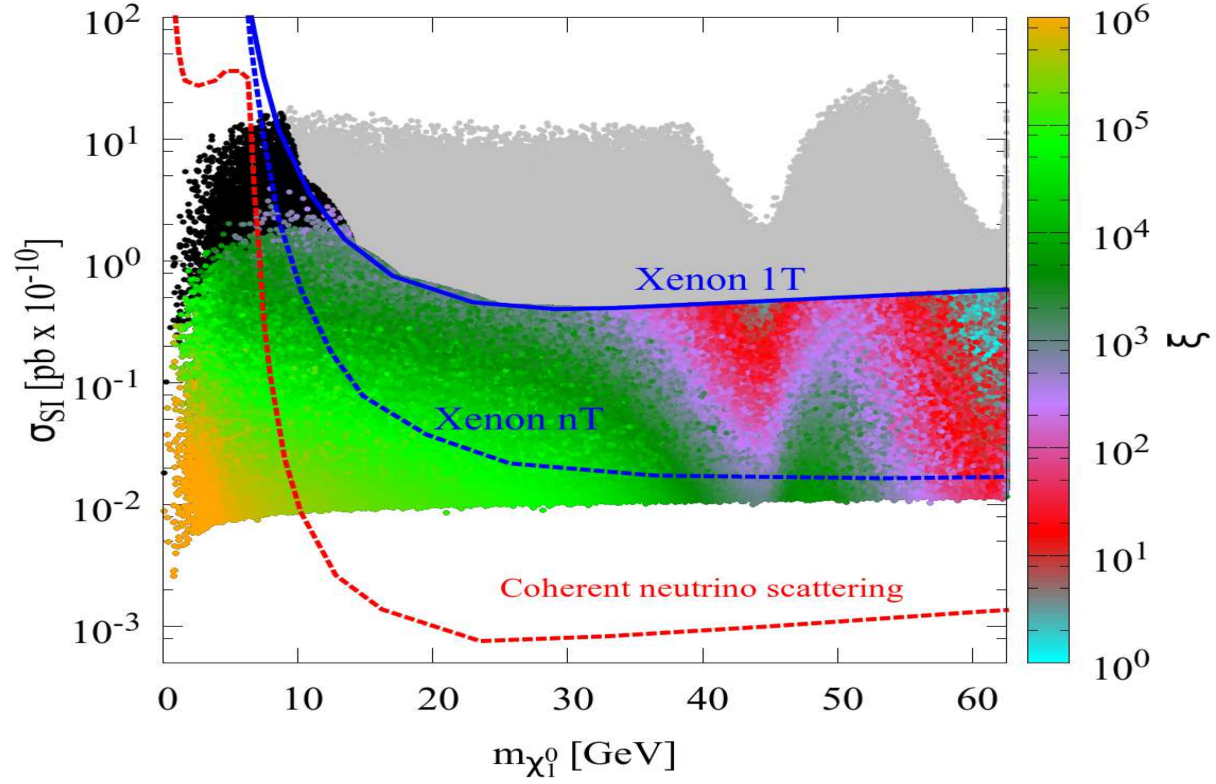


How can one test it at HL/HE LHC? Use efficiency maps made by Rahool (validated by comparing with ATLAS analysis). Combined use of EWeakino production.

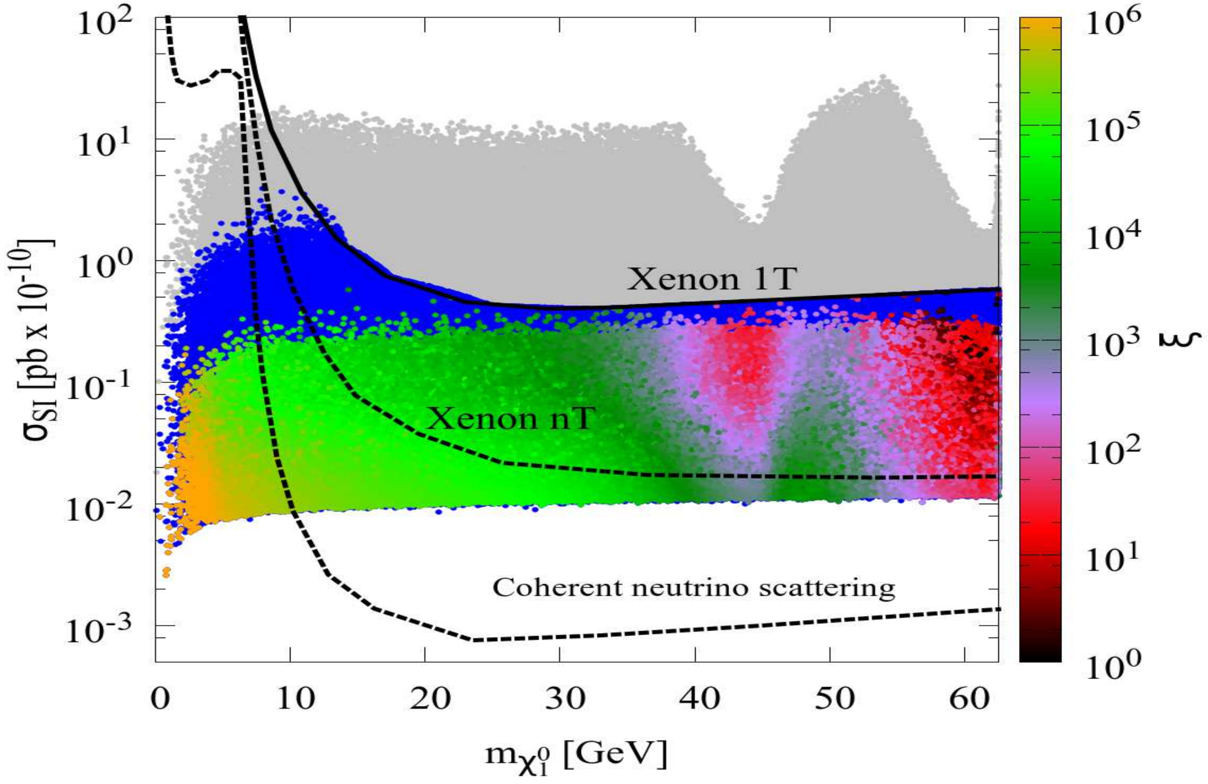
Blue within the discovery reach of 3 l + MET channel.

For Nonthermal DM the light neutralinos can not be detected in the Direct Detection experiments and then invisible decay width might be the only way!





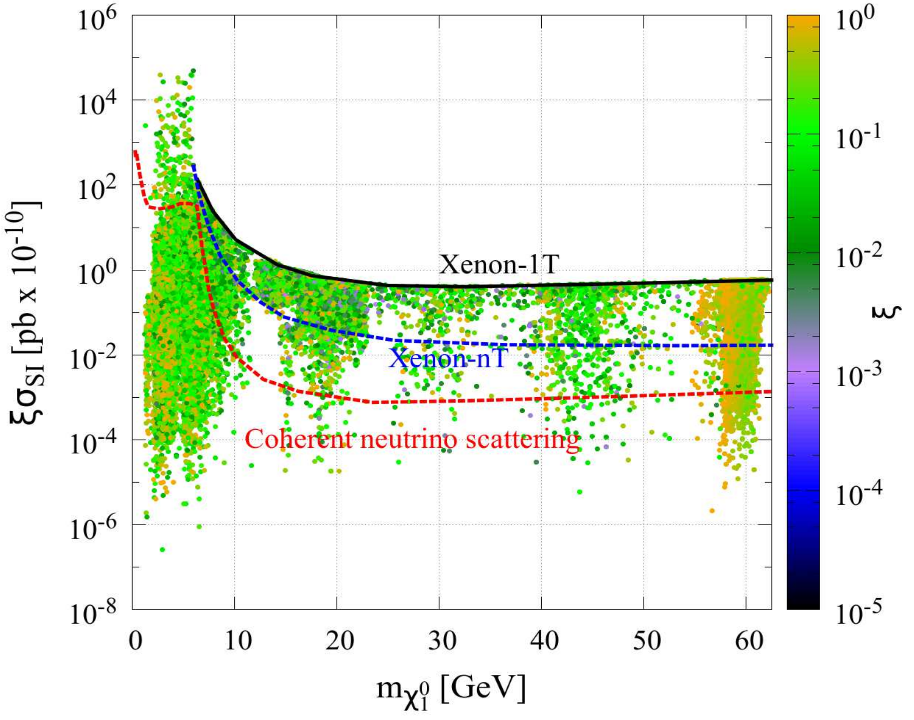
Black points ruled out by current LHC run-II, 35 fb^{-1} data

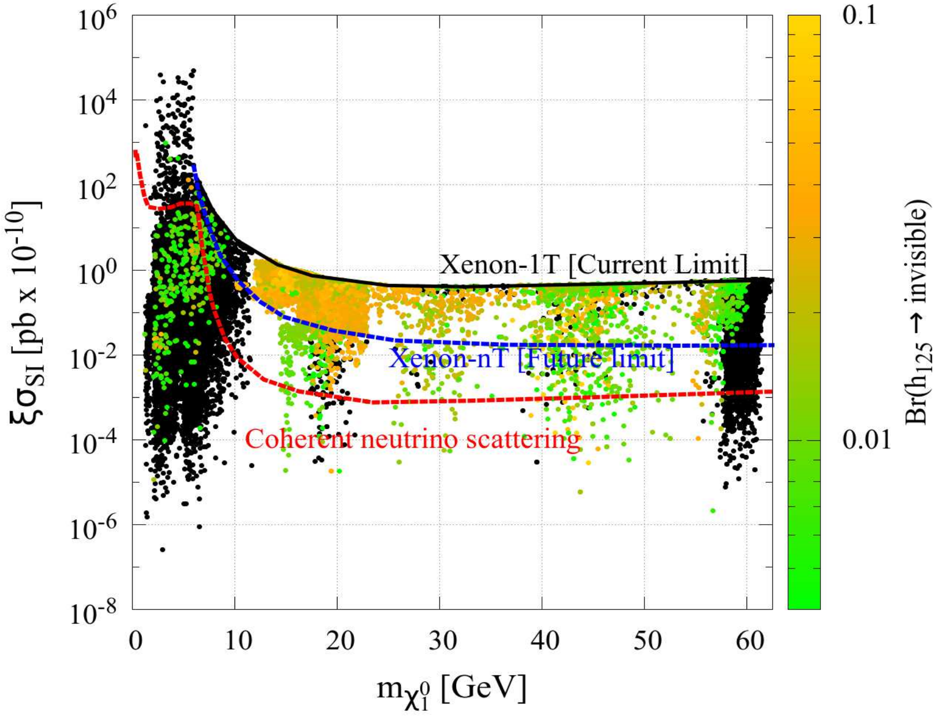


Reach of HL LHC through trilepton, dilepton + MET and 1 l + 2b + MET.

$$\begin{aligned} 0.01 < \lambda < 0.7,\ 10^{-5} < \kappa < 0.05,\ 3 < \tan\beta < 40 \\ 100\ \text{GeV} < \mu < 1\ \text{TeV},\ 1.5\ \text{TeV} < M_3 < 10\ \text{TeV} \\ 2\ \text{TeV} < A_\lambda < 10.5\ \text{TeV},\ -150\ \text{GeV} < A_\kappa < 100\ \text{GeV} \\ M_1 = 2\ \text{TeV},\ 70\ \text{GeV} < M_2 < 2\ \text{TeV} \\ A_t = 2\ \text{TeV},\ A_{b,\tilde{\tau}} = 0,\ M_{U_R^3}, M_{D_R^3}, M_{Q_L^3} = 2\ \text{TeV},\ M_{e_L^3}, M_{e_R^3} = 3\ \text{TeV} \end{aligned} \tag{2}$$

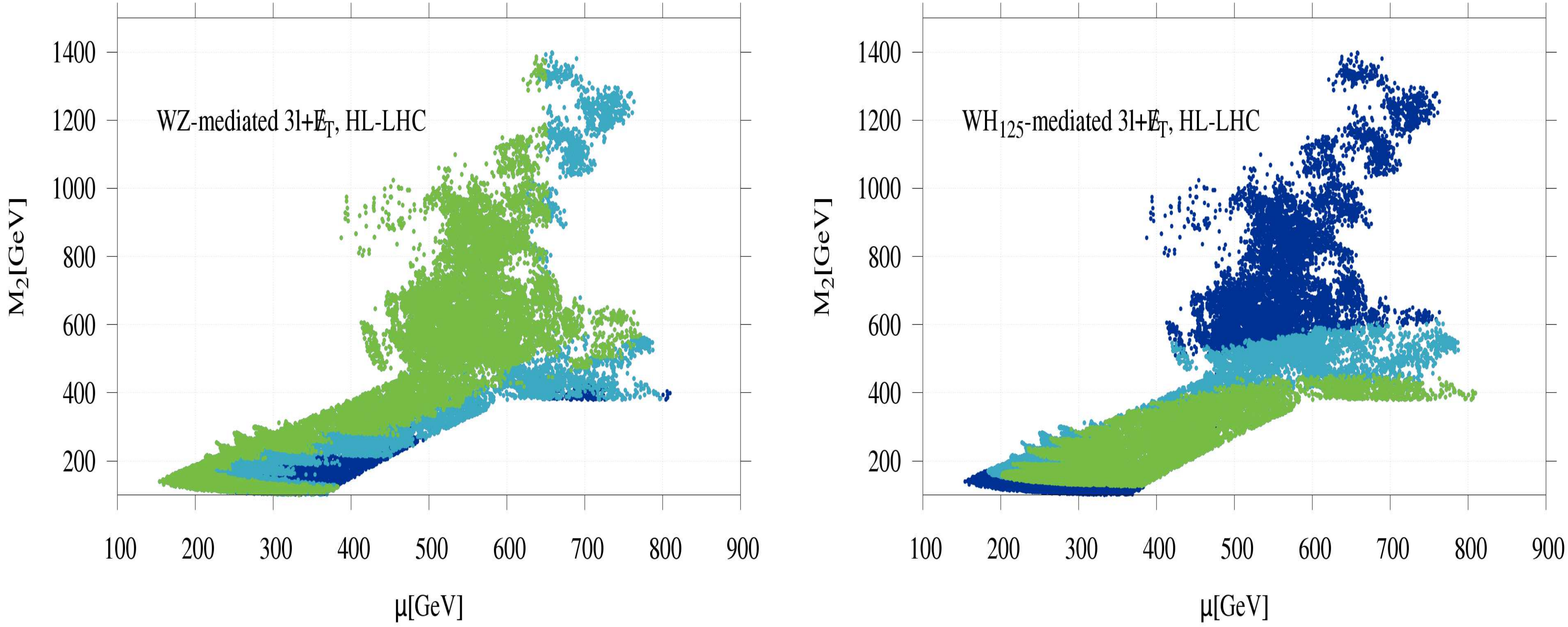
The $\tilde{\chi}_1^0$ is a linear combination of singlino, bino and higgsino/wino.





Low mass LSP regions allowed by DD as well as relic. Black points not rechable even by CEPC in the invisible channel.

How can they be probed at HL/LHC or HE/LHC? Again through WZ mediated and WH mediated EWeakino signals



Green- Discovery reach, Light blue exclusion reach(ie 2 σ)

A light LSP in pMSSM is still possible: light $\tilde{\chi}_1^0$. Only h_{125} funnel region is allowed.

pMSSM extended with a $\tilde{\nu}_R$: a light $\tilde{\nu}_R$ still possible. Characteristic signals.

We can see that this WIMP paradigm for a light LSP in pMSSM and NMSSM can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

The Quest Continues!!