Dark Matter Particles? WIMPs?

Graciela Gelmini - UCLA

U.S. DEPARTMENT OF ENERGY | Office of Science DE-SC0009937

Cosmic Controversies, Chicago Oct. 5-8, 2019

- **Dark Matter Particles or Not**
  Has two parts:

  -Dark Matter or not? So far there is no alternative to dark matter...

  -Particles or not? Could be PBH, ... (Juan Garcia Bellido)

- **WIMPs: dead?, alive? in good shape?**
  The meaning of WIMP was not well defined since its inception, but not even in the most restrictive sense of the word WIMPs are dead... Words evolve- let us not be held up by the word. Many models rejected, many others not.

  There are mature background free techniques (based on Xe and Ar) to get to the multi-tonne scale in Direct Detection- we should continue with them without giving a bad rap to WIMP searches.... But also diversify, there are many beautiful ideas for lighter DM... (Elena Aprile, Rouven Essig)

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Dark Matter Particles or Not

What we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM is non-baryonic and is not observed to interact with light**

  i.e. it is either neutral or with a very small electromagnetic coupling such as:

  "Milli-Charged DM" which can be part of "Atomic DM", with dark protons and dark electrons forming dark atoms or "Mirror DM" whose Lagrangian is a copy of that of the SM, but for the mirror particles,

  or "electric or magnetic dipole DM", or"anapole DM"

What we know about DM:

- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**

After 2013, no proposed "alternative to Dark Matter" explained the CMB anisotropy spectrum and the BAO

From any theory that claims to "replace Dark Matter" we should ask for its prediction of the matter power spectrum and the CMB angular power spectrum (stop discussing endlessly only about galaxy rotation curves!) (Constantinos Skorkis)

Eloquently expressed in Dan Hooper's talk "In Defense of Dark Matter" - KITP 4/30/2018- in debate with Eric Verlinde ("emergent gravity" is a theory without cosmology)

What we know about DM:

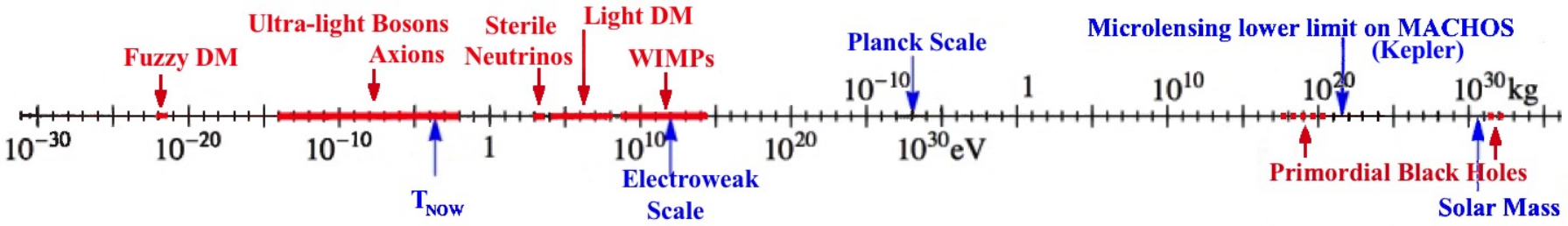
- **1- Attractive gravitational interactions and lifetime $>> t_U$**
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**
- **4- The bulk of the DM must be nearly dissipationless but $\leq$10% of it could be dissipative.**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit $\sigma_{\rm self}/{\rm m} \leq$ 2 barn/GeV**
  (by comparison e.g. ^{235}U-neutron capture cross section is a few barns!)
  Self Interacting DM (SIDM) just below limit (WIMPs: σ_{DM-p} <10^{-46}cm^2/10GeV)

- **6- The mass of the major component of the DM has only been constrained within some 90 orders of magnitude.**

10^{-31}GeV$\leq$**M** $\leq$ $10^{-10}M_\odot = 10^{47}GeV= 2\ 10^{20}$kg (window $\simeq 10M_\odot = 10^{58}$GeV??)

Lower limit:"Fuzzy DM", boson with de Broglie wavelength 1 kpc Hu, Barkana, Gruzinov, 2000

Upper limit on MACHOS (Massive Astrophysical Compact Halo ObjectS): Moniez 0901.0985, Yoo, Chaname, Gould, ApJ**601**, 311, 2004; Griest, Cieplak and Lehner 1307.5798, Niikura *et al.* 1701.02151



Problem with MACHOS: how would they form? Could be Primordial Black Holes

Dark Matter: could be Primordial Black Holes (PBH)?

PBH are a hypothetical type of black hole not formed by the gravitational collapse of a large star but in an early phase transition, before BBN (thus non-baryonic)

Zel'dovich and Novikov, 1966; Hawking, 1971; Carr and Hawking, 1974

Many limits exclusively applying to BH:

- $M > 10^{15}$g $= 6 \times 10^{38}$ GeV, lighter would have evaporated by now
- $M > 10^{17}$g or evaporating BH would have been observed (by EGRET and Fermi)
- 5 10^{17}g$< M < 10^{20}$g excluded by non-observation of "femtolensing" of GRB 1204.2056

Revised: wave effects (wavelength larger than Schwartzschild radius) and finite source size effects

- 10^{16}g$< M < 10^{22}$g excluded- its accretion in stars would destroy compact remanent 1209.6021
- 3 10^{18}g$< M <$ 5 10^{24}g excluded- its accretion in n stars in GC would destroy them (NS limit) 1301.4984 Revised: required a too high density in GC1807.11495
- $M >$ 100 $M_\odot = 2\ 10^{35}$g excluded by absence of CMB spectral distortions 0709.0524

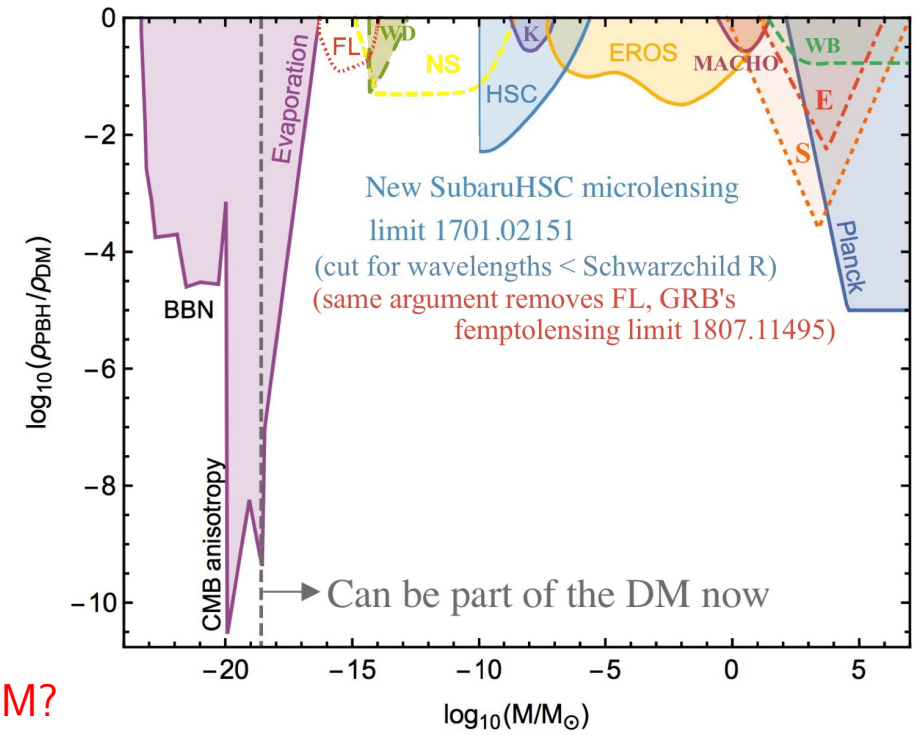
Many limits revised after LIGO's BH-BH mergers events! Bird etal. 1603.00464, Clesse&Garcia-Bellido 1501.07565, 1603.05234

Could Dark Matter be Primordial Black Holes (PBH)?

compilation of bounds on PBH DM density fraction f for single mass PHB (dashed limits can be avoided with special assumptions)

Carr, Tenkanen and Vaskonen 1706.03746 + modified

($M_\odot = 10^{57}$GeV)

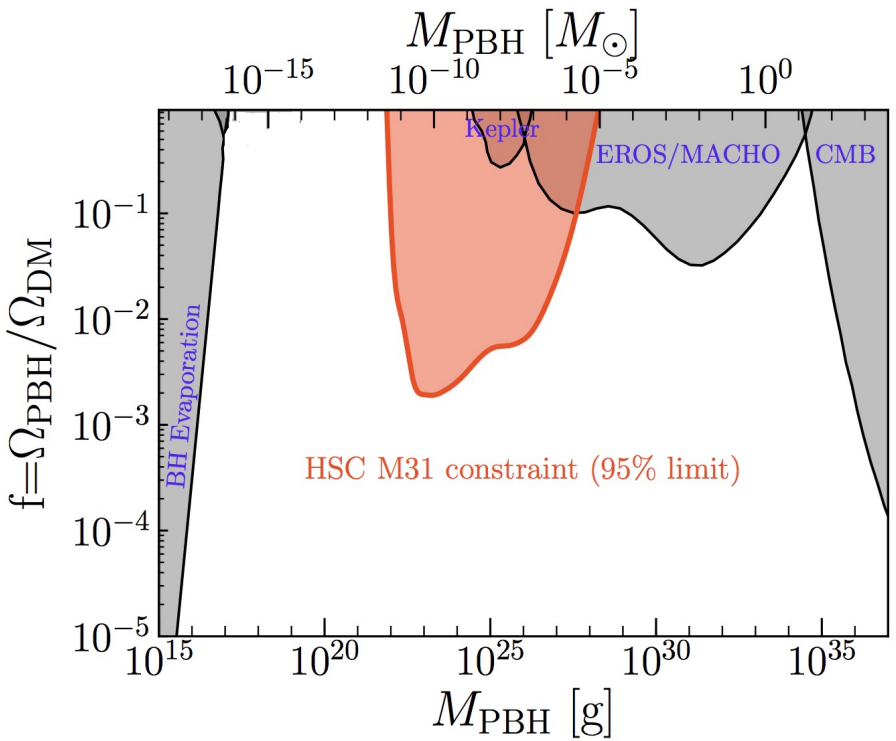


Could LIGO BH ∼10's $M_\odot$ be most of the DM?

Bird etal. 1603.00464, Clesse&Garcia-Bellido 1603.05234, 1501.07565; and before the LIGO events Frampton 0905.3632, Frampton, Kawasaki, Takahashi &Yanagida 1001.2308

Could Dark Matter be Primordial Black Holes (PBH)?

compilation of bounds on PBH DM density fraction f for single mass ($M_\odot = 10^{57}$GeV)



New Subaru/HSC camera limit Niikura et al. Nat. Astron. **3**, no. 6, 524, 2019 (1701.02151)

They also have a candidate PBH event consistent of a PBH of mass 10^{-7} $M_\odot$.

What we know about DM:

- **1- Attractive gravitational interactions and lifetime** $>> t_U$
- **2- DM is non-baryonic and is not observed to interact with light**
- **3- So far DM and not modified dynamics + only visible matter**
- **4- The bulk of the DM must be nearly dissipationless**
- **5- DM has been mostly assumed to be collisionless, but huge self interaction upper limit** $\sigma_{\rm self}/{\rm m} \leq$ **barn/GeV**
- **6- Mass within 90 orders of magnitude.**
- **7- The bulk of the DM is Cold or Warm** (NR or quasi when $T \sim$ keV)
- **8- Particle DM requires Beyond Standard Model physics**
  In the SM neutrinos are part of the DM, but Hot DM

.

WIMPs: dead?, alive?
in good shape?

What are WIMPs? When in doubt...consult wikipidia

Weakly interacting massive particles

From Wikipedia, the free encyclopedia

"WIMPs" redirects here. For other uses, see WIMPS (disambiguation).

Weakly interacting massive particles (**WIMPs**) are hypothetical particles that are thought to constitute dark matter. There exists no clear definition of a WIMP, but broadly, a WIMP is a new elementary particle which interacts via gravity and any other force (or forces), potentially not part of the standard model itself, which is as weak as or weaker than the weak nuclear force, but also non-vanishing in its strength. A WIMP must also have been produced thermally in the early Universe, similarly to the particles of the standard model according to Big Bang cosmology, and

Agree with 1st two sentences- but WIMP not necessarily produced thermally...

What are WIMPs? WIMP name invented in 1985 by Steigman and Turner
June 1985 M. Turner's lectures:

Fermi National Accelerator Laboratory

FERMILAB-Conf-86/18-A
January 1986

A COSMOLOGIST'S TOUR THROUGH THE NEW PARTICLE ZOO (CANDY SHOP?)

Michael S. Turner
Departments of Astronomy and Astrophysics and Physics
The University of Chicago
Chicago, IL 60637

and

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Batavia, IL 60510

To be published in Dark Matter in the Universe, eds. J. Knapp and J. Kormendy (Reidel, 1986), proceedings of IAU Symposium 117, held at Princeton, June 24-28, 1985.

What are WIMPs? WIMP name invented in 1985 by Steigman and Turner

June 1985 M. Turner's lectures:

WIMP	MASS	T_{WIMP}/T	λ_{FS}(Mpc)
Neutrino	light	$(4/11)^{1/3}$	40 Mpc/(m/30eV)
Axion	10^{-5}eV	$< 10^{-14}$	$< 10^{-5}$Mpc
Axino/RH Neutrino/Light Gravitino	keV	1/4	1 Mpc
Heavy Neutrino/ LSP	GeV	1	10^{-5}Mpc

The scale 1 Mpc corresponds to a galactic scale. The relationship of λ_{FS} to the galactic scale neatly divides the WIMPs into three categories: (i) Cold, $\lambda_{FS} << 1$ Mpc -- the characteristic damping scale is much smaller than a galactic scale, and galactic-sized perturbations survive freestreaming; (ii) Warm, $\lambda_{FS} \approx 1$ Mpc -- the characteristic damping scale corresponds to a galactic scale; (iii) Hot, $\lambda_{FS} >> 1$ Mpc -- only perturbations on scales much larger than a galactic scale survive freestreaming. Almost all of the WIMPs fall into the category of cold dark matter. Only the neutrino is a hot WIMP. At present there are a couple of warm dark matter candidates -- a 1 keV gravitino, 1 keV right-handed neutrino, or a 1 keV axino (supersymmetric partner of the axion).

What are WIMPs? WIMP changed meaning very fast

Ann. Rev. Nucl. Part. Sci. 1988. 38: 751–807

DETECTION OF COSMIC DARK MATTER

Joel R. Primack and David Seckel

Santa Cruz Institute for Particle Physics, Ur
Santa Cruz, California 95064

Bernard Sadoulet

Physics Department, University of Californi

CONTENTS

1. INTRODUCTION .....
- 1.1 *How Much DM Is There?* .....
- 1.2 *Arguments That DM Is Nonbaryonic* .....
- 1.3 *Nonbaryonic DM Candidates* .....

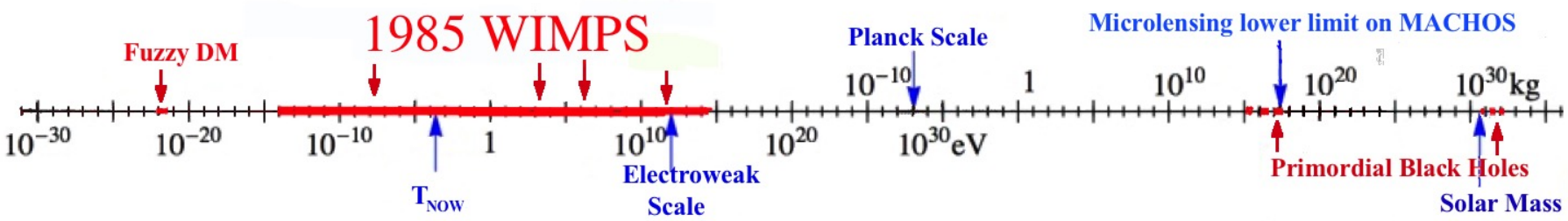
2. WEAKLY INTERACTING MASSIVE PARTICLES .....
- 2.1 *Motivation for and Properties of WIMP Candidate*
- 2.2 *Interaction Rates of WIMPs with Ordinary Matter*
- 2.3 *Direct Detection by Nuclear Recoil* .....
- 2.4 *Indirect Detection by Annihilation* .....
- 2.5 *Present Constraints and Future Prospects* .....

3. AXIONIC DARK MATTER .....
- 3.1 *Motivation* .....
- 3.2 *Cosmological and Astrophysical Constraints* .....
- 3.3 *Detection by Conversion to Photons in Laboratory*
- 3.4 *Theoretical Uncertainties* .....

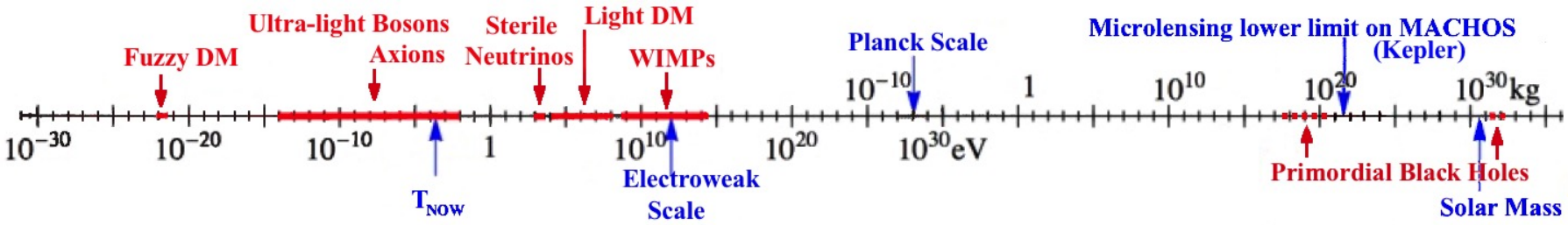
4. LIGHT NEUTRINOS .....

However WIMP not restricted to 1 to 100 GeV in mass

What are WIMPs?



WIMPs have allowed themselves to be expelled from whole regions of parameter space! WIMPs now...



Words evolve, but reducing WIMPs to the "WIMP miracle" WIMPs is too much!! WIMPs could always be produced in other ways

What are WIMPs? June 1988 M. Turner's talk:

DARK MATTER CANDIDATES MICHAEL S. TURNER

To be published in The Proceedings of the Third CERN/ESO Symposium, held in Bologna Italy, eds. G. Giacomelli, etal. Conference held 16-20 May 1988.

II. RELIC WIMPS AS THE DARK MATTER

dark matter in the Universe! The candidates can be organized into 4 categories: Thermal Relics (hot and cold); Asymmetric Relics; and Non-Thermal Relics.

• **Thermal Relics**—At very high temperatures ($T \gg m_X$), the equilibrium

• **Asymmetric Relics**—Above it was tacitly assumed that the abundance of particle and antiparticle species were identically equal, so that the annihilation rate (and hence cross section) determines freeze out and the relic abundance. If an asymmetry exists between particle and antiparticle species, say more particles than antiparticles, then the relic abundance can actually be determined by the size of the

• **Non-thermal Relics**—There are a handful of very interesting potential relics whose interactions are so feeble that they should never have been thermal equilibrium at early times. Nevertheless, such relics may have been produced by other,

• **Truly Exotic Relics**—There are even more exotic possibilities for the dominant form of matter in the Universe. For example, if the relic WIMP is unstable and

The original GeV thermal-WIMP 2GeV for Ω_{DM}=1, now 4GeV for 0.25

PHYSICAL REVIEW
LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

"Thermal WIMPs"

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs **reach equilibrium** while

Universe is radiation dominated

- **No particle asymmetry**
- Chemical decoupling (freeze-out) when

  $\Gamma_{ann} = \langle \sigma v \rangle \, n \leq H$,
- **No entropy change** in matter+radiation

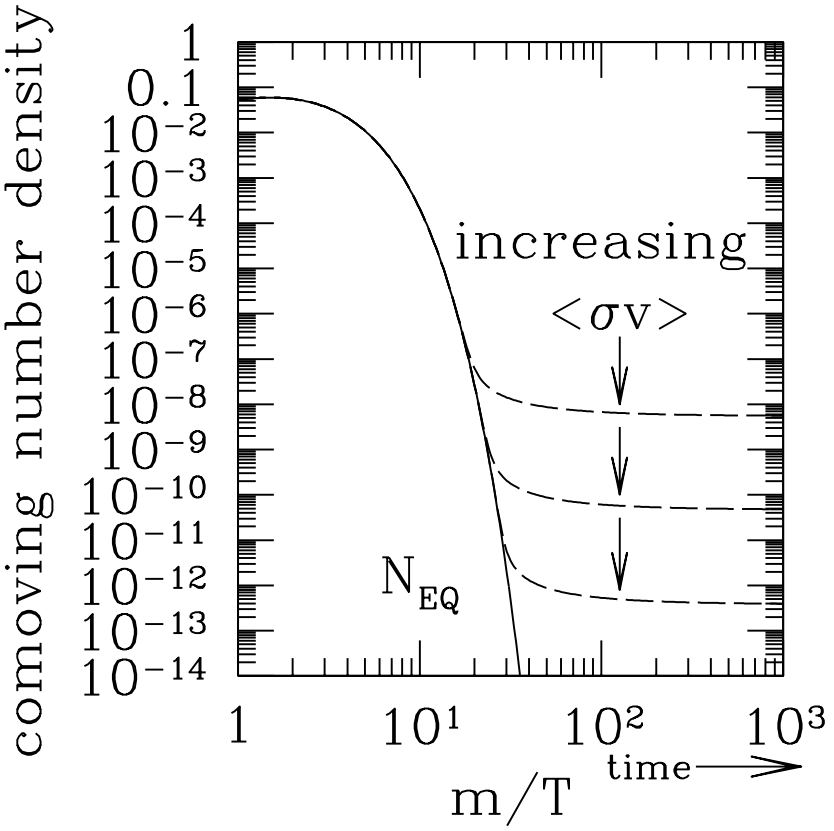
$$\Omega_{std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} cm^3/s}{\langle \sigma v \rangle}$$

Weak annihilation cross section

$\sigma_{annih} v \simeq G_F^2 m^2 \simeq 3 \times 10^{-26} cm^3/s$

$m \simeq$ GeV is enough to get

$\Omega = \Omega_{DM} \simeq 0.2$! "WIMP Miracle"

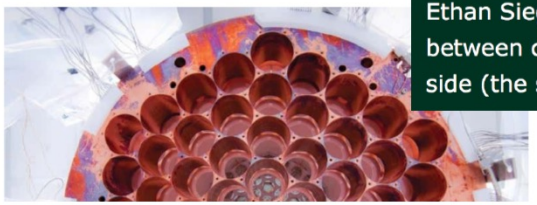


ARE WIMPS DEAD?

Dark matter no-show puts WIMPs in a bind

SPACE 30 October 2013

By Lisa Grossman



50,667 views | Feb 22, 2019, 02:00am

The 'WIMP Miracle' Hope For Dark Matter Is Dead

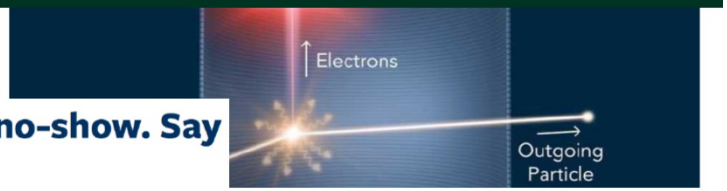
Ethan Siegel Contributor
Starts With A Bang Contributor Group

Science

saturday, february 23, 2019 ...

Rumors of the WIMP miracle's death have been greatly exaggerated

Ethan Siegel has shown us another example of the profound difference between careful scientists on one side and zealous activists on the other side (the side where he sadly belongs) when he wrote



MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs.

By Robert Sanders, Media relations | DECEMBER 4, 2017

Tweet

The intensive, worldwide search for dark matter, find an abundance of dark, massive stars or scad new candidate is slowly gaining followers and ob

WIMPs on Death Row

Posted on July 21, 2016 by woit

One of the main arguments given for the idea of supersymmetric extensions of the standard model has been what SUSY enthusiasts call the "WIMP Miracle" (WIMP=Wea Interacting Massive Particle). This is the claim that such SUSY models include a stable very massive weakly interacting particle that could provide an explanation for dark mat

The rumors of WIMPs death are greatly exaggerated!

WIMPs dead? Not to be held up by the word...

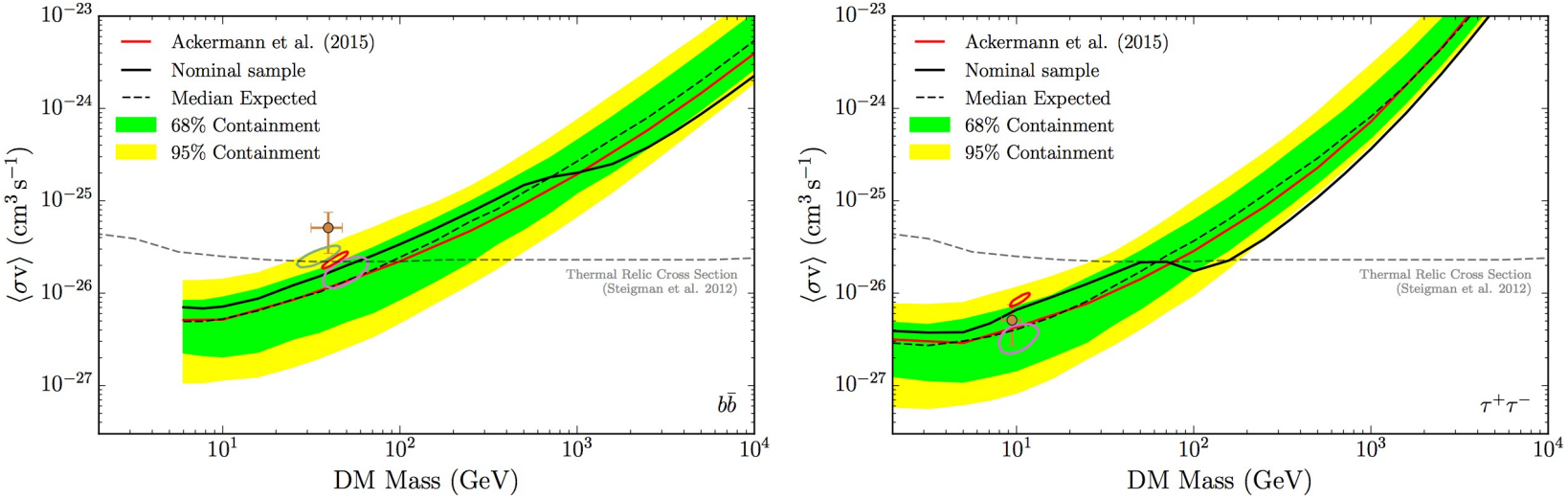
- Are WIMPs coupled to the W/Z bosons dead? Mostly- not entirely

- Are "WIMP miracle" WIMPs dead? NO, but constrained...
  (Notice that here I use "WIMP miracle" WIMPs to indicate the usual set of assumptions made when defining them. I do not call them "thermal WIMPs" because WIMPs produced thermally which decouple before the temperature of the Universe was 5 MeV, during an epoch yet untested, could have a different cross section to be the dark matter, if the standard assumptions we make about cosmology are not right)

- Why consider only "WIMP miracle" WIMPs? NO REASON.....

- Are SUSY WIMP models dead? NO, many rejected many not...

Upper limit on "WIMP miracle" from Fermi ST 95% CL upper limits, 6 y of Fermi Large Area Telescope (LAT)- 15 stacked dwarfs 1611.03184



Shown are model for the GC excess. They are in tension with the upper limit.

"WIMP miracle" annihilation at decoupling cannot be smaller than the benchmark annihilation cross section ($< \sigma_{annih} v > \simeq 2 \times 10^{-26}$ cm^3/s).

Indirect limits on "WIMP miracle" cross sections

1- FermiLAT observations of stacked dwarf galaxies

Constrain annihilation at present of DM particles bound to galactic haloes

2- Positron spectrum measured by AMS-02 (more precise that earlier measurements) Constrain annihilation at present of DM particles close to Earth

3- CMB anisotropy precision measurements (Planck and others)

Constrain DM annihilations (or decays) at recombination or after

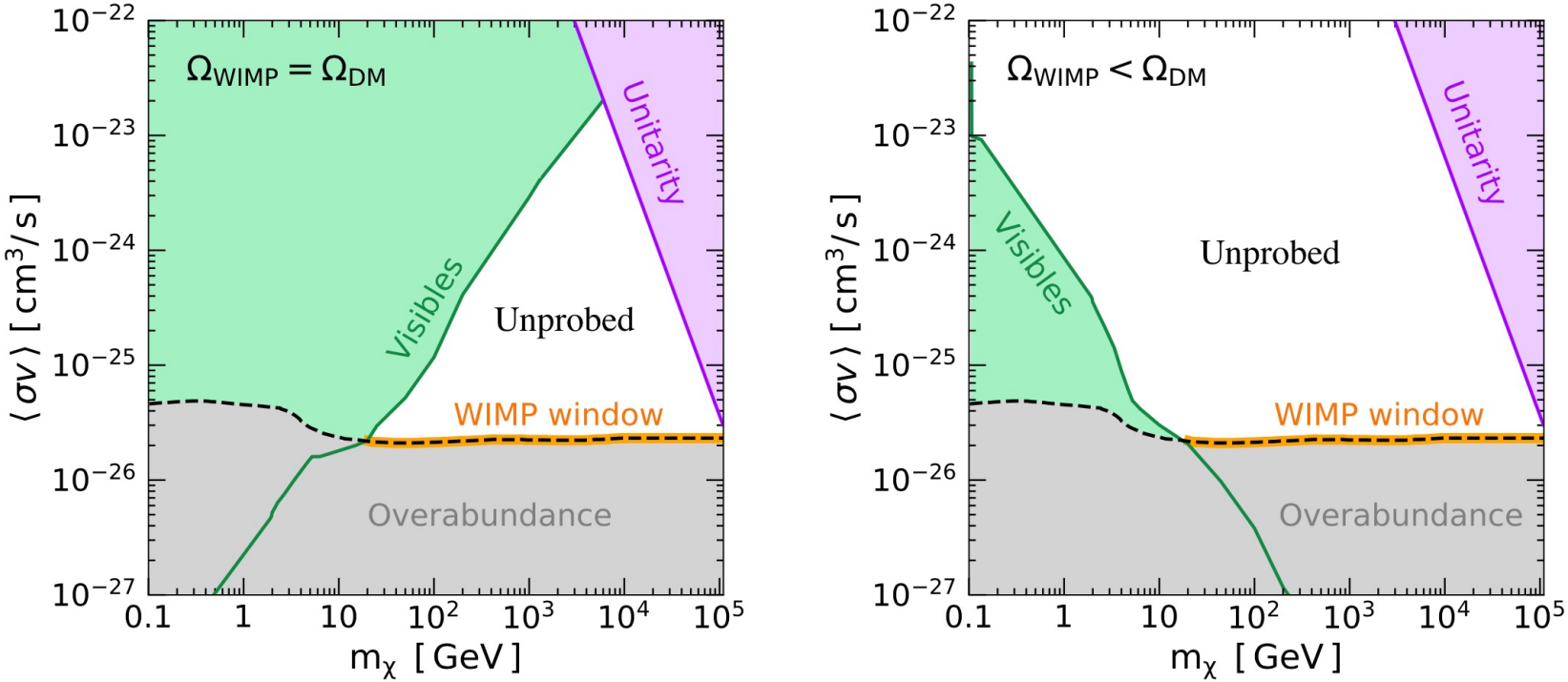
They all imply $< \sigma v >< 3 \times 10^{-26}$ cm^3/s for WIMP $m < O(10)$ GeV (exact limit depends on annih. mode). This rejects thermal WIMPs $m < O(10)$ GeV if annihilation is in s-wave:$< \sigma v >$ is v independent.

Not constraining for p-wave annihilation: $< \sigma v > \sim v^2$, because at freeze-out $v \simeq c/3$ and v is much smaller at recombination and within galaxies

Indirect limits on s-wave "WIMP miracle" cross sections

"GeV-Scale Thermal WIMPs: Not Even Slightly Dead" Leane, Slatyer, Beacom and Ng,1805.10305

s-wave 2→2 annihilation, standard cosmological history, conservative limits



Caveats to Thermal WIMPs as Dark Matter

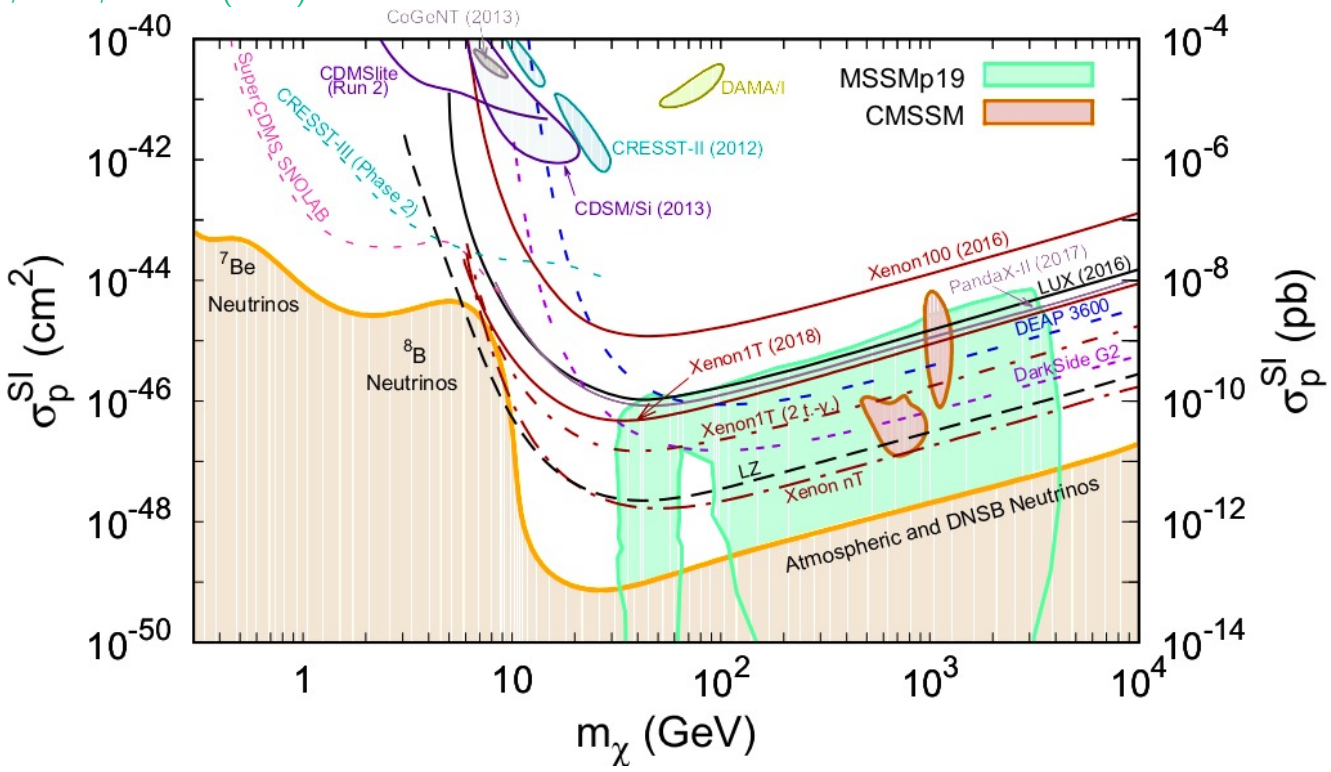
- Asymmetric DM We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates- neutralinos are Majorana particles instead) (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Non-Standard Pre-Big bang Nucleosynthesis (pre-BBN) cosmology WIMP relic abundance is fixed before BBN, a moment in the Universe from which we have so far no data. (See e.g. Gelmini et al hep-ph/0605016, or Gelmini, Gondolo 1009.3690 and refs. therein)
  $T_{f.o.} \simeq (m/20) > 5$ MeV for $m > 100$ MeV!
  Salas *et al* "Bounds on very low reheating scenarios after Planck" 1511.0067
- WIMPs may be unstable and decay into the dark matter (Super-WIMP scenario). (Feng, Rayaraman, Takayama 03; Feng, Smith 04)
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05)

If DM is Warm, cold WIMP DM could be a subdominant DM component or

WIMPs could be WDM but in this case particle models must be very different from usual- e.g. WIMPs are created late in decays and never reach kinetic equilibrium with the thermal bath

Neutralino models to be found in DD! Roszkowski, Sessolo and Trojanowski, Rept.

Prog. Phys. **81**, no. 6, 066201 (2018)



SUSY "light vanilla" models rejected by LHC- but those remaining could be seen in DD. Green region allowed (notice tend to be heavy WIMPs)

Proceed phenomenologically- consider all types of WIMP couplings
Context: The scope of DM particle models has changed:

- 1980's: DM candidates were an afterthought. Models proposed exclusively to solve problems in Standard Model, such as SUSY, Technicolor, Peccei-Quinn symmetry, neutrino masses - which also contain DM candidates (WIMPs, axions, sterile neutrinos)

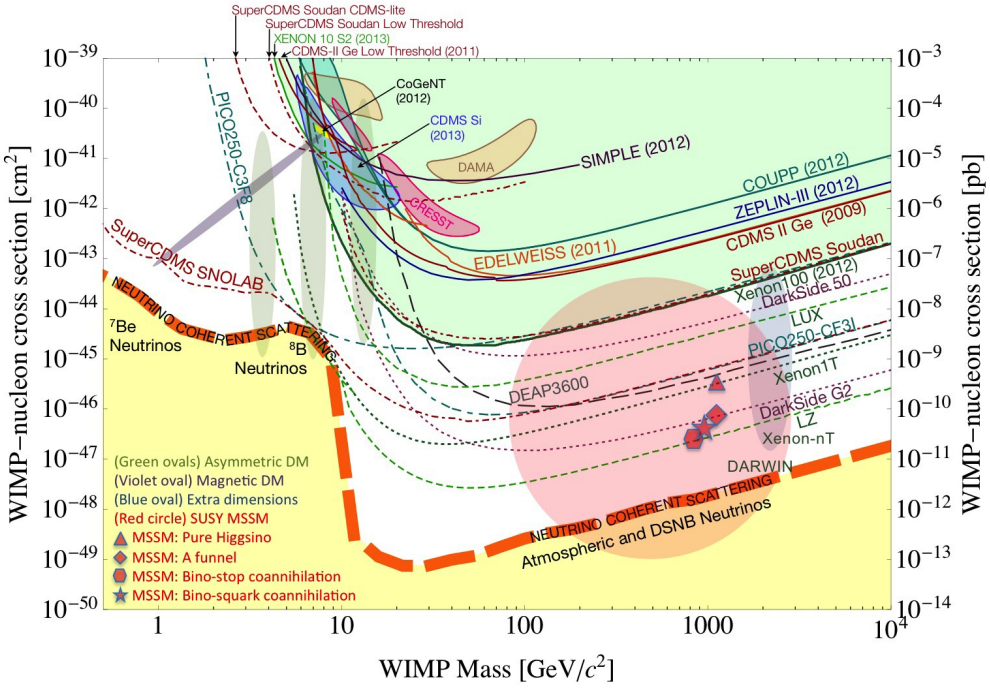
- 1990's: DM candidates were mandatory. Models required to have a DM candidate in SM extensions.

- Since 2000's: DM model independent of the SM. Models made to fit DM hints and/or predict novel DM signals and experiments to detect them, without regard for completion of the SM (but may have implications for colliders e.g. search for light mediators, displaced vertices...)
Lead to all types of DM interactions, to "dark sectors" seen through "portals" i.e. very small couplings (with photons, with neutrinos, with the Higgs....)

An example - the relevance of the neutrino floor:

Future of Direct Detection and its neutrino floor- from Snowmass 2013

This is for Spin-Independent interactions Gelmini, Takhistov and Witte, 1804.01638

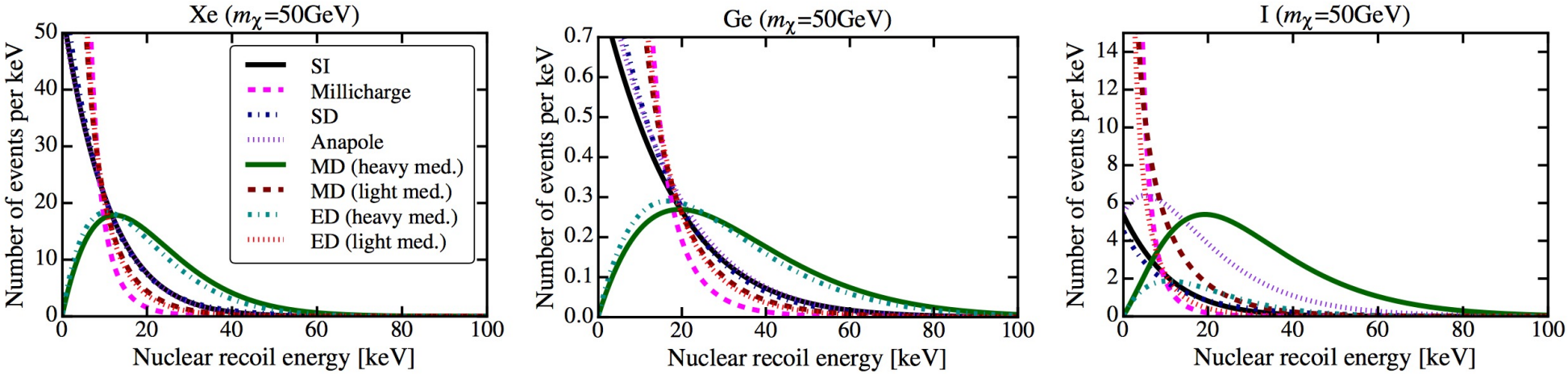


Future of non-directional Direct Detection

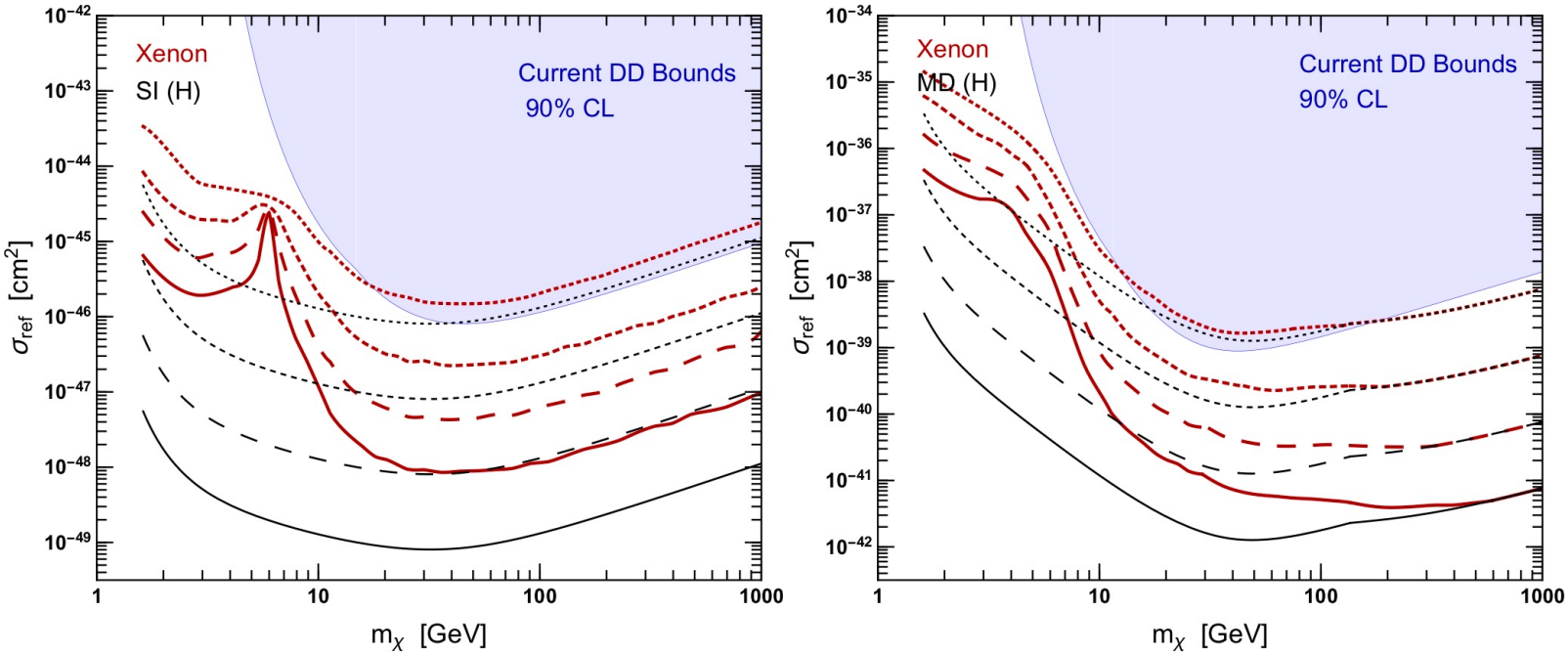
Consider all types of WIMP interactions

Differential rates can be very different than for SI

Fig. from Gluscevic, Gresham, McDermott, Peter and Zurek 1506.04454

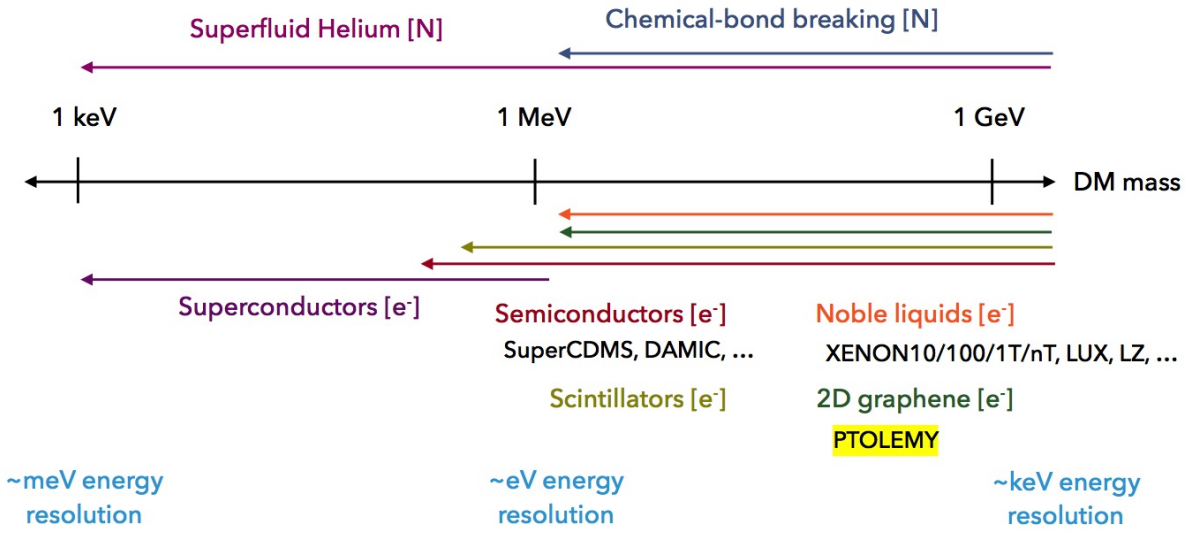


Future of Direct Detection The relevance of the neutrino floor depends on the WIMP interaction



The Xe discovery limit of heavy q^x (q is the momentum exchanged) interacting DM is not affected by the neutrino floor (for exposures $\leq$ 100 tonne y) but require experiments to extend the energy range and change their data analysis!

+ Diversify into unexplored domains light DM, dark photons and other light mediators, boosted DM. "Dark Sector Workshop"1608.08632; "U.S. Cosmic Visions: New Ideas in DM" 3/2017- KITP 2018 workshop "HEP at the Sensitivity Frontier" e.g. for sub-GeV "Light Dark Matter" direct detection (Rouven Essig)



Scattering off e [e^-] or inelastic scatt. on nuclei [N] (γ emission in nuclear recoil, breaking chemical bonds in molecules/crystals, multi-phonon processes in superfluid He or insulator crystals)

Axions: besides ADMX G2- with cavities at KAIST, Korea; New ideas: "dielectric haloscope" in MADMAX (m =40 to 300μeV), CASPER and ABRACADABRA ($<.\mu$eV)...

Continue strong diversified program of DM searches
Consider each proposed experiments on its merits

Direct detection with several target materials and strategies (continue mature background free multitonne experiments with Xe and Ar, axion cavity searches, and explore and exploit new ideas for lighter particles, such as SENSEI, FASER, CASPER, ABRACADABRA...)

Indirect detection with multi-messenger approach (although there are exceptions, due to astrophysical uncertainties may constitute a confirmation but not a discovery of DM) (Tracy Slatyer)

Collider searches LHC, DUNE, fixed target... (but if DM candidate is discovered, will need to confirm it is the DM)

for WIMPs, they are as interesting as ever..., sub GeV DM, axions/ALPs/ WISPs, sterile neutrinos,...
for all types of interactions, production models, mass ranges...
Very vibrant field, will continue to be so for many years to come