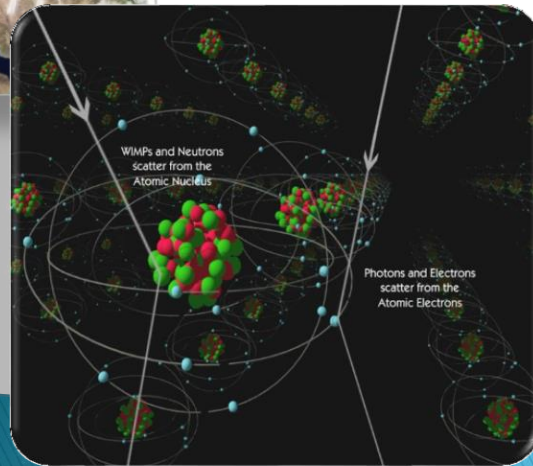
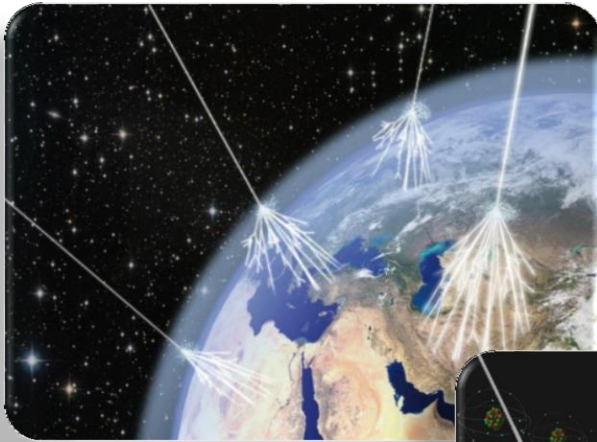


Dark Matter: Theorist's (Imperfect) Overview



Jong-Chul Park

CNU 충남대학교
CHUNGNAM NATIONAL UNIVERSITY

September 20, 2019

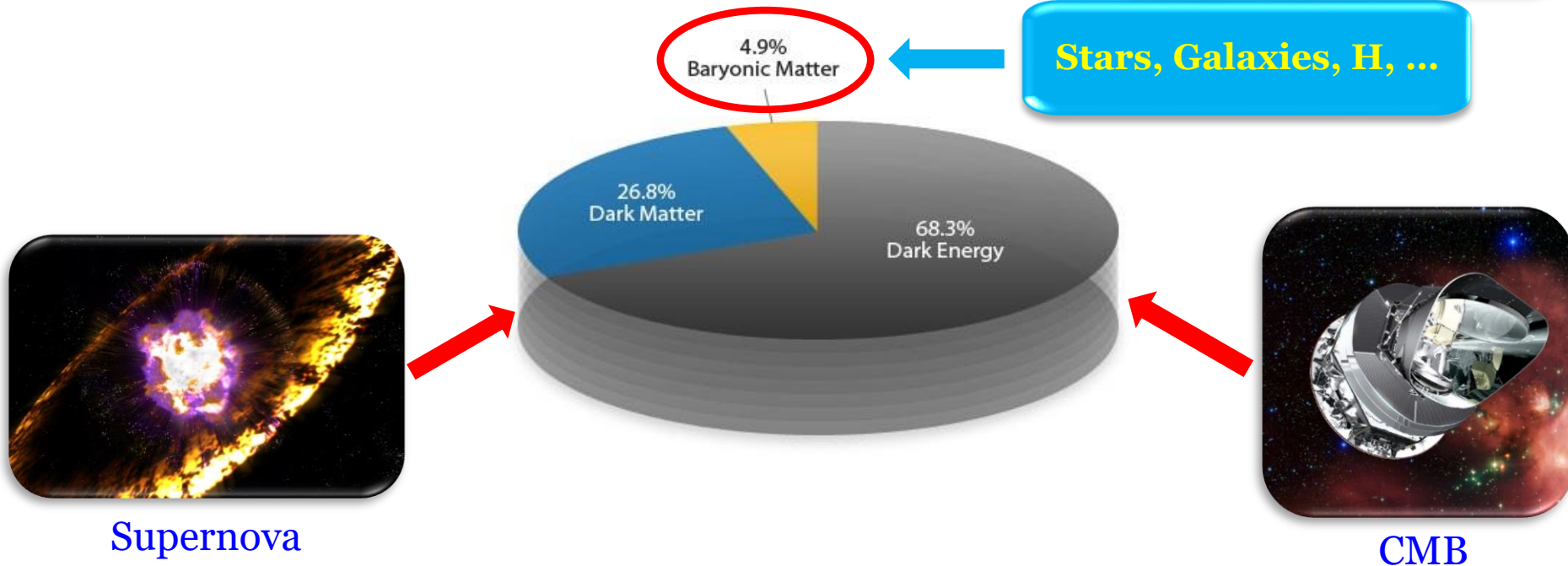
Meeting for Long-term Strategy of High Energy Physics in Korea

Message from Cosmology

❖ Modern cosmology → Cosmic pie



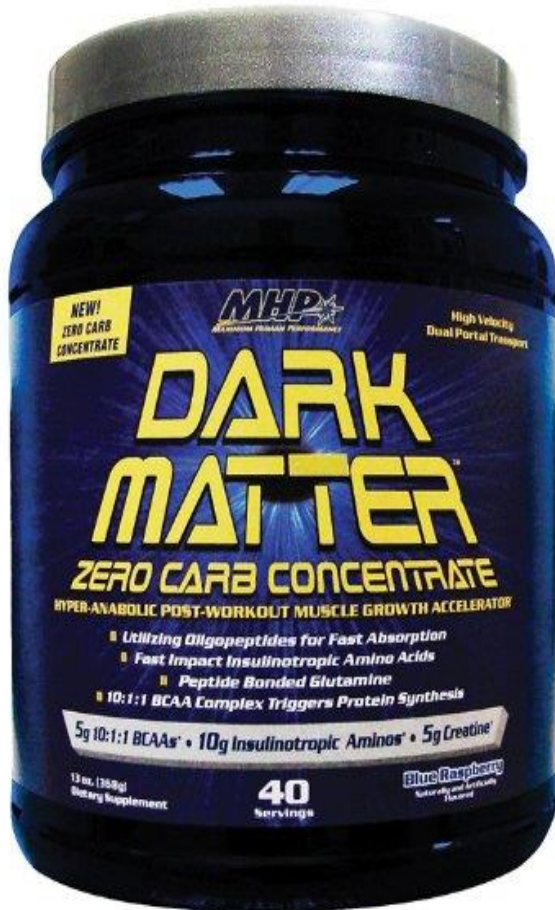
Stars, Galaxies, H, ...



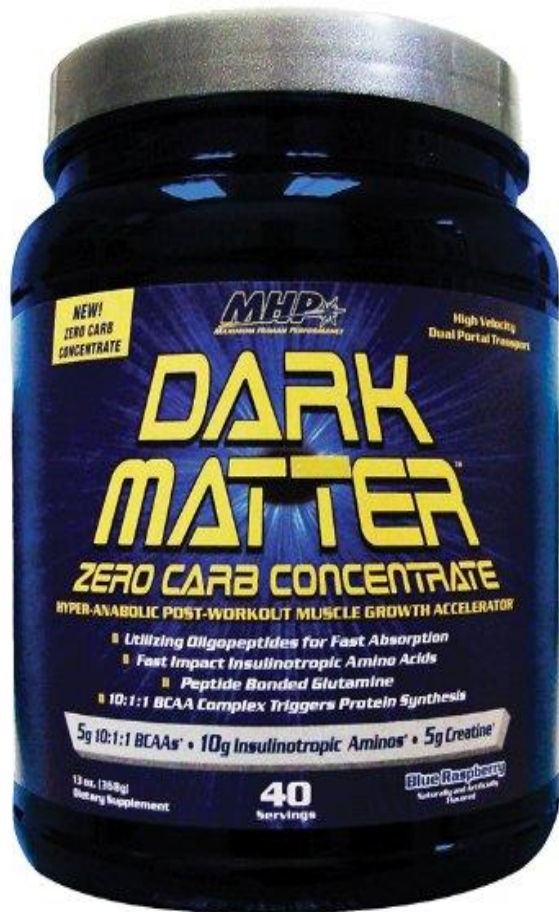
❖ The Standard Model explains only ~5% of the total E of the Universe.

Question in the 20th Century!

What's
the matter?



Question in the 21th Century!

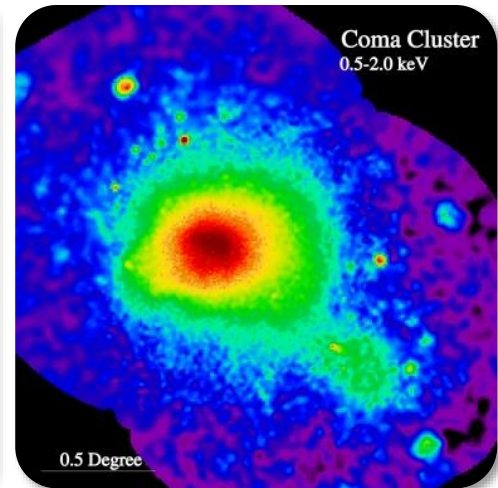
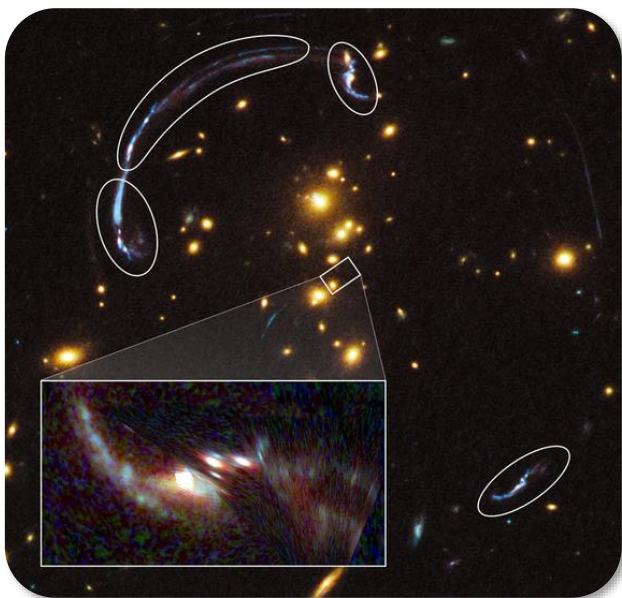
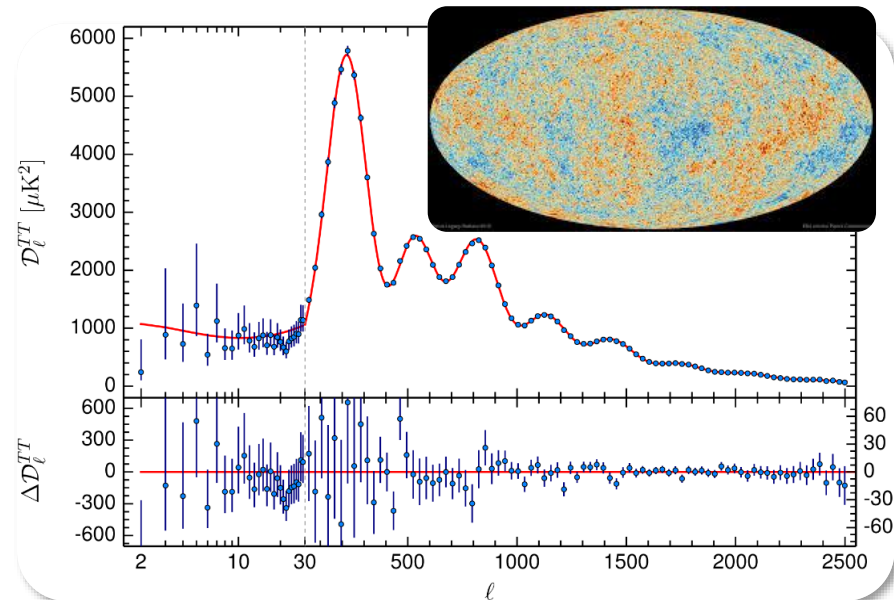
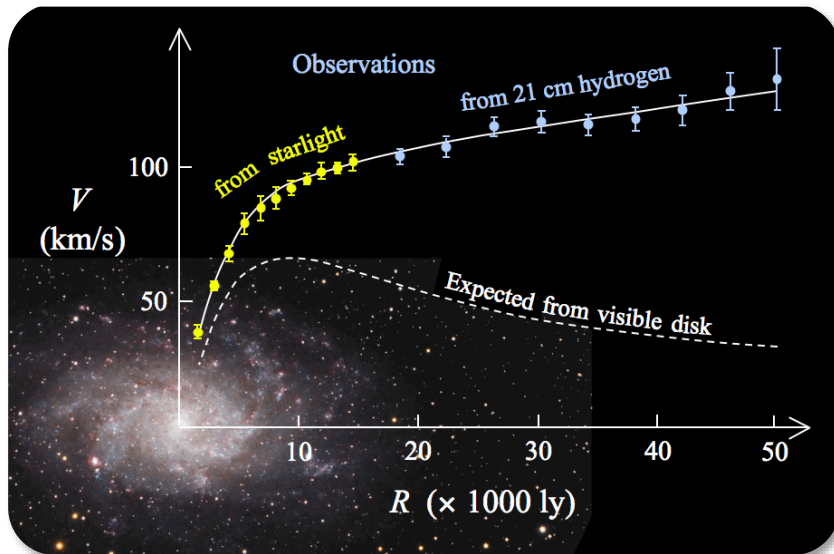


What's
the matter?



What's
Dark Matter?

Observational Evidence for DM



Observational Evidence for DM

- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ ...

Classic Solution*: WIMP

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee^(a)

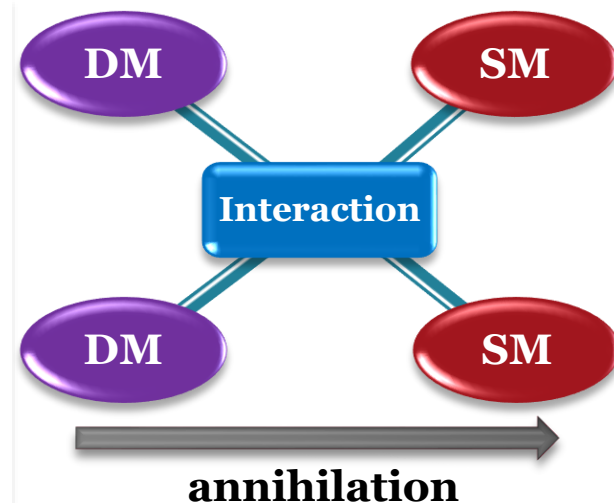
Fermi National Accelerator Laboratory, ^(b) Batavia, Illinois 60510

and

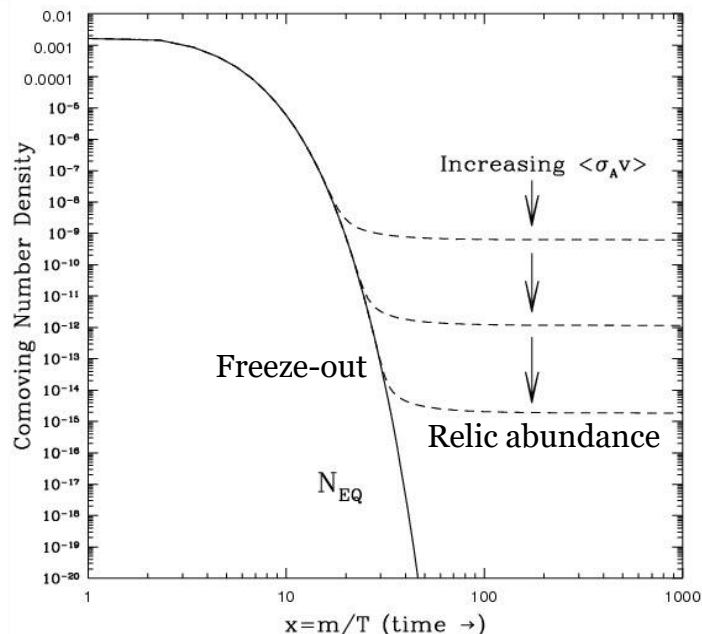
Steven Weinberg^(c)

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 $2 \times 10^{-29} \text{ g/cm}^3$, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



- Correct thermal relic abundance:

$$\Omega h^2 \sim \frac{0.1 \text{ pb}}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\alpha_X^2 m_X^2}{M^4} \text{ (} M: \text{ dark scale/mediator)}$$

- Weak coupling \rightarrow **naturally** weak scale mass:
~1 GeV – 10 TeV mass range favored
 \rightarrow weak scale (new) physics

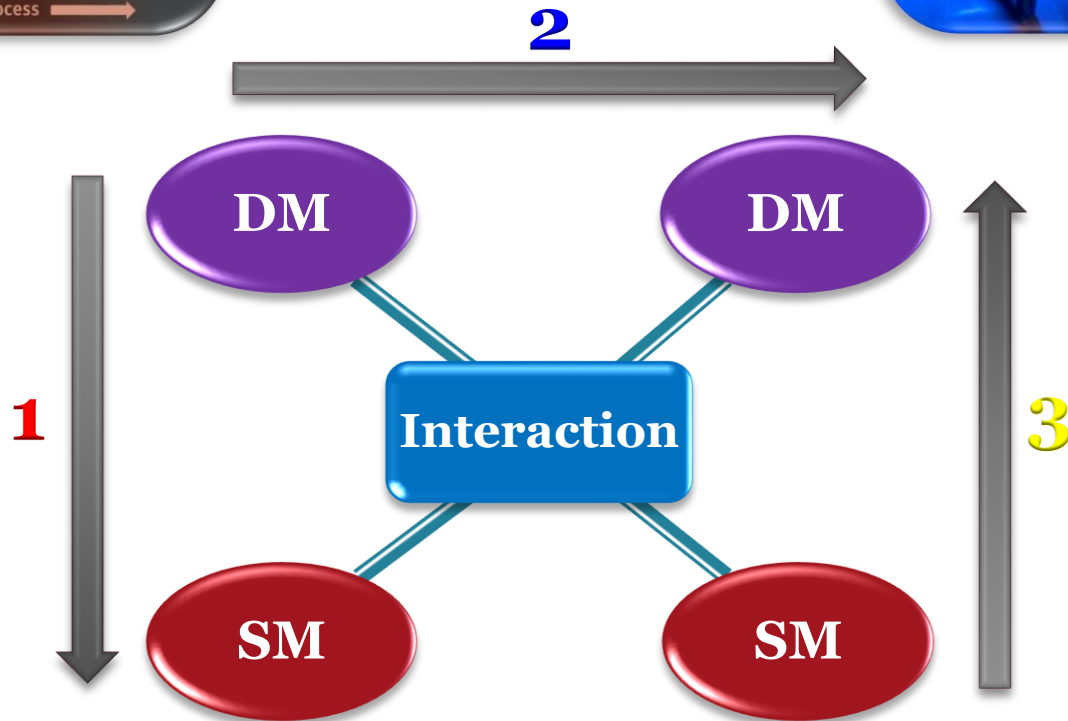
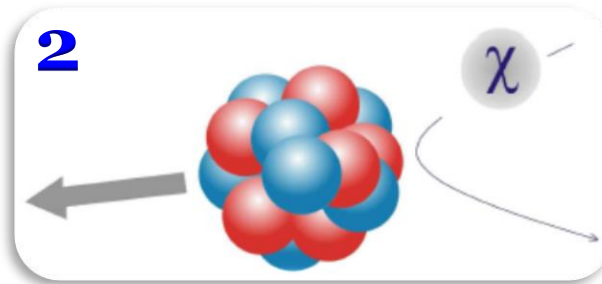
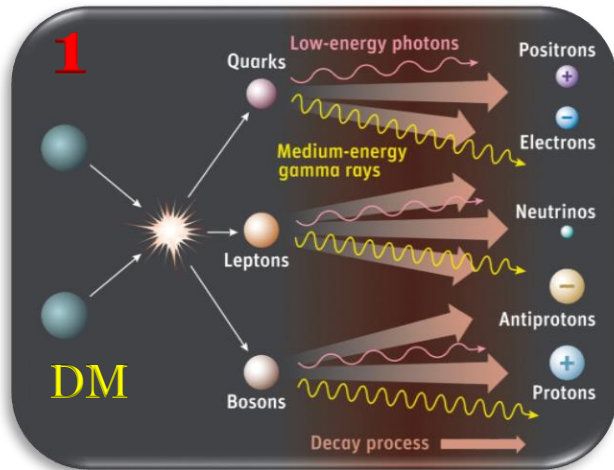
* Of course also **axion**: Woohyun's talk

Observational Evidence for DM

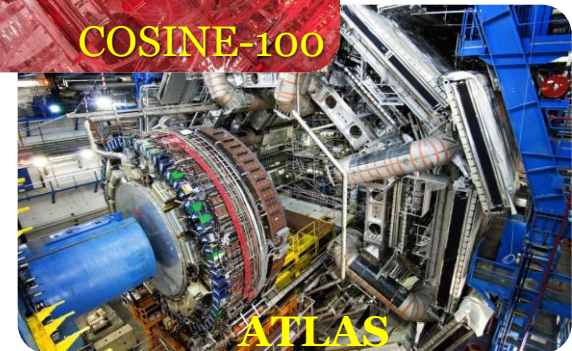
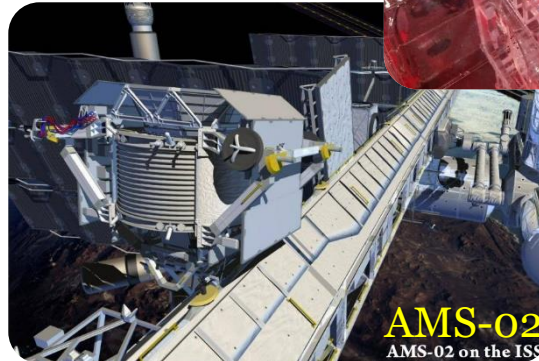
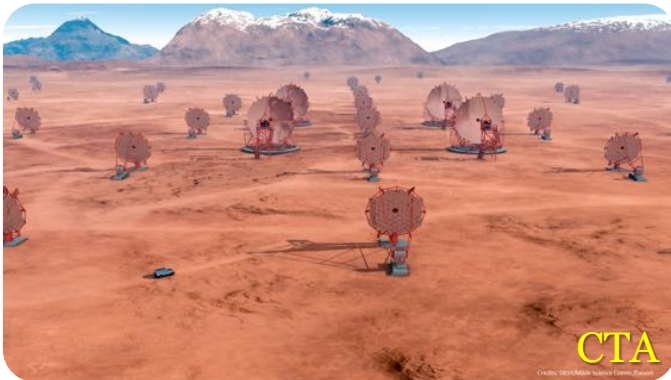
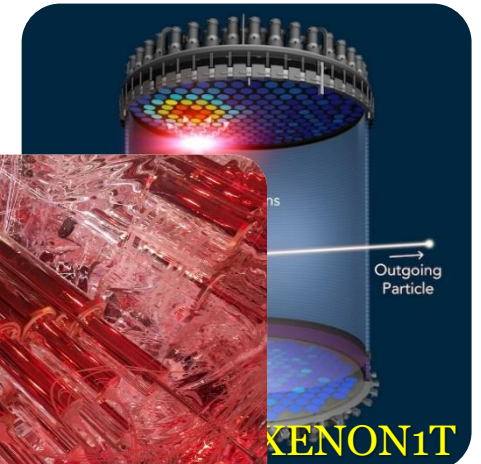
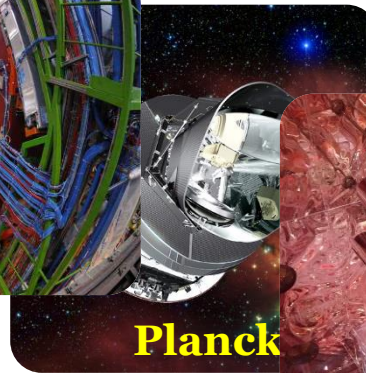
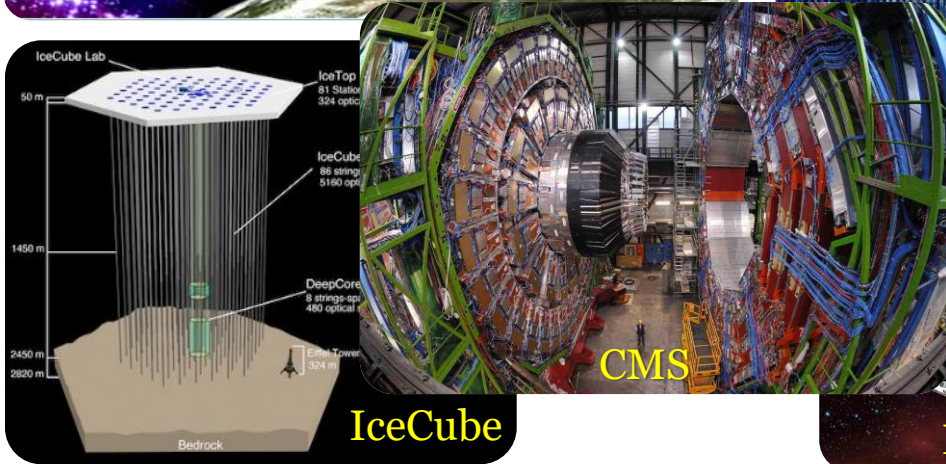
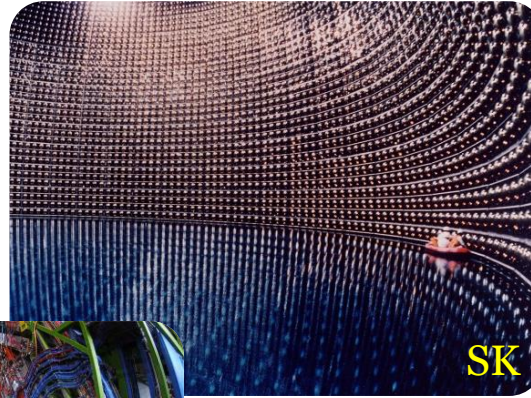
- ✓ Galaxy rotation curve
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- ✓ Type Ia supernovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ ...

Only Gravitational

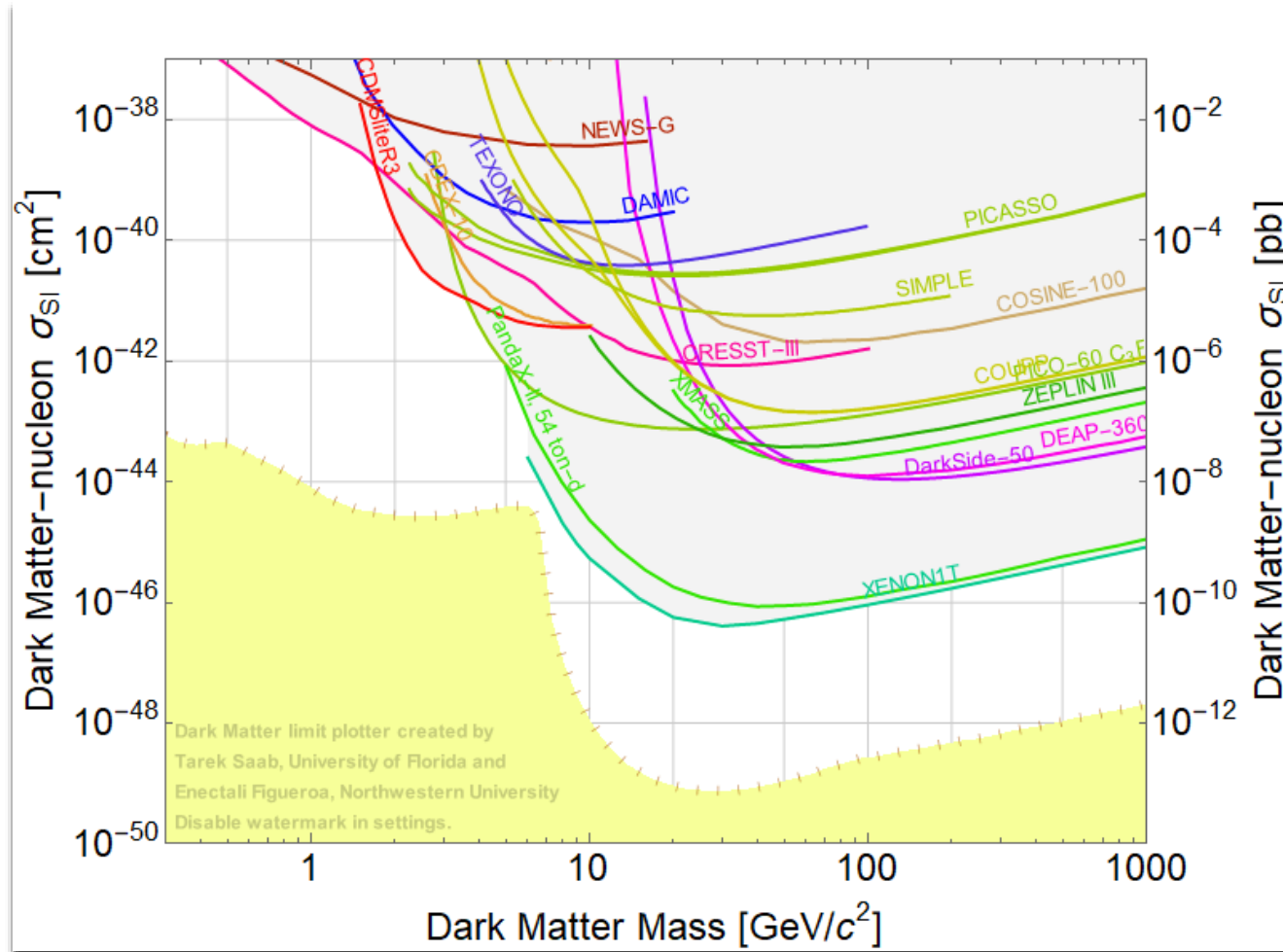
DM (WIMP) Search Strategies



Diverging Efforts for WIMP Searches

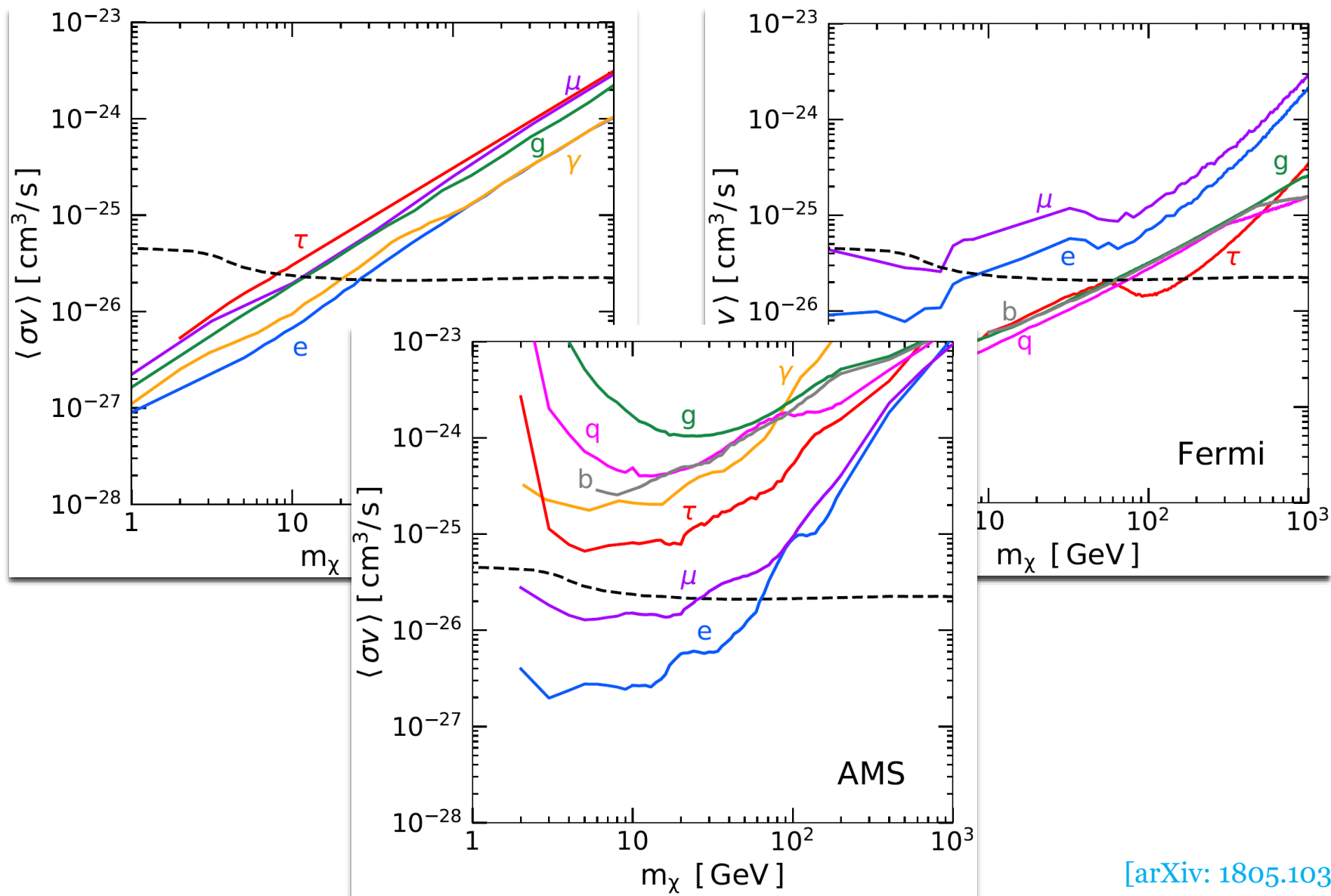


Current Status of Direct Searches

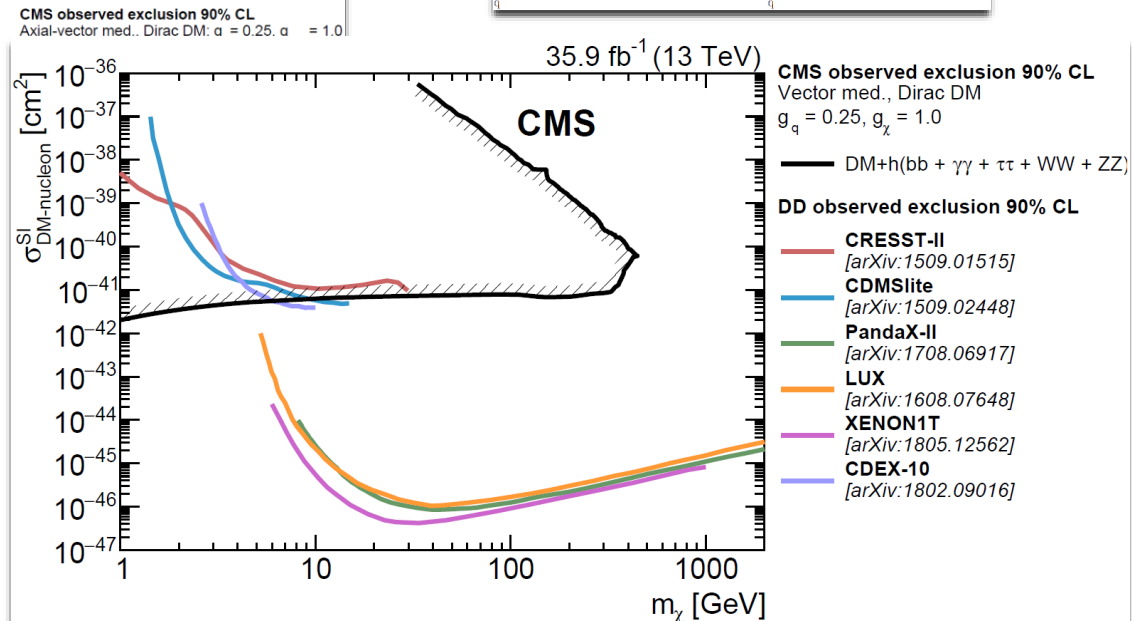
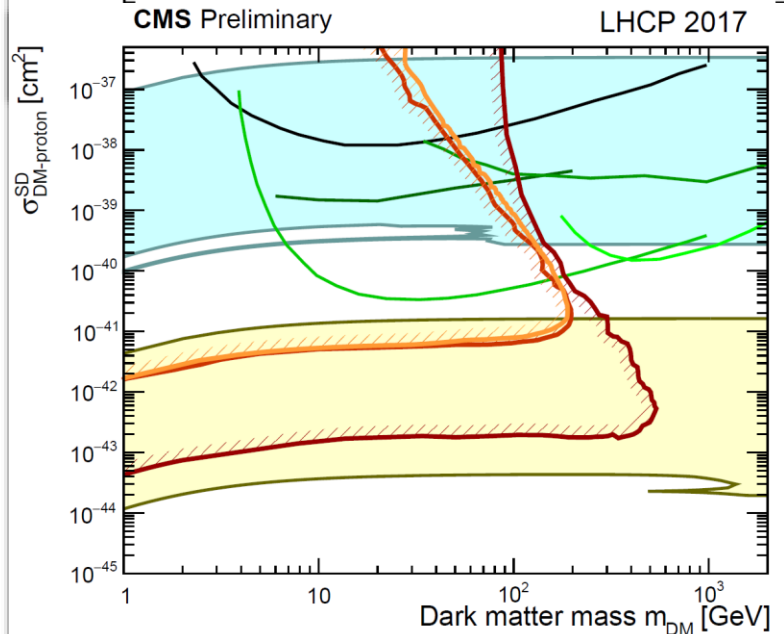
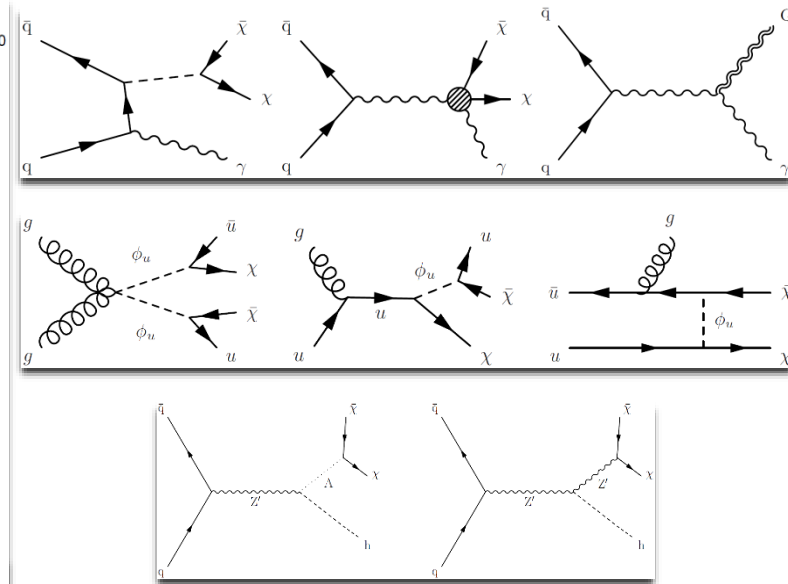
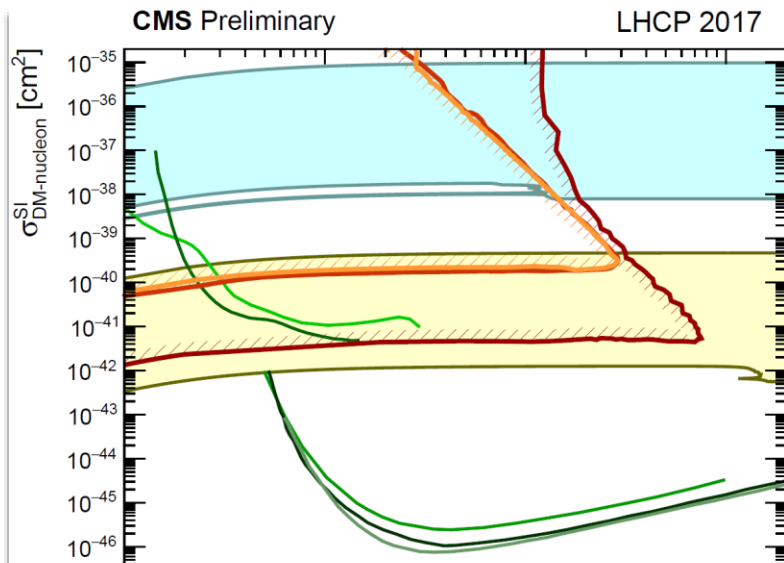


Dark Matter Limit Plotter v5.12, updated May 16, 2019

Current Status of Indirect Searches



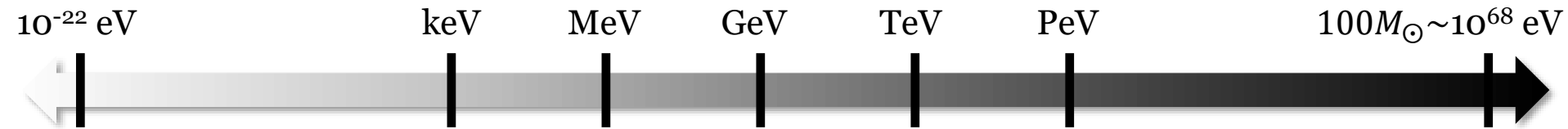
Current Status of LHC Searches



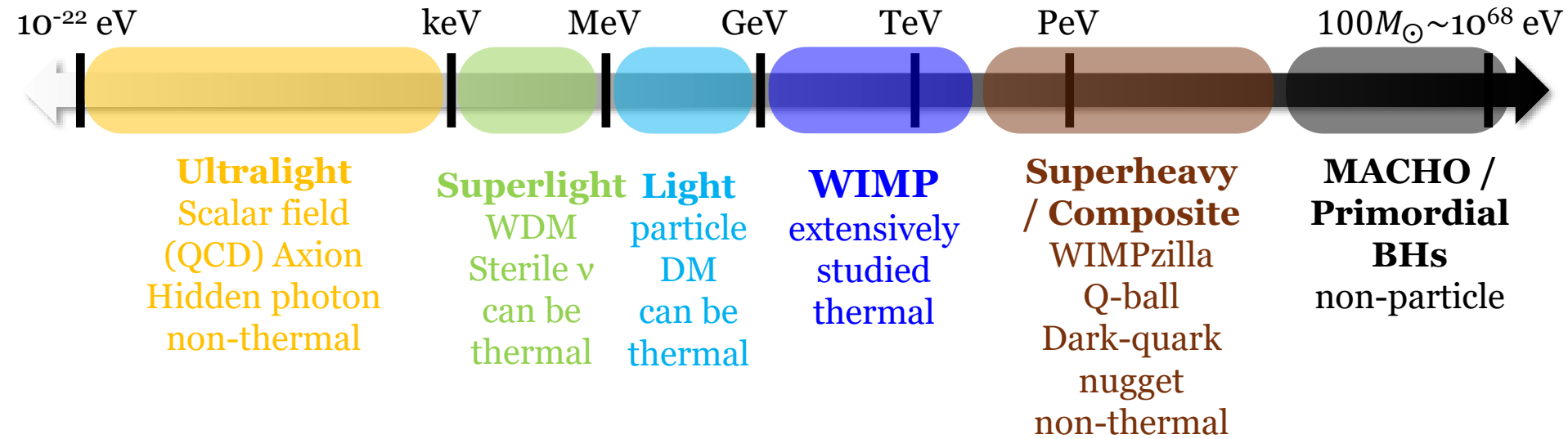
**Only
WIMP?**



Mass Scale of Dark Matter



Mass Scale of Dark Matter



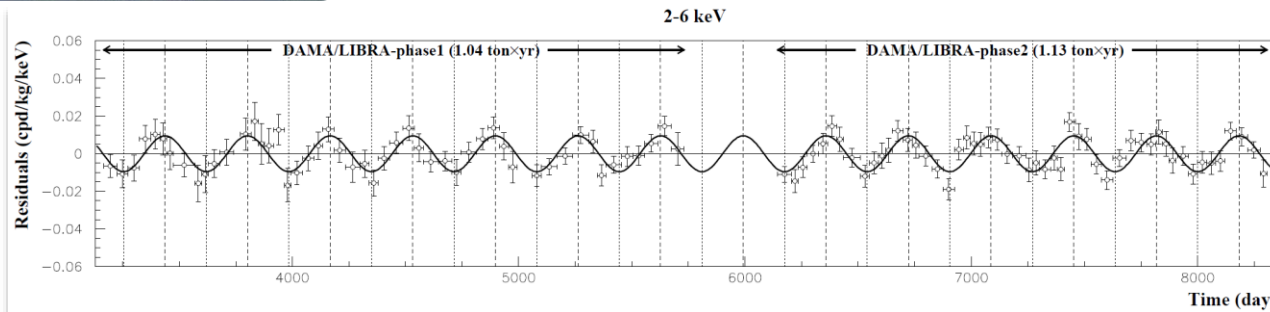
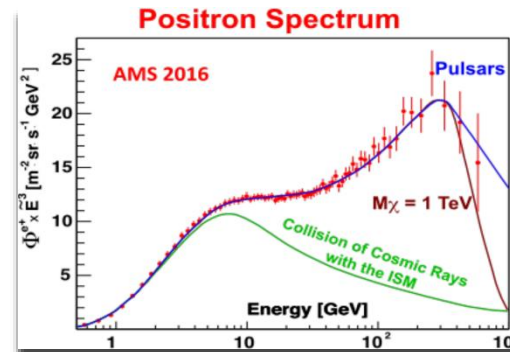
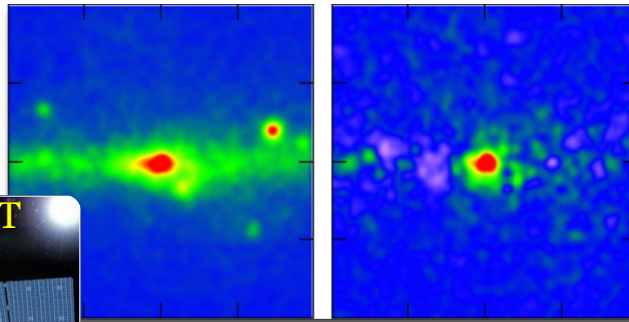
Mass Scale of Dark Matter



- ✓ **Well-motivated Many models:** LSP of SUSY models, LKP of ExD. Models, ...
- ✓ **Various experimental searches:** Direct scattering, Cosmic-ray, Direct production

WIMP
extensively
studied
thermal

- ✓ **Various anomalies:** O(GeV) γ -ray excess, O(100 GeV) e⁺ excess, DAMA annual modulation, ...



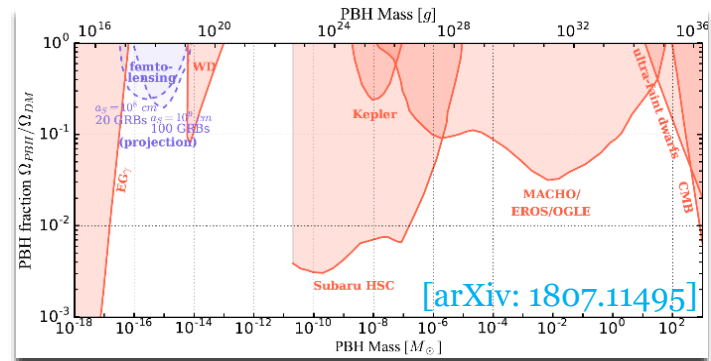
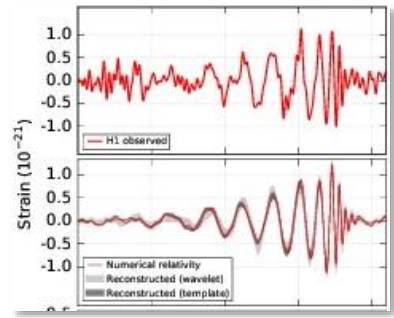
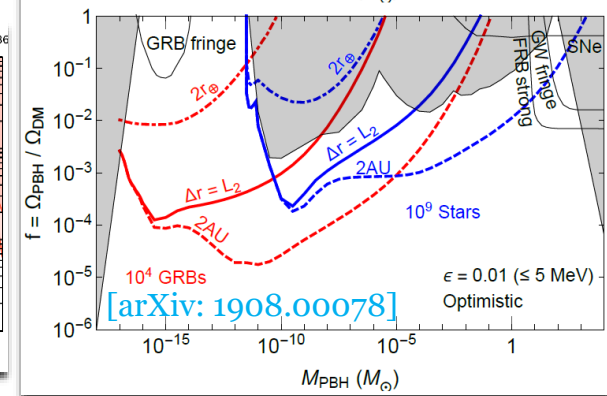
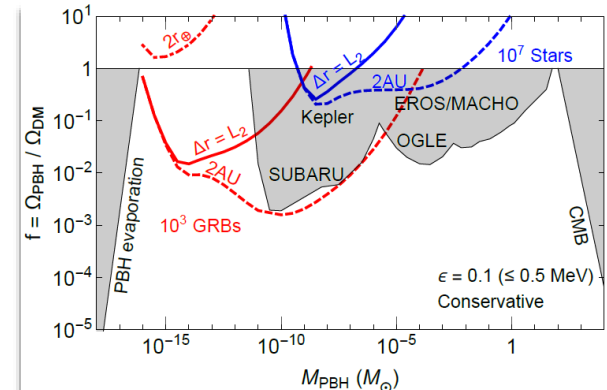
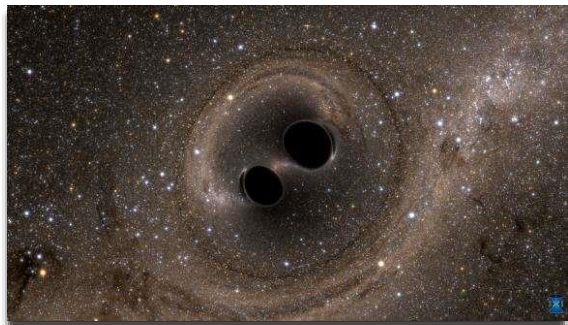
See also Hyun Su's talk!

Mass Scale of Dark Matter



- ✓ Massive astrophysical compact halo object = MACHO: black holes, neutron stars, brown dwarfs, unassociated planets, ...
- ✓ **Experimental searches:** gravitational wave, gravitational lensing, CMB, ...

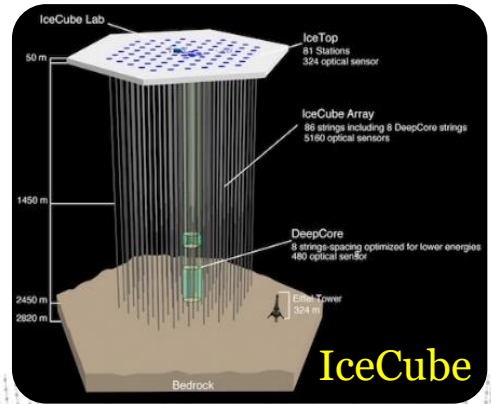
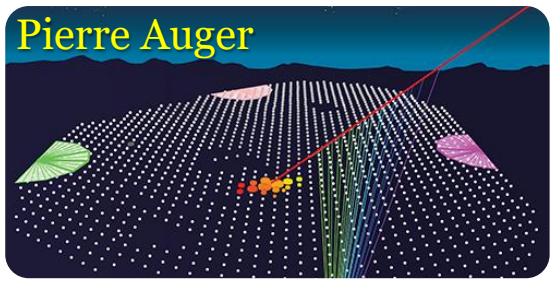
**MACHO /
Primordial
BHs**
non-particle



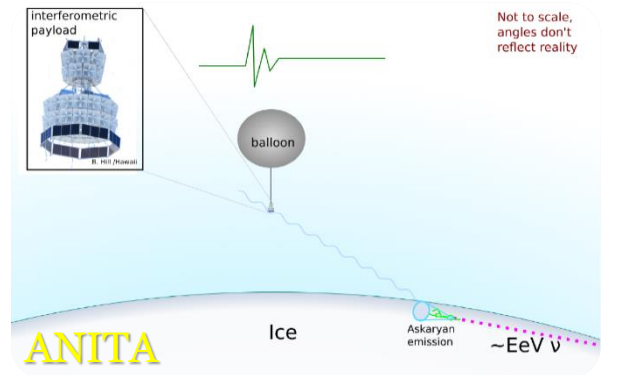
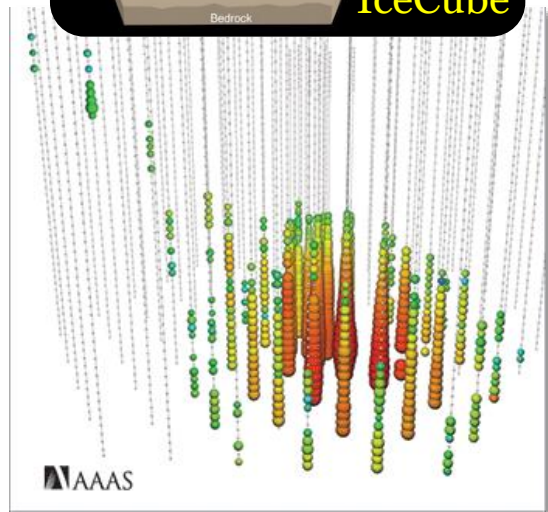
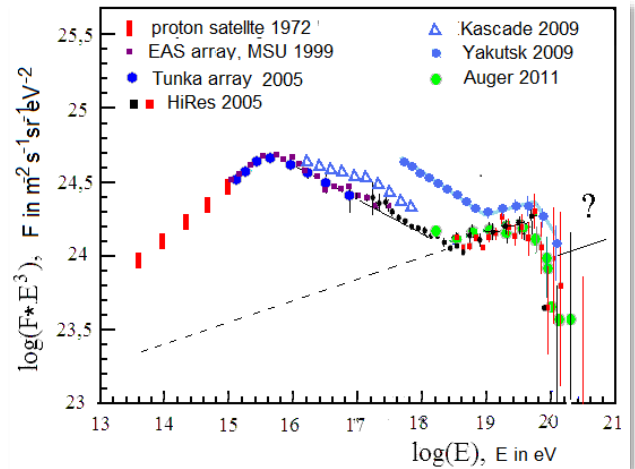
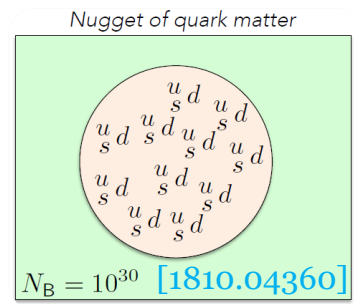
Mass Scale of Dark Matter



- ✓ **Anomalous cosmic-ray signals:**
Ultra-high-energy cosmic ray observation at Pierre Auger, PeV ν events at IceCube, EeV events at ANITA



Superheavy / Composite WIMPzilla
Q-ball
Dark-quark nugget
non-thermal

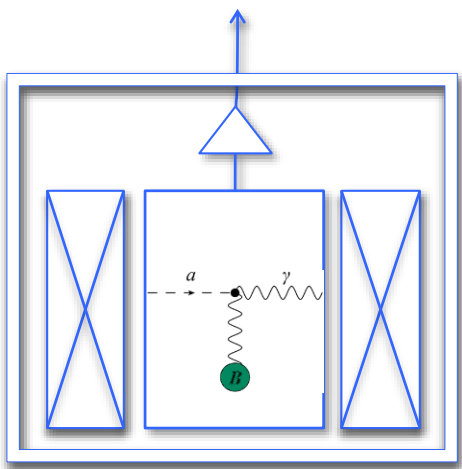
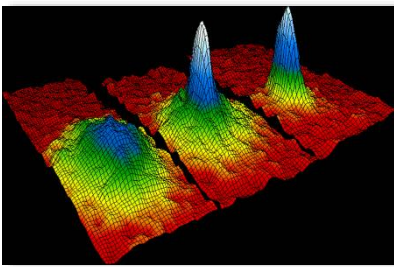


event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon. ⁽¹⁾	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3^\circ, 159.62 \pm 0.7^\circ$	$-35.0 \pm 0.3^\circ, 61.41 \pm 0.7^\circ$
RA, Dec ⁽²⁾	282.14064, +20.33043	50.78203, +38.65498
$E_{\text{shower}}^{(3)}$	$0.6 \pm 0.4 \text{ EeV}$	$0.56^{+0.3}_{-0.2} \text{ EeV}$

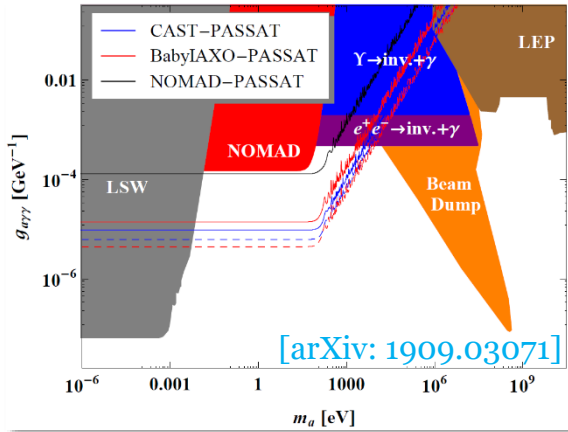
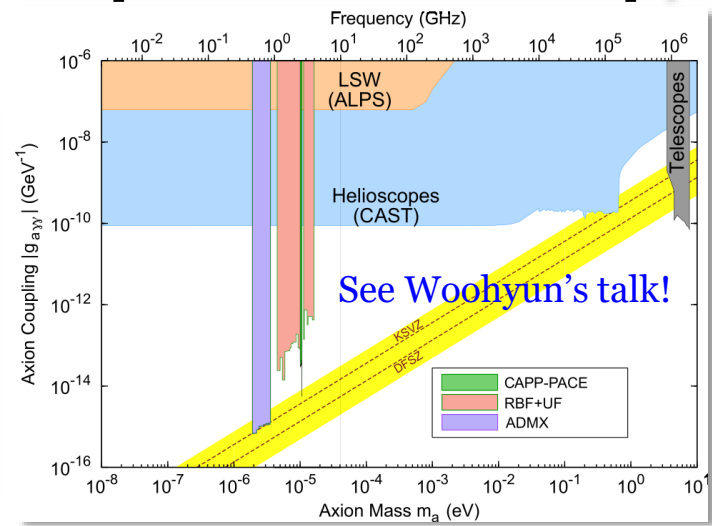
Mass Scale of Dark Matter



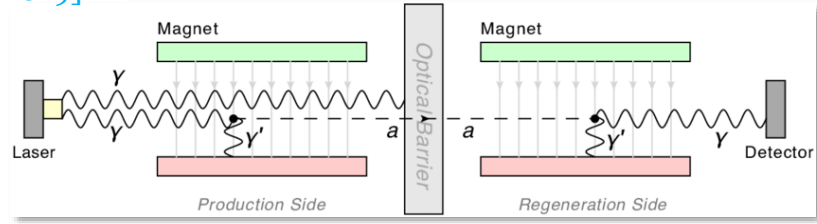
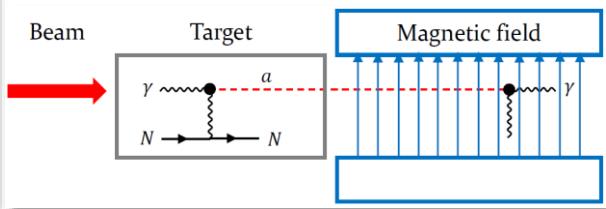
Ultralight
Scalar field
(QCD) Axion
Hidden photon
non-thermal



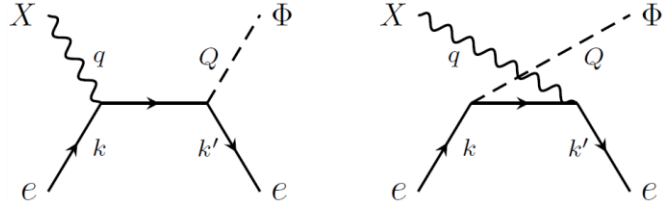
[Sung Woo Youn's @ LP2019]



ALS Production



DM Absorption [arXiv: 1604.06800]

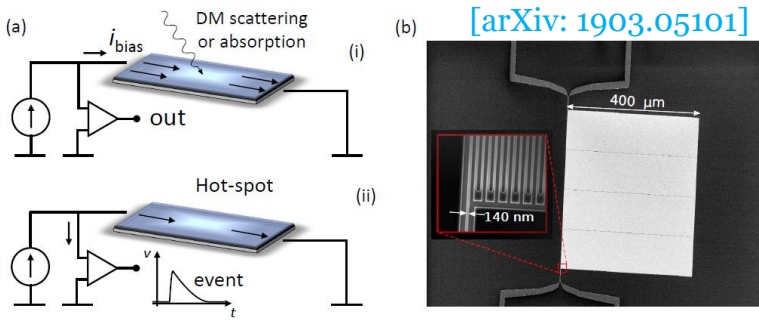


Mass Scale of Dark Matter

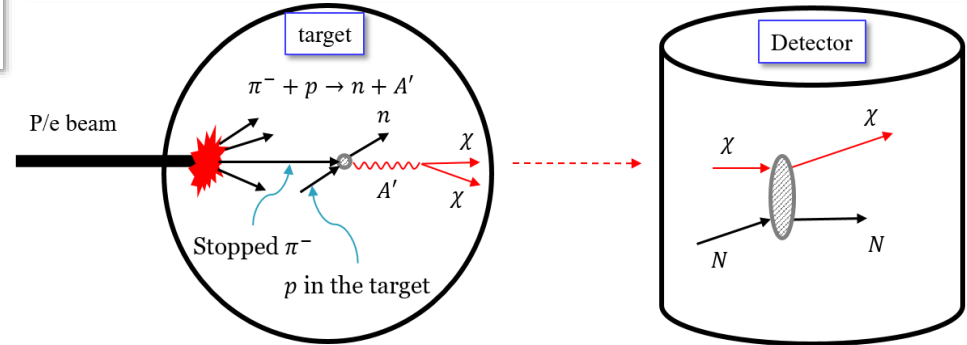


- ✓ $E_k \sim mv^2 < \text{keV}$ with $v \sim 10^{-3} \rightarrow$ **Light particle DM can be thermal**
- ✓ $< E_{th}$ of typical DM direct detectors
- ✓ **New ideas are required!** \rightarrow graphene, superconducting target, nanowire, superfluid He, 3-D Dirac material, Polar material, ... (w/ TES, MKID, SNSPD)

- ✓ For heavy mediator, $\langle \sigma v \rangle \sim \frac{\alpha_X^2 m_X^2}{M^4}$
- ✓ For weak scale physics, **sub-GeV DM overproduction** (Lee-Weinberg) \rightarrow **New mediator $< M_W$** for thermal freeze-out or freeze-in
- ✓ **New DM relic determination mechanisms:** SIMP ($3 \rightarrow 2$ annihilation), co-annihilation, co-decaying, assisted freeze-out, ...



- ❖ **Particle beam \rightarrow Active production of energetic DM:** Babar, BDX, Belle, COHERENT, DUNE, FASER, JSNS2, LDMX, LHCb, NA48/2, NA64, SHiP, T2SK/HK, ...



$$\pi^0 \rightarrow \gamma + A', \pi^-/+ + p/n \rightarrow \pi^0 + n/p$$

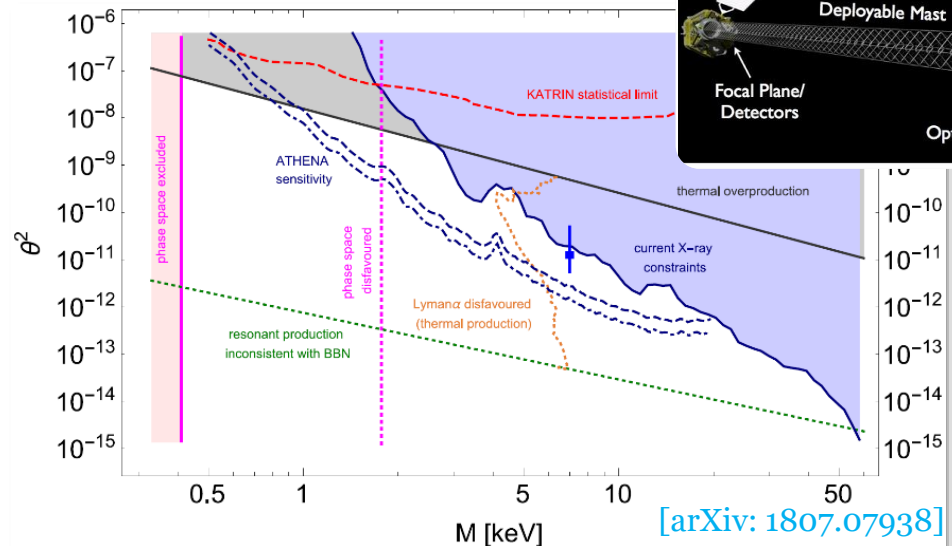
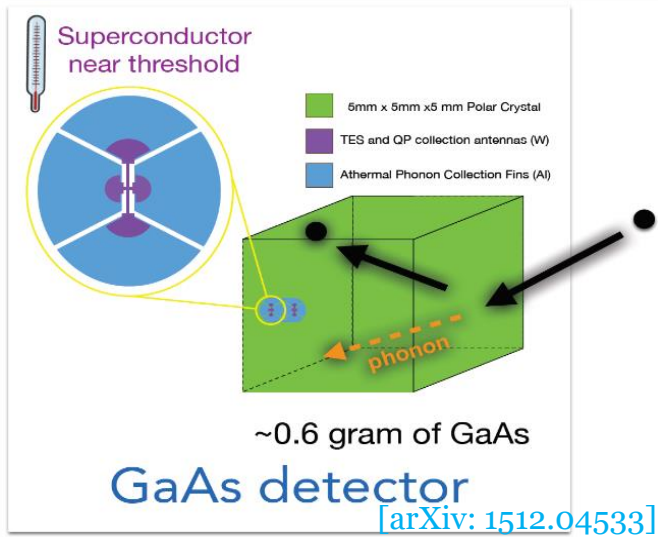
See also Eunil's & Chun Sil's talk!

Mass Scale of Dark Matter



Superlight
WDM
Sterile ν
can be
thermal

- ✓ $E_k \sim mv^2 < eV \rightarrow$ Very low E_{th} exps. required! (~ 1 meV or less)
- ✓ Sterile neutrino: a good candidate, well-studied
- ✓ WDM: lower mass limit from Lyman- α forest
- ✓ 3.5 keV X-ray line anomaly by XMM-Newton



New Ideas for Portals & Dark Sector

❖ Portals between dark (hidden) & SM sectors

✓ **Vector** portal (kinetic mixing): $\frac{\sin \epsilon}{2} B_{\mu\nu} X^{\mu\nu}$

✓ **Scalar** portal (Higgs portal): $\lambda_{H\phi} |H|^2 |\phi|^2$

✓ **Fermion/neutrino** portal: $\lambda_\chi HL\chi$

✓ **Axion/pseudo-scalar** portal: $\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

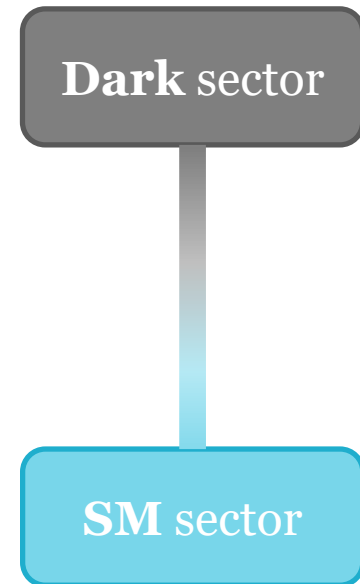
❖ Dark sector

✓ DM **spin**: fermion, scalar, vector

✓ DM **species**: single-/two-/multi-component

✓ DM **mass**: light, heavy, light & heavy

✓ DM **interaction**: flavor-conserving (elastic), flavor-changing (inelastic)

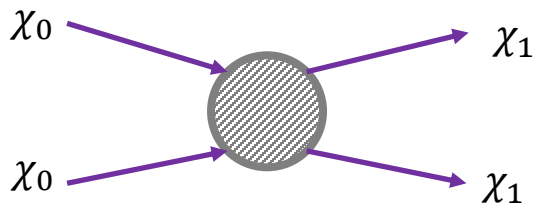


New Ideas for DM Relic Abundance

- ✓ ...
- ✓ Assisted freeze-out [[arXiv:1112.4491](#)]
- ✓ Asymmetric dark matter [[arXiv:0901.4117](#)]
- ✓ Cannibal dark matter [[arXiv:1602.04219](#), [1607.03108](#)]
- ✓ Co-annihilation [[PRD43\(1991\)3191](#)]
- ✓ Co-decaying dark matter [[arXiv:1105.1652](#), [1607.03110](#)]
- ✓ Co-scattering mechanism [[arXiv:1705.08450](#)]
- ✓ ELDER (ELastically DEcoupling Relic) [[arXiv:1512.04545](#)]
- ✓ Freeze-in [[arXiv:0911.1120](#)]
- ✓ Forbidden channels [[PRD43\(1991\)3191](#) , [arXiv:1505.07107](#)]
- ✓ Semi-annihilation [[arXiv:0811.0172](#), [1003.5912](#)]
- ✓ SIMP (Strongly Interacting Massive Particle) [[arXiv:1402.5143](#)]
- ✓ ...

Energetic/Boosted Dark Matter

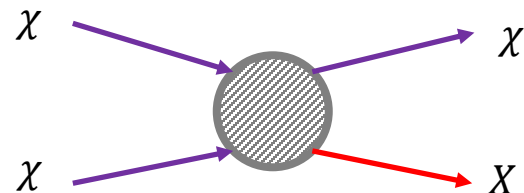
Energetic DM coming from the universe



✓ Multi-component model

[arXiv:1112.4491,
1405.7370]

$$m_0 \gg m_1$$

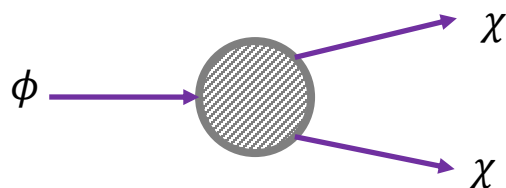


✓ Semi-annihilation model

$$m_\chi \gg m_X$$

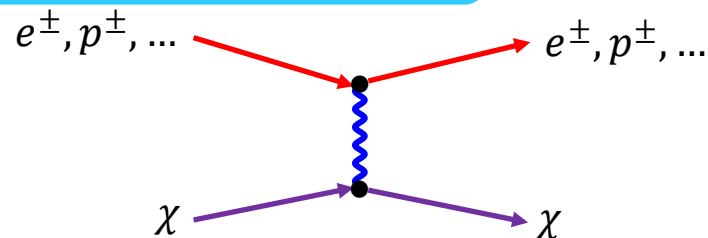
[arXiv:1003.5912,
1410.2246]

Large E_k^{DM} due to mass gap or E_k^{CR} transfer



✓ Decaying multi-component DM

[arXiv:1407.3280] $m_\phi \gg m_\chi$



✓ Energetic cosmic-ray induced DM

$E_{e^\pm, p^\pm, \dots} \gg m_\chi$ [arXiv:1810.10543]

❖ Relic component DM: **non-relativistic!**

Experimental Anomalies/Issues

❖ Direct detection

- ✓ Annual modulation signals by DAMA
- ✓ Lowering E_{th} , Neutrino floor → directionality?

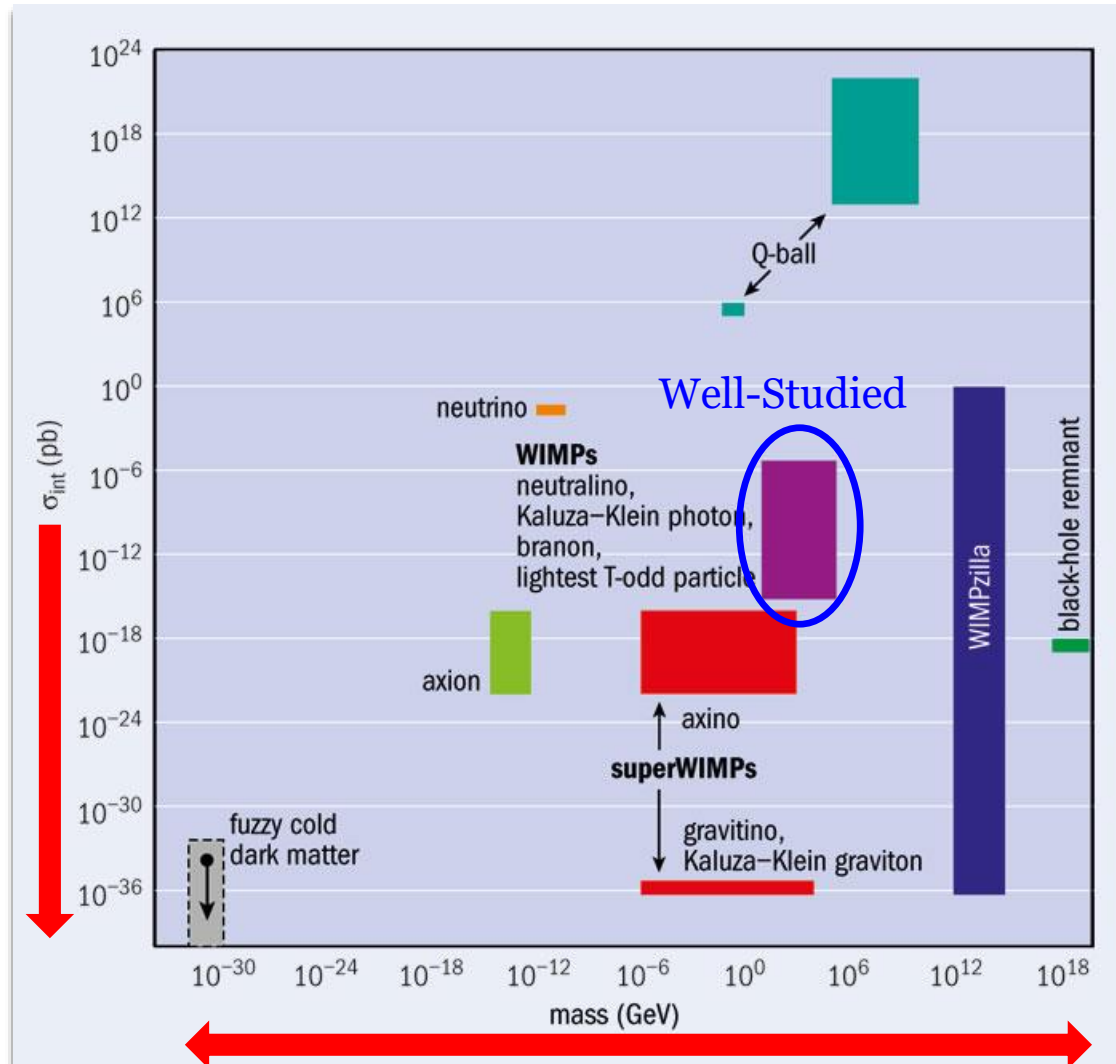
❖ Indirect detection (cosmic ray)

- ✓ Photon: 3.5 keV line (XMM-Newton), GC 511 keV line (SPI/INTEGRAL), GC O(GeV) excess (Fermi-LAT)
- ✓ e^+e^- : O(10 – 100 GeV) excess (PAMELA, Fermi-LAT, AMS-02)
- ✓ \bar{p} : O(10 GeV) excess (AMS-02)
- ✓ ν : PeV events (IceCube), EeV events (ANITA → observed: EM shower)

❖ Direct production or Particle beam

- ✓ e-like event excess (MiniBooNE)
- ✓ an excess in the timing-spectra (COHERENT)

Mass Scale & Interaction of DM



Summary & Outlook

- **WIMP**: well-motivated → **well-studied** → various anomalies but **no strong evidence yet**
- **Rising interest** in **other mass scale DM** (super/ultra-light DM, superheavy DM) and also **extended dark sector** scenarios, **energetic DM**, ...
- **New ideas** for **portals** between DM-SM sectors & DM **relic abundance**
- Thus, **New DM search ideas** are **strongly required**.
- **Various experiments are coming soon!** (e.g. CAPP, CTA, DUNE, FASER, HK/KNO, IceCube-Upgrade, JSNS2, LZ, XENONnT, ...)

"Alexa"

again, this time try Alexa \$10 credit

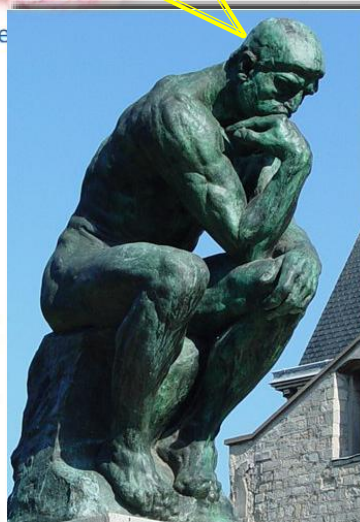


Learn more

Back to search results for "dark matter"

MHP Dark Matter Post-Workout Muscle Growth Accelerator, Blue Raspberry, 3.22 Pound

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