Title: Exploring the dark side of the Universe

Date: May 10, 2017 02:00 PM

URL: http://pirsa.org/17050063

Abstract: <p>Dark matter is all around us, however its particle physics nature is still mysterious. Searches for dark matter have largely focused on candidates with weak scale interactions to the standard model particles, the so-called WIMP paradigm. However, the parameter space of the WIMP paradigm is becoming increasingly constrained by both the LHC and direct detection experiments. Another possibility that is well motivated both theoretically and observationally is to have a dark sector connected with the visible one via a mediator whose coupling to the visible one is tiny. In this talk, based on my own work, I will discuss models in this direction and how to search for signals from the dark sector using various experiments including particle accelerators, dark matter direct detection experiments, cosmic ray experiments, and cosmic microwave background observation. </p>

Exploring the Dark Side of the Universe

Haipeng An (Caltech)

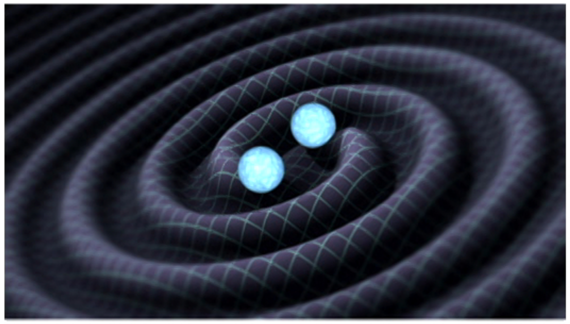
Colloquium

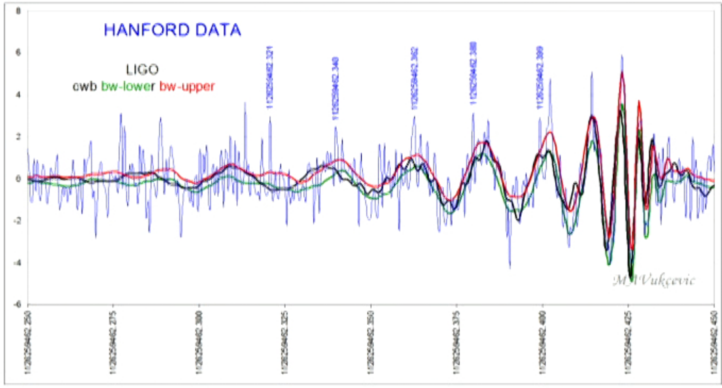
Perimeter Institute

05/10/2017

Gravitational Wave

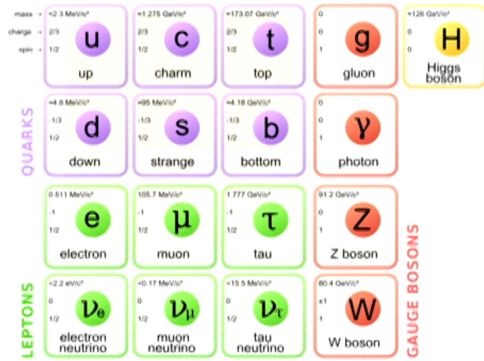
- LIGO discovered the gravitational wave!

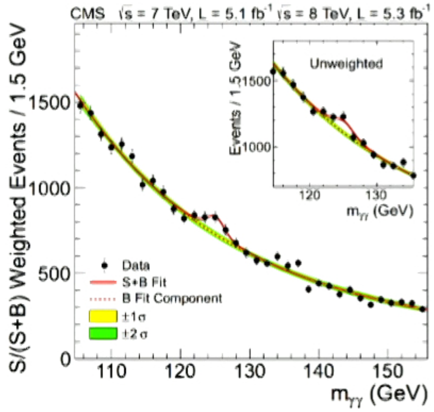


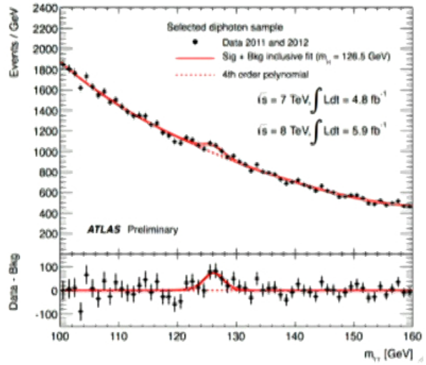


The Higgs Boson

- Discovery of the Higgs boson (the last piece of the Standard Model)



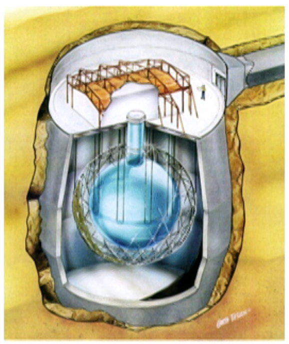




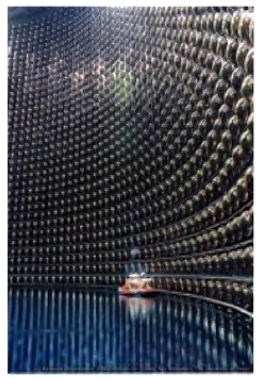
Neutrino Mass

- Neutrino oscillation

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



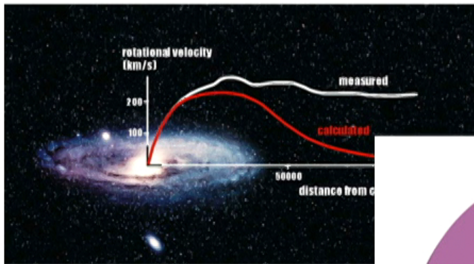
SNO

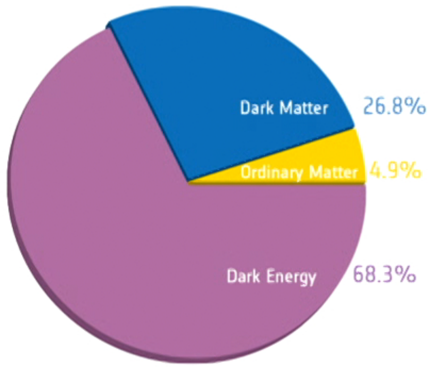


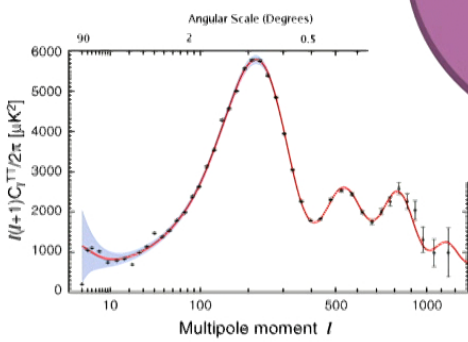
Super Kamiokande

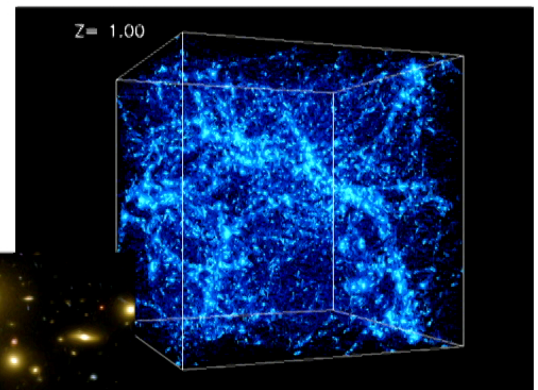
- Neutrinos are massive, clear sign of beyond standard model physics

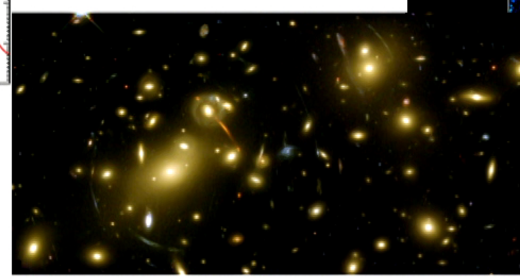
Evidence for Dark Matter





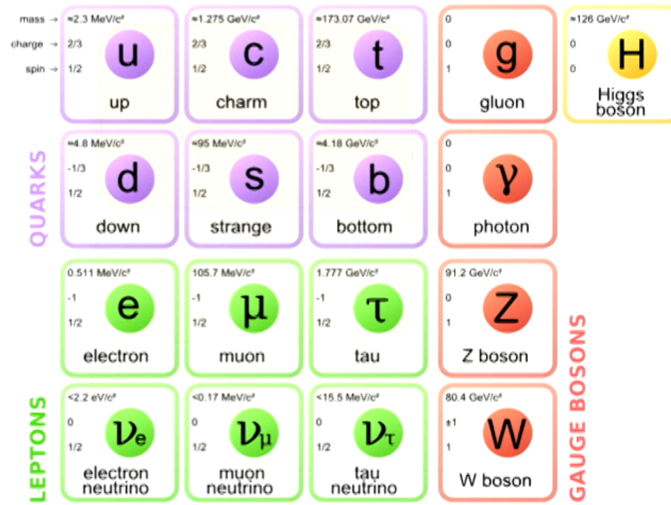






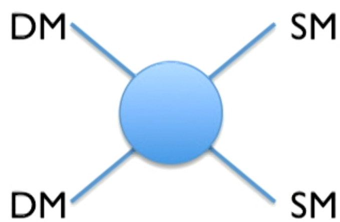
What do We Know?

- Dark
  - Or we would see it
- Long lived
  - Age of the Universe
- Cold (warm)
  - Structure formation



- No known particles satisfy all these conditions.
- New particles are in need!

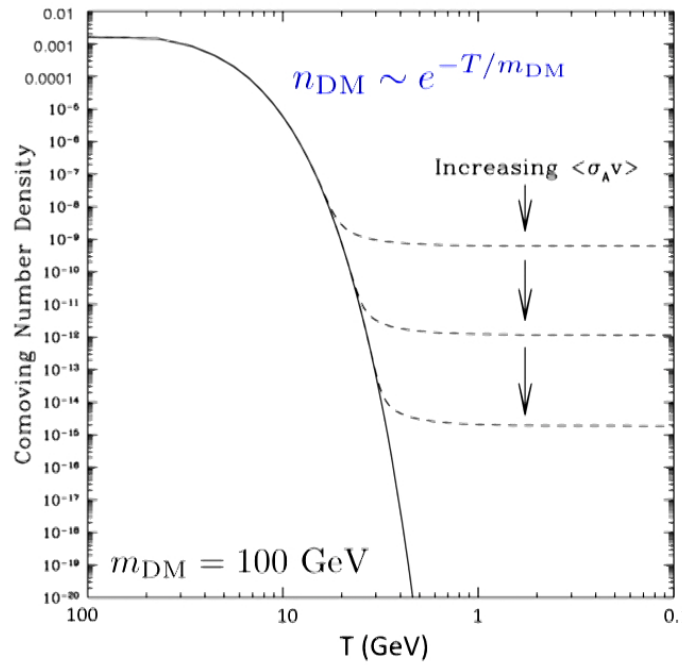
The WIMP Miracle



– Thermal freeze-out

$$\Gamma_A = n_{\rm DM} \langle \sigma_A v \rangle \lesssim H$$

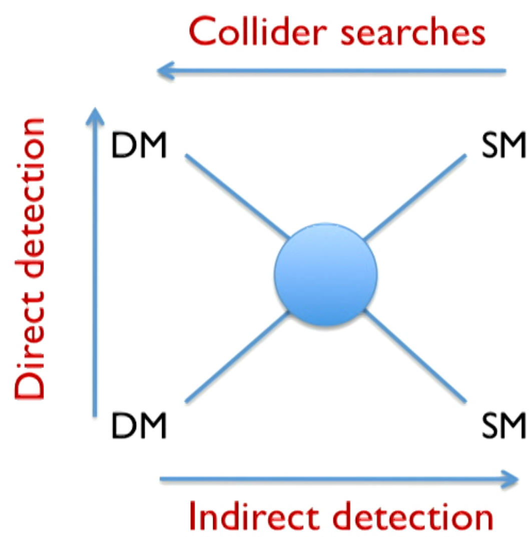
$$\langle \sigma_A v \rangle \approx 3 \times 10^{-26}\ {\rm cm}^3/{\rm sec} \approx \left(\frac{\alpha}{200\ {\rm GeV}} \right)^2$$



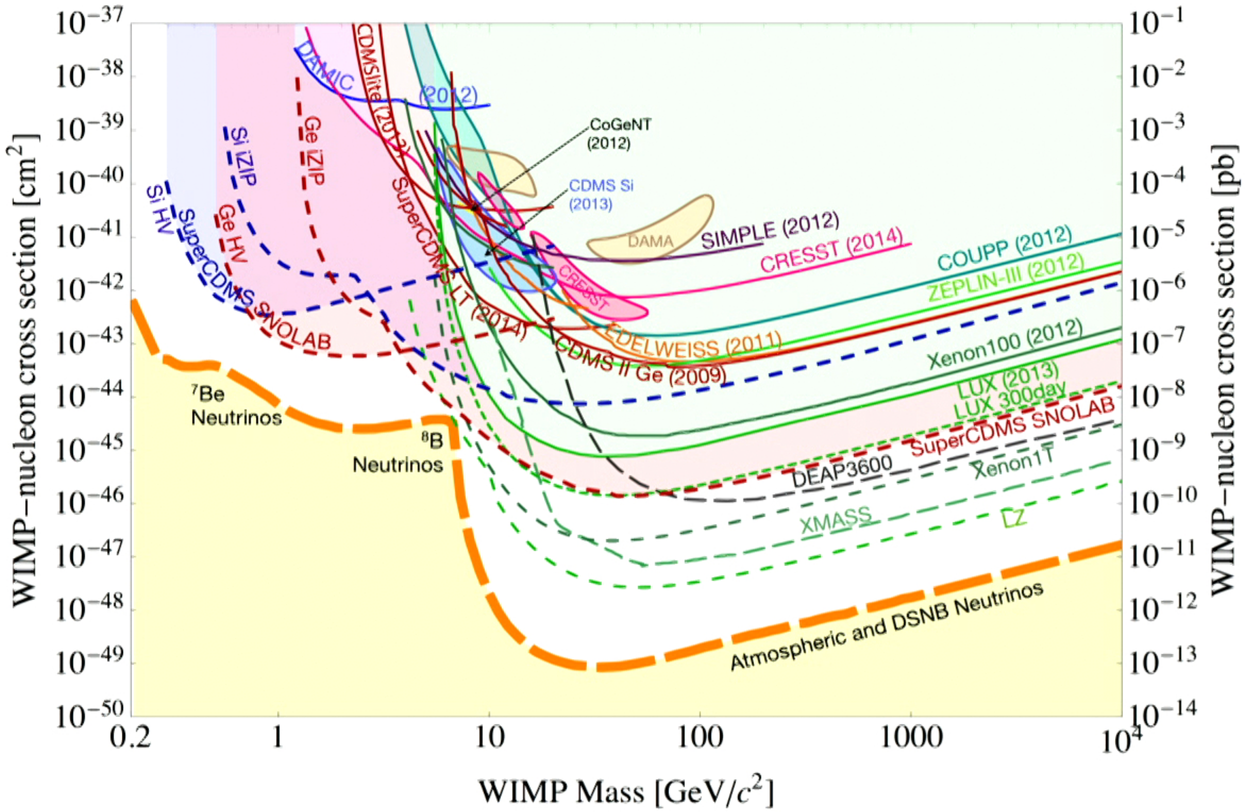
- Weakly interacting massive particle (WIMP)

Searching for WIMPs

- It is very predictive.

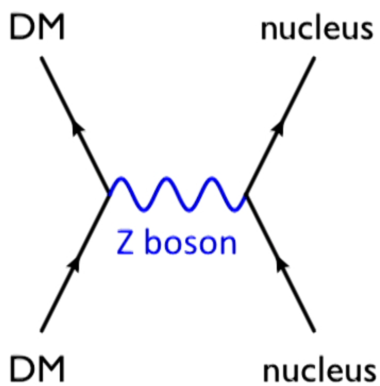


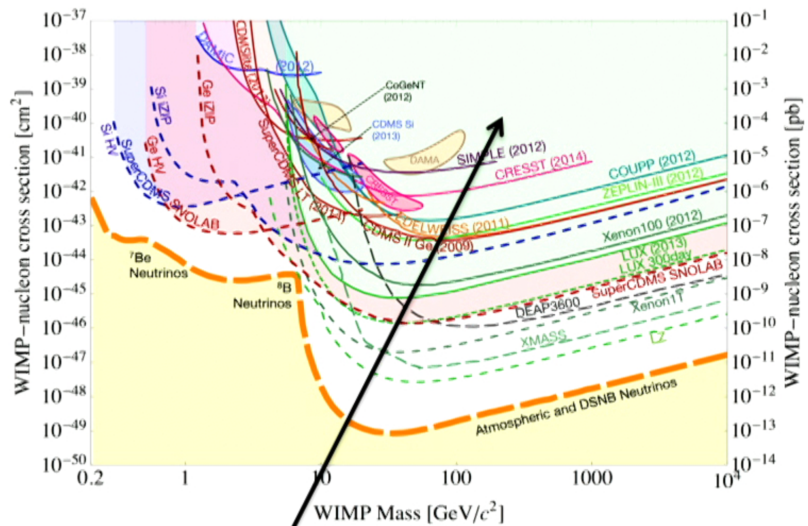
Direct Detection



Direct Detection

- If DM is charged under the weak interaction
  - The simplest model has already been excluded.

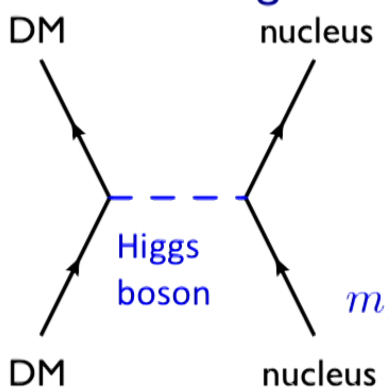




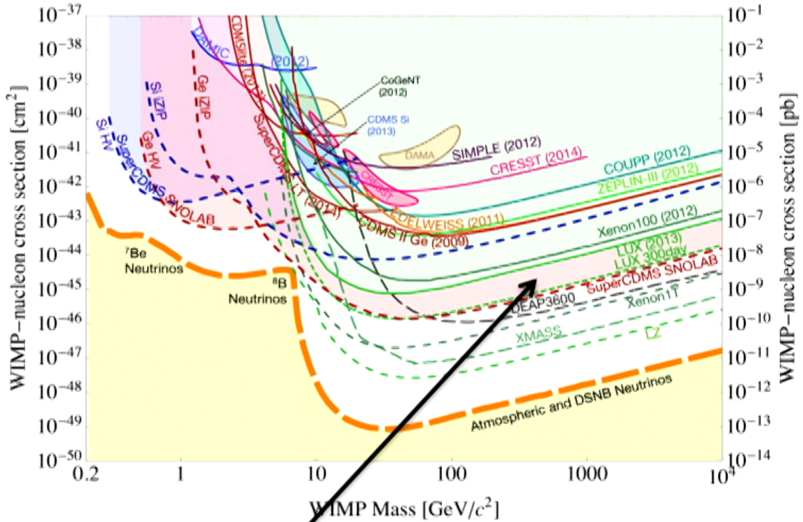
$$\sigma \sim 10^{-40}\ \mathrm{cm}^2$$

Direct Detection

- If DM is charged under the weak interaction
  - Higgs mediation model is very interesting.



$m_H = 125\ \mathrm{GeV}$



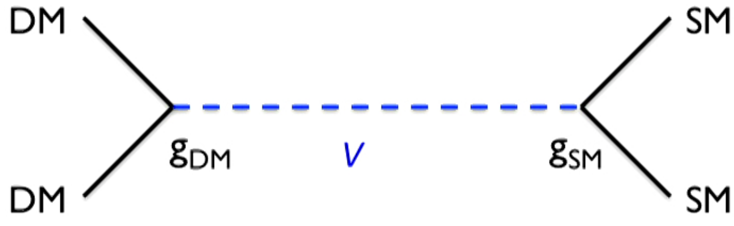
$\sigma \sim 10^{-45}\ \mathrm{cm}^2$

Beyond the WIMP paradigm

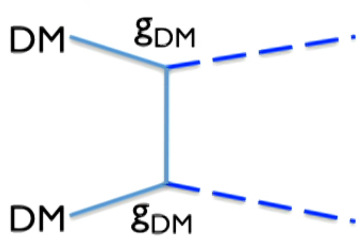
- We have made a great progress in the search for WIMPs.
- The direct detection constraint is strong, and getting stronger, reaching the neutrino background.
- While we are still searching for WIMPs, it might be the time to think about new models beyond the WIMP paradigm.

Beyond the WIMP paradigm

- Model with a dark portal



- What does the WIMP miracle really tell us?

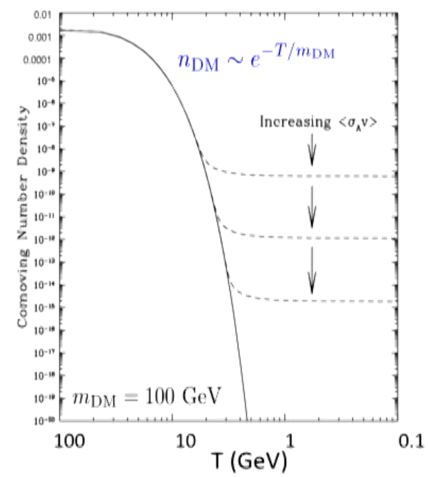


$\sigma_A v \sim g_{\rm DM}^4$

Independent of $g_{\rm SM}$

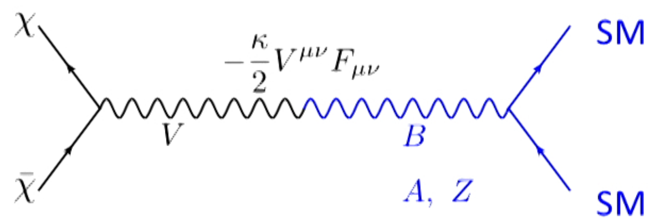
$m_V << m_{\rm DM}$

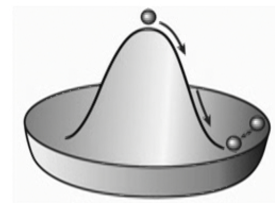
- BBN requires $g_{\rm SM} > 10^{-12} - 10^{-11}$



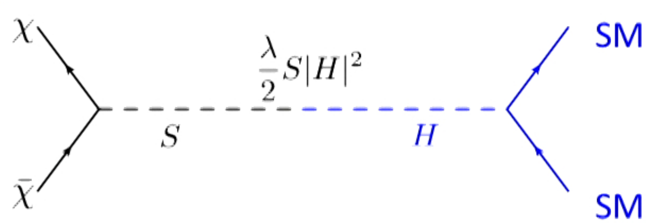
Dark Sector Models

- Vector portal (dark photon)



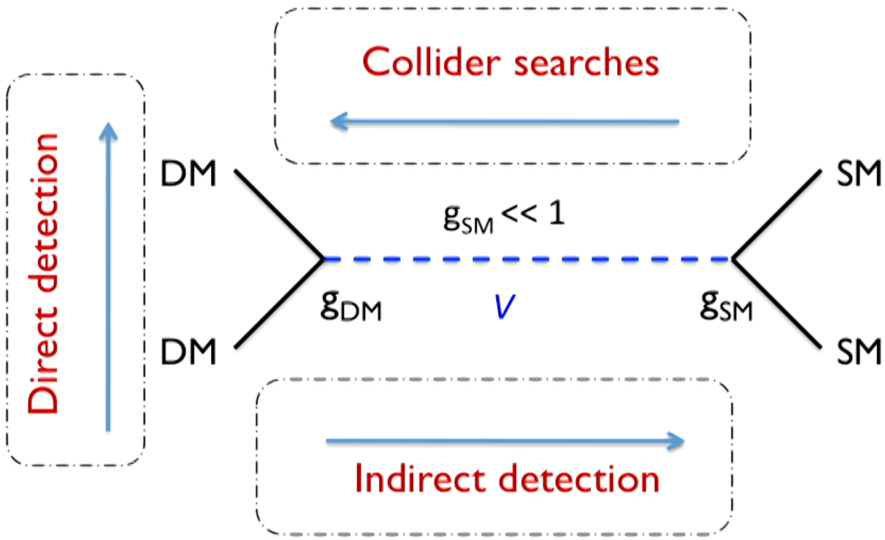


- Higgs portal



Probing the Dark Sector

- The dark matter could be darker than we thought. We need rethink about how to search for it.

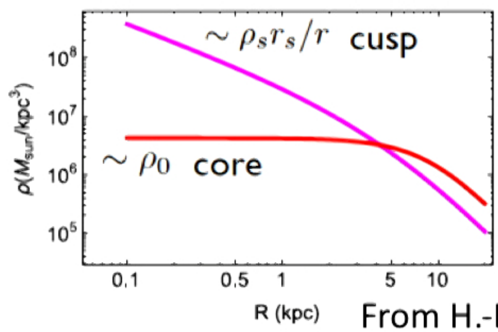


Signals from the Dark Sector

- Produce dark matter bound states at colliders
  - No background from SM (enhanced sensitivity)

- Boosted annihilation of dark matter
  - Additional source of cosmic rays from the galactic center
  - Distort the CMB spectrum

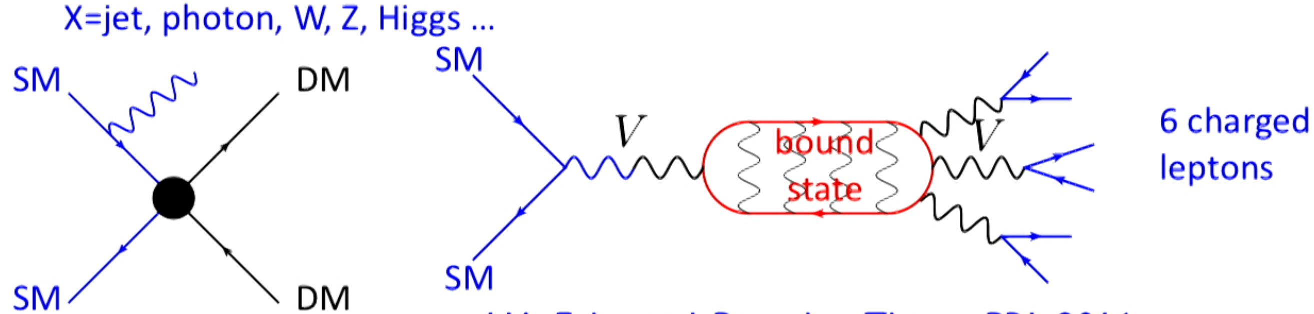
- Shapes of dark matter halos
  - Core-cusp problem
  - "Too big to fail problem"
  - …



From H.-B. Yu

Dark Bound States at Colliders

- Produce dark bound states at high luminosity colliders

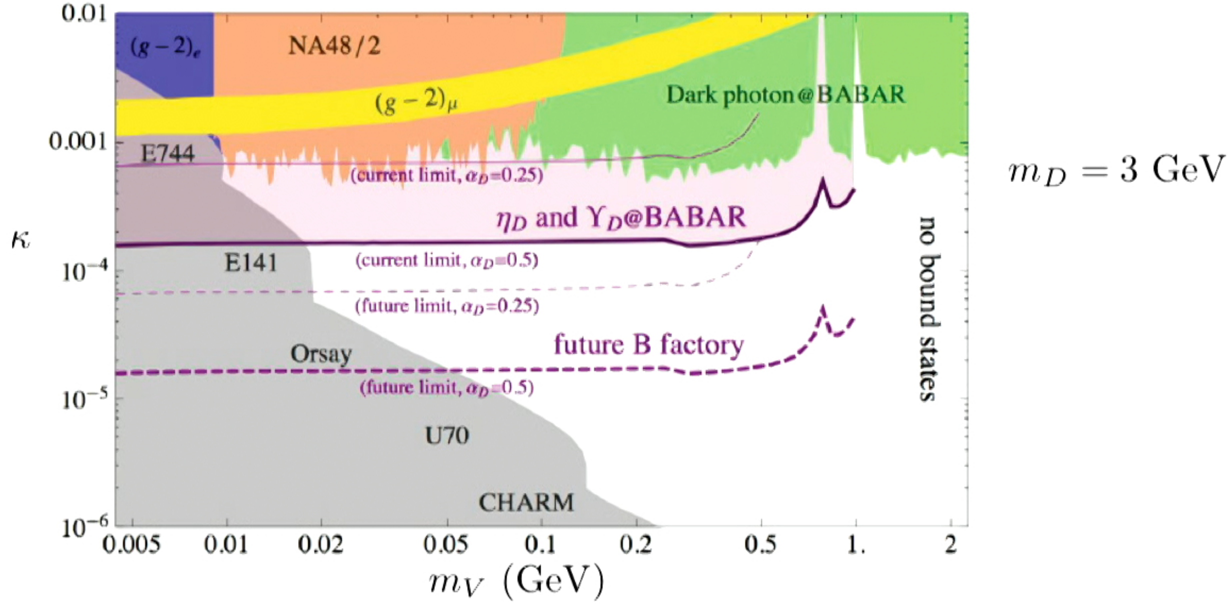


HA, Echenard, Pospelov, Zhang, PRL 2016

  - The signal is striking!
  - No SM background!

Dark Bound States at Colliders

- Produce dark bound states at high luminosity colliders HA, Echenard, Pospelov, Zhang, PRL 2016



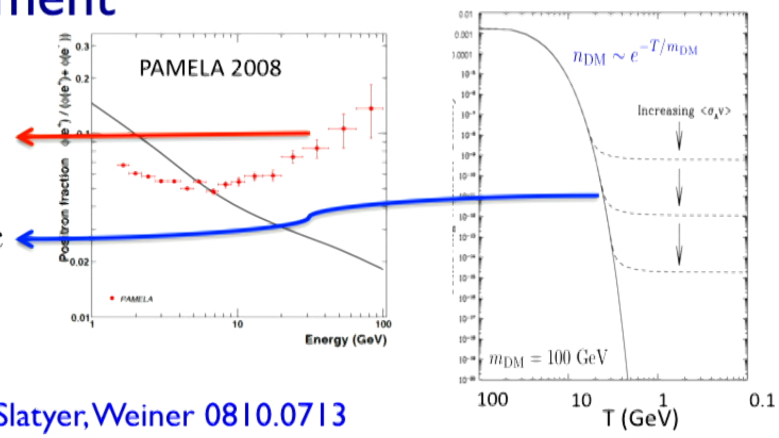
- BaBar collaboration has been doing this analysis.

Boosted Annihilation

- Sommerfeld enhancement

$$\langle \sigma_A v \rangle \approx 10^{-23}\ \mathrm{cm}^3/\mathrm{sec}$$

$$\langle \sigma_A v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$$



$$\sigma v \sim \frac{1}{v}$$

Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Pospelov, Ritz 0810.1502

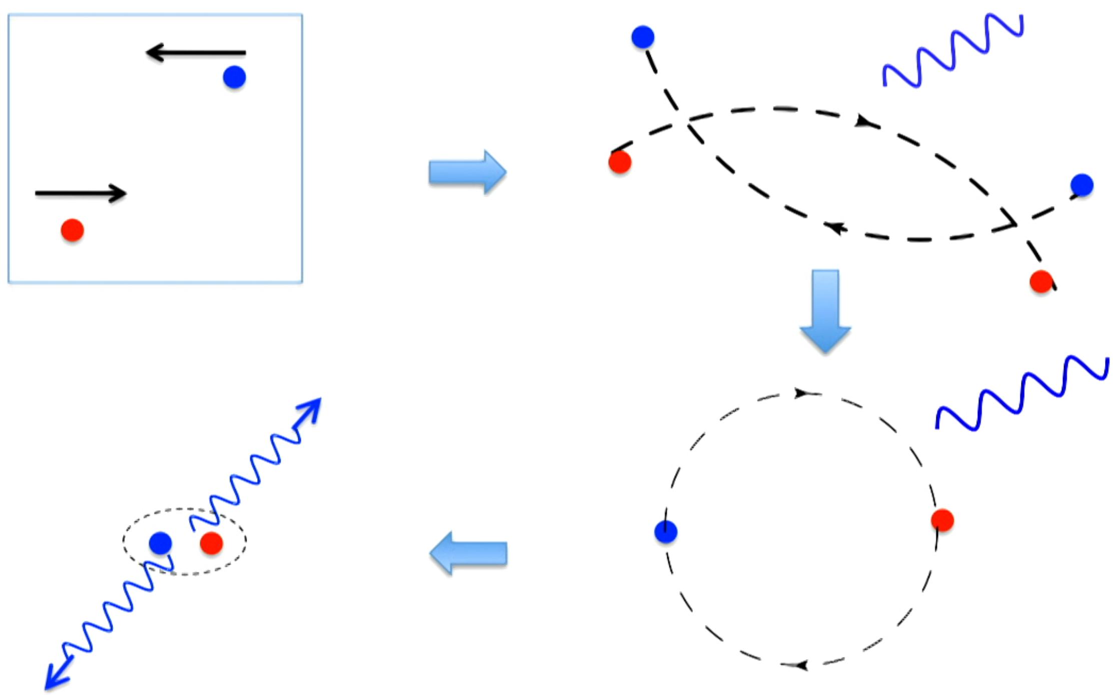
Attractive force

Initial velocity = 0

100% collide

Boosted Annihilation

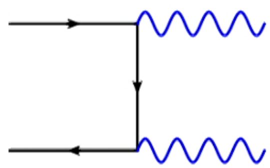
- Electron-positron annihilation

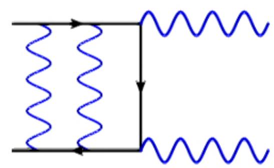


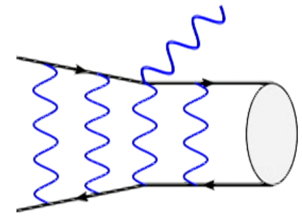
Boosted Annihilation

- Dark bound states
  - vector mediator $m_V \to 0$

HA, Wise, Zhang, PRD (2016)







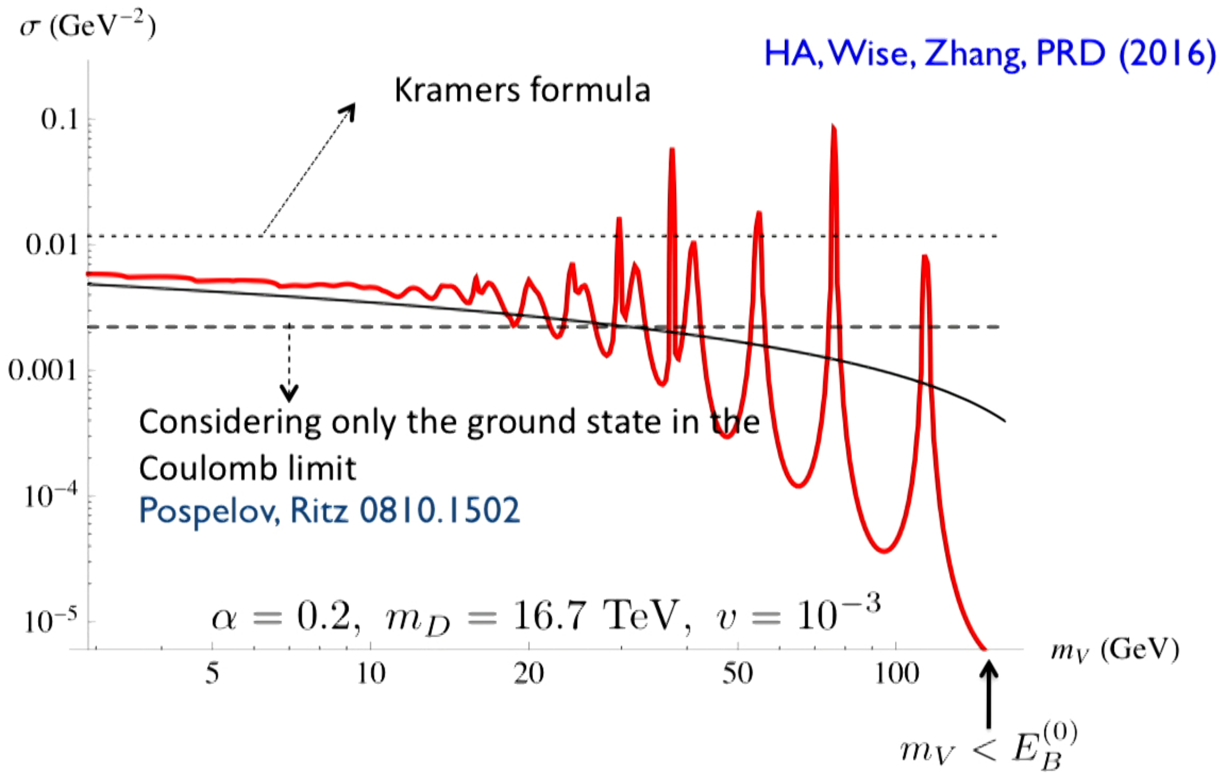
$(\sigma v)_{\rm Born}$ $\quad$ $\frac{2\pi\alpha_D}{v}(\sigma v)_{\rm Born}$ $\quad$ $\frac{8\pi\alpha_D}{v}\log\left(\frac{\alpha_D}{v}\right)(\sigma v)_{\rm Born}$

Galactic Center: $\quad 1 \quad 300 \quad 20\times 300$

Sommerfeld enhancement

Kramers formula

Boosted Annihilation

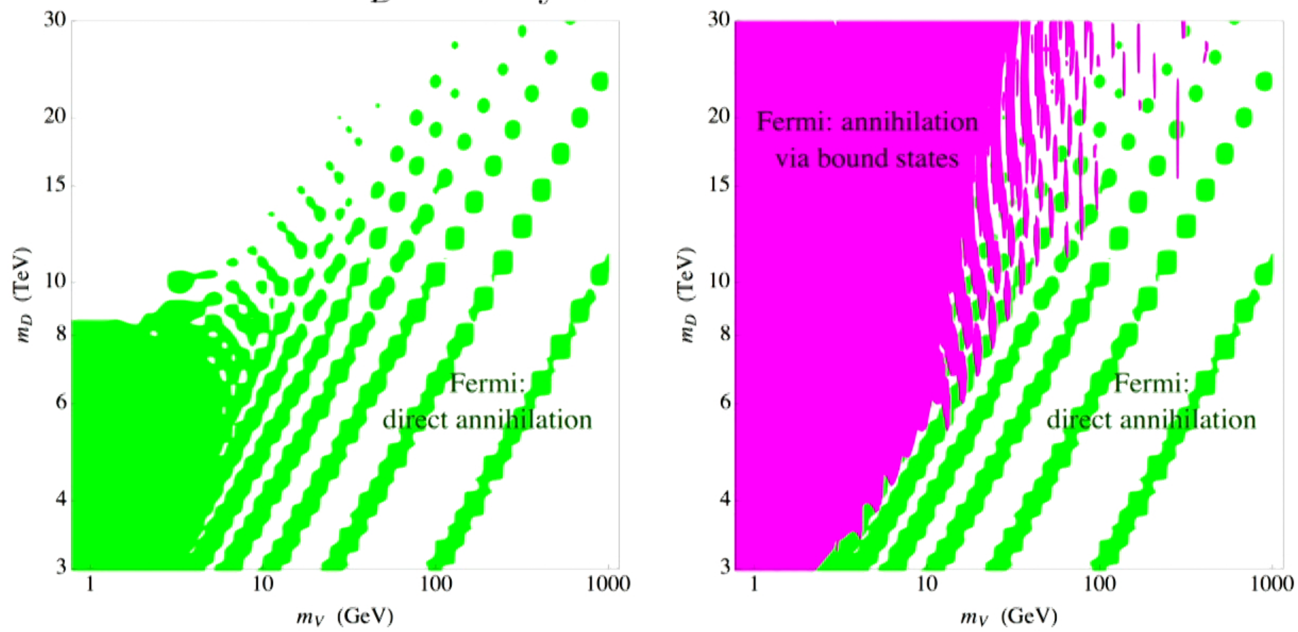


Boosted Annihilation

- Constraints from the Galactic center gamma rays

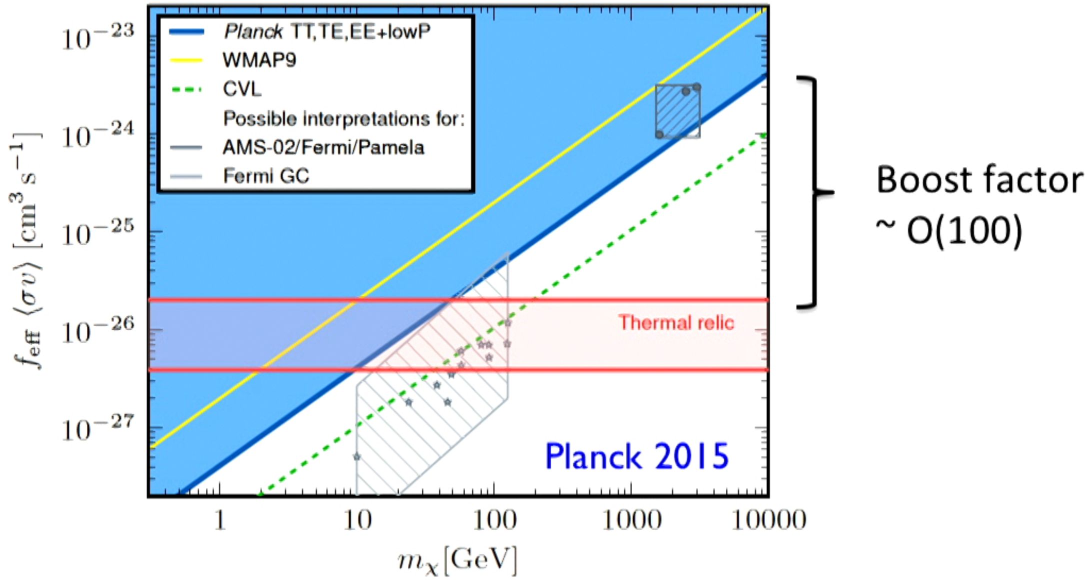
HA, Wise, Zhang, PRD (2016)

α_D fixed by relic abundance



CMB Constraint

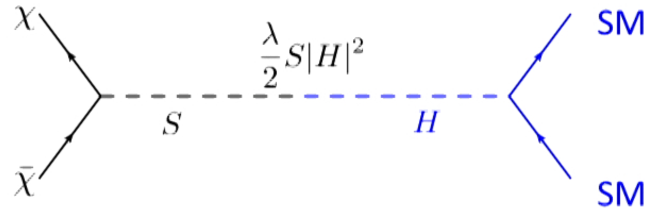
- CMB spectrum is very sensitive to energy deposition during the recombination era.



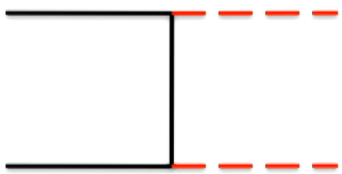
- Strong constraint for models with light mediators.

P-wave Annihilation

- Scalar mediator



- Dark parity

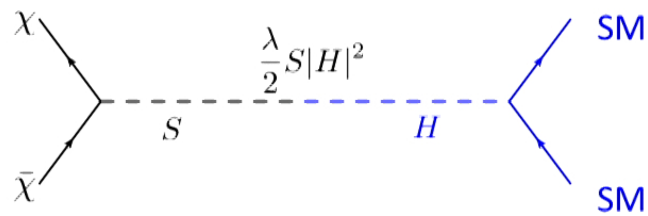


P = $(-1)^{L+1}$ for DM-anti-DM system
P = 0 for two scalars
L = 1, p-wave $\sigma_A v \sim v^2$

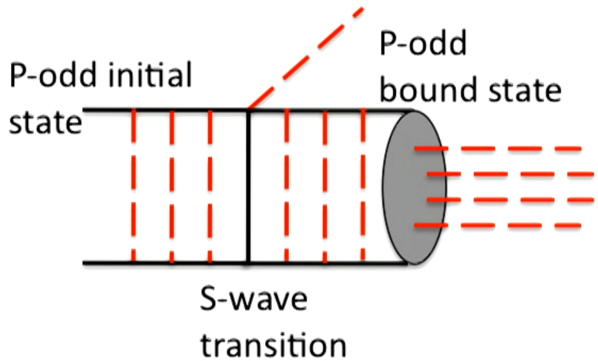
  – During recombination $v \approx 10^{-9}$
  – Center of galaxy $v \approx 10^{-3}$

Parity Odd Bound State

- Scalar mediator



- Dark bound state formation



HA, Wise, Zhang, 1606.12305

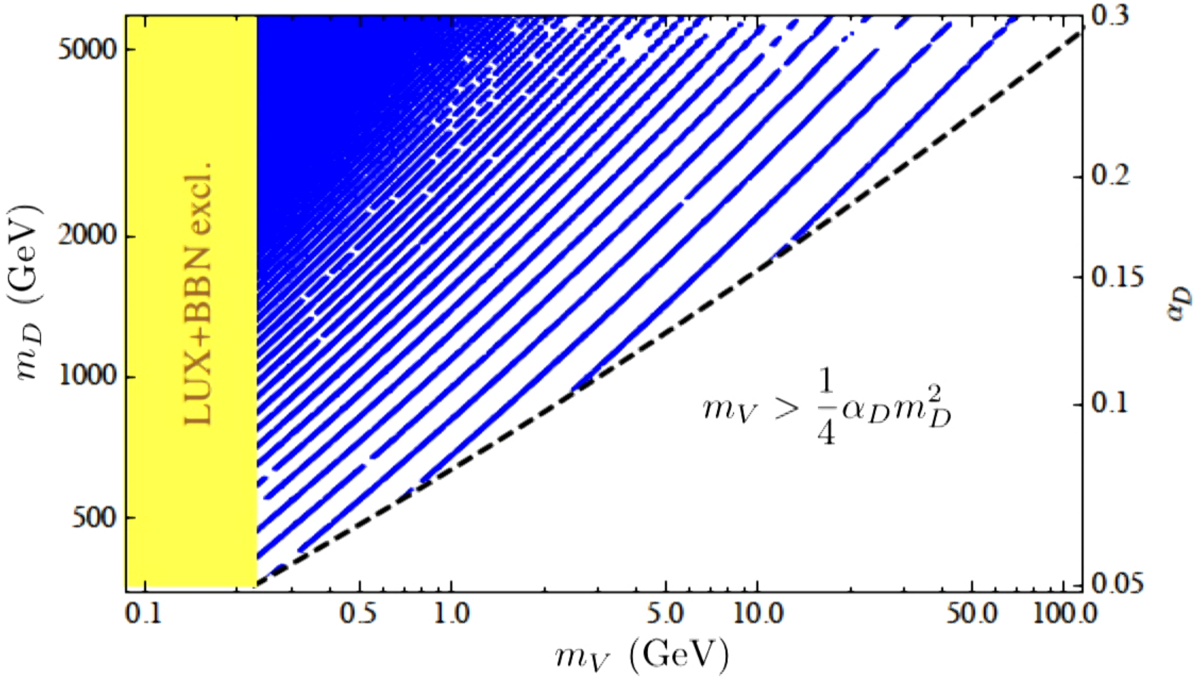
Four scalars can form P-odd states.

- No suppression from the small velocity!

Parity Odd Bound State

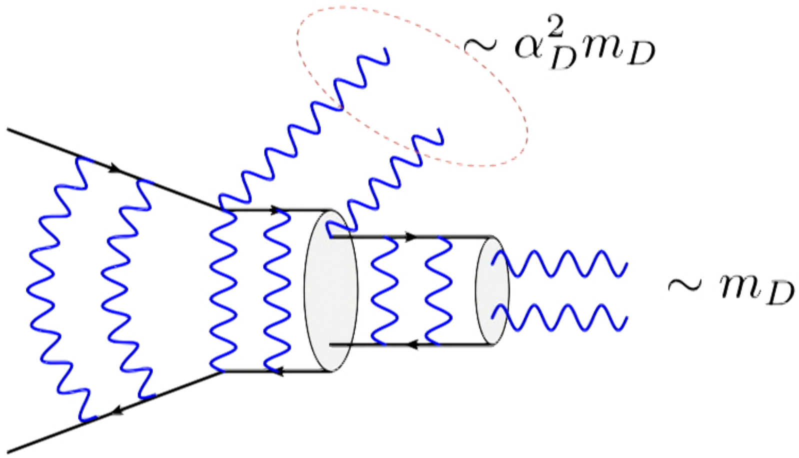
- Constraint from the CMB spectrum

HA, Wise, Zhang, 1606.12305



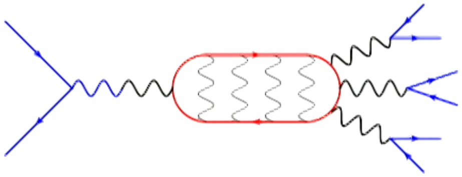
Searching for Dark Bound State

- Double bump structure (future work)

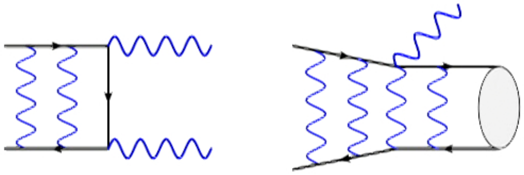


Dark Sector Paradigm

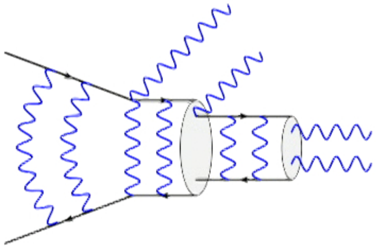
- With the light mediator
  - Striking collider signals



  - Boosted indirect signals

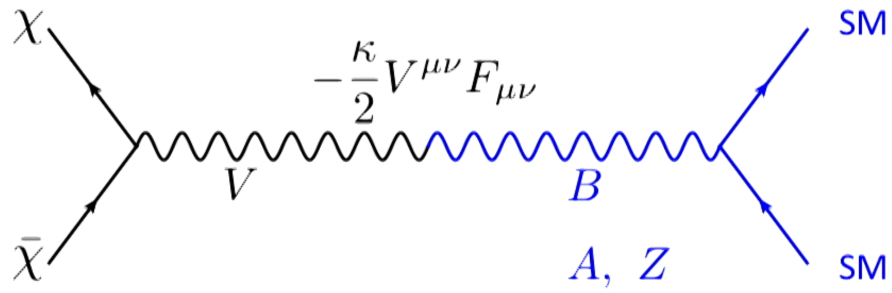


  - Double bump structure (future work)



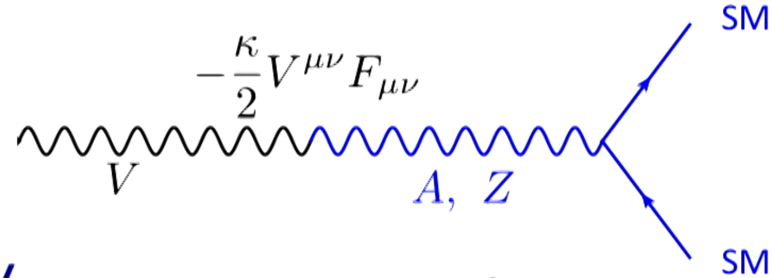
Dark Sector Paradigm

- Vector portal (dark photon)

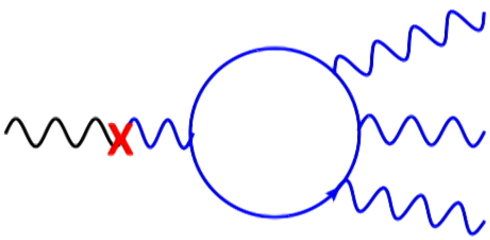


Dark Sector Paradigm

- Only keep the dark photon



- $m_V < 1$ MeV



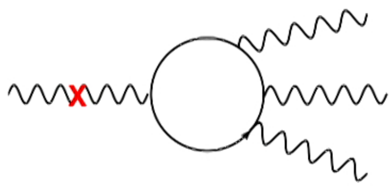
$$\Gamma \sim \frac{\kappa^2 \alpha^4 m_V^9}{m_e^8}$$

- Cosmologically stable!
- Dark matter candidate!

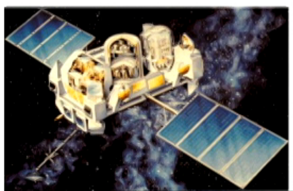
Dark Photon Dark Matter

- Constraint from the diffuse gamma ray and CMB

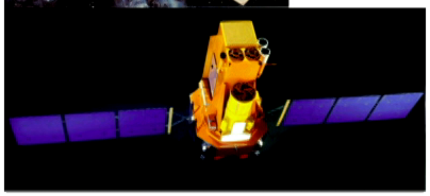
HA, Pospelov, Pradler, Ritz PLB 2015



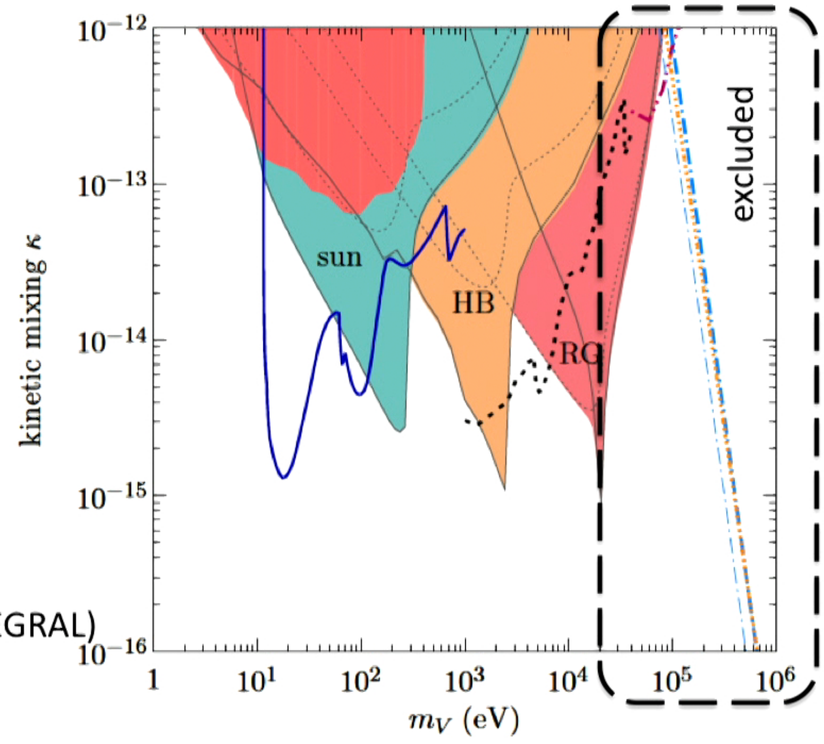
$$\Gamma \sim \frac{\kappa^2 \alpha^4 m_V^9}{m_e^8}$$



COMPTEL (CGRO)

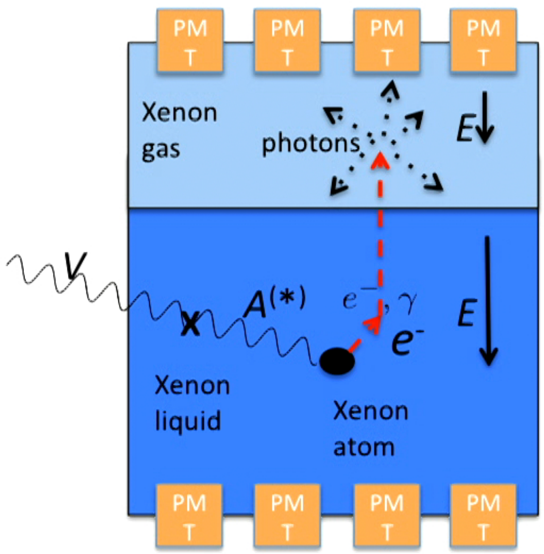


SPI (INTEGRAL)

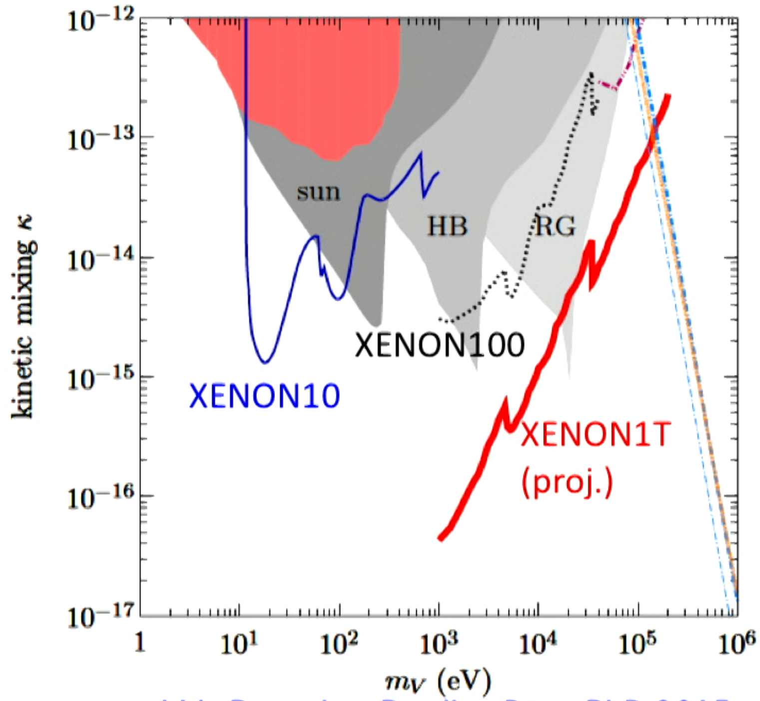


Dark Photon Dark Matter

- Constraint from dark matter detector
  - Electron recoil signal

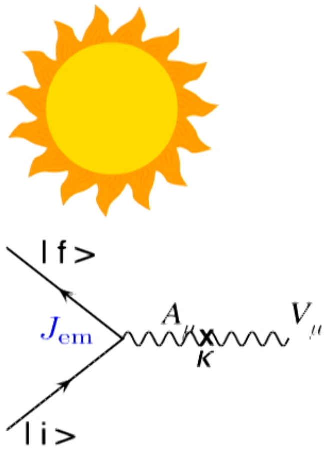


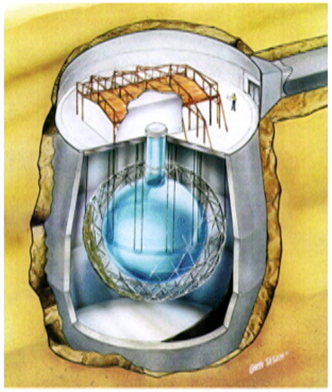
S1: scintillation ($m_V > 1$ keV)
S2: ionization ($m_V > 12$ eV)



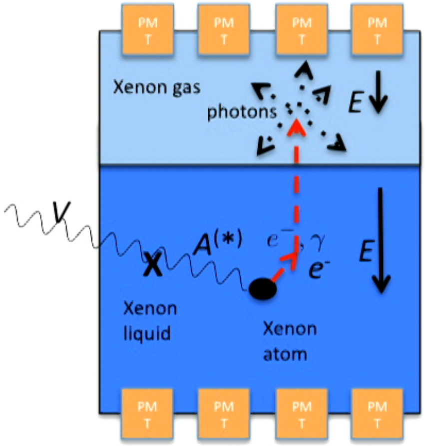
HA, Pospelov, Pradler, Ritz PLB 2015
HA, Pospelov, Pradler, Ritz, K. Ni*, 1510.04530

Dark Photon from the Sun





SNO experiment



XENON experiment

- Increase the flux of ^{8}B neutrinos constrained by SNO experiment.
- The dark photon can be detected by dark matter detector directly.

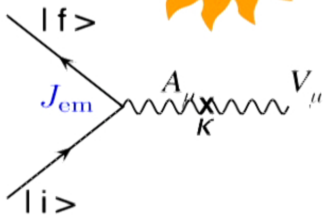
Dark Photon from the Sun

- Dark photon production rate

$$m_V^2 \ll \omega_p^2$$

  - Transverse mode

$$\Gamma_T \sim \frac{\kappa^2 m_V^4}{\omega_p^4}$$



  - Longitudinal mode

$$\Gamma_L \sim \frac{\kappa^2 m_V^2}{T^2}$$

$$T \approx 1 \text{ keV}$$
$$\omega_p \approx 0.3 \text{ keV}$$

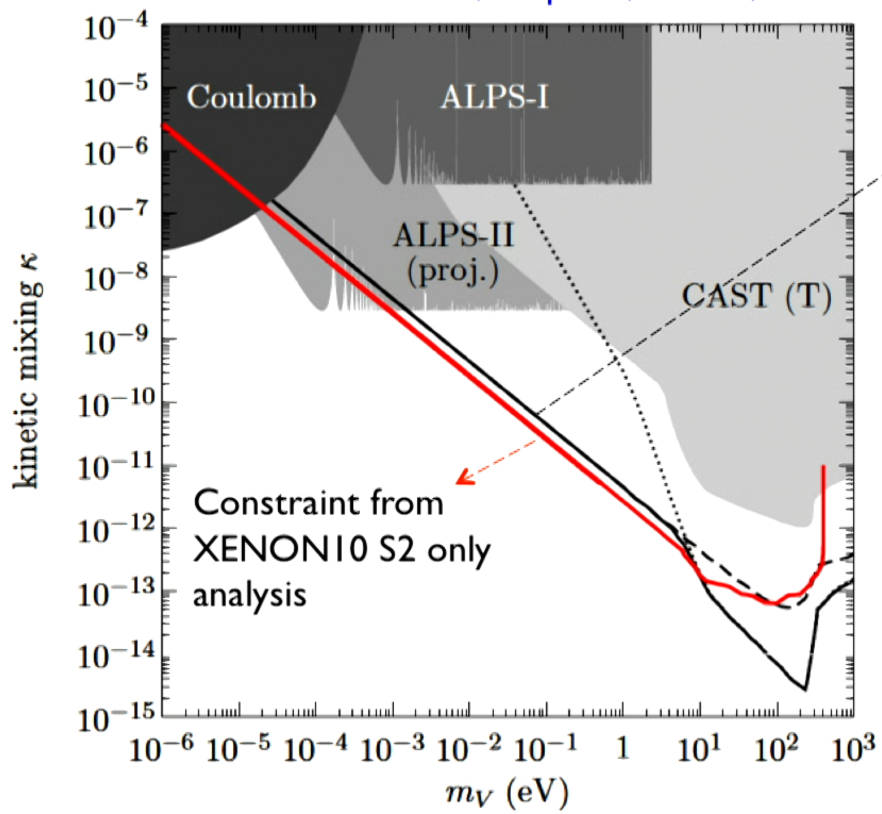
  - Longitudinal flux dominates in the small m_V region

HA, Pospelov, Pradler, PLB 2013

Dark Photon from the Sun

- Searching for dark photon from the Sun

HA, Pospelov, Pradler, PRL 2013

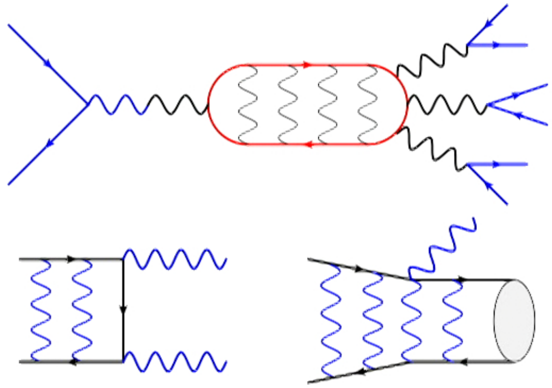


Constraint from solar dark radiation (SNO ^{8}B neutrino)

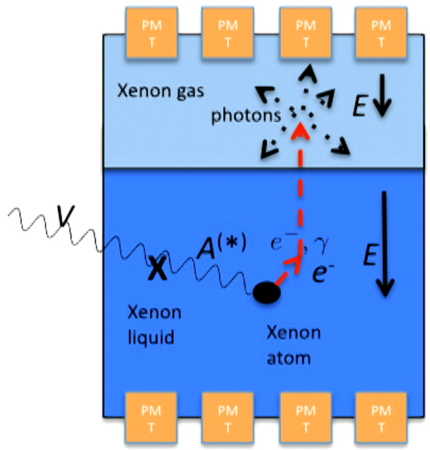
$L_{\rm dark} < 0.1 L_\odot$

Summary

- Dark bound state
  - Striking signals at colliders
  - Boost the annihilation



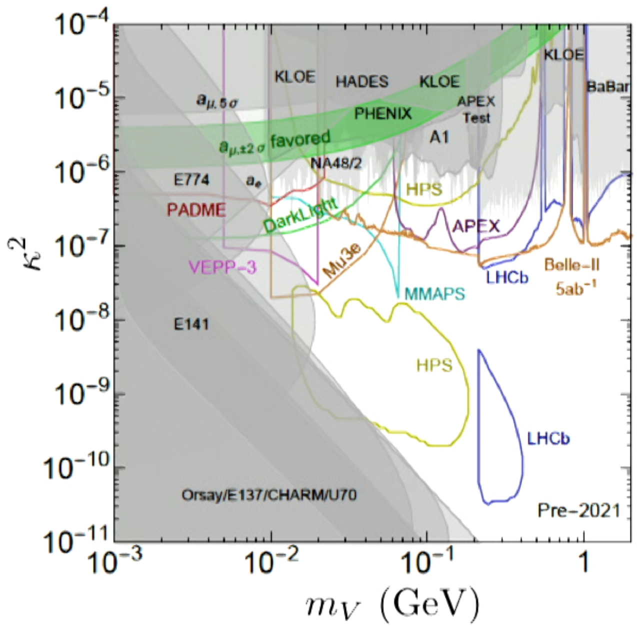
- Dark photon dark matter
  - Direct detection experiments are very important.

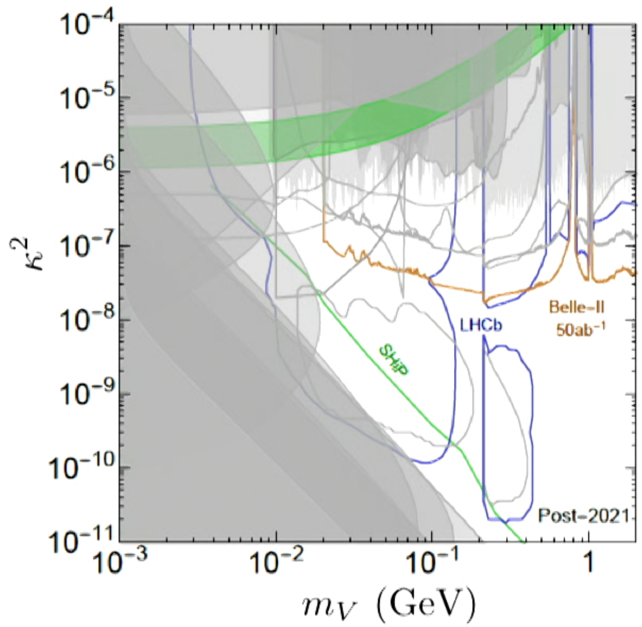


Outlook

- A great effort in the search for the dark mediator

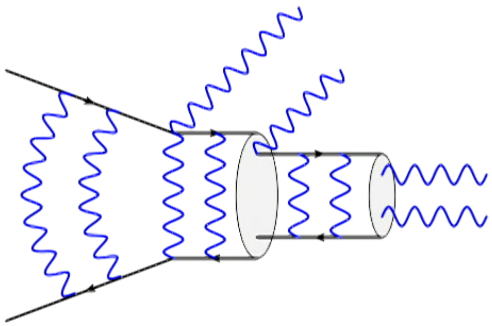
Dark sectors 2016 report

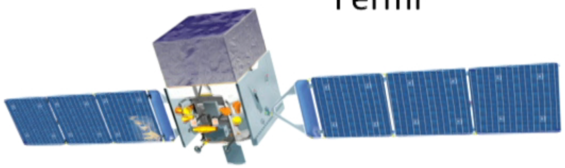




Outlook

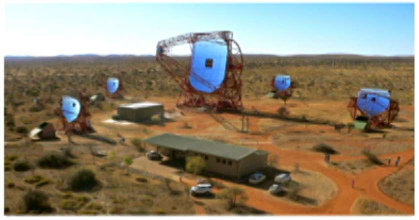
- Cosmic ray observatories





A few hundred GeV

VERITAS



A few hundred TeV

HESS

Conclusion

- We have been making a great progress to explore the WIMP paradigm.
- The dark sector paradigm is also very well motivated both theoretically and experimentally.
- Fortunately, we are in a data-rich era. Let's explore the dark side of the universe.