

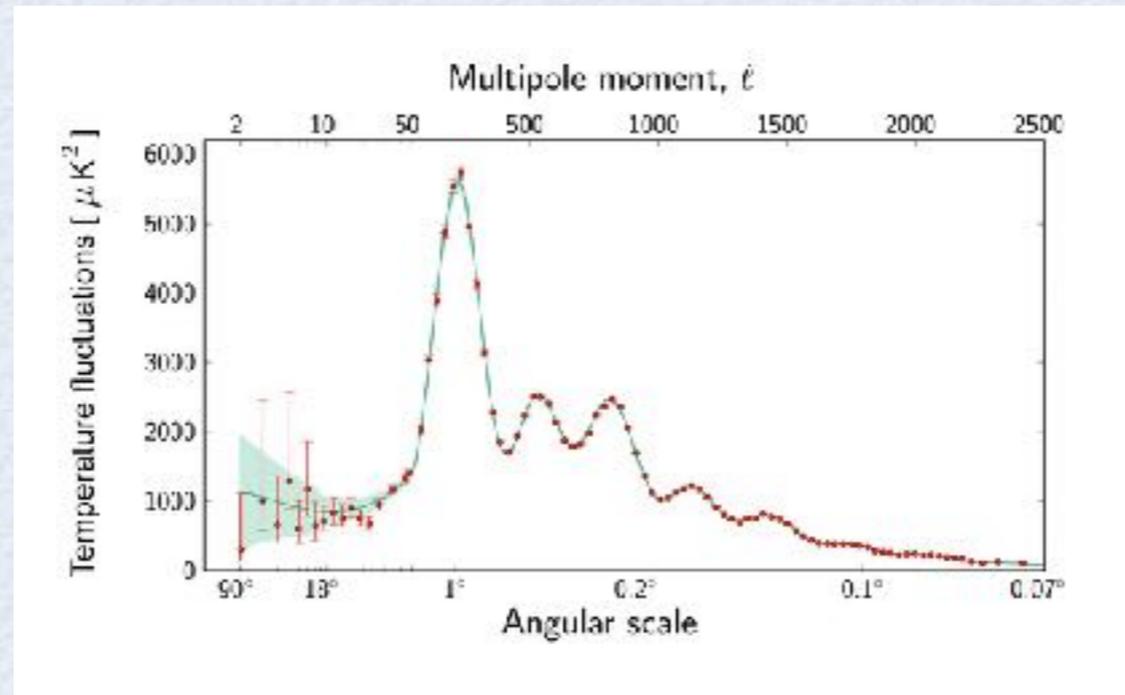
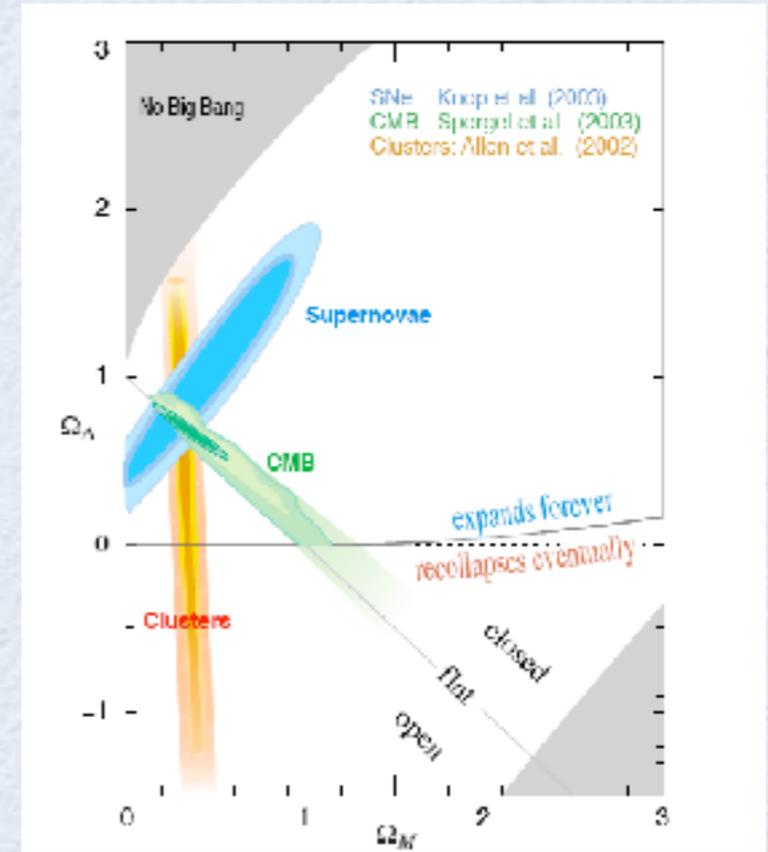
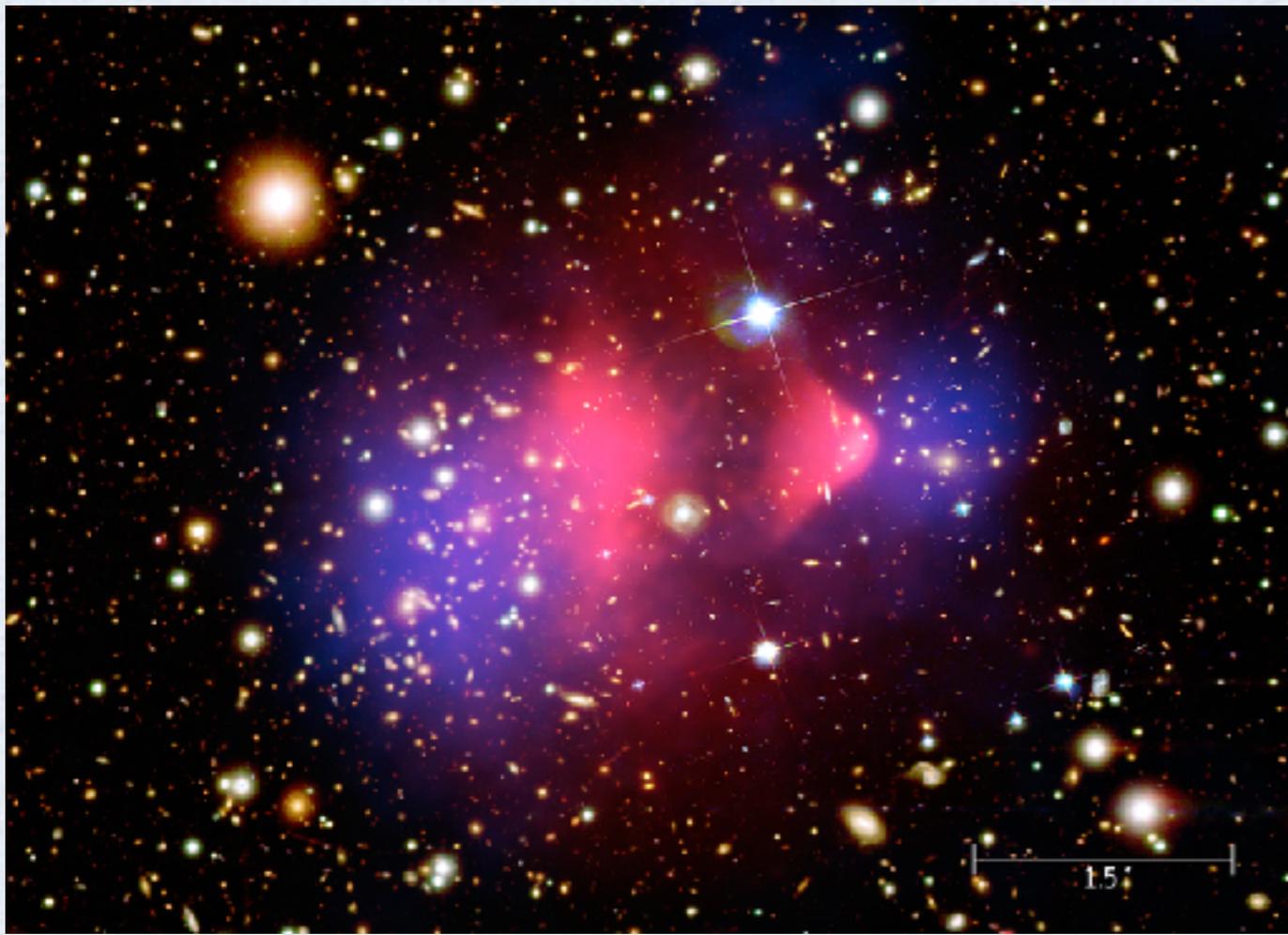


# COMPLEMENTARITY FOR DARK SECTOR BOUND STATES

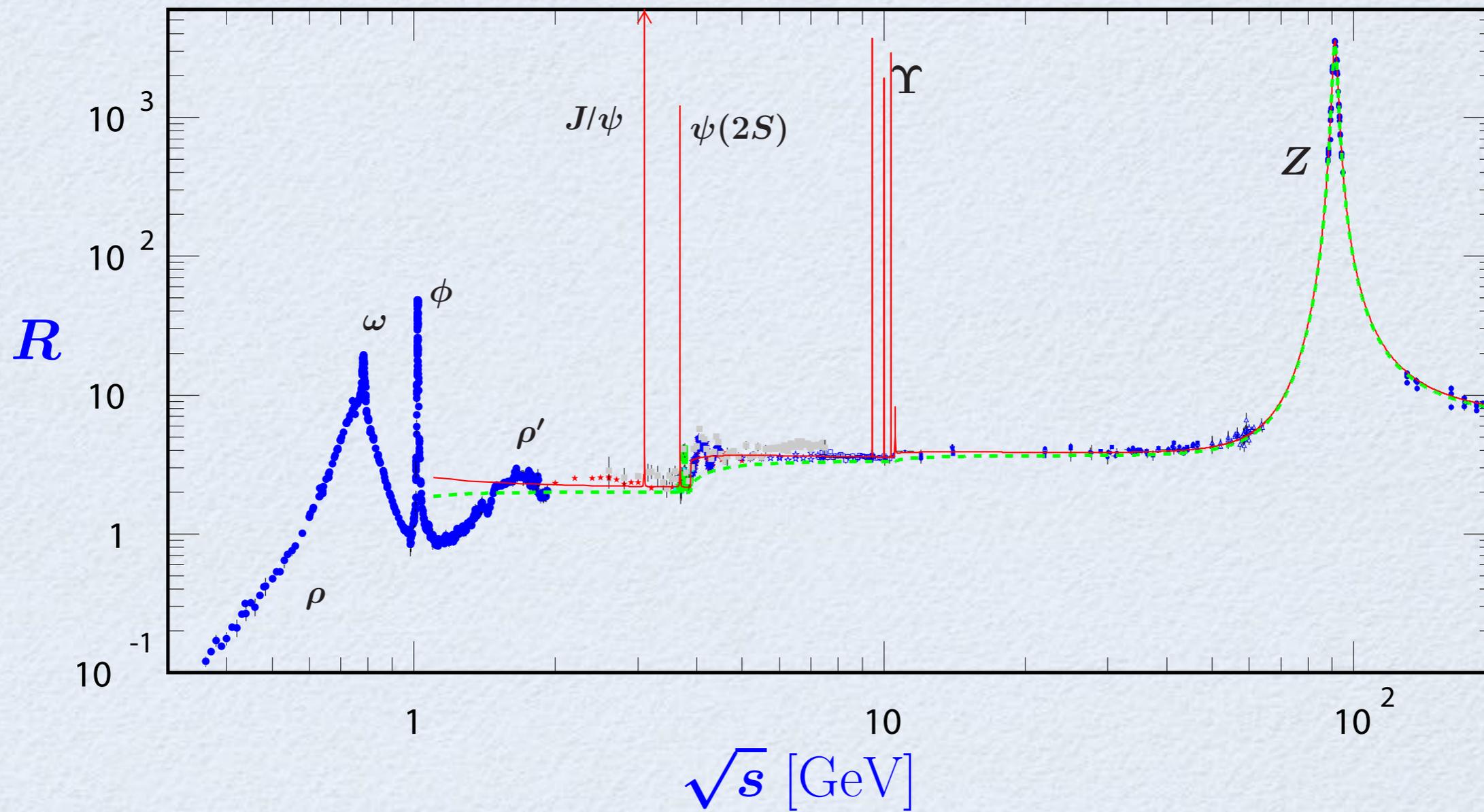
Yotam Soreq

G. Elor, H. Liu, T. Slatyer, YS - 1801.07723

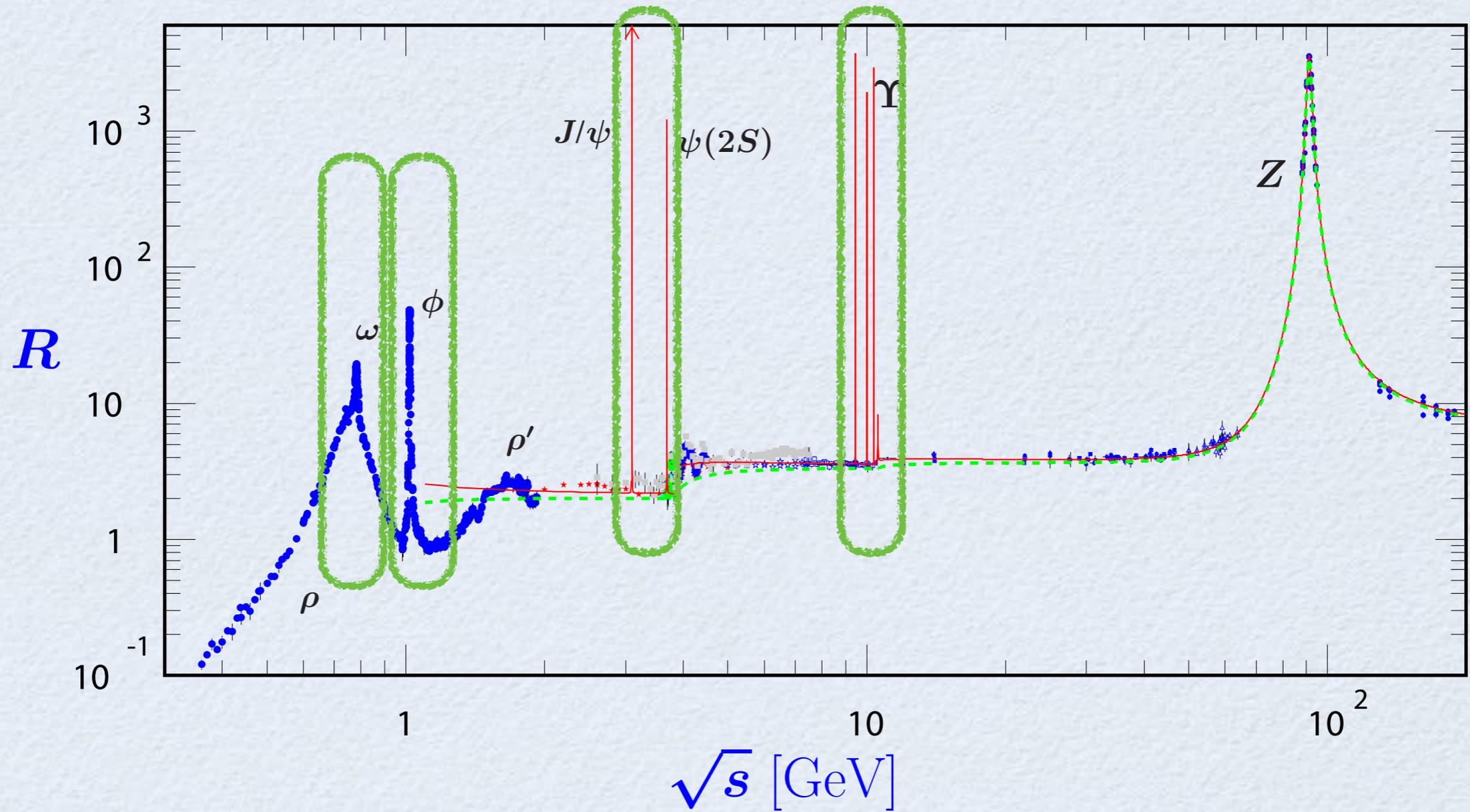
IDM 2018, July 24, 2017



$$R_\mu = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

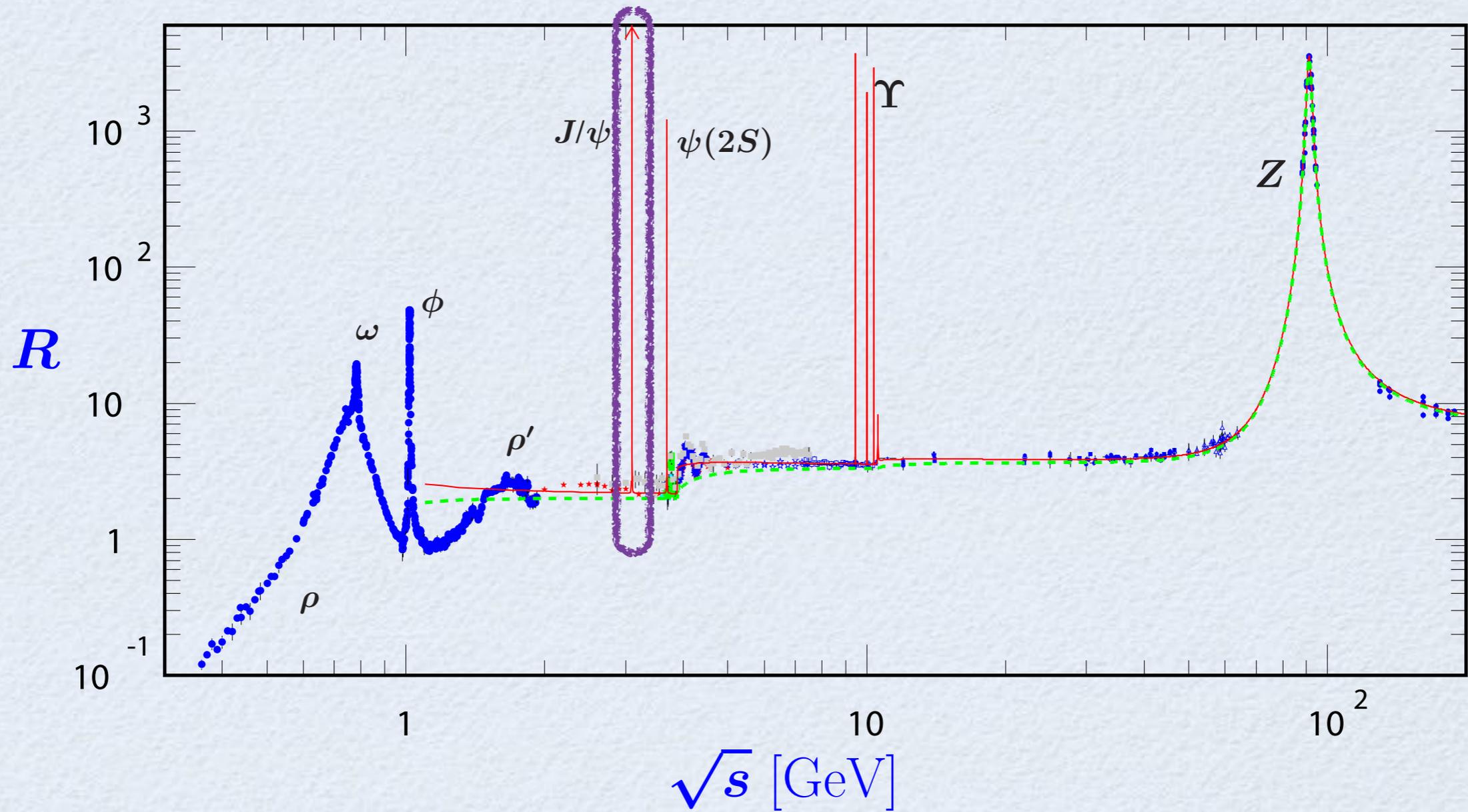


$$R_\mu = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



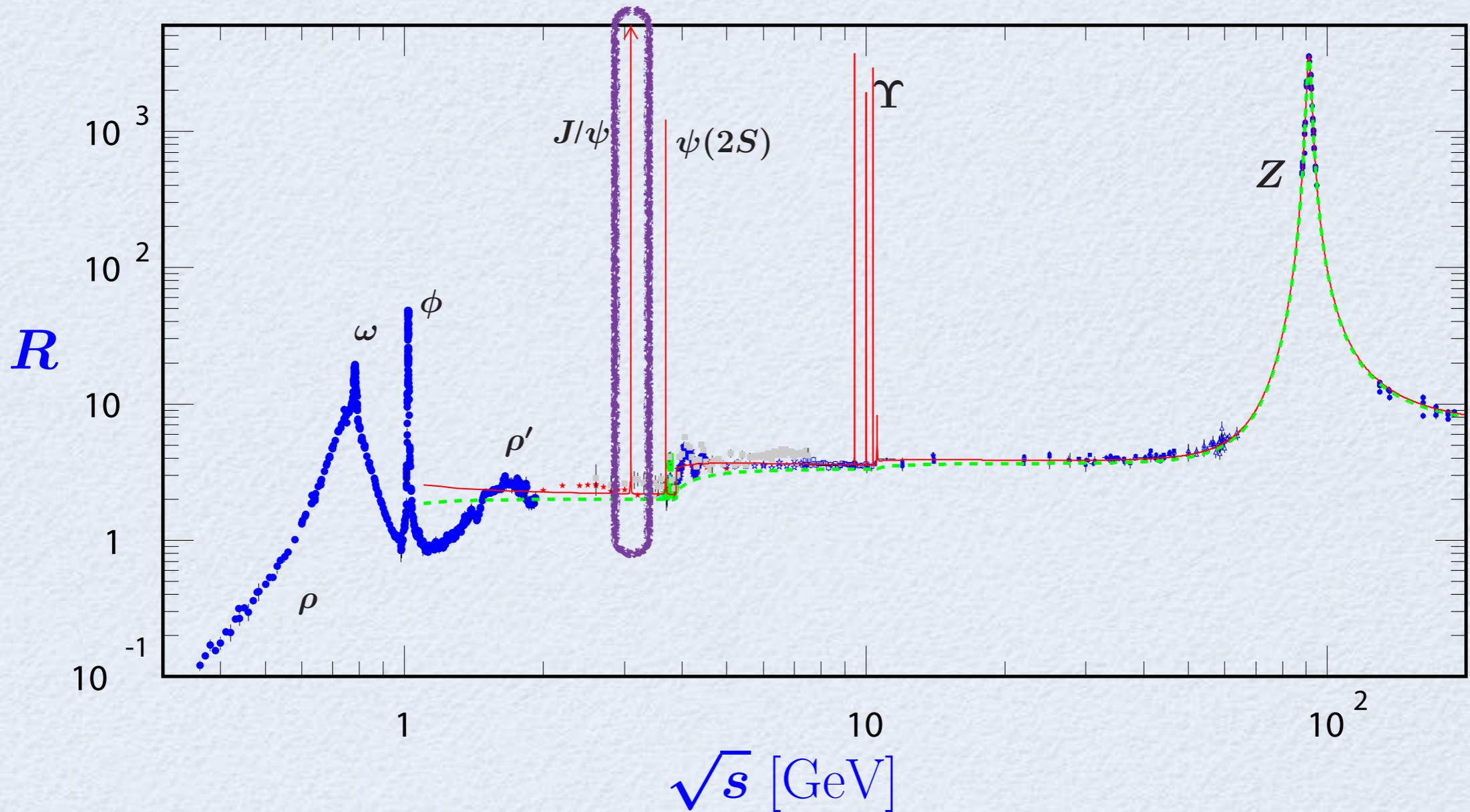
bound states are common within the standard model

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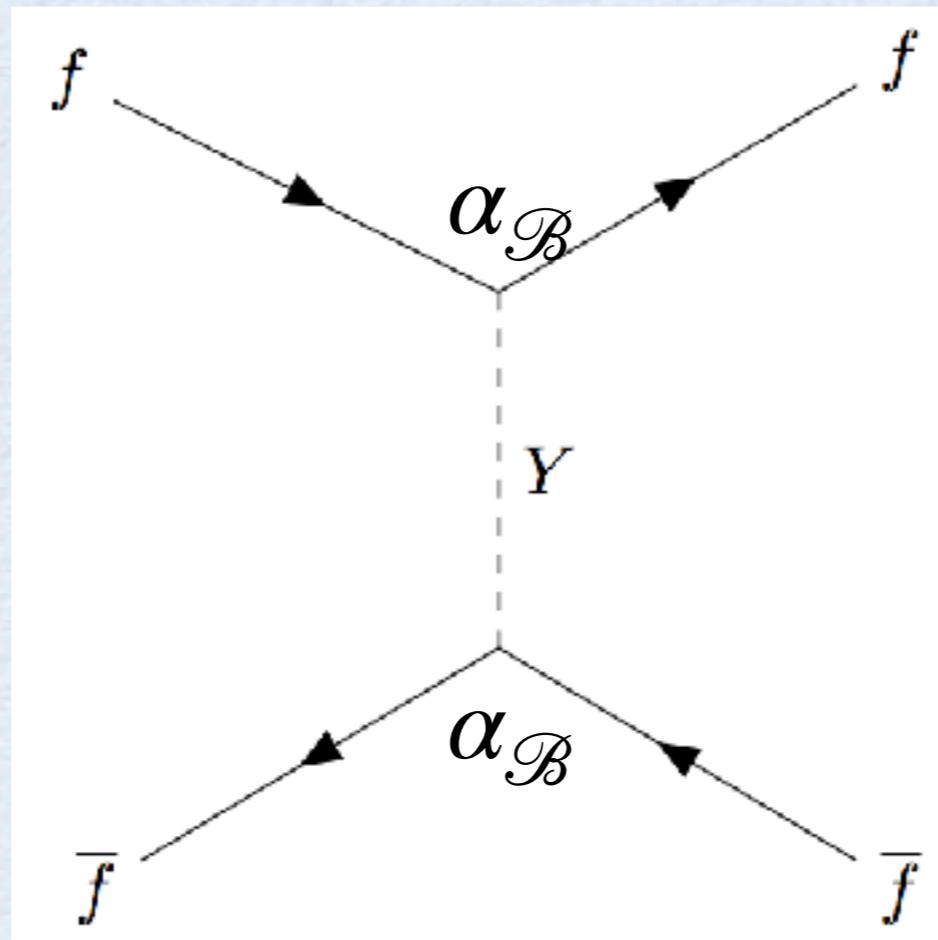


bound states are common within the standard model

bound states can appear in non trivial dark sectors

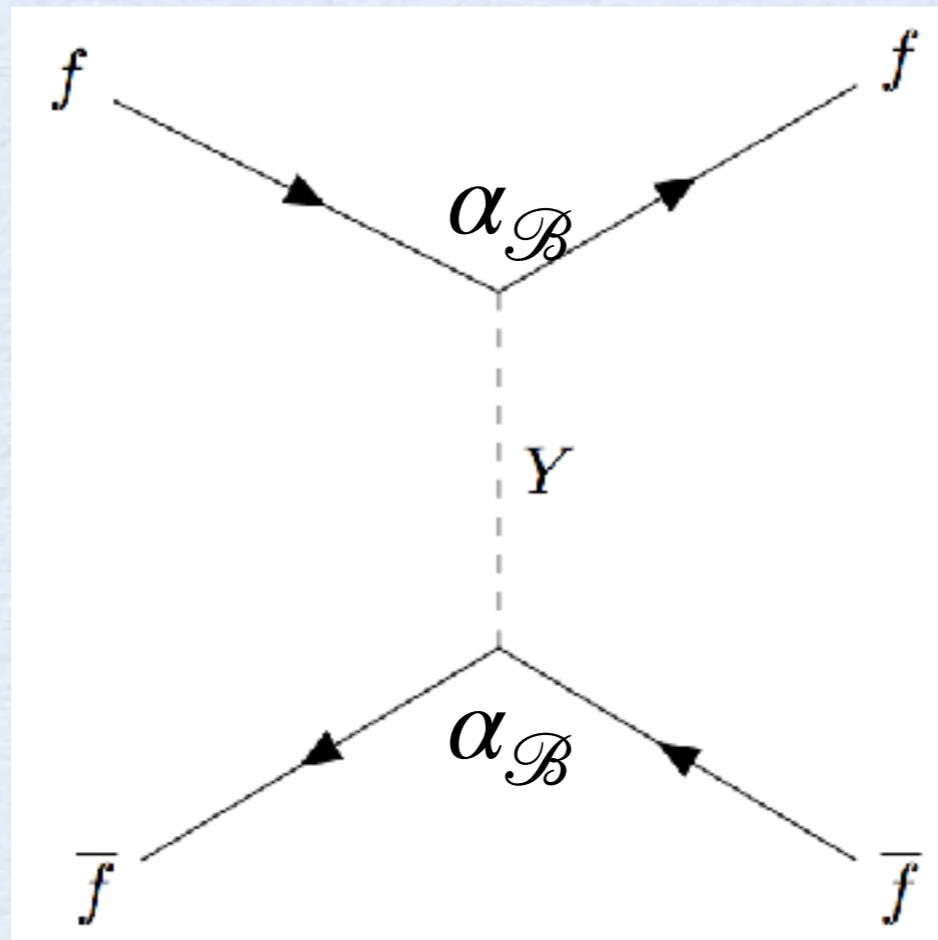
# DARK MATTER AND BOUND STATES

bound state condition  
(non relativistic)



# DARK MATTER AND BOUND STATES

bound state condition  
(non relativistic)



$$V(r) \sim \alpha_{\mathcal{B}} \frac{e^{-rm_Y}}{r}$$

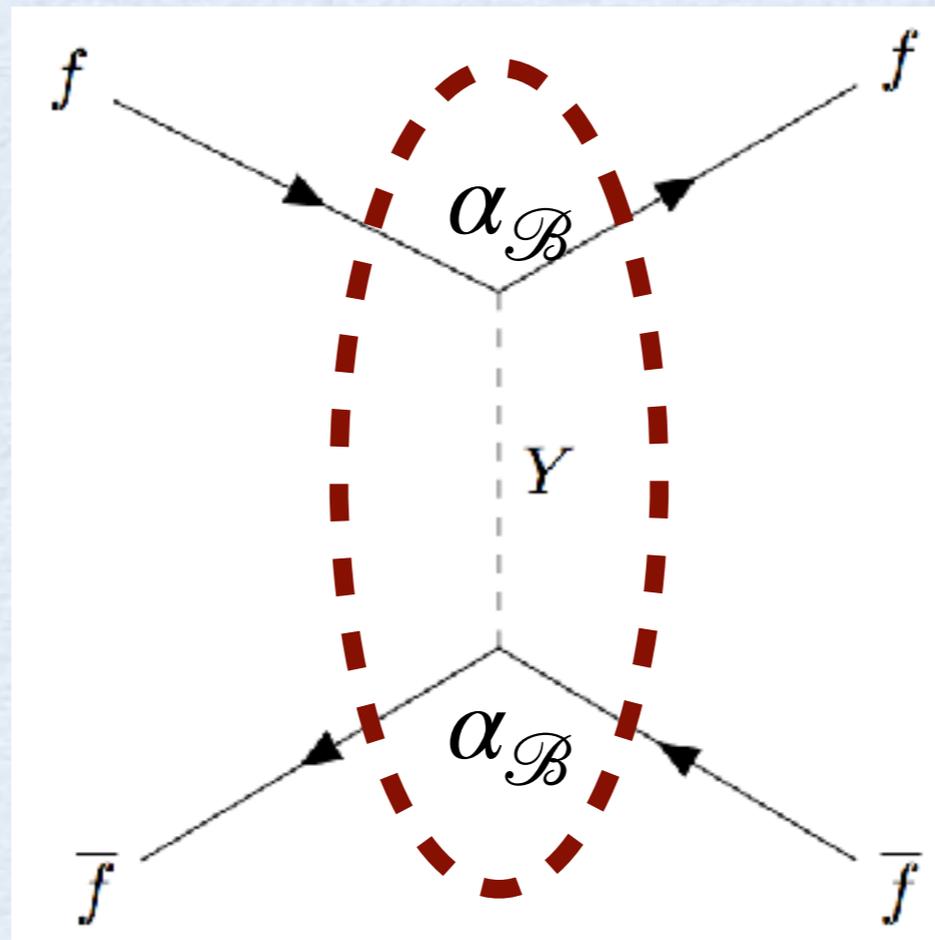
# DARK MATTER AND BOUND STATES

bound state condition  
(non relativistic)

interaction  
range

$$\frac{1}{m_Y} \gtrsim \frac{1}{\alpha_{\mathcal{B}} m_f}$$

Bohr  
radius



$$V(r) \sim \alpha_{\mathcal{B}} \frac{e^{-r m_Y}}{r}$$

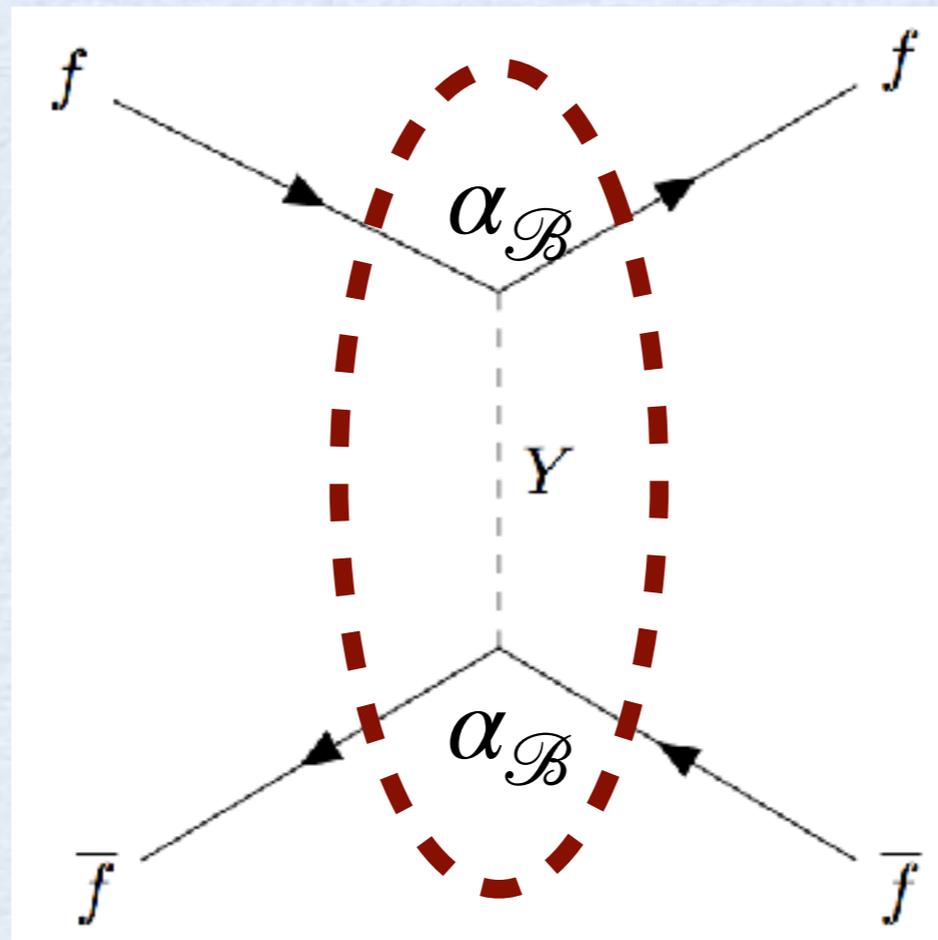
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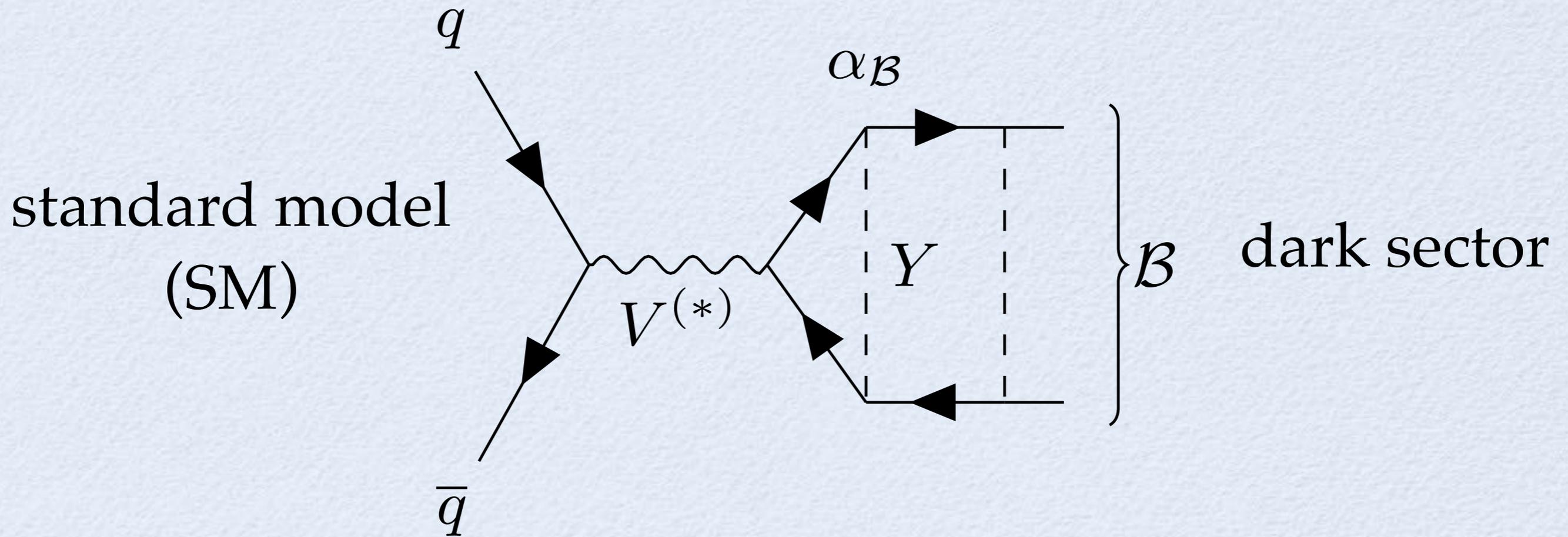


large  $\alpha_{\mathcal{B}}$

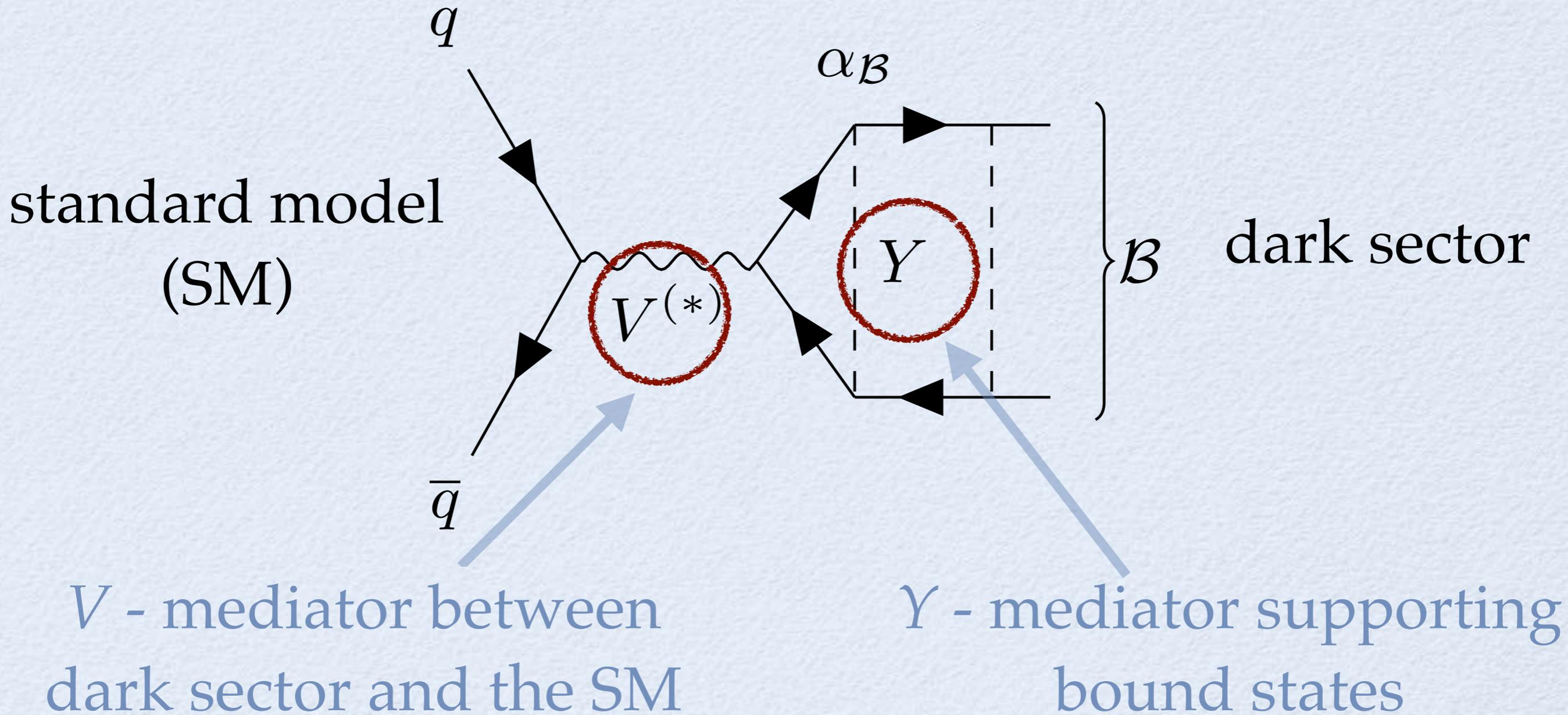
light  $m_Y$

$$V(r) \sim \alpha_{\mathcal{B}} \frac{e^{-rm_Y}}{r}$$

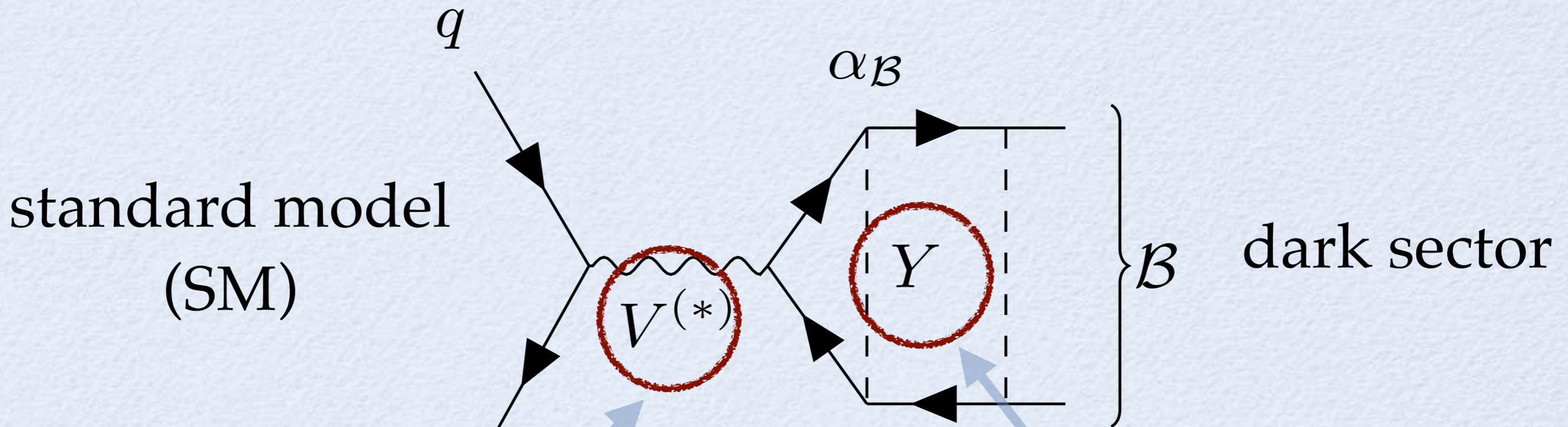
# DARK MATTER AND BOUND STATES



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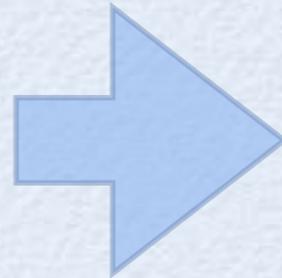
$V$  - mediator between dark sector and the SM

$Y$  - mediator supporting bound states

generically -  $V \neq Y$

# DARK MATTER AND BOUND STATES

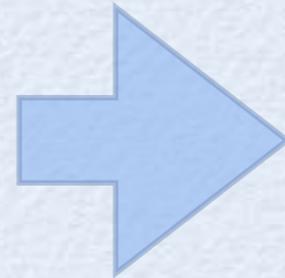
dark matter with long  
range self interaction



dark matter  
bound states

# DARK MATTER AND BOUND STATES

dark matter with long  
range self interaction



dark matter  
bound states

collider

direct detection

indirect detection

Shepherd, Tait, Zaharijas, 0901.2125

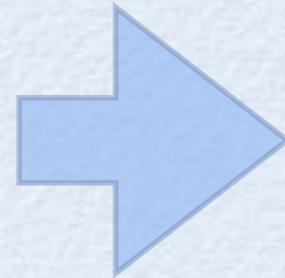
Tsai, Wang, Zhao, 1511.07433

An, Echenard, Pospelov, Zhang, 1510.05020

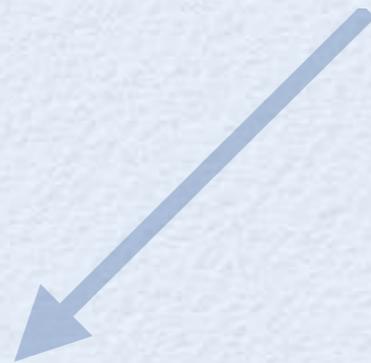
Krovi, Low, Zhang 1807.07972

# DARK MATTER AND BOUND STATES

dark matter with long  
range self interaction



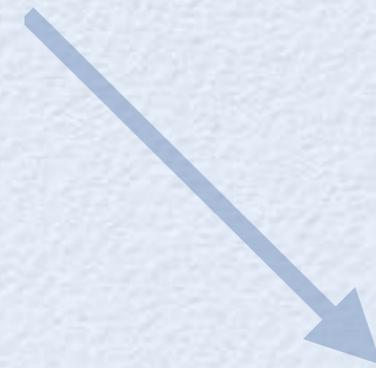
dark matter  
bound states



collider



direct detection



indirect detection

the interplay between the above?

what are the model building considerations here?

Shepherd, Tait, Zaharijas, 0901.2125

Tsai, Wang, Zhao, 1511.07433

An, Echenard, Pospelov, Zhang, 1510.05020

Krovi, Low, Zhang 1807.07972

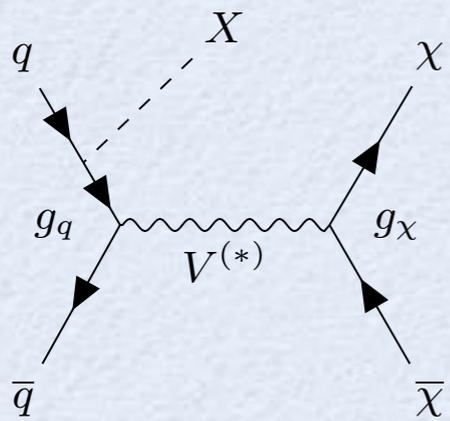
# COLLIDER PHENOMENOLOGY

collider

# COLLIDER PHENOMENOLOGY

collider

mono- $X$

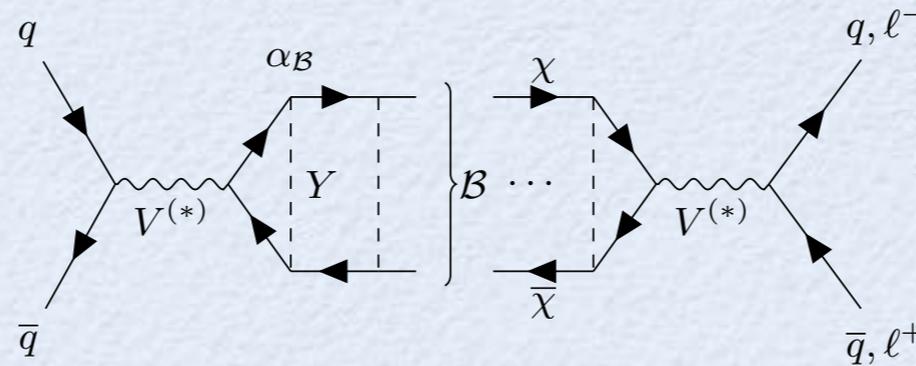
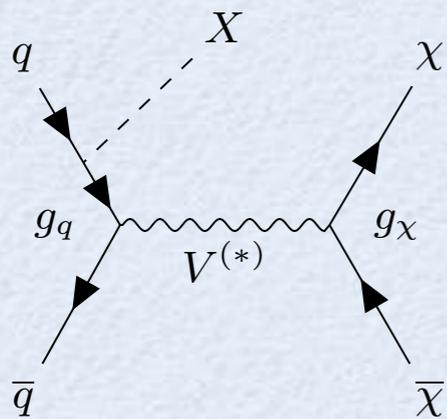


# COLLIDER PHENOMENOLOGY

collider

mono- $X$

DM bound state



bound state properties  
are determined by DM

production is:

suppressed by  $|\Psi(0)|^2 \propto (\alpha_B m_\chi)^3$

enhanced near  $m_V \approx 2m_\chi$

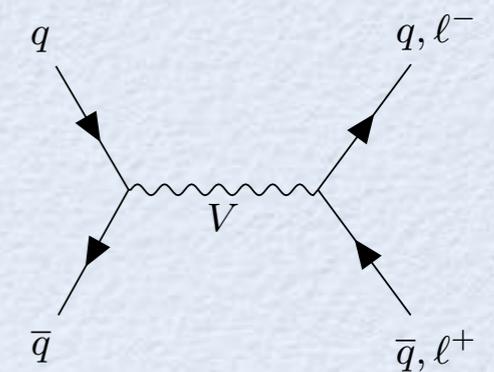
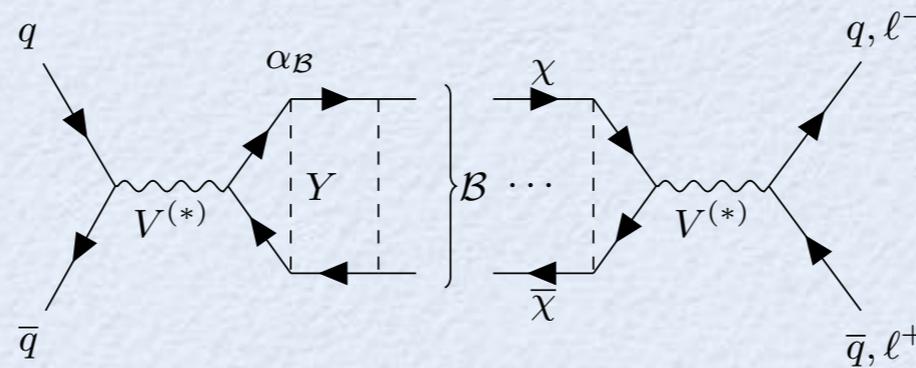
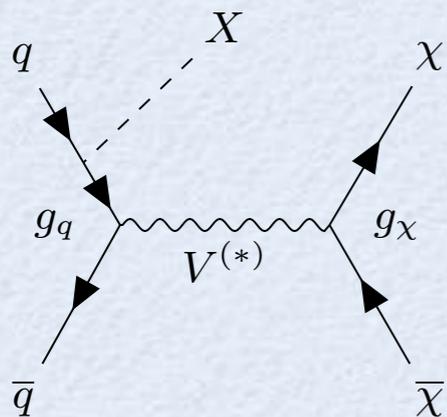
# COLLIDER PHENOMENOLOGY

collider

mono- $X$

DM bound state

mediator production



bound state properties  
are determined by DM

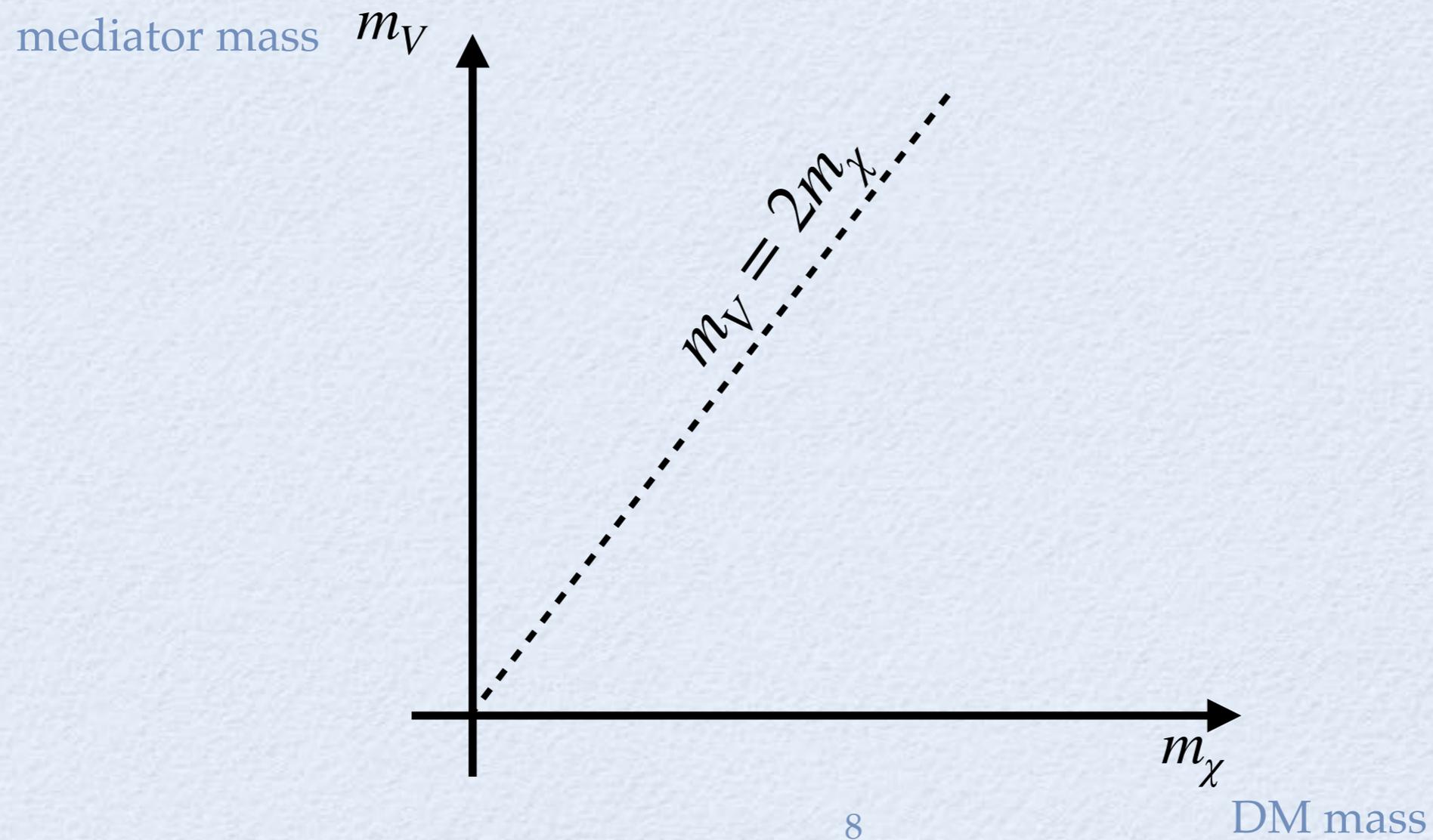
not directly  
related to DM

production is:

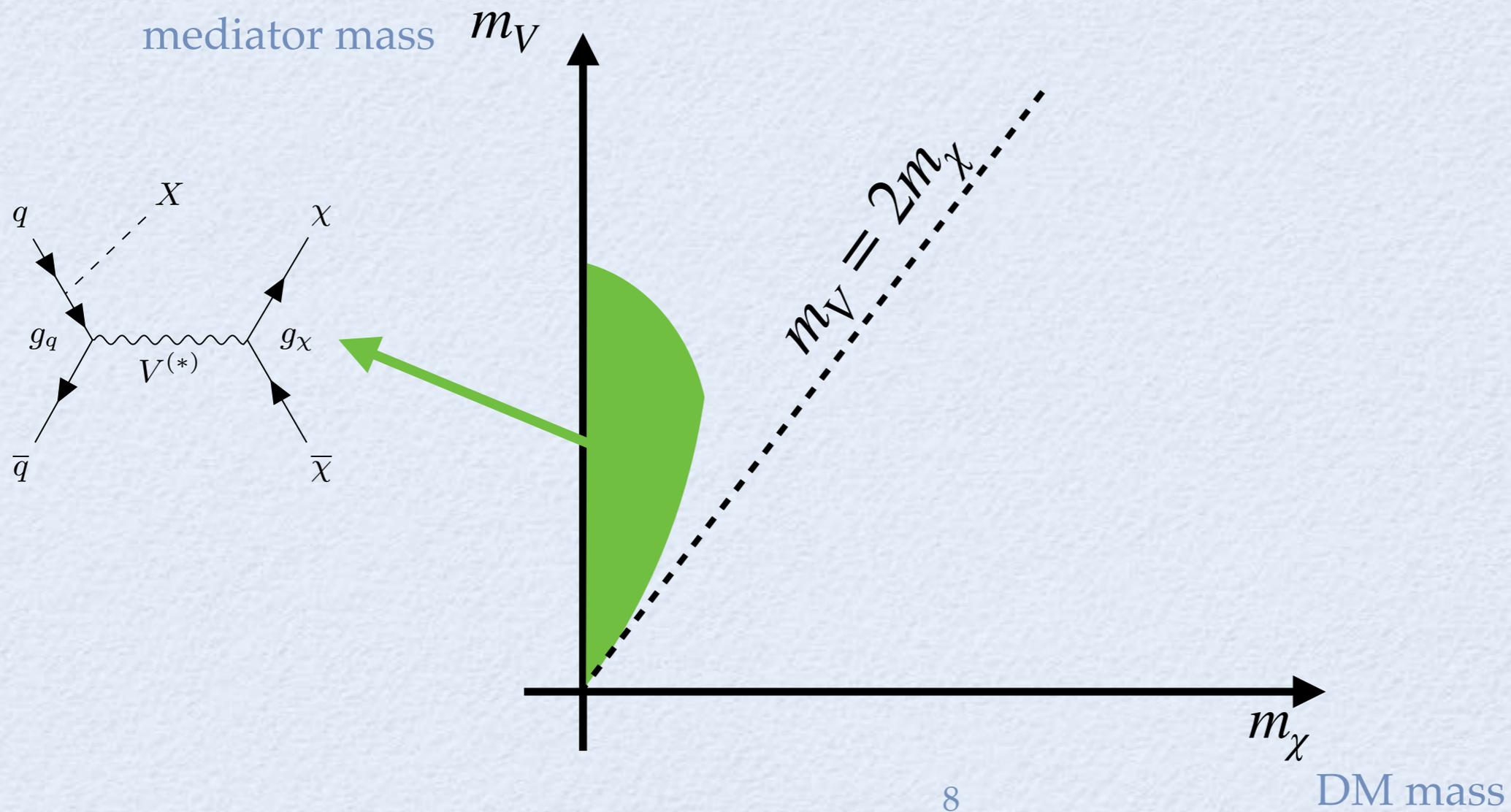
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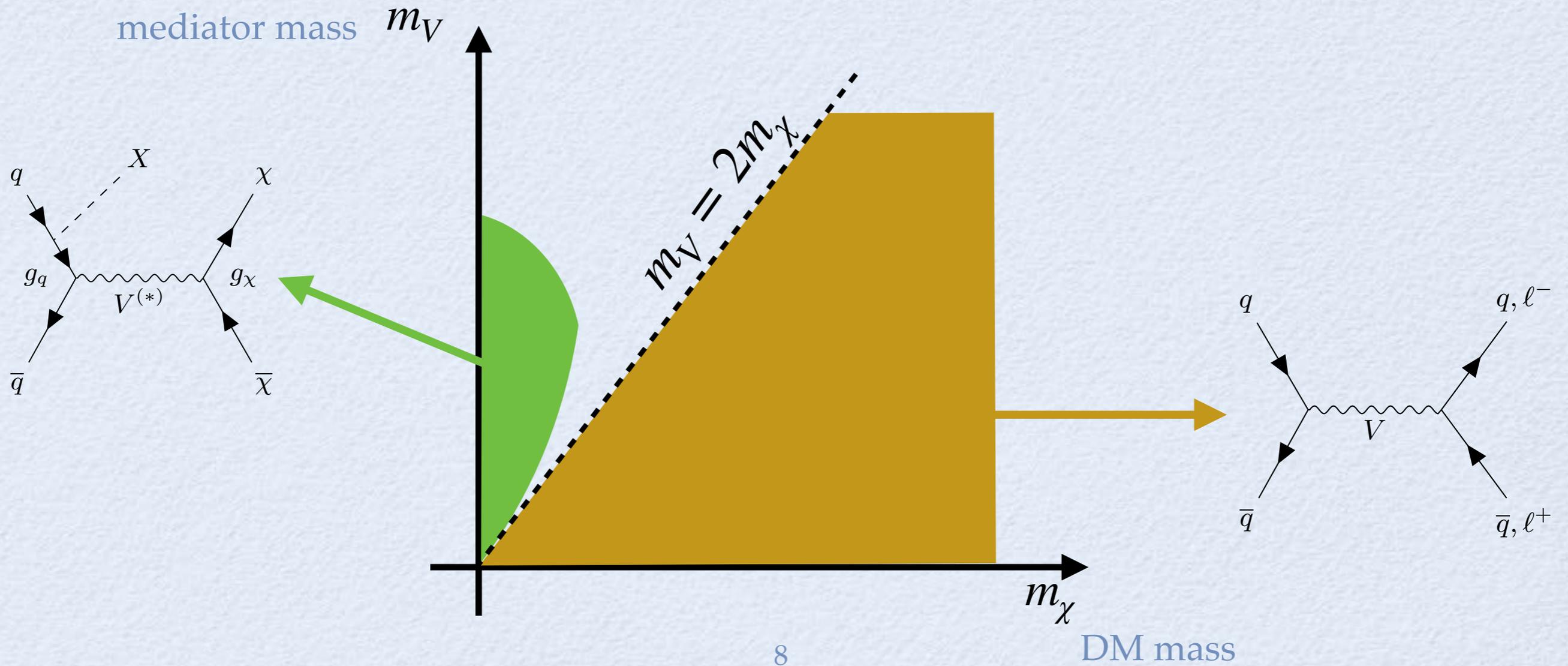
# COLLIDER PHENOMENOLOGY



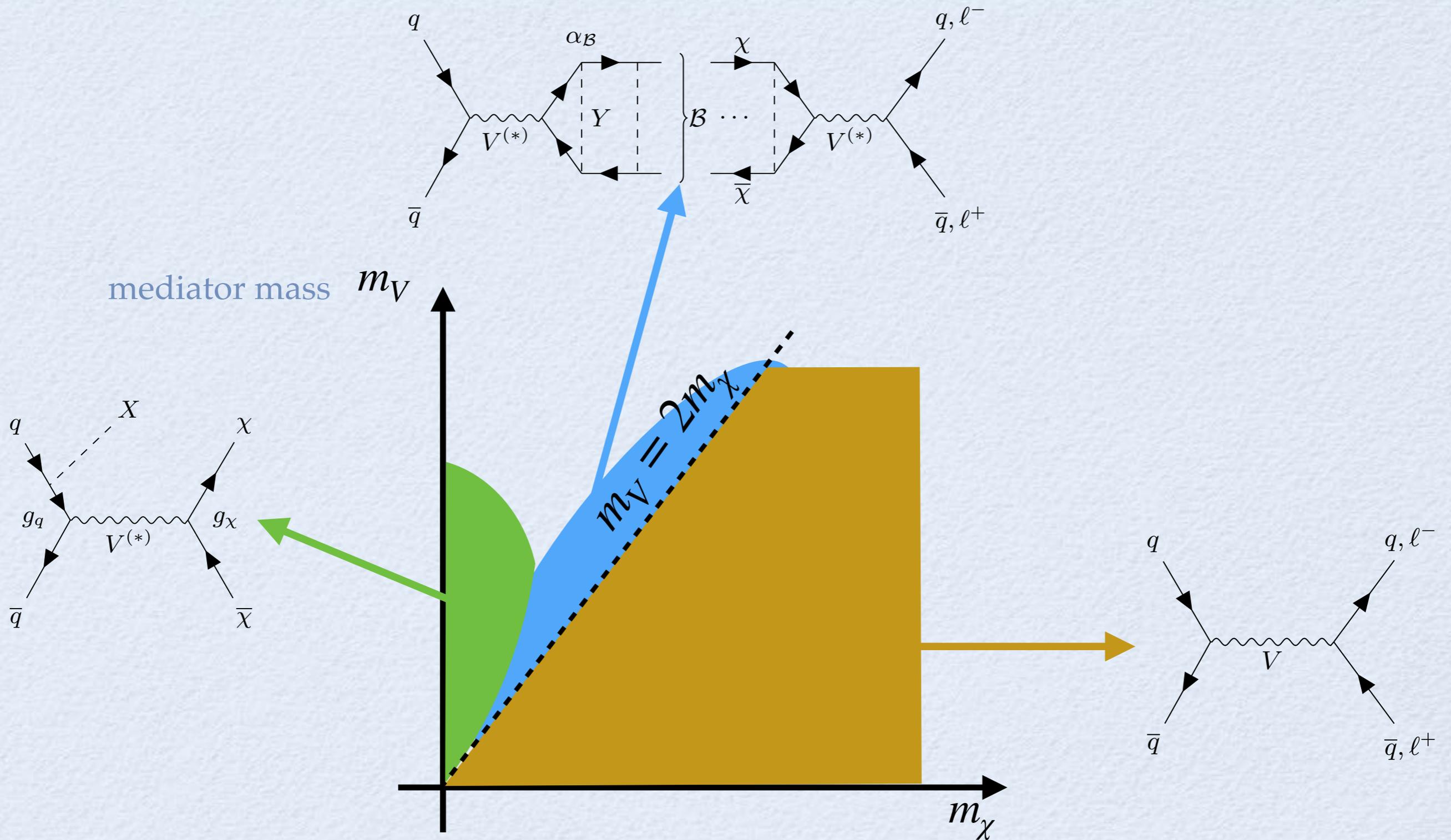
# COLLIDER PHENOMENOLOGY



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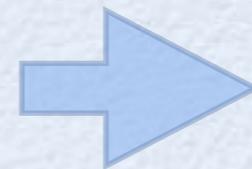
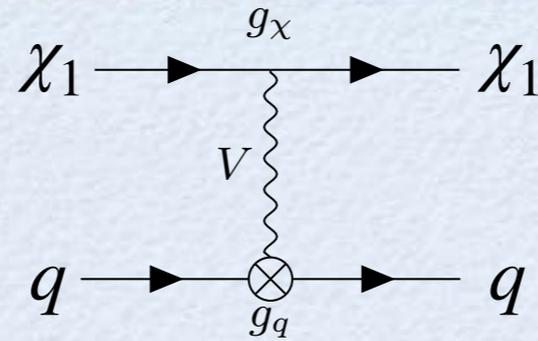


# COLLIDER PHENOMENOLOGY



# DIRECT DETECTION

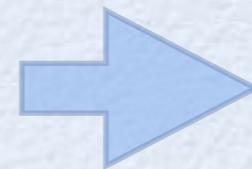
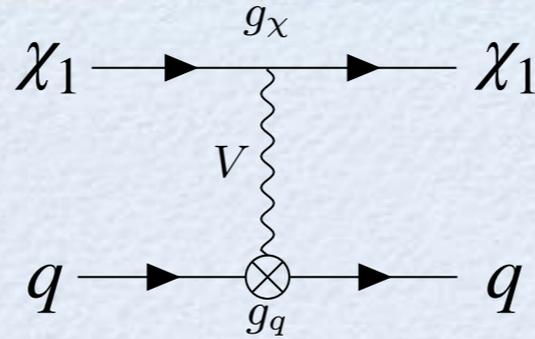
standard case



highly  
constrained

# DIRECT DETECTION

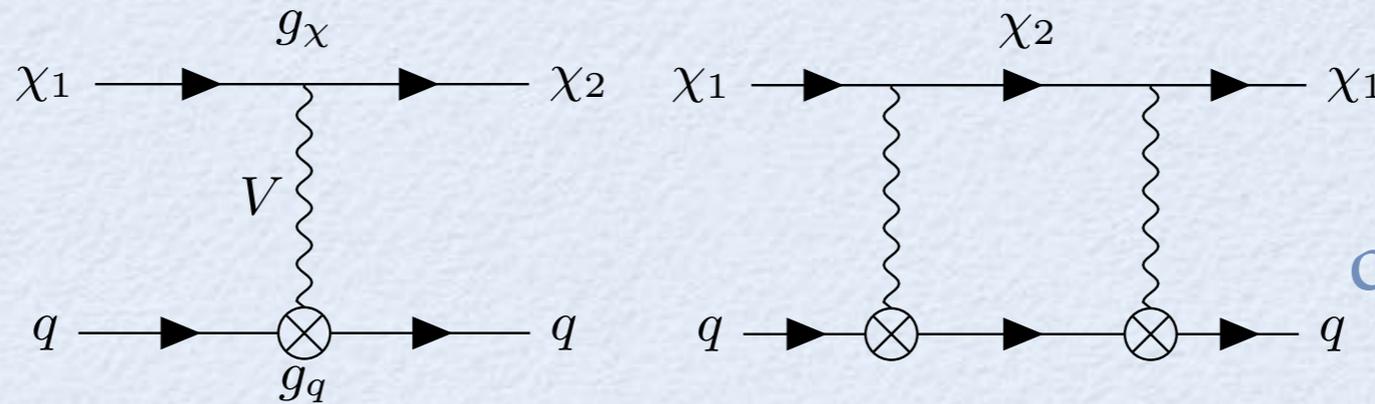
standard case



highly  
constrained

off diagonal  
coupling  
+ mass splitting

$$\langle K_{\text{DM}} \rangle \lesssim m_2 - m_1 \ll m_1, m_2$$



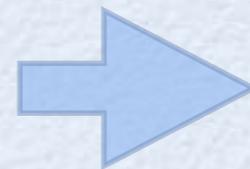
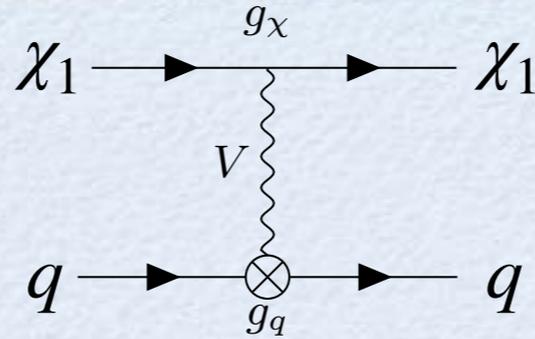
relaxes direct  
detection bounds

tree level - inelastic scattering

one loop - elastic scattering

# DIRECT DETECTION

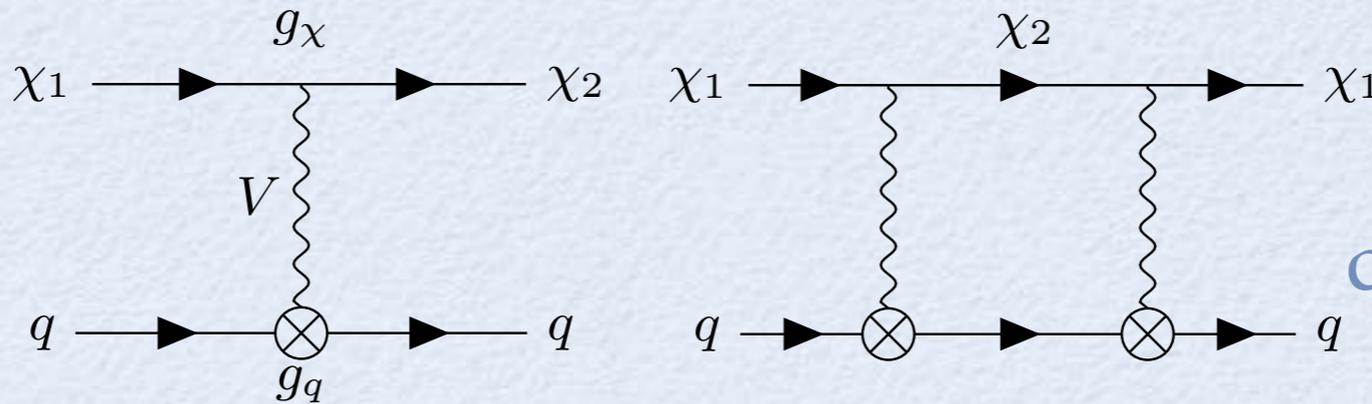
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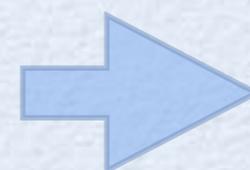
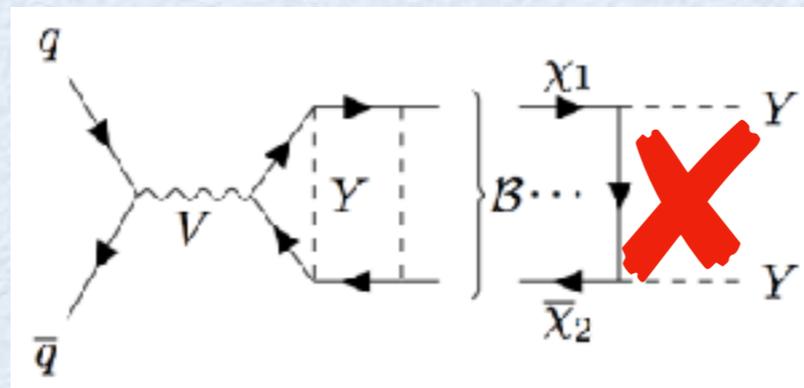


relaxes direct  
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tree level - inelastic scattering

one loop - elastic scattering

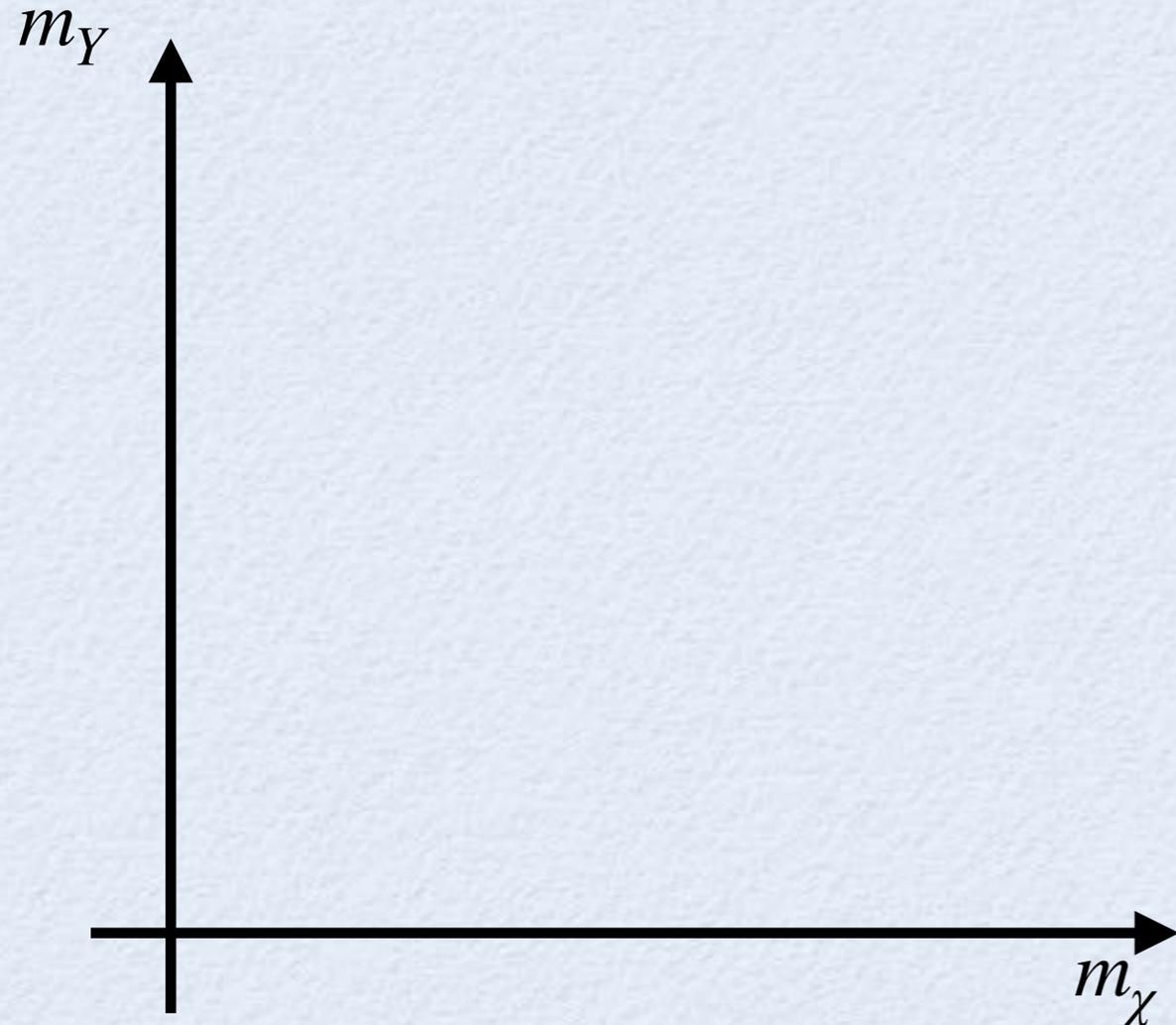
forbids decay to  
light bound state  
mediators



large rate of the  
bound state to SM

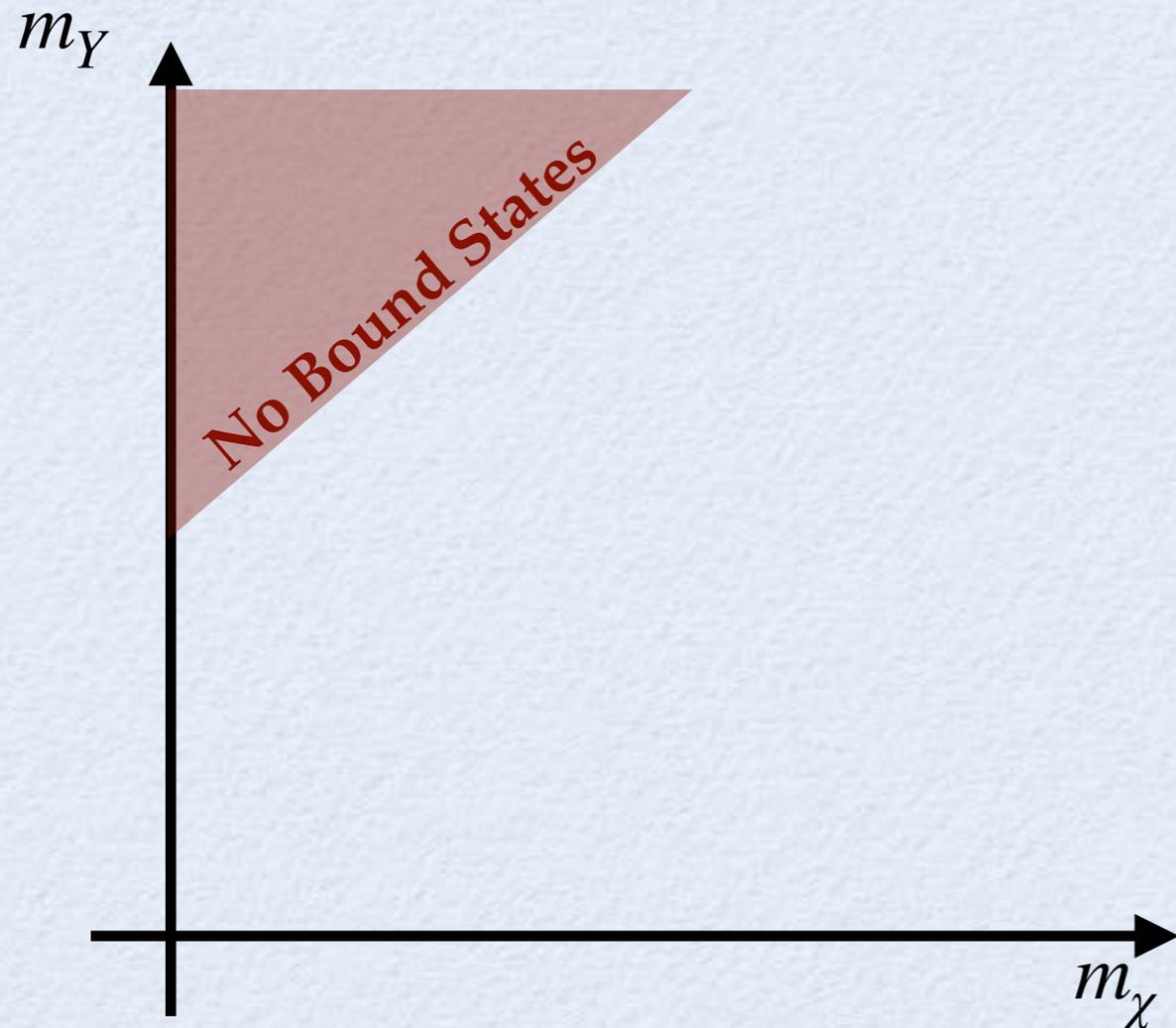
# INDIRECT DETECTION

light mediator  DM bound states  
affect DM annihilation (early universe and indirect detection)



# INDIRECT DETECTION

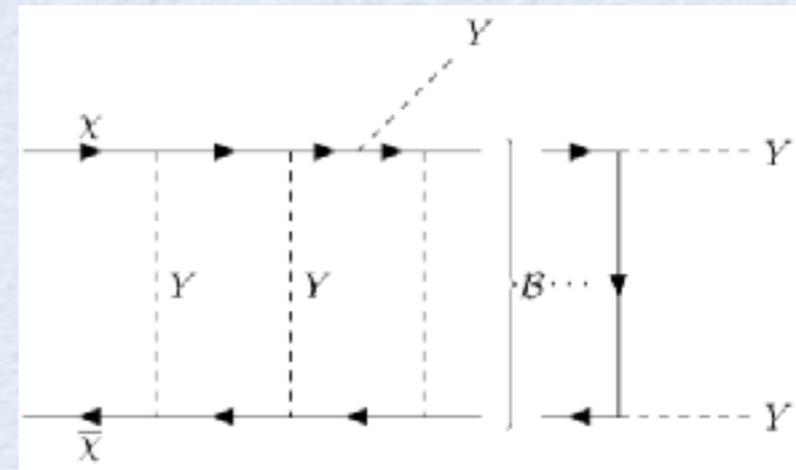
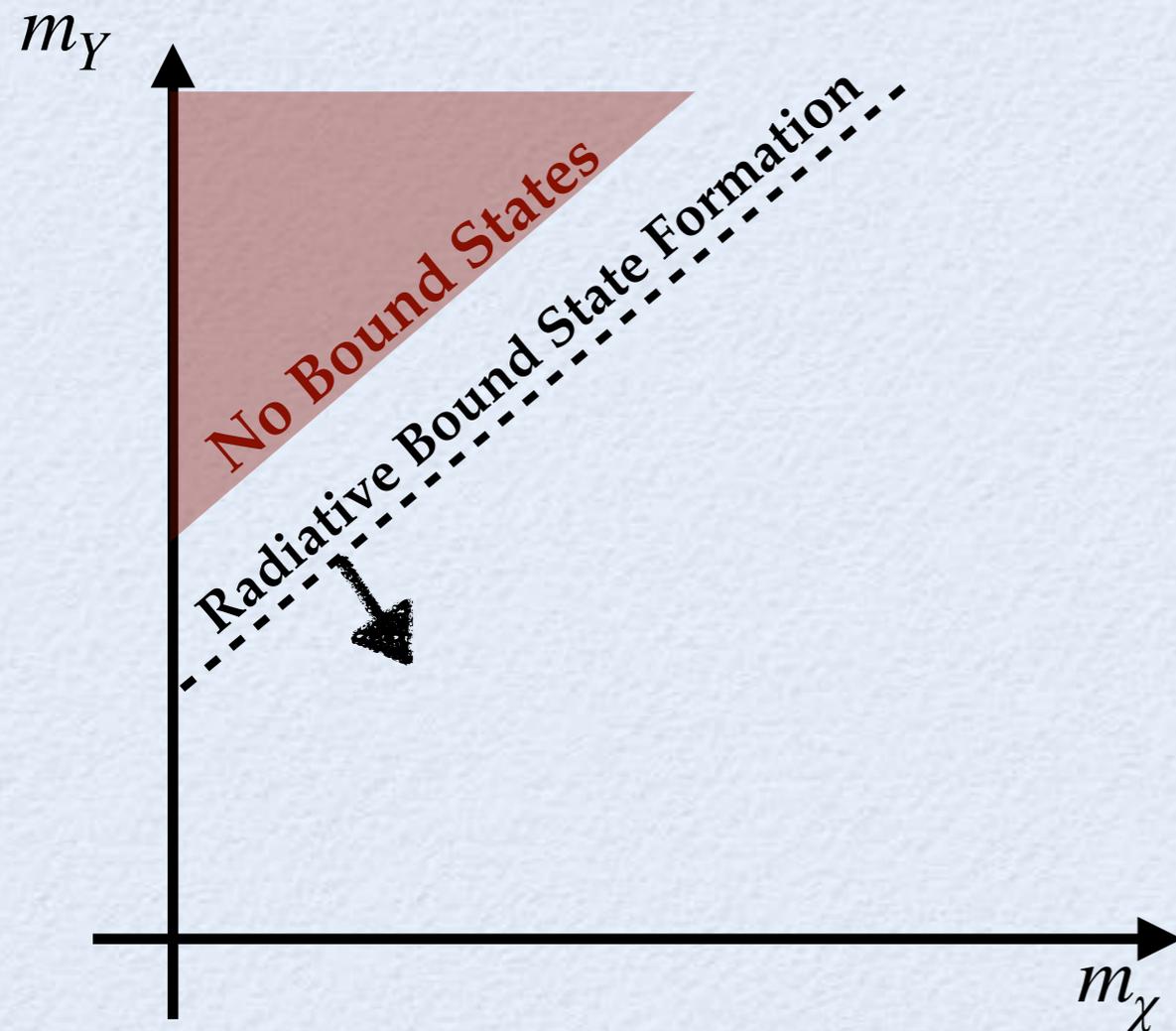
light mediator  $\begin{cases} \rightarrow \text{DM bound states} \\ \rightarrow \text{affect DM annihilation} \end{cases}$  (early universe and indirect detection)



# INDIRECT DETECTION

light mediator  $\leftrightarrow$  DM bound states  
affect DM annihilation (early universe and indirect detection)

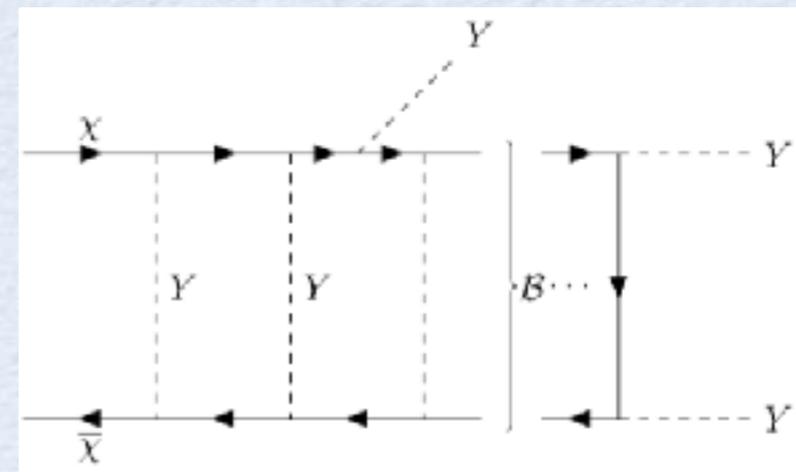
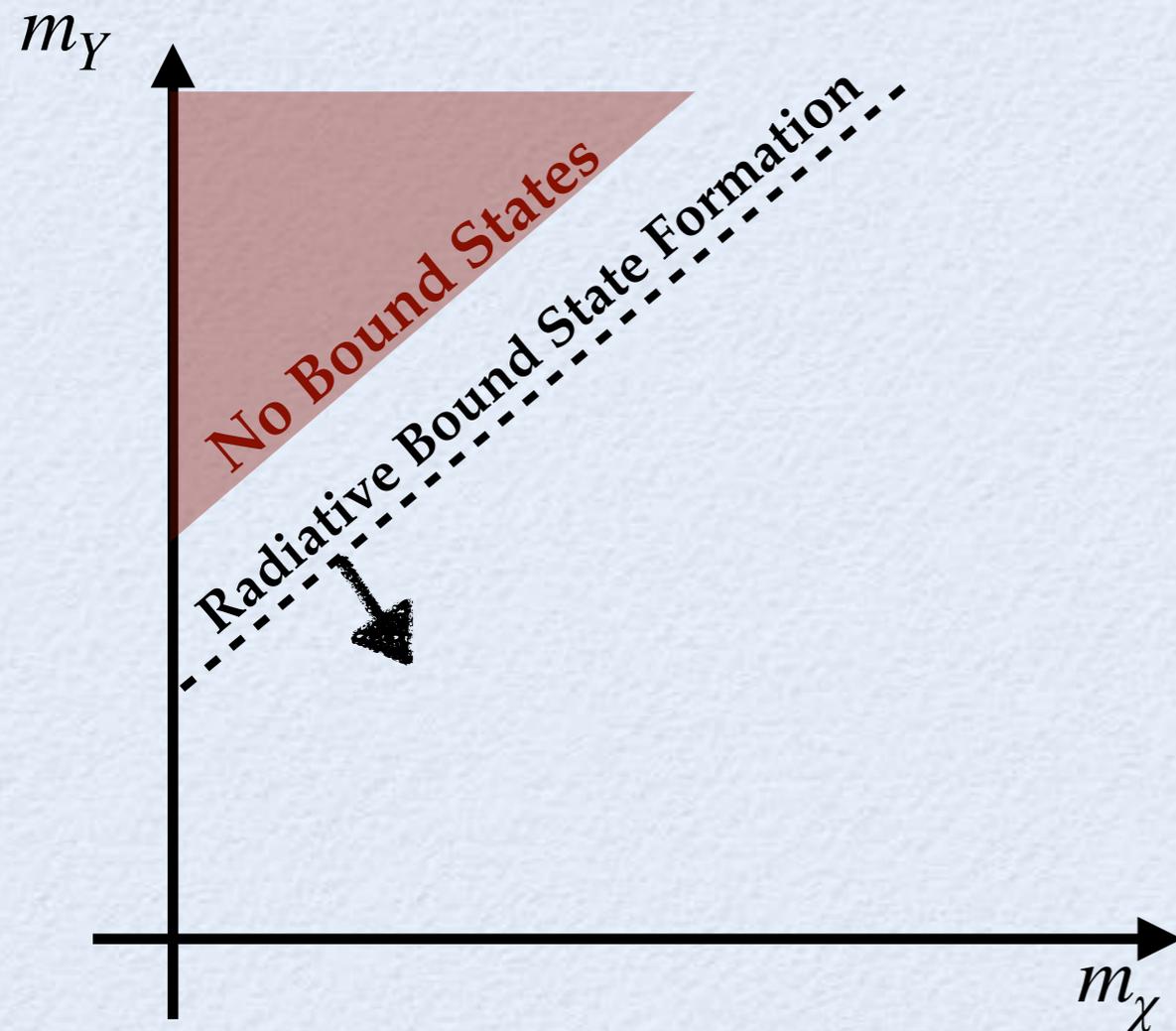
radiative bound state formation



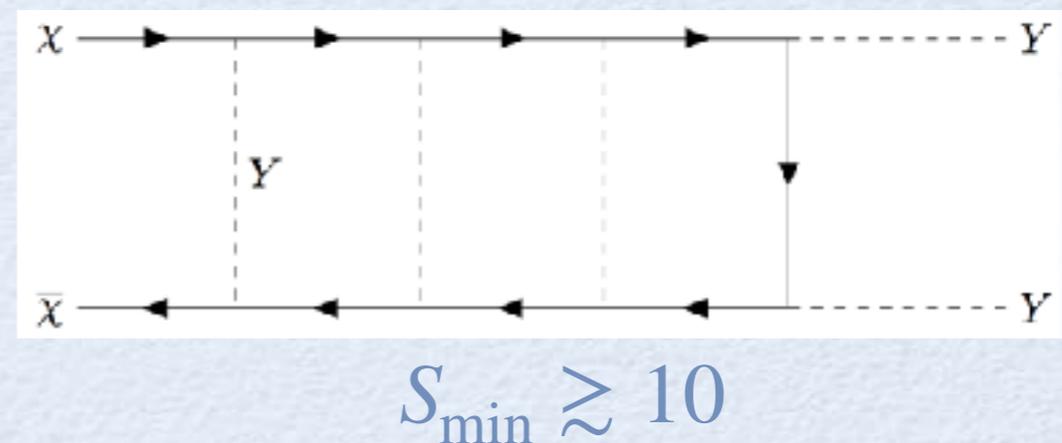
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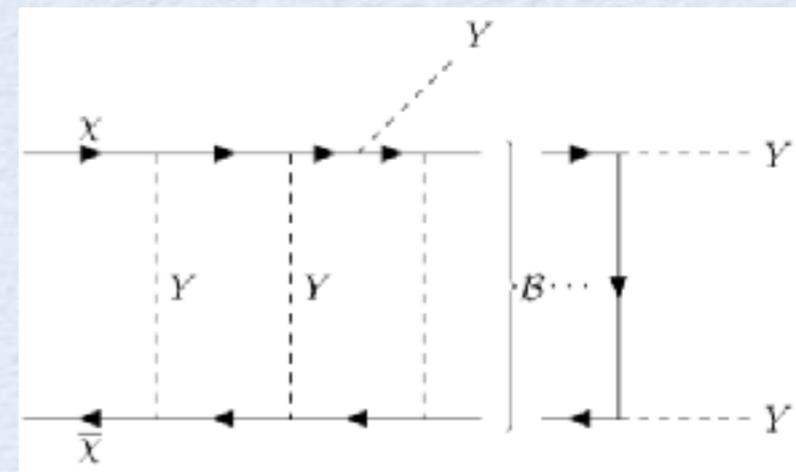
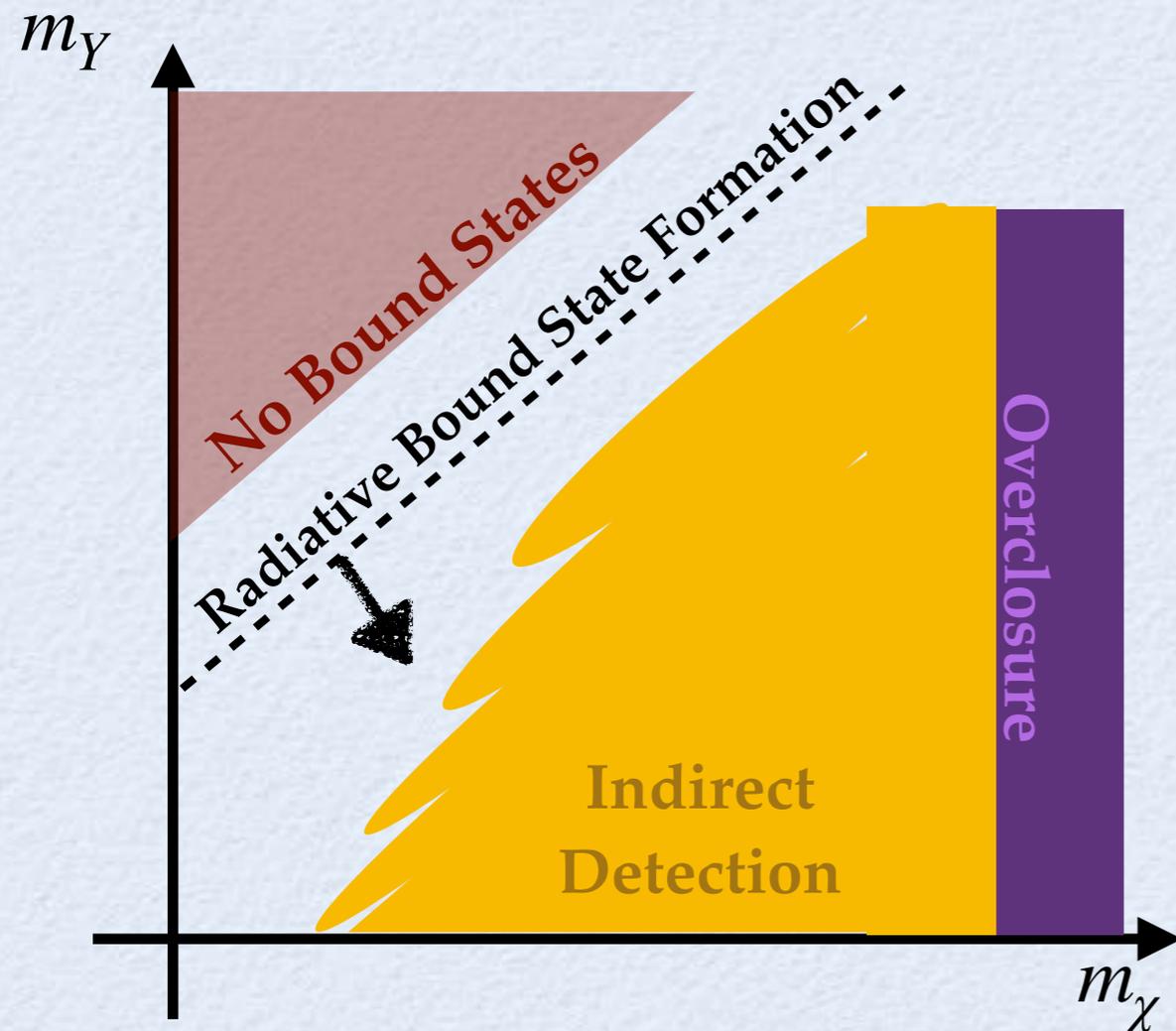
Sommerfeld Enhancement



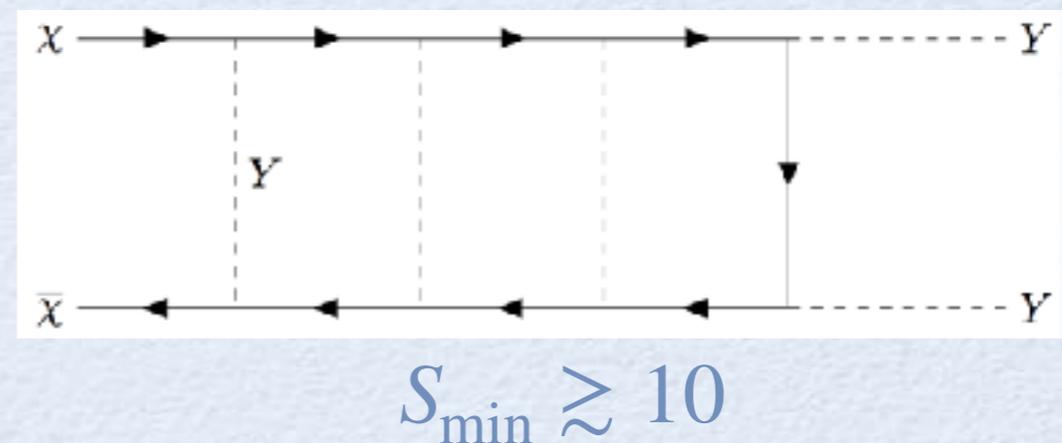
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Sommerfeld Enhancement

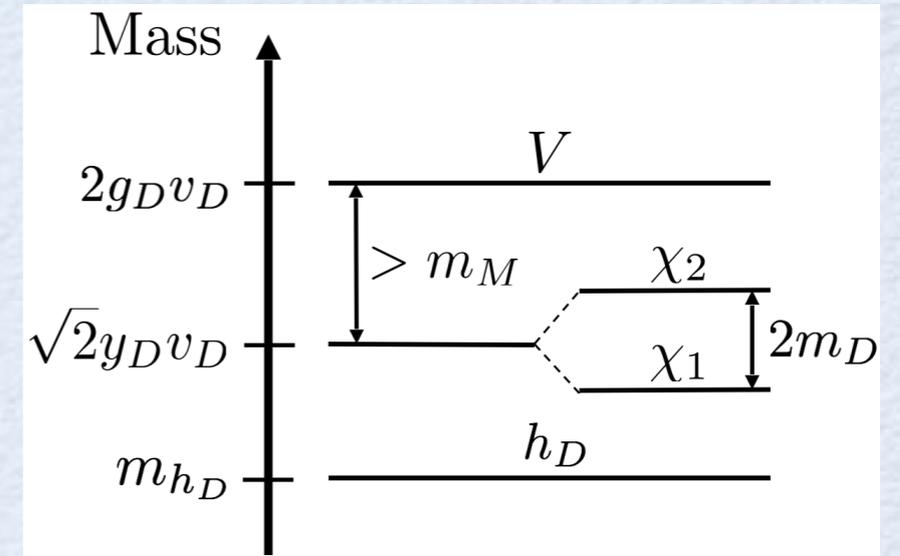


# TOY MODEL: PSEUDO DIRAC DM

$$\mathcal{L}_{\text{dark-Maj}} = i\bar{\Psi}\not{D}\Psi + (D_\mu\Phi_D)^\dagger(D^\mu\Phi_D) - m_D\bar{\Psi}\Psi$$

$$- y_D \left( \bar{\Psi}^C \Psi \Phi_D^* + \text{h.c.} \right) + \mathcal{L}_{\text{kin-mix}},$$

+ kinetic mixing with the SM

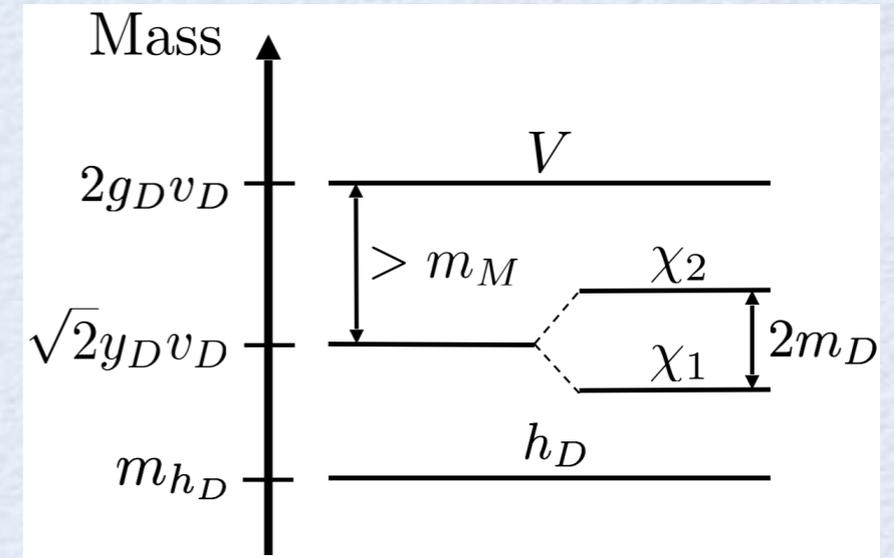


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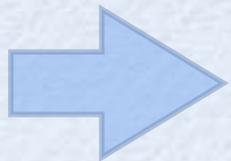


interaction with SM

$$-ig_D \left( V_\mu - r^2 \frac{\epsilon S_w}{1-r^2} Z_\mu \right) \left( \chi_1^\dagger \bar{\sigma}^\mu \chi_2 - \chi_2^\dagger \bar{\sigma}^\mu \chi_1 \right)$$

DM self interaction

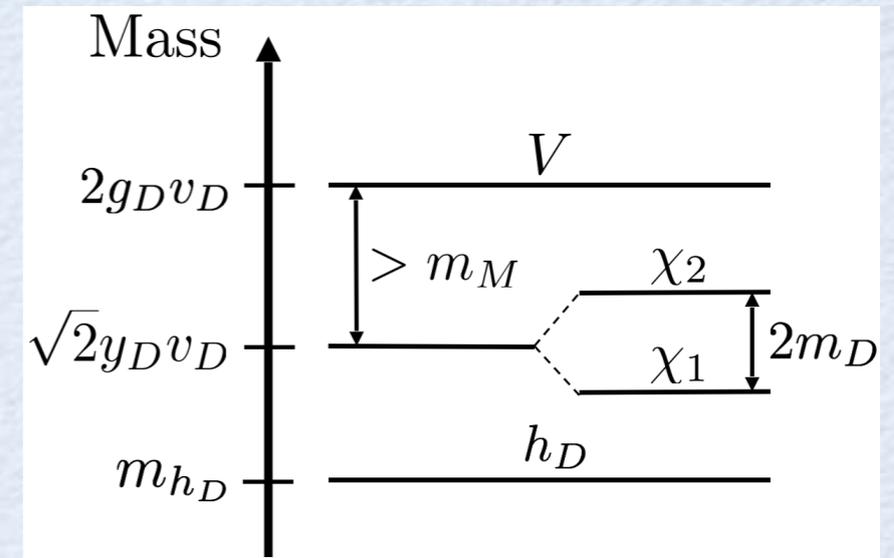
$$-\frac{y_D}{\sqrt{2}} (\rho + v_D) (\chi_1 \chi_1 - \chi_2 \chi_2 + \text{h.c.})$$



# TOY MODEL: PSEUDO DIRAC DM

$$\mathcal{L}_{\text{dark-Maj}} = i\bar{\Psi}\not{D}\Psi + (D_\mu\Phi_D)^\dagger(D^\mu\Phi_D) - m_D\bar{\Psi}\Psi - y_D\left(\bar{\Psi}^C\Psi\Phi_D^* + \text{h.c.}\right) + \mathcal{L}_{\text{kin-mix}},$$

+ kinetic mixing with the SM



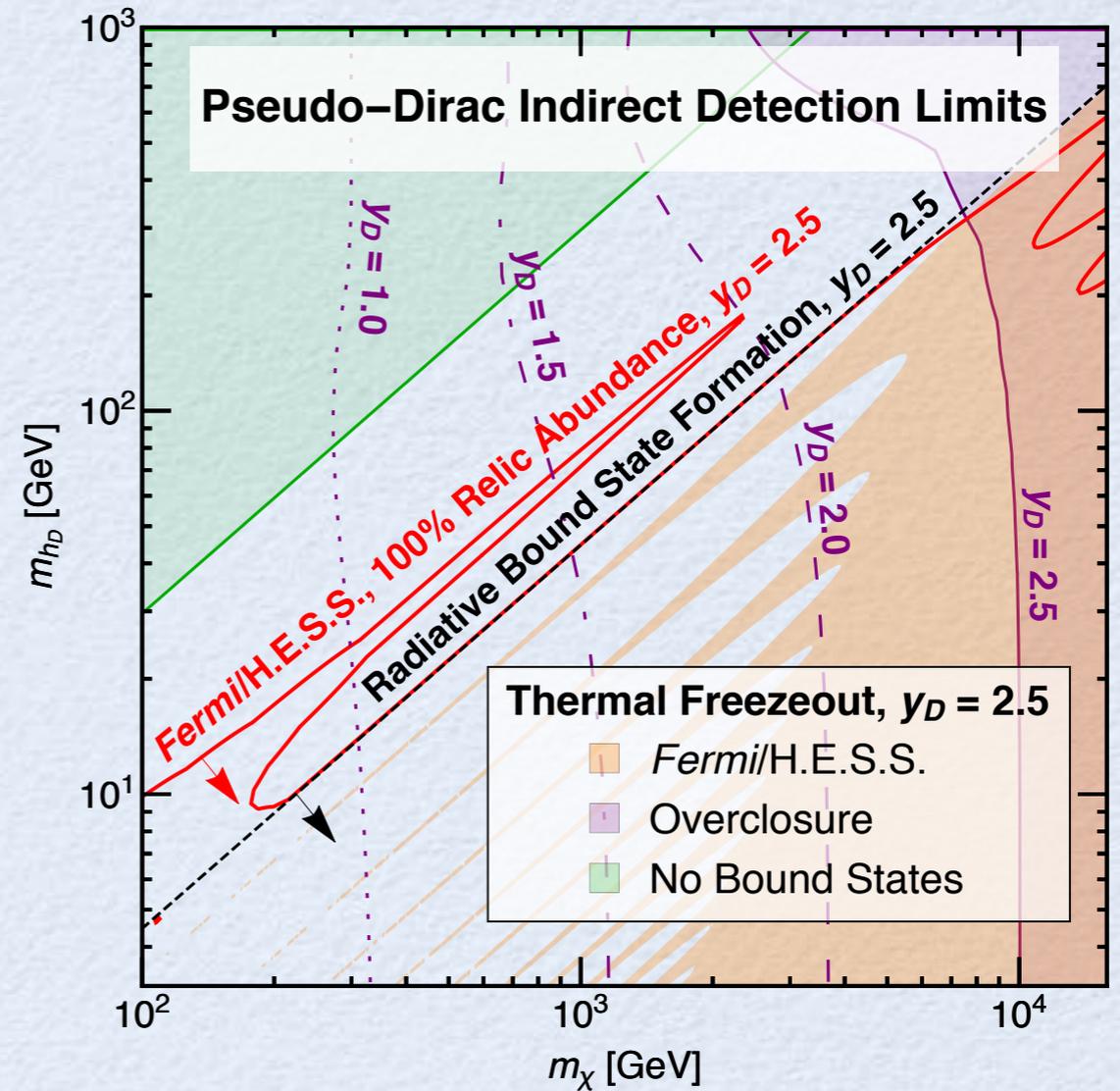
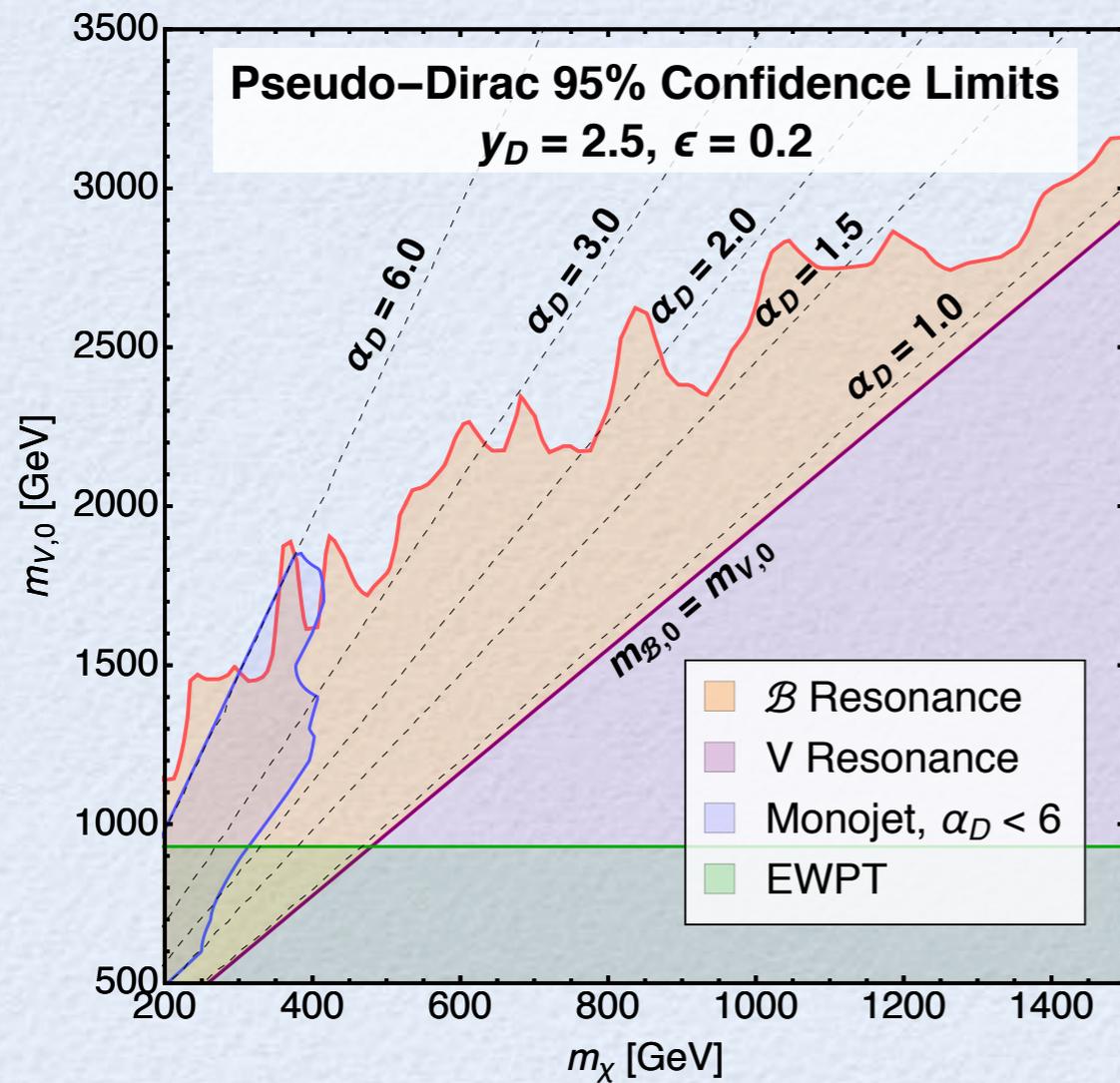
interaction with SM  $-ig_D\left(V_\mu - r^2\frac{\epsilon S_w}{1-r^2}Z_\mu\right)\left(\chi_1^\dagger\bar{\sigma}^\mu\chi_2 - \chi_2^\dagger\bar{\sigma}^\mu\chi_1\right)$

DM self interaction  $-\frac{y_D}{\sqrt{2}}(\rho + v_D)(\chi_1\chi_1 - \chi_2\chi_2 + \text{h.c.})$

direct detection are suppressed

$\chi_1\chi_2$  bound state production at LHC  
(cannot decay to dark Higgs)

# TOY MODEL: PSEUDO DIRAC DM



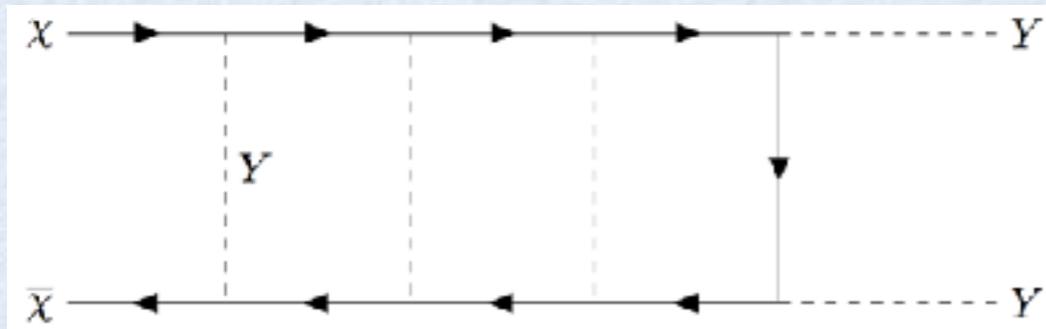
# SUMMARY

- non trivial dark sector with self interaction can result in formation of bound state, which leads to rich phenomenology
- bound state resonance search at the LHC can be a complementary search for dark sectors
- these models have interesting interplay between direct search, indirect searches and LHC phenomenology

# BACKUP SLIDES

# INDIRECT DETECTION

## Sommerfeld Enhancement



$$\frac{\alpha_{\mathcal{B}} m_{\chi}}{m_{\mathcal{Y}}} \geq 1.68$$

$$S \geq \frac{2\pi\alpha_{\mathcal{B}}}{v_{\text{rel}}} \tanh\left(\frac{3m_{\chi}v_{\text{rel}}}{\pi m_{\mathcal{Y}}}\right)$$

$$S \geq \frac{2\pi\alpha_{\mathcal{B}}}{v_{\text{rel}}} \tanh\left(\frac{1.6v_{\text{rel}}}{\alpha_{\mathcal{B}}}\right) \approx 10$$

$$S_{\text{min}} \gtrsim 10$$

overclosurei - freeze out

$$\langle\sigma v\rangle \sim \frac{\pi\alpha_{\mathcal{B}}^2}{m_{\chi}^2} \gtrsim \langle\sigma v\rangle_{\text{thermal}} \implies m_{\chi} \geq \alpha_{\mathcal{B}} \times 43 \text{ TeV}$$