# Characterizinging GeV Dark Matter

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# SPARC Rotation Curves

Nicolas Loizeau & GRF (ApjL2021; 2105.00119)

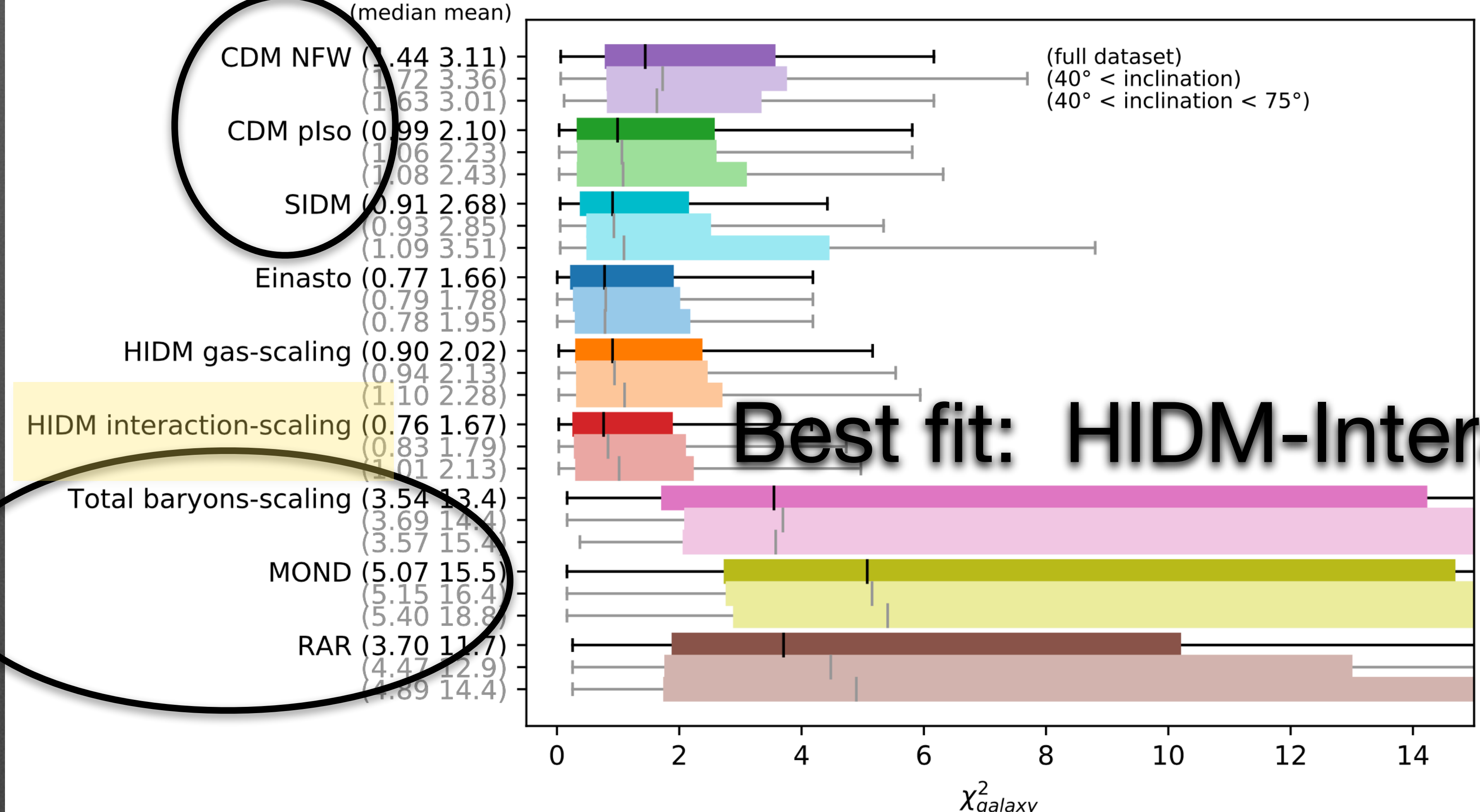
- 129 well-measured galaxies (SPARC) with > 10 datapoints
- impose observed mass-to-light ratio (mean and spread) on ensemble of galaxies
- HIDM-InteractionScaling: disky component + pseudo-isothermal

$$\Sigma_{\rm DM}(r) = m_{\rm DM}\, T_i\left(\frac{\rho_{\rm halo}(r)}{m_{\rm DM}}\right)\left(\frac{\Sigma_{\rm gas}(r)}{m_{\rm gas}}\right) \sigma_{\rm DM-gas}\, v_{\rm rel}(r) \equiv \zeta_i\, \rho_{{\rm halo},i}(r)\, v_{{\rm obs},i}(r)\, \Sigma_{\rm gas}(r)$$

The Astrophysical Journal Letters, 920:L10 (20pp), 2021 October 10 Loizeau & Farrar

**Table 1**
Summary of the Models and Their Free Parameters; for Details, See Appendix A

| Model | Global Parameter | Galaxy-dependent Free Parameter | Components |
|---|---|---|---|
| CDM NFW halo | | $\Upsilon_*$, $R_s$, $\rho_0$ | Baryons, DM halo |
| CDM pIso halo | | $\Upsilon_*$, $R_c$, $\rho_0$ | Baryons, DM halo |
| Einasto | | $\Upsilon_*$, $R_s$, $\rho_0$, $\alpha$ | Baryons, DM halo |
| SIDM | | $\Upsilon_*$, $\sigma_{v0}$, $\rho_0$ | Baryons, DM halo |
| HIDM-GS | | $\Upsilon_*$, $R_c$, $\rho_0$, $\theta$ | Baryons, DM halo, DM disk |
| HIDM-IS | | $\Upsilon_*$, $R_c$, $\rho_0$, $\zeta$ | Baryons, DM halo, DM disk |
| Total baryon scaling | | $\Upsilon_*$, $\theta_b$ | Baryons, DM disk |
| MOND | $a_0$ | $\Upsilon_*$ | Baryons |
| RAR | $a_0$ | $\Upsilon_*$ | Baryons |




Poor fits

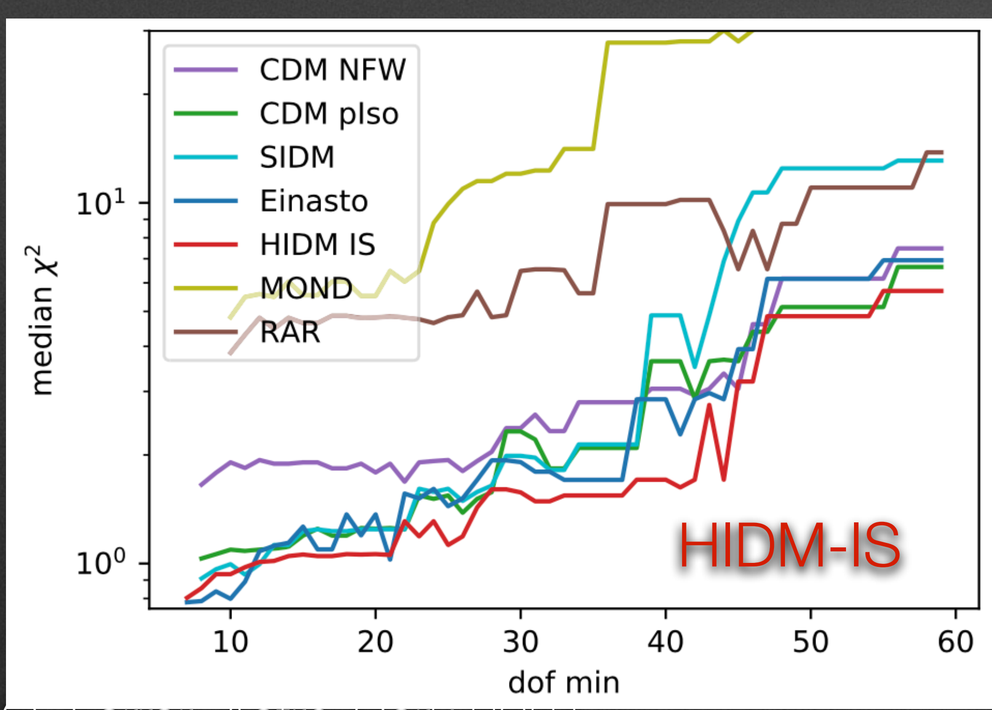
Best fit: HIDM-InteractionScaling

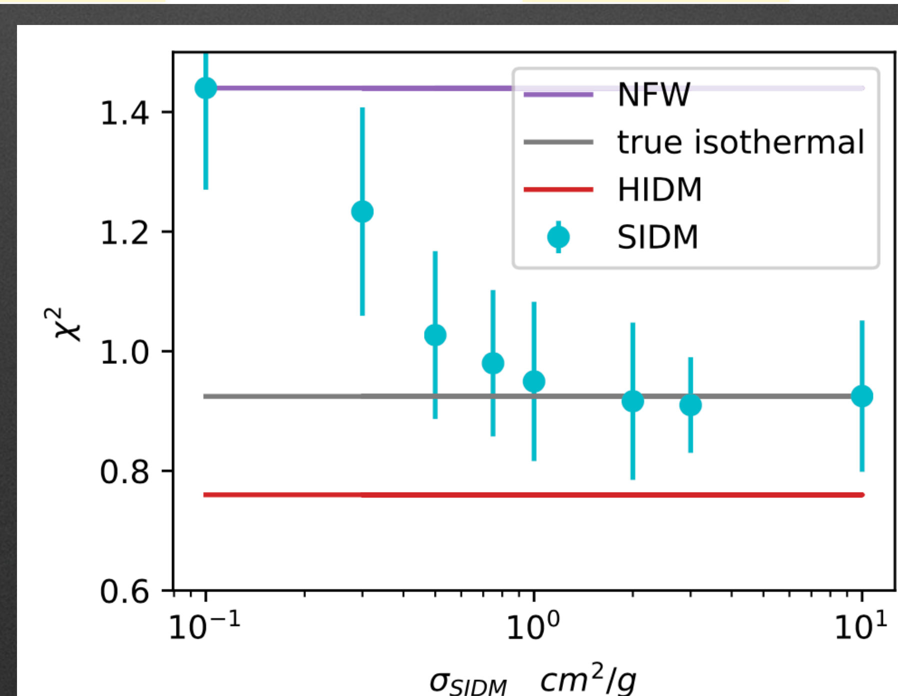
Bad fits

**Table 2**

Median Reduced $\chi^2$ for the Different Models with Jackknife Uncertainty Estimates

| NFW | pIso | SIDM | Einasto | HIDM-GS | HIDM-IS | TBS | MOND | RAR |
|---|---|---|---|---|---|---|---|---|
| $1.44 \pm 0.17$ | $0.99 \pm 0.08$ | $0.91 \pm 0.08$ | $0.77 \pm 0.07$ | $0.90 \pm 0.10$ | $0.76 \pm 0.09$ | $3.54 \pm 0.53$ | $5.07 \pm 0.71$ | $3.70 \pm 0.45$ |




HIDM-IS:
best for virtually all galaxies

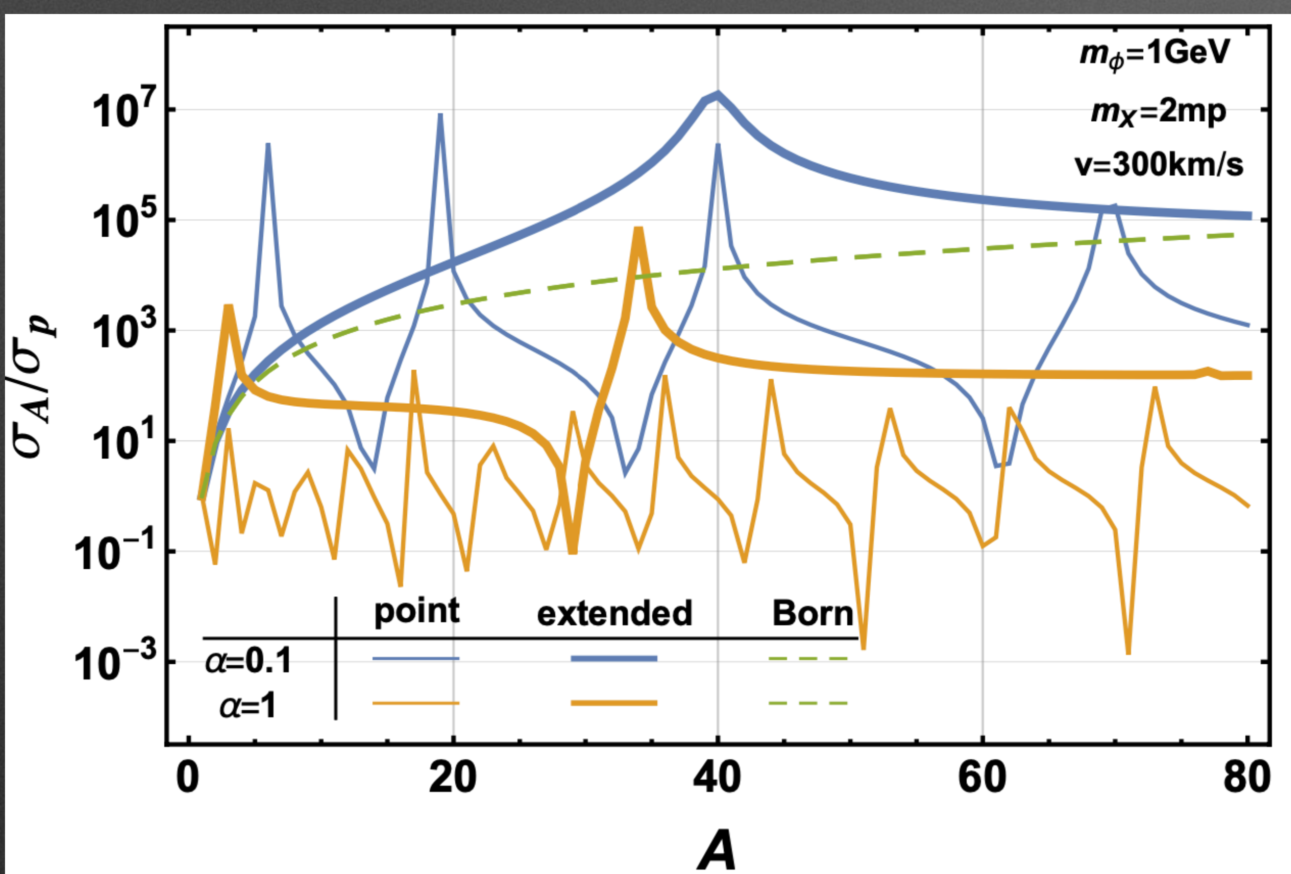
SIDM:
$\sigma \gtrsim$ cm$^2$/g: equivalent to isothermal
$\sigma <$ cm$^2$/g: worse than isothermal

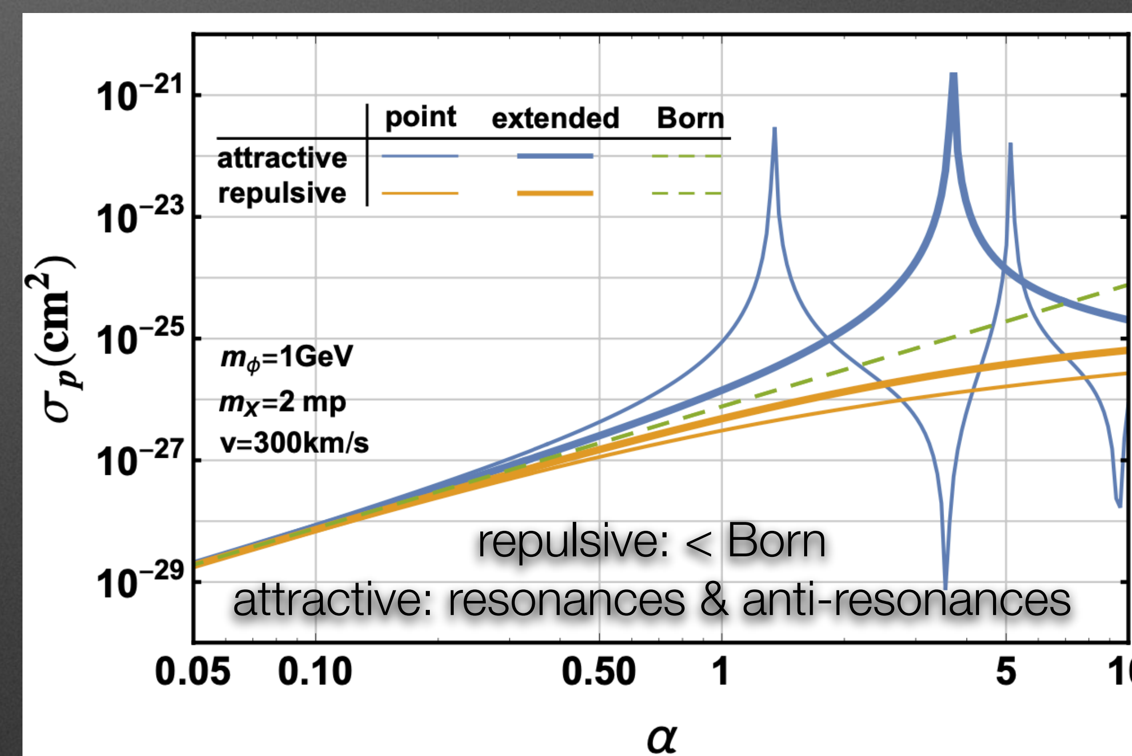
MOND, Radial Acceleration Ratio, Rescale Baryons:
much worse fits.

# Revising Limits on $\sigma_{\text{DM-p}}$

Xingchen Xu & GRF (arxiv: 2101.00142 & 2112.00707)

- **Problems to overcome:**
  - no simple relationship between $\sigma_A$ & $\sigma_p$ when non-perturbative
  - standard form factor treatment of nuclear size is not valid



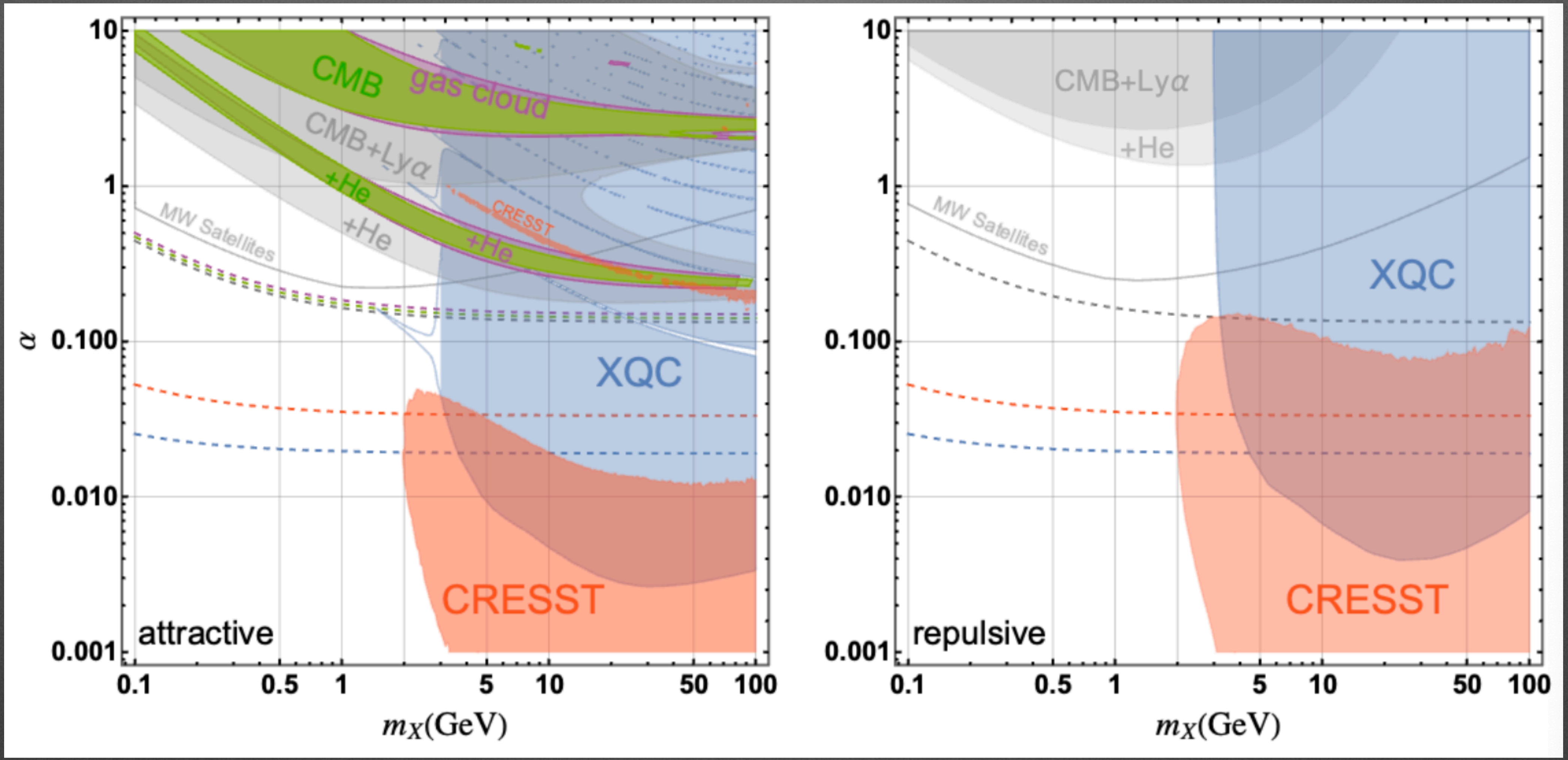

$$\sigma_A^{\text{Born}} = \sigma_p \left(\frac{\mu_A}{\mu_p}\right)^2 A^2.$$

Cannot use

Model: nucleus/nucleons are spheres of radius (1fm) $A^{1/3}$ sourcing Yukawa; plots are for $m_\phi$=1 GeV

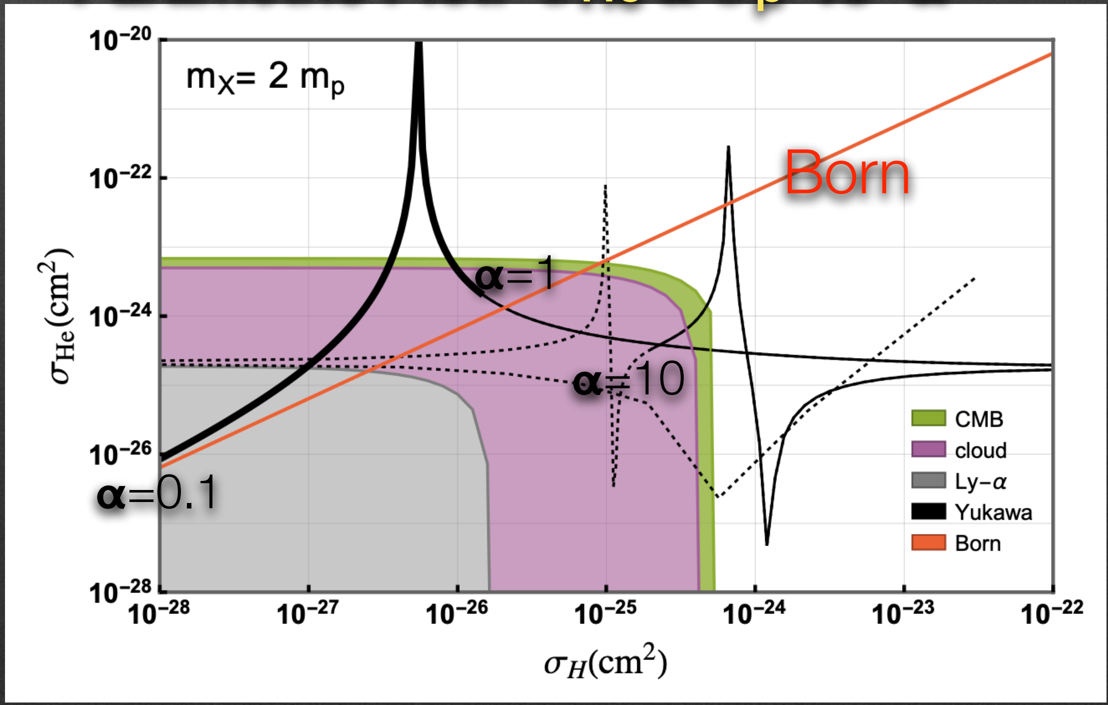
$$V(r) = -\frac{\alpha}{r} e^{-m_\phi r},$$

# Constraints on α




- Plot illustrates problem in non-pert. regime ➜
- Wadekar-GF gas clouds limits are slightly stronger than CMB (have been redone)
- Shown but not presently trustworthy:
  - CMB+Ly-**α** : May not reflect small scale CMB due to patchy reionization (Hui,Ostriker+17) &
    instabilities (Mandelkar,vandenBosch,Springel+18)
  - Milky Way satellites (Nadler+DES). Need to better understand galaxy assembly. Many observational problems with present models
- *Must measure thermalization efficiency in Si (XQC) & sapphire (CRESST) - low $m_X$ boundary not robust until then.*

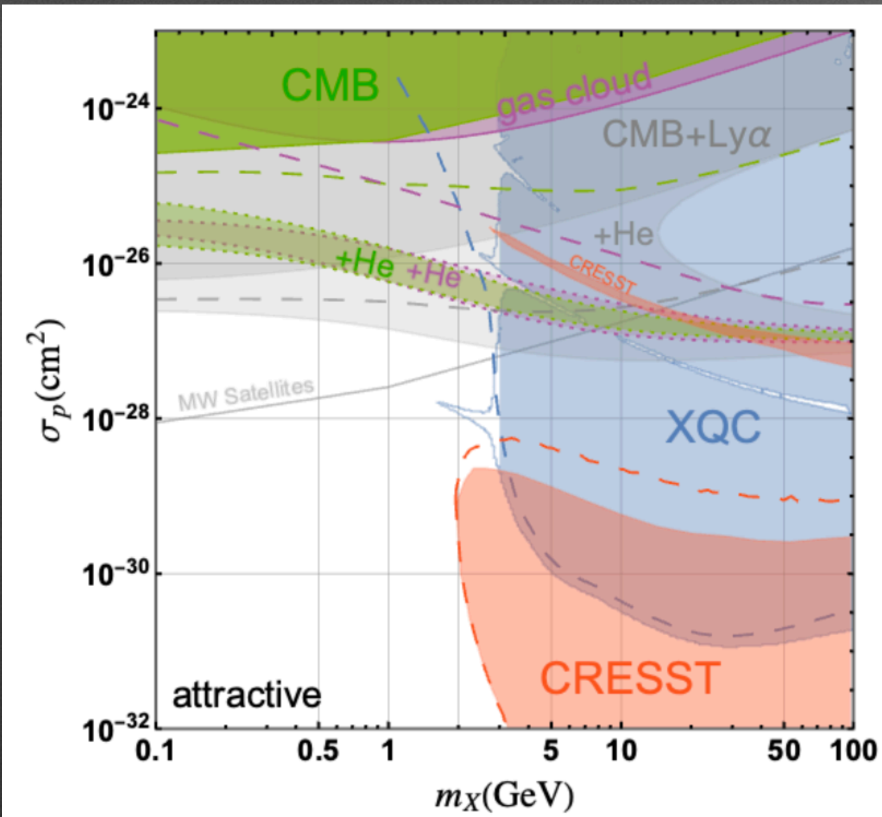
Parametric Plot: $\sigma_{He}$ & $\sigma_p$ vs α



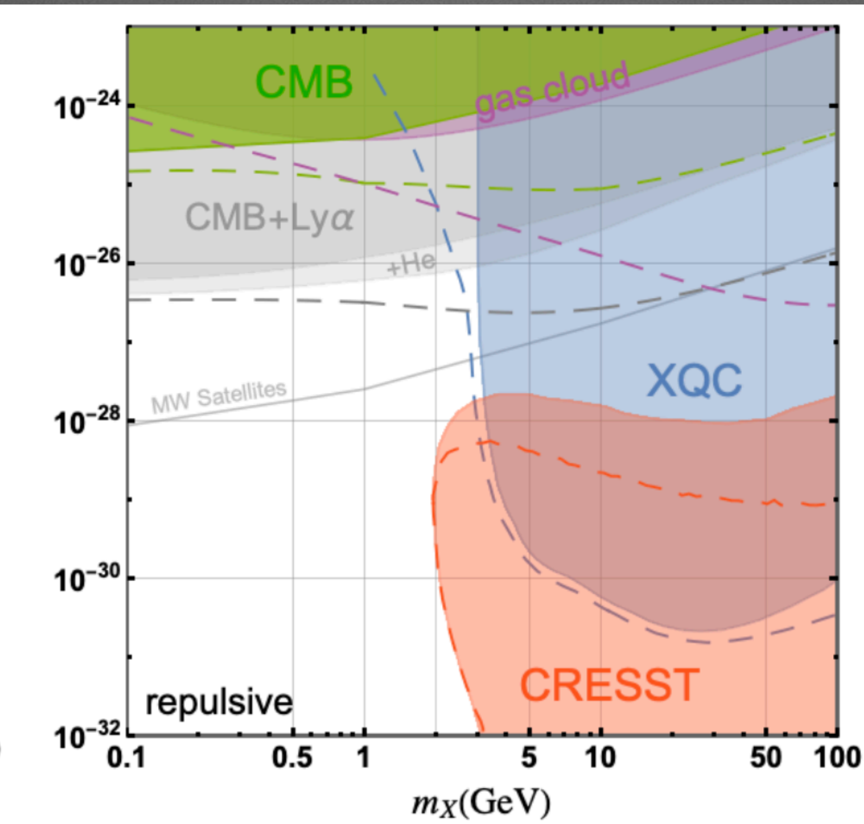
# Limits on $\sigma_p$

Xingchen Xu & GRF (arxiv: 2101.00142_v2)

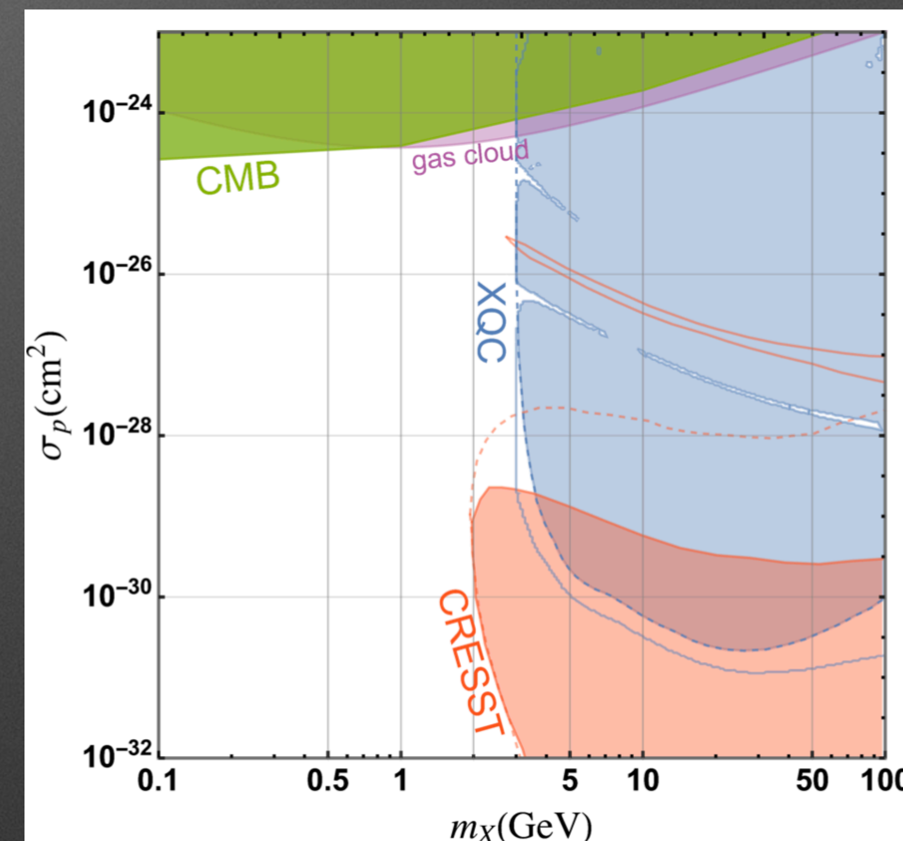
if attractive




if repulsive




if unknown




N.b., cross sections > $10^{-25}$cm$^2$ does not imply DM is extended or composite rather than pointlike (Capiello+). For attractive interactions, unitarity limit is

$$\sigma_{\rm res} = \frac{4\pi}{\mu^2 v^2} = 4.9 \times 10^{-21}\,\mathrm{cm}^2 \left(\frac{\mathrm{GeV}}{\mu}\frac{10^{-3}c}{v}\right)^2$$

# Earth's Dark Matter Atmosphere

D. Neufeld, GRF, C. McKee (ApJ 2018)

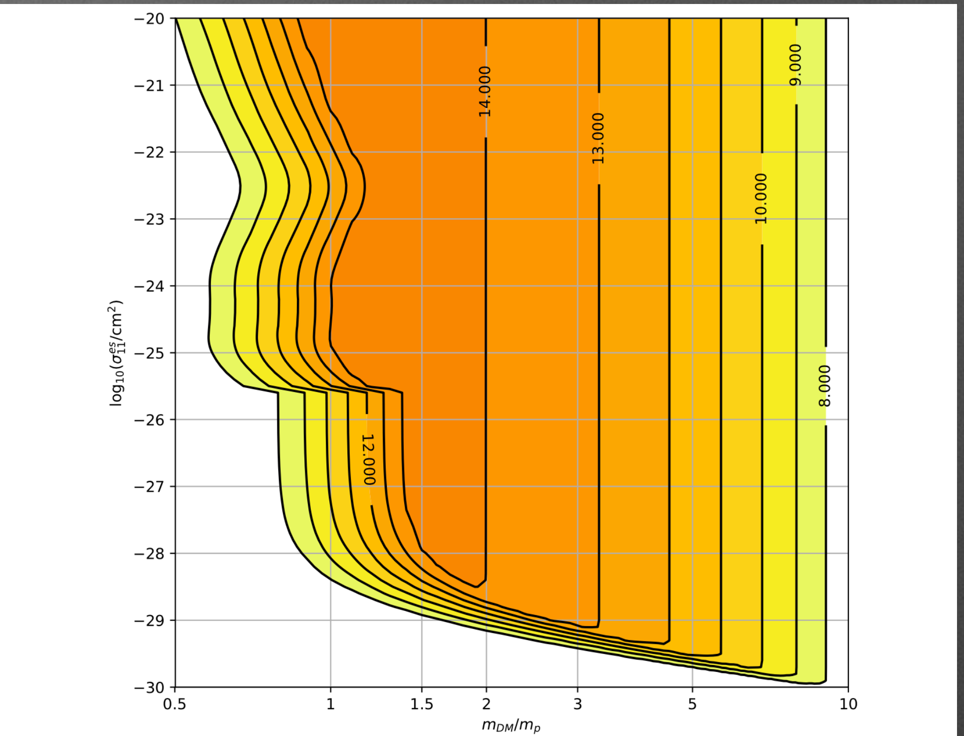
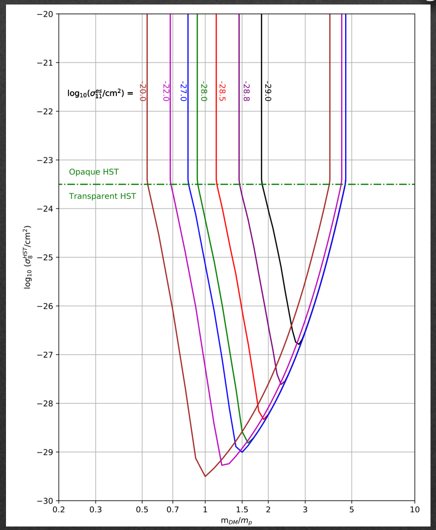
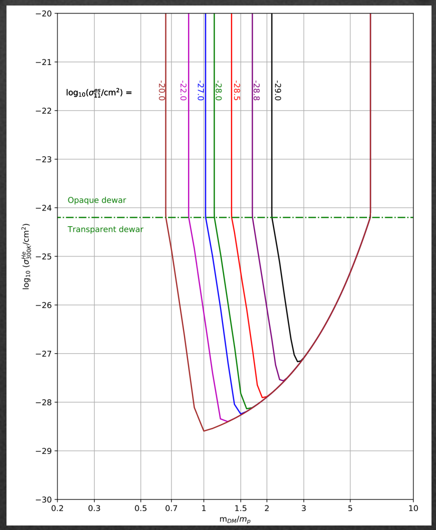
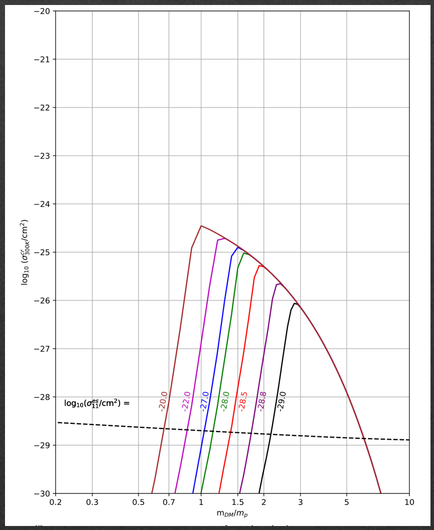


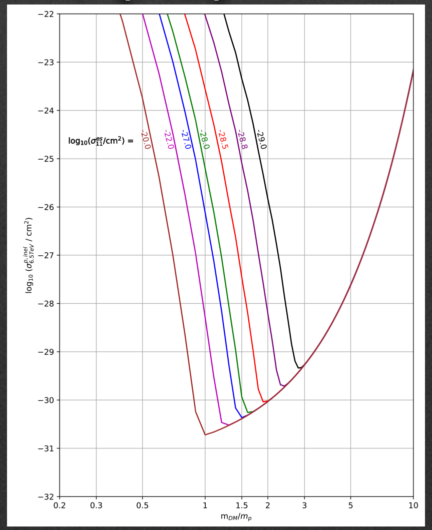

**Figure 6.** Number density of HIDM at the Earth's surface, $n_{DM}(R_\oplus)$, in the $m_{DM} - \sigma_{11}^{es}$ plane. Contours are labeled by $\log_{10}(n_{DM}/cm^{-3})$.

- **Take into account:**
  - Fraction captured
  - Jeans escape
  - thermospheric escape
  - density, composition & temperature profiles
- **Results:**
  - Max DM density at Earth surface ~$10^{14}cm^{-3}$, reached for $m_{DM}$ 1-2 GeV
  - constraints derived from limit on HST orbital decay, evaporation rate in cryogen dewars, thermal conductivity of Earth crust, LHC beam lifetime (HE)
  - But hard to interpret.



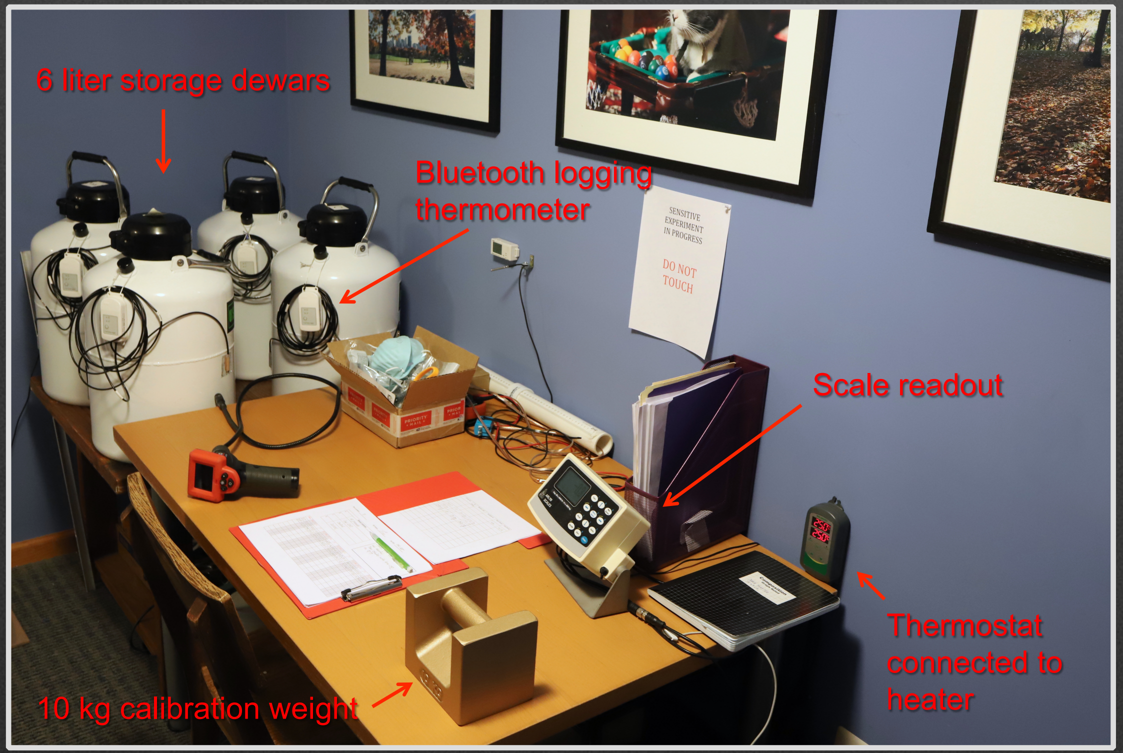



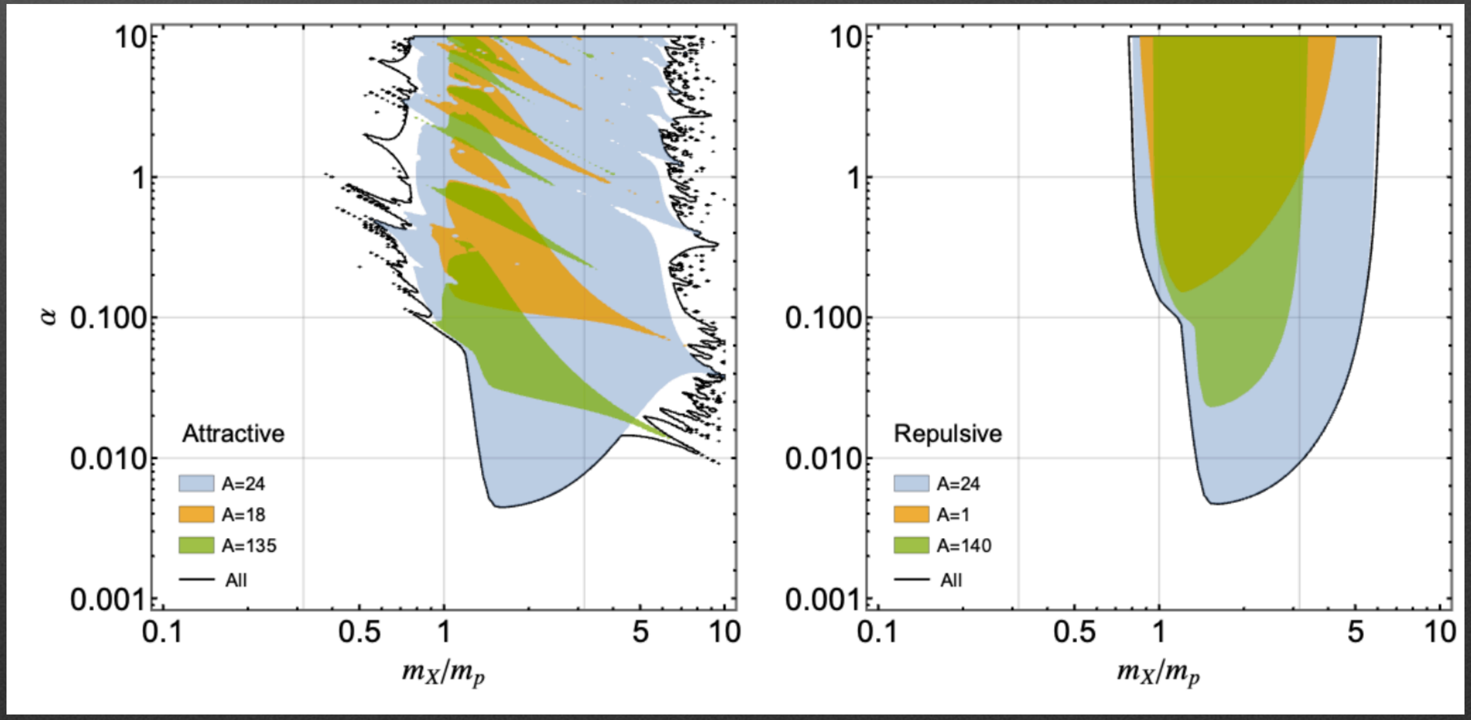


# Dewar Experimental Limits

Xingchen Xu & GRF (arxiv: 2112.00707 [hep-ph] )

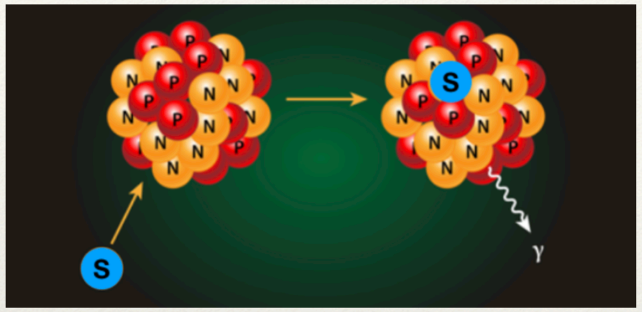
- Evaporation rate of liq. N in dewars with 74 different isotopes
  D. Neufeld, D. Brach-Neufeld (ApJ 2019)
- For each ($\alpha$,$m_X$) calculate $\sigma^{es}$ (crust & atm), then loss-rate-function, then $n_{DM}$. Then compare to NBN bound.

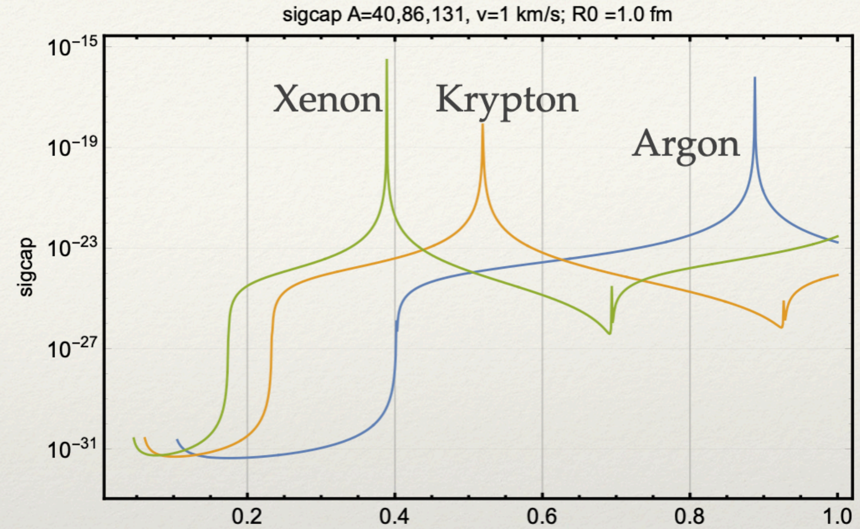


Xingchen Xu

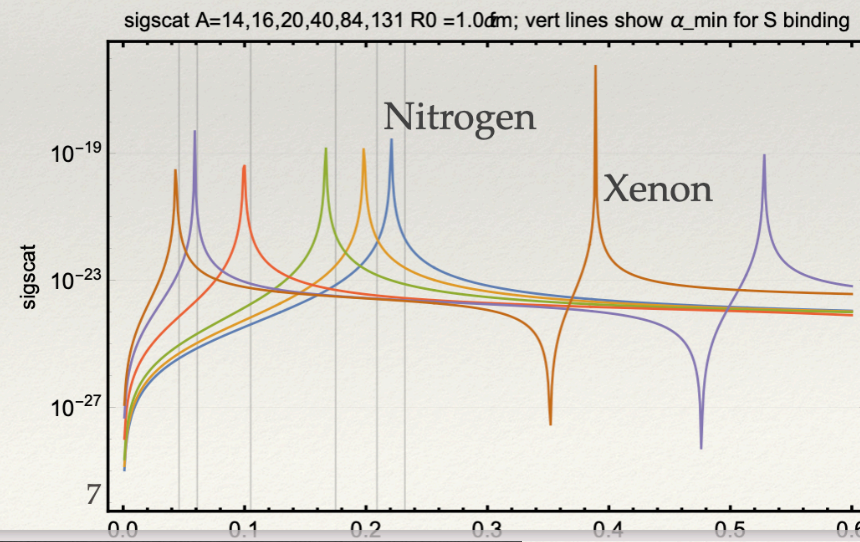
# Predictions for S-nucleus capture




S + A ➜ A(S) + γ

Analogous to neutron capture on nuclei - well-understood theoretically, non-trivial to implement




DM absorption length = √(interaction length x capture length)

- **Helium does not bind DM**

(otherwise we'd have "4+DM"He )

➜ upper limit on **α**

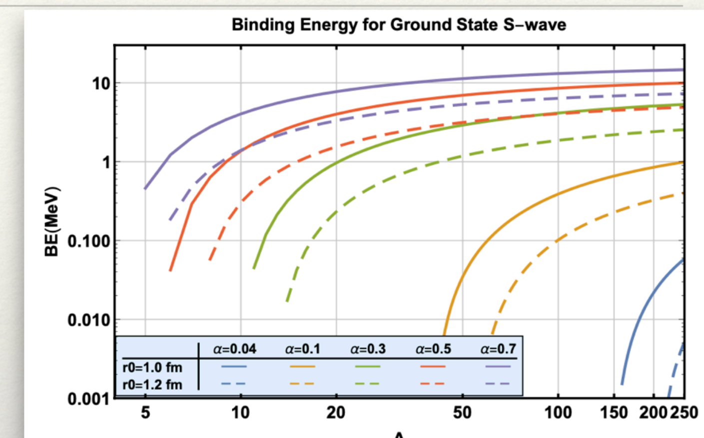
- **Lab search underway**

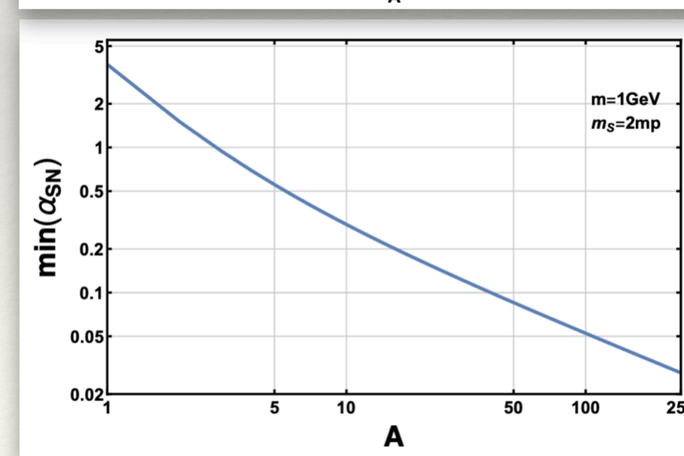
# … nuclei bind depends on **α**

For **α** ≳ 0.2, $^{16}O(S)$ can form

For **α** ≲ 0.1, only A ≳ 40 bind

Have to consider all options…



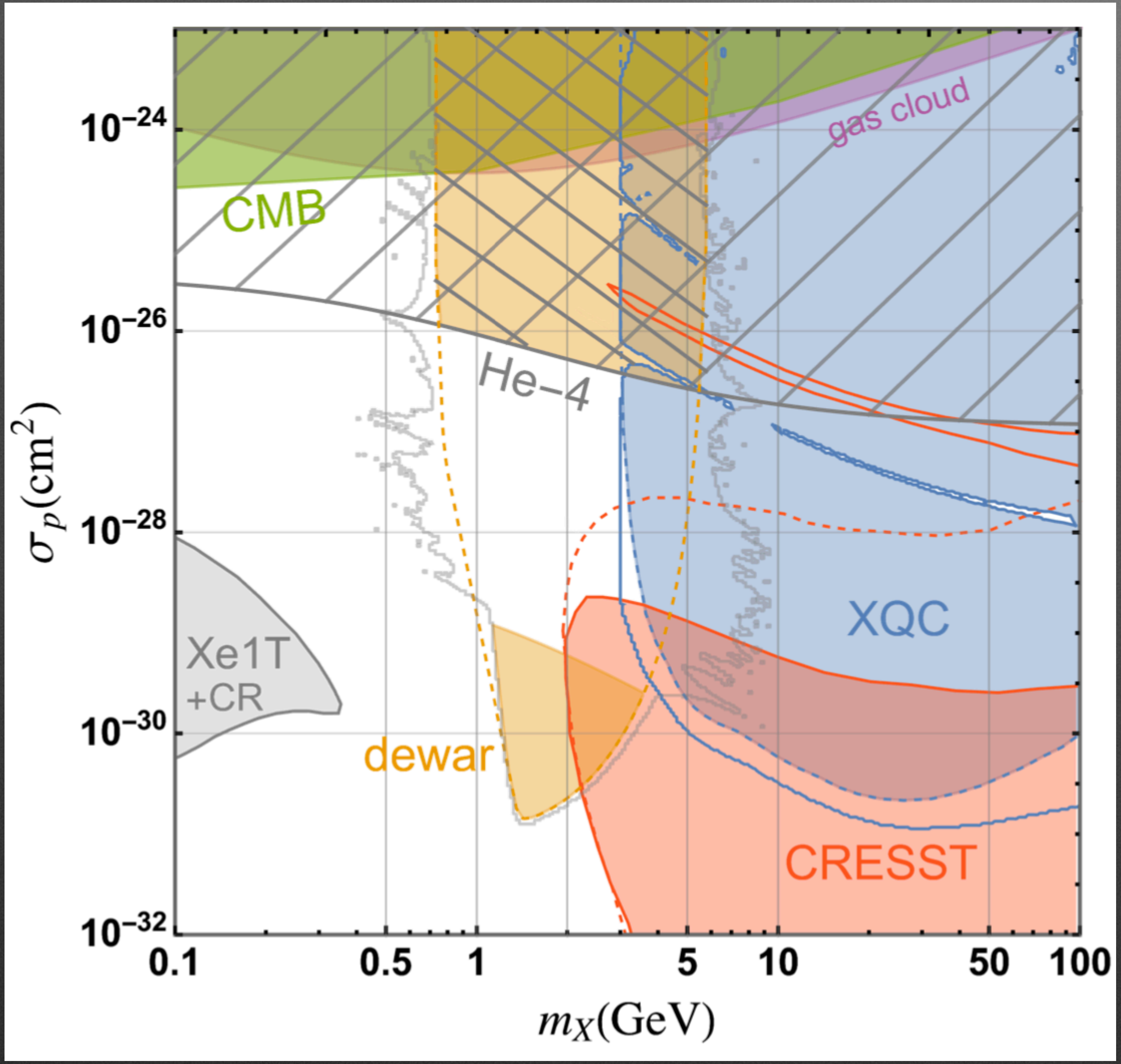






G. Farrar, Astro-Dark 2021

# Final Exclusion for ~ GeV DM

Xingchen Xu & GRF (arxiv: 2101.00142 & 2112.00707)




- Big improvements, but the most interesting parameter space for Sexaquark matter is still unconstrained
- Need to explore and constrain attractive interactions — search for exotic isotopes
- N.b., cross section up to un

# Sexaquark Dark Matter

## How sexaquarks interact

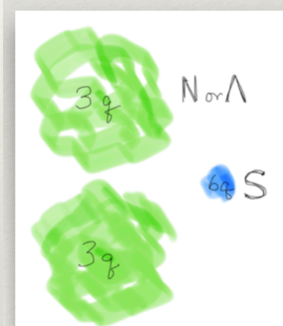
- No EM interactions (Q=0, no dipole moment)
- QCD flavor singlet.
  - Known mediator (not pion!)

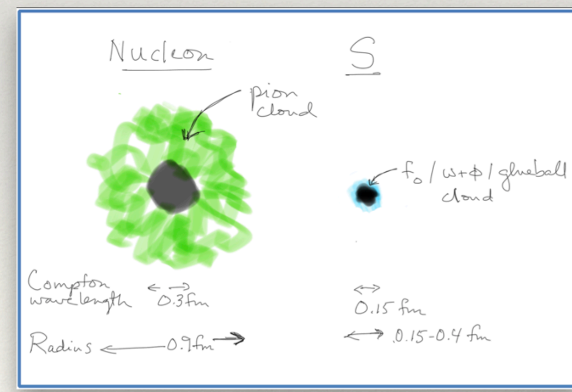
$$V(r) = \frac{\alpha}{r}\, e^{-r\, m_\phi}$$

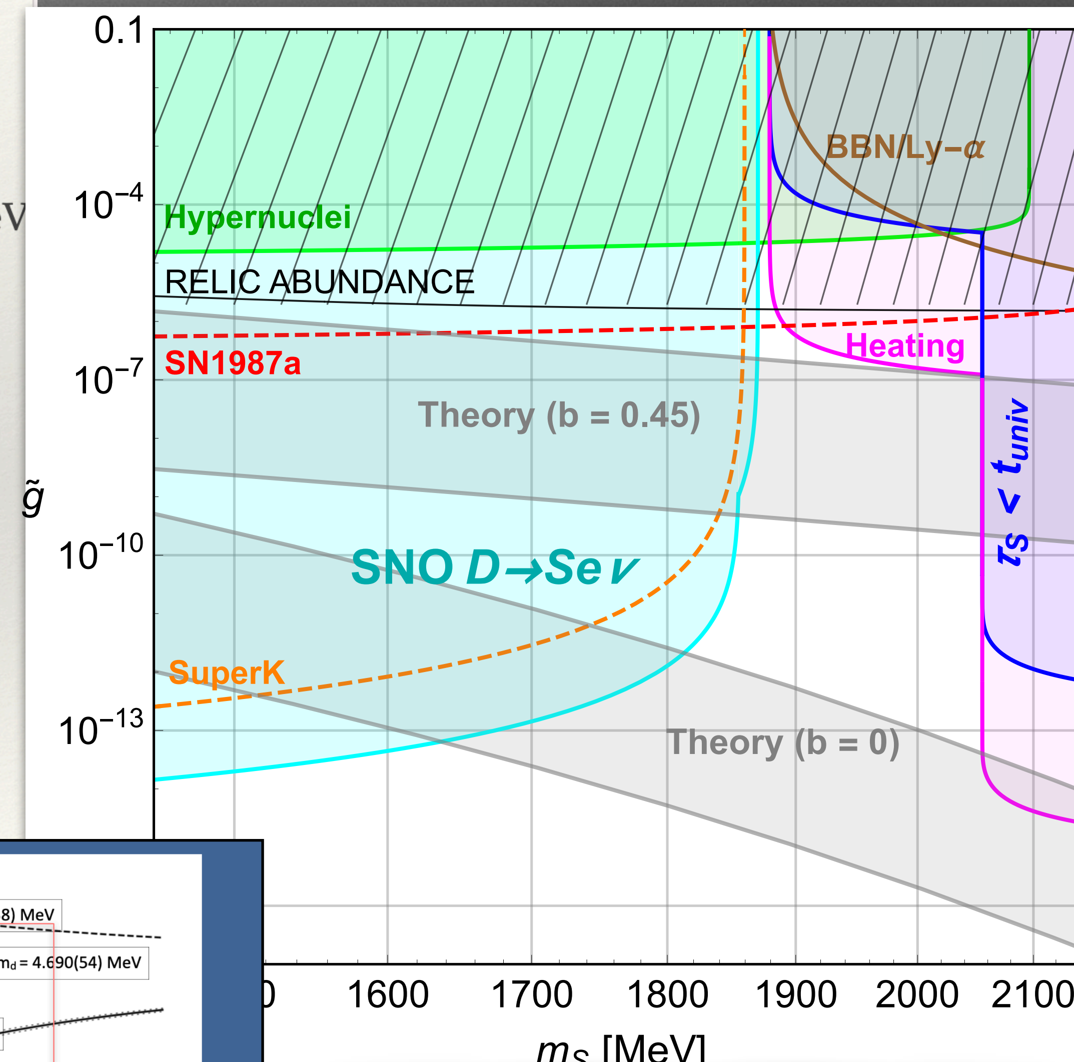
$\alpha$ = 0.01-1, $m_\phi$ = 1 GeV

  - Hard to break up if small overlap or large energy barrier

- S=uuddss
  - Neutral, stable, $m_S \approx 2\, m_p$
- Correct DM abundance
  - Would have escaped detection in accelerator experiments
  - Consistent with direct&indirect detection, astrophysics & cosmology limits



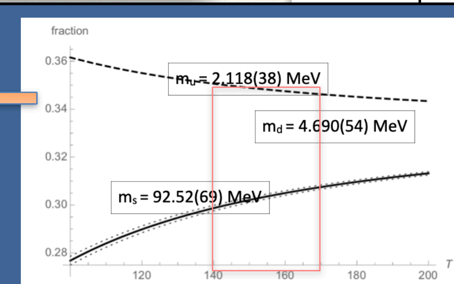

## Constraints on S breakup amplitude

Zihui Wang + GF in prep

$$\frac{\Omega_{DM}}{\Omega_b} \triangleq \frac{y_b\, \kappa_s\, 3 f_s}{1 - \kappa_s\, 3 f_s}$$

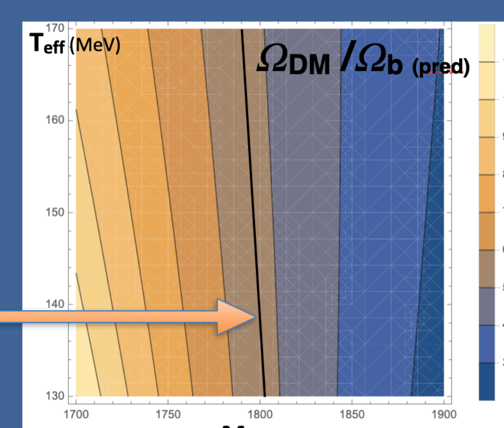
$$\kappa_s(m_S, T) = \frac{1}{1 + (r_{\Lambda,\Lambda} + r_{\Lambda,\Sigma} + 2 r_{\Sigma,\Sigma} + 2 r_{N,\Xi})}$$

$$r_{1,2} \equiv \exp[-(m_1 + m_2 - m_S)/T]$$




$\Omega_{DM}$ / $\Omega_b$ (pred) = 3-10

$\Omega_{DM}$ / $\Omega_b$ (obs) = 5.3 ± 0.1




## DM relic density determined by quark masses + stat mech

GF1805.03723