Stable Sexaquark as Dark Matter

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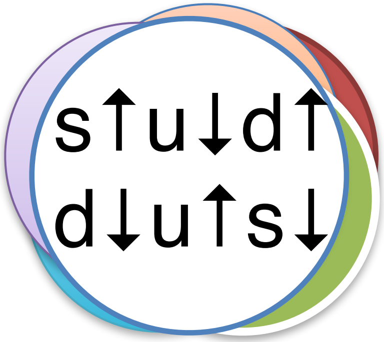
seminar LPTHE, Dec. 1, 2017

Unique among multi-quark states:

Fermi statistics is compatible with a
totally symmetric spatial wave function

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
m ~ 1.7-2 GeV



S

(Most-Attractive Channel)^3 :

singlet in:
- color
- flavor
- spin

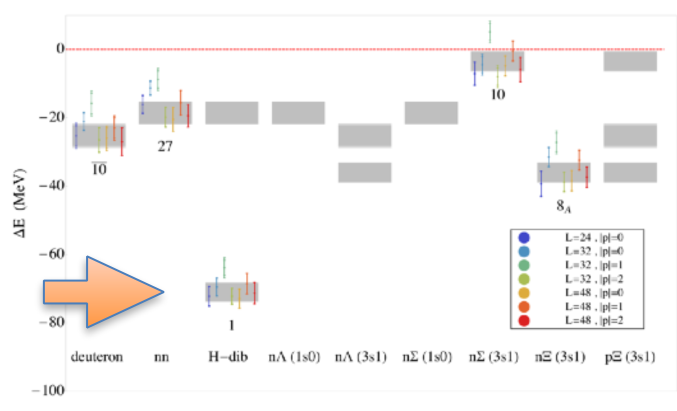
totally Symmetric in space

Mass of S

- **Options for stability** $(\tau > \tau_{\text{Univ}})$
  - $\mathbf{M_S < 2\, m_p + 2\, m_e}$ = 1877.6 MeV ➜ **absolutely stable**
  - $M_S < m_p + m_e + m_\Lambda$ = 2054.5 MeV ➜ $\Gamma \sim G_F^2$ x (wave function overlap)^2

  ➜ lifetime ~10^{27} yr.
- **Is $\mathbf{M_S}$ < 1.7-2 GeV reasonable?**
  - Hyperfine attraction ⇒ $M_S < 2\, m_\Lambda$ = 2230 MeV (Jaffe, 1977) (Most-Attractive Channel)^3
  - Constituent quark model unreliable/inapplicable
    - m_π = 135, 140 MeV; $m_{\eta'}$ = 958 MeV (*not 600 MeV*)
    - Chiral symmetry breaking not necessary for mass of S (unlike baryons)
    - π K K: same quark content and total mass 1131 MeV
    - Only 16% (10%) binding for $M_S < 2\, m_p$ $(m_p + m_\Lambda)$
- **Lattice predicts binding (Beane+13)**
- **Experiments exclude decaying S**

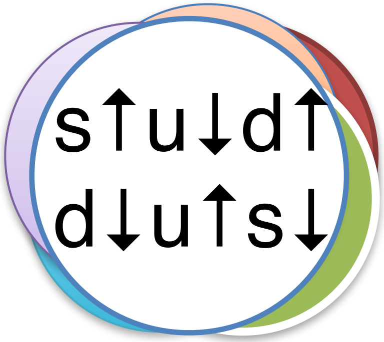
  => it must be STABLE ! ;-)



Stable Sexaquark

Same quark content as H-dibaryon (Jaffe 1977), but different physics: not a loosely bound di-Λ!

Deeply bound: **$m_S \sim 2\, m_p$ and stable** (or $\tau >> \tau_{\mathrm{Univ}}$)



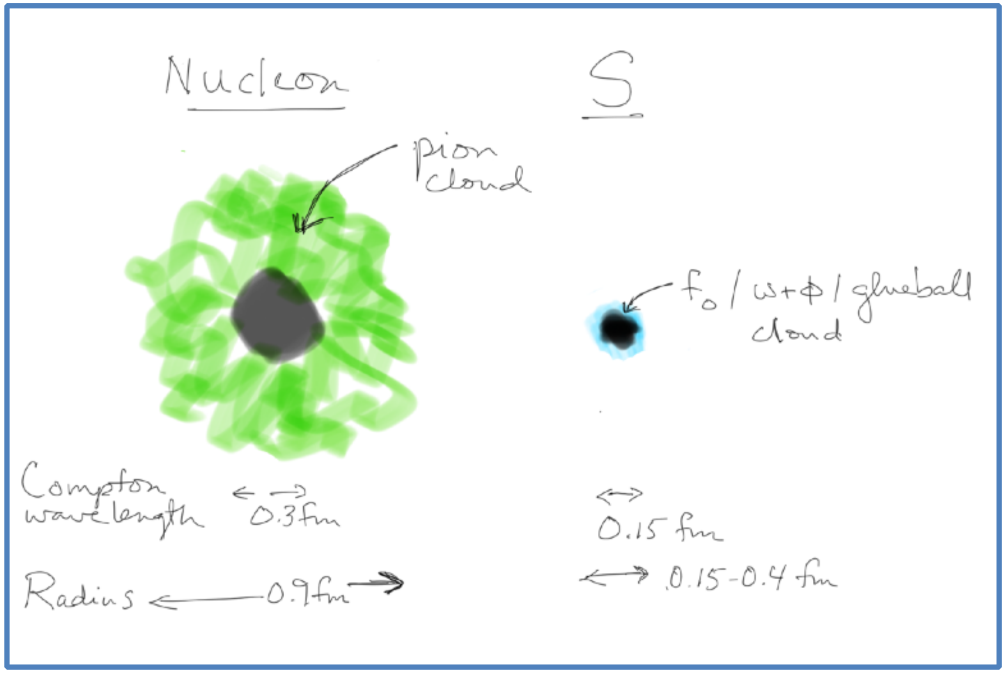
s↑u↓d↑
d↓u↑s↓

S

6-quark, Q=0, B=2
Spin-0, scalar
Flavor singlet
m ~ 1.7-2 GeV

Crucial features:

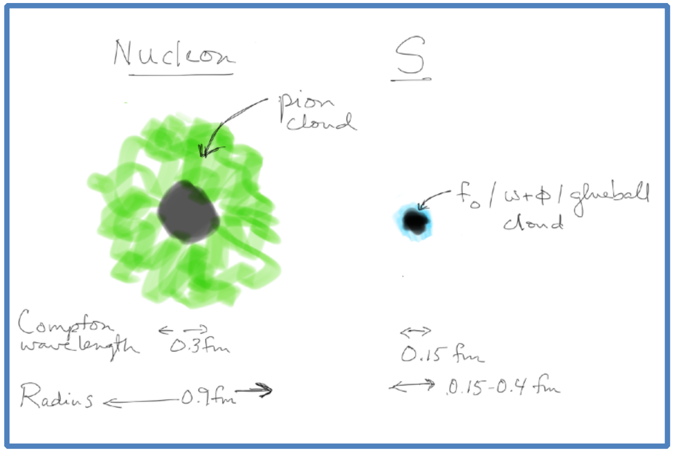
S does not couple to pions and is much smaller than usual hadrons (proton, pion,…)



Structure of the S: $u_\uparrow u_\downarrow d_\uparrow d_\downarrow s_\uparrow s_\downarrow$

- Flavor SU(3) singlet ⇒
  - *no coupling to SU(3) octets π, ρ*
  - ***No pion cloud***
- No pion cloud ⇒
  - $r_S \sim$ Compton wavelength **~ *0.15 fm*** *(compare $r_p = 0.9$ fm)*
  - ***S does not bind to nuclei*** *(no exotic isotopes)*

  "Non-binding of Flavor-Singlet Hadrons to Nuclei", GRF and G. Zaharijas Phys. Lett. B.559: 223-228, 2003.



- Couples to f_0 , glueball , SU(3) singlet ω-φ
  - ***$r_S \sim$ 0.15 - 0.4 fm*** depending on strength of f_0 coupling
  - $\sigma_{SN} \sim$ 5 to 20 mb (at v/c ~ 1 ; may grow as v/c → 0, as σ_{NN} does)

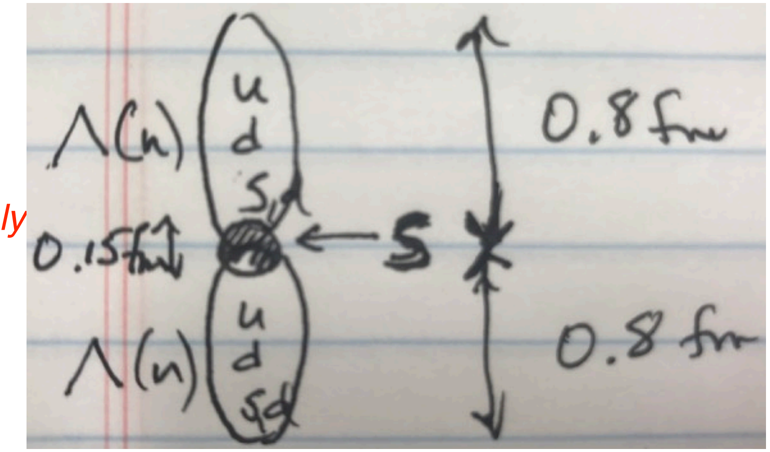
"Nucleon and Nuclear Transitions of the H dibaryon", GRF and G. Zaharijas. Phys. Rev. D70:014008,2004.

⇒ ***Small wave function overlap with 2 nucleons***

- not created in hypernuclear expts
- Amp (NN -> S) very suppressed (small wavefunction overlap)

⇒ *Nuclei and neutron stars are stable;*

- *S lifetime can be > age of Universe even if not absolutely stable (doubly-weak decay & wfn overlap)*

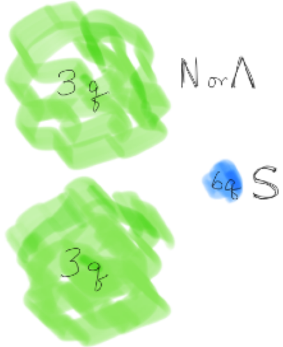


- Scalar (spin-0, even parity)

"A STABLE H DIBARYON: DARK MATTER CANDIDATE WITHIN QCD?" Int. J. Theor. Phys. 42:1211-1218, 2003. Also in *Minneapolis 2002, Continuous advances in QCD* 582-590.

S has not been discovered because it is <u>elusive</u>

- **Many negative searches, but all are inapplicable.** They either:
  - looked for H-dibaryon through decays (but S is stable)
  - restricted to mass > 2 GeV (but $m_S < 2$ GeV)
  - required fast production in S=-2 hypernuclei (but small overlap with baryons)



- **Wavefunction overlap with baryons is very small.** Extremely rare fluctuation required for S ⇔ ΛΛ; S⇔NN is G_F^2 smaller =>
  - nuclei are stable ($\tau > 10^{29}$ yr)
  - hard to produce in fixed target experiments

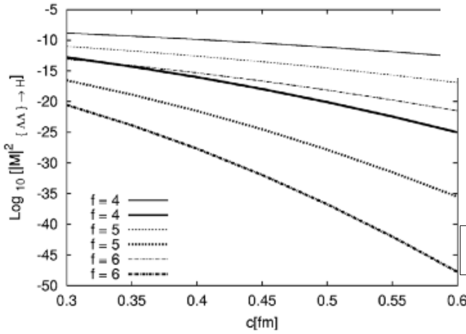


FIG. 1. Log_{10} of $|\mathcal{M}|^2_{\Lambda\Lambda\to H}$ versus hard core radius in femtometers, for ratio $f = R_N/R_H$ and two values of the Isgur-Karl oscillator parameter: $\alpha_B = 0.406$ GeV (thick lines) and $\alpha_B = 0.221$ GeV (thin lines).

GRF+G.Zaharijas 2004

- **S is similar to** (much more copious) **neutrons**

- **Promising accelerator detection strategies**
  - **Apparent lack of baryon number and strangeness conservation:**
    - $\Delta B = \pm 2$ with $\Delta S = \mp 2$
  - **Reconstruct missing mass, e.g.:**
    - $\Upsilon \to \Lambda\,\Lambda\,\overline{S}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$

Experimental Searches

- Require M > 2 GeV:
    - Gufstafson+ FNAL1976 : Beam-dump + tof *Limit on production of neutral stable strongly interacting particle with mass > 2 GeV.*
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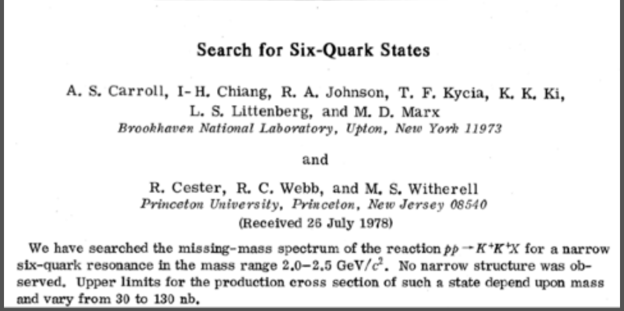

Search for Six-Quark States

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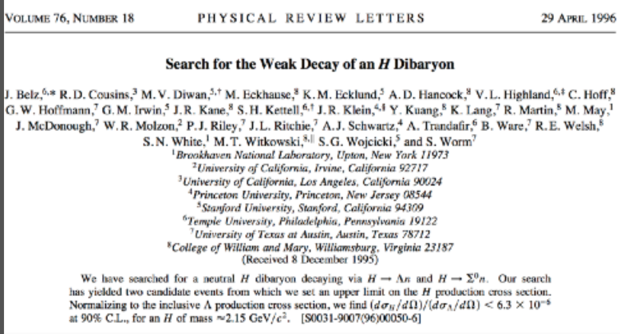

VOLUME 76, NUMBER 18 PHYSICAL REVIEW LETTERS 29 APRIL 1996

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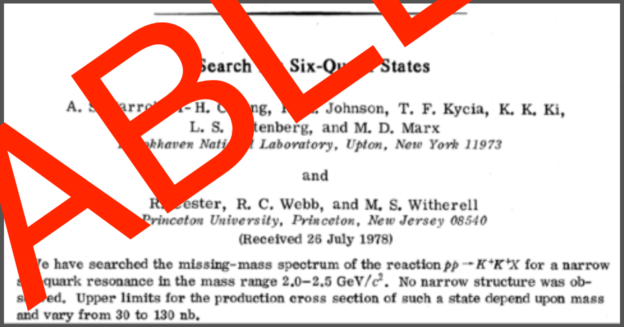

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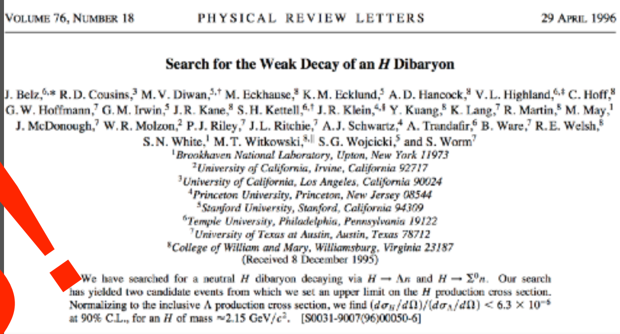

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NOT APPLICABLE to S!

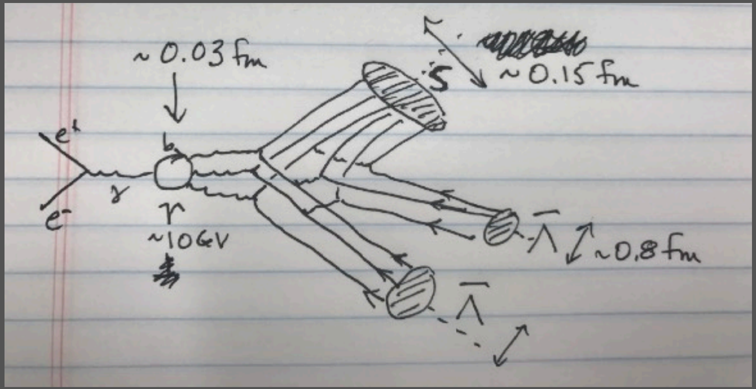
Discovery Strategy

- Apparent lack of B and S conservation:
  - $\boldsymbol{\Delta B = \pm 2 \quad + \quad \Delta S = \mp 2}$
- Reconstruct missing mass, e.g.:
  - $\boldsymbol{\Upsilon \rightarrow \Lambda\,\Lambda\,\bar{S}}$ (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$
  - $K^- p \rightarrow \bar{\Lambda}\, S$ (+ pions) $M_S^2 = (p_{K-} + p_p - p_{\bar{\Lambda}} - \sum p_{\pi_i})^2$
  - $\boldsymbol{\bar{S}} + p,n \rightarrow \bar{\Lambda} + K^{+,0}$ $M_S^2 = (p_K + p_{\bar{\Lambda}} - p_p)^2$

    or $\bar{\Xi}^{+,0} + \pi$

Υ -> $\Lambda\ \Lambda\ \bar{S}$ & $\bar{\Lambda}\ \bar{\Lambda}\ S$

(+ pions)



- **Υ is *localized* source of ggg**

  ⇒ production of S is (relatively) enhanced

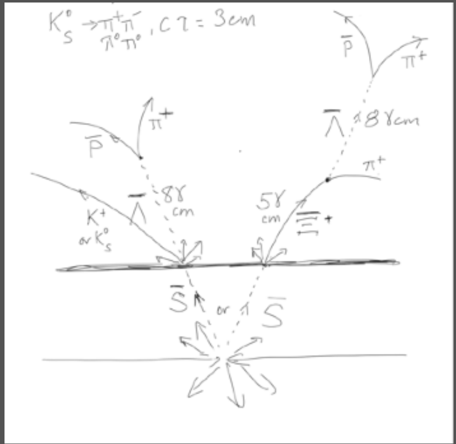
- Many x 10^8 events collected (CLEO, Babar, Belle)
  - detectors pretty hermetic, have good mass resolution, O(10 MeV)
  - Λ decays quickly to $p\pi^-$ so easy to ID. $c\tau$ = 8 cm
- **Can MEASURE m_S via missing mass**
- ***Very clean***
  - Main bkg is $K_S\, K_S\, K_L\, K_L$ (+ pions)
    - K_S's mis-ID'd as Λ's and K_L's escaping before decay : *negligible for Belle*
      - rare and can model accurately
      - $K_S\, K_S\, K_L\, K_L$ (+ pions) ***is measurable***, from $K^+\, K^+\, K^-\, K^-$ (+ pions)
  - "Conspiracy" of missed particles producing $\Delta B = \pm 2$, $\Delta S = \mp 2$ very hard

Background does not have narrow peak in missing mass!

Other search options

besides Upsilon decay

- Production in accelerator expts
    - fixed target: too low production rate due to small wfn overlap
    - LHC strategies
        - statistical examination of correlation between $\Delta B = \pm 2$, $\Delta S = \mp 2$
        - 2nd exponential in scattering length distribution of n-like interactions, due to S
        - $\bar{S}$ annihilation in tracker, followed by $\bar{\Xi}^{+,0} \rightarrow \bar{\Lambda}\, \pi^{+,0}$ ($c\tau = 5\gamma$ cm) $\bar{\Lambda} \rightarrow \bar{p}\, \pi^{+}$ (63%, $c\tau = 8\gamma$ cm)



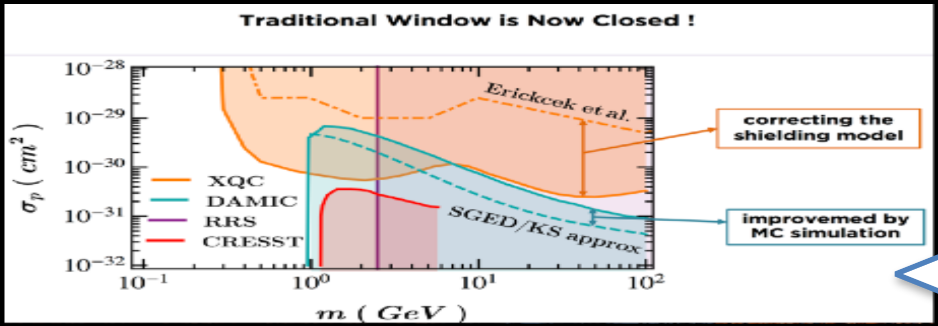
- Production at SuperK or SNOlab (nuclear decay) p n -> S e+ …

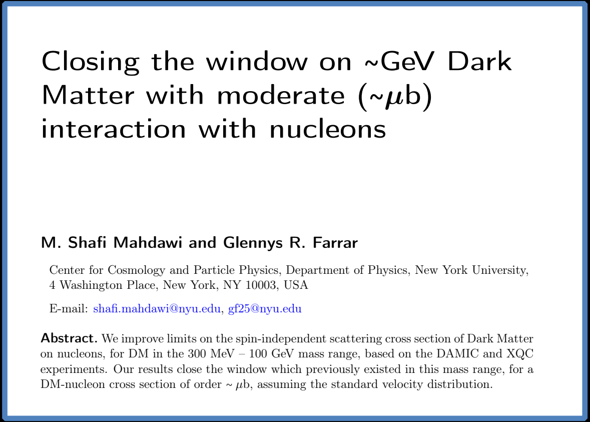
Conditions on QCD Dark Matter

- ✓ $\tau_{DM} > \tau_{Univ}$, cold, neutral
- ✓ primordial nucleosynthesis
- ✓ Particle must not be already excluded
  - accelerator searches
  - exotic isotopes
  - DM searches
  - indirect impacts (heating planets, helioseismology,…)
  - stability of nuclei
  - equation of state of neutron stars (and their stability)
- ✓ Correct relic density (for natural m_{DM} & $\boldsymbol{\sigma}_{f.o.}$)

Stable S as Dark Matter

10^{-26} - 10^{-25} cm^2





Closing the window on ~GeV Dark Matter with moderate (~μb) interaction with nucleons

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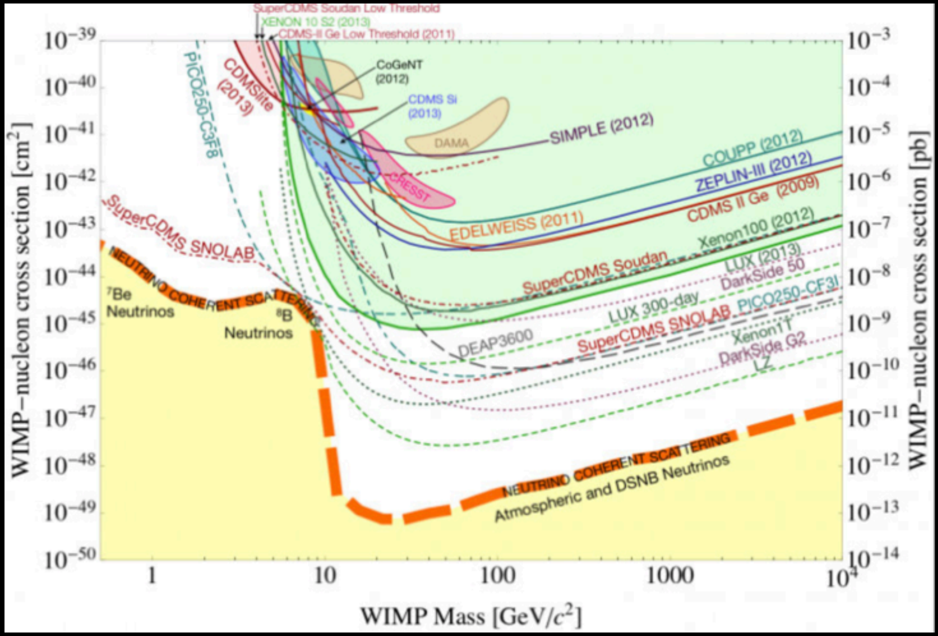
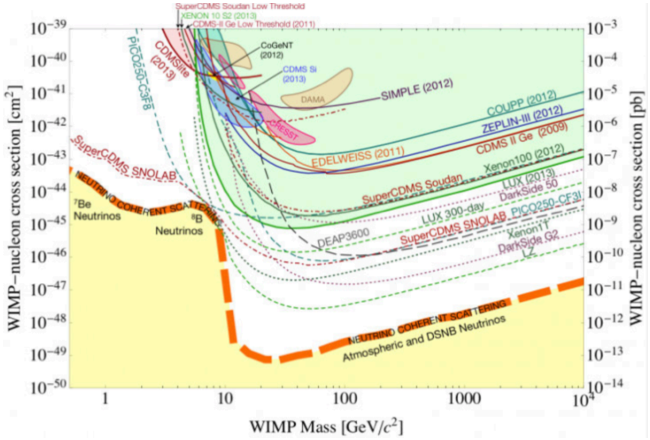
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order ~ μb, assuming the standard velocity distribution.

Shielded (e.g. underground) detectors are not sensitive

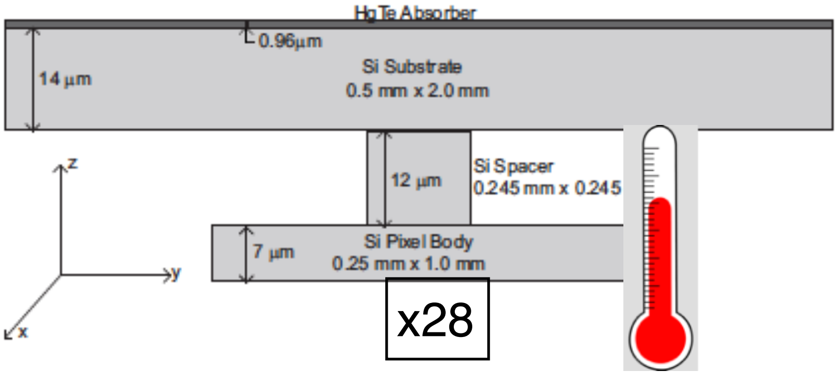


Directly Detecting the S

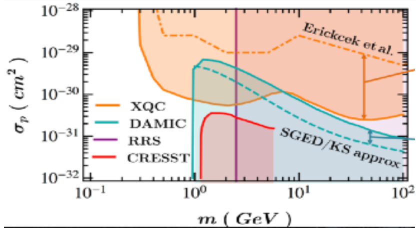
- ***Light, slow-moving, strongly interacting* DM is not visible in current detectors:**
  - $KE_{DM} = 500\ \mathrm{eV}\ (m_{DM} / 2\ m_p)\ \ v^2 / (220\ \mathrm{km/s})^2$
  - $\langle E_{deposit} \rangle / KE_{DM}$ = **0.12** for Si target
    = **0.02** for Hg target
    = **0.44** for H or He target
  - **Energy-loss length in Earth crust:** $\lambda = 2\ cm / \sigma_{10mb}$
  - **CRESST, Xenon1T, LUX, DAMIC are not sensitive**

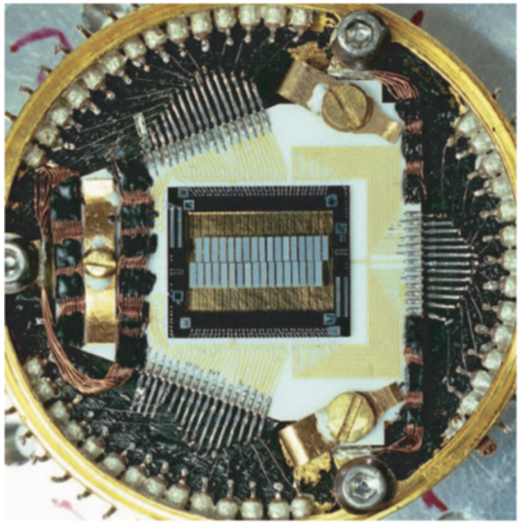


X-Ray Quantum Calorimeter (XQC)



- On sounding rocket, 200 km above earth
- Best limit for high x-secn (McCammon+02,Wandelt+02,GF+Zaharijas05, Erickcek+07, Mahdawi & GF 17)
    - sensitive to X-rays with E ≳ 29 eV
    - 100 sec flight, ~ 100 events
    - nuclear recoil => X-rays, which thermalize *(assumption)*





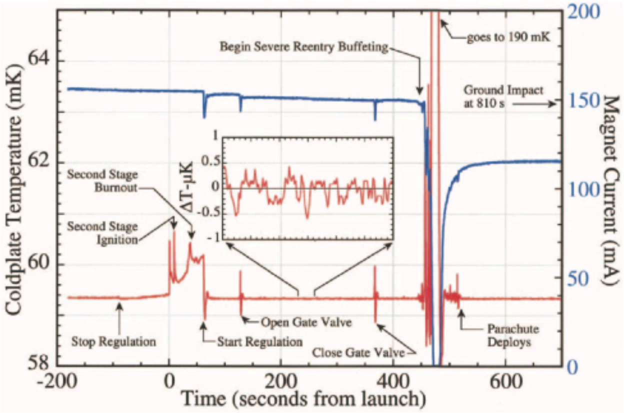


Fig. 7.—In-flight performance of the temperature control system, showing the coldplate temperature and magnet current. Temperature fluctuations during data taking are about 210 nK rms. The gate-valve motor is located on the vacuum jacket and caused the most serious thermal disturbance up to reentry. Accelerations during reentry exceeded 20 g with tumbling at ~1 Hz, introducing heat to the cold stage faster than it could be removed. Temperature regulation is recovered once tumbling stops, allowing calibration data to be obtained.

Calibrate with X-rays

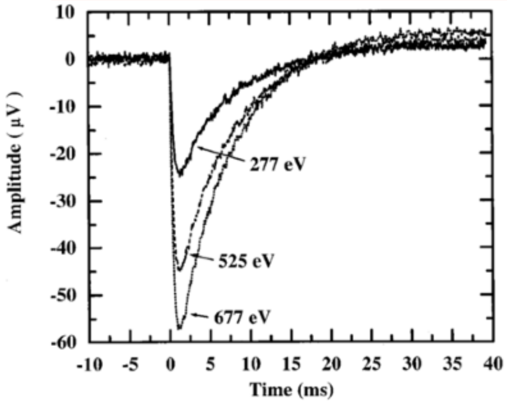


Fig. 8.—Unfiltered X-ray pulses from the gate-valve calibration source.

Challenge to Direct Detection of S

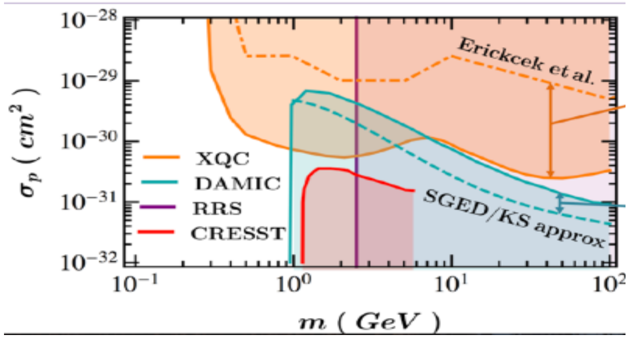
- **Taking XQC sensitivity at face value:**

  XQC above atmosphere is best. $E_{thresh} = 30$ eV

  (McCammon+02,Wandelt+02,GF+Zaharijas05, Erickcek+07, Mahdawi+GRF 2017)

  - Mahdawi+GRF 2017: ***$\sigma_{DM} < 10^{-29}$ cm² for standard velocity dispersion* — *SDM has $\sigma_{DM} \sim$ 10-100 mb***

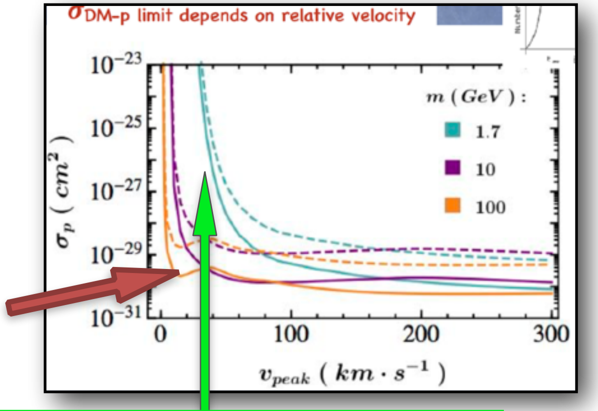
  - ***$v_{min,XQC} = 100$ km/s $(2 m_p / m_{DM})^{1/2}$***



- ***BUT:***

  - ***velocity distribution?***
    - ***(gas co-rotates, red vel ~ 10 km/s)***

  - ***does E_{rec} really thermalize?***



Co-rotation reduces SDM signal

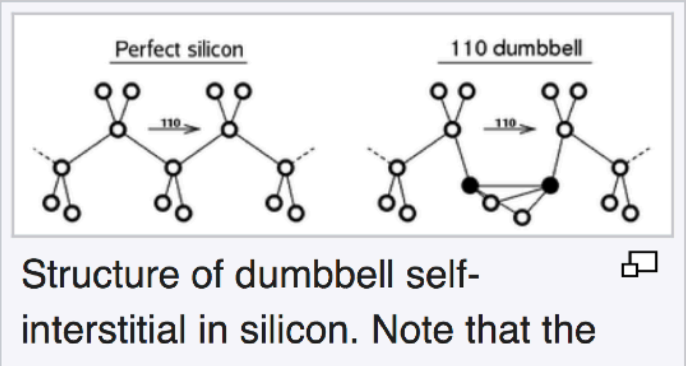
Closer look at XQC sensitivity

Silicon nucleus recoil: $KE_{max} \sim 500$ eV => $v_{max} \sim 20$ km/s $<< v_e$ =>

- atomic interaction is adiabatic =>
- negligible ionization.

Si atom moving in semiconductor crystal:

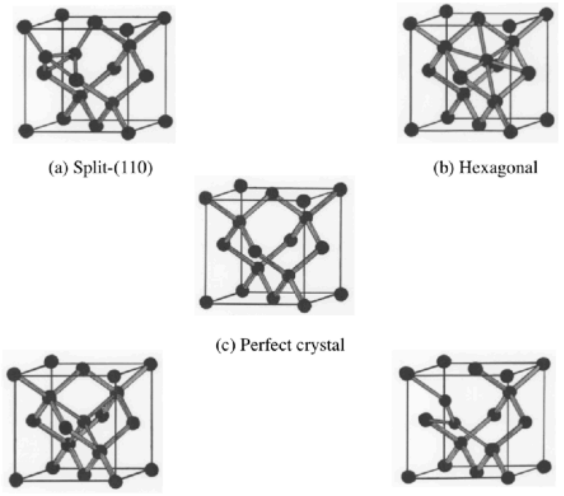
- rearranges covalent bonds
- produces interstitial defects
- 500eV atom produces Frenkel pairs (V+I)
  - $E_{Fp\_min} = 5$ eV
  - $E_{migration} \sim 0.1$ eV
- Cascade energy loss producing
  - $N \sim (KE_{rec} / 5$ eV$)$ Frenkel pairs,



Structure of dumbbell self-interstitial in silicon. Note that the

<~2% of KE_{rec} goes to thermalization

=> $KE_{rec,min} > 1.5$ keV => $KE_{DM,min} > 6$ keV => $v_{DM,min} > 300$ km/s



(a) Split-⟨110⟩

(b) Hexagonal

(c) Perfect crystal

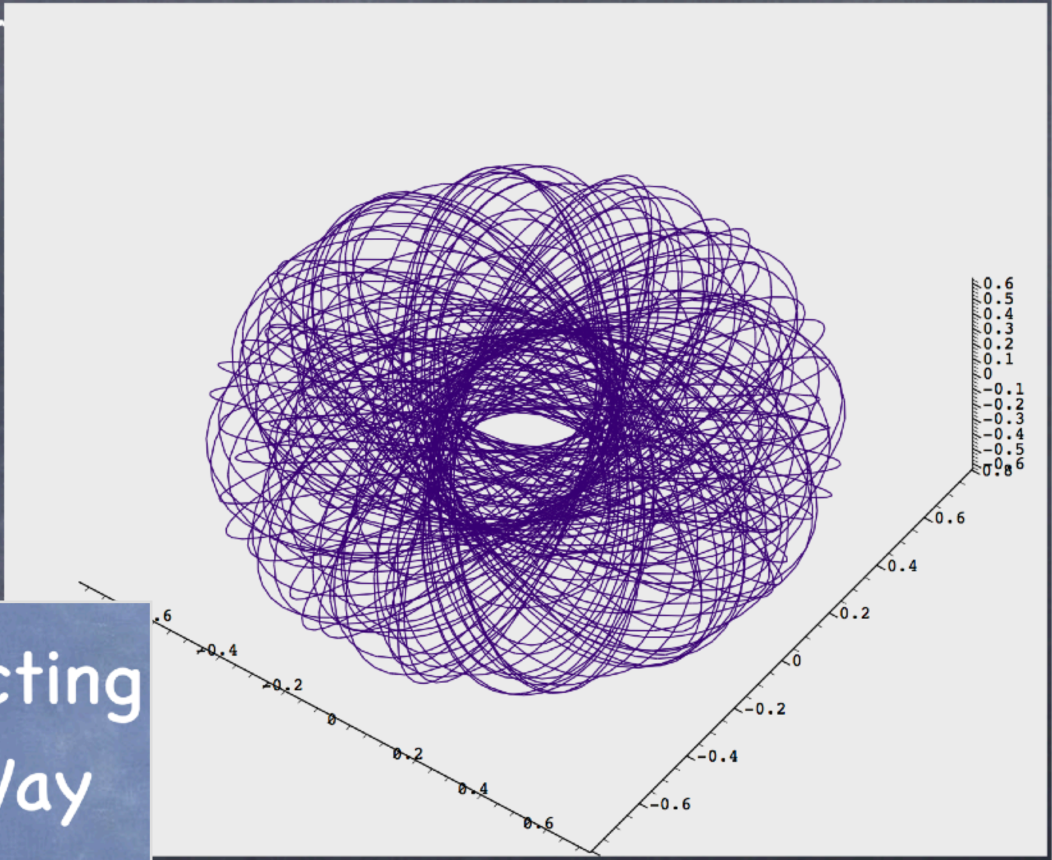
(d) Tetrahedral

(e) Concerted exchange

Figure 1. Illustrations of the split-⟨110⟩, hexagonal, and tetrahedral self-interstitial defects, together with the perfect crystal and the saddle point of Pandey's concerted exchange.

Schwarzchild Modelling

1. Choose a potential (NFW)
2. Follow an orbit in this potential

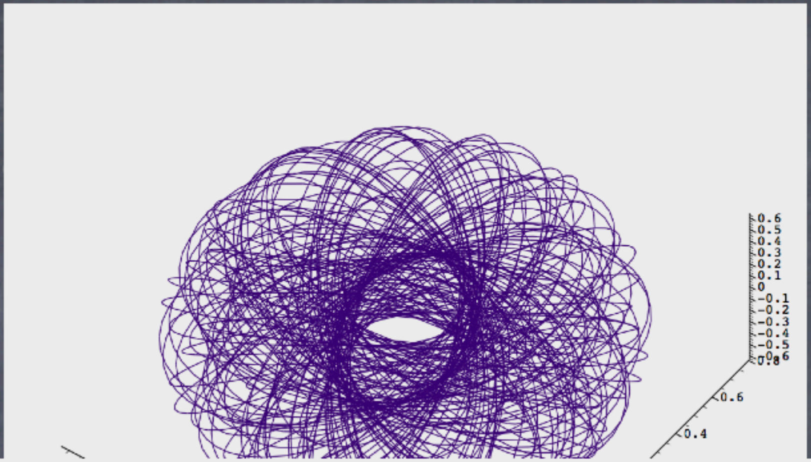


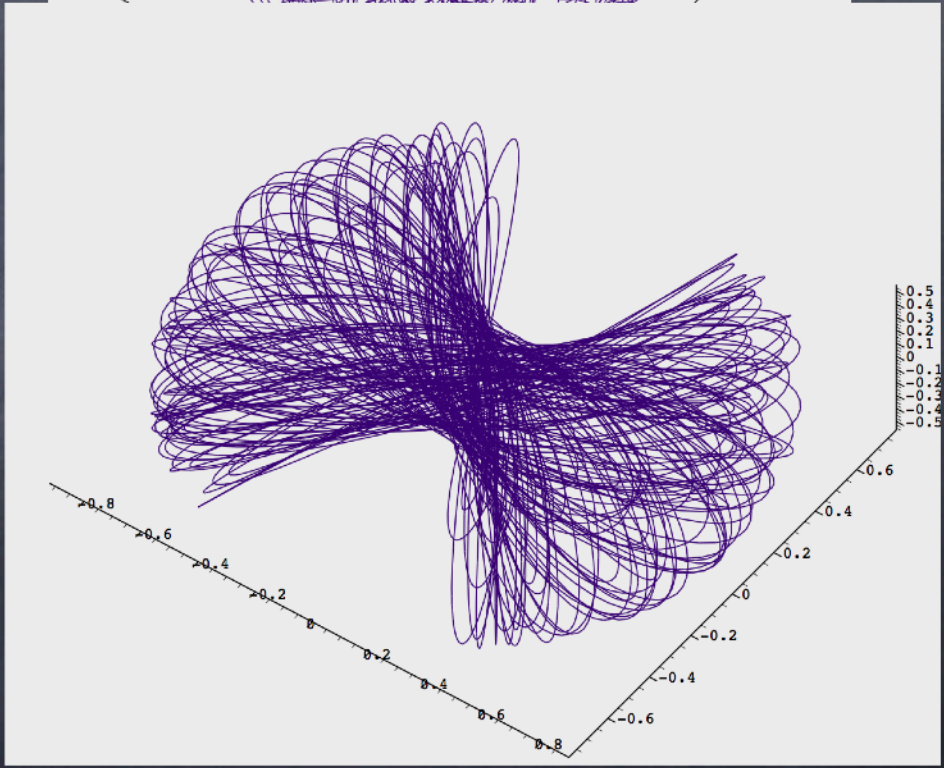
Simulations of DM interacting with gas in the Milky Way

(Jay) Digvijay Wadekar (NYU)
in collaboration with G. R. Farrar

Schwarzchil

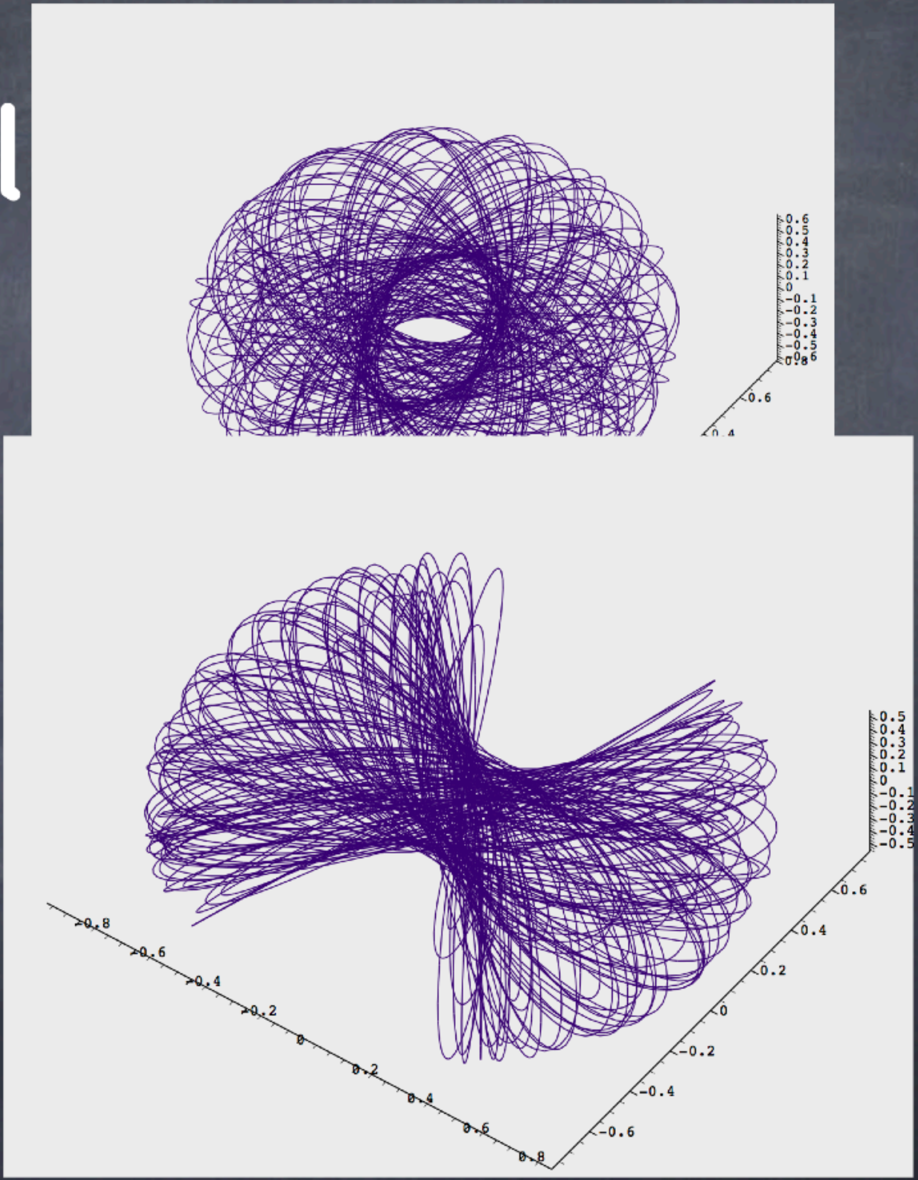
1. Choose a potential (NFW)
2. Follow an orbit in this potential
3. Generate a library of orbits





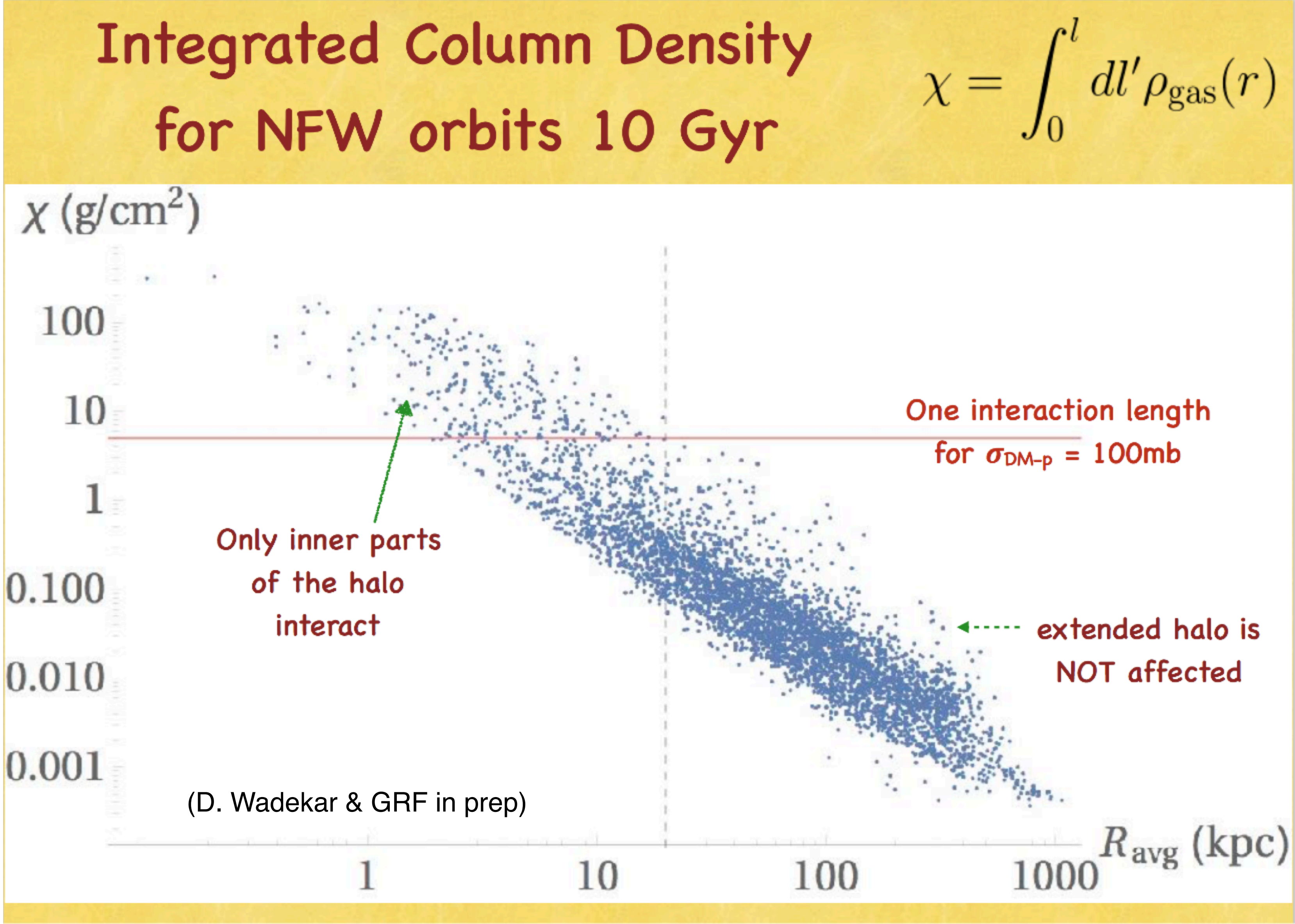
Schwarzchil

1. Choose a potential (NFW)
2. Follow an orbit in this potential
3. Generate a library of orbits
4. Weighted sum of orbits gives density corresponding to NFW



Dark Matter-Gas Scattering

$v_f \sim (2/3)^N \; v_i$ => only a few interactions are enough for co-rotation scenario to work



Integrated Column Density for NFW orbits 10 Gyr

$$\chi = \int_0^l dl' \rho_{\mathrm{gas}}(r)$$

One interaction length for $\sigma_{\mathrm{DM-p}}$ = 100mb

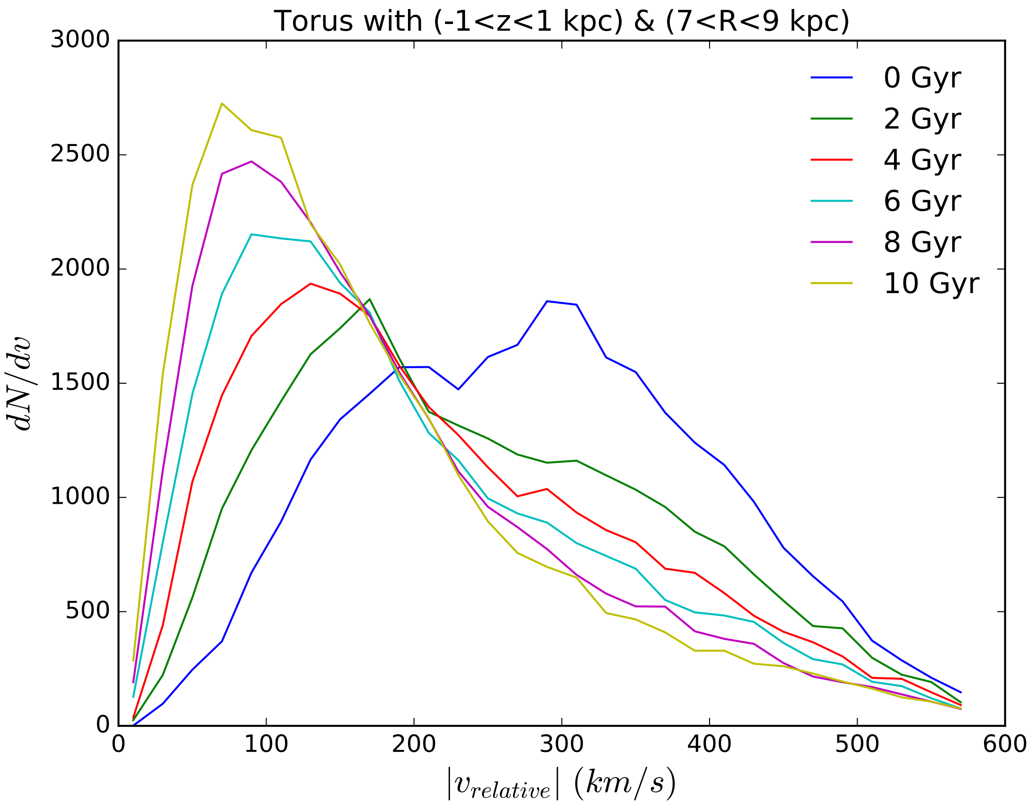
Only inner parts of the halo interact

extended halo is NOT affected

(D. Wadekar & GRF in prep)

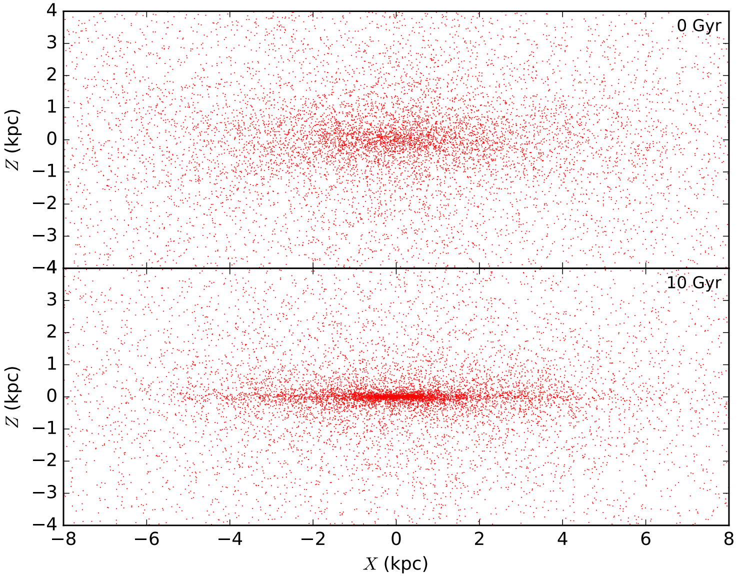
- Select a DM particle and follow its orbit
- Monte-carlo choose its scattering point on gas
- Isotropically scatter -> kinematics of new orbit

(D. Wadekar & GRF in prep)


Torus with (-1<z<1 kpc) & (7<R<9 kpc)

Highly idealized analysis:

- static potential & gas
- actually grows by accretion
- c.f. Bruch-Read+
- proof of concept, shows cross-section needed is reasonable.



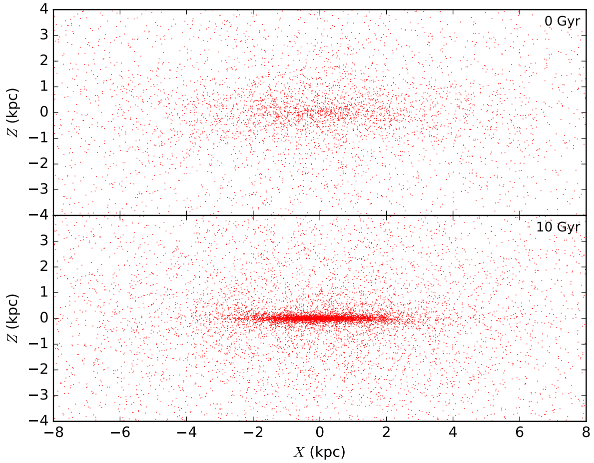
Tends to Co-rotation.

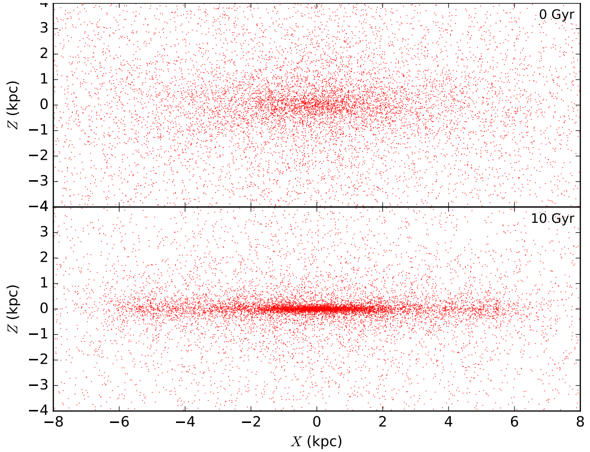
For large enough σ, forms disk

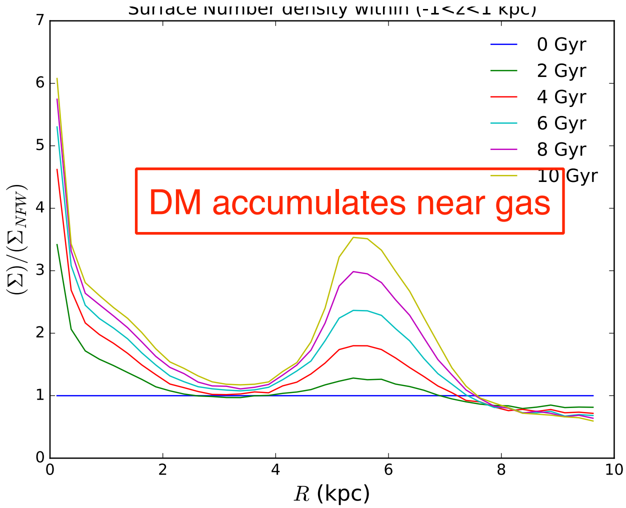
DM distribution follows gas?

in realistic galaxies, gas is inhomogeneous ⇒

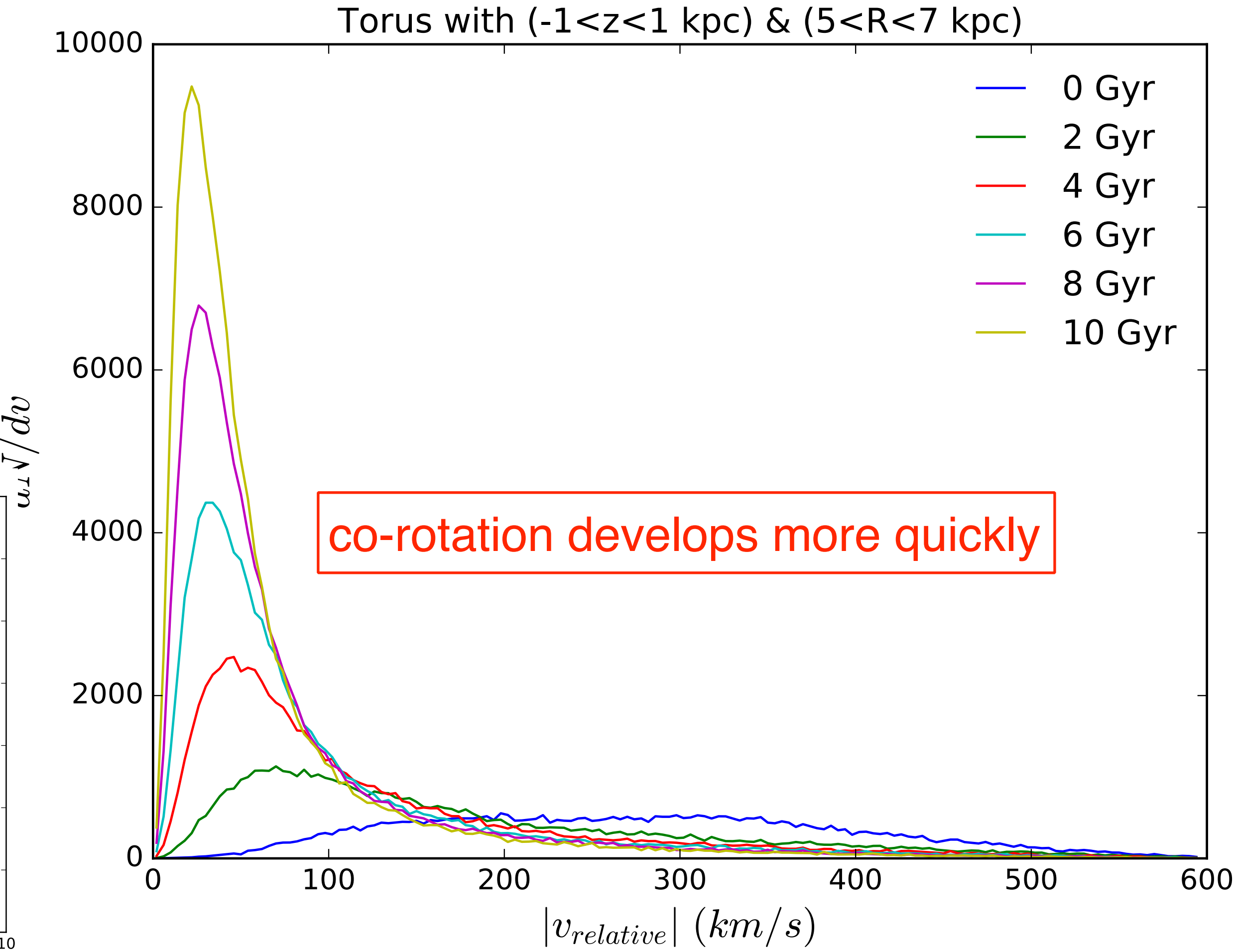
test with extra torus







DM accumulates near gas



co-rotation develops more quickly

Rotation Curves ⇔ DM reflects gas

Swaters+12: precise rotation curves & baryons, for dozens of galaxies

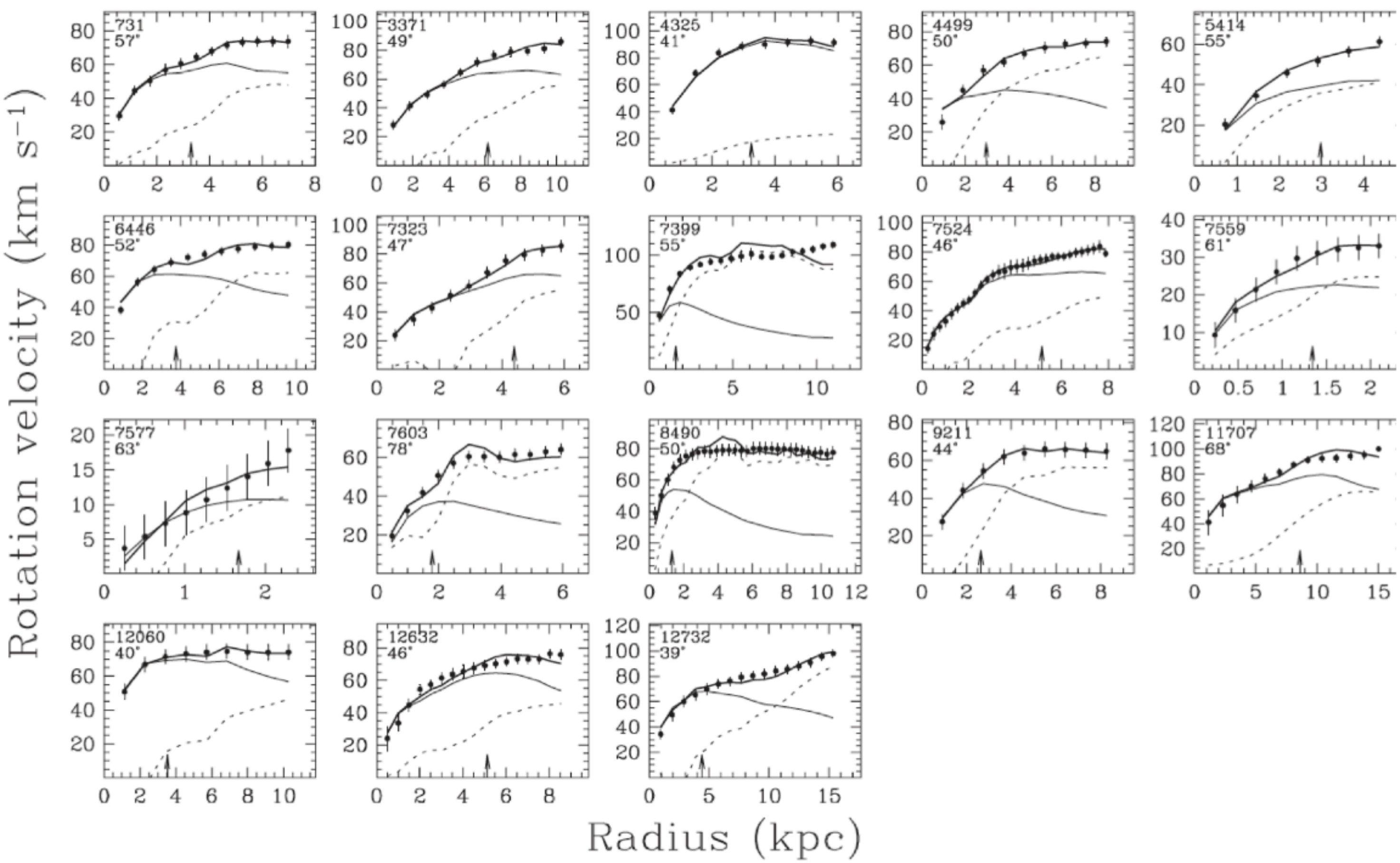
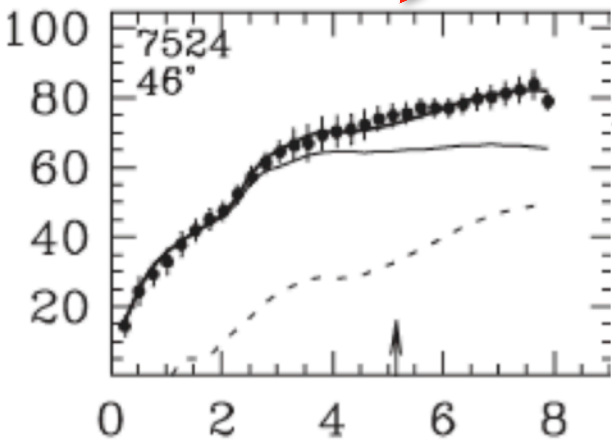
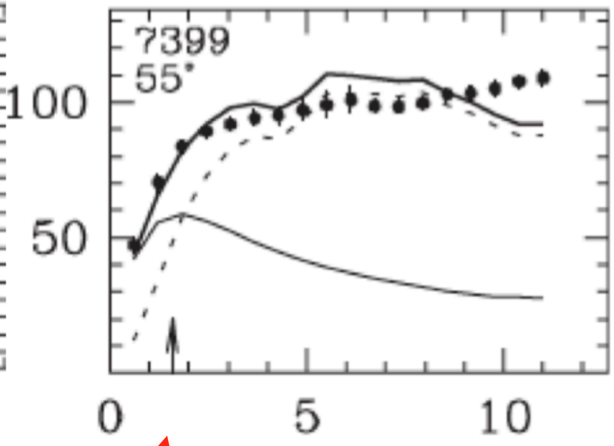


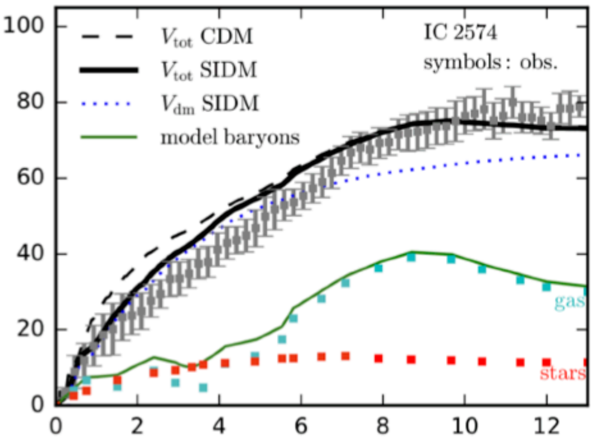
Figure 1. Mass models based on scaling the stellar disc and the H I component for the late-type dwarf galaxies in our sample. The filled circles represent tl derived rotation curves. The thin full lines represent the contribution of the stellar discs to the rotation curves and the dotted lines that of the gas. The thic solid lines represent the best-fitting model based on scaling the contributions of the stars and the gas. The arrows at the bottom of each panel indicate a radiu of two optical disc scale lengths. In the top left corner of each panel, the UGC number and the inclination are given.

Rotation Curves ⇔ DM reflects gas

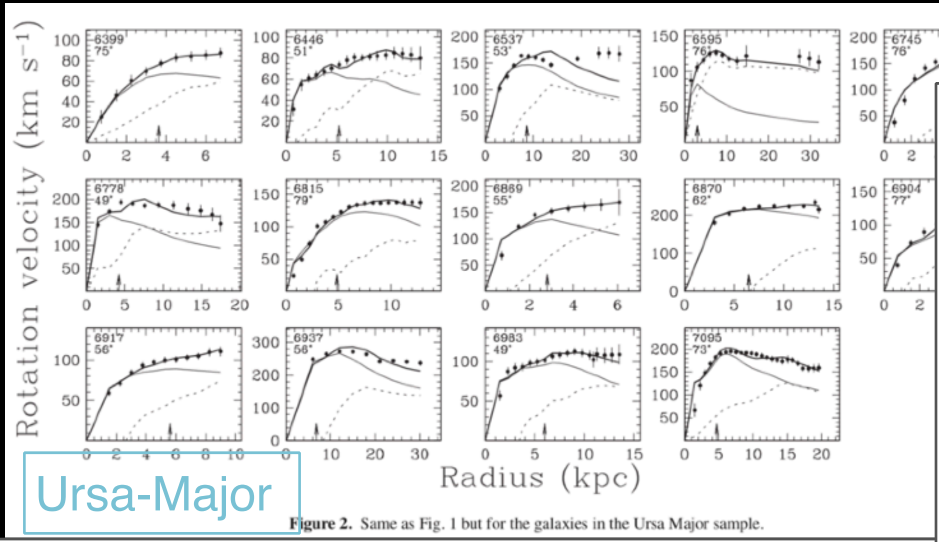
Sharp increases in overall RC, amplifying structure in gas





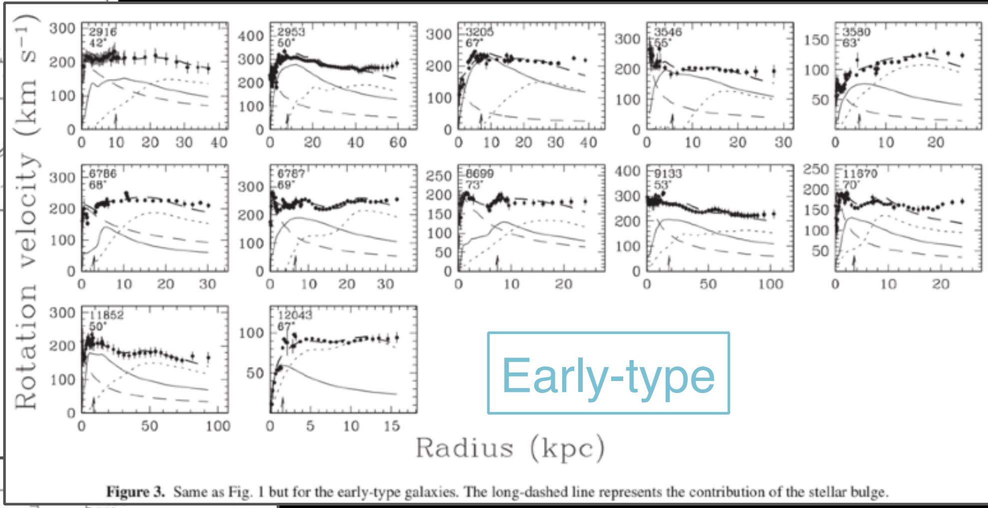


But not always… !



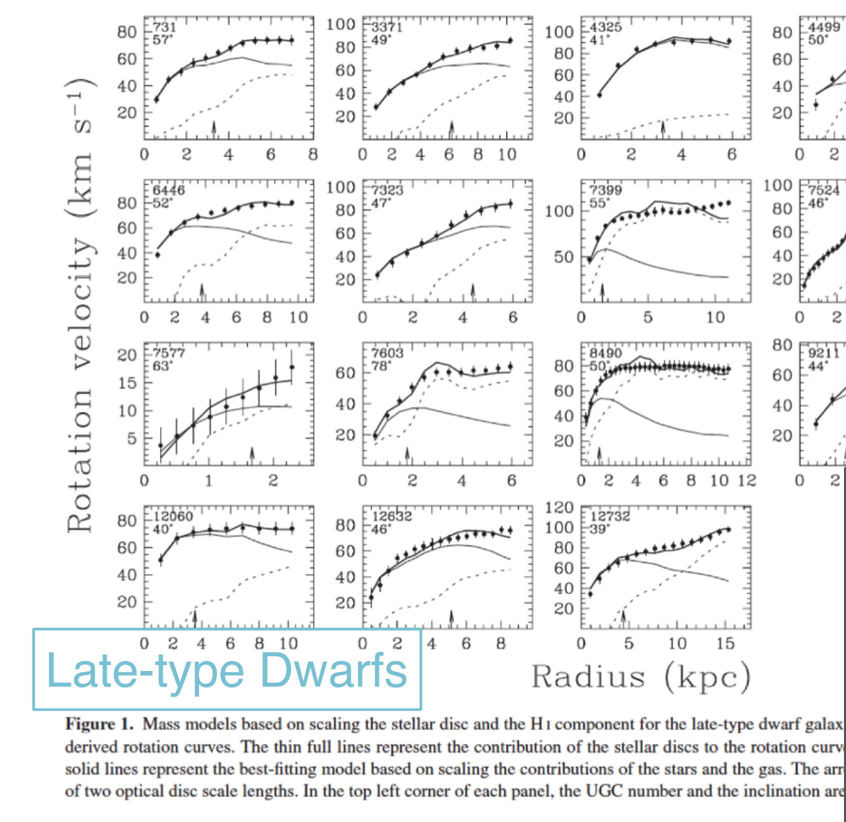
Ursa-Major

Figure 2. Same as Fig. 1 but for the galaxies in the Ursa Major sample.



Early-type

Figure 3. Same as Fig. 1 but for the early-type galaxies. The long-dashed line represents the contribution of the stellar bulge.



Late-type Dwarfs

Figure 1. Mass models based on scaling the stellar disc and the H I component for the late-type dwarf galax
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Mon. Not. R. Astron. Soc. **425,** 2299–2308 (2012) doi:10.1111/j.1365-29

The link between the baryonic mass distribution and the rotation curve shape

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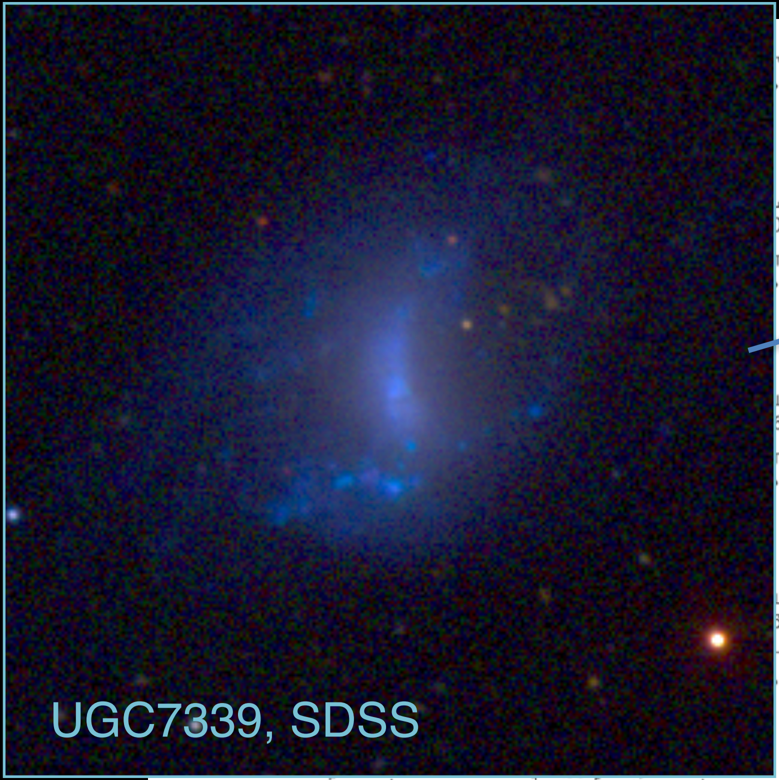
[3]*Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, the Netherlands*

SDM provides a natural explanation for the exceptions: major merger

Swaters+12


UGC7339, SDSS

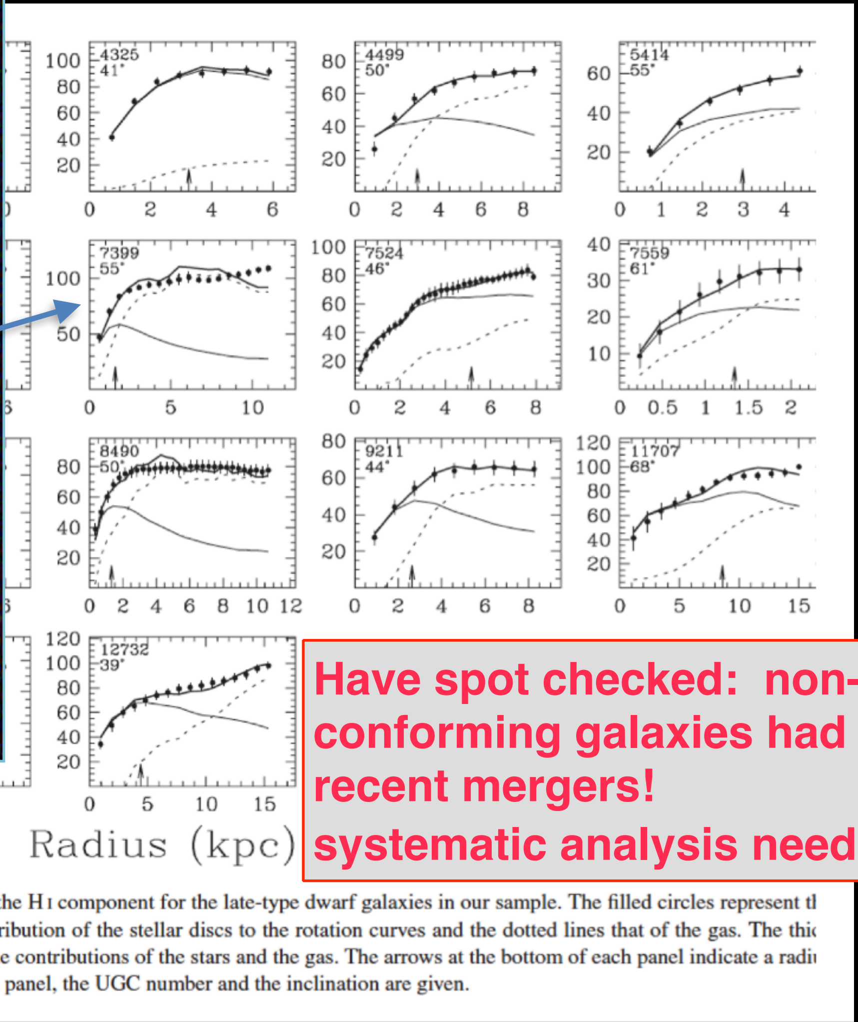


Figure 1. Mass models based on scaling the stellar disc and the H I component for the late-type dwarf galaxies in our sample. The filled circles represent tl derived rotation curves. The thin full lines represent the contribution of the stellar discs to the rotation curves and the dotted lines that of the gas. The thic solid lines represent the best-fitting model based on scaling the contributions of the stars and the gas. The arrows at the bottom of each panel indicate a radii of two optical disc scale lengths. In the top left corner of each panel, the UGC number and the inclination are given.

Have spot checked: non-conforming galaxies had recent mergers!

systematic analysis needed…

Cosmology & structure formation

- DM-baryon interaction: momentum transfer => *slight drag on DM during structure formation*
  - Dvorkin, Blum, Kamionkowski (2014):
    - **Ly-alpha forest: $\sigma <\sim 10$ mb if v-indept**
  - Buen-Abad, Marques-Tavares, Schmaltz (2015):
    - **momentum transfer helps reconcile H_o & σ_8**
  - Problem or opportunity? To be determined…
- S-S self interactions + S-baryon interactions:
  - expect similar benefits as Self Interacting DM
  - resolves core-cusp, “too-big-to-fail” & missing sub-halos problems.

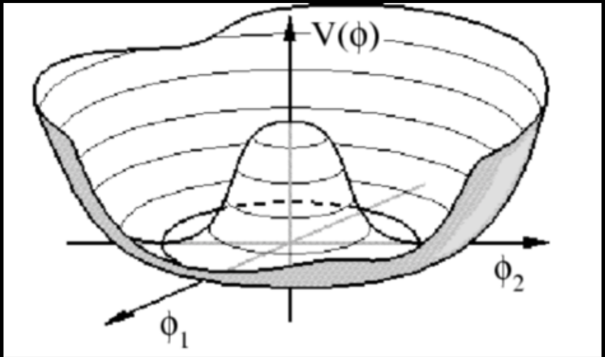
Galaxies & Clusters

DM-gas scattering provides a source of heating, needed for:

- Milky Way’s extended hot gas halo — 2 x10^6 K
- Quenching star formation
- Avoiding “cooling flow catastrophe” in X-ray clusters

Baryon Asymmetry of the Universe

- S described by complex scalar field, like the Higgs
  - may have VEV in early Universe
  - phase rotates at no cost in energy ⇒
  - ***Non-zero baryon number density is generic***



$$n_B \sim < \phi_S^\dagger \overleftrightarrow{\partial}_t \phi_S >$$

Baryon number is non-zero. After reheating it looks like it was just an initial condition.

Dark Matter Relic Abundance

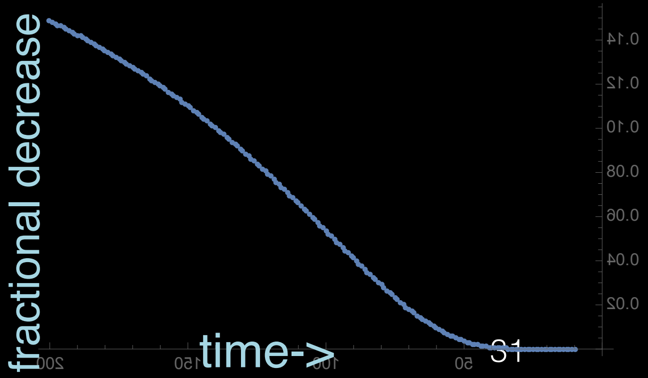
- Reheating: production of photons & fragmentation of $<\phi_S>$ into particles
- Breakup: $\gamma + S \rightarrow \Lambda\,\Lambda$

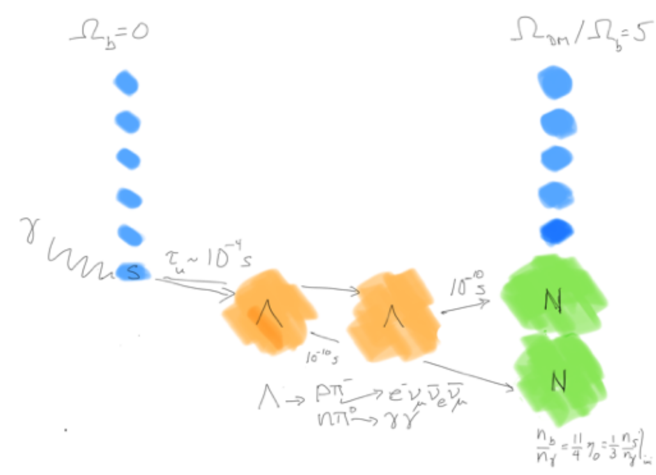
$$\frac{d\,n_S}{n_S\,dT} = -\Gamma(\gamma + S \rightarrow \Lambda\Lambda)\frac{dt}{dT}$$

$$\Gamma(\gamma + S \rightarrow \Lambda\Lambda)(T) = < n_\gamma(T)\sigma_{\gamma+S\rightarrow\Lambda\Lambda}(T)v(T) >$$

- ~16% of S's are broken up before freeze out ⇒

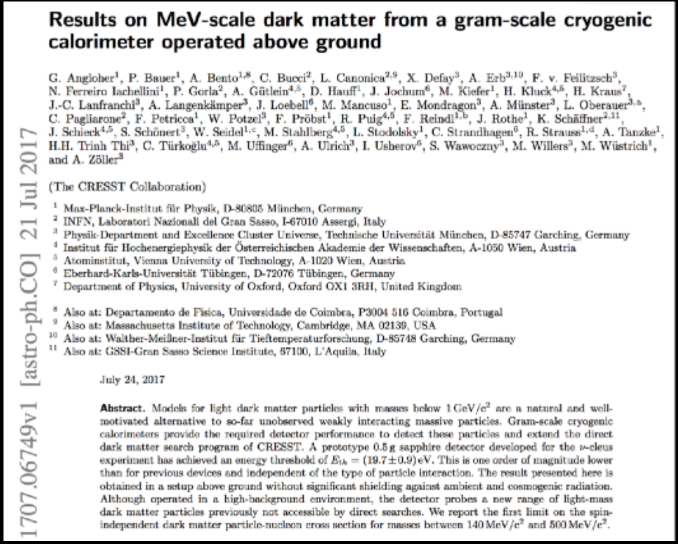
Ω_{DM} / Ω_b = 5 . Natural!





Strategies to detect DM

if DM is comprised of S’s



Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground

G. Angloher[1], P. Bauer[1], A. Bento[1,8], C. Bucci[2], L. Canonica[2,9], X. Defay[3], A. Erb[3,10], F. v. Feilitzsch[3], N. Ferreiro Iachellini[1], P. Gorla[2], A. Gütlein[4,5], D. Hauff[1], J. Jochum[6], M. Kiefer[1], H. Kluck[4,5], H. Kraus[7], J.-C. Lanfranchi[3], A. Langenkämper[3], J. Loebell[6], M. Mancuso[1], E. Mondragon[3], A. Münster[3], L. Oberauer[3,a], C. Pagliarone[2], F. Petricca[1], W. Potzel[3], F. Pröbst[1], R. Puig[4,5], F. Reindl[1,b], J. Rothe[1], K. Schäffner[2,11], J. Schieck[4,5], S. Schönert[3], W. Seidel[1,c], M. Stahlberg[4,5], L. Stodolsky[1], C. Strandhagen[6], R. Strauss[1,d], A. Tanzke[1], H.H. Trinh Thi[3], C. Türkoğlu[4,5], M. Uffinger[6], A. Ulrich[3], I. Usherov[6], S. Wawoczny[3], M. Willers[3], M. Wüstrich[1], and A. Zöller[3]

(The CRESST Collaboration)

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[8] Also at: Departamento de Fisica, Universidade de Coimbra, P3004 516 Coimbra, Portugal
[9] Also at: Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[10] Also at: Walther-Meißner-Institut für Tieftemperaturforschung, D-85748 Garching, Germany
[11] Also at: GSSI-Gran Sasso Science Institute, 67100, L’Aquila, Italy

July 24, 2017

Abstract. Models for light dark matter particles with masses below 1 GeV/c^2 are a natural and well-motivated alternative to so-far unobserved weakly interacting massive particles. Gram-scale cryogenic calorimeters provide the required detector performance to detect these particles and extend the direct dark matter search program of CRESST. A prototype 0.5 g sapphire detector developed for the ν-cleus experiment has achieved an energy threshold of $E_{th} = (19.7 \pm 0.9)$ eV. This is one order of magnitude lower than for previous devices and independent of the type of particle interaction. The result presented here is obtained in a setup above ground without significant shielding against ambient and cosmogenic radiation. Although operated in a high-background environment, the detector probes a new range of light-mass dark matter particles previously not accessible by direct searches. We report the first limit on the spin-independent dark matter particle-nucleon cross section for masses between 140 MeV/c^2 and 500 MeV/c^2.

arXiv:1707.06749v1 [astro-ph.CO] 21 Jul 2017

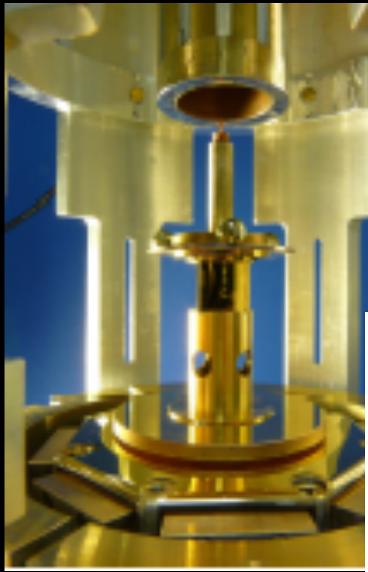
- With v_{rel} = 30 km/s , KE_{DM} ~ 10 eV
  - **$\langle E_{deposit} \rangle / KE_{DM}$ = 0.12** for Si target
    = 0.02 for Hg target
    = 0.44 for H or He target
  - **Energy-loss length of S in Earth crust:**
    $\lambda = 2\ cm / \sigma_{10mb}$
  - **Present detectors shielded or too high threshold (new CRESST expt has E_{th} = 19 eV, but 30 cm shielding ⇒ not sensitive)**
- Heating rate liquid He: ~ nW/mol ~ CR muon energy deposit rate.
  - can’t *shield* muons & other CRs: veto? but what about neutrons?

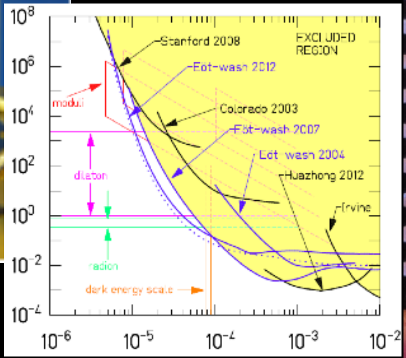
S dark matter detection with a torsion balance on the ISS

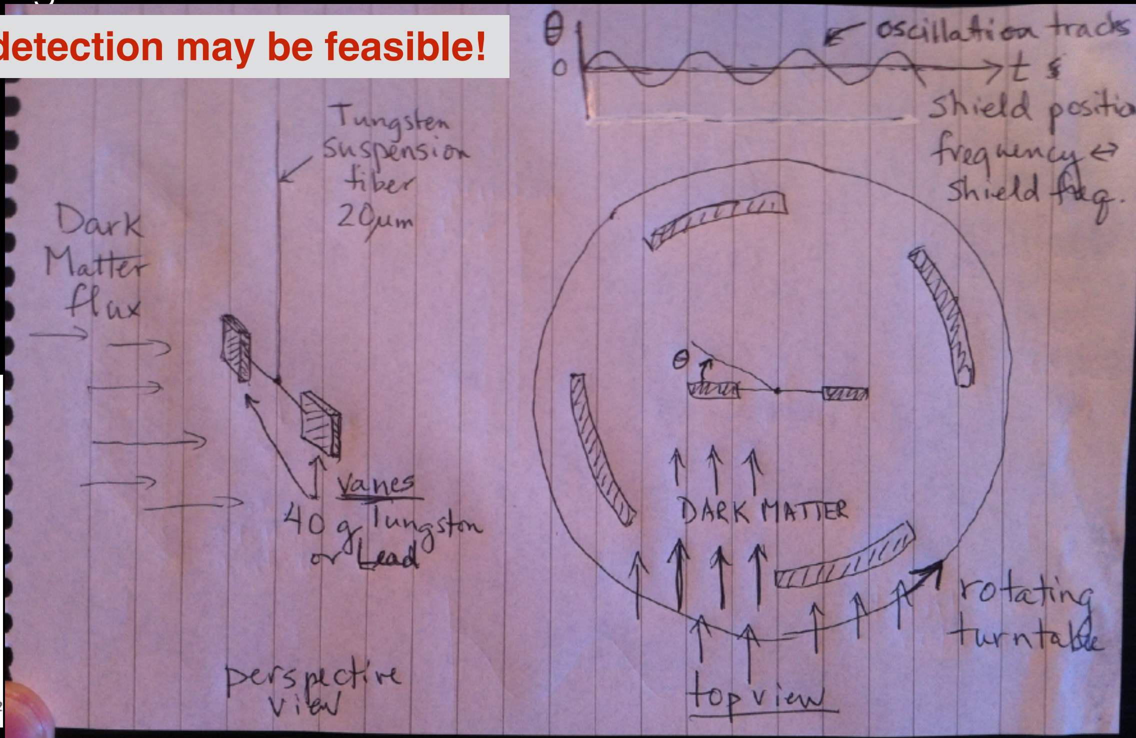
W. Terrano & GRF, in preparation

- Individual S collision deposits too little E to detect, but an S flux exerts a tiny pressure.
- Torsion balance: (Eotwash) 1 yr torque sensitivity ~ 2 10^{-11} dyne-cm (erg)
- Modulate DM pressure by rotating absorber

directional S-detection may be feasible!







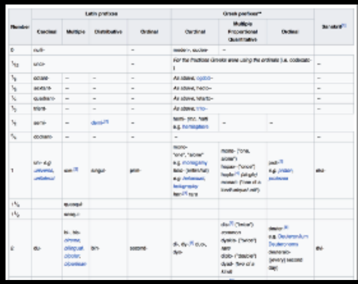
Key points to take home

- ***There may a tightly bound 6-quark state* S= uuddss**
  - **Unique, symmetric structure ⇒ other hadrons don't provide guidance**
    - mass is not driven by chiral symmetry breaking (unlike baryons)
    - constituent quark model probably completely misleading
  - ***If $M_S < 2\, m_p + 2\, m_e$, S is absolutely stable***
- ***If S is stable, its an excellent Dark Matter candidate***
  - Relic abundance is natural.
  - Usual WIMP detection strategy isn't applicable.
  - Baryon asymmetric Universe is expected
  - May reconcile tension in H_0 & σ_8 and explain astrophysics puzzles ("quenching", core-cusp, DM rotation curves…)
- ***S may be waiting to be discovered in existing Υ-decays or LHC experiments… mass can be accurately measured in Υ-decay exclusive final states.***
- ***SDM will be challenging to detect, but not impossible. Astrophysical and cosmological effects may allow it to be constrained, excluded or confirmed.***

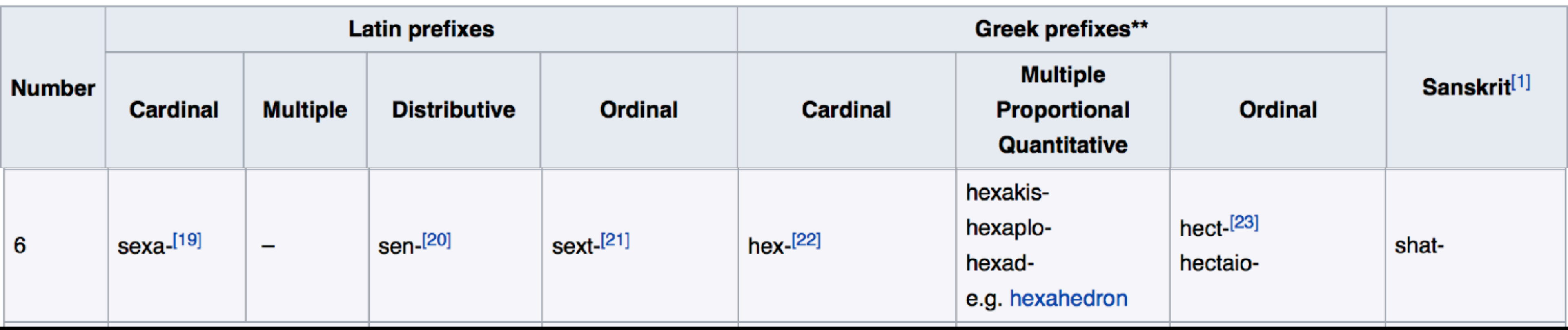
Backup Slides

Sexa vs Hexa…

- https://en.wikipedia.org/wiki/Numeral_prefix



- If sexaquark is DM it, should be renamed R for Rubin!

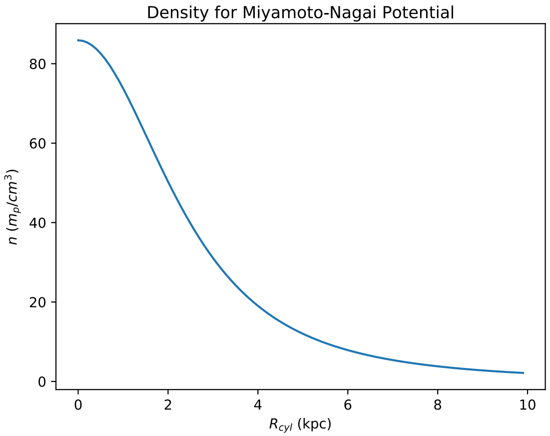


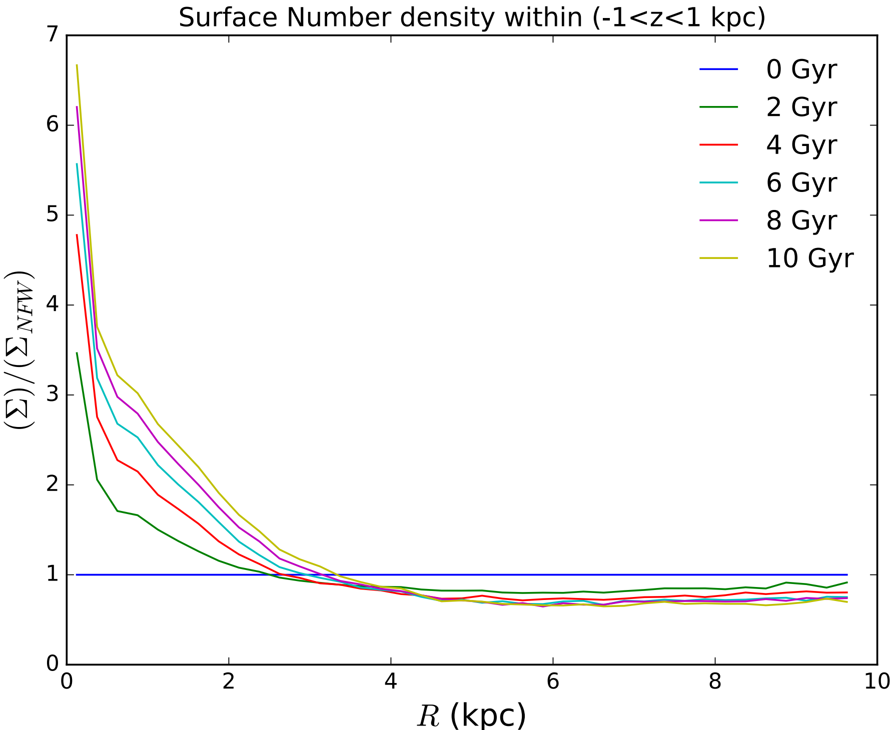
Number	Latin prefixes				Greek prefixes**			Sanskrit[1]
	Cardinal	Multiple	Distributive	Ordinal	Cardinal	Multiple Proportional Quantitative	Ordinal	
6	sexa-[19]	–	sen-[20]	sext-[21]	hex-[22]	hexakis- hexaplo- hexad- e.g. hexahedron	hect-[23] hectaio-	shat-

[a] [b] Sometimes Greek *hexa-* is used in Latin compounds, such as *hexadecimal*, due to taboo avoidance with the English word *sex*.

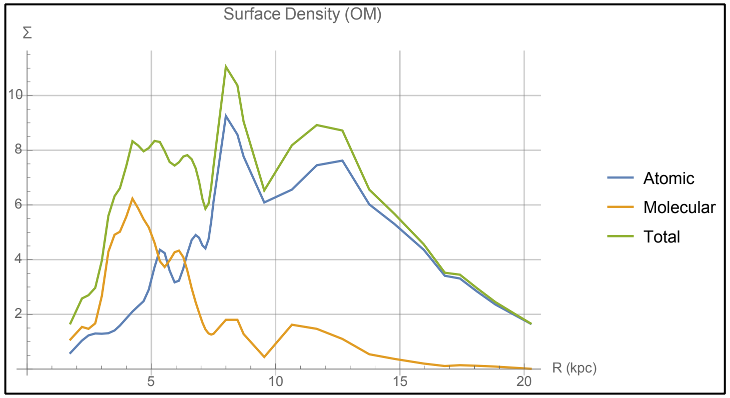
Sensitivity to gas density structure

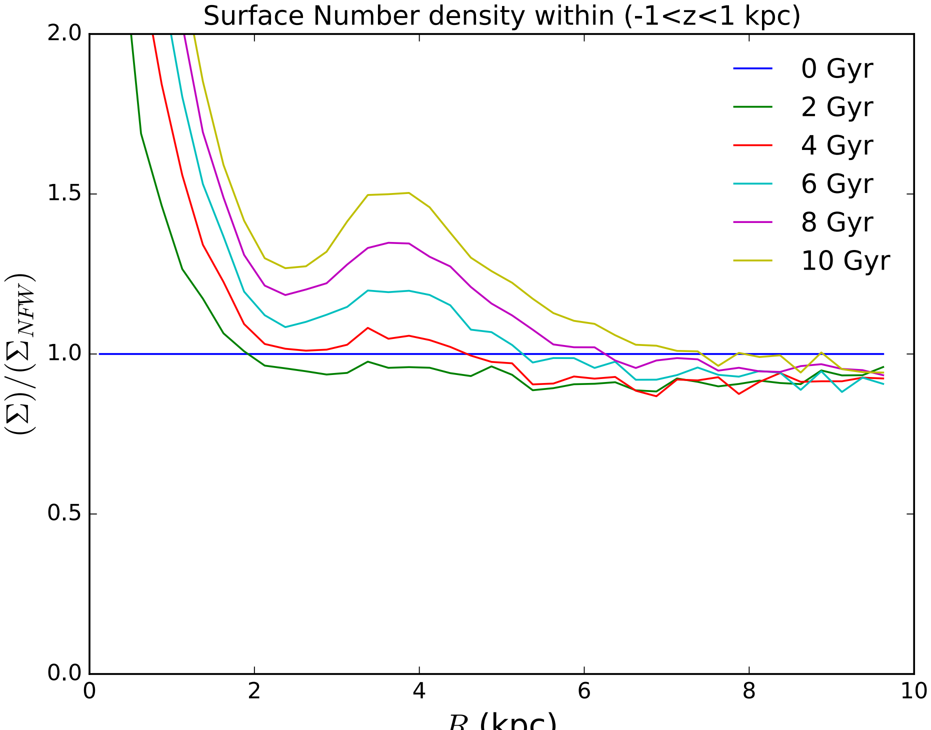
Galpy Baryons





Olling-Merrifeld

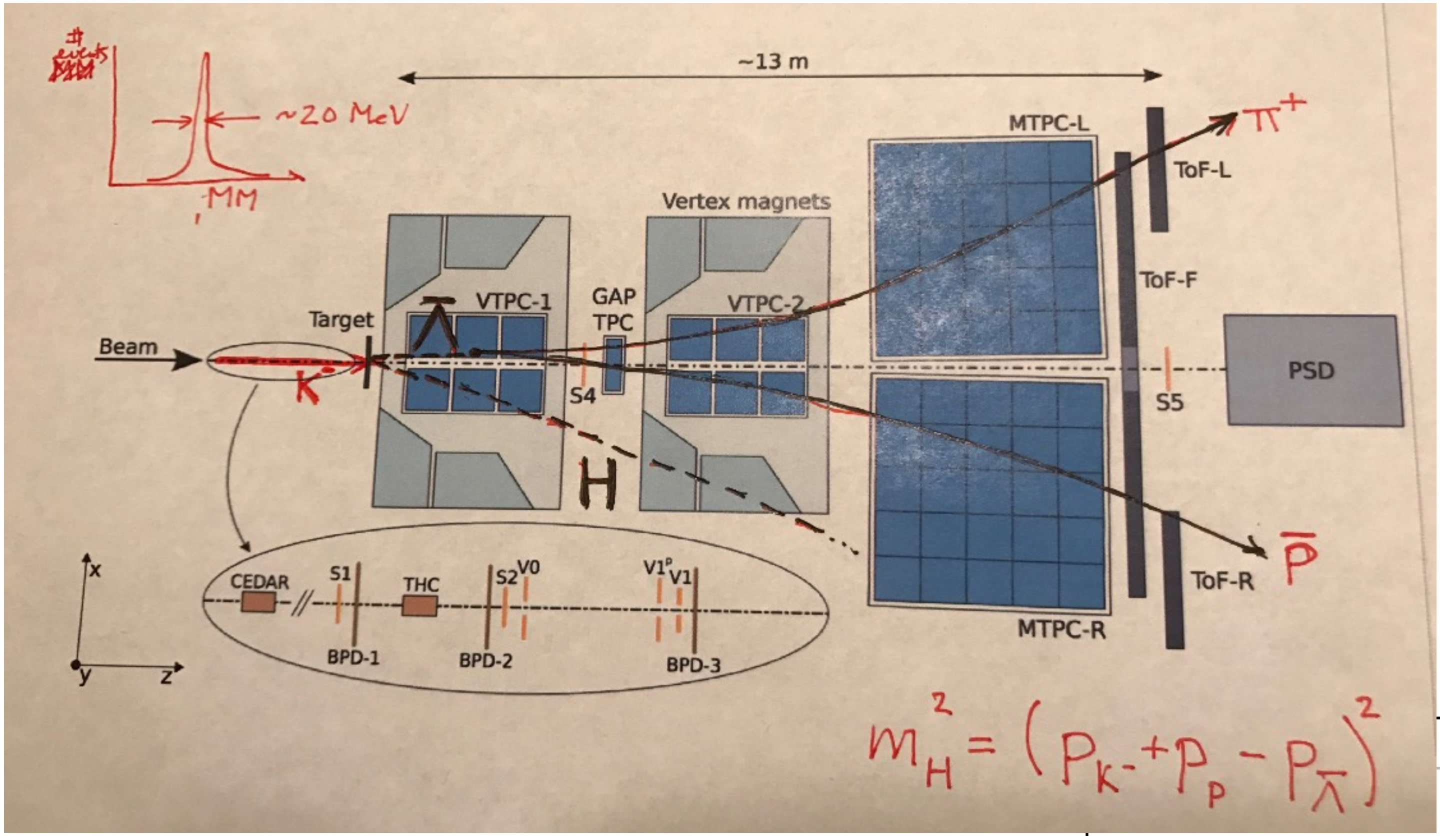




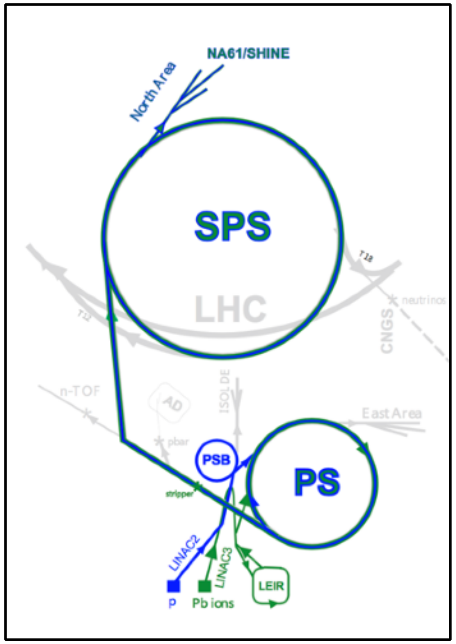
$$\begin{array}{lccccc} B: & & +1 & & -1 & +2 \\ & K^- & p & -> & \bar{\Lambda} & S \\ S: & s & & & \bar{s} & ss \end{array}$$

- $\bar{\Lambda}$ is a gold-plated signature : $\bar{\Lambda} -> \pi^+ \bar{p}$
  - Easy to ID & reconstruct 4-momentum
  - $c\tau = 8$ cm   all $\bar{\Lambda}$ are ID'd
- S: undetected, but 4 momentum determined
  - $p_S = p_K + p_p - p_{\bar{\Lambda}}$
  - NA61: est.~ 20 MeV accuracy on “missing-mass” of S
  - For $p_{beam} < 5.35$ GeV/c , no conventional source of $\bar{\Lambda}$ ‘s
- NA61: 9 GeV/c K- beam, need trigger to

NA61/SHINE



$$m_H^2 = (P_{K^-} + P_p - P_{\bar\Lambda})^2$$



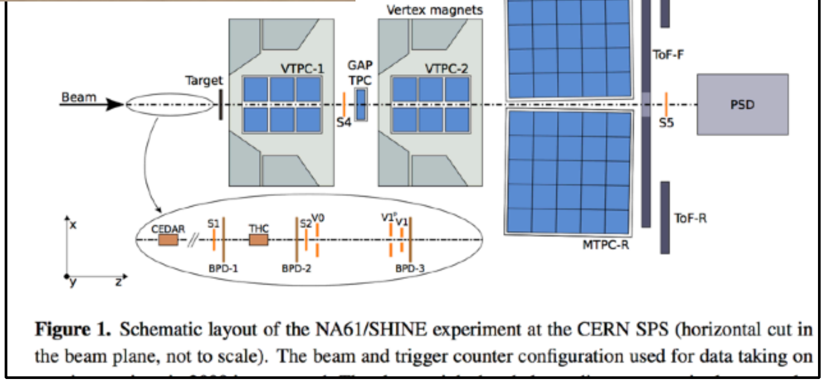


Figure 1. Schematic layout of the NA61/SHINE experiment at the CERN SPS (horizontal cut in the beam plane, not to scale). The beam and trigger counter configuration used for data taking on

NA61

- Trigger rate ~100 Hz => 10^7 events per day
    - GEANT: ~ 0.5% K^0 n + neutrals => must refine trigger

- Schedule mostly fixed till shutdown in 2018; restarts 2020.

- *? short K-p run at 9 GeV/c before shutdown, to evaluate rejection efficiency and background?*

- Maybe 9 GeV/c beam is ok! => longer run in 2020…

Background to K$^-$ p -> $\bar{\Lambda}$ R$_H$

- K- p -> K^0 n + neutrals

  ↳ π+ π-

DANGER: mis-ID π- as $\bar{p}$ & interpret n + neutrals as **H**.

- NA61: *good rejection of* K^0 *faking* $\bar{\Lambda}$
  - ToF, dEdX, kinematic cuts to reject in dangerous regions
  - GEANT sims running to quantify…

“Armenteros Podolanski” plot