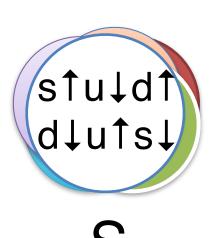
Stable Sexaquark as Dark Matter



Glennys R. Farrar New York University

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

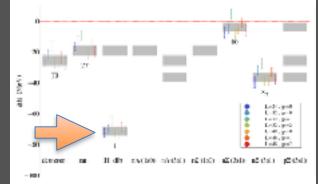
m ~ 1.7-2 GeV
```

(Most-Attractive Channel)³:

```
totally Antisymmetric in:
    color
    flavor
    spin
totally Symmetric in space
```

Mass of S

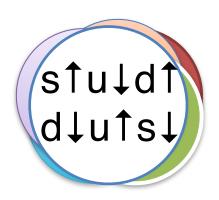
- Options for stability $(\tau > \tau_{\text{Univ}})$
 - M_S < 2 m_p + 2 m_e = 1877.6 MeV → absolutely stable
 - $M_S < m_p + m_e + m_\Lambda = 2054.5$ MeV \rightarrow decay rate $\sim G_F^2$ x wave function overlap \rightarrow lifetime up to 10^{27} yr.
- Is M_S < 1.7-2 GeV reasonable?
 - Hyperfine attraction \Rightarrow M_S < 2 m_A = 2230 MeV (Jaffe, 1977) (Most-Attractive Channel)³
 - Constituent quark model unreliable/inapplicable
 - $m_{\pi} = 135$, 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
 - Need only 16% (10%) binding energy 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 $\tau >> \tau_{Univ}$)



S

6-quark, Q=0, B=2

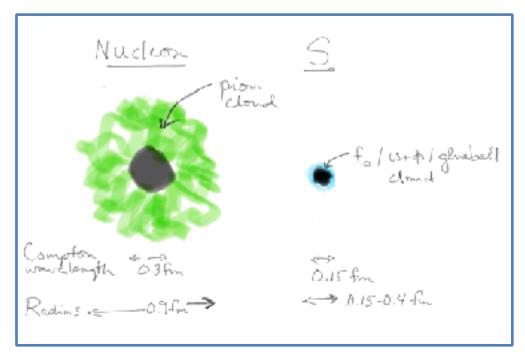
Spin-0, scalar

Flavor singlet

m ~ 1.7-2 GeV

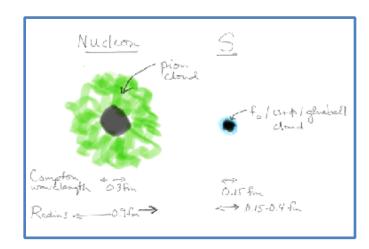
Crucial features:

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 ⇒
 - $r_S \sim \text{Compton wavelength } \sim 0.15 \text{ fm} \text{ (compare } r_p = 0.9 \text{ fm)}$
 - 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.

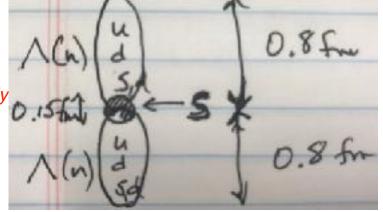


- Couples to f_0 , glueball, SU(3) singlet ω - φ
 - $r_s \sim 0.15 0.4 \text{ fm}$ depending on strength of f_0 coupling
 - $\sigma_{\rm SN} \sim 5$ to 20 mb (at v/c ~ 1 ; may grow as v/c $\rightarrow 0$, as $\sigma_{\rm NINI}$ does)

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

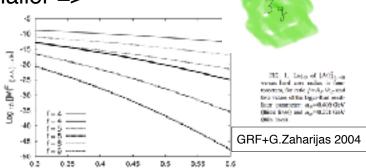
⇒ Small wave function overlap with 2 nucleons

- · 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)



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 $m_S < 2 \text{ GeV}$)
 - required fast production in S=-2 hypernuclei (but small overlap with baryons)
- Wavefunction overlap with baryons is very small. Extremely rare fluctuation required for $S \Leftrightarrow \Lambda\Lambda$; $S \Leftrightarrow NN$ is G_F^2 smaller =>
 - nuclei are stable ($\tau > 10^{29} \, \text{yr}$)
 - hard to produce in fixed target experiments
- S is similar to (much more copious) neutrons
- Promising accelerator detection strategies



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

Experimental Searches

- Require M > 2 GeV:
 - Gufstafson+ FNAL1976: Beam-dump + tof Limit on production of neutral stable strongly interacting particle with mass > 2 GeV.
 - Carroll+ BNL 1978: No narrow missing mass peak above 2 GeV in pp -> K K X
- Require H-dibaryon decay:
 - Badier+ NA3 1986
 - Bernstein+ FNAL 1988: Limit on production of neutral with $10^{-8} < \tau < 2 \times 10^{-6} \text{ s}$
 - Belz+ BNL 1996: $H /-> \Lambda$ n or Σ n [c.f., issue raised by L. Littenberg]
 - Kim+ Belle 2013: no narrow resonance in Y → Λ p K
- Limits from production in doubly-strange hypernuclei:
 - Ahn+ BNL 2001
 - Takahashi+ KEK 2001

Search for Six-Quark States

A. S. Carroll, I.-H. Chiang, R. A. Johnson, T. F. Kycia, E. K. Ki, L. S. Littenberg, and M. C. Mare

Brookhaven National Laboratory, Cylon, Ben Brek 11:73

R. Cester, R. C. Wold, and M. S. Witherell. Princeton Intreveity. Princetin, New Jersey 06:568 Observiced 95 July 1970)

We have searched the missing-mass spectrum of the reaction gp - H"X X for a narrow sto-starts resonance in the mass range 2.0-2.0 GeV/c. Ne service structure was observed. Egger limits for the production cross section of such a state depend upon mass and vary from 26 to 120 pb.

PALENC 74, NUMBER 15.

PHYSICAL REVIEW LETTERS

Search for the Weak Decay of an If Diburyon

 Bela^{5,*} K.D. Corens, ² M.Y. Divine, ³ M. Bithmer, ³ K.M. Bithmet, ³ A.D. Hancott, ³ V.L. Eighland, ³ C. Hoff, ³ G.W. Hoffman, J.G.M. Lwin, J. E. Kama, S.H. Hondi, J.B. Khin, J.Y. Kanag, E. Lung, B. Marin, M. May, Littlebough, W.R. Mohoo, J. J. E. Bay, J. L. Dache, A. J. Schwarz, A. Trandari, D. War, D. E. Welse, S. R. When, M.T. Welsen, M. S. Welse, J. S. Welse, J. S. Welse, J. Welse

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PHYSICAL REVIEW LETTERS

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Production of , H Hyperredia

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Experimental Searches

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Search Six-On States

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N. Joher, R. D. Wolde, and M. S. Witherest. Princeton University. Princeton, New Jersey 08368 (Becelved 95 July 1970)

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PHYSICAL REVIEW LETTERS.

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Search for the Weak Decay of an If Diburyon

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PRESIDED REVIEW LETTERS

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Production of , H Hypermedia

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Discovery Strategy

Apparent lack of B and S conservation:

$$\cdot \Delta B = \pm 2 + \Delta S = \mp 2$$

· Reconstruct missing mass, e.g.:

•
$$\Upsilon \rightarrow \Lambda \Lambda \bar{S}$$
 (+ pions) $M_S^2 = (p_Y - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_{\pi_i})^2$

•
$$K^- p \rightarrow \overline{\Lambda} S$$
 (+ pions) $M_S^2 = (p_{K^-} + p_p - p_{\overline{\Lambda}} - \sum p_{\pi_i})^2$

•
$$\bar{\mathbf{S}}$$
 + p,n $\rightarrow \bar{\Lambda}$ + K+,0 $M_S^2 = (p_K + p_{\bar{\Lambda}} - p_p)^2$
or $\bar{\Xi}^{+,o} + \pi$

$\Upsilon \rightarrow \Lambda \Lambda \overline{S} \ _{\&} \overline{\Lambda} \overline{\Lambda} S$

(+ pions)

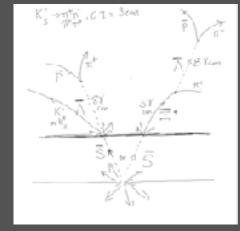
~ 0.03 Fm

- · Y is *localized* source of ggg
 - \Rightarrow production of S is (relatively) enhanced
- Many x 10⁸ 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 $K^+ K^- K^-$ (+ 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 discovery 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
 - \overline{S} annihilation in tracker, followed by $\overline{\Xi}^{+,\circ} \to \overline{\Lambda} \pi^{+,\circ} \ (c\tau = 5\gamma \text{ cm}) \ \overline{\Lambda} \to \overline{p} \pi^+ (63\%,c\tau = 8\gamma \text{ cm})$



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

1

Conditions on QCD Dark Matter

- √ T_{DM} > T_{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} $\sigma_{f.o.}$)

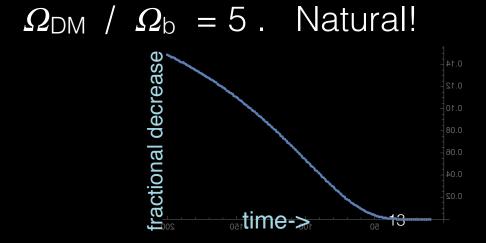
Dark Matter Relic Abundance

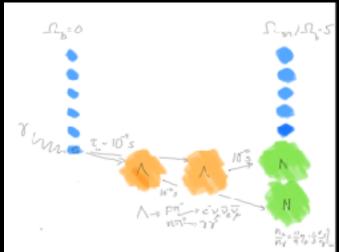
- Reheating: production of photons & fragmentation of $<\phi_{\rm S}>$ into particles
- Breakup: $\gamma + S \rightarrow \Lambda \Lambda$

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

$$\Gamma(\gamma + S \to \Lambda\Lambda)(T) = \langle n_{\gamma}(T)\sigma_{\gamma+S\to\Lambda\Lambda}(T)v(T) \rangle$$

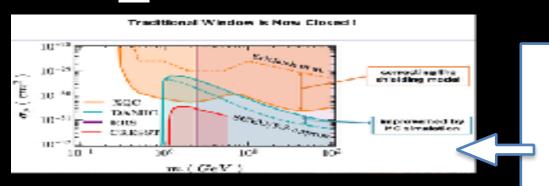
~16% of S's are broken up before freeze out ⇒







Stable S as Dark Matter



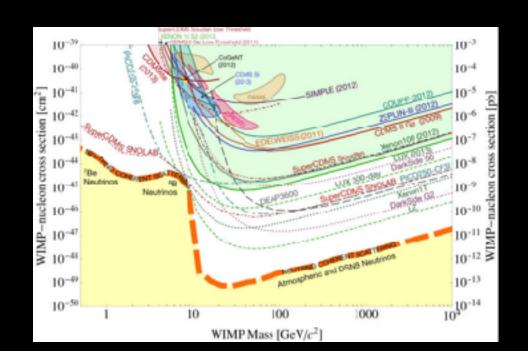
Closing the window on \sim GeV Dark Matter with moderate ($\sim \mu$ b) interaction with nucleons

M. Shafi Mahdawi and Glennys R. Farrar

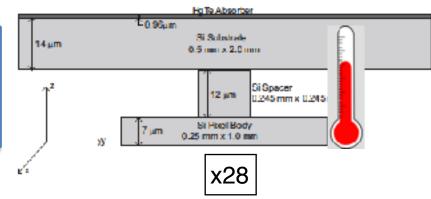
Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA

E-mail: shafi.mahdawi@nyu.edu, gf25@nyu.edu

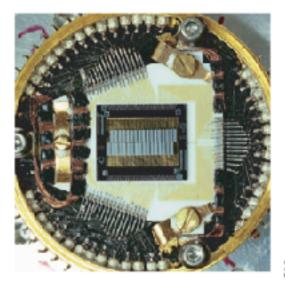
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleous, for DM in the 300 MeV - 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order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

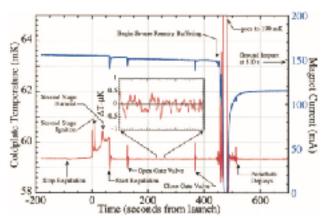


X-Ray Quantum Calorimeter (XQC)



- 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 ≥ 30 eV
 - 100 sec flight, ~ 100 events
 - nuclear recoil => X-rays, which thermalize (assumption)







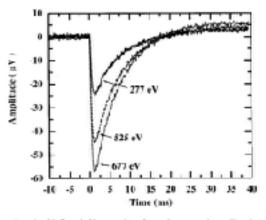
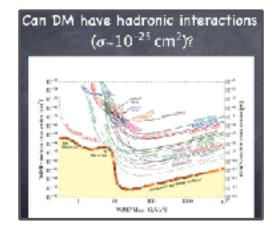


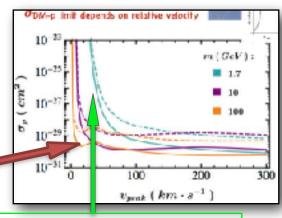
Fig. 8.—Unfiltered X-ray pulses from the guto-valve calibration ource.

Evading Direct Detection II. XQC applicability

Evading Direct Detection II. Co-Rotation

- Light, slow-moving DM is not visible in current detectors
 - KE _{DM} = 500 eV $(m_{DM} / 2 m_p) v^2 / (220 \text{ km/s})^2$
 - <E_{deposit}>/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: $\lambda = 2 \text{ cm} / \sigma_{10\text{mb}}$
 - CRESST, Xenon1T, LUX, DAMIC
- * 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
 - $v_{min,XQC} = 107 \text{ km/s} (2 \text{ m}_p/\text{m}_{DM})^{1/2}$



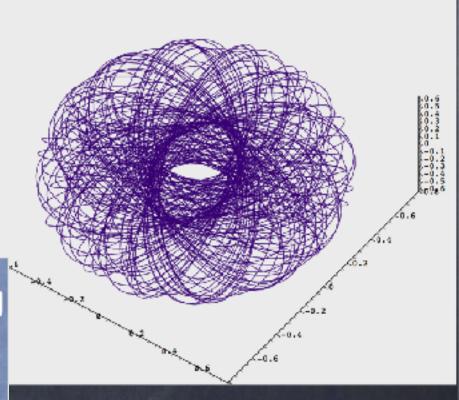


Viability of Co-Rotation Scenario

Schwarzchild Modelling

- Choose a potential (NFW)
- Follow an orbit in this potential

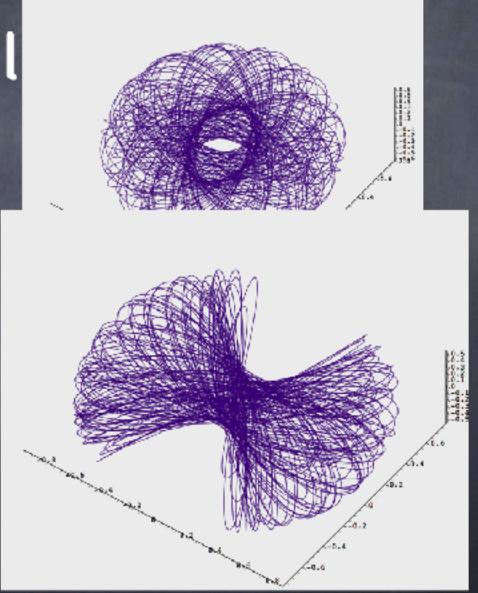
Simulations of DM interacting with gas in the Milky Way



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

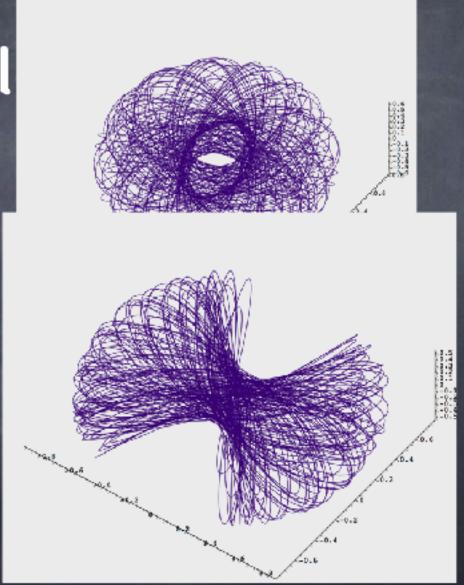
Schwarzchil

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



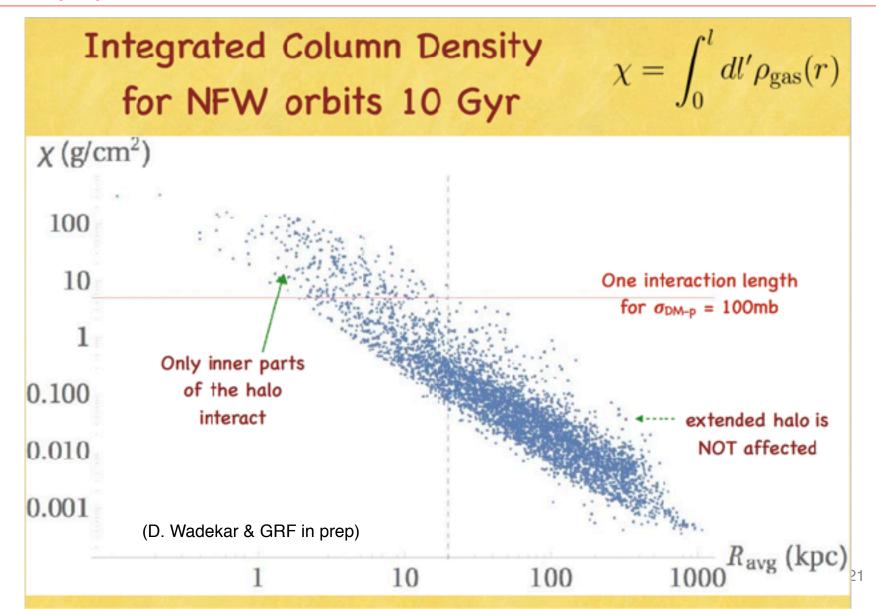
Schwarzchil

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



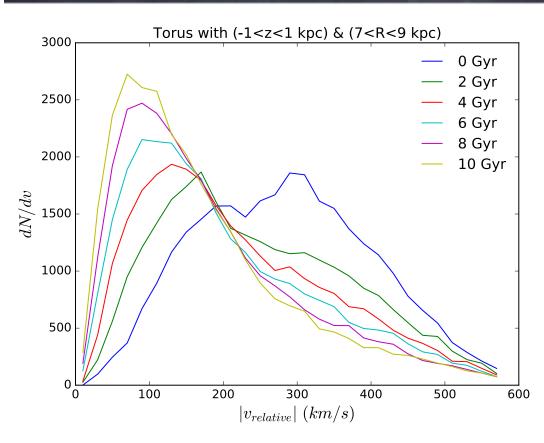
Dark Matter-Gas Scattering

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



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

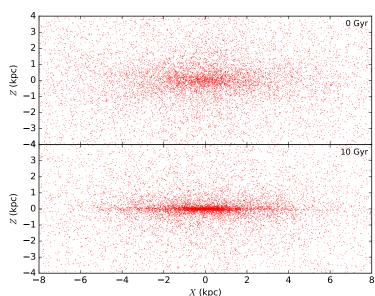
(D. Wadekar & GRF in prep)

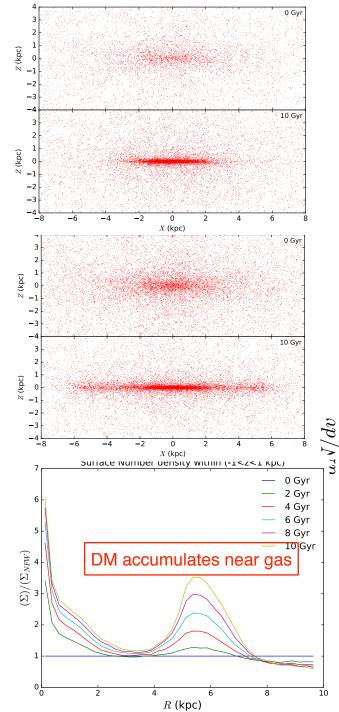


Co-rotation!

Highly idealized analysis:

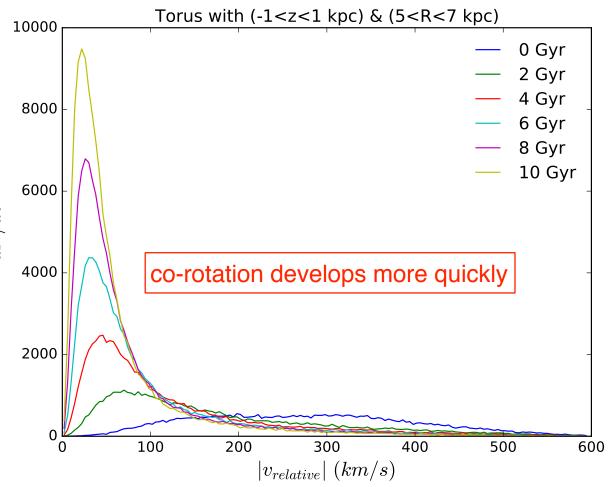
- static potential & gas
- actually grows by accretion
- c.f. Bruch-Read+
- proof of concept, shows crosssection needed is reasonable.





in realistic galaxies, gas is inhomogeneous ⇒

test with extra torus



Rotation Curves ⇔ DM reflects gas

Swaters+12: hundreds of galaxies of all types

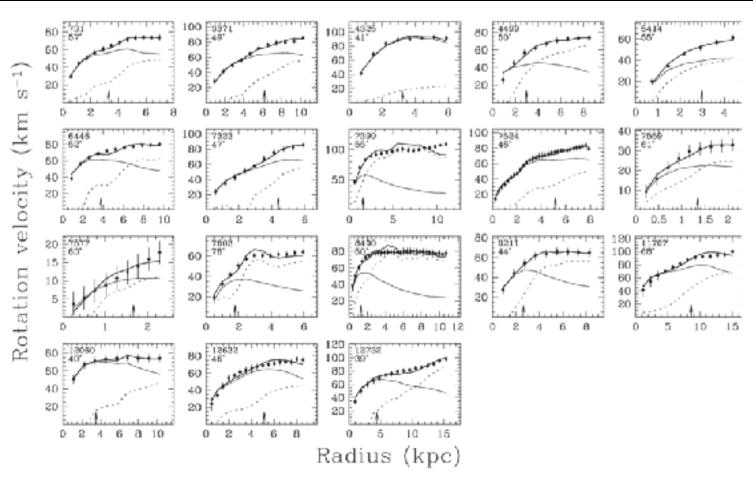
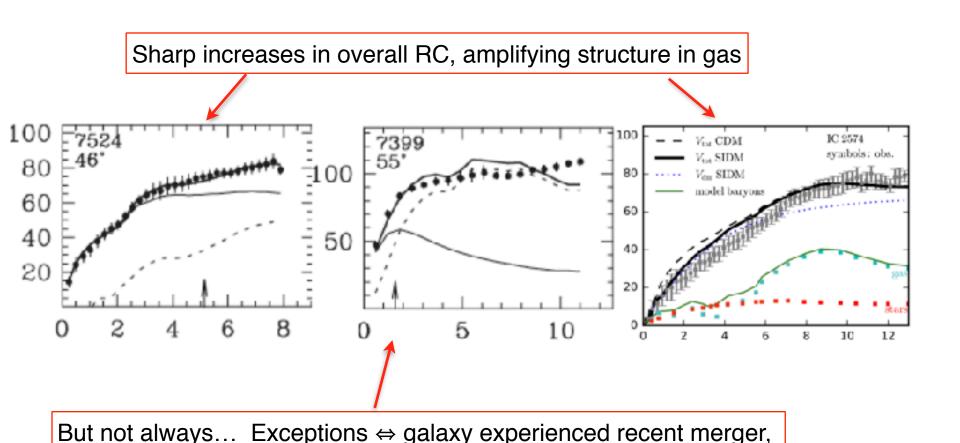


Figure 1. Mass models based on scaling the stellar disc and the H i component for the late-type dwarf galaxies in our sample. The filled circles represent the derived rotation curves. The thin full lines represent the contribution of the stellar discs to the rotation curves and the dotted lines that 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.

Rotation Curves ⇔ DM reflects gas



as predicted by SDM!

"Exceptions prove the rule" SDM provides natural explanation...

Swaters+12

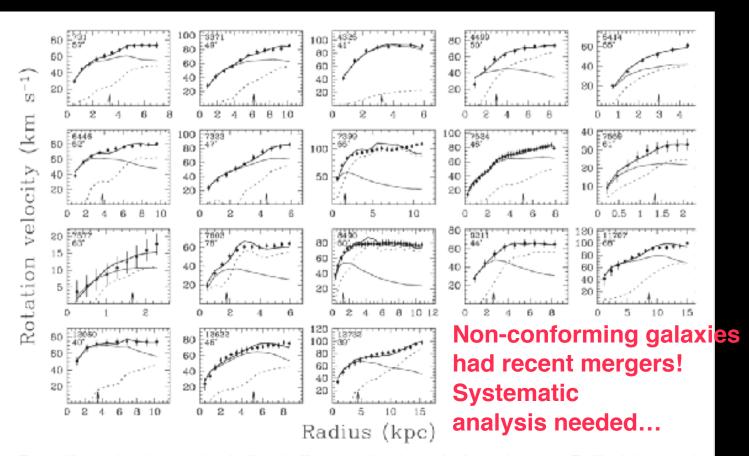


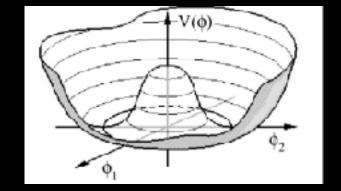
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Cosmology & structure formation

- 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 & σ₈
 - Problem or opportunity? To be determined...
- S-S self interactions + S-baryon interactions:
 similar benefits as Self Interacting DM
 - core-cusp, "too-big-to-fail", subhalo problems, etc.

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 $n_B \sim <\phi_S^\dagger \stackrel{\leftrightarrow}{\partial_t} \phi_S>$



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

Strategies to detect DM if DM is comprised of S's

- With $v_{rel} = 30 \text{ km/s}$, $KE_{DM} \sim 10 \text{ eV}$
 - <E_{deposit}>/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: $\lambda = 2 \text{ cm} / \sigma_{10mb}$
 - 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!

Tagging

Taggin

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 Y-decays or LHC experiments... mass can be accurately measured in Y-decay.
- 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**			
	Cardinal	Multiple	Distributive	Ordinal	Cardinal	Multiple Proportional Quantitative	Ordinal	Sanskrit ^[1]
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.

Potential impediments to SDM scenario

- Direct detection limits from X-ray Quantum
 Calorimeter co-rotation!
- Existence of Neutron Stars, Eqn of State NS

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Constraints on scalar asymmetric dark matter from black hole formation in neutron stars

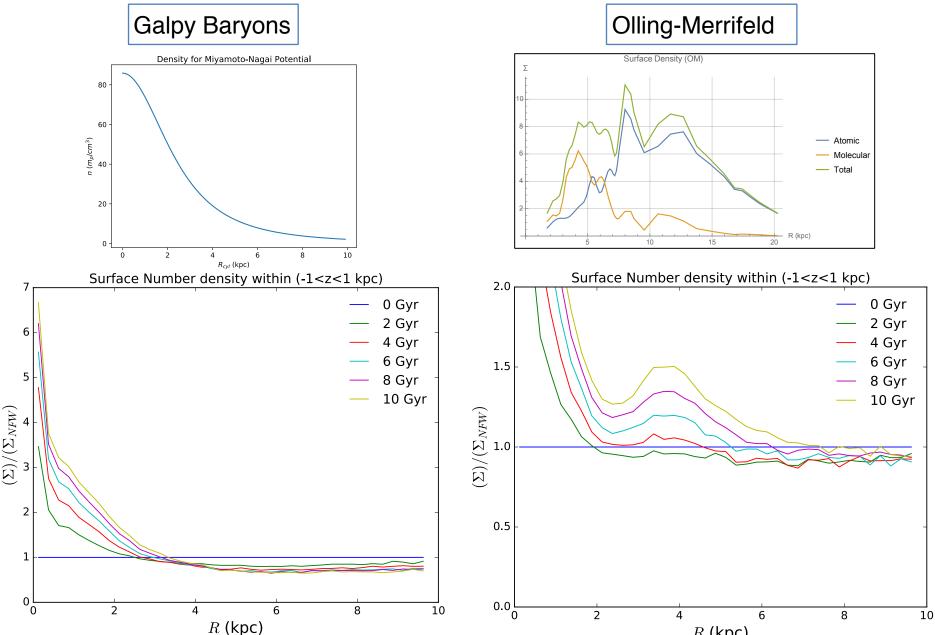
Samuel D. McDermott, Hai-Bo Yu, and Kathryn M. Zurek

Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA (Received 21 April 2011; published 13 January 2012)

We consider possibly observable effects of asymmetric dark matter (ADM) in neutron stars. Since dark matter does not self-annihilate in the ADM scenario, dark matter accumulates in neutron stars, eventually reaching the Chandrasekhar limit and forming a black hole. We focus on the case of scalar ADM, where the constraints from Bose-Einstein condensation and subsequent black hole formation are most severe due to the absence of Fermi degeneracy pressure. We also note that in some portions of this constrained parameter space, nontrivial effects from Hawking radiation can modify our limits. We find that for scalar ADM with mass between 5 MeV and 13 GeV, the constraint from nearby neutron stars on the scattering cross section with neutrons ranges from $\sigma_n \approx 10^{-45} \text{ cm}^2$ to 10^{-47} cm^2 .

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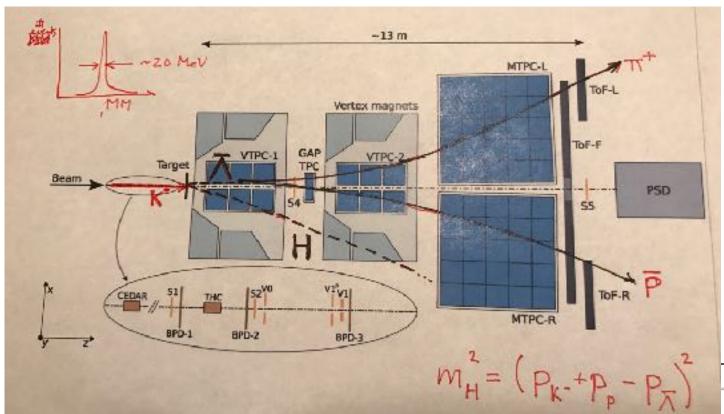
Sensitivity to gas density structure

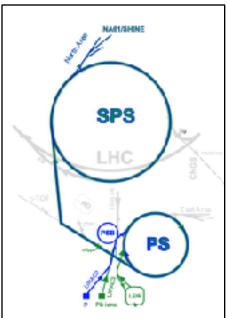


B:
$$+1 -1 +2 K^- p -> S$$
S: s \bar{s} ss

- $\overline{\Lambda}$ is a gold-plated signature : $\overline{\Lambda}$ -> π^+ \overline{p}
 - Easy to ID & reconstruct 4-momentum
 - $c\tau = 8$ cm all $\overline{\Lambda}$ 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 $\overline{\Lambda}$'s
- NA61: 9 GeV/c K- beam, need trigger to

NA61/SHINE





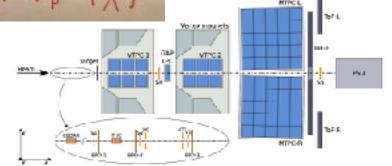


Figure 1. Schematic layout of the NA61/SHINE experiment at the CERN SPS (horizontal cut in the beam plane, not to scale). The beam and trigger counter configuration used for data taking on

NA61

- Trigger rate ~100 Hz => 10⁷ events per day
 - GEANT: ~ 0.5% K⁰ 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-> 1 RH

• K-p-> K⁰ n + neutrals

$$\rightarrow \pi + \pi$$

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

- NA61: good rejection of K⁰ faking Λ
 - ToF, dEdX, kinematic cuts to reject in dangerous regions
 - GEANT sims running to quantify...

