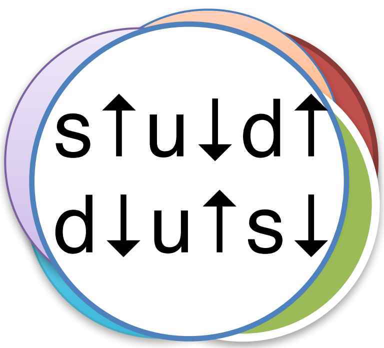
Stable Sexaquark as Dark Matter

Glennys R. Farrar
New York University

Unique among multi-quark states:

Fermi statistics is compatible with a
totally symmetric spatial wave function



S

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

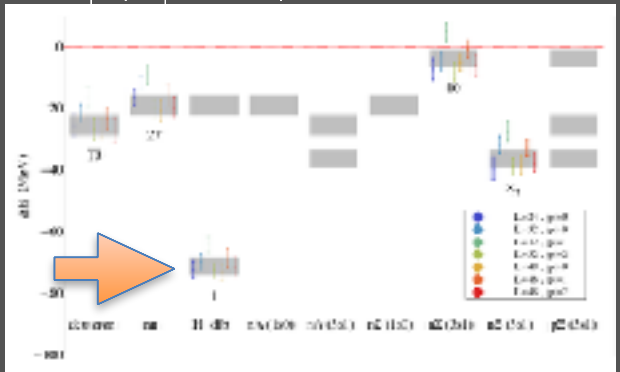
Mass of S

- Options for stability ($\tau > \tau_{Univ}$)
  - **$M_S < 2\, m_p + 2\, m_e$** = 1877.6 MeV ➜ **absolutely stable**
  - $M_S < m_p + m_e + m_\Lambda$ = 2054.5 MeV ➜ decay rate ~ G_F^2 x wave function overlap ➜ lifetime up to 10^{27} yr.

- Is 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
    - 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**

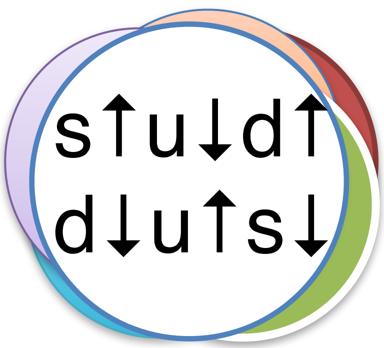
  => it must be STABLE ! ;-)



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 $\tau >> \tau_{Univ}$)

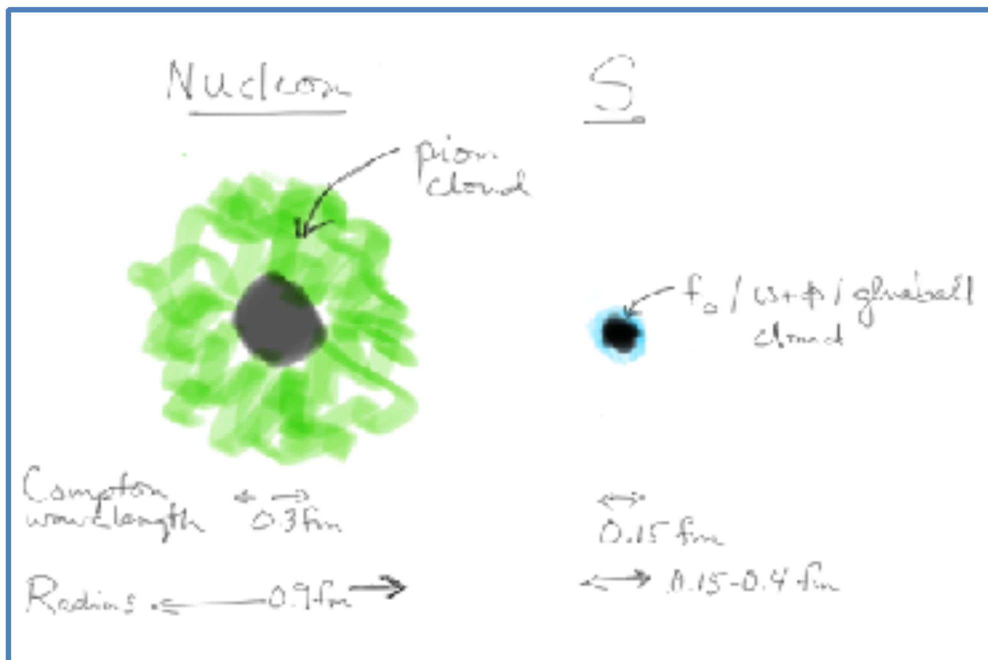


S

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,…)

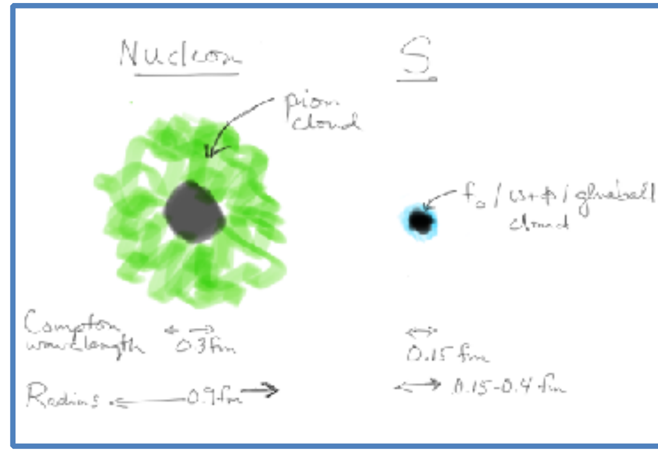


Structure of the S: $u_\uparrow u_\downarrow d_\uparrow d_\downarrow s_\uparrow s_\downarrow$

- Flavor SU(3) singlet ⇒
  - *no coupling to SU(3) octets π, ρ*
  - ***No pion cloud***

- No pion cloud ⇒
  - r_S ~ 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 ~ 0.15 - 0.4 fm*** depending on strength of f_0 coupling
  - σ_{SN} ~ 5 to 20 mb (at v/c ~ 1 ; may grow as v/c → 0, as σ_{NN} does)

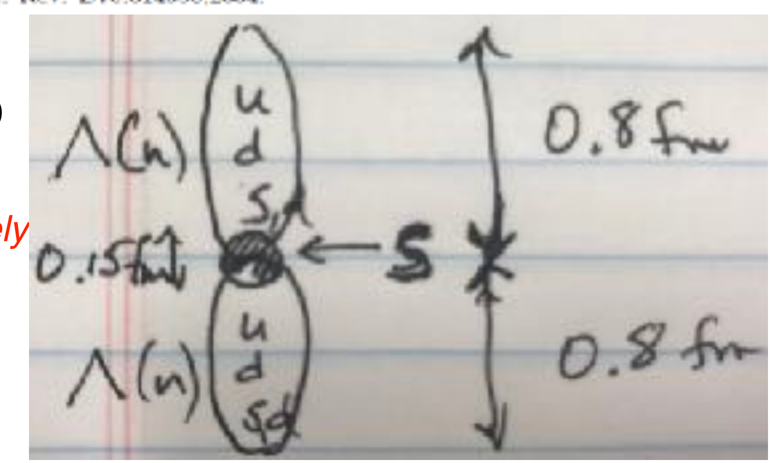
"Nucleon and Nuclear Transitions of the H dibaryon", GRF and G. Zaharijas.
Phys. Rev. D70:014008,2004.

⇒ ***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)*

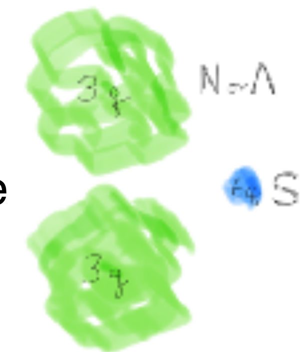


- Scalar (spin-0, even parity)

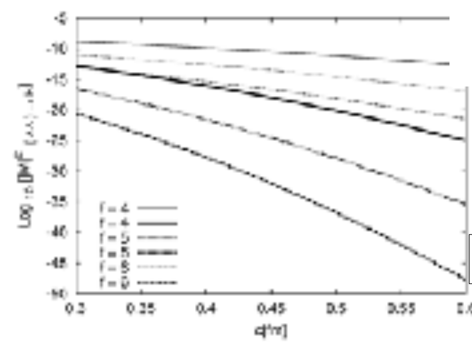
"A STABLE H DIBARYON: DARK MATTER CANDIDATE WITHIN QCD?" Int. J. Theor. Phys. 42:1211-1218, 2003. Also in "Minneapolis 2002, Continuous advances in QCD" 582-590.

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

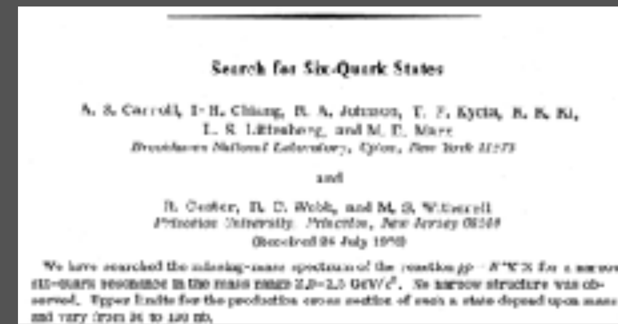


GRF+G.Zaharijas 2004

- **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.:**
    - $\Upsilon \to \Lambda\,\Lambda\,\bar{S}$ (+ 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.*
  - 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 $10^{-8} < \tau < 2 \times 10^{-6}$ s
  - Belz+ BNL 1996: H -/-> Λ n or Σ n [c.f., issue raised by L. Littenberg]
  - Kim+ Belle 2013: no narrow resonance in $\Upsilon \rightarrow \Lambda$ 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, K. K. Li, L. S. Littenberg, and M. D. Marx

Brookhaven National Laboratory, Upton, New York 11973

and

R. Cester, R. C. Webb, and M. S. Witherell

Princeton University, Princeton, New Jersey 08540

(Received 26 July 1978)

PHYSICAL REVIEW LETTERS

Search for the Weak Decay of an H Dibaryon

PHYSICAL REVIEW LETTERS

Production of ${}_{\Lambda\Lambda}^{4}$H Hypernuclei

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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  - Kim+ Belle 2013: no narrow resonance in Υ -> Λ p K
- Limits from production in doubly-strange hypernuclei:
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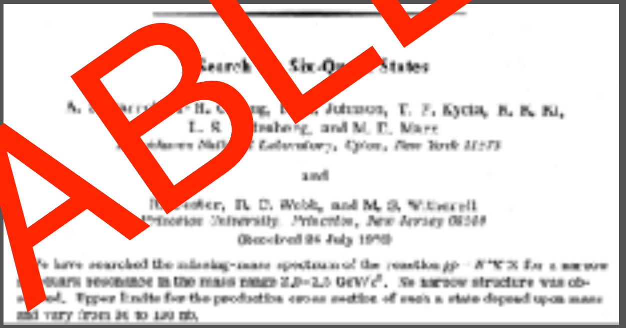
  - Takahashi+ KEK 2001

NOT APPLICABLE to S!



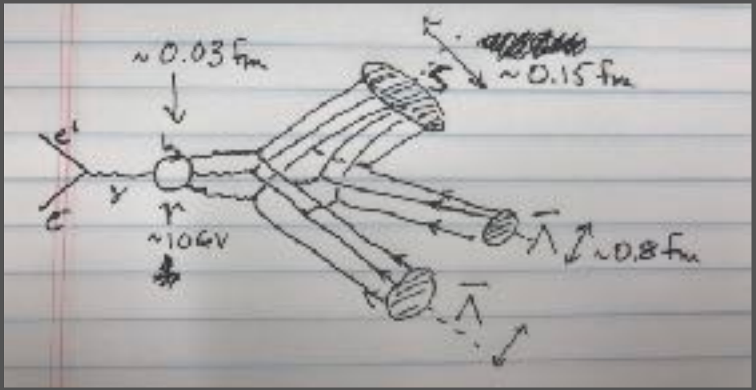
Discovery Strategy

- Apparent lack of B and S conservation:
  - **$\Delta B = \pm 2 \quad + \quad \Delta S = \mp 2$**

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

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

$\Upsilon \to \Lambda\,\Lambda\,\bar{S}$ & $\bar{\Lambda}\,\bar{\Lambda}\,S$
(+ pions)



- Υ is ***localized*** **source of ggg**

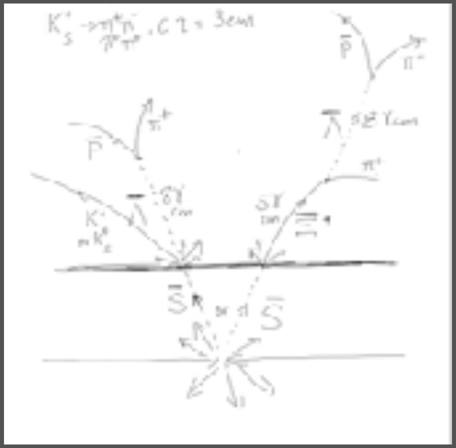
  ⇒ production of S is (relatively) enhanced

- 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 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
    - $\bar{S}$ 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} - $\boldsymbol{\sigma}_{f.o.}$)

Dark Matter Relic Abundance

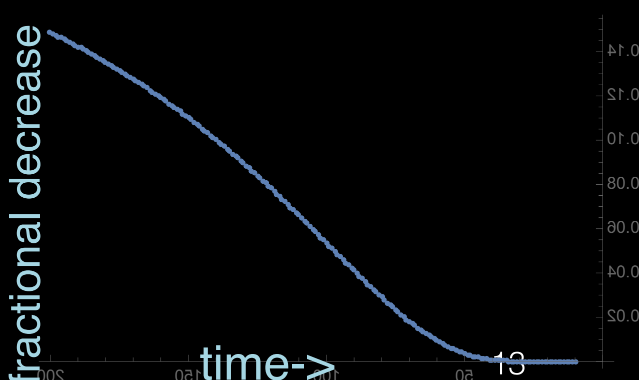
- Reheating: production of photons & fragmentation of $< \phi_S >$ into particles
- Breakup: $\gamma + S \rightarrow \Lambda\,\Lambda$

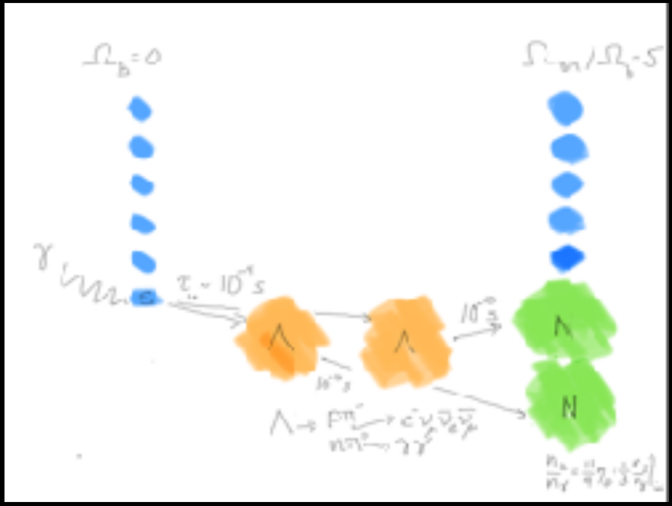
$$\frac{d\,n_S}{n_S\,dT} = -\Gamma(\gamma + S \to \Lambda\Lambda)\frac{dt}{dT}$$

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

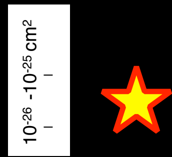
- ~16% of S's are broken up before freeze out ⇒

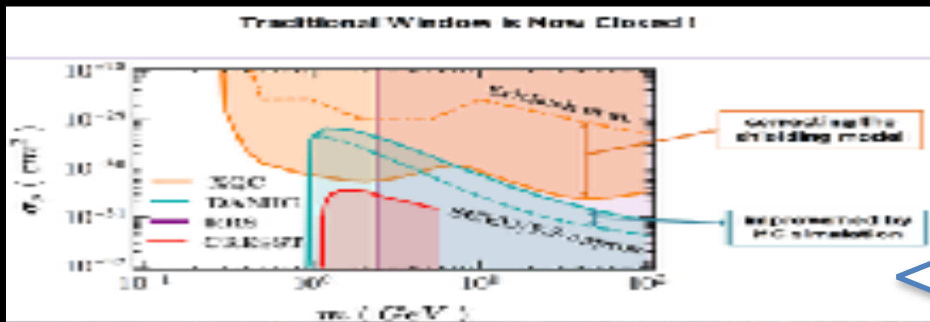
Ω_{DM} / Ω_b = 5 . Natural!





Stable S as Dark Matter





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

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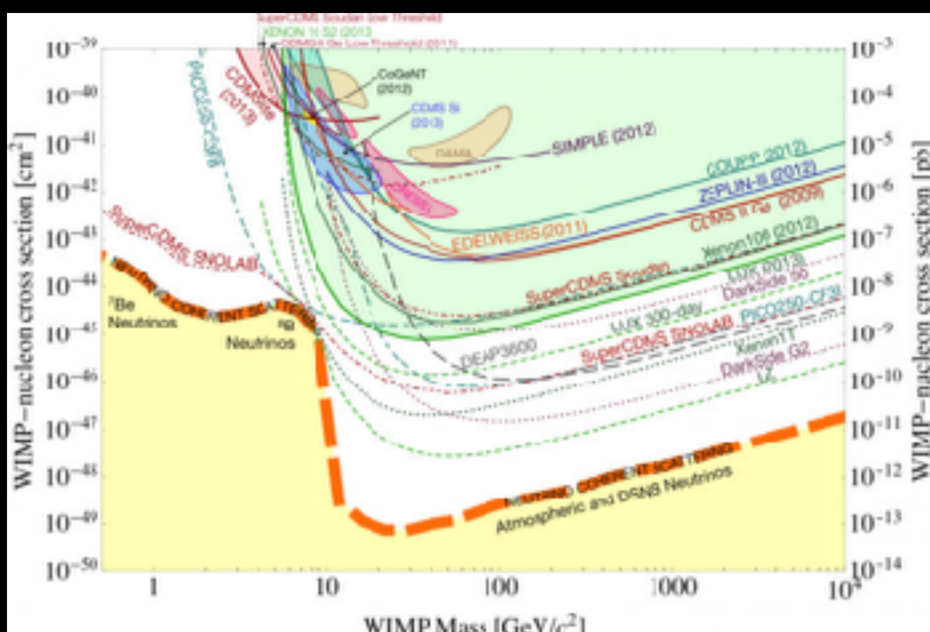
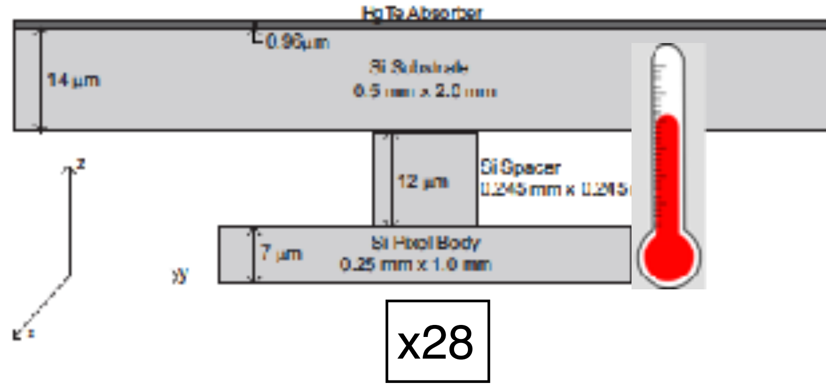
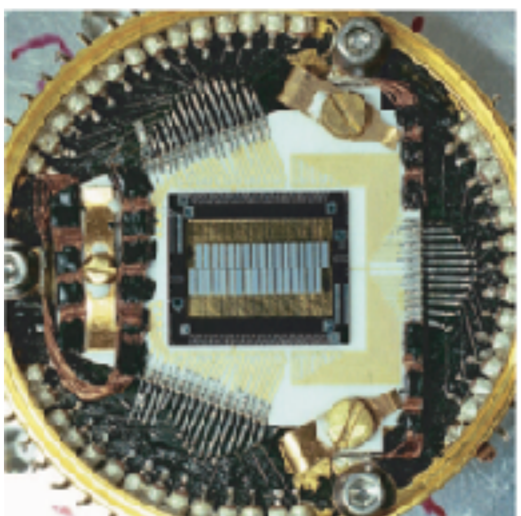
Abstract. We improve limits on the spin-independent scattering cross section of Dark Matter on nucleons, for DM in the 300 MeV – 100 GeV mass range, based on the DAMIC and XQC experiments. Our results close the window which previously existed in this mass range, for a DM-nucleon cross section of order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

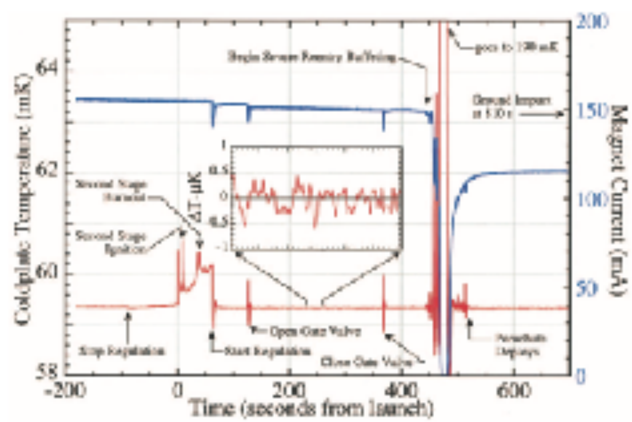


X-Ray Quantum Calorimeter (XQC)



- 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)*





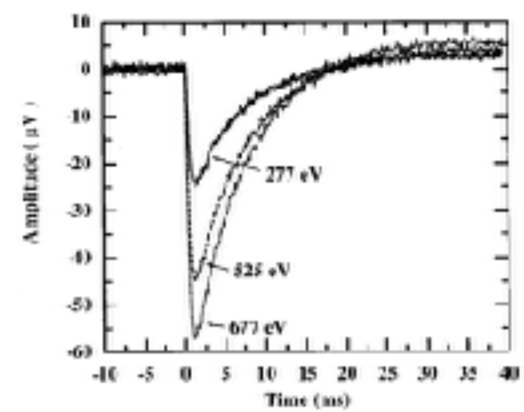
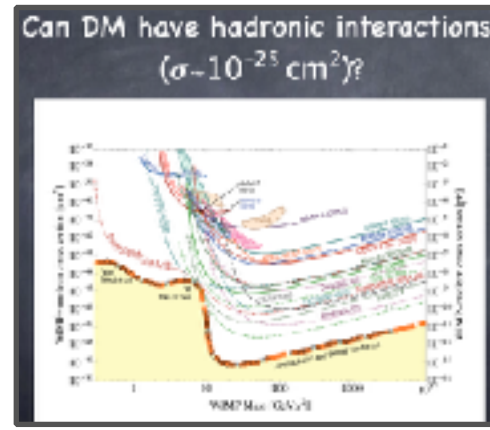


Fig. 9.—Unfiltered X-ray pulses from the gate-valve calibration source.

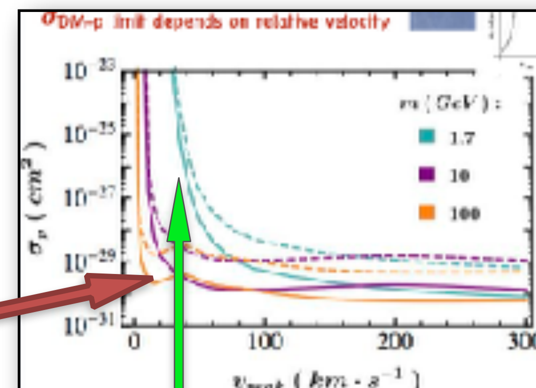
Evading Direct Detection II. XQC applicability

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 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: *λ = 2 cm / σ_{10mb}***
    - **~~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: ***σ_{DM} < 10^{-29} cm^2 for standard velocity dispersion — SDM has σ_{DM} ~ 10-100 mb***
  - ***$v_{min,XQC}$ = 107 km/s (2 m_p / m_{DM})$^{1/2}$***

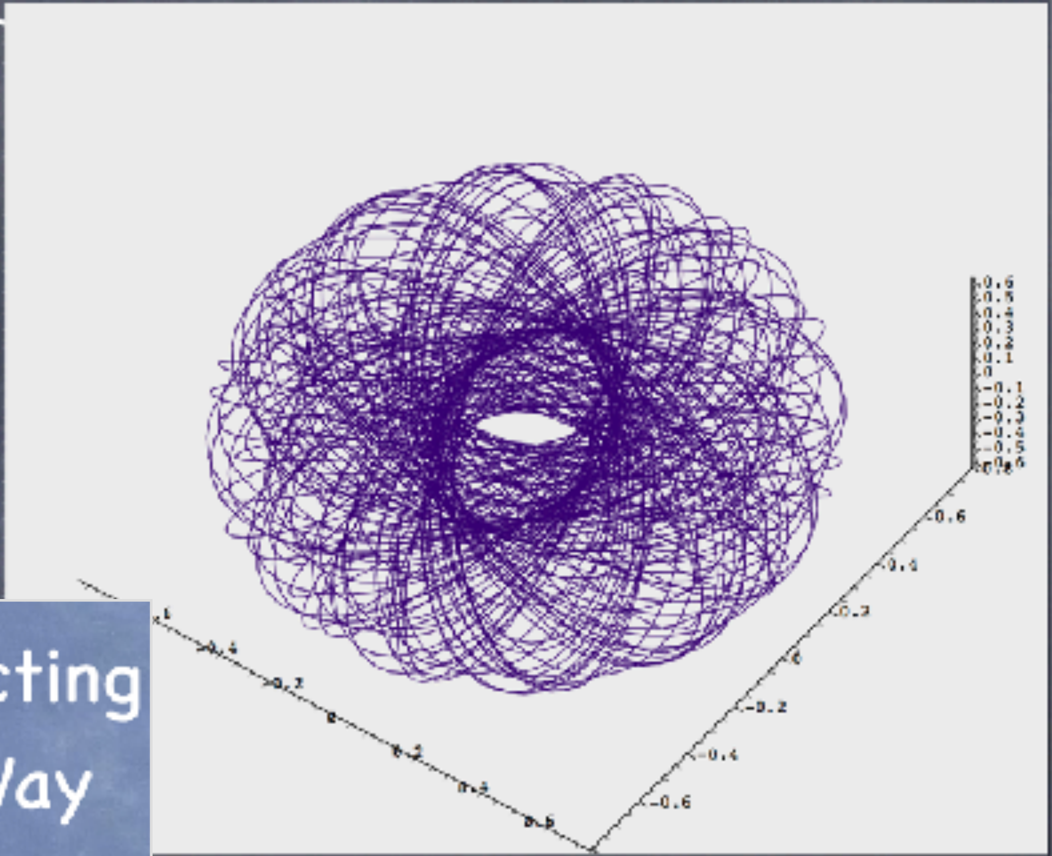


Co-rotation reduces SDM signal

Viability of Co-Rotation Scenario

Schwarzchild Modelling

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

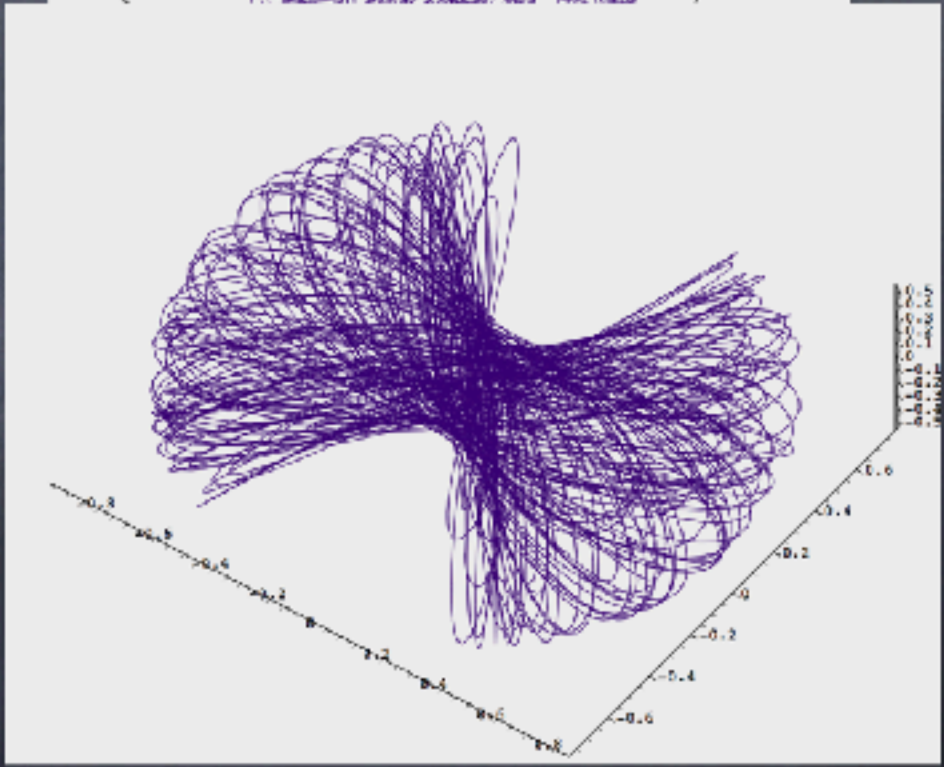


Simulations of DM interacting with gas in the Milky Way

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

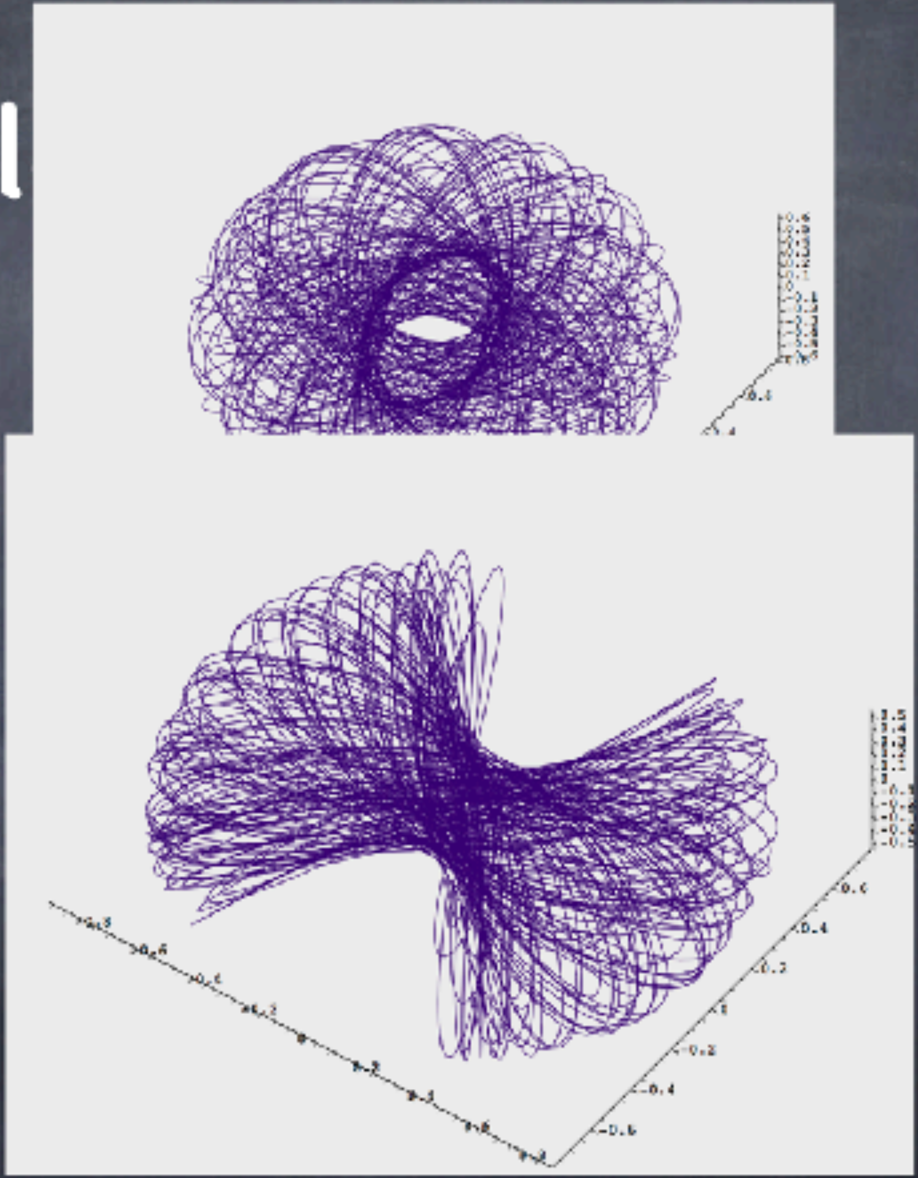
Schwarzchil

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



D. Wadekar, NYU

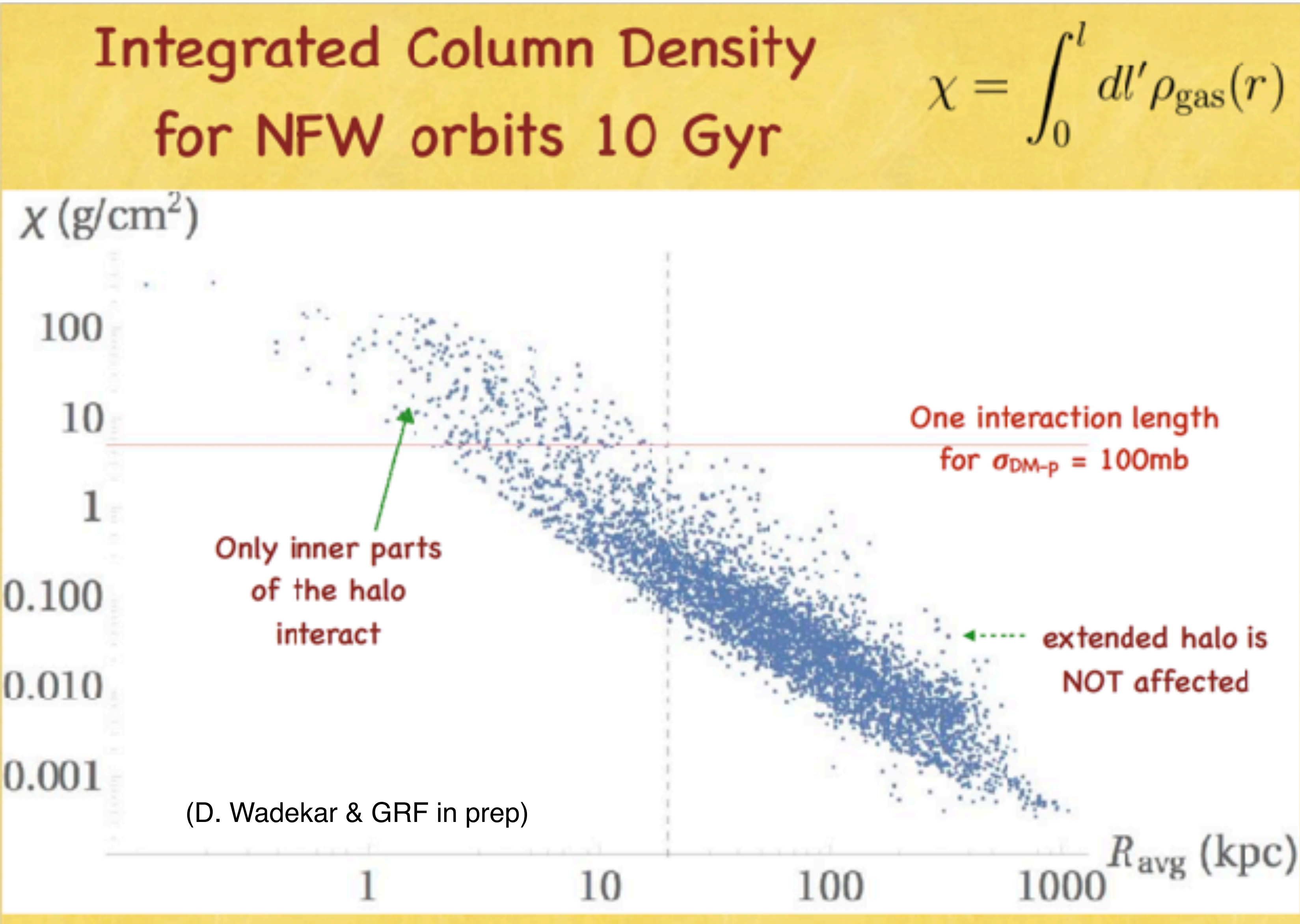
Schwarzchil



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

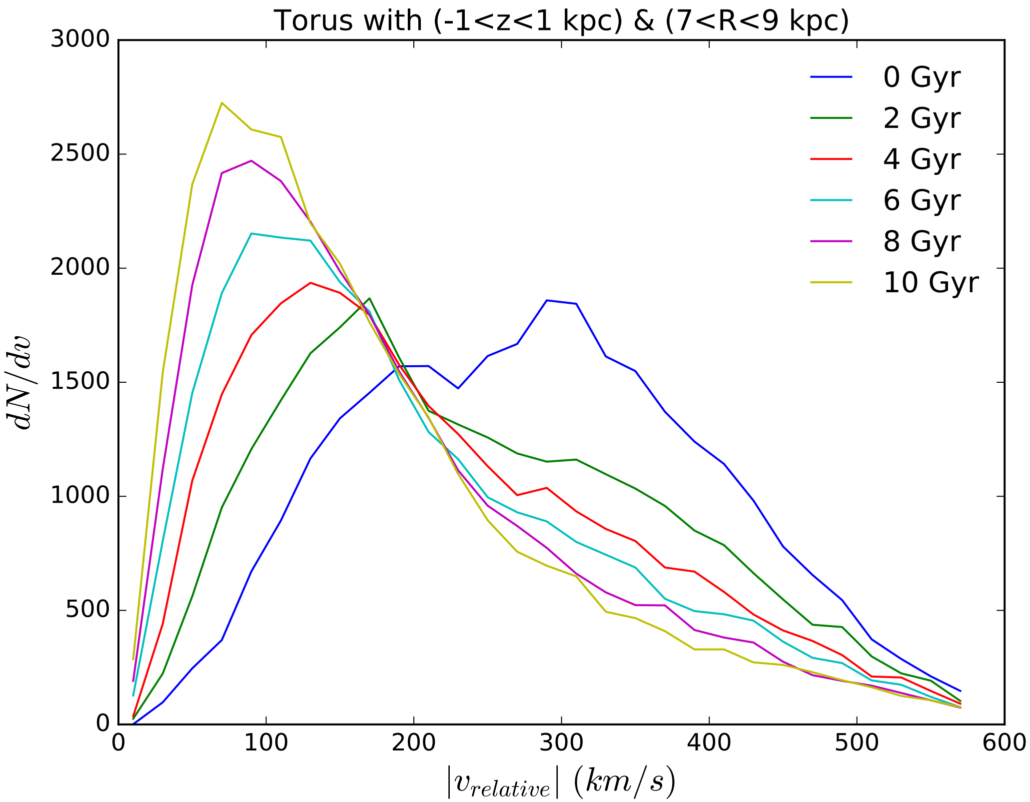
Dark Matter-Gas Scattering

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



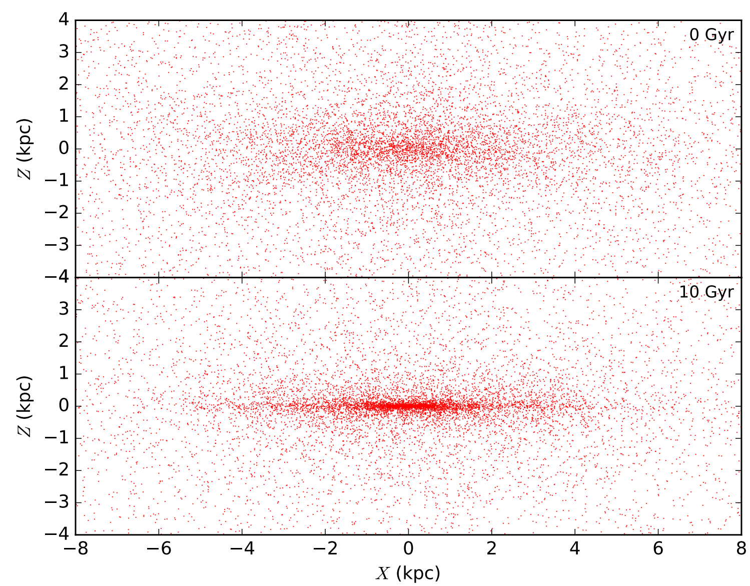
- Select a DM particle and follow its orbit
- Monte-carlo choose its scattering point on gas
- Isotropically scatter -> kinematics of new orbit

(D. Wadekar & GRF in prep)



Highly idealized analysis:

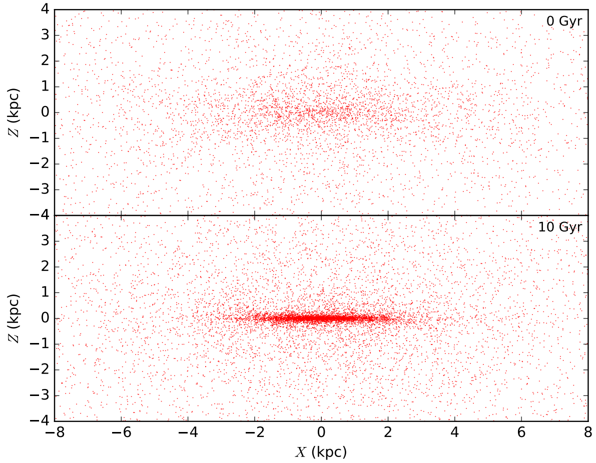
- static potential & gas
- actually grows by accretion
- c.f. Bruch-Read+
- proof of concept, shows cross-section needed is reasonable.

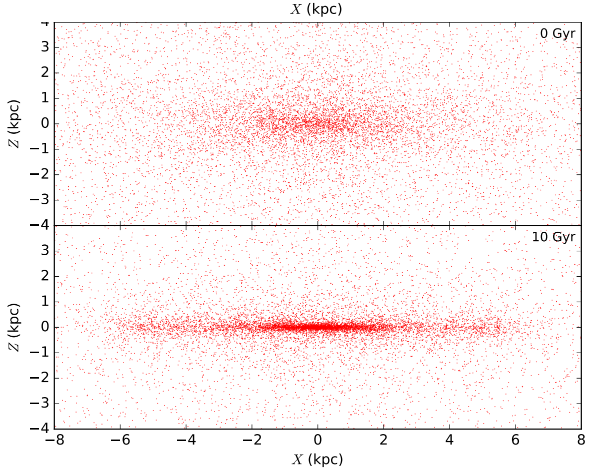


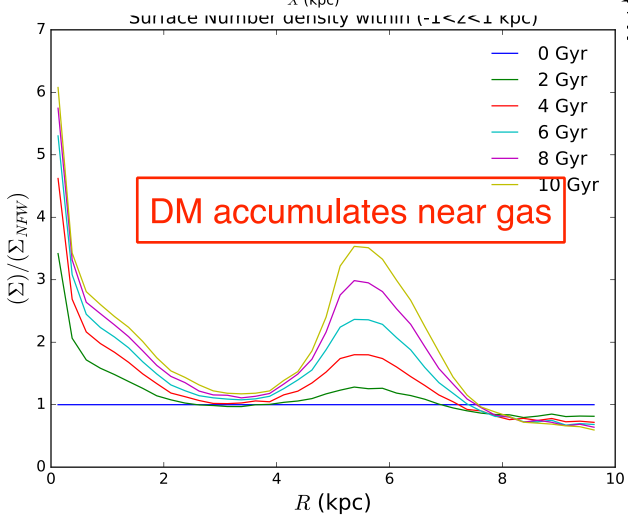
Co-rotation!

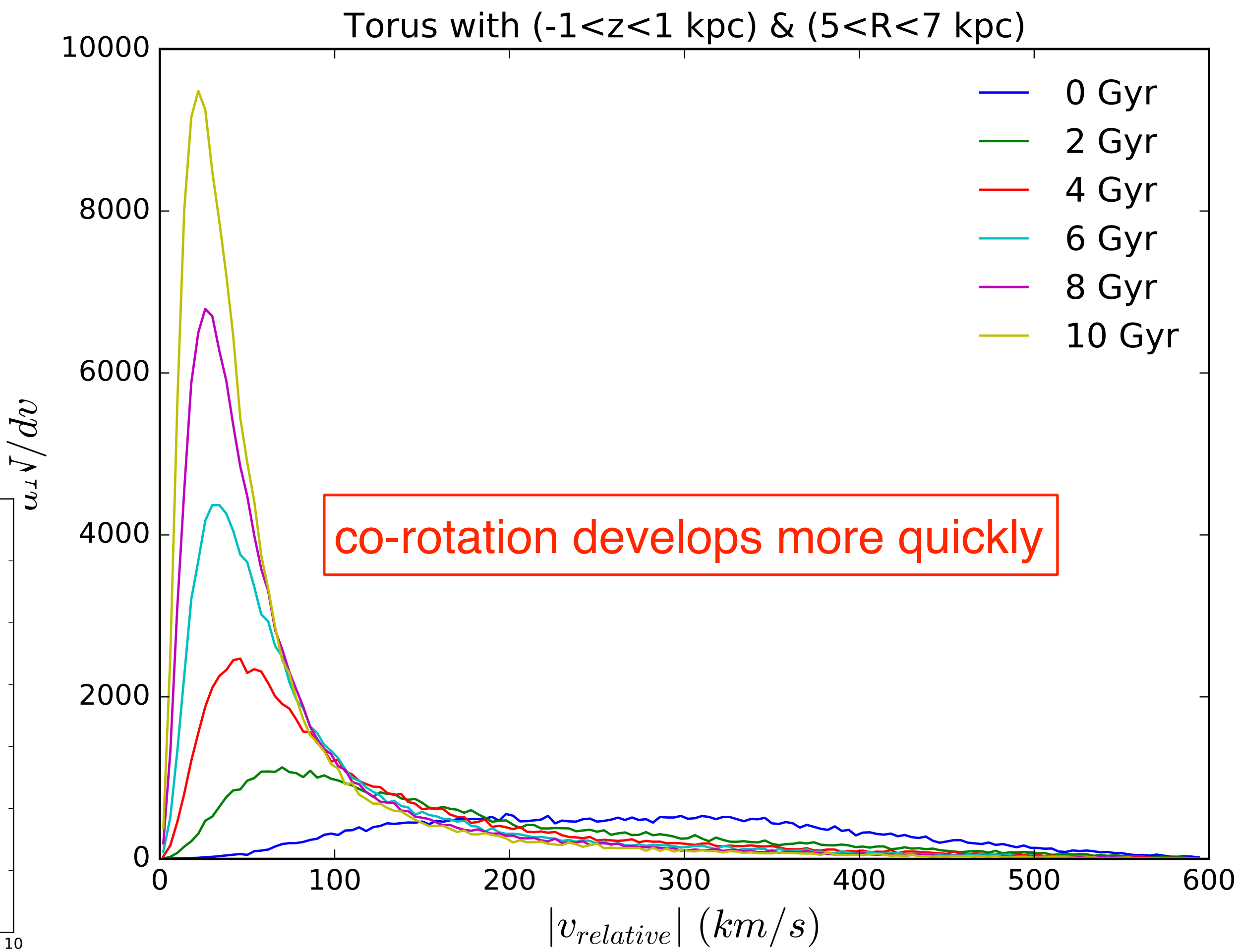
in realistic galaxies, gas is inhomogeneous ⇒

test with extra torus









Rotation Curves ⇔ DM reflects gas

Swaters+12: hundreds of galaxies of all types

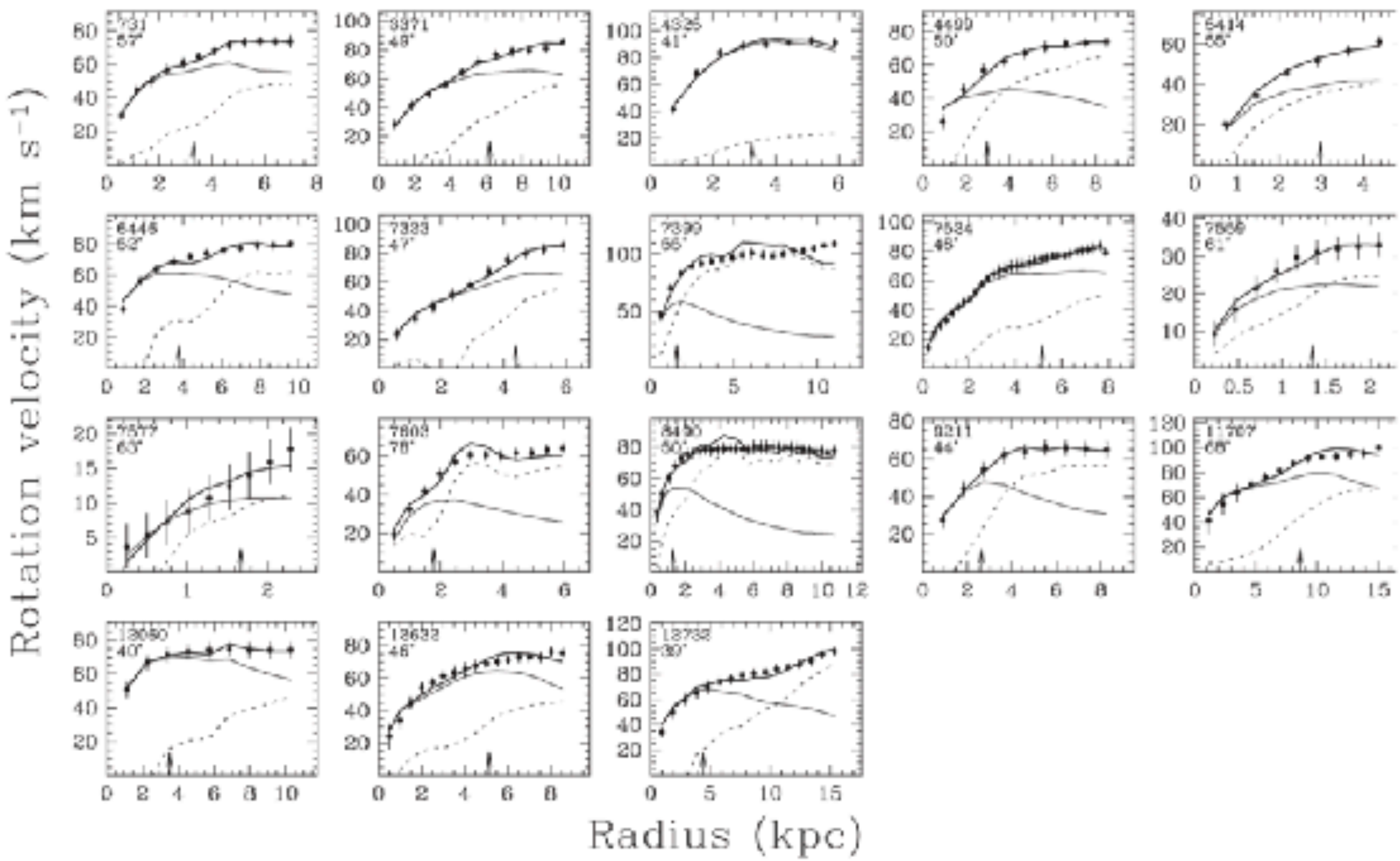
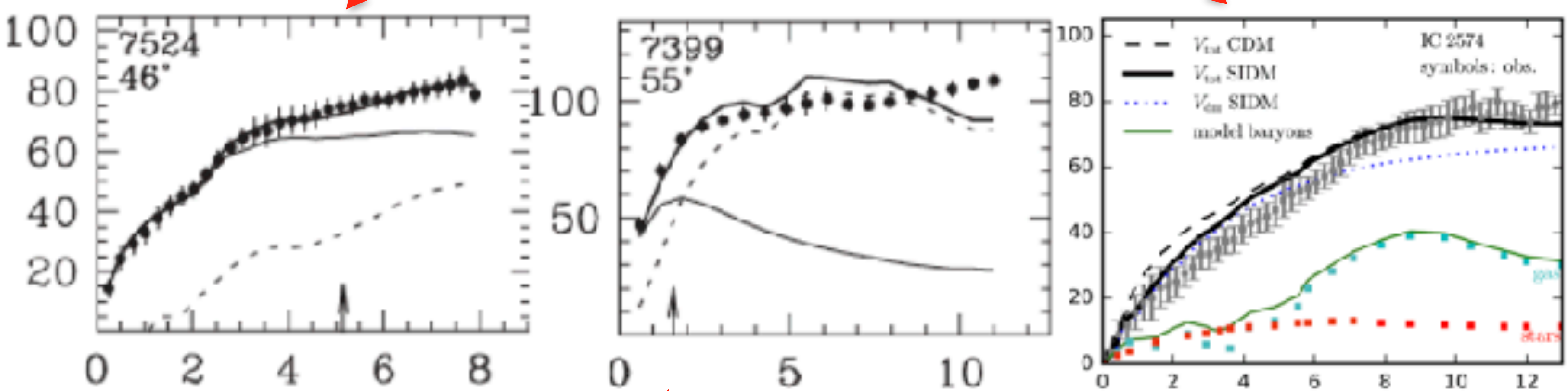


Figure 1. Mass models based on scaling the stellar disc and the H I component for the late-type dwarf galaxies in our sample. The filled circles represent tl derived rotation curves. The thin full lines represent the contribution of the stellar discs to the rotation curves and the dotted lines that of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

Rotation Curves ⇔ DM reflects gas

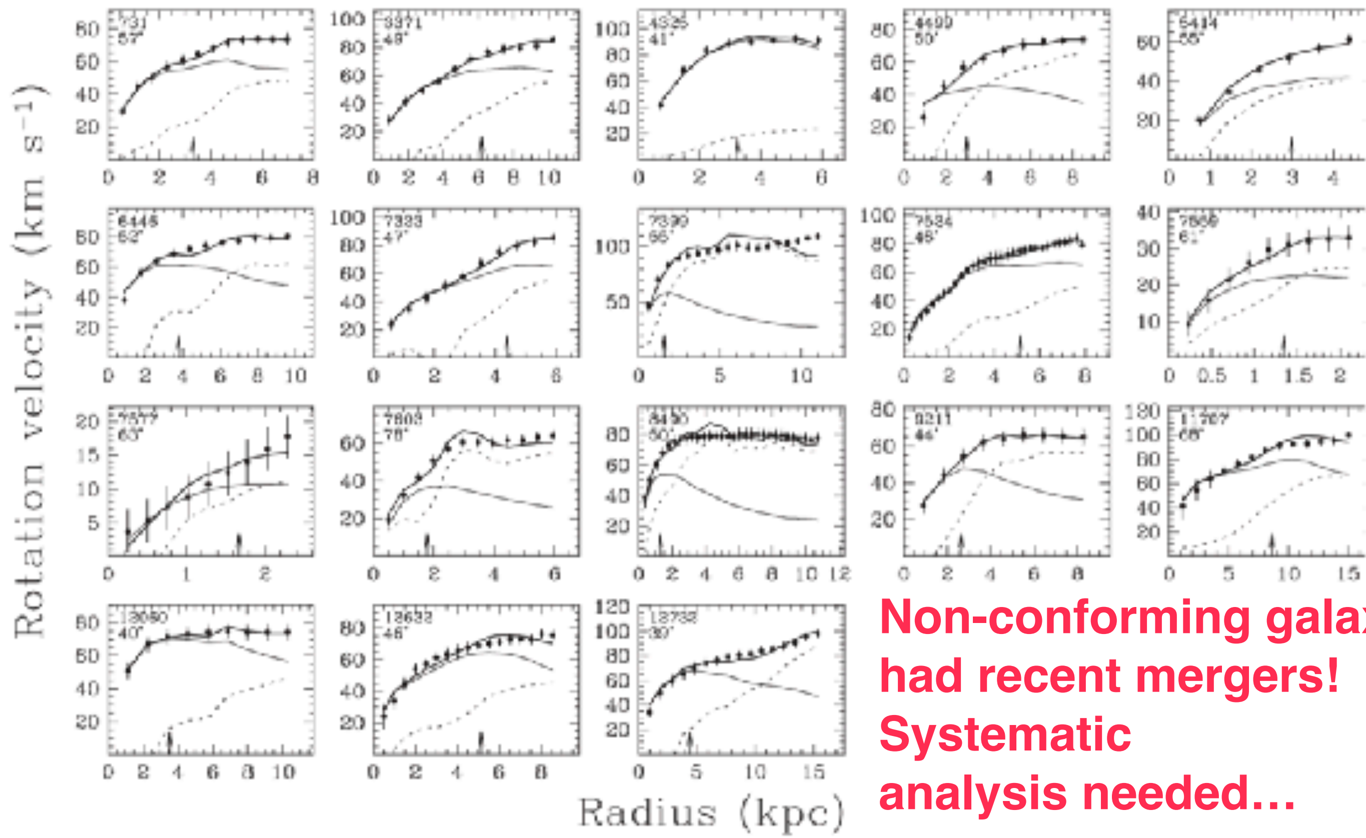
Sharp increases in overall RC, amplifying structure in gas



But not always… Exceptions ⇔ galaxy experienced recent merger, as predicted by SDM!

“Exceptions prove the rule”
SDM provides natural explanation…

Swaters+12



Non-conforming galaxies had recent mergers! Systematic analysis needed…

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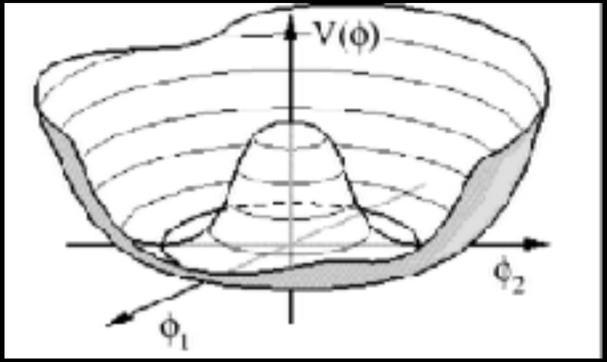
Cosmology & structure formation

- 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_0 & σ_8**
  - 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***

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

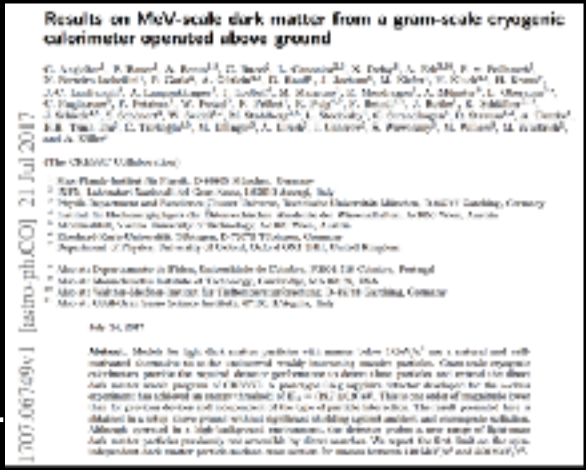


Baryon number is non-zero. After reheating it looks like it was just an initial condition.

Strategies to detect DM

if DM is comprised of S's

- With v_{rel} = 30 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:**
    λ = 2 cm / σ_{10mb}
  - **Present detectors shielded or too high threshold (new CRESST expt has E_{th} = 19 eV, but 30 cm shielding ⇒ not sensitive)**


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

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

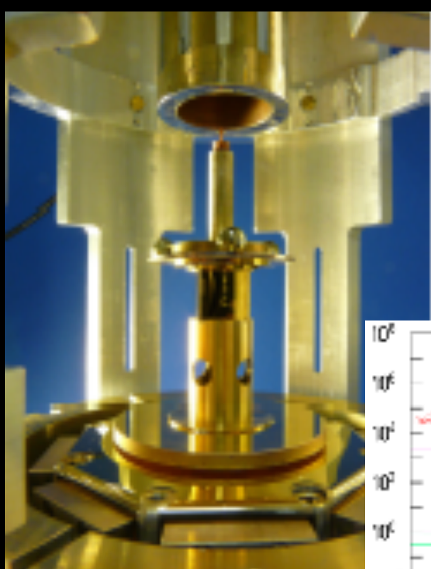
- Heating rate liquid He: ~ nW/mol ~ CR muon energy deposit rate.
  - can't *shield* muons & other CRs: veto? but what about neutrons?

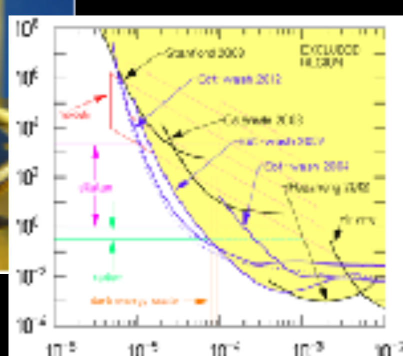
S dark matter detection with a torsion balance on the ISS

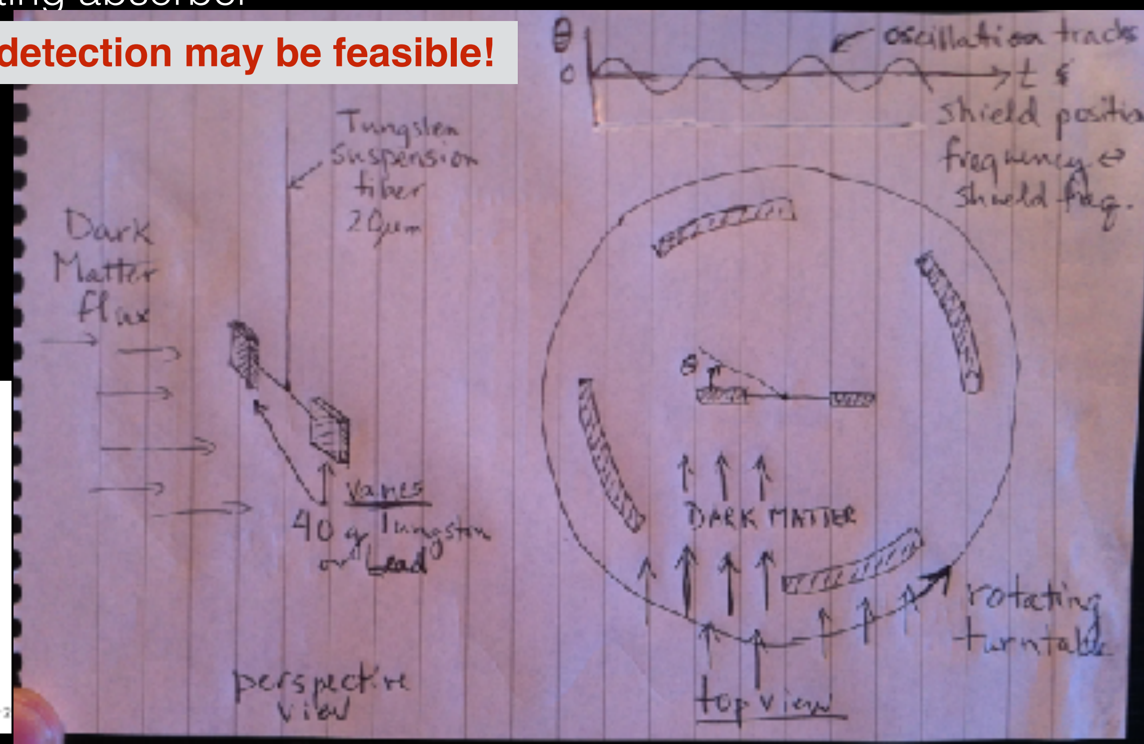
W. Terrano & GRF, in preparation

- 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.***
- ***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] hectaic-	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

PHYSICAL REVIEW D 85, 023519 (2012)

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

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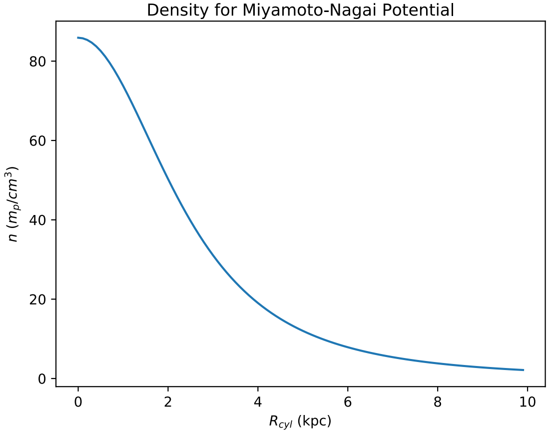
(Received 21 April 2011; published 13 January 2012)

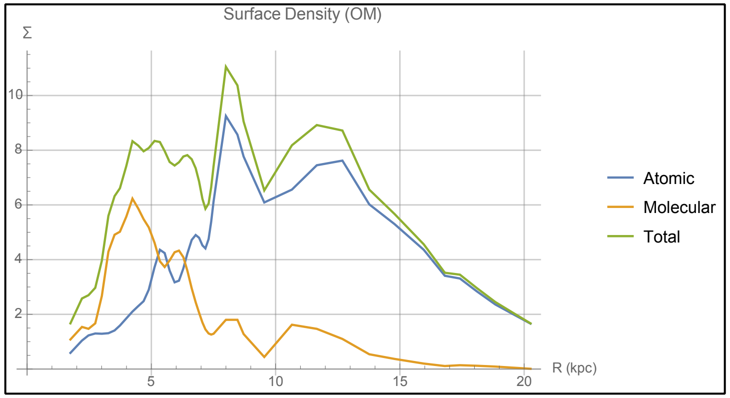
We consider possibly observable effects of asymmetric dark matter (ADM) in neutron stars. Since dark matter does not self-annihilate in the ADM scenario, dark matter accumulates in neutron stars, eventually reaching the Chandrasekhar limit and forming a black hole. We focus on the case of scalar ADM, 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 $\sigma_n \lesssim 10^{-45}$ cm^2 to 10^{-47} cm^2.

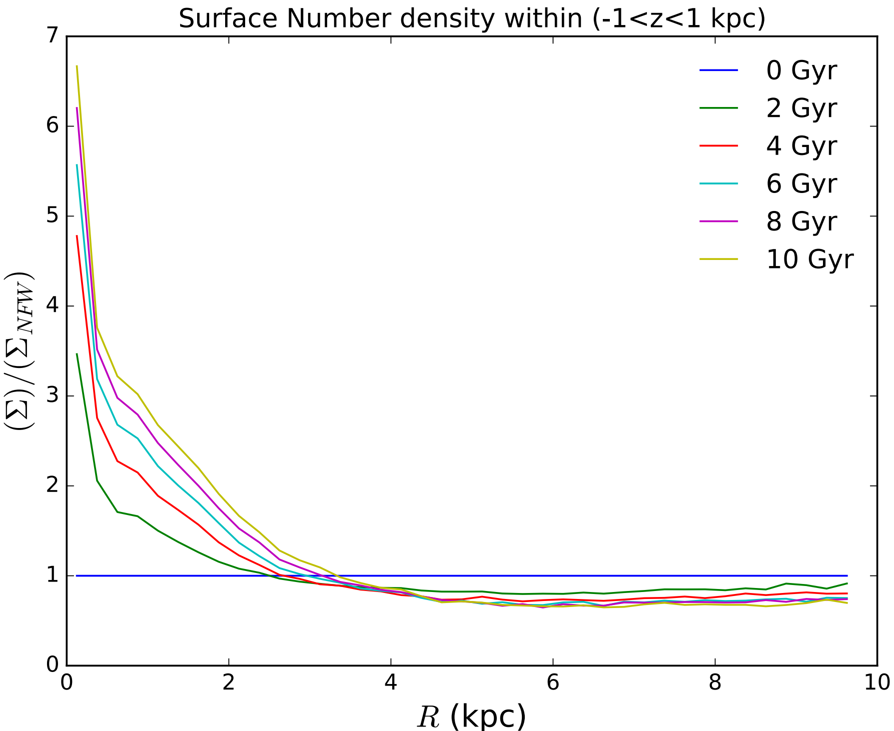
Sensitivity to gas density structure

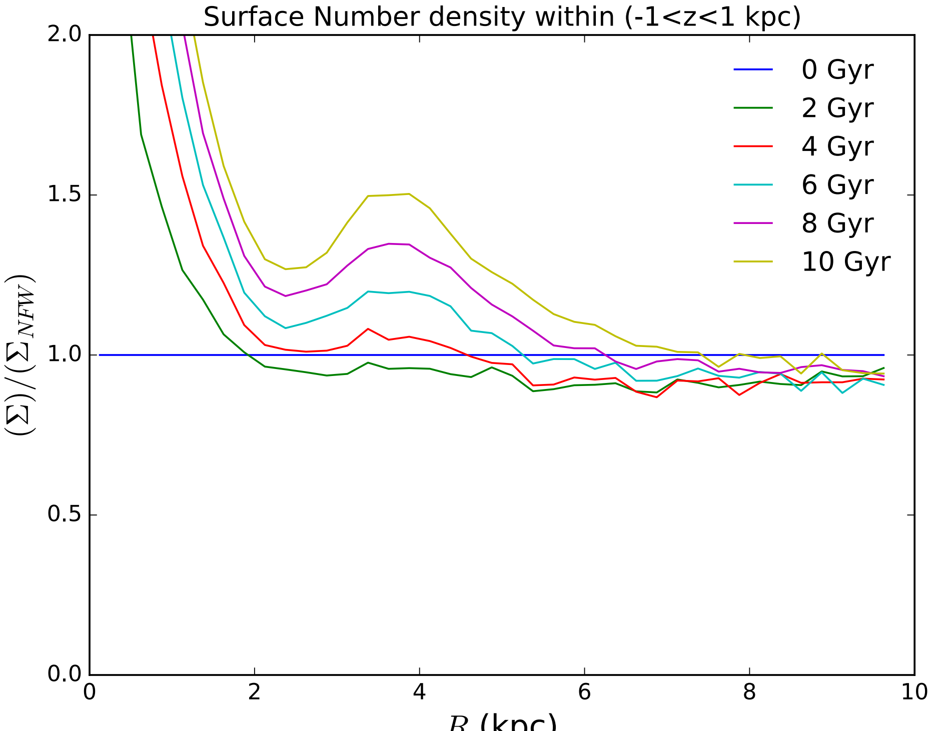
Galpy Baryons

Olling-Merrifeld









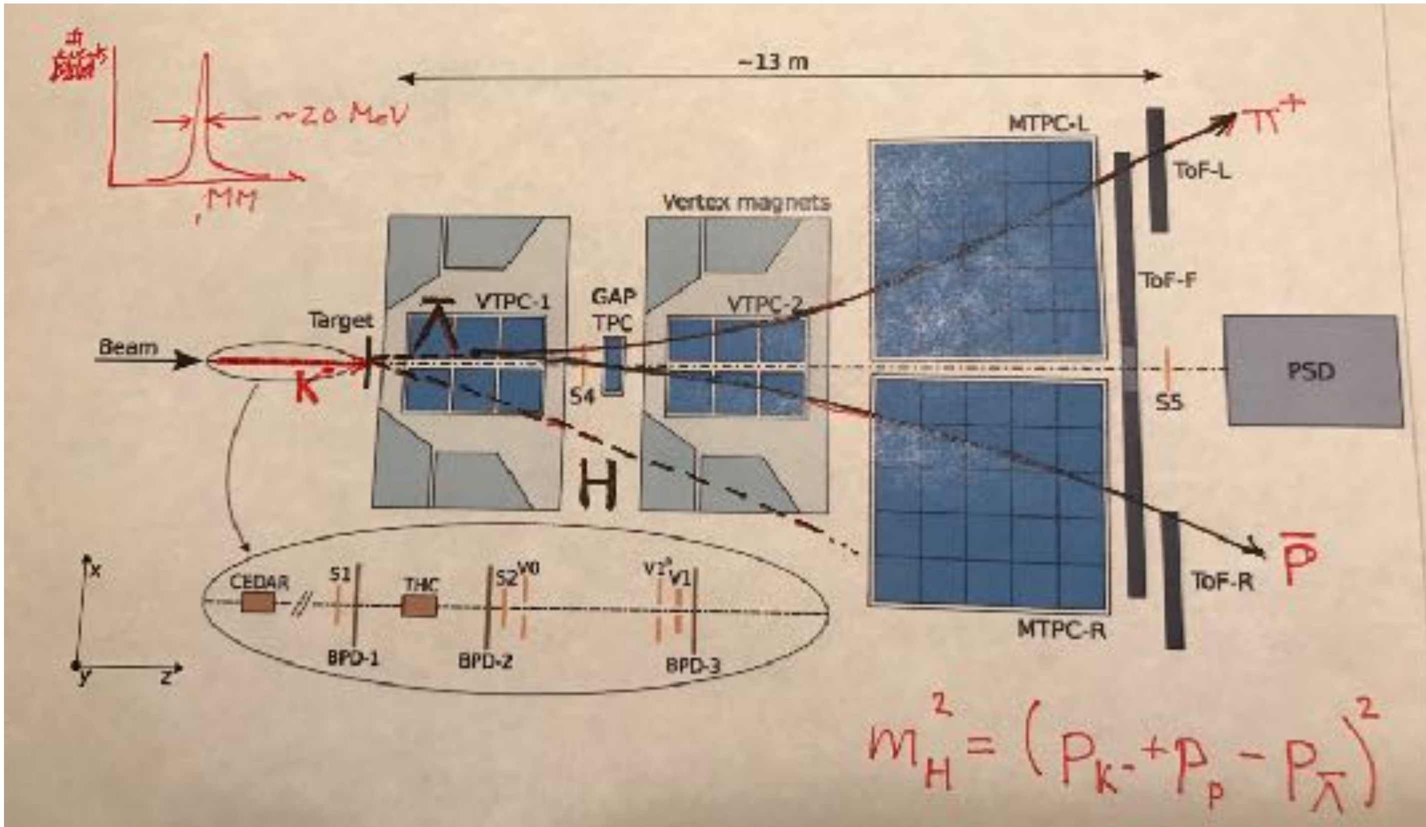
B: +1 -1 +2

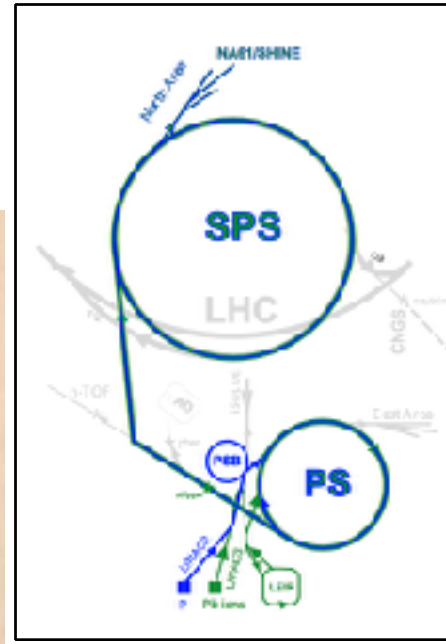
$$K^- p \rightarrow \bar{\Lambda} S$$

S: s $\bar{s}$ ss

- $\bar{\Lambda}$ is a gold-plated signature : $\bar{\Lambda} \rightarrow \pi^+ \bar{p}$
  - 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





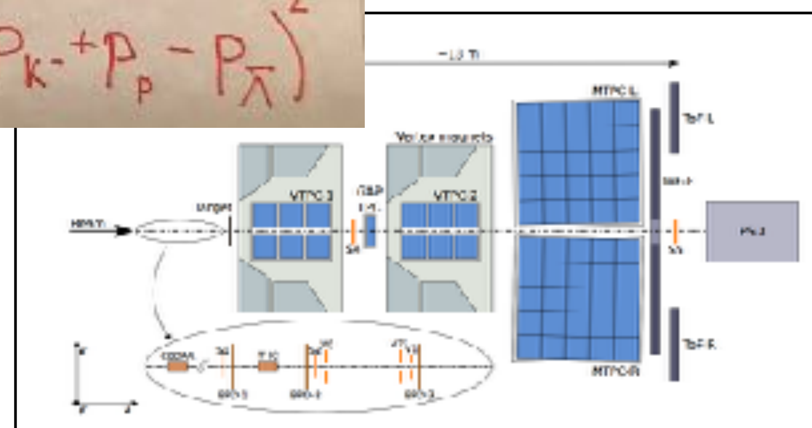


Figure 1. Schematic layout of the NA61/SHINE experiment at the CERN SPS (horizontal cut in the beam plane, not to scale). The beam and trigger counter configuration used for data taking on

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