IMPLICATIONS OF PLANET-BOUND DARK MATTER

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- GRAVITATIONALLY BOUND DARK MATTER
- PLACING DIRECT LIMITS ON THE MASS OF EARTH-BOUND DARK MATTER
- CAN THE FLYBY ANOMALY BE ATTRIBUTED TO EARTH-BOUND DARK MATTER?
- PLANET-BOUND DARK MATTER AND THE INTERNAL HEAT OF URANUS, NEPTUNE, AND HOT-JUPITER EXOPLANETS

GRAVITATIONALLY BOUND DARK MATTER

COSMOLOGY SUGGESTS THAT ONLY ~4% OF THE MASS-ENERGY DENSITY OF THE UNIVERSE IS ORDINARY BARYONIC MATTER

~23% IS GRAVITATIONALLY ATTRACTIVE
"DARK MATTER"

~73% IS GRAVITATIONALLY REPULSIVE
"DARK ENERGY"

LITTLE IS KNOWN ABOUT DARK MATTER:

- IS IT BOSONIC OR FERMIONIC ?
- IS IT SELF-ANNIHILATING (EITHER ITS OWN ANTIPARTICLE, OR EQUAL ABUNDANCES OF PARTICLE AND ANTIPARTICLE)

OR NON-SELF-ANNIHILATING ?

- WHAT ARE MASS (MASSES) AND NON-GRAVITATIONAL INTERACTIONS ?
- HINTS OF DIRECT DETECTION DAMA/LIBRA
PAMELA

DARK MATTER CAN BE GRAVITATIONALLY BOUND ON DIFFERENT SCALES

- GALACTIC HALO DARK MATTER

  MASS DENSITY $\rho \sim 0.3 \ GeV/c^2 \ cm^{-3}$

- SOLAR SYSTEM-BOUND DARK MATTER?

  $\rho < 10^5 \ GeV/c^2 \ cm^{-3}$

  FROM STUDY OF PLANETARY ORBITS

  (Frère, Ling + Vertongen
  Sereno + Jetzer
  Iorio
  Khriplovich + Pitjeva)

- EARTH AND PLANET-BOUND DARK MATTER?

  SUBJECT OF THIS TALK:

  BOUNDS

  IMPLICATIONS

PLACING DIRECT LIMITS ON THE MASS OF EARTH-BOUND DARK MATTER

CAN SET A DIRECT LIMIT ON THE TOTAL EARTH-BOUND DARK MATTER MASS LYING BETWEEN THE RADIUS ~384,000 km OF MOON'S ORBIT, AND THE RADIUS ~12,300 km OF LAGEOS GEODETIC SATELLITE ORBIT

FOR A SATELLITE OF NEGLIGIBLE MASS IN CIRCULAR ORBIT AROUND BODY OF MASS M, MEASUREMENT OF ORBIT RADIUS R AND ORBIT PERIOD T GIVES GM:

$$GM = \frac{4\pi^2 R^3}{T^2}$$

- LAGEOS TRACKING GIVES $GM_\oplus$

  EARTH MASS $M_\oplus$ INCLUDES DARK MATTER WITHIN THE LAGEOS ORBIT

- LUNAR ORBITERS GIVE GM_m

  (ASSUME MOON-BOUND DARK MATTER MASS TO BE NEGLIGIBLE)

- MORE ACCURATE DETERMINATION OF M_m COMES FROM TRACKING EROS ASTEROID, WHICH IS INFLUENCED BY EARTH'S AND MOON'S GRAVITY - GIVES

$$R_{\oplus/m} \equiv \frac{G M_\oplus + G \Delta M_\oplus}{G M_m}$$

← POSSIBLE EARTH-BOUND DARK MATTER CONTRIBUTION

$$= \frac{G M_\oplus}{G M_m} (1 + \delta) \qquad \delta = \frac{\Delta M_\oplus}{M_\oplus}$$

- COMBINED EARTH-MOON SYSTEM

LUNAR LASER RANGING DETERMINES THE COMBINED MASS (TIMES G) OF THE EARTH-MOON SYSTEM:

$$G M_{combined} = G M_\oplus + G M_m + G M_{dm}$$

M_{dm} = DARK MATTER MASS LYING BETWEEN THE RADIUS OF MOON AND LAGEOS ORBITS

SO

$$G M_{dm} = G M_{combined} - G M_\oplus - G M_m$$

LUNAR ORBITER DETERMINATION

OR USING EROS

$$GM_{\text{combined}} - GM_{\oplus} - \frac{GM_{\oplus}}{R_{\oplus/m}}$$

$$\simeq GM_{dm} + GM_m\delta = GM_{dm} + \frac{M_m}{M_{\oplus}} G\Delta M_{\oplus}$$

SINCE $M_m / M_{\oplus} \simeq 0.0123$, THIS GIVES

$$GM_{\text{combined}} - GM_{\oplus} - \frac{GM_{\oplus}}{R_{\oplus/m}} \simeq GM_{dm} + 0.0123\, G\Delta M_{\oplus}$$

$$> GM_{dm}$$

$$\simeq GM_{dm}(1 + O(.01)) \quad \text{IF} \quad \Delta M_{\oplus} \sim M_{dm}$$

<u>NUMERICAL</u> (ALL CONVERTED TO BARYCENTRIC DYNAMICAL TIME)
(Slava Turyshev, JPL)

LAGEOS $\Rightarrow GM_{\oplus} = 398,600.4356 \pm 0.0008 \text{ km}^3 \text{ s}^{-2}$

LUNAR RANGING $\Rightarrow GM_{\text{combined}} = 403,503.2357 \pm 0.0014 \text{ km}^3 \text{ s}^{-2}$

EROS $\Rightarrow R_{\oplus/m} = 81.300570 \pm 0.000005$

+LAGEOS $GM_{\oplus} \Rightarrow GM_m = 4902.8000 \pm 0.0003 \text{ km}^3 \text{ s}^{-2}$

COMBINING THESE,

$$G M_{dm} \simeq (0.0001 \pm 0.0016) \text{ km}^3 \text{ s}^{-2}$$

$$= (0.3 \pm 4) \times 10^{-9} \, G M_\oplus$$

DOMINANT ERROR COMES FROM

$G M_{combined}$ FROM LUNAR LASER RANGING

SO $\quad M_{dm} \lesssim 4 \times 10^{-9} M_\oplus$

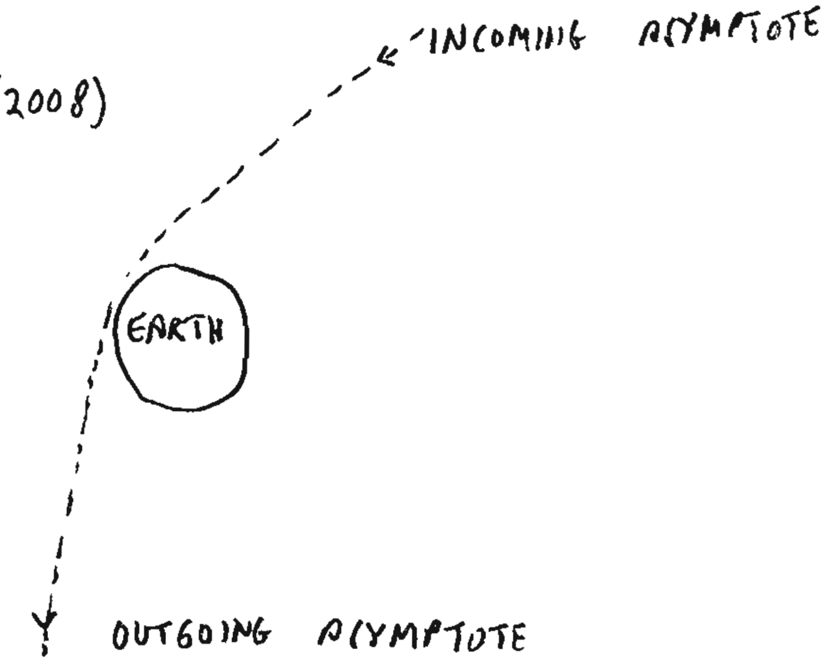
IF THIS BOUND WERE ATTAINED, AND THE MASS WERE UNIFORMLY DISTRIBUTED BELOW THE MOON'S ORBIT, THE DENSITY WOULD BE

$$\rho \sim 6 \times 10^{10} \text{ GeV}/c^2 \text{ cm}^{-3}$$

MUCH LARGER THAN THE LIMIT ON SUN-BOUND DARK MATTER ($\sim 10^5$ GeV/c^2 cm^{-3}) AND EVEN STILL LARGER THAN THE GALACTIC HALO DENSITY – SO THERE IS ONLY A WEAK CONSTRAINT ON EARTH-BOUND DARK MATTER

CAN THE FLYBY ANOMALY BE ATTRIBUTED TO EARTH-BOUND DARK MATTER?

Anderson et. al.
PRL 100, 091102 (2008)



OUTGOING VELOCITY EXTRAPOLATED FROM INCOMING VELOCITY DOES NOT AGREE WITH MEASURED VALUE

PARAMETER	GALILEO I	GALILEO II	NEAR	CASSINI	ROSETTA	MESSENGER
DATE	12/8/90	12/8/92	1/23/98	8/18/99	3/4/05	8/2/05
ΔV_∞ ($\frac{mm}{s}$)	3.92	−4.6	13.46	−2	1.80	0.02
σV_∞ ($\frac{mm}{s}$)	0.3	1.0	0.01	1	0.03	0.01
FIT	4.12	−4.67	13.28	−1.07	2.07	0.06

$$\frac{\Delta V_\infty}{V_\infty} = \frac{1}{2}\frac{\Delta E}{E} = K\left(\cos\delta_i - \cos\delta_o\right)$$

$\delta_{i,o}$ = INCOMING, OUTGOING DECLINATION

↗ LATITUDE ANALOG IN CELESTIAL COORDINATE SYSTEM

$$K = \frac{2 \omega_E R_E}{c} = 3.099 \times 10^{-6}$$

ω_E = EARTH ANGULAR ROTATION VELOCITY

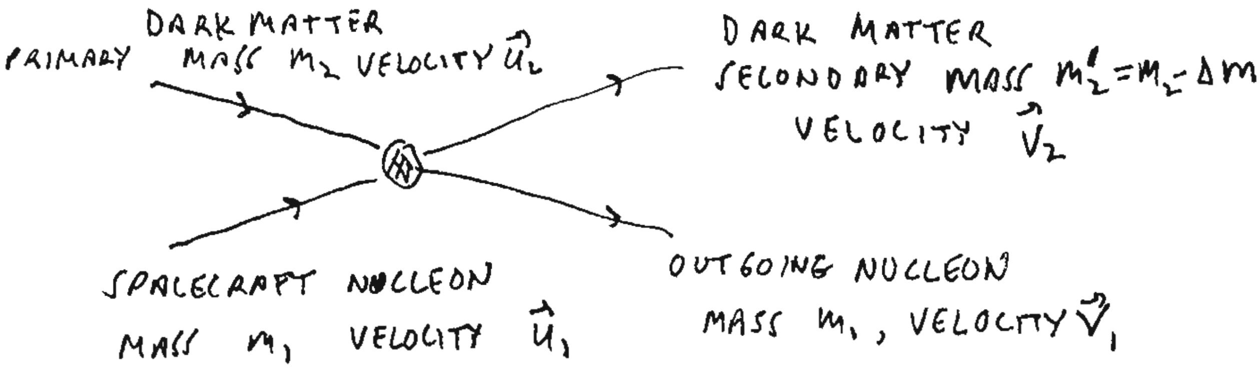
R_E = EARTH RADIUS $\approx$ 6,371 km

(AS WE SHALL SEE, ANALYSIS OF DRAG-FREE CLOSED ORBITS DOES NOT SUGGEST THIS FORMULA, WHICH SHOULD BE TREATED AS PURELY EMPIRICAL)

FOUR POSSIBILITIES:

- EFFECT IS AN ARTIFACT - SOME ESSENTIAL PHYSICS HAS BEEN OMITTED FROM THE ORBITAL CALCULATION
- NEW ELECTROMAGNETIC PHYSICS
- NEW GRAVITATIONAL PHYSICS (NON-MOND)
- EFFECT COMES FROM COLLISIONS WITH EARTH-BOUND DARK MATTER ... ANALYZE THIS

• ELASTIC AND INELASTIC DARK MATTER SCATTERING



ASSUME:

- BOTH INITIAL PARTICLES NONRELATIVISTIC

$$|\vec{u}_1| \ll c \qquad |\vec{u}_2| \ll c$$

- CENTER OF MASS SCATTERING AMPLITUDE $f(\theta)$ DEPENDS ONLY ON POLAR SCATTERING ANGLE θ $\Rightarrow$

OUTGOING NUCLEON VELOCITY CHANGE, AVERAGED OVER SCATTERING ANGLES, IS

$$\langle \delta \vec{v}_1 \rangle = \frac{m_2 \vec{u}_2 - m_2' \vec{u}_1}{m_1 + m_2'} + t \, \langle \cos\theta \rangle \, \frac{\vec{u}_1 - \vec{u}_2}{|\vec{u}_1 - \vec{u}_2|}$$

WITH t THE POSITIVE SQUARE ROOT OF

$$t^2 = \frac{m_2 m_2'}{(m_1 + m_2)(m_1 + m_2')} (\vec{u}_1 - \vec{u}_2)^2 + \frac{\Delta m \, m_2'}{m_1 (m_1 + m_2')} \left[2c^2 - \frac{(m_1 \vec{u}_1 + m_2 \vec{u}_2)^2}{(m_1 + m_2)(m_1 + m_2')} \right]$$

AND WITH

$$\langle \cos\theta \rangle = \frac{\int_0^\pi d\theta \, \sin\theta \, \cos\theta \, |f(\theta)|^2}{\int_0^\pi d\theta \, \sin\theta \, |f(\theta)|^2}$$

ELASTIC SCATTERING CASE:

$$\Delta m = 0 \qquad m_2' = m_2 \qquad \Rightarrow$$

$$\langle \delta \vec{v}_1 \rangle = -2 \frac{m_2}{m_1 + m_2} (\vec{u}_1 - \vec{u}_2) \left\langle \sin^2 \frac{\theta}{2} \right\rangle$$

INELASTIC CASE: ASSUME $\frac{\Delta m}{m_2}$, $\frac{m_2'}{m_2}$ ARE $O(1)$

$\Rightarrow$ x^2 DOMINATED BY SECOND TERM

$$\langle \delta \vec{v}_1 \rangle \simeq \frac{\vec{u}_1 - \vec{u}_2}{|\vec{u}_1 - \vec{u}_2|} \left(\frac{2 \Delta m \, m_2'}{m_1 (m_1 + m_2')} \right)^{1/2} c \, \langle \cos\theta \rangle$$

FOR $\vec{u}_{1,2} \sim 10 \text{ km s}^{-1} = 10^6 \text{ cm s}^{-1}$, THE VELOCITY CHANGE IN THE INELASTIC CASE IS LARGER THAN THAT IN THE ELASTIC CASE BY $\frac{c}{|\vec{u}_1|} \sim 10^4$, AND OPPOSITE IN SIGN

$$\frac{\text{FORCE}}{\text{UNIT MASS}} = \delta \vec{F} = \int d^3 u_2 \, \langle \delta \vec{v}_1 \rangle \, |\vec{u}_1 - \vec{u}_2| \, \sigma \, \rho(\vec{x}, \vec{u}_2)$$

VELOCITY CHANGE IN SINGLE SCATTER

FLUX

CROSS SECTION

DARK MATTER SPATIAL + VELOCITY DISTRIBUTION

INTEGRATING $\frac{\text{WORK}}{\text{UNIT MASS}}$ ALONG SPACECRAFT TRAJECTORY $\Rightarrow$

$$\delta \tfrac{1}{2}\left(\vec{V}_f^2 - \vec{V}_i^2\right) = \vec{V}_f \cdot \delta \vec{V}_f = \int_{t_i}^{t_f} dt \, \frac{d\vec{x}}{dt} \cdot \delta \vec{F}$$

$$= \int_{t_i}^{t_f} dt \int d^3 u_2 \, \frac{d\vec{x}}{dt} \cdot \langle \delta \vec{v}_1 \rangle \, |\vec{u}_1 - \vec{u}_2| \, \sigma \, \rho(\vec{x}, \vec{u}_2)$$

IF $\rho(\vec{x}, \vec{u}_2) = \rho(\vec{x}, -\vec{u}_2)$ THEN :

- ELASTIC: AVERAGED VELOCITY CHANGE OPPOSITE TO $\frac{d\vec{x}(t)}{dt}$

  $\Rightarrow$ POSITIVE DRAG COEFFICIENT

  REDUCTION IN SPACECRAFT VELOCITY

- INELASTIC: AVERAGED VELOCITY CHANGE PARALLEL TO $\frac{d\vec{x}(t)}{dt}$

  $\Rightarrow$ NEGATIVE DRAG COEFFICIENT

  INCREASE IN SPACECRAFT VELOCITY

TO GET NEGATIVE DRAG ON SOME TRAJECTORIES, POSITIVE ON OTHERS, NEED EITHER

- TWO-COMPONENT DARK MATTER, WITH DIFFERENT SPATIAL DENSITIES $\rho(\vec{x}, \vec{u}_2)$ GOVERNING THE INELASTIC AND ELASTIC CASES

OR

- SINGLE COMPONENT WITH $\rho(\vec{x}, \vec{u}_2) \neq \rho(\vec{x}, -\vec{u}_2)$

- QUANTITATIVE ESTIMATES: 10^{-6} FRACTIONAL VELOCITY CHANGE OVER TIME INTERVAL T NEEDS

$$10^{-6} \sim T \bar{f} \sigma \bar{\rho} \, |\langle \delta \vec{v}_1 \rangle| / |\vec{v}_f|$$

$$\Rightarrow \quad \sigma \bar{\rho} \sim 10^{-6} |\vec{v}_f| / \left(T \bar{f} |\langle \delta \vec{v}_1 \rangle|\right)$$

"NEAR" FLYBY $\quad T = 3.7 \text{ h} \sim 10^4 \text{ s}$

$\bar{f} \sim 10^6 \text{ cm s}^{-1}$

DEFINE $\bar{\rho}_m = m_2 \bar{\rho}$ = DARK MATTER MASS DENSITY

ELASTIC: $\sigma \bar{\rho}_m \sim 10^{-16} \text{ cm}^{-1} (m_1 + m_2) \geq 10^{-16} \frac{\text{GeV}}{c^2} \text{ cm}^{-1}$

INELASTIC: $\sigma \bar{\rho}_m \sim 10^{-20} \text{ cm}^{-1} \left[m_1 (m_1 + m_2^2)\right]^{1/2} \geq 10^{-20} \frac{\text{GeV}}{c^2} \text{ cm}^{-1}$

FOR $\sigma = 1$ picobarn $= 10^{-36} \text{ cm}^2$, ELASTIC $\bar{\rho}_m \sim 10^{20} \frac{\text{GeV}}{c^2}/\text{cm}^3$

INELASTIC $\bar{\rho}_m \sim 10^{16} \frac{\text{GeV}}{c^2}/\text{cm}^3$

FOR $\sigma = 1$ millibarn $= 10^{-27} \text{ cm}^2$, ELASTIC $\bar{\rho}_m \sim 10^{11} \frac{\text{GeV}}{c^2}/\text{cm}^3$

INELASTIC $\bar{\rho}_m \sim 10^{7} \frac{\text{GeV}}{c^2}/\text{cm}^3$

ALL MUCH GREATER THAN GALACTIC HALO $\bar{\rho}_m \approx 0.3 \frac{\text{GeV}}{c^2}/\text{cm}^3$

FLYBY VELOCITY CHANGES OCCUR WITHIN RADIUS 70,000 km FOR DARK MATTER MASS WITHIN THIS RADIUS NOT TO EXCEED $4 \times 10^{-9} M_\oplus$, NEED $\bar{\rho}_m \lesssim 10^{13} (\text{GeV}/c^2) \text{ cm}^{-3}$

REQUIRES $\quad \sigma_{inel} > 10^{-33} \text{ cm}^2$

$\sigma_{el} > 10^{-29} \text{ cm}^2$

- DARK MATTER ACCUMULATION CASCADE?

SOLAR SYSTEM MOVES THROUGH GALAXY WITH $V_{s.s.} \sim 220 \text{ km s}^{-1}$

LET $f_{s.s.}$ = PROBABILITY OF CAPTURE OF A DARK MATTER PARTICLE IN EARTH ORBIT RADIUS $A \simeq 1.5 \times 10^8$ km

CAPTURE PARTICLES IN ANNULUS OF AREA $2\pi A dA$ OVER $T_{s.s.} \sim 1.5 \times 10^{17}$ s, REDISTRIBUTE INTO VOLUME $4\pi A^2 dA$ $\Rightarrow$ AT RADIUS A

$$\frac{\rho_{m;s.s.}}{\rho_{m;\,halo}} \sim \frac{f_{s.s.}}{2A} V_{s.s} T_{s.s.} \sim 10^{11} f_{s.s.}$$

KNOWN LIMIT ON $\rho_{m;ss}$ IS $3 \times 10^5 \rho_{m;\,halo}$

$\Rightarrow$ $f_{s.s.} \leq 3 \times 10^{-6}$

ANALOGOUS CALCULATION FOR EARTH MOVING IN SOLAR SYSTEM $\Rightarrow$

$$\frac{\rho_{mse}}{\rho_{m;ss}} \sim \frac{f_e}{4R} V_e T_{s.s.} \sim 2 \times 10^{13} f_e$$

$\uparrow$

70,000 km

$\Rightarrow$ EVEN WITH SMALL f_e, COULD GET DARK MATTER DENSITIES LARGE ENOUGH TO EXPLAIN THE FLYBY ANOMALY, IF σ IS LARGE ENOUGH

- CONSTRAINTS

  - CLOSED ORBIT CONSTRAINTS

MOST GENERAL FORM OF DRAG FORCE THAT GIVES ZERO CUMULATIVE DRAG FOR ALL CLOSED SATELLITE ORBITS

$$\delta W = \int d\theta \; D(\vec{x},\vec{v}) \qquad D(\vec{x},\vec{v}) = \frac{d\vec{x}}{d\theta} \cdot \delta \vec{F}$$

$$\int_0^{2\pi} d\theta \; D(\vec{x}(\theta), \vec{v}(\theta)) = 0 \quad \Rightarrow$$

$$D(\vec{x},\vec{v}) = \sum_{\ell=1}^{\infty} \left(a_\ell \sin \ell\theta + b_\ell \cos \ell\theta \right) \qquad b_0 \equiv 0$$

FOR A HYPERBOLIC FLYBY ORBIT WITH DEFLECTION ANGLE $2\theta_D$,

$$\delta \tfrac{1}{2} \left(\vec{V}_f^{\,2} - \vec{V}_i^{\,2} \right) = 2\, b_0\, \theta_D + 2 \sum_{\ell=1}^{\infty} \frac{b_\ell}{\ell} \sin \ell\theta_D$$

DETAILS OF NEAR-EARTH ENVIRONMENT APPEAR THROUGH THE b_ℓ

KINEMATICS OF VANISHING DRAG ANOMALY FOR CLOSED ORBITS DOES NOT GIVE THE ANDERSON ET. AL FITTING FORMULA $\Rightarrow$ THERE MAY BE DRAG ANOMOLIES IN SATELLITE ORBITS

QUESTION: IF ONE FITS ALL SATELLITES TO

$$\text{DRAG} = D_1 \times \text{AREA} + D_2 \times \text{MASS},$$

- IS THERE EVIDENCE FOR D_2?
- IF NOT, WHAT BOUNDS CAN ONE PLACE ON D_2?

ASSUMING NOW NO FINE-TUNING TO CANCEL b_0, THE RATE AT WHICH THE RADIUS OF AN ORBITING BODY INCREASES OR DECREASES CAN BE USED TO BOUND A DRAG FORCE ACTING ON IT $\Rightarrow$ A BOUND ON $\sigma \bar{\rho}_m$ ACTING ON ORBIT. WHEN OPTICAL DEPTH IS $\ll$ RADIUS OF ORBITING BODY, σ DROPS OUT AND WE GET A BOUND ON $\bar{\rho}_m$

<u>EARTH</u> $\quad A \sim 1.5 \times 10^8$ km $\quad$ ORBIT RADIUS

$dA \lesssim 1.5$ cm / ORBIT

$\Rightarrow \bar{\rho}_{m;\, s.s.} < 2 \times 10^{2}\ (\text{GeV}/c^2)\ \text{cm}^{-3}$

BASED ON INELASTIC DARK MATTER SCATTERING

$\Rightarrow$ EARTH CAPTURE FRACTION IN CASCADE SCENARIO MUST OBEY

$$f_e \geq \frac{0.2 \times 10^{-35}\ \text{cm}^2}{\sigma}$$

$\sigma = 10^{-33}\ \text{cm}^2 \Rightarrow f_e \geq 0.2 \times 10^{-2} \qquad \sigma = 10^{-27}\ \text{cm}^2 \Rightarrow f_e \geq 0.2 \times 10^{-8}$

MOON

$$R_M \sim 384{,}000 \text{ km}$$
$$dR_M \lesssim 0.28 \text{ cm/ORBIT}$$

$$\Rightarrow \quad \bar{\rho}_{m;e} \lesssim 10^{4} \,(\text{GeV}/c^2)\ \text{cm}^{-3}$$

$\Rightarrow$ DARK MATTER DENSITY AT MOON'S ORBIT MUST BE $\ll$ DENSITY WITHIN 70,000 km

LAGEOS

BOUNDS ON RESIDUAL ACCELERATIONS

$$\Rightarrow \quad \sigma\,\bar{\rho}_{m;e} \lesssim 3 \times 10^{-26} \,(\text{GeV}/c^2)\ \text{cm}^{-1} \qquad \text{(INELASTIC)}$$

$\Rightarrow$ DARK MATTER DENSITY AT LAGEOS ORBIT RADIUS MUST BE $\ll$ DENSITY AT RADII RELEVANT FOR FLYBY ANOMALY

•• STELLAR (AND SOLAR) DYNAMICS CONSTRAINTS

EFFECT OF DARK MATTER CAPTURE ON STELLAR DYNAMICS DISCUSSED BY FAIRBAIRN, SCOTT + EDSJÖ

$$\Rightarrow \quad \bar{\rho}_{m;s.s.} \lesssim \frac{10^{-33}\ \text{cm}^2}{\sigma}\,(5 \text{ TO } 50)\ \text{GeV}/c^2\ \text{cm}^{-3}$$

FOR SELF-ANNIHILATING DARK MATTER

FOR NON-SELF-ANNIHILATING DARK MATTER, THIS RESTRICTION CAN BE WEAKENED BY FACTOR $\sim 10^5$, WHEN DARK MATTER

SECONDARY ESCAPES FROM SUN

•• EARTH AND SATELLITE HEATING CONSTRAINTS

<u>EARTH HEATING</u> - IF DARK MATTER SECONDARY ESCAPES FROM EARTH, ONLY KINETIC ENERGY OF RECOILING NUCLEON IS DEPOSITED

$$\delta T_1 \sim \frac{m_1 (\delta \vec{v}_1)^2}{2}$$

$$\frac{\delta T_1}{\Delta m c^2} \sim \frac{m_2}{2 m_1}$$ DEPENDS ON DARK MATTER MASS m_2

FOR $m_2 \sim 10$ keV, GET BOUND

$$\rho_{m_i} R_\oplus \lesssim 10^9 \ (\text{GeV}/c^2) \ \text{cm}^{-3}$$

AGAIN, IMPLIES THAT DARK MATTER DENSITY MUST BE DEPLETED NEAR EARTH (SIMILAR TO CONCLUSION FROM LAGEOS CONSTRAINT)

FLYBY TEMPERATURE GAIN

TEMP GAIN $\sim \frac{\delta T_1}{|\delta \vec{v}_1|} 10^{-6} |\vec{u}_1| \sim \frac{1}{2} m_1 |\delta \vec{v}_1| 10^{-6} |\vec{u}_1|$

INELASTIC: TEMP GAIN $\sim \frac{1}{2} 10^{-6} m_2 |\vec{u}_1| c$

$$\sim 0.2\ {}^{\circ}K \left(\frac{m_2 c^2}{MeV}\right)$$

ELASTIC: TEMP GAIN $\sim \frac{1}{2} 10^{-6} m_2 |\vec{u}_1| |\vec{u}_1 - \vec{u}_2|$

$$\sim 10^{-5}\ {}^{\circ}K \left(\frac{m_2 c^2}{MeV}\right)$$

$\Rightarrow$ DARK MATTER MASS $\ll$ GeV

COULD CALORIMETRY IN HIGH ORBITING SPACECRAFT BE USED FOR DARK MATTER DETECTION?

FLYBY STRUCTURAL DISRUPTION

IF EACH INDIVIDUAL NUCLEON RECOIL SHOULD NOT PRODUCE STRUCTURAL CHANGES, NEED

$$\delta T_1 < E_{binding}$$

INEL: $m_2 c^2 < (m_1 c^2 E_{binding})^{1/2} \sim 100$ keV

FOR

$E_{binding} \sim 10$ eV

SUMMARY ON FLYBY - ESTIMATES DO NOT RULE OUT DARK MATTER EXPLANATION (FOR EXAMPLE, DO NOT REQUIRE $f_e \gg 1$)

- BUT CONSTRAINTS ARE SEVERE

- NEED EXOTHERMIC INELASTIC SCATTERING OF DARK MATTER ON ORDINARY MATTER

- DARK MATTER MUST BE WELL WITHIN MOON'S ORBIT AND DEPLETED NEAR EARTH'S SURFACE

- CASCADE ACCUMULATION MECHANISM REQUIRED TO REACH NEEDED DARK MATTER DENSITY

- DARK MATTER MASS MUST BE WELL BELOW A GeV

- INTERACTION CROSS SECTION WITH NUCLEONS MUST BE RELATIVELY HIGH

  ($10^{-33}\ \mathrm{cm}^2 < \sigma < 10^{-27}\ \mathrm{cm}^2$)

- DARK MATTER MUST BE NON-SELF-ANNIHILATING

PLANET-BOUND DARK MATTER, AND THE INTERNAL HEAT OF URANUS, NEPTUNE, AND HOT-JUPITER EXOPLANETS

LET f = FRACTION OF DARK MATTER ANNIHILATION ENERGY THAT IS DEPOSITED IN A PLANET WHEN A DARK MATTER PARTICLE IS ACCRETED

f CAN BE $\ll 1$ FOR EXAMPLE, IF THE SECONDARY m_2' IS VERY WEAKLY INTERACTING AND ESCAPES, $f \sim \frac{1}{2} \frac{m_2}{m_1}$

IF $m_2 \ll m_1 =$ NUCLEON MASS, THEN $f \ll 1$

CONSIDER A PLANET WITH OUTWARD ENERGY FLOW PER UNIT AREA OF SURFACE $\equiv H$

ASSUME IT IS IMMERSED IN A DARK MATTER CLOUD, WITH MASS DENSITY ρ_m AND MEAN VELOCITY $V \sim \left(\frac{G M_{planet}}{R_{planet}}\right)^{1/2}$ NEAR PLANET'S SURFACE

INCLUDING A SOLID ANGLE FACTOR OF 1/2, THE CONDITION FOR ALL OF H TO BE SUPPLIED BY DARK MATTER CAPTURE IS

$$\frac{1}{2} \rho_m c^2 v f = H$$

$\Rightarrow$ DARK MATTER DENSITY AT ENERGY FLUX EQUILIBRIUM IS

$$\rho_m = \frac{K_{planet}}{f}$$

$$K_{planet} = \frac{2H}{c^2 v} \sim \frac{2H}{c^2} \left(\frac{R_{planet}}{G M_{planet}} \right)^{1/2}$$

FROM PLANETARY HEAT FLOW DATA (de Pater + Lissauer) GET

$K_{Earth} = 0.12 \ \text{GeV}/c^2 \ \text{cm}^{-3}$

$K_{Jupiter} = 1.6 \ \text{GeV}/c^2 \ \text{cm}^{-3}$

$K_{Saturn} = 1.0 \ \text{GeV}/c^2 \ \text{cm}^{-3}$

$K_{Uranus} < 0.04 \ \text{GeV}/c^2 \ \text{cm}^{-3}$

$K_{Neptune} = 0.3 \ \text{GeV}/c^2 \ \text{cm}^{-3}$

FOR $f \ll 1$, ρ_m FOR EQUILIBRIUM IS IN THE POSSIBLE RANGE FOR SUN-BOUND OR PLANET-BOUND DARK MATTER

THUS, A SUBSTANTIAL FRACTION OF PLANETARY INTERNAL HEAT GENERATION COULD COME FROM DARK MATTER ACCRETION: COULD ACCOUNT FOR UNEXPLAINED RESIDUAL HEAT PRODUCTION IN EARTH, JOVIAN PLANETS, AND "HOT-JUPITER" EXOPLANETS

URANUS ANOMALIES: ROTATION AXIS TILTED 98° WITH RESPECT TO PLANE OF SOLAR SYSTEM, AND VERY LOW HEAT PRODUCTION H - MUCH LESS THAN NEPTUNE

IF HEAT PRODUCTION IS LARGELY ASSOCIATED WITH A PLANET-BOUND DARK MATTER CLOUD, THEN THE COLLISION THOUGHT TO HAVE TILTED THE AXIS OF URANUS COULD ALSO HAVE KNOCKED IT OUT OF ITS ASSOCIATED DARK MATTER CLOUD, LEAVING URANUS WITH A MUCH REDUCED INTERNAL HEAT PRODUCTION