EARTH ORBITING DARK MATTER AS A POSSIBLE EXPLANATION OF THE FLYBY ANOMALIES

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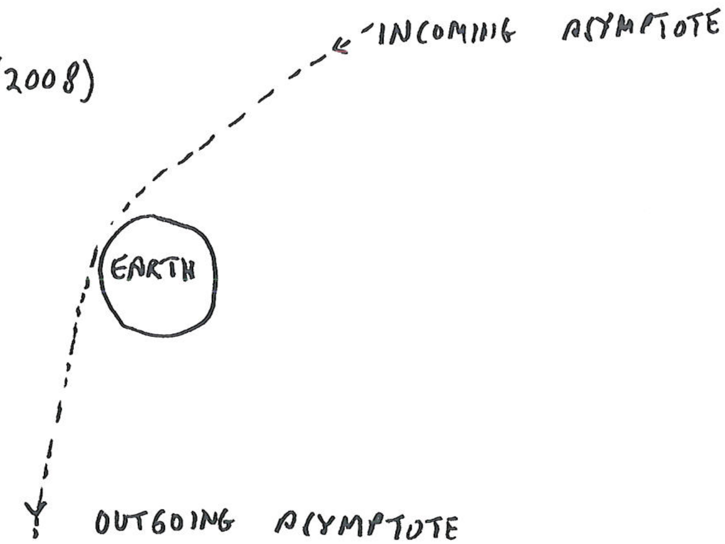
- EXPERIMENTAL DATA — Anderson et al PRL 100 091102 (2008)
- POSSIBLE EXPLANATIONS
- DARK MATTER SCATTERING? — S.L.A. Phys. Rev. D 79 023505 (2009)
- BOUNDING THE MASS OF EARTH ORBITING DARK MATTER — S.L.A. J. Phys. A Math. Theor. 41 (2008) 412002
- DARK MATTER MODELING — S.L.A. arXiv: 0908.2414
- SPACECRAFT CALORIMETRY AS A TEST — S.L.A. arXiv: 0910.1564 "white paper" for decadal review on space science
- OUTLOOK

EXPERIMENTAL DATA

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

Anderson + Nieto
Physics Today Oct 2009
pp 76-77



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

ANDERSON et al FIT (EMPIRICAL - NO THEORETICAL BASIS)

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

$\delta_{i,o}$ = 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 ≙ 6,371 km

- DECLINATION DEPENDENCE INDICATES THAT MAXIMAL SYMMETRY OF ANY MECHANISM CAN BE AXIAL SYMMETRY AROUND EARTH ROTATION AXIS
- SPHERICAL SYMMETRY CANNOT GIVE A DECLINATION DEPENDENCE

MAGNITUDE AS AN ACCELERATION

NEAR FLYBY: $\Delta V_\infty = 13.46$ mm/s $\sim 1.3 \cdot 10^{-2}$ m/s

OVER $\Delta T \sim 4$ HOURS $\sim 10^4$ s

$\Rightarrow$ ACCELERATION $\sim 10^{-6}$ m/s^2

SOME COMPARISONS:

PIONEER ANOMALOUS ACCELERATION $\simeq 8.74 \cdot 10^{-10}$ m/s^2

MOND CUTOFF ACCELERATION $\sim 10^{-10}$ m/s^2

COSMOLOGICAL SCALE $H_0 c \sim 2.3 \cdot 10^{-18} s^{-1} \cdot 3 \cdot 10^8 \frac{m}{s} \sim 7 \cdot 10^{-10} \frac{m}{s^2}$

FLYBY ANOMALY, INTERPRETED AS AN ACCELERATION, IS 3 ORDERS OF MAGNITUDE LARGER THAN THESE

POSSIBLE EXPLANATIONS

FOUR POSSIBILITIES:

- EFFECT IS AN ARTIFACT - SOME ESSENTIAL CONVENTIONAL PHYSICS HAS BEEN OMITTED FROM THE ORBITAL CALCULATION
  - THERMAL EFFECTS (WHICH MAY EXPLAIN MOST OF THE PIONEER ANOMALY) ARE TOO SMALL TO EXPLAIN FLYBY (BEAN WORKSHOP REPORTS)
  - OTHER POSSIBILITIES UNDER STUDY

- NEW ELECTROMAGNETIC PHYSICS
  - QED TESTED TO HIGH PRECISION
  - PVLAS - DIDN'T FIND AXIONS, BUT SHOWED VACUUM LINEAR TO 1 IN 10^{18} IN 2.5 TESLA FIELD

- NEW GRAVITATIONAL PHYSICS
  - PPN DEVIATIONS FROM GENERAL RELATIVITY AT LEAST A FACTOR OF 100 TOO SMALL (SEE MEMO ON S.L.A. WEB PAGE TALKS + MEMOS SECTION)

EXPLANATIONS – CONTINUED

SO A GRAVITATIONAL EXPLANATION MUST BE OUTSIDE THE PPN FRAMEWORK OF METRIC THEORIES THAT OBEY THE EQUIVALENCE PRINCIPLE

– BUT EQUIV. PRIN. TESTED TO HIGH PRECISION

- MOND OR COSMOLOGY: ACCELERATIONS TOO SMALL

- DARK MATTER

COSMOLOGY ⇒ ONLY ~4% OF THE MASS-ENERGY DENSITY OF THE UNIVERSE IS BARYONIC MATTER

~23% IS GRAVITATIONALLY ATTRACTIVE "DARK MATTER"

~73% IS GRAVITATIONALLY REPULSIVE "DARK ENERGY"

LITTLE IS KNOWN ABOUT DARK MATTER:

BOSONIC OR FERMIONIC?

SELF-ANNIHILATING?

MASS (ES) ?

NON-GRAVITATIONAL INTERACTIONS ?

DARK MATTER SCATTERING?

DARK MATTER CAN BE GRAVITATIONALLY BOUND ON DIFFERENT SCALES

- GALACTIC HALO DARK MATTER

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

- SOLAR SYTEM-BOUND DARK MATTER?

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

  FROM STUDY OF PLANETARY ORBITS

- EARTH-BOUND DARK MATTER?

  CAN SCATTERING FROM EARTH-BOUND DARK MATTER EXPLAIN THE FLYBY ANOMALIES?

SCATTERING - CONTINUED

- ELASTIC SCATTERING - GIVES NORMAL DRAG - VELOCITY DECREASE

- INELASTIC EXOTHERMIC SCATTERING

  $$D(m_2) + N(m_1) \rightarrow D'(m_2') + N(m_1) \qquad m_2 > m_2'$$

  CAN GIVE A VELOCITY INCREASE - WILL GIVE DETAILED FORMULAS

- TO GIVE OBSERVED VELOCITY ANOMALIES, NEED

ELASTIC $\sigma \, \bar{\rho}_m \gtrsim 10^{-16} \ \mathrm{GeV/c^2 \ cm^{-1}}$

(↗ σ: CROSS SECTION)

INELASTIC

$$\text{“}\sigma\text{”} \, \bar{\rho}_m \gtrsim 10^{-20} \ \mathrm{GeV/c^2 \ cm^{-1}}$$

(INELASTIC / ELASTIC $\sim c/V_{ORBITAL} \sim 10^4$)

$\sigma \sim 10^{-33} \ \mathrm{cm^2} \rightarrow \bar{\rho}_{m\ ELASTIC} \sim 10^{17} \ \mathrm{GeV/c^2 \ cm^{-3}}$; $\tilde{\rho}_{m\ INELASTIC} \sim 10^{13} \ \mathrm{GeV/c^2 \ cm^{-3}}$

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

MOON ORBIT RADIUS ~ 384,000 km

LAGEOS GEODETIC SATELLITE ORBIT RADIUS ~ 12,300 km

FOR A CIRCULAR ORBIT, MEASURING RADIUS R AND PERIOD T GIVES GM OF ATTRACTING BODY,

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

- LAGEOS TRACKING GIVES $G M_{\oplus}$

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

DIRECT LIMITS - LUNAR ORBITER, EROS TRACKING, LUNAR LASAR RANGING

- LUNAR ORBITERS GIVE GM_m
- MORE ACCURATE M_m FROM TRACKING EROS ASTEROID GIVES

$$R_{\oplus/m} = \frac{GM_\oplus + G\Delta M_\oplus}{GM_m}$$

← POSSIBLE DARK MATTER EFFECT ON EROS

$$= \frac{GM_\oplus}{GM_m}(1+\delta) \qquad \delta = \frac{\Delta M_\oplus}{M_\oplus}$$

- LUNAR LASAR RANGING GIVES COMBINED GM_{TOT} OF EARTH-MOON SYSTEM:

$$GM_{TOT} = GM_\oplus + GM_m + GM_{dm}$$

↑ MASS OF DARK MATTER LYING BETWEEN MOON AND LAGEOS ORBITS

DIRECT LIMITS - FINAL FORMULA

COMBINING FORMULAS

$$GM_{TOT} - GM_{\oplus} - \frac{GM_{\oplus}}{R_{\oplus/m}} \simeq GM_{dm} + \frac{M_m}{M_{\oplus}} G\Delta M_{\oplus}$$

$$\simeq GM_{dm} + 0.0123\, G\Delta M_{\oplus} > GM_{dm}$$

$$= GM_{dm}\left[1 + O(0.01)\right] \quad \text{IF } \Delta M_{\oplus} \sim M_{dm}$$

NUMERICAL (ALL CONVERTED TO BARYCENTRIC DYNAMICAL TIME)
(Slava Turyshev, JPL)

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

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

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

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

DIRECT LIMITS – RESULTS

COMBINING THESE GIVES

$$G M_{dm} \simeq (0.0001 \pm 0.0016)\ km^3 s^{-2} = (0.3 \pm 4) \times 10^{-9}\ G M_\oplus$$

($\nearrow$ DOMINANT ERROR FROM LUNAR LASER RANGING)

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

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

$$\rho_m \sim 6 \cdot 10^{10}\ GeV/c^2\ cm^{-3} \gg$$

GALACTIC HALO DENSITY AND LIMIT ON SUN-BOUND DARK MATTER

IF CONFINED TO A NARROW BAND, ρ_m FOR EARTH-BOUND DARK MATTER COULD BE EVEN HIGHER: FOR A SHELL OF RADIUS R AND THICKNESS D,

$$\rho_m \lesssim 2 \cdot 10^{10}\ GeV/c^2\ cm^{-3}\ \frac{(384{,}000\ km)^3}{R^2 D}$$

DARK MATTER MODELING FOR FLYBY

SOME FLYBYS GAIN VELOCITY (ANOMALOUS DRAG)

SOME FLYBYS LOSE VELOCITY (NORMAL DRAG)

MODEL ASSUMES TWO SPECIES OF DARK MATTER ORBITING EARTH

- INELASTIC, EXOTHERMIC SCATTER

  $D(m_2) + N(m_1) \rightarrow D'(m_2') + N(m_1) \qquad m_2 > m_2'$

  CAN GIVE VELOCITY GAIN IF $N(m_1)$ SCATTERS FORWARD

- ELASTIC SCATTER

  $D''(m_2'') + N(m_1) \rightarrow D''(m_2'') + N(m_1)$ GIVES NORMAL DRAG

VELOCITY CHANGE FORMULAS

$\vec{u}_1$ = VELOCITY OF INITIAL NUCLEON (IN SPACECRAFT)

$\vec{u}_2$ = VELOCITY OF INCIDENT DARK MATTER

$\langle \delta \vec{v} \rangle$ = CROSS-SECTION AVERAGED NUCLEON VELOCITY CHANGE
(ASSUME NO AZIMUTHAL ANGLE DEPENDENCE)

INELASTIC

$$\langle \delta \vec{v} \rangle = \frac{\vec{u}_1 - \vec{u}_2}{|\vec{u}_1 - \vec{u}_2|} A_I \qquad A_I = \left[\frac{2\,(m_2 - m_2')\, m_2'}{m_1\,(m_1 + m_2')} \right]^{1/2} c \;\langle \cos\theta \rangle_I$$

ELASTIC

$$\langle \delta \vec{v} \rangle = -(\vec{u}_1 - \vec{u}_2)\, A_E \qquad A_E = \left(\frac{m_2''}{m_1 + m_2''} \right) \left[1 - \langle \cos\theta \rangle_E \right]$$

WILL LUMP CROSS SECTION x DENSITY INTO THE
PARAMETERS A_I, A_E

CHANGE IN OUTGOING SPACECRAFT VELOCITY

FORCE = VELOCITY CHANGE IN SINGLE SCATTER $\cdot$ NUMBER OF SCATTERS PER UNIT TIME

$$\delta \vec{F} = \int d^3u_2 \; \langle \delta \vec{V} \rangle \; |\vec{u}_1 - \vec{u}_2| \, \sigma \, \rho(\vec{x}, \vec{u}_2)$$

$$\vec{u}_1 = d\vec{x} / dt$$

INTEGRATING $\delta \vec{F} \cdot d\vec{x}$ ALONG TRAJECTORY

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

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

CROSS SECTION AND SCATTERING-ANGLE AVERAGE

W = CENTER OF MASS SCATTERING ENERGY

$$\frac{W}{(m_1+m_2)\,c^2} \simeq 1 + \frac{m_1 m_2}{2(m_1+m_2)^2}\,\frac{(\vec{u}_1-\vec{u}_2)^2}{c^2}$$

FOR $m_2 \leq m_1$ AND NON-RELATIVISTIC $\vec{u}_1, \vec{u}_2$, $W \simeq 1$

→ CROSS SECTION DOMINATED BY LOWEST PARTIAL WAVES

ELASTIC

S-WAVE DOMINATED $\quad \sigma \simeq \sigma_{el}$ = CONSTANT

$\langle \cos\theta \rangle_E = 0 \qquad 1 - \langle \cos\theta \rangle_E = 1$

INELASTIC

ENTRANCE CHANNEL MOMENTUM $\quad k = \dfrac{m_1 m_2}{m_1+m_2}\,|\vec{u}_1 - \vec{u}_2|$

$$\frac{d\sigma}{d\Omega} = \frac{A_{inel}}{4\pi}\,k^{-1} + B_{inel}\,\frac{3}{4\pi}\cos\theta + \cdots \quad \text{NEAR THRESHOLD}$$

$\sigma \simeq A_{inel}\,k^{-1} \qquad \langle \cos\theta \rangle \simeq B_{inel} / (A_{inel}\,k^{-1})$

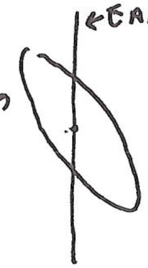
$\sigma \langle \cos\theta \rangle_I \simeq B_{inel}$ = CONSTANT

DARK MATTER ORBITAL GEOMETRY

ASSUME AXIAL SYMMETRY AROUND EARTH ROTATION AXIS

SIMPLEST MODEL - DISK IN EQUATORIAL PLANE - DOES NOT WORK - "NEAR" GETS SMALLEST VELOCITY CHANGE

NEXT SIMPLEST MODEL -



E, L_z CONSERVED, BUT ORBIT WILL PRECESS BECAUSE OF EARTH QUADRUPOLE - WILL FILL SHELL OBTAINED BY AVERAGING ORBIT OVER AZIMUTHAL ANGLE AROUND EARTH AXIS

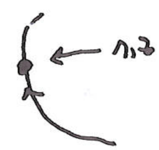
GET THIS

$$\text{DENSITY} \propto \underbrace{\frac{1}{r}\,\frac{1}{\sqrt{(r\sin\psi)^2 - z^2}}}_{\text{JACOBIAN}}\; w(r,\psi)$$

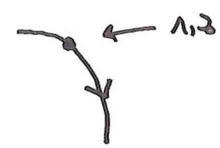
↑ WEIGHTING FUNCTION

DARK MATTER VELOCITY $\vec{u}_2$

FOR GIVEN r, ψ, z, THERE ARE TWO $\vec{u}_2$ VALUES, ONE FOR AN UP-GOING SEGMENT



AND ONE FOR A DOWN-GOING SEGMENT



$$\vec{u}_2 = \sqrt{\frac{GM_\oplus}{r}}\left(c_\pm\,\hat{n}_\parallel + d_\pm\,\hat{n}_\perp\right)$$

$\hat{n}_\parallel$ PARALLEL TO EQUATORIAL PLANE

$\hat{n}_\perp$ PERPENDICULAR TO $\hat{r}$ AND $\hat{n}_\parallel$

$$c_\pm = \frac{r\cos\psi}{\sqrt{r^2-z^2}} \qquad d_\pm = \pm\frac{\sqrt{r^2\sin^2\psi - z^2}}{\sqrt{r^2-z^2}}$$

$$c_\pm^2 + d_\pm^2 = 1$$

SIMPLE CHOICE OF $w(r, \psi)$

SINGLE TILT ANGLE ψ_i, ψ_e FOR INELASTIC, ELASTIC SHELLS

GAUSSIAN r PROFILE

$$w_i(r,\psi) = K_i \, e^{-(r-R_i)^2/D_i^2} \, \delta(\psi - \psi_i) \qquad \text{INELASTIC}$$

$$w_e(r,\psi) = K_e \, e^{-(r-R_e)^2/D_e^2} \, \delta(\psi - \psi_e) \qquad \text{ELASTIC}$$

$N =$ TOTAL NUMBER OF PARTICLES IN SHELL $= \int d^3x \int d^3u_2 \, \rho(\vec{x}, \vec{u}_2)$

$$= 4\pi^{5/2} K_\ell D_\ell \qquad \ell = i, e$$

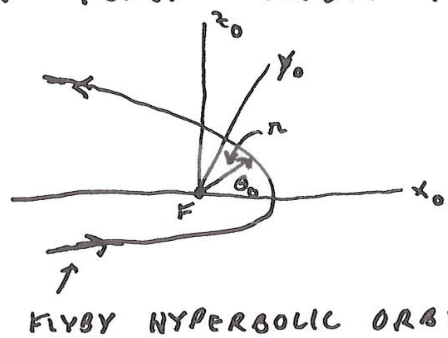
DENSITY TIMES CROSS SECTION PARAMETERS :

$$\rho_i \equiv A_I \, B_{inel} \, K_i$$

$$\rho_e \equiv A_E \, \sigma_{el} \, K_e$$

FLYBY ORBITAL GEOMETRY

WORK IN FLYBY ORBIT PLANE

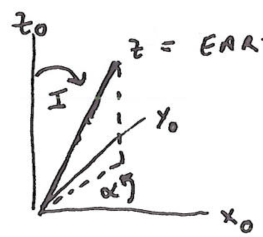


$$r = \frac{p}{1 + e\cos\theta_0}$$

$$\vec{r} = (x_0, y_0, 0)$$

$$x_0 = r\cos\theta_0$$
$$y_0 = r\sin\theta_0$$

EARTH AXIS AS SEEN FROM FLYBY ORBIT PLANE



POLAR ANGLES I, α

- FIRST, EXPRESS DARK MATTER ORBIT ON EARTH-FIXED AXES
- THEN, REWRITE ON FLYBY PLANE AXES TO GET

  z, $\hat{n}_{\parallel}$, $\hat{n}_{\perp}$

FLYBY PARAMETERS ON FLYBY PLANE AXES (AND INTRINSIC PARAMETERS p, e)

	GLL-I	GLL-II	NEAR	CASSINI	ROSETTA	MESSENGER
I (°)	142.9	138.7	108.0	25.4	144.9	133.1
α (°)	−45.1	−147.4	−55.1	−158.4	−53.1	0.0
p (km)	25,473	22,155	19,448	51,689	19,262	20,563
e	2.473	2.319	1.814	5.851	1.312	1.360

$$e = 1 + \frac{2V_\infty^2}{V_f^2 - V_\infty^2} \qquad p = \frac{4GM_\oplus}{V_\infty^2}\left[\left(\frac{V_\infty^2}{V_f^2 - V_\infty^2}\right)^2 + \frac{V_\infty^2}{V_f^2 - V_\infty^2}\right]$$

α REQUIRES ATTENTION TO ± IN ARC COSINE; ABOVE VALUES REPRODUCE THE δ_i, δ_o, $\alpha_i - \alpha_o$ VALUES IN ANDERSON ET AL PRL

NUMERICAL RESULTS

MINIMIZE LIKELIHOOD FUNCTION $\chi^2 = \sum_{k=1}^{6} (\delta V_{k;th} - \delta V_{k;A})^2 / \sigma^2_{k;A}$

$\delta V_{k;th} = \rho_i \, \delta V_{k;i} + \rho_e \, \delta V_{k;e}$ LINEAR IN ρ_i, ρ_e ; χ^2 QUADRATIC

$\Rightarrow$ MINIMIZATION WITH RESPECT TO $\rho_{i,e}$ CAN BE DONE ALGEBRAICALLY

REDUCES PARAMETER SPACE FOR NUMERICAL SEARCH TO 6 PARAMETERS: $\psi_i, R_i, D_i \quad \psi_e, R_e, D_e$

- WITH SMOOTHED JACOBIAN, DO COARSE MESH SURVEY TO IDENTIFY REGIONS WITH LOW χ^2 TO USE AS STARTS FOR MINIMIZATION
- WITH ORIGINAL JACOBIAN, AND ADAPTIVE INTEGRATION, DO MINIMIZATION USING CERN PROGRAM "MINUIT"

0908.2419 ↴

ILLUSTRATIVE GOOD FIT (2d FROM PREPRINT)

	χ^2	GLL-I	GLL-II	NEAR	Cassini	Rosetta	Messenger
δV_A (mm/s)		3.92	-4.6	13.46	-2	1.80	0.02
σ_A (mm/s)		0.3	1.0	0.01	1	0.03	0.01
FIT 2d	0.51	3.90	-4.6	13.46	-2.7	1.80	0.020

↓

PARAMETERS

$10^6 \times \rho_i$ (km)	$10^2 \times \rho_e$ (km)	ψ_i (rad)	ψ_e (rad)	R_i (km)	D_i (km)	R_e (km)	D_e (km)
1.000	0.288	1.372	0.3902	34520	3030	29370	6678

OVERFITTING?

- WITH ONLY INELASTIC, CANNOT FIT NEAR + MESSENGER $\chi^2 = 0.61 \times 10^5$
- WITH FULL MODEL, FITTING TO 5 OF 6 FLYBYS GIVES QUALITATIVELY REASONABLE VALUE FOR 6th:

3.71	-4.6	16.03	-2.7	1.62	0.12

⇒ NOT JUST FITTING A WIGGLY CURVE THROUGH DATA POINTS

IMPLICATION OF DARK MATTE MASS BOUND

LUNAR LASER RANGING $\Rightarrow$ $G(M_\oplus + M_m + M_{DM})$

LAGEOS $\Rightarrow$ $GM_\oplus$ LUNAR ORBITER / EROS TRACKING $\Rightarrow$ GM_m

COMBINING $\Rightarrow$ $M_{DM} < 4 \times 10^{-9} M_\oplus \sim 1.4 \times 10^{43}$ GeV/c^2

FIT 2d: $\rho_i D_i = 0.00304$ km^2

$\rho_e D_e = 19.2$ km^2

USE

$$M_e \equiv m_2 N_e = 4\pi^{5/2} \rho_e D_e \, m_1 / \sigma_{el}$$

$$M_i \equiv m_2 N_i = 4\pi^{5/2} \rho_i D_i \, m_1 / \sigma_{inel}$$

$M_e \leq 4 \times 10^{-9} M_\oplus \Rightarrow \sigma_{el} \geq 9.4 \times 10^{-31}$ cm^2

$M_i \leq 4 \times 10^{-9} M_\oplus \Rightarrow \sigma_{inel} \geq 1.5 \times 10^{-34}$ cm^2

TEMPERATURE CHANGE

FLYBY VELOCITY CHANGE USED $\langle \delta \vec{v} \rangle = \dfrac{\int_0^\pi d\theta \sin\theta \, \delta\vec{v} \, |f(\theta)|^2}{\int_0^\pi d\theta \sin\theta \, |f(\theta)|^2}$

FLUCTUATION

$$\langle (\delta\vec{v} - \langle \delta\vec{v} \rangle)^2 \rangle$$

GIVES A TEMPERATURE INCREASE

$$\delta T_{\text{single collision}} = \frac{m_1}{2 k_B} \langle (\delta\vec{v} - \langle \delta\vec{v} \rangle)^2 \rangle$$

$$\frac{dT}{dt} = \int d^3u_2 \; \delta T_{s.c.} \; \sigma \; |\vec{u}_1 - \vec{u}_2| \, \rho(\vec{x}, \vec{u}_2)$$

$$T_f - T_i = \int_{t_i}^{t_f} dt \, \frac{dT}{dt}$$

SIMPLE MODIFICATION TO PROGRAMS

DEFINE: $\dfrac{A_{inel}}{B_{inel}} \equiv R_{inel} \, m_2 c \qquad S_{inel} = R_{inel} \dfrac{[2(m_2' - m_2)m_2']^{1/2}}{m_2}$

GET THEN: $\dfrac{\Delta T}{{}^\circ K} = \left(\dfrac{m_2 c^2}{MeV}\right)\left[Z_e + S_{inel} \, Z_i\right]$

FIND: $Z_e \sim (0.3 - 0.9) \times 10^{-5} \qquad Z_i \sim (0.2 - 0.7) \times 10^{4}$

KEY THINGS NEEDED FROM FLYBY REANALYSIS

- REAL EFFECT (NEW PHYSICS) OR ARTIFACT ?
- δV_f VALUES
- σ VALUES

  σ = .01 MESSENGER, NEAR
  .03 ROSETTA

  GIVES THEM A VERY BIG WEIGHT IN χ^2

- FLYBY ORBITAL PLANE PARAMETERS

  AND EARTH AXIS POLAR ANGLES I
  AZIMUTH α

ALSO LOOK FOR

- RESULTS FROM DIRECT DARK MATTER SEARCHES
- LHC SEARCH FOR SUPERSYMMETRY