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Celestial and Spaceflight Mechanics Laboratory

Detecting Internal Shifts Within Apophis Across its Earth Flyby

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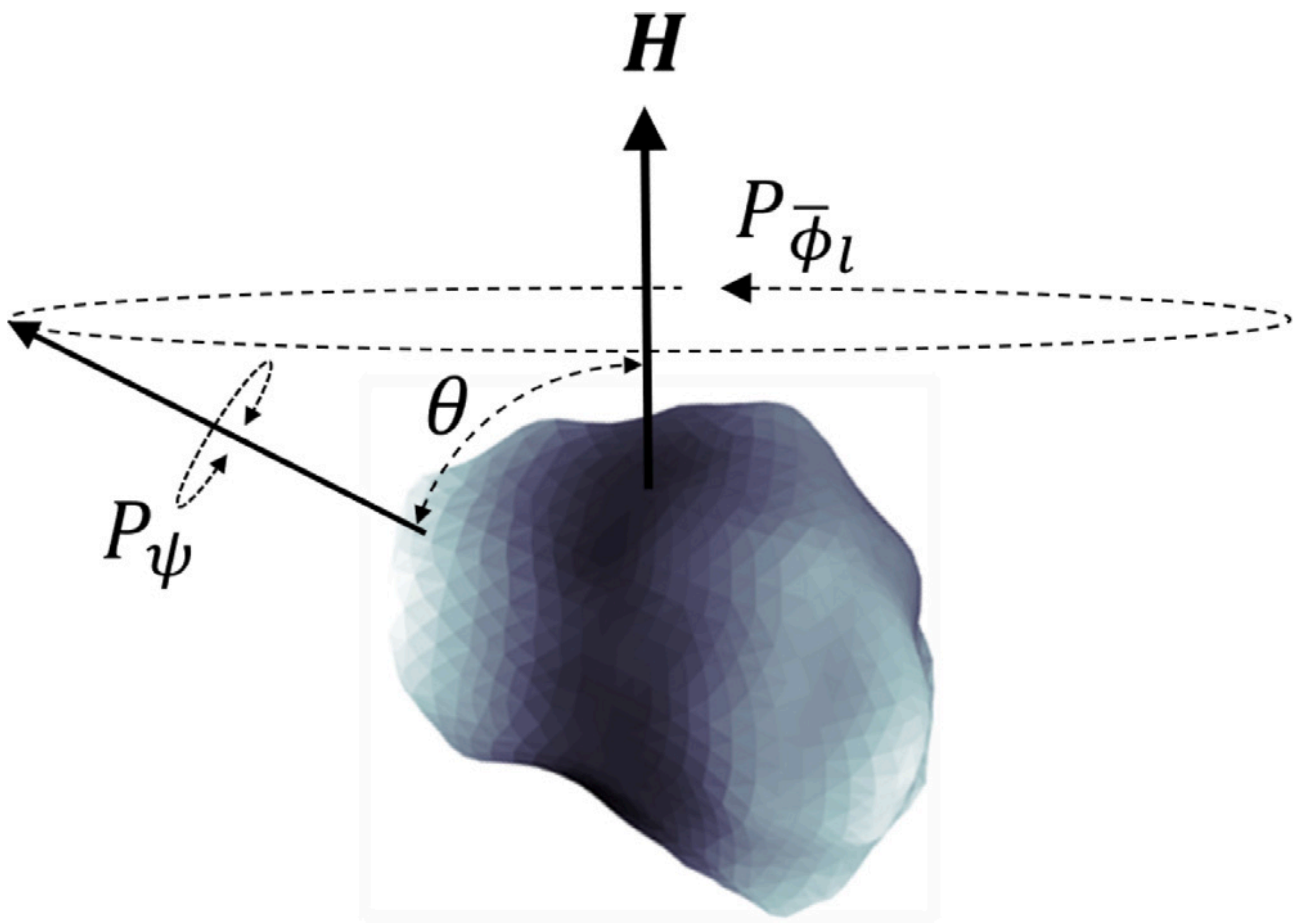
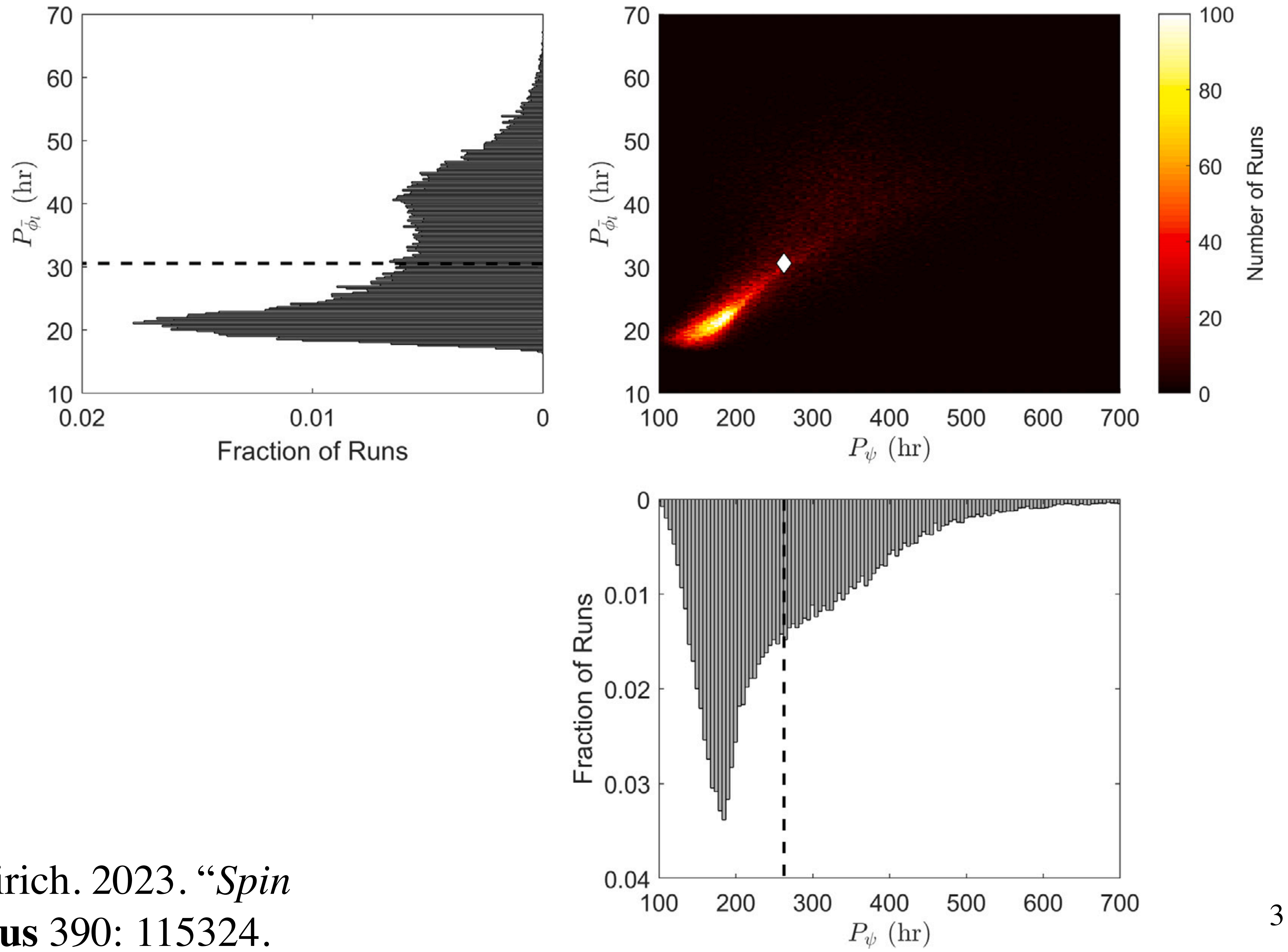
The Effect of the Earth Flyby on Apophis

Apophis Flyby Effects

- The most notable effect of the Apophis Earth flyby is that the spin state of the tumbling asteroid will undergo a major change:
  - Simulations show a change in the complex rotation state periods by a factor of two or more





C.J. Benson, D.J. Scheeres, M. Brozović, S. Chesley, P. Pravec and P. Scheirich. 2023. "*Spin State Evolution of (99942) Apophis during its 2029 Earth Encounter*," **Icarus** 390: 115324.

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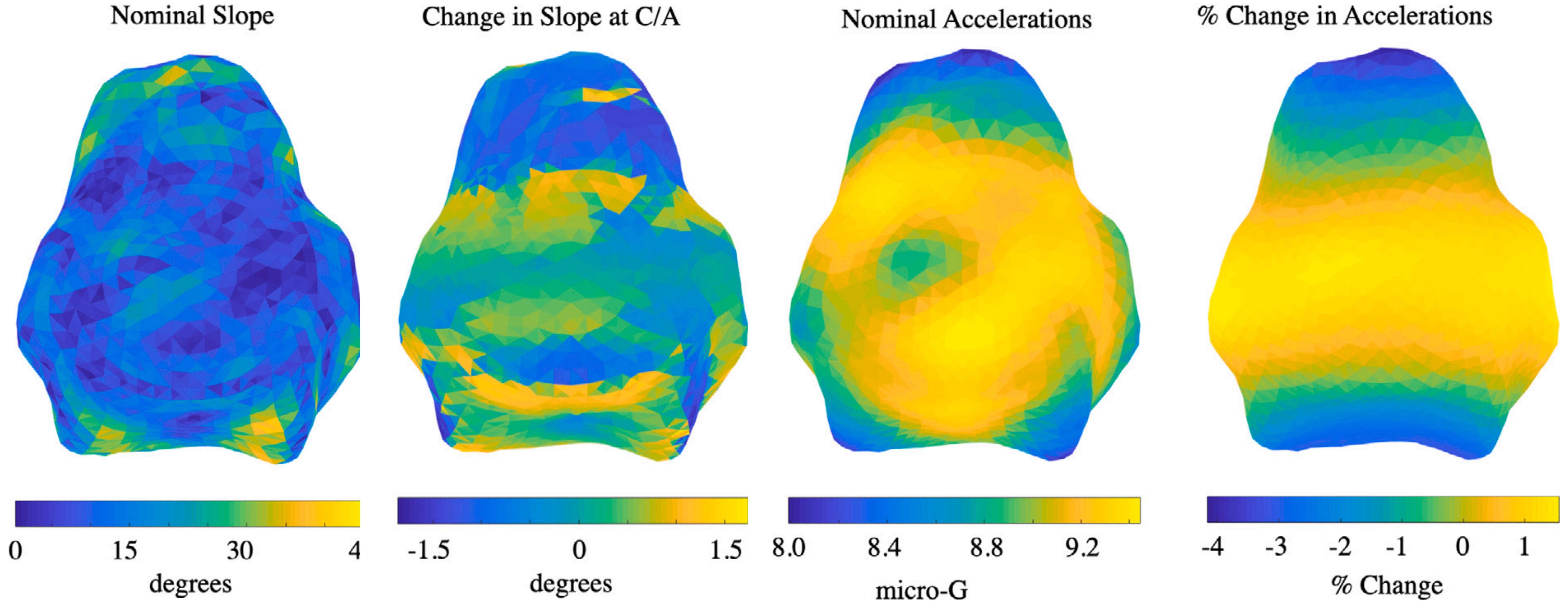
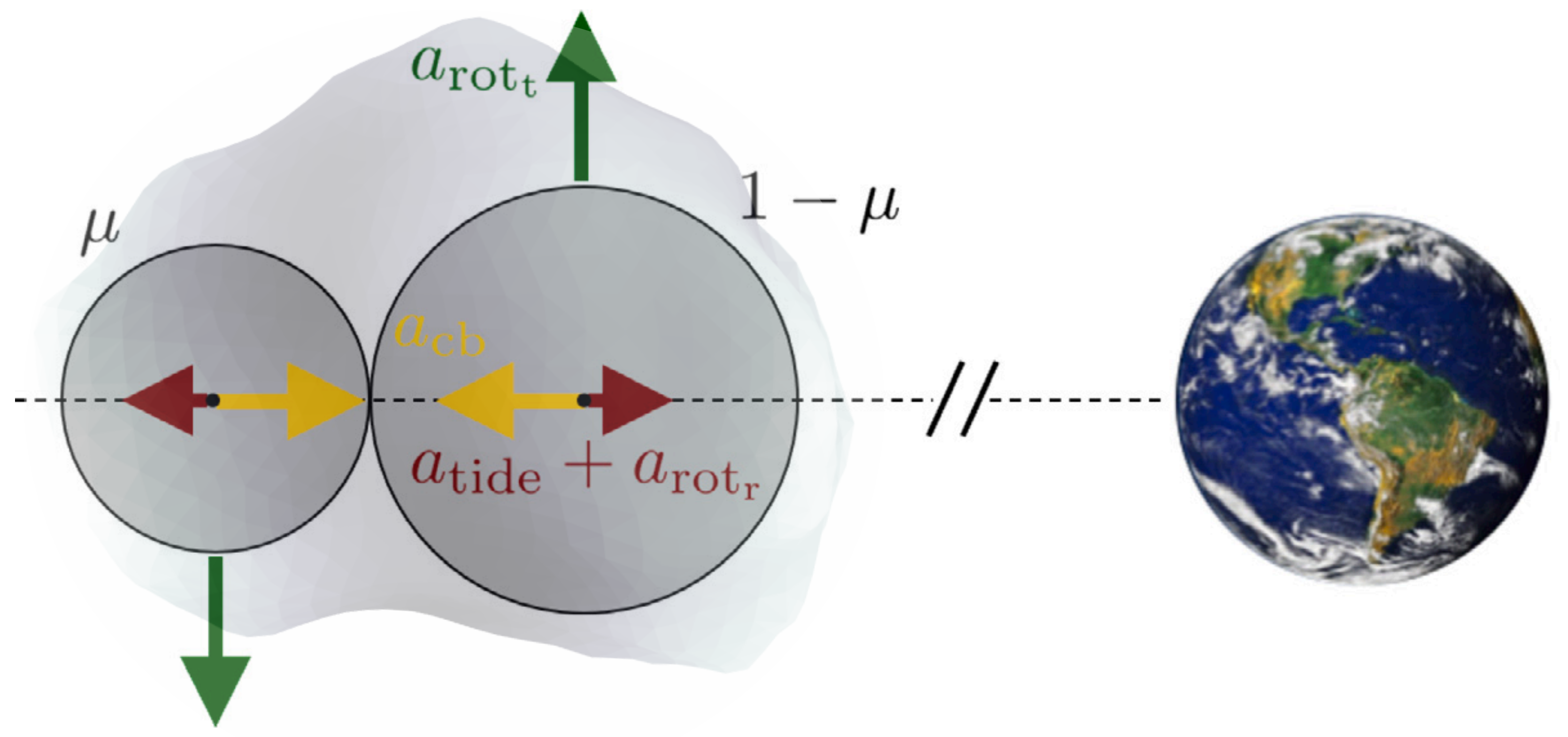
Apophis Flyby Effects

- Apophis ***will not*** fly close enough for significant perturbation of surface material
  – Relatively modest surface acceleration changes and slope changes mean that only limited regions of the surface may be disturbed, as concluded by several different research groups
- Most likely scenario for a noticeable change is if Apophis is a "contact binary" or consists of several larger components at rest on each other
  – Maximizes tidal stresses at component contact points and may cause them to reconfigure and shift

Relatively modest changes in surface environment



Possible pathway to a larger reorientation of components (Benson et al. 2023)



Tracking the Apophis Spin State

Estimating Apophis' Spin State

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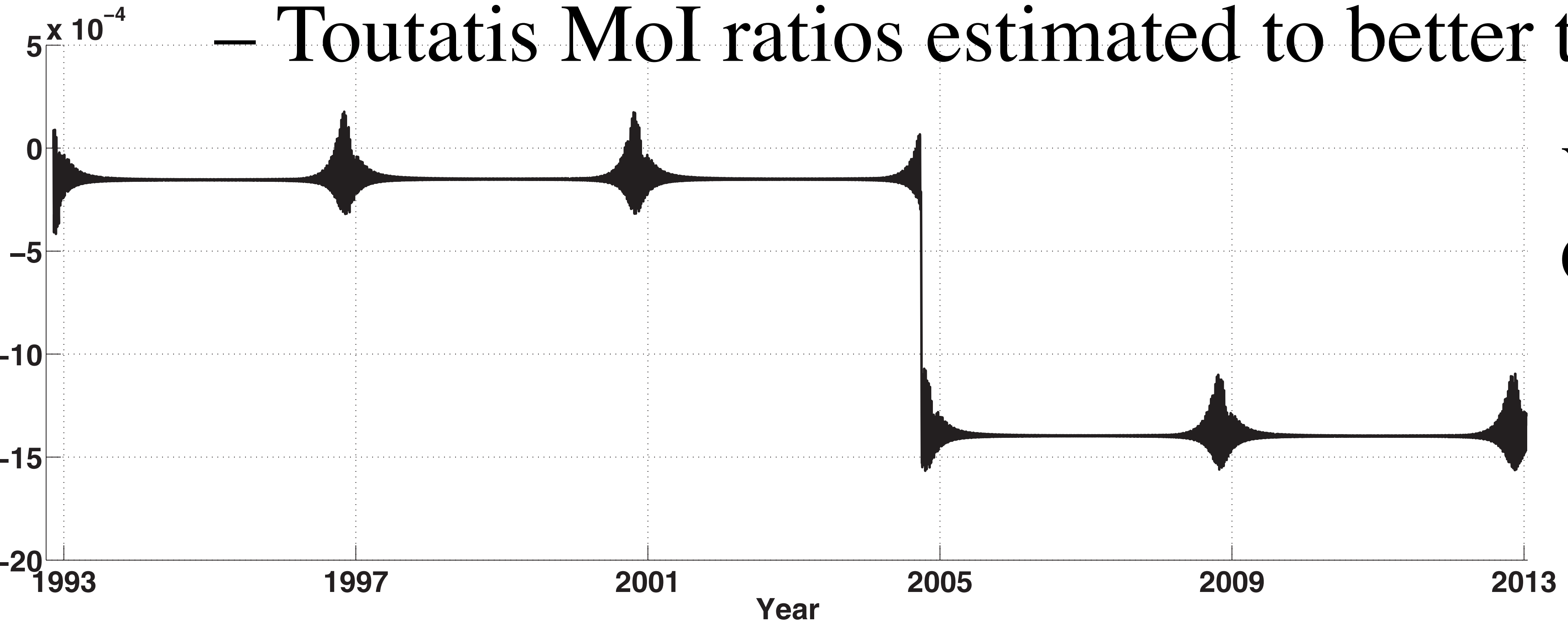
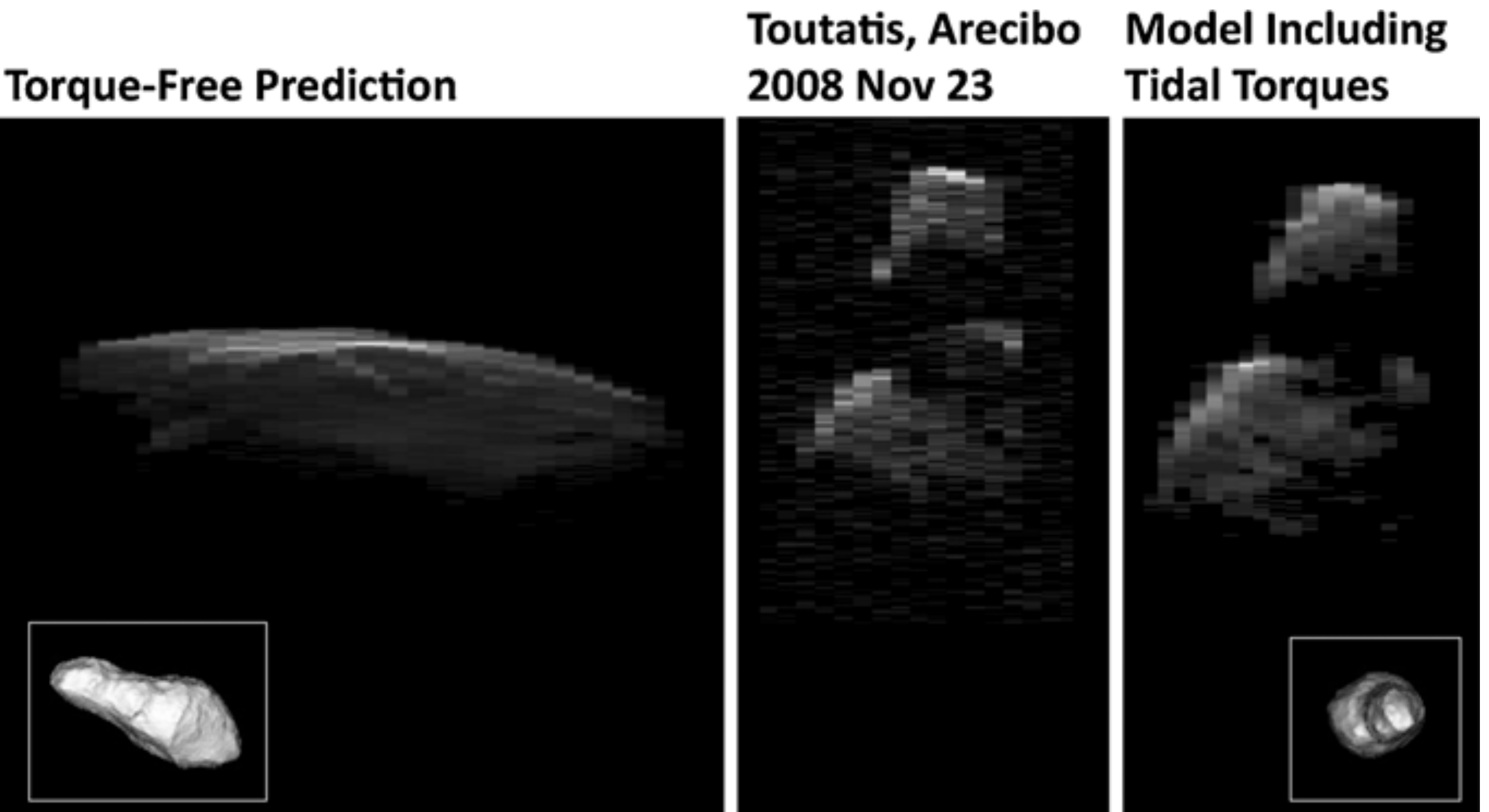
- Radar observations can generate attitude sequences of Apophis
  - These can be fit dynamically to estimate the spin state and moment of inertia ratios
  - Plans are to acquire high SNR radar images of Apophis ± 30 days from C/A (SAT Report)
- Using techniques previously applied to Toutatis over multiple Earth C/A it is possible to perform before / after estimates of spin state and inertia ratios, which can detect changes across the flyby
  - Toutatis MoI ratios estimated to better than 2%, Apophis observations will enable significant improvements





Y. Takahashi, M.W. Busch and D.J. Scheeres. 2013. "Spin State and Moment of Inertia Characterization of 4179 Toutatis," The Astronomical Journal 146:95, October 2013.

Parameter	Initial Value	A Priori 1σ Uncertainty	Estimated Value	Estimated 1σ Uncertainty
α (deg)	144.863	15	145.498	3.762
β (deg)	65.467	15	65.865	2.388
γ (deg)	241.785	15	241.524	2.586
ω_1 (deg day^{-1})	14.514	0.1	14.510	0.0994
ω_2 (deg day^{-1})	33.532	0.1	33.529	0.0971
ω_3 (deg day^{-1})	−98.713	0.1	−98.709	0.0957
$\bar{I}_{xx}$ (n.d.)	3.091	1×10^{-1}	3.0836	0.02822
$\bar{I}_{yy}$ (n.d.)	3.2178	1×10^{-1}	3.235	0.0714
$\bar{I}_{zz}$ (n.d.)	1	1×10^{-9}	1	1×10^{-9}
$\bar{I}_{xy}$ (n.d.)	0	1×10^{-2}	-7.1082×10^{-4}	0.00994
$\bar{I}_{yz}$ (n.d.)	0	1×10^{-2}	1.1707×10^{-3}	0.00939
$\bar{I}_{xz}$ (n.d.)	0	1×10^{-2}	1.3252×10^{-3}	0.00753

Tracking Apophis' Spin State through C/A

- Spin state estimates also allow precise predictions through C/A, enabling the MoI ratio estimates to be further improved by measuring deviations from the nominal
  - A 1% variation in MoI yields a variation in angular velocity of 4%, and in attitude by 2.5 degrees across a < 2 hour closest approach window and increasing by several degrees per day afterwards
  - This level of sensitivity provides additional improvement in the mass parameters, given the precisely known flyby conditions and Earth gravitational parameters
  - Additional observational data types can be used to track attitude around the close approach epoch
- Reconfigurations of the body will appear as abrupt deviations from these predicted profiles, and can provide precise timing of failure events
  - This would allow the internal stresses at failure to be constrained, and would provide unique insight into the interior structure and strength of the body
- Moment of Inertia ratio measurements combined with improved shape models can constrain internal density inhomogeneities, providing additional insight on the interior

Update on Janus to Apophis

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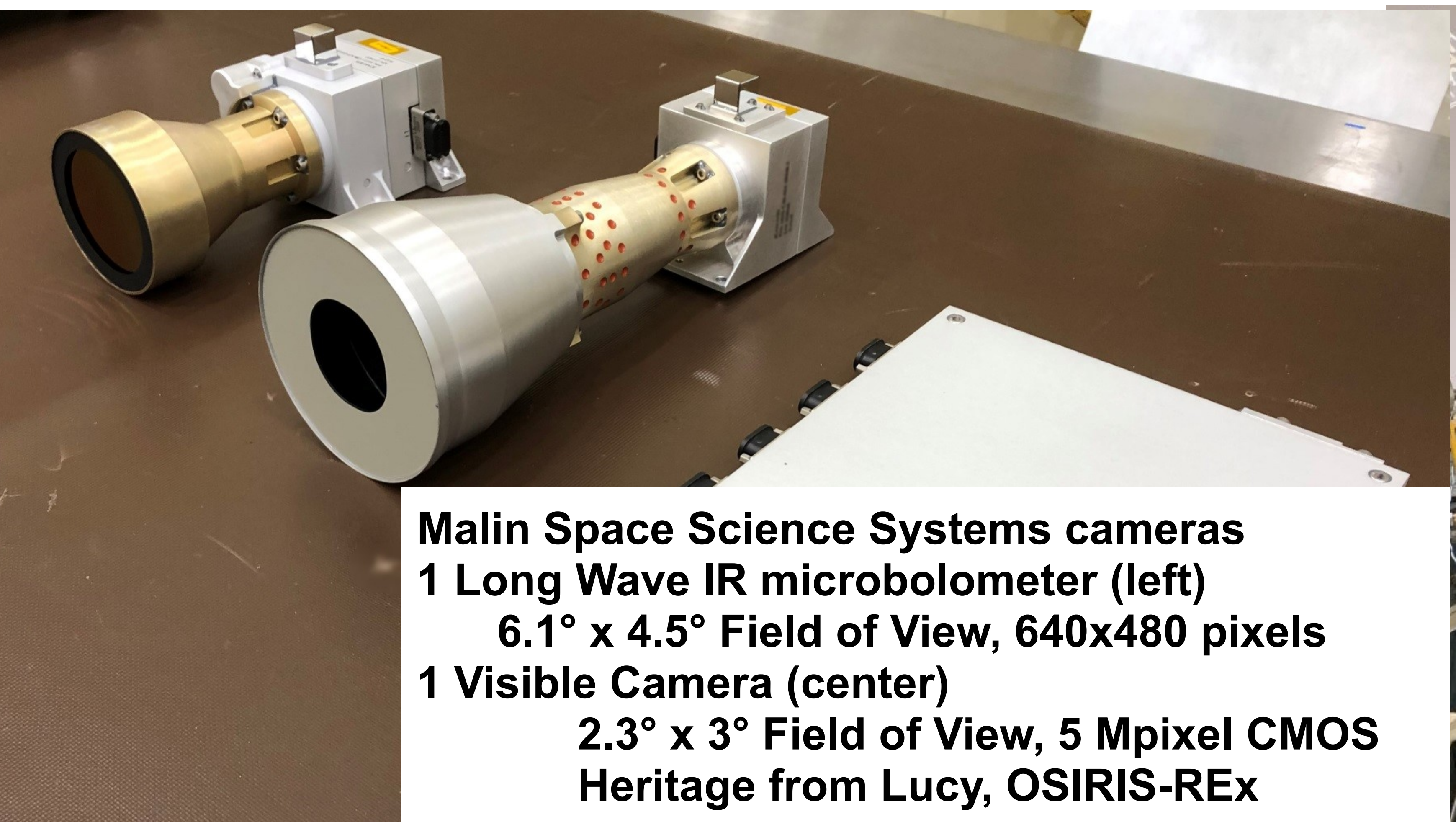
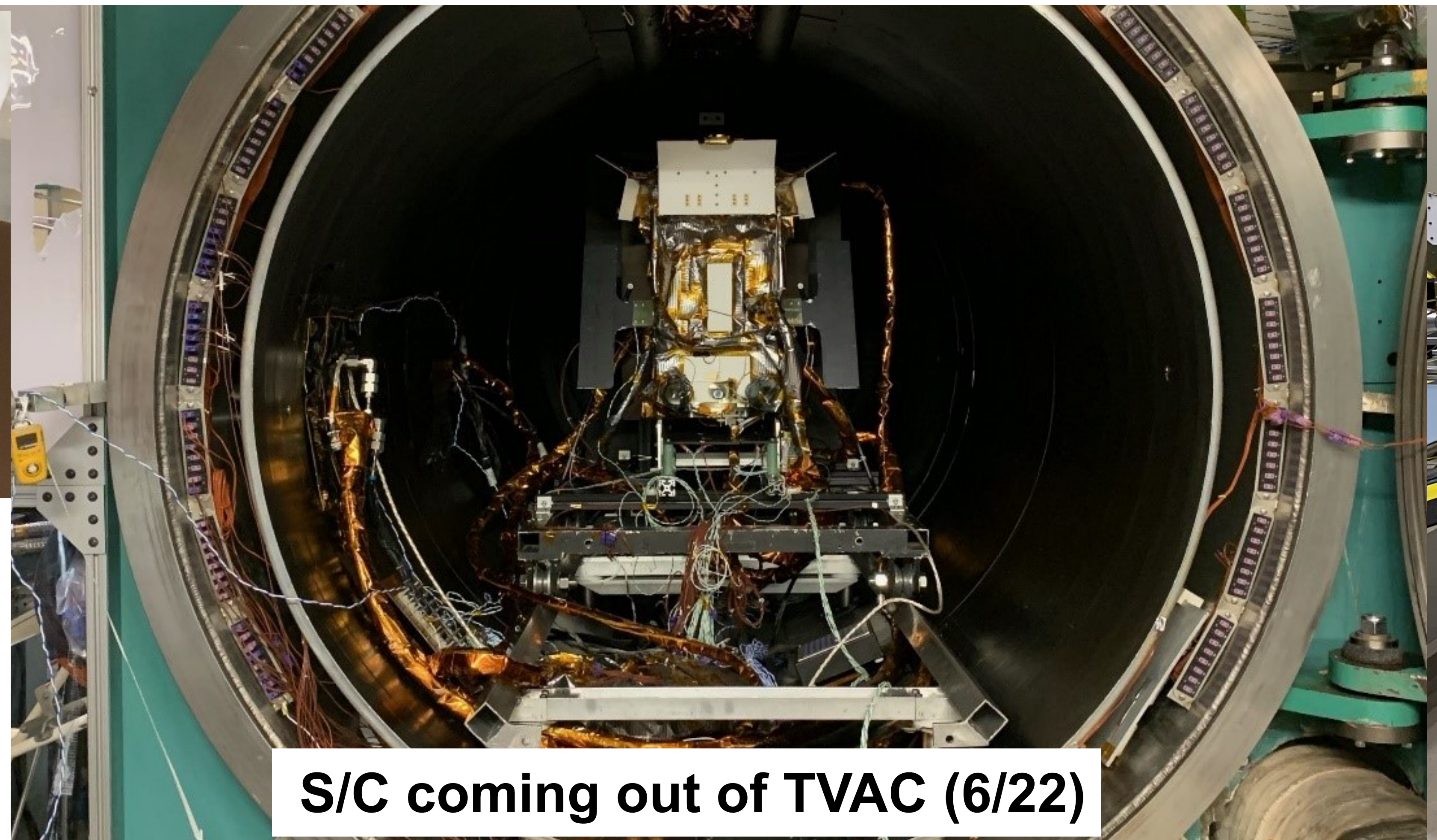
Janus Mission Status: *Apophis*

- The ***Janus*** Spacecraft are currently being transitioned to storage
- The ***Janus*** team continues to analyze new possible targets, with a focus on ***Apophis***
  - Currently evaluating several different rideshare opportunities that can send the S/C to Apophis, with flybys prior to its Earth C/A in 2029; plan to brief NASA on possibilities later this year
- Science Goals are being formulated for this activity, draft goals include…
  - Utilizing both spacecraft in phased flybys to maximize surface area coverage
  - Characterize the pre-close encounter shape, MoI and surface morphology of the asteroid, enabling rigorous evaluation of the flyby effect compared with ground-based and post-Earth C/A space-based observations
  - Provide improved predictions for the flyby attitude orientation and state



Malin Space Science Systems cameras
1 Long Wave IR microbolometer (left)
6.1° x 4.5° Field of View, 640x480 pixels
1 Visible Camera (center)
2.3° x 3° Field of View, 5 Mpixel CMOS
Heritage from Lucy, OSIRIS-REx



S/C coming out of TVAC (6/22)

NASA ATLO visit (4/22)