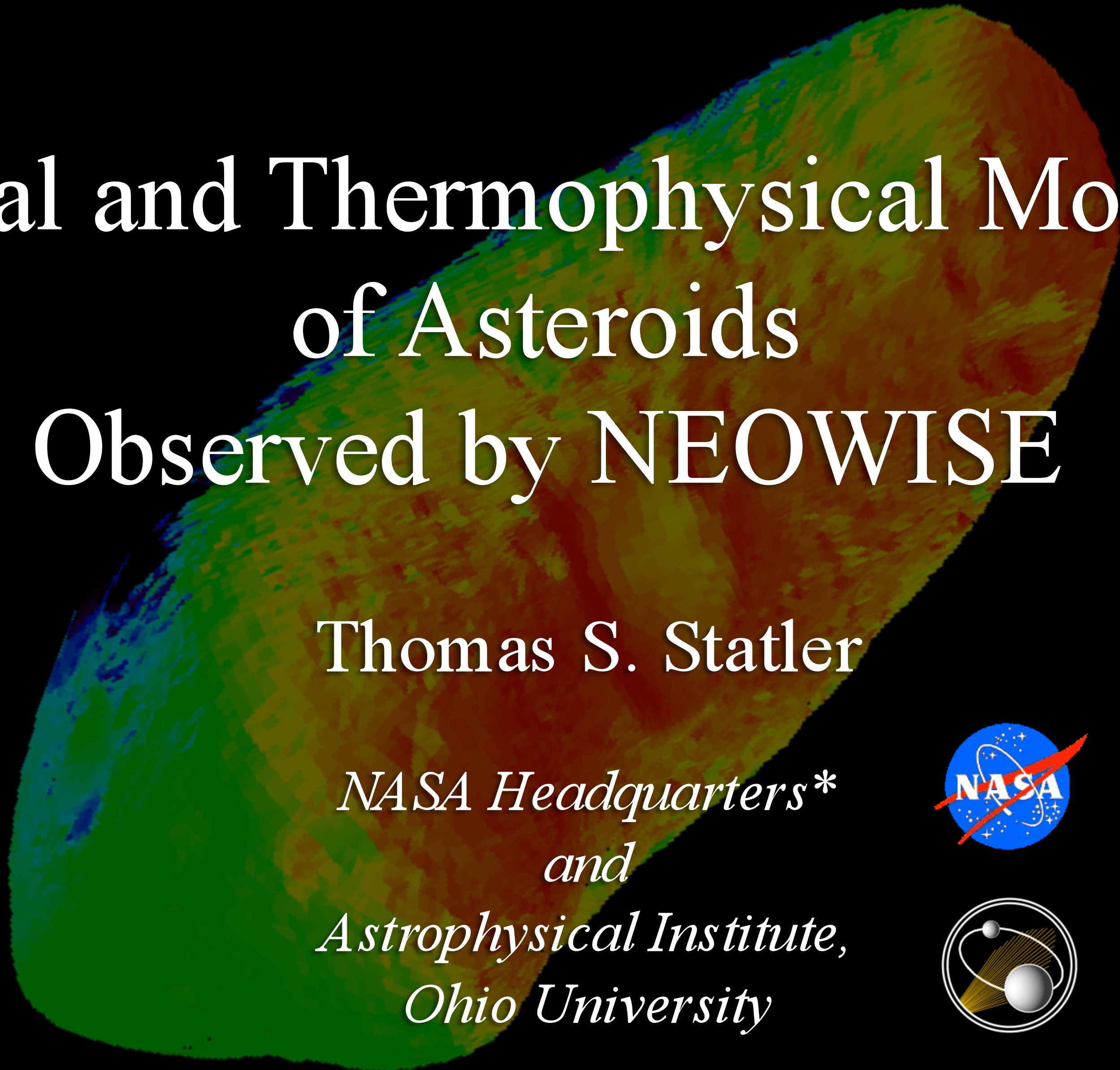
Thermal and Thermophysical Modeling of Asteroids Observed by NEOWISE



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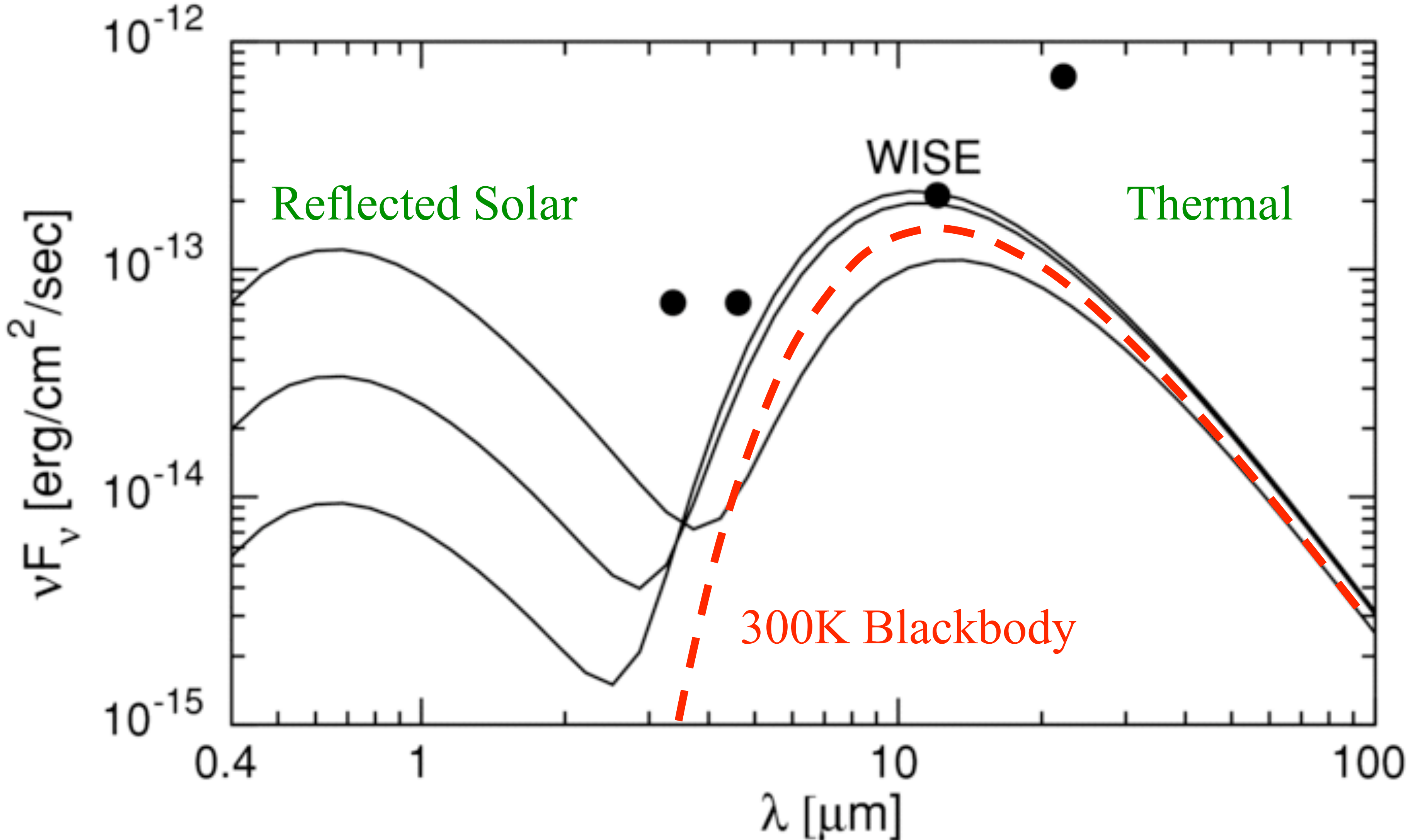
*The content of this talk represents the viewpoint of the author and not NASA.

NEO Science – or – Getting Past the Hazard

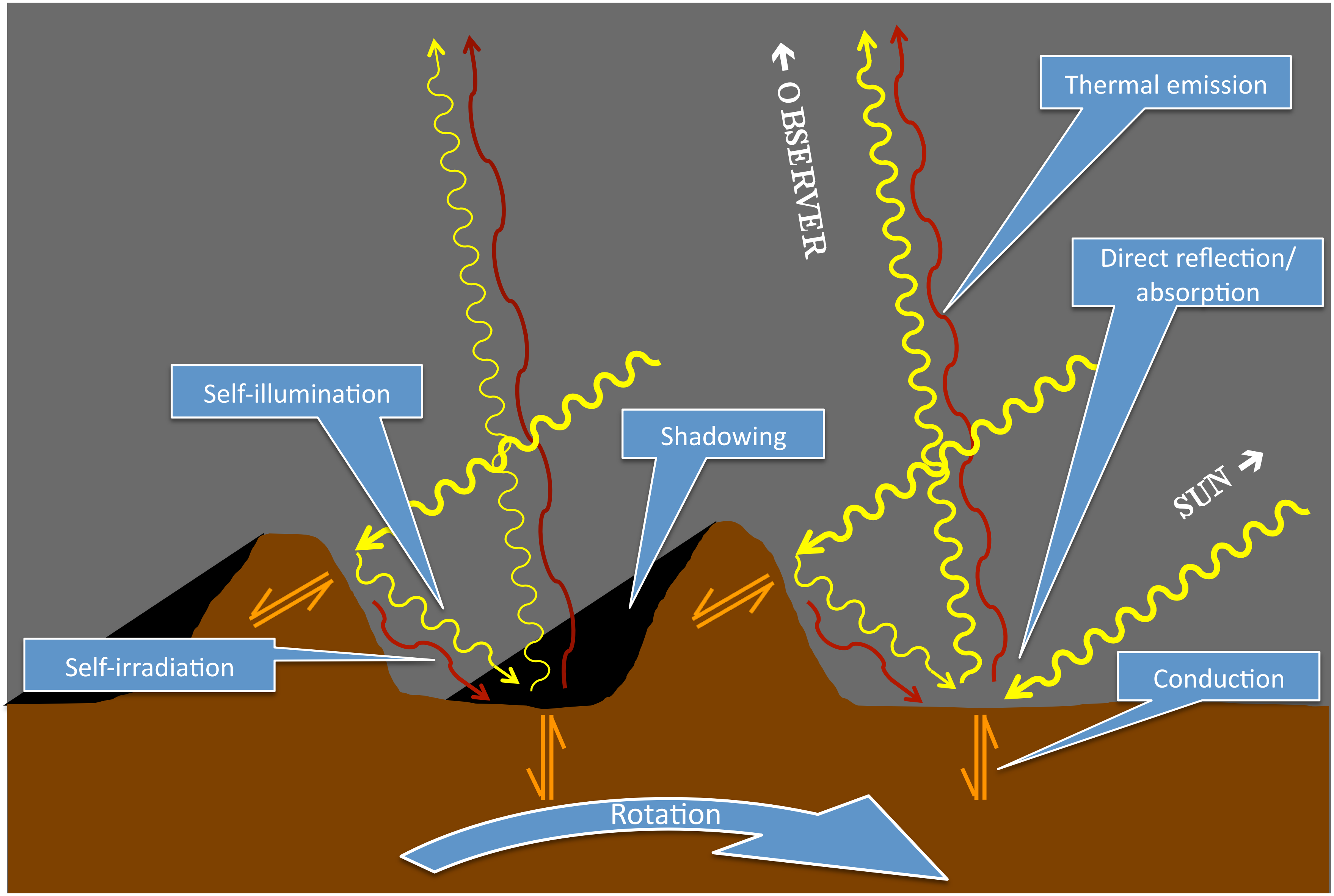
- Small bodies are leftover material – but not necessarily leftover *objects* – from planet formation.
- In-situ (Wild 2 via *Stardust*) and meteorite (2008 TC_3 = Almahata-Sitta) evidence suggest surprising amount of mixing in the protoplanetary nebula and in individual objects.
- Not just differentiation, but catastrophic impacts, shattering, reaccumulation, reshaping, etc., have altered the populations in poorly understood ways.
- Small-body orbit distributions (especially MBAs, TNOs) hold fossil footprints of planet migration.
- NEOs may be old objects but they are in young orbits (~ 10 Myr).
- NEOs are samples delivered from parts of the Main Belt, but we don't know which parts or with what efficiencies.
- Present-day NEOs may or may not be representative of the objects that delivered volatiles to the terrestrial planets.

Typical Expected NEO Spectra



Wright et al. 2010 AJ 140 1868

Basic Ingredients of a Thermophysical Model



Differences Between Thermophysical and Thermal Models

Thermophysical

- Asphericity
- Concavities (shadows)
- Anisotropic reflectivity
- Anisotropic emissivity
- Self-illumination
- Self-irradiation
- Heat conduction
- Rotation

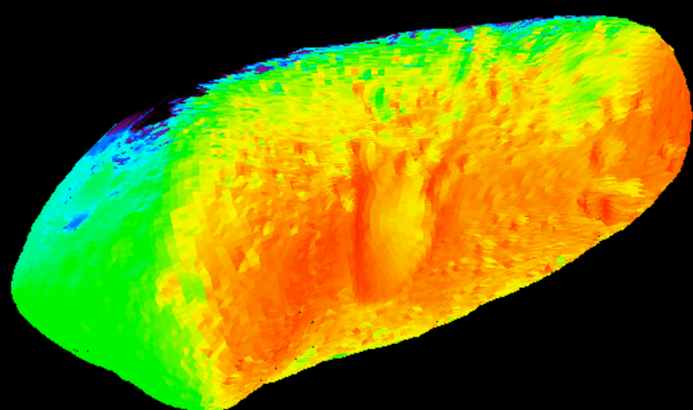
Thermal (NEATM*)

- “Beaming parameter” η

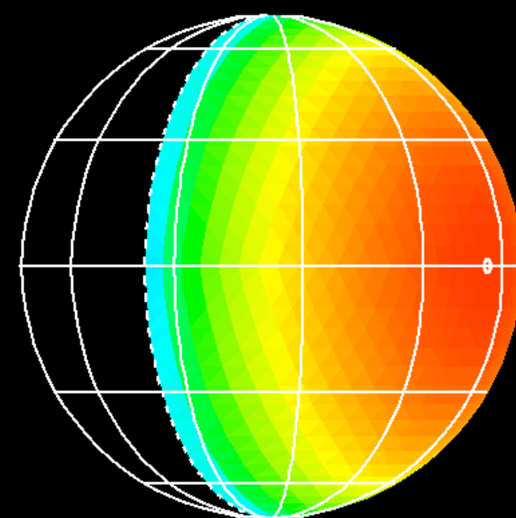
*Near Earth Asteroid Thermal Model (Harris 1998)

Models of Eros

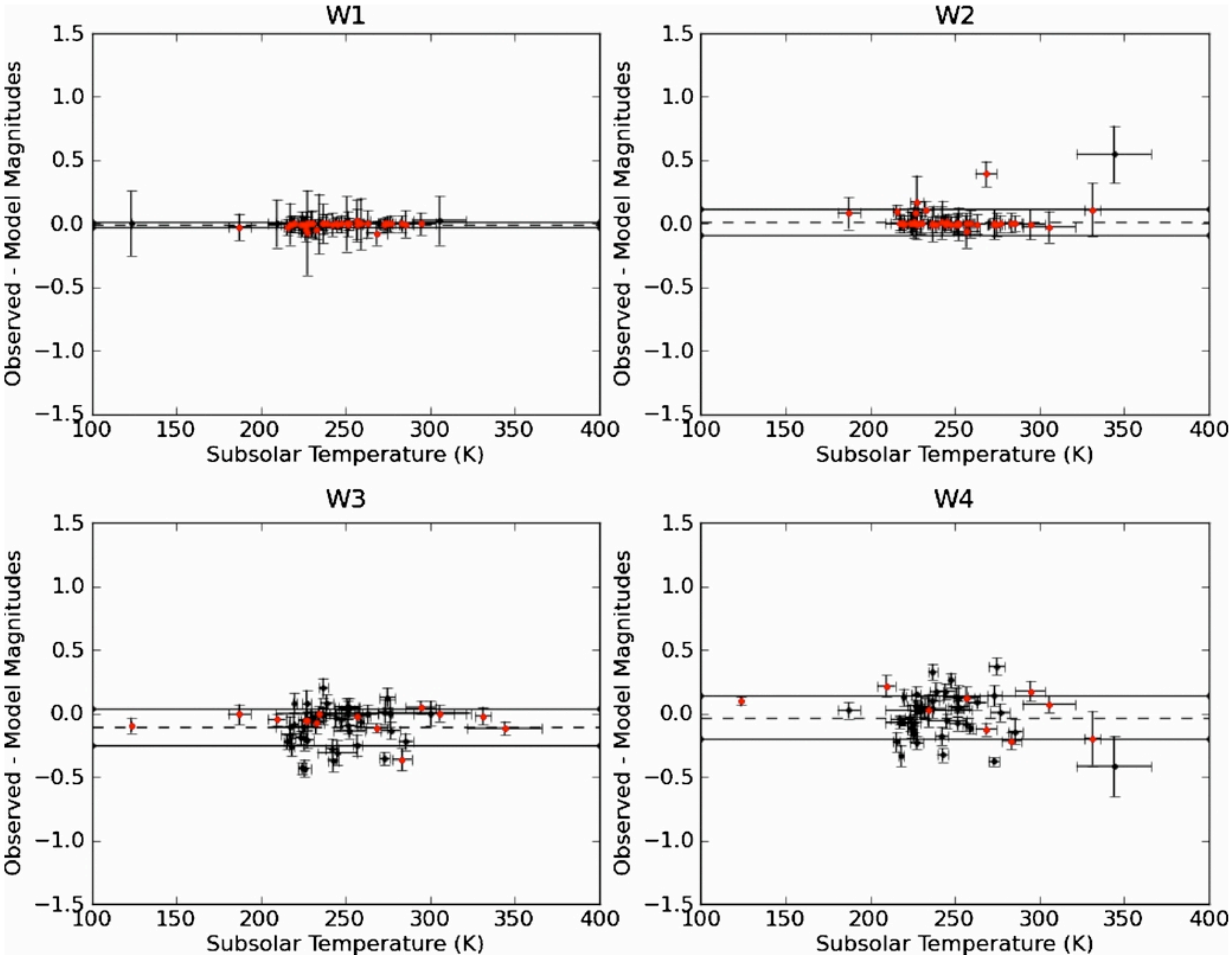
Thermophysical (TACO)



NEATM



NEATM Does Surprisingly Well



Mainzer et al. 2011 ApJ 736 100

- 50 asteroids with known effective diameters (from radar, occultations, spacecraft)
- Fold through NEATM to predict WISE fluxes

- Thermal bands good to ~ 20% (1σ)
- NEATM diameters good to ~ 10%

Why Thermophysical Modeling is Hard

<u>Thermophysical</u>

- Asphericity
- Concavities (shadows)
- Rotation
- Self-illumination
- Self-irradiation
- Anisotropic reflectivity
- Anisotropic emissivity
- Heat conduction

Constrainable with other observations (optical light curves, radar)

Follows (in part) from geometry

We're relying on few-tens-of-percent differences in the broadband spectra to constrain this stuff.

Linked to surface roughness

Constrains thermal & physical properties of near-surface layers (cm to m)

Observable Signatures of Heat Conduction

Surface fluxes depend on **thermal inertia** $\Gamma = (\rho k C)^{1/2}$

ρ = density

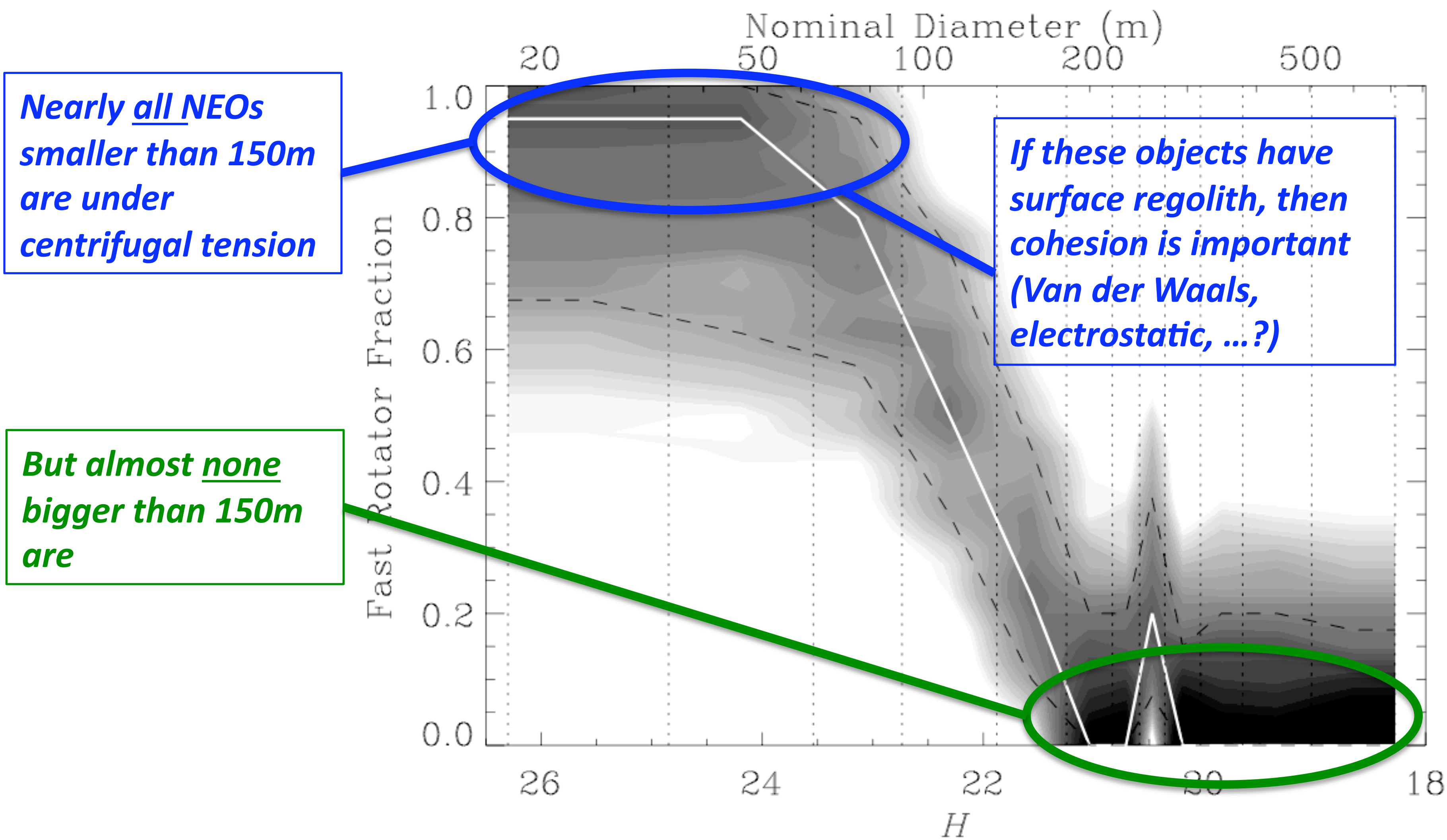
k = thermal conductivity

C = heat capacity

$\Gamma \sim$ J m^{-2} K^{-1} s$^{-1/2}$ (When all else fails, use SI units!)

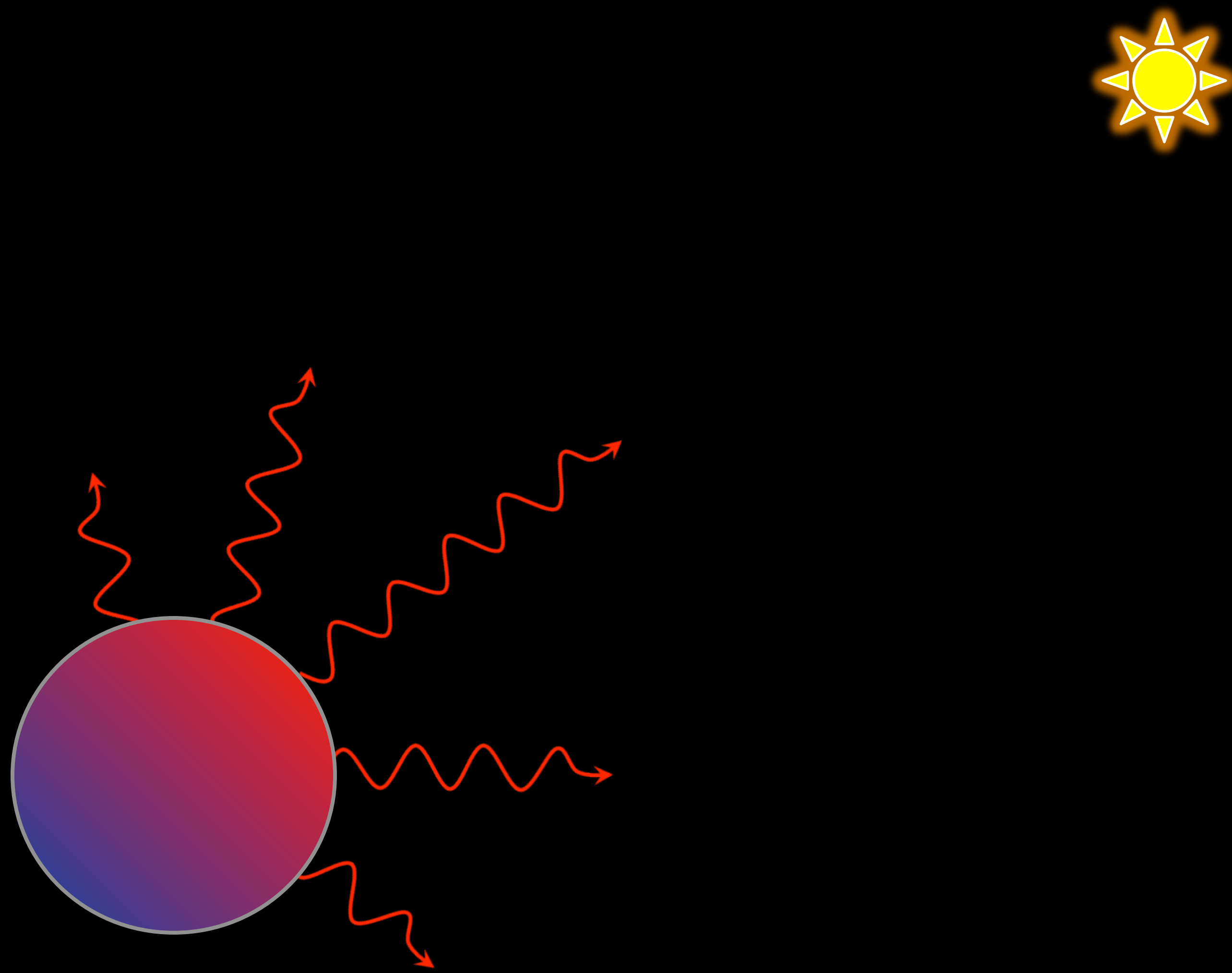
$\Gamma \sim 10^1$	Regolith, fluff
$\Gamma \sim 10^2$	Gravel, fractured rock
$\Gamma \sim 10^3$	Solid rock
$\Gamma \sim 10^4$	Solid metal

Why Should We Care?

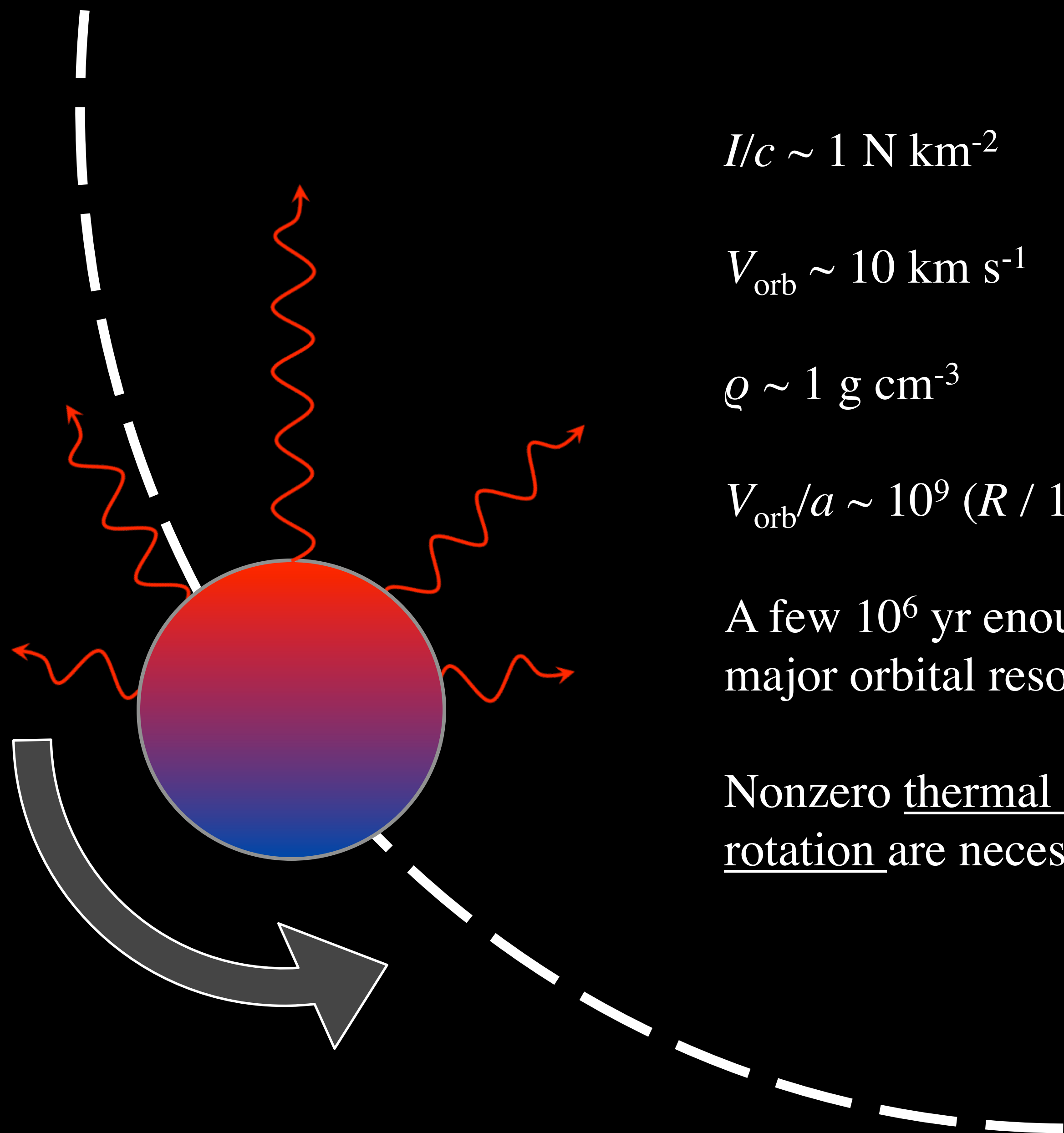


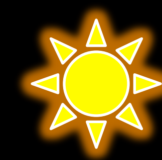
Statler et al. 2013 Icarus 225 141

Radiation Recoil Force = Yarkovsky Effect



Radiation Recoil Force = Yarkovsky Effect





$I/c \sim 1$ N km^{-2}

$V_{orb} \sim 10$ km s^{-1}

$\varrho \sim 1$ g cm^{-3}

$V_{orb}/a \sim 10^9$ (R / 1 km) yr

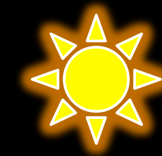
A few 10^6 yr enough to move to major orbital resonances

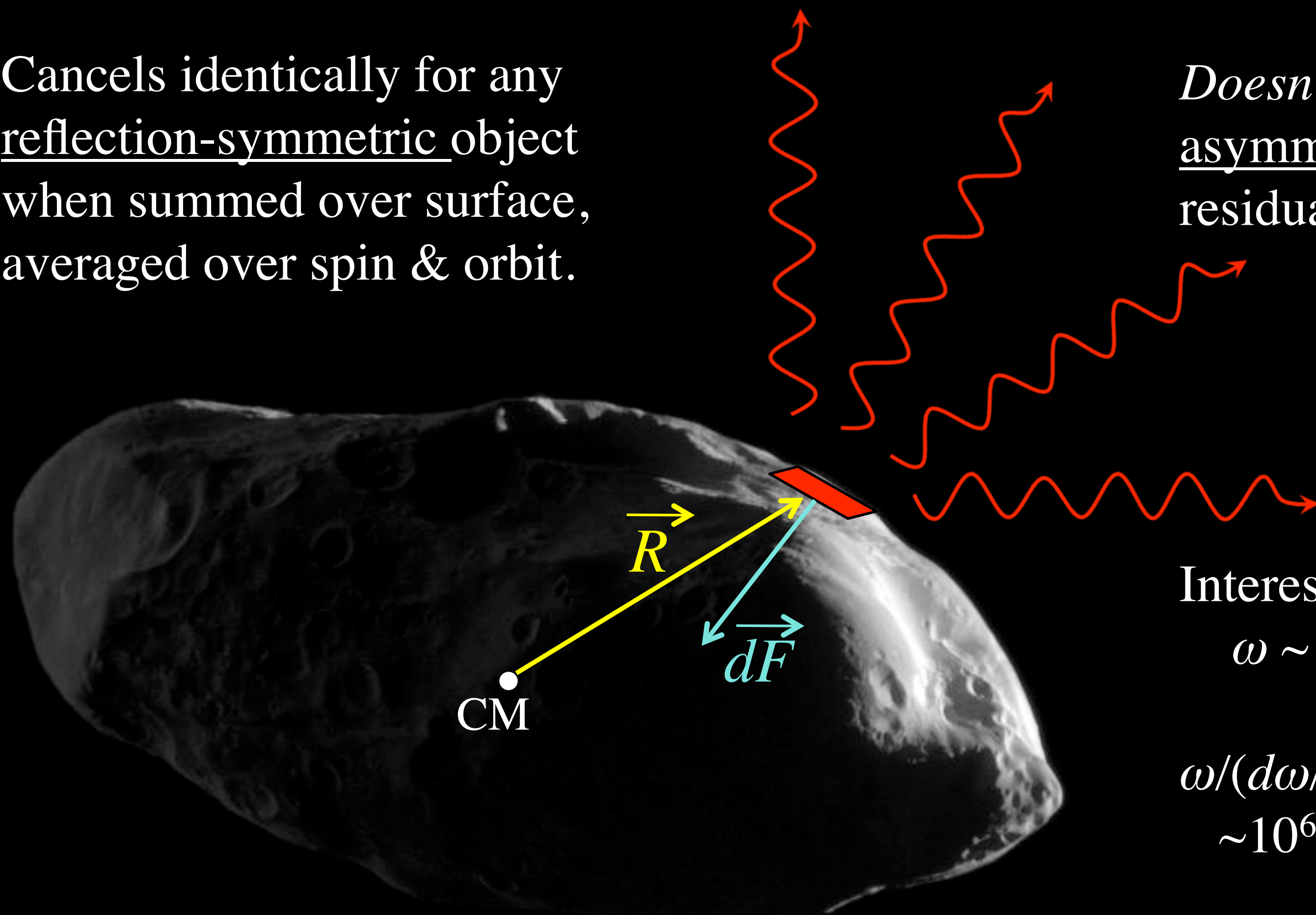
Nonzero thermal conductivity and rotation are necessary for Yarkovsky

Radiation Recoil Torque = YORP Effect

$$\overrightarrow{d(\text{torque})} = \vec{R} \times \overrightarrow{dF}$$

Cancels identically for any <u>reflection-symmetric</u> object when summed over surface, averaged over spin & orbit.





Doesn't cancel for <u>asymmetric</u> objects. Net residual torque is **YORP**.

Interesting spin periods

$\omega \sim$ hours

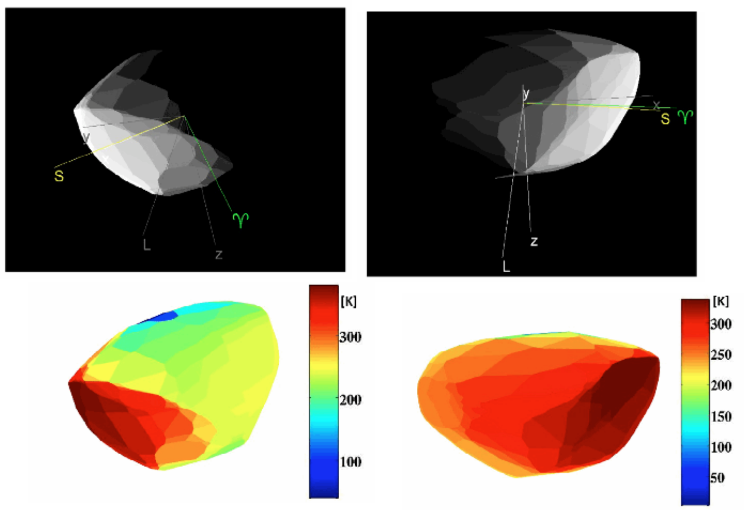
$\omega/(d\omega/dt)$

$\sim 10^6 \, (R \,/\, 1 \text{ km})^2$ yr

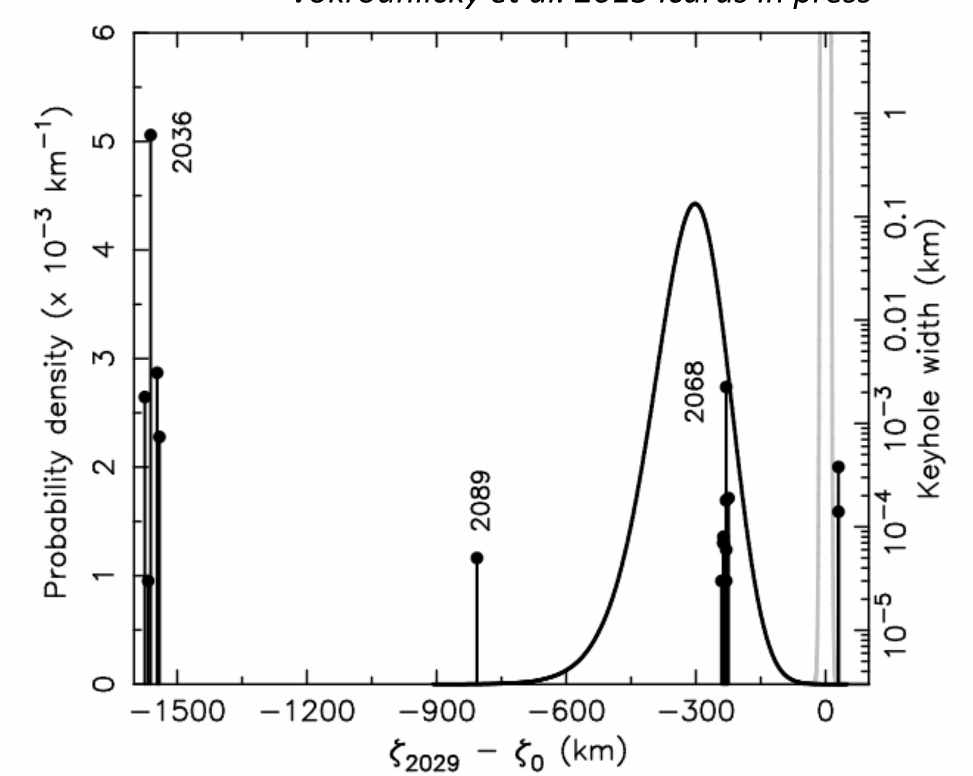
<u>Chirality</u> is necessary for YORP.

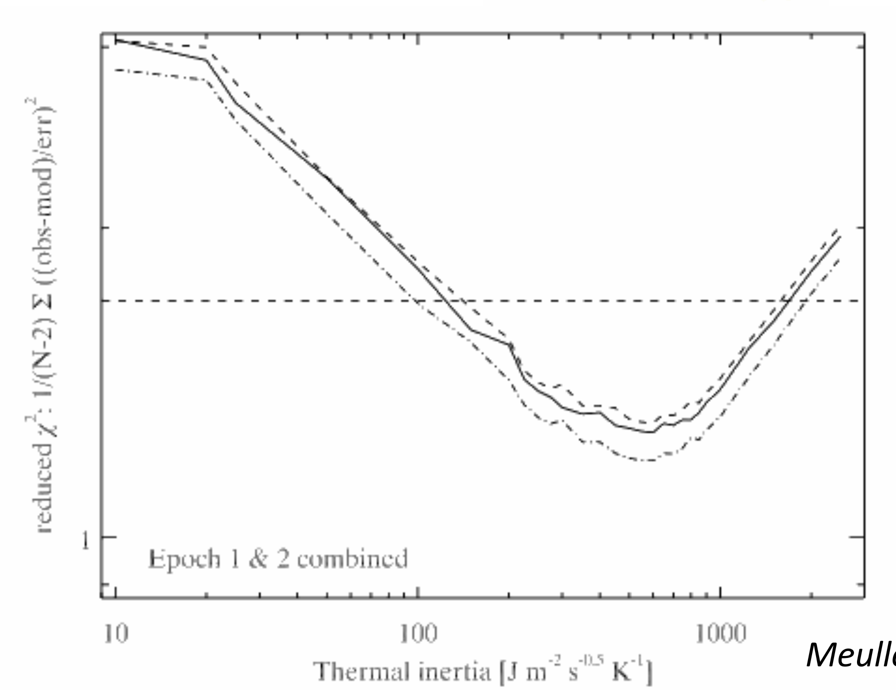
Thermal Inertia of 99942 Apophis (from *Herschel* data)

Yarkovsky has been the largest uncertainty in the 2029 close pass by Earth, relative to keyholes that lead to impacts after 2060.



Vokrouhlicky et al. 2015 Icarus in press

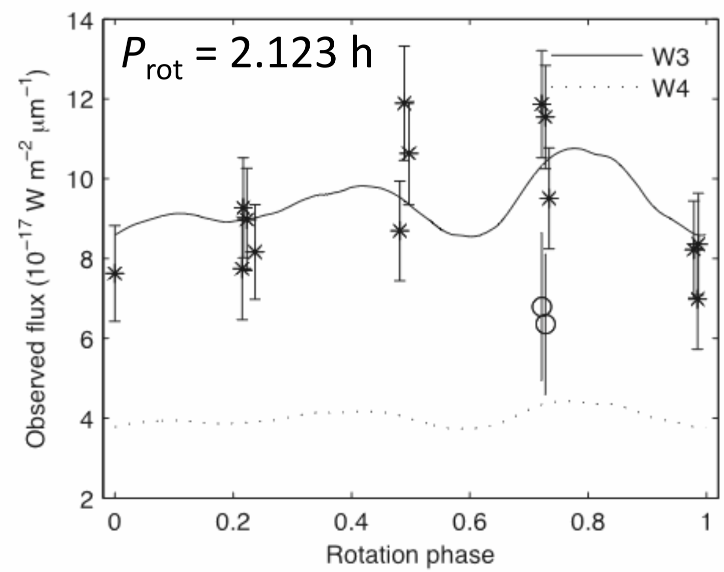


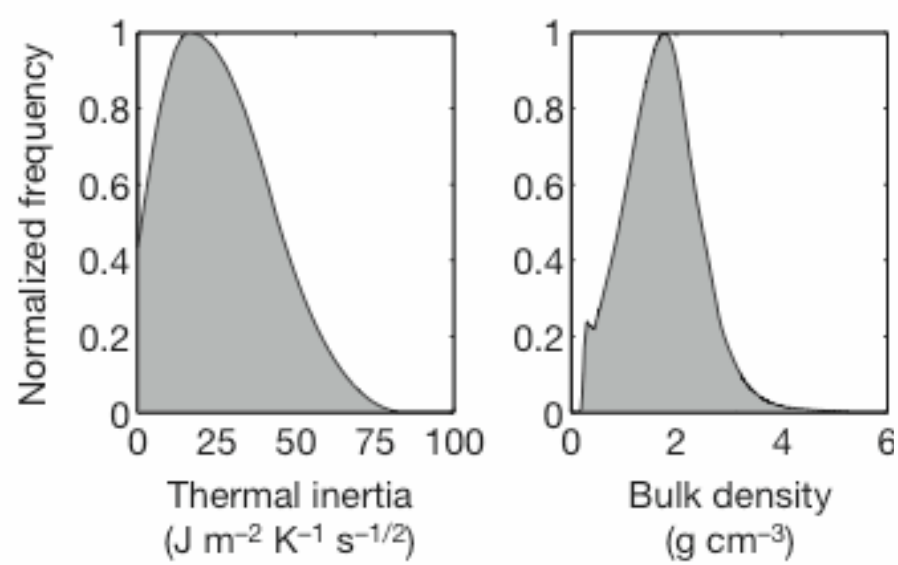


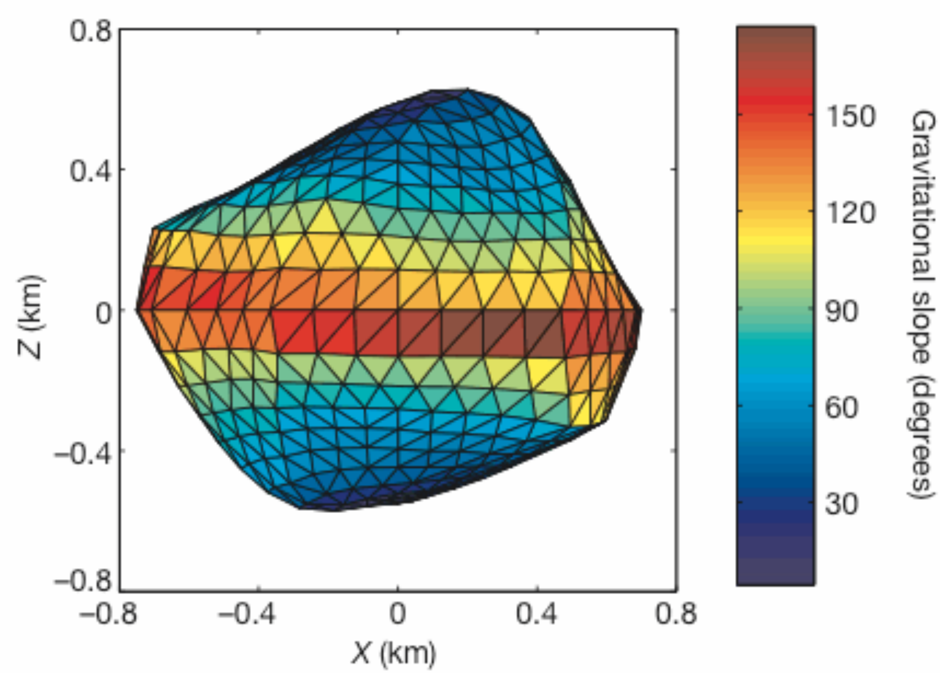
Meuller et al. 2014 A&A 566 A22

1950 DA – A Cohesively Bound Rubble Pile?

- Radar ⇨ shape model
- Radar + (WISE + thermal model) ⇨ size
- WISE + thermophysical model ⇨ Γ
- Γ + spin + <u>assumed</u> ρ ⇨ Yarkovsky acceleration
- Yarkovsky + astrometry ⇨ ρ
- ρ + size + shape + spin ⇨ surface gravity (−ve!)
- Low Γ ⇨ surface regolith
- Regolith + surface gravity ⇨ cohesion





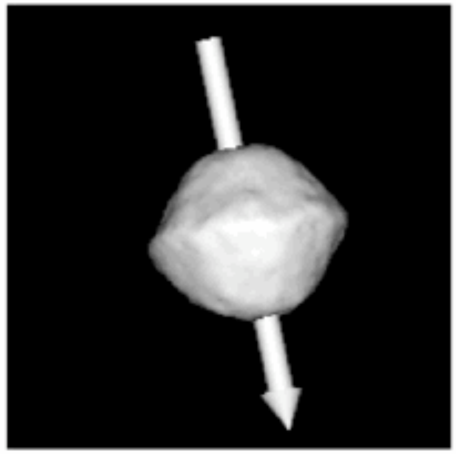


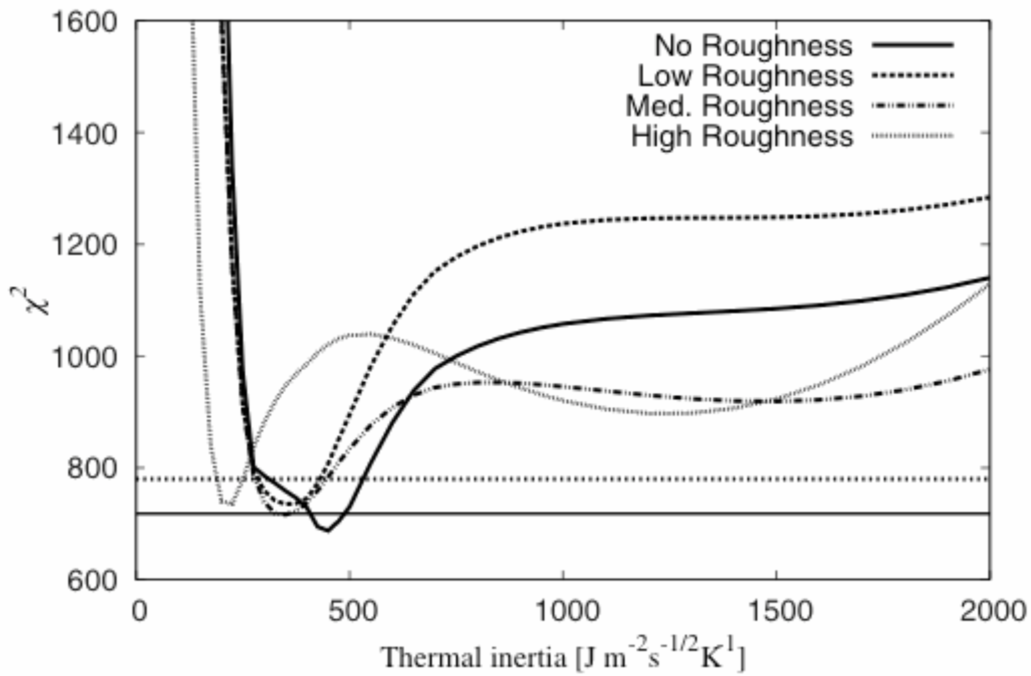
Rozitis et al. 2014 Nature 512 174

2008 EV_5 – Using Multi-Epoch Data

Thermal inertia
+ regolith conductivity model
⇨ mean particle size
5 – 15 mm

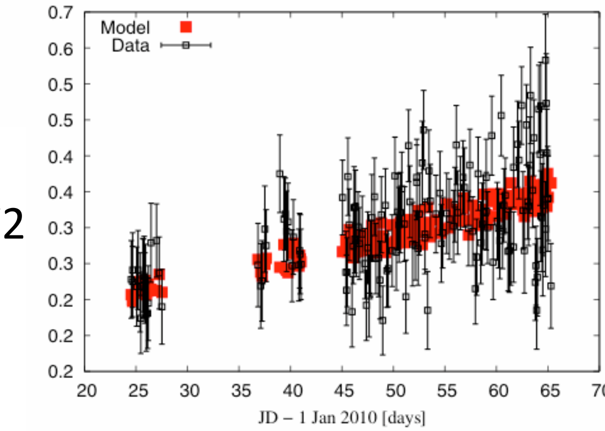
Rotation P = 3.725 hours
So regolith not unexpected



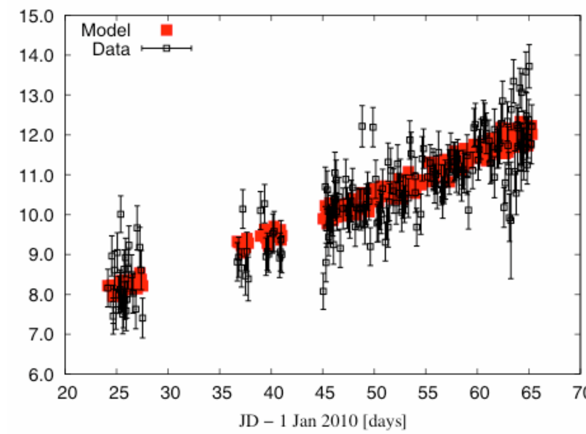


Ali-Lagoa et al. 2014 A&A 561 A45

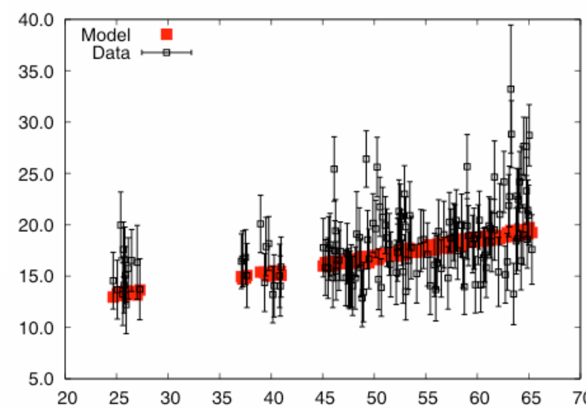
W2



W3



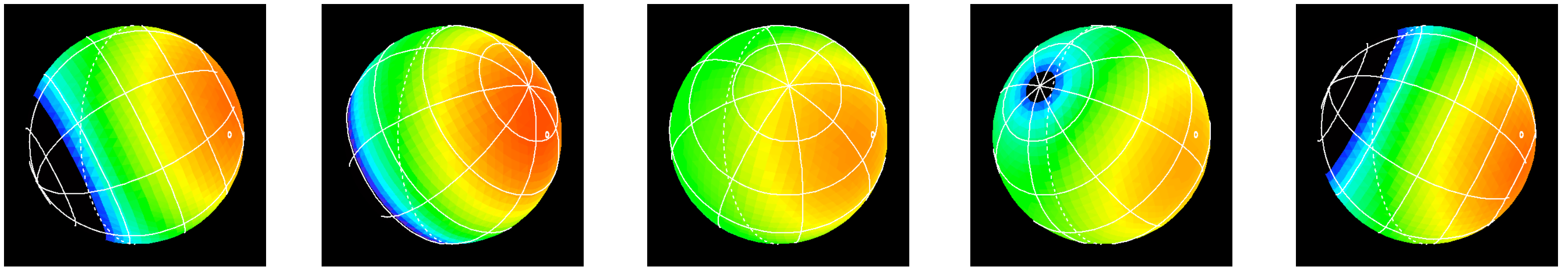
W4



← 50 days →

What Next?

- Multi-epoch observations (at widely different geometries) are key.



- Modeling problem is highly degenerate: Γ *vs.* shape *vs.* size.
- Shape models from optical light curves are strictly convex – insensitive to concavities.
- But concavities influence thermal IR light curves.
- Understanding and breaking degeneracies is challenging. Multiple groups working on this.
- NEOWISE-R will provide additional epochs, but limitation to W1 and W2 will increase model-dependence of the results.
- *Stay tuned for more action-packed excitement!*