EVOLUTIONS OF SMALL BODIES IN OUR SOLAR SYSTEM

Dynamics and collisional processes

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Plan

- Chapter I:

A few concepts on dynamics and transport mechanisms in the Solar System; application to the origin of Near-Earth Objects (NEOs)

- Chapter II:

On the strength of rocks and implication on the tidal and collisional disruption of small bodies

Preliminaries: orbital elements

a= semi major axis

e=eccentricity

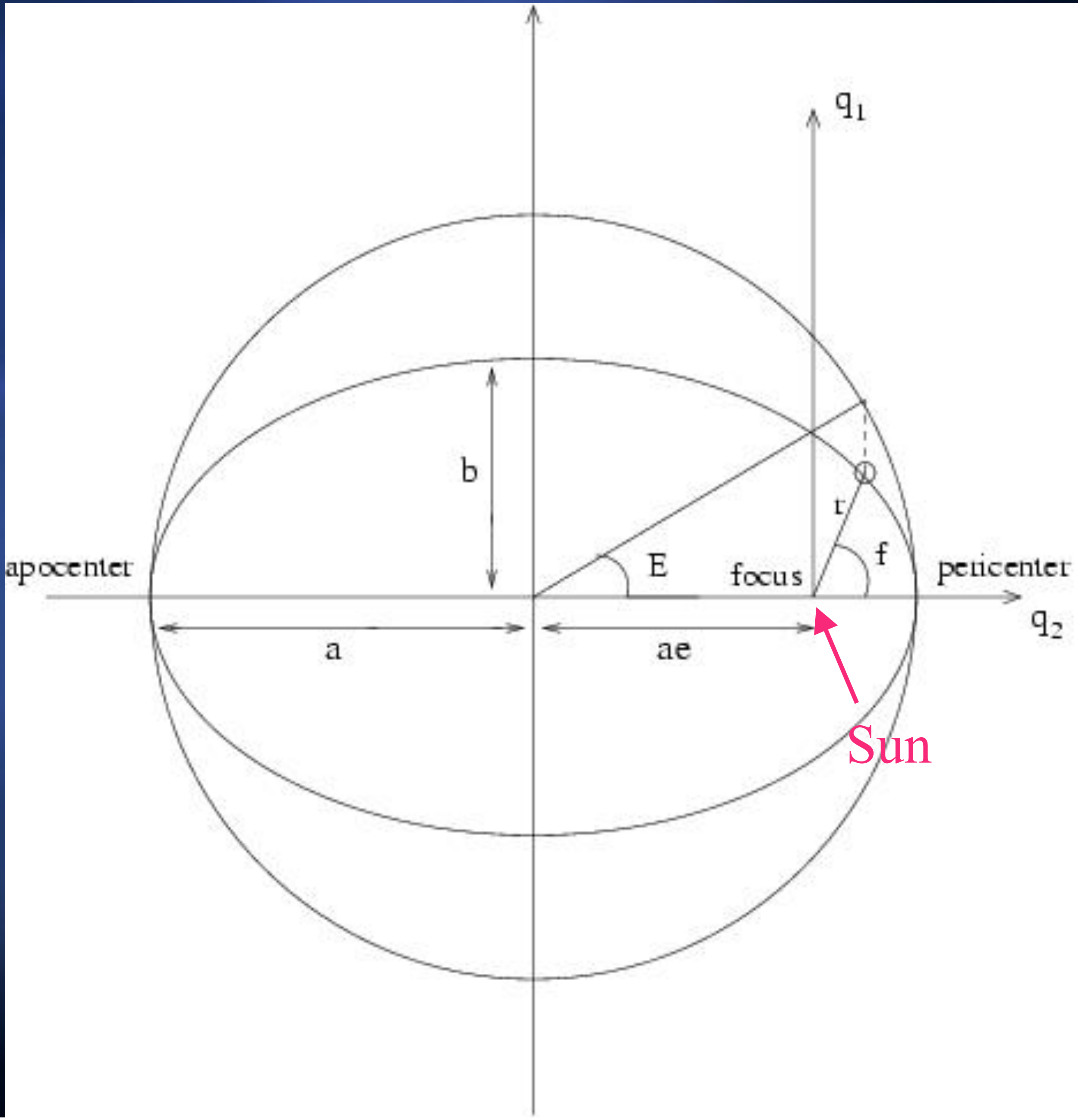
f=true anomaly

E=eccentric anomaly

Mean anomaly:

M=E-e sin E= n t

with $n=(GM_*)^{1/2}/a^{3/2}$
(orbital frequency)



Preliminaries: orbital elements

i = inclination

Ω = longitude of node

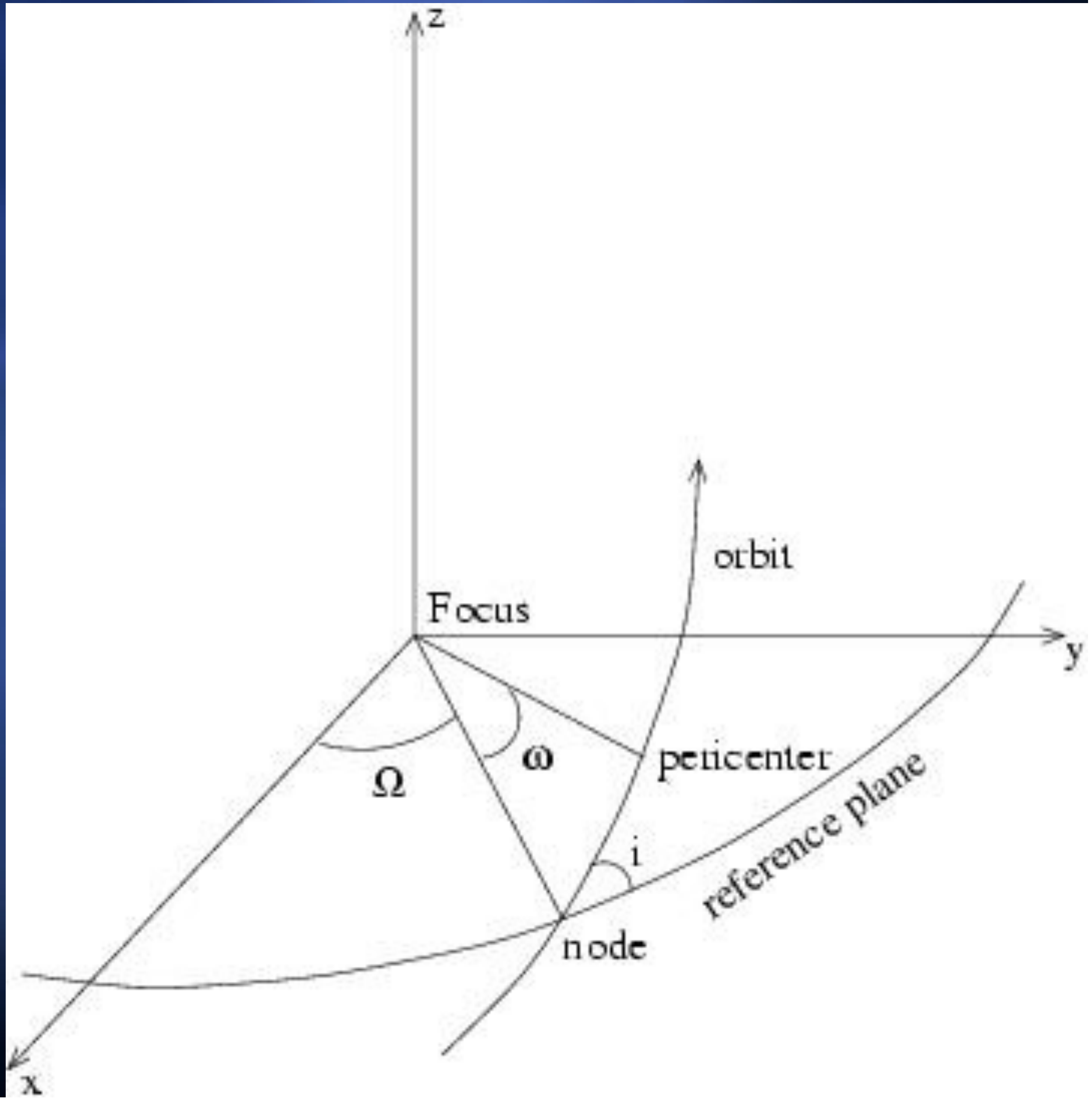
ω = argument of pericenter

Longitude of pericenter:

$\varpi = \omega + \Omega$

Mean longitude:

$\lambda = M + \varpi$

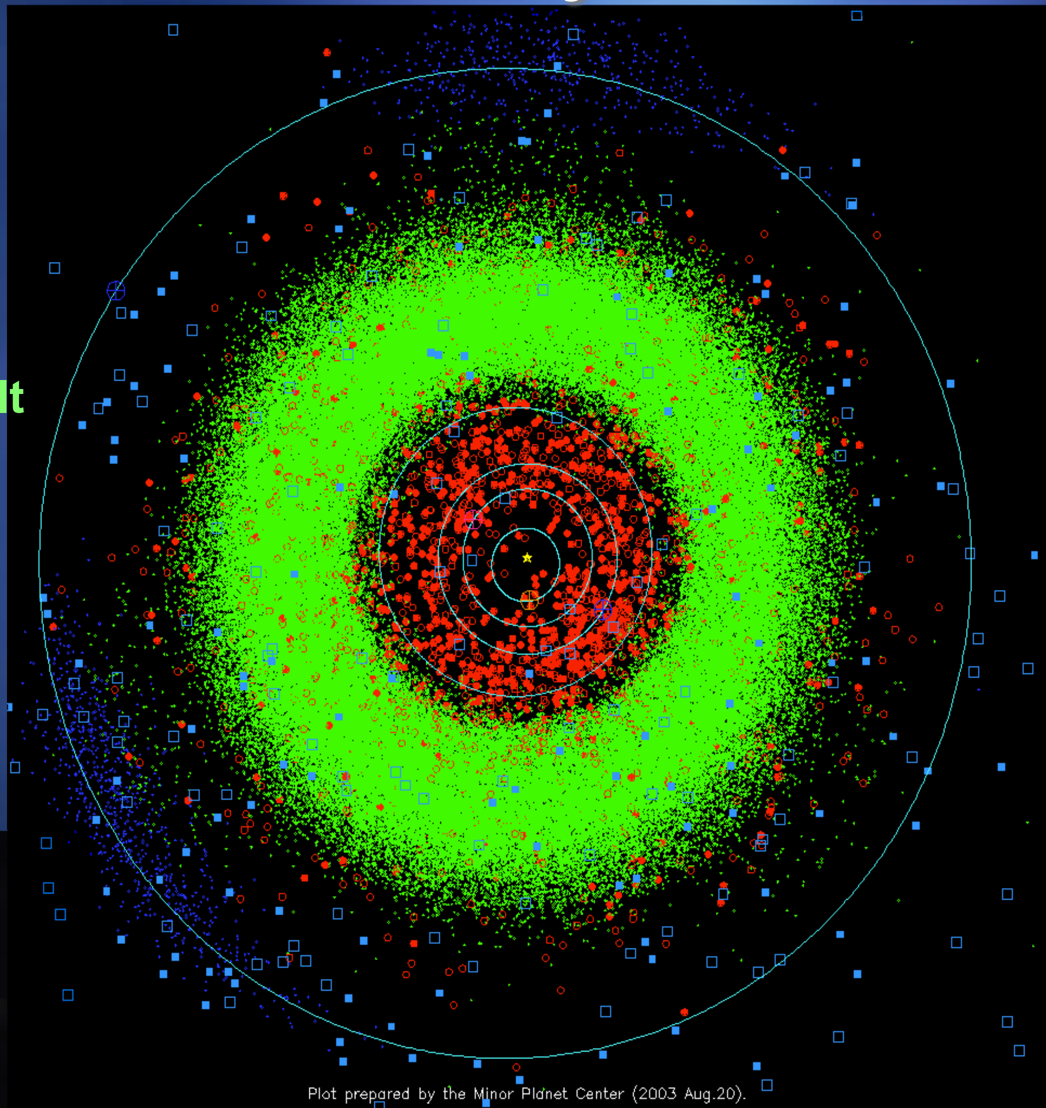


The small body populations in the Inner Solar System

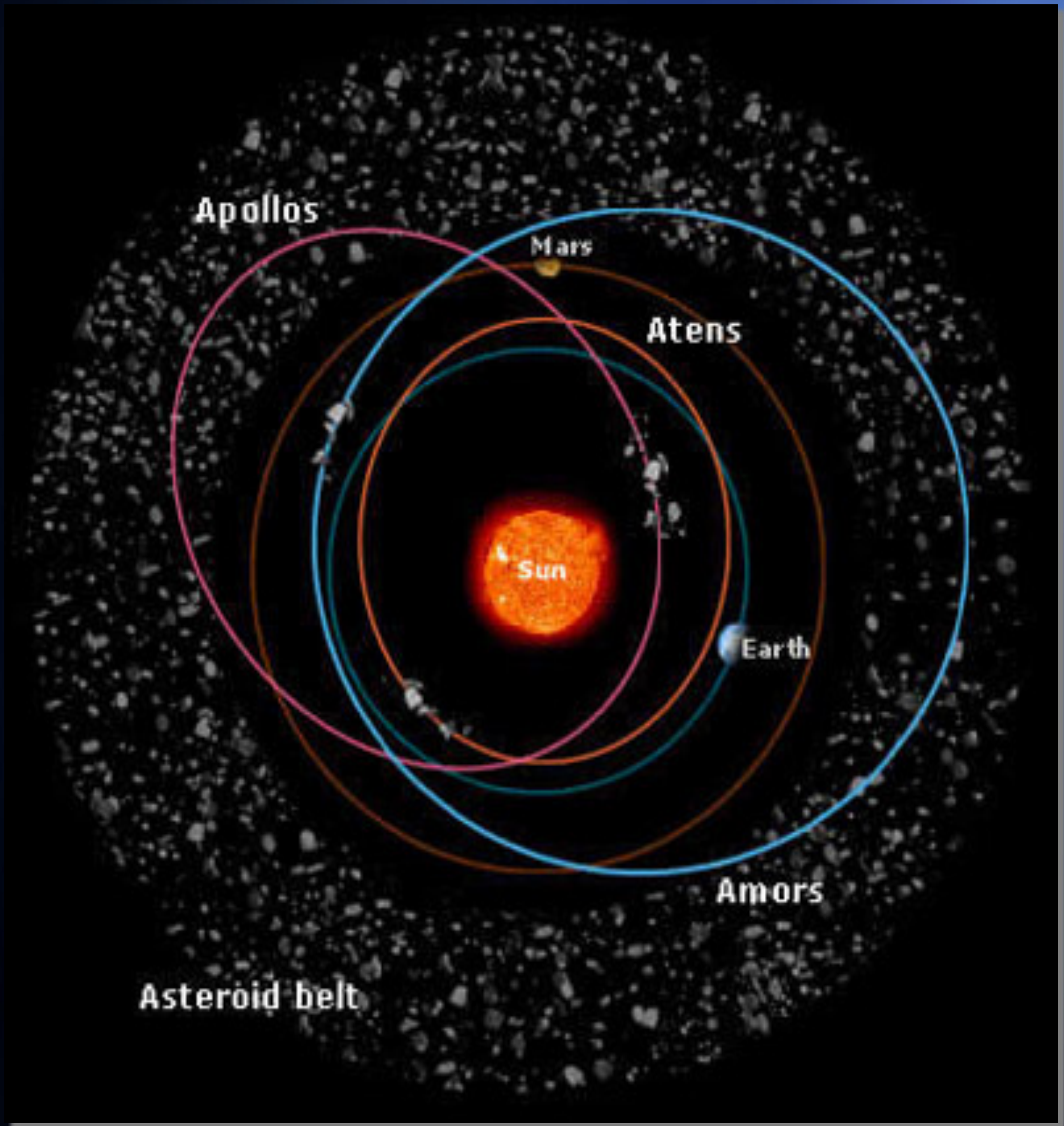
Green:Asteroid Main Belt

Blue squares:Comets

Red: objects with perihelion distance q<1.3 AU



The NEO population



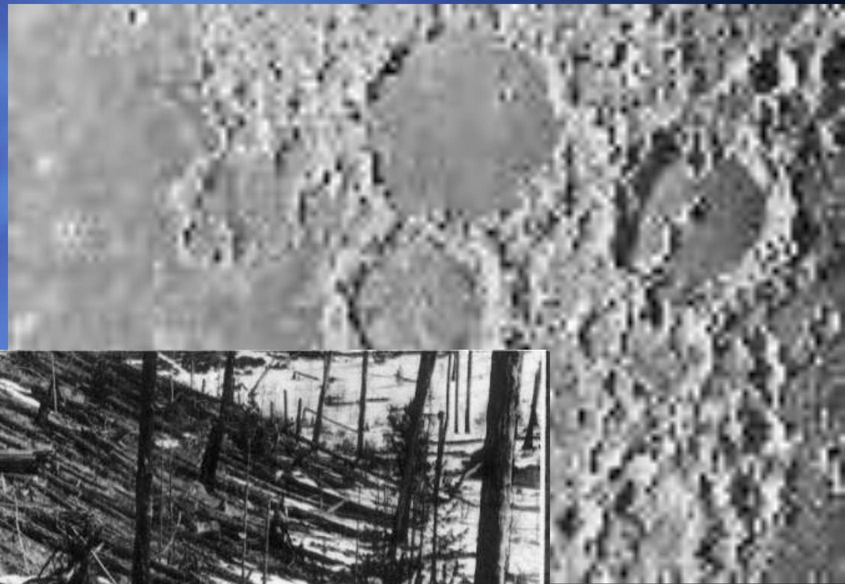
- **Amors**: a>1 AU
  1.017<q<1.3 AU
- **Apollos**: a>1 AU
  q<1.017 AU
- **Atens**: a<1 AU
  Q>0.987 AU
- **IEOs**: a<1 AU
  Q<0.987

1000 Objects
with D>1 km,
≈500 discovered

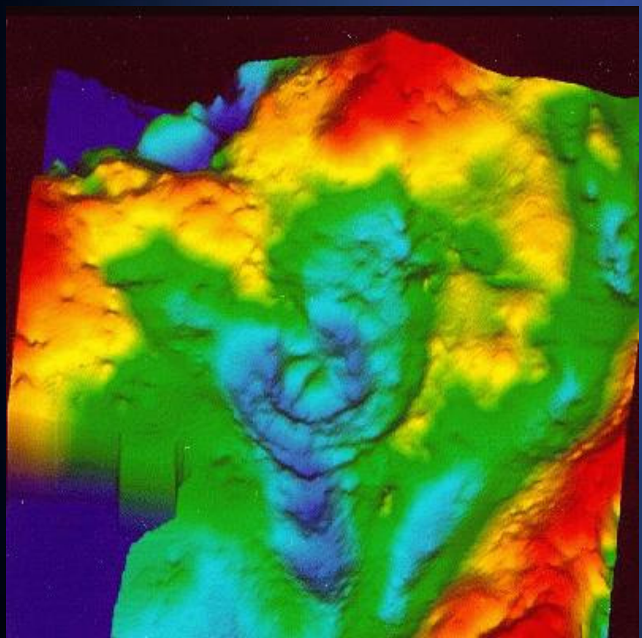
The NEO threat!

Impacts are real facts!

Moon



Venus



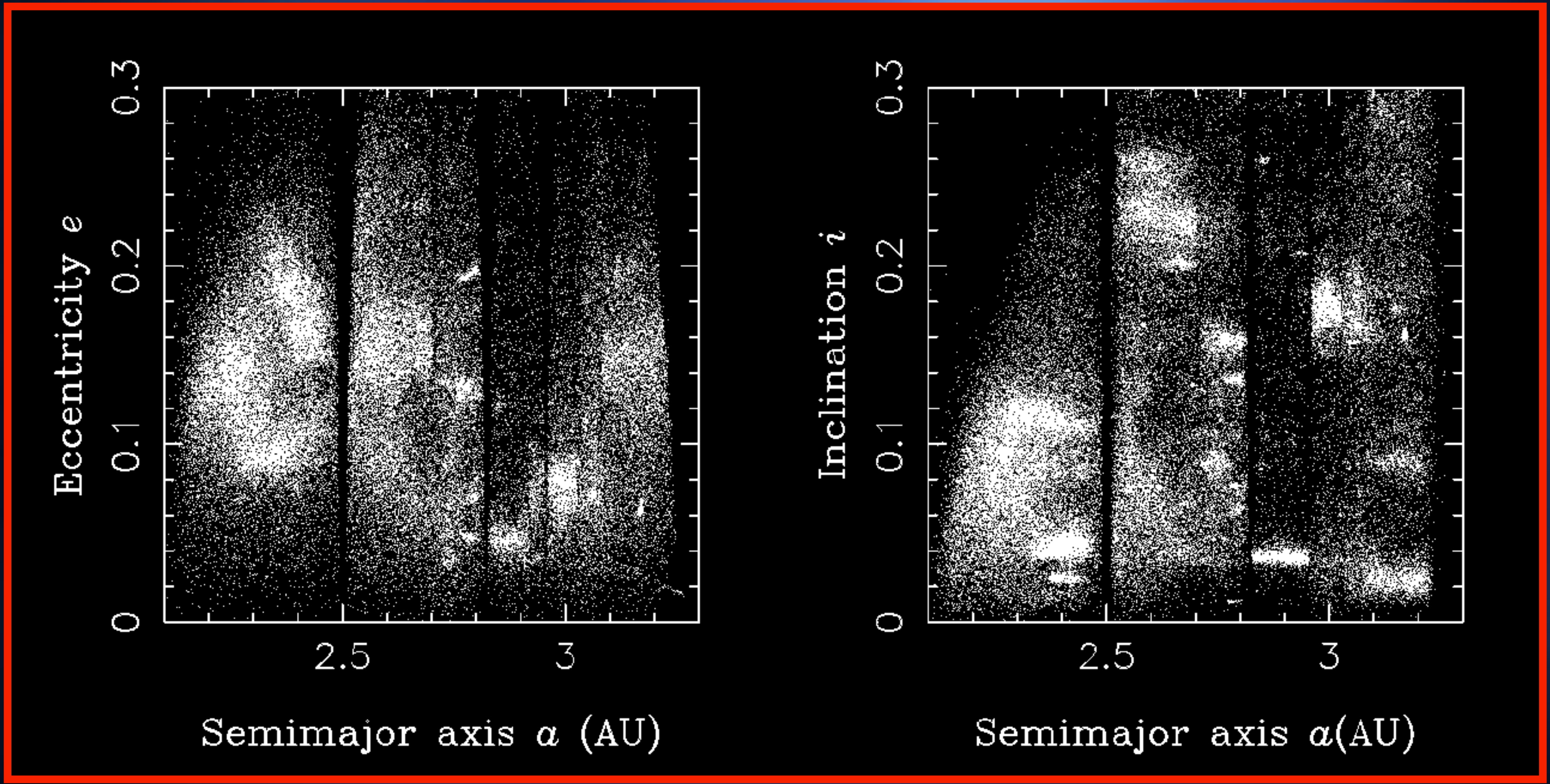
Earth:
Tunguska, 1908

The least likely natural disaster BUT the only that may be predicted and avoided!

Main transport mechanisms in the Solar System

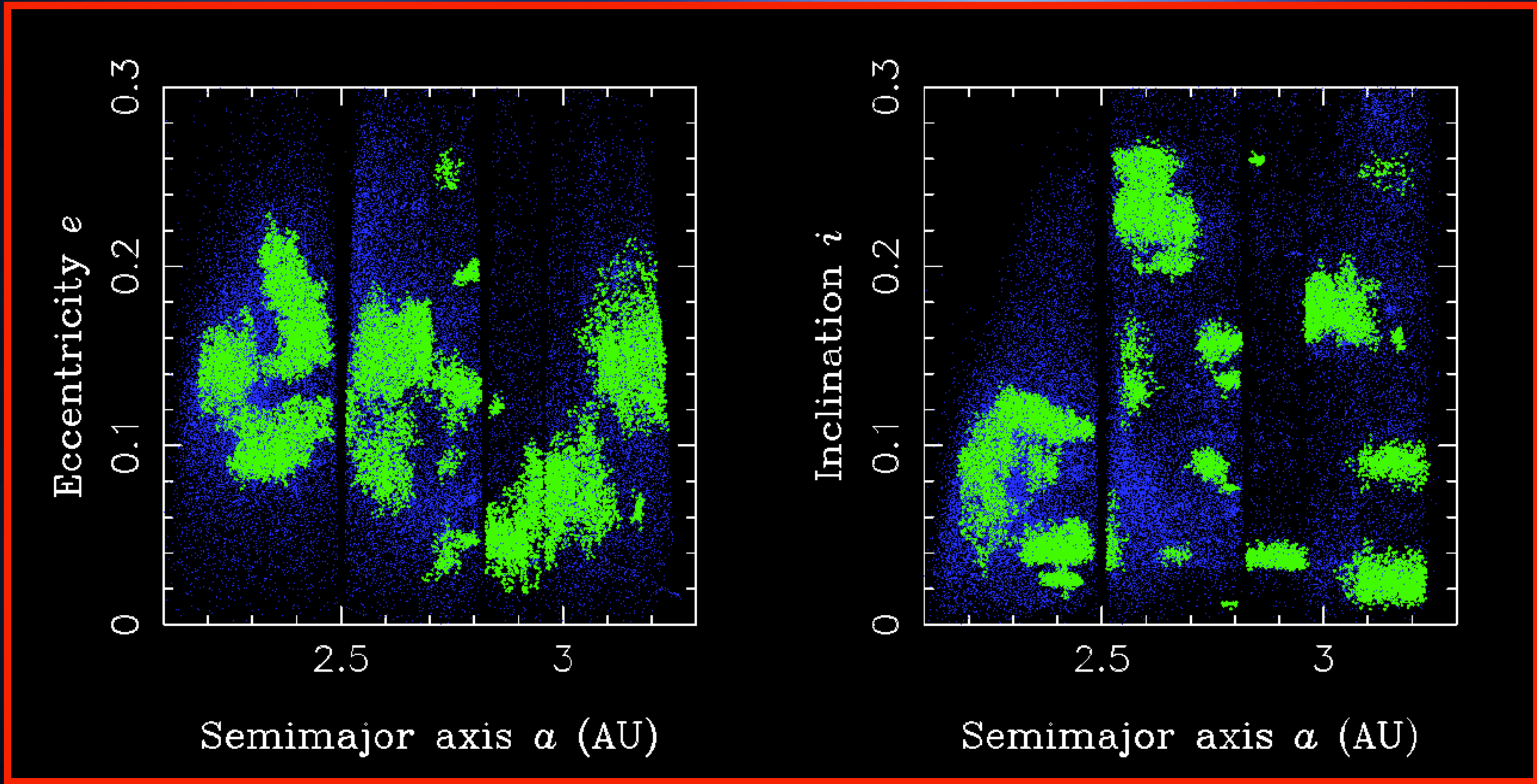
- Fast mechanisms:
  - Mean motion resonances with planets
  - First-order secular resonances with planets
- Slow diffusions (not described in this lecture):
  - Non-gravitational effects (Yarkovsky)
  - High-order and three-body resonances

The Kirkwood gaps in the asteroid Main Belt

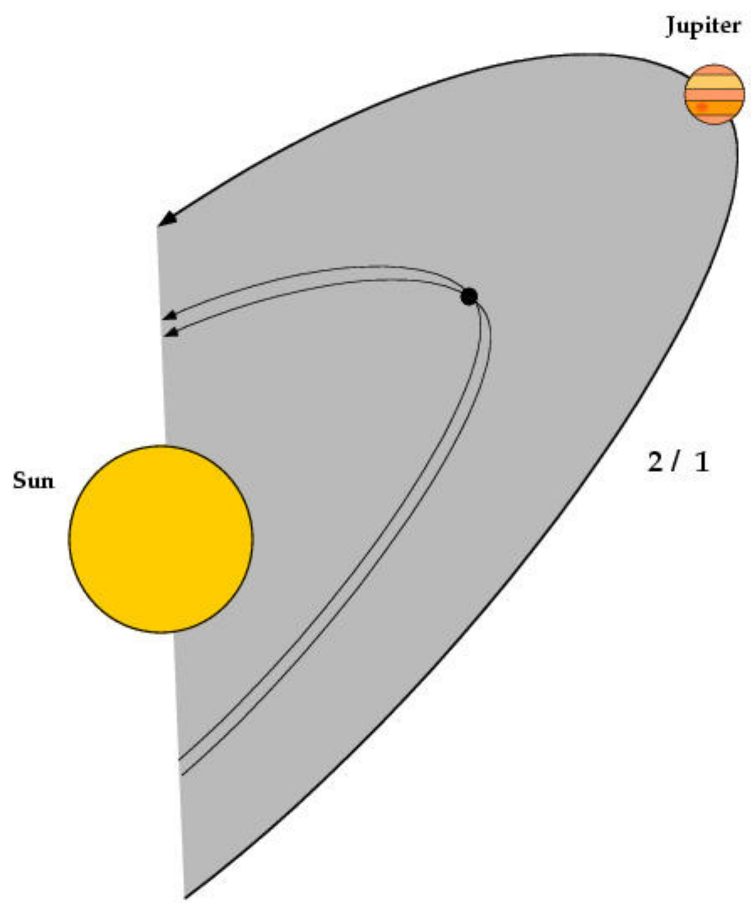


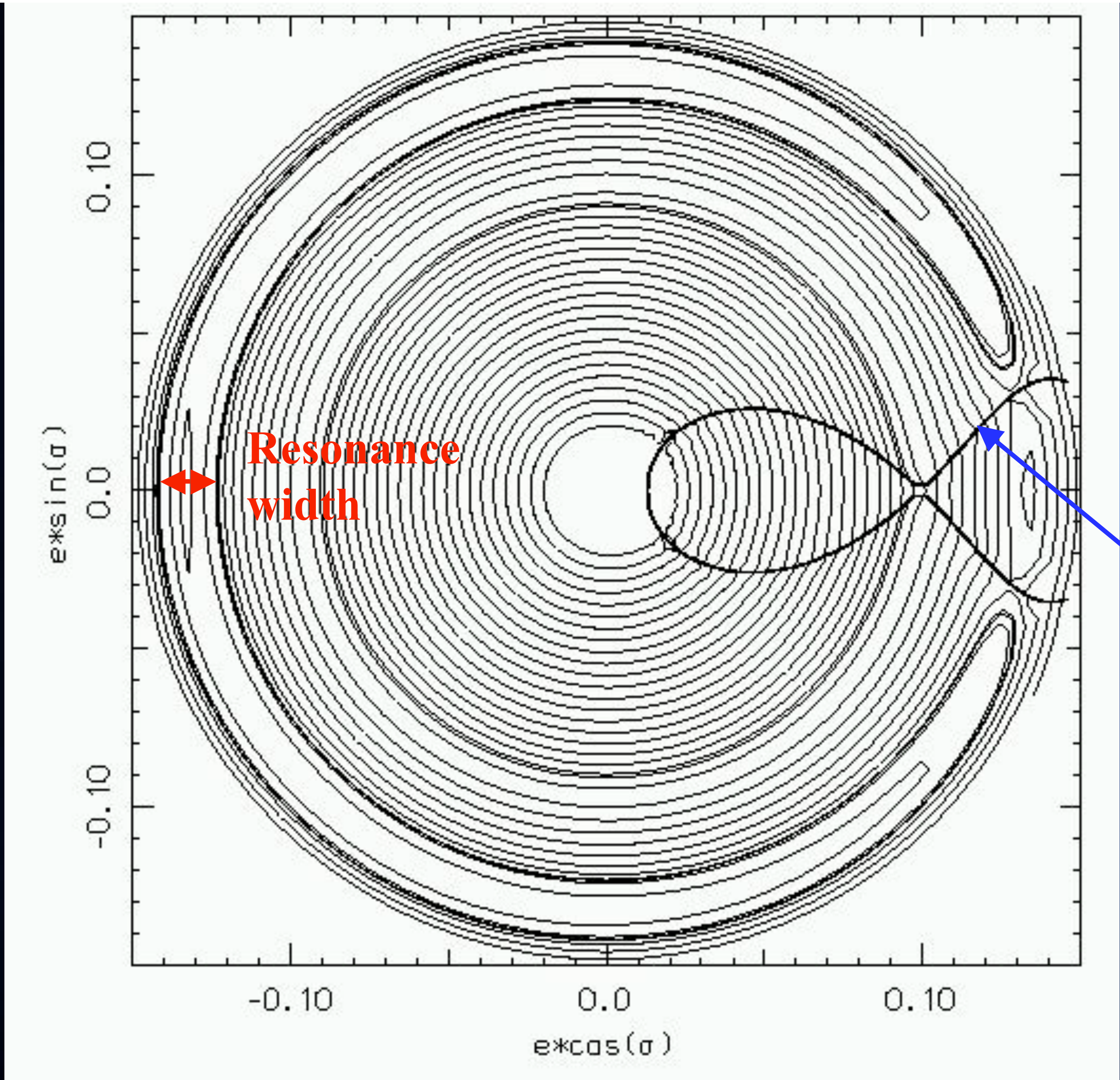
Collisions produce asteroid families!

This will be addressed in Chapter II



Mean Motion Resonances



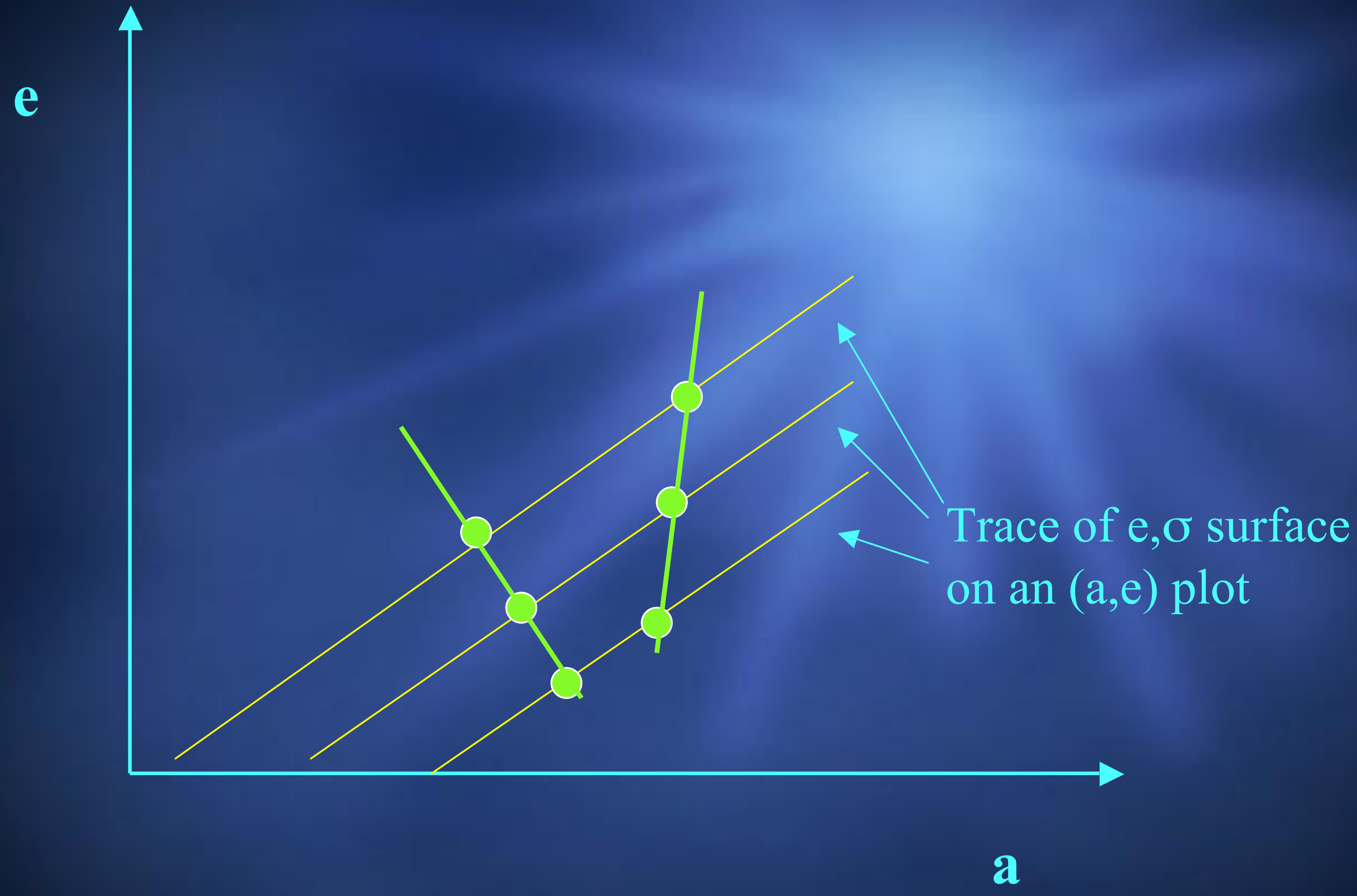


MM Resonance

(e,σ) surface plot

$\sigma_{i/j} = i\lambda_p - j\lambda - (i-j)\varpi$

Planet collision line

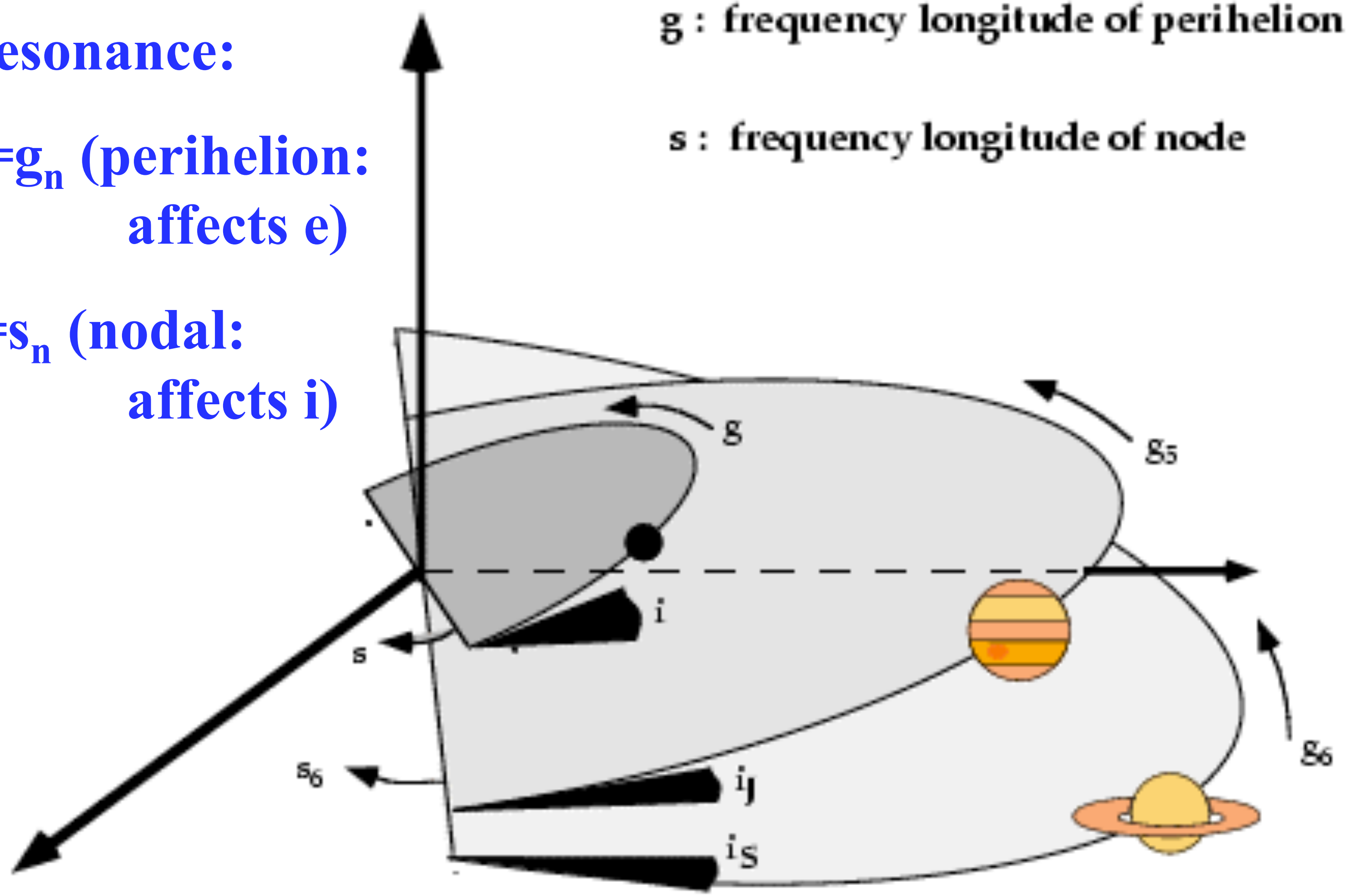

e
a
Trace of e,σ surface
on an (a,e) plot

SECULAR RESONANCES

Resonance:

$g=g_n$ (perihelion: affects e)

$s=s_n$ (nodal: affects i)



Main principle

$$H(\dot{\mathbf{r}},\dot{\mathbf{r}}_j;\mathbf{r},\mathbf{r}_j) = \frac{1}{2}\|\dot{\mathbf{r}}\|^2 - \frac{1}{\|\mathbf{r}\|} - \sum_{j=1}^{N_p} m_j \left[\frac{1}{\|\Delta_j\|} - \frac{\mathbf{r}_j \bullet \mathbf{r}}{\|\mathbf{r}_j\|^3}\right]$$

At first order in planetary mass (*j* = planet index), the hamiltonian of a massless body expresses as:

$$\mathrm{H}{=}{-}\frac{1}{2L^2} - \sum_{j=2}^{N_P} m_j P_j(L,G,H,L_j,G_j,H_j;l,g,h,l_j,g_j,h_j),$$

Keplerian part

Planetary perturbations

$$L = \sqrt{a} \qquad l = M$$

$$G = \sqrt{a(1-e^2)} \qquad g = \omega$$

$$H = \sqrt{a(1-e^2)}\cos i \qquad h = \Omega$$

Delaunay variables

Assumption: the small body is not in a mean motion resonance

- The Hamiltonian (at 1st order in planet masses) can be averaged over all mean anomalies *l* and l_j (fast angles)

$$\overline{\mathrm{H}} = -\frac{1}{2L^2} - \sum_{j=2}^{N_P} m_j \overline{P}_j(-,G,H,-,G_j,H_j;-,g,h,-,g_j,h_j)$$

L = cste, so we omitt the first term and expand the perturbation w.r.t. planetary eccentricities and inclinations:

$$\overline{\mathrm{H}} = -\sum_{j=2}^{N_P} m_j \left[K_0^j + (e_j,i_j)K_1^j + (e_j,i_j)^2 K_2^j + \ldots\right]$$

$(e_j,i_j)^r$ are terms prop. to $e_j^a i_j^b$, with $a+b = r$ and $a,b \geq 0$

Isolate the first term K_0

- It can be shown that:

$$K_0 = \sum_{\substack{\geq 0 \\ p,q \in \mathbb{N}}} c_{0,-v,v,0,p,q,0,0}\, e^{|2v|+2p} i^{|2v|+2q} \cos(2v(\underbrace{\varpi - \Omega}_{\omega}))$$

Thus, $K_0 = f(\varpi - \Omega) = f(g)$

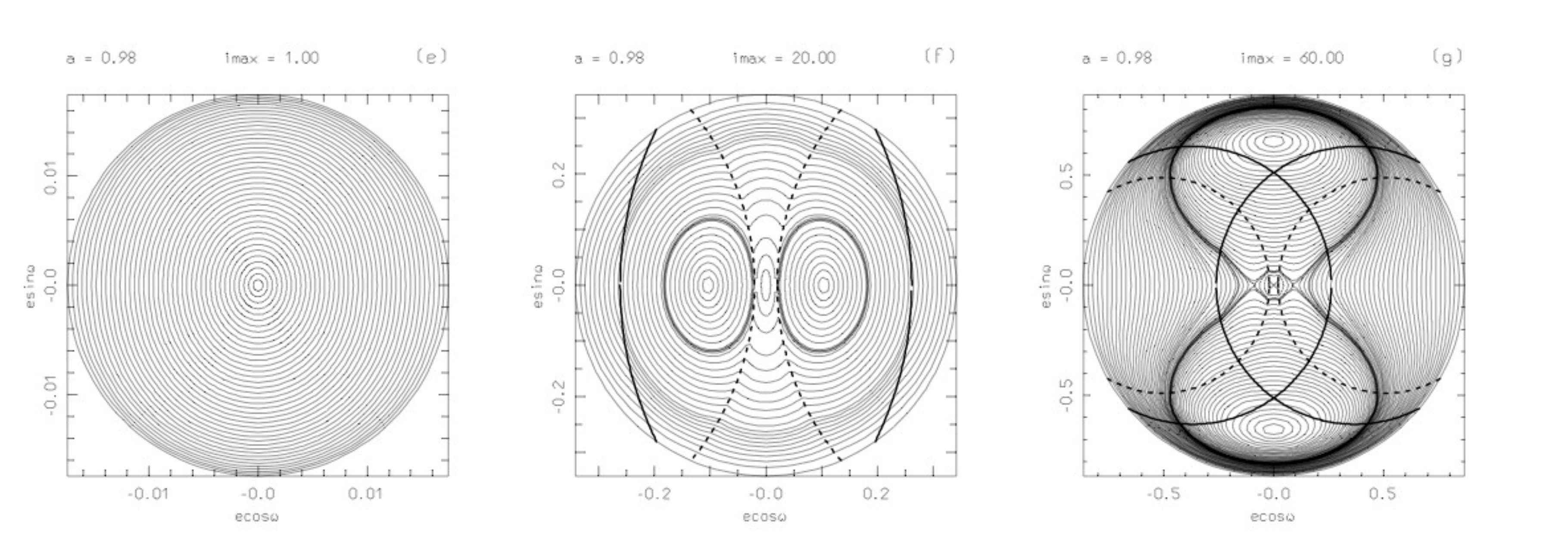
K_0 = 1 degree of freedom integrable hamiltonian in the variables G,g as it depends only on the angle g (= ω).

It is parametrized by the constants actions L and H.

Its highly non-linear dynamics can be studied in details (Kozai 1962) by drawing level curves in the (e, ω) plane on a surface H = constant.

Dynamics of K_0 at a=0.98 AU on 3 different surfaces of H=cst, each characterized by a value of i_{max} (1°, 20°, 60°)

- Polar diagram (e,ω)



From Michel & Thomas (1996, AA 307)

Location of secular resonances

- The free frequencies of ϖ and Ω of the asteroid's orbit in the (a,e,i) space are obtained by integrating wrt time:

$$\dot{G} = -\left(\frac{\partial K_0}{\partial g}\right),$$

$$\dot{g} = \left(\frac{\partial K_0}{\partial G}\right),$$

$$\dot{h} = \left(\frac{\partial K_0}{\partial H}\right)$$

Proper frequencies = average values over a complete cycle of the free oscillations with period T (from g=0 to g=g(T)=2π)

Secular resonance: (a,e,i) for which:

$$< \dot{\varpi} >= g_{planet}$$

or

$$< \dot{\Omega} >= s_{planet}$$

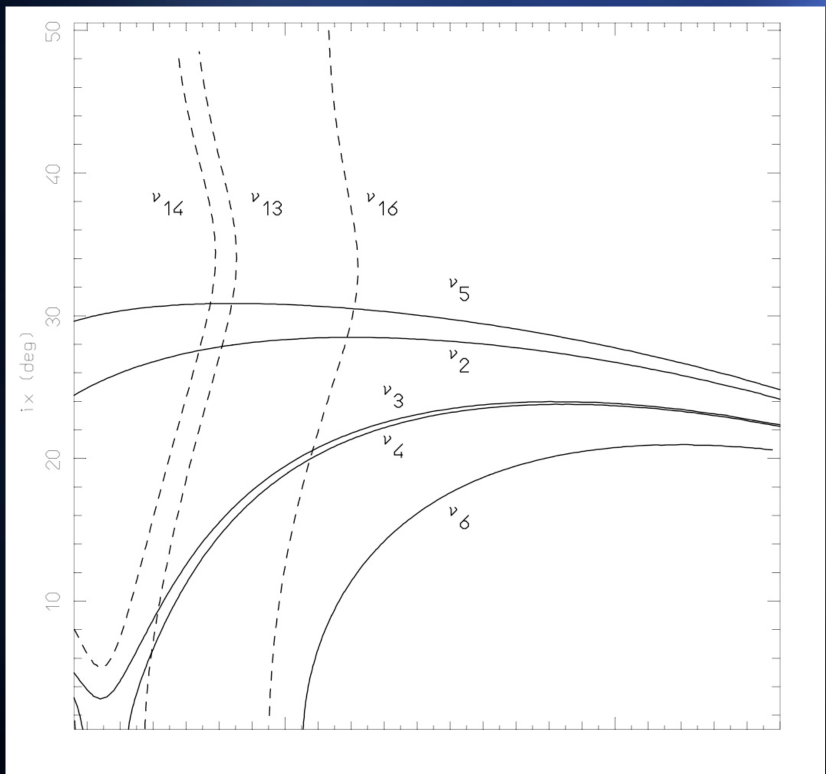
Ex: $\nu_6 \rightarrow g_6 \approx 28.22$ ''/yr

Some secular resonance locations (left: main belt, right: NEO region)

From Michel & Froeschlé (1997, Icarus 128)

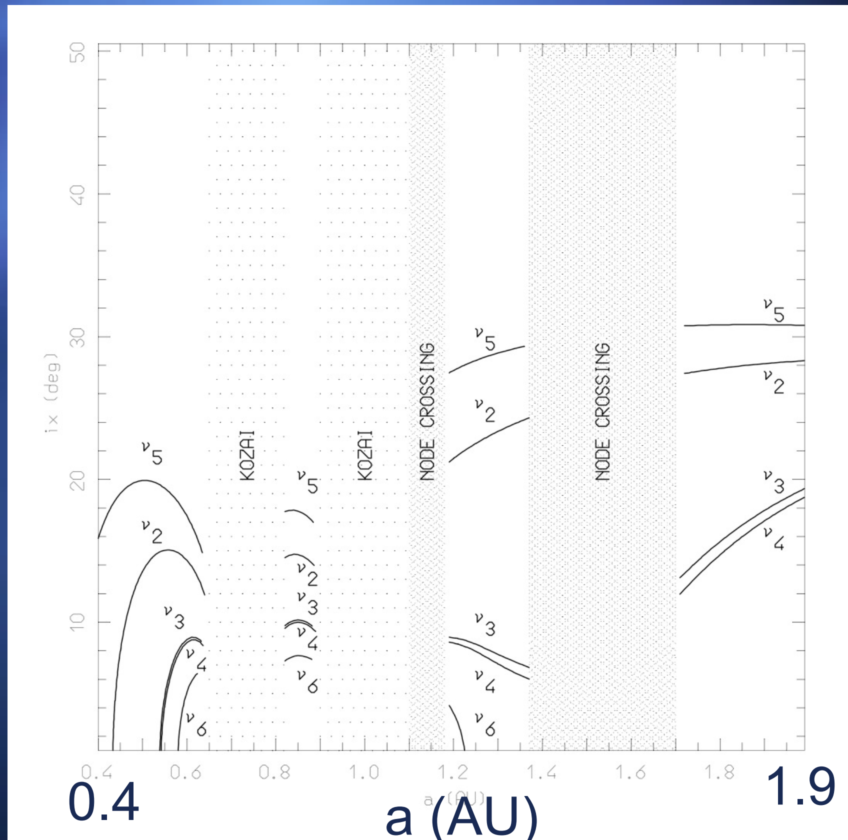
50°

i°



1.5 a (AU) 3.5

e=0.1



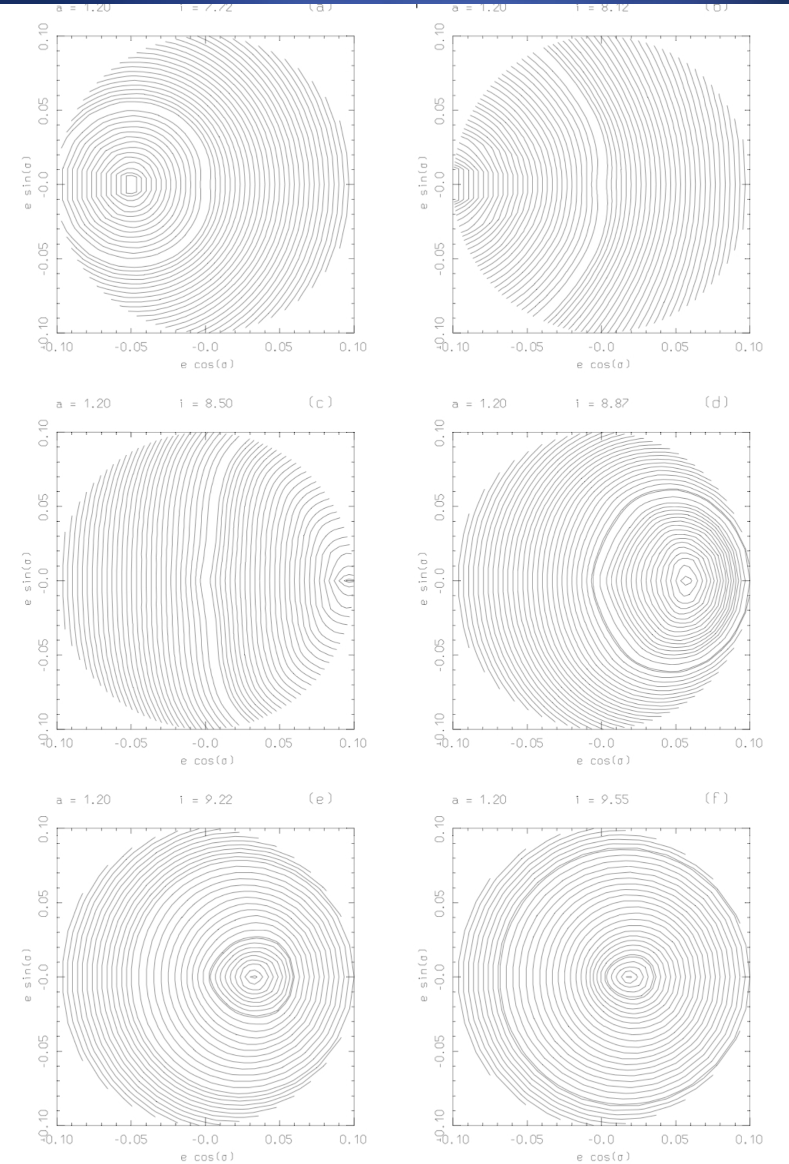
0.4 a (AU) 1.9

Effect of secular resonances

Needs to consider the first-order term in e_j and i_j of the Hamiltonian (K_1)

Ex: effect on eccentricity of ν_4 at a=1.2 AU

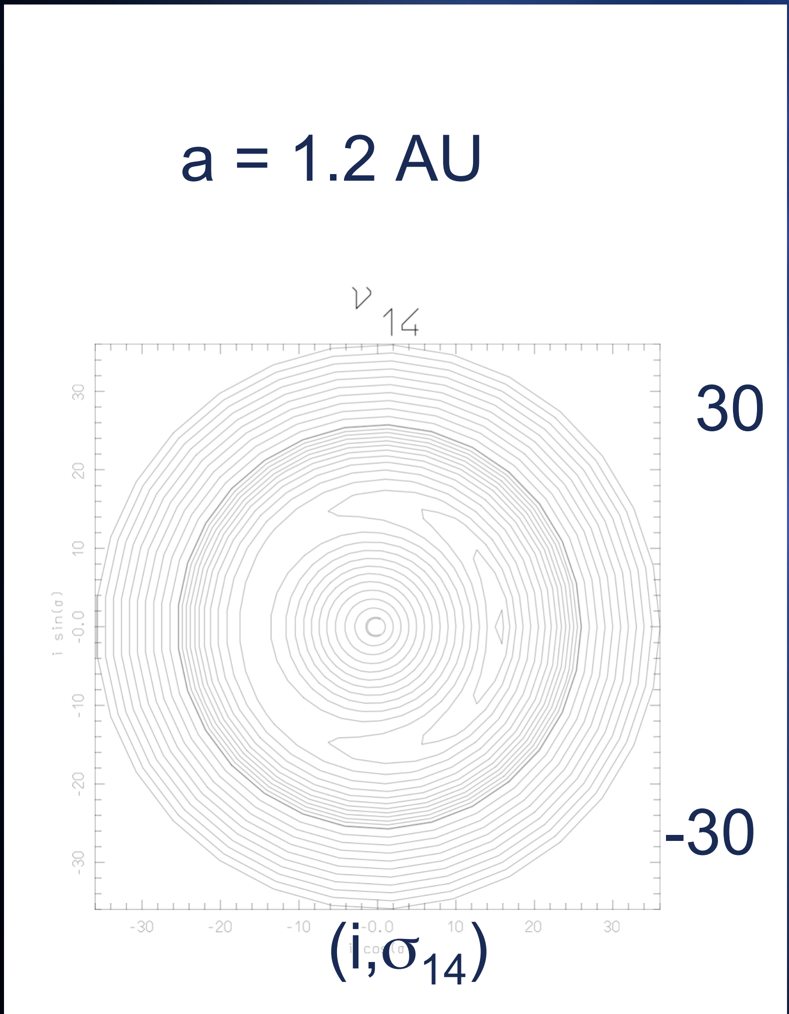
0.1



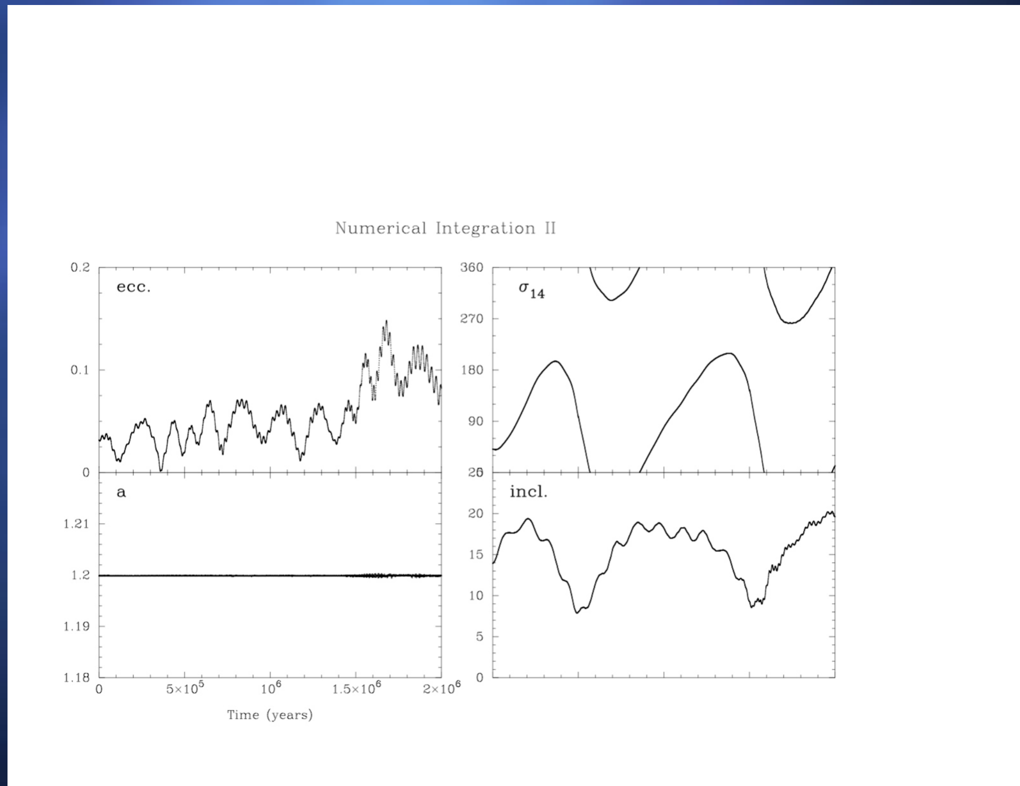
(e, σ_4)

Effect of secular resonances (II)

Semi-analytical theory



Numerical integration



Effect of resonance overlapping

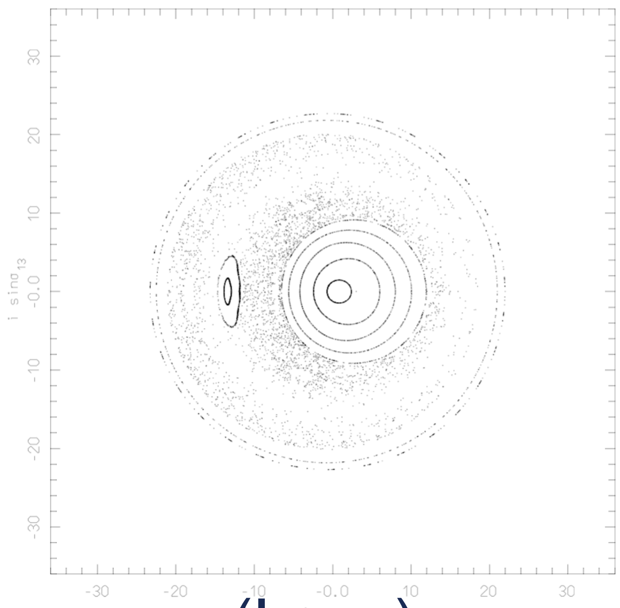
Overlapping of
ν_{13} and ν_{14}

Surface of section
at $\sigma_{14} = \pi$

a = 1.2 AU

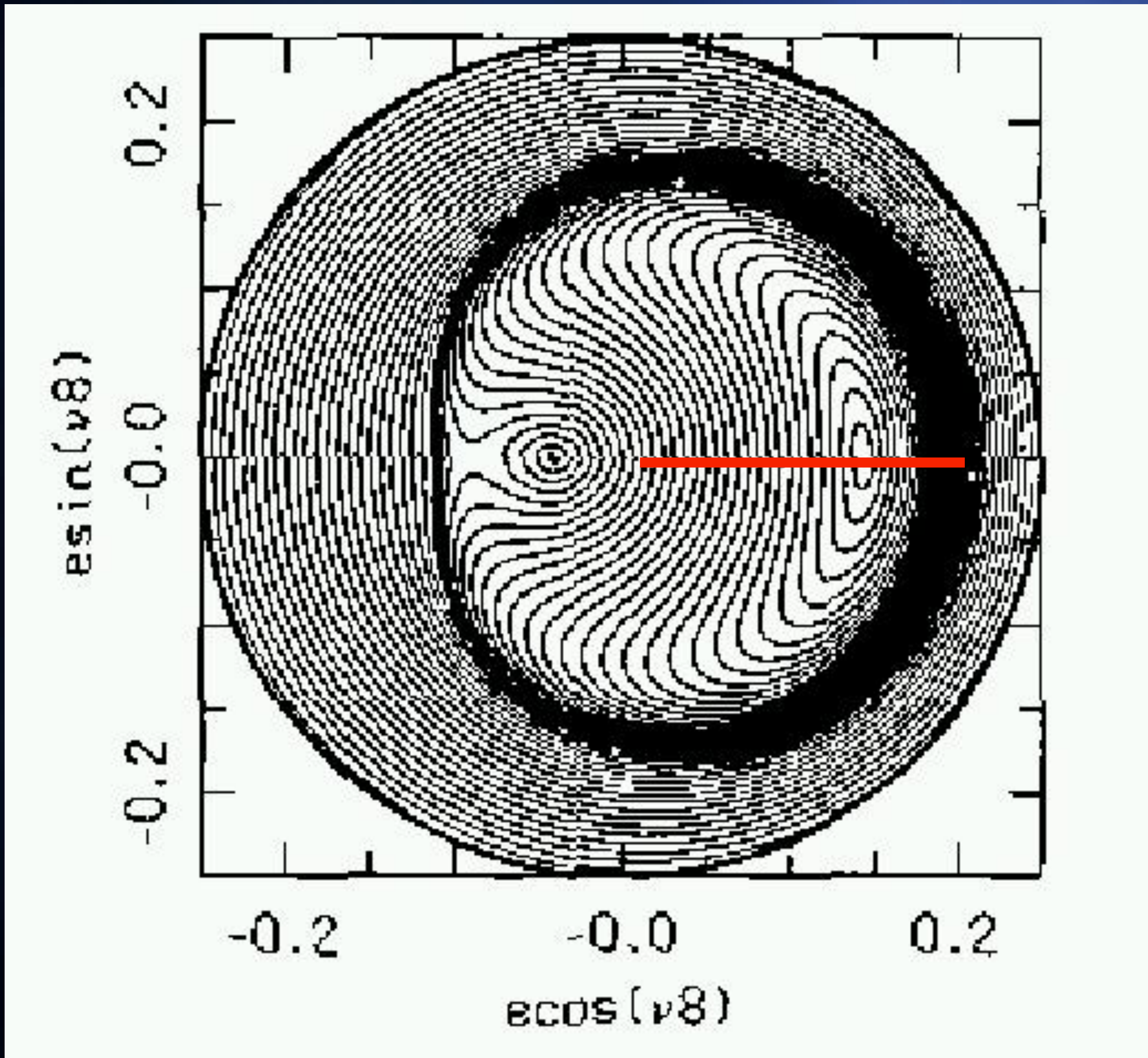
30

-30



(I, σ_{13})

Example: Dynamics of the g=g8 resonance at 41 AU

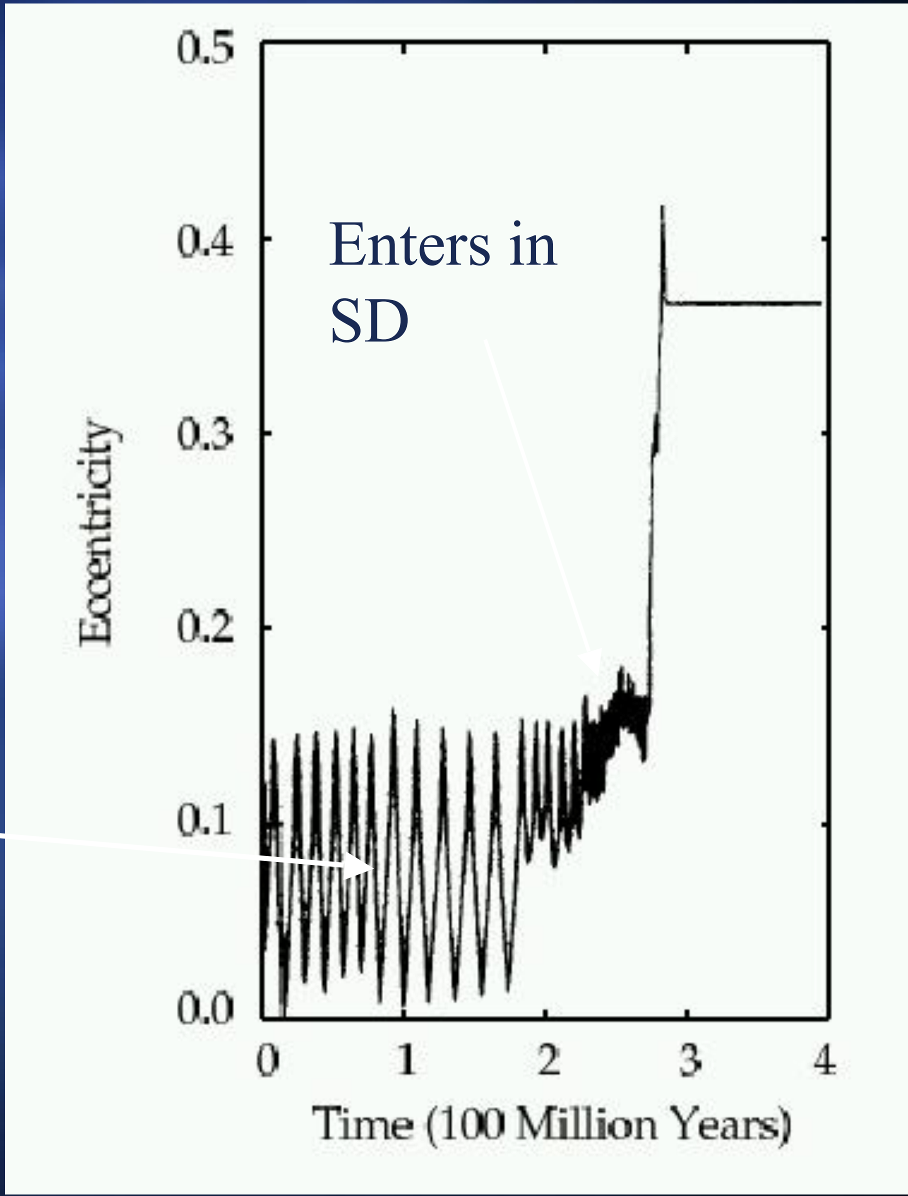


ν_8

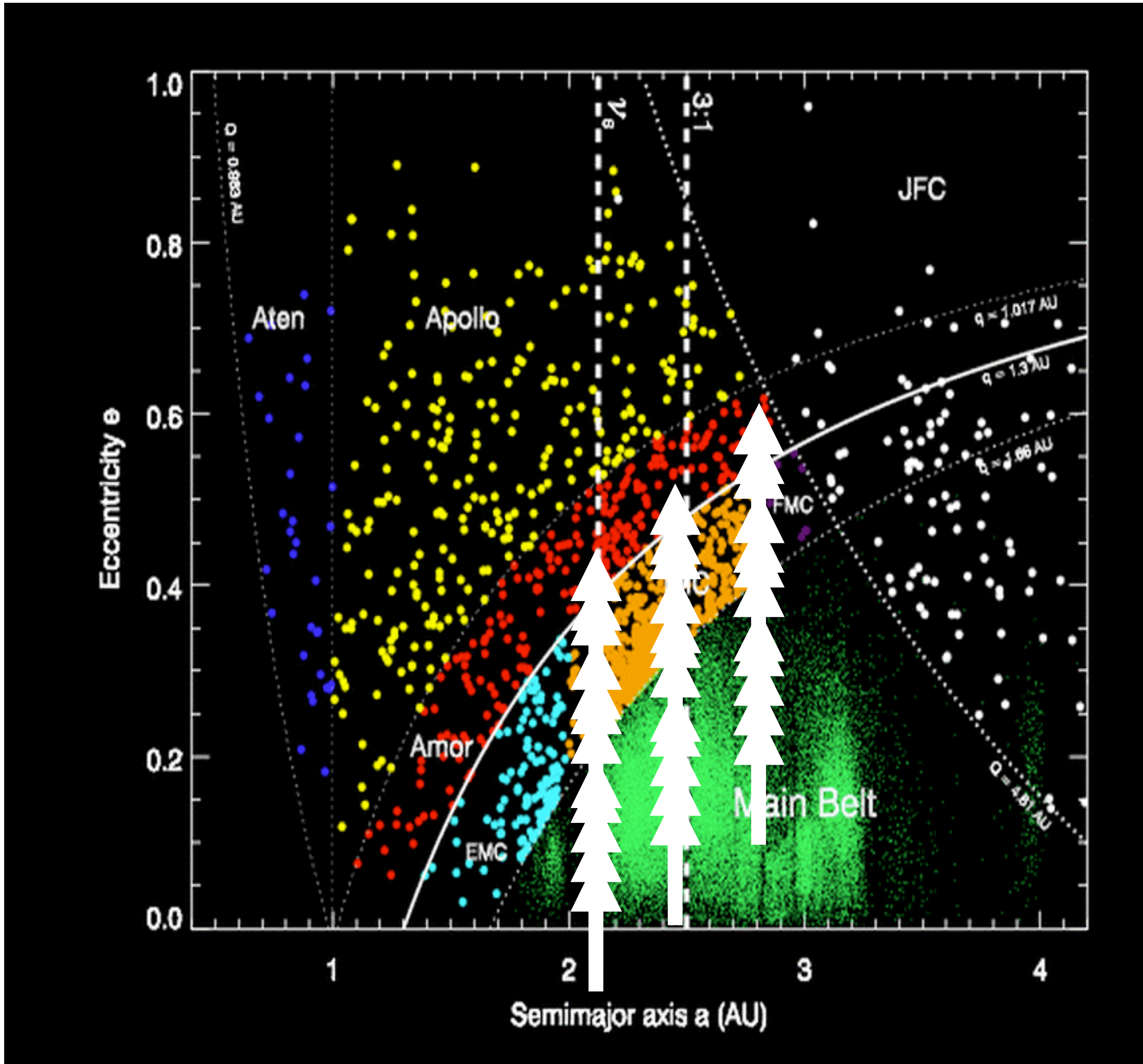
$\sigma_8 = \varpi - \varpi_N$

Morbidelli et al., 1995

Simulation of the evolution of a body in the g=g8 resonance by Holman and Wisdom, 1993



Secular resonance driven slow oscillations



Origin of NEOs

Asteroids from different regions of the Main Belt (MB) are injected into resonances which transport them on Earth-crossing orbits

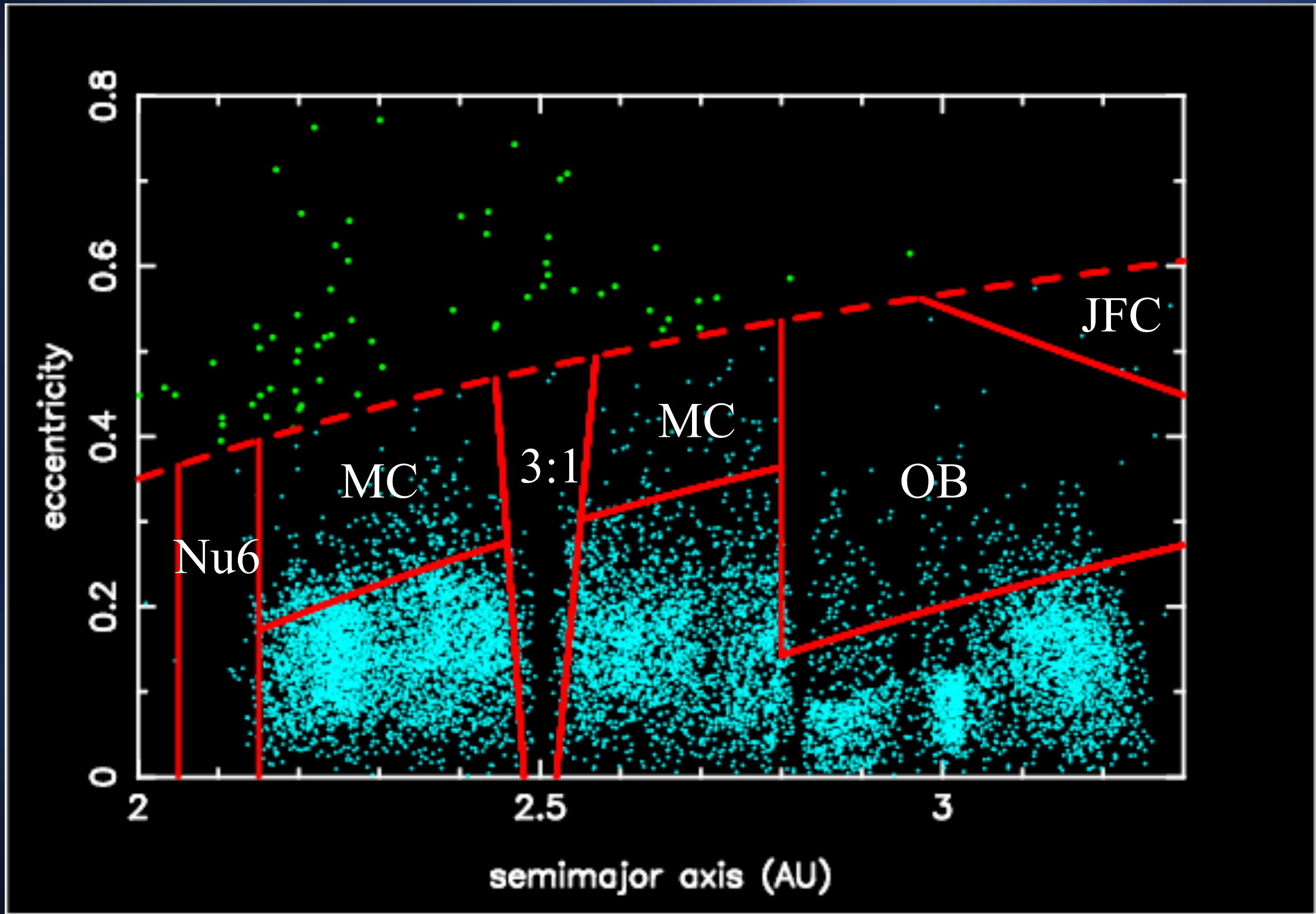
Hamiltonian describing the evolution of a massless body:

(heliocentric frame)

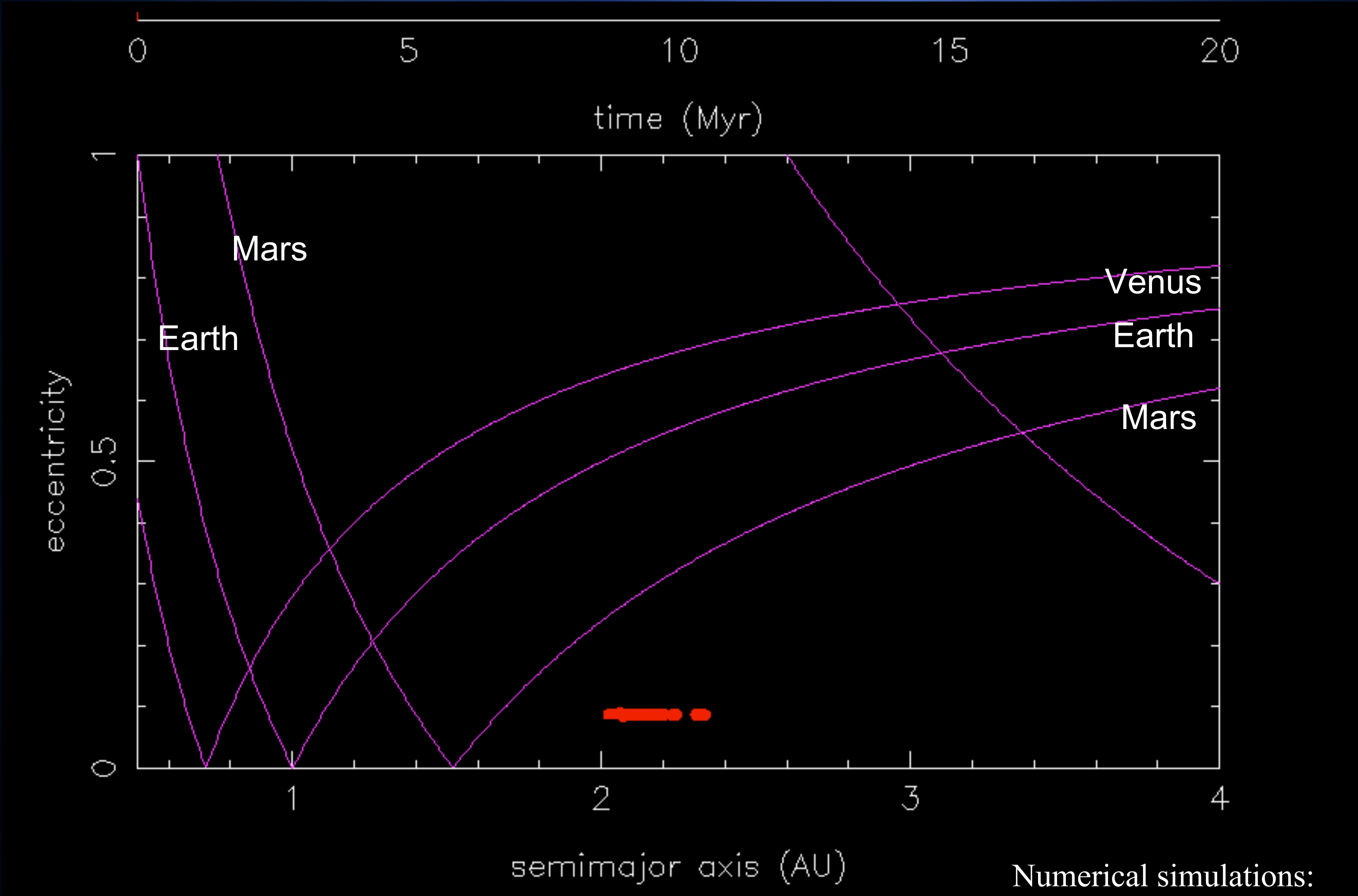
$$H(\dot{\mathbf{r}},\dot{\mathbf{r}}_j;\mathbf{r},\mathbf{r}_j) = \frac{1}{2}\left\|\dot{\mathbf{r}}\right\|^2 - \frac{1}{\left\|\mathbf{r}\right\|} - \sum_{j=1}^{N_p} m_j\left[\frac{1}{\left\|\Delta_j\right\|} - \frac{\mathbf{r}_j \bullet \mathbf{r}}{\left\|\mathbf{r}_j\right\|^3}\right]$$

$\Delta_j = \mathbf{r}_j - \mathbf{r}$ $\quad$ $G = M_{sol} = 1$

SPECIFIC SOURCES OF NEOs:

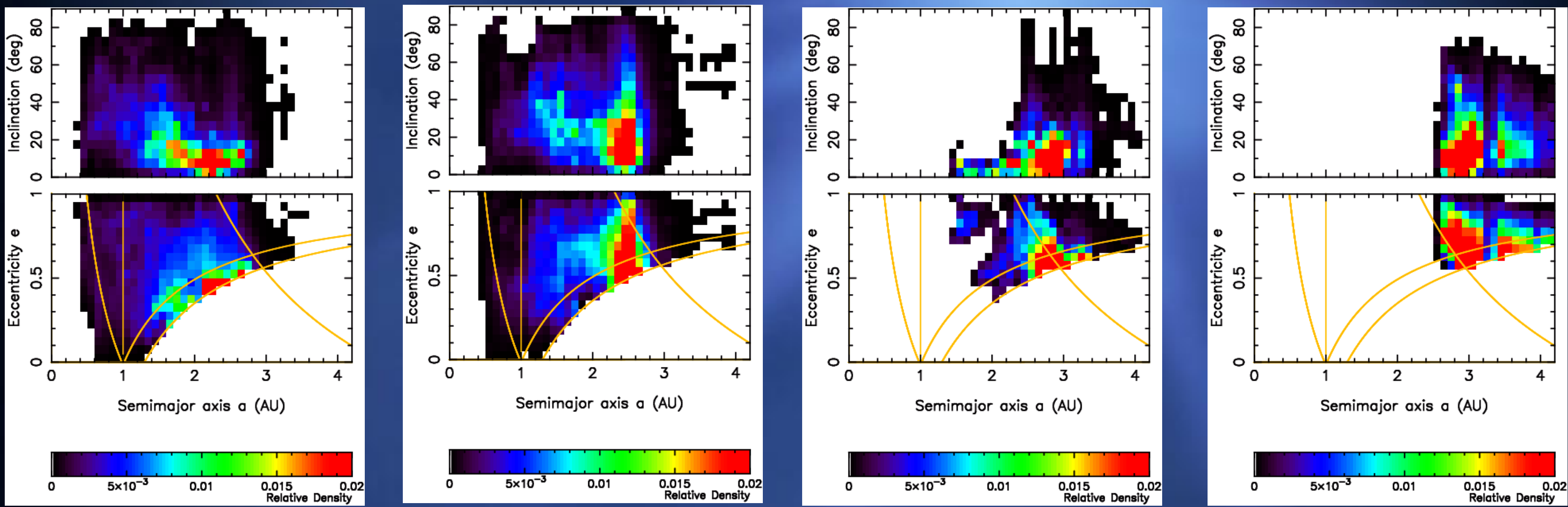


Fast resonances: Main Belt Asteroids become rapidly NEOs by dynamical transport from a source region (in a few million years)



Numerical simulations:
Several 1000 particles

Combine the sources of NEOs so that applying observational biases on the total distribution reproduces the observed distribution

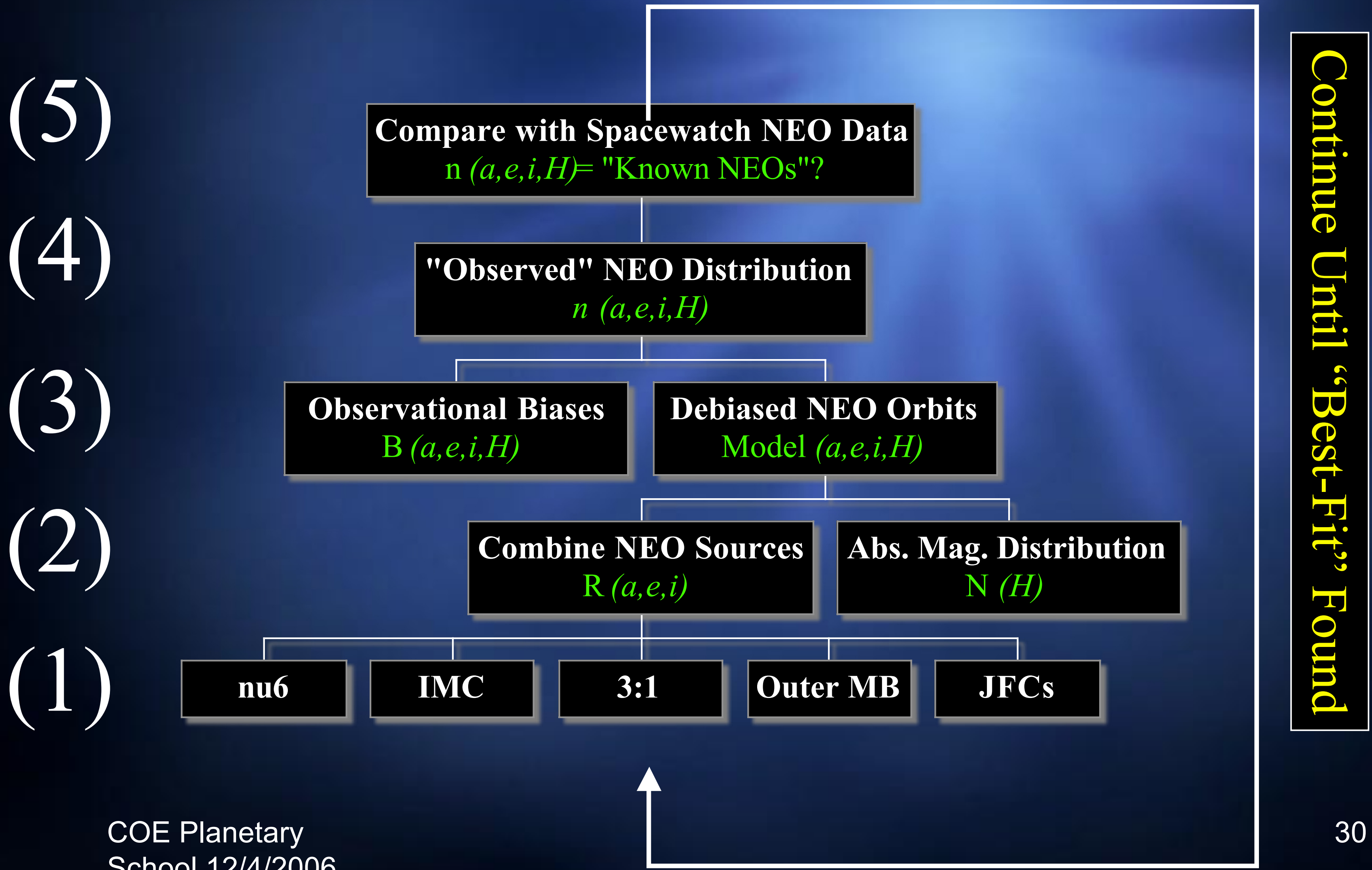


Mars Crossers | 3:1 | External Belt | Comets (Jup.)

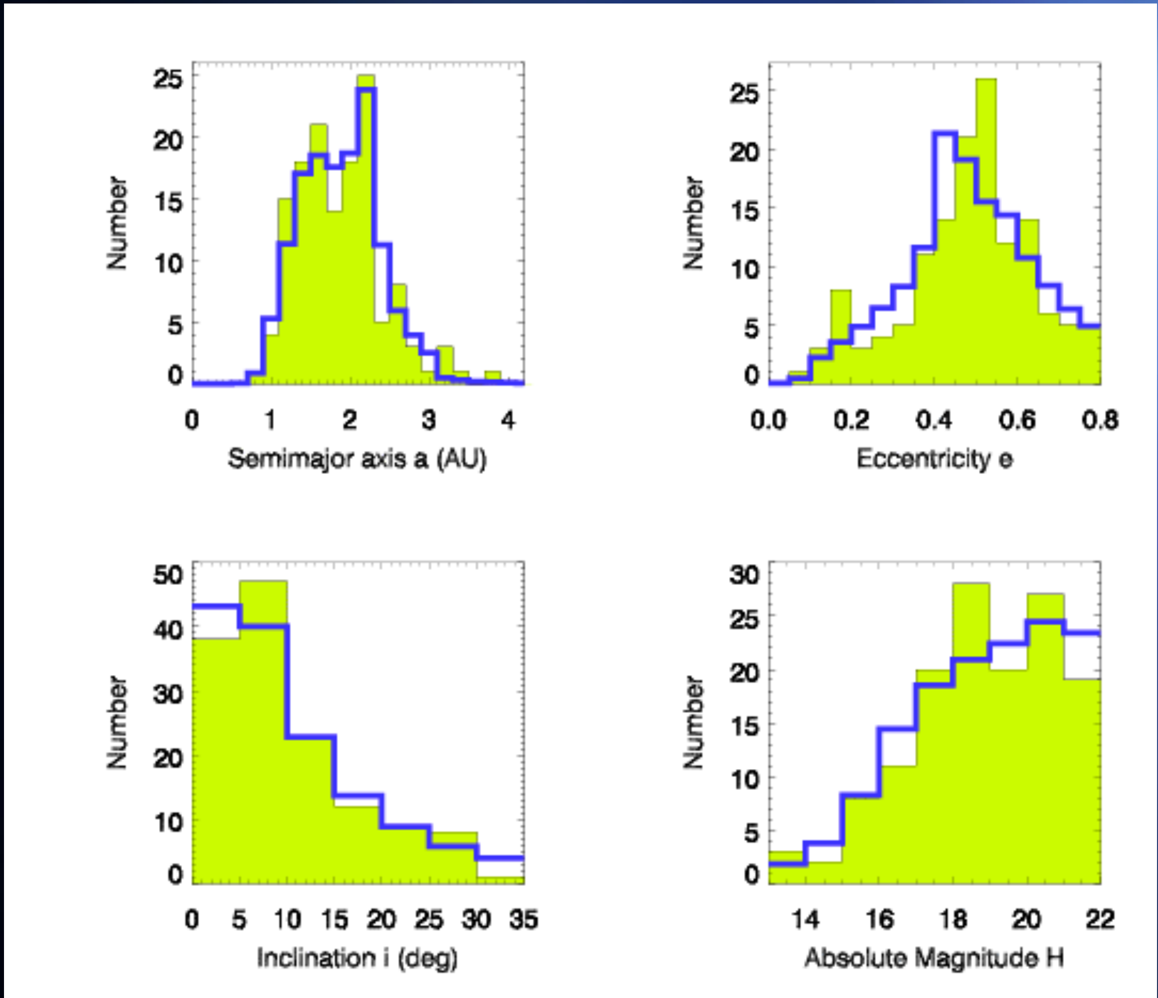
Combine NEO Sources
R *(a,e,i)*

nu6 | **IMC** | **3:1** | **Outer MB** | **JFCs**

Comparison between the *biased* model of NEOs and real data



Comparison Between Discovered NEOs and Best-Fit Model



Weighting factors

ν_6	0.36 ± 0.09
IMC	0.29 ± 0.03
3:1	0.22 ± 0.09
Outer MB	0.06 ± 0.01
JFC	0.07 ± 0.05

Model fit to 138 Spacewatch NEOs with $H < 22$

Our model of real orbital and absolute magnitude distributions of *Near Earth Objects*

~1000 NEOs with H<18 and *a*<7.4 AU

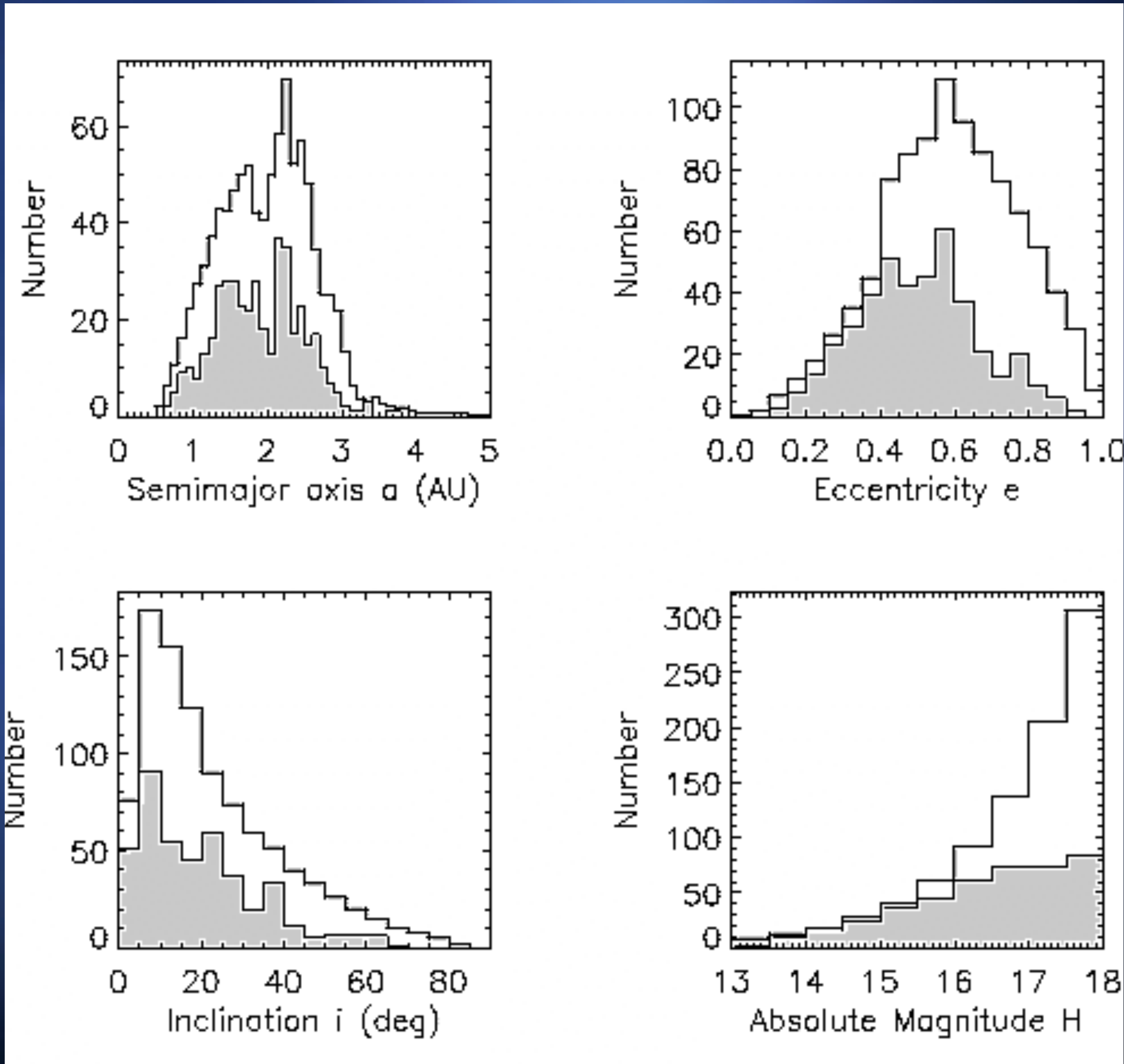
32% Amors

61% Apollos

6% Atens

94% of asteroidal origin

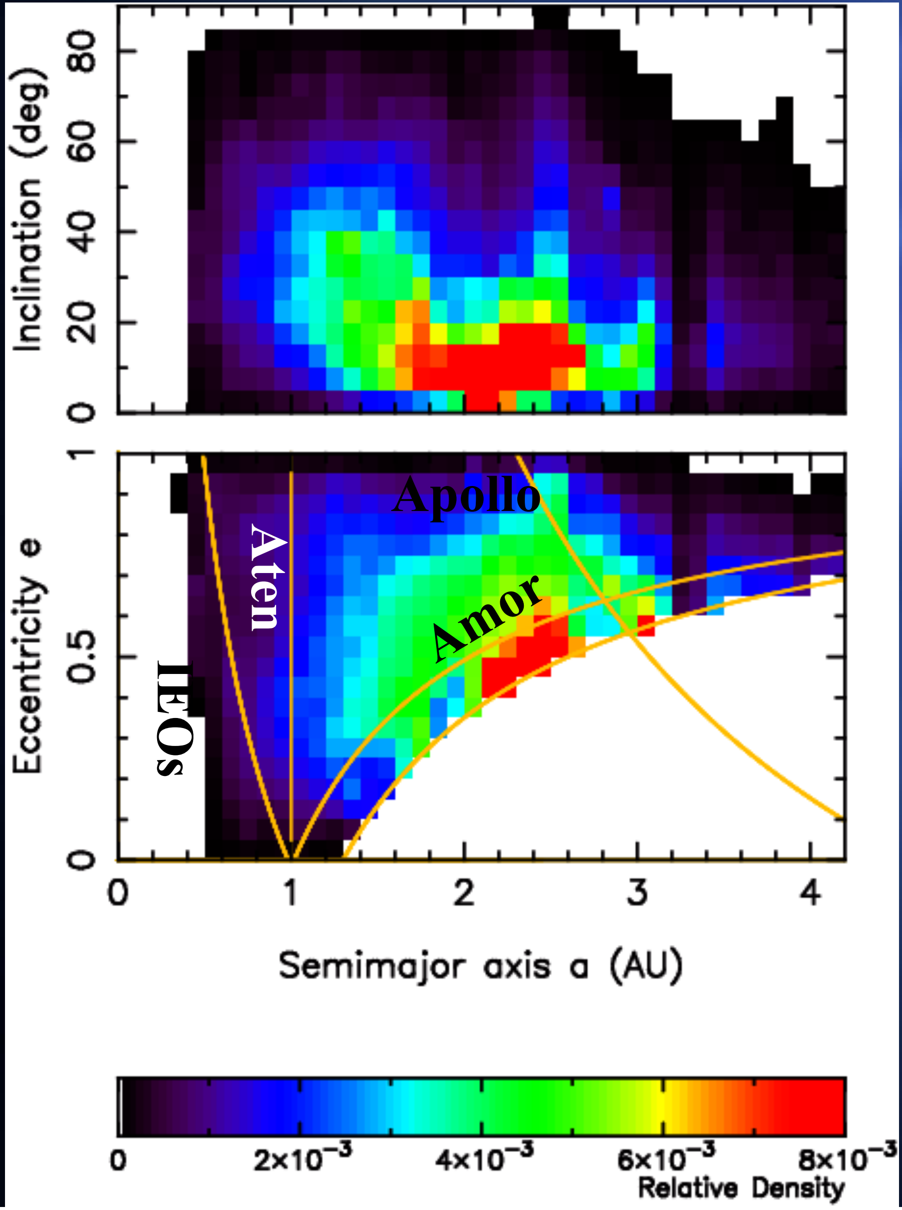
6% dormant comets (Jupiter family)



(Bottke et al., 2000, 2002)

White = model; Gray = observations

Debiased NEO Orbital Distribution



- **The NEO population having *H* < 22 and *a* < 7.4 AU consists of:**
  - **→ 32% Amors.**
  - **→ 61% Apollos.**
  - **→ 6% Atens.**
- **2% are IEOs (Inside Earth's Orbit).**

Bottke et al. 2002

Estimate of 1 impact with energy > 1,000MT per 64,000 years

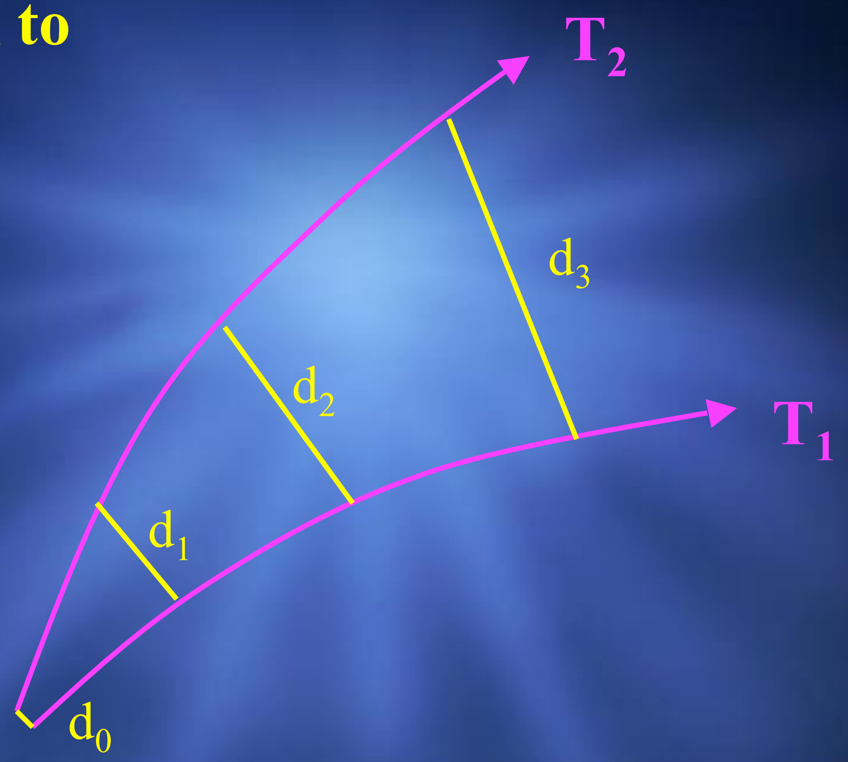
Known NEOs carry only 18% of this total collision probability (H<20.5)

Morbidelli et al. 2002

Impact Energy	Mean Frequency (years)	Mean projectile's size	Completeness
1,000 MT	63,000	277 m (H=20.5)	16%
10,000 MT	241,000	597 m (H=18.9)	35%
100,000 MT	935,000	1,287 m (H=17.5)	50%
1,000,000MT	3,850,000	2,774 m (H=15.6)	70%

The Lyapunov exponent: a tool to characterize the chaotic nature of an evolution

$$L = \lim_{t \to \infty} \mathrm{Log}(d_t)/t$$



NEOs have positive Lyapunov exponent indicating chaotic evolutions

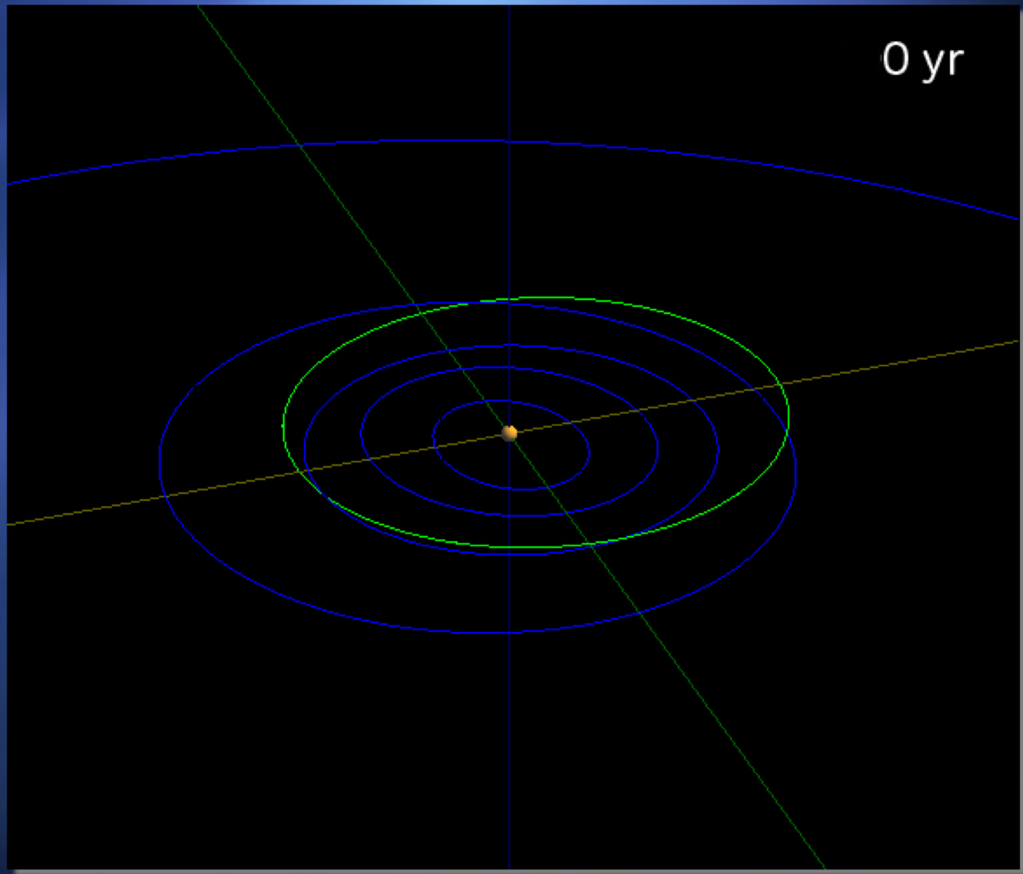
⇒impossible to make long term predictions of individual trajectories

NEOs have chaotic evolutions Example of Itokawa

Computation of the evolutions of **100 initially very close orbits**

Expected timescale for a Collision of Itokawa with the Earth: 1 Myr

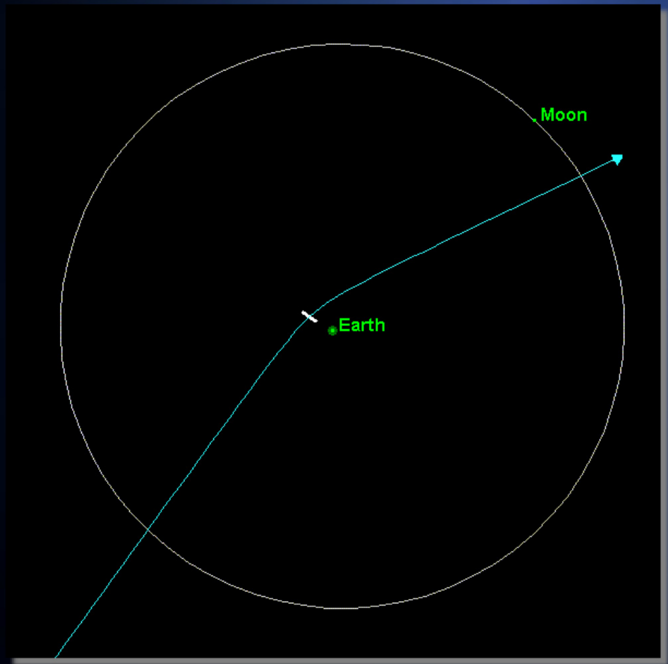
P. Michel & M. Yoshikawa, 2005, Icarus 179, 291-296.

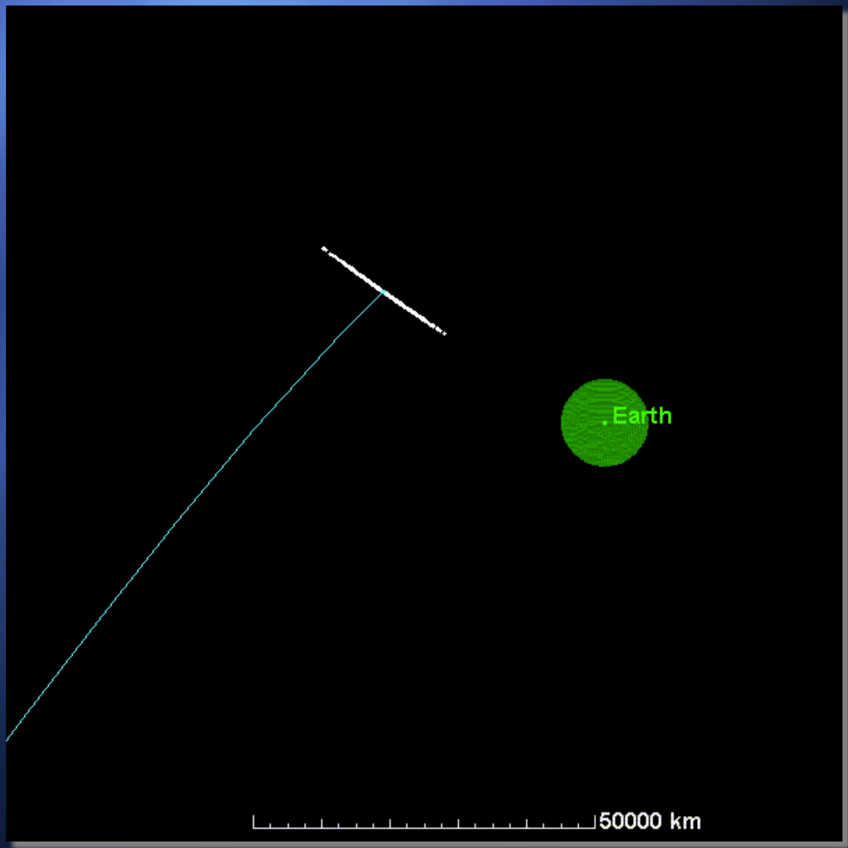


On a shorter term: the threatening object Apophis (size: 300 m)

Trajectory uncertainty: 600 m within which a solution leads to a collision in 2036

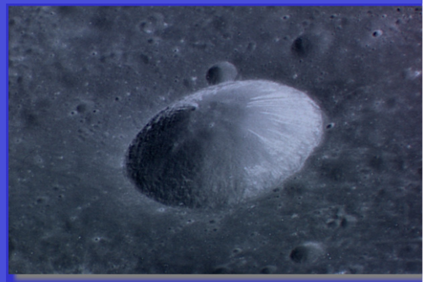
In 2029: approach within 32,000 km!!



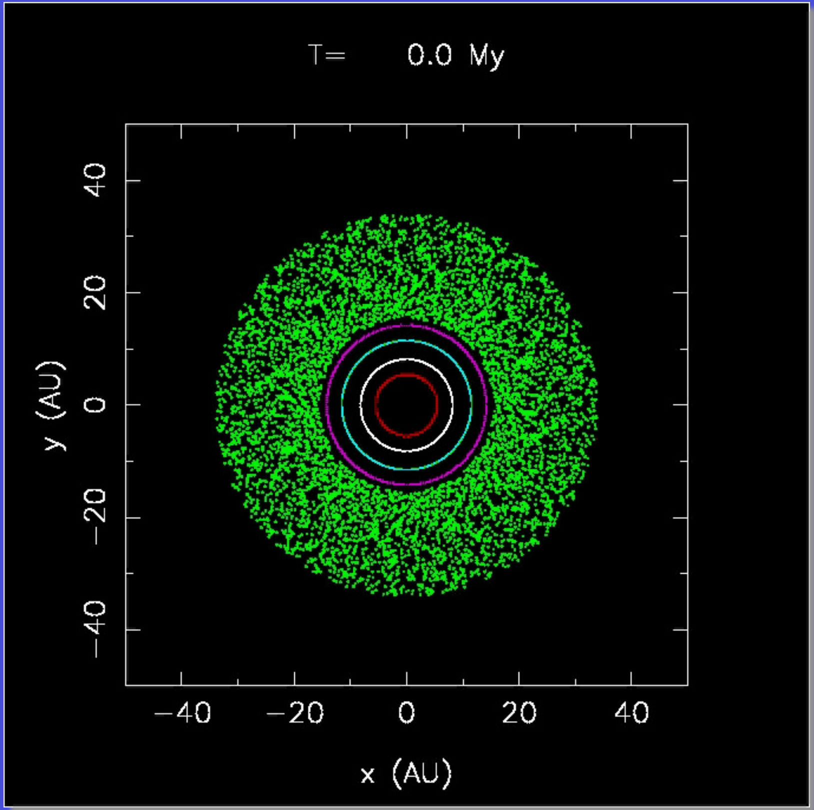


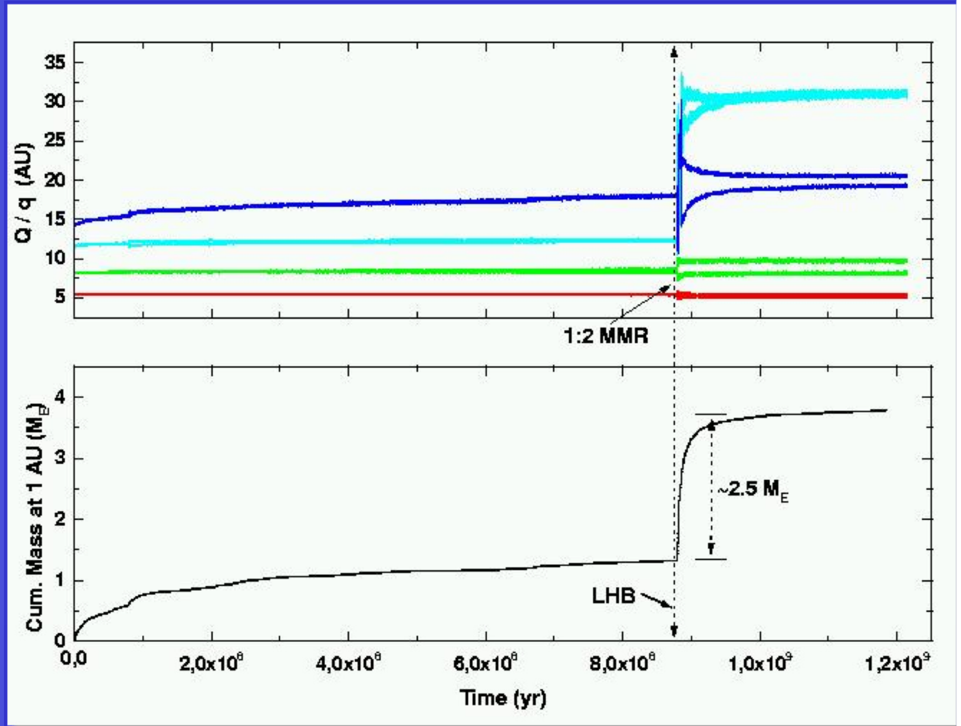
Origin of the Late Heavy Bombardment (3.9 Byr ago)

Lunar craters



3 articles published in Nature (Vol. 435, 2005)





External Solar System (in red: Jupiter)
In green: disk of planetesimals

1st scenario which simulatneously explains: giant planet excentricities, origin of Trojans, LHB, and structure of the Kuiper Belt !

Conclusion I

- Mean motion and secular resonances = efficient transport mechanisms by increasing eccentricities or inclinations
- Most NEOs come from the main belt through resonance channels
- LHB can be explained by passage of Jupiter and Saturn in the ½ MM resonance

Nice Observatory

Cannes

sand and water:
2 cohesionless materials!

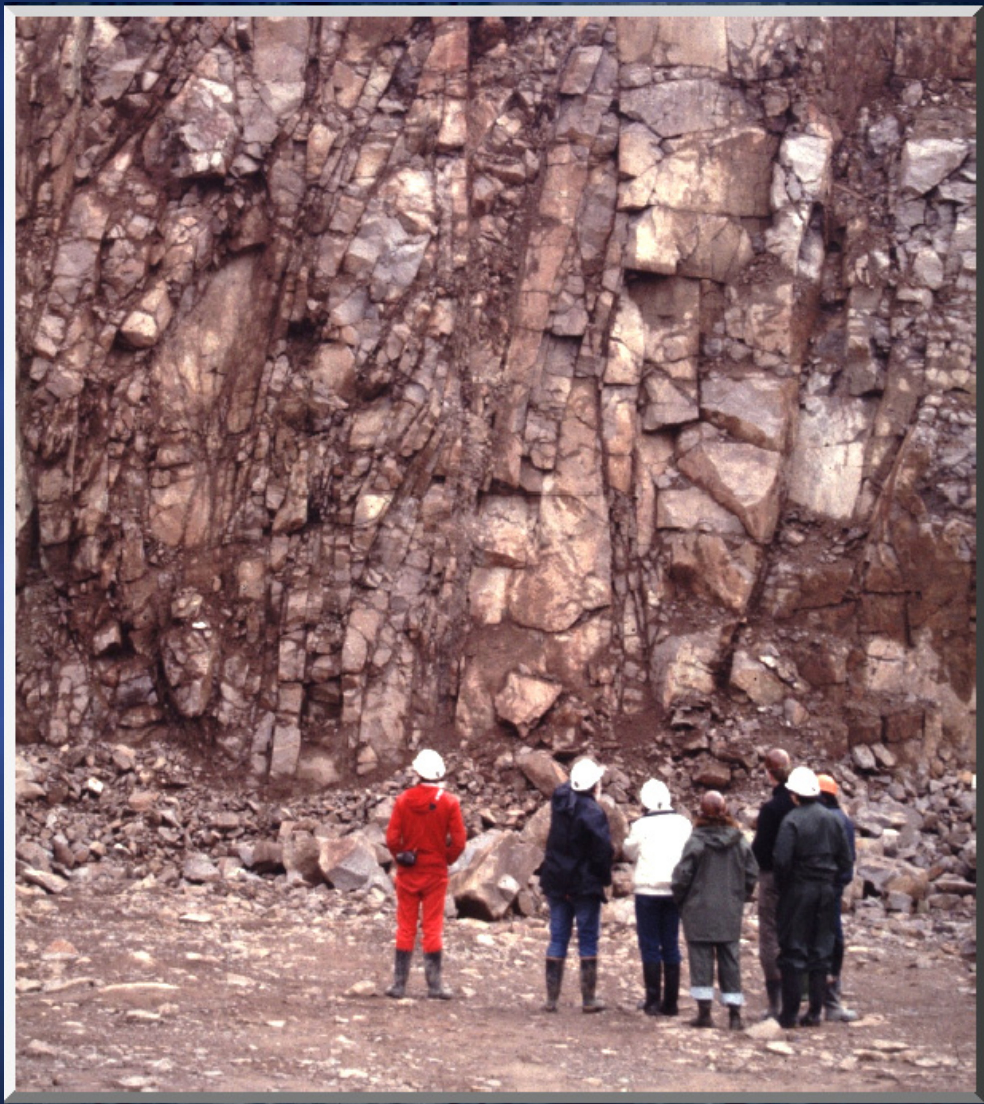
The Alpes
in the snow (another material)!

Both dynamical AND physical properties must be characterized

- To determine the global (collisional and dynamical) evolution of small body populations
- To determine the origin of observed properties (e.g. existence of binaries)
- To define efficient mitigation strategies

Rocks:

A Modeling Challenge



The modeling of material behavior is the biggest shortcoming in code calculations, and the primary reason for bad results..

What I won't talk about, but are important:

Eulerian v. Lagrangian codes

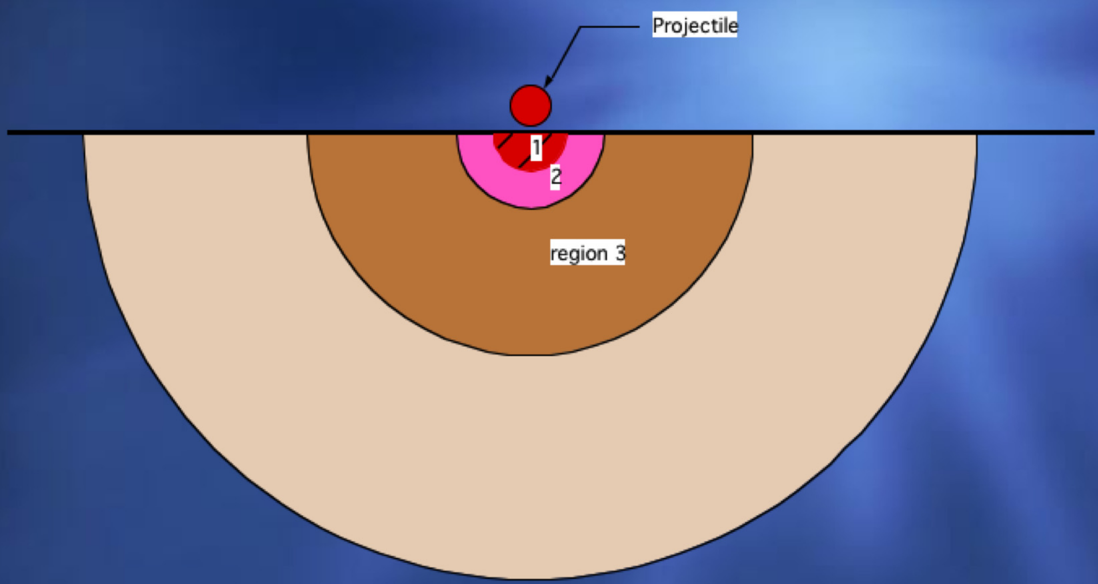
Handling Mixtures in Eulerian codes

Boundaries in Eulerian codes

Grid distortion in Lagrangian

Equations of States of rock materials

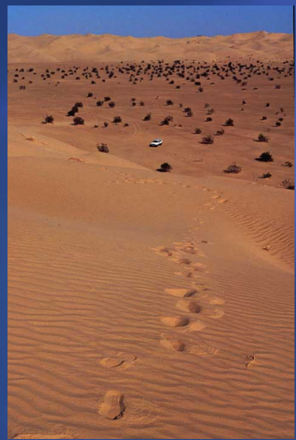
Understanding the process: Regions of Impact Process



1. r ~0-> a: Coupling of the energy and momentum of the impactor into the asteroid
2. r ~ a -> 2a: Transition into point source solution, shock breakaway.
3. r ~ 2a ->+∞ : Shock decays with distance, strength (& gravity) become important

Strength v. Strength v. Strength

Rock Strength

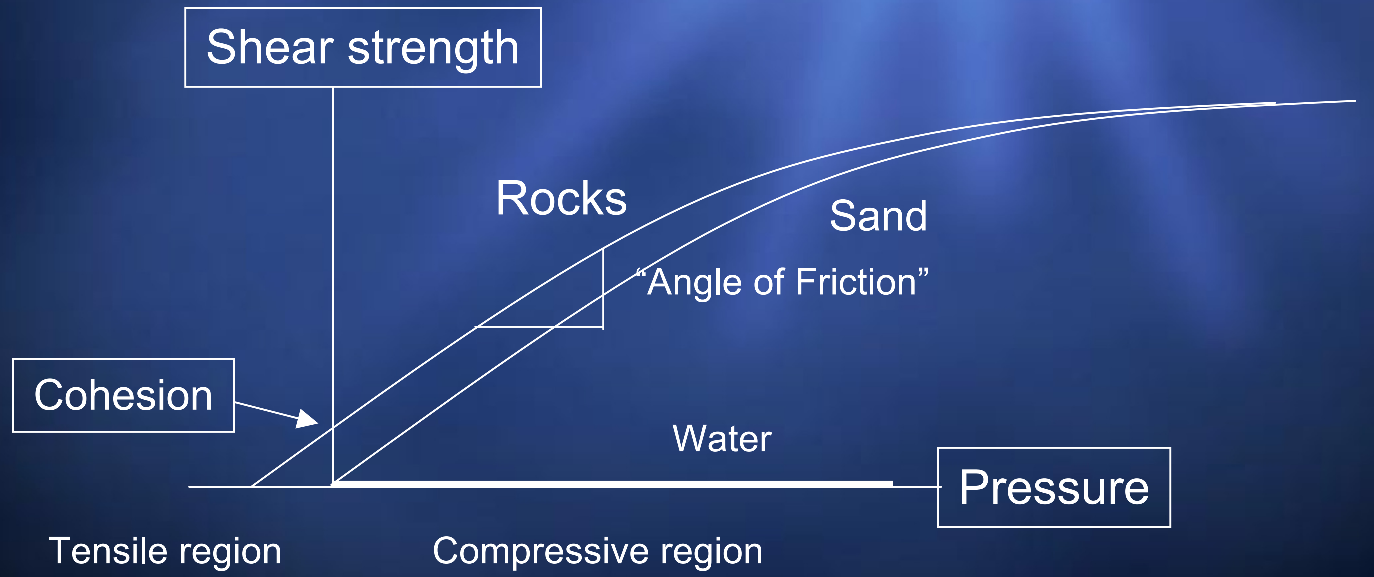


Sand Strength

Water Strength

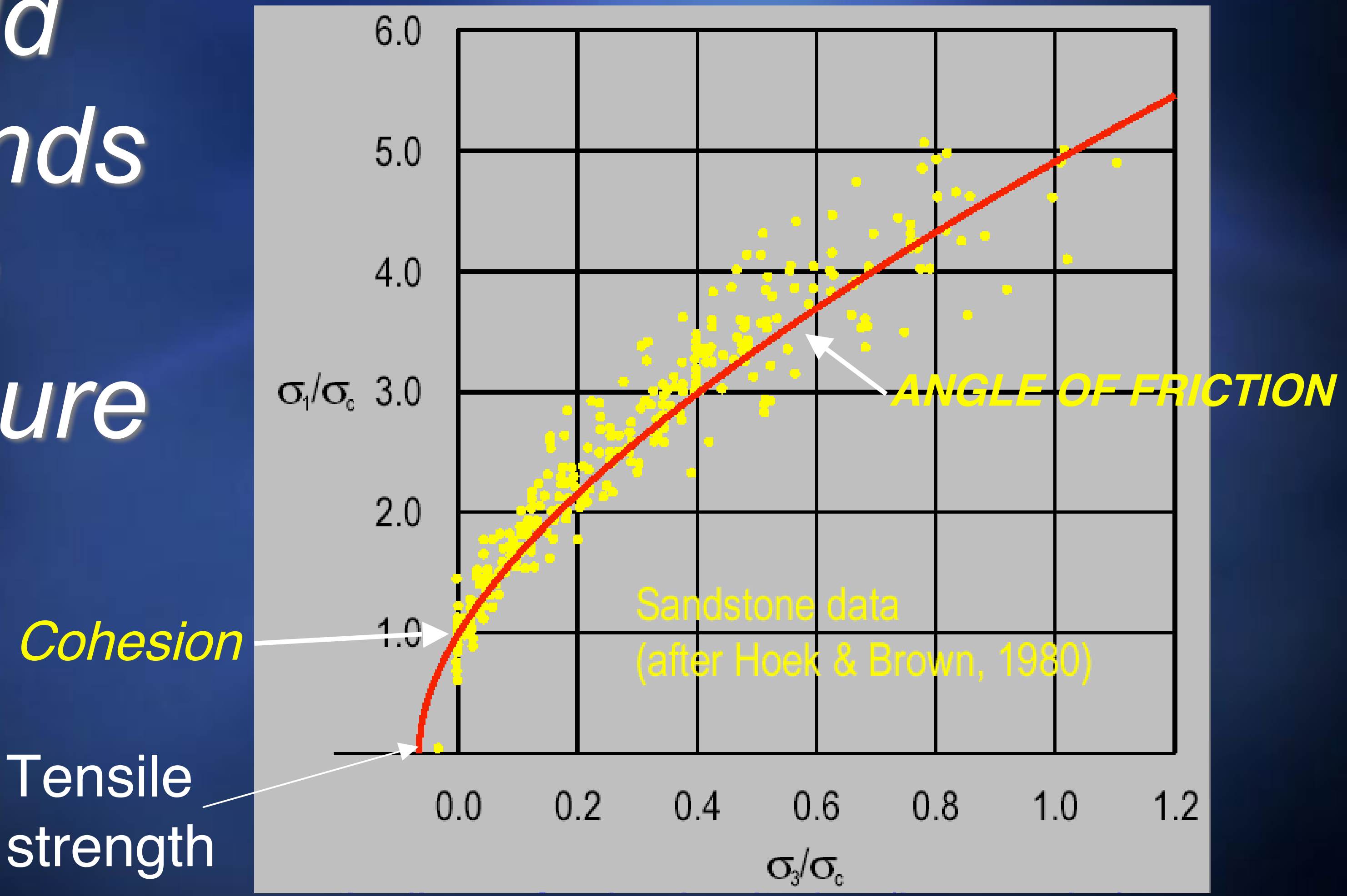
Strength:

- The Mohr-Coulomb (or Drucker-Prager) model:



Some real data

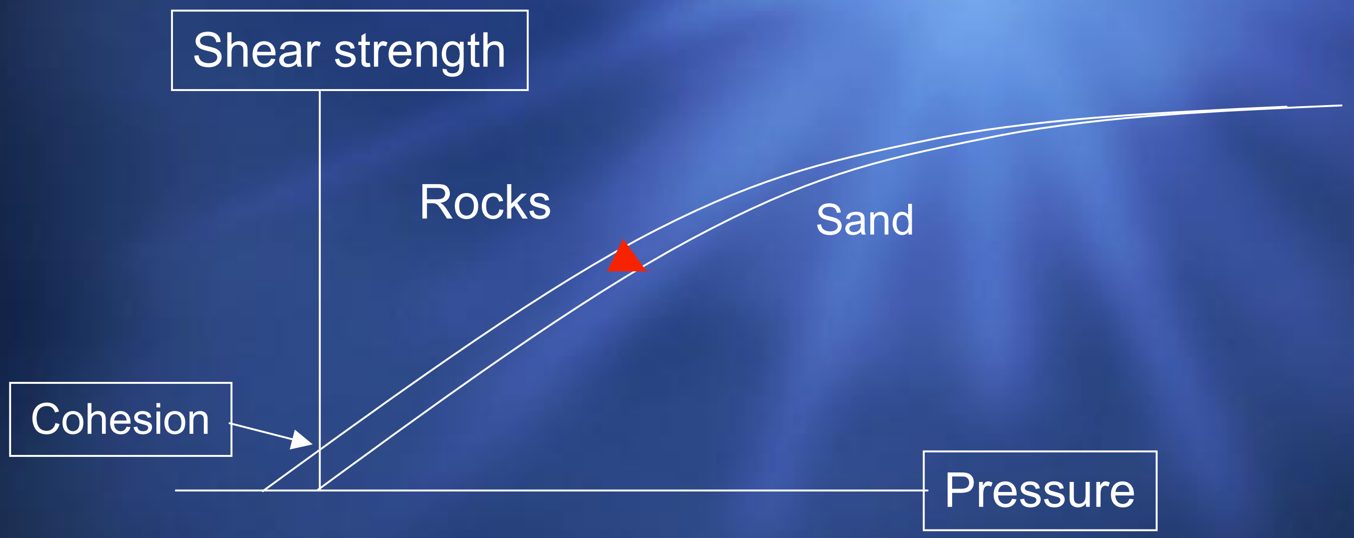
Yield depends on pressure



Strength

- A rock has each of:
  - Tensile strength
  - Shear strength (cohesion) ~same as tensile
  - Compressive strength ~5-7* tensile
- But at large pressure, the cohesion can be ignored…

And we have the model for large cohesion- less bodies or rubble piles:



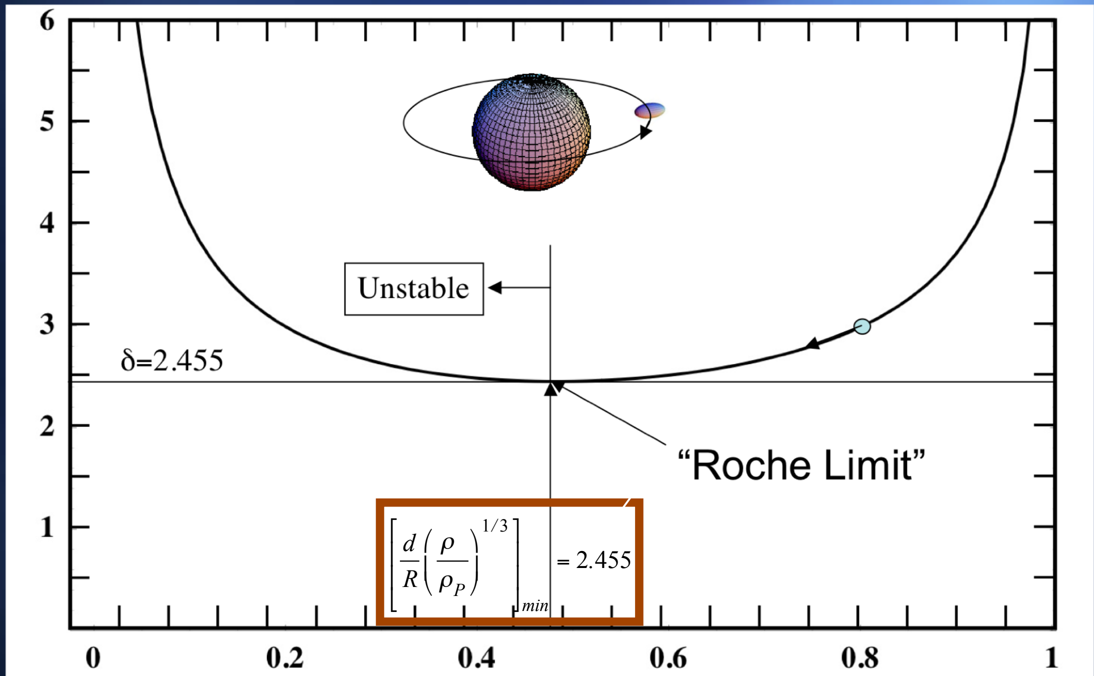
The ‘strength’ is due to the pressure, which is a result of self gravity holding the body together *(but it has no tensile strength)*

First application: Roche limit of cohesionless bodies

- THE ROCHE LIMIT IS A WELL KNOWN FEATURE FOR SMALL Orbiting (or passing) BODIES.

- But:
  - It assumes a fluid body
  - It requires an almost prolate shape with aspect ratios ~2.1:1

So here is the fluid tidal disruption problem



Semi-major Axes: a, b, c

Aspect ratios:

$$\alpha = \frac{c}{a}$$

$$\beta = \frac{b}{a}$$

Aspect ratio α

An Example (Phobos):

Does this look fluid to You??

Is it anywhere near the required shape for a fluid body?? (No: a=0.7, not 0.49)

A fluid model is not mandatory for any solid body, even when dominated by gravity (see further)

So:

"Satellites can orbit within their Roche limit because they have non-zero strength"

But, what is "strength"?

Here, we do not mean cohesion

BUT shear strength under pressure

The Problem Solved:

- Determine the tidal disruption limits for a geological material such as rock or sand.
  - Rubble Piles (Ignore cohesion)
  - Then what are the limit tidal disruption distances?

Ref: Holsapple and Michel, 2006, Icarus 183, 331.

Step 1: Determine the stress state

- Include spin, gravity, and tidal forces
- But there are different ways to do this:
  - Elastic Theory: Can determine state for "first yield"
    (but that depends on residual stresses, which cannot be known)
  - Plastic Limit Theory: Can determine states for "final failure" irrespective of past history.

The stresses at ‘final failure’ in an ellipsoidal body

$$\sigma_x = -\rho k_x a^2 \left[1 - (x/a)^2 - (y/b)^2 - (z/c)^2\right]$$
$$\sigma_y = -\rho k_y b^2 \left[1 - (x/a)^2 - (y/b)^2 - (z/c)^2\right]$$
$$\sigma_z = -\rho k_z c^2 \left[1 - (x/a)^2 - (y/b)^2 - (z/c)^2\right]$$

The magnitudes are determined by k_x, k_y and k_z which have specific components from each of gravity, spin and tidal forces. For the long x-axis is pointed toward the primary center:

$$k_x = \left(-2\pi\rho G A_x + \omega^2 + 2\frac{GM}{d^3}\right)x,$$
$$k_y = \left(-2\pi\rho G A_y + \omega^2 - \frac{GM}{d^3}\right)y,$$
$$k_z = \left(-2\pi\rho G A_z - \frac{GM}{d^3}\right)z$$

Ax=Ay=Az=2/3 for a sphere and are expressed in terms of elliptic integrals for an ellipsoid

ω= spin magnitude (about z)

M = primary’s mass, ρ = body’s density

d = distance (primary’s and body’s center)

Step 2: Solve the failure criterion for the tidal disruption limit distance

- The failure criterion is the Druker-Prager one (zero-cohesion):

$$\frac{1}{6}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_2)^2\right]=s^2\left[\sigma_1+\sigma_2+\sigma_3\right]^2$$

Define: $\Omega = \dfrac{\omega}{\sqrt{\pi\rho G}}$

$$s=\frac{2\sin\phi}{\sqrt{3}(3-\sin\phi)}$$

and solve for the dimensionless distance:

$$\delta=\left(\frac{\rho}{\rho_p}\right)^{1/3}\frac{d}{R}=F\left[\alpha,\beta,p,\phi,\Omega\right]$$

$p = m/M$

ϕ = angle of friction

ρ_p, R: primary density and radius

α, β: aspect ratios

This corresponds to solve for “LIMIT” State where no further plastic re-adjustments are possible.

We have done that for many combinations of distance, spin, shape, and secondary size..

as a function of the angle of friction…
(so the fluid case with zero angle of friction is a special case)

Example: prolate bodies, spin-locked

$\delta = d/R$

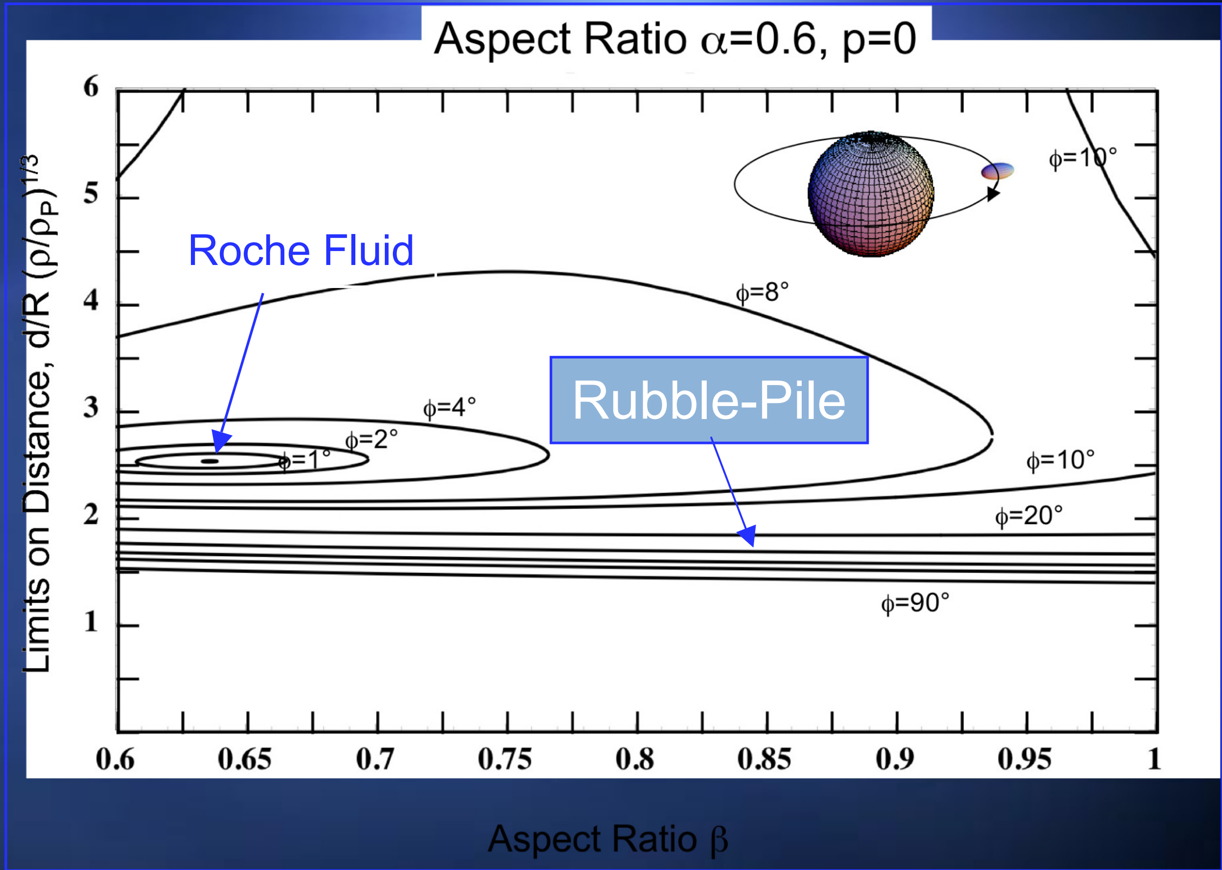
(for $\rho = \rho_p$)

Semi-major Axes: a, b, c

Aspect ratios:

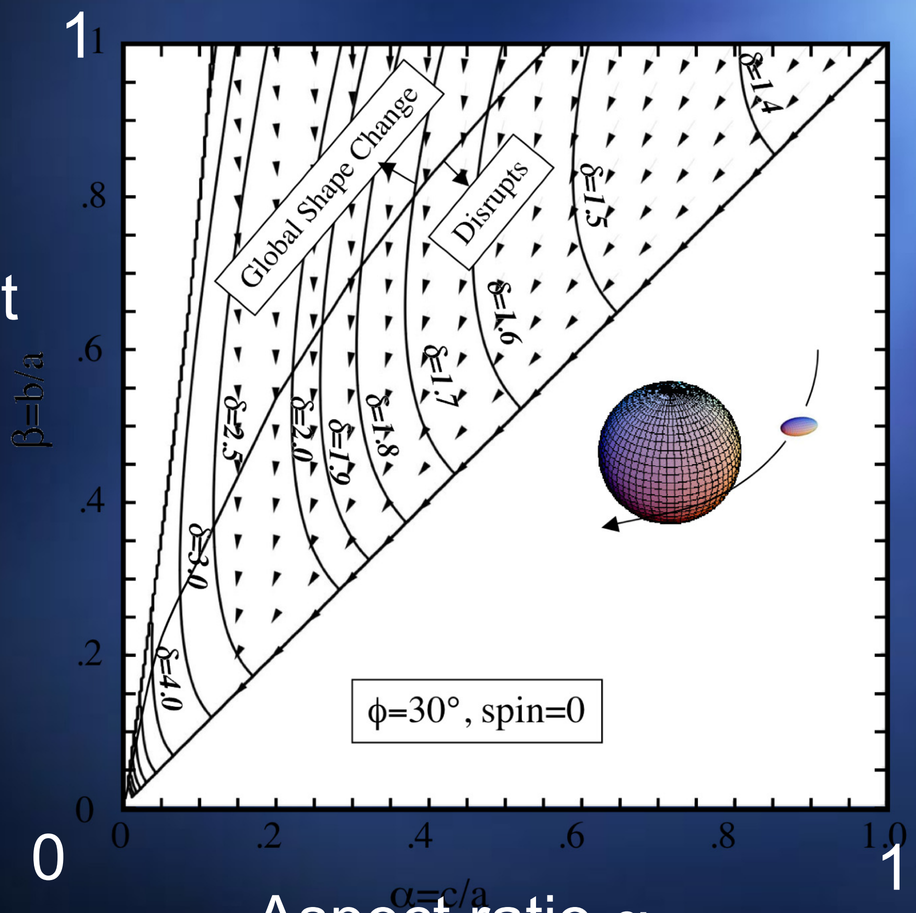
$$\alpha = \frac{c}{a}, \quad \text{(equal 0.6 here)}$$

$$\beta = \frac{b}{a}$$



Aspect ratio β

And finally, what if it does have 'final failure'?



Aspect ratio β

Aspect ratio α

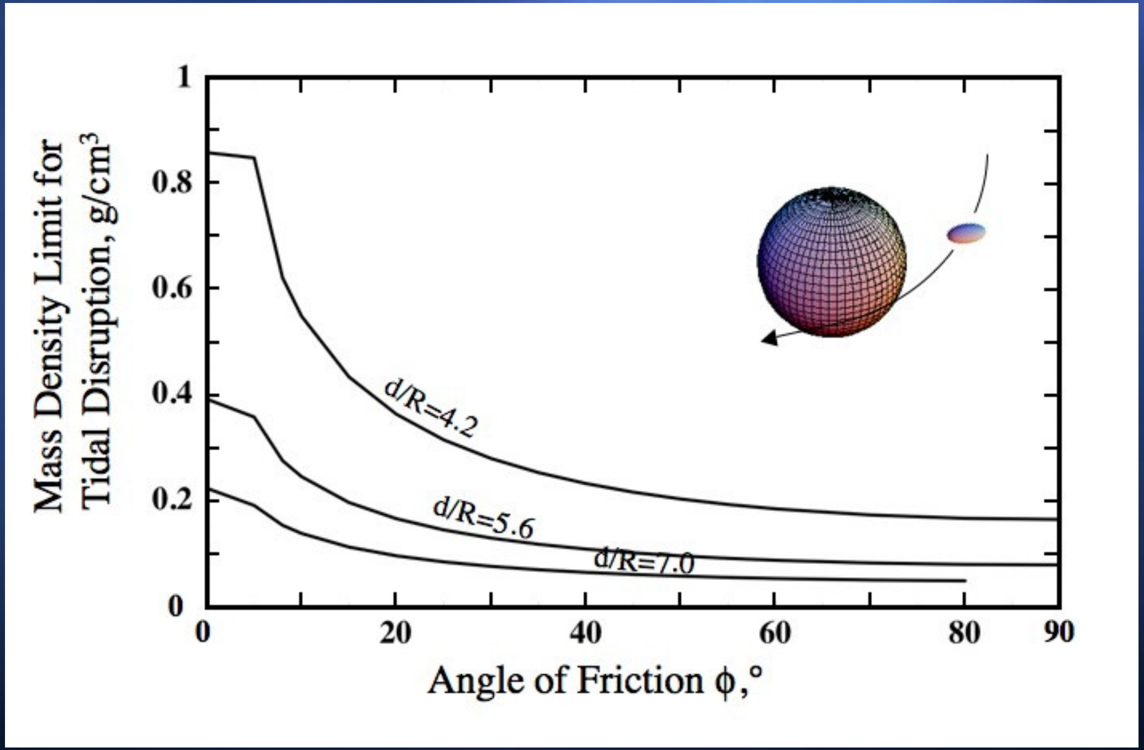
Prolate passing body,
Long axis 'down',
No spin,
30˚ friction angle

Application:
99942 **Apophis** *(2004 MN4)*

- In 2029: approach within 5.6 +/- 1.4 Earth's radii from Earth 's center.
- Ellipsoid with aspect ratios a=0.57, b=0.71 (Scheeres et al. 2005), rotation period=30 h.
- We can determine the bulk density for tidal disruption or reshaping vs. the angle of friction f

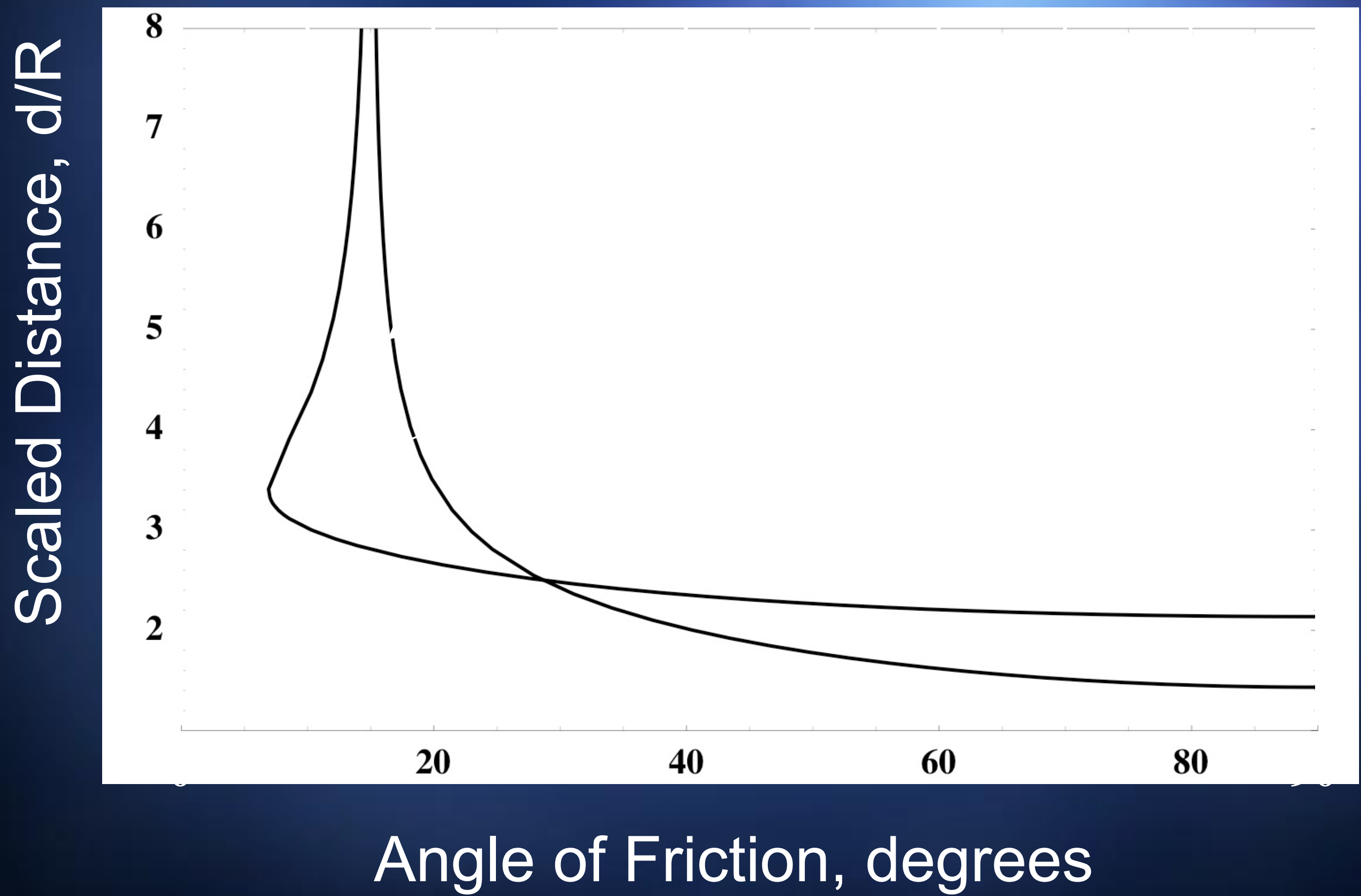
Application:
99942 **Apophis** *(2004 MN4)*

Minimum bulk density of Apophis for survival without tidal breakup during the passage by the Earth at d/R=5.6, 4.2, and 7.0, for various angles of friction (assumes the worst-case orientation of the longest axis pointed down)

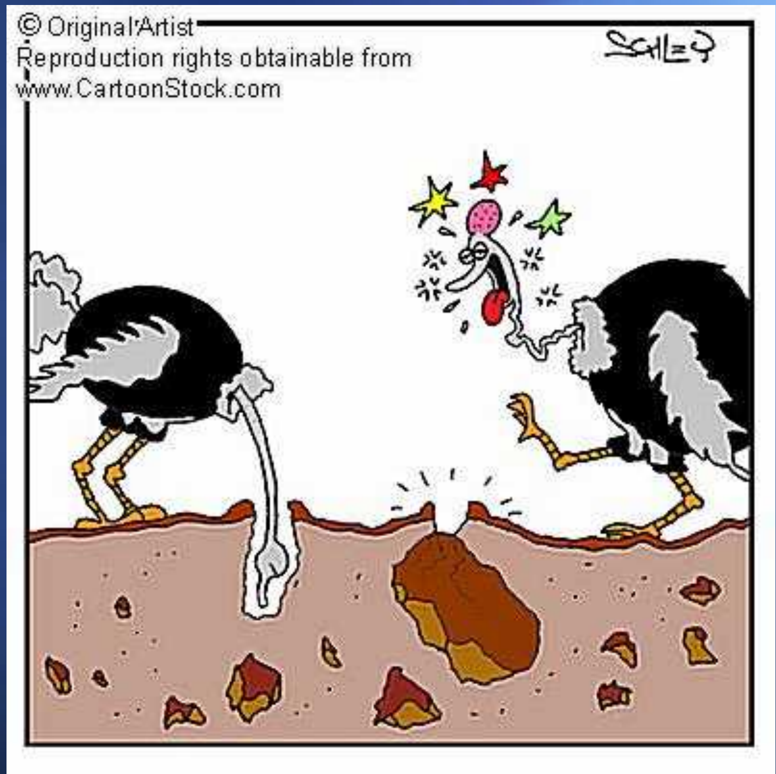


Application: (25143) Itokawa

Minimal distance to Earth for tidal effects



FUTURE STEP: ADD COHESION



« Ostriches trying to stick their heads in the sand »

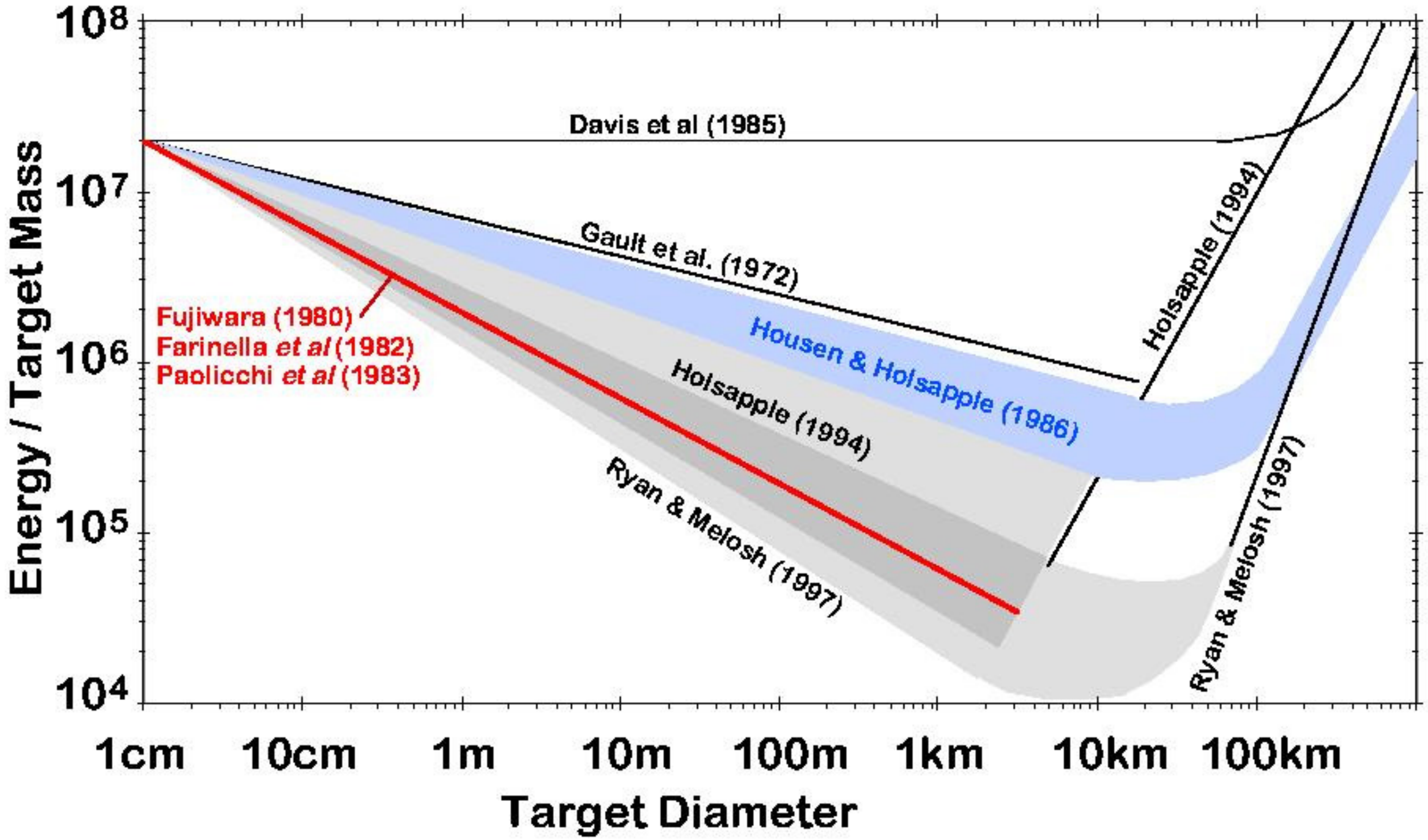
Simulating the collisional disruption of a small body: what do we need to know?

- Balance Laws (easy: continuum mechanics: balance of mass, momentum, energy)

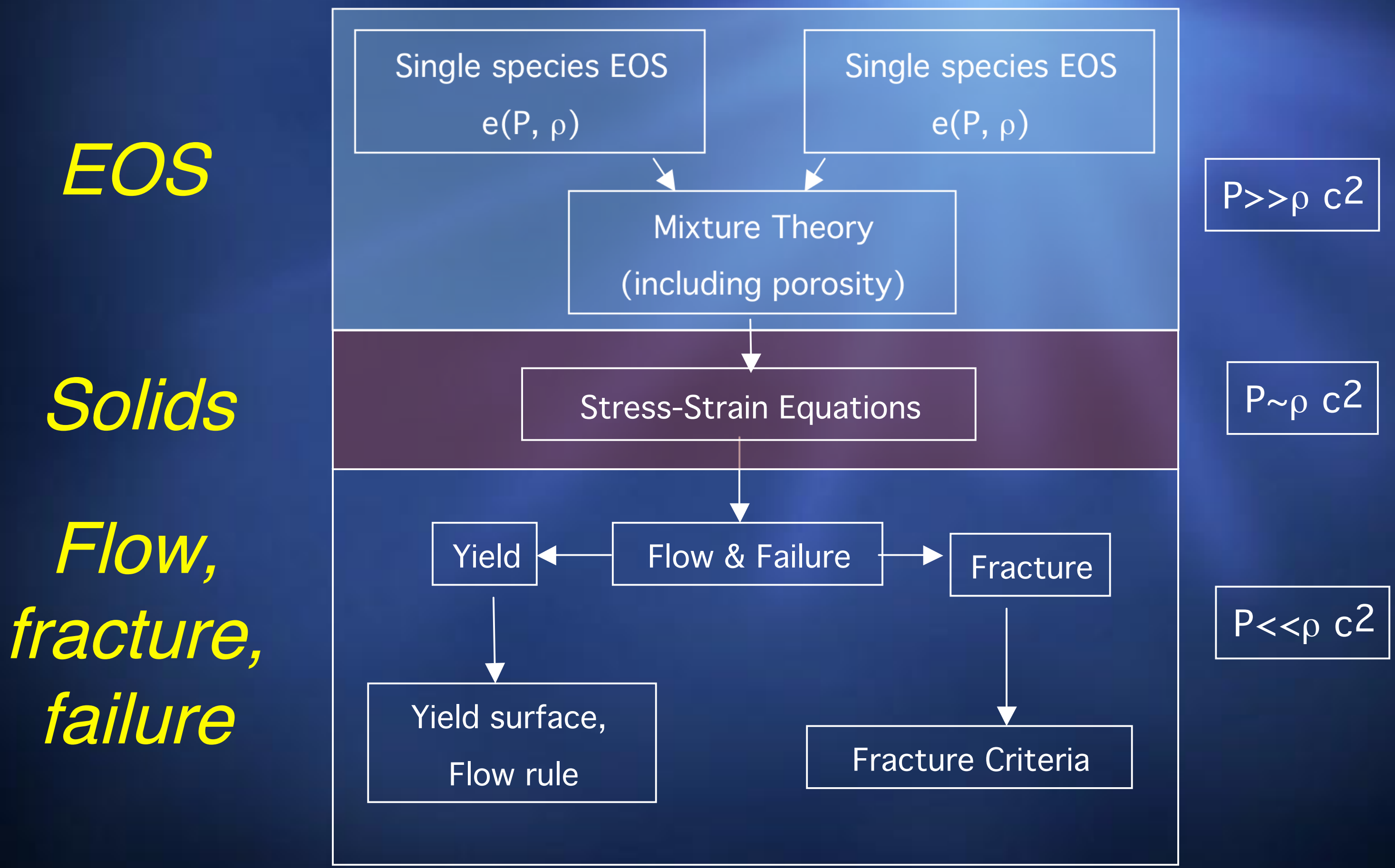
- Material behavior (very hard: 100 Mbar down to partial bars!)

- Robust computer codes

Comparison of scaling models



Material Behavior: Three regimes



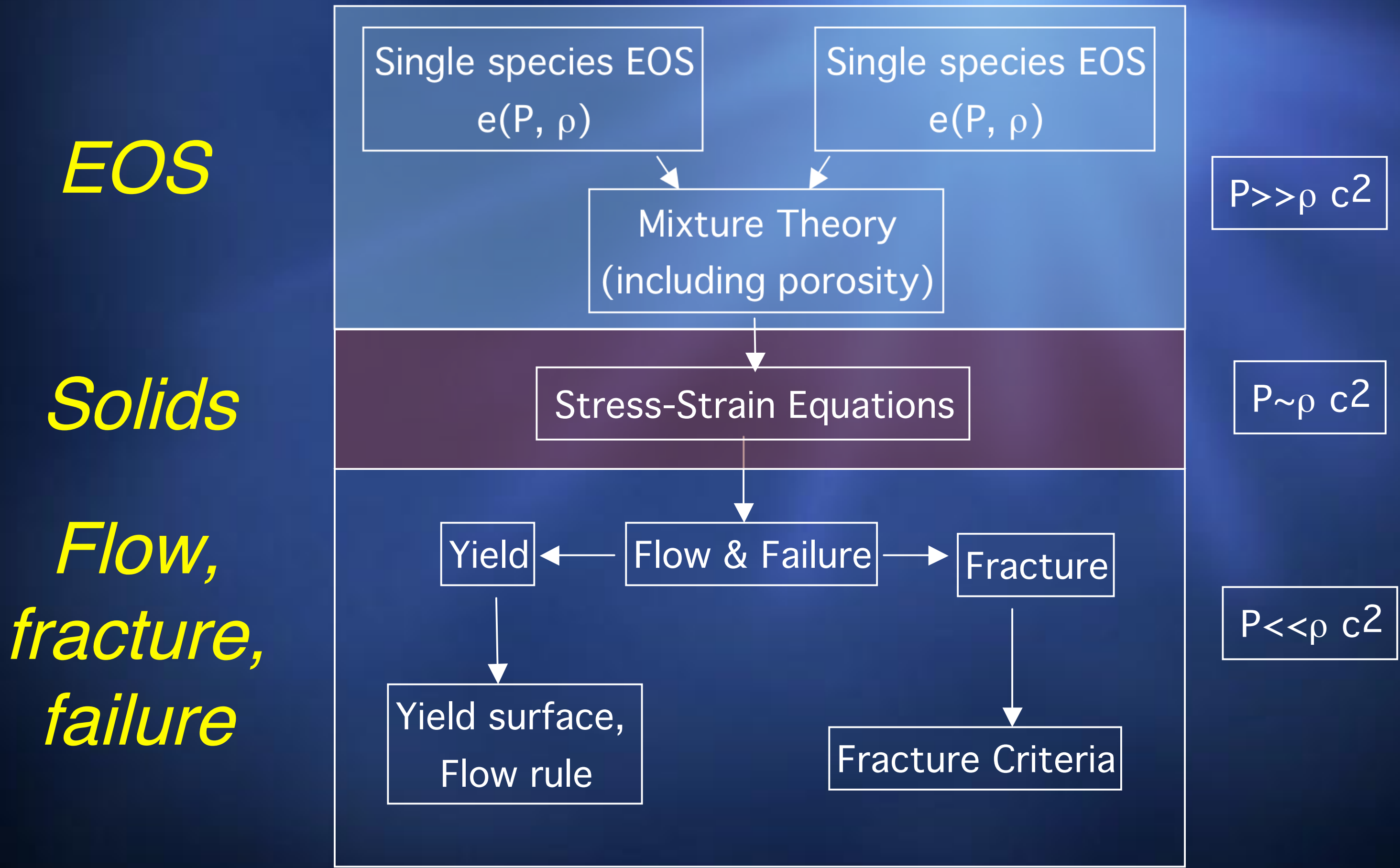
Stress-Strain behavior

- When $\mathbf{P \approx \rho c^2}$ the material no longer behaves as a fluid.

- Then we need a constitutive equation for the stress-strain behavior

- Almost always, in wave codes that is simply an isotropic linear elastic relation (which is undoubtedly extremely crude).

Which brings us to the strength parts..

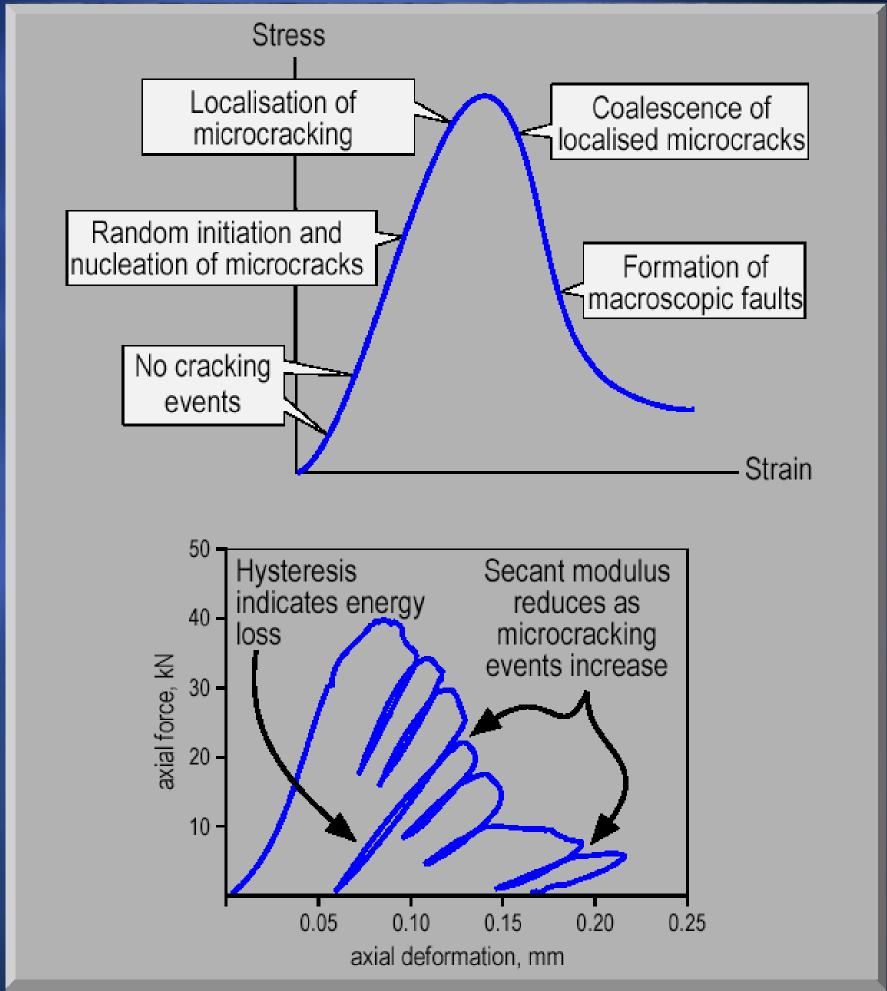


The "F" words: Flow, Fracture and Failure

- Models for these fall into three groups:
  - *"Degraded Stiffness", no explicit flow or fracture.*
  - *"Flow" including plasticity and damage, used to model microscopic voids and cracks leading to an inability to resist stress.*
  - *"Fracture", involving actual macroscopic cracks and voids which are tracked, leading to an inability to resist stress.*

In a continuum theory, the first two can be included directly, the latter is difficult, unless some statistical approach is used to smear them out.

Damage and degradation leading to ultimate failure occur at some limiting strain



Flow and Fracture: Yielding and Cracking

Initial Yield=F(stresses) or G(strains)

- Isotropic=> σ_1, σ_2, σ_3
  (Or three stress invariants)
- Commonly only 2, e.g.
  J_2=F(P)
  Or max shear=f(pressure)

The Grady-Kipp Model

Special nature

- It is a Tensile Brittle Fracture Mechanism
  - For fragmentation in mining
- One-Dimensional Model
- Synthesized for constant strain rate histories only

- Governed by Crack Distributions (Weibull) and growth
- Implies rate and size-dependent strength

But Attractive Physics

There exists an initial distribution of incipient flaws in the target

- Weibull distribution:

$$N(\varepsilon) = k\, \varepsilon^{m}$$

where:

N = density number of flaws activating at or below the strain ε

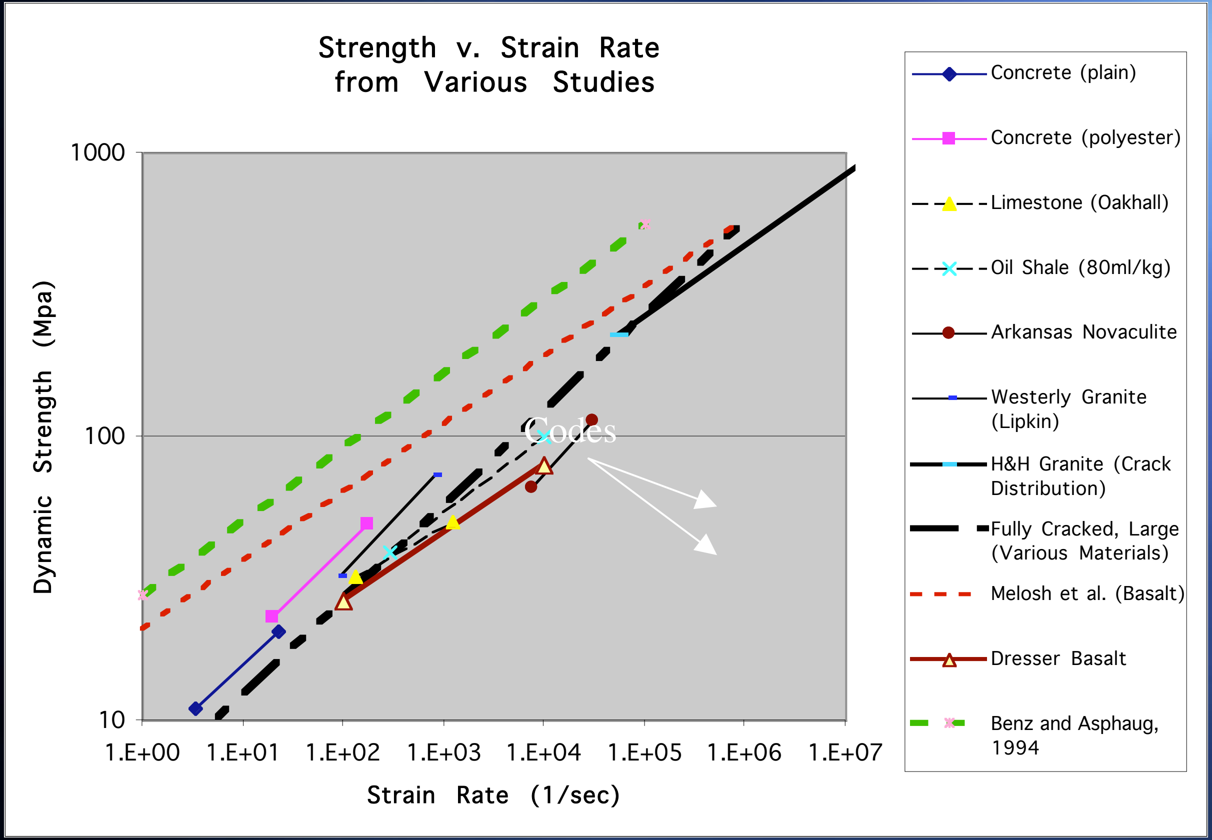
k, m: Weibull parameters (large m= more homogeneous material)

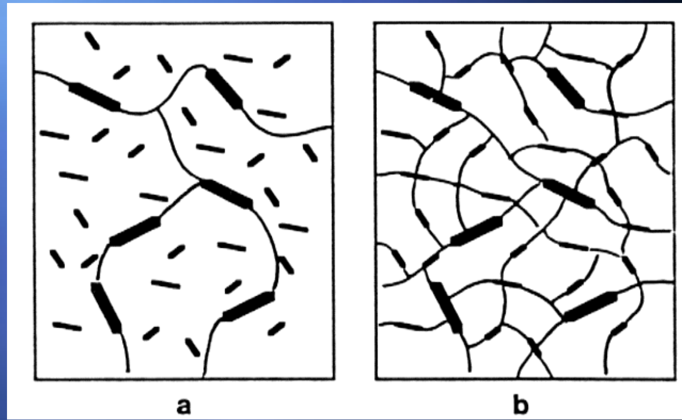
$$\varepsilon_{min} = (1/\, kV)^{-m}$$

Larger targets (volume V) activate largest crack at lower strain

$\Rightarrow$ Larger targets are weaker

Tensile fracture depends strongly on strain rate





Low strain rate

High strain rate

(From Asphaug)

A Grady Kipp Implementation in 3D

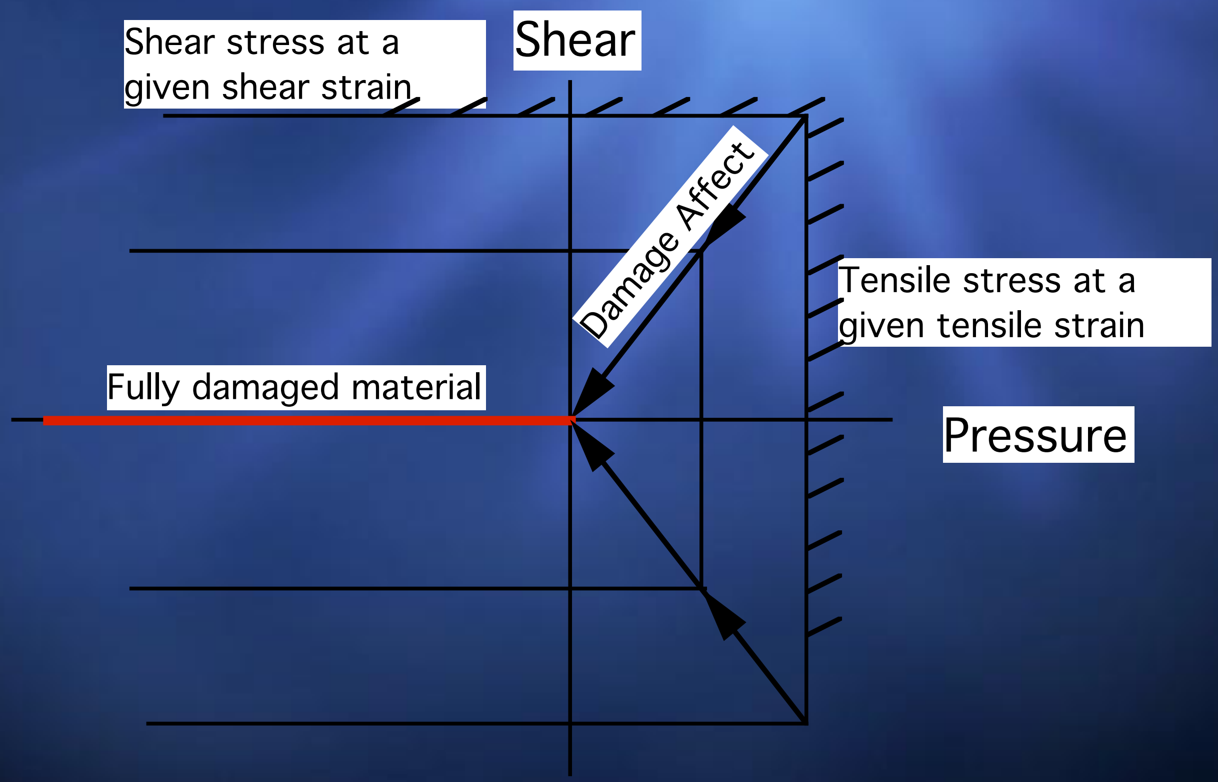
- Damage is isotropic, so that when a crack is formed in one directions, <u>all directions</u> lose stiffness

- As damage accumulates, the stiffness in both tension and in shear decrease, eventually to zero.

- Therefore, material failed by the outgoing shock behaves as water.

- *Calibrated to disruption test, by adjusting the strength (Weibull) parameters*

The Grady-Kipp Approach



Fragmentation phase: principles

Equation of state
P=f(E,ρ)

Model of brittle Failure

Yielding criterion:
$S_{\alpha\beta} \rightarrow f\, S_{\alpha\beta}$

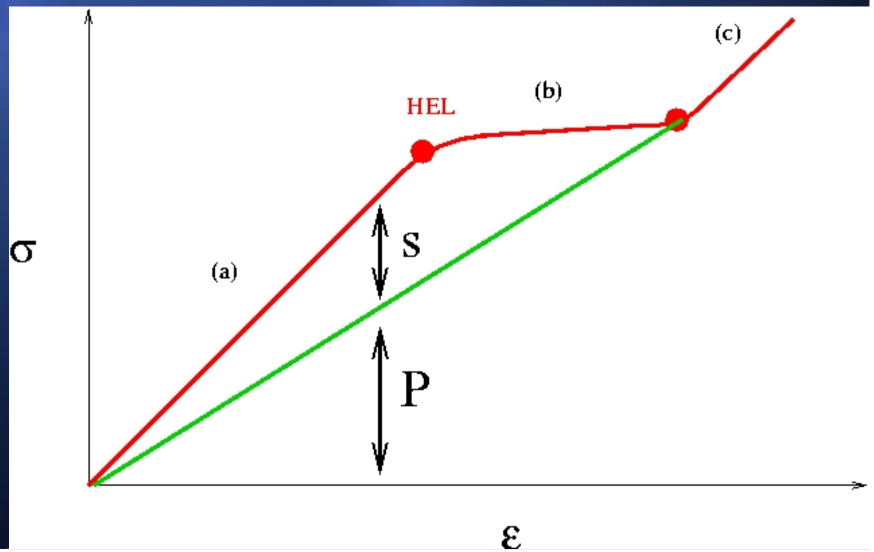
Stress tensor

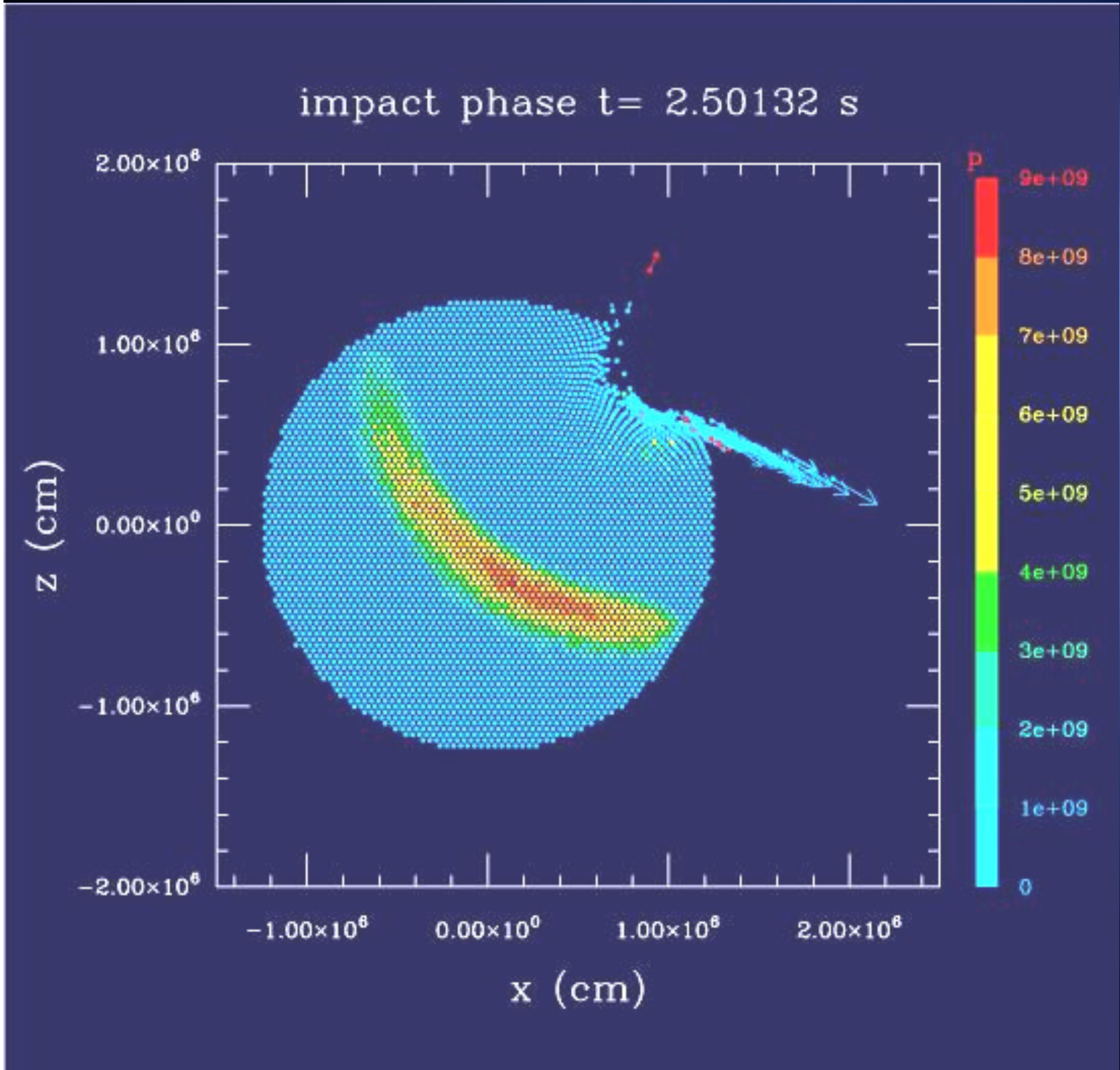
$$\sigma_{\alpha\beta} = -P\,\delta_{\alpha\beta} + S_{\alpha\beta}$$

$$S_{\alpha\beta} = \mu(\varepsilon_{\alpha\beta} - 1/3\,\varepsilon_{\gamma\gamma}\delta_{\alpha\beta})$$

Conservation equations

SPH techniques





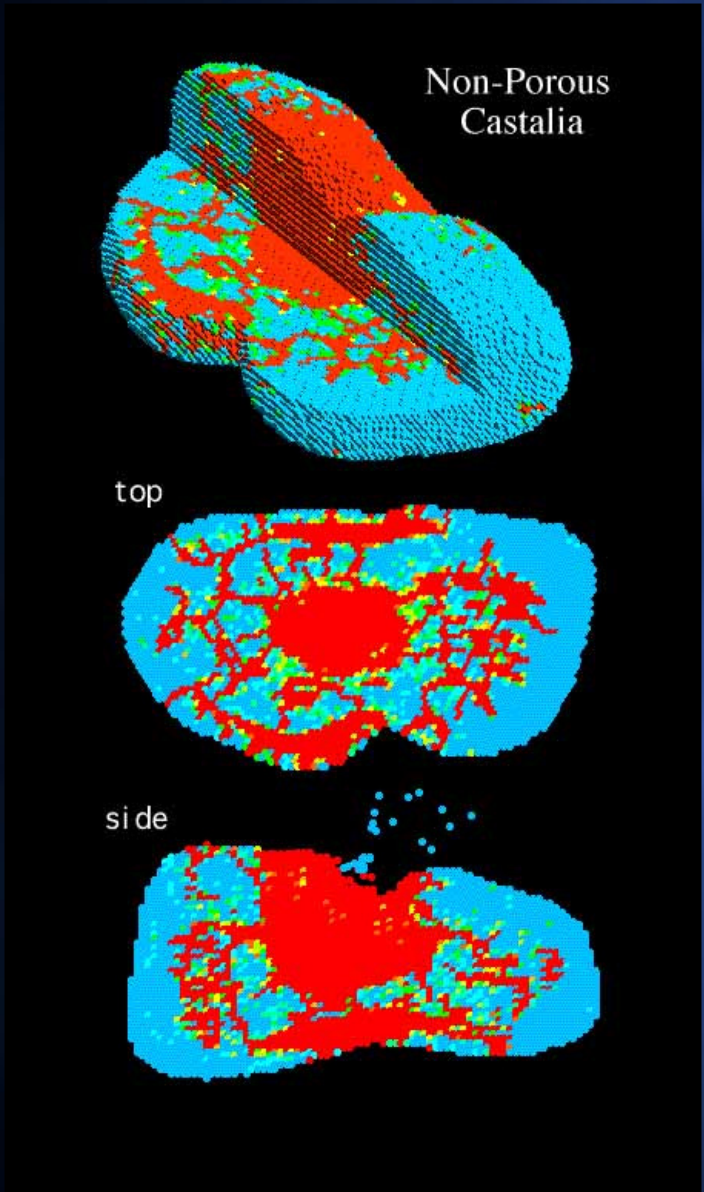
Fragmentation Phase

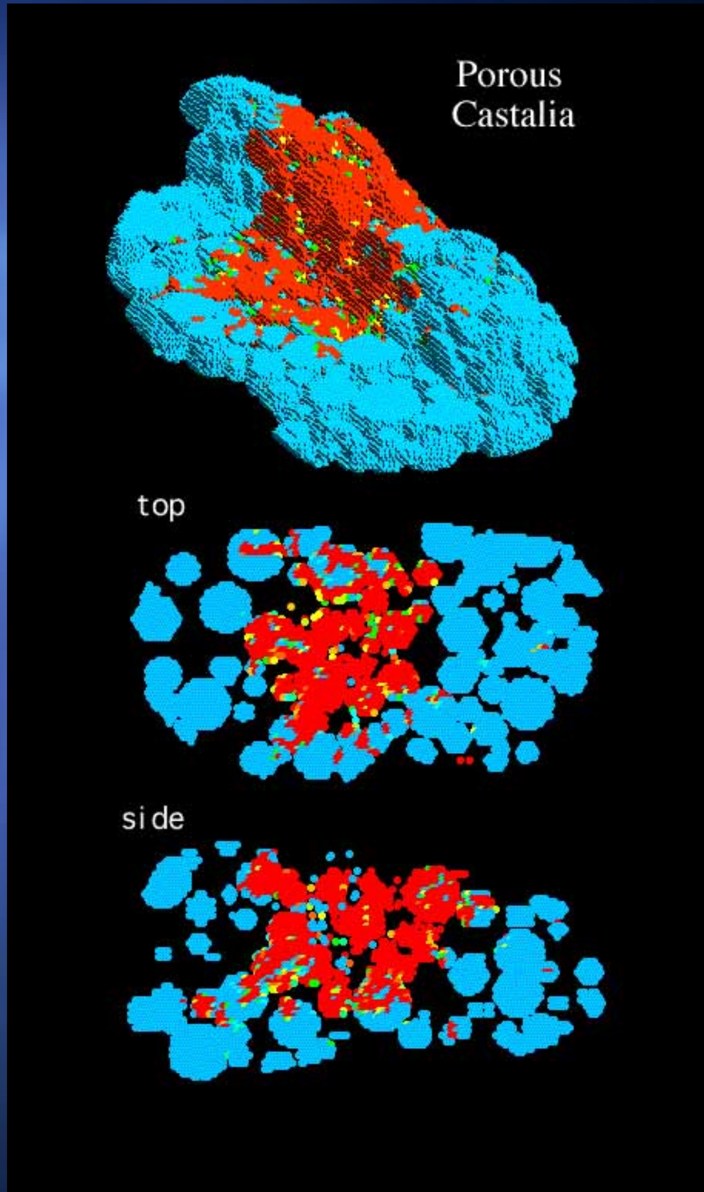
Shock wave Propagation

Impact velocity: 5 km/s

Impact angle: 45°

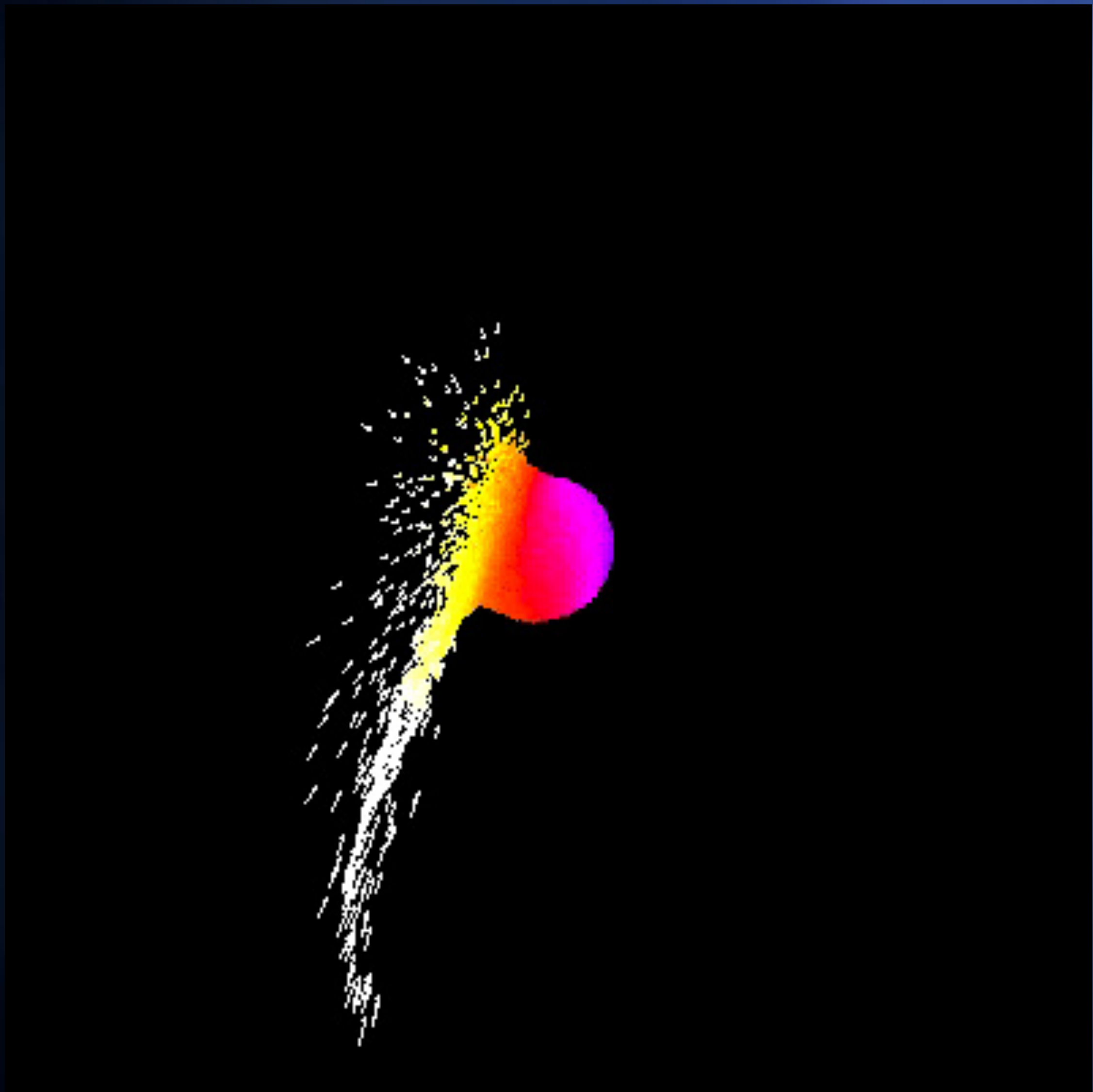
P. Michel & W. Benz





From Asphaug et al. 1998, Nature **393**.

Impact angle: 66°, V = 5 km/s D=164 km



Velocity distribution At the end of the fragmentation phase

Colors from Yellow to Blue indicate velocities from large to small

Intermediate impact regime

Gravitational Phase: parallel N-Body simulations

- Several hundreds of thousands km-size fragments can be generated by the fragmentation phase

→ Impossible to compute their gravitational interaction by classical methods:

The CPU time required to compute N interactions between N particles is of O(NxN) !!

Using the so-called hierarchical tree method (tree code):

CPU Time = O(N log N)

Gravitational Phase: parallel N-Body simulations

- Parallel N-Body code: *pkdgrav* (Parallel K-D tree GRAVity code); developed at UW by T. Quinn, J. Stadel, D.C. Richardson

- Detects and handles collisions between massive particles. Several options:

1. Systematic particle merging
2. Merging/Bouncing of particles depending on impact speed and spins.

Particle shape: spherical

Simulations of Collisions in the Gravity Regime

- SPH hydrocode → crack propagation through the target
- Nbody code → gravitational interaction between intact fragments

↓

Simulation of target shattering + fragment dispersion and/or reaccumulation

Michel et al. (2001), Science Vol. 294, pp 1696-1700.

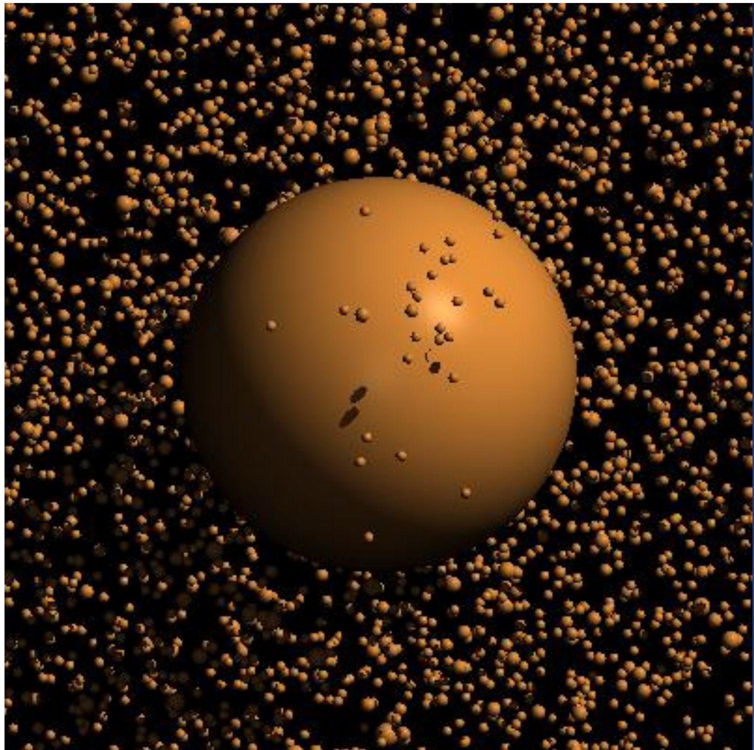
Results!

Simulations of asteroid disruptions have
1. successfully reproduced asteroid families
2. suggest that most kilometer-sized objects are gravitational aggregates

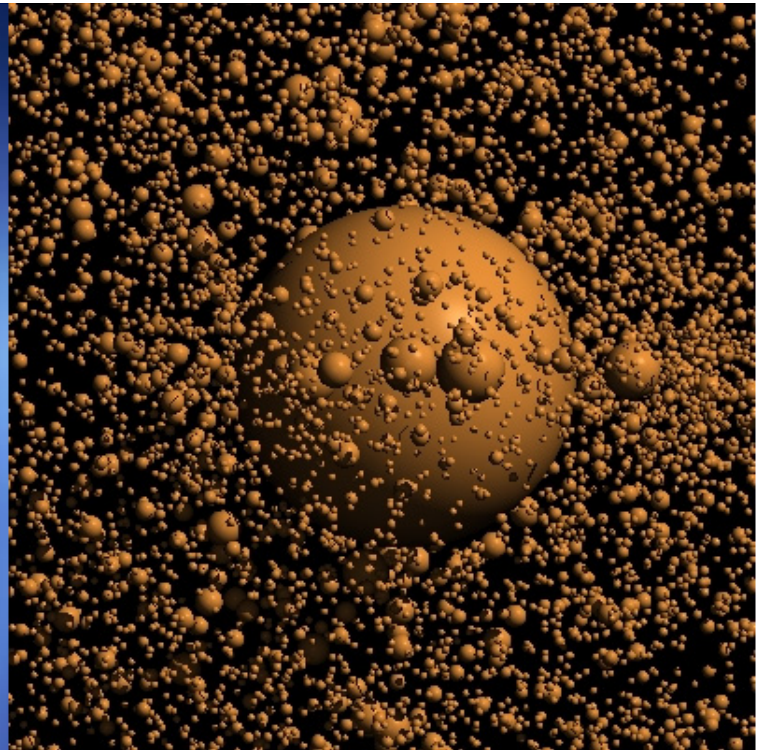
Michel et al., *Science* 294 (2001)

Impact energies and collisional outcomes depend highly on the internal structure of the parent body

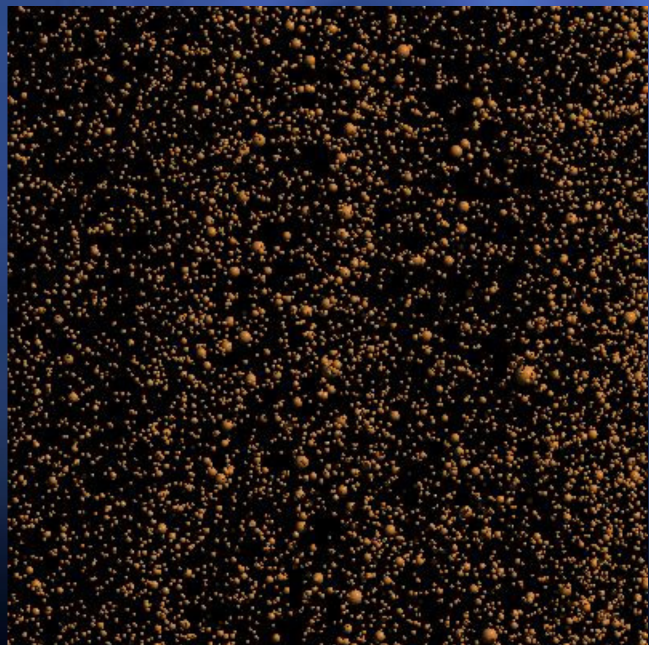
Michel et al., *Nature* 421 (2003)



Michel, Benz, Tanga, Richardson, *Icarus*, **160**, 2002.



T=84 minutes



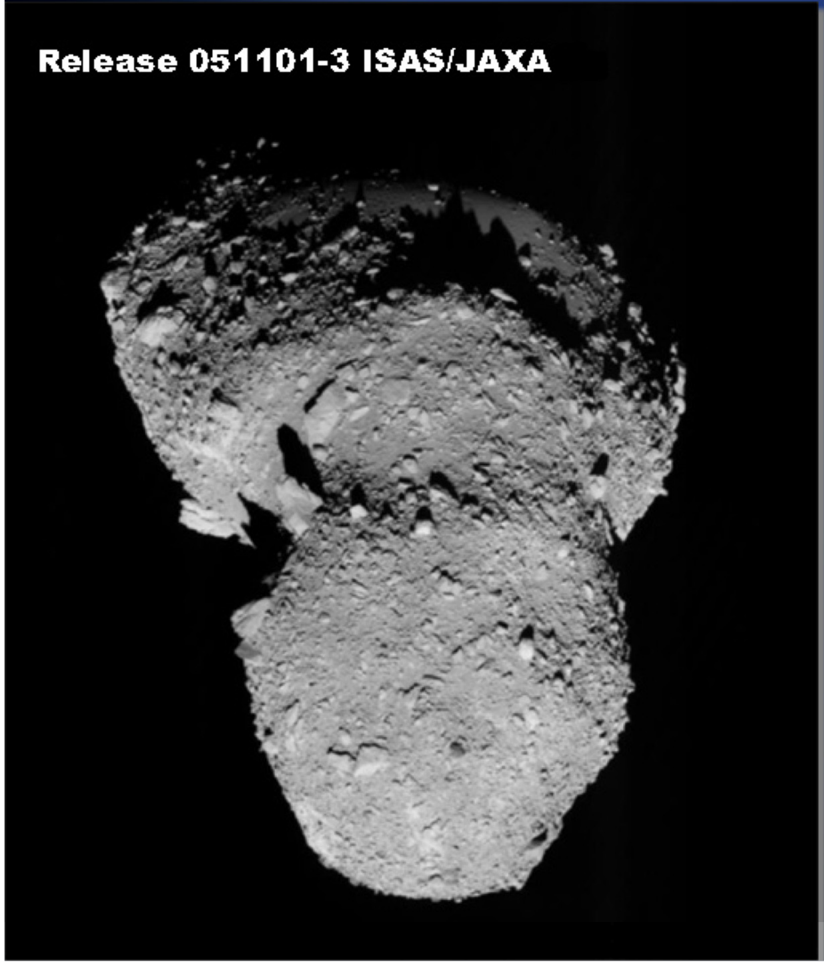
T=2 minutes

T=2 seconds

Different phases of the reaccumulation process

Implication: most asteroids originating from the disruption of a larger one - such as most NEOs - should be rubble piles

The japanese mission Hayabusa brought us some evidence in this direction: where are the craters?? why so many debris ?? What about the small bulk density (< 2 g/cm3)



From Velocities to Orbital Elements

Gauss Formulae: transformation velocities to orbital elements

$$\frac{\partial a}{a} = \frac{2}{n a \sqrt{1-e^2}} [(1+e\cos f)V_t + e\sin f\, V_r]$$

$$\partial e = \frac{\sqrt{1-e^2}}{n a} [\frac{e+2\cos f + e\cos^2 f}{1+e\cos f} V_t + \sin f\, V_r]$$

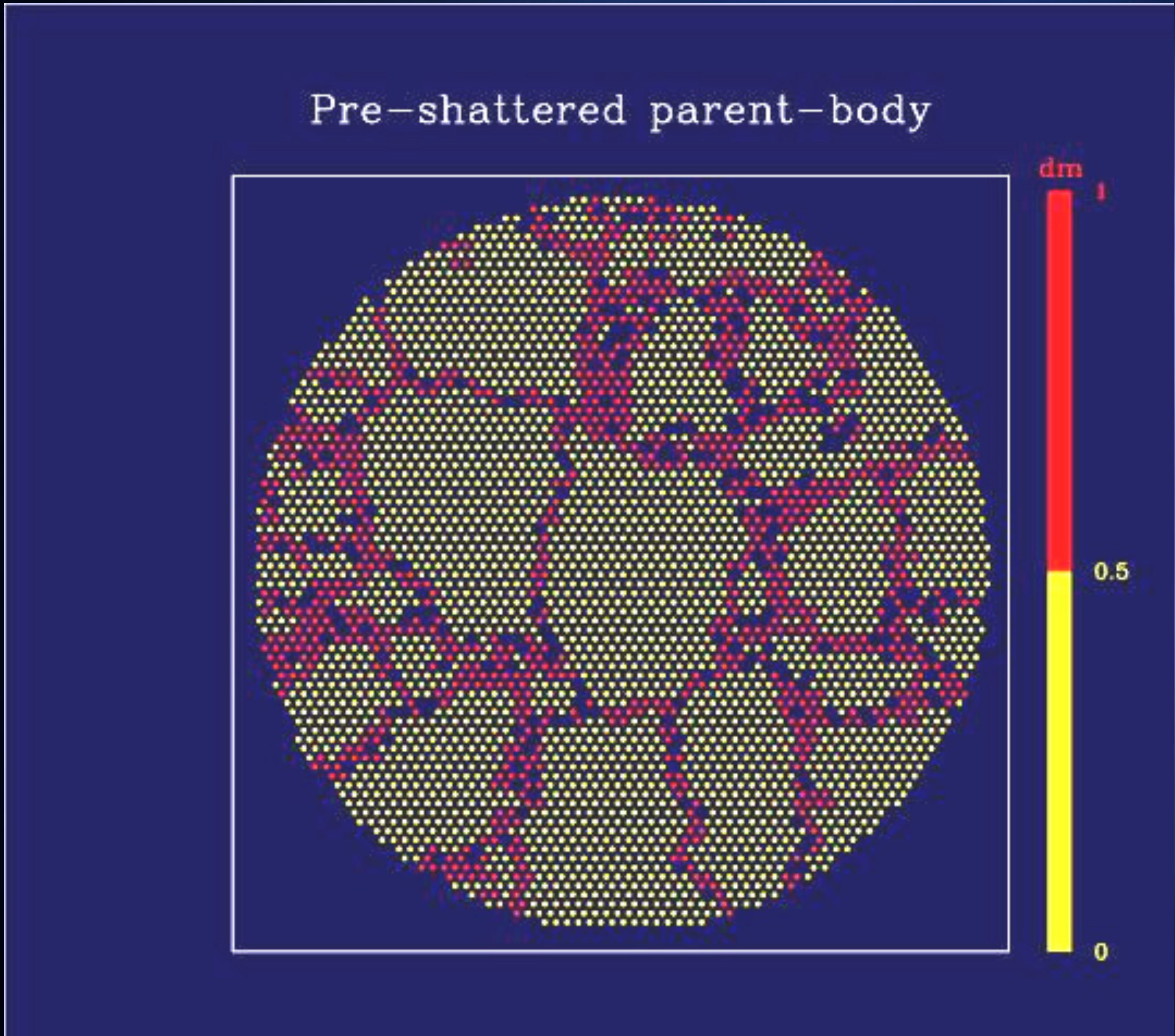
$$\partial i = \frac{\sqrt{1-e^2}}{n a} [\frac{\cos(\omega + f)}{1+e\cos f} V_w]$$

(a, e, i, w, f, n)=orbital elements of Parent body (family barycenter)

Requires to assume *a priori* ω and f of the parent body at the impact instant

Effect of the Parent Body's Internal Structure

- Previous simulations assumed monolithic parent bodies
- Large asteroids are likely to undergo shattering events before disruptive ones
- **What is the outcome of the disruption of a pre-shattered parent body?**



Yellow zones= fragments

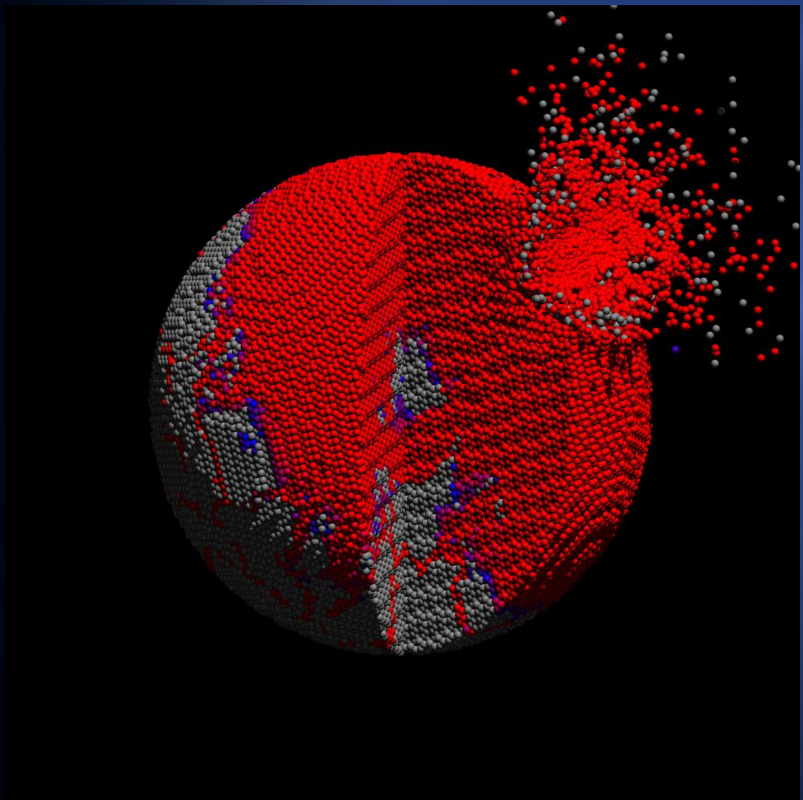
Red zones= dammage (separation between fragments)

Black points= void

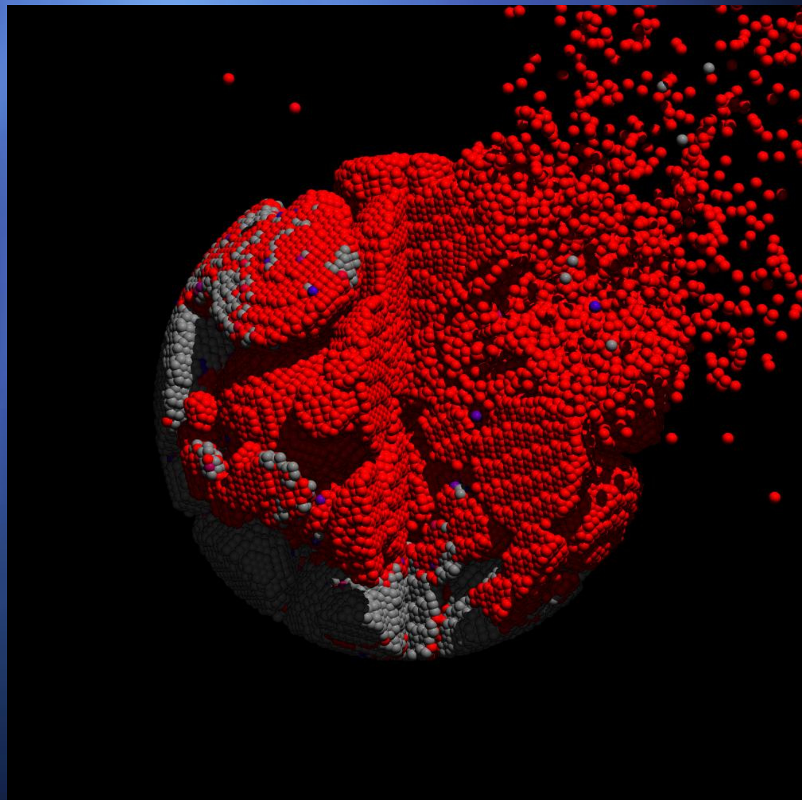
W. Benz & P. Michel

Two types of pre-shattered internal structures

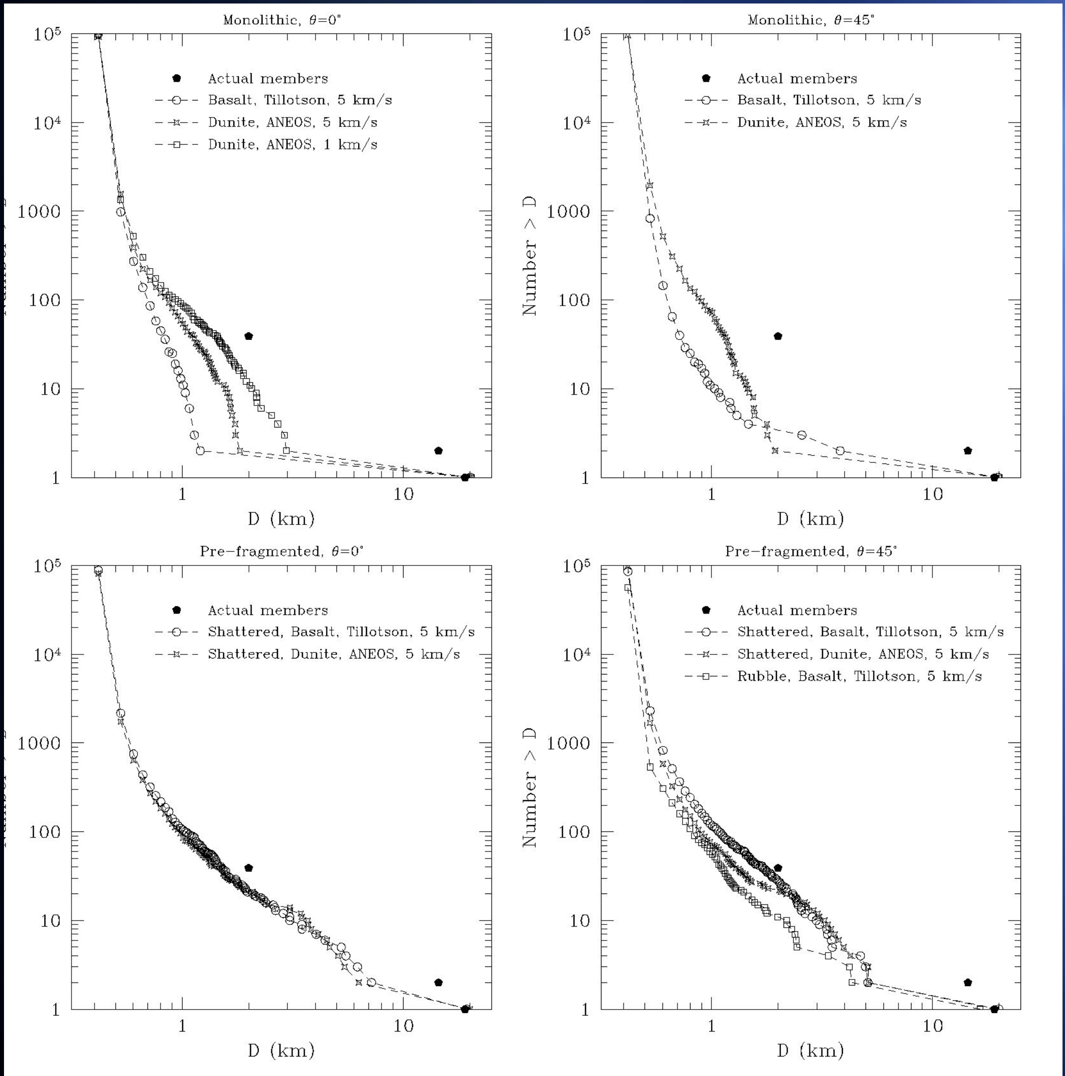
Presence of damage zones



Presence of damage zones + voids



Monolithic/Pre-shattered Parent Body



Monolithic Parent Body

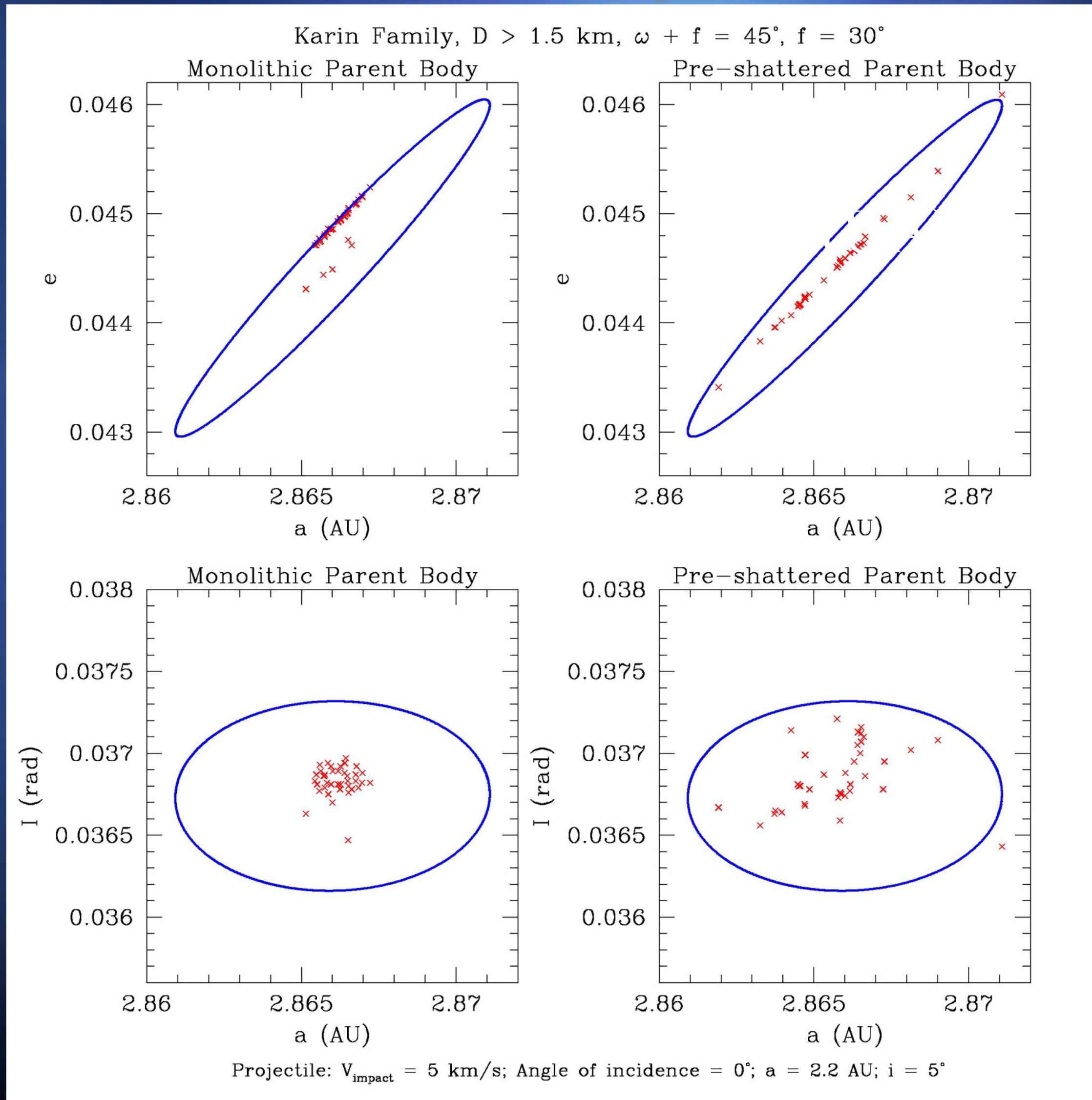
N>D vs D (km)

Pre-shattered Parent Body

Monolithic/Pre-shattered Parent Body

Ellipses = spreading of the real family

Crosses = simulation

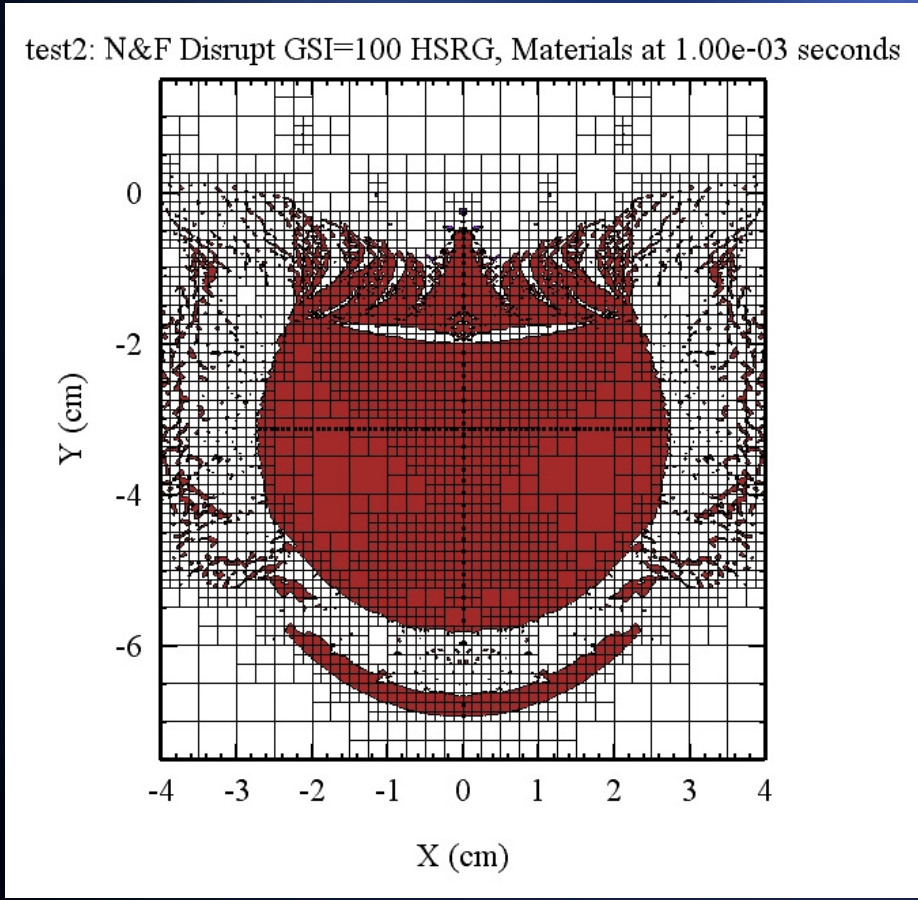


I (rad) vs a (UA)

So how can we improve the models?

- Compare, Compare, Compare
  - to real experiments
    - Large explosive field tests
    - Carefully controlled lab tests
  - to impact craters
    - (but what was the impactor?)
- Test, Test, Test
  - real materials
    - Crushability
    - Strength in different states

Experiments = first and crucial step for code validation



Example:

Simulation by an Hydrocode of the Impact experiment on basalt of Nakamura & Fujiwara in 1992

The core fragment is successfully reproduced

“Some” Current Shortcomings:

- Most strength models do not address all types of “strength”
- Codes often have “hidden features”
- Equations of state of some materials are still uncertain
- We do not often enough make comparisons to any experiments

Some more specific shortcomings

- We cannot model well enough to distinguish details for a particular crater
- *We cannot handle mixtures well*
- *Mixing rocks and atmospheres, and porosity makes for very difficult code calculations*
- *We don't do chemistry*

However, on the positive side

- In the gravity regime: we were able to reproduce qualitatively the main properties of asteroid families → reaccumulation processes may dominate and « accurate » modeling of fragmentation may not be so crucial (needs to be checked) for qualitative studies
- In the strength regime: the SPH hydrocode including a model of brittle failure has at least reproduced successfully some experiments on basalt targets
- Future challenge: characterizing the behavior of porous materials and differentiated objects, first in the strength regime (with confrontation to experiments) and then in the gravity regime (formation of C-type asteroid families, impact response of comets, KBOs …)

Arigato Gozai-Masu

Thank you for your attention

Merci beaucoup …