Towards a theoretical determination of the geographical distribution of meteoroids impacts on Earth

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Meteoroids 2016
6-10 June, Noordwijk (NL)

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Are impacts on Earth spatially (and/or temporarily) uniform?

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Where could be the next Chelyabinsk?

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Caution
Men at
work

30 Junio, 1908, ~ 7:14 a.m. LMT

15 February, 2013, ~ 9:20 a.m. LMT

Where did they happen?...

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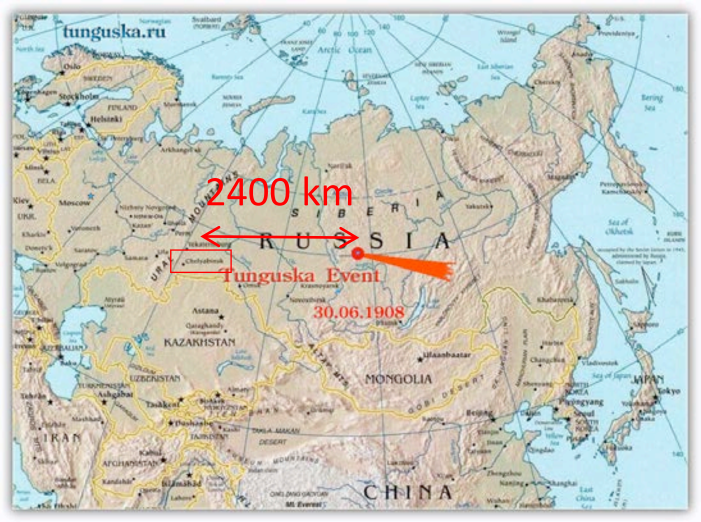
tunguska.ru
2400 km
Tunguska Event
Chelyabinsk
RUSSIA
SIBERIA
Arctic Ocean

Probability 2 independent events (similar type)
~2,400 km away (uniform distribution)

$p \sim 0.8\%$



Probability of having event pairs separated by more than 2,400 km after N impacts is

$P = (1-p)^N$

Expected number of events before having at least 1 spatial coincidence:

$\langle N \rangle = 1/p \sim 100$

Assuming a mean periodicity of ~40 years for Chelyabinsk-like events we need to wait ~40,000 years to see similar spatial coincidence

brown+2016

Are impacts uniformly distributed on Earth's surface?

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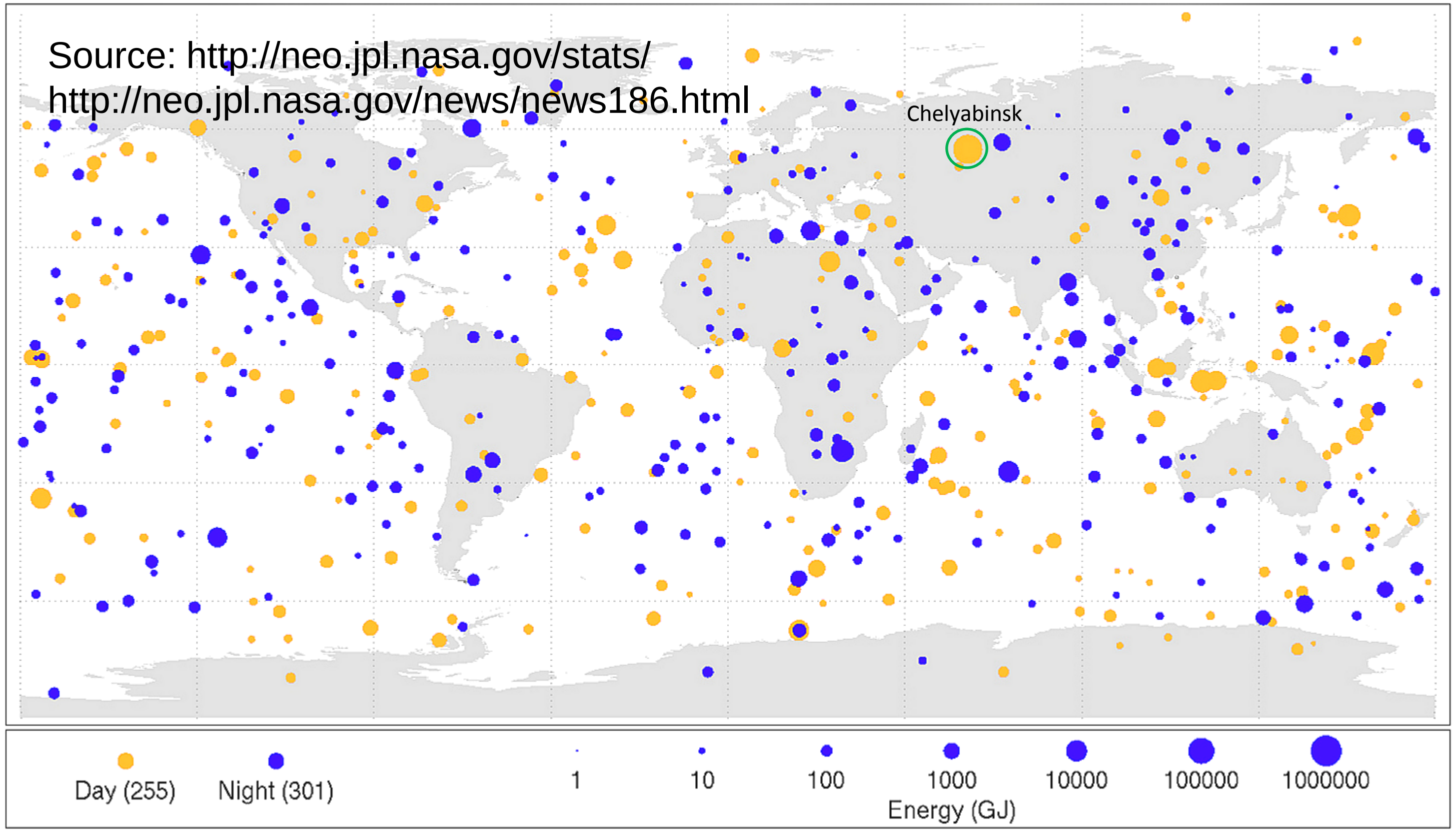
Impacts observed distribution

Bolide events 1994-2013

(Small asteroids that disintegrated in the Earth's atmosphere)



Biases & Caveats:

- Large fireballs
- Low rate events

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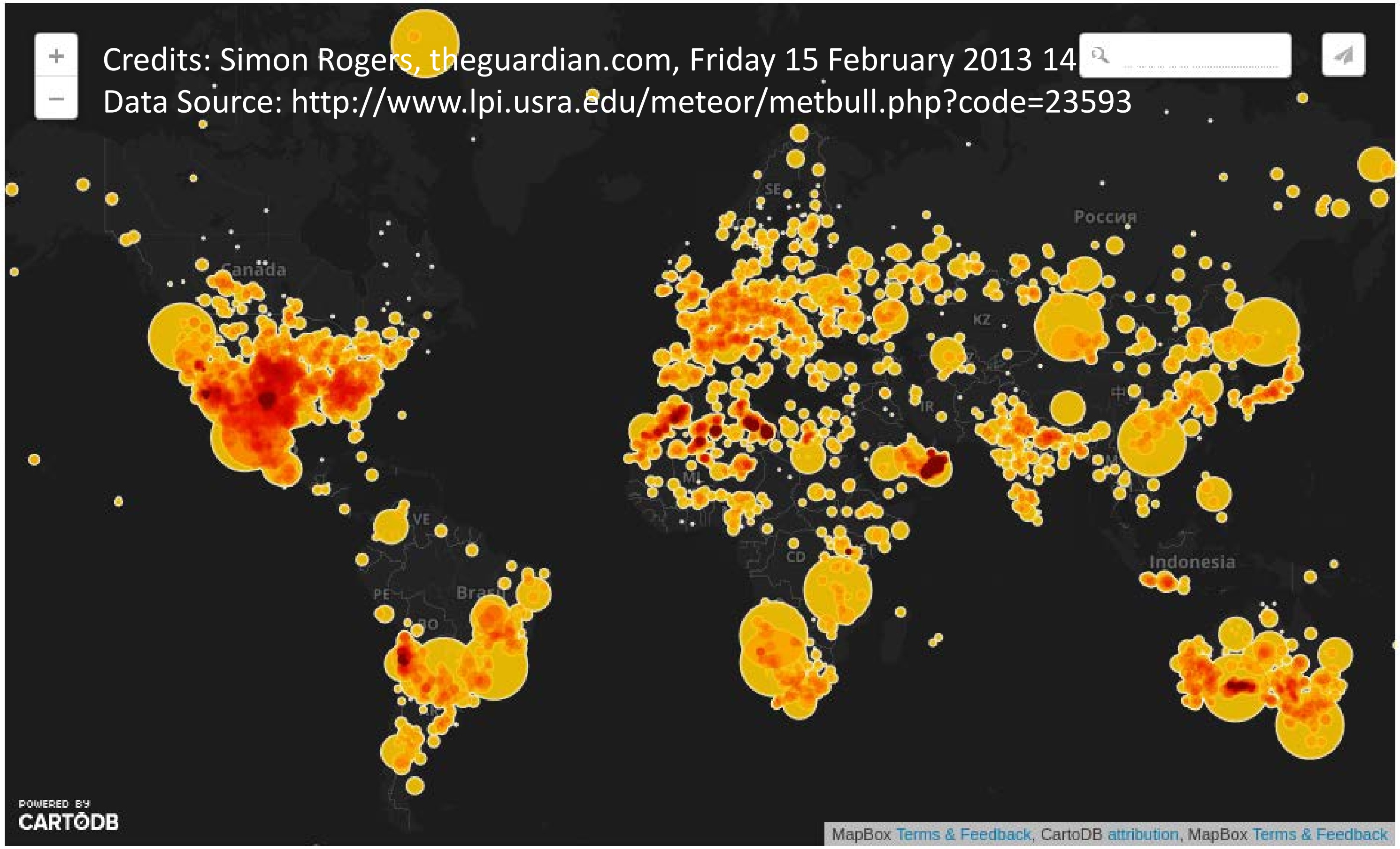
Impacts observed distribution

Meteor & Meteorites

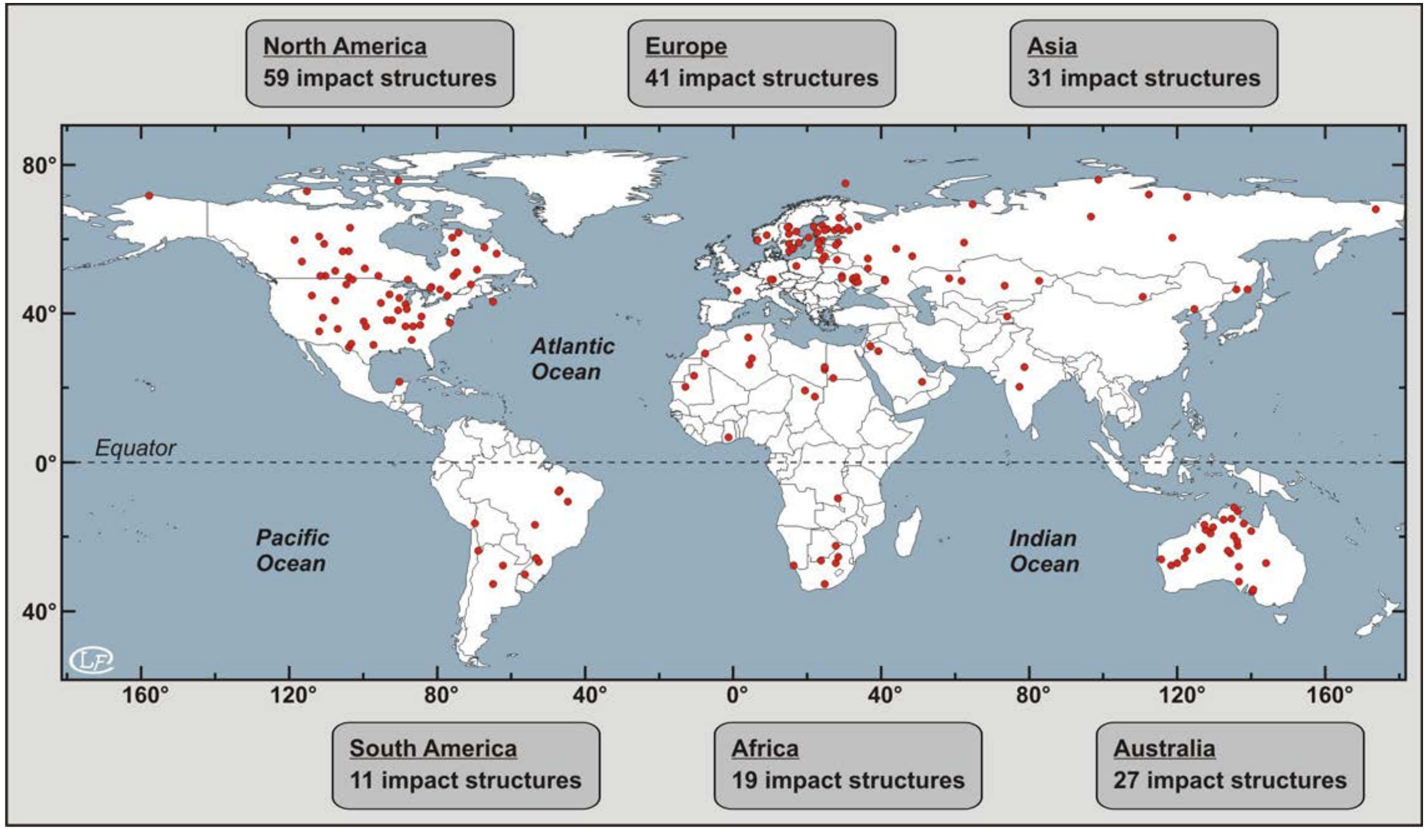


Biases & Caveats:

- Continents
- Populated & Developed areas
- Mostly nocturnal events
- Large meteoroids

Impacts observed distribution

Large Craters



Credits: Ludovic Ferriere

Data Source: http://www.meteorimpactonearth.com/meteorite.html

Biases & Caveats:

- Very large impacts
- Continental areas
- Geological conditions
- Low weathering areas

Can we determine theoretically the distribution of impacts?

(regardless impactor size)

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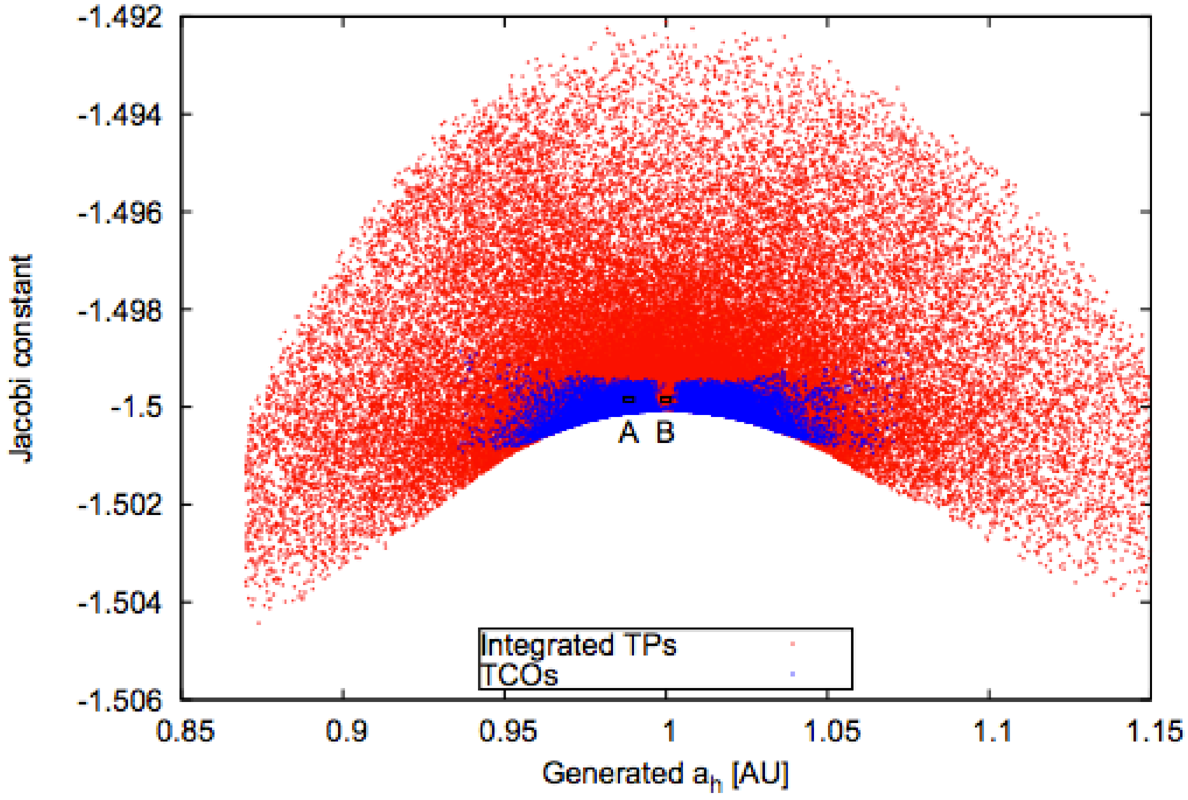
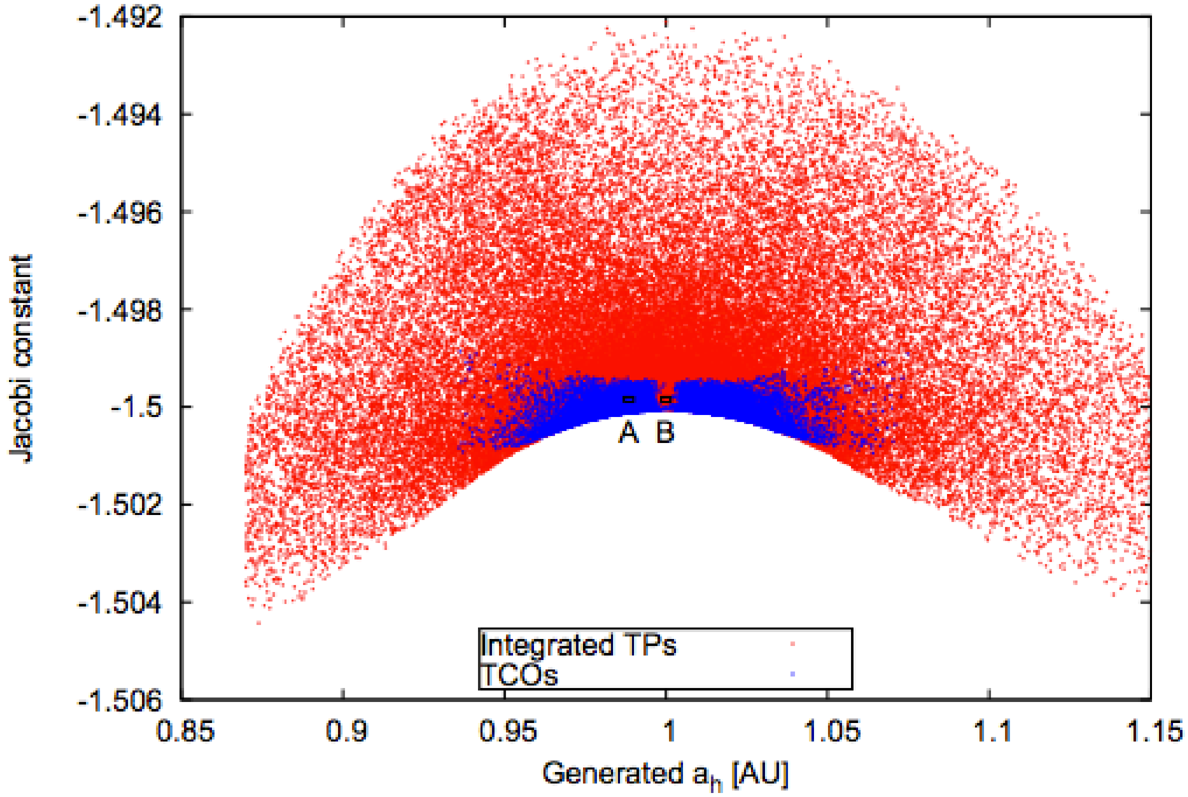
Test Particle Integration



Granvik, Vaubaillon & Jedicke (2012)

Bulk properties of the generated test particles and captured objects	
$N_{\rm tot}$	$9,346,396,100$
$N_{\rm int}$	$10,000,000$
Nominal model	
$N_{\rm TCF,short}$	$209,917$
$N_{\rm TCF,long}$	$23,771$
$N_{\rm TCO}$	$18,096$
$\bar{L}_{\rm TC}$	(62.2 ± 1.3) d
$\bar{\tau}_{\rm TC}$	(0.383 ± 0.059) rev
$\bar{L}_{\rm TCO}$	(286 ± 18) d
$\bar{\tau}_{\rm TCO}$	(2.88 ± 0.82) rev
Fraction of TCOs with	
$\tau_{\rm TCO} > 2.88$ rev	11%
$\tau_{\rm TCO} > 5$ rev	3.4%
$\tau_{\rm TCO} > 50$ rev	0.1%
$_{\rm TCO} > 271$ d	26%
$_{\rm TCO} > 365$ d	15%
$_{\rm TCO} > 3650$ d	0.1%
Barycentric model	
$N_{\rm TCF,short}$	$320,748$
$N_{\rm TCF,long}$	$34,843$
$N_{\rm TCO}$	$4,494$
$\bar{L}_{\rm TC}$	(53.76 ± 0.11) d
$\bar{\tau}_{\rm TC}$	(0.21751 ± 0.00037) rev
$\bar{L}_{\rm TCO}$	(334.6 ± 1.7) d
$\bar{\tau}_{\rm TCO}$	(1.1280 ± 0.0019) rev

Test Particle Integration

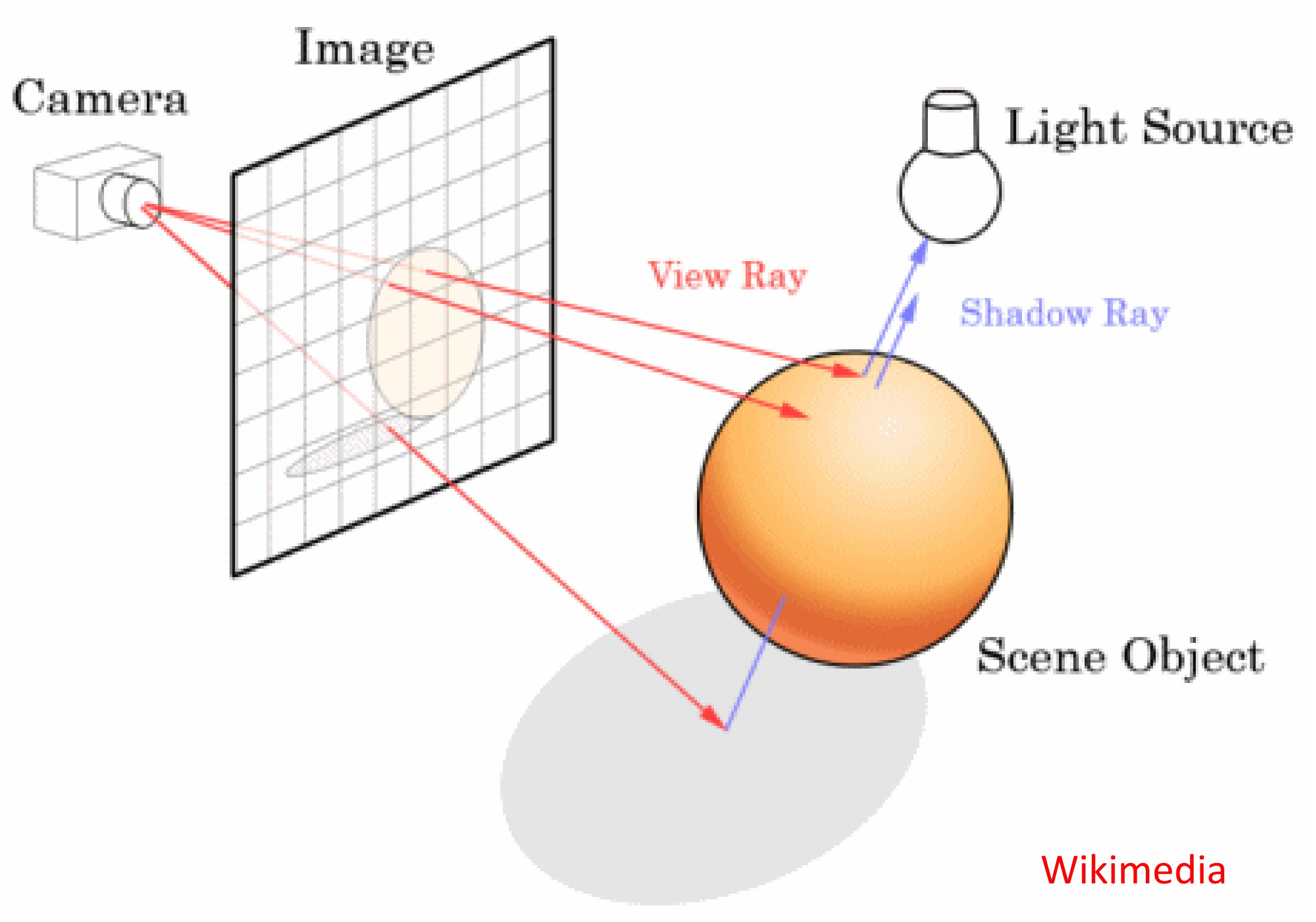


Granvik, Vaubaillon & Jedicke (2012)

Caveats:

- Low efficiency (many TPs a few impacts)
- Partial covering of the configuration space.
- Sensitive to numerical integration precision

Ray Tracing Algorithm

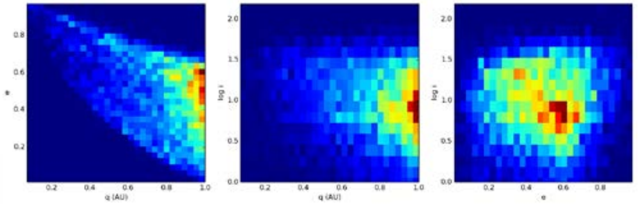


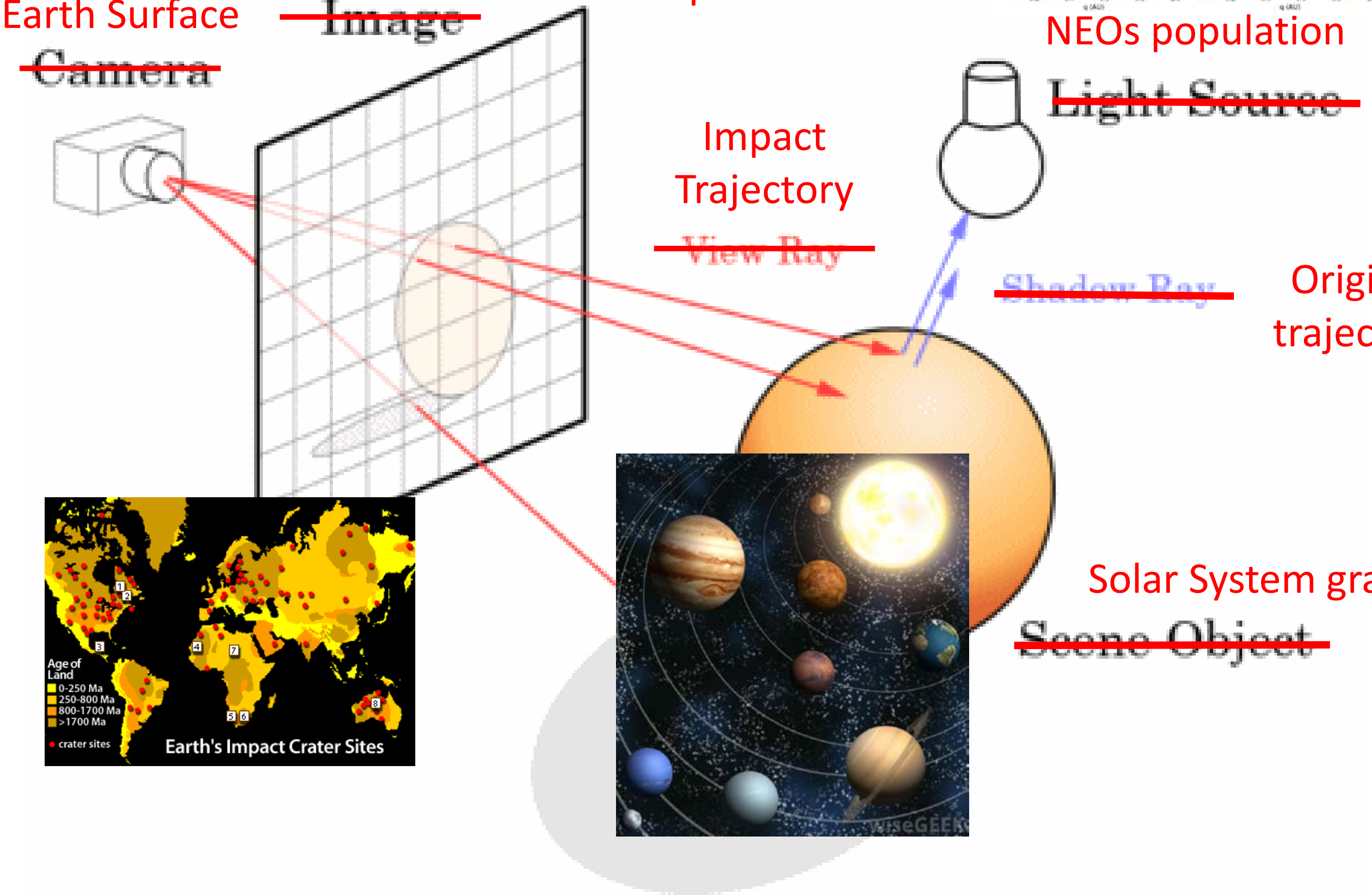
Wikimedia

Ray Tracing Algorithm

Credit: Rikk the Gaijin

Gravitational Ray Tracing (GRT)





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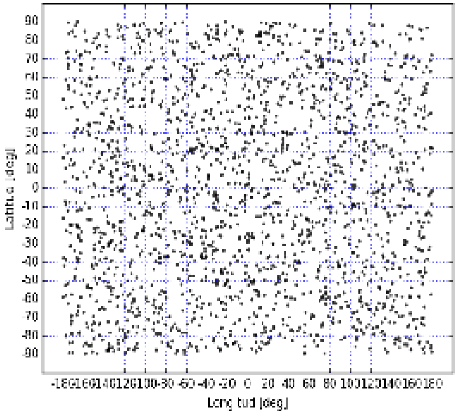
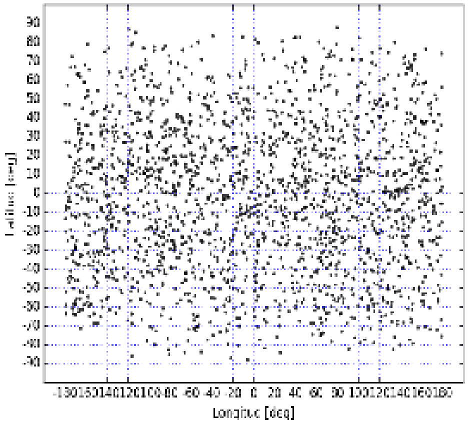
GRT: initial conditions

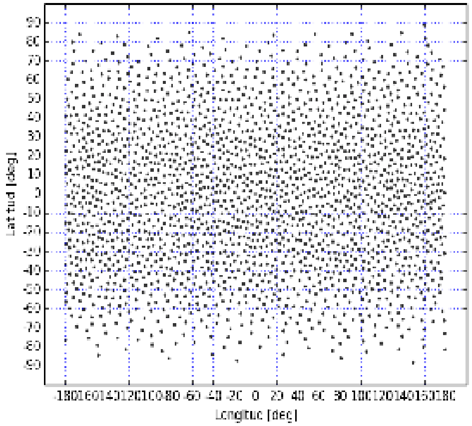
Uniform Distribution

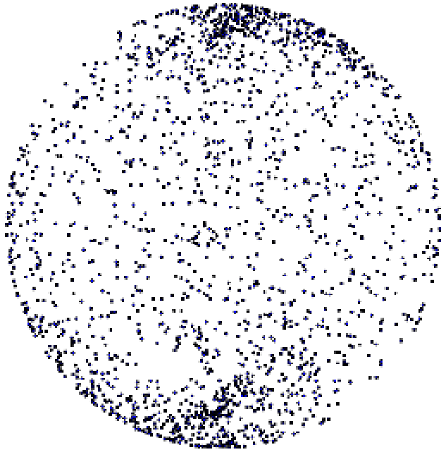
Blue Noise Distribution

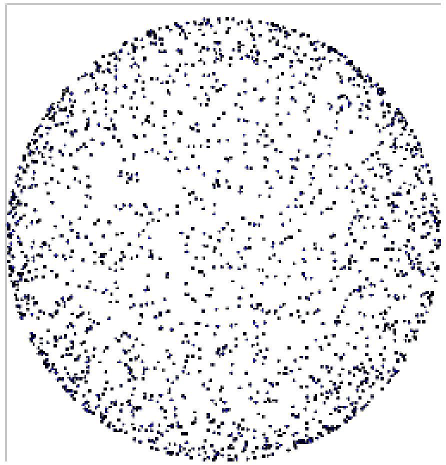
Sampling the Earth Surface

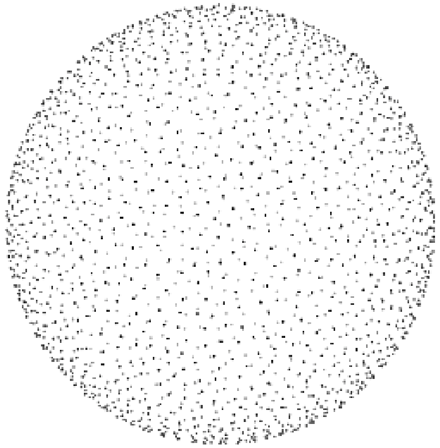






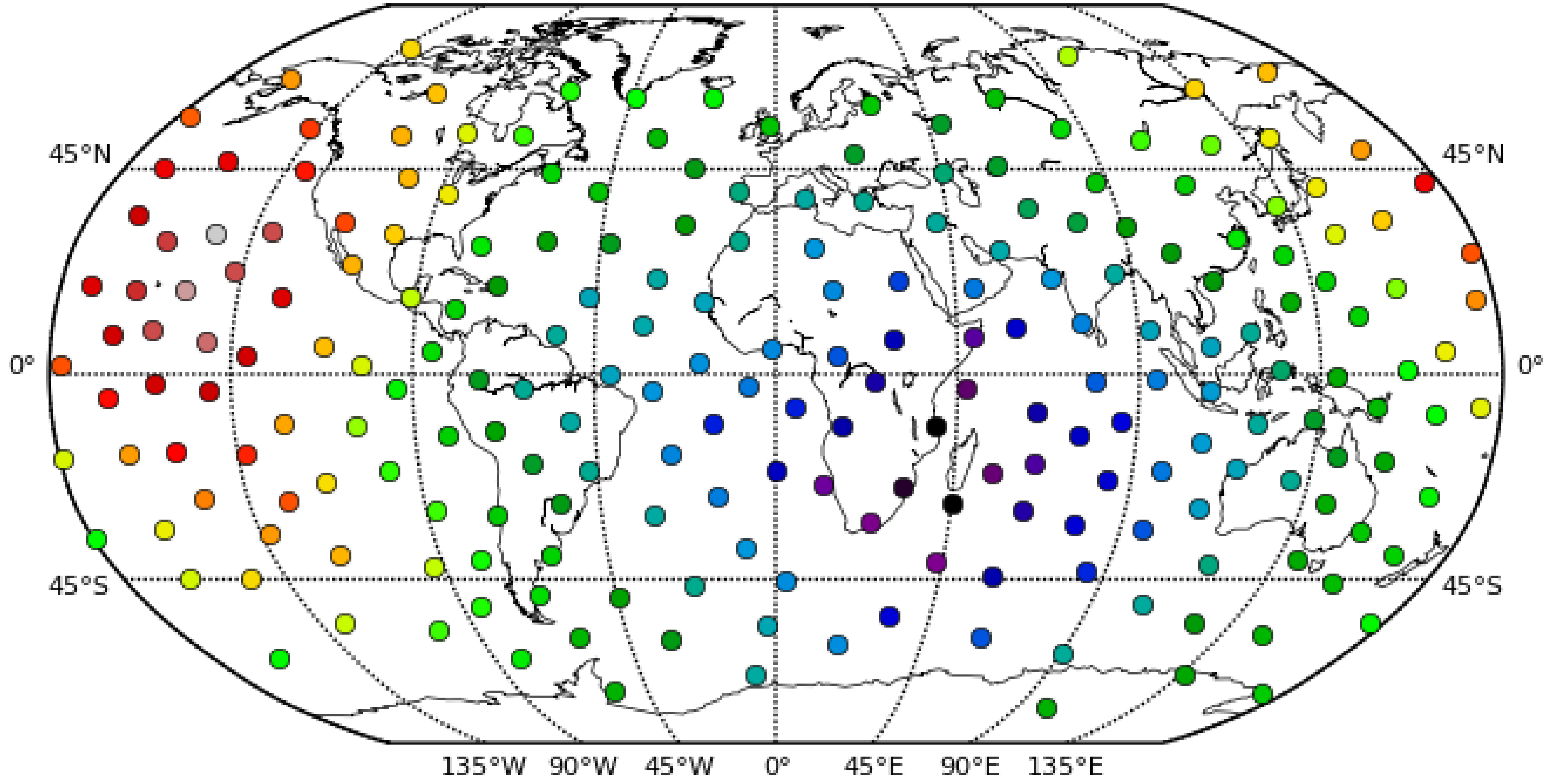






GRT: Initial conditions

Distribution of 223 geographical sites with minimum separation of 10 degrees



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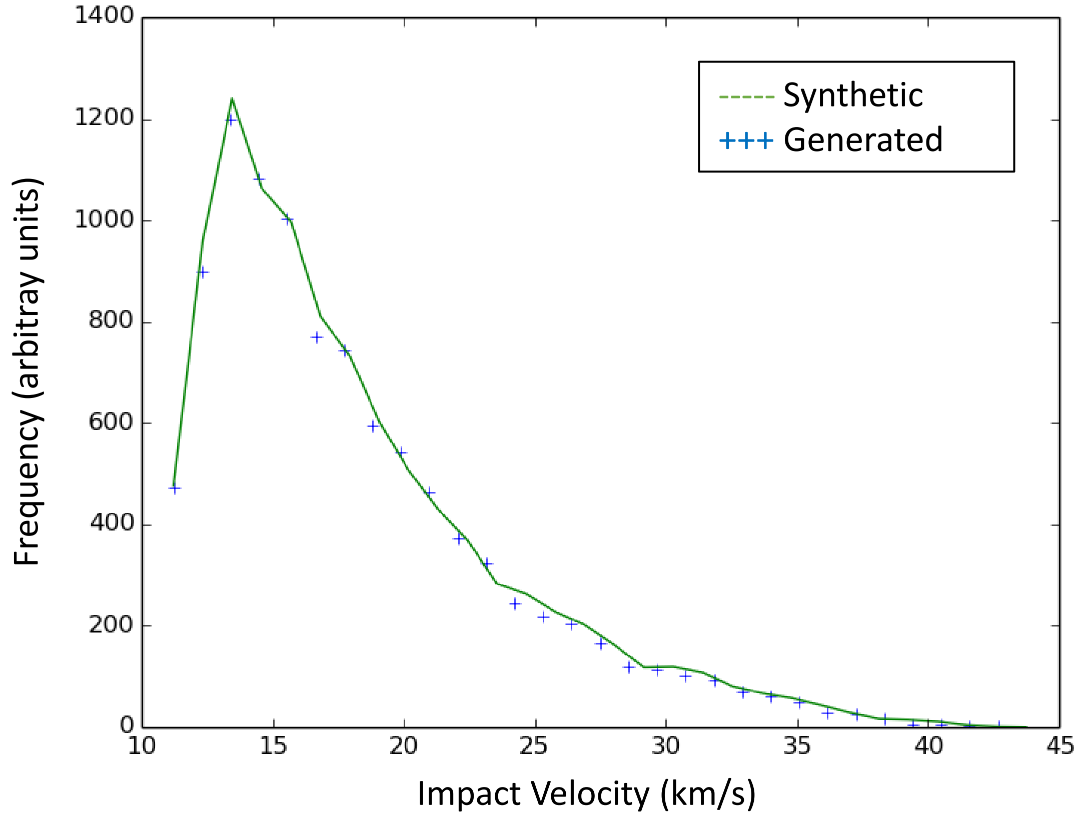
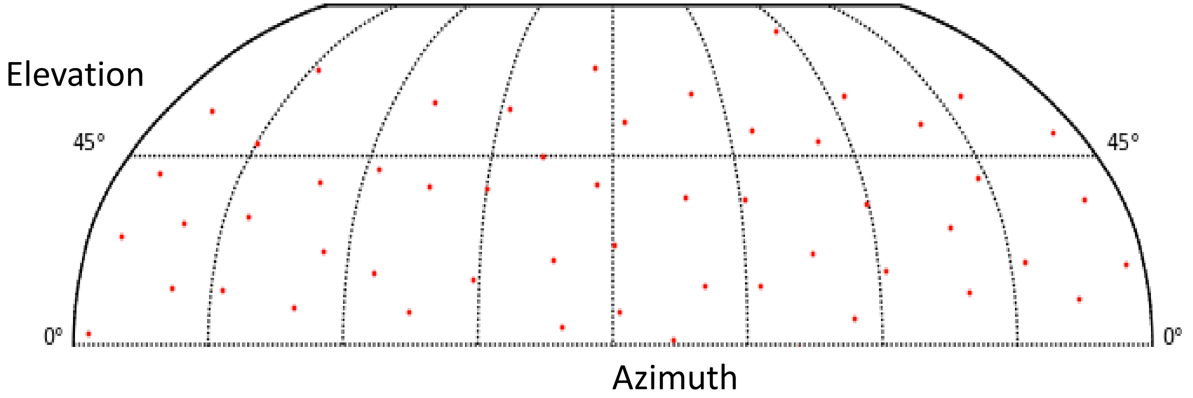
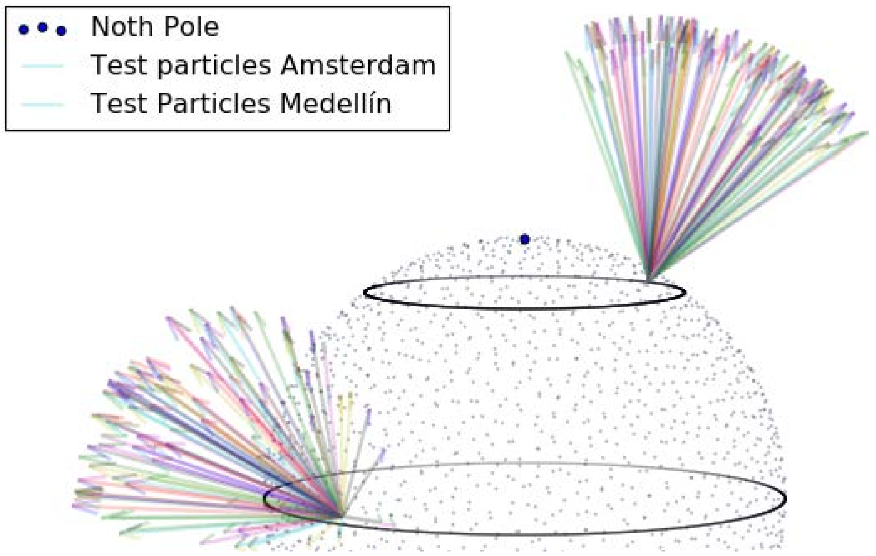
GRT: Initial conditions







We generate local configuration: Azimuth (A), elevation (a), impact velocity (v)

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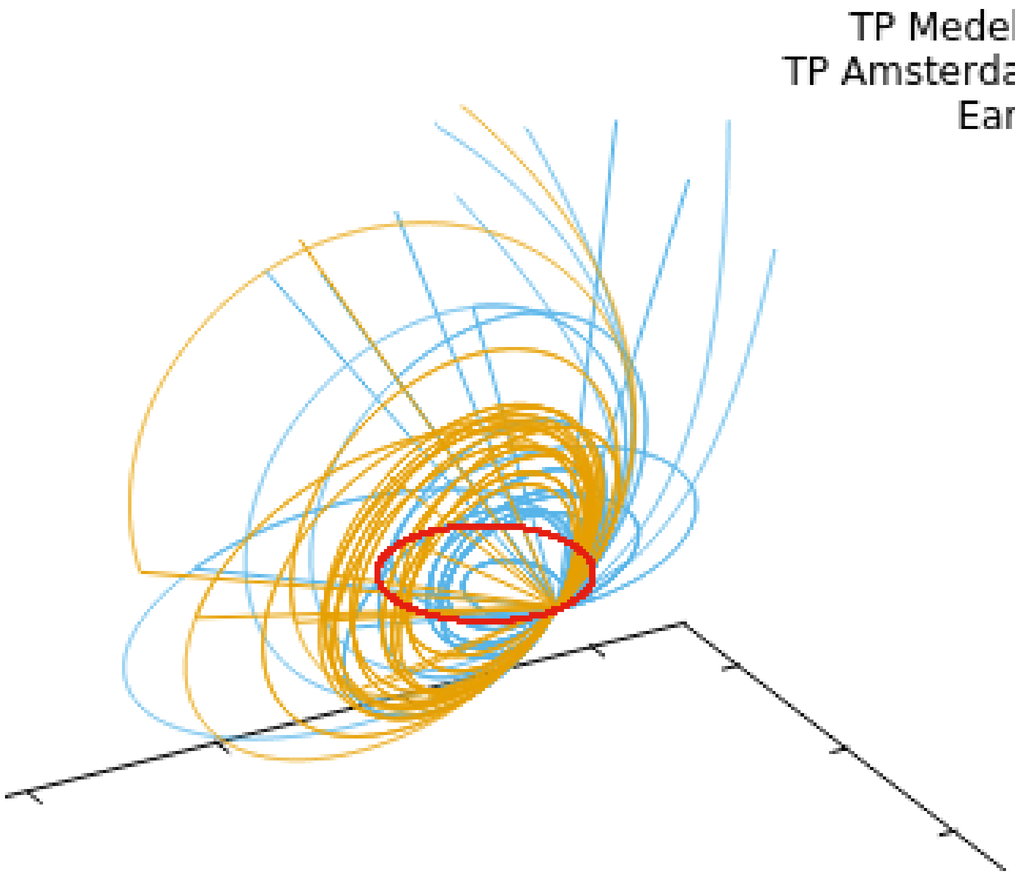
GRT: Ray trajectories

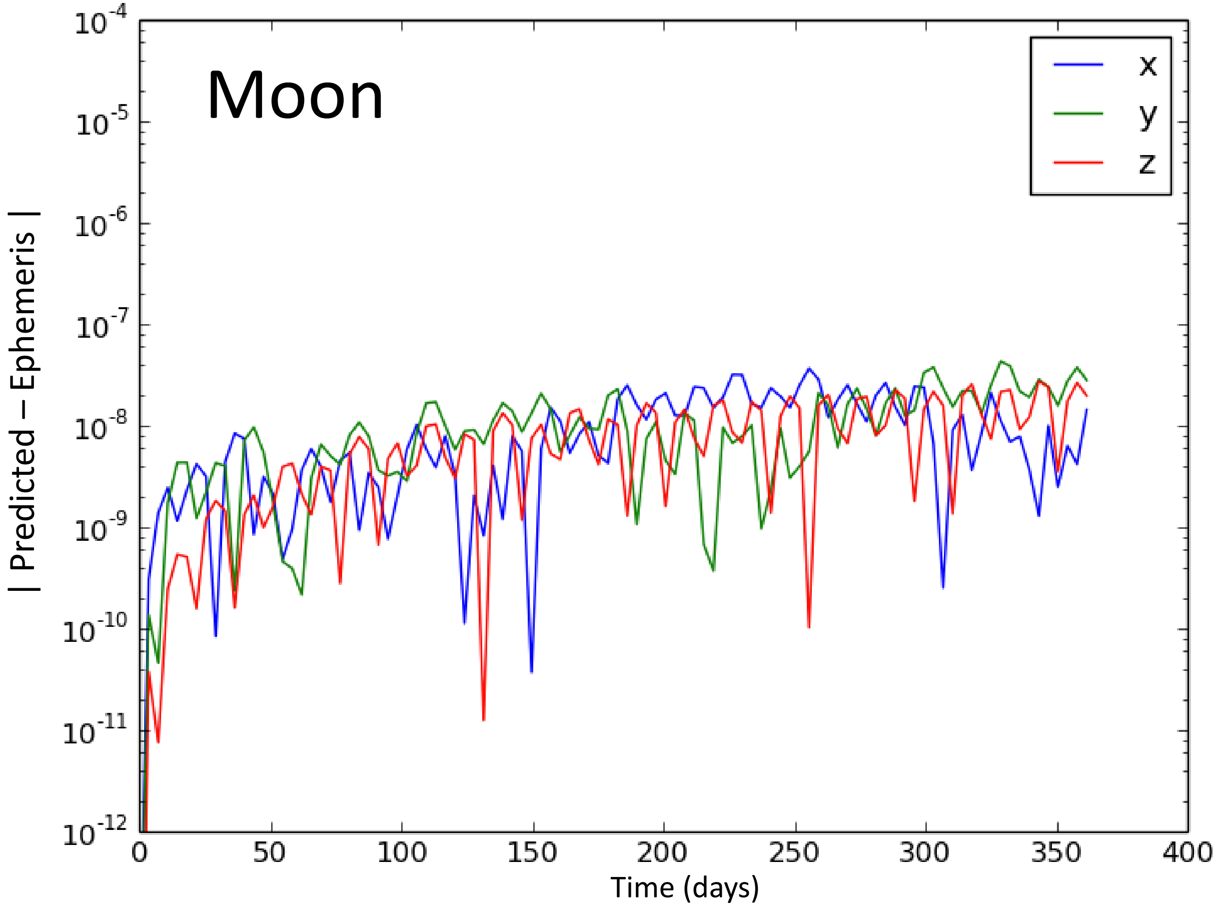
Integration convert local configuration (A,a,v) to orbital configuration (q,e,i)



Integration characteristics:

- Gragg-Burlish-Stoer Method
- Time of integration:
  Max (2 years, 2 Orbital Period)
- All 8 planets + Moon
- Planetary positions:
  JPL Ephemeris DE430

GRT: Ray trajectories

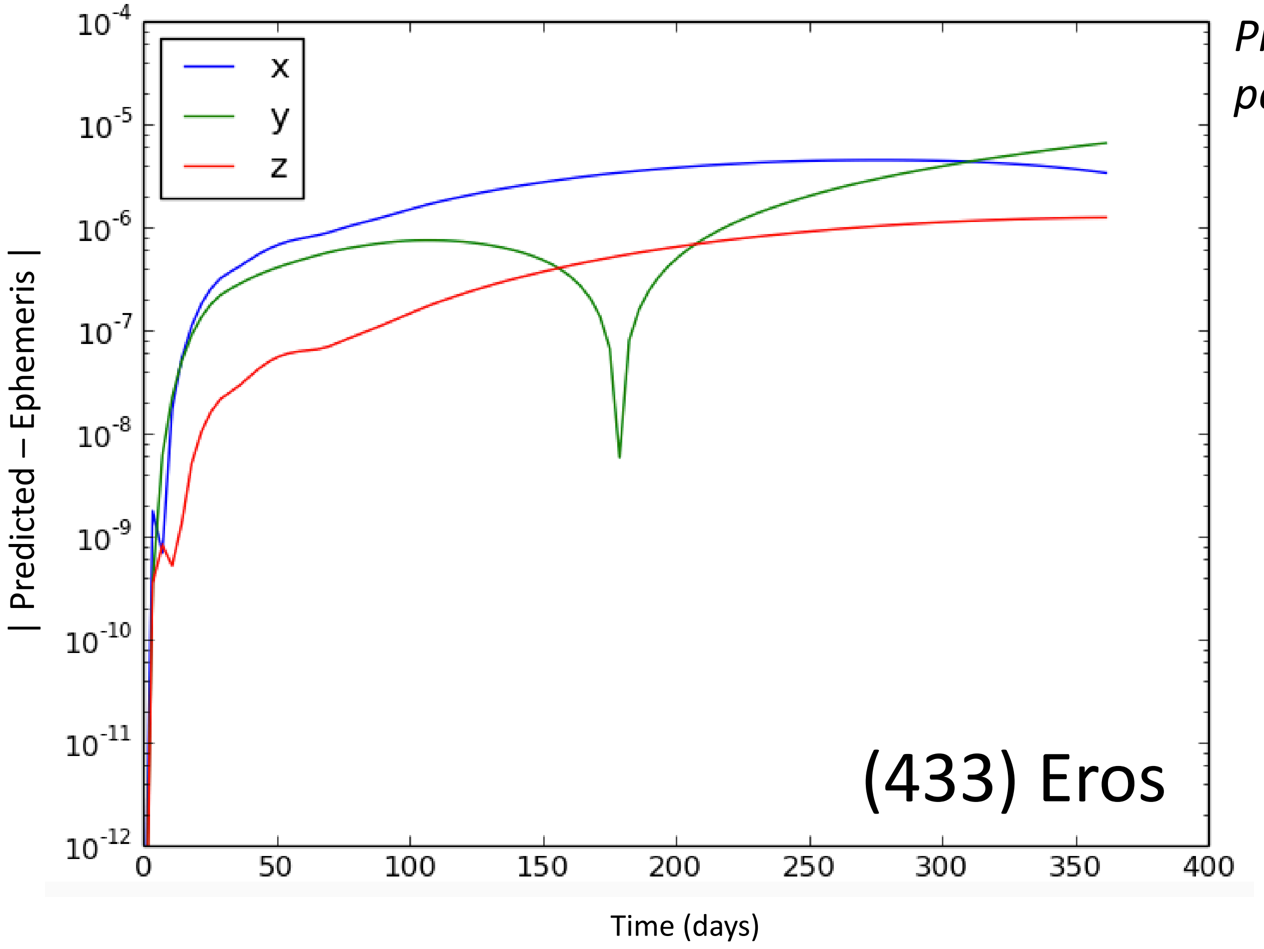


Precission test with the moon as a test particle

Integration characteristics:

- Gragg-Burlish-Stoer Method
- Time of integration:
  Max (2 years, 2 Orbital Period)
- All 8 planets + Moon
- Planetary positions:
  JPL Ephemeris DE430

GRT: Ray trajectories

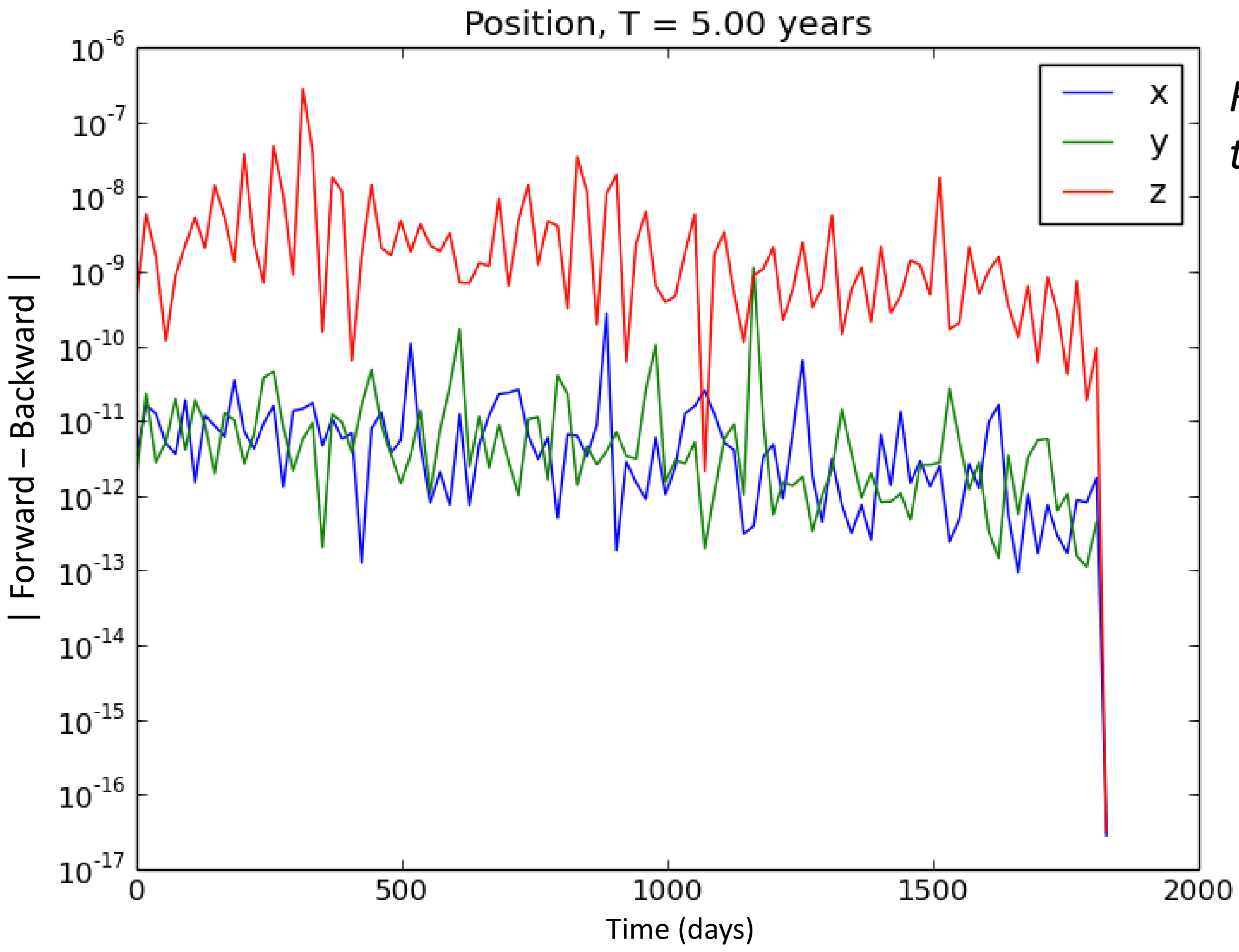


Precission test with EROS as a test particle

Integration characteristics:

- Gragg-Burlish-Stoer Method
- Time of integration:
  Max (2 years, 2 Orbital Period)
- All 8 planets + Moon
- Planetary positions:
  JPL Ephemeris DE430

GRT: Ray trajectories



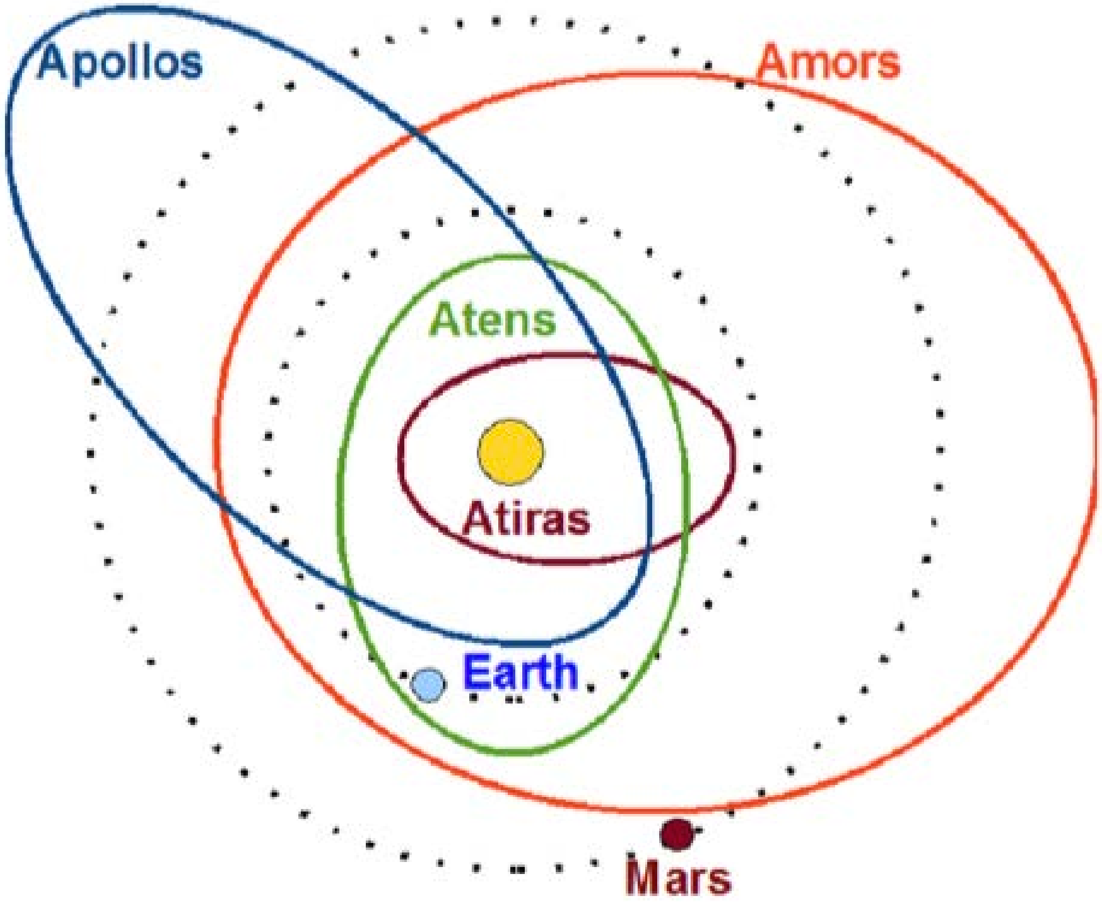
Forward and backword integration test

Integration characteristics:

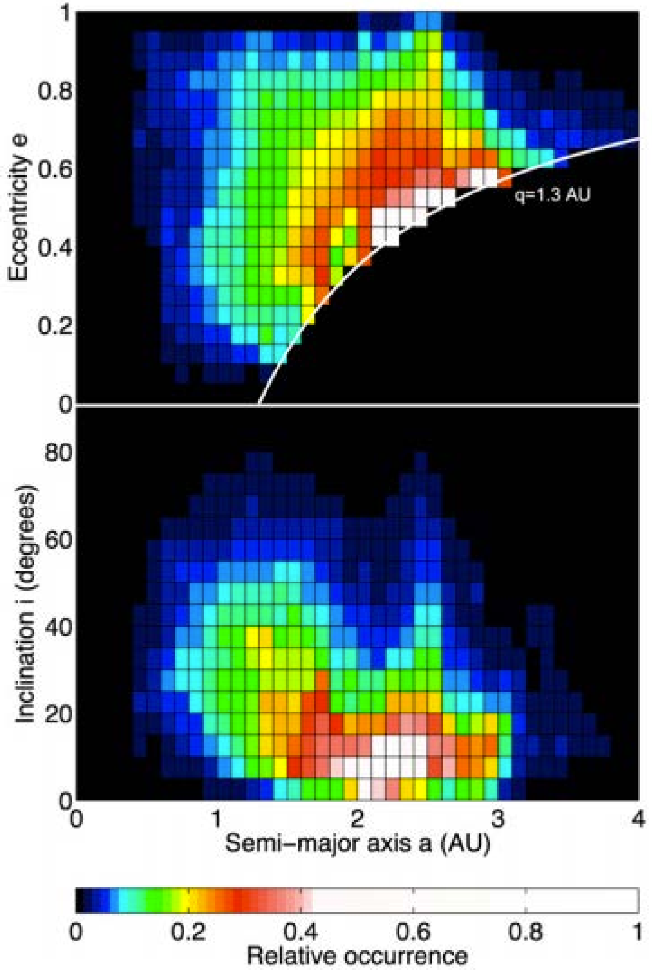
- Gragg-Burlish-Stoer Method
- Time of integration:
  Max (2 years, 2 Orbital Period)
- All 8 planets + Moon
- Planetary positions:
  JPL Ephemeris DE430

GRT: Source Intensity (aka. NEOs distribution)

Greenstreet (2007)

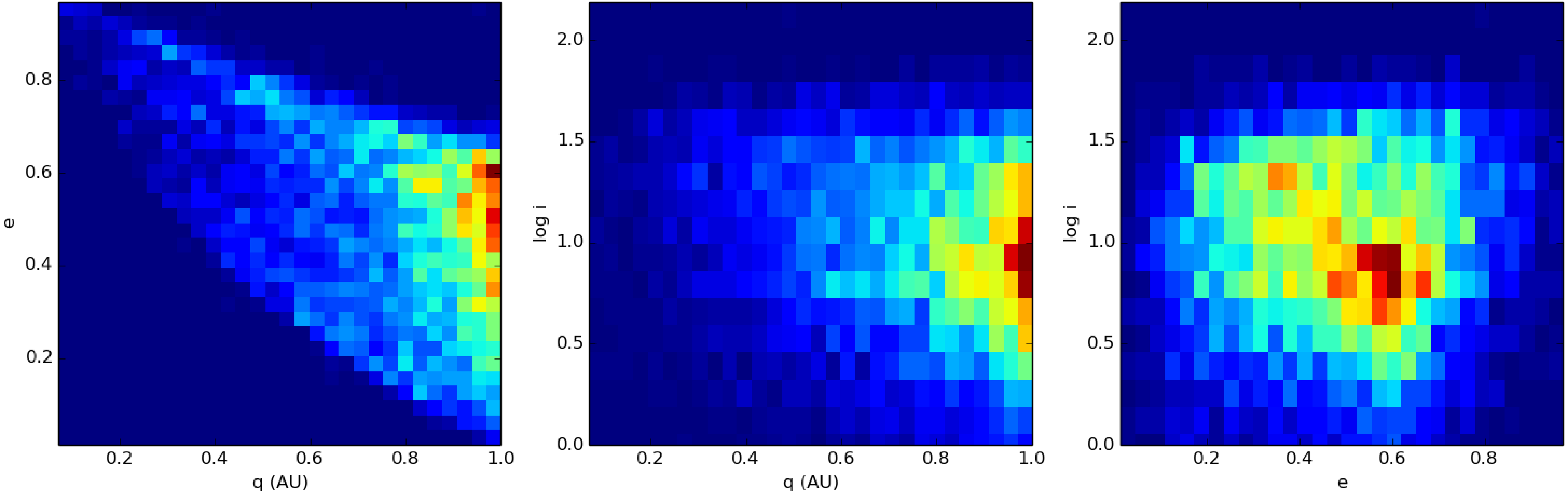


Le Feuvre & Wieczorek (2008)



GRT: Source Intensity (aka. NEOs distribution)

Marginal distributions (14291 NEOs)



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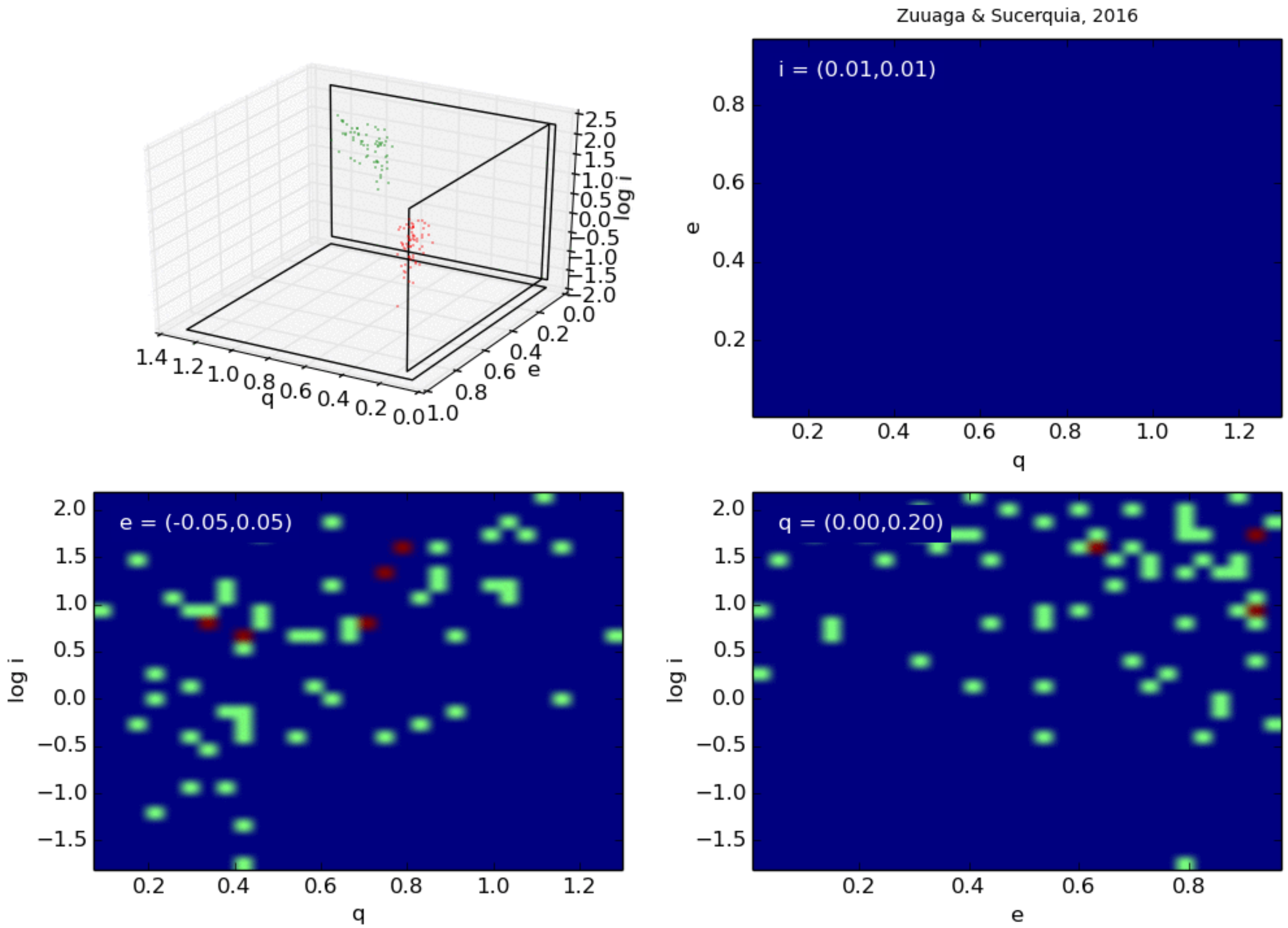
GRT: Source Intensity (aka. NEOs distribution)

"3D" Distribution



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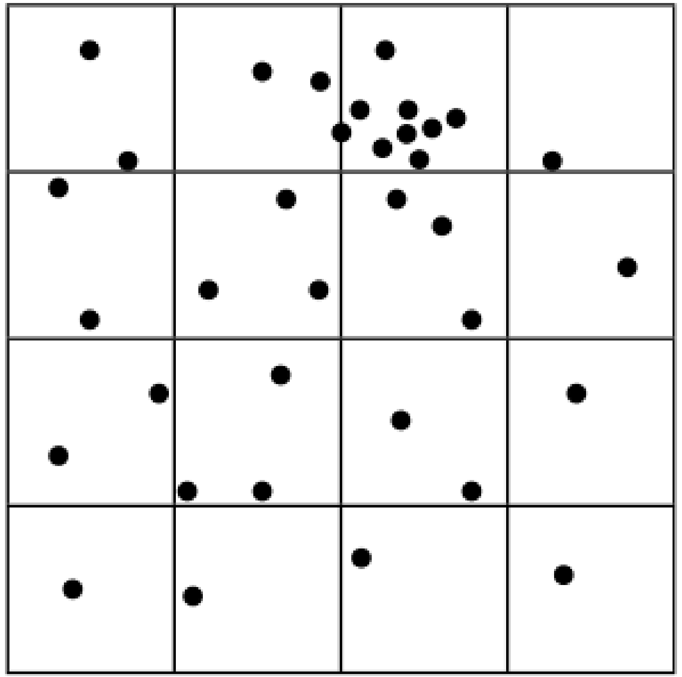
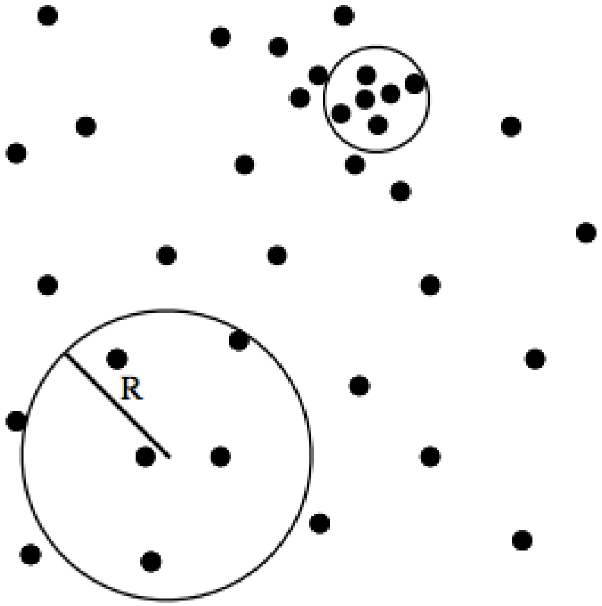
GRT: Source Intensity (aka. NEOs distribution)

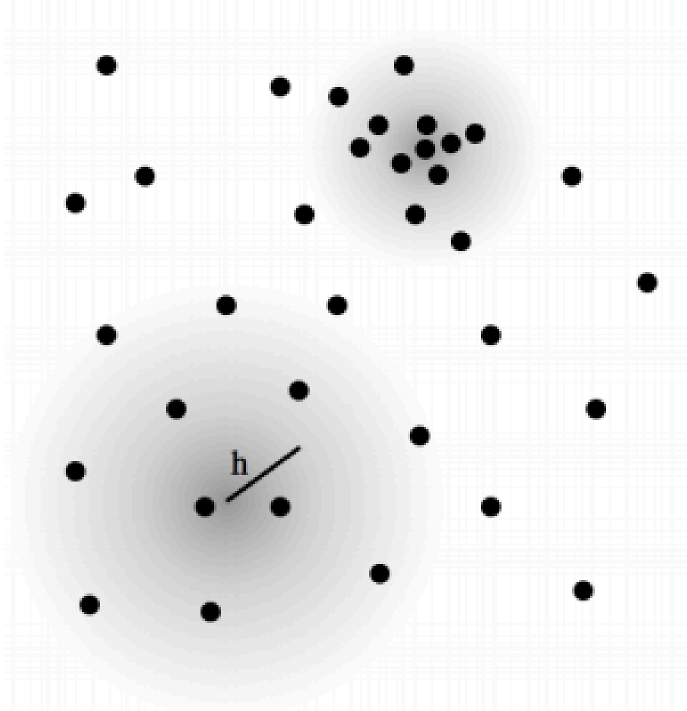
In particle-mesh



Local volume

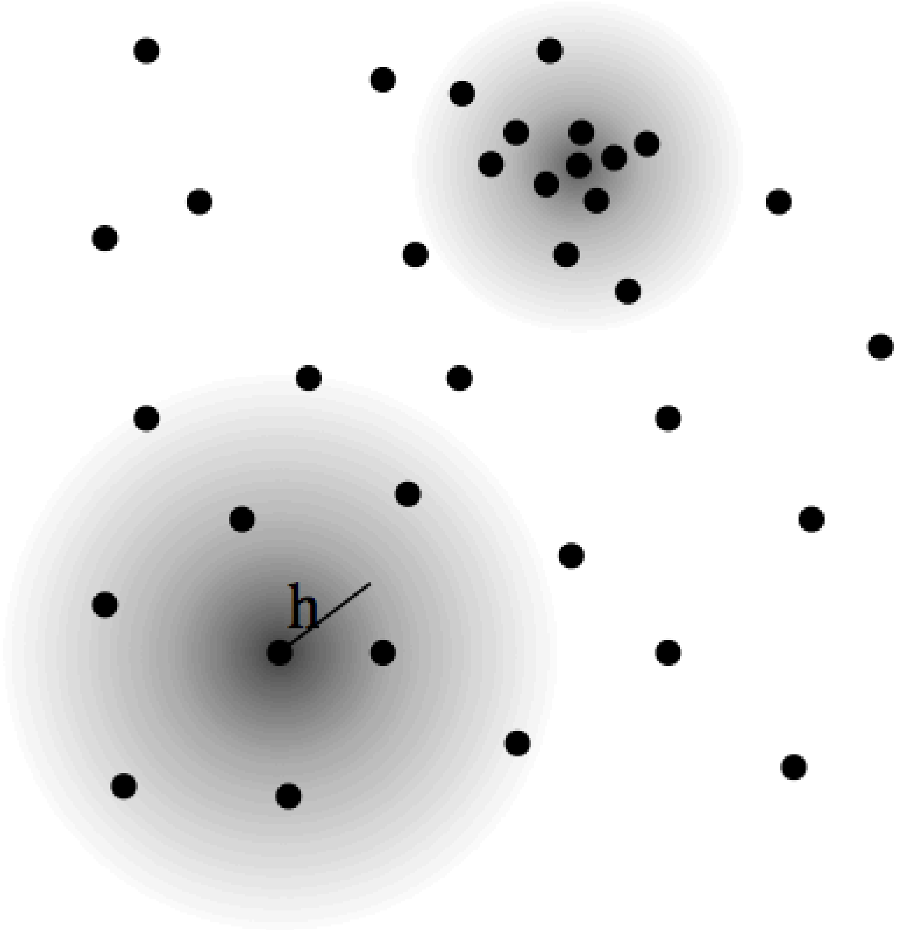


Weighted Sum



Price, 2012

GRT: Source Intensity (aka. NEOs distribution)



Kernel-weighted sum:

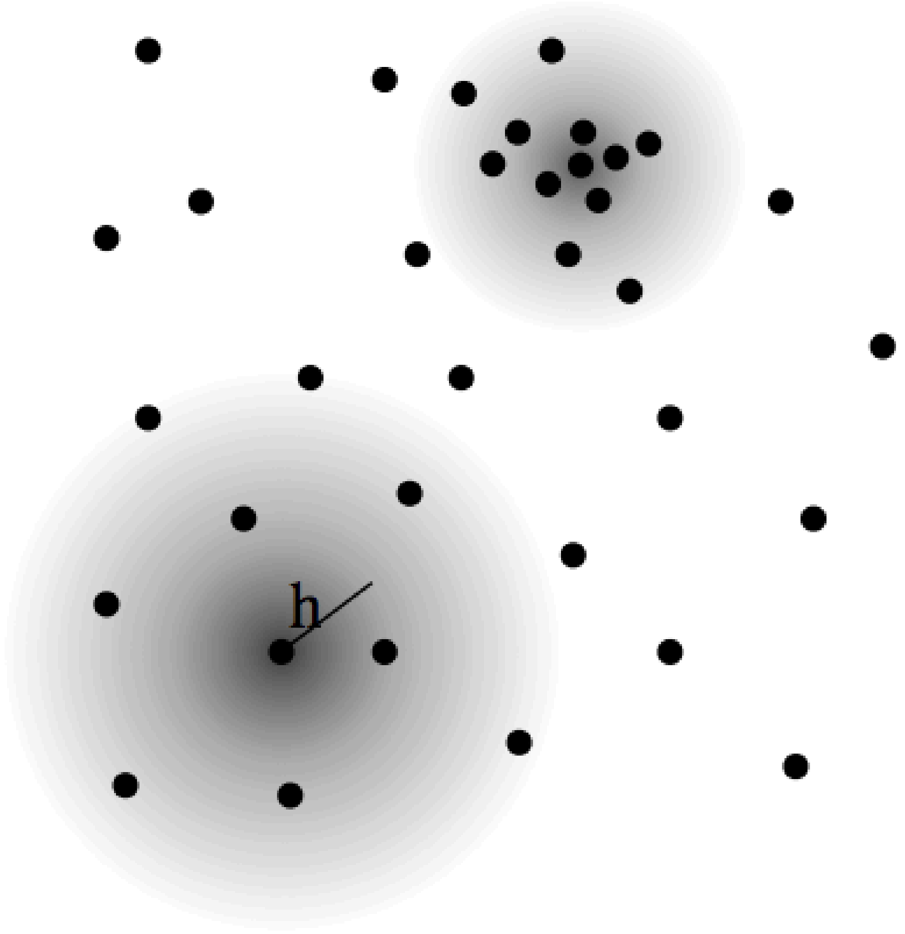
SPH

$$\rho(\mathbf{r}) = \sum_{j=1}^{N} m_j W(|\mathbf{r} - \mathbf{r}_j|, h)$$

$$w(q) = \sigma \begin{cases} \frac{1}{4}(2-q)^3 - (1-q)^3, & 0 \leq q < 1; \\ \frac{1}{4}(2-q)^3, & 1 \leq q < 2; \\ 0. & q \geq 2, \end{cases}$$

Price, 2012

GRT: Source Intensity (aka. NEOs distribution)



For distances in the q-e-i space we use a **simplified Drummond metric** (Drummond, 1981):

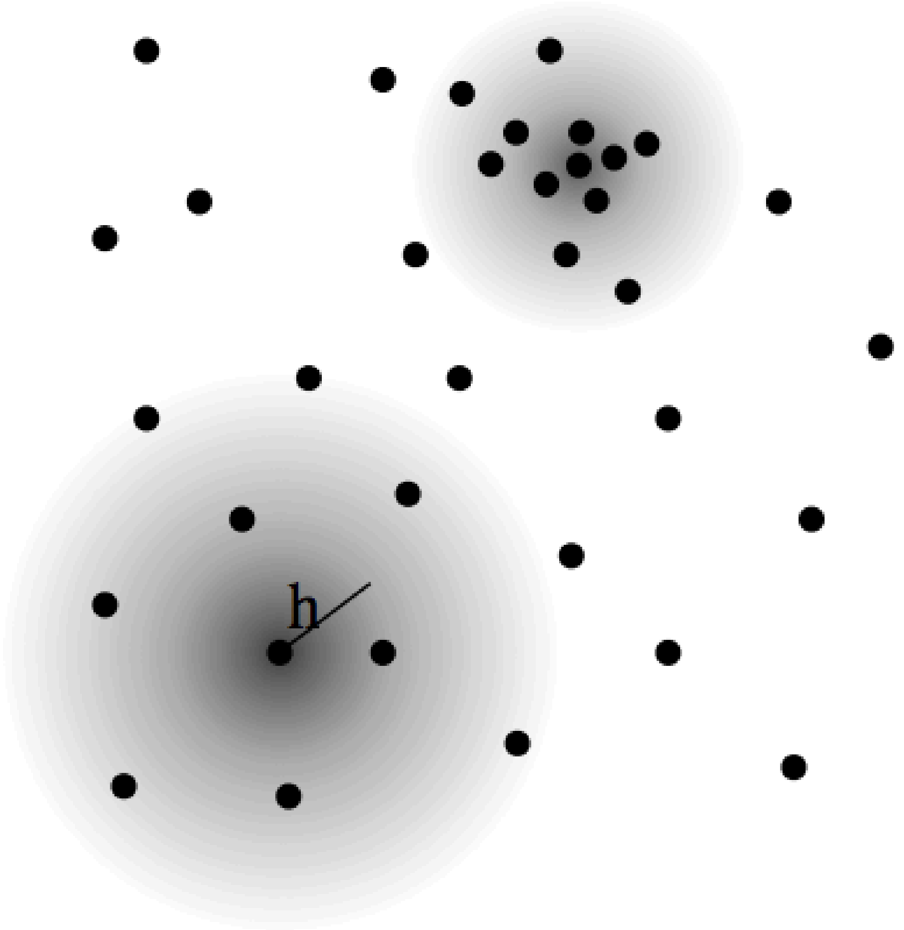
$$D_D^2 \equiv |\vec{x}-\vec{x}_i|^2 = \left(\frac{e-e_i}{e+e_i}\right)^2 + \left(\frac{q-q_i}{q+q_i}\right)^2 + \left(\frac{i-i_i}{180^\circ}\right)^2$$

Source intensity (number density) around a given "ray" footprint **x**:(q,e,i) is given by an SPH-like formula (Price ,2012):

$$n(\vec{x}) = \sum_i W(|\vec{x}-\vec{x}_i|, h)$$

After experiencing with different scale lengths, we find that $h = 0.1$ better fits our purposes.

GRT: Source Intensity (aka. NEOs distribution)



Probability of having an impact with parameters A, a, v which is associated with a ray terminal configuration **x** = (q,e,i) is given by:

$$P(A_j, a_j, v_j) \sim n(\vec{x}_j)$$

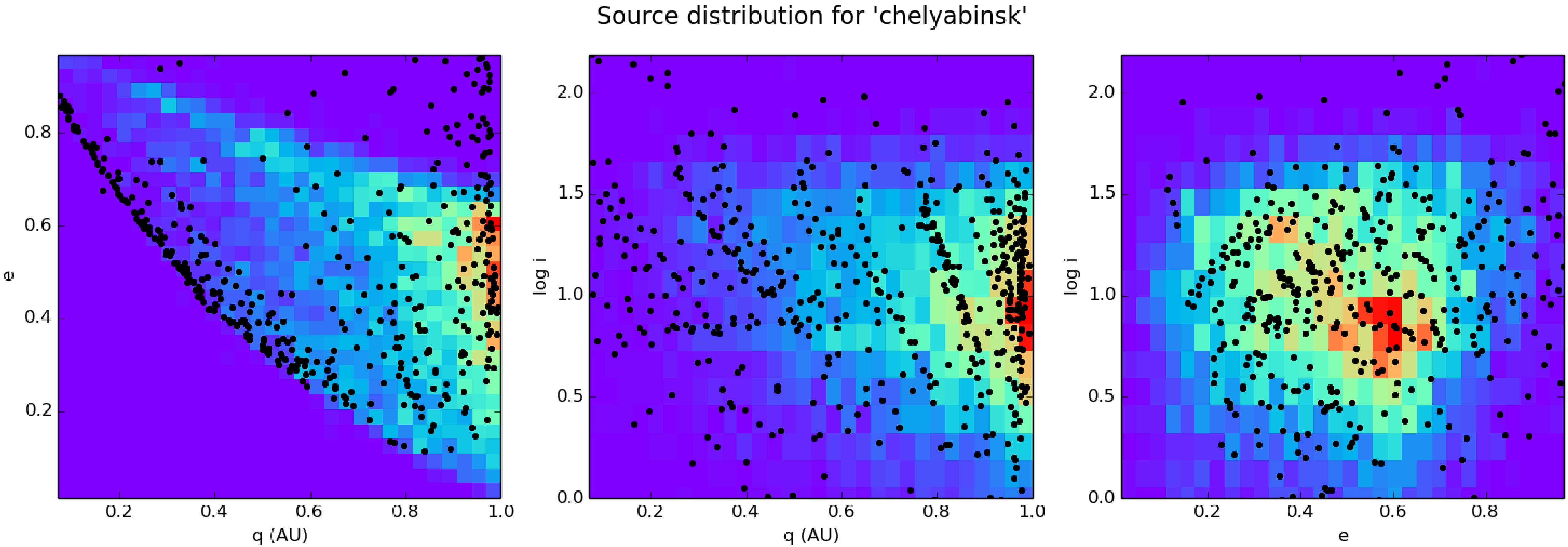
The total relative probability of having an impact on a given site is approximated as:

$$P(\text{site}) \sim \sum_j P(A_j, a_j, v_j)$$

* biased

GRT: Preliminary* results

15 February 2013, 03:20 UTC



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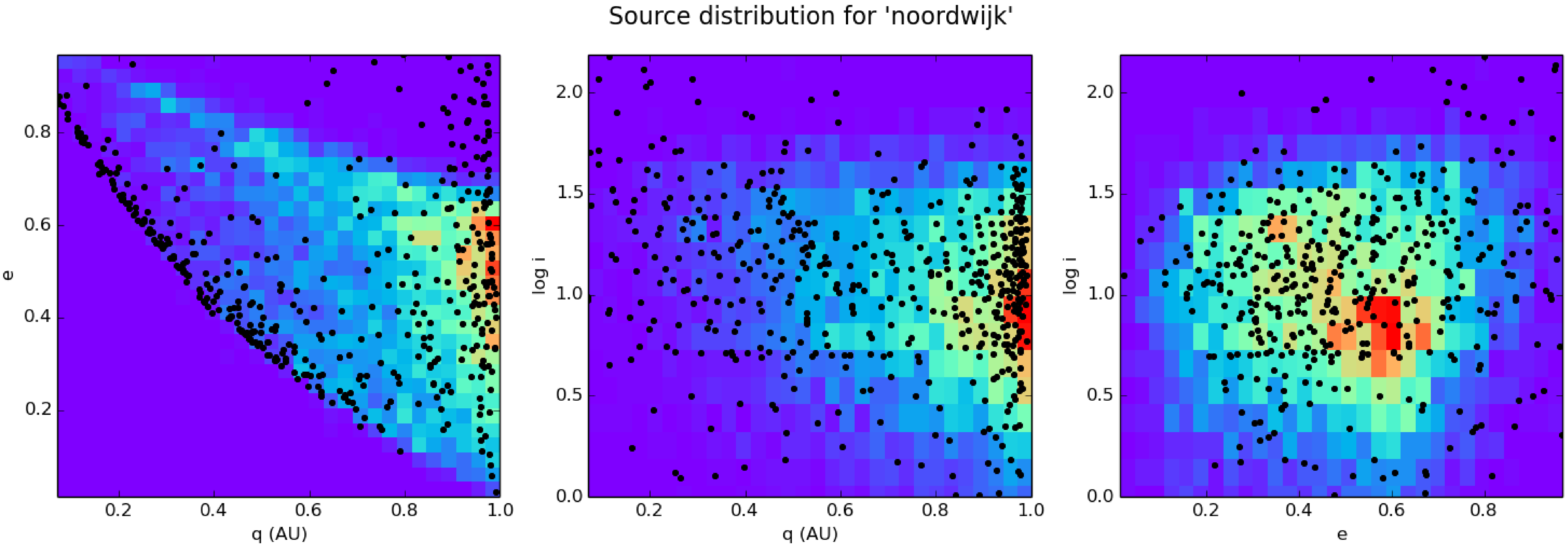

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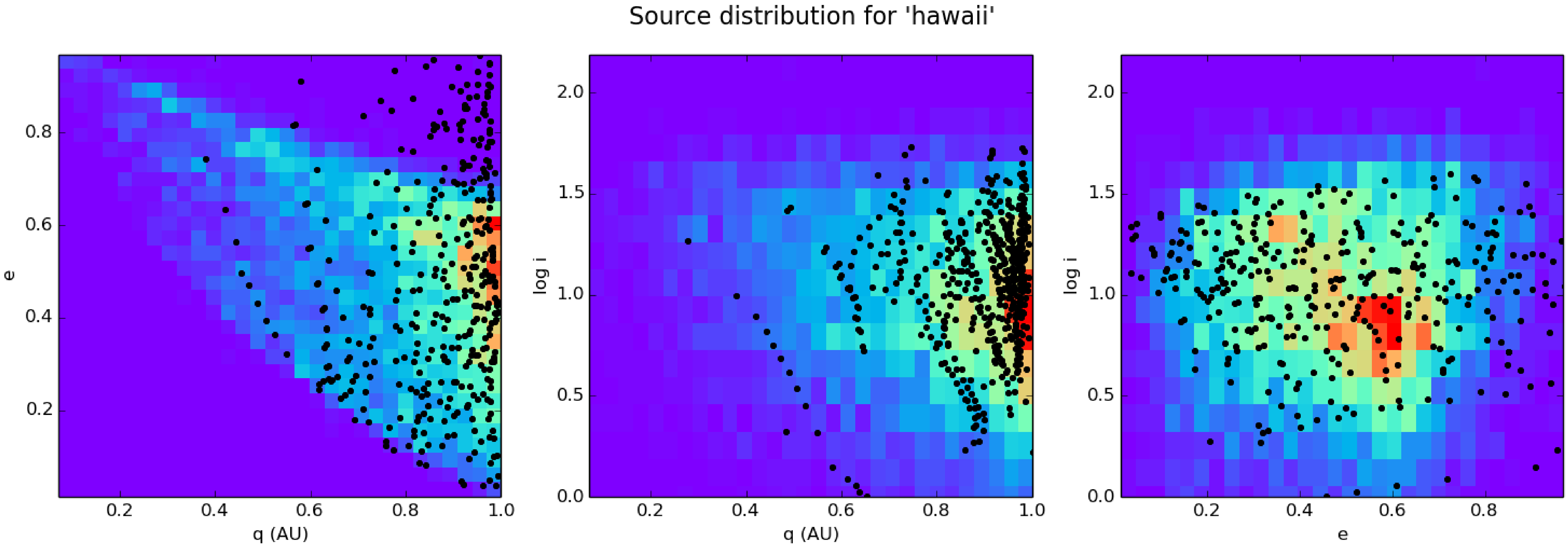

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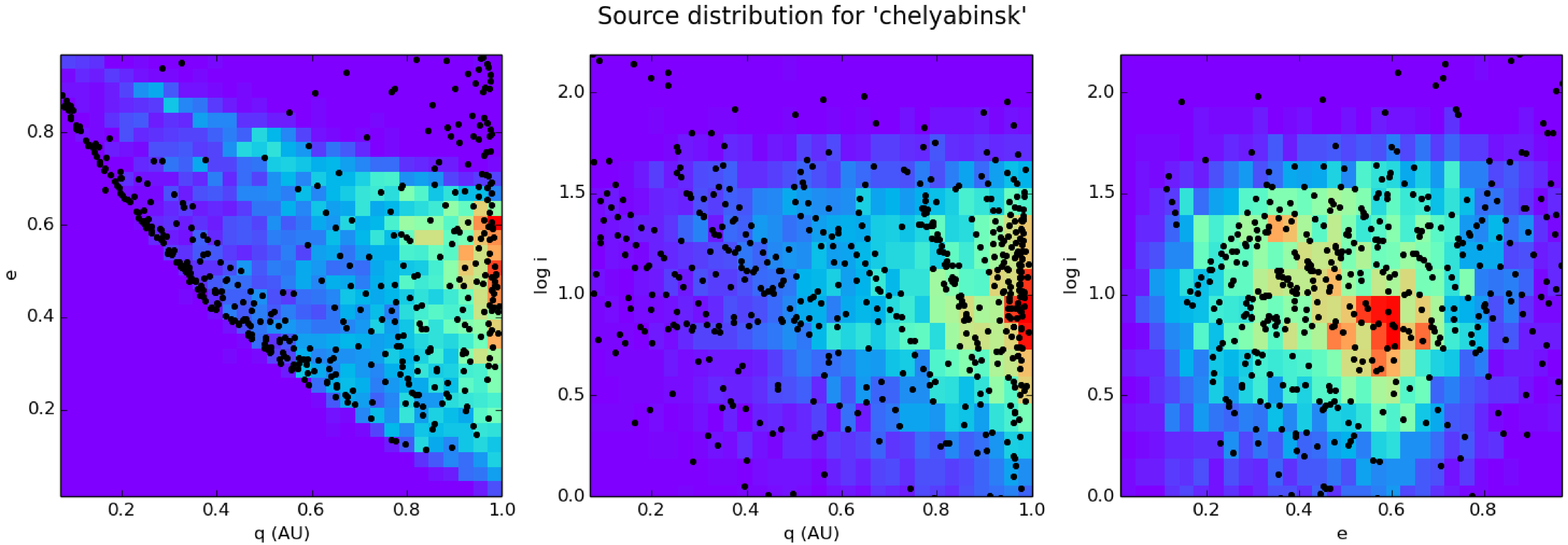

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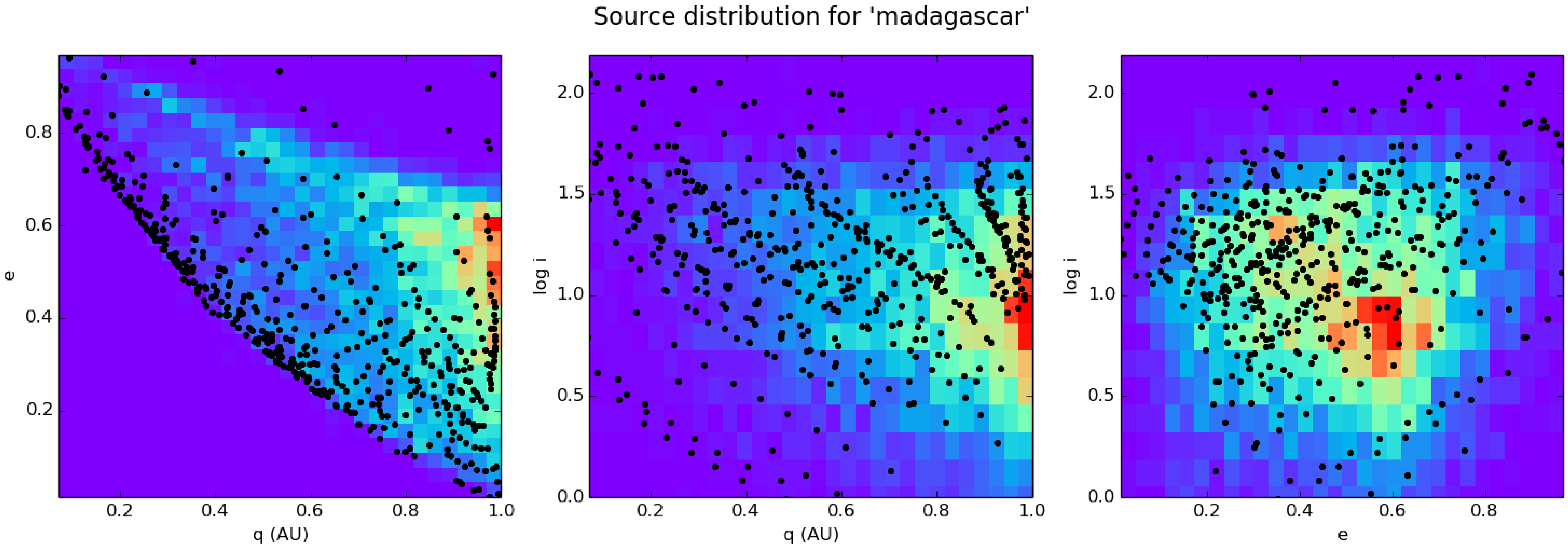

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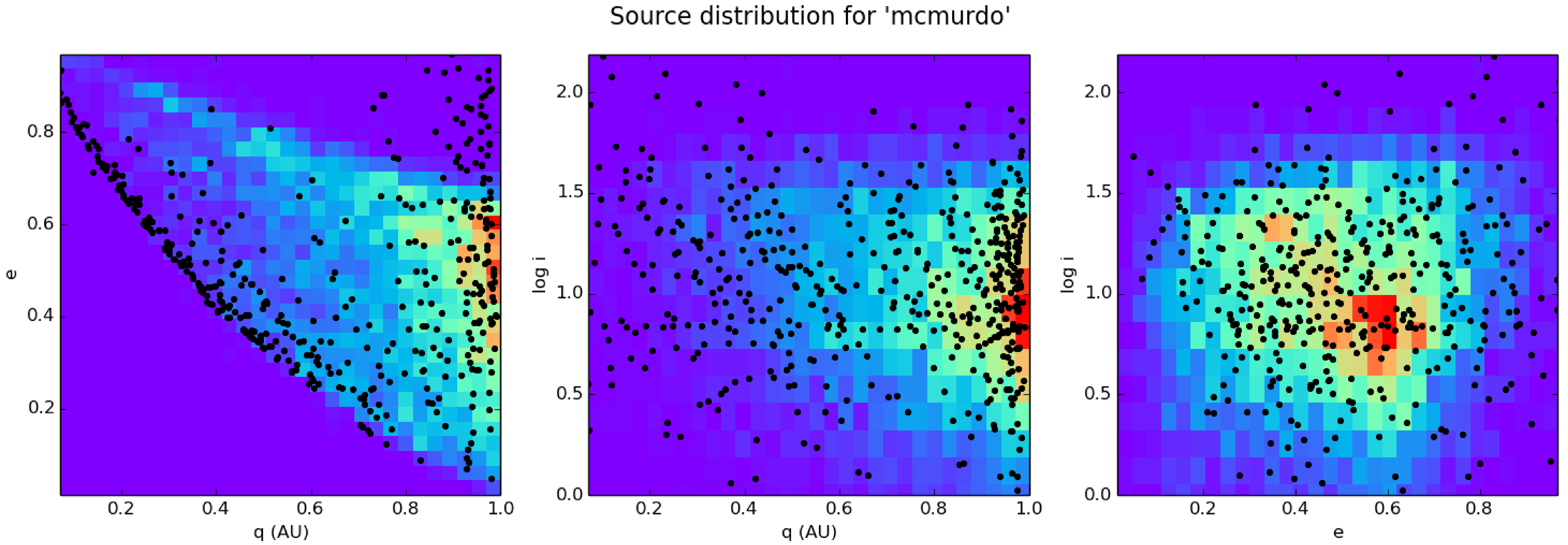

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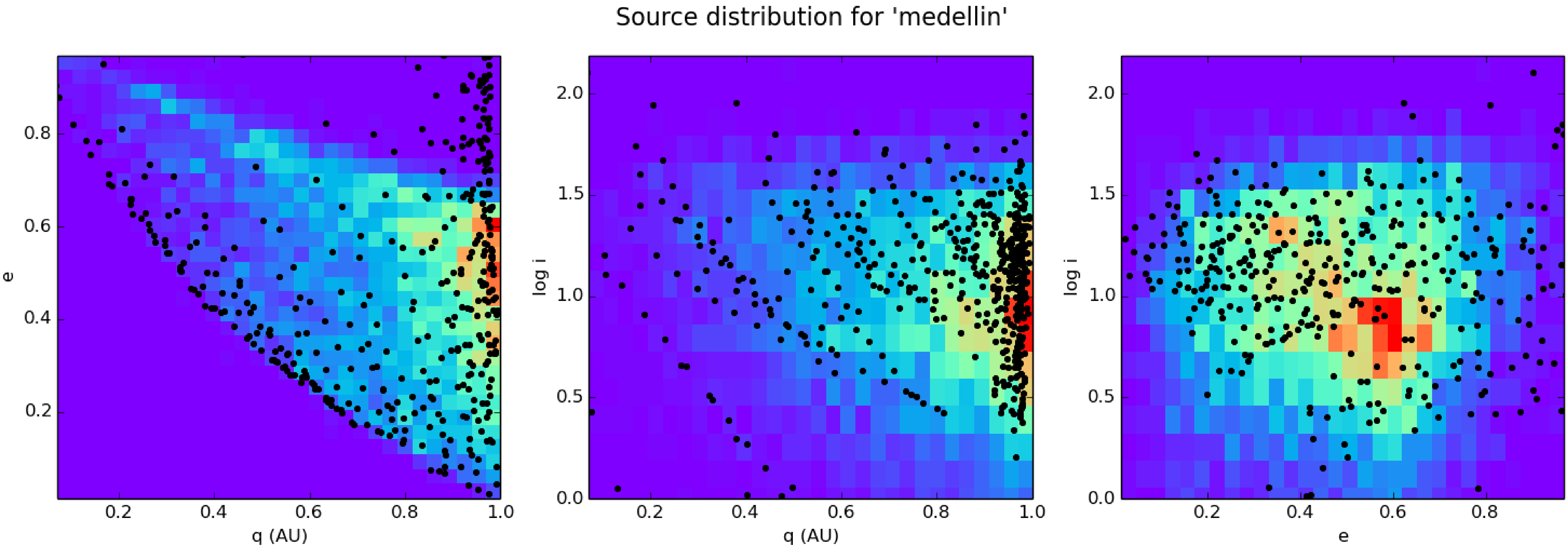

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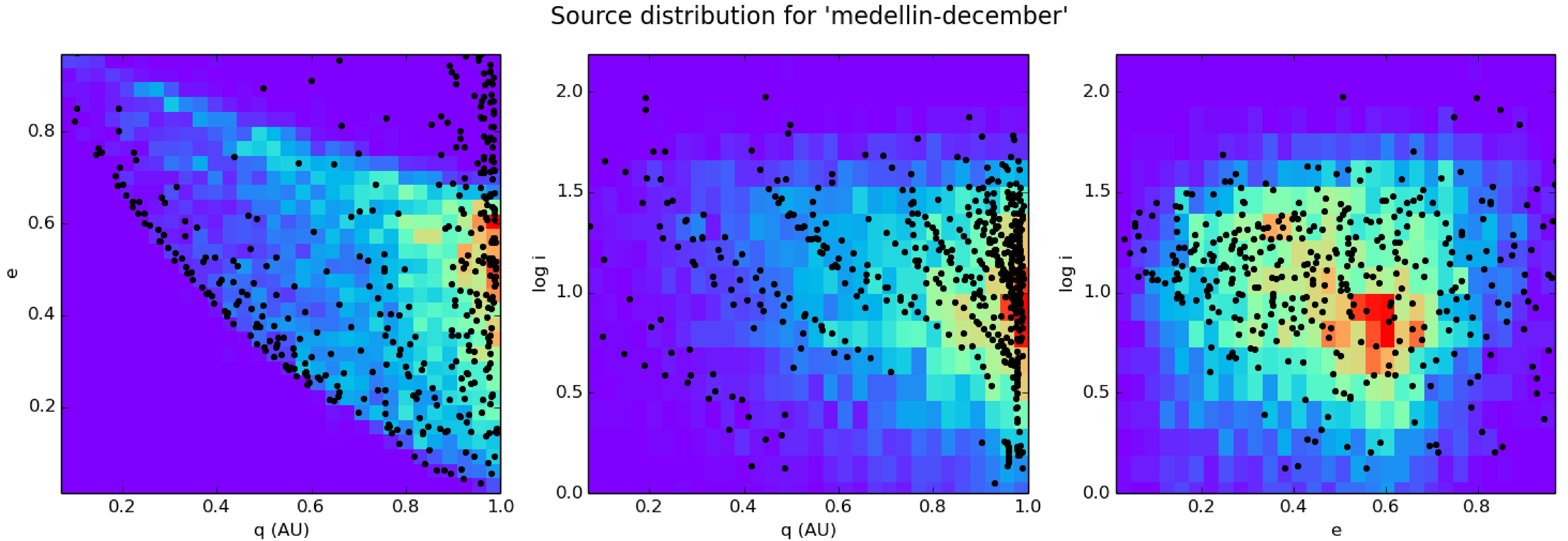

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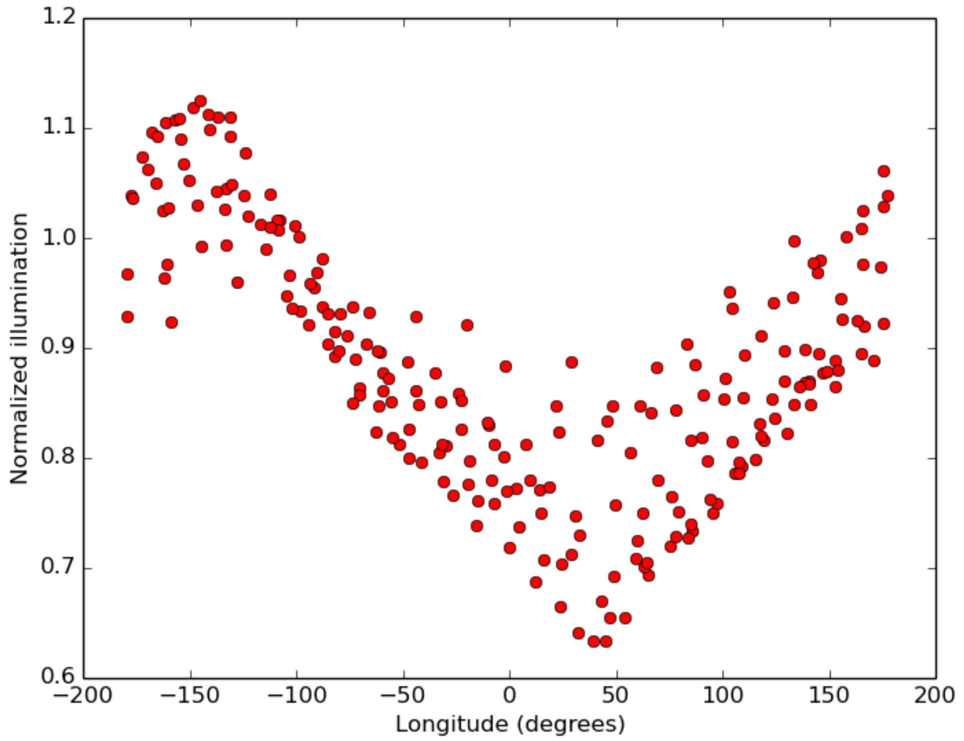

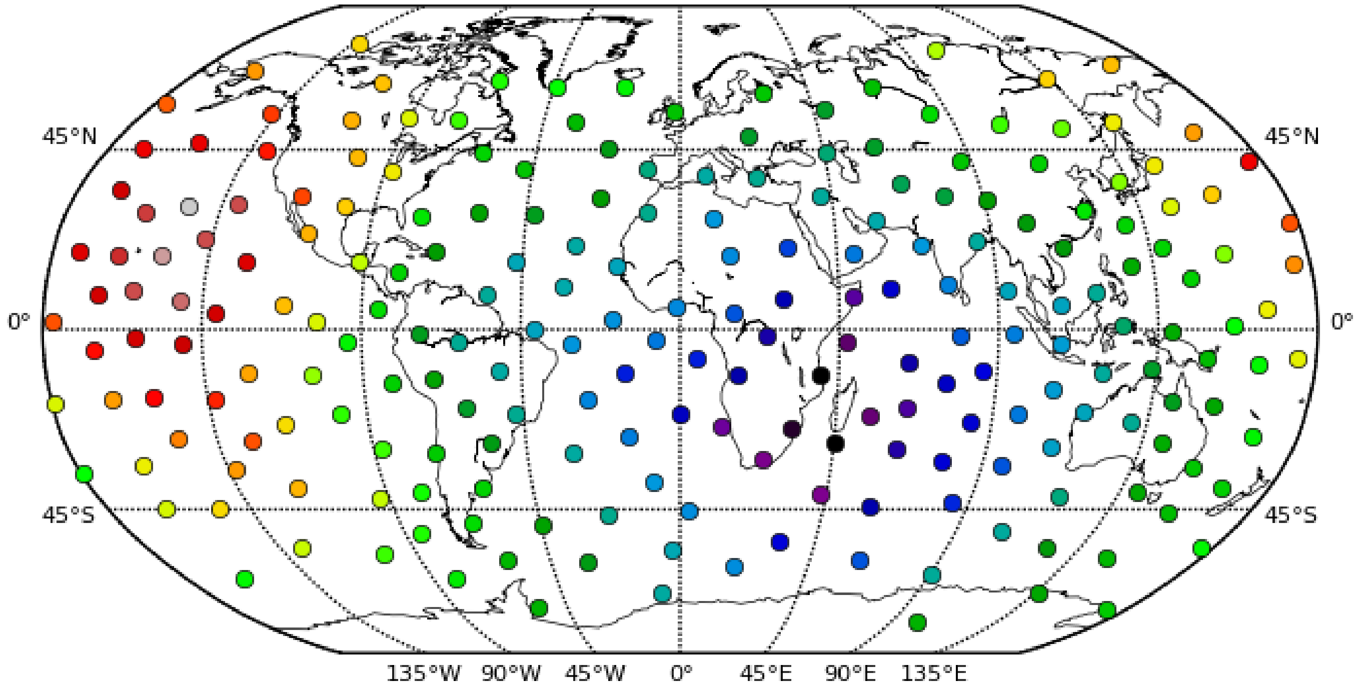

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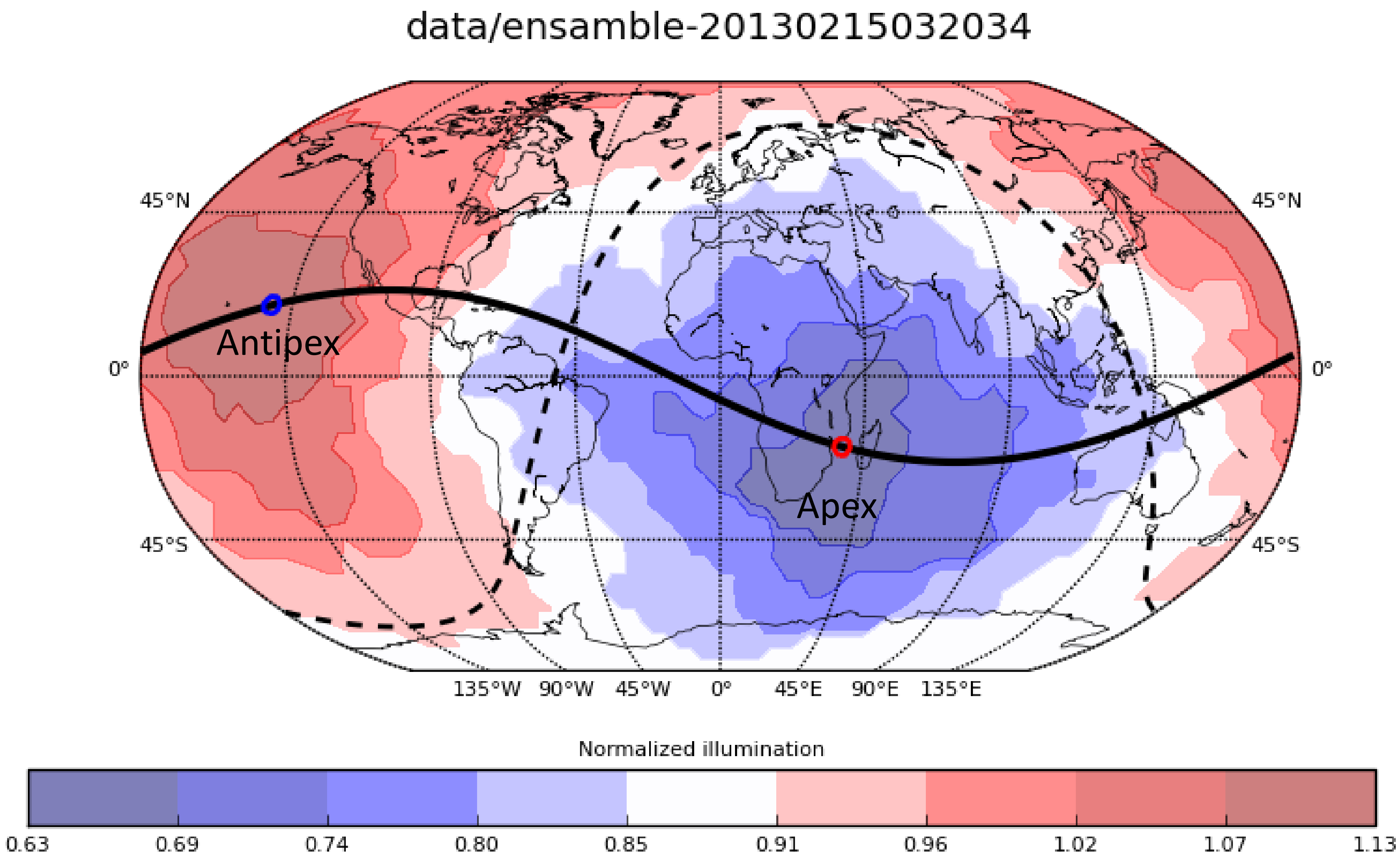
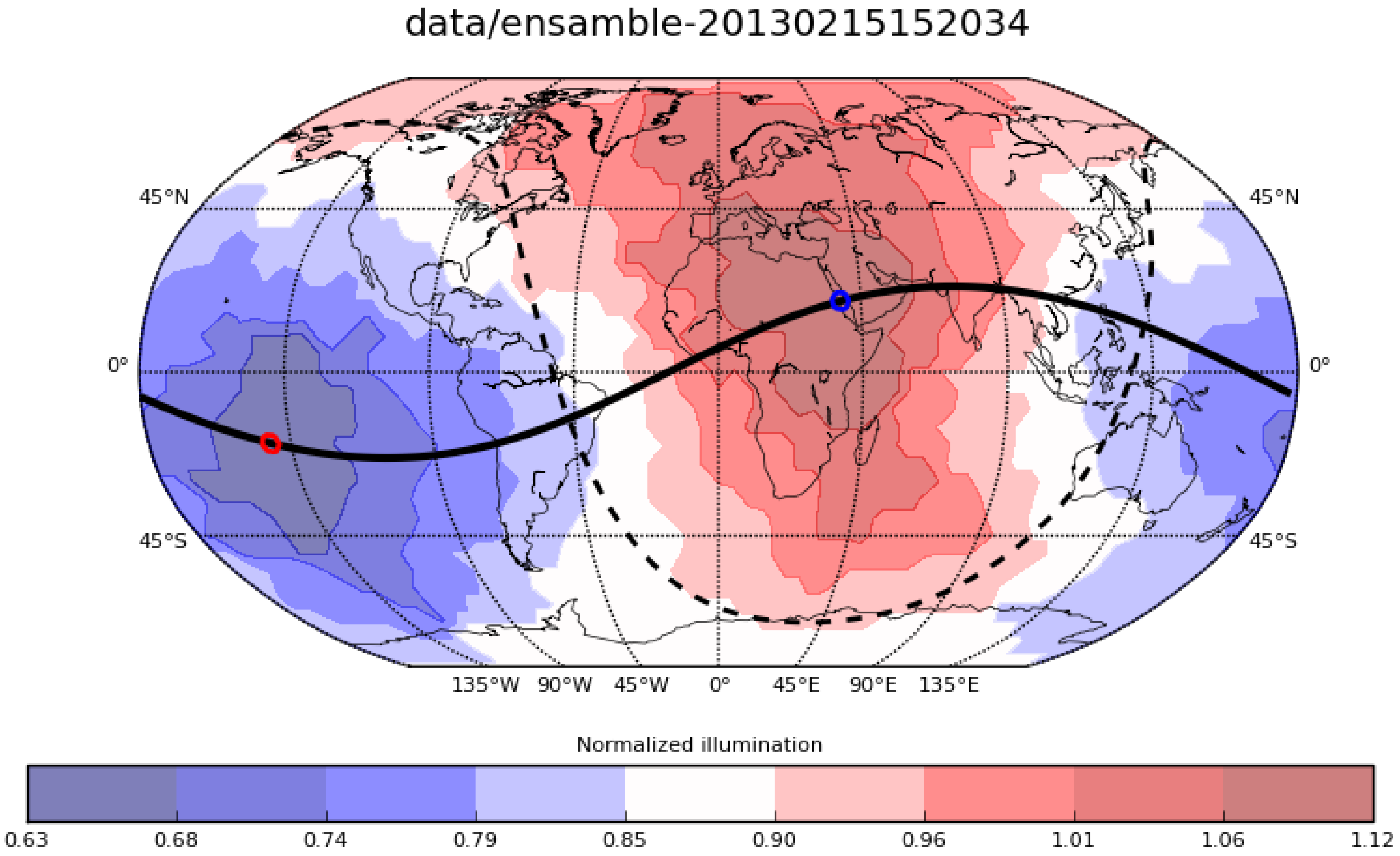
GRT: Preliminary Results



GRT: Preliminary Results



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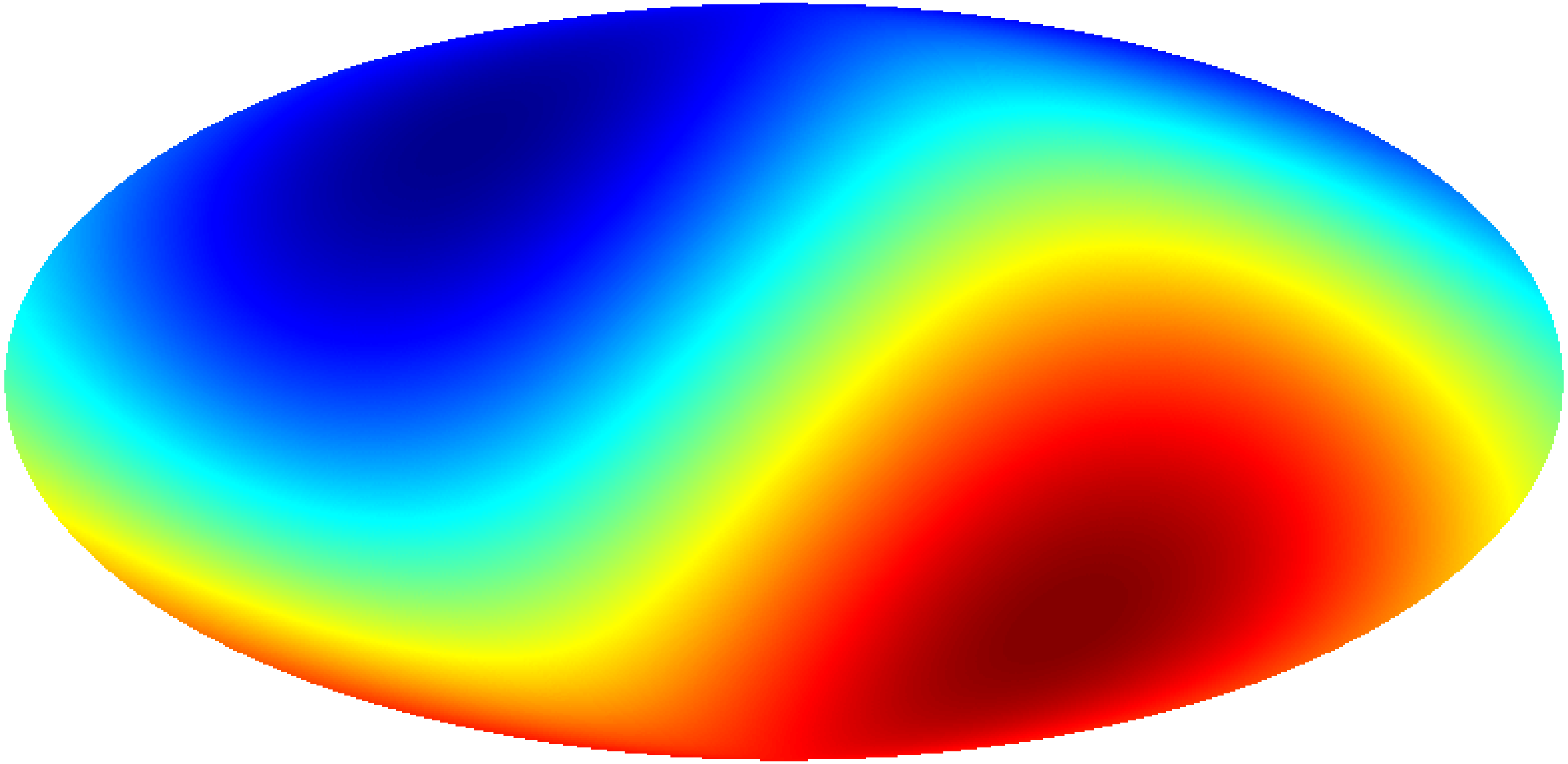
GRT: Preliminary Results

An analogy (with cosmology)
The Dipole component of the CMBR



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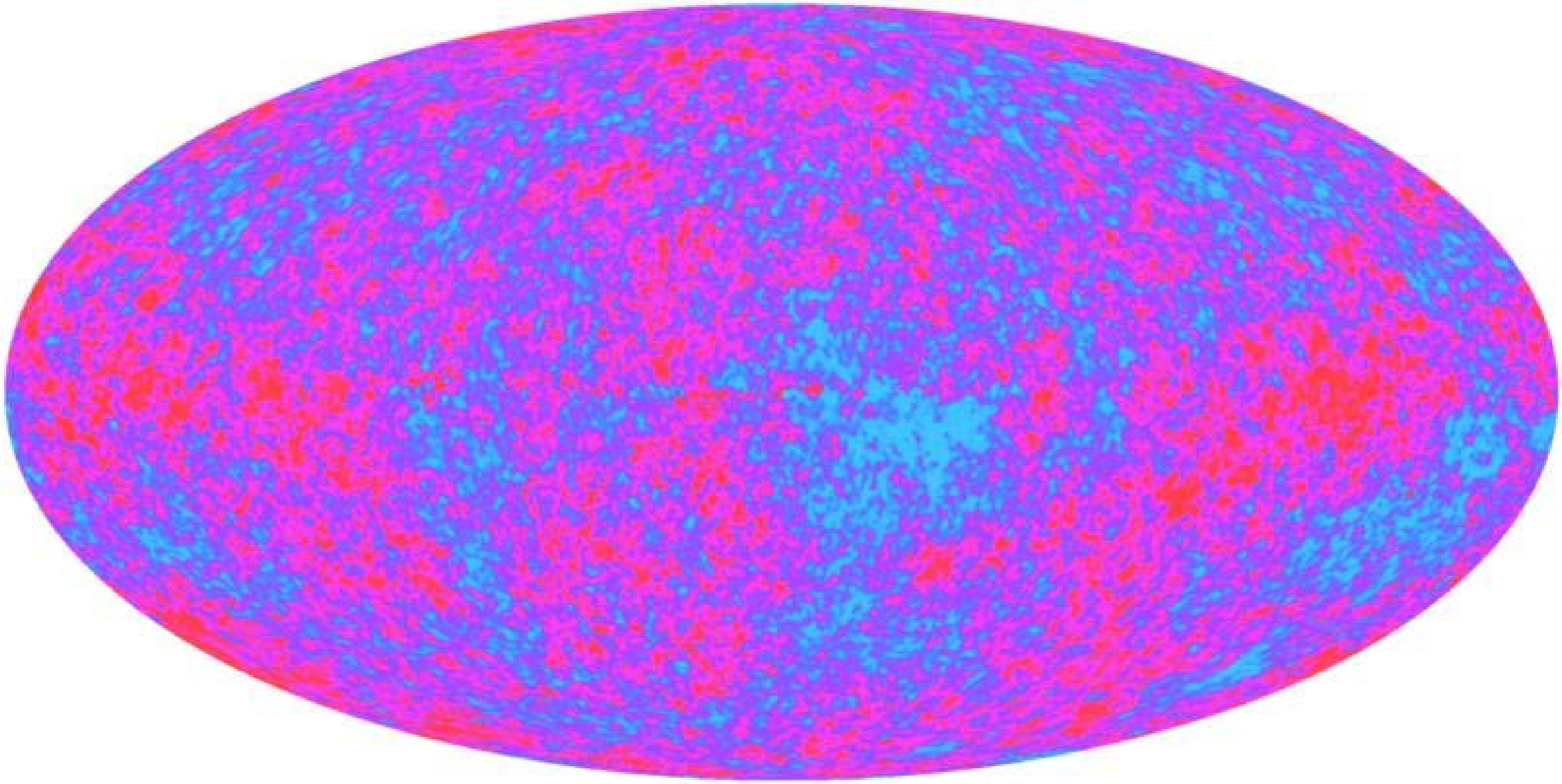
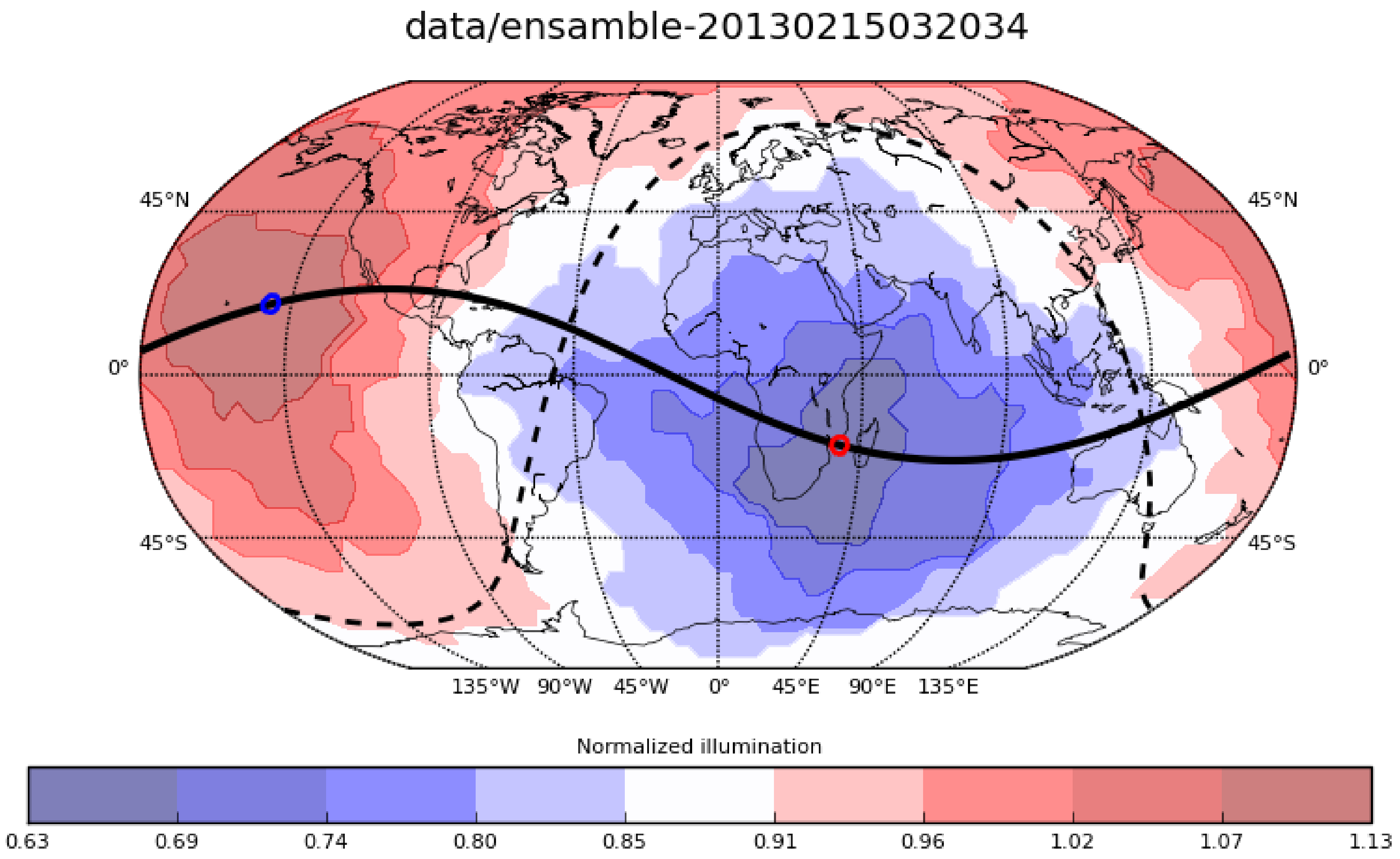
An analogy (with cosmology)
We don't want a trivial dipole, we want a signal!



GRT: Preliminary Results



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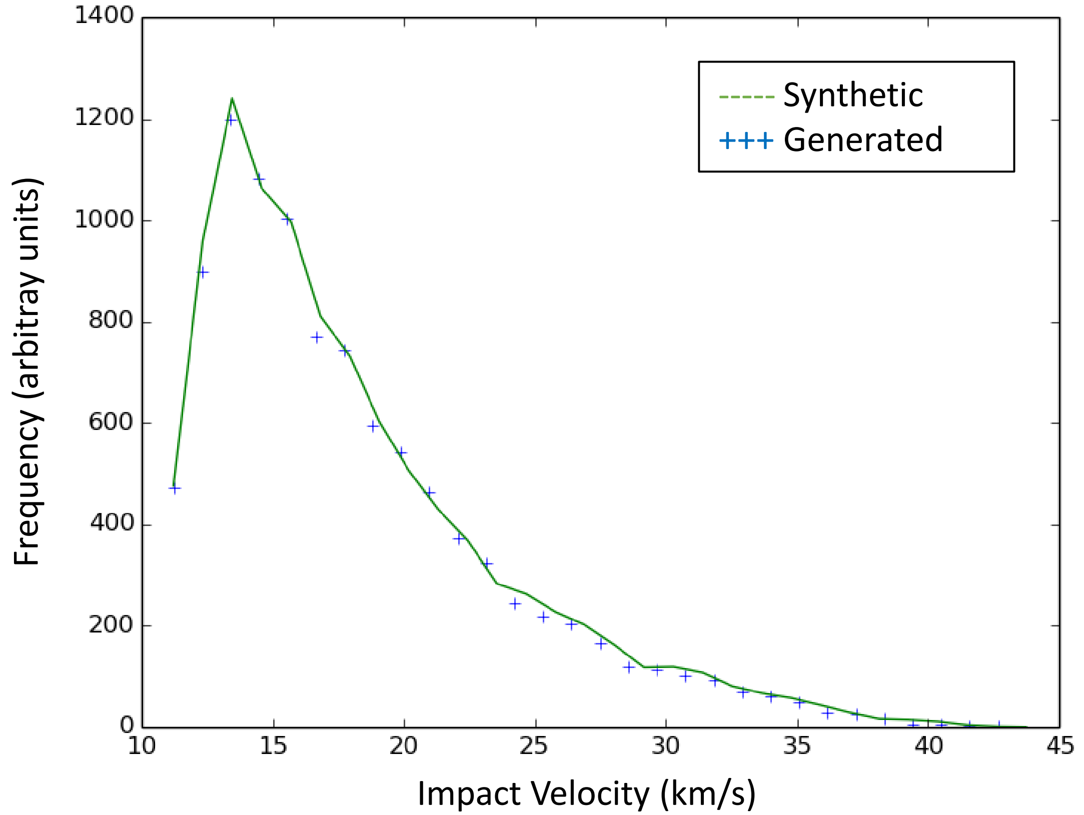
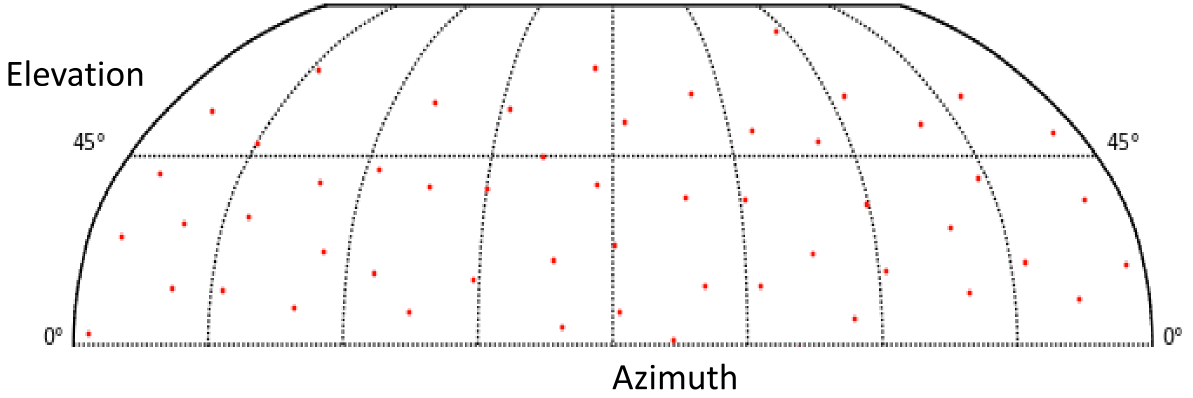
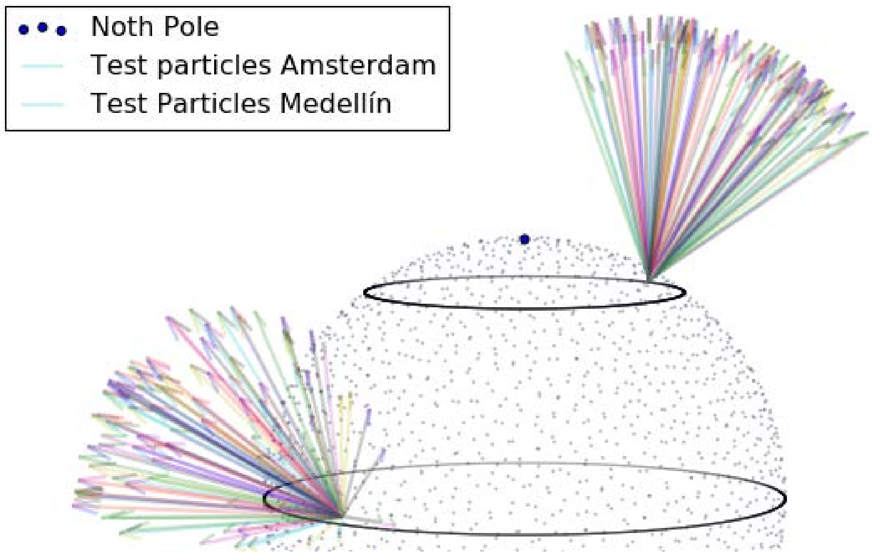
GRT: Initial conditions







We generate local configuration: Azimuth (A), elevation (a), impact velocity (v)

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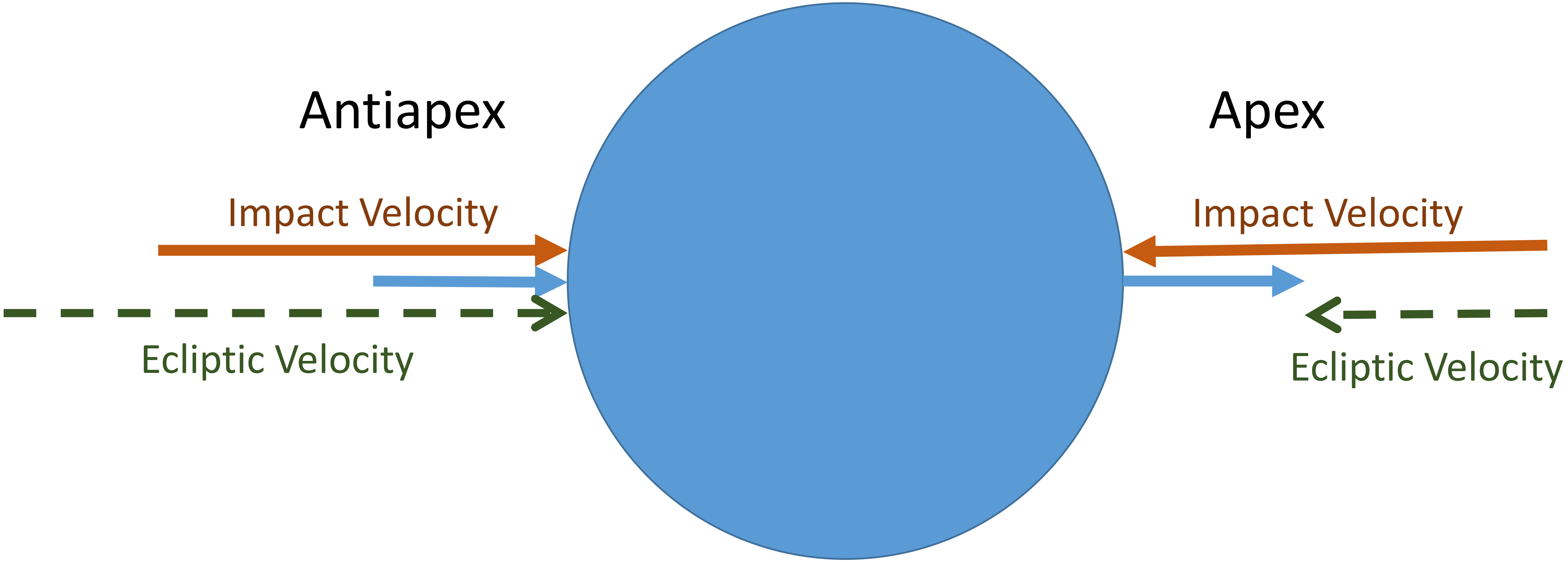

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Meteoroids 2016

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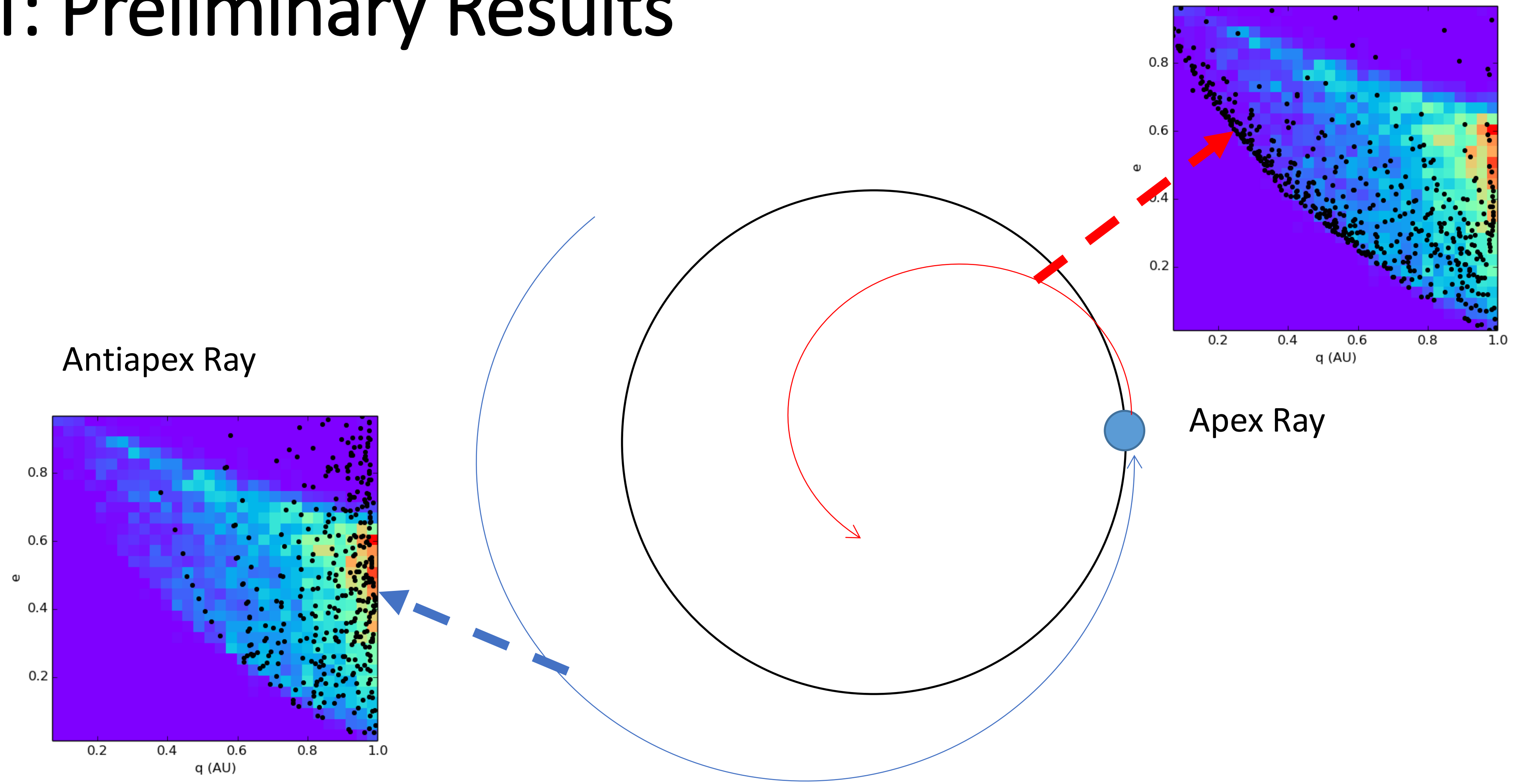

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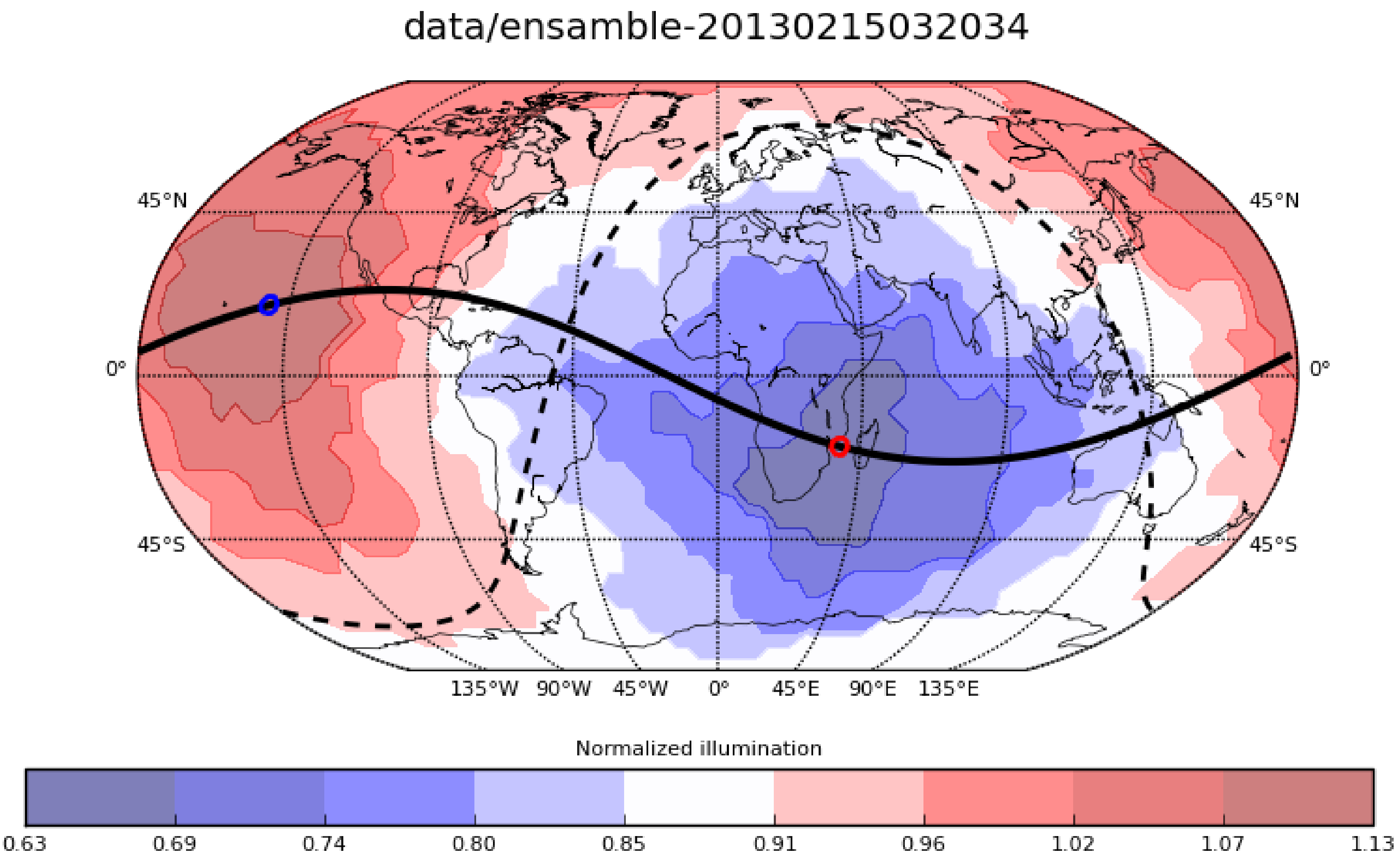

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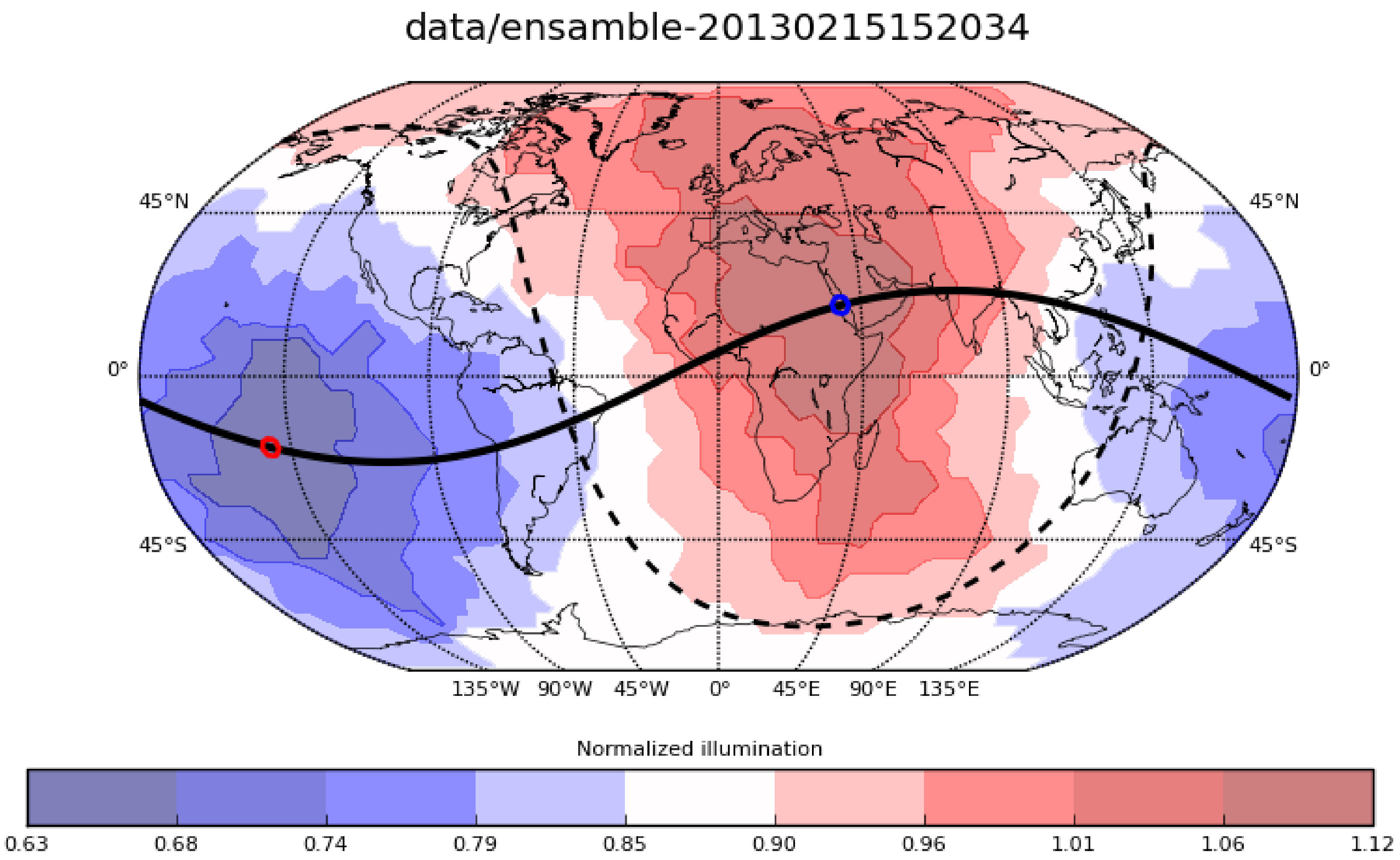

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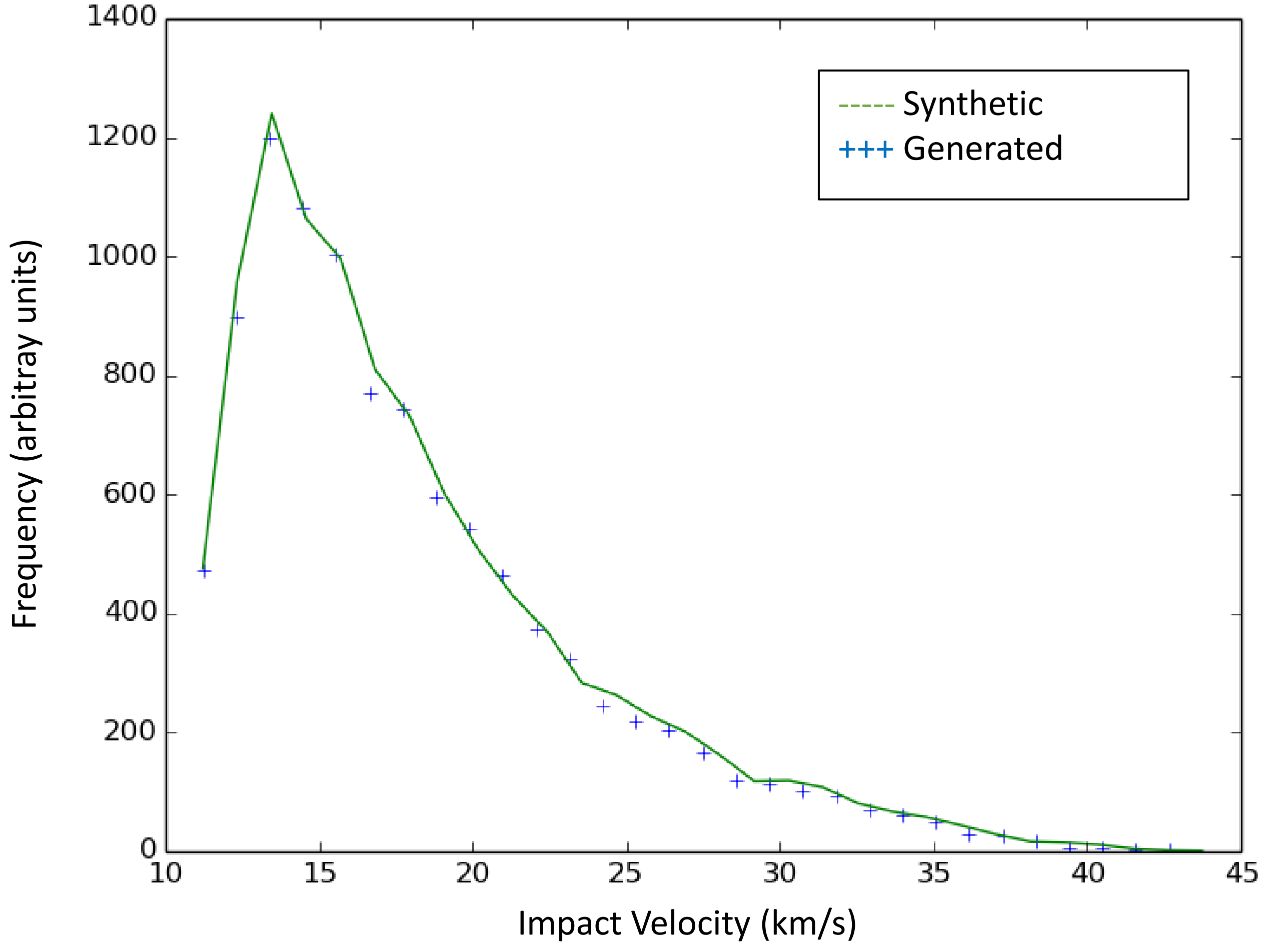
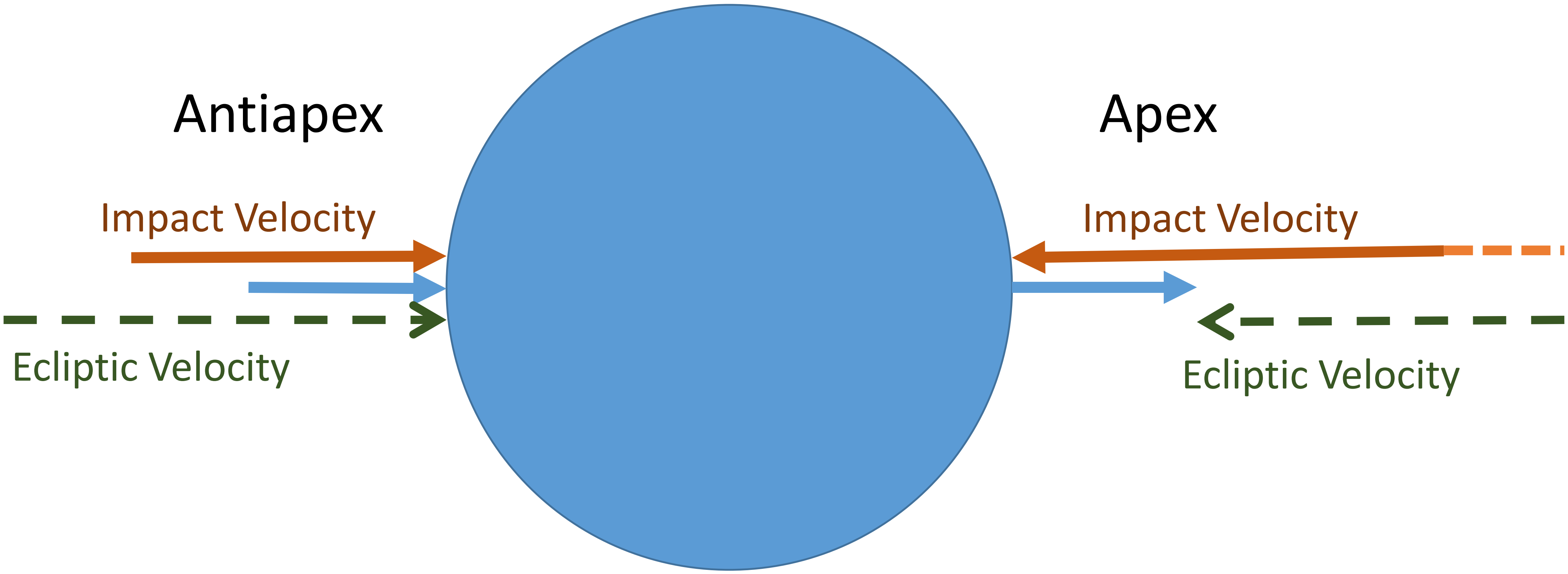


This is the average speed distribution

GRT: Preliminary Results



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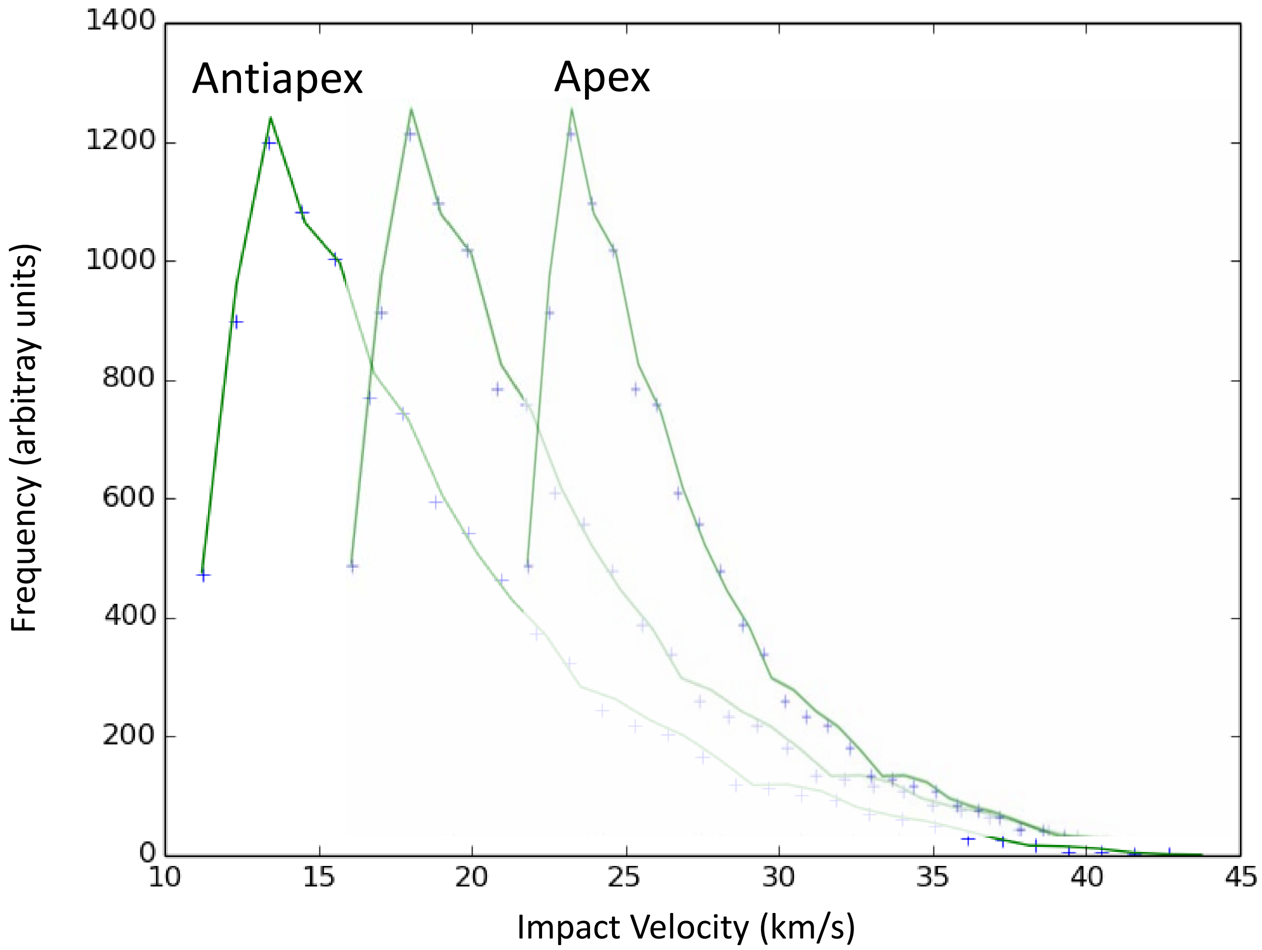

Summary and Conclusions

- We [adapted, reinvented, coined the name] of a (new) method to calculate the spatial/temporal distribution of impacts on Earth

Gravitational Ray Tracing

- **Pros**: Complex gravitational settings, efficiency.
- **Contras**: Computationally intensive.
- Range of problems where it can be applied: lunar impacts, rate and differential flux of cratering, Jupiter impacts, temporarily captured objects
- Stay tunned!: http://github.com/seap-udea

Questions?

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Don't forget to cite us: Zuluaga & Sucerquia (2016)

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