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Supplementary material

# Doublet craters on Charon and implications for km-sized binaries in the outer solar system

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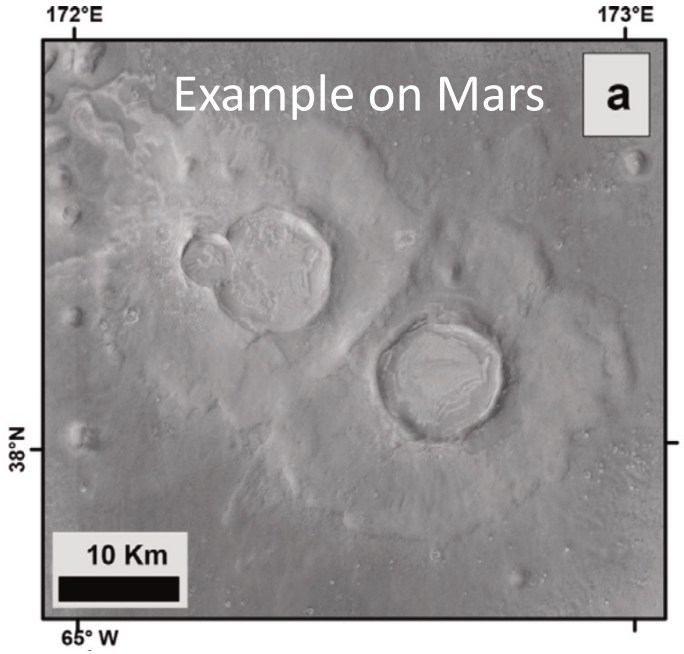
Acknowledgements
JSPS (KAKENHI, 23KJ1566) and SwRI

# 1. What are “doublet craters”

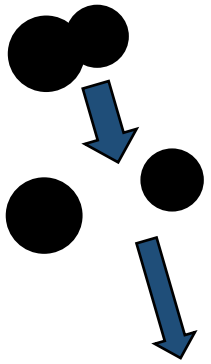
A crater pair that formed

- ☐ adjacent to each other
- ☐ with nearly-equal size
- ☐ simultaneously




Vavilov+2022
(Modified)

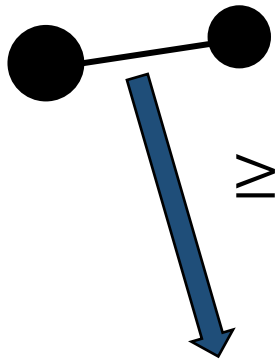
Contact



Separated
by tidal force

Melosh & Stansberry 1991

Widely-separated



$\geq$ several $d_{\mathrm{primary}}$

Bottke & Melosh 1996a,b

# 1. Previous studies on doublet craters and binaries

Doublet craters can tell us about binaries.

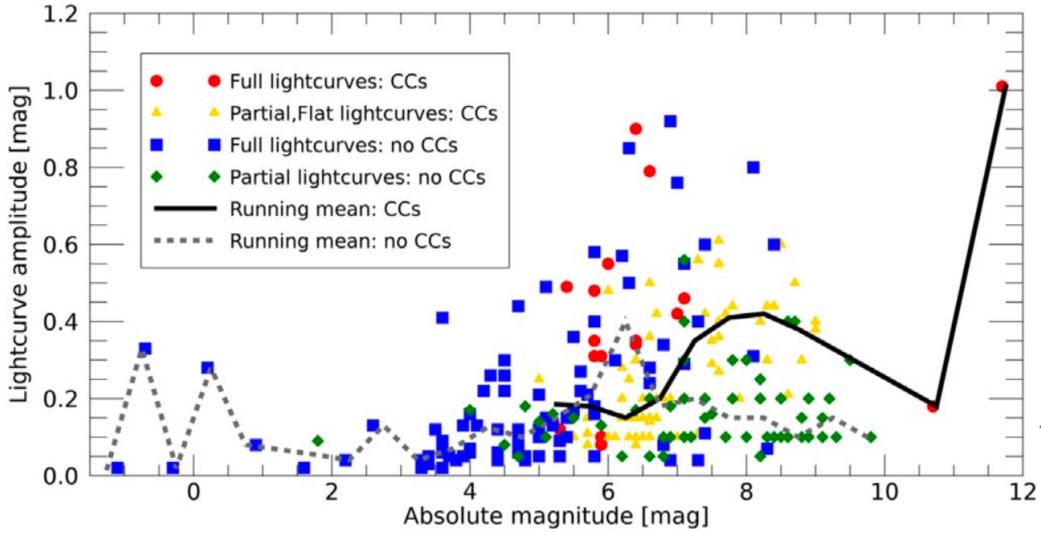
e.g.,
- Fraction
- Separation
- Orientation (inclination)
- Size ratio

| **Body** | **Works** | **Est. binary frac.** |
|---|---|---|
| Earth | Melosh & Stansberry 1991 | ~10-20% of NEAs |
| Mars | Melosh+1996<br>Vavilov+2022 | ・Much less binaries among Mars impactors<br>・Isotropic inclination |
| Venus | Cook+2003 | ~10-20% of NEAs |
| Ceres, Vesta | Wren 2018, Wren & Fevig 2018, 2019 | < ~5-10 % of MBAs |
| Pluto, **Charon** | Parker 2021 | ~54 % |

# 1. Binaries in the outer solar system

- A lot of binaries
  - Hot TNOs ~10% Noll+ 2008
  - Cold TNOs ~30% Grundy+2011
- Nearly equal size
- Various types: from contact to ultra-wide
- Challenging to observe km-sized TNOs

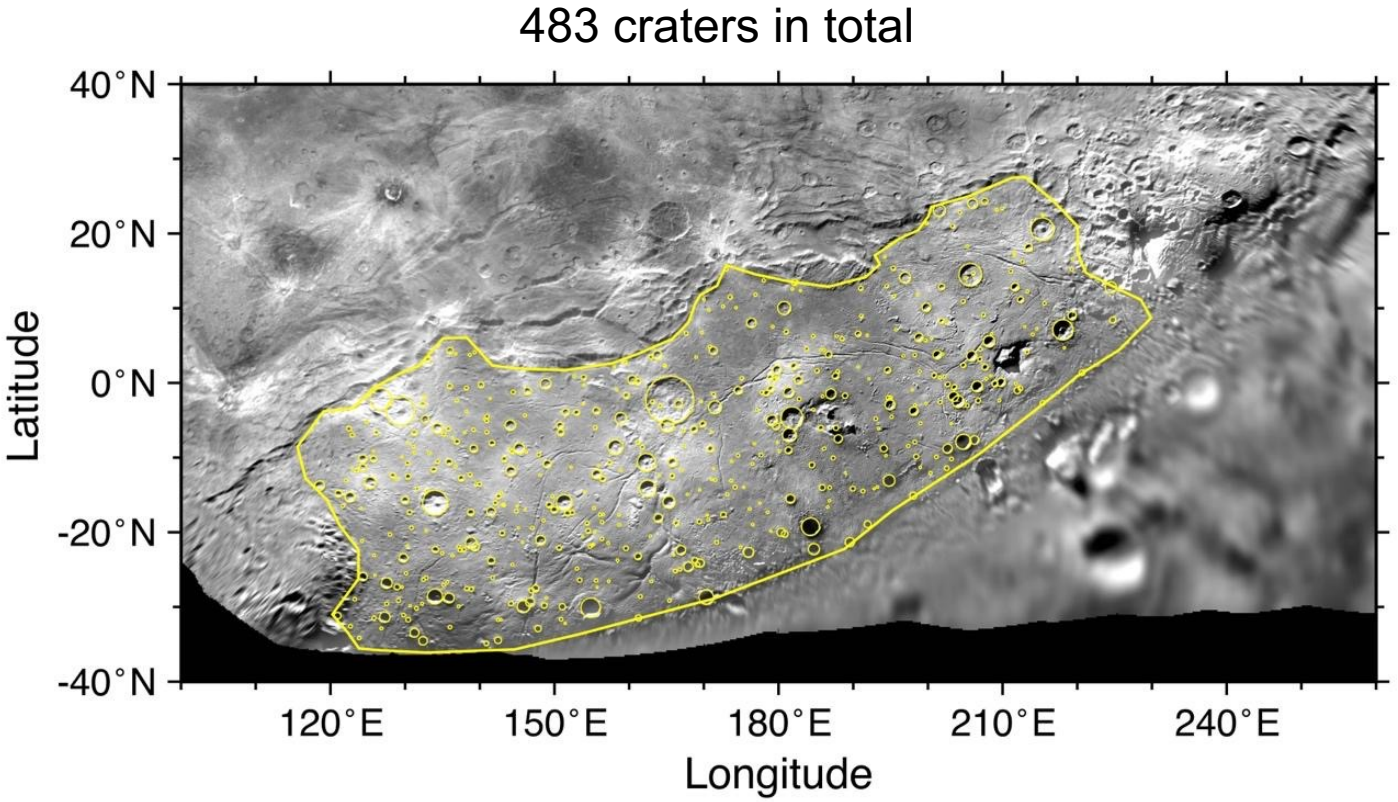
Doublet craters on Charon
= Window for
"km- and equally-sized, widely-separated" binaries

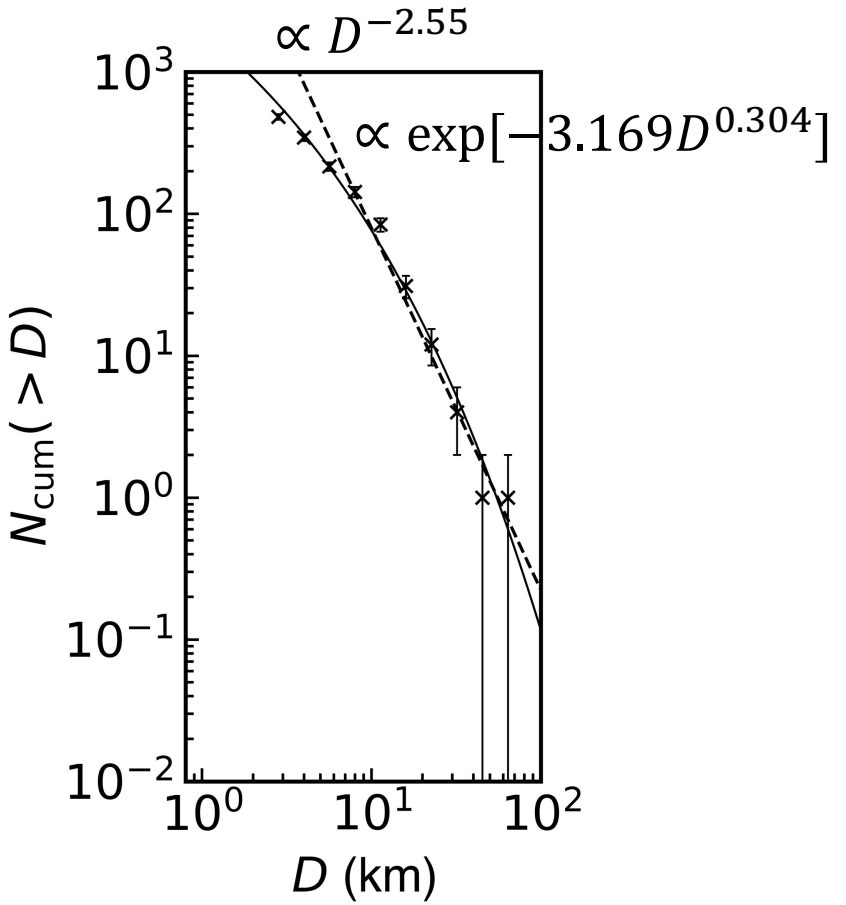



Thirouin & Sheppard, 2019

# 2. Crater dataset: Robbins & Dones 2023

- Confidence lev. 3 and 4 in Vulcan Planitia (4 being the most confident)
- $D$ > 3 km



# 2. Definition in this study

- Maximum separation distance allowed: $\Delta_{max}$
- Diameter ratio: $D_2/D_1$

  $D_1$: primary's diameter (larger one)

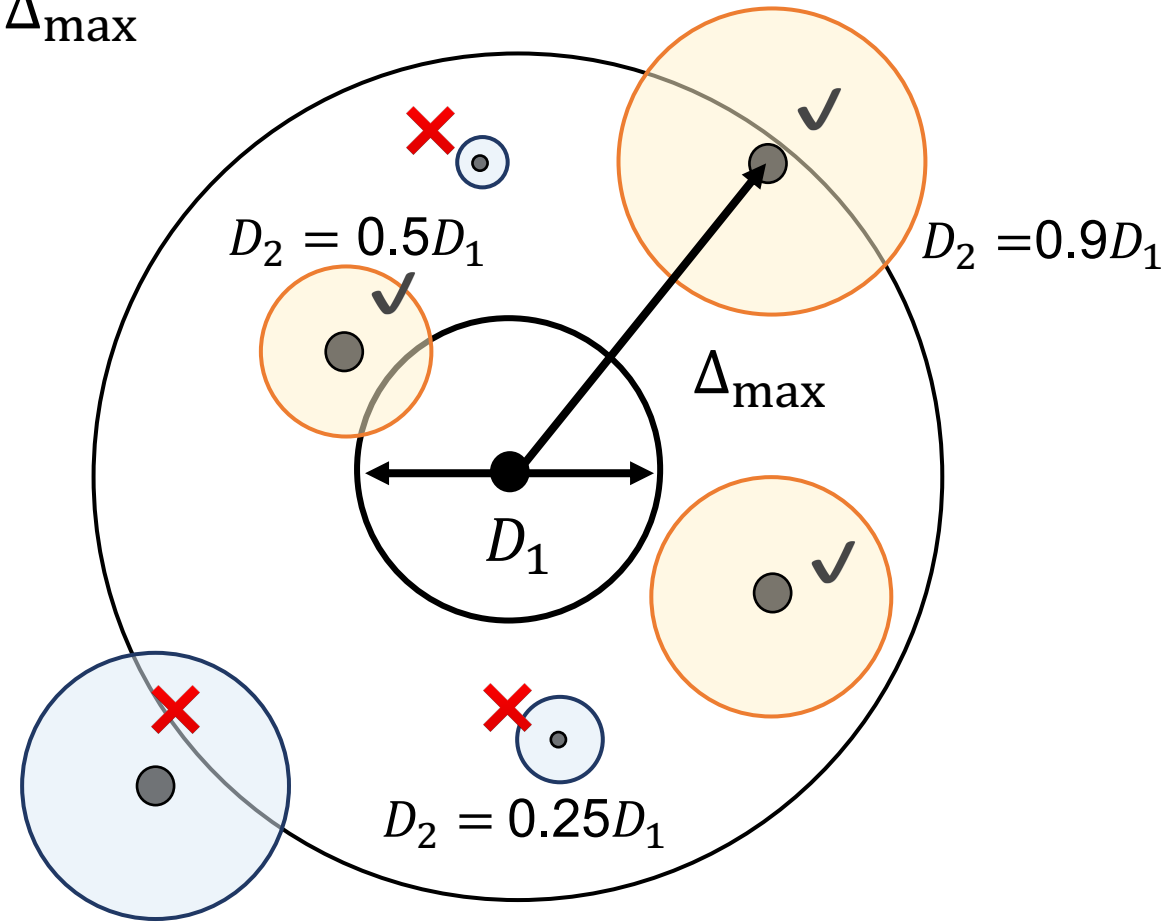
  $D_2$: secondary's diameter (smaller one)

483 craters in total

$\Delta_{max} = 1.4\ D_1$

$D_2/D_1 > 0.4$

98 potential pairs



# 2. Categorization

- ☐ Superposition
- ☐ Ejecta overlapping
- ☐ Different degree of degradation

Yes → “Unlikely”

No → “Possible”

- ☐ Septum? (straight segment in between)
- ☐ Similar ejecta texture, looks continuous

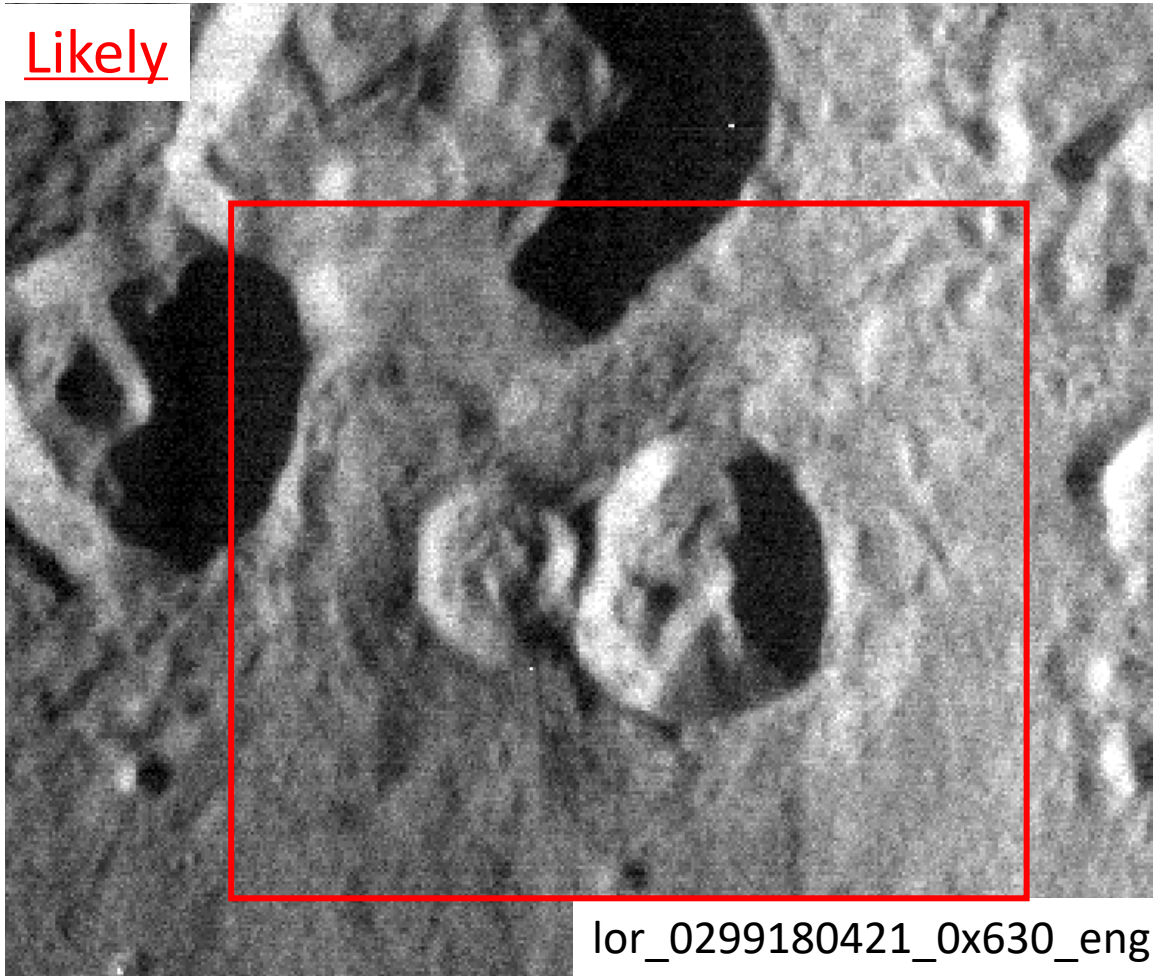
Yes → “Likely”

- “Possible” is basically those without negative evidence
- “Likely” is a highly subjective category
  → basically, treated similarly with ”possible”

# 3.1 Examples

# 519-520, D~10 km

Likely



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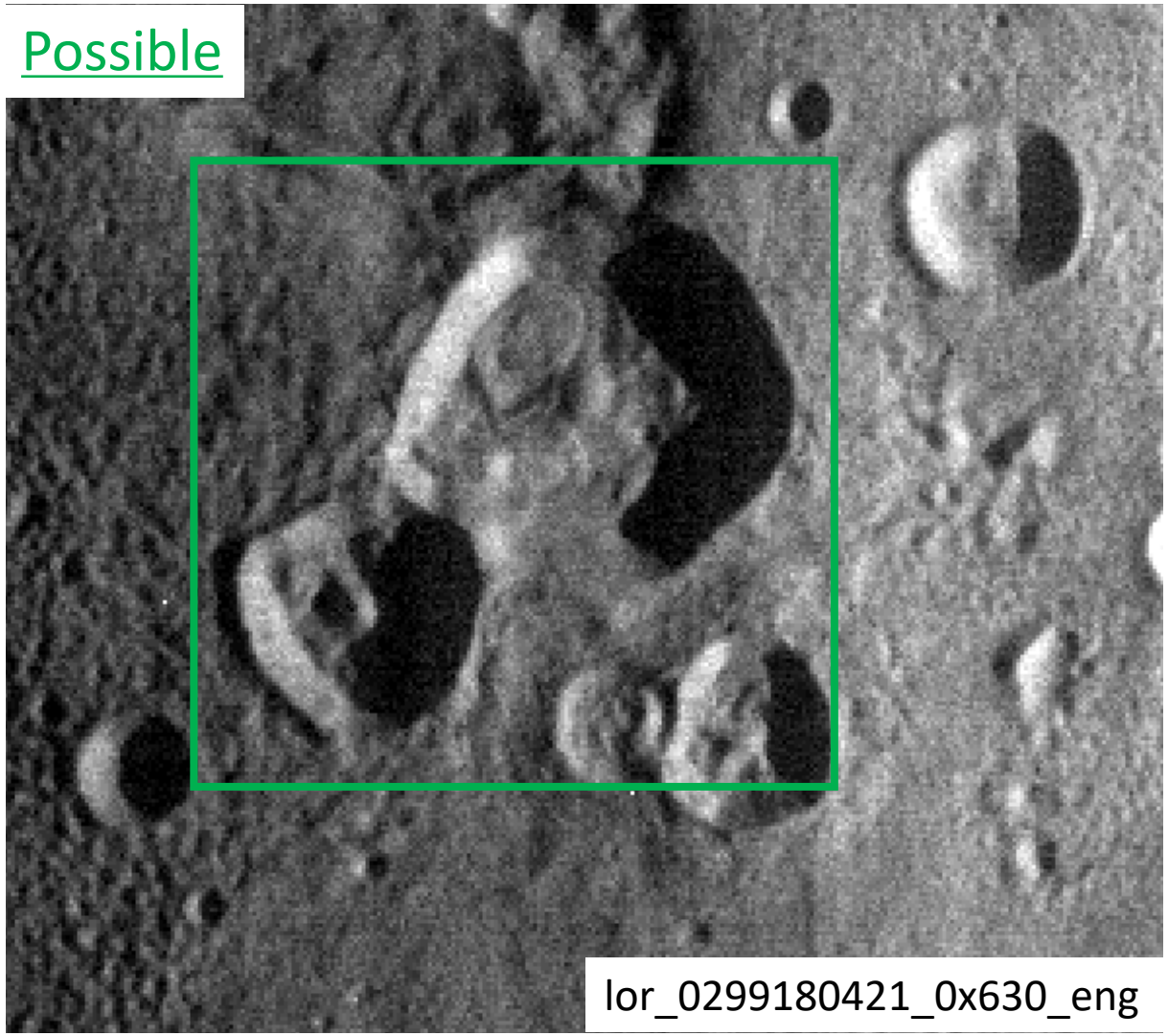
# 544-543 D~20 km

Possible



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# 3.1 General results and observation

*N pairs/483 craters

| Category | #pairs | Doublet (%)* |
|---|---|---|
| Likely | 16 | **3.31** |
| Possible | 23 | **4.76** |

| Author(s) | Target | Doublet (%) |
|---|---|---|
| Melosh & Stansberry 1991 | Earth | ~ 10 % |
| Melosh+1996 | Mars | ~2 % |
| Cook+2003 | Venus | ~ 2 % (craters)<br>~ 14 % (splotches) |
| Wren & Fevig 2018, 2019 | Ceres<br>Vesta | 0.7 % for Ceres<br>1.4 % for Vesta |
| Vavilov+2022 | Mars | 0.5 % |

Miljkovic+2013

Only ~15% of binary impacts result in doublet

Likely + Possible = 8.07%

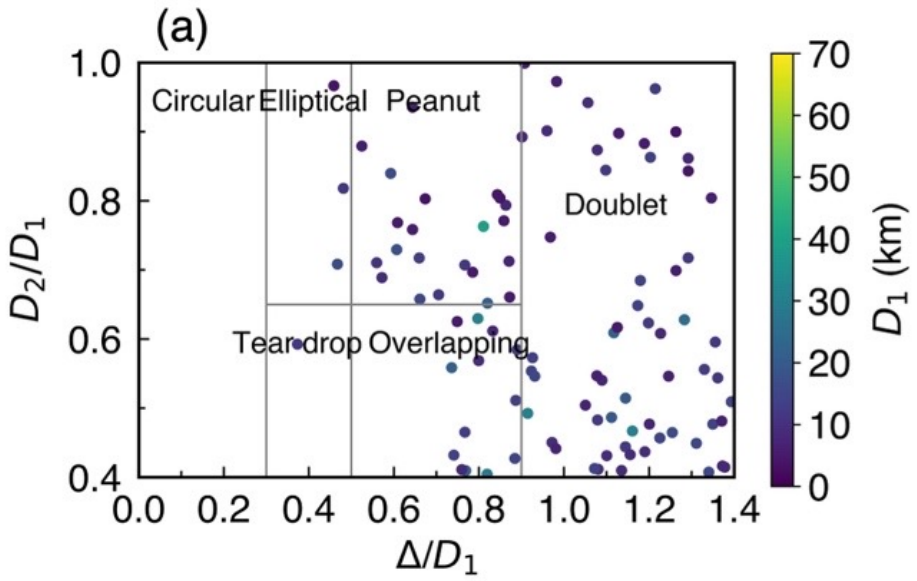
→ **~54%** is the max fraction of equally-sized, well-separated binaries among km-sized TNOs.

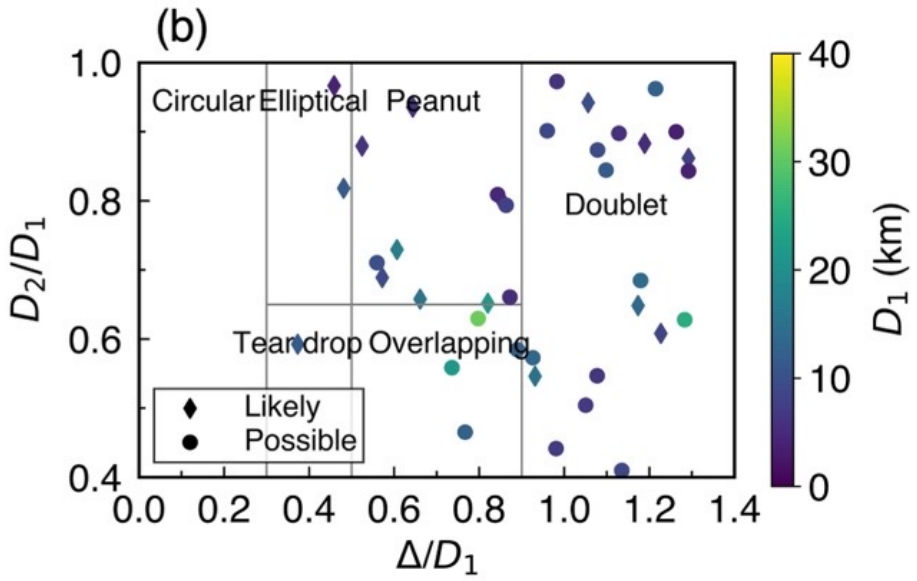
Only with Likely, **~22%**

# 3.1 Classifications from Miljković et al. (2013)

| Category | Potential doublets (pairs) | "Likely" (pairs) | "possible" (pairs) |
|---|---|---|---|
| Circular | 0 | 0 | 0 |
| Tear drop | 1 | 1 | 0 |
| Elliptical | 3 | 2 | 0 |
| Overlapping | 13 | 0 | 4 |
| Peanut | 22 | 7 | 4 |
| Doublet | 59 | 6 | 15 |

Few detection due to substantial overlap.
…difficult to confidently identify as two distinct craters without very high-res images or features like septum or ejecta interactions.

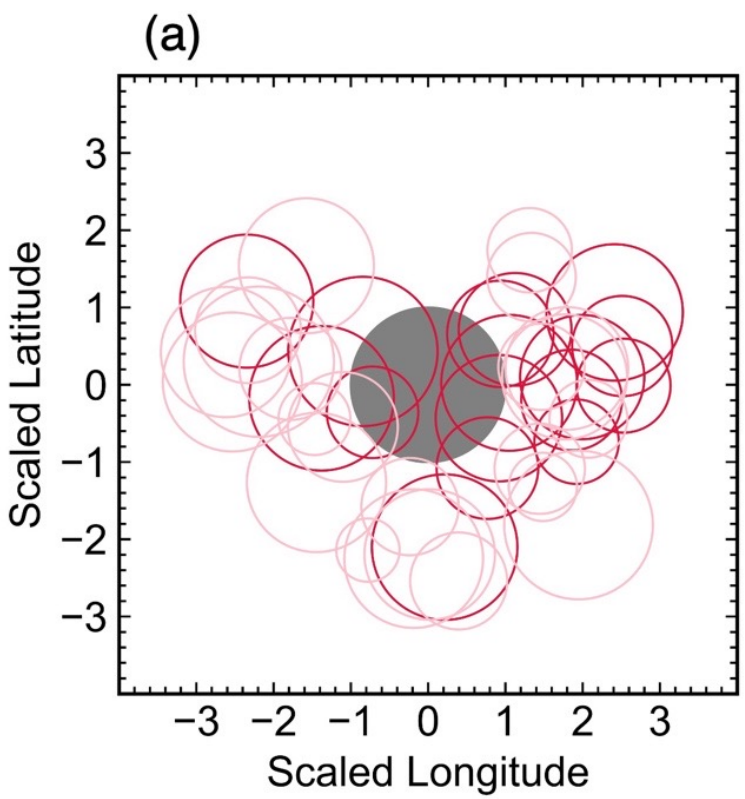


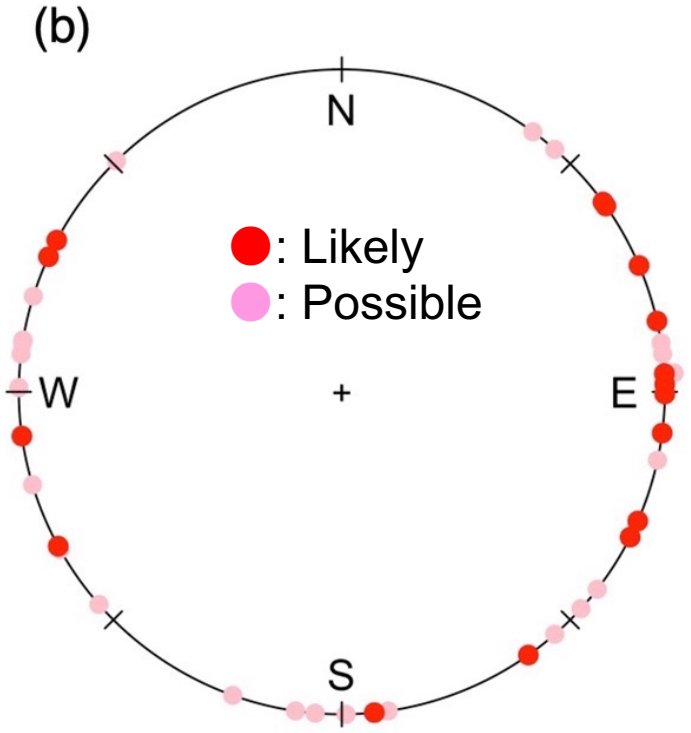




Properties are widely spread.
No clear trend was found

# 3.2 Orientation distribution

No statistically distinct difference from an isotropic distribution




Rao's spacing test

Rao (1969, 1976)

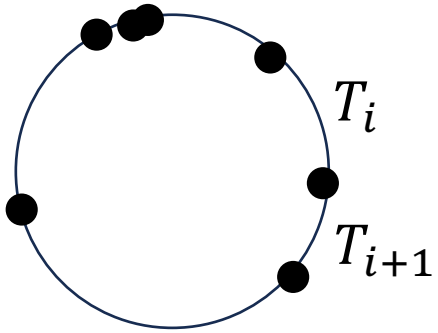
$p$ ~0.374 for Likely + Possible

$p$ ~0.075 for Likely

→ Not statistically significantly deviated from isotropic distribution

# NOTE: Rao's spacing test

Consider the deviation from the expected spacing




TEST STATISTIC

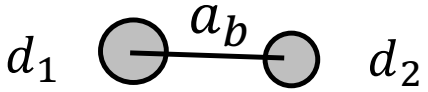
$$U = \frac{1}{2}\sum_{i=1}^{n}\left|T_i - \frac{2\pi}{n}\right|$$

- Null hypothesis in this study: the observed data comes from isotropic distribution.

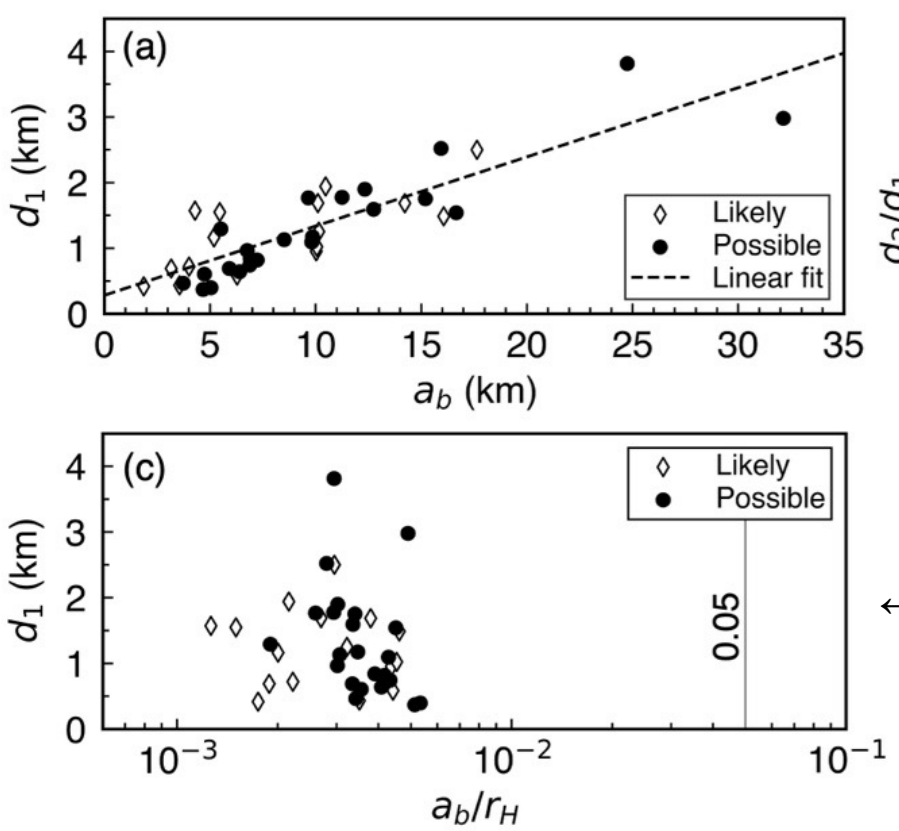
- If the multi-modality is really present,
  Rao's test is more powerful than the Rayleigh and
  Hodges' and Ajne's test for rejecting the randomness. Batschelet 1981

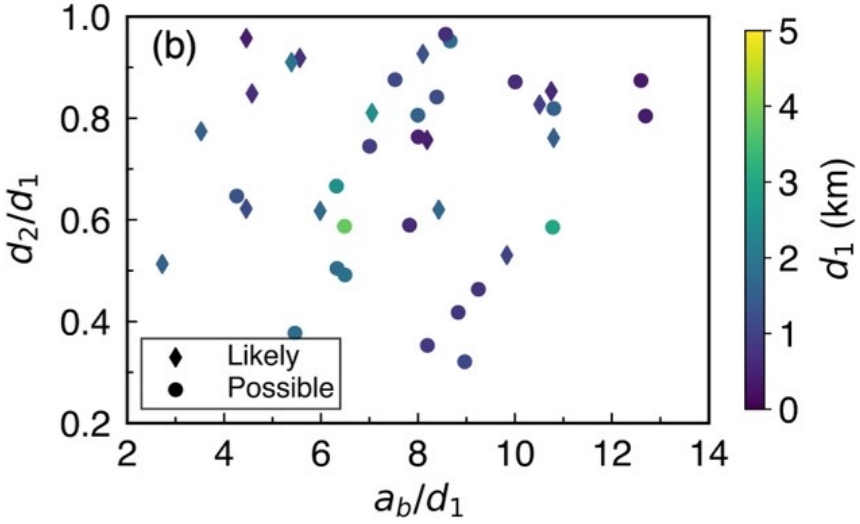
# 3.3 Properties of inferred binaries

km-sized binary




- Impacting binaries have $d_1$ <4.5 km and $a_b$ <35 km.
- In terms of $\underline{a_b/r_H}$, the inferred binaries are dynamically tight.
  measure of wideness in terms of the Hill radius, $r_H$




← Assuming the density of 500 kg m$^{-3}$ and
the heliocentric semi-major axis of 39.236 au (Pluto's semimajor axis)

# 4. Spatial analysis: Inclusion of the effect of binaries

**Implementation**

① The number of doublet pairs ~ $N_{crater} \times f_{bin} \times f_{doublet}$

- $N_{crater}$ : total number of craters
- $f_{bin}$ : **fraction of binaries that can form doublet craters**
- $f_{doublet}$ : fraction of binaries to result in doublet craters (here fixed to 15%)

② Diameter ratio $D_2/D_1$: uniform distribution 0.4-1

③ Separation $\Delta/D_1$ : uniform distribution 0-1.4

④ Orientation : uniform distribution 0-2$\pi$

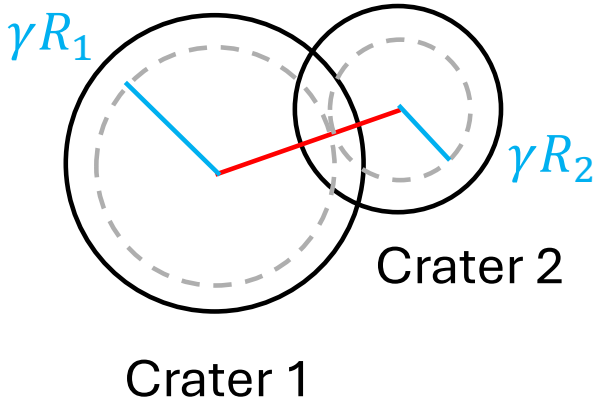
Simplest assumptions.
But the conclusion is the same with different distribution or thresholds.

⚠ Craters must be within Vulcan Planitia.

⚠ Secondaries must be $D_2$ >3 km.

# 4. Spatial analysis: a factor $\gamma$

The distance between
two craters must be $\geq \boldsymbol{\gamma}(R_1 + R_2)$.



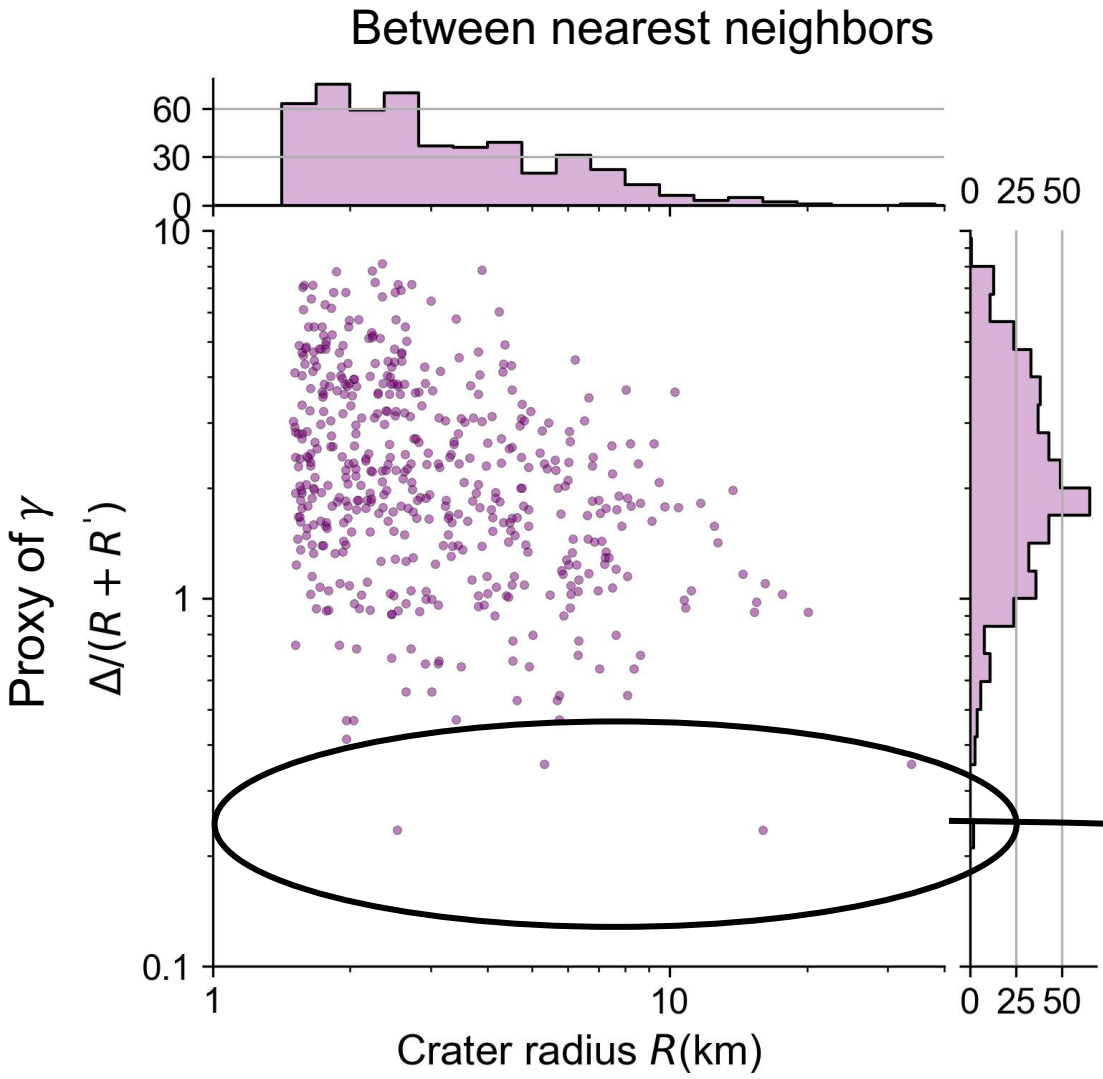

Conceptually,

$\gamma = 0$ : Poisson process (craters can form anywhere and can fully overlap).
$0 < \gamma < 1$ : Partial overlapping is allowed but occur near the edge of craters.
$\gamma = 1$ : Craters are like woods. No overlapping.

1. Assign locations (lon, lat) for each crater.
2. If the distances are $\geq \gamma(R_1 + R_2)$ with all pre-existing craters,
   this candidate is placed as a new crater.
3. If the distance between a pre-existing crater and the candidate is $< \gamma(R_1 + R_2)$,
   the candidate is too close to a pre-existing crater.
   → Go back to (1), assign a new location for this candidate crater.

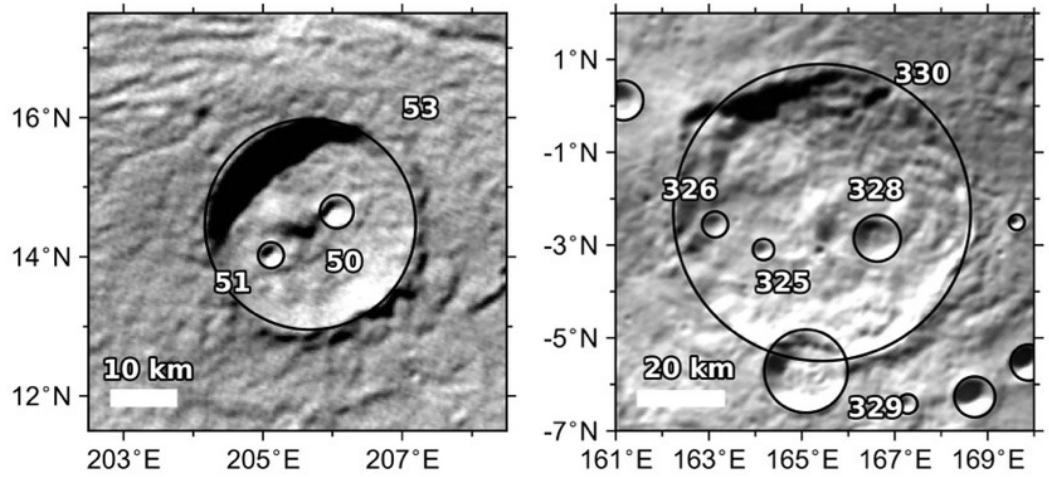
# 4. Spatial analysis: viable range of a factor $\gamma$

The distance between two craters must be $\boldsymbol{\gamma}(R + R')$.




Small $\gamma$ happens when
(i) two similarly sized craters significantly overlap
or
(ii) a smaller crater lies near the center of a much larger one

- In Vulcan Planitia, $\gamma$ >~0.3-0.4.
  …Except for these craters with $\gamma$ ~0.1-0.2 with the reason (i).



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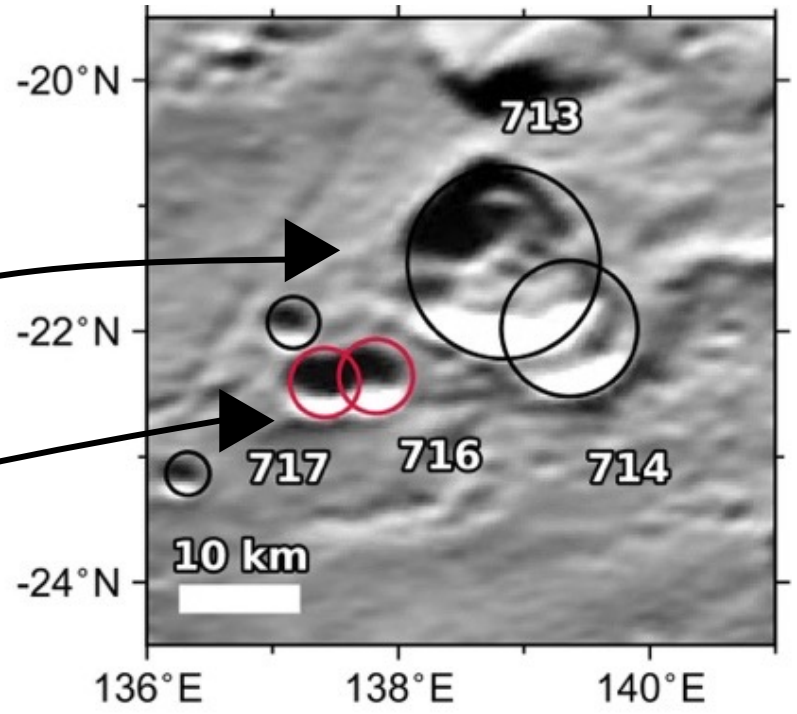
(i) two similarly sized craters significantly overlap
or
(ii) a smaller crater lies near the center of a much larger one

- In Vulcan Planitia, $\gamma >\sim 0.3$-$0.4$.
  …Except for these craters with $\gamma \sim 0.1$-$0.2$ with the reason (i).

This crater pair overlaps significantly.
But $\gamma = 0.55$.

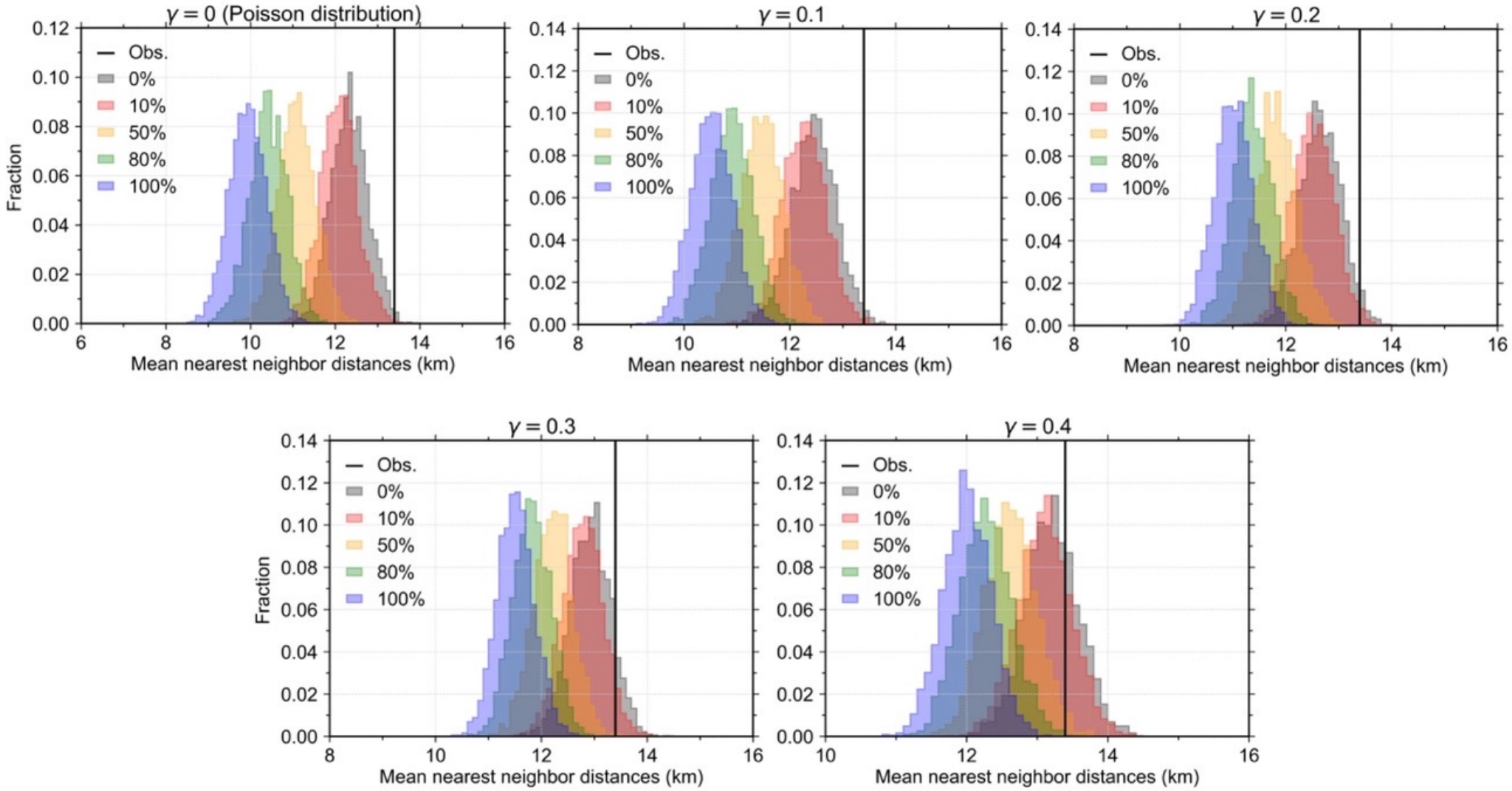
This is a pair categorized as “likely”,
with $\gamma = 0.67$.



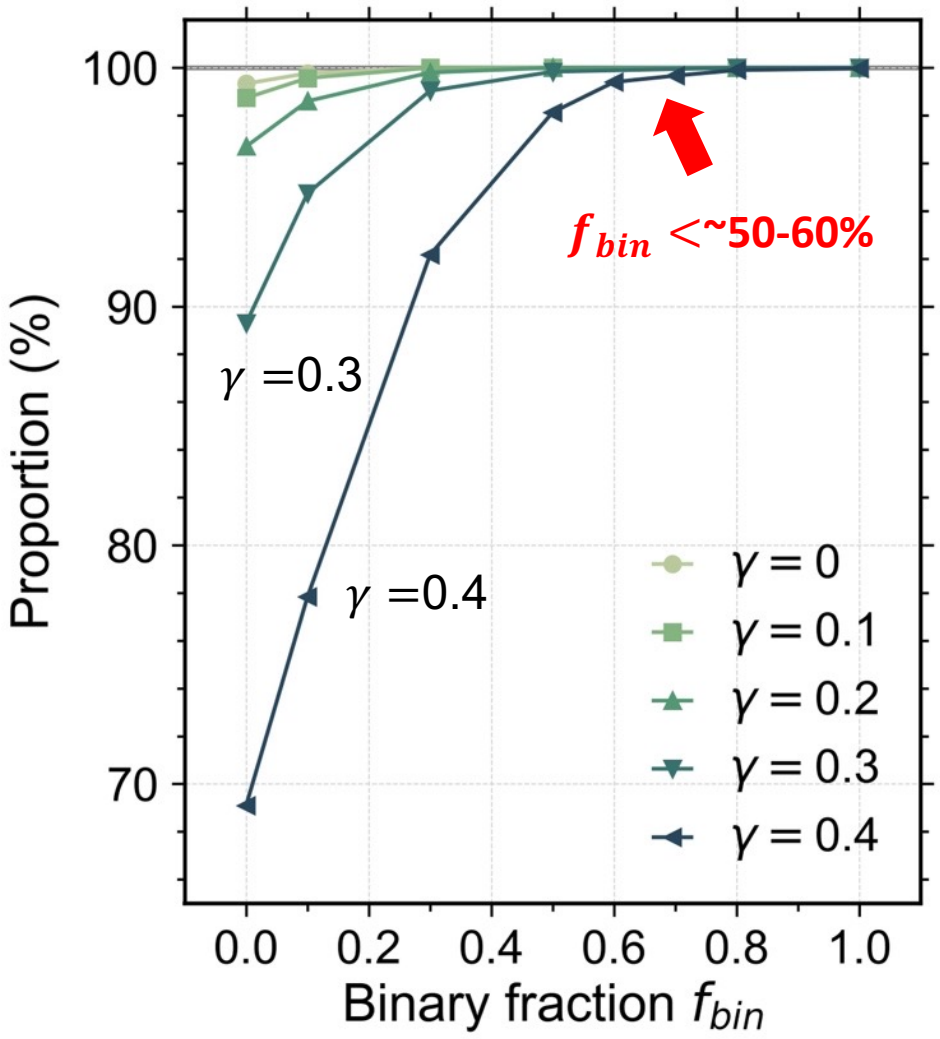
# 4. Spatial analysis

$\overline{x_{\mathrm{obs}}}$ comes near the right edge of histograms
→ the observed distribution is more uniform than expected

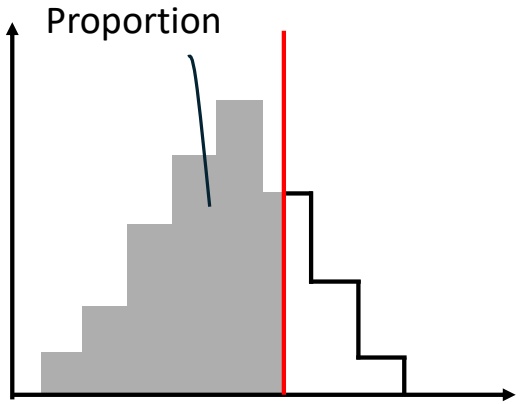
Consistent with Noviello+2025



# 4. Spatial analysis: $f_{bin}$ <50-60%

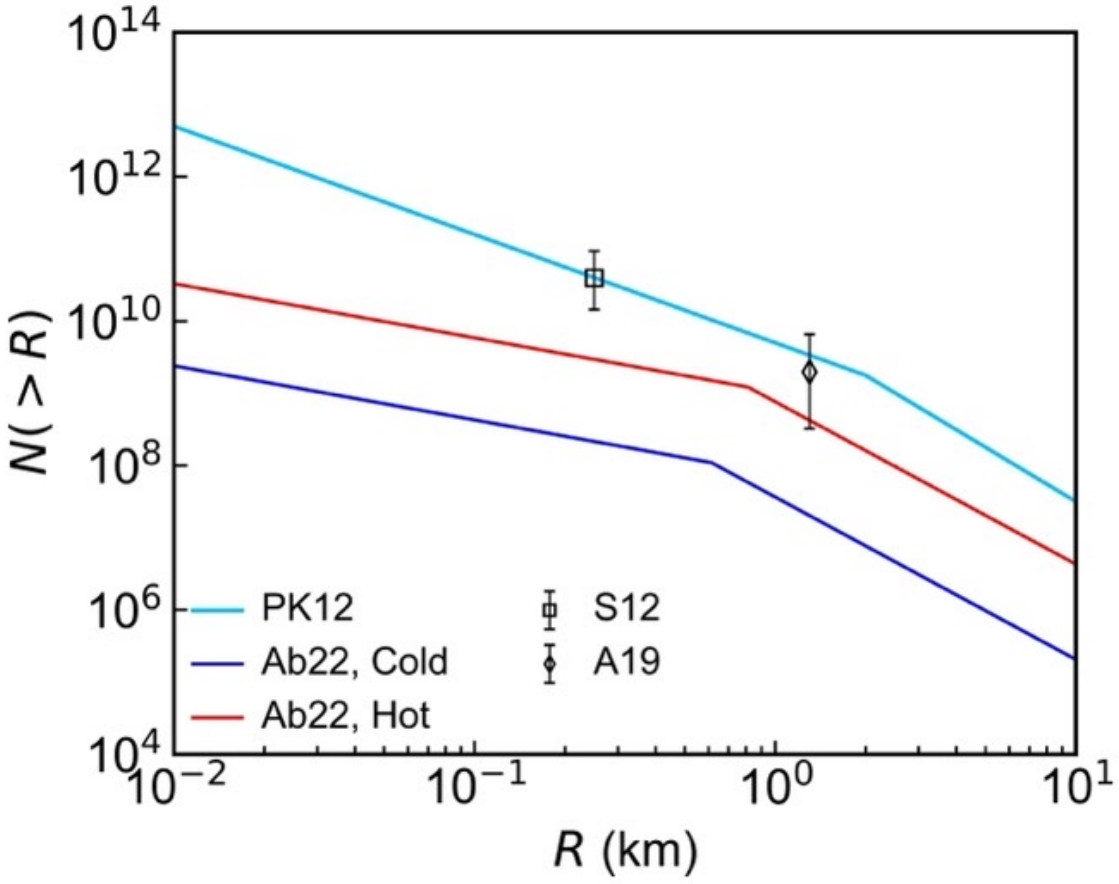



- Large $f_{bin}$ (~80-100%) is unlikely with various $\gamma$.
  …the upper limit is 50-60%
- Low $f_{bin}$ (~0-20%) can explain the observed distribution well and thus likely.



# 5 Collisional evolution

SFDs used



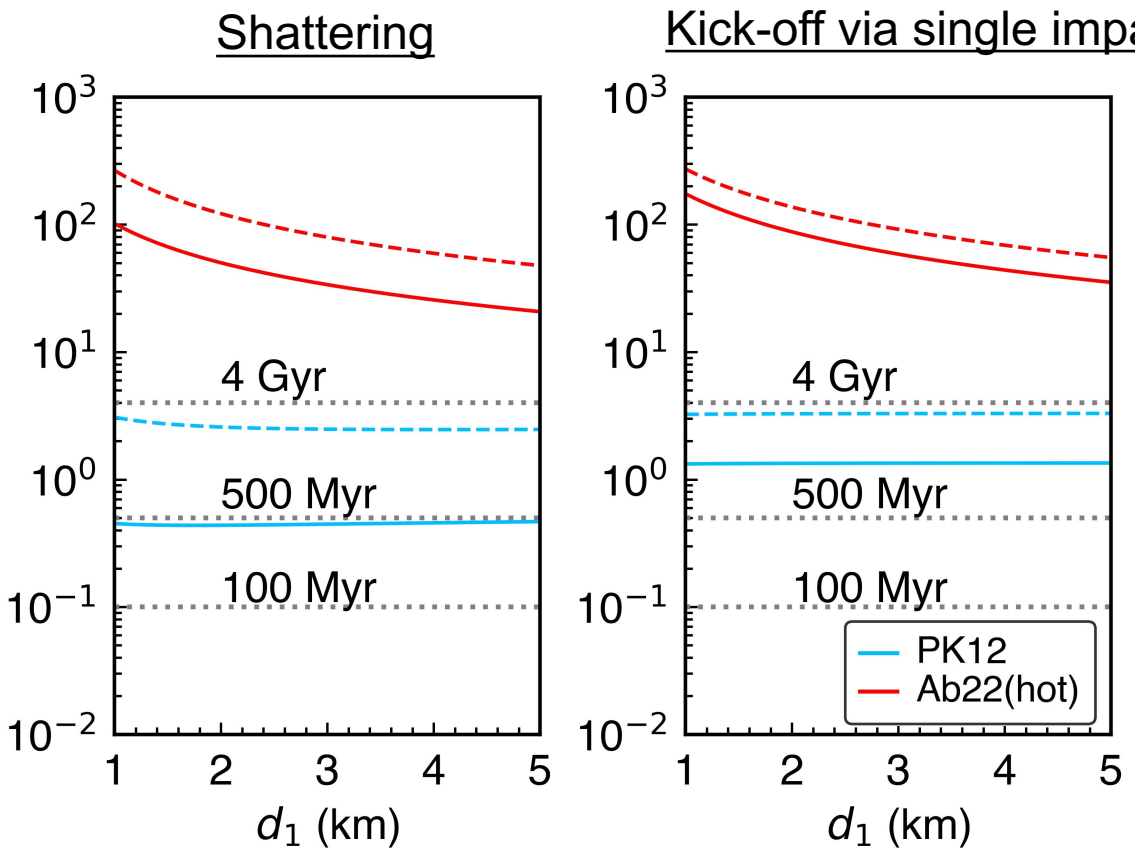

| Abb. | |
|---|---|
| PK12 | Parker & Kavelaars, 2012 |
| Ab22 | Abedin+2022 |
| A19 | Arimatsu+2019 |
| S12 | Schlichting+2012 |

Hot = sum of dynamically excited populations
Cold = the cold classical TNOs

# 5, Collisional evolution

- Binaries can survive for 4 Gyr?
  …depends on parameters.
  but likely able to survive with the SFD from Abedin+2022.

based on recent observations



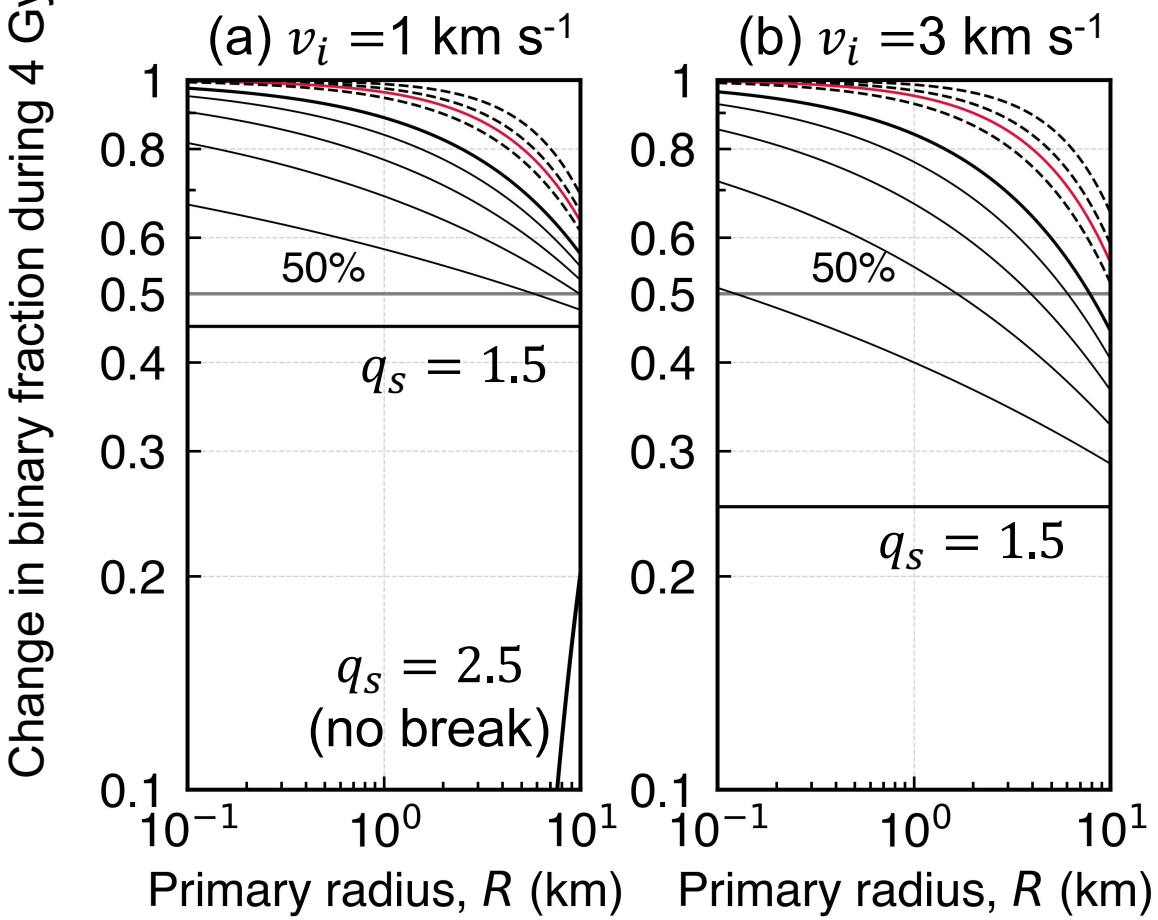

- $\rho$ =500 kg m$^{-3}$
- $P_i$ =4×10$^{-22}$ km$^{-2}$ yr$^{-1}$
- Equally-sized binaries

- - $v_i$ =0.5 km s$^{-1}$
— $v_i$ =3 km s$^{-1}$

Davis & Farinella 1997, Dell'Oro+2001)

# 5, Collisional evolution

Based on the model from Parker & Kavelaars 2012
(This calculation was with the SFD from Parker & Kavelaars 2012)




- Binary fraction may not be changed through time.

…if binary formation was efficient, high binary fraction can be maintained

# Summary

**Motivation**

Trans-neptunian region is very distant and ground observation of km- and equally-sized, widely-separated binaries is highly challenging

**What we did**

- Search for doublet craters in Vulcan Planitia on Charon
- Visual inspection and Monte Carlo simulations are performed

**What we found**

- 39 pairs/483 craters ~8 % were categorized as “Likely” and “Possible”
  → **At most ~54%** could be km-, equally-sized, widely-separated binaries
- Crater spatial distribution in Vulcan Planitia is relatively uniform than expected from random with/without binaries.
  → **At most ~50-60%** could be km-, equally-sized, widely-separated binaries but likely less.

**Discussion**

- High binary rate could be maintained if km-sized TNOs are less populated and the SFD is very shallow
- Massive disk should have been dispersed early if they are primordial.