「A big bonus:
火星から火星衛星への物質輸送」

Hyodo et al. (2019) Scientific Reports

「地球潮汐によってアシストされる
月揮発性元素の枯渇」

Charnoz,.. Hyodo,.. Nature Geo, under review

A big bonus:

火星から火星衛星への物質輸送

MMXを盛り上げる為の研究

火星の衛星表面から”火星地表のサンプル”を採取できる可能性が示される

1/18(土) 11:25配信

宇宙へのポータルサイト sorae

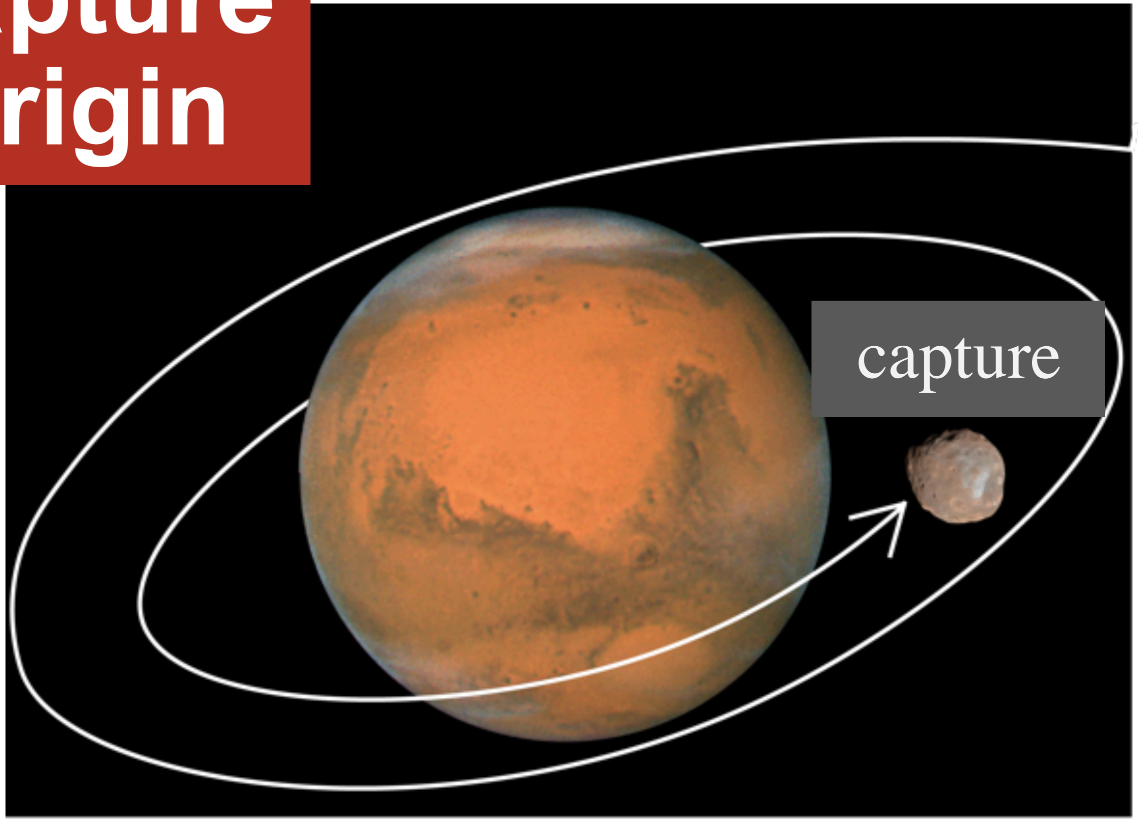
現在、宇宙航空研究開発機構（JAXA）では、火星の衛星表面からのサンプル採取と回収を目指す「火星衛星探査計画（MMX：Mars Moons eXploration）」を進めています。今回、火星の衛星から火星そのものの地表サンプルを間接的に採取できる可能性を示した研究成果が発表されました。

兵頭龍樹（ITYF）
JAXA
with H. Genda, T. Usui, K. Fujita, K. Kurosawa, H. Sugahara

Two Leading Hypothesis

Dark & Featureless: D-tyep?

capture origin

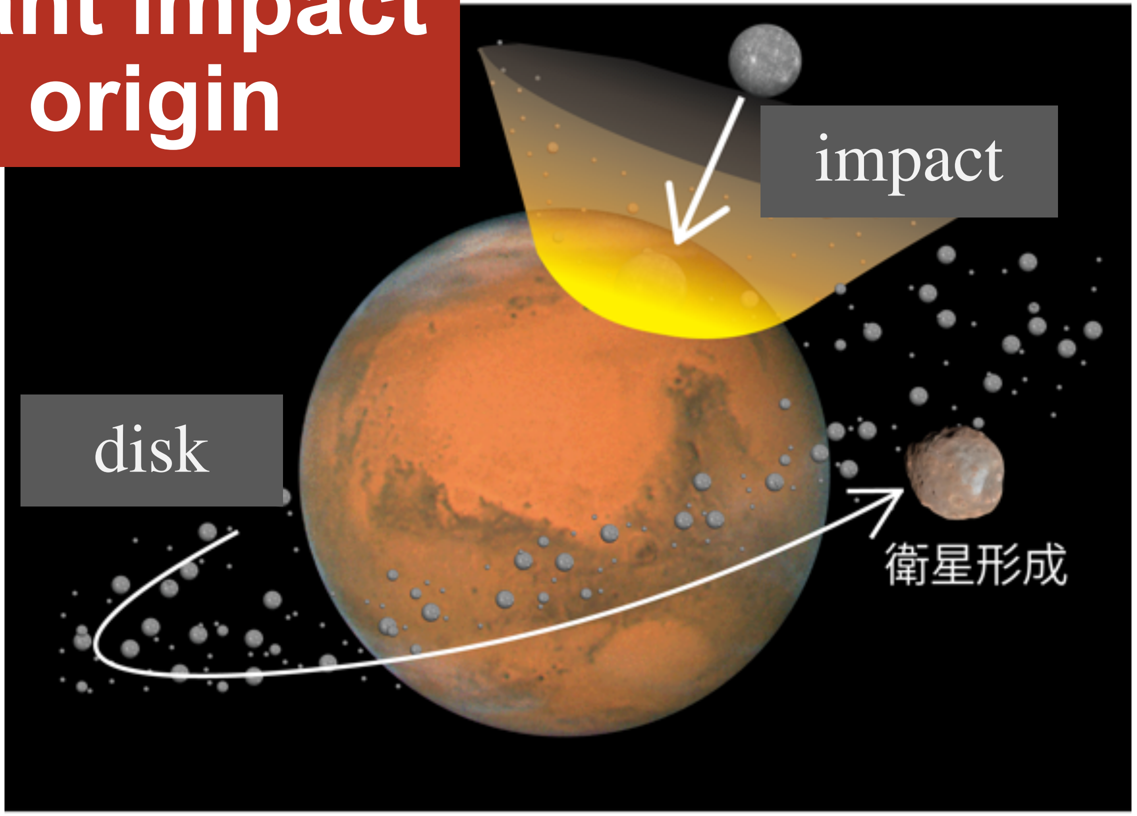


supported by spectral features

Burns (1978)
Murchie et al. (1991)

Circular & Equatorial

giant impact origin



supported by orbital elements

Craddock (1994, 2011)
Citron et al. (2015)
Rosenblatt et al. (2016)
Hesselbrock & Minton (2017)
Hyodo et al. (2017ab, 2018b)
Canup & Salmon (2018)

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Circular & Equatorial

cap
or

You can forget about this during my talk

supported by spectral features

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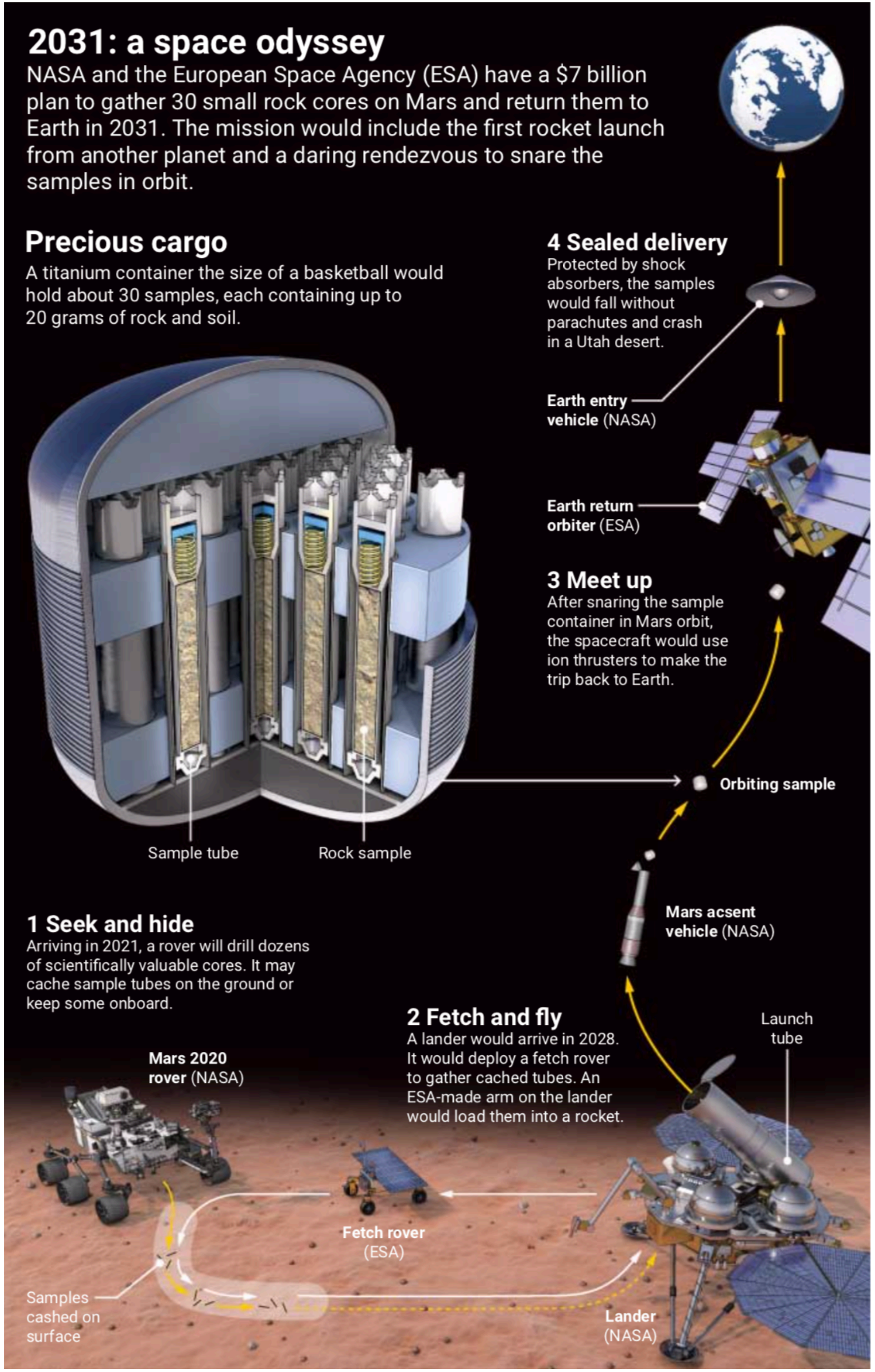
Mars system exploration



2031: a space odyssey

NASA and the European Space Agency (ESA) have a $7 billion plan to gather 30 small rock cores on Mars and return them to Earth in 2031. The mission would include the first rocket launch from another planet and a daring rendezvous to snare the samples in orbit.

Precious cargo

A titanium container the size of a basketball would hold about 30 samples, each containing up to 20 grams of rock and soil.

4 Sealed delivery

Protected by shock absorbers, the samples would fall without parachutes and crash in a Utah desert.

3 Meet up

After snaring the sample container in Mars orbit, the spacecraft would use ion thrusters to make the trip back to Earth.

1 Seek and hide

Arriving in 2021, a rover will drill dozens of scientifically valuable cores. It may cache sample tubes on the ground or keep some onboard.

2 Fetch and fly

A lander would arrive in 2028. It would deploy a fetch rover to gather cached tubes. An ESA-made arm on the lander would load them into a rocket.

C. BICKEL/*SCIENCE*; MARS 2020 ROVER MODEL/NASA/JPL-CALTECH

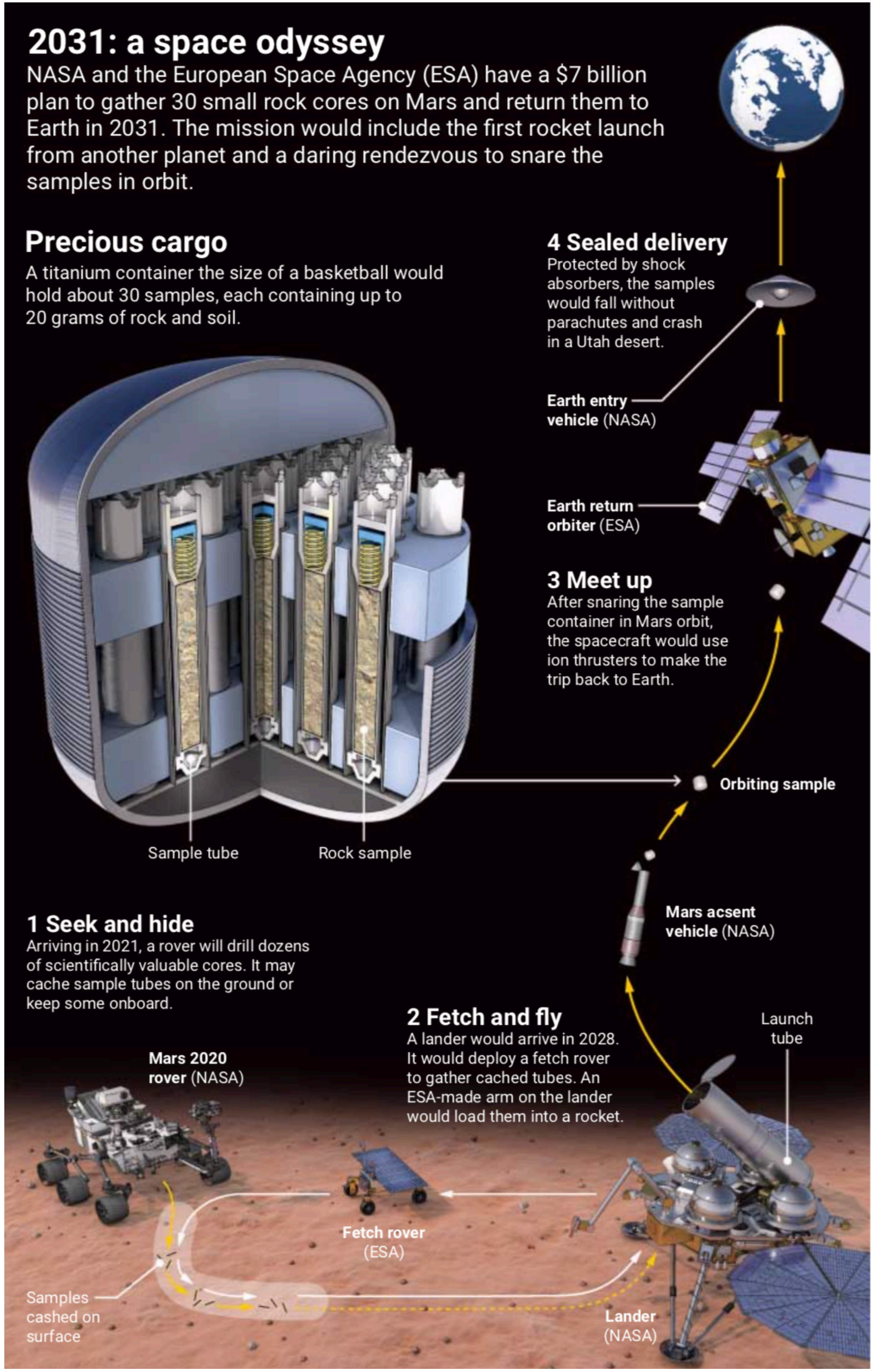
Mars 2020

- Combination of several missions
- Sample from Jezero crater
- 2020-2031(?) mission

MMX

- Sample from Phobos
- 2024-2029 mission

Mars system exploration



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C. BICKEL/*SCIENCE*; MARS 2020 ROVER MODEL/NASA/JPL-CALTECH

Mars 2020

- Combination of several missions
- Sa r
- 2020-2031(?) mission

Mars science

MMX

- S from Phobos
- 202

Martian moon science

Two days ago:
Finally, I can say it’s Phobos!

JAXA、目指すは「フォボス」　火星の衛星、無人探査機の計画

2/19(水) 0:04配信

KYODO

宇宙航空研究開発機構（JAXA）が火星を回る二つの衛星のいずれかに無人探査機を着陸させ、岩石試料を持ち帰ることを目指す世界初の計画「MMX」で、目指す衛星を「フォボス」に決めたことが18日分かった。2024年の出発を目指す。

19日の文部科学省の宇宙開発利用部会で報告する。小惑星への着陸や試料持ち帰りで実績のあるはやぶさ初号機、2号機の経験を生かす。

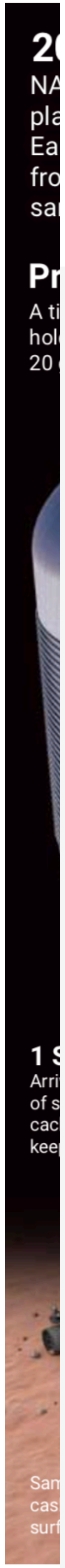
米国の火星探査機が2008年に撮影した衛星「フォボス」（NASA提供）

もう一方の衛星「ダイモス」も候補だったが、着陸に必要なデータが多いことや、探査の意義がより大きいことなどからフォボスを選んだ。

missions

r

science



JAXA、目指すは「フォ
画

2/19(水) 0:04配信

米国の火星探査機が2008年に撮影した衛星「フォボス」（NASA提供）

の
料
で
分
る
や

もう一方の衛星「ダイモス」も
や、探査の意義がより大きいことなどからフォボスを選んだ。

prs***** | 10時間前

フォボスとダイモスを比較検討の表とか、結論に至る議論が知りたい。

▼ 返信 0 👍3 👎1

sak***** | 7時間前

他の惑星の重力圏からのサンプルリターンはすごい

▼ 返信 0 👍1 👎0

hogex | 8時間前

ロマンがある。
無人探査機なら人命にかかわらないからどんどんやってほしいです。

▼ 返信 0 👍1 👎1

No more ABE | 9時間前

なんの目的でフォボス？

素直に火星で、十分有意義ではと思うが。

▼ 返信 0 👍1 👎7

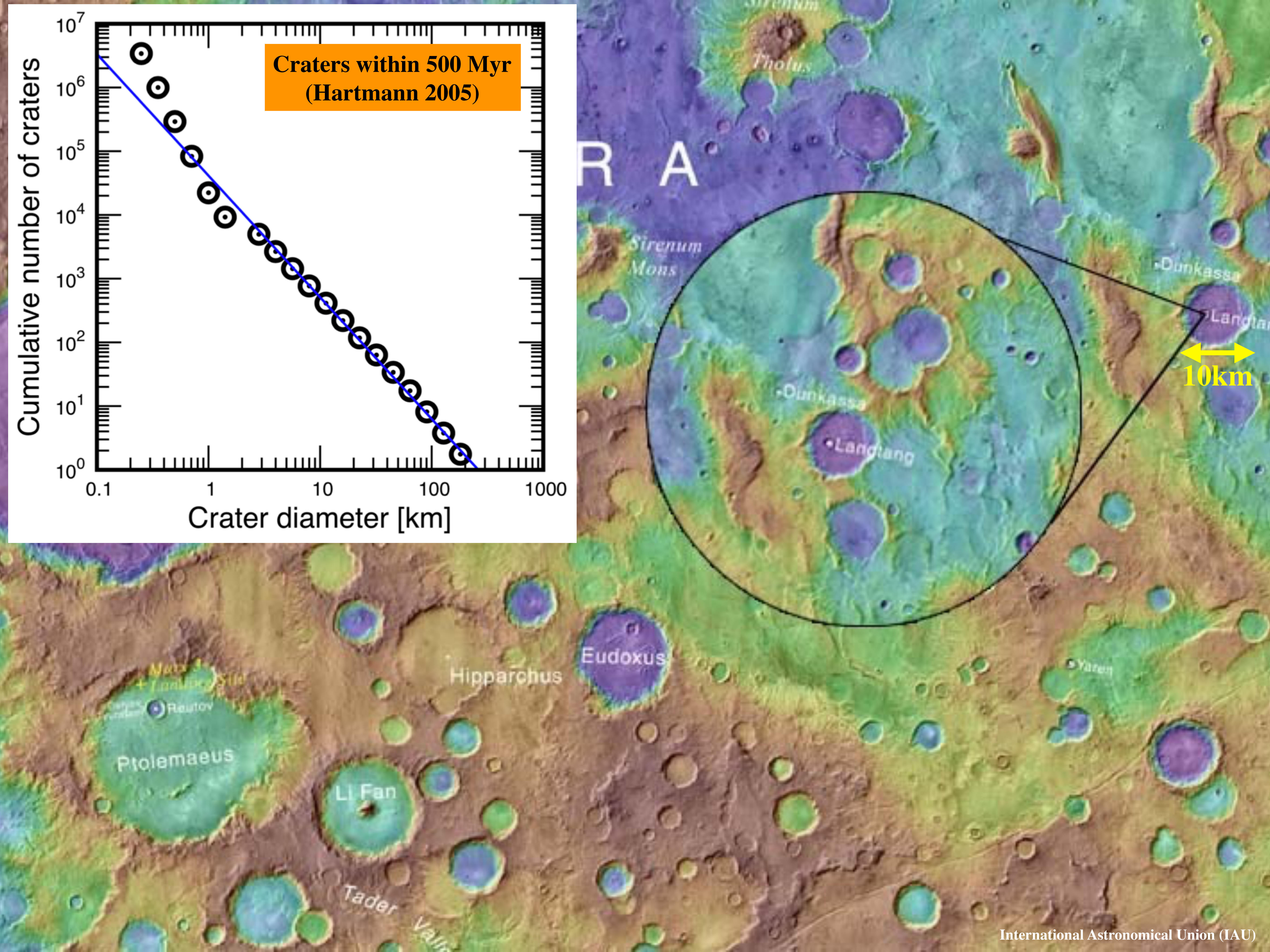
ggn***** | 10時間前

ダイモス、ダイモス闘将ダイモス〜♪
あ、今回はフォボスなのね♪
マーズダイレクトの露払いなのかしら？
タイタンだと星を継ぐものなんだけどね、もうちょい未来なのね(^—^)

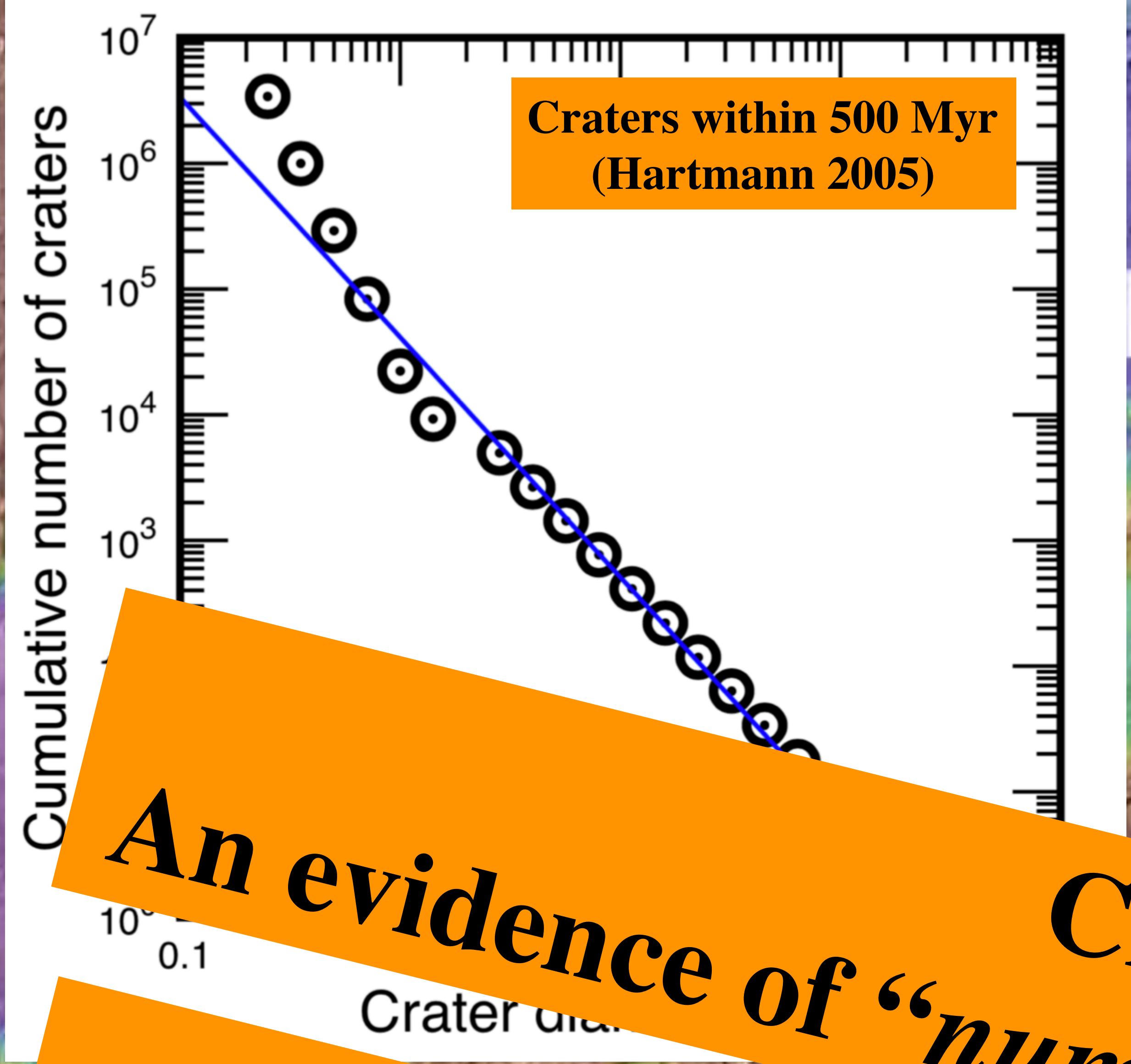
▼ 返信 0 👍2 👎0

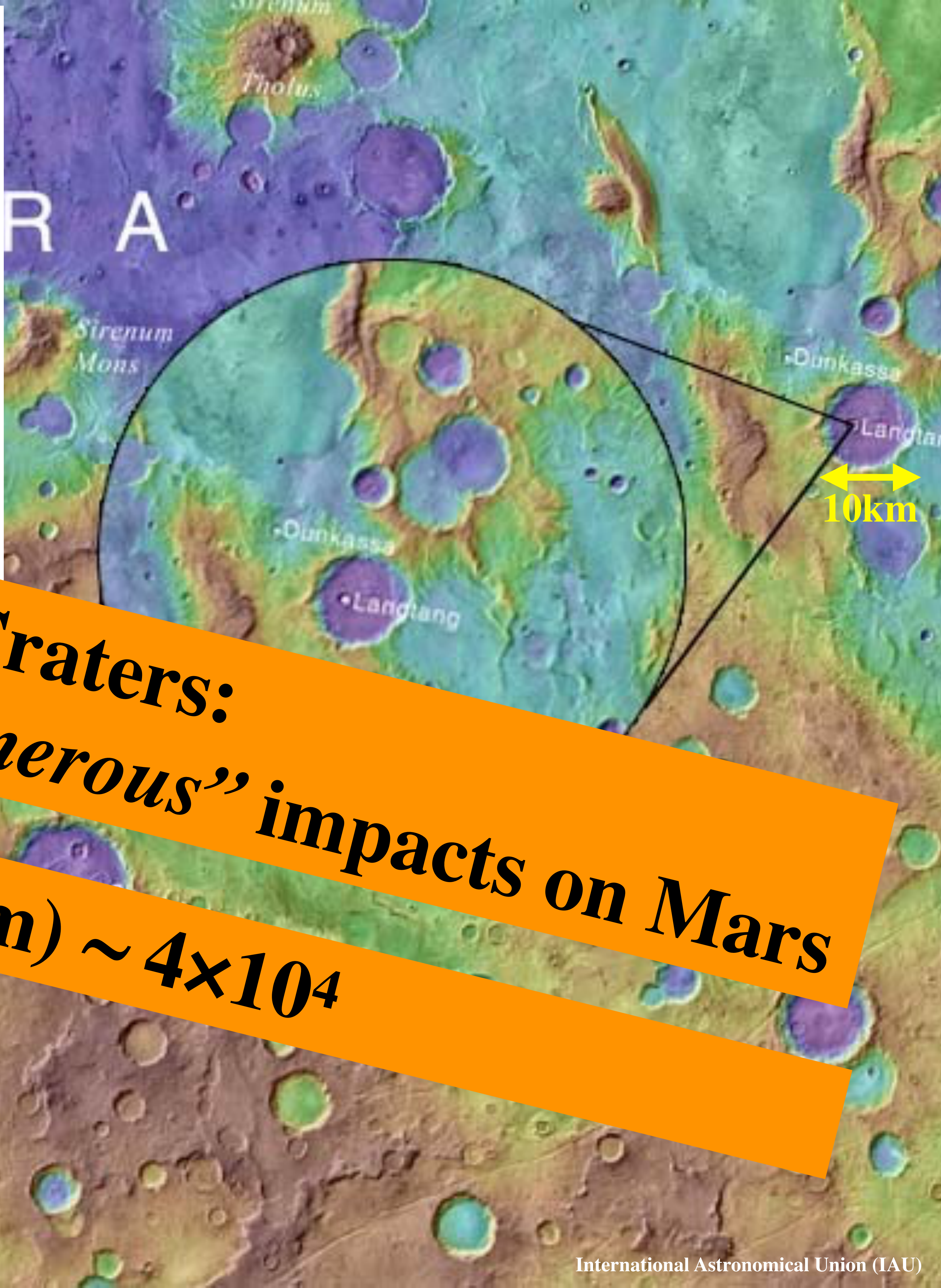
Why Phobos?

Why not Mars?



International Astronomical Union (IAU)





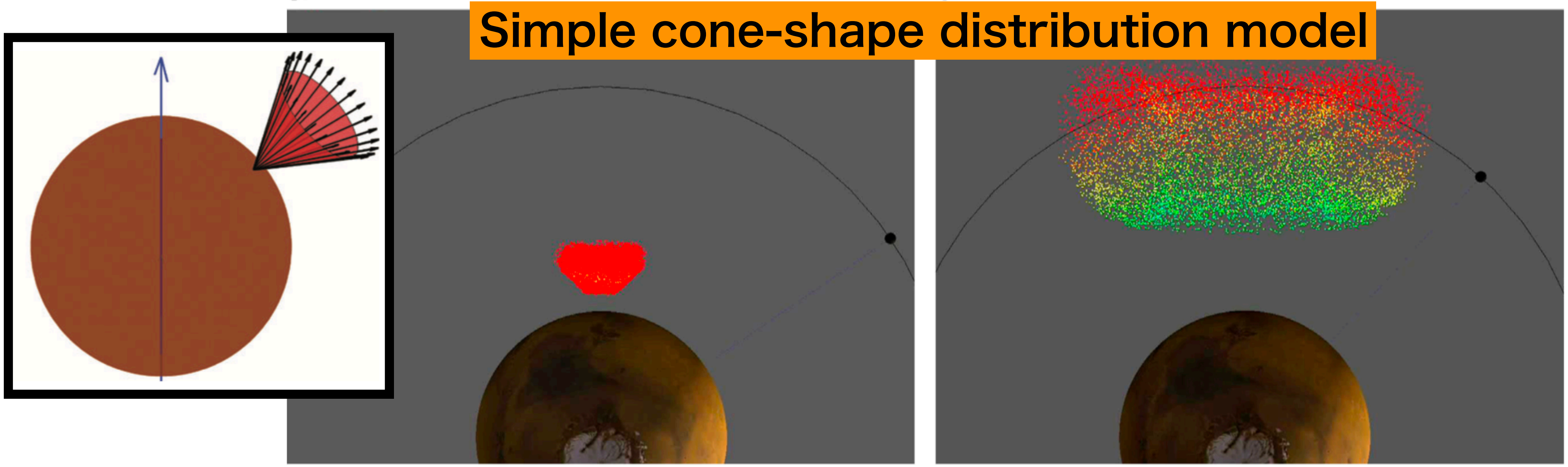
International Astronomical Union (IAU)

Craters:

An evidence of “*numerous*” impacts on Mars

$N(>1\text{km}) \sim 4\times10^4$

Impact ejecta from Mars to its moons

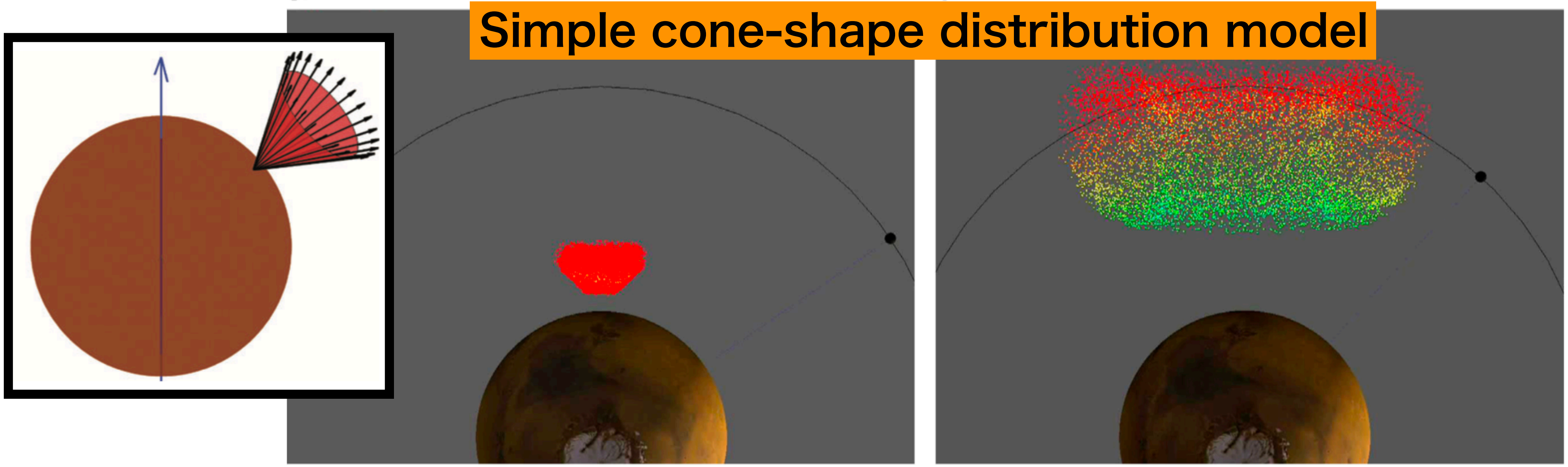


Simple cone-shape distribution model

Chappaz et al. (2013), Ramsley&Head (2013)

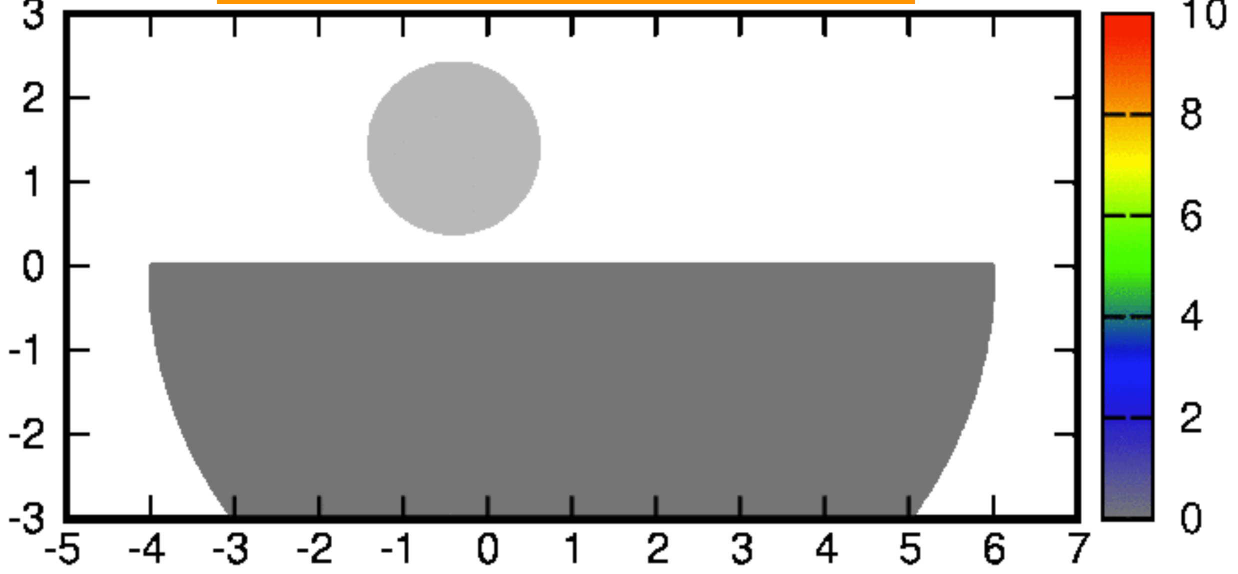
Impact ejecta from Mars to its moons

Simple cone-shape distribution model



Chappaz et al. (2013), Ramsley&Head (2013)

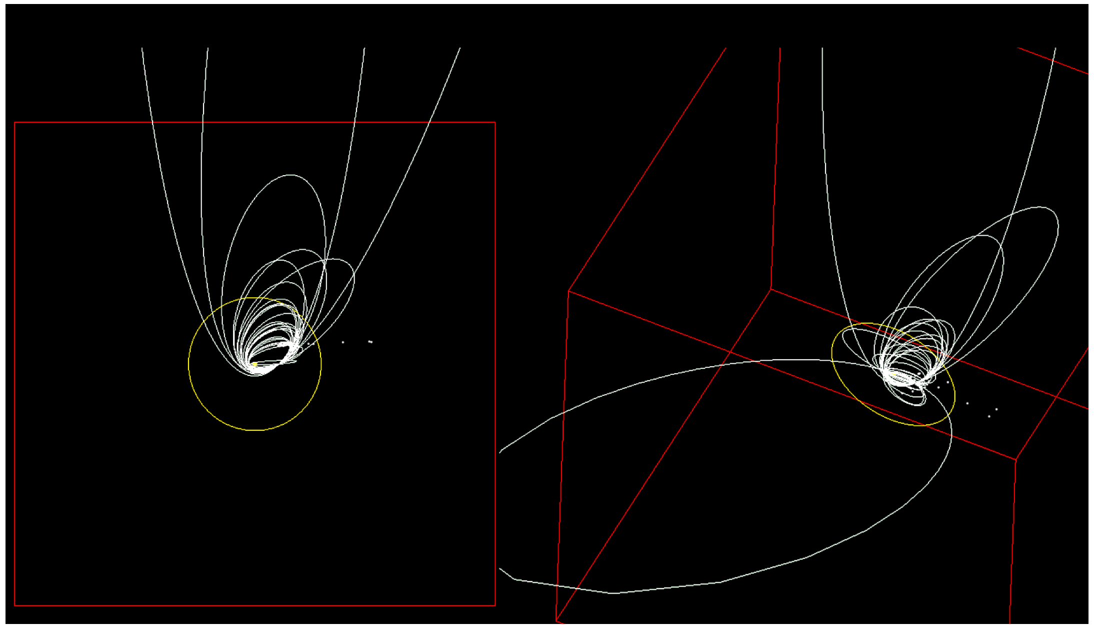
3D SPH simulations



e.g. v_{imp}=12km/s, θ=45deg

×

Orbital calculations



Hyodo et al. (2019) SciRep

A Big Bonus on Phobos sample I

Significant update of the impact ejecta from Mars to its moons

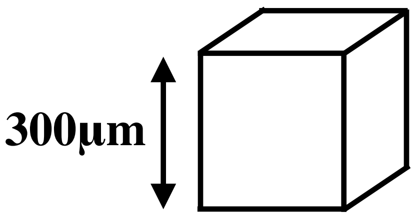
✦**10-100 times larger** in mass than the previous estimation (Chappaz et al. 2013 Ramsley&Head 2013)

✦Total of ~1000 ppm Mars fraction in Phobos regolith

↪ **more than 34 Martian particles in 10 g sample *(median value)***

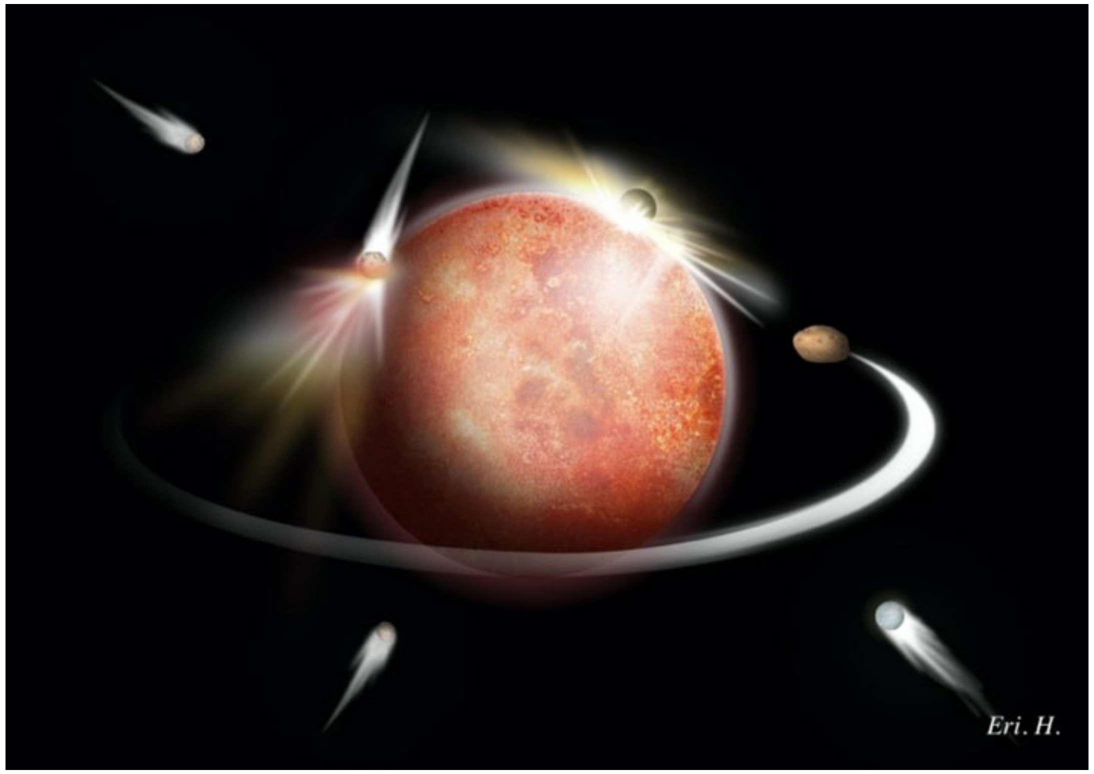
A statistical argument

Cubic Martian particles



SCIENTIFIC REPORTS

natureresearch



OPEN

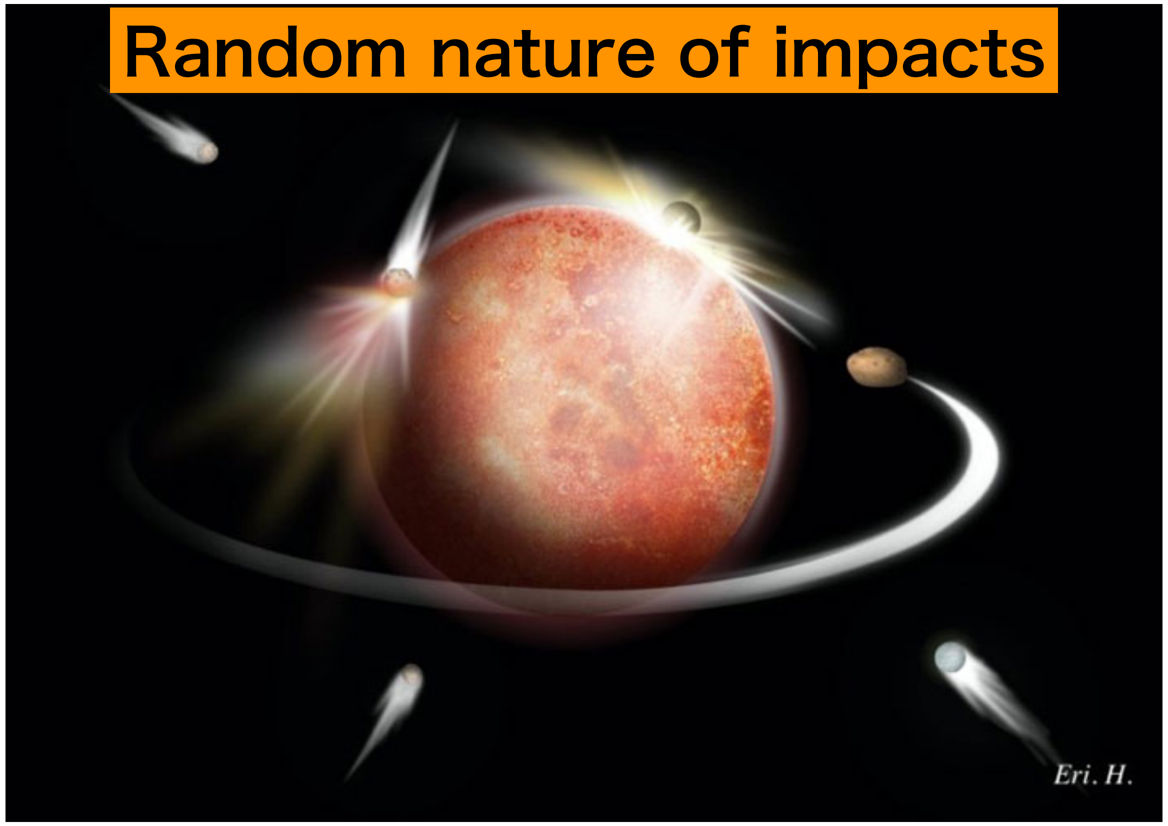
Transport of impact ejecta from Mars to its moons as a means to reveal Martian history

Ryuki Hyodo[1,2]*, Kosuke Kurosawa[3], Hidenori Genda[2], Tomohiro Usui[1] & Kazuhisa Fujita[1]

Throughout the history of the solar system, Mars has experienced continuous asteroidal impacts. These impacts have produced impact-generated Mars ejecta, and a fraction of this debris is delivered to Earth as Martian meteorites. Another fraction of the ejecta is delivered to the moons of Mars, Phobos and Deimos. Here, we studied the amount and condition of recent delivery of impact ejecta from Mars to its moons. Using state-of-the-art numerical approaches, we report, for the first time, that materials delivered from Mars to its moons are physically and chemically different from the Martian meteorites, which are all igneous rocks with a limited range of ages. We show that Mars ejecta mixed in the regolith of its moons potentially covers all its geological eras and consists of all types of rocks, from sedimentary to igneous. A Martian moons sample-return mission will bring such materials back to Earth, and the samples will provide a wealth of "time-resolved" geochemical information about the evolution of Martian surface environments.

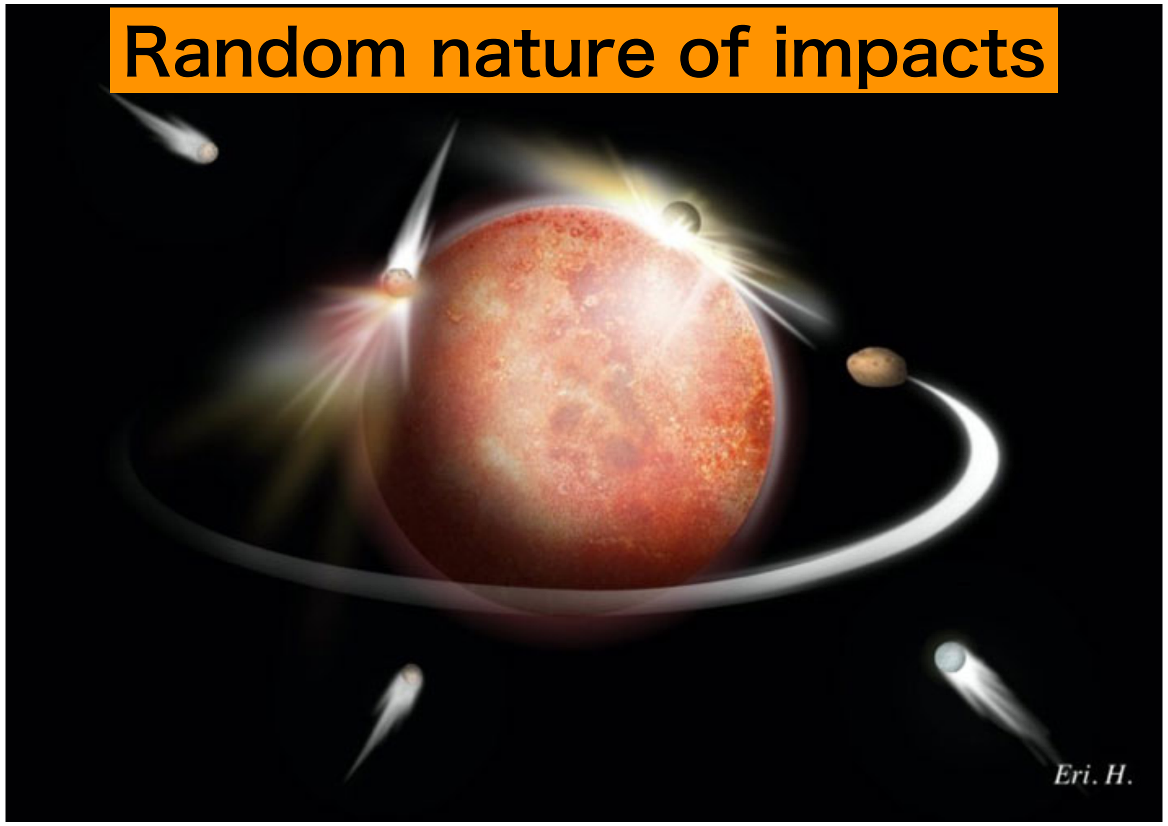
A Big Bonus on Phobos sample II

Hyodo et al. 2019, SciRep



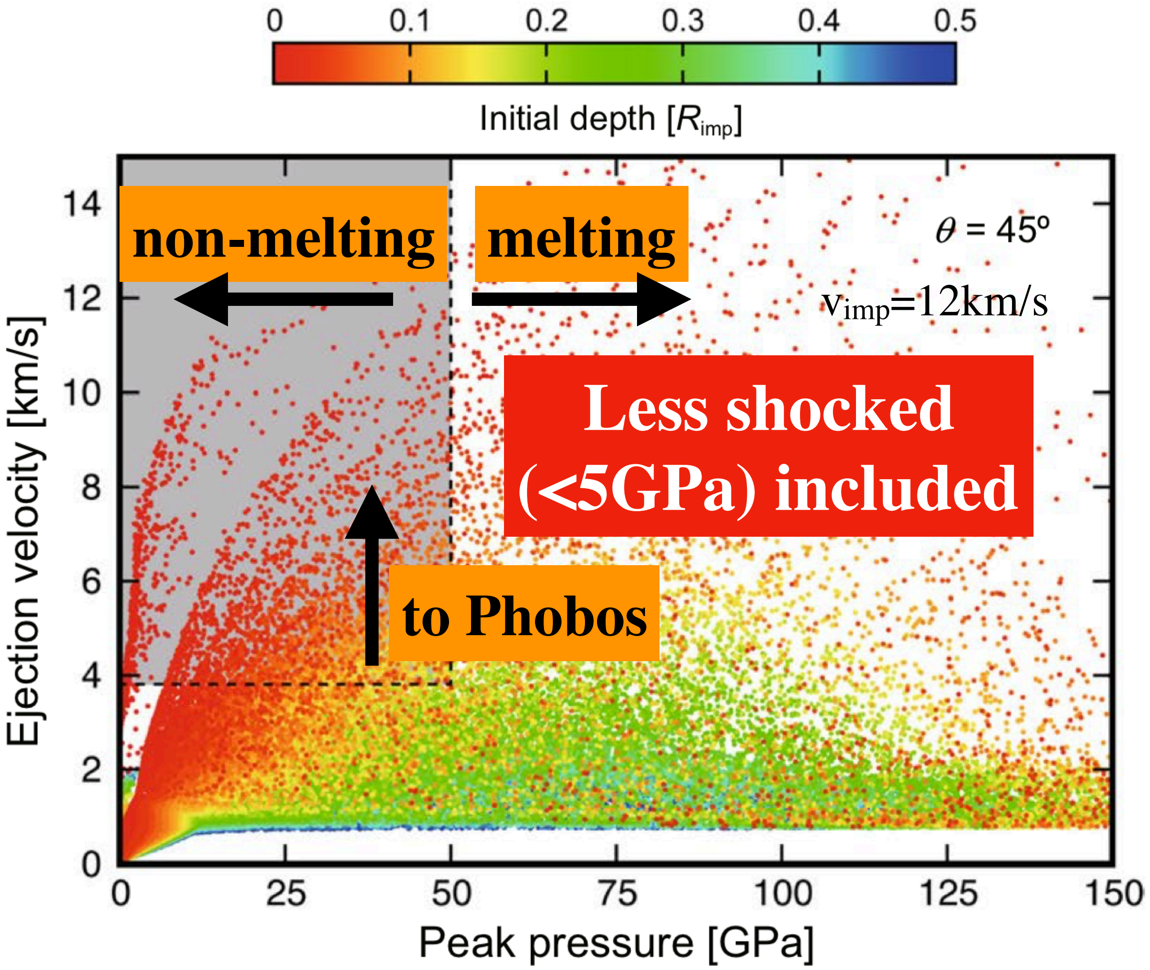
A Big Bonus on Phobos sample II

Hyodo et al. 2019, SciRep



Random nature of impacts

×



non-melting

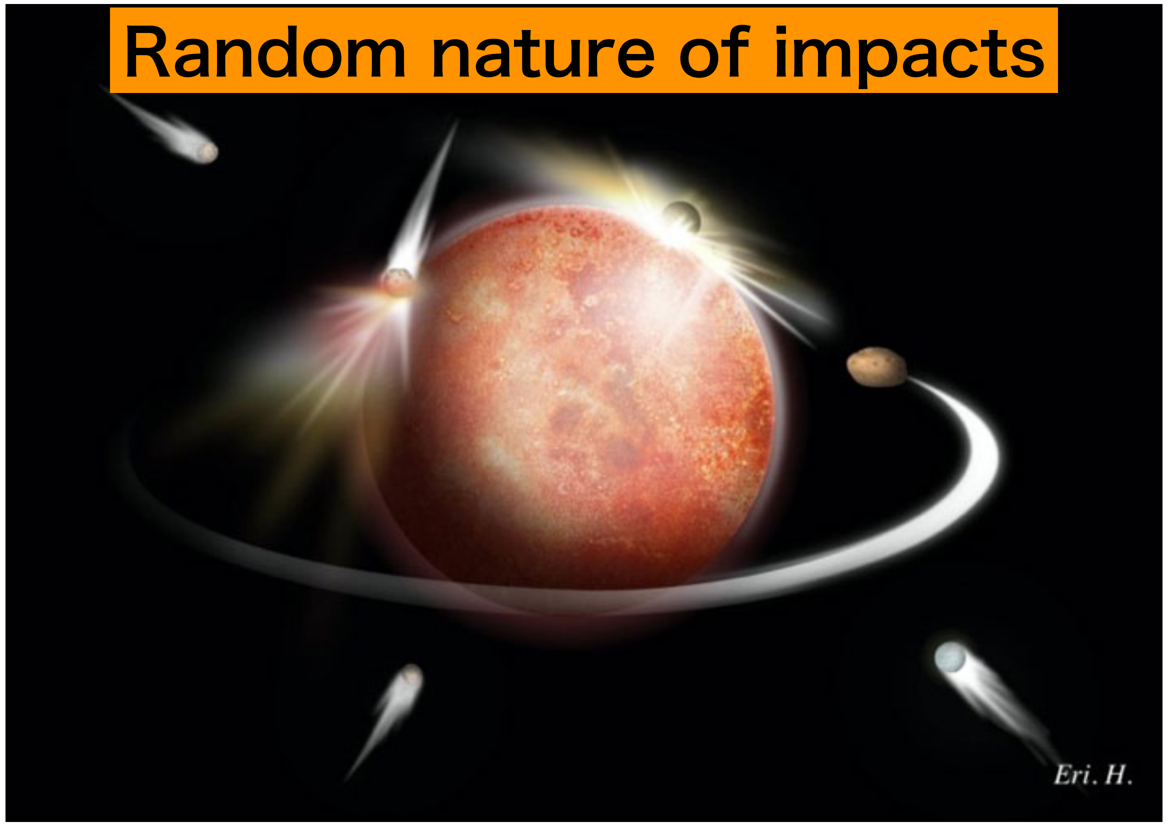
melting

Less shocked (<5GPa) included

to Phobos

A Big Bonus on Phobos sample II

Hyodo et al. 2019, SciRep



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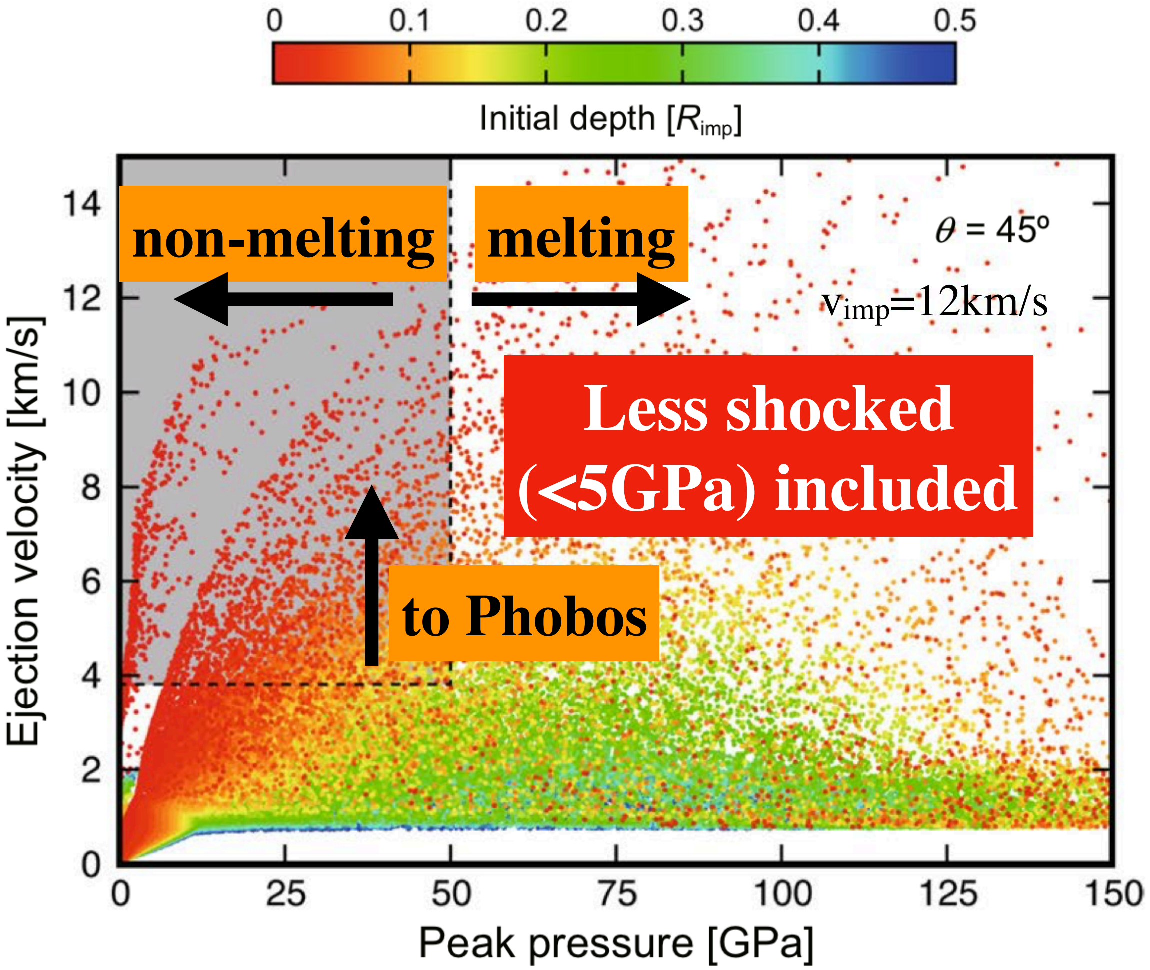


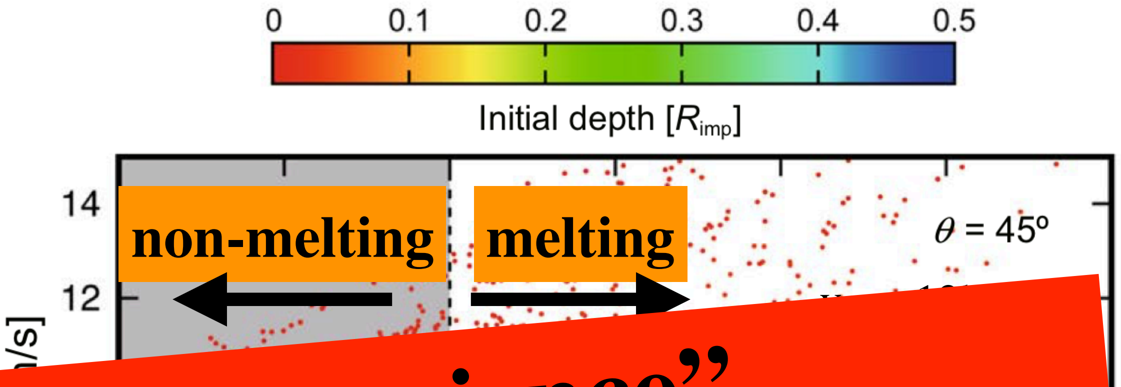
cf. Martian meteorites:

- all igneous rocks
- mostly young (<1.3Ga)
- relatively shocked (>5GPa)

Phobos sample potentially covers all its geological eras and consists of all types of rocks, from sedimentary to igneous

A Big Bonus on Phobos sample II

Hyodo et al. 2019, SciRep



MMX is *not* just “Mars moon science”

↓

“Mars system science” (and the 1st MSR!?)

↪that can “time-resolve” geochemical information about the evolution of Martian surface environments

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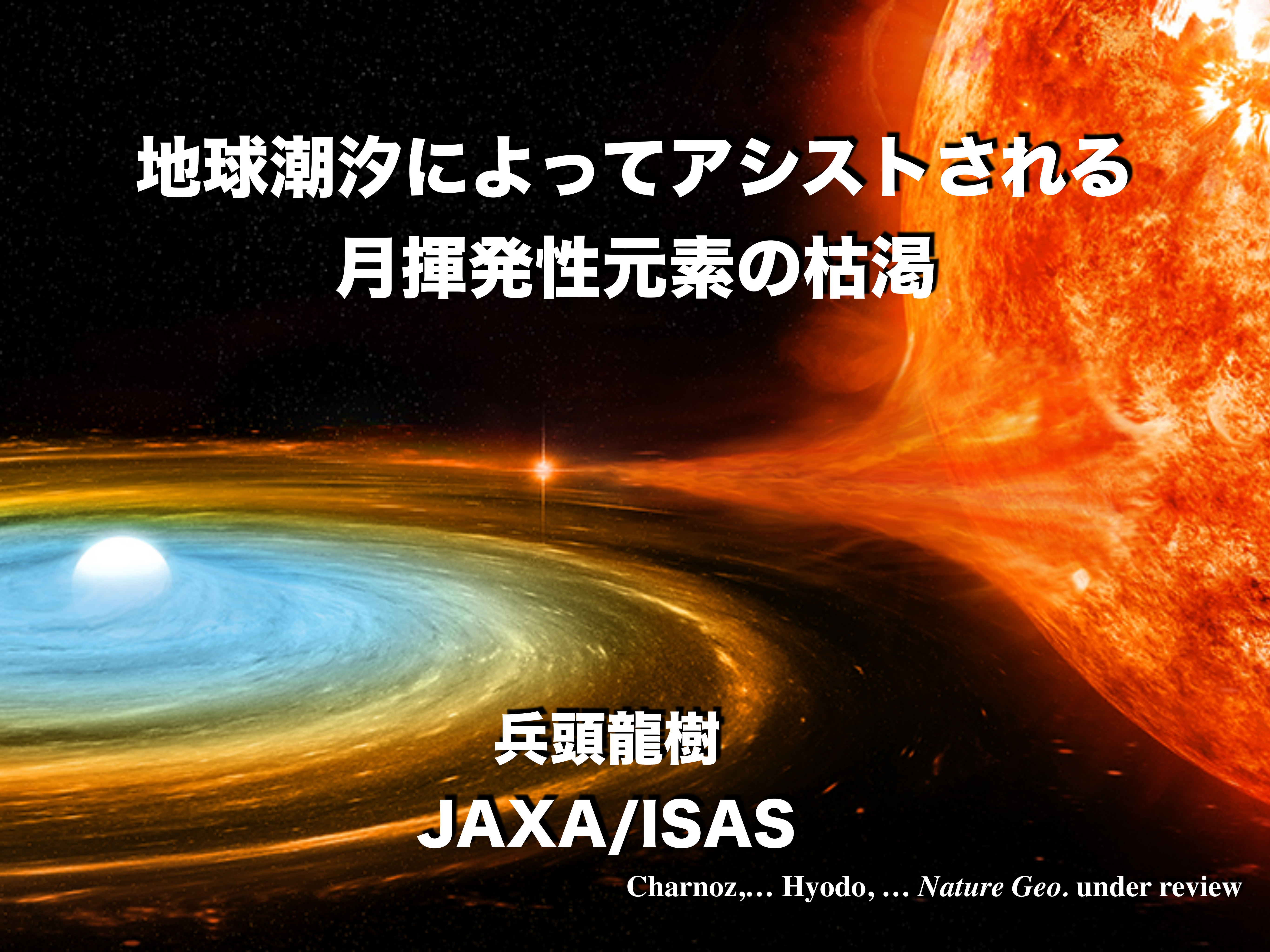


地球潮汐によってアシストされる 月揮発性元素の枯渇

兵頭龍樹

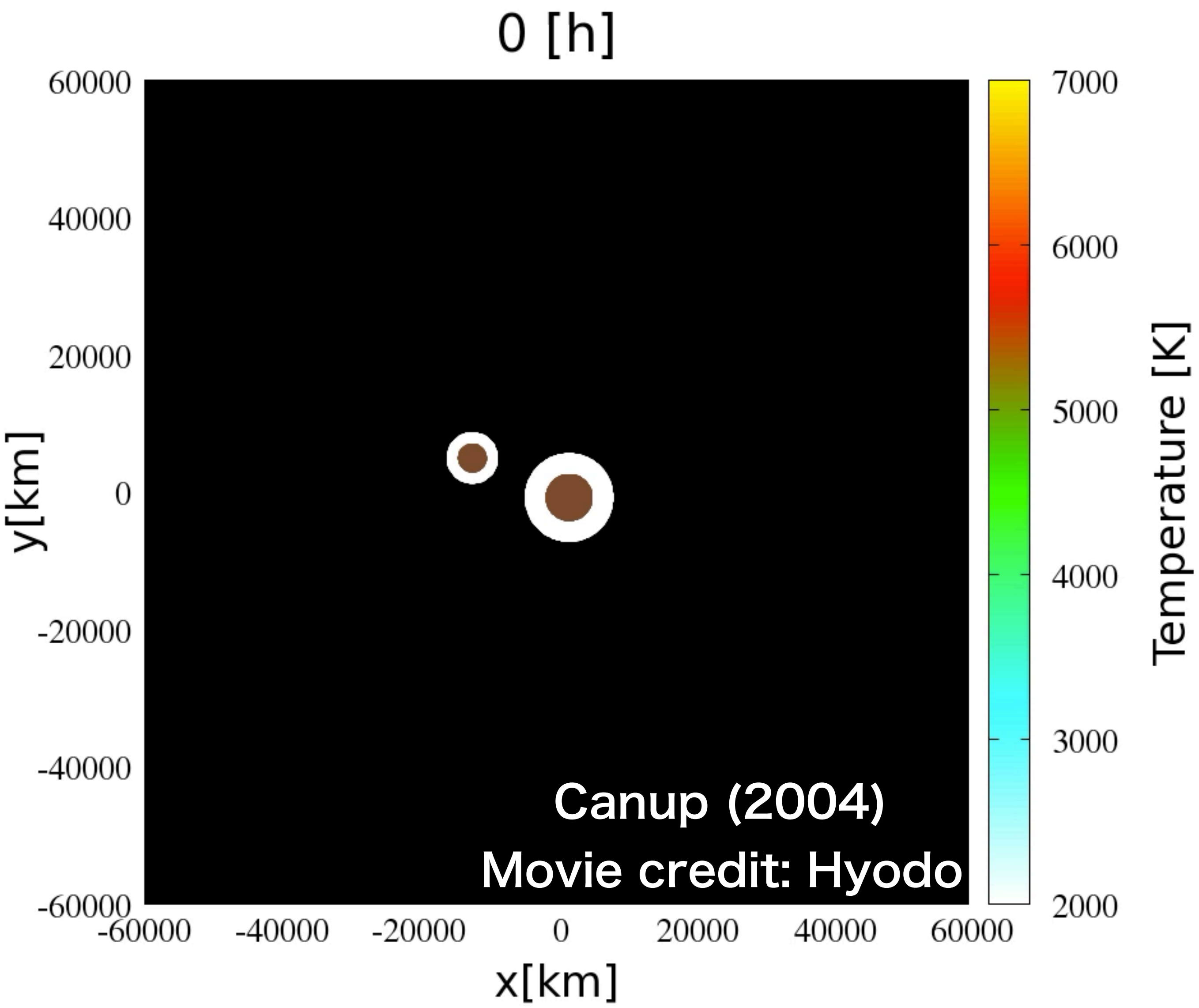
JAXA/ISAS

Charnoz,… Hyodo, … *Nature Geo.* under review

Impact origin of the Moon

A giant impact forms an impact debris

(e.g. Canup 2004, Cuk et al. 2016)



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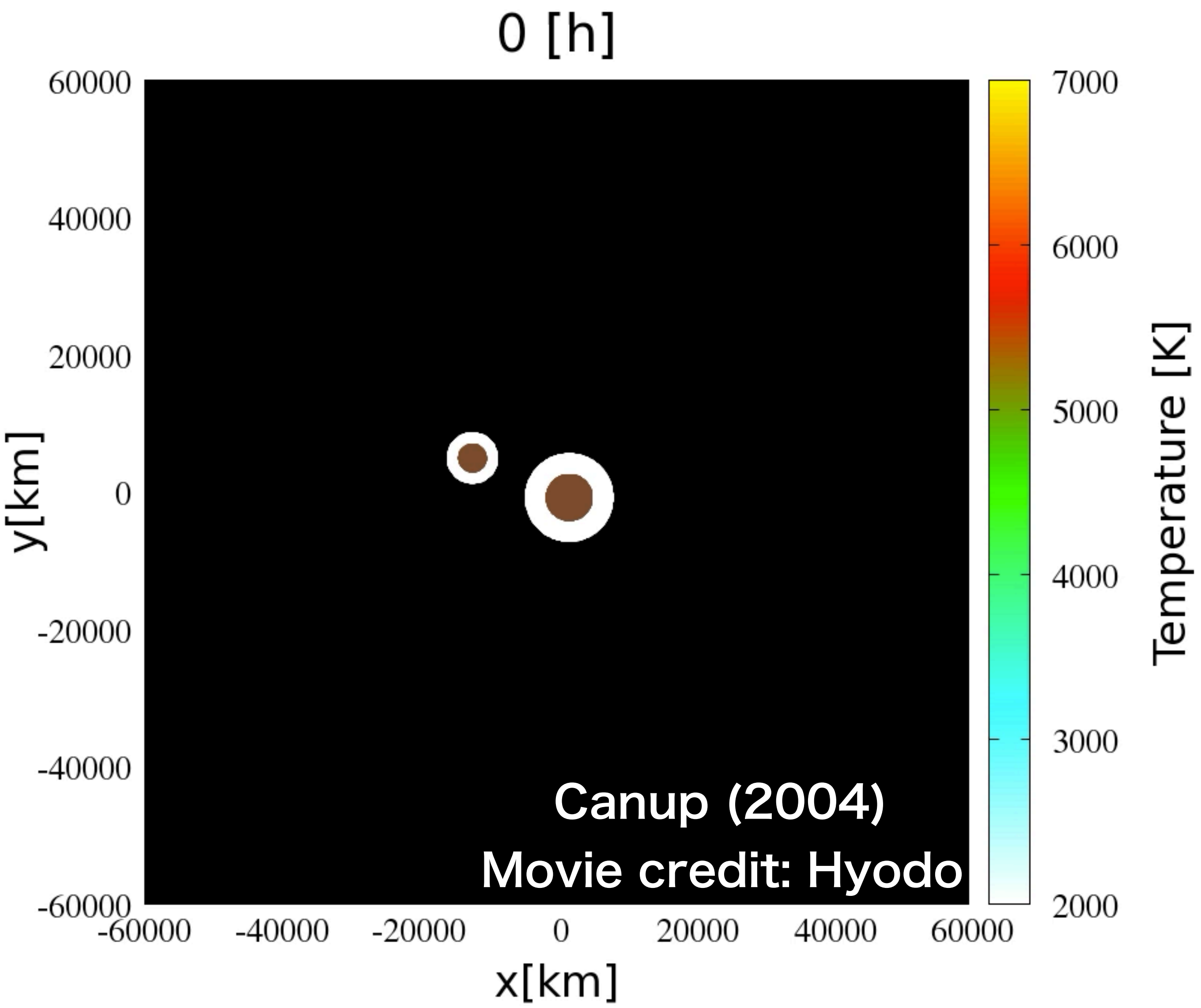
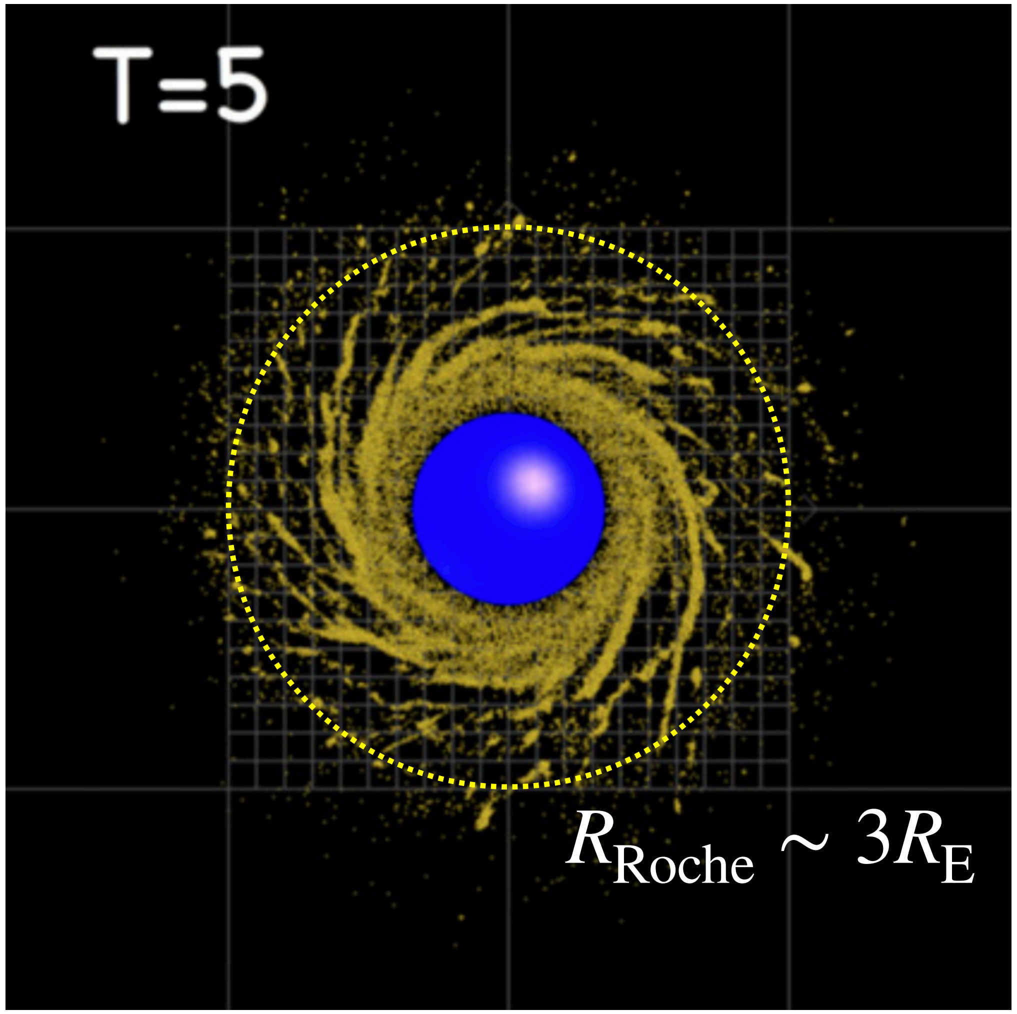
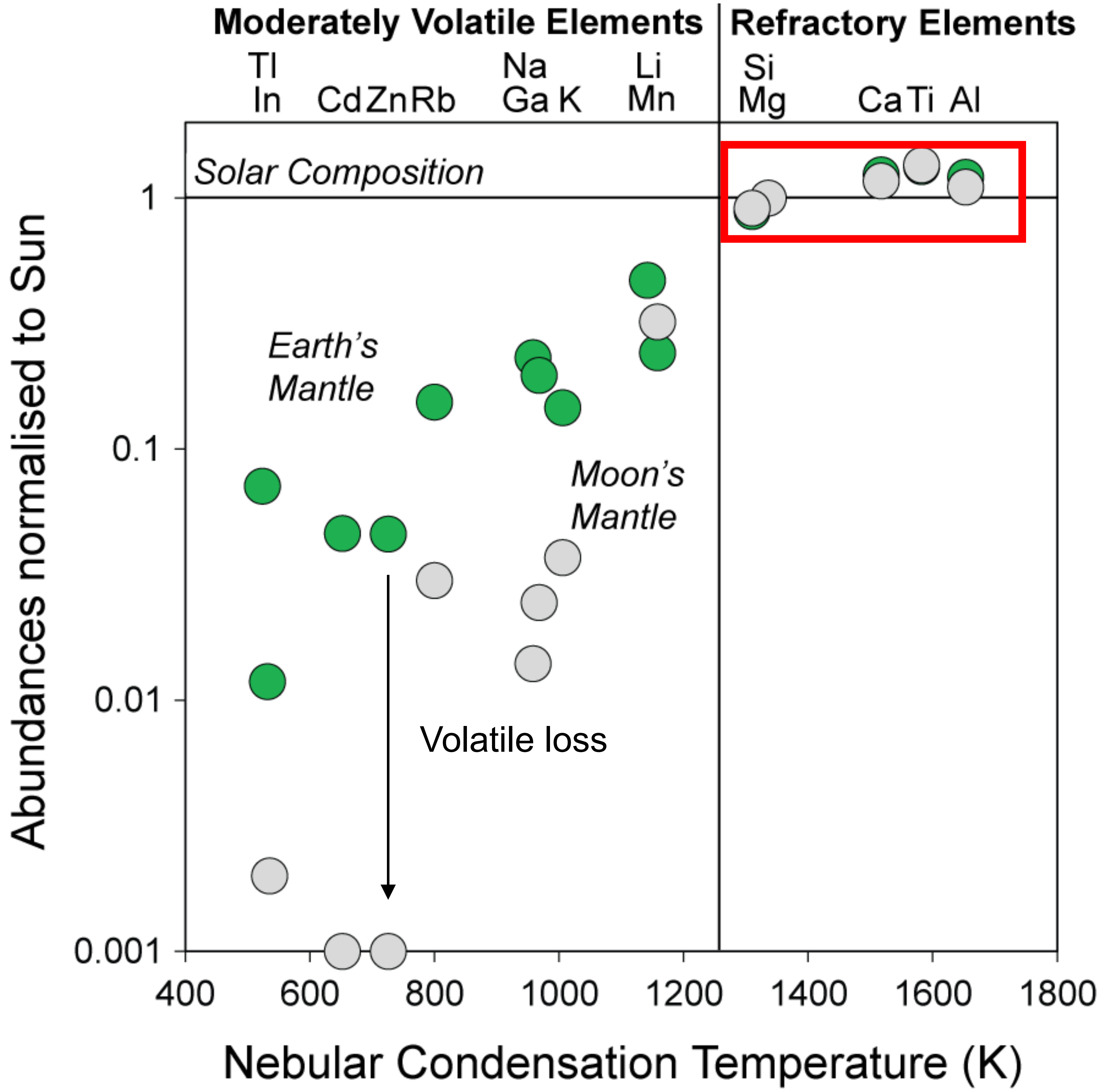


The Moon accretes from spreading debris
(e.g. Ida et al. 1997, Kokubo et al. 2000, Hyodo et al. 2015)



Accretion of the Moon completes at ~3R_E (e.g. Salmon & Canup 2010)

Elemental abundances in Earth & Moon



1. Constancy in abundance (& isotopes!) of refractory elements

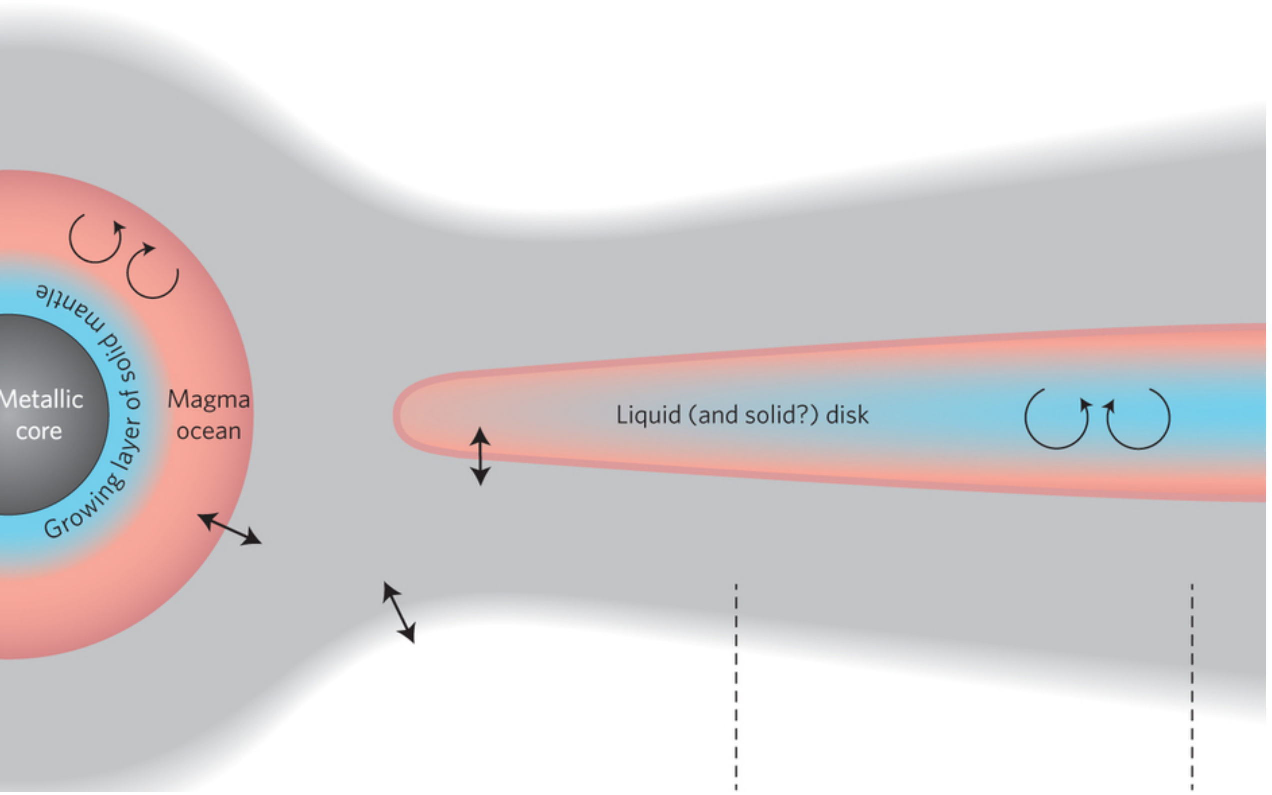
2. Strong depletion in volatile elements relative to Earth's mantle

Credit: P. Sossi

Existing Models

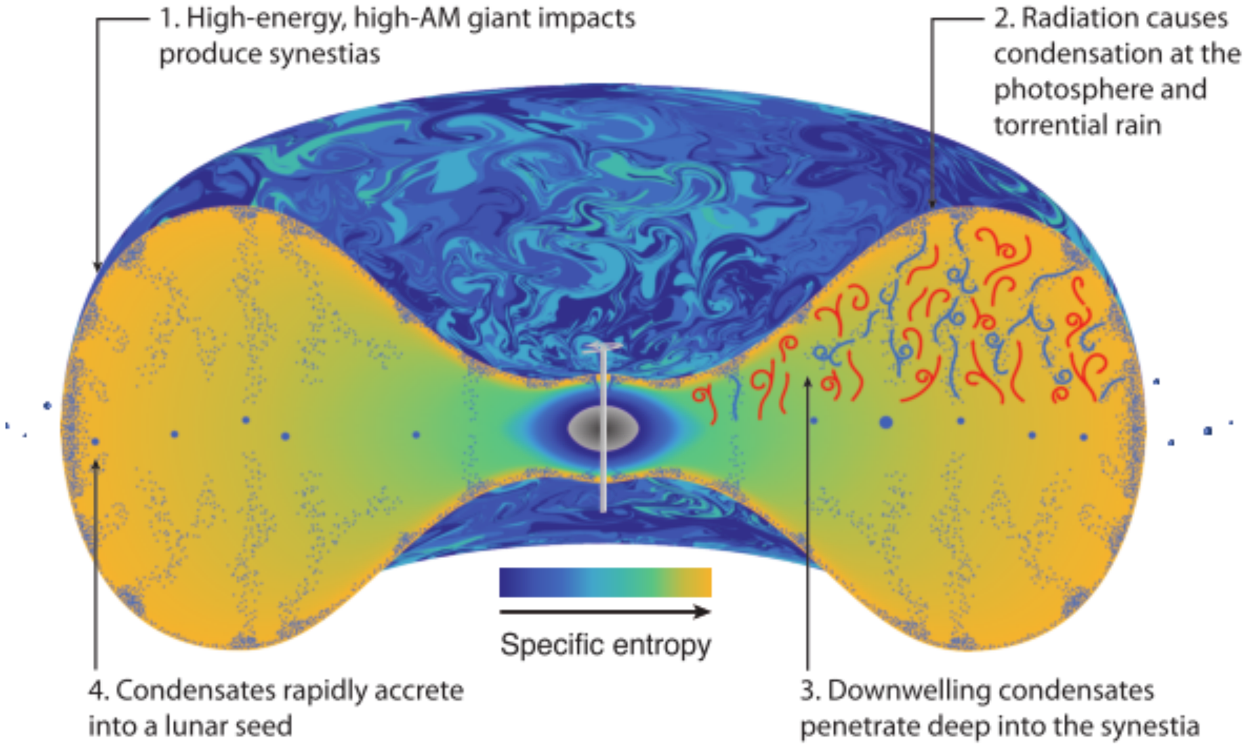
Viscous spreading & vap/liq separation

(Charnoz & Michaut, 2015, Canup et al. 2015)



Synestia & Rain-out

(Lock et al. 2018)



1)Mass loss from Earth-Moon disk requires unrealistically high temperatures (>100,000 K)

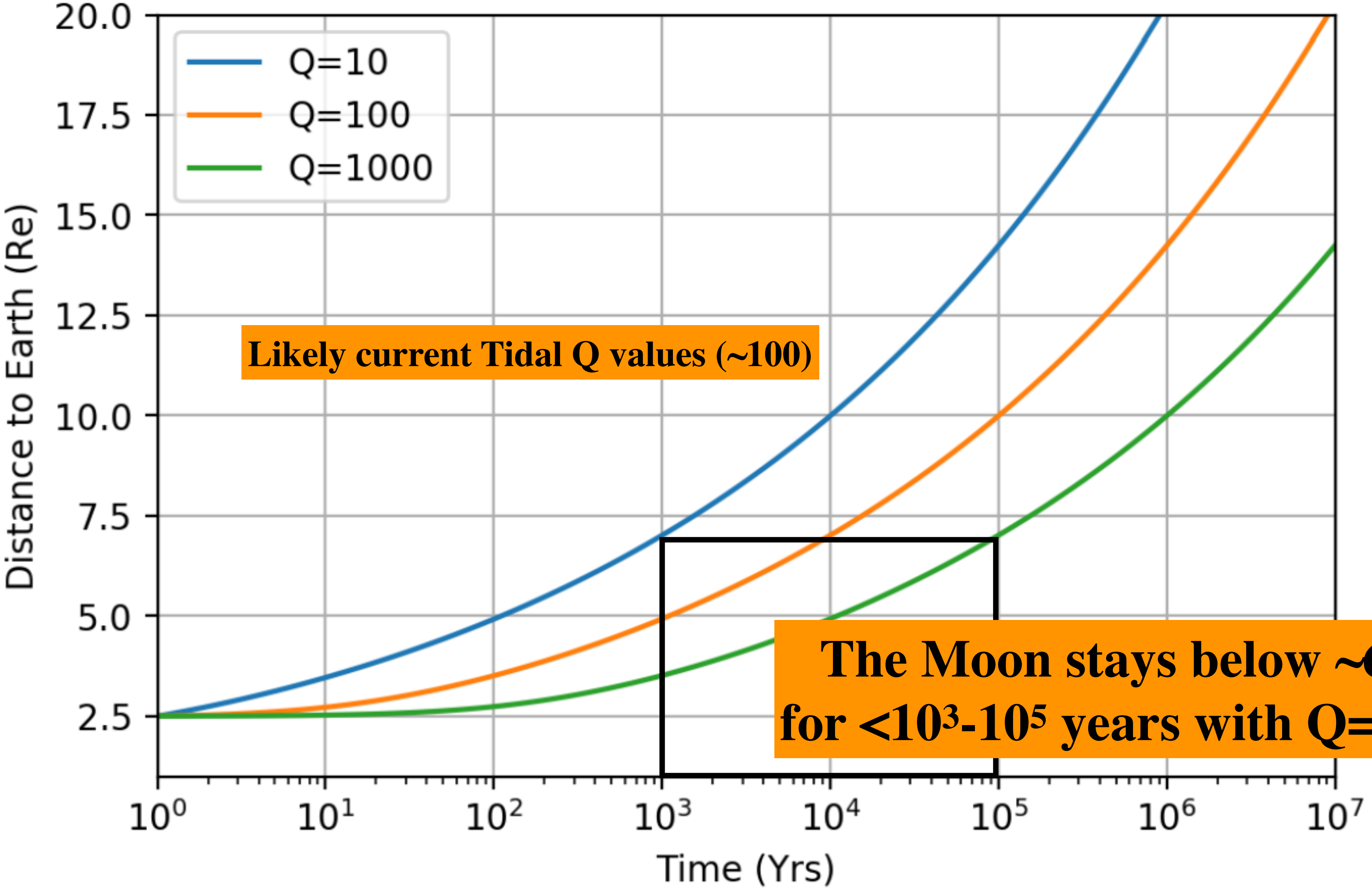
2) Physics of these disks are poorly known

3) Fraction of material ejected beyond Roche Limit uncertain

Distance btw Earth and Moon

Outward migration of the Moon proportional to $1/Q$ (Tidal ‘Q’ factor)

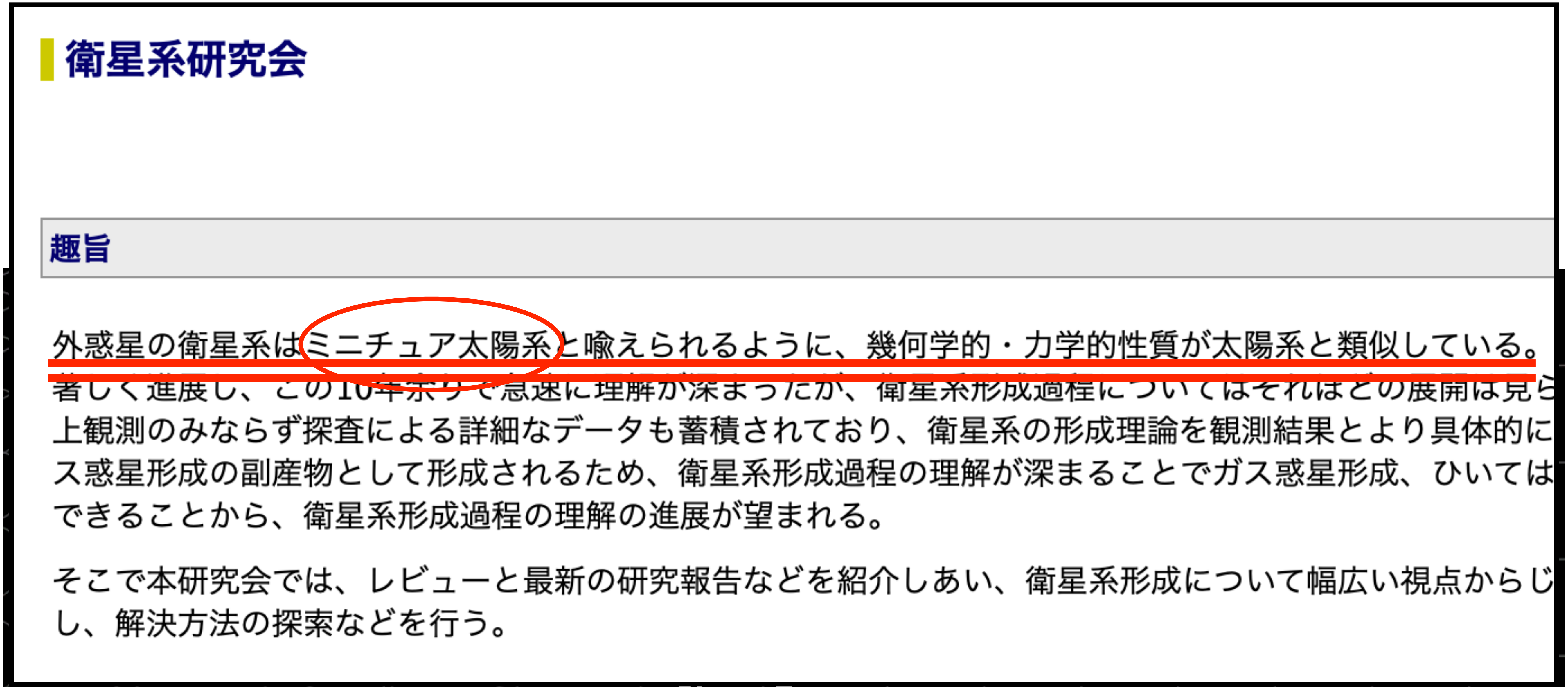
Poorly known



Likely current Tidal Q values (~100)

The Moon stays below ~$6R_{Earth}$ for $<10^3$-10^5 years with $Q=10$-1000

Tides



衛星系研究会

趣旨

外惑星の衛星系はミニチュア太陽系と喩えられるように、幾何学的・力学的性質が太陽系と類似している。
著しく進展し、この10年余りで急速に理解が深まったが、衛星系形成過程についてはそれほどの展開は見ら
上観測のみならず探査による詳細なデータも蓄積されており、衛星系の形成理論を観測結果とより具体的に
ス惑星形成の副産物として形成されるため、衛星系形成過程の理解が深まることでガス惑星形成、ひいては
できることから、衛星系形成過程の理解の進展が望まれる。

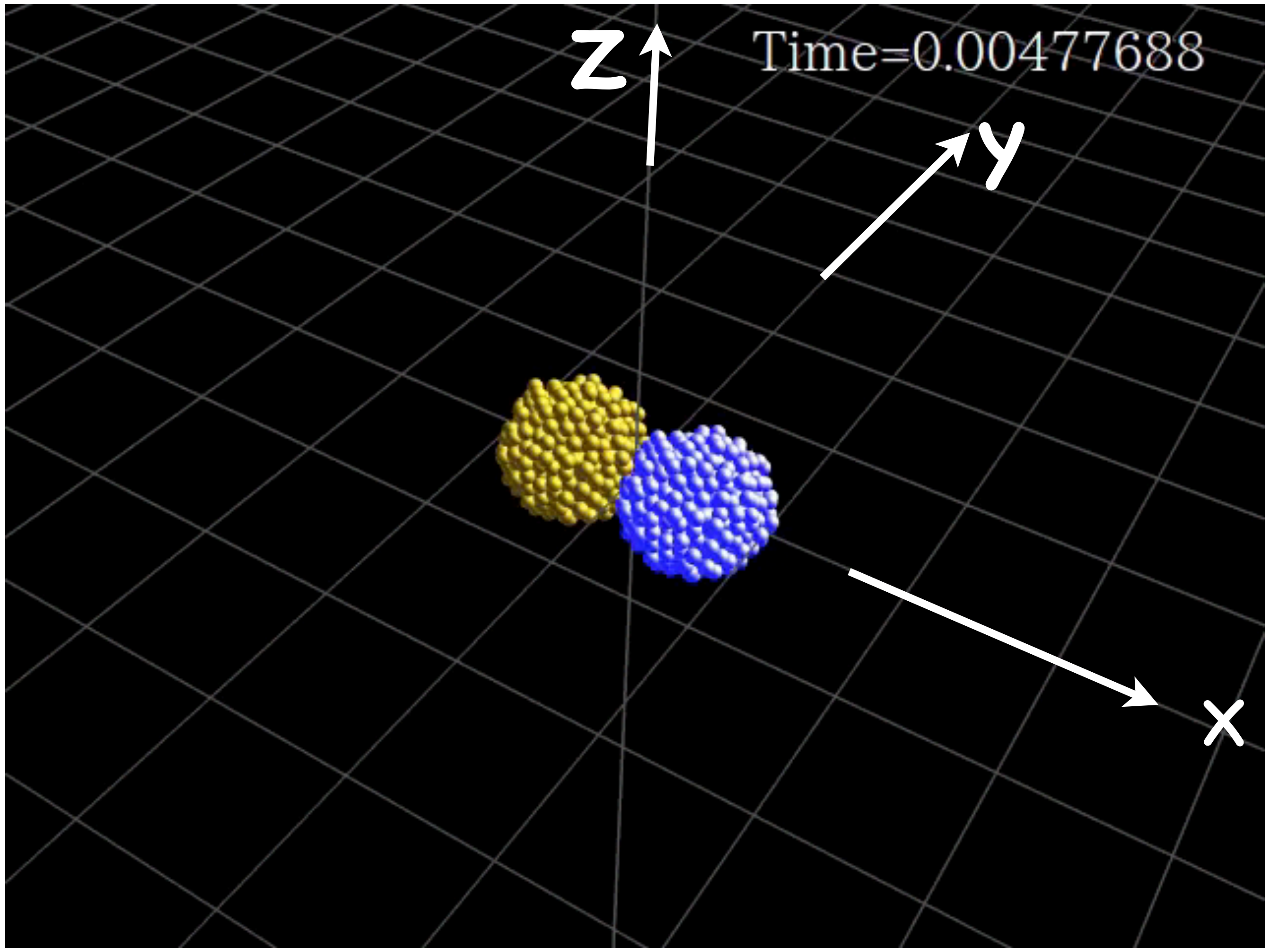
そこで本研究会では、レビューと最新の研究報告などを紹介しあい、衛星系形成について幅広い視点からじ
し、解決方法の探索などを行う。

Hyodo & Ohtuski (2014) ApJ
Hyodo & Ohtsuki (2015) Nature Geo.

Tides

Satellite system is *not* always a miniature version of planetary system

Free space ($v_{imp} << v_{esc}$)



Hyodo & Ohtuski (2014) ApJ
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Tides

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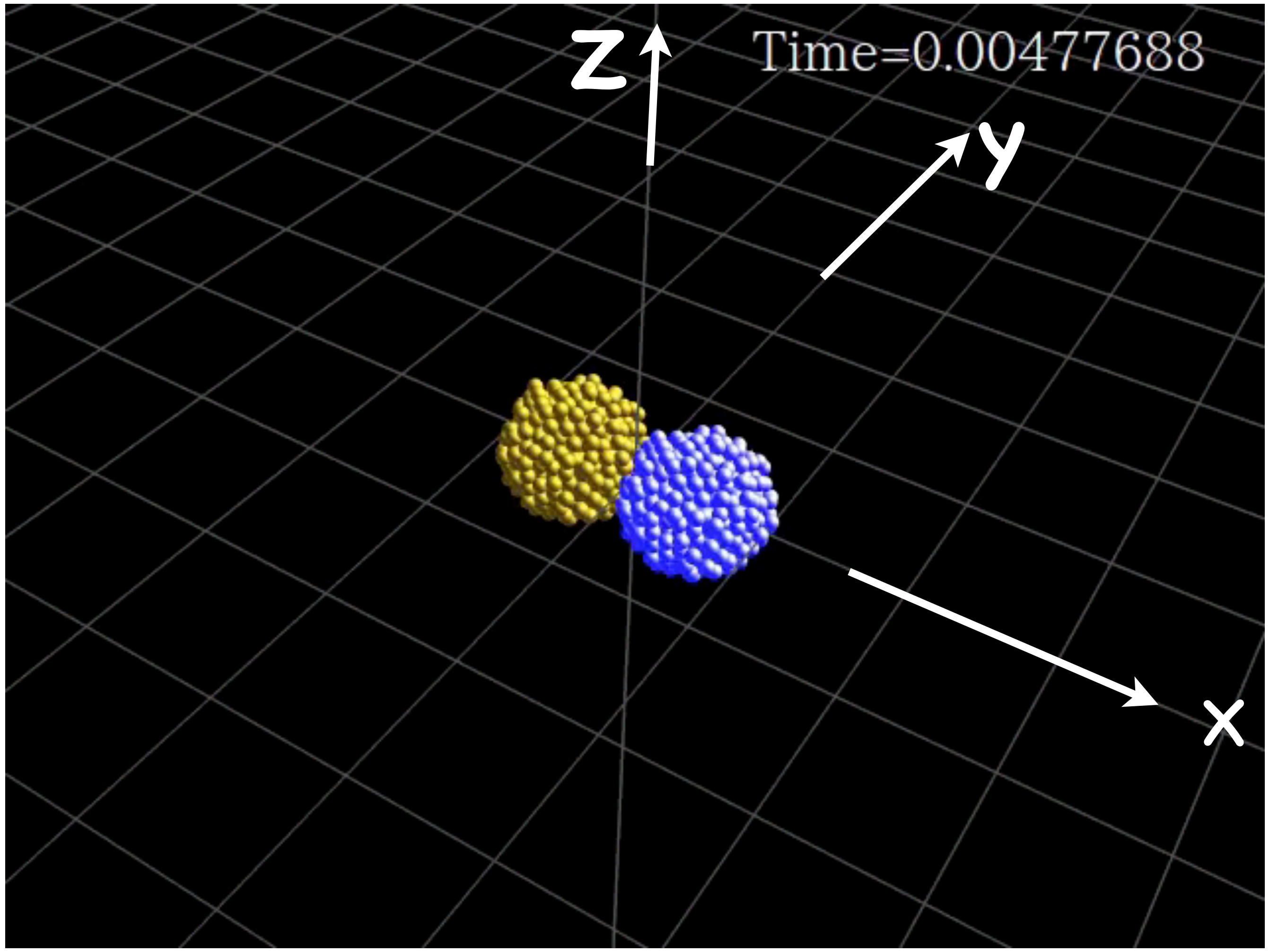
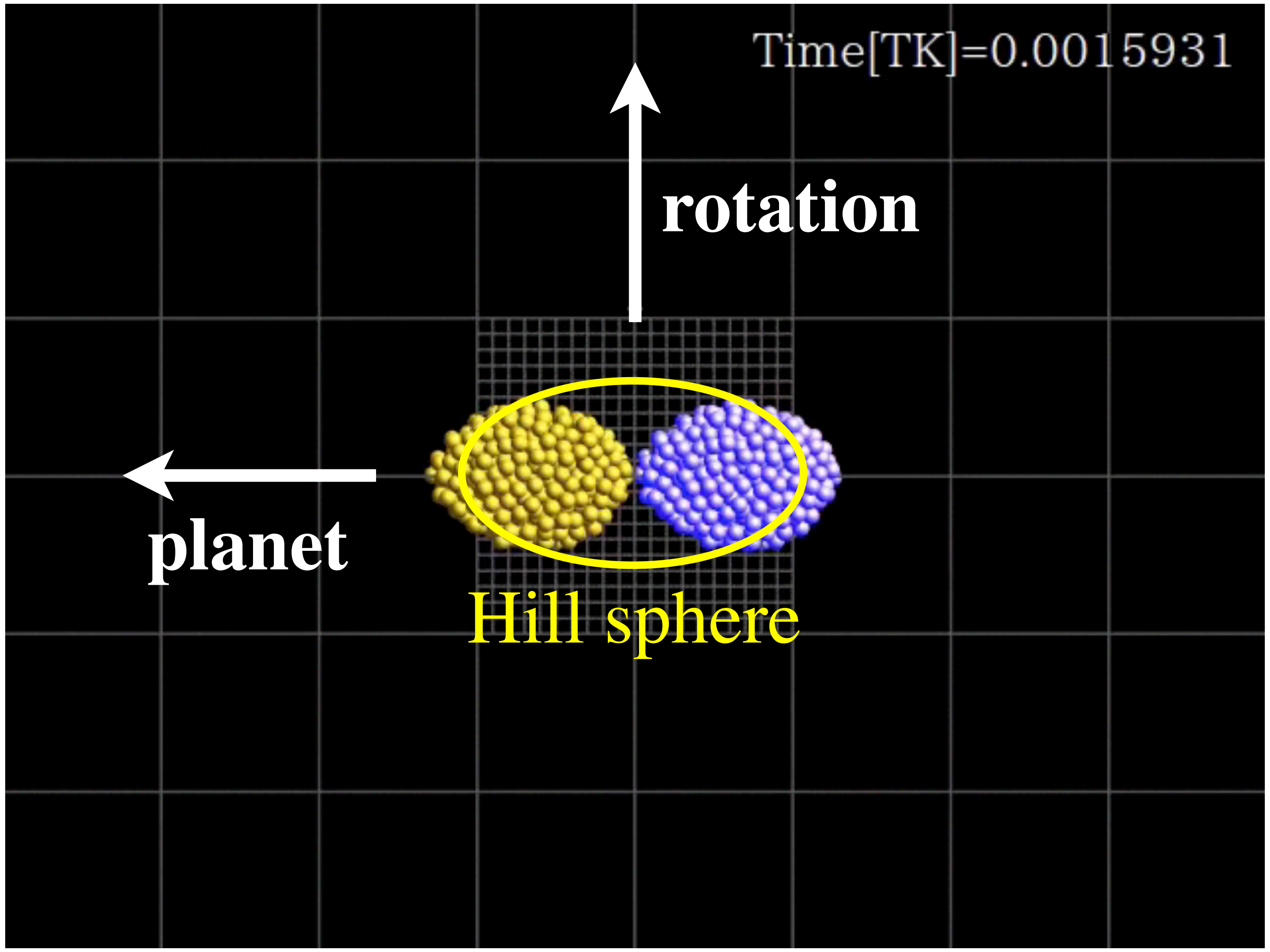


Tital field: @1.1R_{Roche} (v_{imp}~$0.6v_{esc}$)

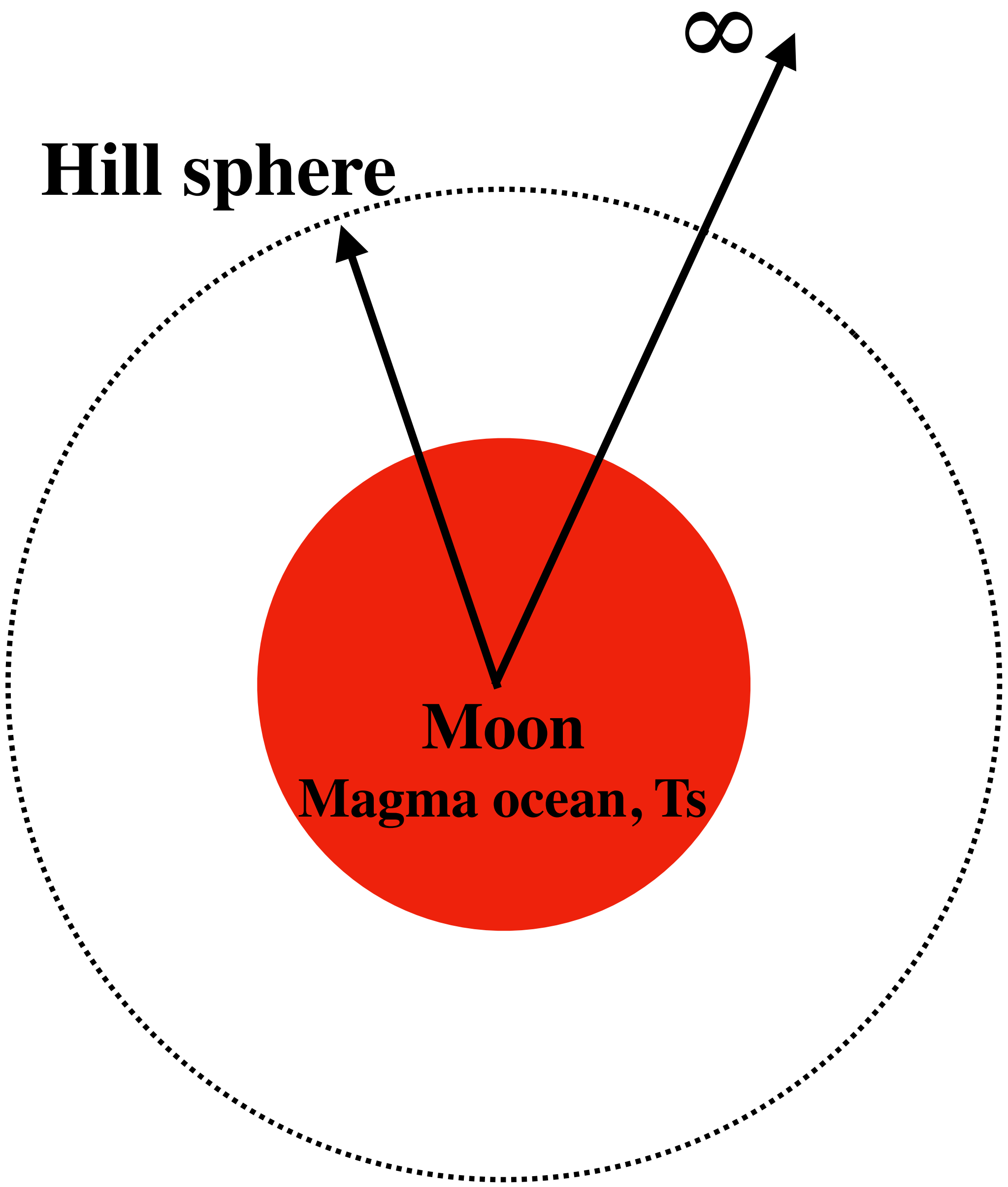


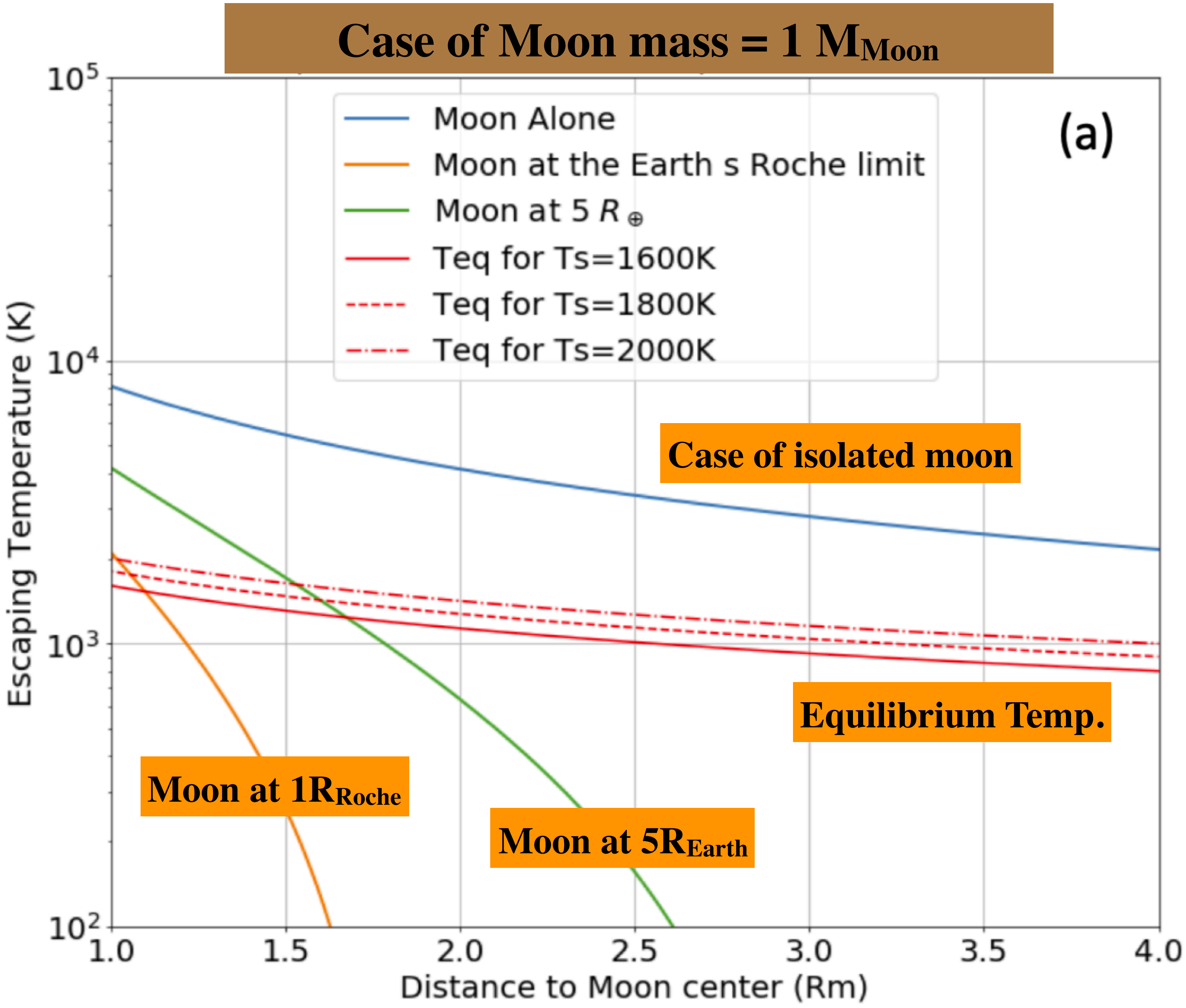
Hyodo & Ohtuski (2014) ApJ
Hyodo & Ohtsuki (2015) Nature Geo.

Temperature required to escape from the Moon

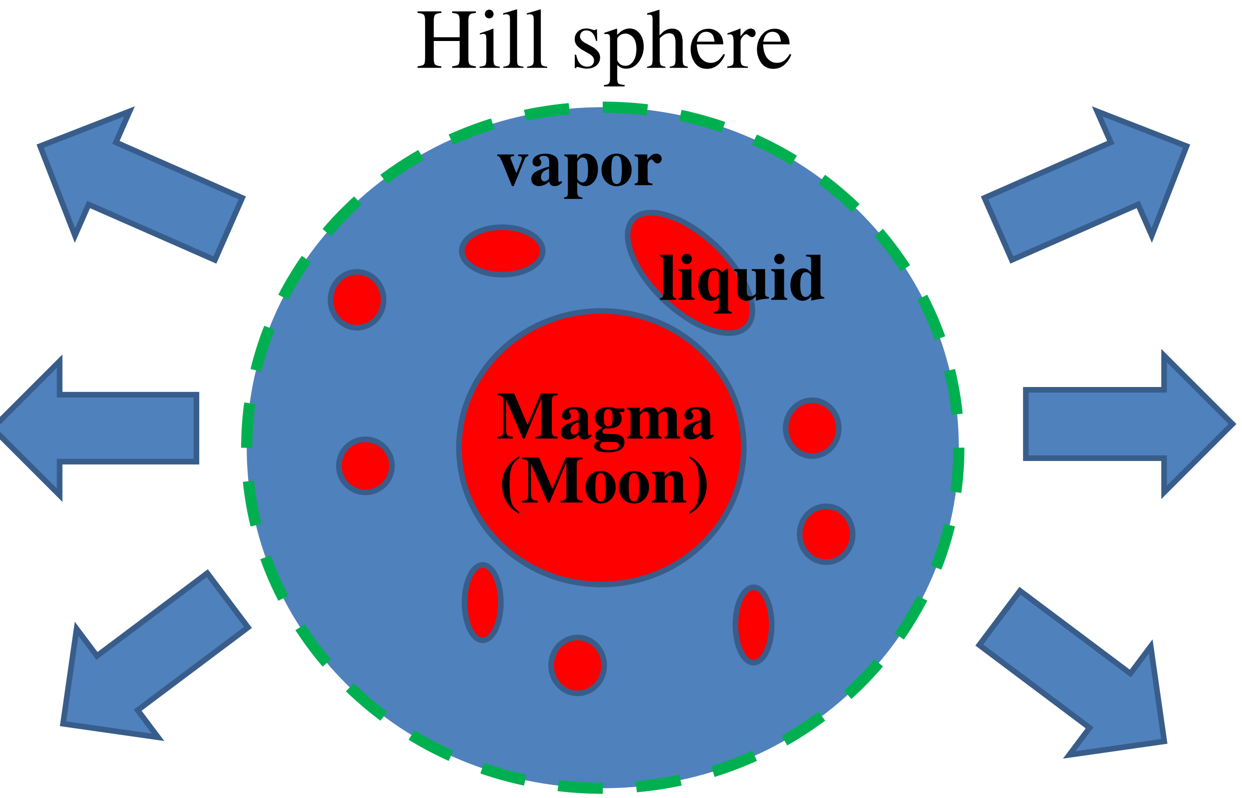
$$\frac{1}{2}v_{\mathrm{the}}^{2} > \frac{GM}{R}$$

Ts >10^5K(!) is required to escape from the Earth-Moon system
(e.g. molecular mass > 20g/mol for moderately volatile elements)





Research question:
Is hydrodynamical escape assisted by Earth Tide?



<u>Temperature constrains:</u>

Li/Na systematics (Magna et al. 2006)

and

Cr isotope systematics (Sossi & Fegley 2018)

↓

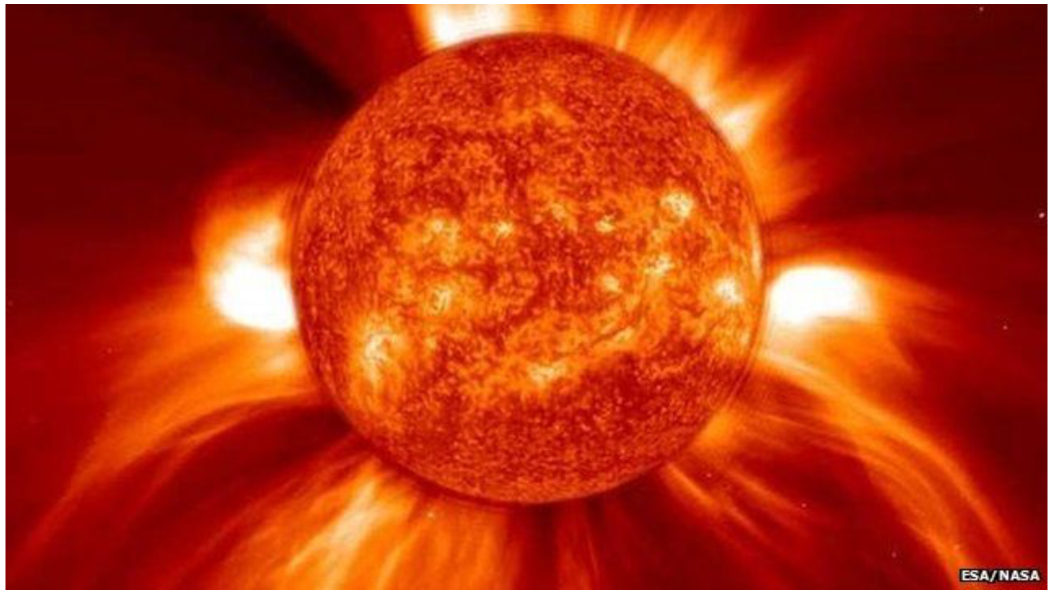
Magma ocean temperature of Ts=1600-1800K
for volatile loss

Governing equations

Structure

- Assume a surface temperature set by the lunar magma ocean T_s
- Solve the 'Parker wind' equations (Parker, 1963) in Earth's tidal field

Euler Equations
For two-phase flow:



$$\frac{\partial \rho v r^2}{\partial r} = 0$$

Mass conservation in steady state

$\rho = \rho_{\text{liq}} + \rho_{\text{vap}}$

$$\rho v \frac{\partial v}{\partial r} = -\frac{\partial P}{\partial r} + \rho A(r)$$

Conservation of linear momentum

Acceleration due to the rotating frame

$$\rho \frac{\partial \bar{C}_{\text{V}} T}{\partial r} = \frac{P}{\rho}\frac{\partial \rho}{\partial r} + L(T)\rho\frac{\partial X}{\partial r}$$

Energy budget

X(r): liquid fraction $\left(\frac{\rho_{\text{liq}}}{\rho_{\text{liq}} + \rho_{\text{vap}}}\right)$

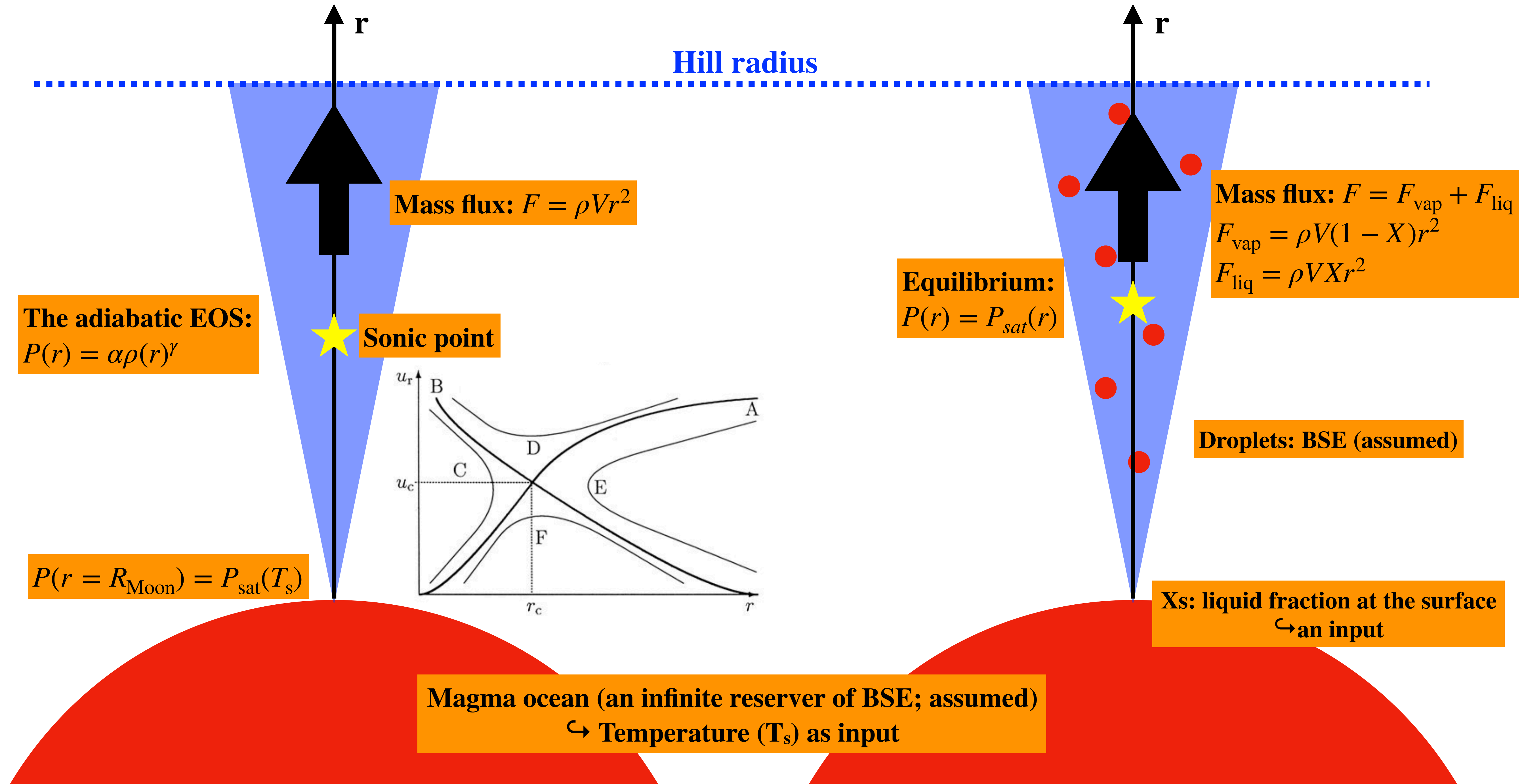
Allows calculation of exact velocity of the gas at the Lagrange points

Models

Solve the ‘Parker wind’ equations (Parker, 1963) **in Earth’s tidal field**

Dry model: adiabatic gas with no condensation
↪ lowest energy case (no release of latent heat)

Wet model: vap/liq equilibrium with the surface
↪ energy gain from the release of latent heat



Mass flux: $F = \rho V r^2$

The adiabatic EOS:
$P(r) = \alpha \rho(r)^{\gamma}$

Sonic point

$P(r = R_{\mathrm{Moon}}) = P_{\mathrm{sat}}(T_s)$

Mass flux: $F = F_{\mathrm{vap}} + F_{\mathrm{liq}}$
$F_{\mathrm{vap}} = \rho V (1 - X) r^2$
$F_{\mathrm{liq}} = \rho V X r^2$

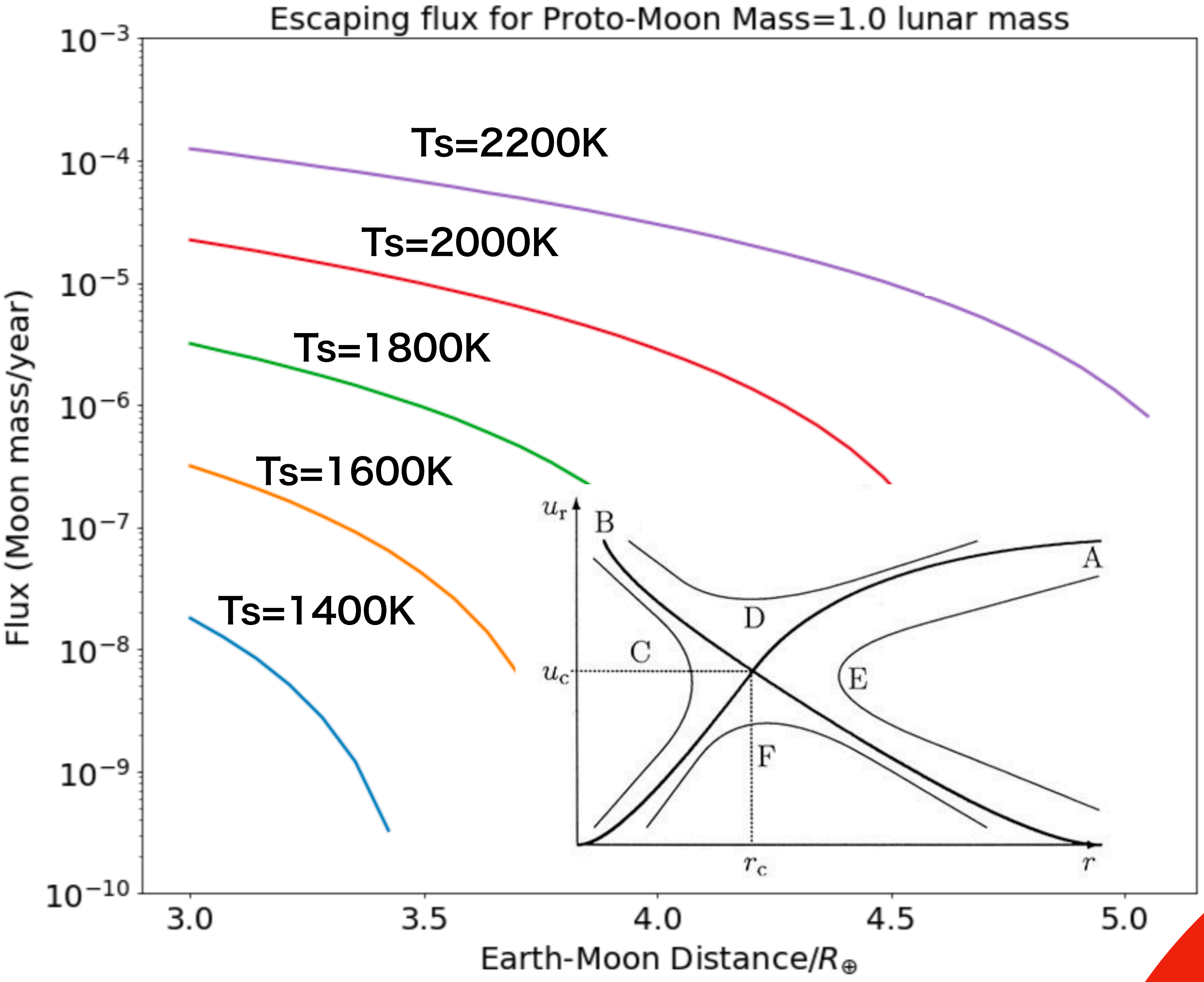
Equilibrium:
$P(r) = P_{sat}(r)$

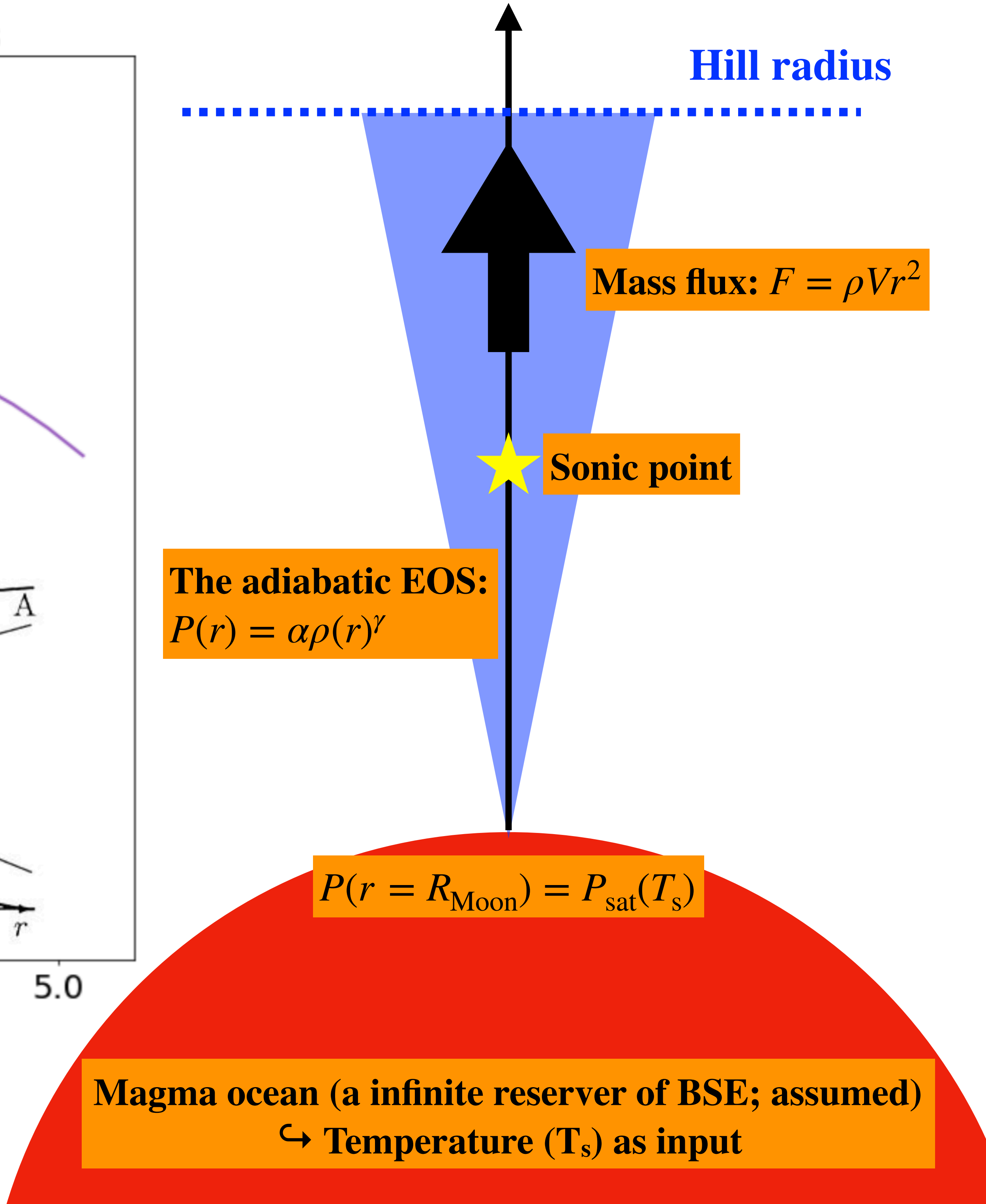
Droplets: BSE (assumed)

Xs: liquid fraction at the surface
↪an input

Magma ocean (an infinite reserver of BSE; assumed)
↪ Temperature (T_s) as input

Escaping of the gas: Dry model





Mass flux: $F = \rho V r^2$

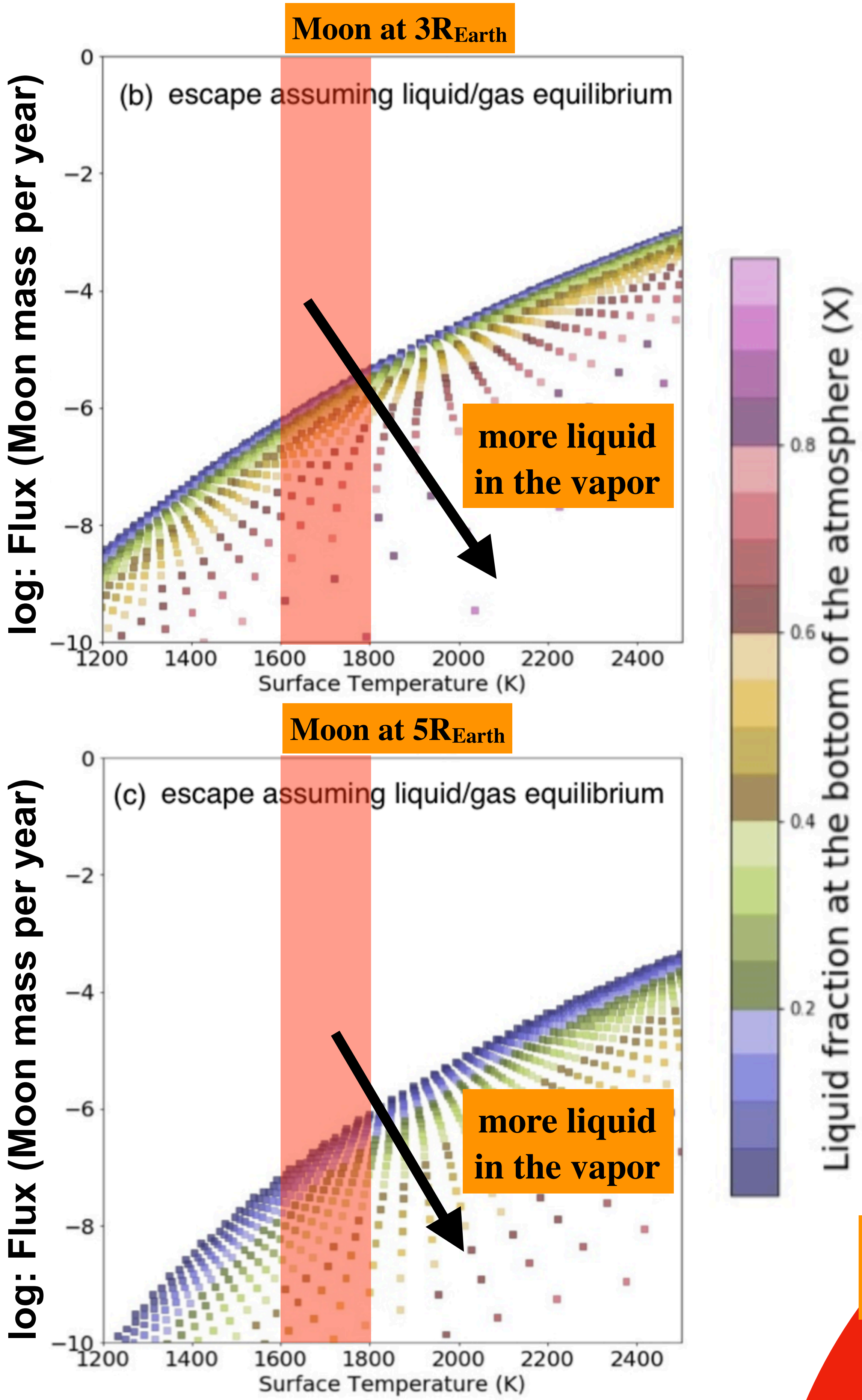
Sonic point

The adiabatic EOS:
$P(r) = \alpha\rho(r)^\gamma$

$P(r = R_{\mathrm{Moon}}) = P_{\mathrm{sat}}(T_s)$

Magma ocean (a infinite reserver of BSE; assumed)
↪ Temperature (T_s) as input

Escaping of the gas: Wet model

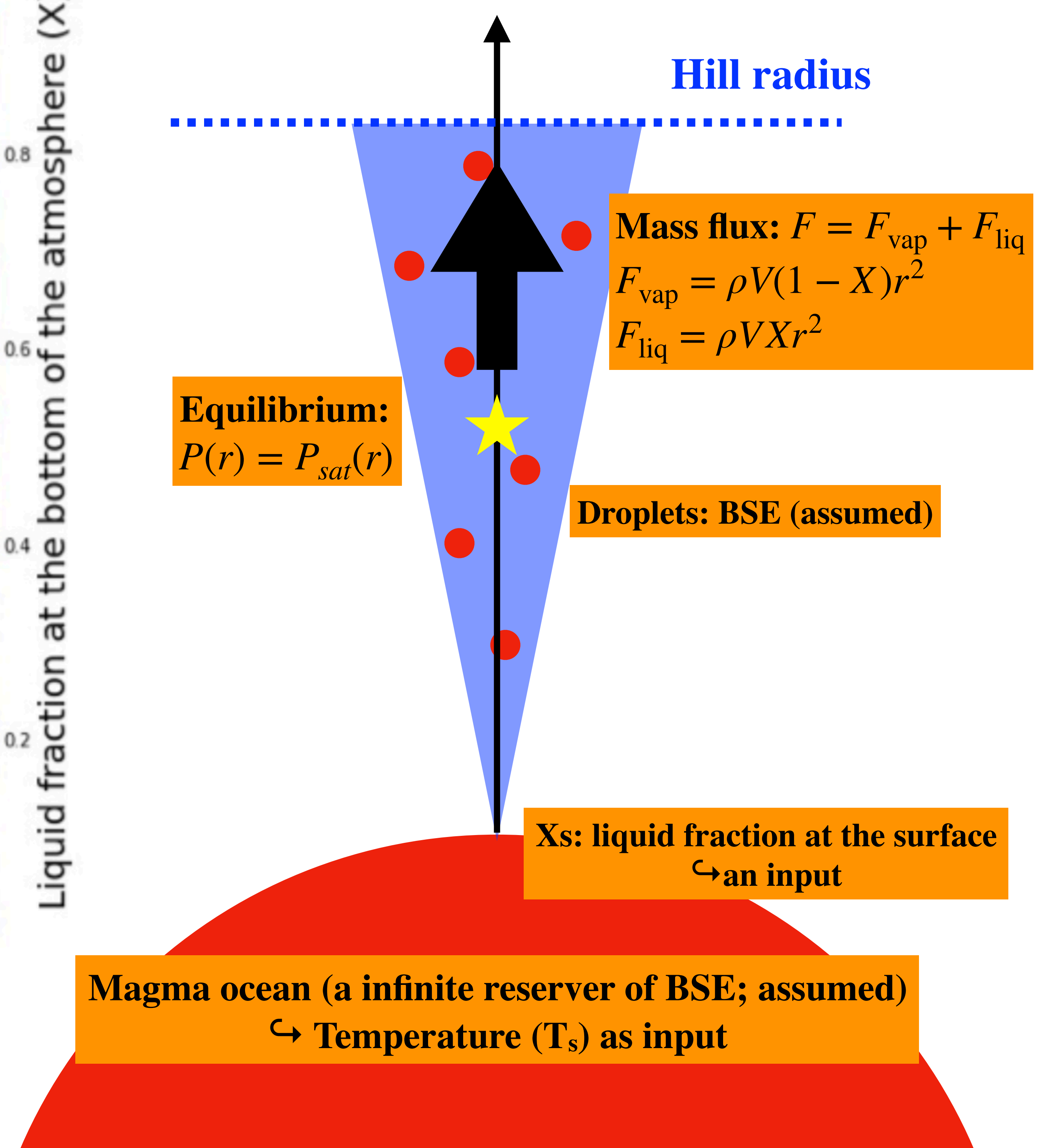


Moon at $3R_{Earth}$

more liquid in the vapor

Moon at $5R_{Earth}$

more liquid in the vapor



Hill radius

Mass flux: $F = F_{vap} + F_{liq}$

$F_{vap} = \rho V(1 - X)r^2$

$F_{liq} = \rho VXr^2$

Equilibrium:
$P(r) = P_{sat}(r)$

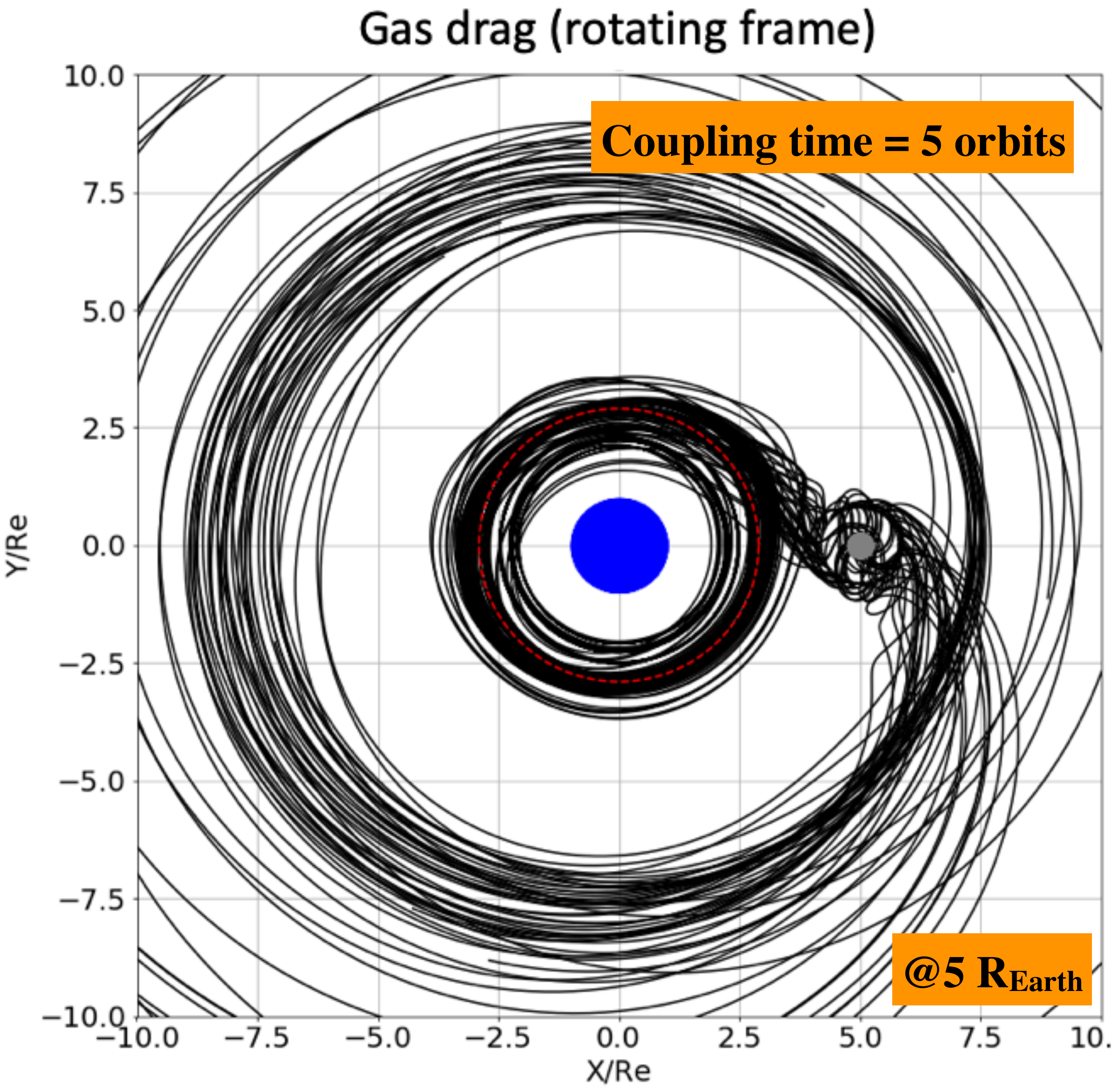
Droplets: BSE (assumed)

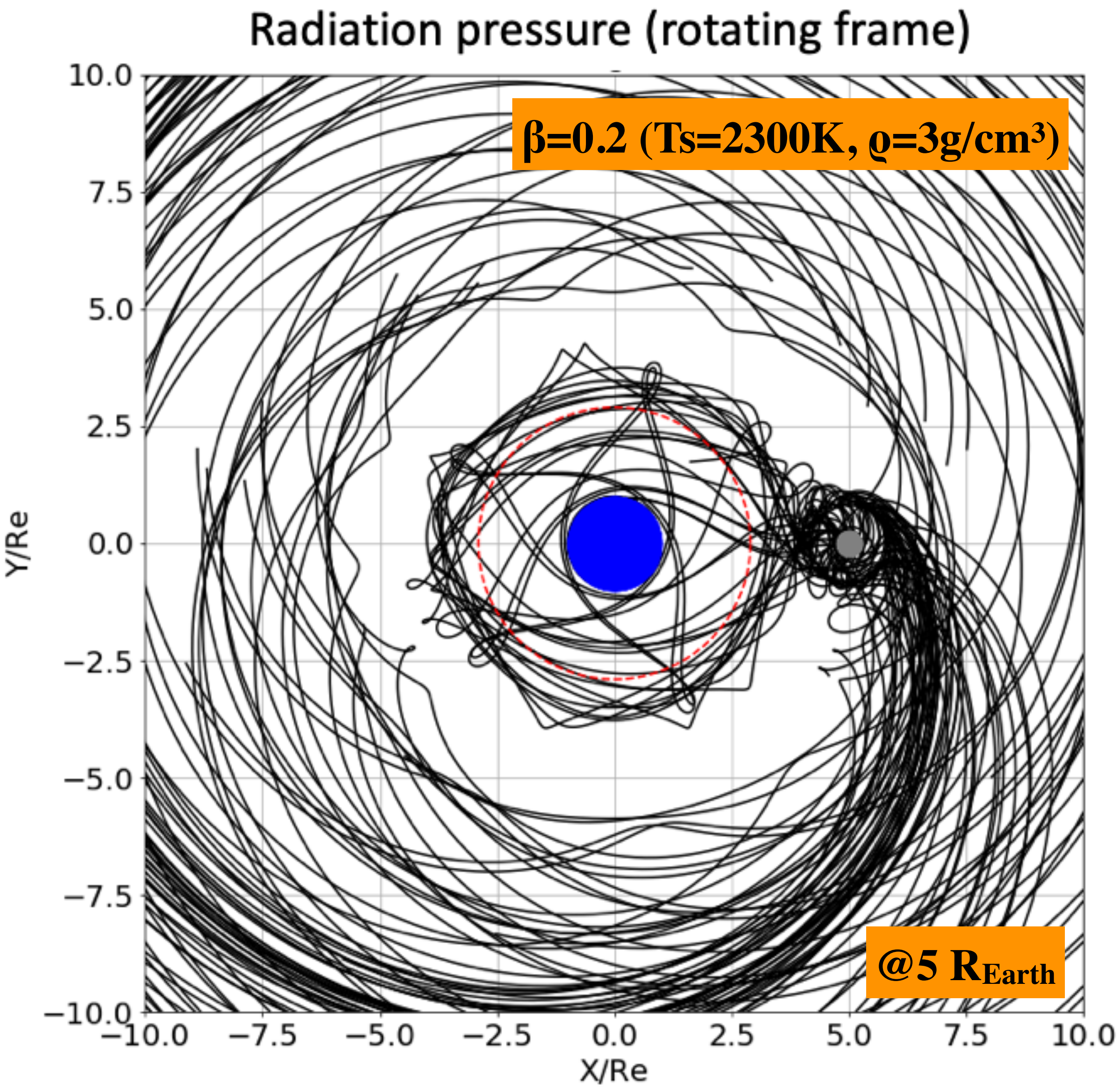
Xs: liquid fraction at the surface
↪an input

Magma ocean (a infinite reserver of BSE; assumed)
↪ Temperature (T_s) as input

Fate of volatile particles

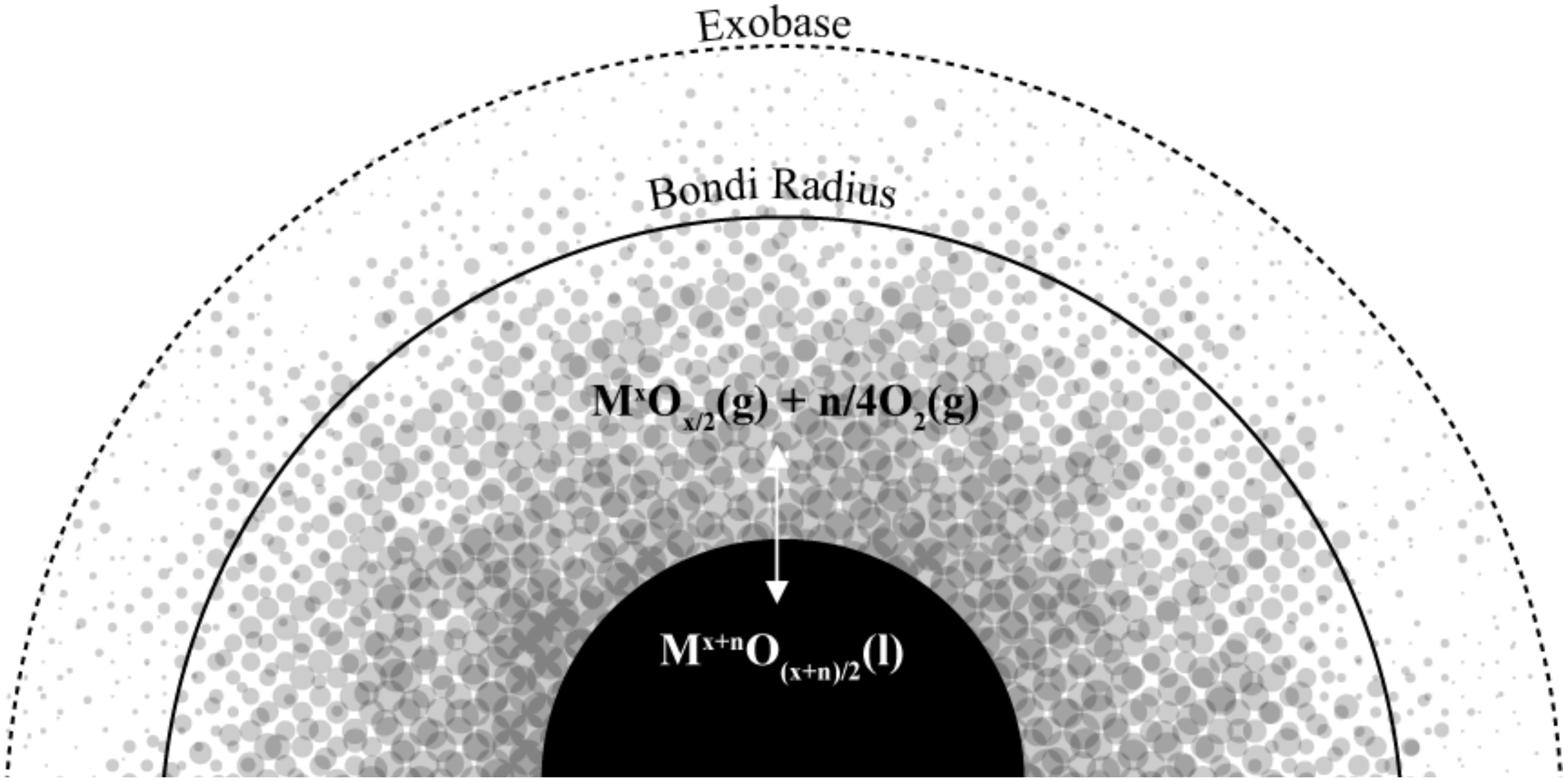
After escaping from Hill sphere of the Moon,
gas/dusts never comes back to the Moon





Composition

(Earth’s Mantle-like initial)



Equilibrium constant

Mole fraction

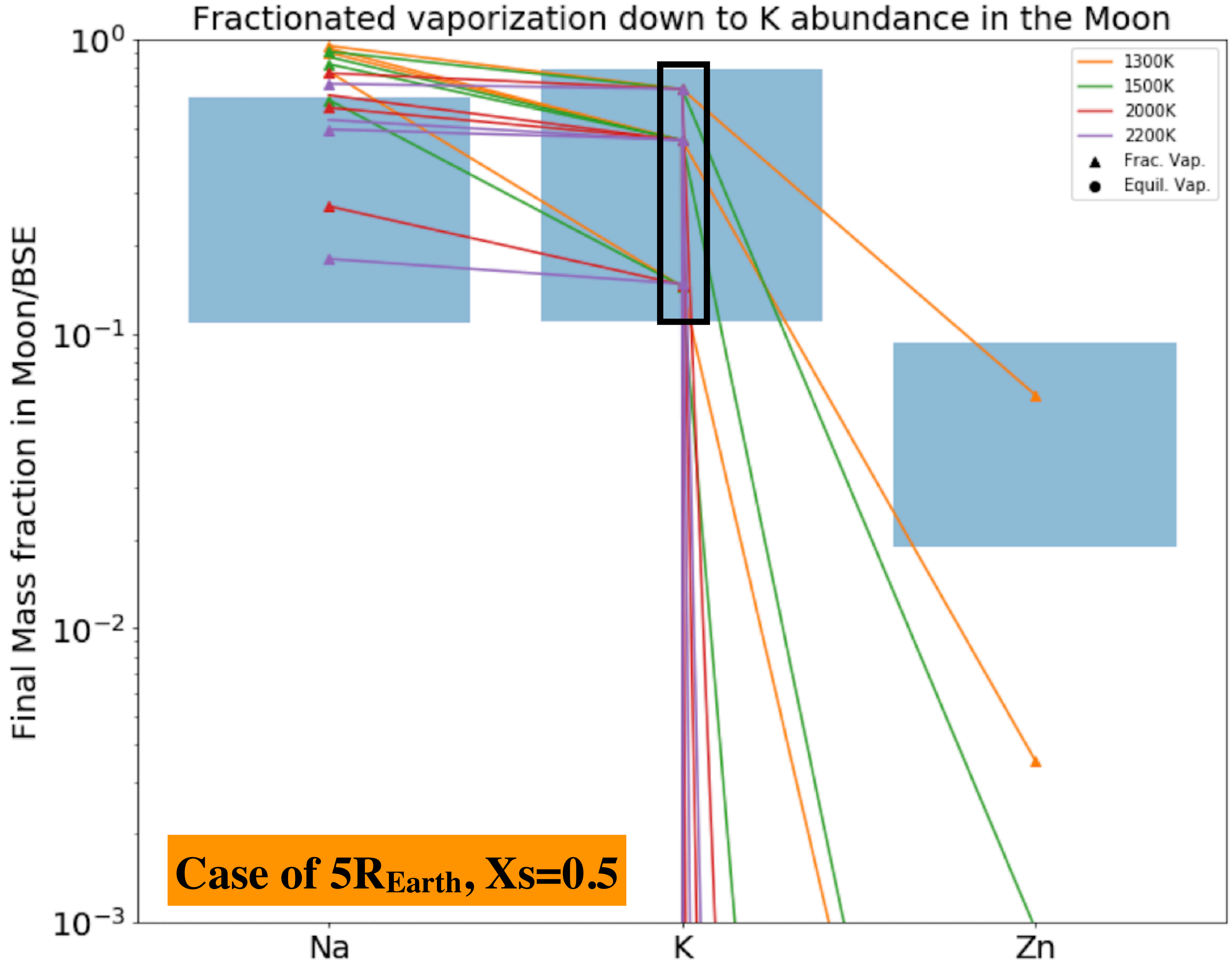
Activity Coefficient

Saturation vapour pressure: $p\left(M^xO_{\frac{x}{2}}\right) = \frac{KX(i)\gamma(i)}{f(O_2)^{n/4}}$

Values of *K* and γ determined experimentally for each metal species (Sossi et al. 2019)

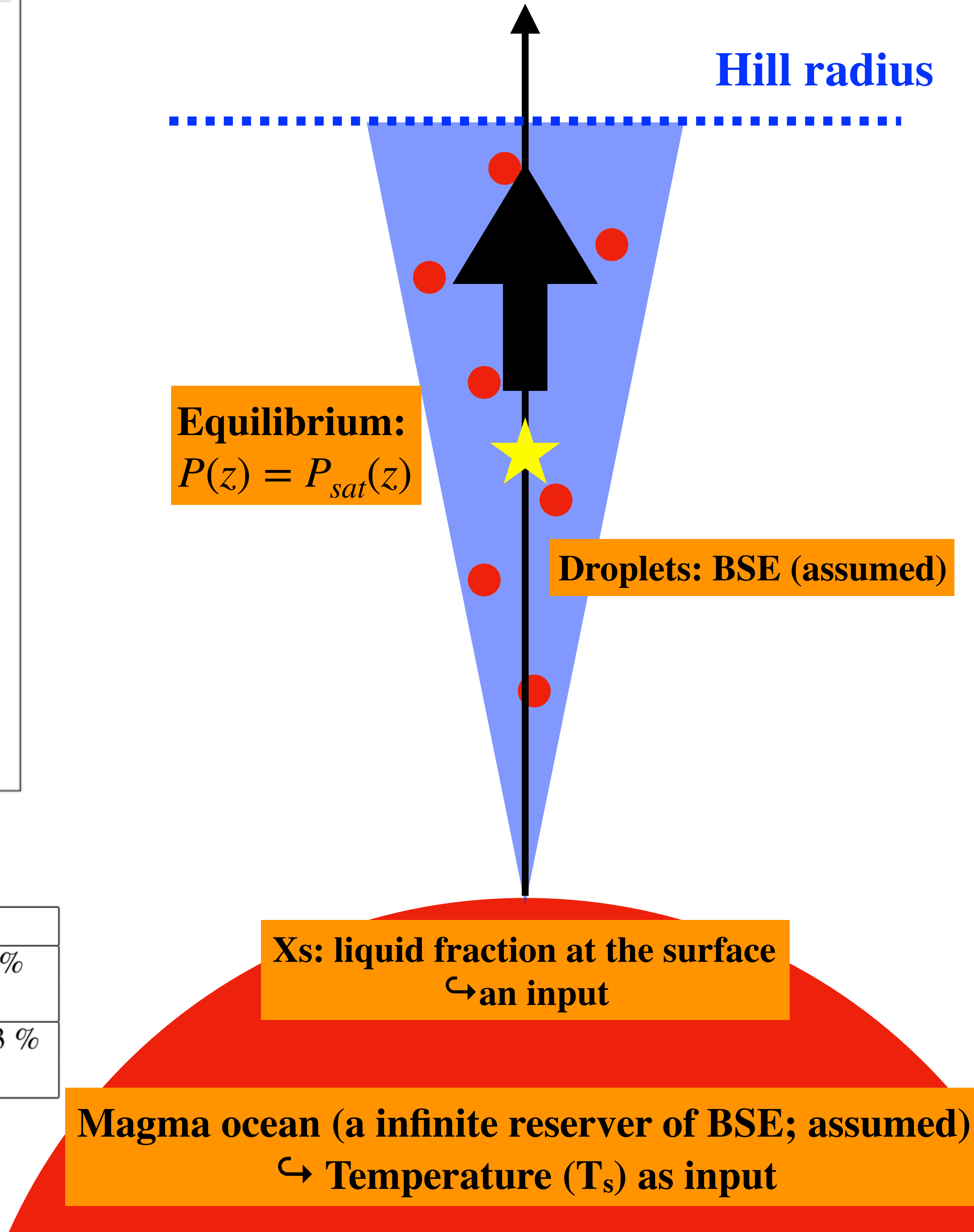
Total pressure: $p\left(M^xO_{\frac{x}{2}}\right) = \frac{KX(i)\gamma(i)}{f(O_2)^{n/4}}$

Na – K – Zn fractionation


Fractionated vaporization down to K abundance in the Moon

Case of $5R_{Earth}$, Xs=0.5

Temperature (K)	1200	1400	1600	1800	2000	2200
Lunar mass fraction evaporated for equilibrium evaporation	0.019 %	0.039 %	0.088 %	0.197 %	0.33%	0.55 %
Lunar mass fraction evaporated for fractionated evaporation/	0.034 %	0.055 %	0.083 %	0.115 %	0.154%	0.223 %


Hill radius

Equilibrium:
$P(z) = P_{sat}(z)$

Droplets: BSE (assumed)

Xs: liquid fraction at the surface
↪an input

Magma ocean (a infinite reserver of BSE; assumed)
↪ Temperature (T_s) as input

Summary

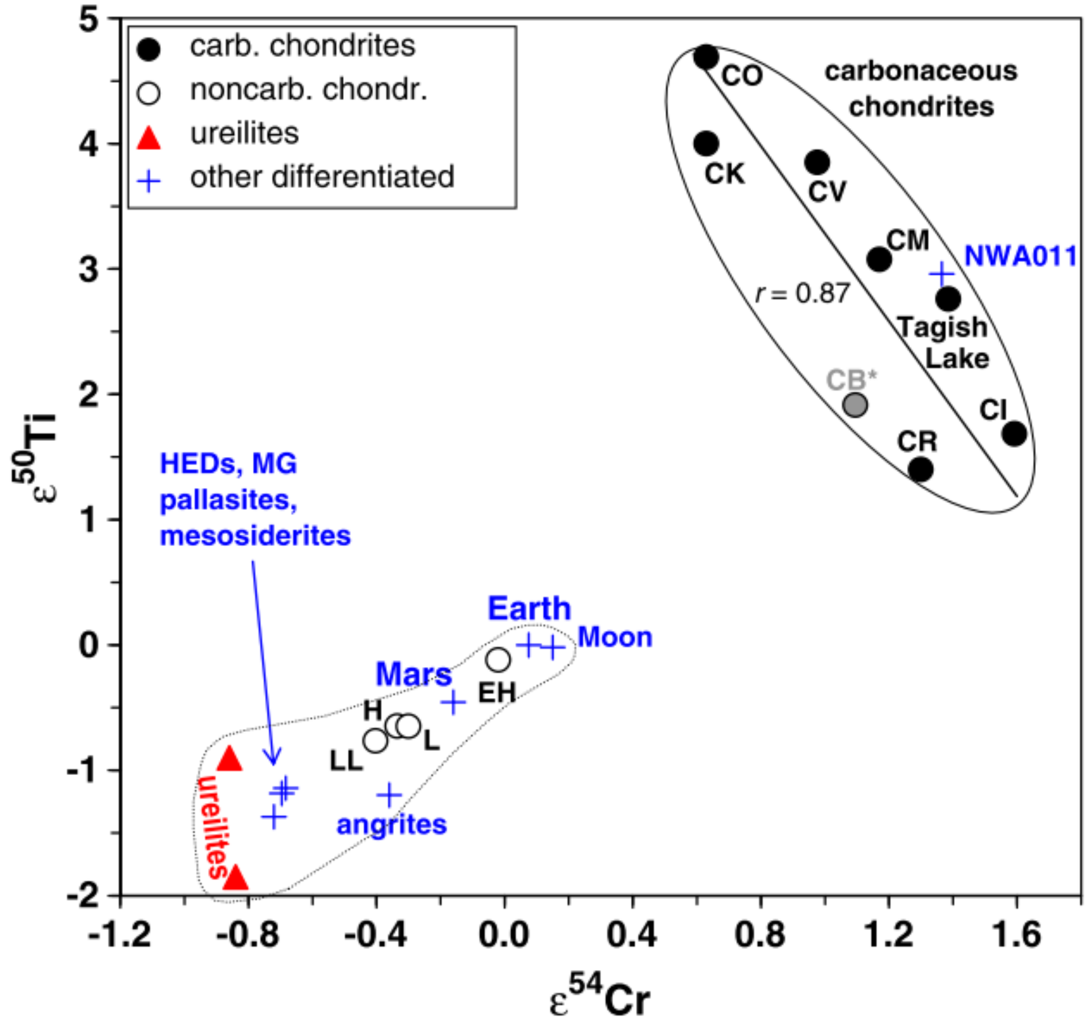
Inspired by binary stars and close-in exoplanets,
Earth's tides are considered for the volatile loss from the Moon

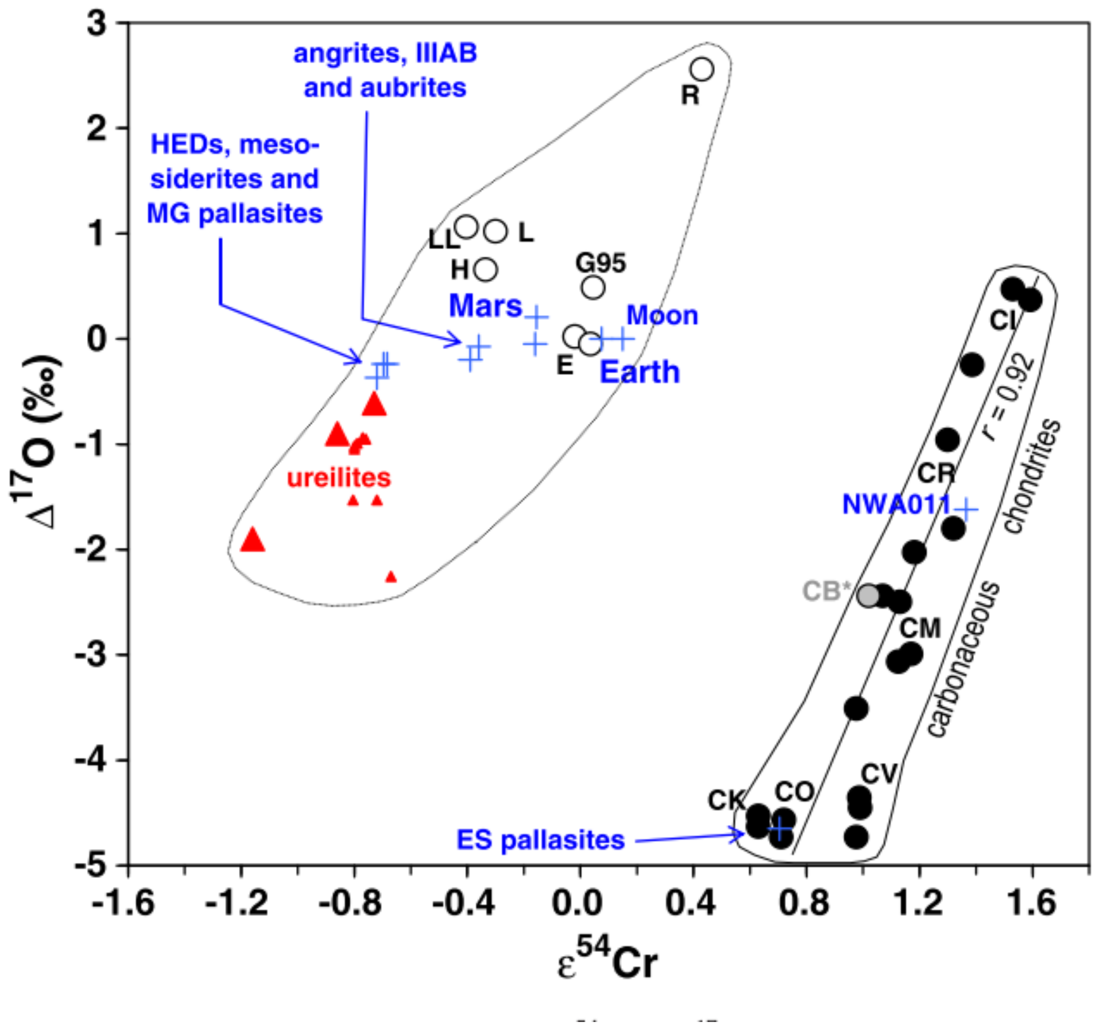
Charnoz,.., Hyodo,.. Nature Geo. Under review

- Vap/liq Parker wind equation is considered
- Tides assisted the loss of volatile vap/liq from the Moon
- 200-20000 yrs at T_s=1500-2000K may reproduce volatile depletion on the Moon (depending on dry/wet models, distance to the Earth and X ← reasonable values)

Future works: Droplets composition, Radiative heating/cooling, 3D calculations, etc

Chemical similarities





Warren (2011)

- Isotopic differences expressed as variations in parts per 10,000
- Variations arise from nucleosynthetic differences (mass-**independent**)
- Earth and Moon are indistinguishable in each system (Cr, Ti, O)

Moon and Earth were formed from identical building blocks

Thermodynamic model of lunar atmosphere

Evaporation reactions determined from experiments are used
to calculate the gas species present in the lunar atmosphere