# Processing of Cometary Nuclei by Cosmic Rays


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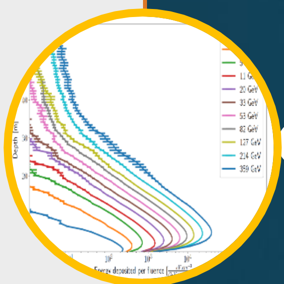
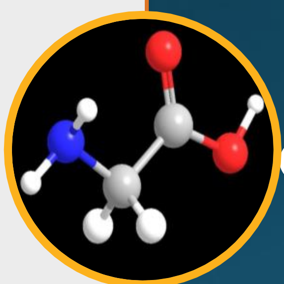
*Cosmic Rays 2, November 8-10 2022, Firenze, Italia*

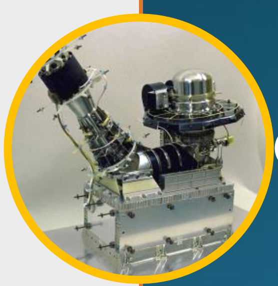
A short introduction about comets



Energy deposition



Effect on cometary nuclei



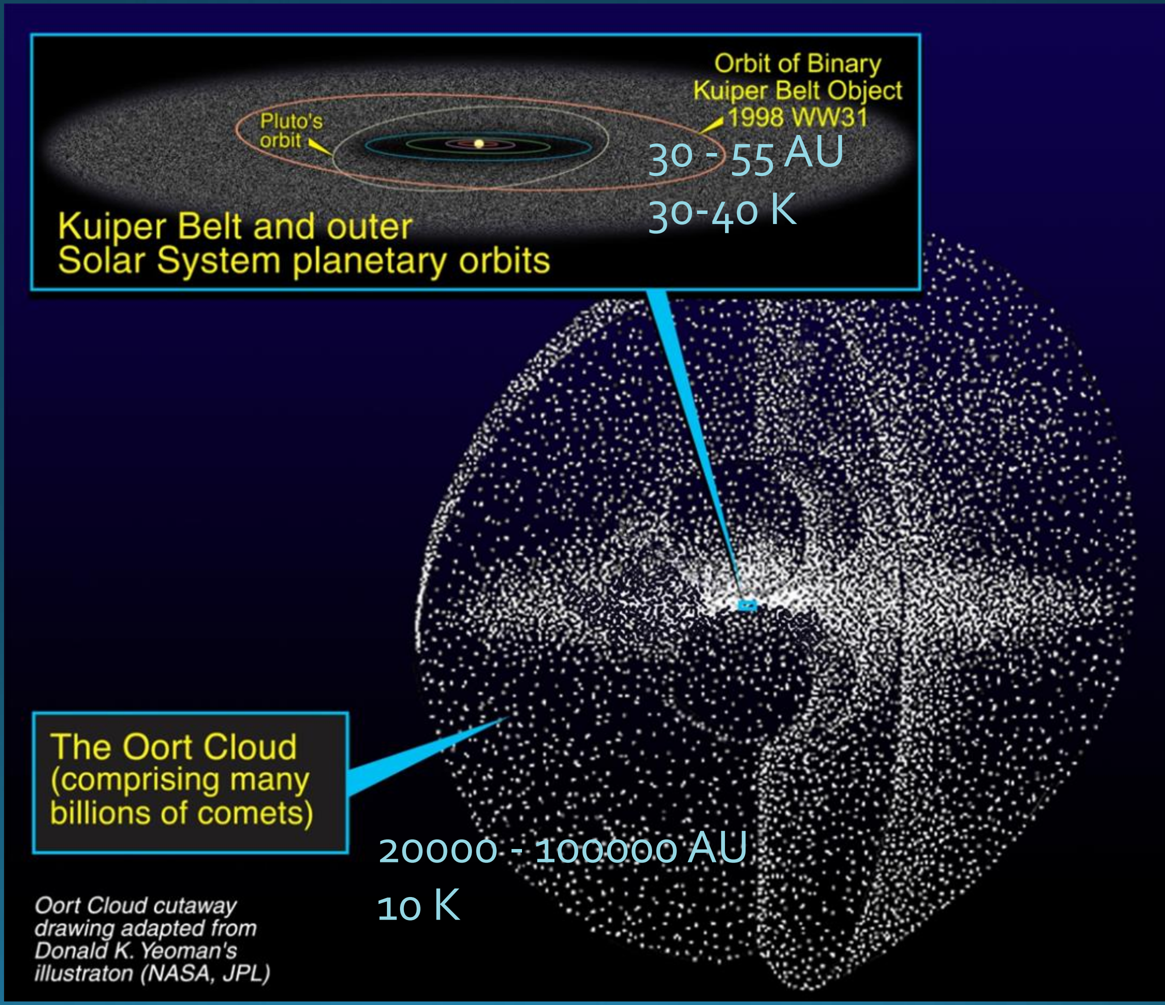
Implications on observations

# Introduction

## Comets as the most pristine bodies in the solar system

During its formation, the material forming the solar system bodies is altered

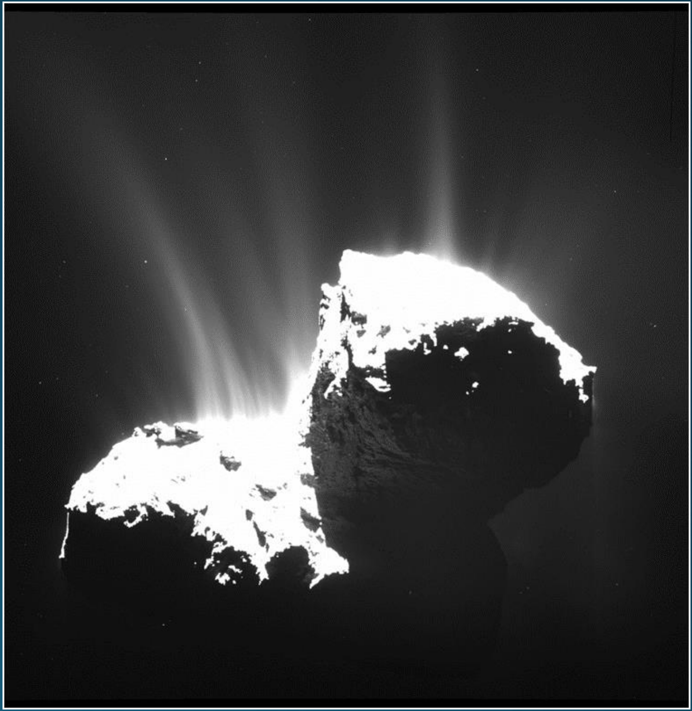
- Comets formed far enough from the Sun to remain cold
- Comets are small (typical size ~km)
- Comets remain stored in the Kuiper Belt and Oort cloud, far from the Sun



# Introduction

Is cometary material really unaltered?

- 2014-2016 Rosetta (ESA) 67P Churyumov-Gerasimenko



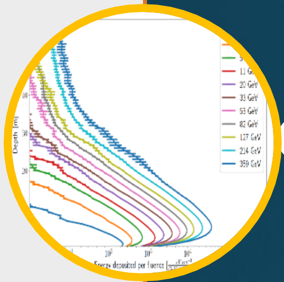
✓ Observation of supervolatiles in the coma of 67P and of hydrogen halides
✓ Low density, high porosity, and homogeneity
✓ of the nucleus
✓ Absence of signatures of aqueous alteration

⇒ the heating of the nucleus remained limited

- 2029 (launch) Comet Interceptor (ESA)

Will wait at the Lagrange L2 point to find a target: a dynamically new comet

A short introduction about comets

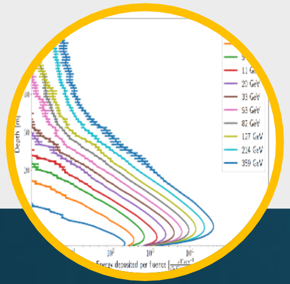


Energy deposition

THE ASTROPHYSICAL JOURNAL, 890:89 (8pp), 2020 February 10 https://doi.org/10.3847/1538-4357/ab67b9


# The Effect of Cosmic Rays on Cometary Nuclei. I. Dose Deposition

G. Gronoff[1,2], R. Maggiolo[3], G. Cessateur[3], W. B. Moore[4], V. Airapetian[5,6], J. De Keyser[3,7], F. Dhooghe[3], A. Gibbons[3,8], H. Gunell[3], C. J. Mertens[2], M. Rubin[9], and S. Hosseini[10]



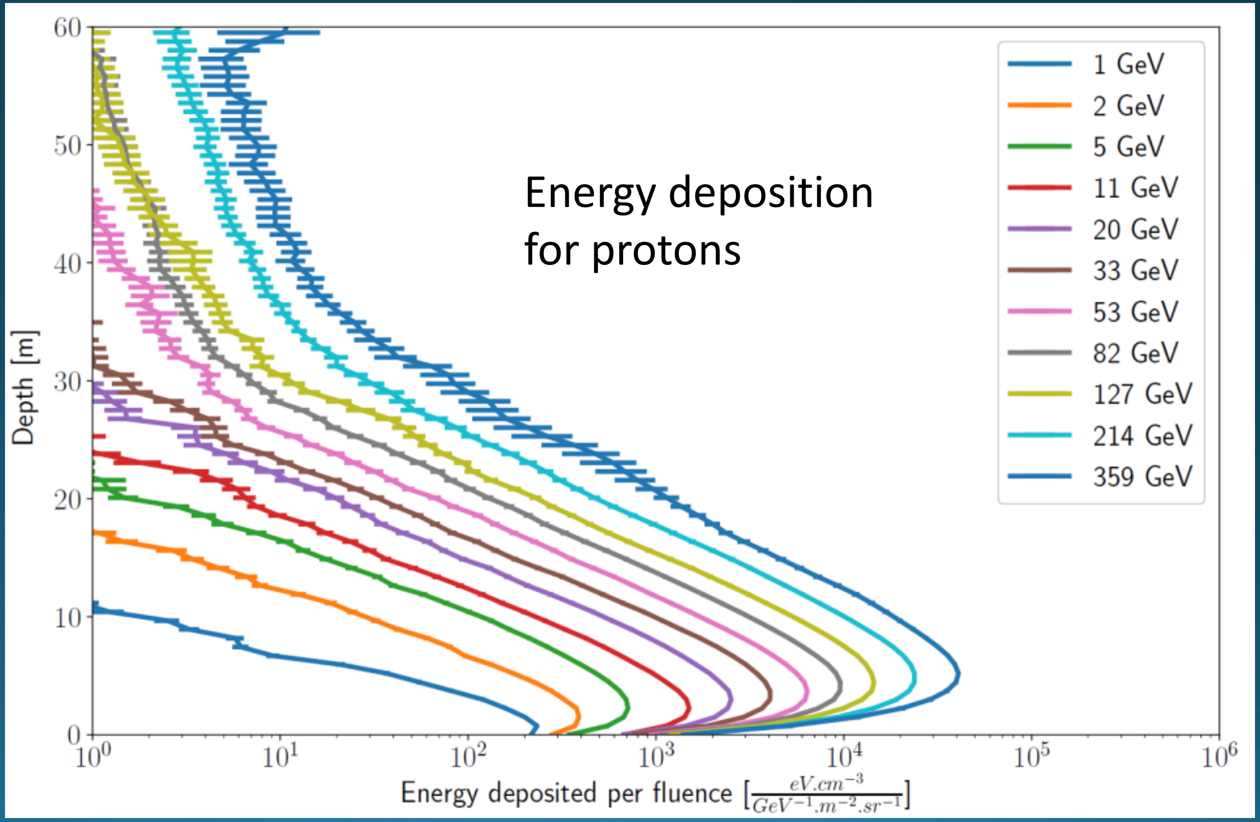
# Energy Deposition

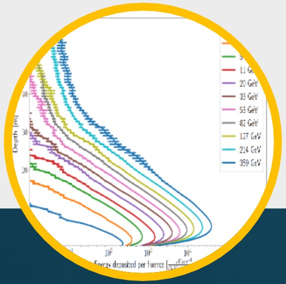
- Model based on Geant-4, Uses the physics list QGSP_BIC_HP
- Fragmentation of nuclei and production of isotopes included
- 4 groups of particles: protons; alpha; M: Z=7, A=14 (mainly C and O); VH: Z=26, A= 56 (mainly iron nuclei),

Comet

5 km radius sphere density 0.5378 kg $m^{-3}$

$H_2O$ (pure water ice) + $SiO_2$ (dust) dust/ICE =4

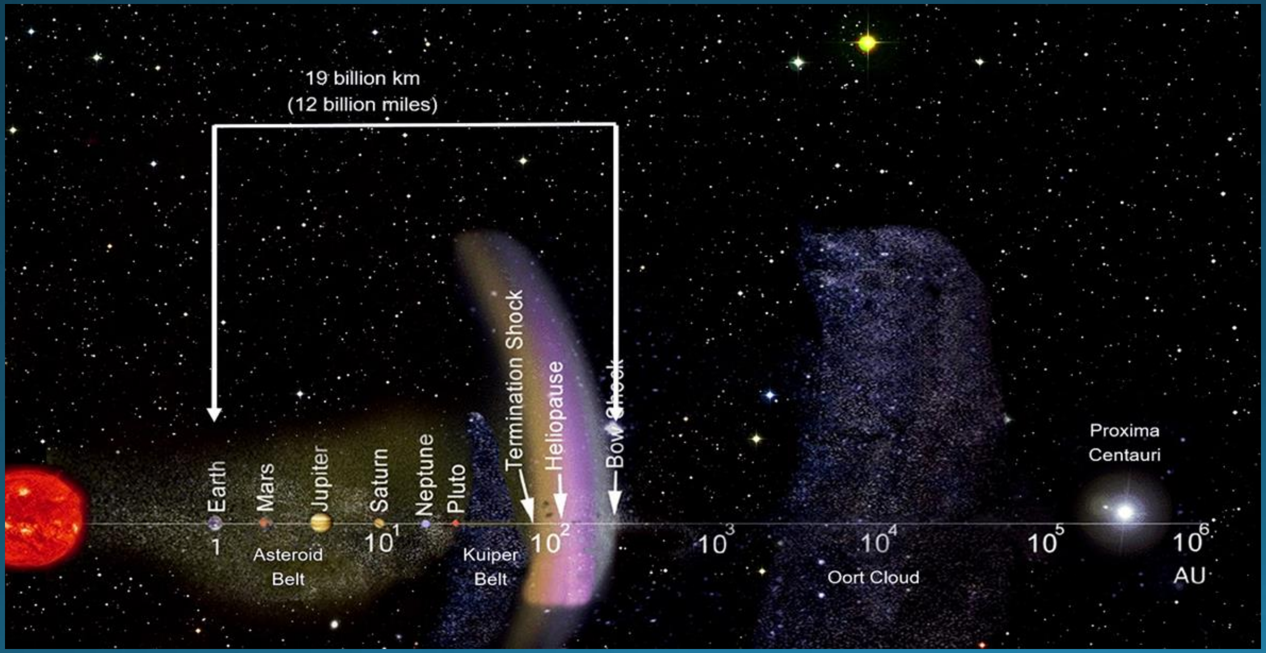


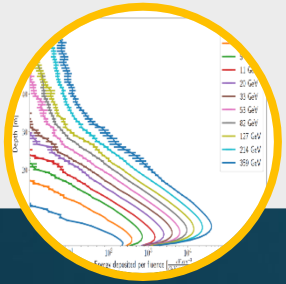


# Energy Deposition

- Gamma Ray Burst
- Solar photons

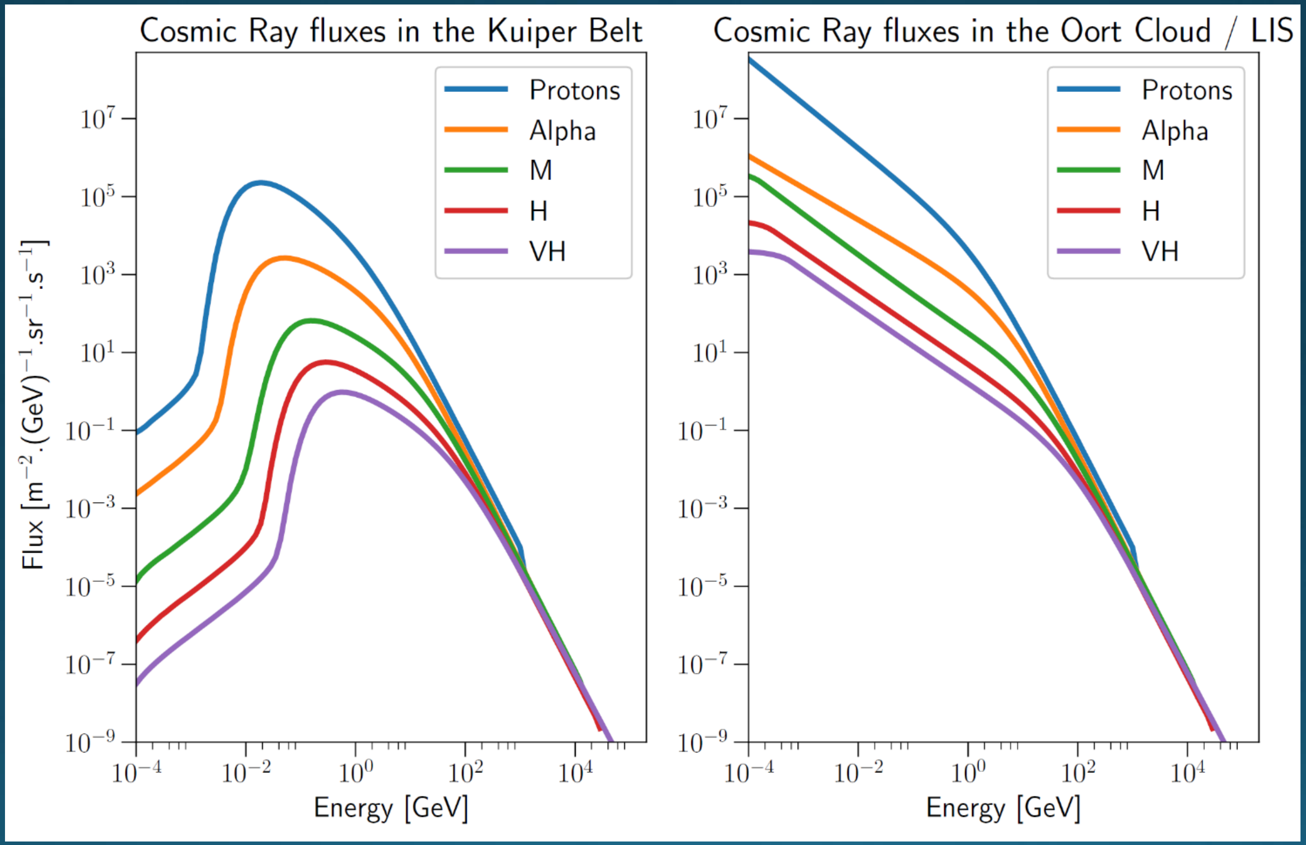
- Galactic Cosmic Rays
- Bulk solar wind and energetic events (SEP)



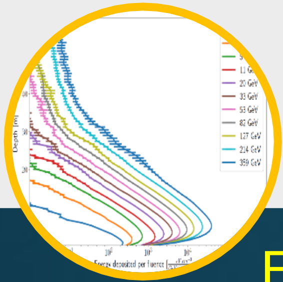


# Energy Deposition: GCRs

GCRS flux as modeled by the Badhwar–O'Neill model
Constant flux during the last 4.5 Gy



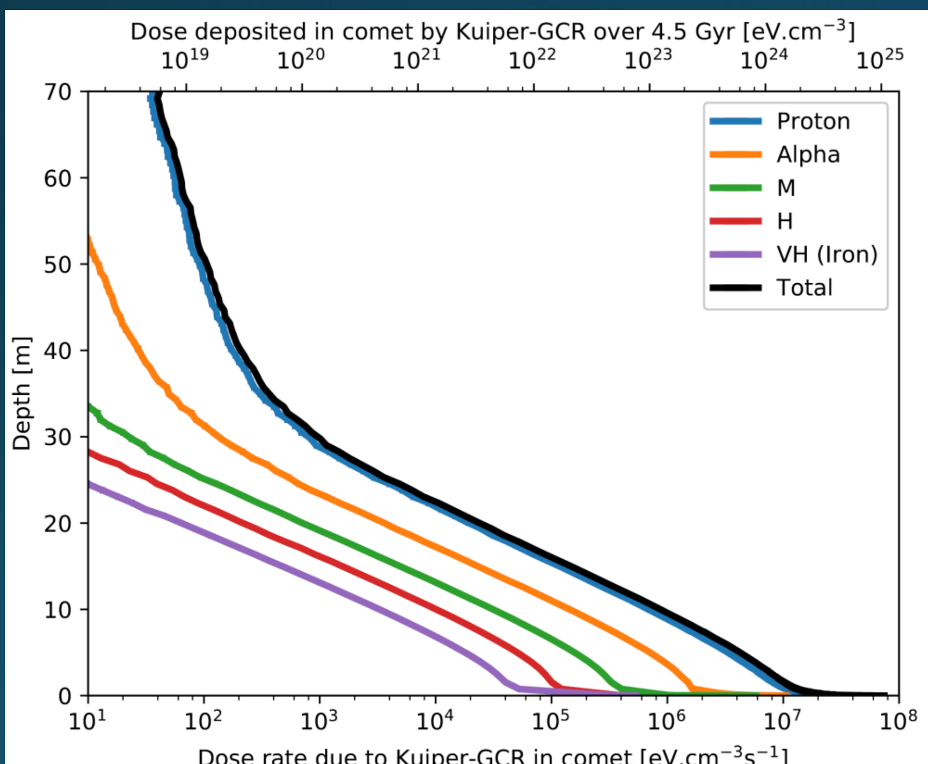

Flux differ at low energy (~below 1 GeV) due to the shielding by the heliosphere

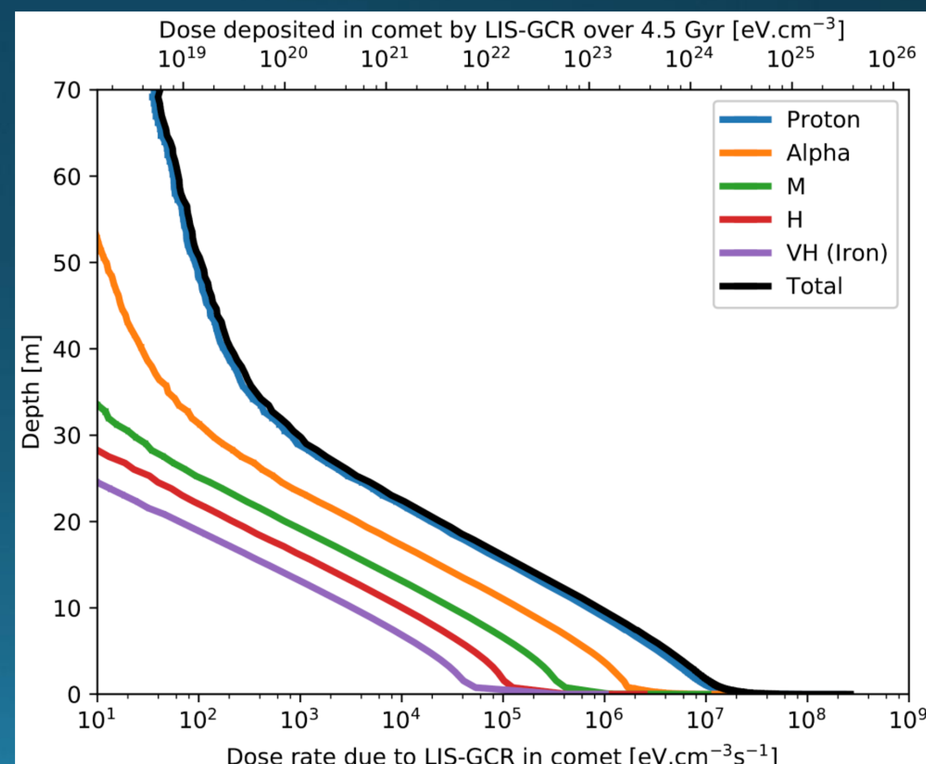


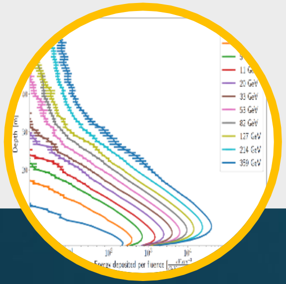
# Energy Deposition: GCRs

Energy deposition dominated by protons
OC – KP difference: only in the first centimeters below the surface

Significant energy deposition down to tens of meters inside the nucleus



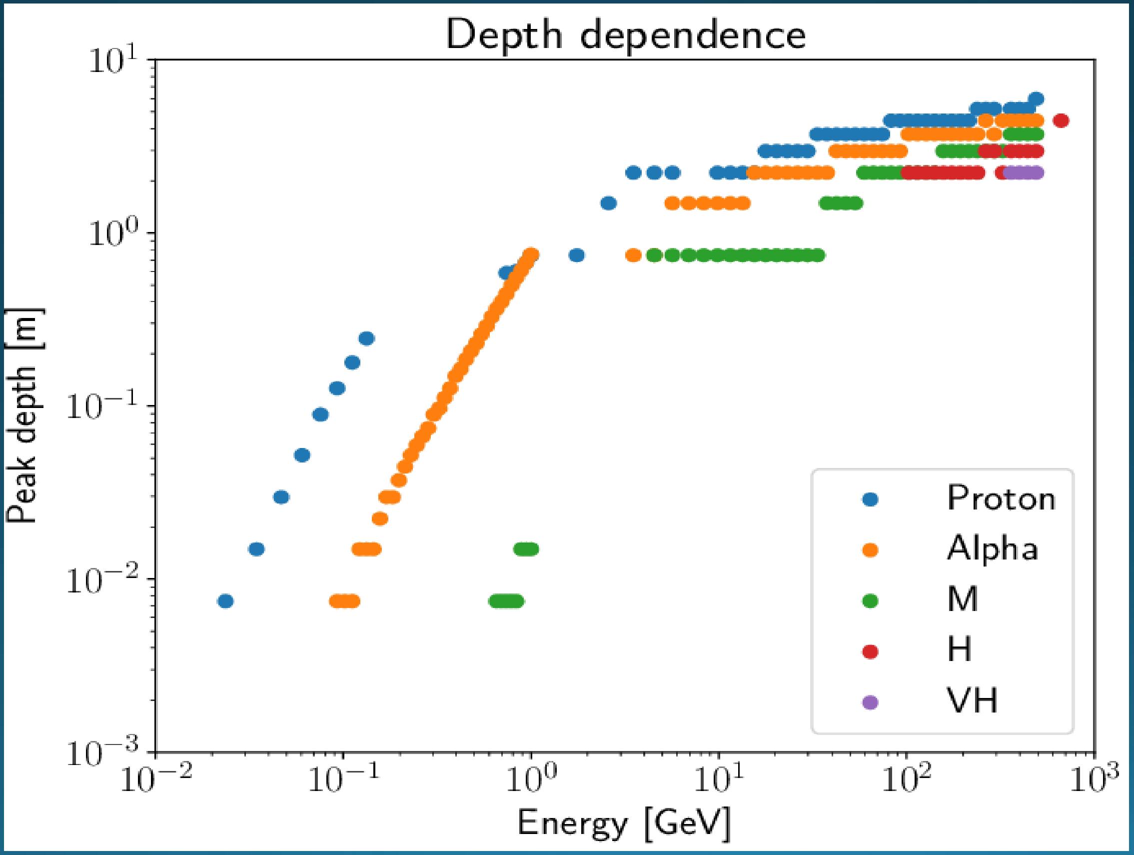



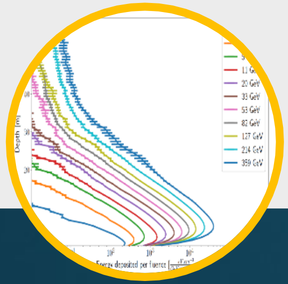


# Energy Deposition: solar wind

Typical energy ~keV
SW propagates at constant velocity
Density decreases with the square of the distance to the Sun

Energy is deposited in the first centimeter below the nucleus surface

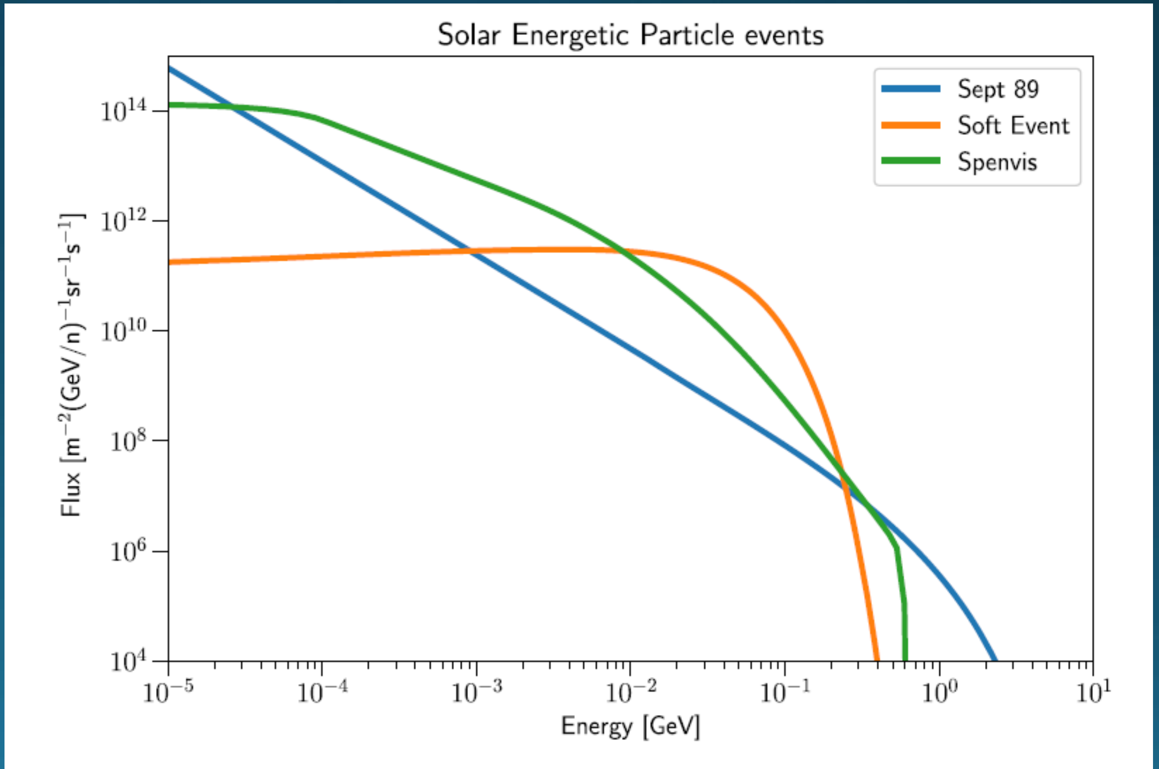




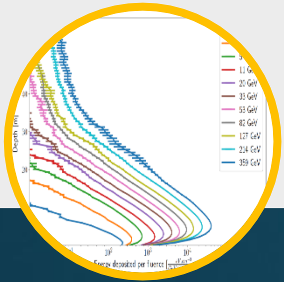
# Energy Deposition: SEP

- SEP events with significant amount of particles above 500 MeV: ~2 per year
- Last for a couple days at most
- May have been more frequent in the early solar system

For present-day SEP events, the dose rate should be reduced by a factor of $10^4$.

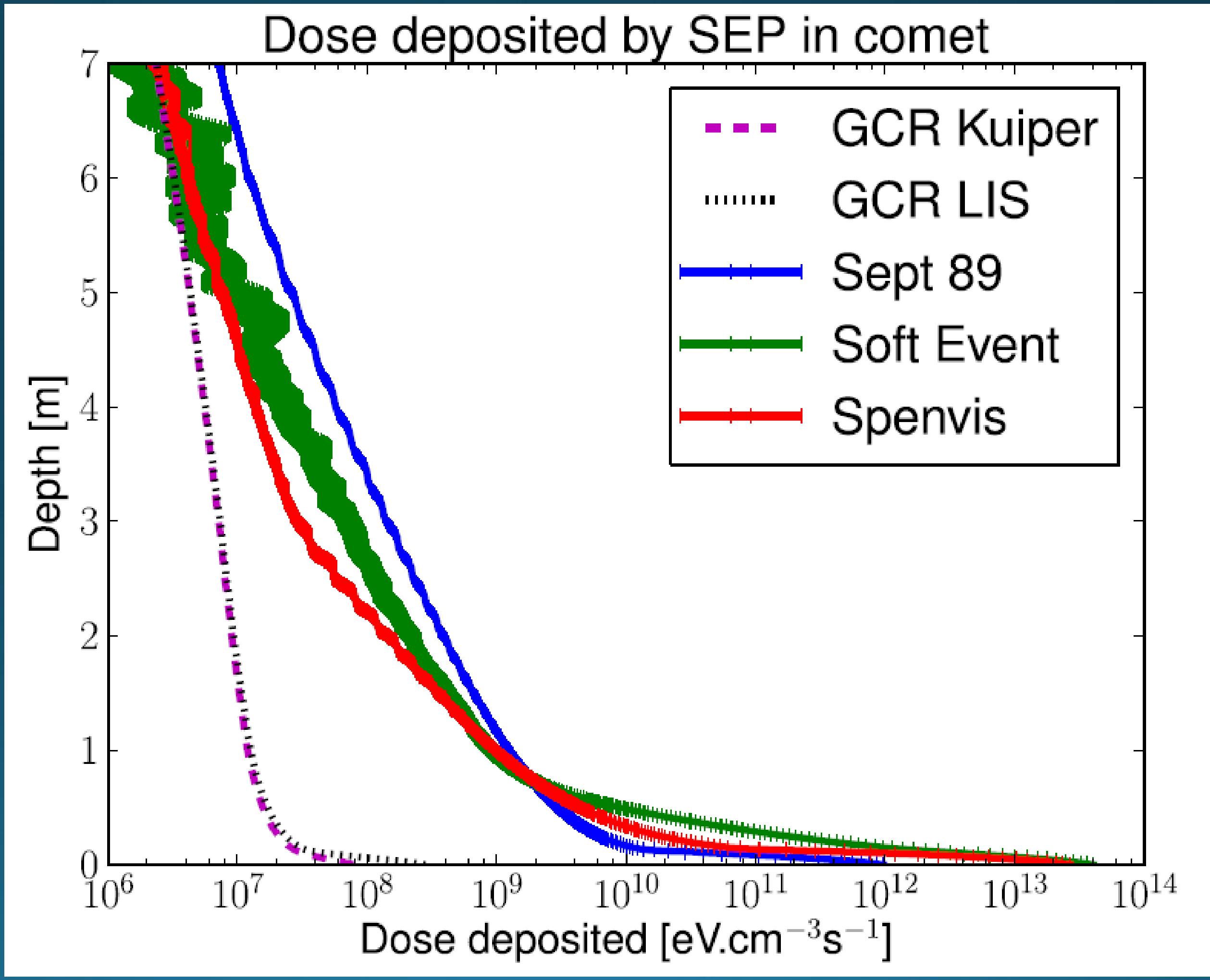


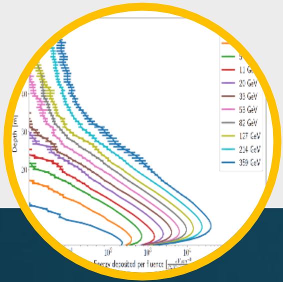
# Energy Deposition: SEP



SEP contribution significant only for KB comets in the first meter below the surface

Total dose difficult to asses as the occurrence frequency of SEP and their spectrum are not well constrained

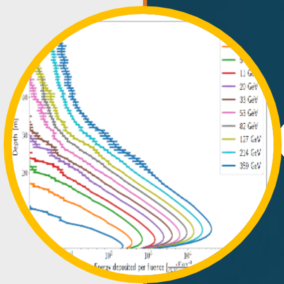




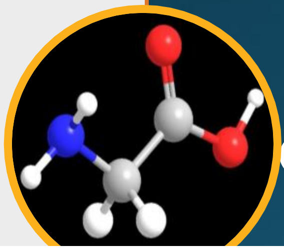
# Energy Deposition

| | KB | OC |
|---|---|---|
| ~1 cm | **Solar wind** $10^{24}$ eVcm$^{-3}$<br>**SEP** < $10^{28}$ eVcm$^{-3}$<br>**GCR** $10^{25}$ eVcm$^{-3}$ | **Solar wind** $10^{17}$ – $10^{19}$ e<br>**SEP** < $10^{21}$ - $10^{23}$ eVcm$^{-3}$<br>**GCR** 2.5 $10^{25}$ eVcm$^{-3}$ |
| ~1 m | **SEP** < $10^{24}$ eVcm$^{-3}$<br>**GCR** $10^{24}$ eVcm$^{-3}$ | **SEP** < $10^{17}$ – $10^{19}$ eVcm<br>**GCR** $10^{24}$ eVcm$^{-3}$ |
| ~10 m | **SEP** < $10^{22}$ eVcm$^{-3}$<br>**GCR** $10^{23}$ eVcm$^{-3}$ | **GCR** $10^{23}$ eVcm$^{-3}$ |
| ~50 m | **GCR** $10^{19}$ eVcm$^{-3}$ | **GCR** $10^{19}$ eVcm$^{-3}$ |

A short introduction about comets



Energy deposition

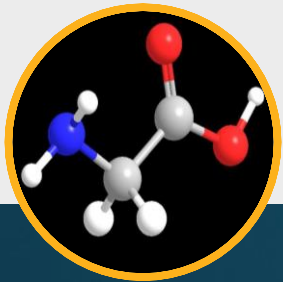


Effect on cometary nuclei

THE ASTROPHYSICAL JOURNAL, 901:136 (13pp), 2020 October 1
https://doi.org/10.3847/1538-4357/abacc3


# The Effect of Cosmic Rays on Cometary Nuclei. II. Impact on Ice Composition and Structure

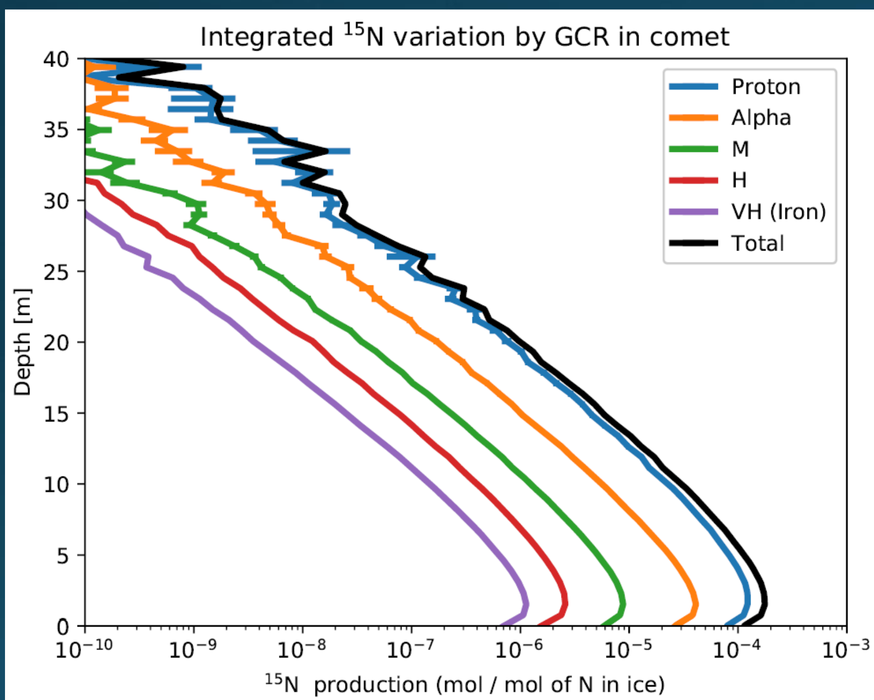
R. Maggiolo[1], G. Gronoff[2,3], G. Cessateur[1], W. B. Moore[4], V. S. Airapetian[5,6], J. De Keyser[1,7], F. Dhooghe[1], A. Gibbons[1,8], H. Gunell[9], C. J. Mertens[3], M. Rubin[10], and S. Hosseini[11]

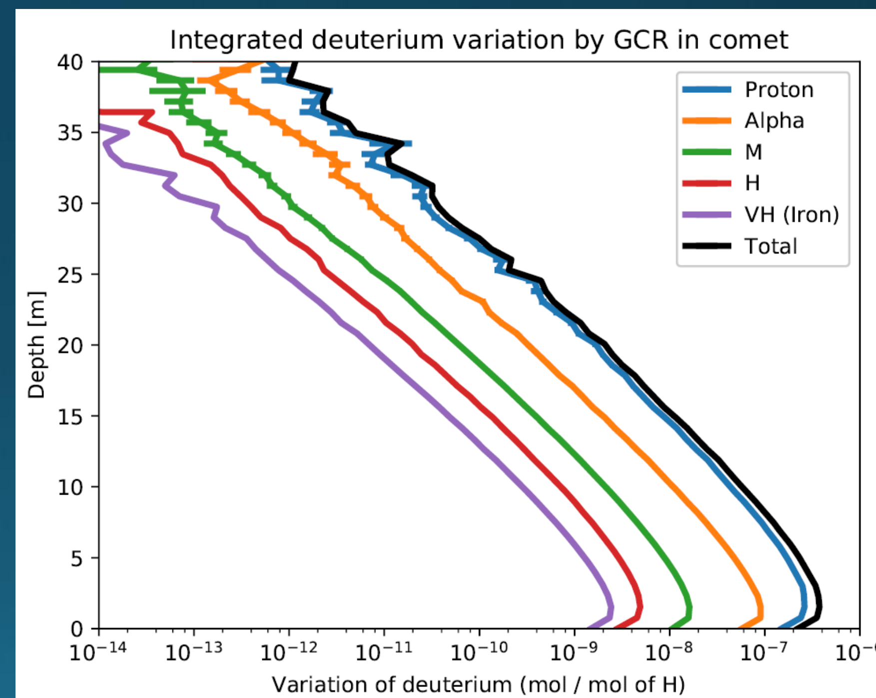


# Effect on cometary nuclei: isotopes

$^{14}N/^{15}N$
Protosolar nebula: 441 ; Earth: 272
Lower in comets (140 for CN)

D/H
Comet 67P 5.3 ± 0.7 $10^{-4}$
(3 times the SMOW value)

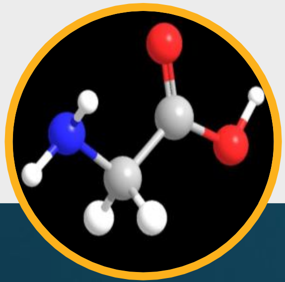



$^{15}N$ production: max $^{15}N/N$ ~2 $10^{-4}$

D production: max D/H ~ 3 $10^{-7}$

Isotopic composition is mostly unchanged



# Effect on cometary nuclei: method

- **Chemical model** (e.g. Garrod et al. 2019)

  Long computing time, low spatial resolution

  More suited to investigate composition changes close to the surface and to characterize the production of minor species

- **Laboratory experiments**

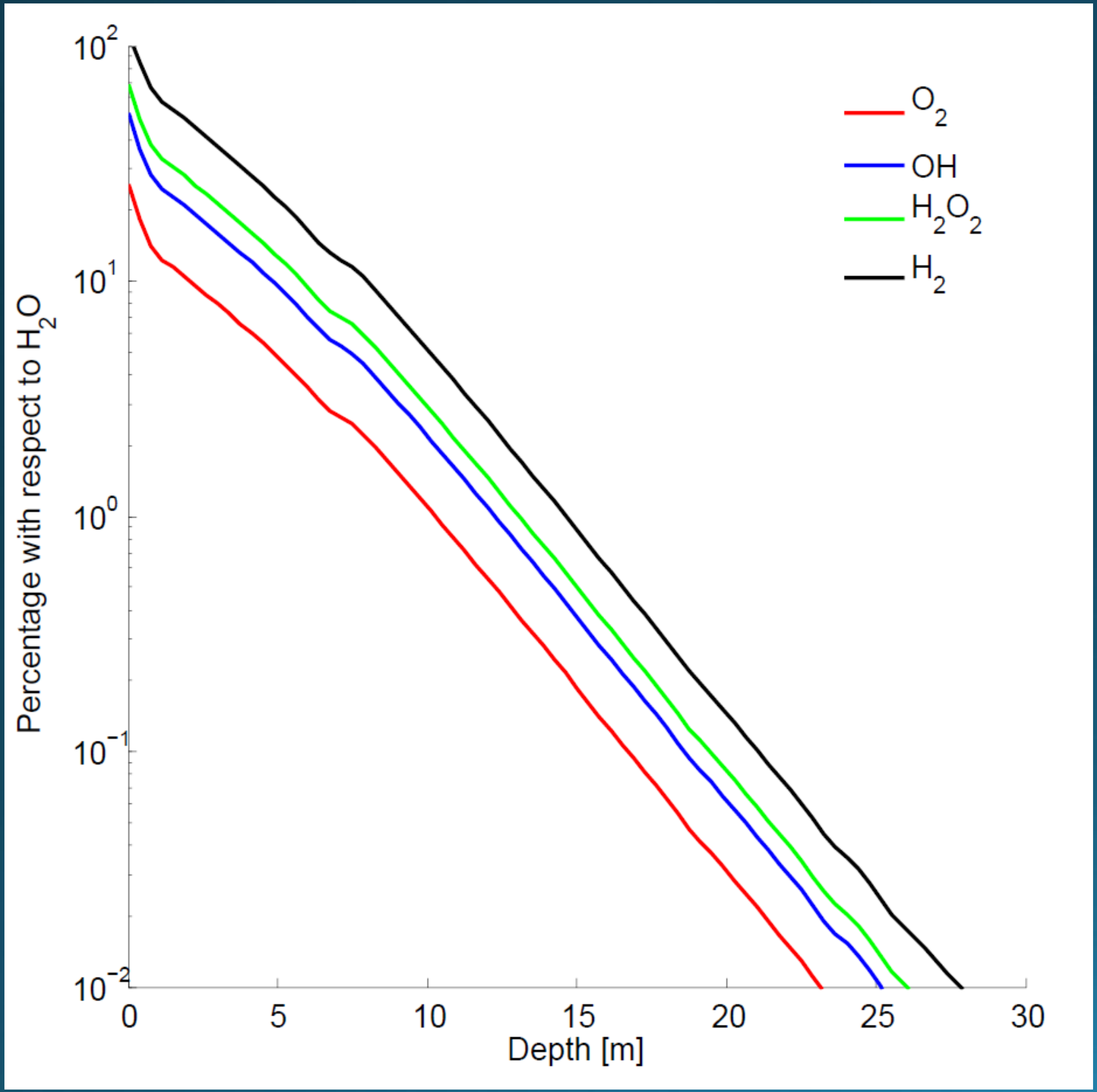
  $\Delta$n = Deposited energy . Yield

  *Deposited energy: from model* *Yield: from laboratory experiments*

  OK for major species, imprecise for minor species

  Fits our goal: determine the depth down to which cometary material is altered

# Effect on cometary nuclei: composition

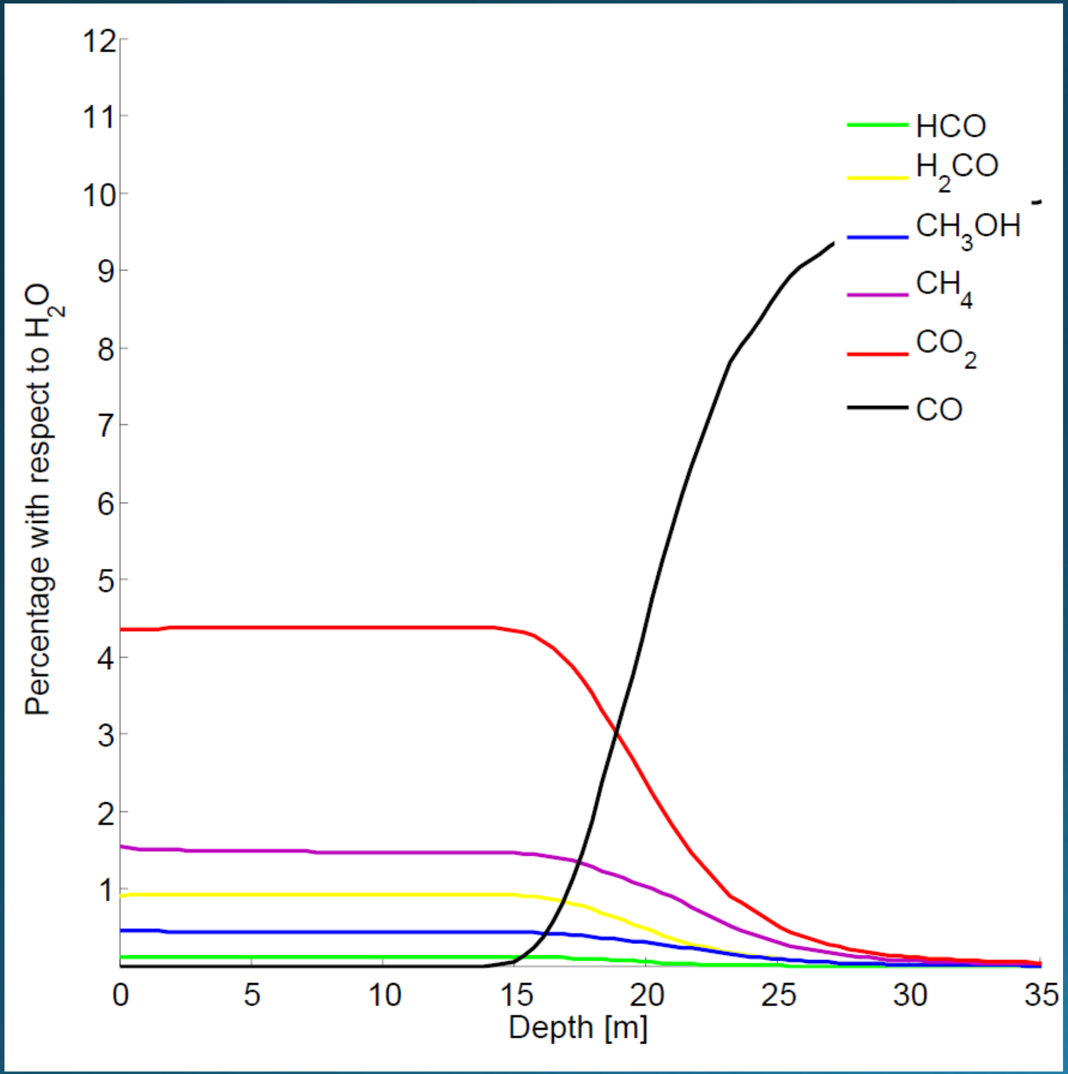



Experimental yields from Jonhson and Quickenden 1997

Pure water ice

Water radiolysis and production of secondary species significant down to ~15 m

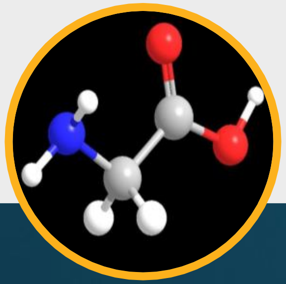
# Effect on cometary nuclei: composition



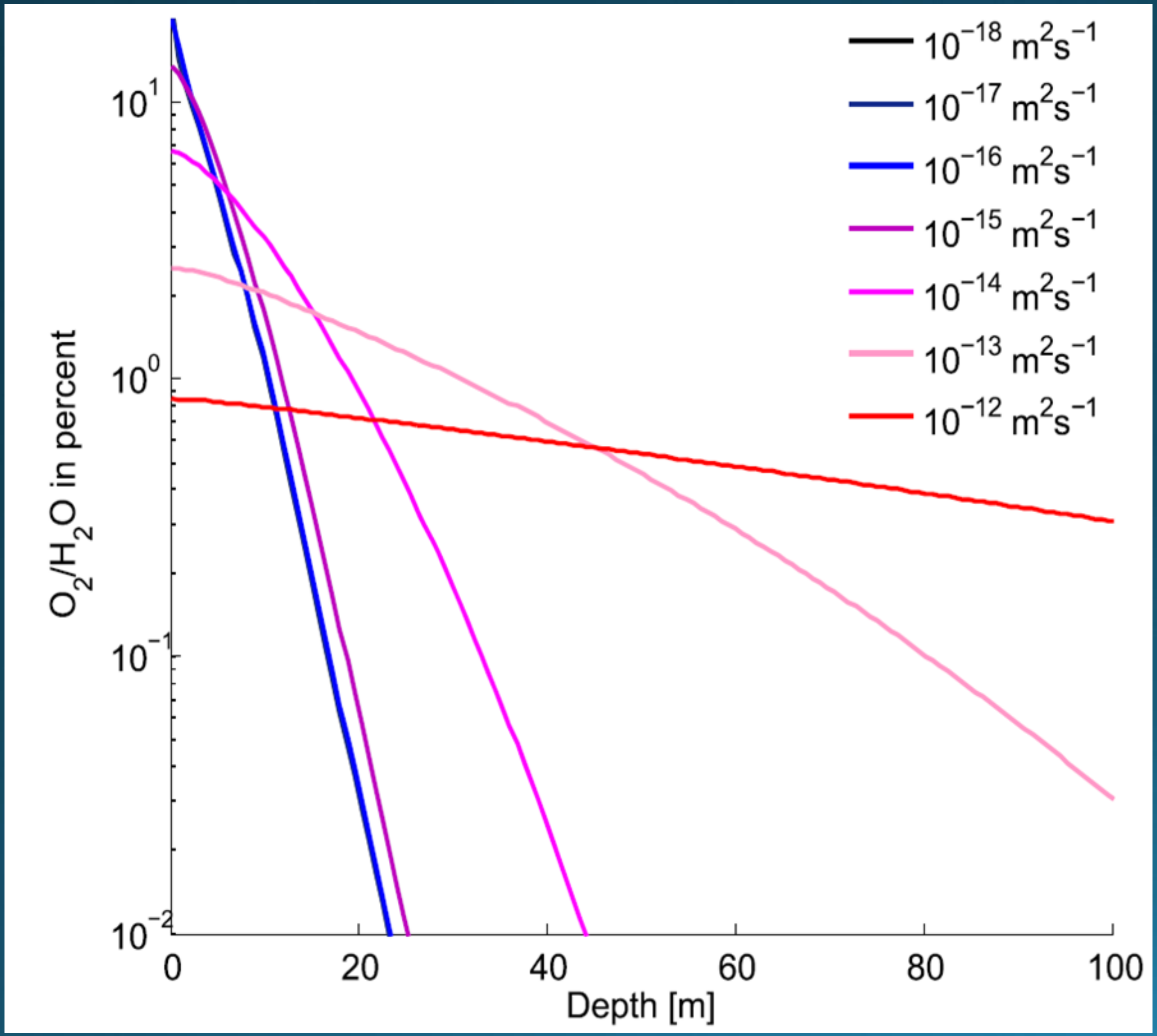

Experimental yields from Hudson and Moore 1999

CO – $H_2O$ ice mixture (1:10)
Variable yields as a function of CO:$H_2O$

All CO is destructed below 10 m
Below ~35 m it remains unaltered
Production of C bearing species significant down to ~25 m



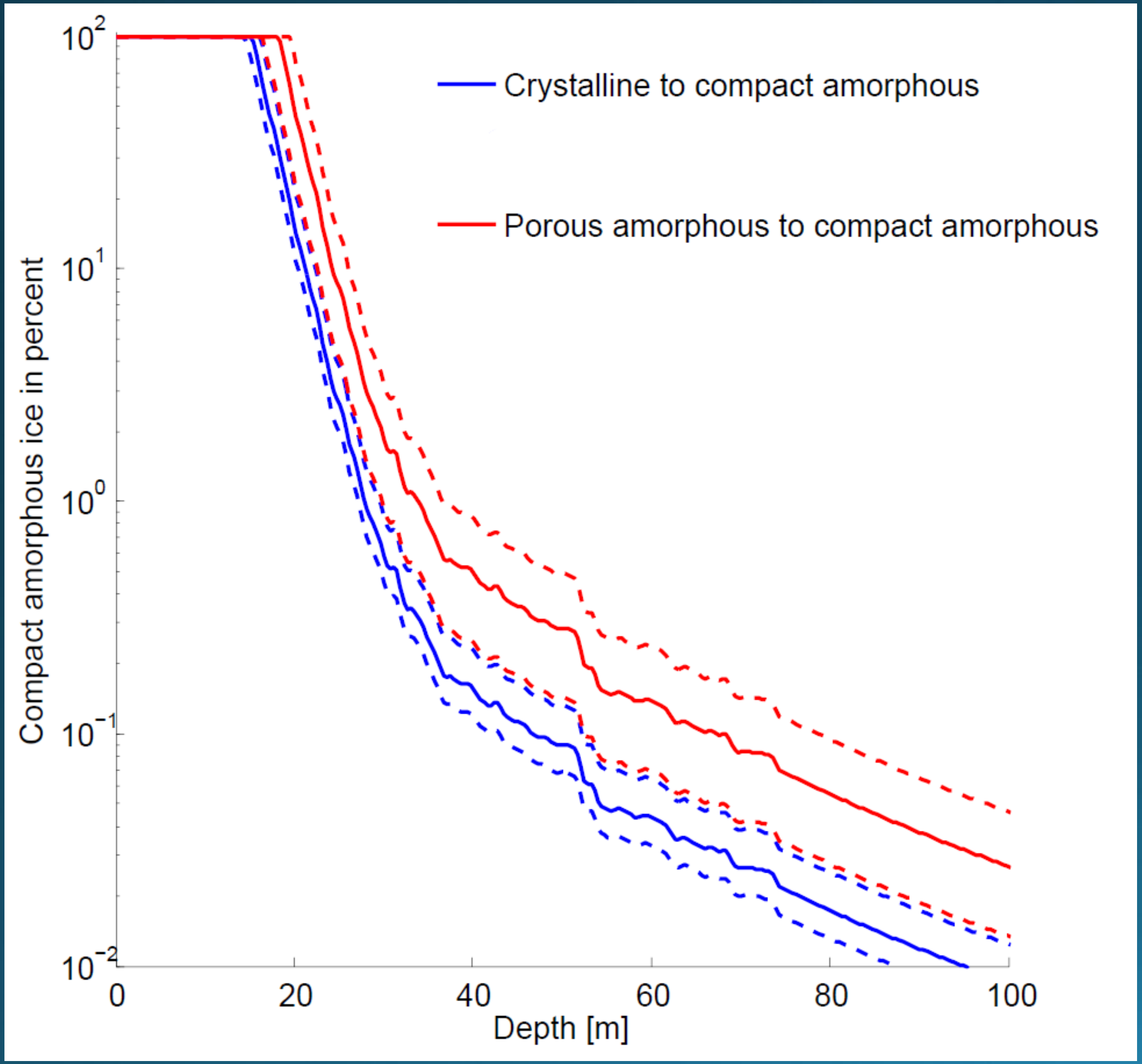
# Energy Deposition




CO diffusion coefficient in amorphous ice @ 40K
8 $10^{-15}$ m²/s (Mispelaer et al. 2013)
8.5 $10^{-15}$ m²/s (Lauk et al. 2015)

Diffusion may bring radiolysis products deeper into the nucleus.

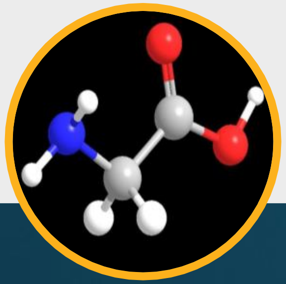
# Effect on cometary nuclei: ice structure




Irradiation converts ice into compact amorphous ice

Energy dose to convert crystalline or amorphous ice into compact amorphous ice has from Dartois et al. 2015

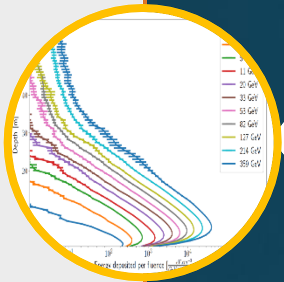
Whatever is the ice structure in comets, GCR convert it into compact amorphous ice down to ~20m



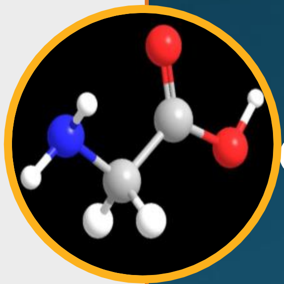
# Effect on cometary nuclei: summary

- Isotopic composition: negligible effect for $^{15}N$ and D
- Chemical composition: significantly altered down to a few tens of meters
- Ice structure: altered down to ~20 m (compact amorphous ice)

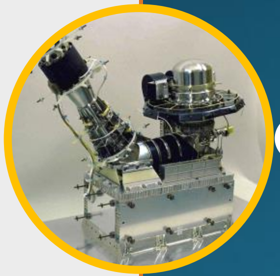
A short introduction about comets



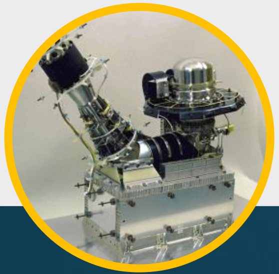
Energy deposition



Effect on cometary nuclei



Implications on observations



# Implications on observations

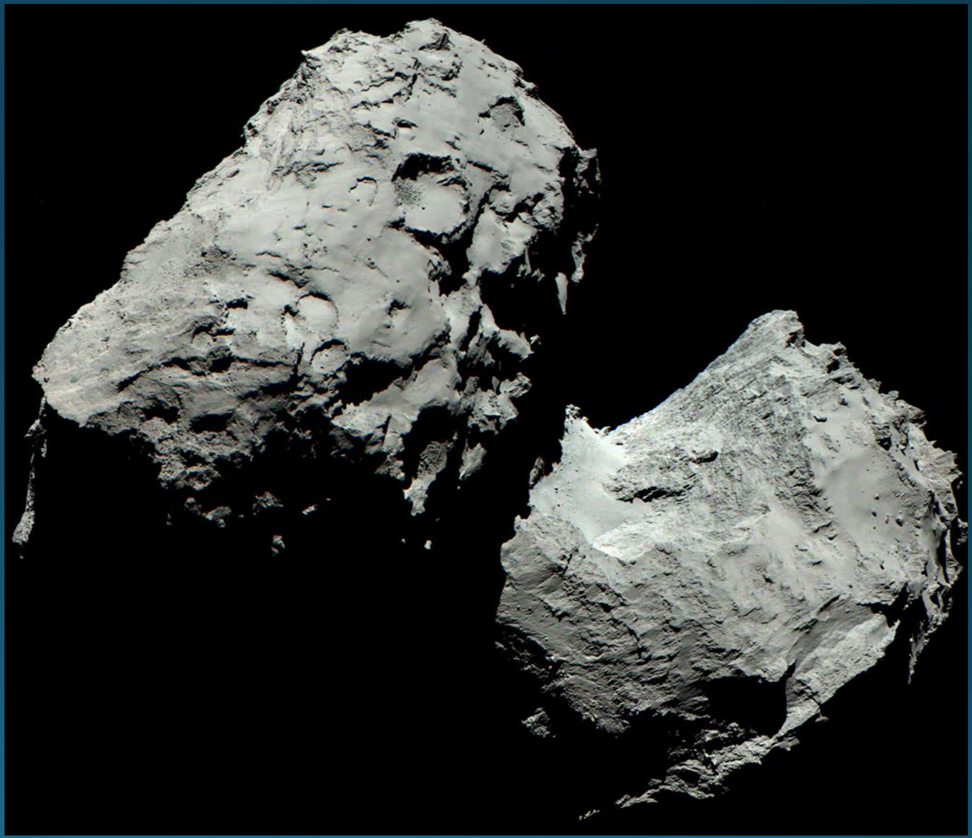
- OC essentially collisionless
- KB collisions are more likely

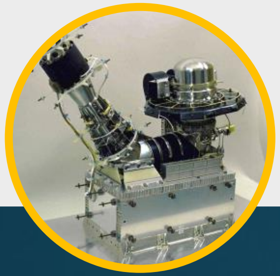
- Collisions may explain bi-lobate comets like 67P

  - Davidsson et al. (2016): merging between lobes

  - Jutzi & Benz (2017): bilobate comets like 67P may have formed due to subcatastrophic collisions

  - Schwartz et al. (2018) : catastrophic collisions may have occurred

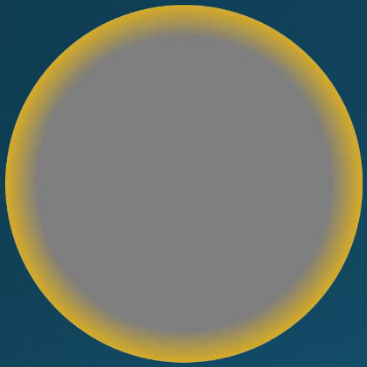




# Implications on observations

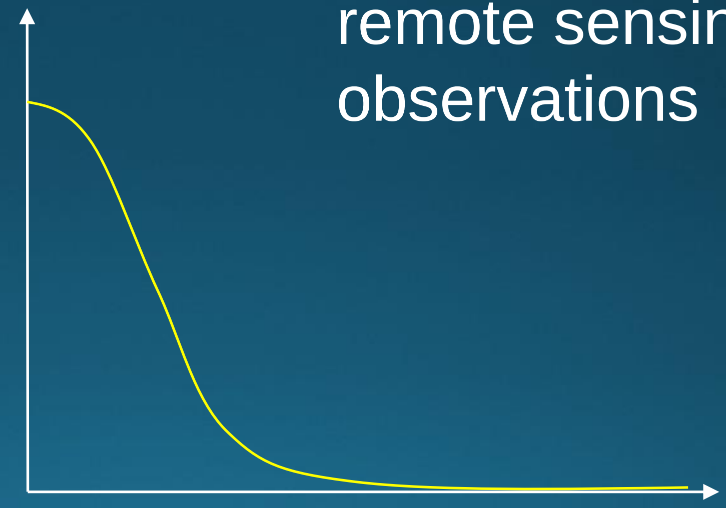
No collisions

Dynamically new comet

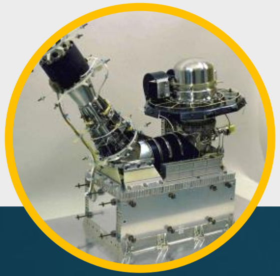


Eroded comet

Altered material



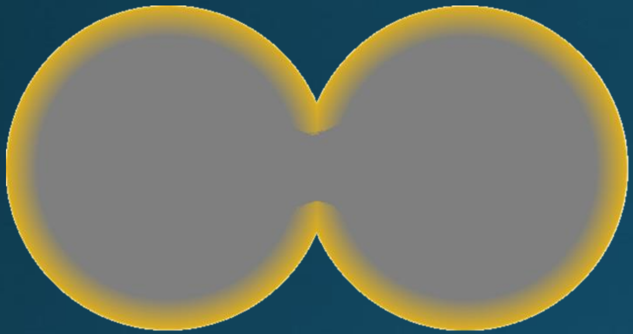

In-situ and remote sensing observations



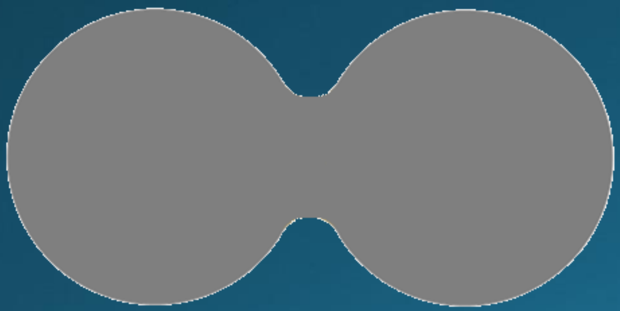
# Implications on observations

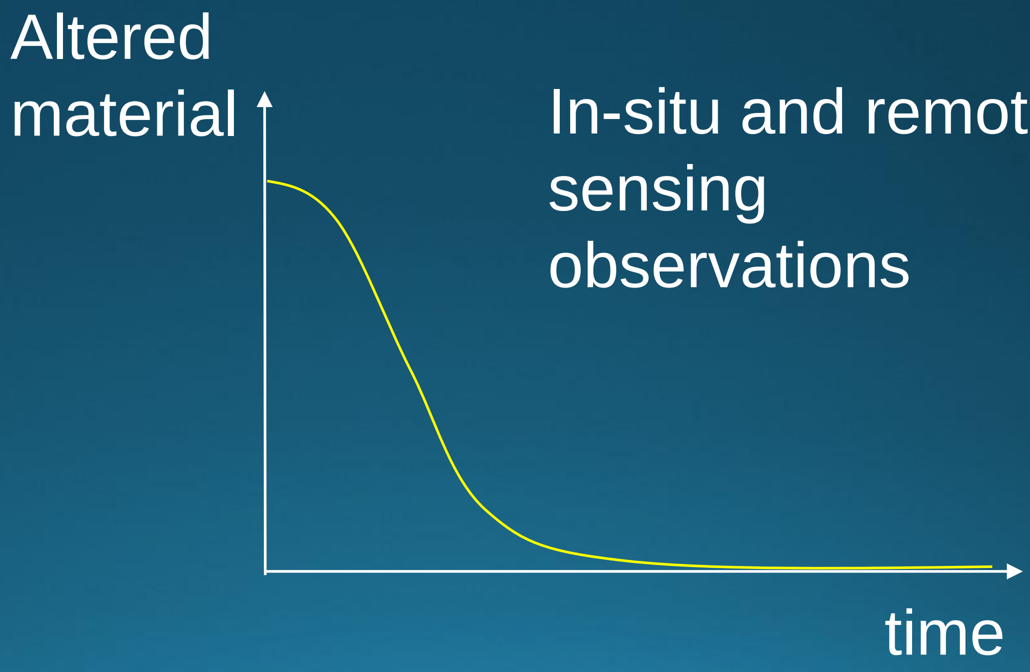
Gentle merging/ subcatastrophic collision at an early stage

Dynamically new comet

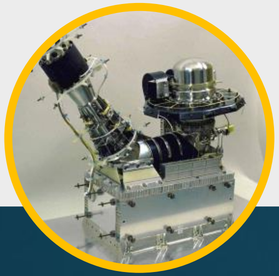


Eroded comet





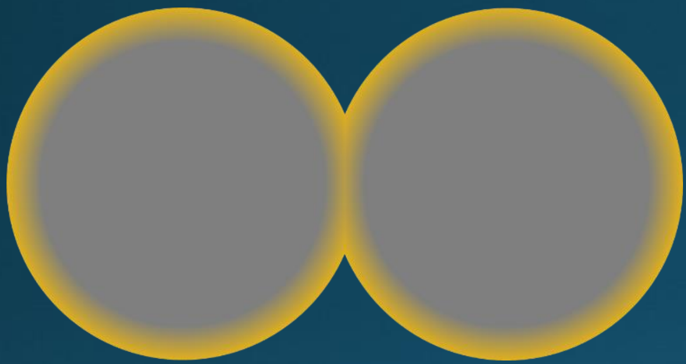

In-situ and remote sensing observations



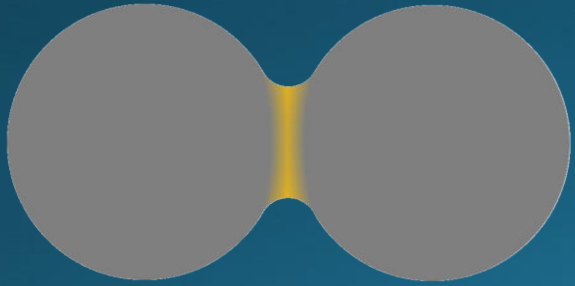
# Implications on observations

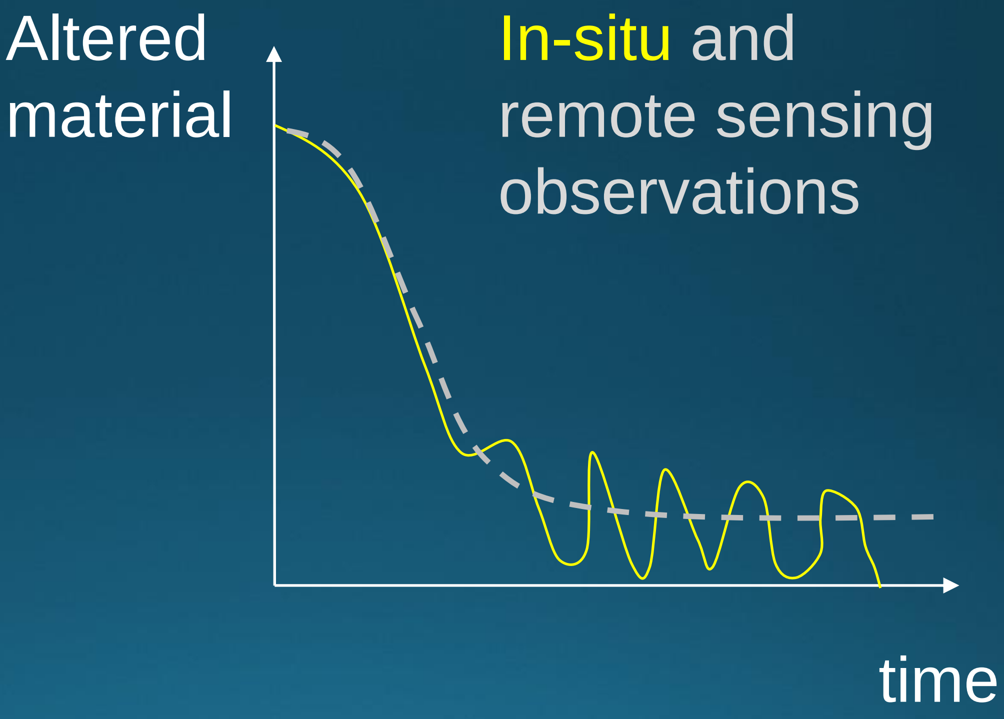
Gentle merging/ subcatastrophic collision at a late stage

Dynamically new comet

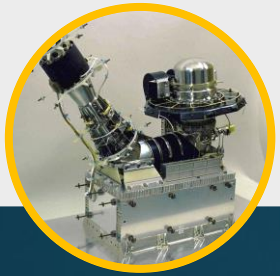


Eroded comet






Large scale inhomogeneities

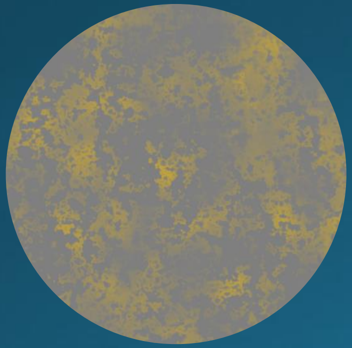


# Implications on observations

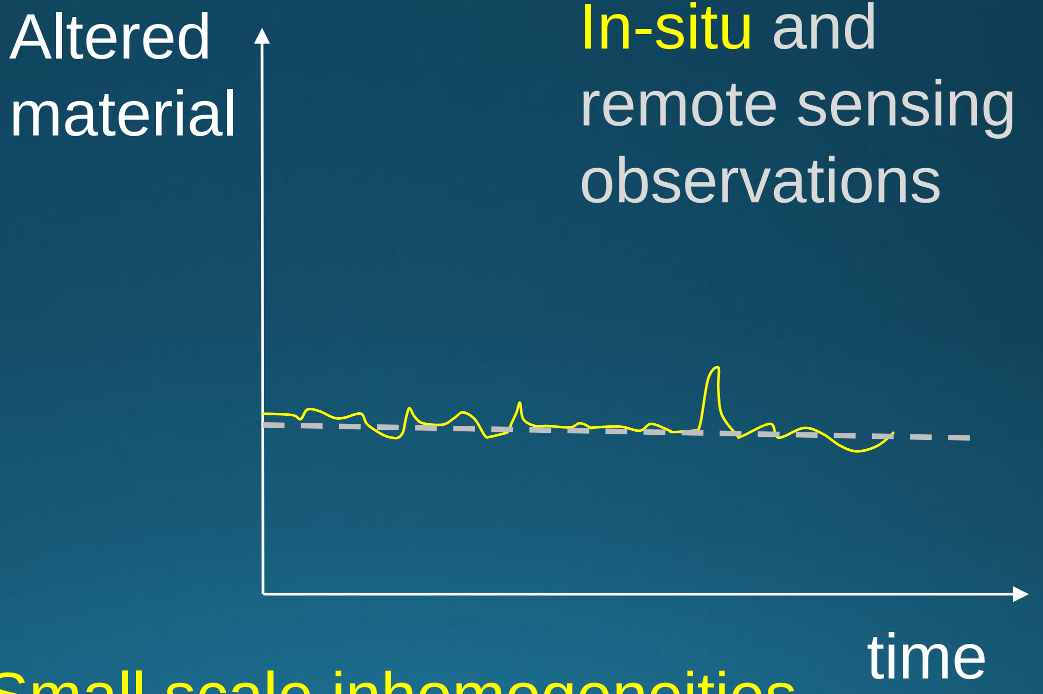
Marginally catastrophic collision + reagregation at a late stage

Dynamically new comet

Eroded comet



In-situ and remote sensing observations




Small scale inhomogeneities

# Conclusion

- GCRs are the main source of alteration of cometary nuclei below 1 m
- GCRs do not alter the $^{15}N$ and D content of cometary nuclei
- GCRs significantly alter the chemical composition of cometary nuclei down to tens of meters depth
- GCRs significantly atler the ice structure of cometary nuclei down to tens of meters depth
- The material outgassed by dynamically new comet is significantly altered by GCRs (see Harrington Pinto 2022)
- Alteration of cometary  material by GCRs should be taken into account when interpreting measurements