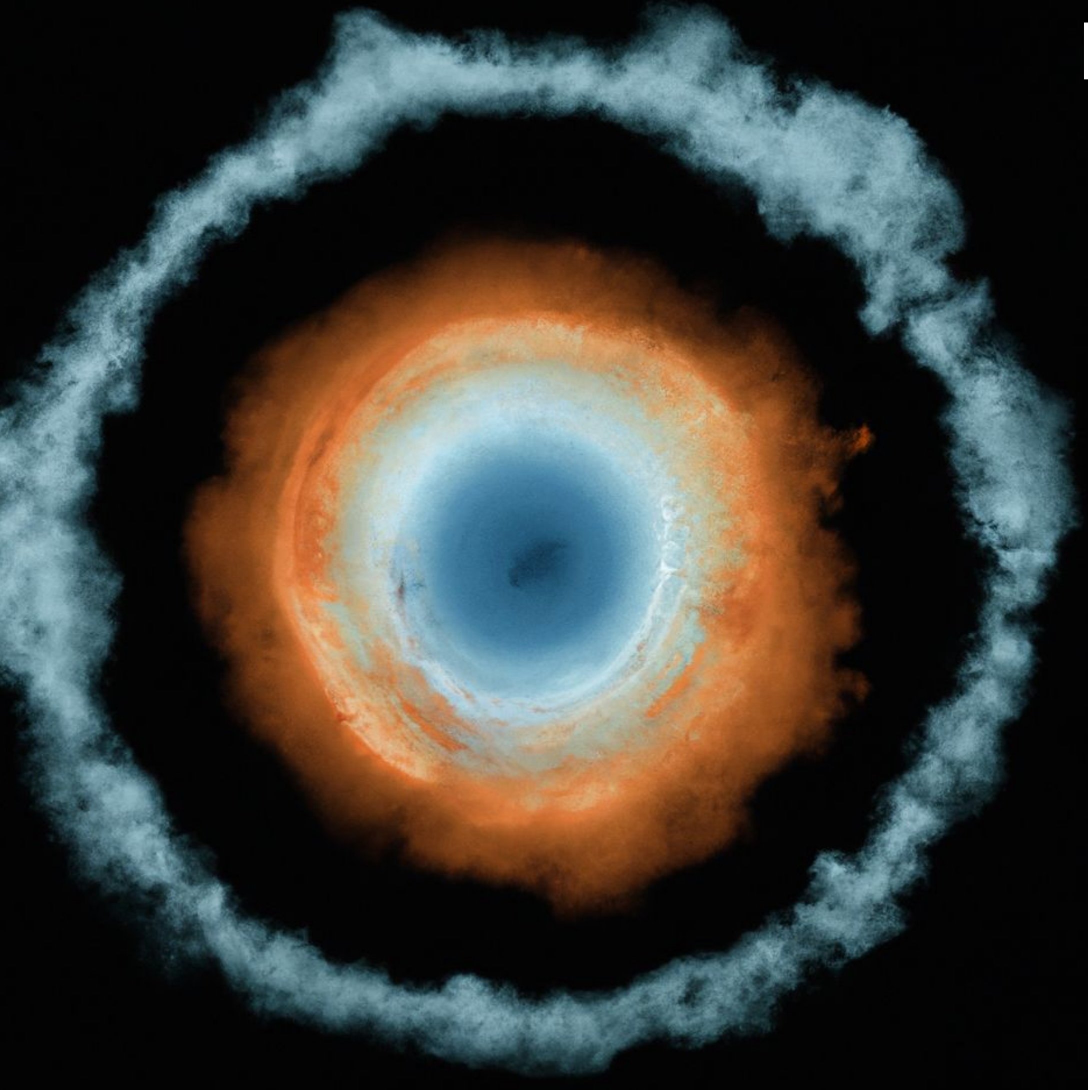

How asteroids and comets help us decipher how our Solar System formed

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Nice, November 28, 2023

European Research Council
Established by the European Commission

How did our Solar System form and evolve?

What properties did the protoplanetary disk of the Solar System have?

Did any of the first solid bodies in the Solar System survive to this day?

Outline

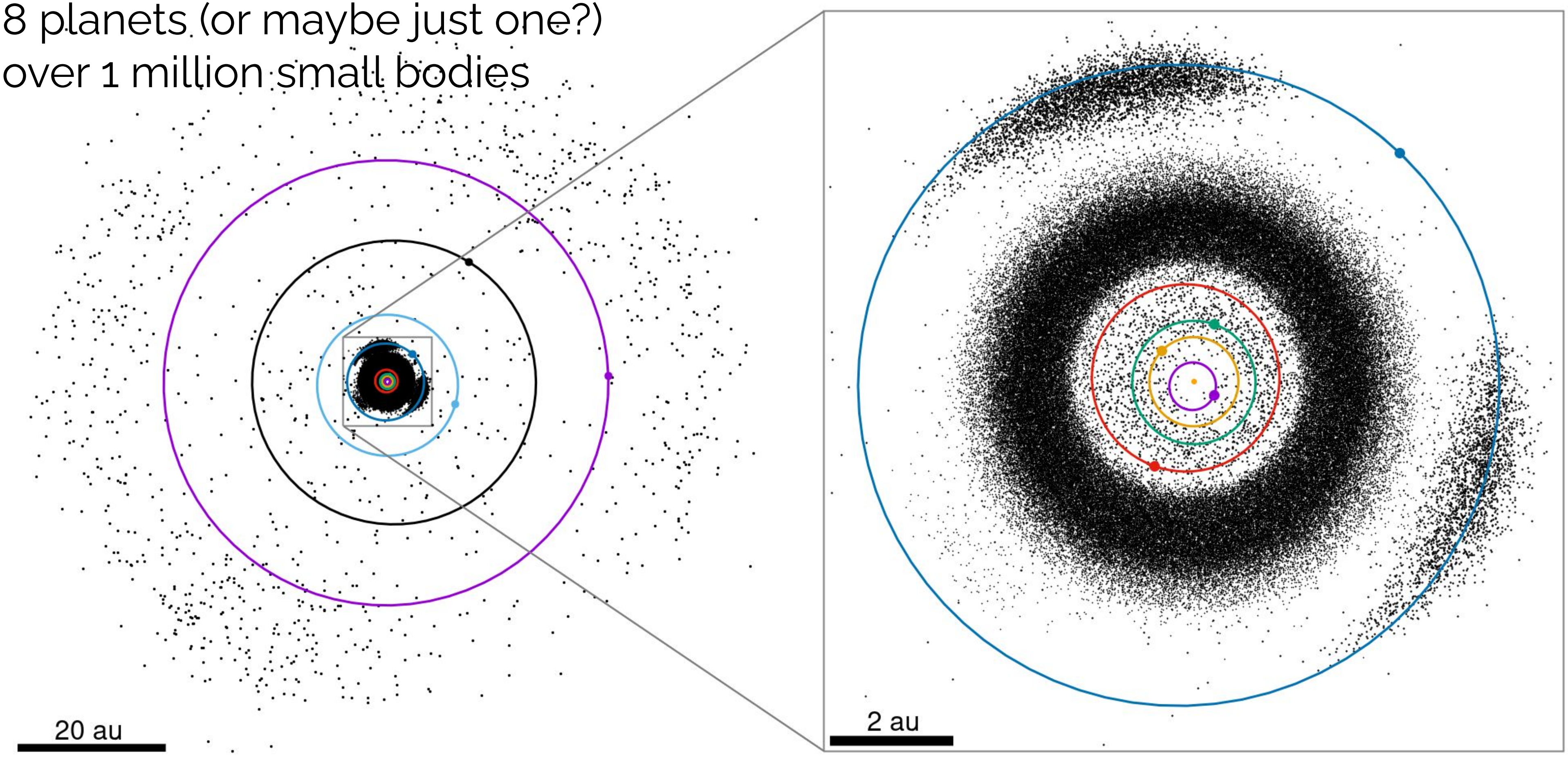
1. **Introduction**
   Where are we and how did we get here?
2. **The isotopic puzzle**
   The early times of the protoplanetary disk
3. **The pristineness of asteroids & comets**
   Their recent history

Part 1: Introduction

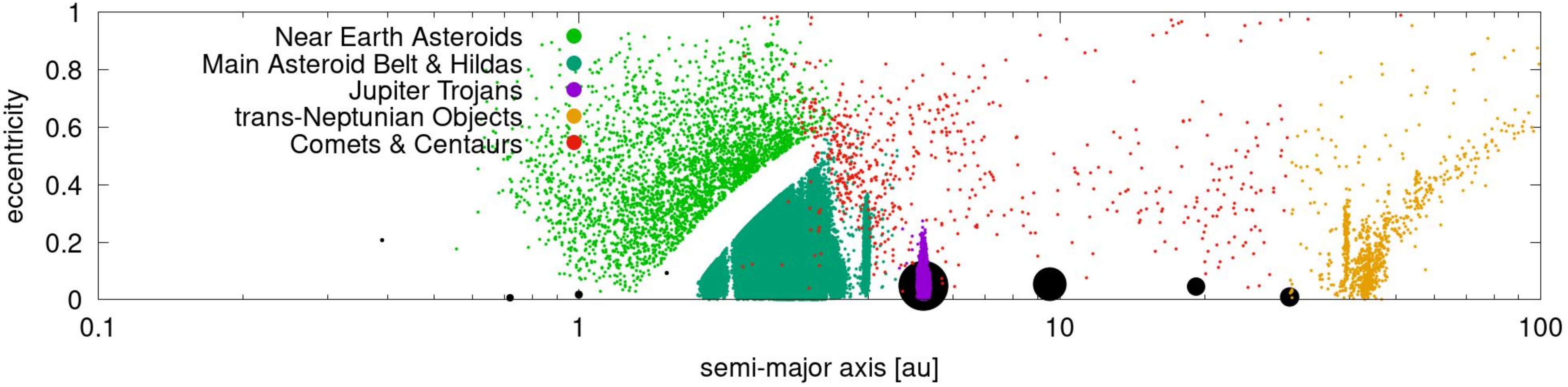
Where are we and how did we get here?

The Solar System today

8 planets (or maybe just one?)
over 1 million small bodies



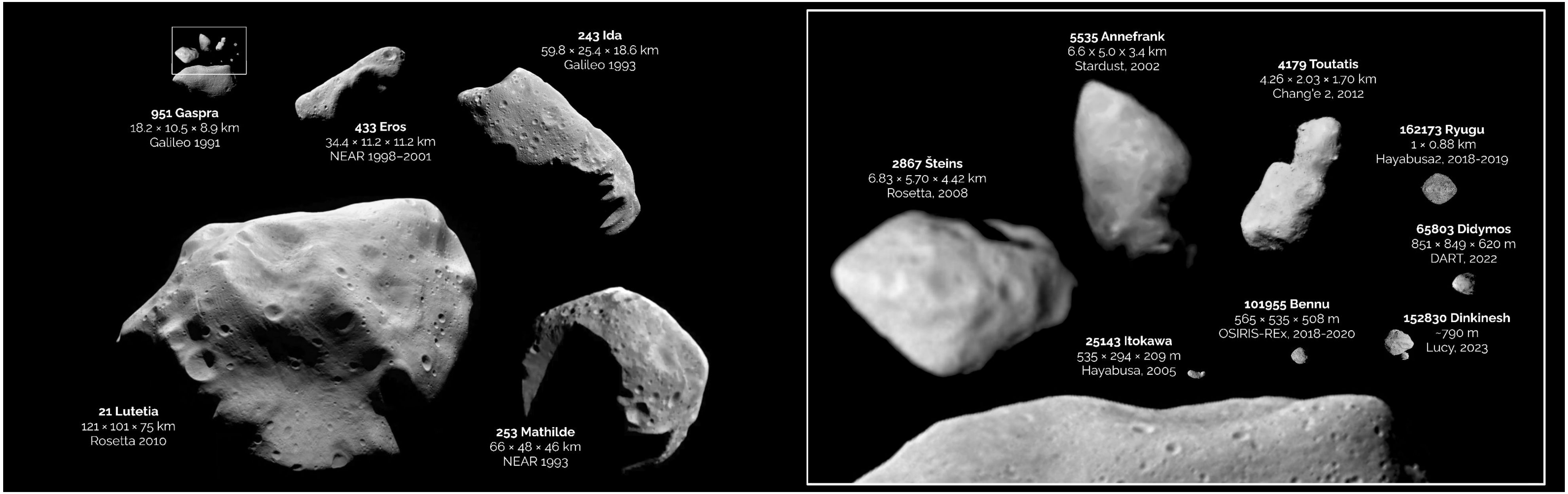
The architecture of the Solar System today



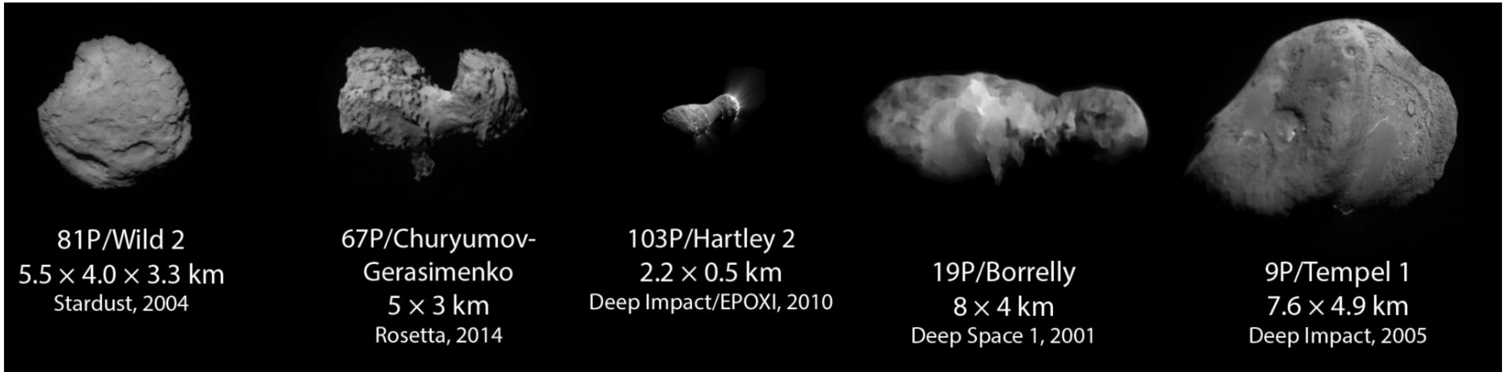
- This architecture (only available for our system) contains crucial information about solar system formation and evolution (i.e, planet migration).
- Asteroids between Mars and Jupiter → meteorites
- High resolution data of Jupiter Trojans, trans Neptunian Objects (TNOs), and comets are only accessible by spacecraft missions (e.g., Rosetta, New Horizons, Lucy, Comet Interceptor).

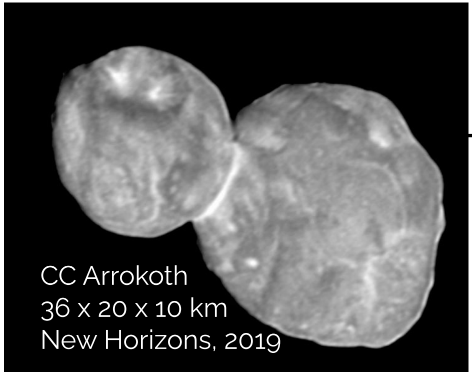
The relics of planet formation

asteroids

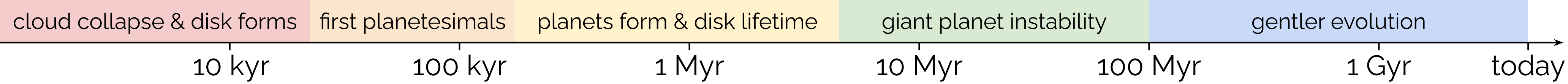


comets





Kuiper-belt



How did we get here?

- Almost 20 years ago: huge leap in our understanding of Solar System formation. Using the Solar System architecture to look back to the end of the protoplanetary disk phase.

- Use small bodies, the relics of planet formation, to peer back to the even further.

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

The last major event in Solar System formation

- Initially a more compact system
- Likely with an additional ice giant
- 0-100 Myr after the protoplanetary disk this compact system went unstable (giant planet instability, aka the “Nice model”)
- Neptune migrates into the primordial Kuiper-belt.
- Scattering of small bodies into Scattered Disk, capture of Jupiter Trojans

E.g., Gomes et al. 2005, Tsiganis et al. 2005, Morbidelli et al. 2005, Levison et al. 2007, Levison et al. 2011, Nesvorný et al. 2013

Credit: Simone Marchi, David Nesvorný, Rogerio Deienno

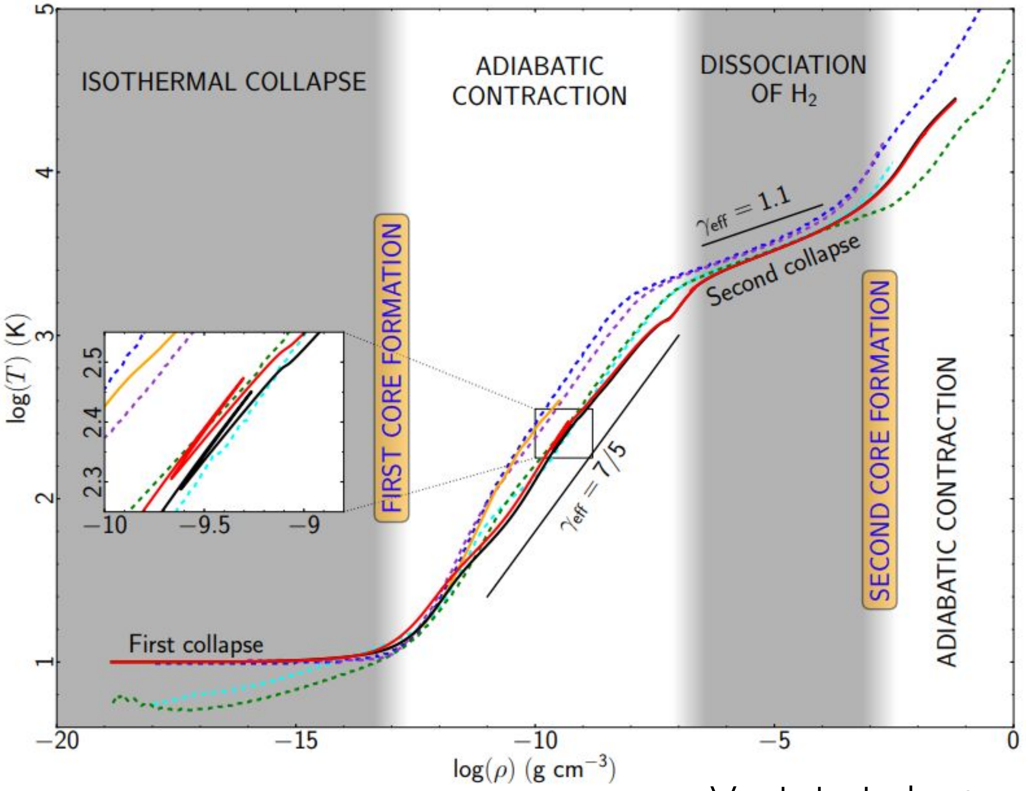
Nesvorný et al. 2013

It begins with a giant molecular cloud

A molecular cloud collapses:

- 1st collapse (isothermal, $10^{4.5}$ yr)
- Formation of 1st Larson core (lifetime few 10^3 yr)
- 2nd collapse (H_2 dissociation) (quasi isothermal, 10^2 yr)
- Formation of 2nd Larson core, aka the proto-star

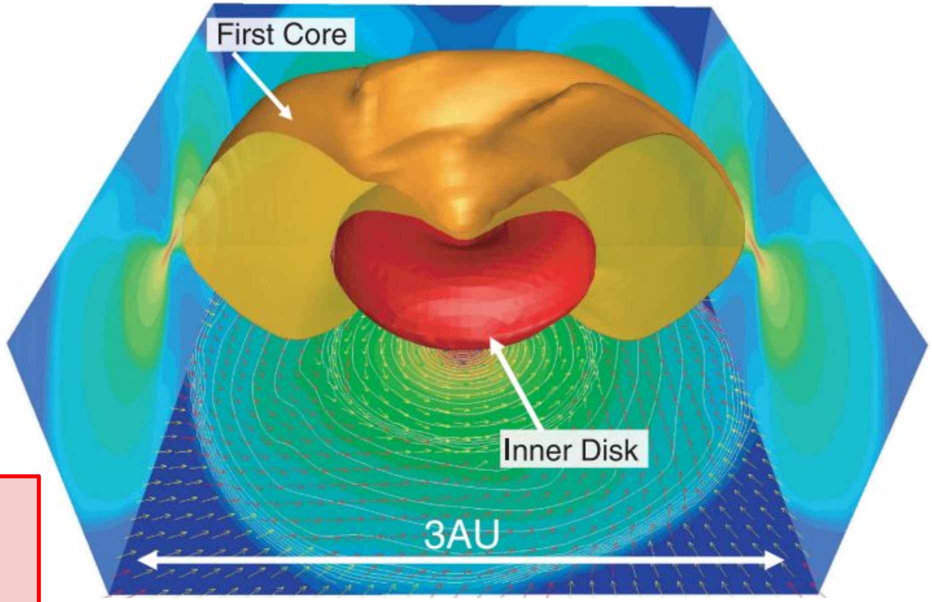
Larson 1969, Lada 1987, André et al. 1993, 2001, Machida et al. 2010, Machida & Matsumoto 2011, Vaytet et al. 2013, Tomida et al. 2013, 2015, Krasnopolsky et al. 2011, Tsukamoto et al. 2015, 2017, Masson et al. 2016, Wurster al. 2016, 2018, Marchand et al. 2018, 2019, Teyssier & Commerçon 2019



Vaytet et al. 2013

The proto-star and protoplanetary disk

- Form a proto-star surrounded by a gas & dust disk that are fed by material from the envelope
- Dust particles grow from micron to cm sizes ("pebbles") through hit and stick *Weidenschilling, 1977; Dominik & Tielens, 1997; Blum & Wurm, 2000; 2008; Wada et al., 2008; 2009; Güttler et al., 2010; Zsom et al., 2010; Blum et al., 2022*



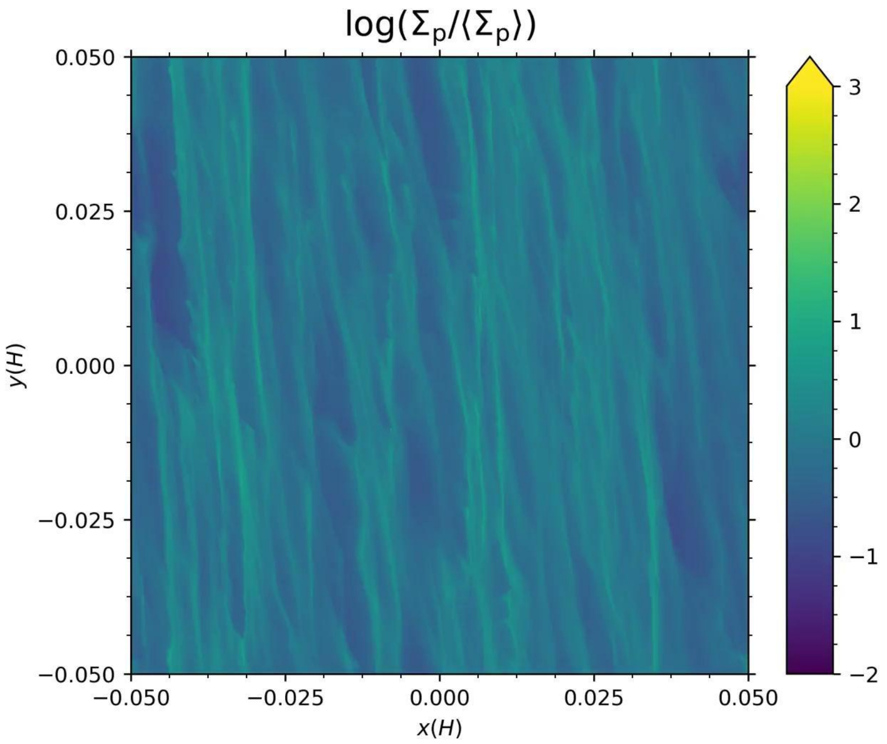
Machida & Matsumoto 2011

The byproduct of stellar formation is the formation of a disk (and planets).
OR
The byproduct of planet formation is a star.

Forming the first solid bodies

- "Meter size barrier" prevents growth beyond cm-dm-m
  (e.g., Blum & Wurm, 2000; Güttler et al., 2010; Zsom et al., 2010; Schräpler et al., 2018)
  → cannot form large solid bodies

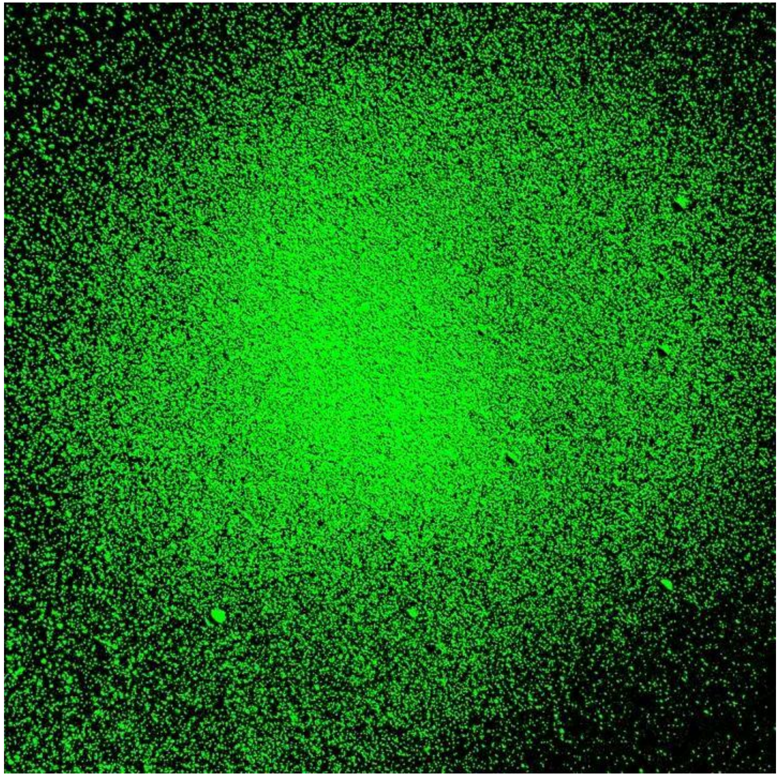
- To make the first large solid bodies we need to jump the meter sized barrier.
- The global disk dust-to-gas ratio ~1%
- When high enough locally (~100%) the streaming instability sets in
  (e.g., Youdin & Goodman, 2005; Johansen et al., 2007; 2014; Simon et al., 2016, 2017; Schäfer et al., 2017)



Nesvorný et al. 2019

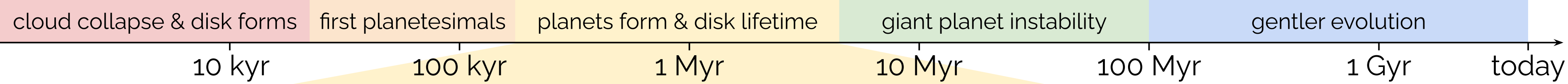
Forming the first solid bodies

- Density of cloud high enough → gravitational collapse of the pebble cloud
- Forms large (~100 km) bodies, so-called planetesimals
  (e.g., Simon et al., 2016; Schäfer et al., 2017; Polak & Klahr 2022)
  - High fraction of binaries (pro/retrograde motion matches what we see in the Kuiper-belt)
    (Nesvorný et al. 2019)
  - The size distribution of asteroids and KBOs are collisionally evolved distributions
    (Morbidelli et al. 2019, Bottke et al. 2023, Marschall et al. 2023)
- First/last planetesimals formed within the first few 100 kyr and up to 4-5 Myr.



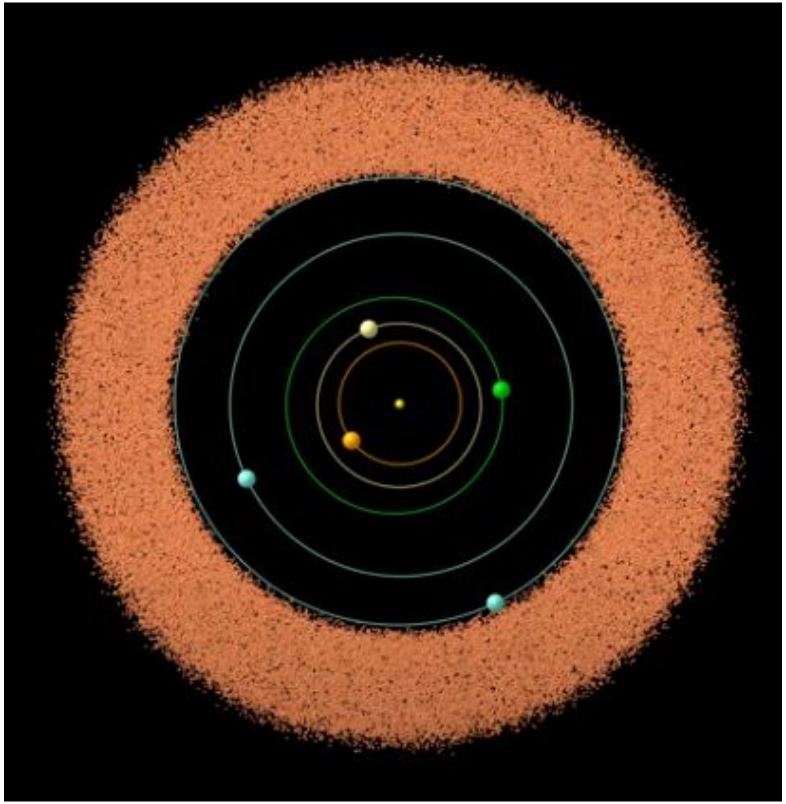
Courtesy: David Nesvorný

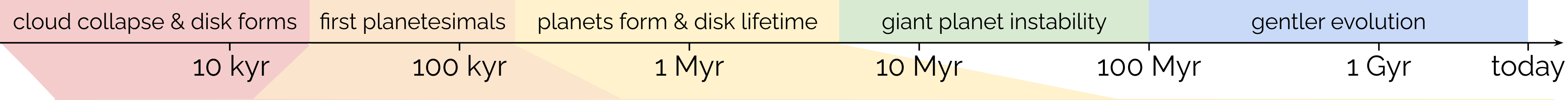
Nesvorný et al. 2019



Planets start forming

- Through collisions planetesimals grow to planet cores, which can grow further by accreting pebbles directly
- Gas accretion onto the outer planets forms gas giants
- Migration of planets because of interactions between the planets and the disk
- The gas disk disappears after 4-5 Myr (accretion onto the star, photo-dissociation)
- Terrestrial planet formation continues until long after the disk is gone (~100 Myr)





There is much we don't know about this phase

- We have come an a long way.
- Many pieces of the story are known.
- But a singular model connecting everything is still missing.

Part 2:
The isotopic puzzle

The early times of the protoplanetary disk

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

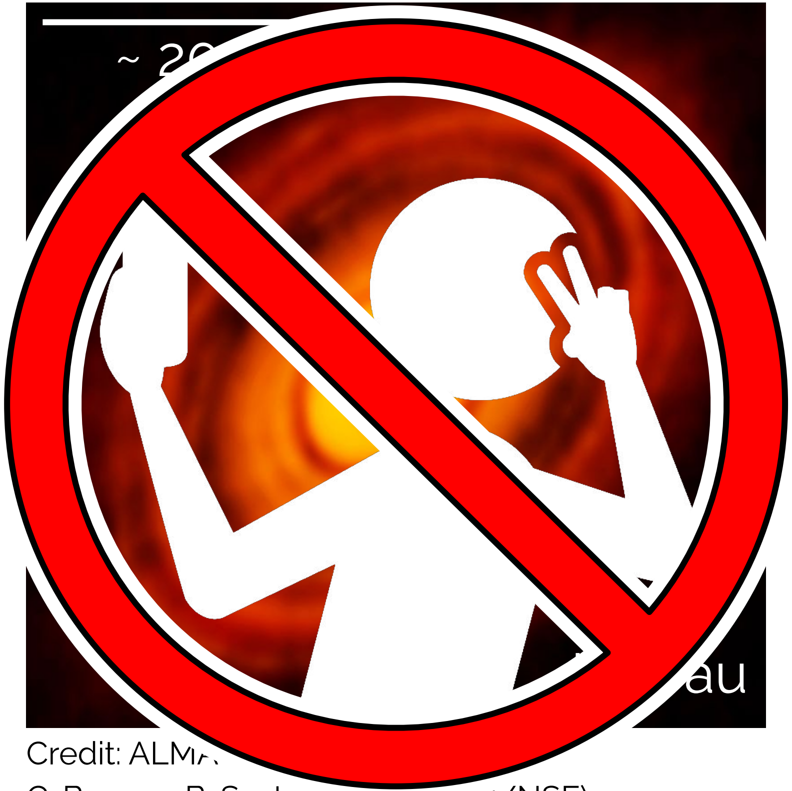
10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

What do we know about the first ~0.5 Myr

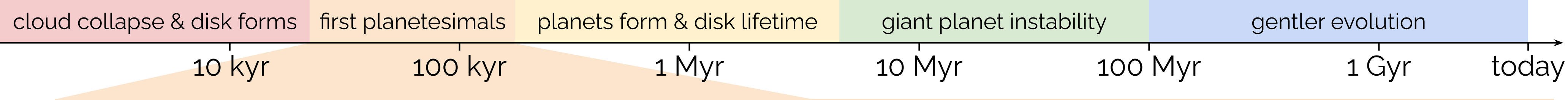
What can we learn about the **formation and evolution** of the **protoplanetary disk (PPD)** of our **Solar System (SS)**?

Where do **planetesimals** form?

There are **three important constraints** on the properties of the early PPD.

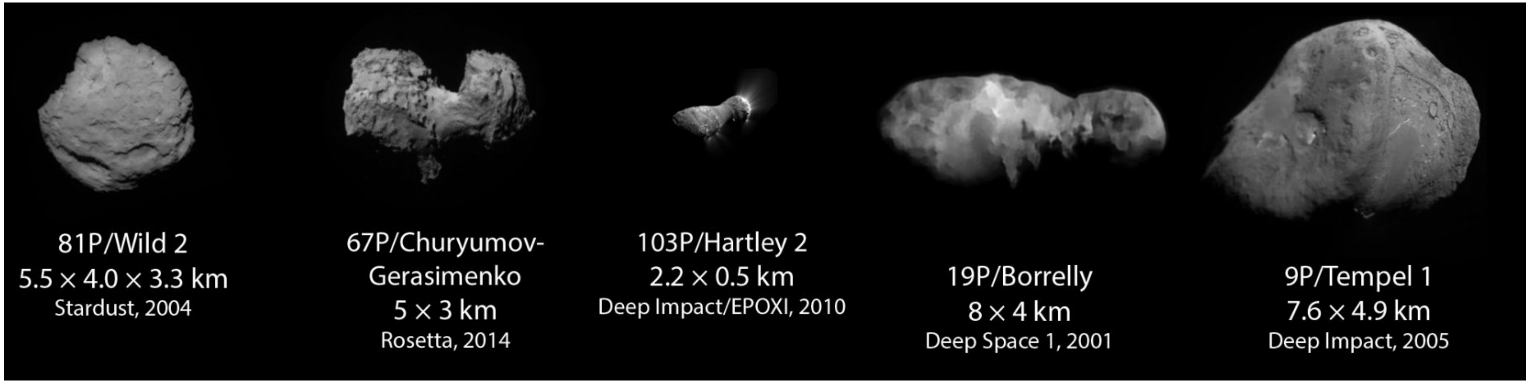


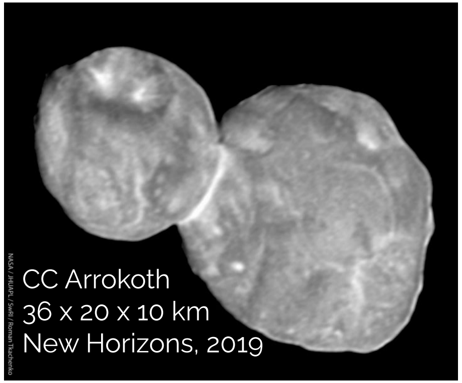
Credit: ALM
C. Brogan, B. Saxton (NRAO/AUI/NSF)

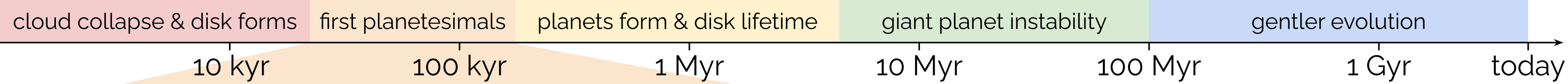


What do we know about the PPD of our SS?

1. The dust disk was at least 45 au large.
    - Comets were formed between 20-40 au
      (e.g., Nesvorný et al. 2017, Nesvorný 2018)
    - Cold classical Kuiper belt objects formed at up to 45 au
      (e.g., Nesvorný et al. 2022)



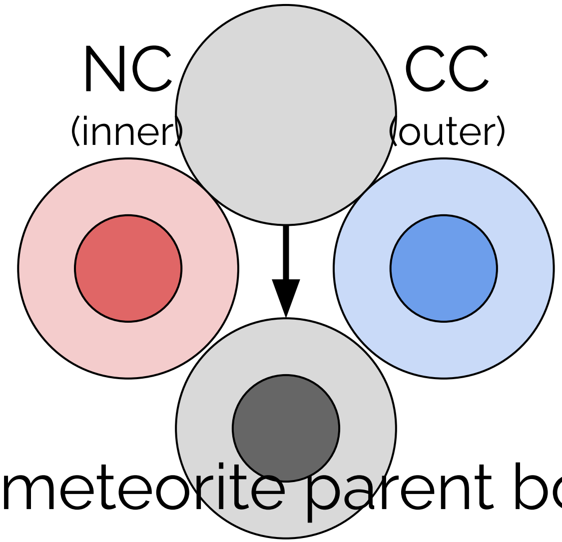




Multiple generations of planetesimals

early formation (~100 kyr)

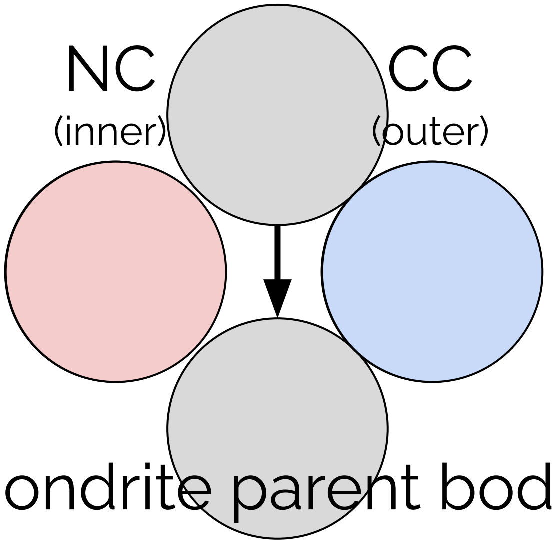
presence of radiogenic isotopes



iron meteorite parent bodies

late formation (~4 Myr)

absence of rad. isot.



chondrite parent bodies

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

What do we know about the PPD of our SS?

1. The dust disk was at least 45 au large.
2. Planetesimal formation at two distinct locations of the disk.
3. CA

•

CAIs - the oldest condensates in our Solar System dating it to 4.5687 Gyr

Piralla et al. 2023

outer disk.

(e.g., Zolensky et al. 2006)

Chaumard et al. 2014

What do we know about the PPD of our SS?

1. The dust disk was at least 45 au large.
2. Planetesimal formation at two distinct locations of the disk.
3. CAIs in the outer not inner disk.

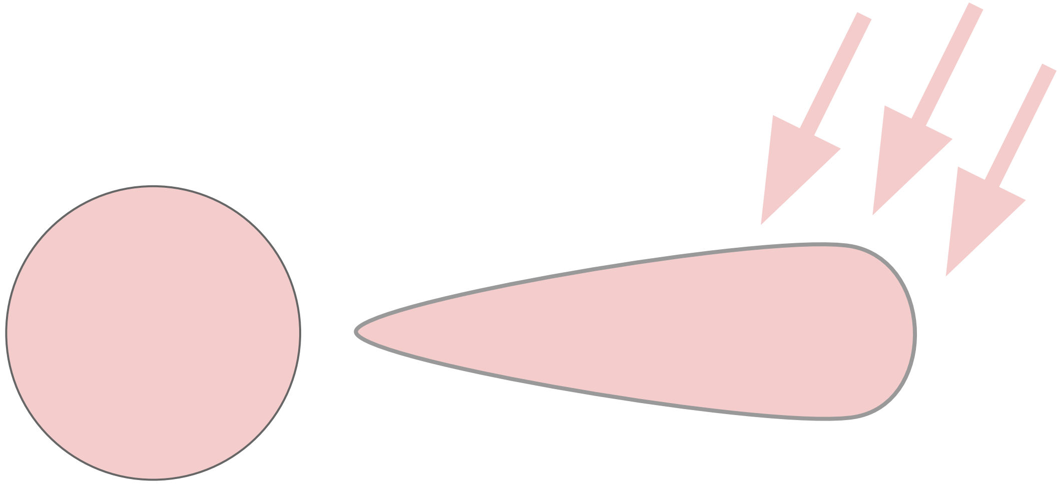
Important work towards understanding how PPDs form and evolve has been conducted over the past decade.

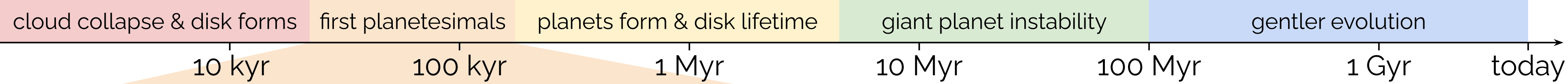
Static disk models: Saito & Sirono 2011; Ida & Guillot 2016; Drążkowska & Alibert 2017; Hyodo et al. 2019, 2021
Time dependant models: Drążkowska & Alibert 2017; Drążkowska & Dullemond 2018; Charnoz et al. 2019; Morbidelli et al. 2022.

Yet, current models can't reproduce these three properties of the Solar System protoplanetary disk simultaneously.

Why are the isotopic dichotomy and CAIs weird?

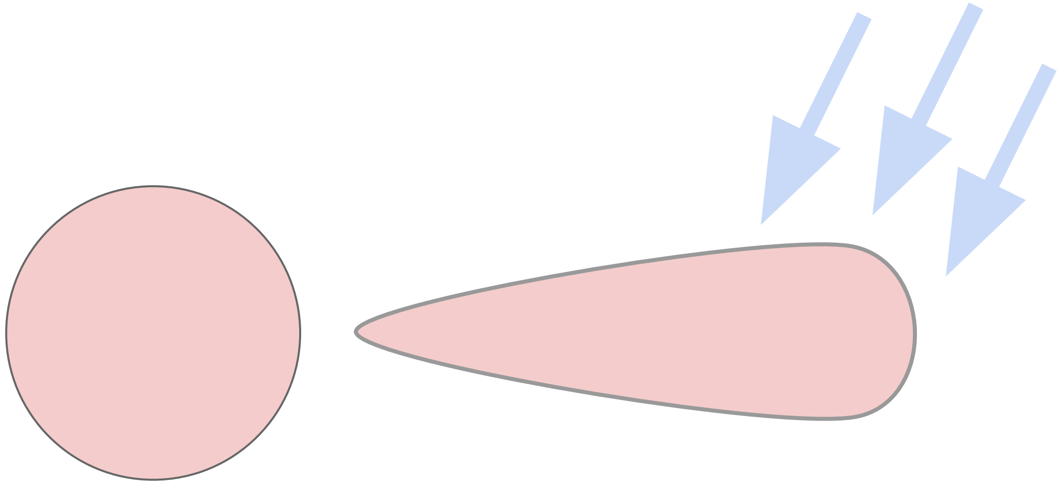
1) Let's start with an initial disk of a certain composition (red)

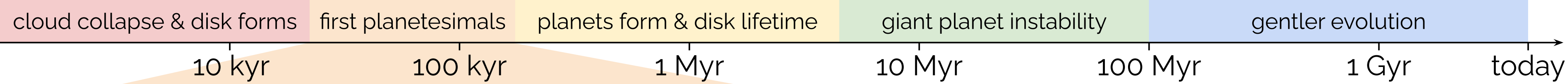




Why are the isotopic dichotomy and CAIs weird?

1) Let's start with an initial disk of a certain composition (red)
2) At some late stage the isotopic composition changes (to blue)





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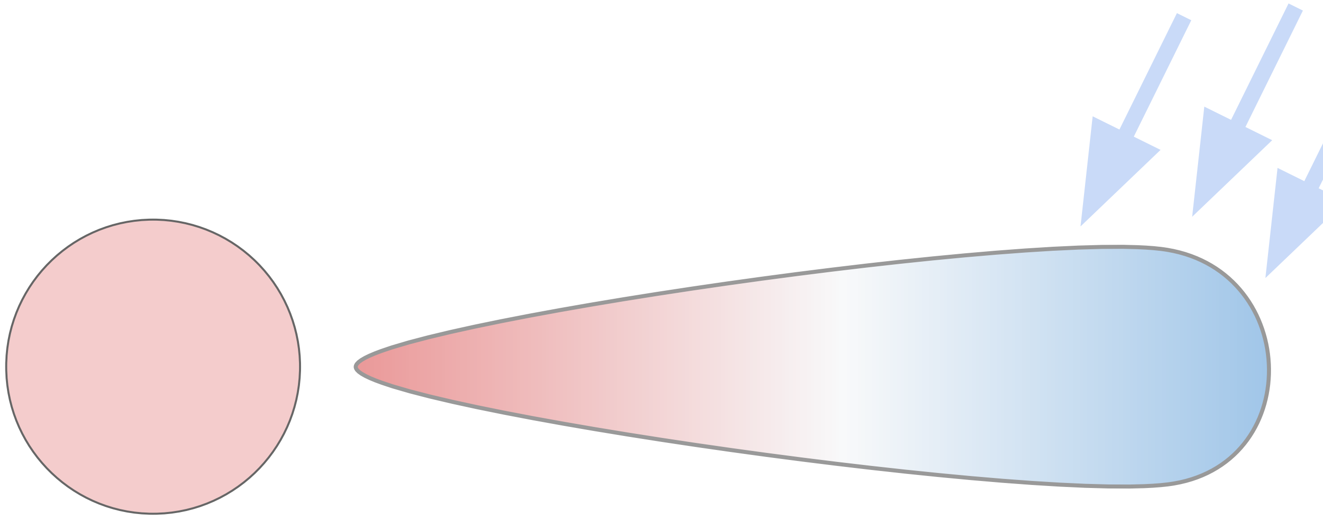
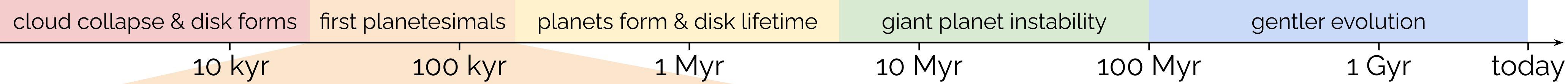
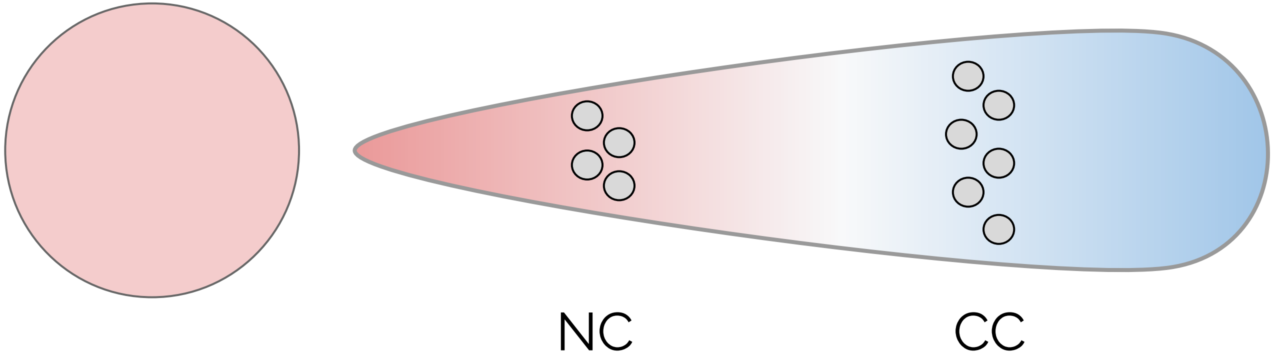
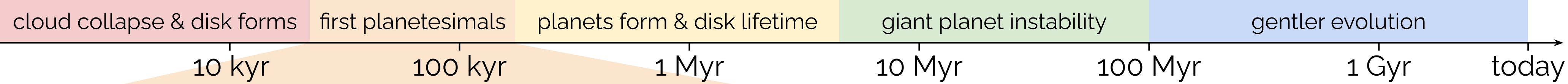




Why are the isotopic dichotomy and CAIs weird?

1) Let's start with an initial disk of a certain composition (red)
2) At some late stage the isotopic composition changes (to blue)
3) You make your planetesimals at two locations…DONE



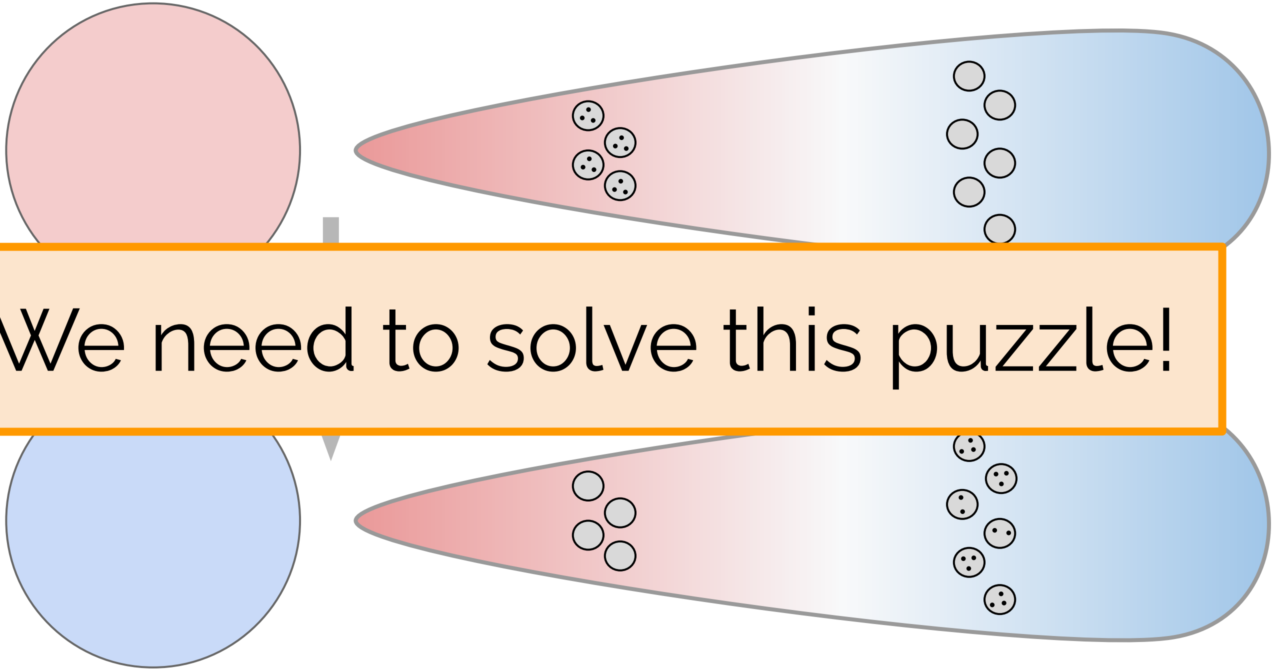


Why are the isotopic dichotomy and CAIs weird?

BUT

1. the Sun is not like NC! CC's are closer to solar than NCs.

2. CAIs are closest to solar but found primarily in CCs.



We need to solve this puzzle!

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

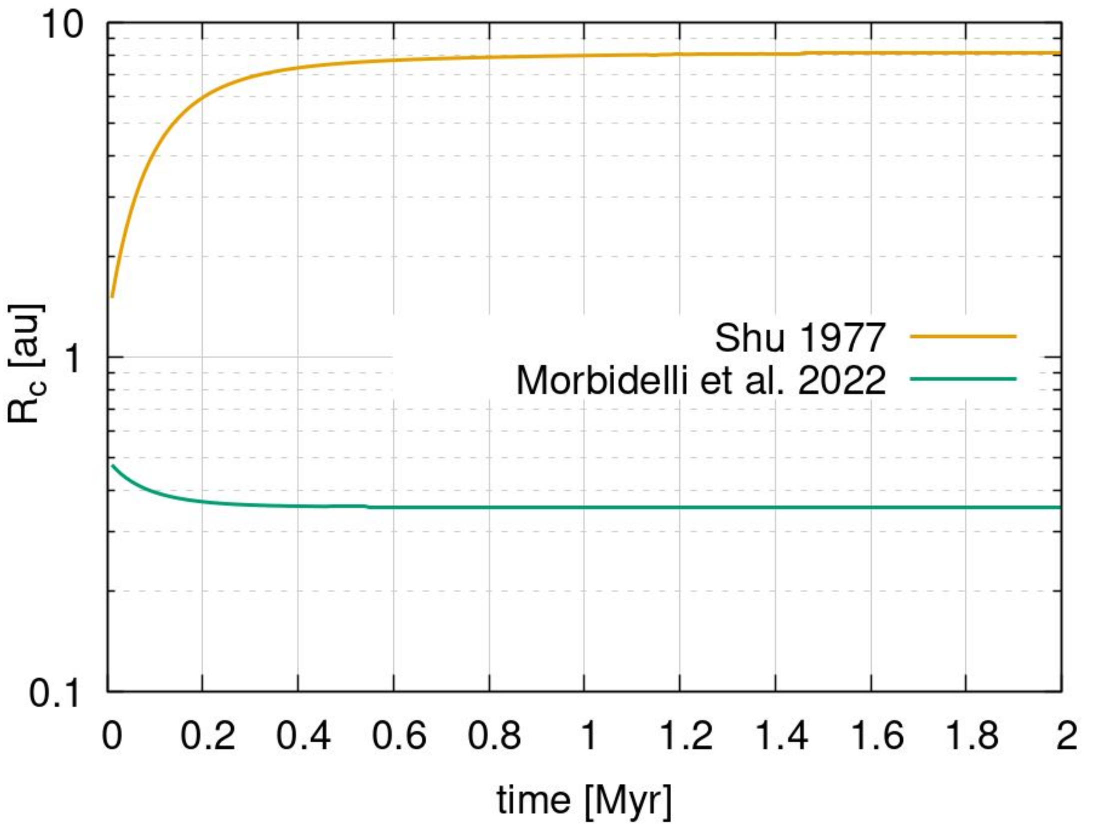
How can we fix this?

Instead of building a disk from the outside in, we build it from the inside out!

Centrifugal radius, R_c: maximum distance at which material falls into the disk.

- A pre-stellar cloud with a constant angular speed throughout: inner shells collapse first and fall close to the protostar. Distant shells fall into the disk later farther away from the star. Therefore, R_C increases with time (yellow).

- Magnetic braking of the infall removes angular momentum. Material falls close to the star (green).

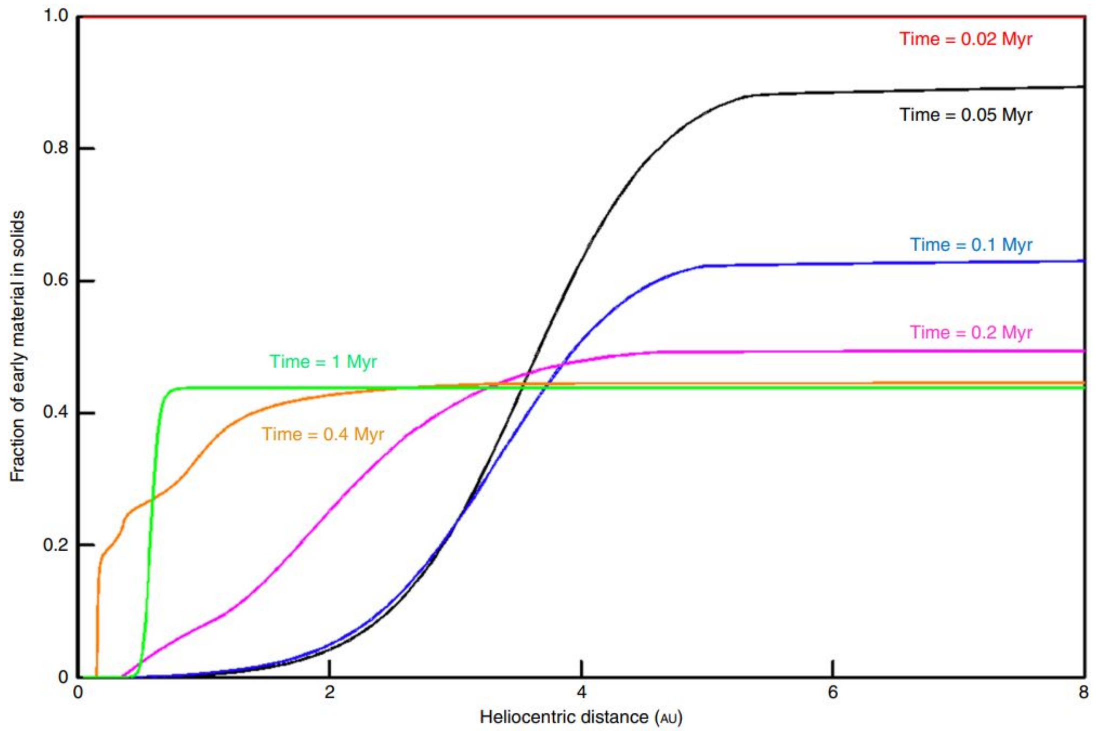


Shu 1977; Lee et al. 2021; Machida & Basu 2019; Vaytet et al. 2018; Machida & Matsumoto 2011; Morbidelli et al. 2022

What does this get you?

It gets you a disk that is stratified in the right way.

BUT, these disks are usually small and it's unclear what happens to CAIs.



Morbidelli et al. 2022

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10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

We need one more ingredient - high viscosity

Timescale of **α** decrease is linked to infall timescale

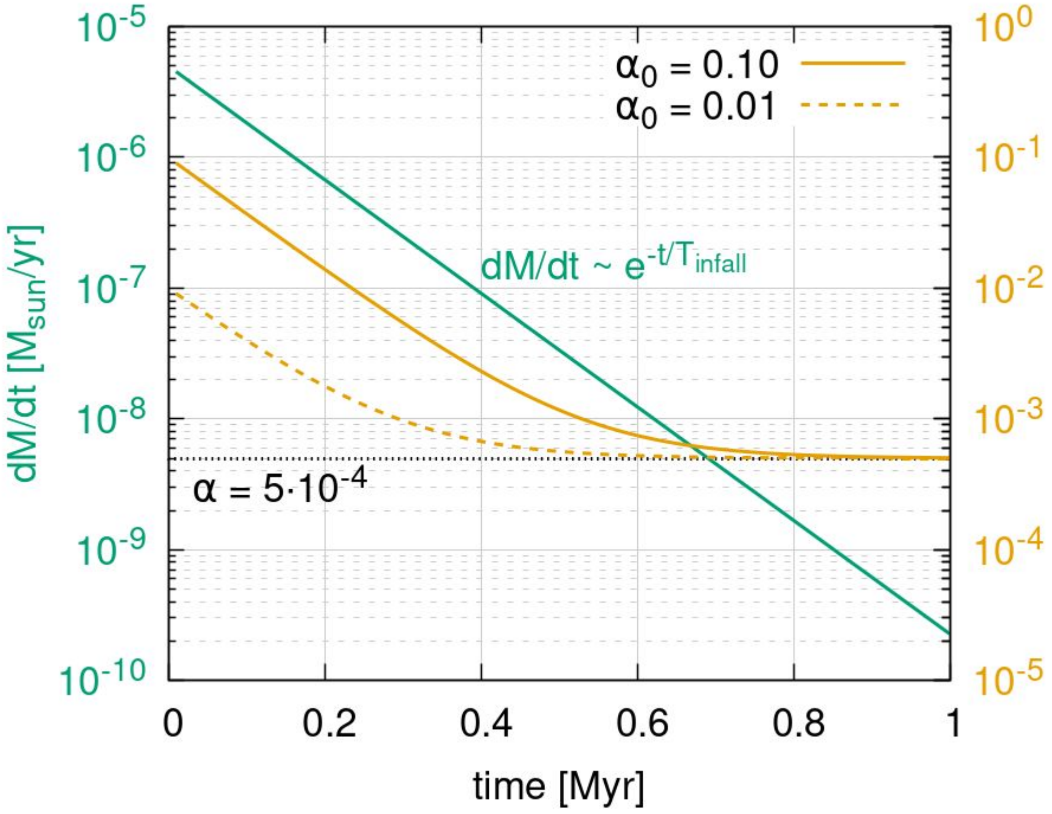
Parameters explored:

$\alpha_0 \in [0.01, 0.1]$

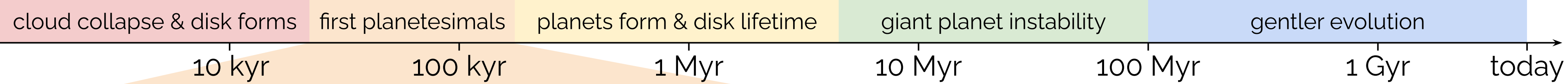
$T_{infall} \in [15\ \text{kyr}, 600\ \text{kyr}]$

Mass infall raises through stresses **α**.

Kuznetsova et al. 2022



Marschall & Morbidelli 2023



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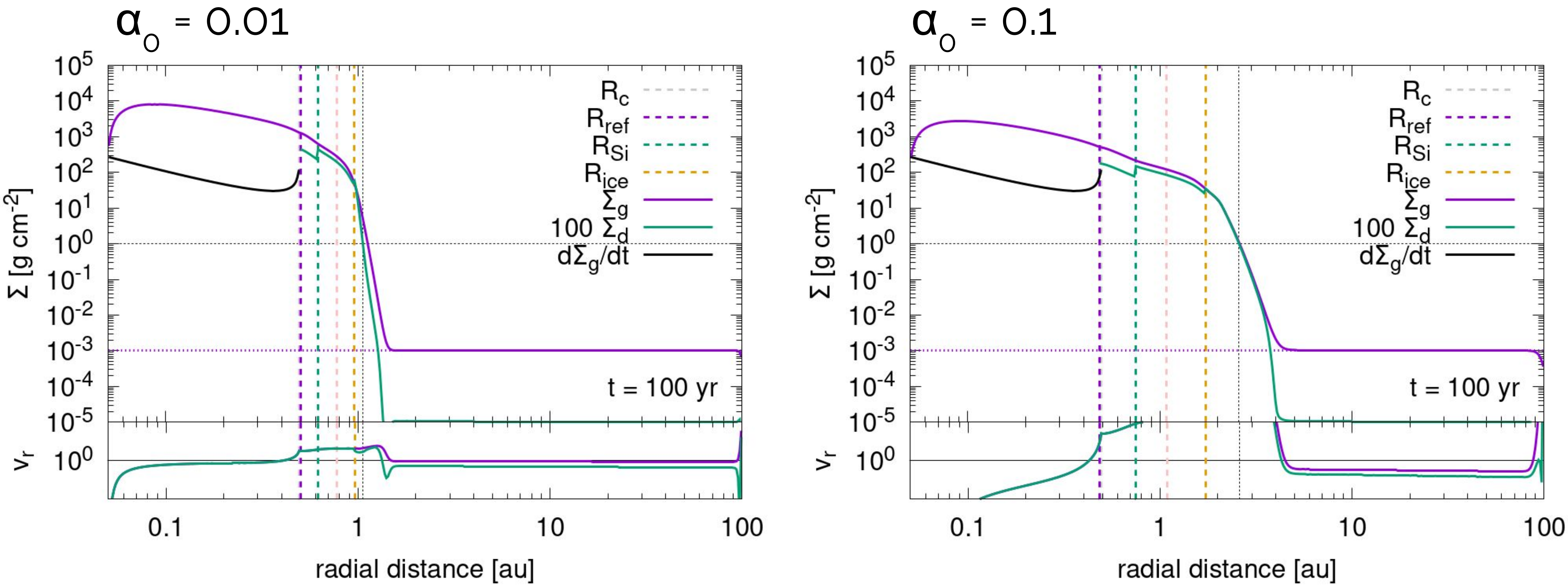

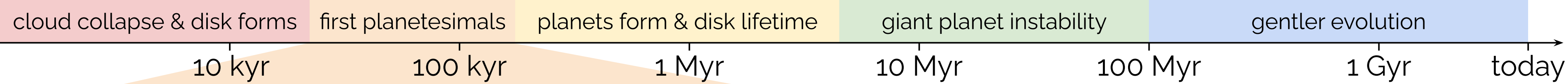

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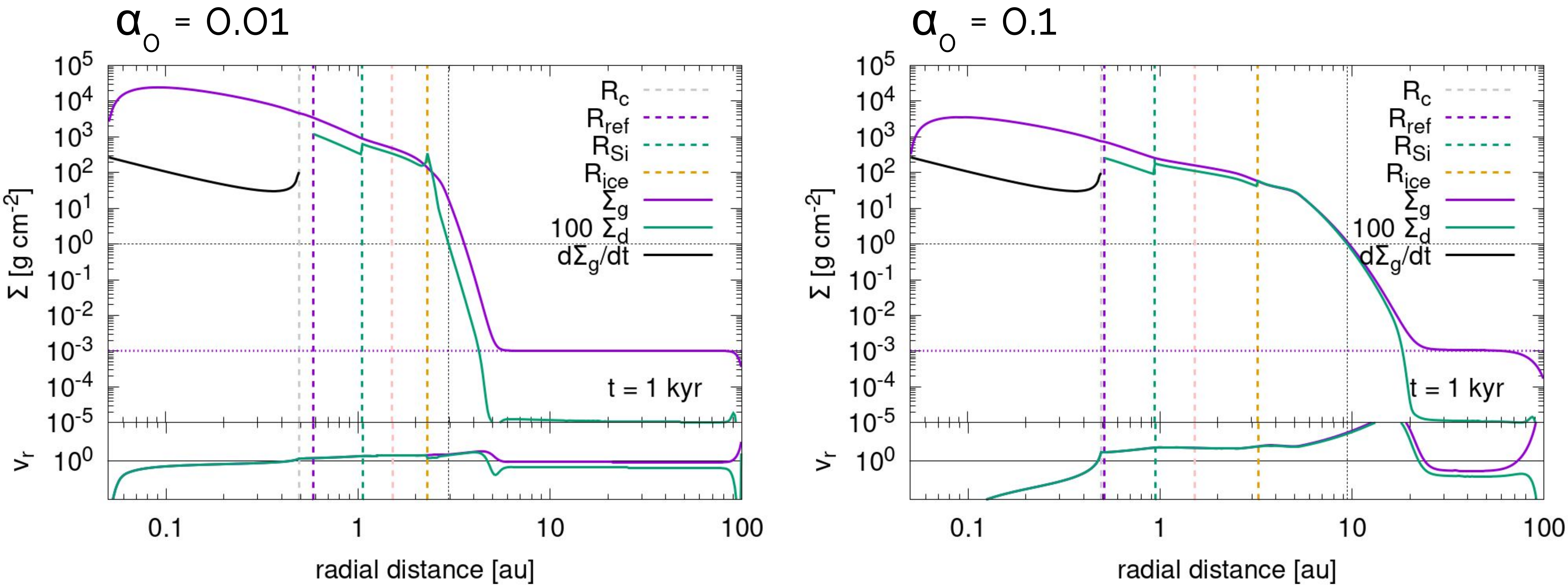


cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

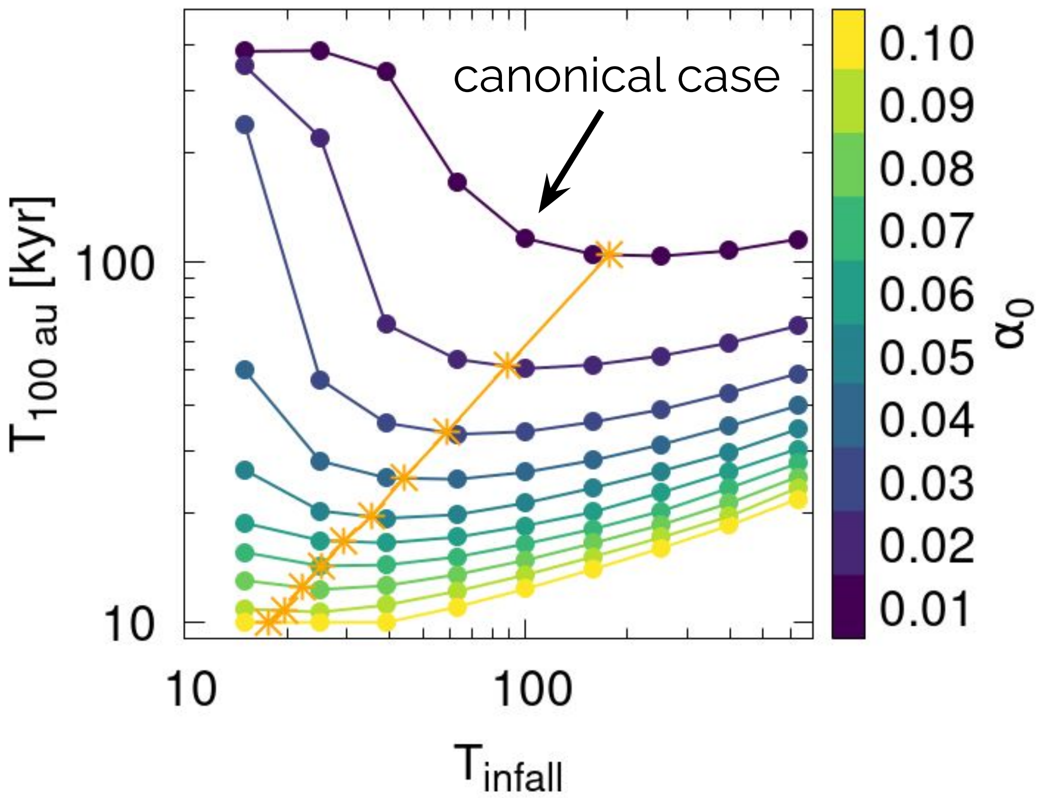
These disks expand very fast!

The larger **α** the faster the disk expands.

In our canonical case it takes **100 kyr** for the gas disk to reaches **100 au**.

The extreme cases do it in just **10-20 kyr → "inflation disks"**

Marschall & Morbidelli 2023



cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

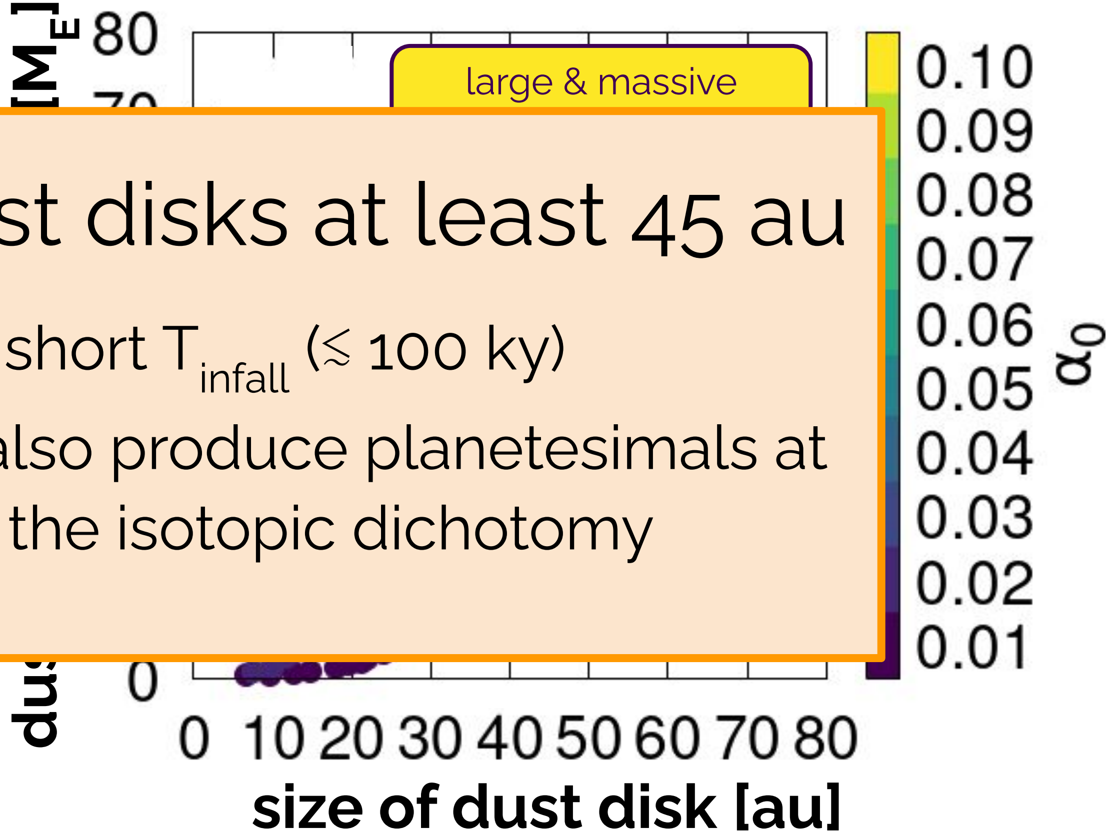
The disks can be large

The larger α_0 the **larger**

the c

more

disk l



Criteria 1 (&2): Dust disks at least 45 au

✅ for large α_0 ($\gtrsim$ 0.05) & short T_{infall} ($\lesssim$ 100 ky)

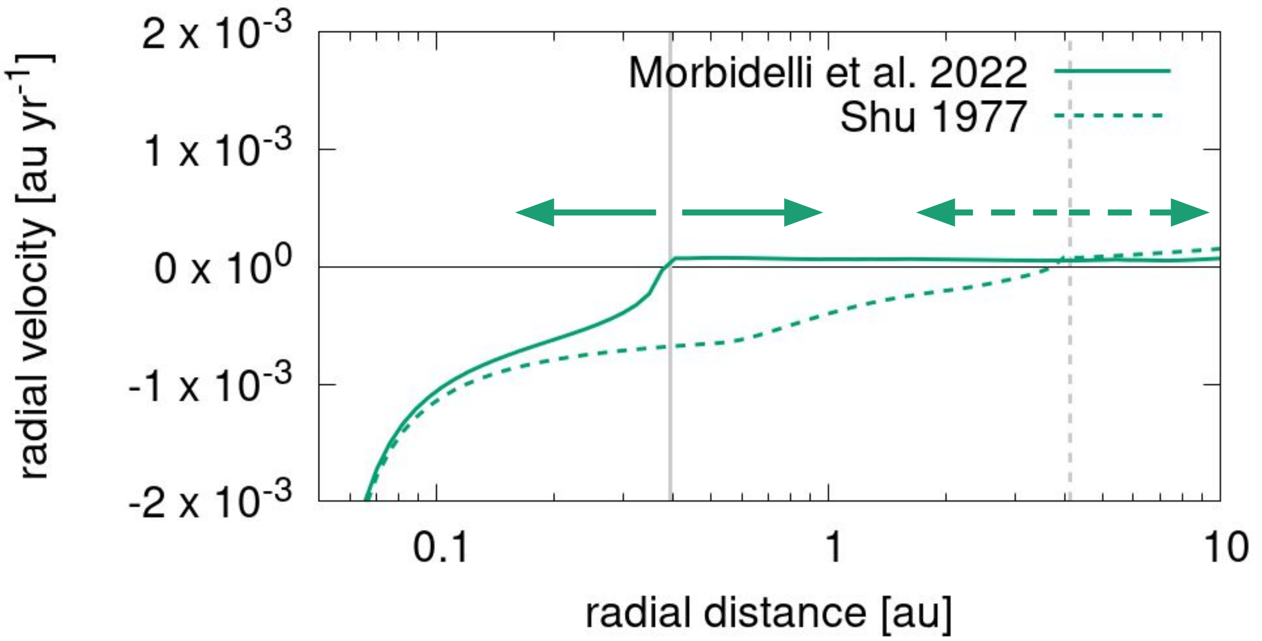
⟶ "inflation disks" that also produce planetesimals at two locations to retrieve the isotopic dichotomy

Marschall & Morbidelli 2023

Transport of potential CAIs to outer disk

We need positive radial gas velocity at the location of the refractory condensation line to bring CAIs to the outer disk.

Gas velocity is initially positive outside of R_C and negative inside of R_C.



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cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

Transport of potential CAIs to outer disk

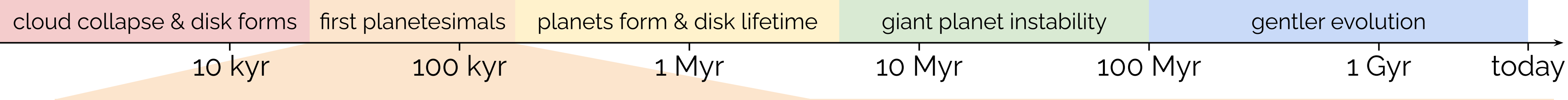
When T_{infall} < 200 ky we find a high[...] CAIs i[...]

No CA[...] T_{infall}>[...]

Criteria 3: CAI transport to the outer disk & depletion in inner disk

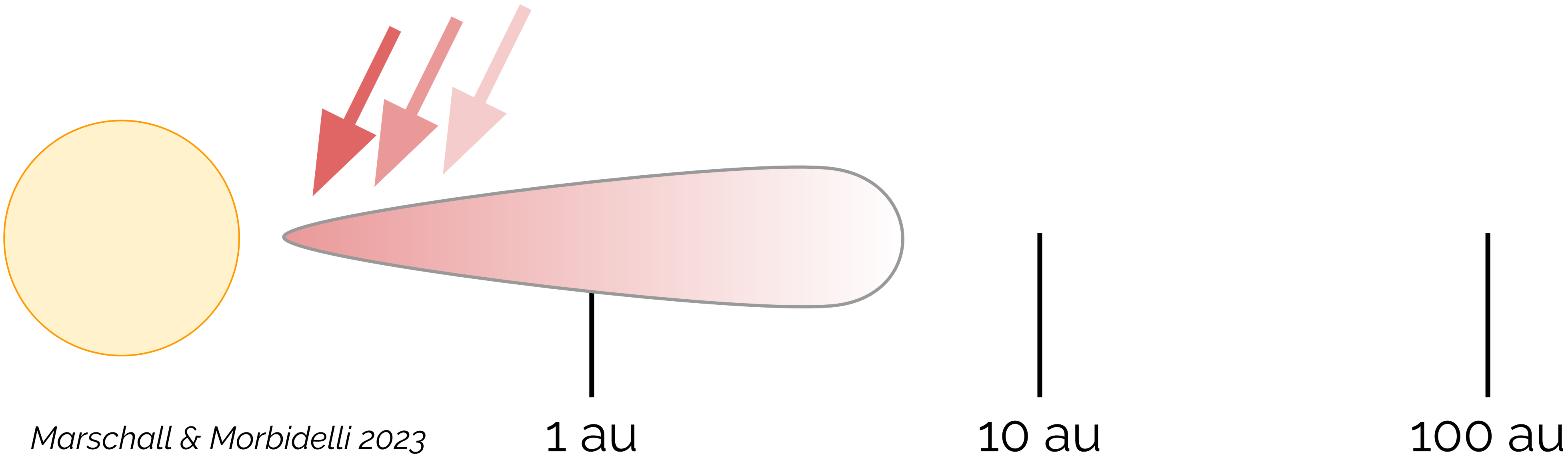
✅ for $T_{infall} \lesssim$ 200 ky and $\alpha_o \gtrsim 0.05$

Marschall & Morbidelli 2023



What does this new scenario look like?

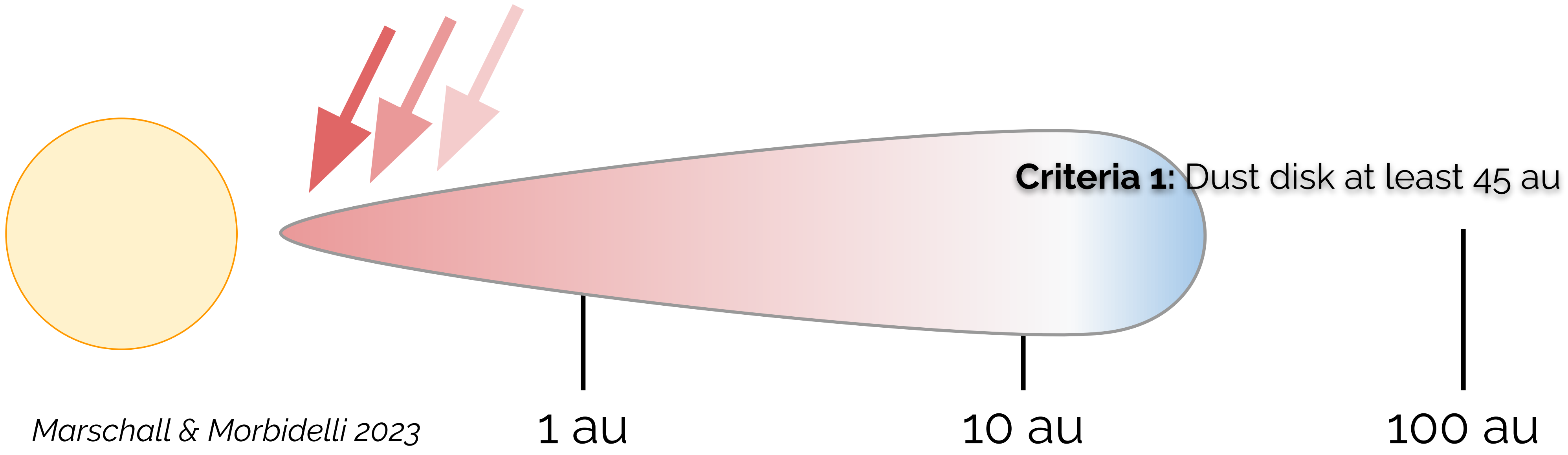
1. Material falls close to the proto-Sun.



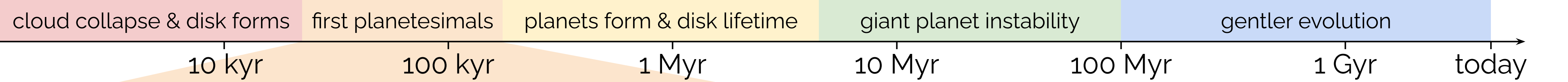
Marschall & Morbidelli 2023

What does this new scenario look like?

1. Material falls close to the proto-Sun.
2. Viscous expansion of the disk. Disk is colder in the outer disk.

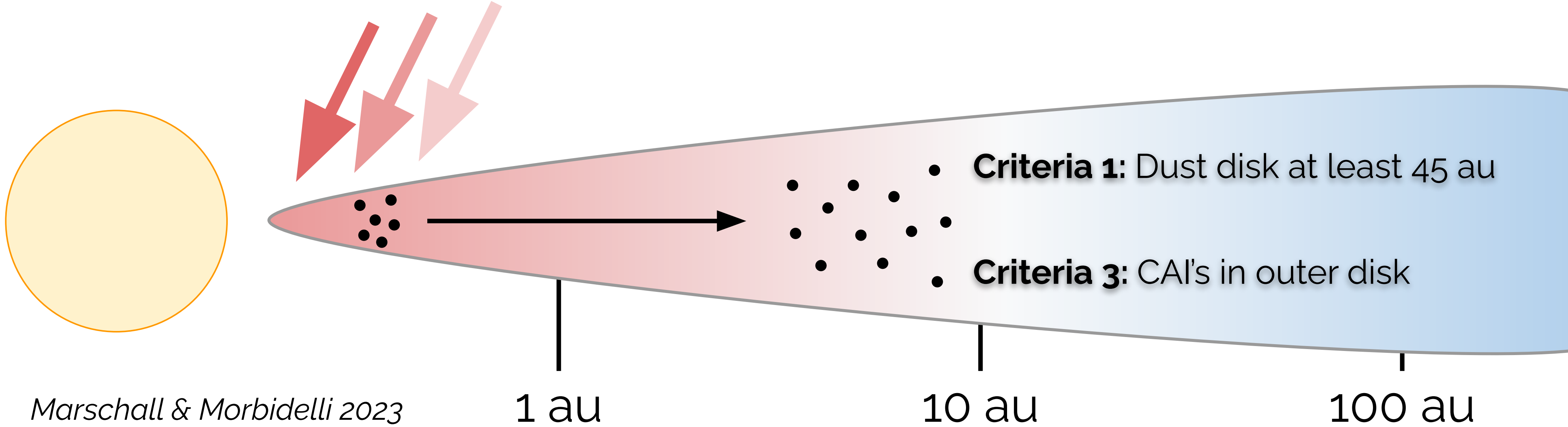


Marschall & Morbidelli 2023



What does this new scenario look like?

1. Material falls close to the proto-Sun.
2. Viscous expansion of the disk. Disk is colder in the outer disk.
3. CAIs form at high temp. and get transported out with the disk.



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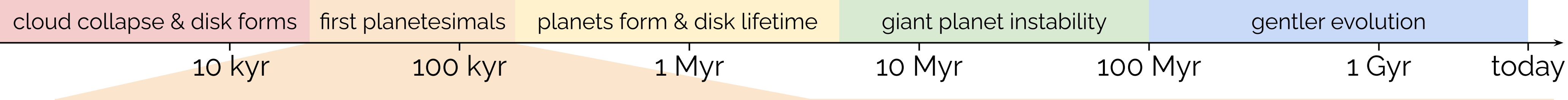
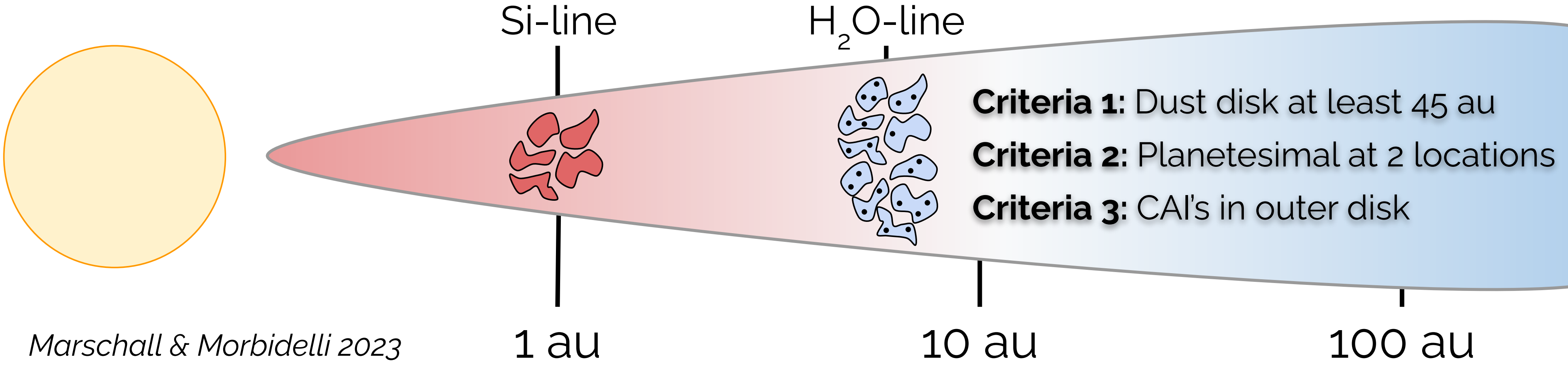


What does this new scenario look like?

1. Material falls close to the proto-Sun.
2. Viscous expansion of the disk. Disk is colder in the outer disk.
3. CAIs form at high temp. and get transported out with the disk.
4. Planetesimals form at the silicate and water sublimation lines.



Marschall & Morbidelli 2023

What does this mean?

- The protoplanetary disk of the Solar System initially had a **high viscosity** ($\alpha_0 > 0.05$) and **short infall time** (T_{infall} < 100-200 ky).
- Most material fell into the disk **within ~0.5 au** from the proto-Sun.
- It thus went through a **very rapid expansion** - inflationary - phase at the very beginning of disk formation.

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

10 kyr — 100 kyr — 1 Myr — 10 Myr — 100 Myr — 1 Gyr — today

So what's next?

- Eventually (~1 Myr), the gas disk starts contracting - accretion disk - leading to the loss of all solids into the star. This also destroyed the isotopic dichotomy.
  What is stopping the drift of particles? Structures in the disk? When do these structures form?

- Without dust in the late disk, we cannot form late planetesimals. Again, how do we retain dust over 4-5 Myr?

- The isotopic dichotomy is reversed for volatiles (D/H, $^{14}N/^{15}N$) suggesting that not all material can fall close to the proto-star. But how much?

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Part 3:
The pristineness of asteroids & comets

Their recent history

cloud collapse & disk forms | first planetesimals | planets form & disk lifetime | giant planet instability | gentler evolution

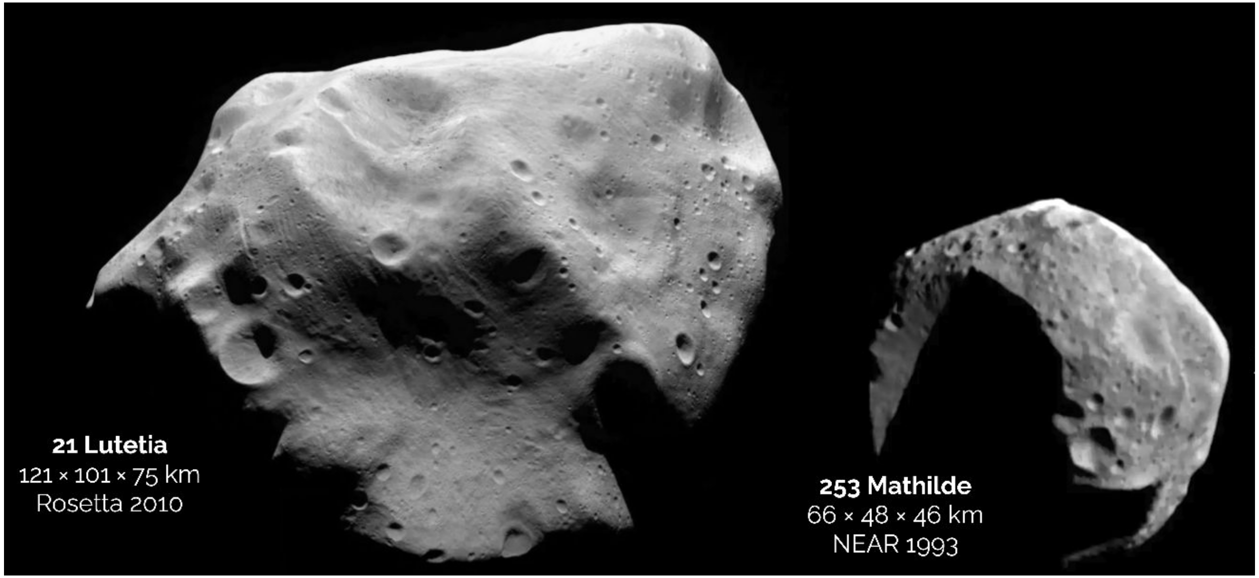
10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

During and after the giant planet instability

Collisions, heating, and sublimation can alter the leftover planetesimals (asteroids, comets, Kuiper-belt objects, …).

And we have a lot of time…

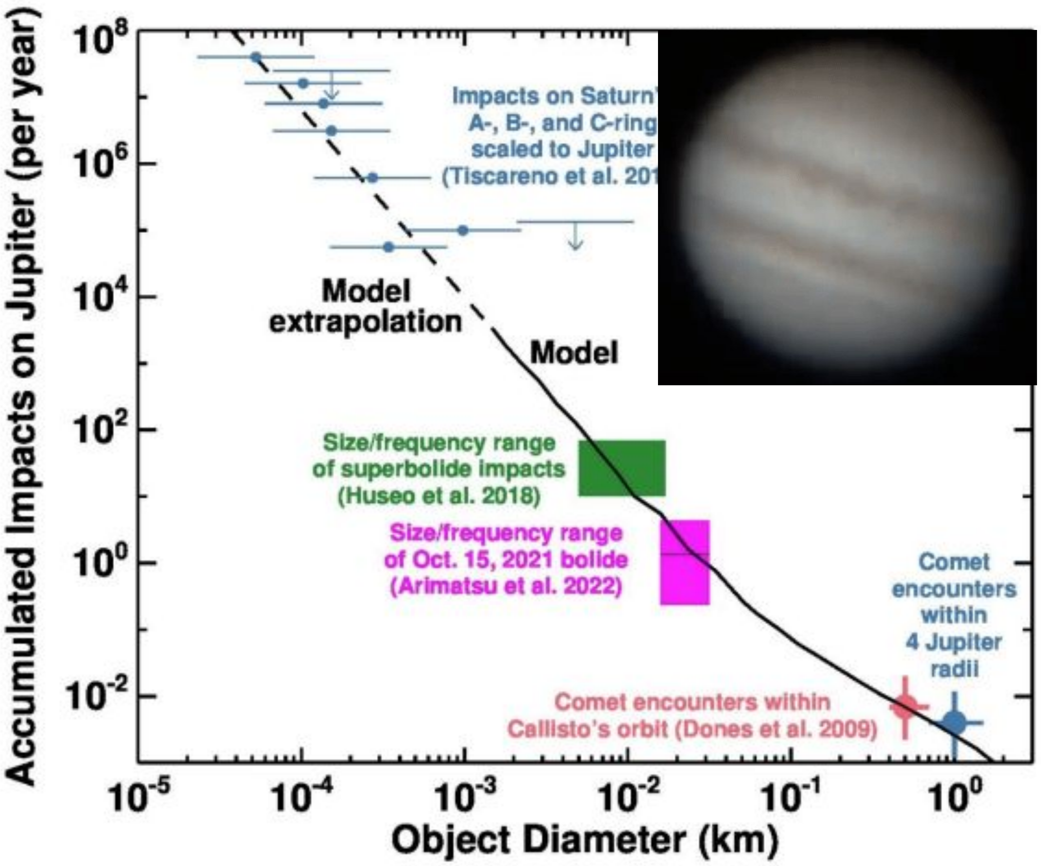
… 4.5 Gyr.

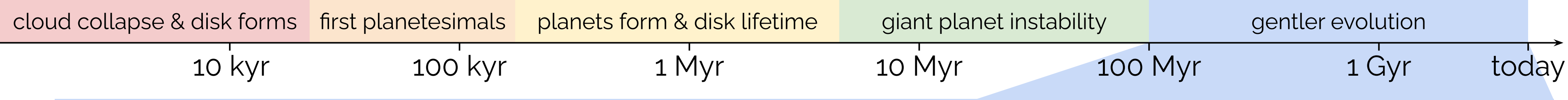


Good agreement with craters on the icy satellites of the outer Solar System

and

impacts onto Jupiter.





What does that mean?

- Most small bodies are fragments?
  → How much heating/volatile loss? Implications for inferred formation regions!

- These bodies record this collisional history on their surfaces through craters. Can we retrieve the initial distribution?
  Marschall et al. 2022, Marchi et al. 2023

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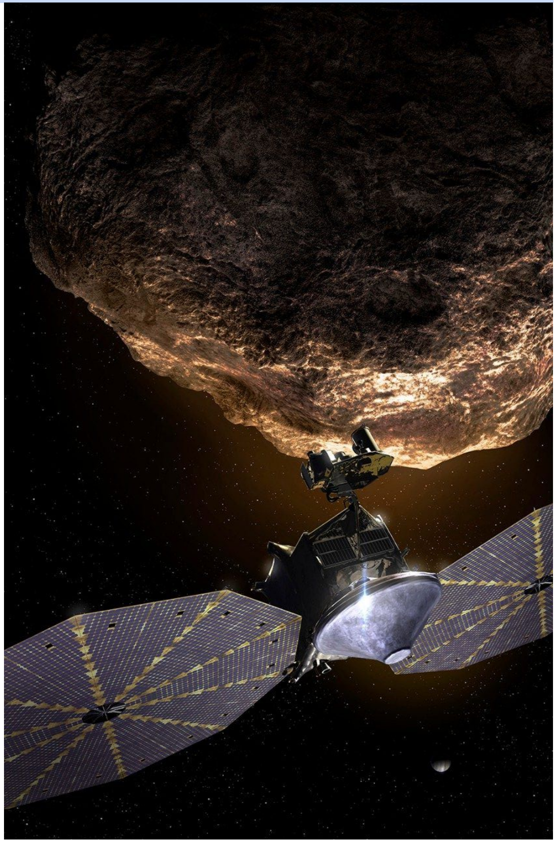
Lucy is going to the Jupiter Trojans

- Jupiter Trojans come from the primordial Kuiper-belt (the same place comets came from).

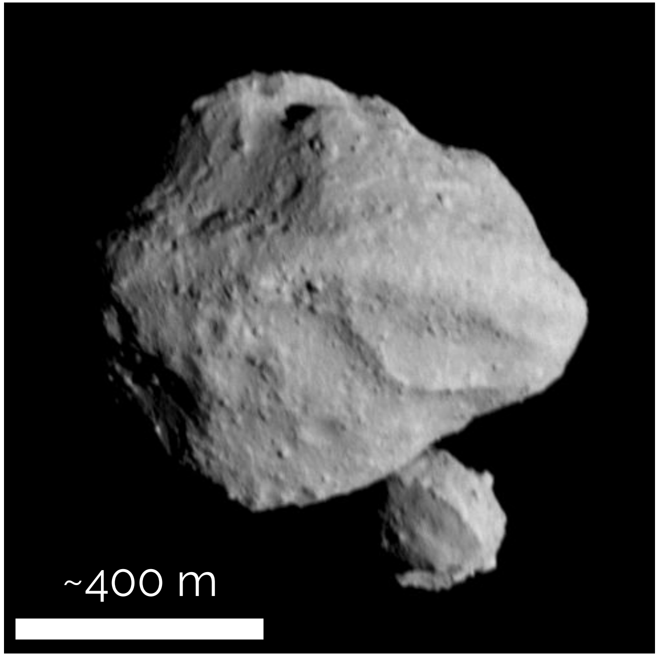
- NASA's Lucy mission will visit 8 of these objects between 2027 and 2033.

- Our dress rehearsal a few weeks ago went perfect!



Lucy's encounter of Dinkinesh

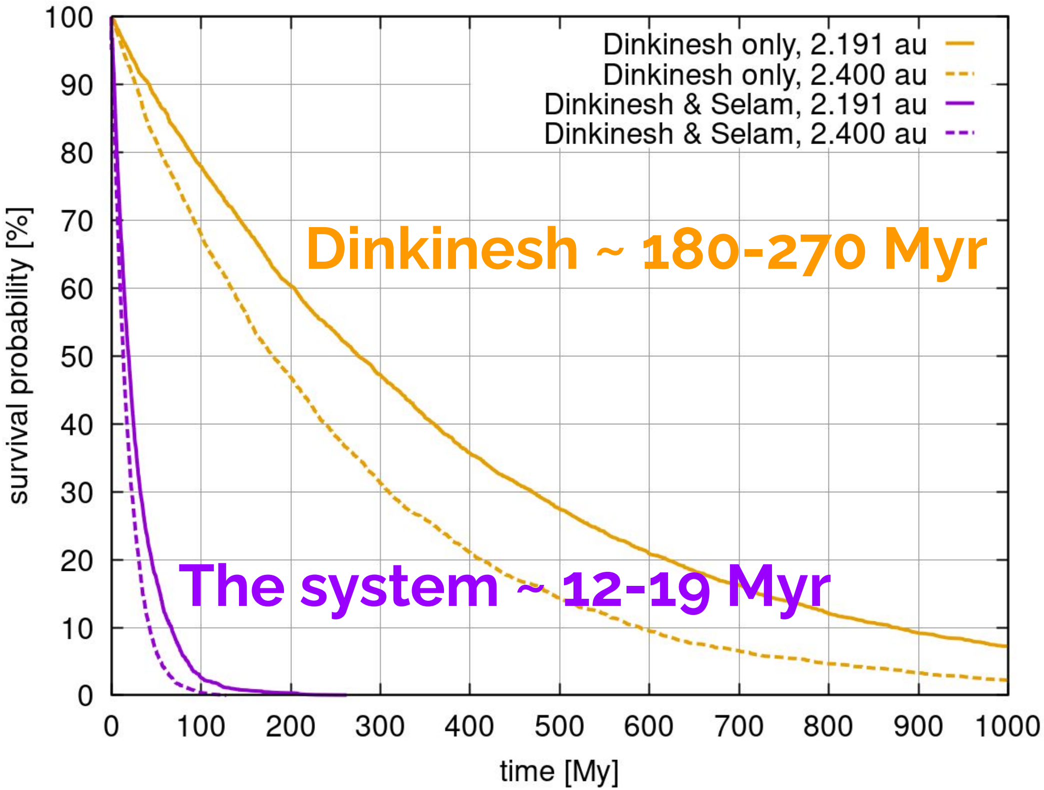
Encounter of smallest ever Main Belt Asteroid on Nov. 1, 2023.



Lucy's encounter of Dinkinesh

How long does the Dinkinesh-Selam system survive?

These small asteroids are satellite factories!



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There is much more to come

Comets are active!

What does a primitive comet look like?

→ Comet Interceptor (launching in 2029)

Does the isotopic dichotomy include comets?

→ Comet Nucleus Sample Return (e.g., proposed CAESAR)

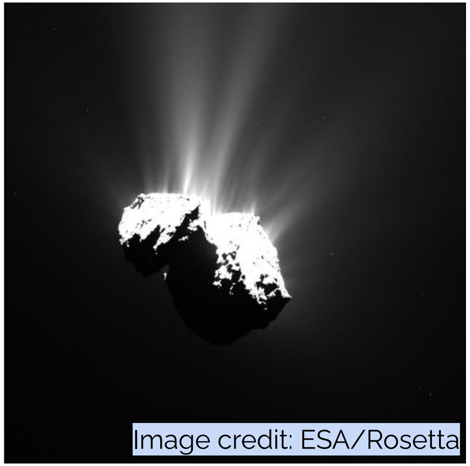

Image credit: ESA/Rosetta

COMET INTERCEPTOR
F-Mission

CAESAR

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10 kyr | 100 kyr | 1 Myr | 10 Myr | 100 Myr | 1 Gyr | today

How did we get here?

- Small Solar System Bodies hold the key.
- They have already revealed so much (e.g., the giant plant instability).
- Samples from asteroids (meteorites & sample return missions) allow us to peer back to the very beginning of our Solar System.
  →an inflationary phase at the beginning of the protoplanetary disk.
- Mission like Lucy, Comet Interceptor, & Comet Nucleus Sample return will revolutionize our understanding of the outer Solar System.

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Thank you!

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