Planetenentstehung I: feste Kerne

Das Sonnensystem und seine nächsten Verwandten für Nicht-Physiker

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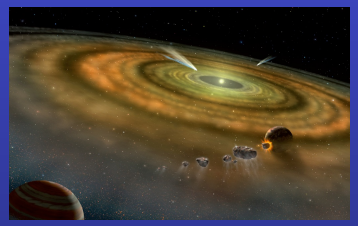
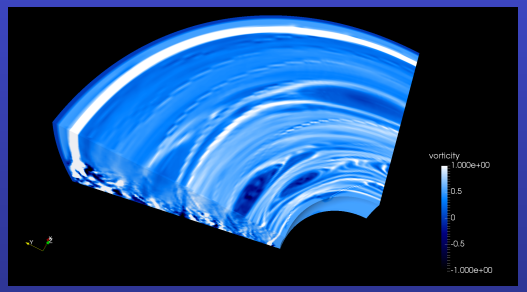
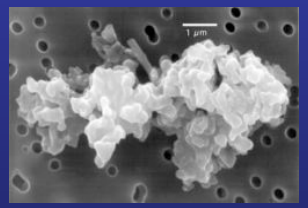
Haus der Astronomie / Max-Planck-Institut für Astronomie

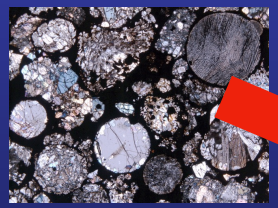
13.11.2018

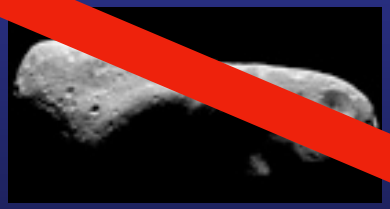
Lecture Staub -> Planetesimale

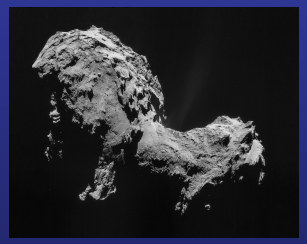






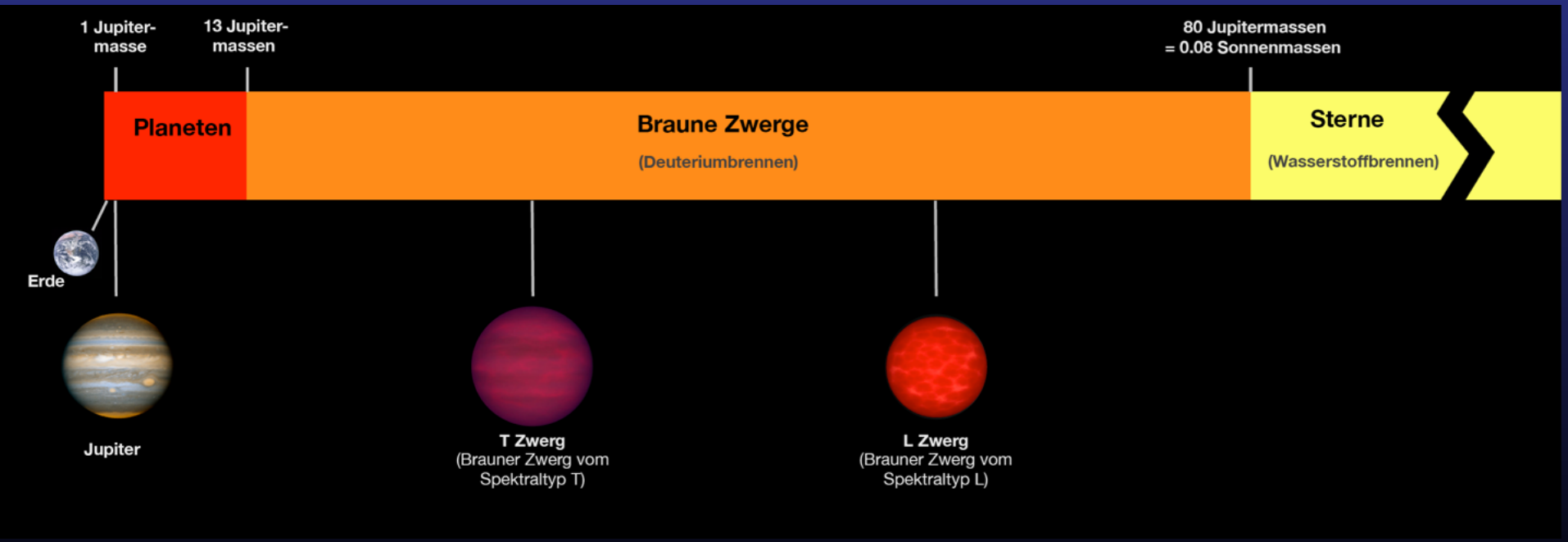




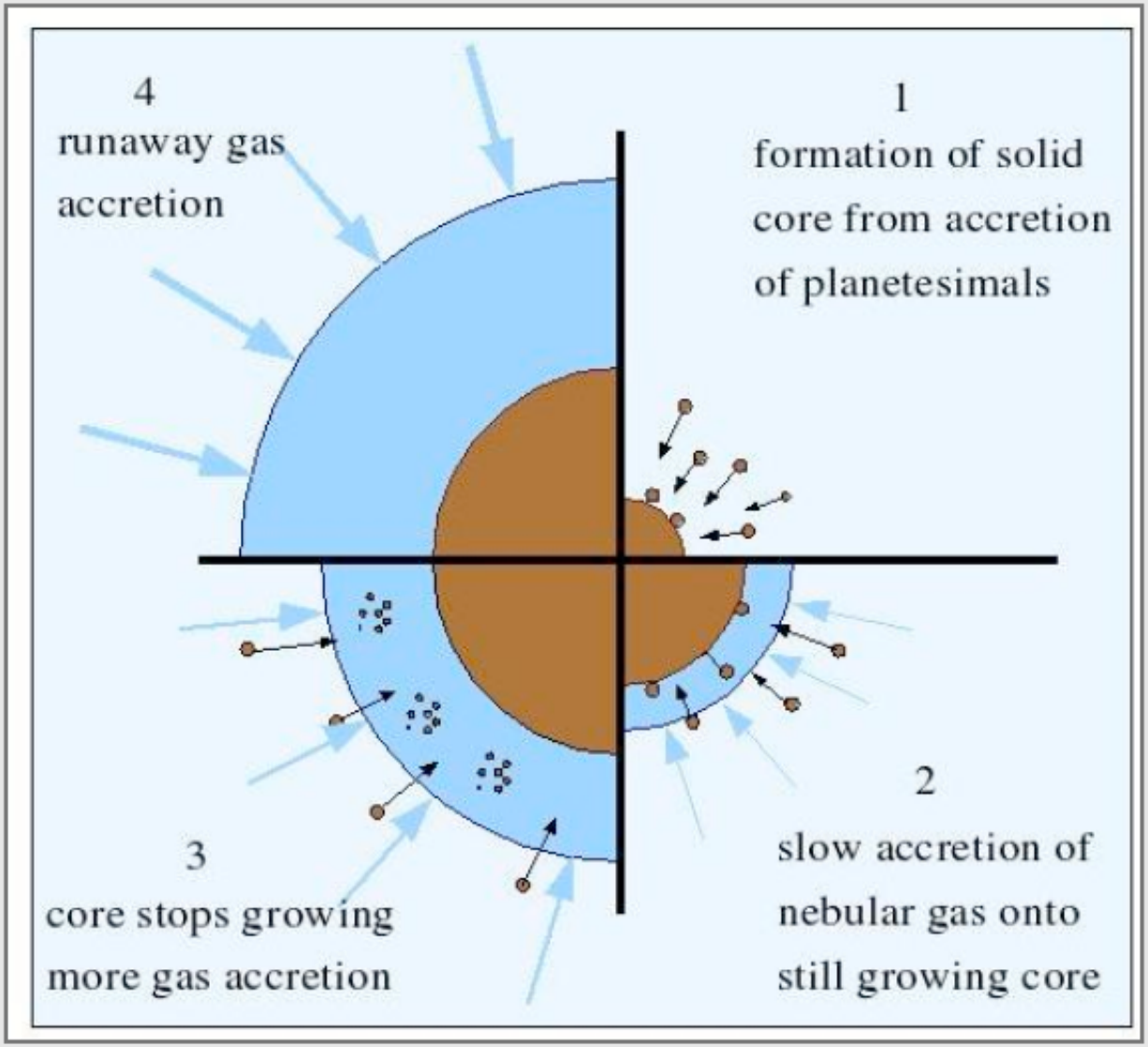


Wie baut man aus Staub Planeten?

Was ist ein Planet? Definition über Masse ist willkürlich. Ein fließender Übergang zu den Sternen. Mögliche Unterscheidung über Entstehung? Planeten brauchen erst einen festen Kern und Sterne kondensieren direkt aus dem Gas aus? Leider keine Überprüfbarkeit am “lebenden” Objekt.

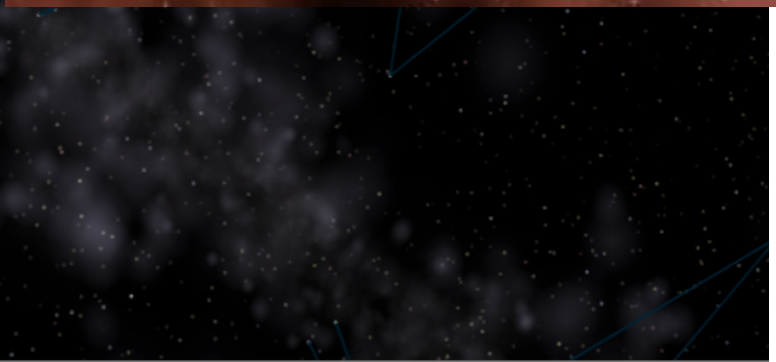


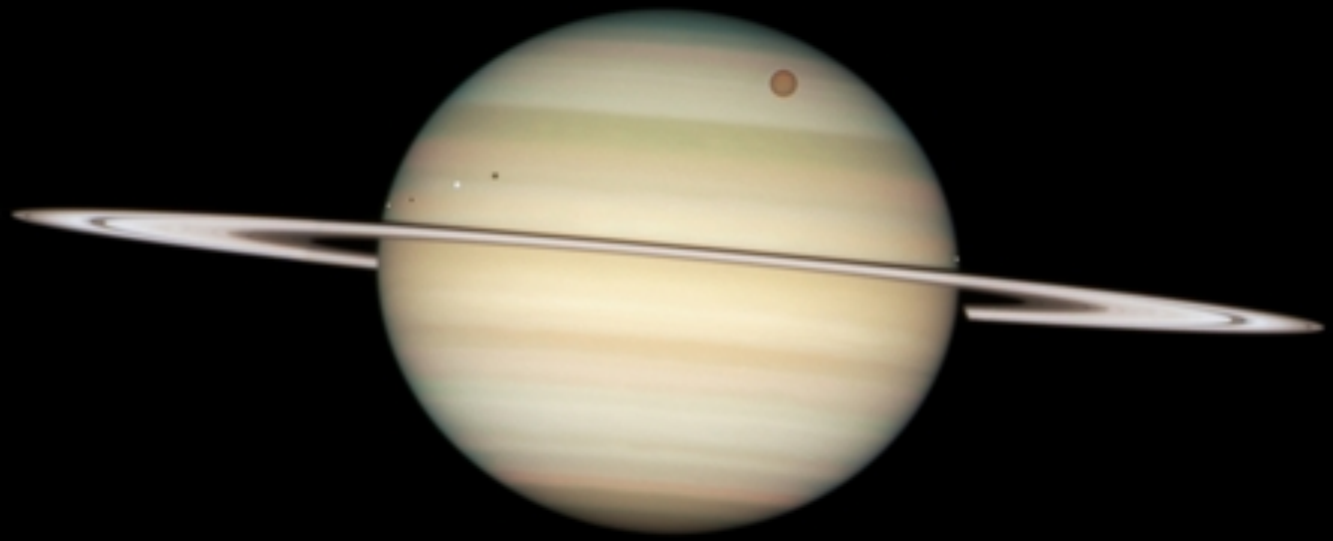
Giant planet formation: core accretion model



Kant / Laplace: Entstehung aus einer Scheibe heraus.

“Geburtsstätten von Planeten:” Gas- und Staubscheiben um junge





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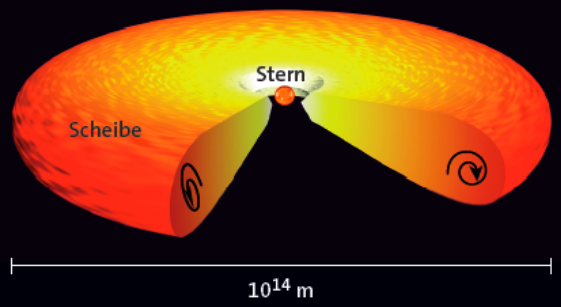
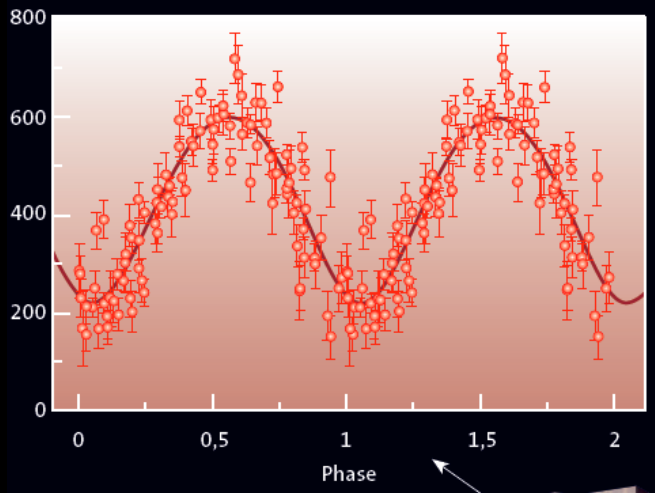
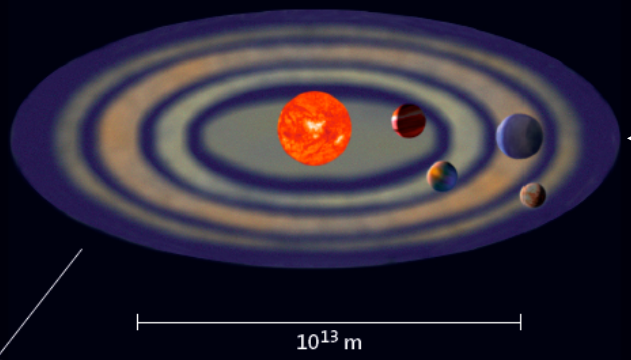
$t = 0$



(a) Turbulente Scheibe aus Gas und Staub

$t = 10^7$

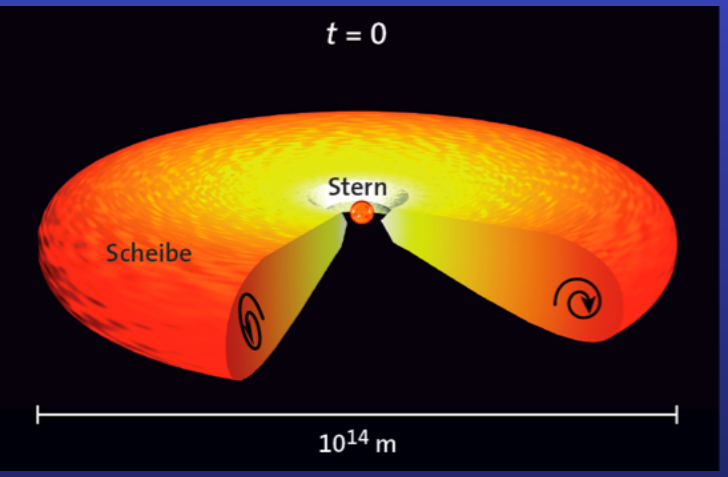


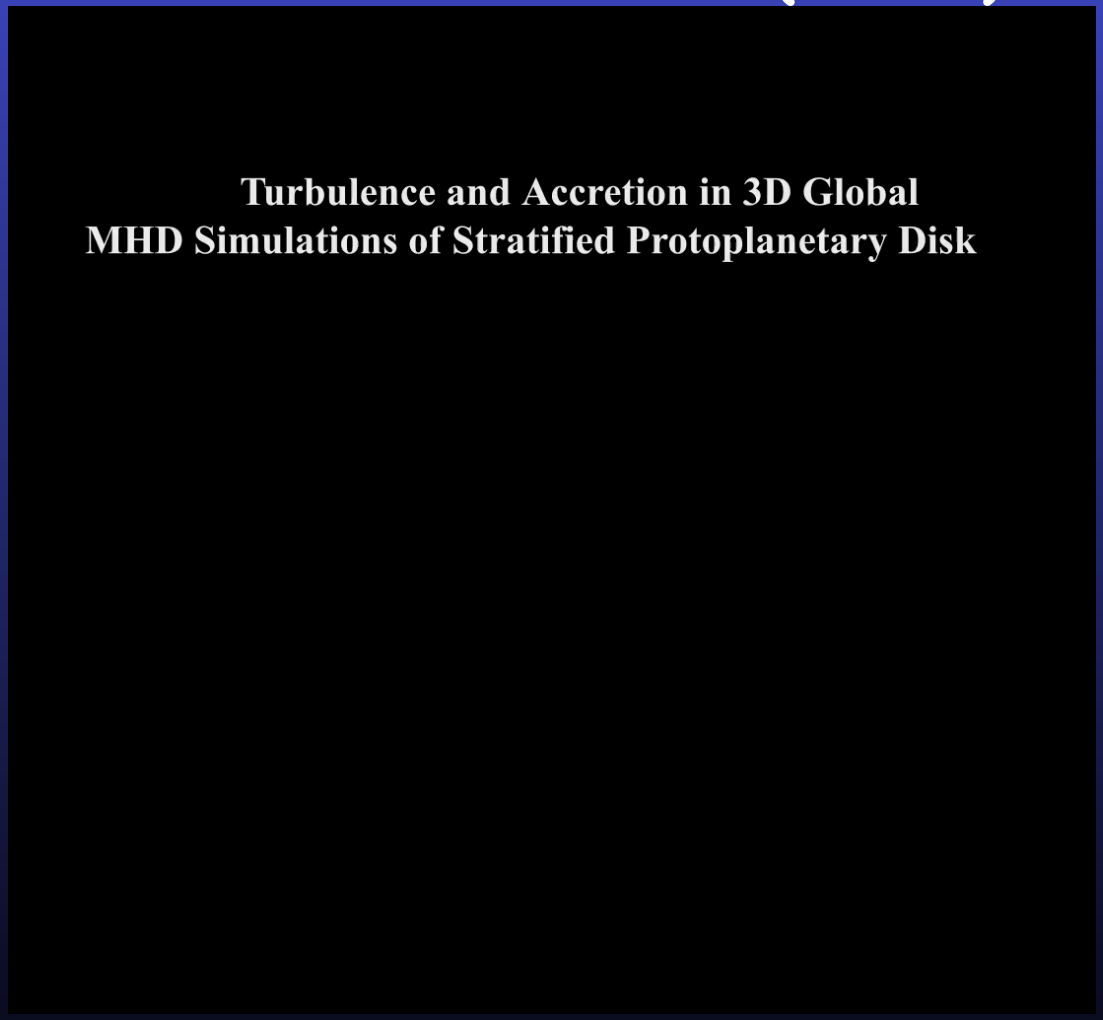


(f) Migration und resonante Wechselwirkung

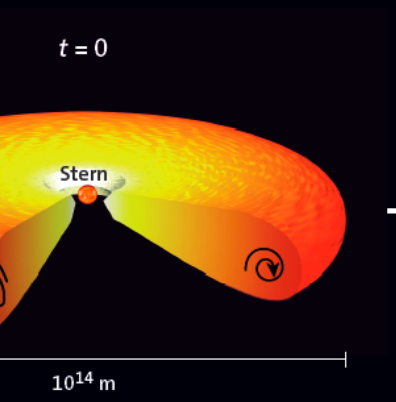
… Ein Wunder geschieht im Dunkel…

Magneto Rotations Instabilität (MRI)

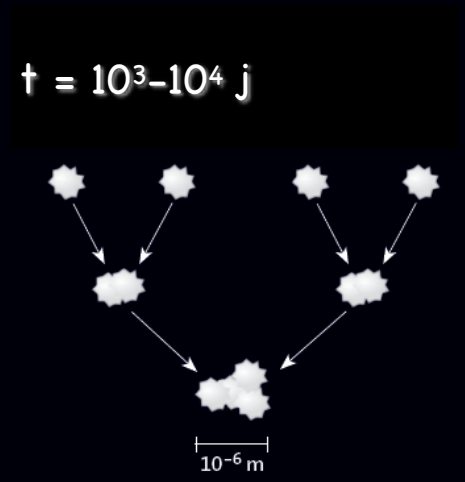




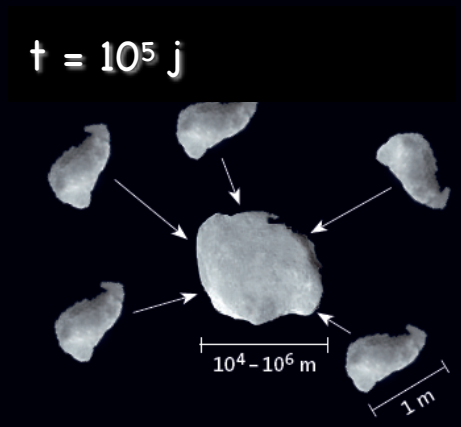
Simulation von Mario Flock mit dem Pluto Code.



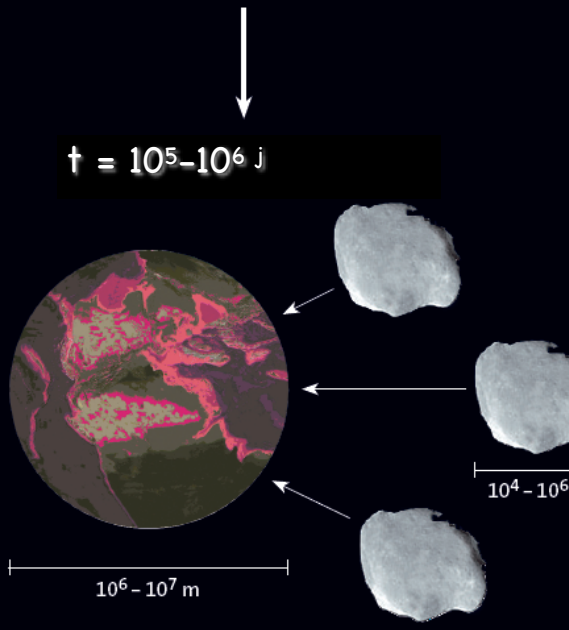
a. Turbulente Scheibe



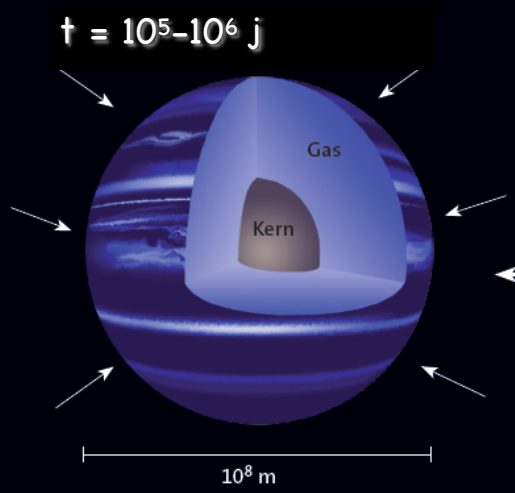
b. Stossen und Kleben



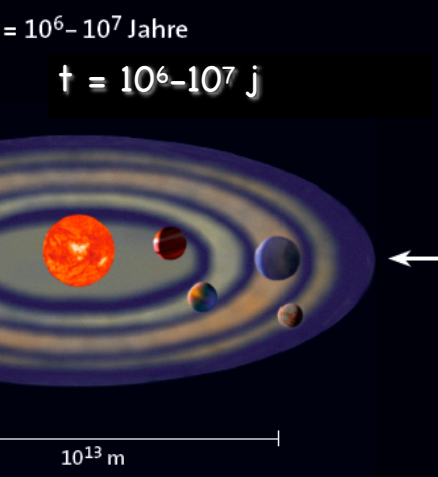
c. Gravotubulente Fragmentation



d. Gravitation



e. Gasakkretion



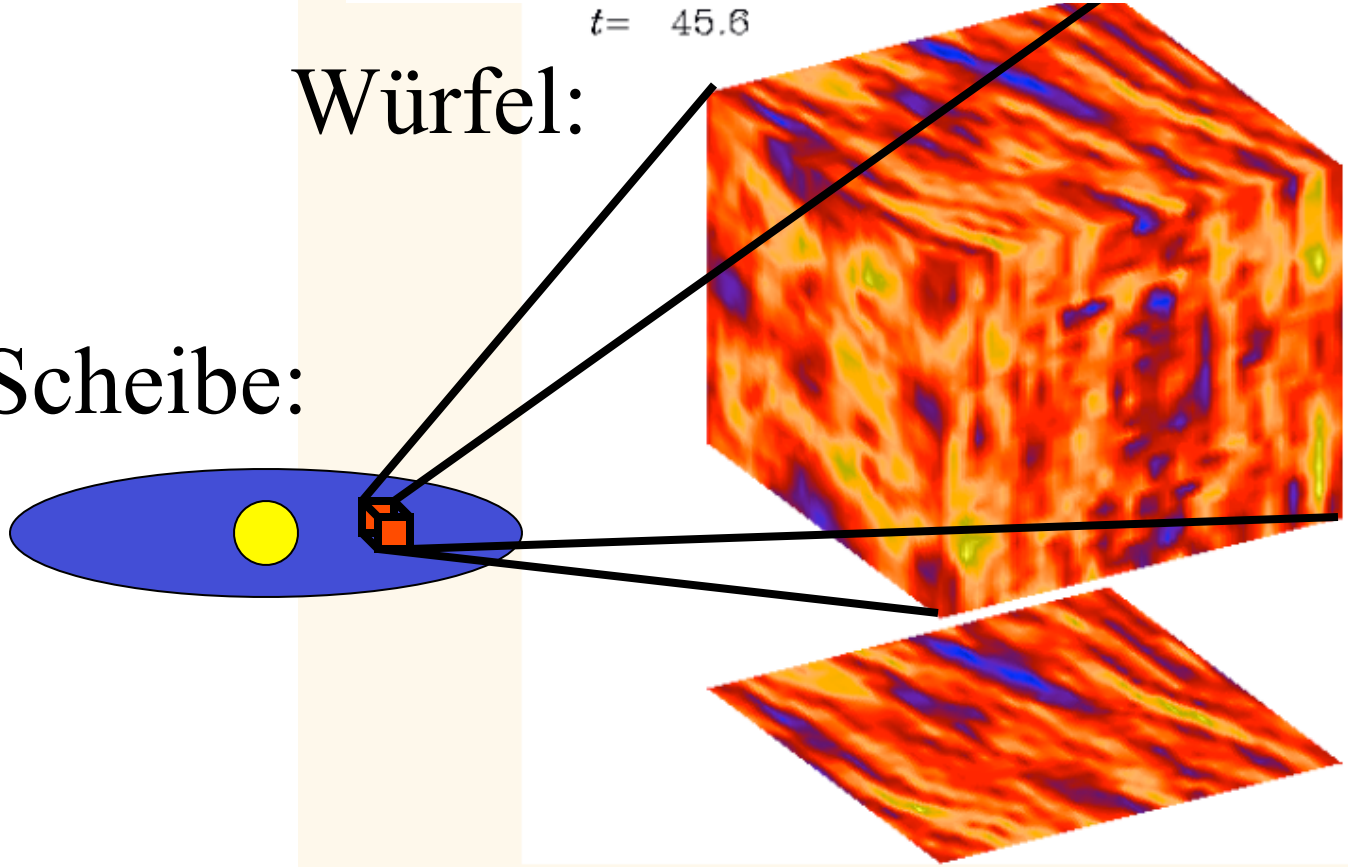
f. Migration

MRI turbulence

Würfel statt Scheiben... Die spinnen die Theoretiker!

Würfel:

Scheibe:



Simulieren, was sich im Dunkel abspielt...

order in space, 3rd order in time, Brandenburg (2003)]

Differentialgleichungen zur Planetenentstehung: Turbulenz, Magnetfelder, Staub, Gravitation

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial \ldots} = 2\Omega u_y \hat{\boldsymbol{x}} - \frac{1}{\ldots}\Omega u_x \hat{\boldsymbol{y}} - \boldsymbol{\nabla}\Phi + \frac{1}{\ldots}\boldsymbol{J}\times\boldsymbol{B}$$

$$\ldots f_\nu(\boldsymbol{u},\rho)\,,$$

$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\ldots$$

$$\frac{\partial \boldsymbol{v}^{(i)}}{\partial t} \ldots (\boldsymbol{x}^{(i)})]\,,$$

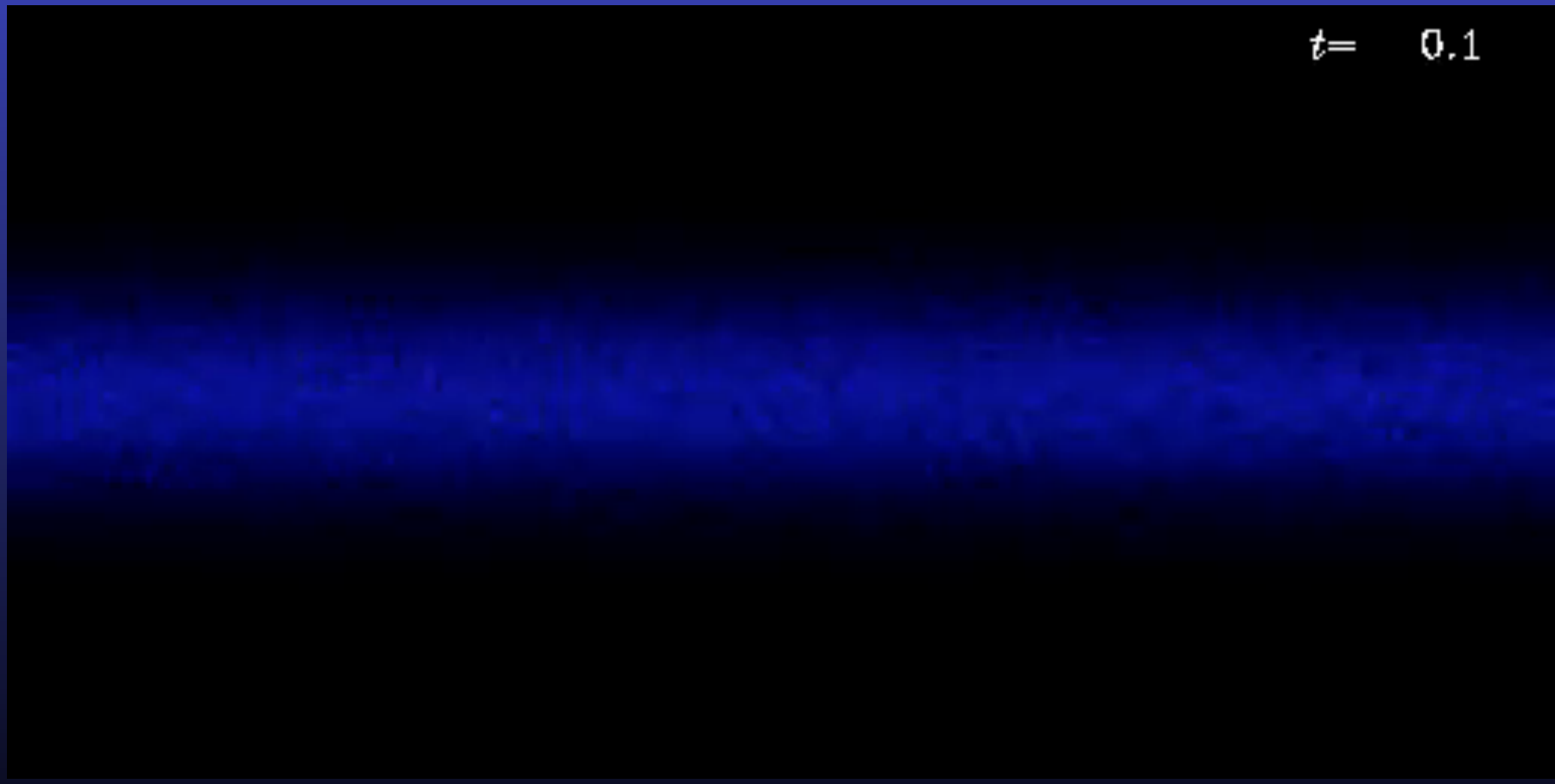
$$\frac{\partial \boldsymbol{x}^{(i)}}{\partial t} = \boldsymbol{v}^{(i)} + u_y^{(0)}\boldsymbol{y}\,.$$

aust

Lösung erfolgt auf Grossrechnern

Gas + Staub = Turbulenz:
Wie verklumpt Staub zu Planeten?

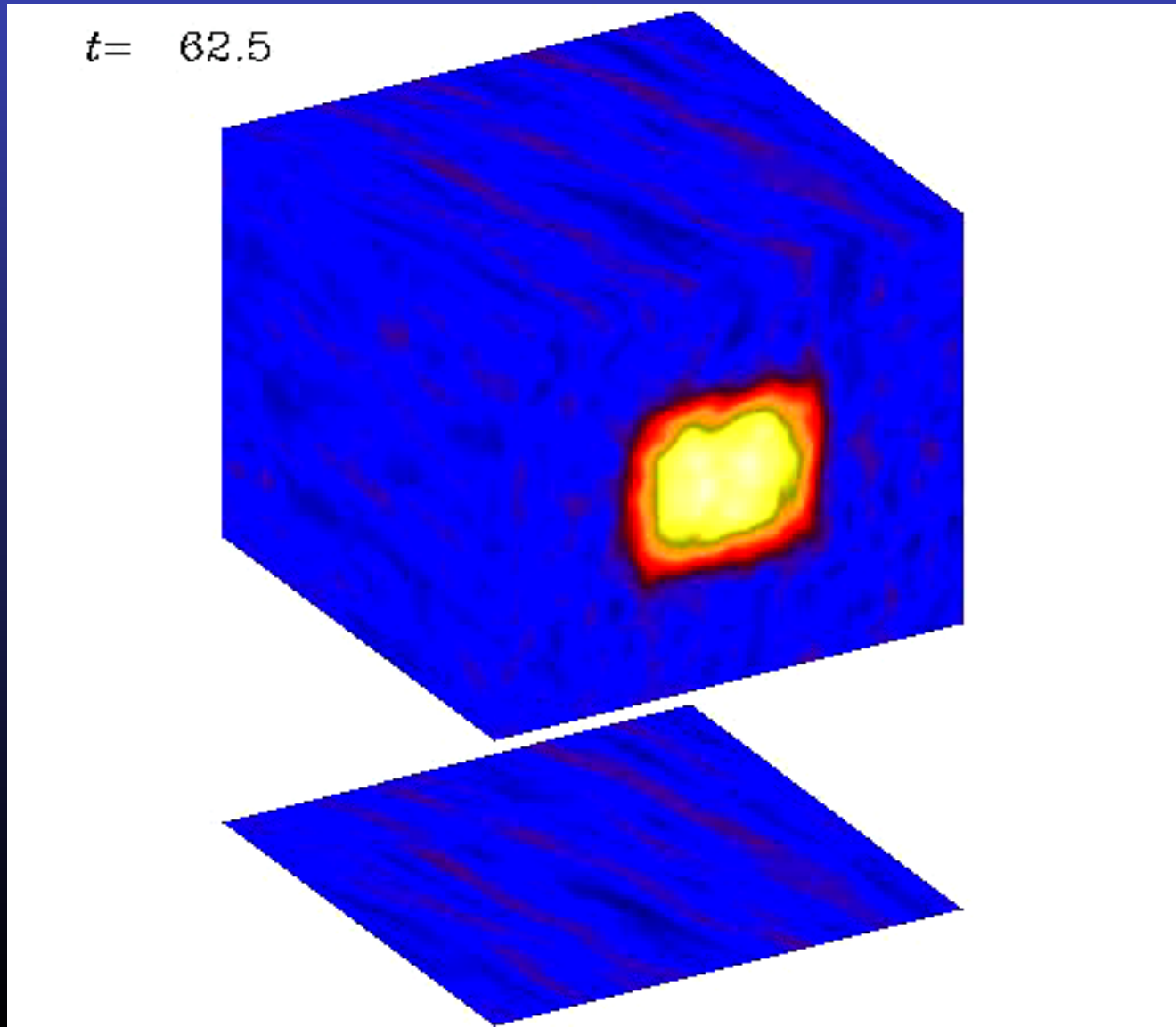
vertikal



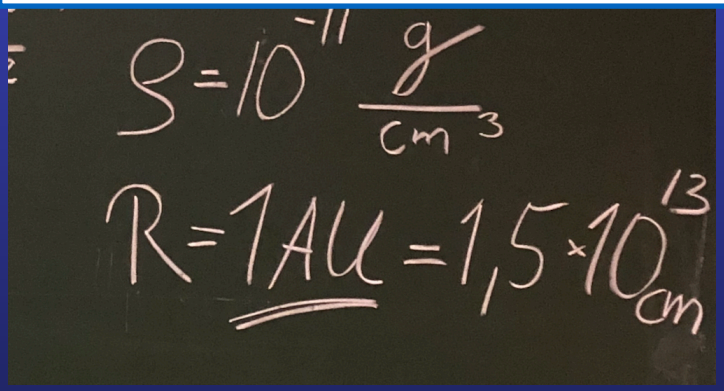
horizontal

Johansen, Henning & Klahr 2006

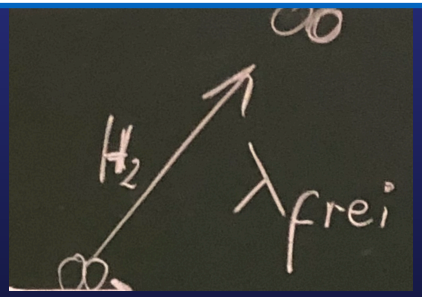
Diffusion von Staub in MHD Turbulenz.



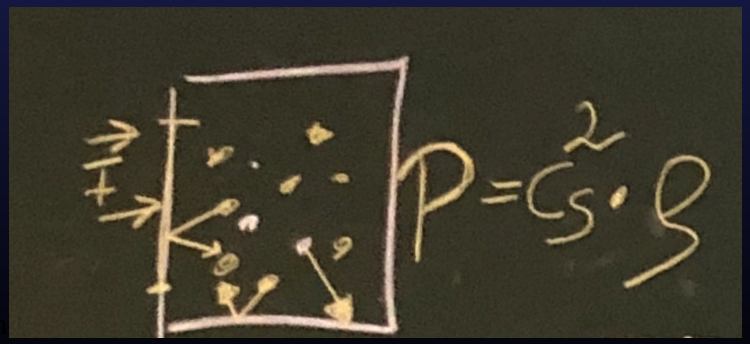
Der Gas Nebel in dem unsere Planeten geboren werden ist ähnlich unserer Erdatmosphäre. Die Dichte ist viel kleiner, aber dafür sind die Dimensionen viel grösser. Beide sind in erster Linie in hydrostatischem Gleichgewicht. Das heisst die Kräfte wie Gravitation halten sich mit dem Gasdruck Gradienten im Gleichgewicht.

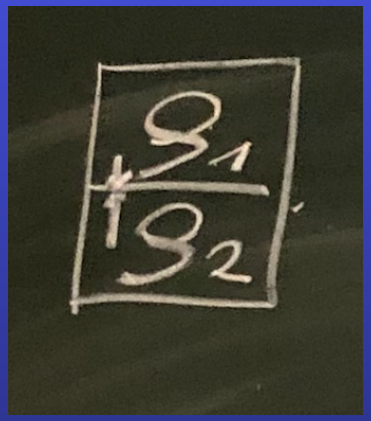


Gas = Freie Weglänge < als betrachtete Dimensionen, also viele Stösse.



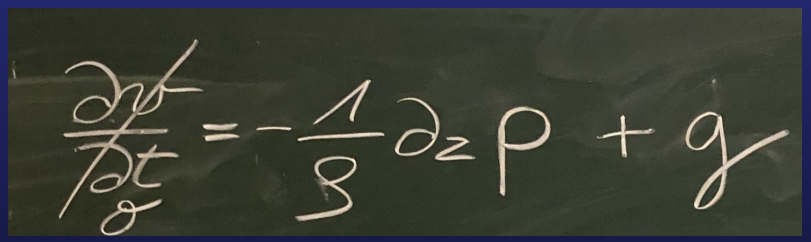
Gasdruck entsteht wenn Gas Moleküle mit der Schallgeschwindigkeit zusammenstossen bzw. an die Wände eines Behälters schlagen. Daher:



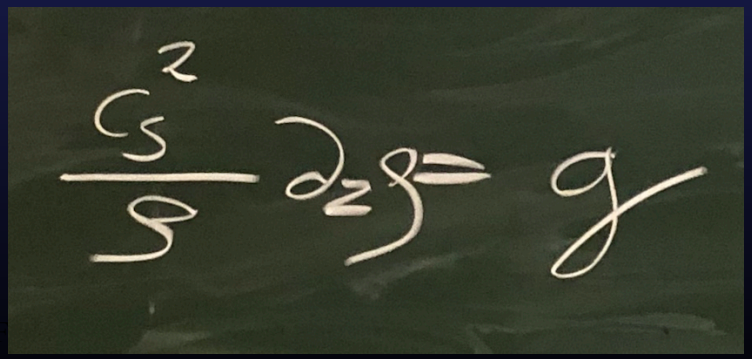


Übung: Wie dick ist die Erdatmosphäre?

Wenn auf Gas Gravitation wirkt, so drückt das obere Gas das untere Gas zusammen, bis der Dichte (~Druck Unterschied **dp/dz**) die wirkende Kraft **g rho** ausgleicht. Dann ändern sich Geschwindigkeit nicht mehr: **dv/dt = 0**



Setzen wir die Relation für den Druck ein so erhalten wir eine Differentialgleichung:



Wie dick ist die Erdatmosphäre?

Die Differentialgleichung…

$$\frac{c_s^2}{\rho}\partial_z \rho = g$$

…hat die Lösungen…

$$\rho(z) = \rho_0 \cdot e^{-\frac{z}{H}}$$

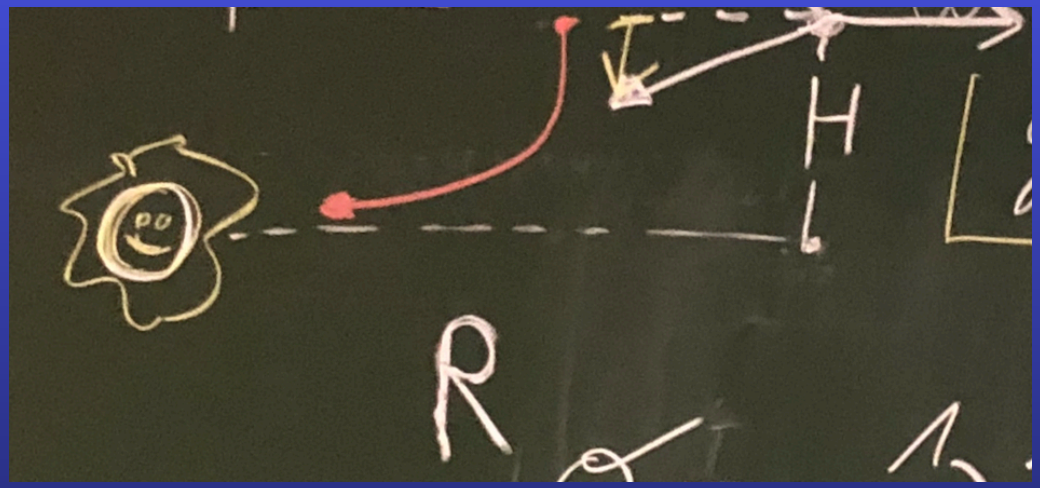
Woraus wir H ableiten können:

$$-\frac{1}{H} = \frac{g}{c_s^2}$$

Setzen wir Schallgeschw. von cs = 330 m/s und g = 10 m/s^2 ein… anders macht man das in der Astrophysik auch nicht.

$$H = \frac{c_s^2}{-g} = \frac{10^5 \frac{m^2}{s^2}}{10 \frac{m}{s^2}} = \underline{\underline{10\,km}}$$

Wie dick war der Solare Nebel?



1. Die Sonne zieht das Gas an.
2. Die Rotation der Scheibe will das Gas radial von der Rotationsachse wegschleudern.
3. So können sich in einer vertikal ausgedehnten Scheibe mit radialen Dichteprofil Rotation und Gravitation nicht perfekt aufheben, wie das im Kepler System war.

$$\Omega_K = \sqrt{\frac{M \cdot G}{R^3}}$$

Vertikal bleibt übrig:

$$g_z = -\Omega_K \cdot z$$

$$\rho(z) = \rho_0 \cdot e^{\frac{-z^2}{2H^2}}$$

Und somit ergibt sich mit **H = cs/OmegaK** eine Gauskurve der Dichte.
Typische Werte **H/R = 0.03 - 0.08**

Radial ergibt sich:

$$0 = -\frac{1}{\rho}\partial_R P - \frac{MG}{R^2} + \Omega_K^2 \cdot R$$

Woraus für die Gasrotation folgt, dass sie langsamer als Keplergeschwindigkeit ist:

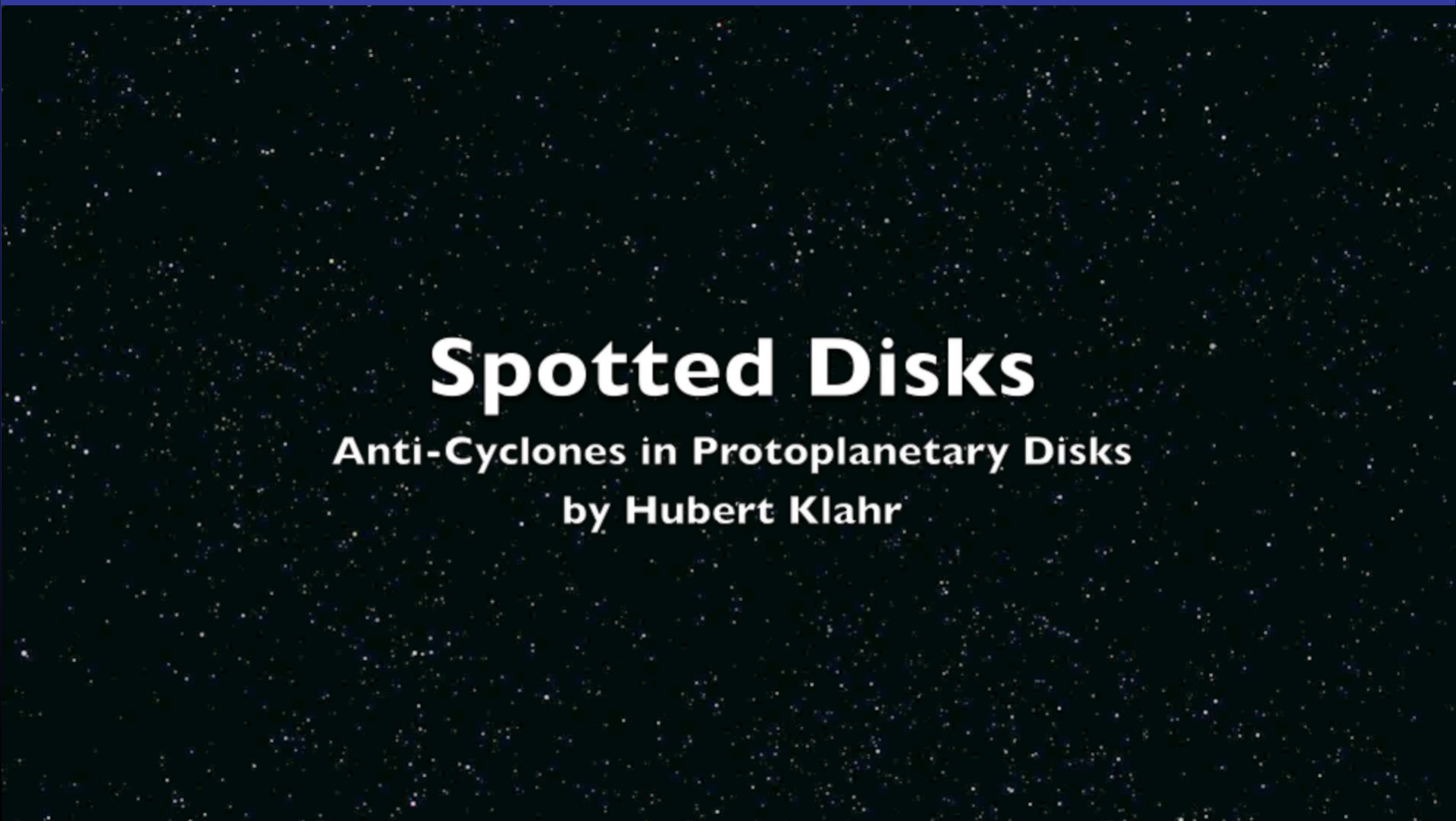
$$\Omega_G = \Omega_K \sqrt{1 - \left(\frac{H}{R}\right)^2}$$

99,17 %

Daher sedimentieren Partikel alle Richtung Stern. Wachstum ist dann nur möglich wenn der Staub und das Eis schnell genug wachsen um vom Gas zu “entkoppeln”.

Convective Overstability: Klahr and Hubbard 2014: NO MHD!
For given radial pressure and entropy gradient:

$$\omega_m^4\left(1+\frac{i}{\gamma\tau\omega}\right)-\omega_m^2\left[\kappa_R^2\left(1+\frac{i}{\gamma\tau\omega}\right)+N_R^2+N_z^2\right]+\Omega^2 z\left(\kappa_r^2\frac{1}{\gamma C_v}\partial_z S_0-\kappa_z^2\frac{1}{\gamma C_v}\partial_R S_0\right)=0$$



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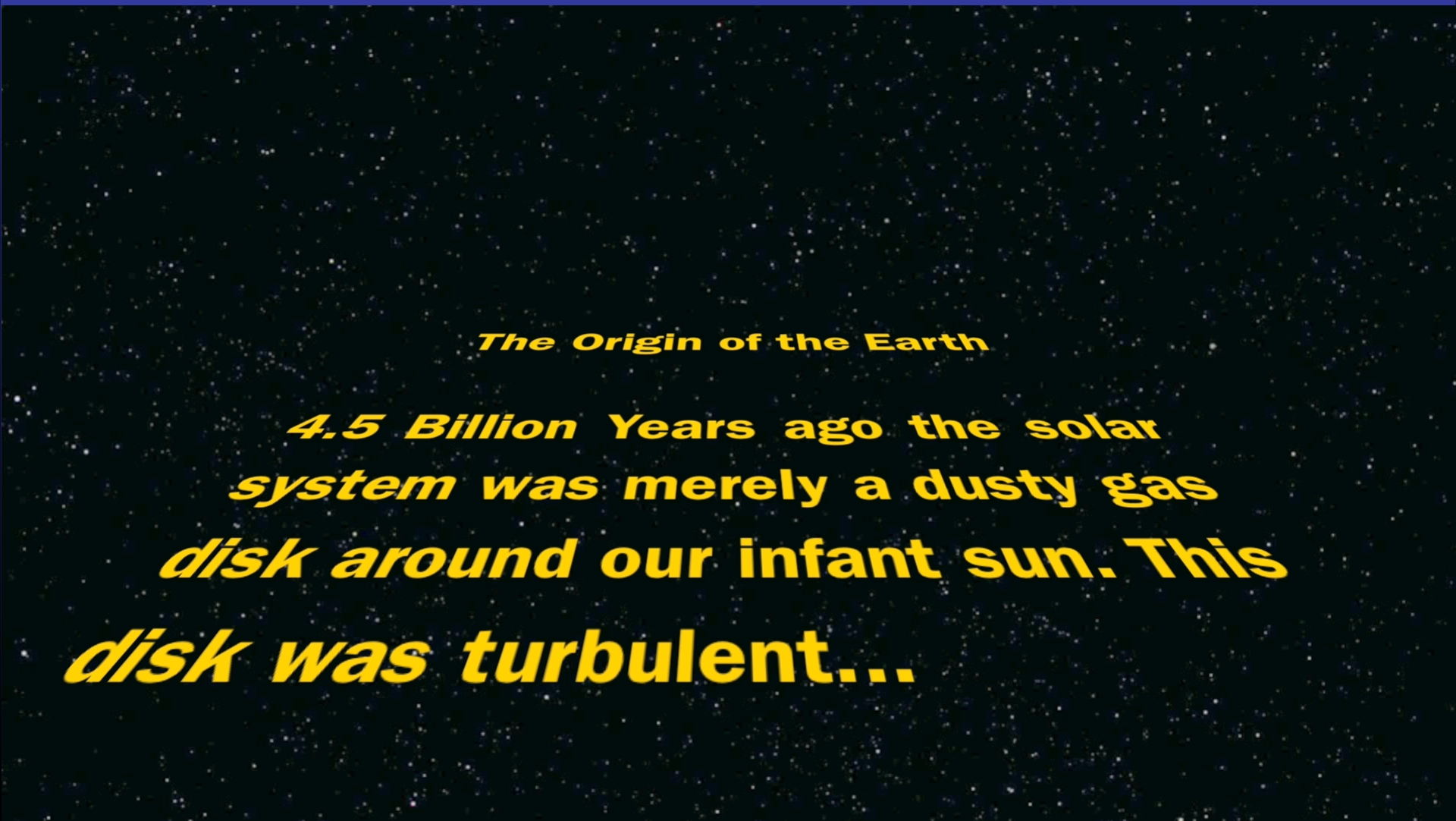

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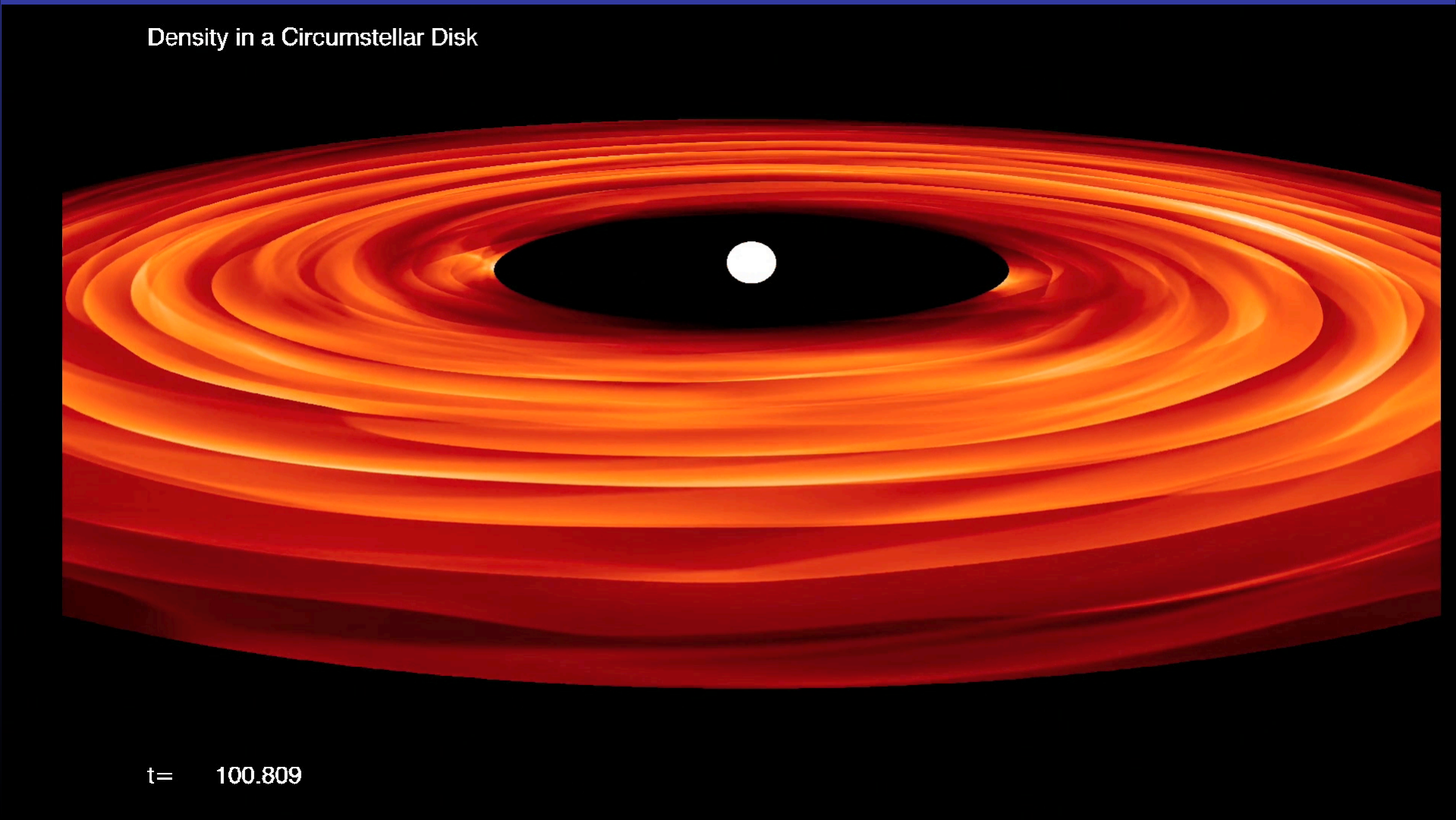

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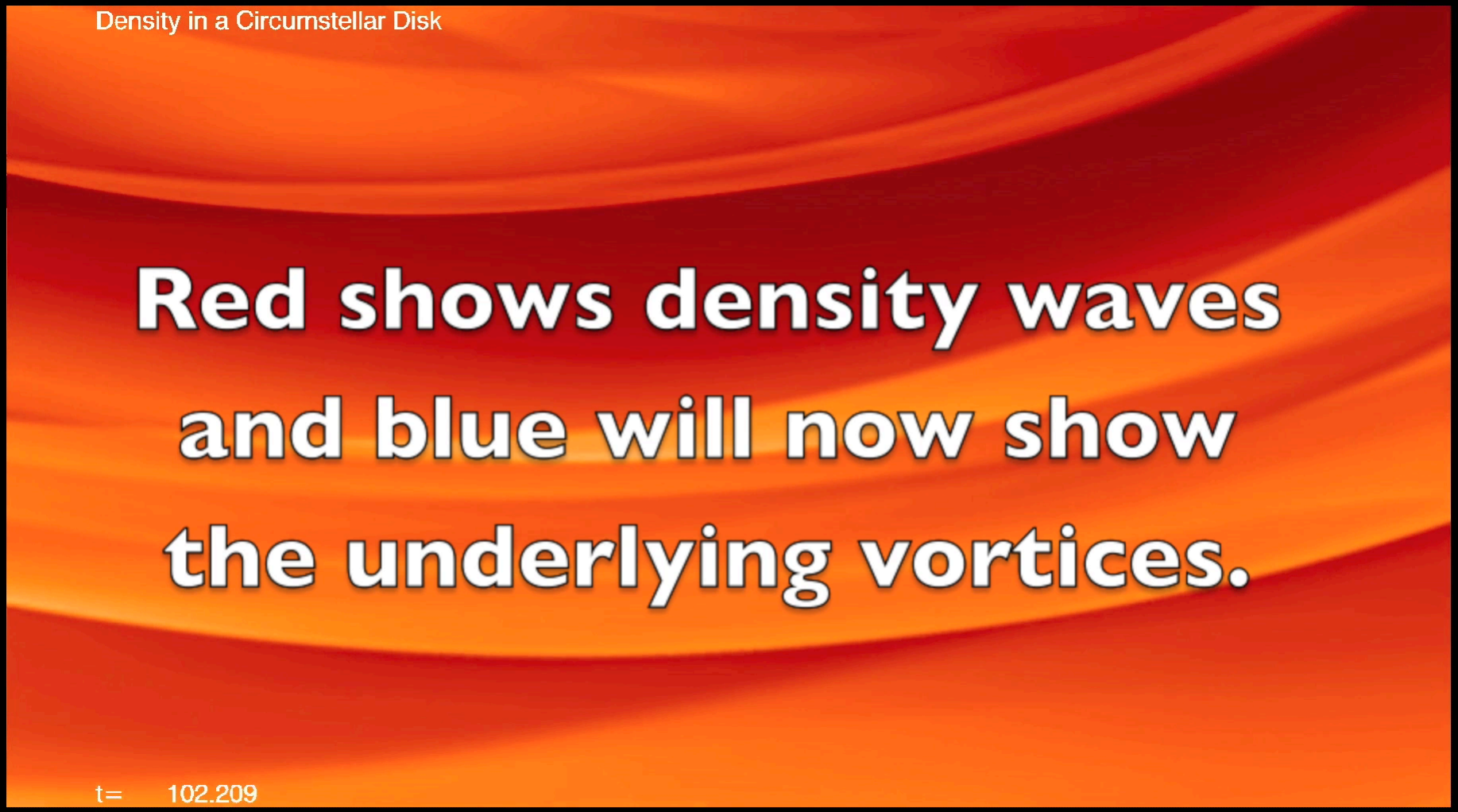

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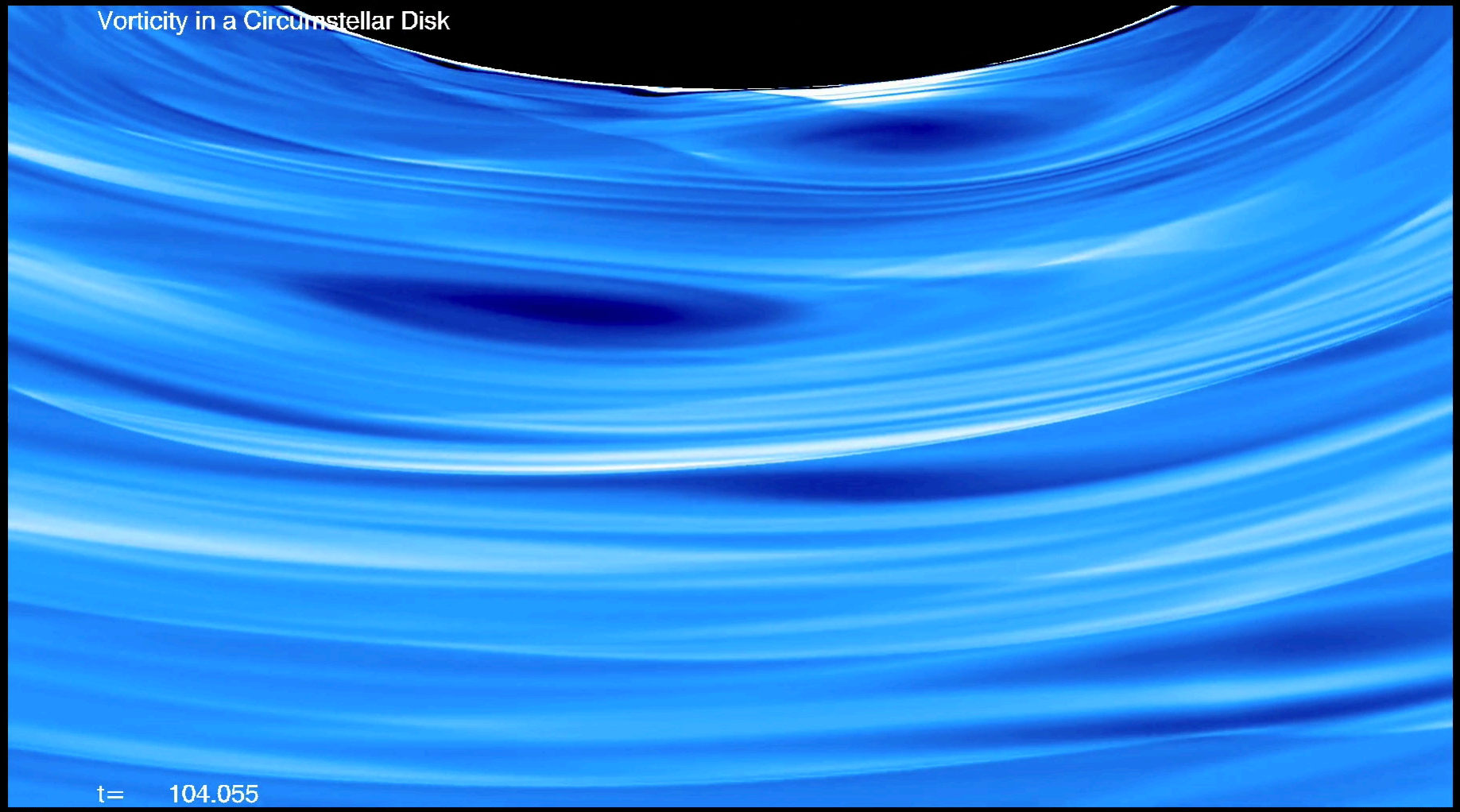

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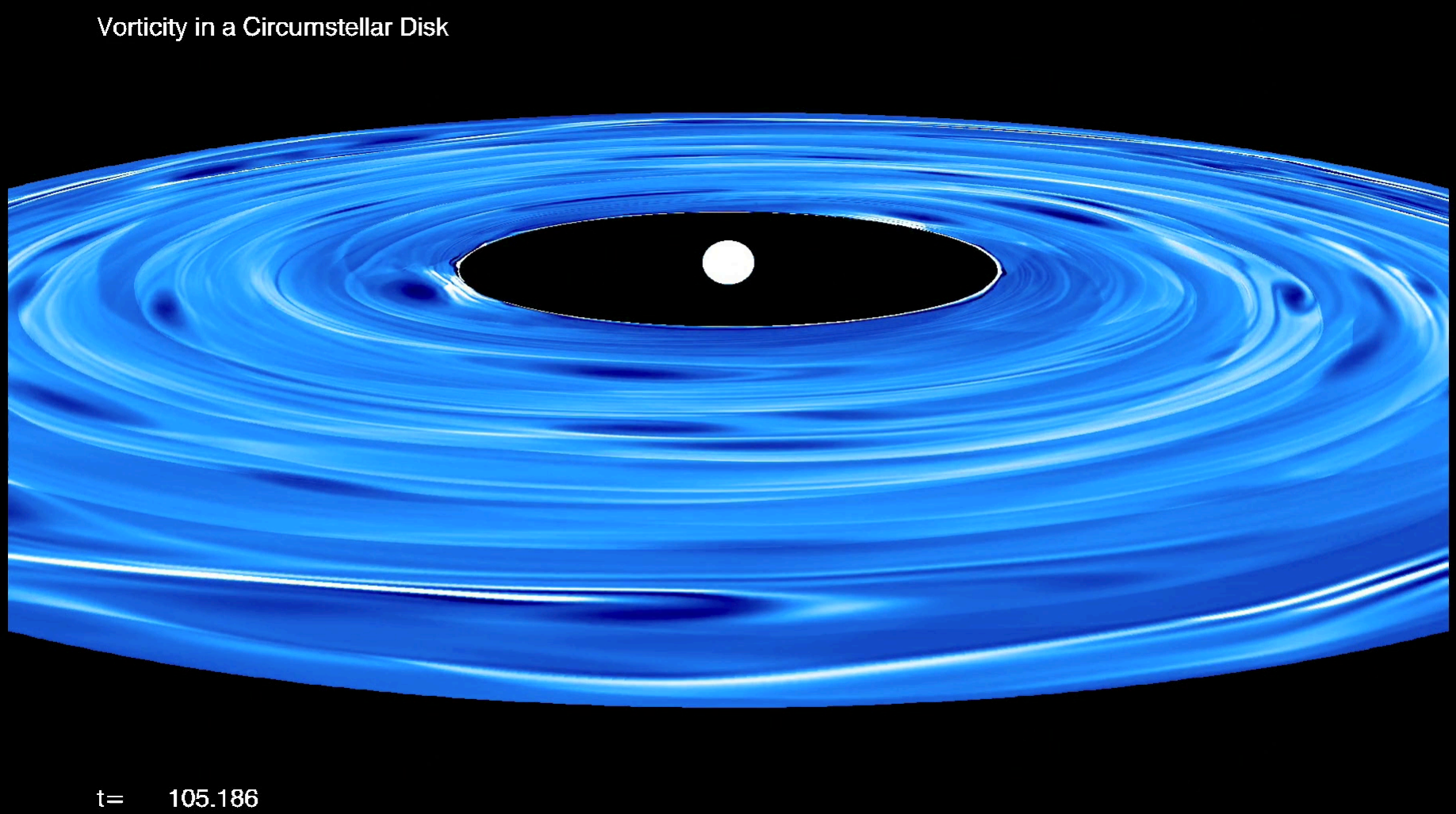

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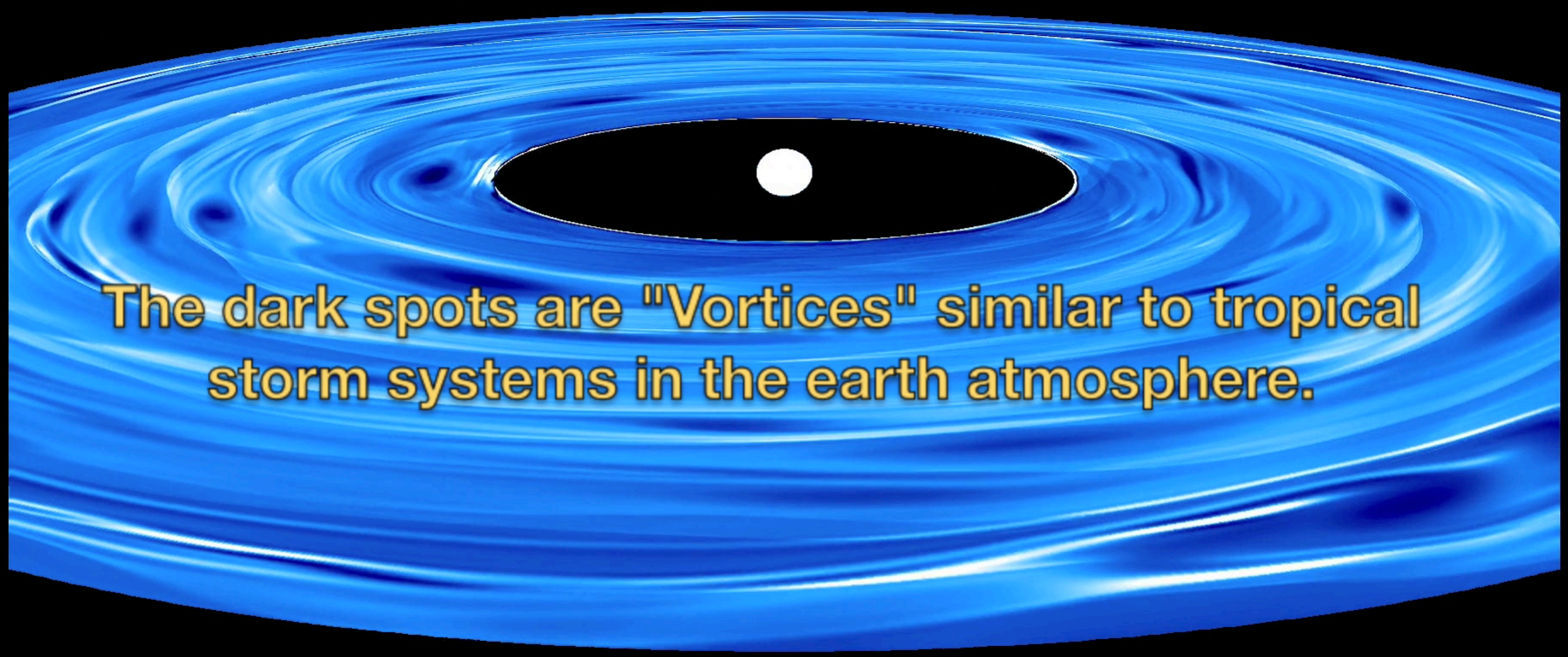

Convective Overstability: Klahr and Hubbard 2014: NO MHD!

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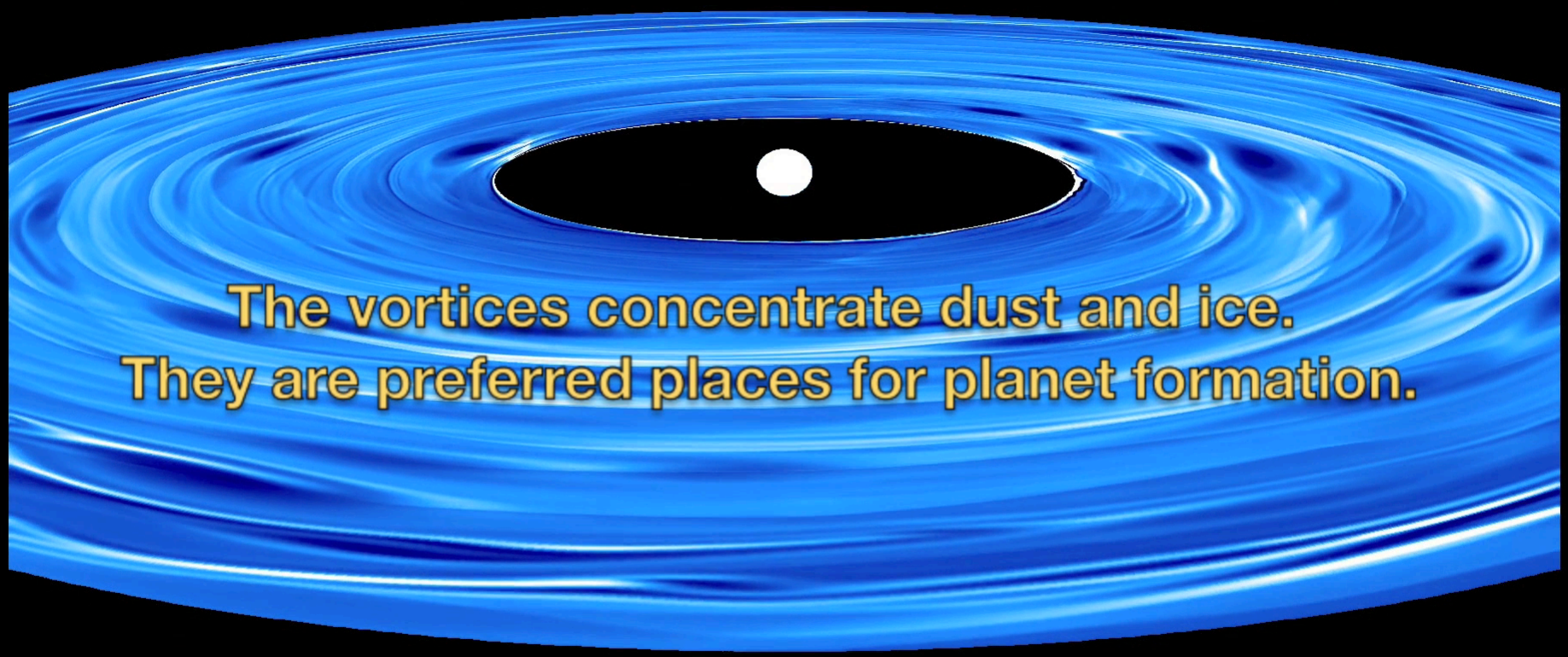
$$\omega_m^4\left(1+\frac{i}{\gamma\tau\omega}\right)-\omega_m^2\left[\kappa_R^2\left(1+\frac{i}{\gamma\tau\omega}\right)+N_R^2+N_z^2\right]+\Omega^2 z\left(\kappa_r^2\frac{1}{\gamma C_v}\partial_z S_0-\kappa_z^2\frac{1}{\gamma C_v}\partial_R S_0\right)=0$$



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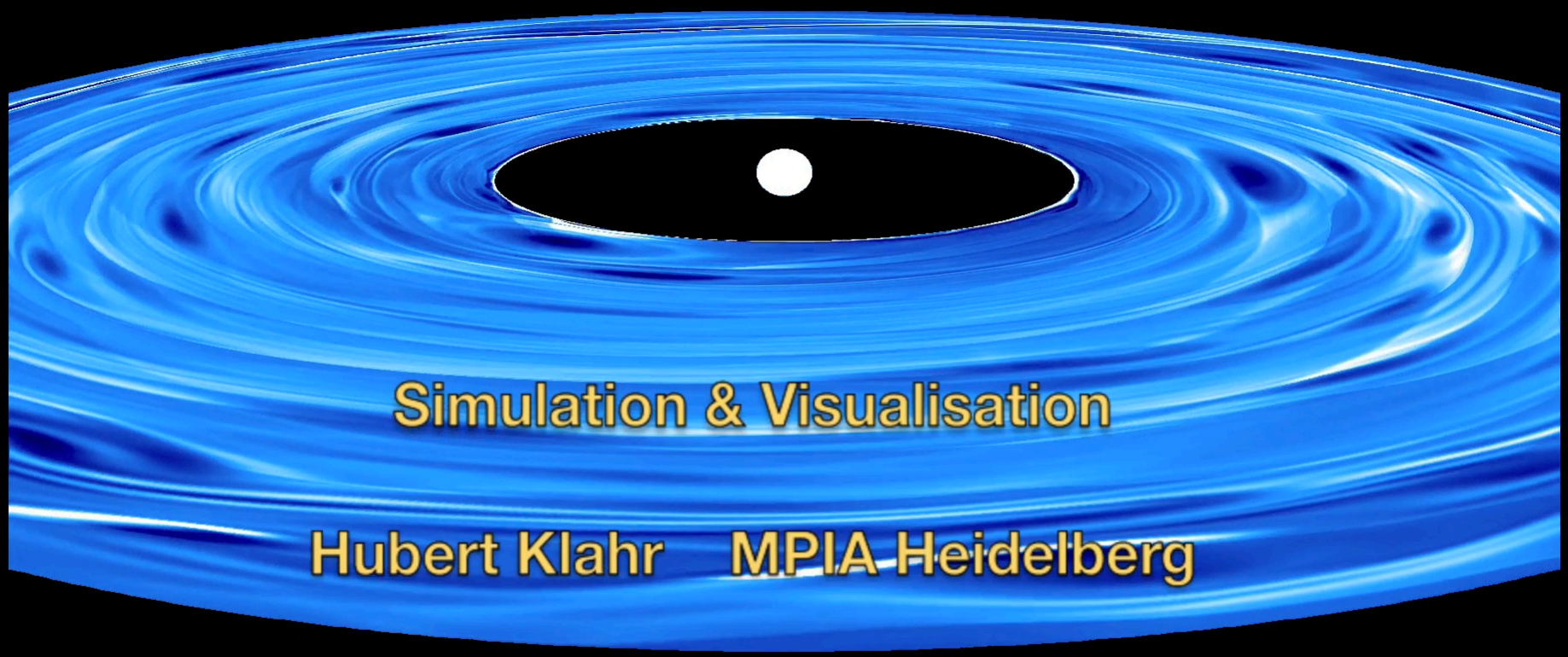
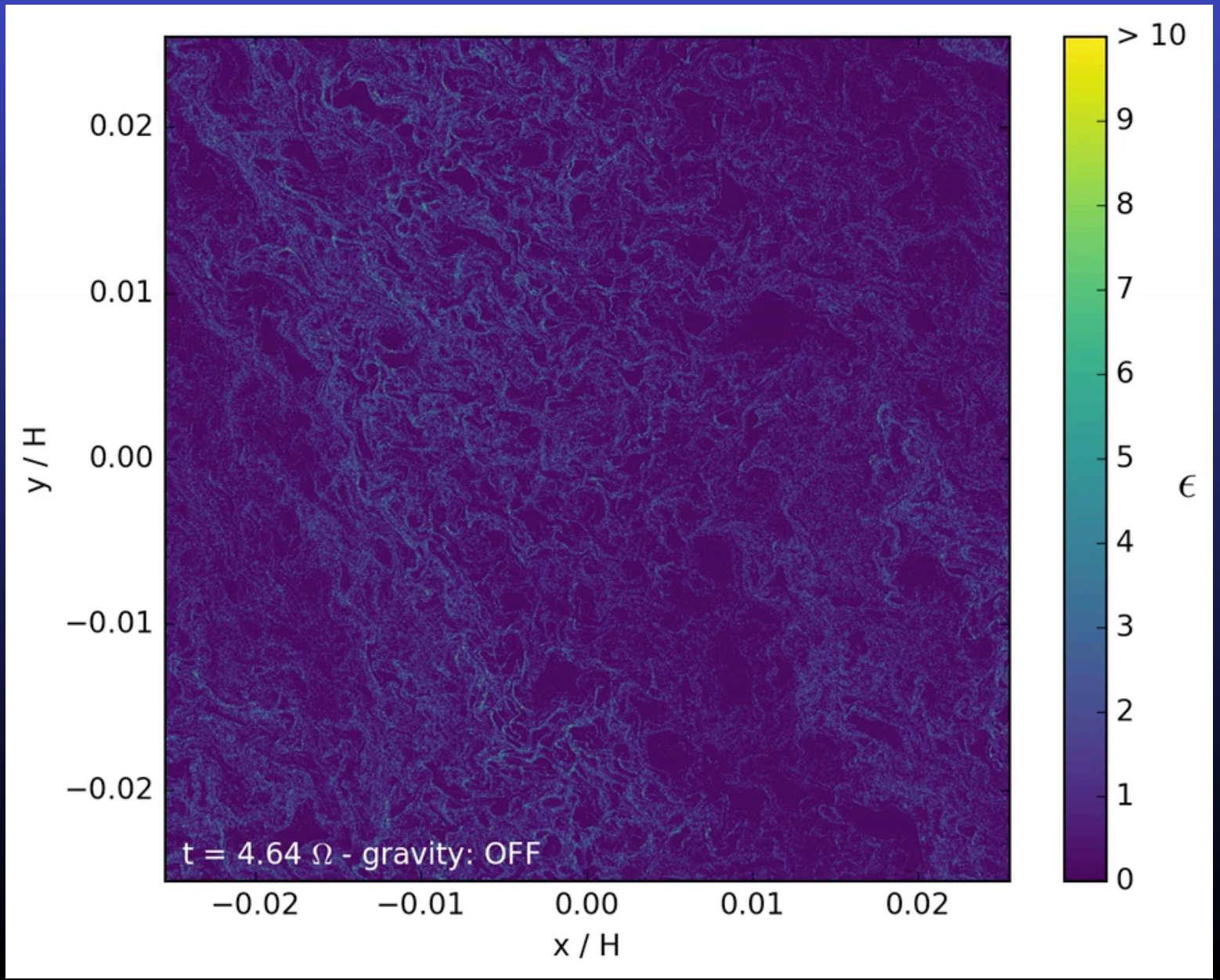


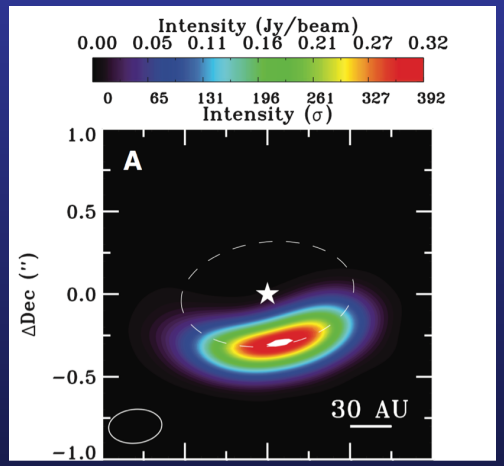
St = 0.01; L = 0.05 H = l_c

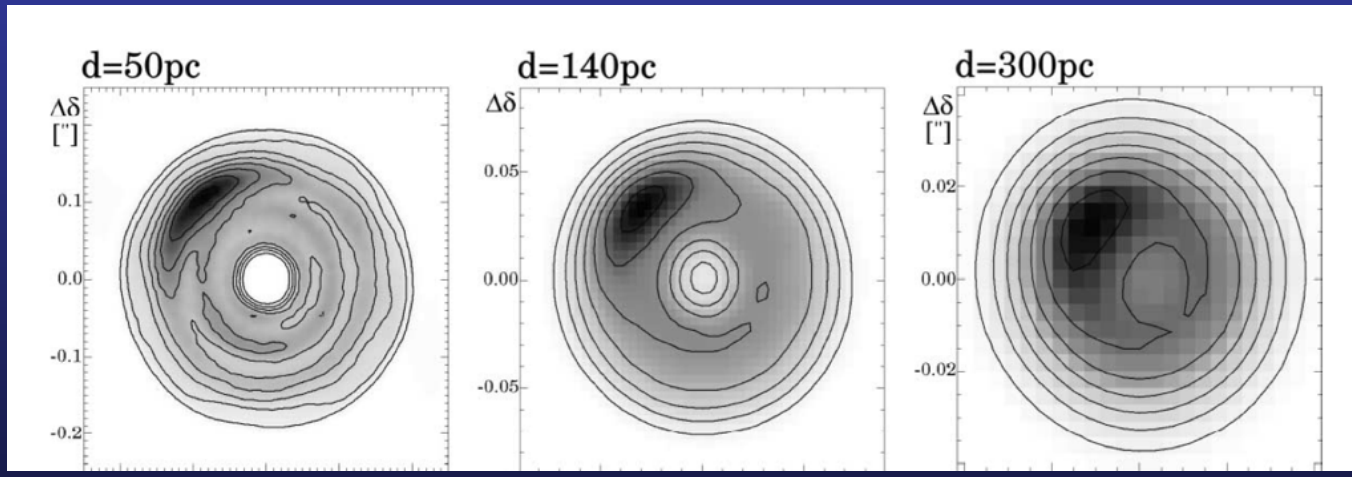
$$l_c = \frac{H}{3}\sqrt{\frac{\delta}{\mathrm{St}}}$$



A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]





THE ASTROPHYSICAL JOURNAL, 578:L79–L82, 2002 October 10
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LARGE-SCALE VORTICES IN PROTOPLANETARY DISKS: ON THE OBSERVABILITY OF POSSIBLE EARLY STAGES OF PLANET FORMATION

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Received 2002 July 26; accepted 2002 August 29; published 2002 September 13

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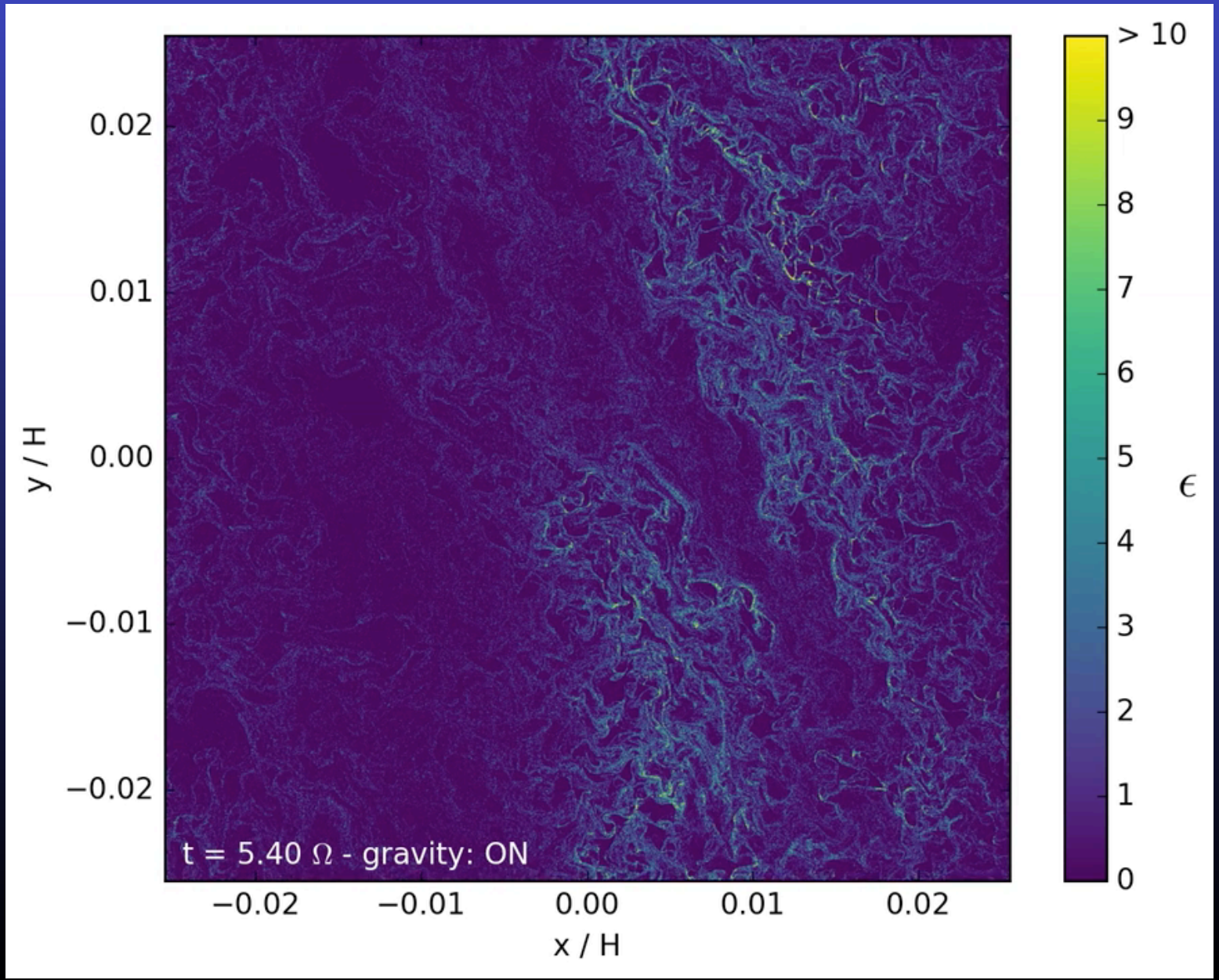

Science REPORTS

Cite as: M. Delbo' *et al.*, *Science* 10.1126/science.aam6036 (2017).

Identification of a primordial asteroid family constrains the original planetesimal population

Marco Delbo',[1]* Kevin Walsh,[2] Bryce Bolin,[1] Chrysa Avdellidou,[3] Alessandro Morbidelli[1]

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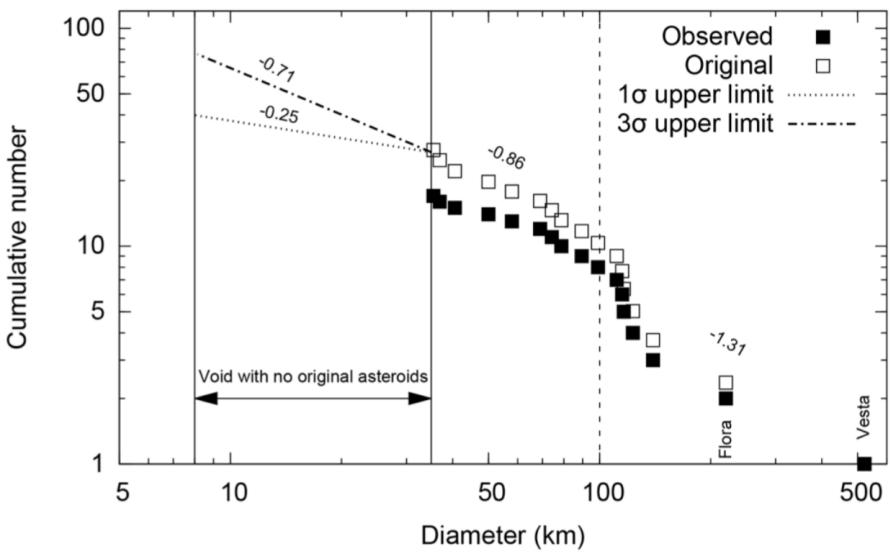
A quarter of known asteroids is associated with over a hundred distinct asteroid families, meaning that these asteroids originate as impact fragments from the family parent bodies. The determination of which asteroids of the remaining population are members of undiscovered families, or accreted as planetesimals from the protoplanetary disk, would constrain a critical phase of planetary formation by unveiling the unknown planetesimal size distribution. We discovered a 4 Gyr-old asteroid family extending across the entire inner part of the Main Belt, whose members include most dark asteroids previously unlinked to families. This allows us to identify some original planetesimals, which are all larger than 35 km, supporting the view of asteroids being born big. Their number matches the known distinct meteorite parent bodies.



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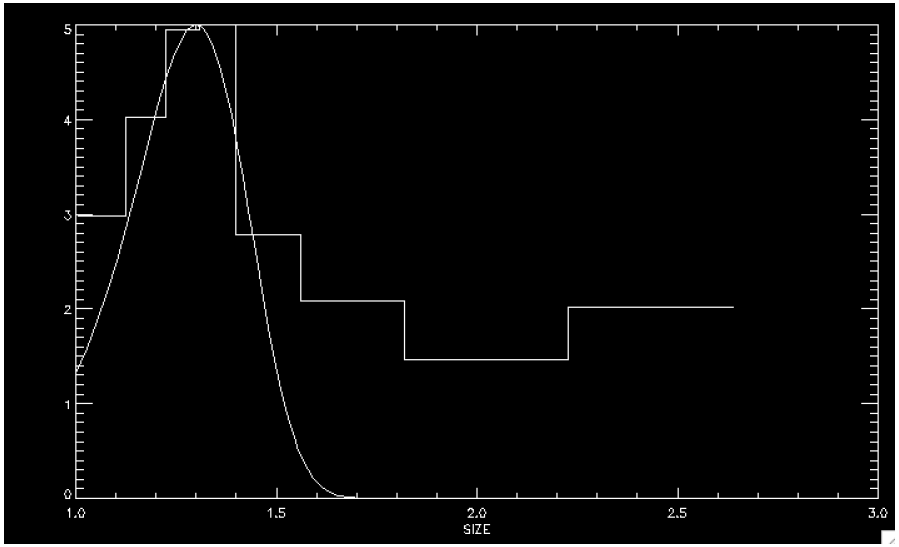
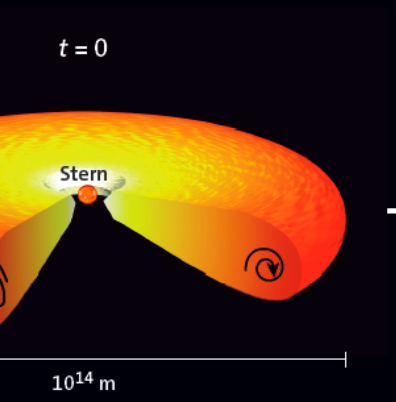
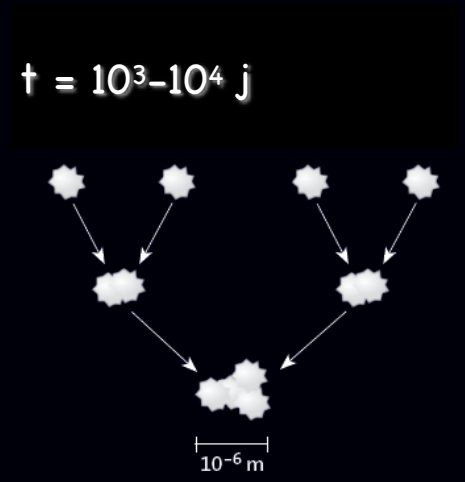
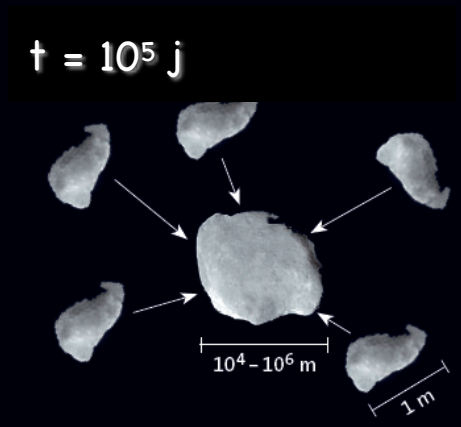




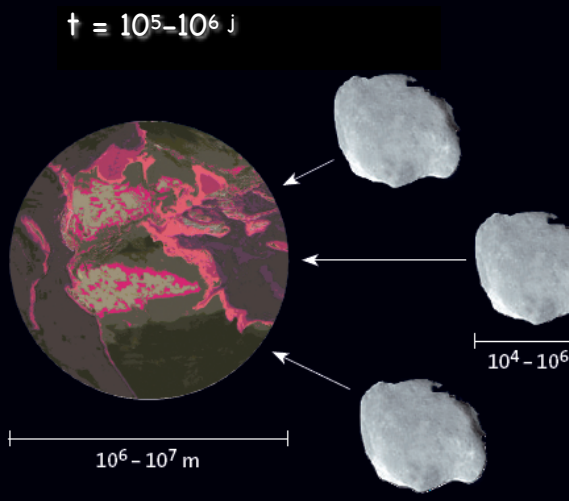
a. Turbulent disk



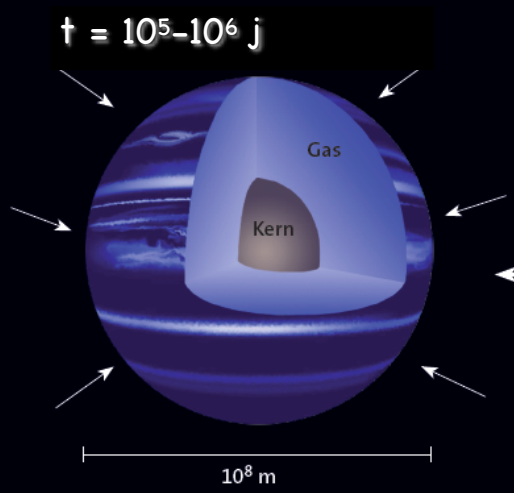
b. Stossen und Kleben



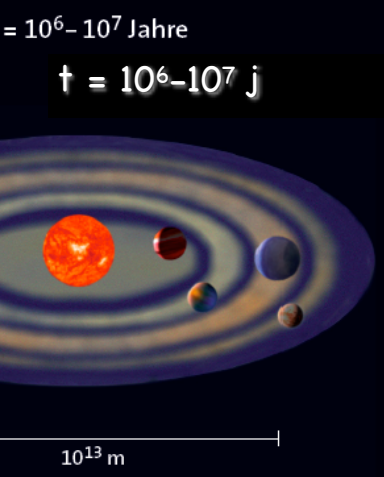
c. Gravotubulente Fragmentation



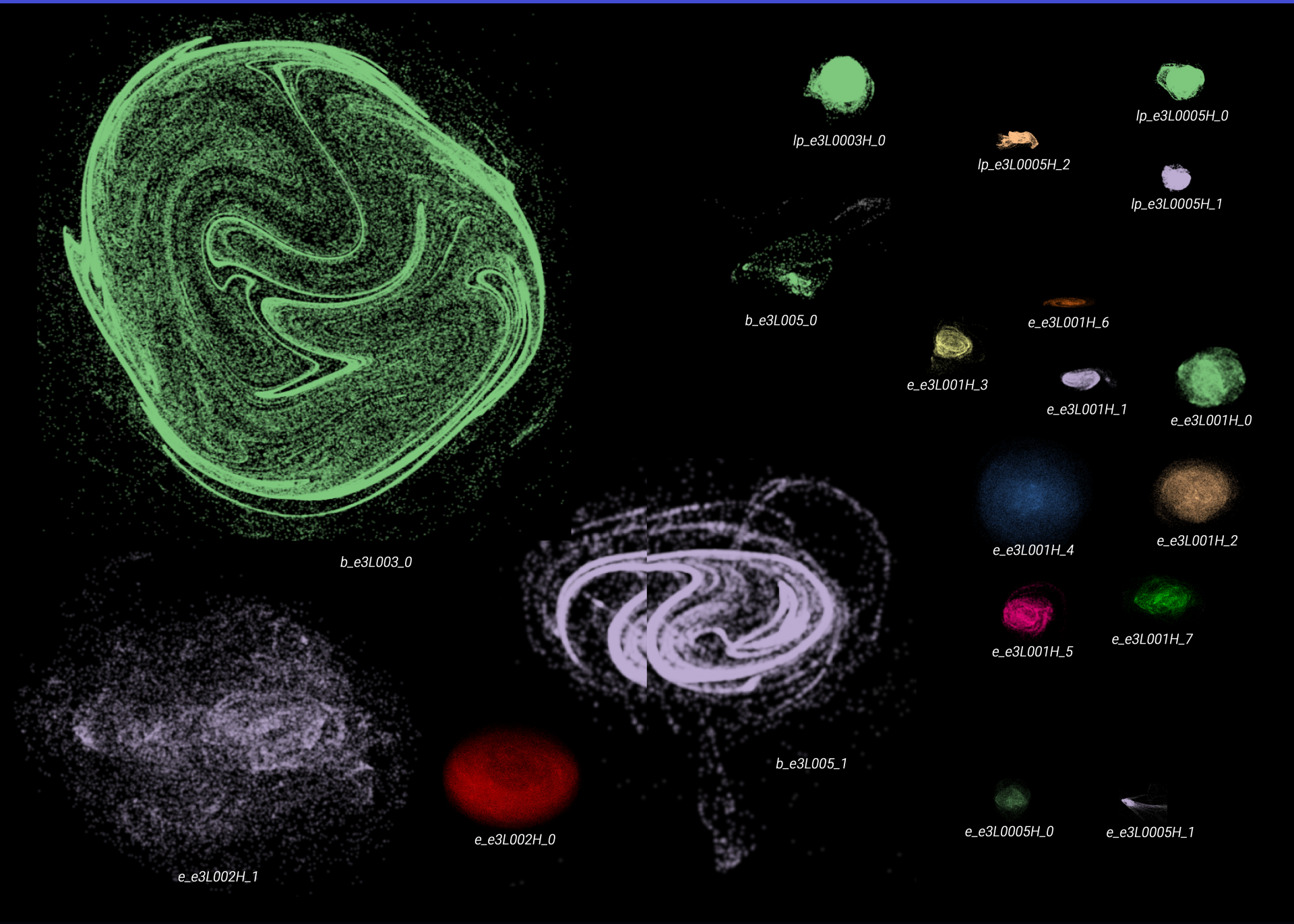
d. Gravitation



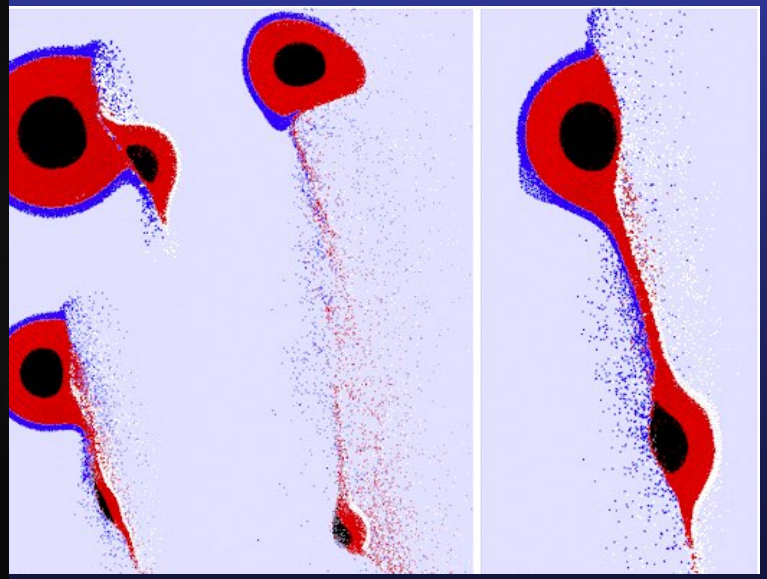
e. Gasakkretion



f. Migration


b_e3L003_0
lp_e3L0003H_0
lp_e3L0005H_0
lp_e3L0005H_2
lp_e3L0005H_1
b_e3L005_0
e_e3L001H_6
e_e3L001H_3
e_e3L001H_1
e_e3L001H_0
e_e3L001H_4
e_e3L001H_2
e_e3L001H_5
e_e3L001H_7
b_e3L005_1
e_e3L002H_0
e_e3L002H_1
e_e3L0005H_0
e_e3L0005H_1

Seit neuestem direkte Simulation von Planetesimal / Asteroid / Comet Collisionen um Entstehung und Entwicklung zu Kernen zu studieren



Burger, Maindl, Schäfer 2017: Water originally on the target/projectile in blue/white, and red and black particles represent basalt and iron, respectively.