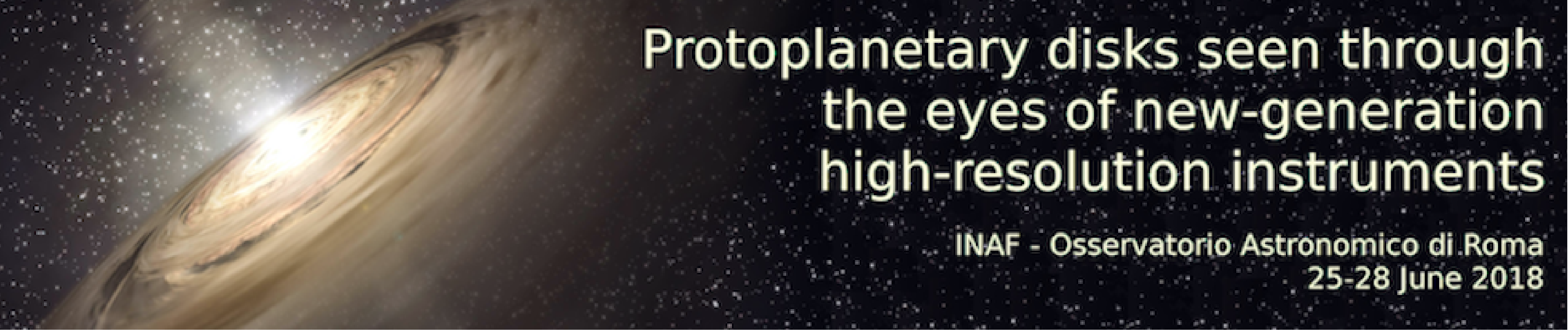

Luis Diego Pinto

Evolution of early Protoplanetary systems embedded in gaseous disks under perturbation of passing-by stars.

ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI DI ROMA
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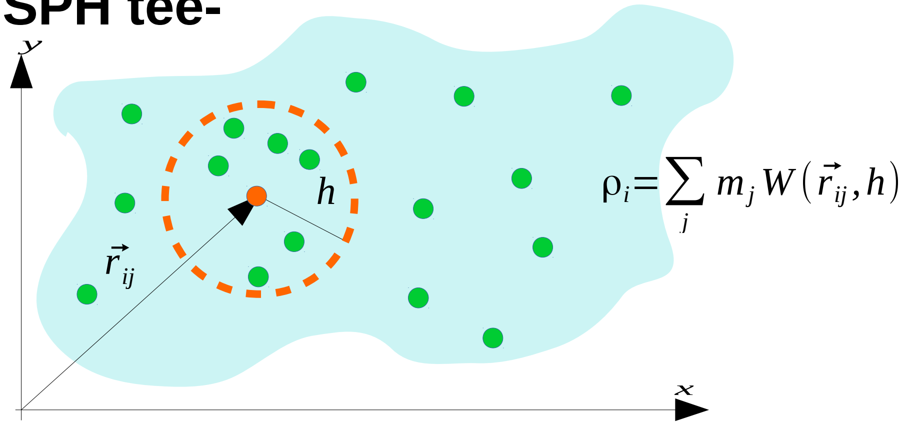
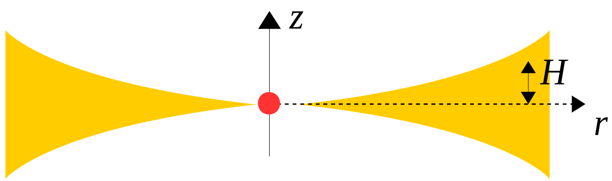
Outline.

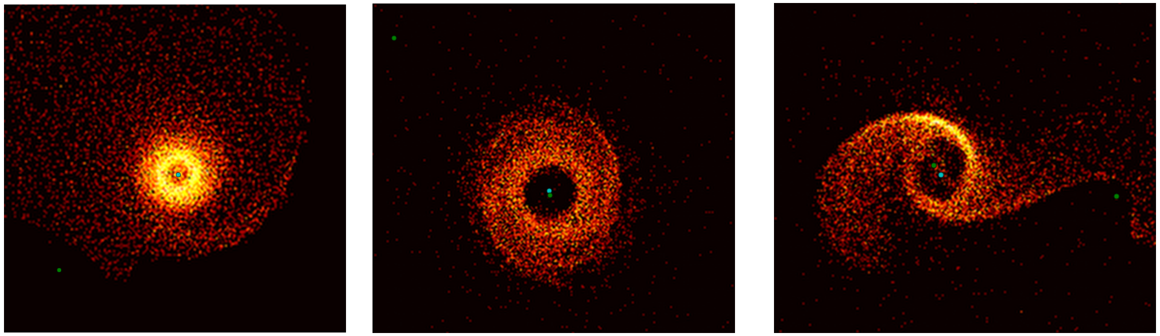
- **Numerical approach for our research: SPH tee-based code**



- **Protoplanetary disks.**



- **Disks in Open clusters: Close encounters.**



Protoplanetary Disks in open clusters.

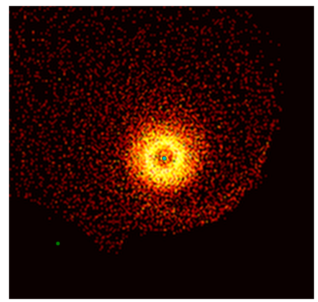
Motivations:

- Very poor amount of work have been done for **binary** and **multiple** systems, still we we don’t have clear answers on how planets can form
- Disks in open clusters (**Hernandéz & al** 2010; **Mann & al.** 2015).
- HARPS-N radial velocity mesurements: Observation of the first multi-planet system in an O.C. (M44) (***Malavolta & al.**, **2016***)
- Solar system formation in OC (Pfalzner 2013)
- Binary stars ev. in O.C. not substantially affected (**Parker & al**. 2009) → **NO GAS**
- A Binary System in the Hyades Cluster Hosting a Neptune-sized Planet (**David R. Ciardi & al**. 2018)

Tree-SPH Algorithm.

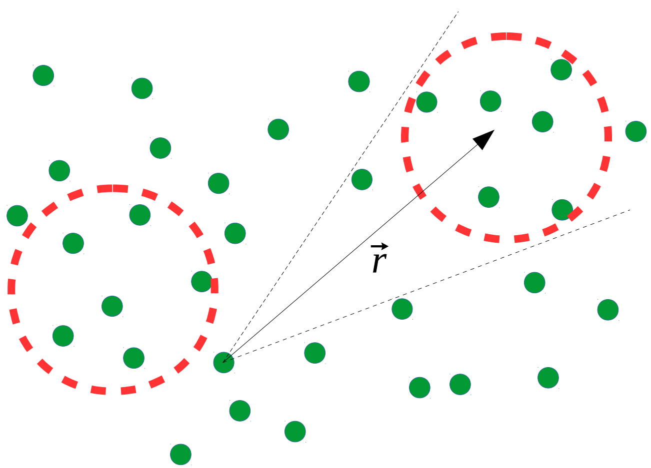
Gaseous systems – small number of point mass objects.

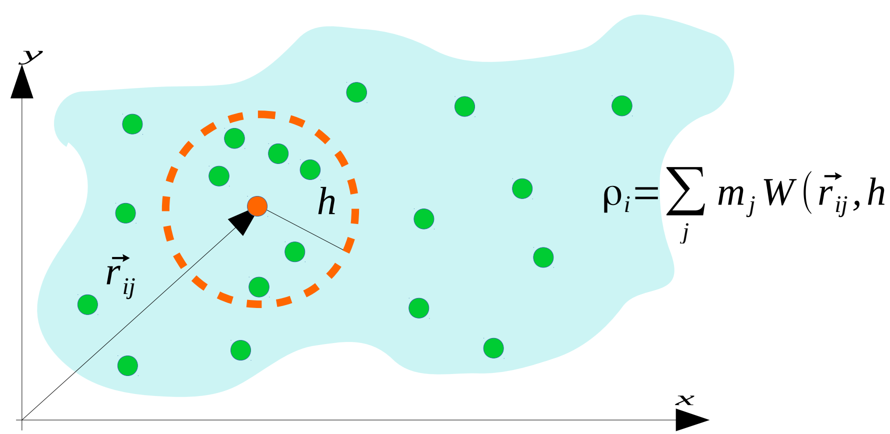
- **Stars** → **Small N-body system**
- **Gas**



★ **Pinto L.D. & al.**
(2018 - submitted)

Lagrangian approach (SPH + TREE structure)



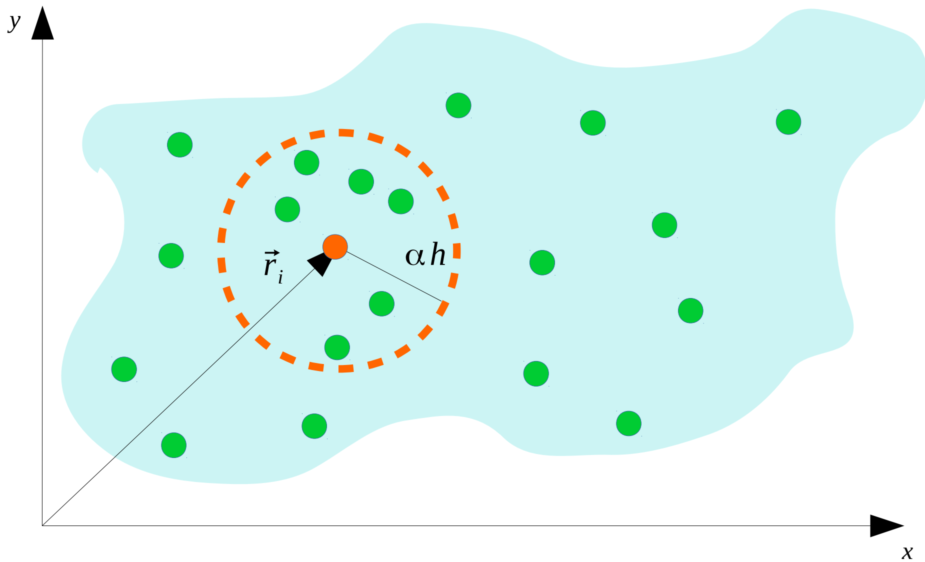


★ ***Barnes** & **Hut*** (1986),
Hernquist (1987) , ***Hernquist** & **Katz*** (1989) ,
***Miocchi** & **Capuzzo-Dolcetta** (1998, 2002)*

★ *Further details in **Monaghan**'s papers (**1989**,**1992**,**2005**)*

Tree-SPH Algorithm.

Monaghan's papers
(***1989***,***1992***,***2005***)



$$P(\vec{r},t),\;\; \rho(\vec{r},t),\;\; T(\vec{r},t),\;\; v(\vec{r},t)$$

⚠ Smoothing Length h, defines
The resolution of interpolation.

⚠ At least ~50 neighbour particles
are needed.

$$\begin{cases} \dfrac{d\rho}{dt} + \rho\vec{\nabla}\cdot\vec{v} = 0 \\ \dfrac{d\vec{v}}{dt} = -\dfrac{1}{\rho}\vec{\nabla}P + \vec{f} \\ \dfrac{du}{dt} = \dfrac{P}{\rho^2}\dfrac{d\rho}{dt} \\ P = f(T,\rho,\ldots) \rightarrow P = \dfrac{\rho}{m}KT = (\gamma-1)\rho u \end{cases}$$

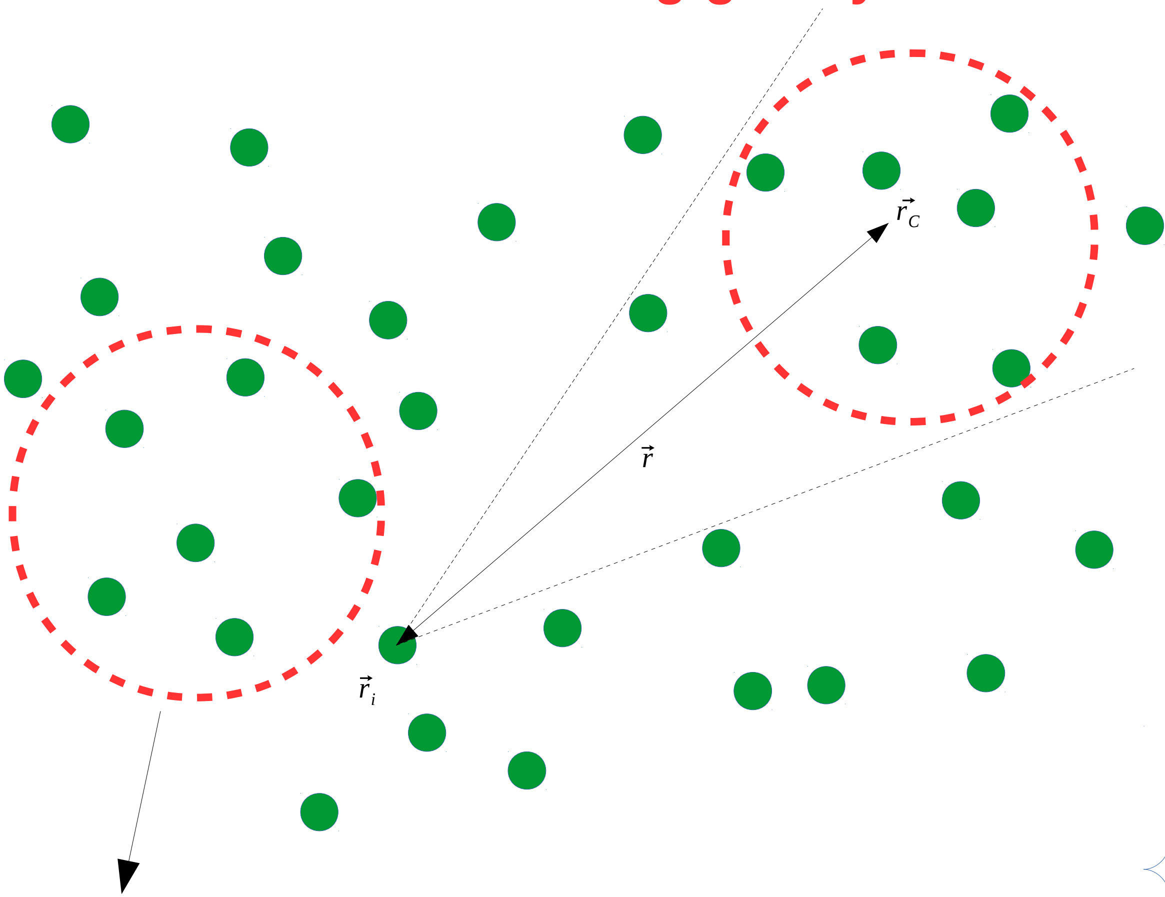
$$\Rightarrow$$

$$\begin{cases} \rho_i = \sum_j m_b W_{ij} \\ \dfrac{d\vec{v}_i}{dt} = -\sum_j m_j\left(\dfrac{P_i}{\rho_i^2} + \dfrac{P_j}{\rho_j^2} + \prod_{ij}\right)\vec{\nabla}_i W_{ij} \\ \dfrac{du_i}{dt} = \dfrac{1}{2}\sum_j m_j\left(\dfrac{P_i}{\rho_i^2} + \dfrac{P_j}{\rho_j^2} + \prod_{ij}\right)\vec{v}_{ij}\cdot\vec{\nabla}_i W_{ab} \\ P_i = (\gamma-1)\rho_i u_i \\ \dfrac{d\vec{r}_i}{dt} = \vec{v}_i \end{cases}$$

CPU time ~ N

Tree-SPH Algorithm.

Tree-base scheme for selg-gravity



Close cluster: NO quadrupole approximation

Far "cluster"

multipole potential field expansion with respect to its M.C.

$$\phi(\vec{r}) = -\frac{MG}{r} - \frac{1}{2}\frac{G}{r^5}\vec{r}\cdot Q\cdot\vec{r}$$

$$\vec{a}_i = -\frac{MG}{r^3}\cdot\vec{r} + \frac{G}{r^5}\cdot(Q\vec{r}) - \frac{5}{2}\frac{G}{r^7}(\vec{r}\,Q\,\vec{r})\cdot\vec{r}$$

$$M = \sum_i m_i$$

$$\vec{R}_C = \frac{1}{M}\cdot\sum_j m_j\vec{r}_j \qquad r = |\vec{r}_{C\ i}| = |\vec{r}_C - \vec{r}_i|$$

$$Q|Qij = \sum_i 3\cdot(x_i - x_{iC})(x_j - x_{jC}) - \delta_{ij}|\vec{r} - \vec{R}_C|^2$$

Advantgage in time consuming~ N LOG(N)

★ ***Barnes*** & ***Hut*** (1986),
Hernquist (1987) , ***Hernquist*** & ***Katz*** **(**1989) ,
Miocchi & ***Capuzzo-Dolcetta*** *(2002)*

Tree-SPH Algorithm.

- Correction terms for variable smoothing length and gas self-gravity added (see ★ **Price** & **Monaghan**, 2004,2007 ; **Hueber** & **al**. 2013)

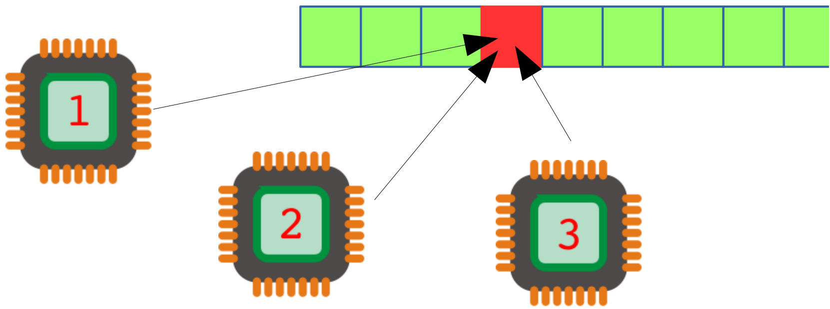
$$\frac{d\boldsymbol{v}_i}{dt} = -\sum_j G m_j \frac{1}{2}\left(\boldsymbol{a}_{soft}(\boldsymbol{r}_{ij}, h_i) + \boldsymbol{a}_{soft}(\boldsymbol{r}_{ij}, h_j)\right) \cdot \frac{\boldsymbol{r}_{ij}}{r_{ij}} - \sum_j G m_j \frac{1}{2}\left(\frac{\zeta_i}{\Omega_i}\boldsymbol{\nabla}_i W(h_i) + \frac{\zeta_j}{\Omega_j}\boldsymbol{\nabla}_i W(h_j)\right) + \sum_j m_j\left(\frac{P_i}{\rho_i^2\Omega_i}\boldsymbol{\nabla}_i W(h_i) + \frac{P_j}{\rho_j^2\Omega_j}\boldsymbol{\nabla}_i W(h_j)\right)$$

- Cache friendly implementation.

- Shared Memory parallelization with **open-MP** modules.

Data race problem easily fixed:

Private memory allocation for $\vec{a}$, $\dot{T}$ needed (every thread needs 32 Bytes per particle)



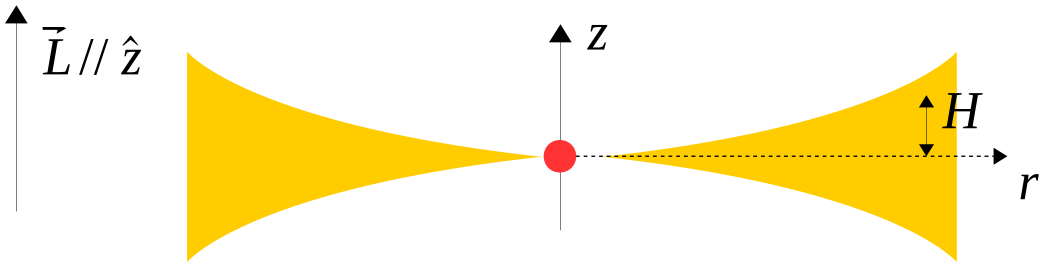
- Interaction with point-mass objects.

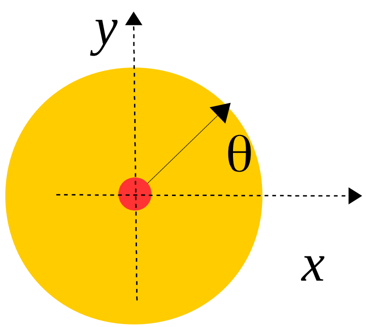
- Individual timestep. $\Delta t \propto \Delta t_{max} \cdot 2^{-n}$

- Different methods.
  - **Gas** : 2nd order Velocity-Verlet
  - **Stars**: 14th order RK

Disk Model.

Simple Flared Disk around a single star.





- **Optically thin** **Geometrically Thin**

  → **Vertical Isothermal approximation** →

  $$\frac{\partial P}{\partial z} = -\rho \frac{G M_{star}}{R^3} \cdot z$$

  State eq. : $P = \rho c_s^2$

  →

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

  $$H = c_s / \Omega_{kep} \propto T^{1/2} R^{3/2}$$

- **Stellar radiation dominates Thermal evolution (accretion negligible)** →

  $F(R) = \sigma T^4$

  Flared Disk

  → $T \sim r^{-3/7}$ (**D'alessio** & al. 1999)

- Velocity field : $v_\theta \sim \sqrt{\frac{G M_{star}}{R}} = R \cdot \Omega_{kep}$
- Surface density: $\Sigma \sim r^{-3/2}$
- Disk self gravity.
- Same model for Circumbinary Disks

- **Euler Equations:**

$$\frac{d\rho}{dt} + \rho \vec{\nabla} \cdot \vec{v} = 0$$

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho} \vec{\nabla} P + \vec{f}$$

$$\frac{du}{dt} = \frac{P}{\rho^2} \frac{d\rho}{dt}$$

$$P = f(T, \rho, \ldots)$$

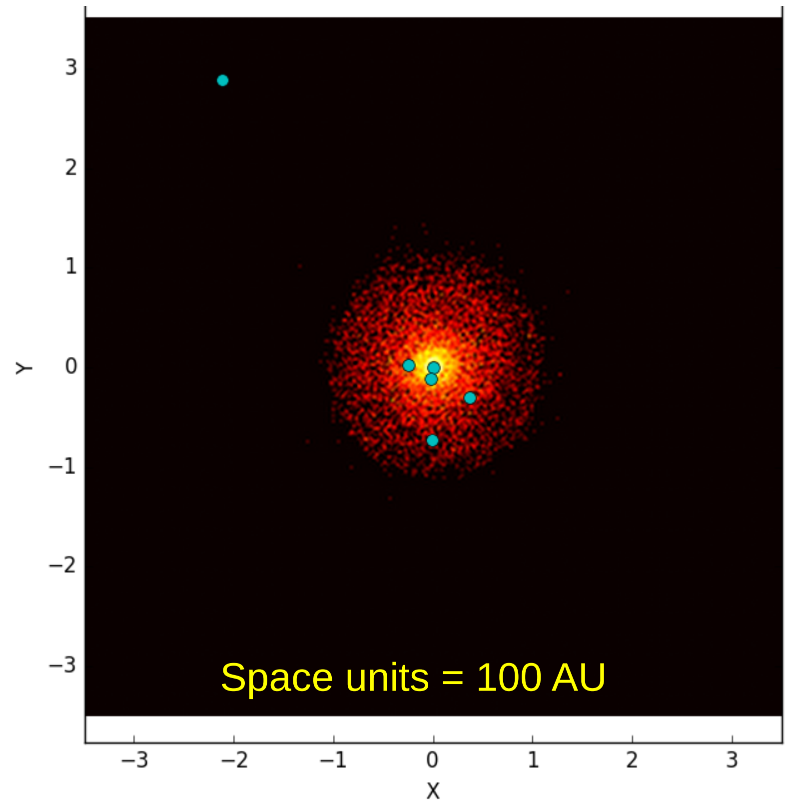
Parametric approach: fly-by perturbation.

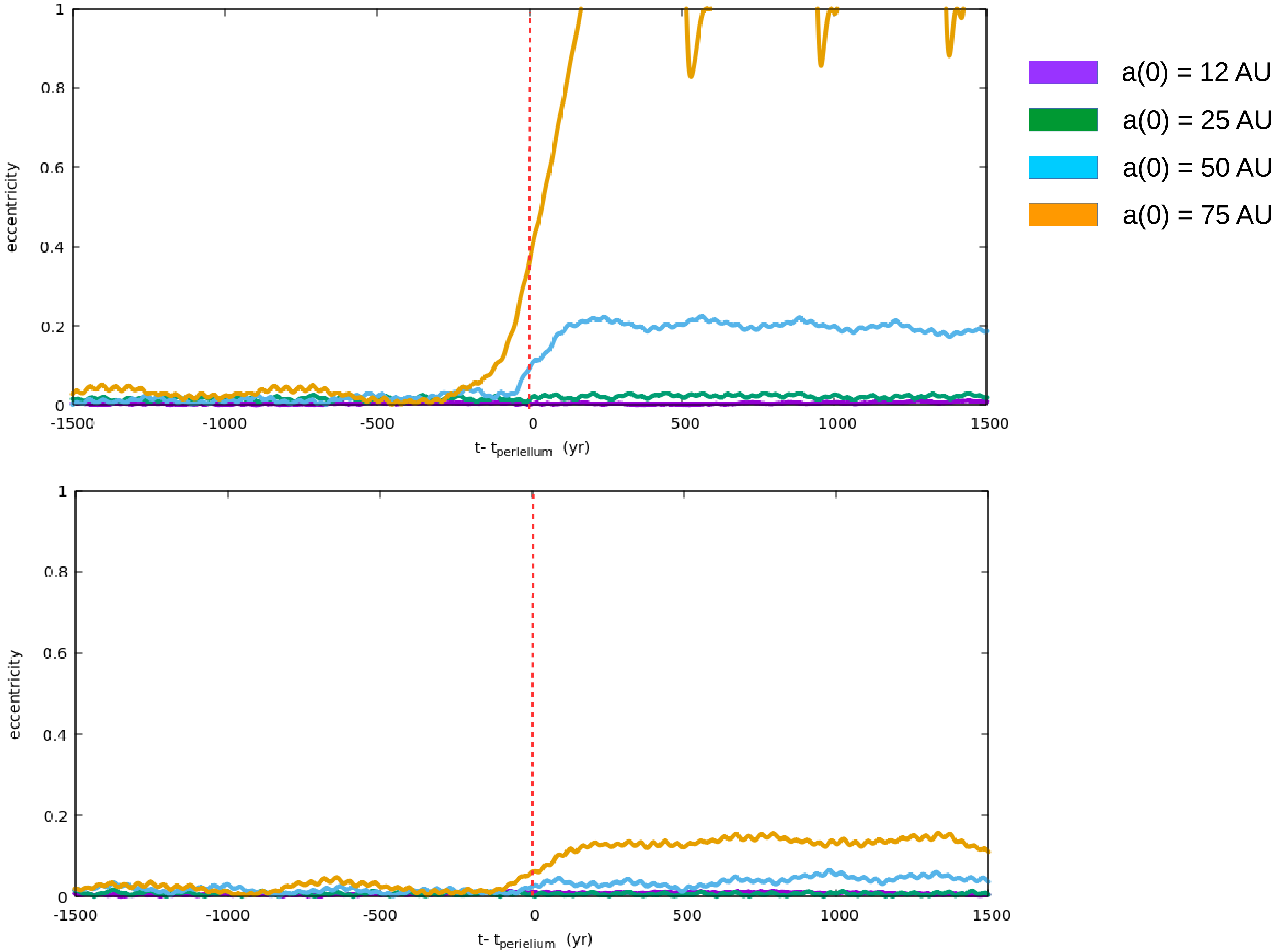
- Gravitational field from other stars perturbs the disk.
- Several simulations at different impact parameters and relative v orientation with respect to the disk midplane.
  (Luis Diego Pinto, Roberto Capuzzo Dolcetta, Stefano Cattolico, ☆ in prep.)

$M_d = 0.01\, M_{SOL}$ $\quad 5\, AU < R < 100\, AU$ $\quad impact\ parameter\ b = 300\, AU$

Passing-by star $M_2 = M_1$

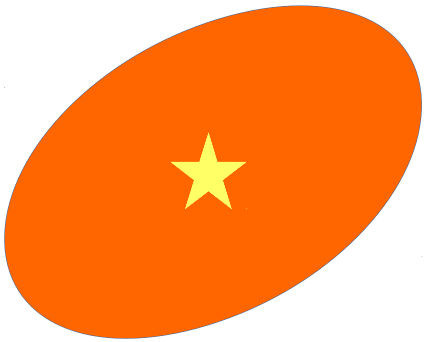
4 e~0 orbiting planets





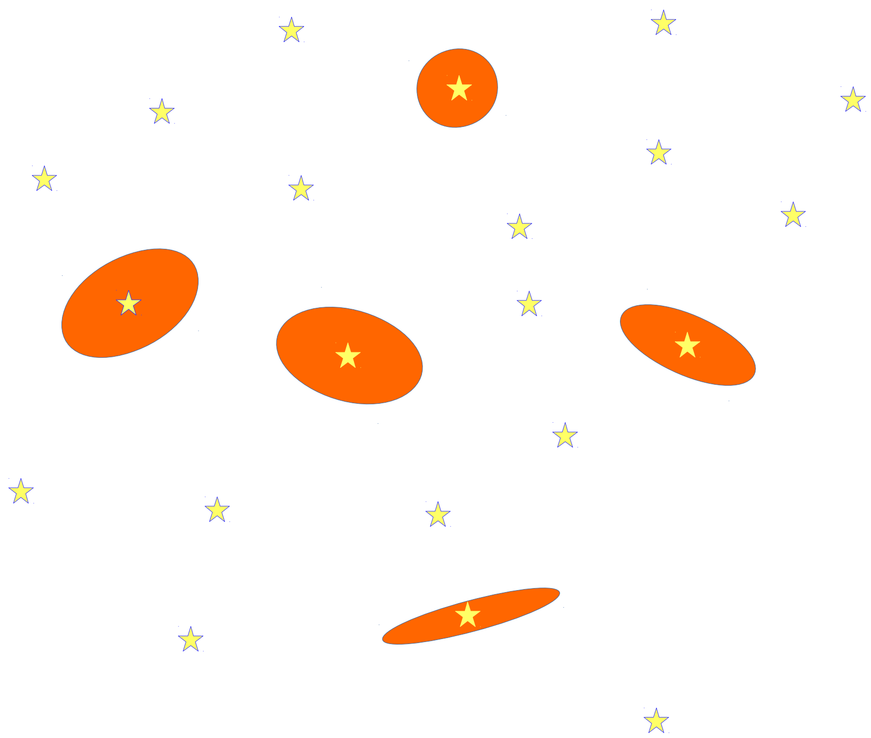
eccentricity
t- $t_{perielium}$ (yr)
0
0.2
0.4
0.6
0.8
1
-1500
-1000
-500
0
500
1000
1500
a(0) = 12 AU
a(0) = 25 AU
a(0) = 50 AU
a(0) = 75 AU

Direct integration.



Scientific goal: **to investigate the perturbation of a non isolated disk, embedded in an open cluster.**

- **Mass loss**
- **Radial cut off**

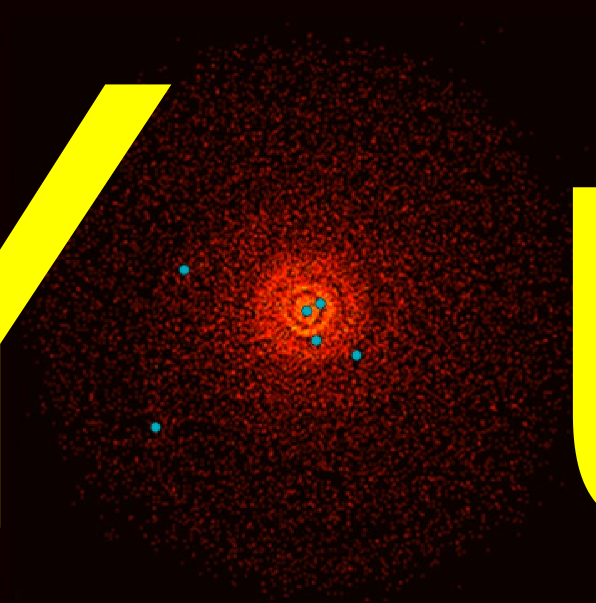


Impulsive perturbations:
- from **passing by** stars
- **strong** but **instantaneous**
- disks can be abundantly truncated in a short timescale (<< T crossing)

Cumulative perturbations
- from **background** stars
- **weak** but **secular**
- disks can be substantially truncated in a long timestcale (>> Tcrossing)

(Rosotti & al., 2014)

Thank

Yu !!!