The cluster origin of the solar system

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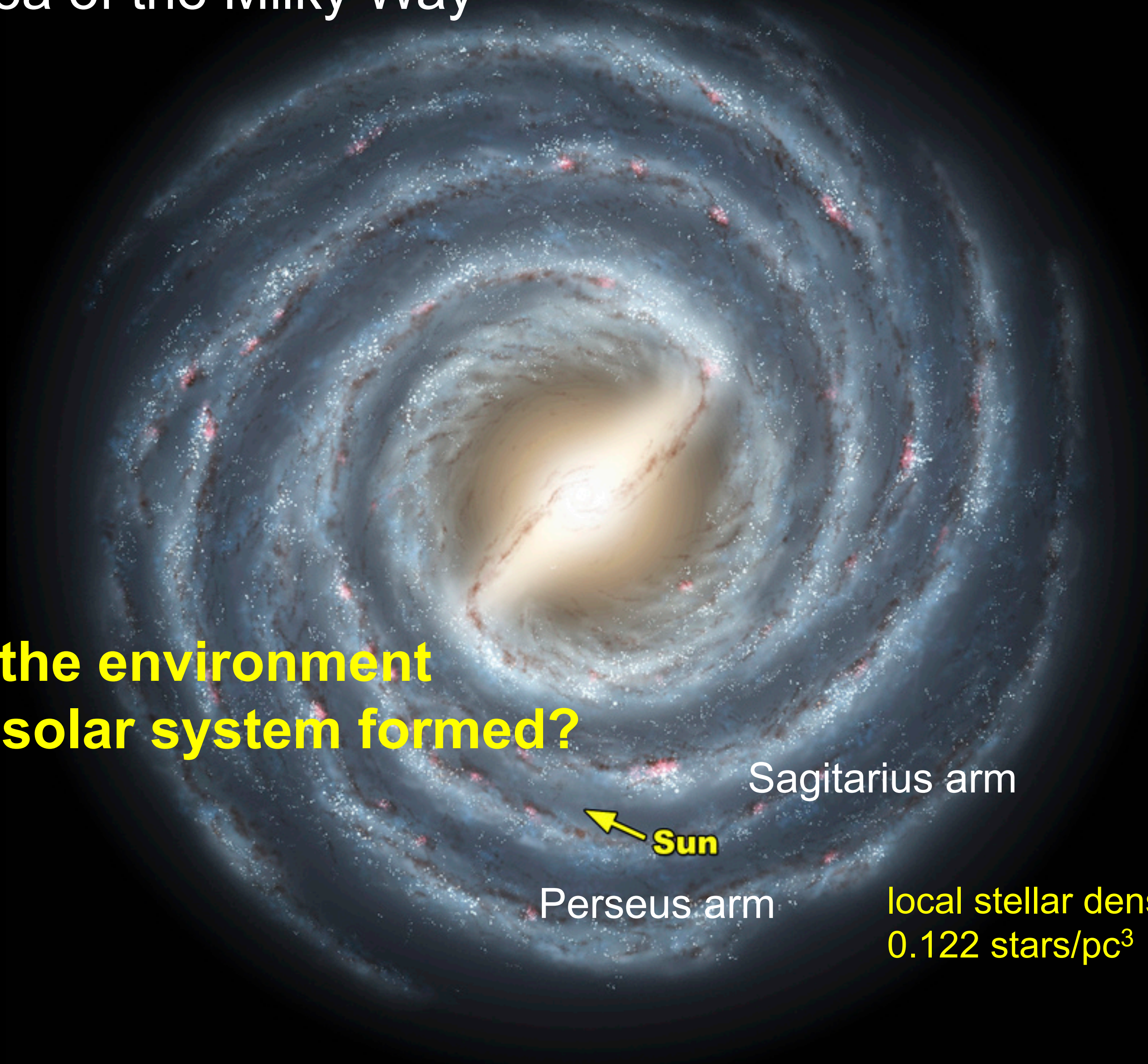
Today the solar system is located in a relatively sparse area of the Milky Way



How was the environment when the solar system formed?

local stellar density:
0.122 stars/pc^3

The Solar System birth cluster:

Most stars form in clusters (Lada&Lada 2003)

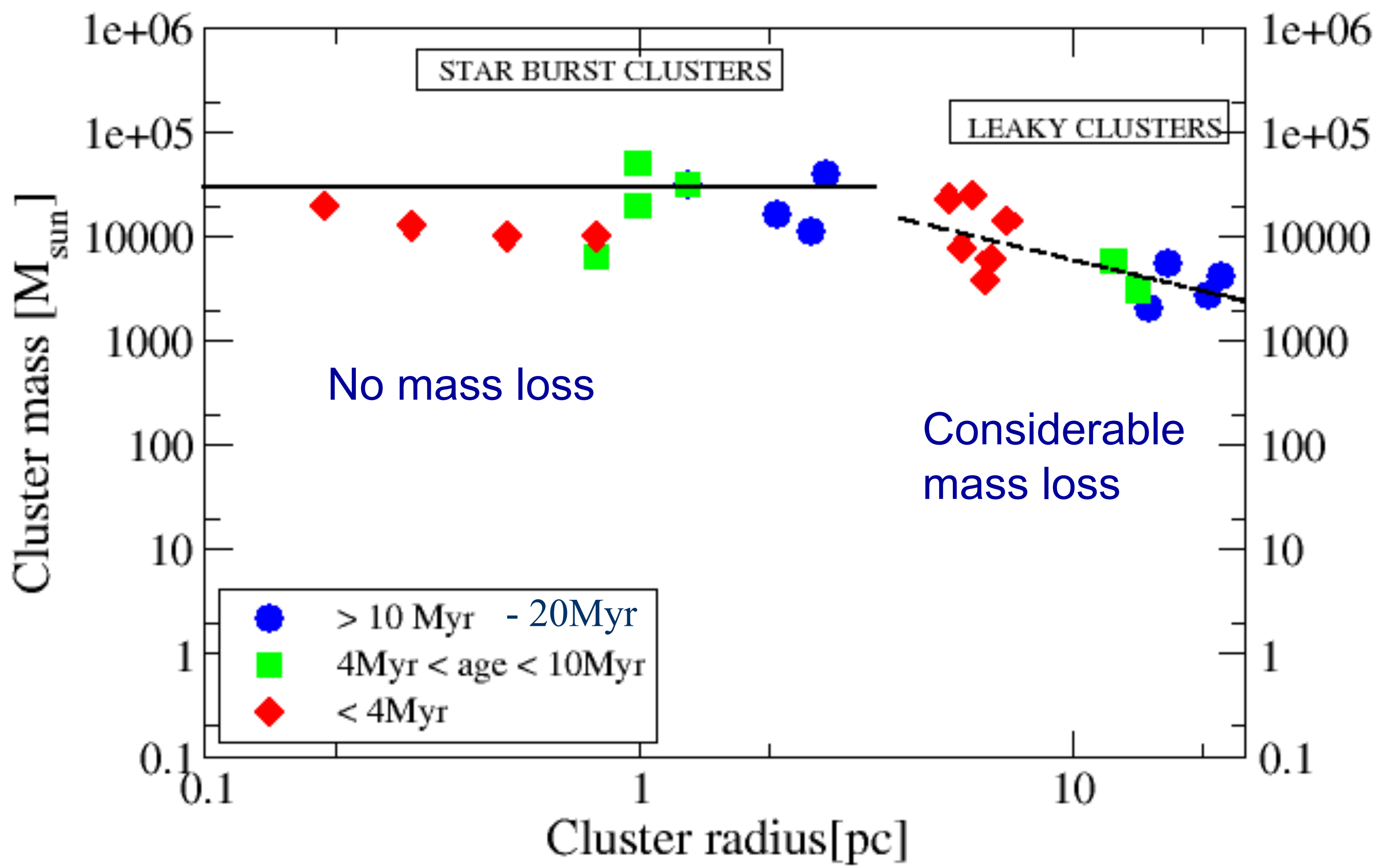
Radio-isotopes Chemical composition Adams (2010) Lee et al. (2008)	Supernova 25 M_{sun} progenitor Cluster origin	$N_{star} > 1000\text{-}4000$	$10^3 < M_{cl} < 10^5$ [M_{sun}]
Radiation field Adams (2010)	**Destruction of discs**	$N_{star} < 10^5$	
30 AU Cut-off in mass distribution	Encounter induced	$10^3\ M_{sun}pc^{-3} < \rho_s < 10^4 M_{sun}pc^{-3}$	$10 < \rho_{cl} < 1000$ [M_{sun}/pc^3]
Sedna orbit Brassser (2008) Schwamb (2011)	Encounter probability		

Mean stellar mass in cluster: 0.5 M_{sun}

Mass segregation: Sun in central cluster area

Temporal evolution of young clusters

Young clusters with same mass as solar birth exist today in Milky Way

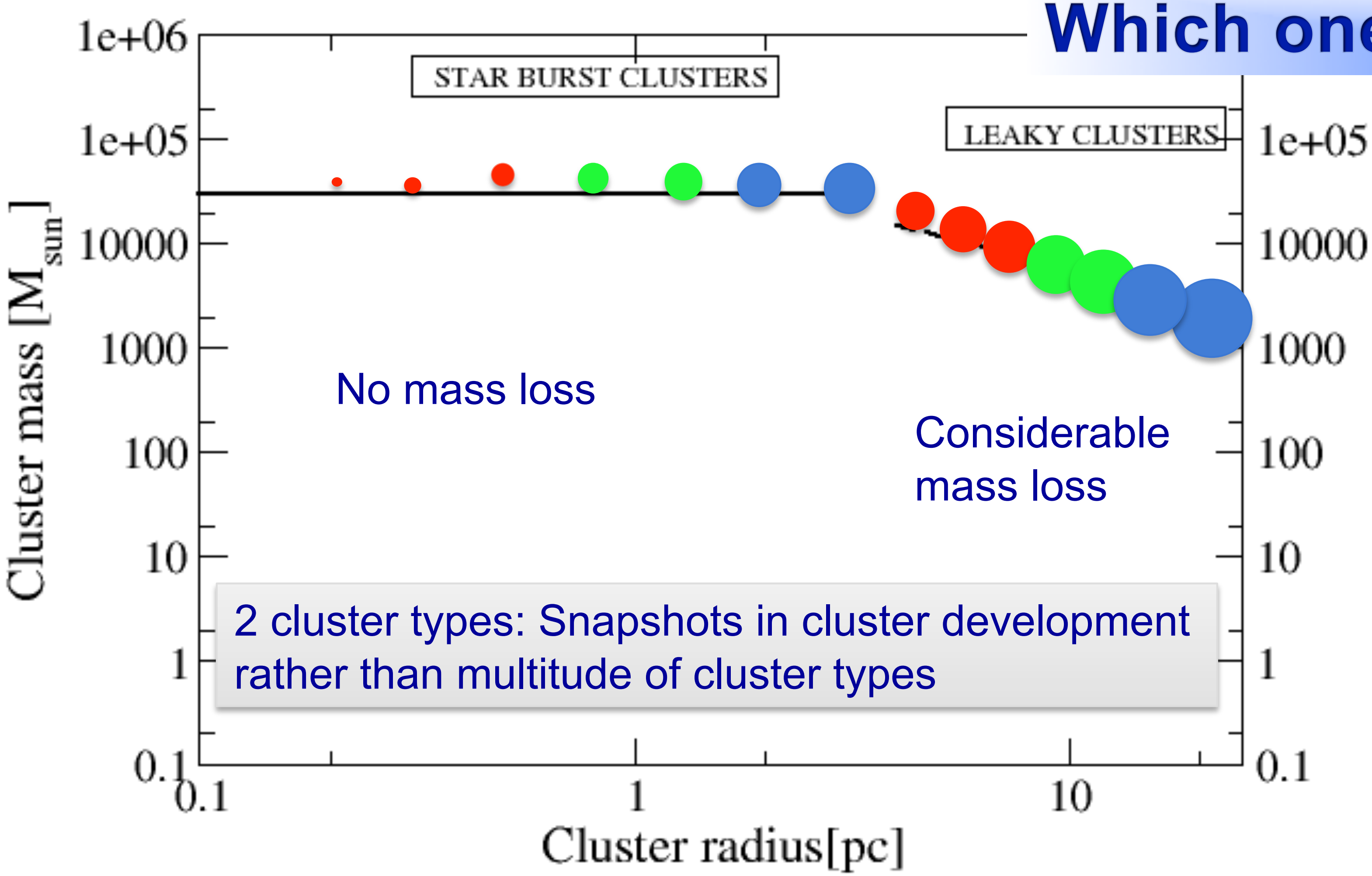


Pfalzner 2011

Temporal evolution of young clusters

Sun formed in a leaky or starburst cluster

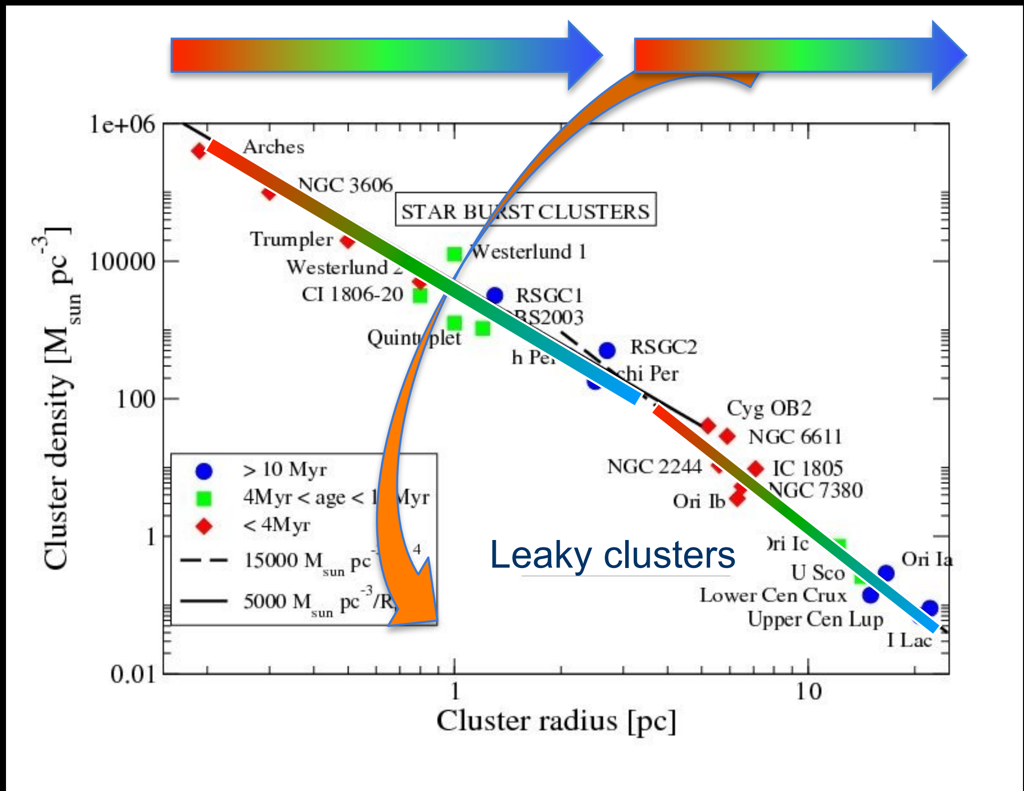
Which one is it?

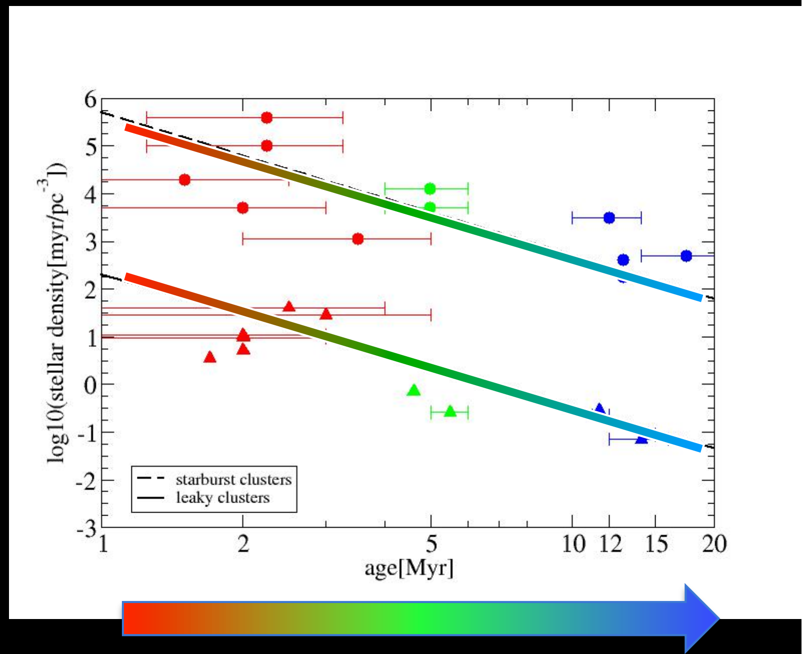


2 cluster types: Snapshots in cluster development rather than multitude of cluster types

Radius-age transformation

1 Myr 20 Myr 1 Myr 20 Myr

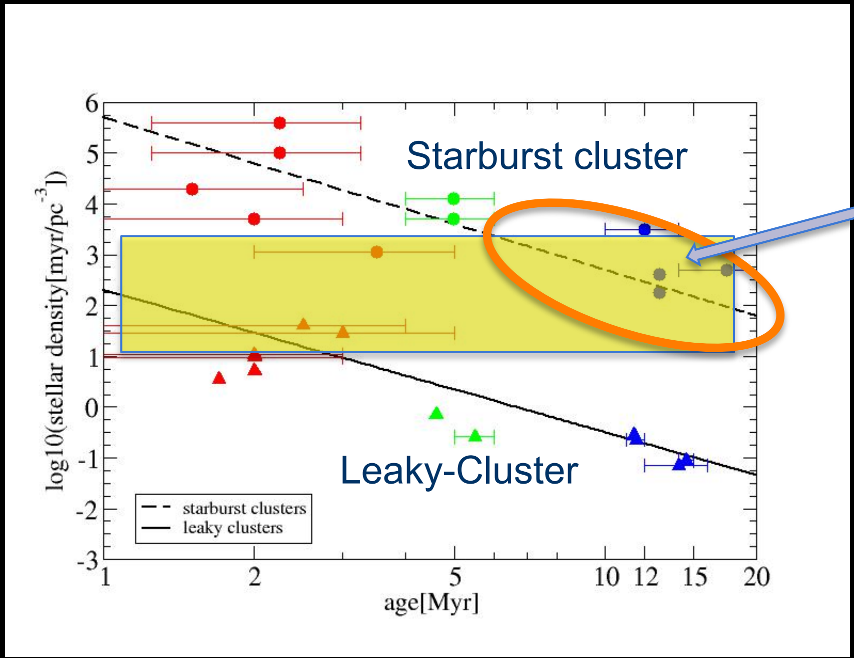




Radial development translates into age development

Age

Solar birth cluster a Starburst-Cluster?



average density of $10 - 10^3$ stars/ pc ^{3}

Overlap with starburst clusters after 5Myr

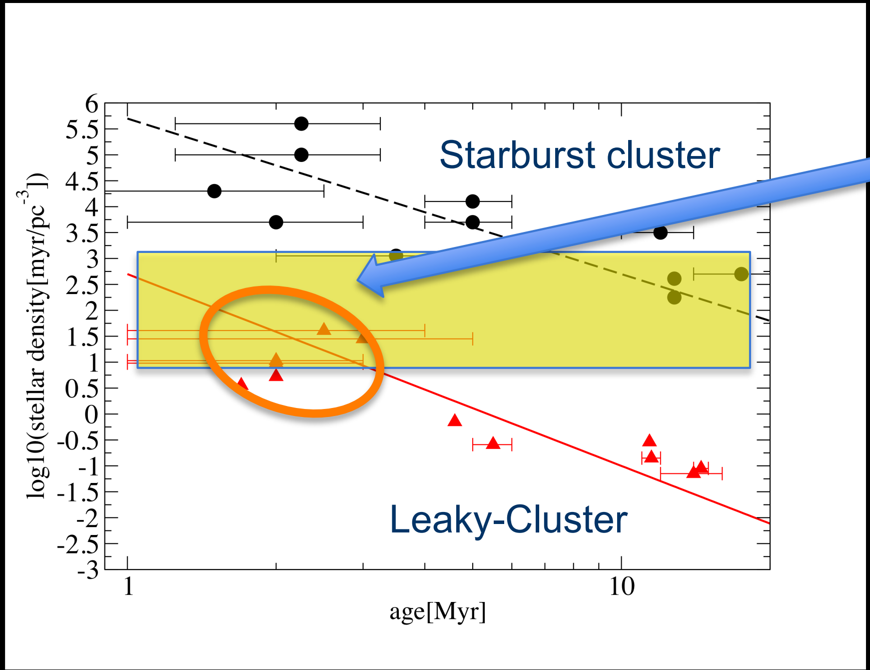
But ...

During first 5 Myr density in starburst clusters extremely high Many close encounters

Discs would be destroyed ➡ **No planetary system**

Starburst cluster unlikely solar birth environment

Solar birth cluster a leaky cluster?



average density of $10 - 10^3$ stars/ pc ^{3}

Overlap in early stages of development

Density development
$\rho_c \sim C\ t^{-3.7}$

Interaction with other stars unlikely after solar system

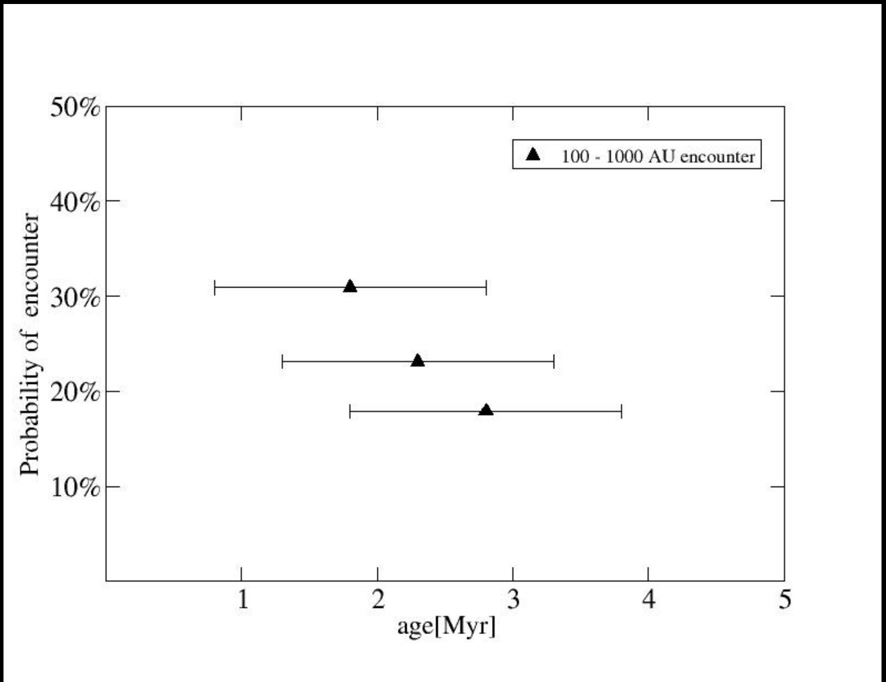
➡ gives naturally circular orbits

Solar system has likely developed in leaky cluster environment

Probability of solar system forming encounter

Higher density = higher likelihood of encounter

Single encounter with 100 AU < r_{peri} < 1000 AU

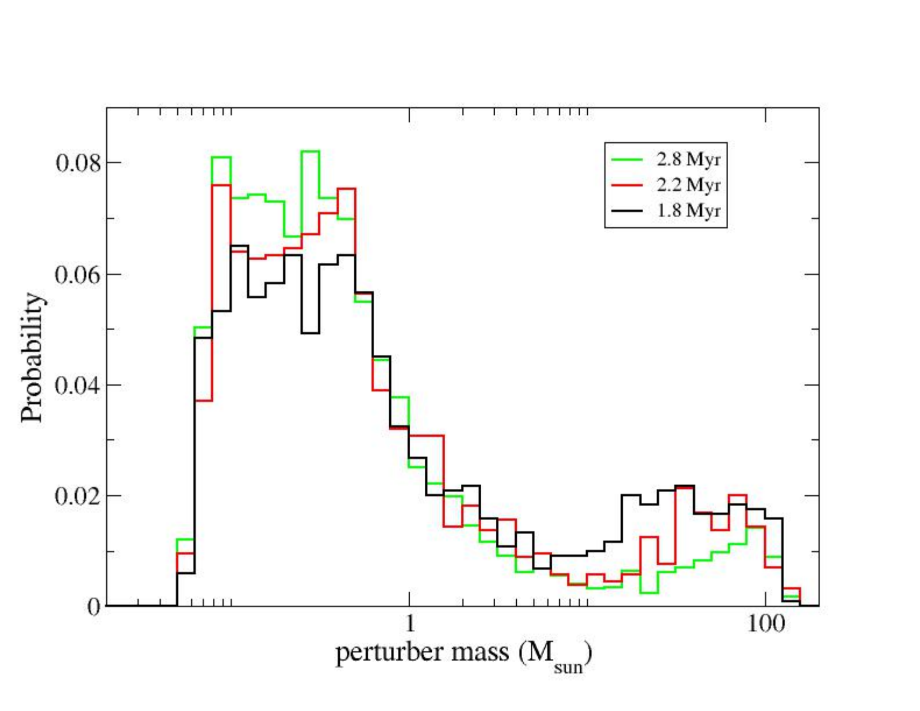


Leaky cluster: $\rho_c \sim C\, t^{-3.7}$

Probability of encounter decreaseing with cluster age

Encounter likely during the first 3 Myr of solar system development

Encounter partner history



Solar-type stars mainly encounters with

- **Low-mass stars m_{star}< 0.5 M_{sun} on strongly hyperbolic orbits**
- **High-mass stars m_{star}< 10 M_{sun} on parabolic orbits**

If encounter was early on in cluster developemnt (< 2Myr) then
Most likely strongly hyperbolic encounter

- ◆Sun formed in a massive cluster
- ◆Such clusters exist in two forms
  Starburst and leaky cluster
- ◆Sun most likely formed in leaky cluster
- ◆Density development $\rho_c \sim C\ t^{-3.7}$
- ◆Solar system forming encounter:
  - low mass star
  - highly eccentric orbit

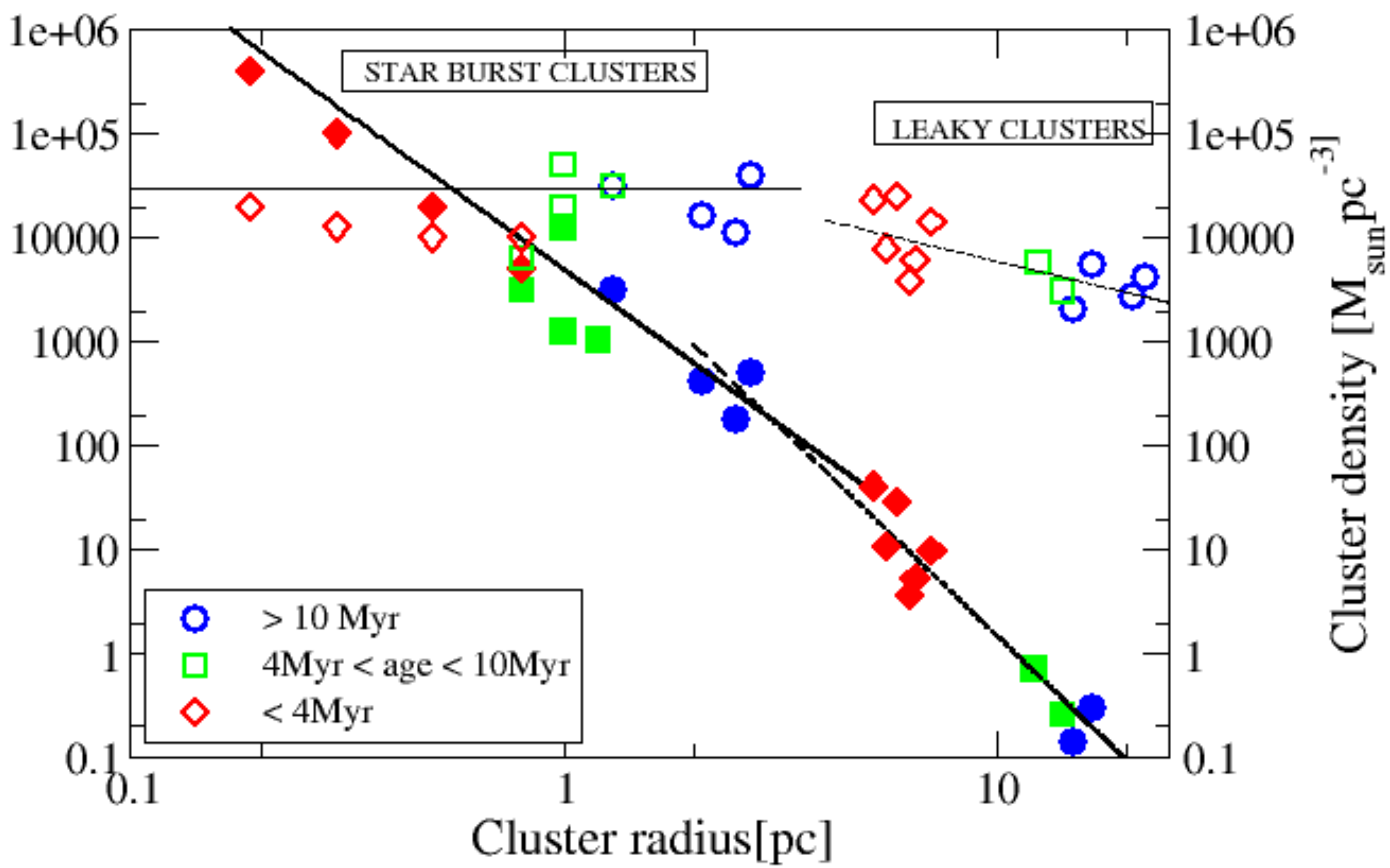
Impression of the night sky when the sun was born

Scientific American, Ron Miller

Limits on Solar System birth environment:

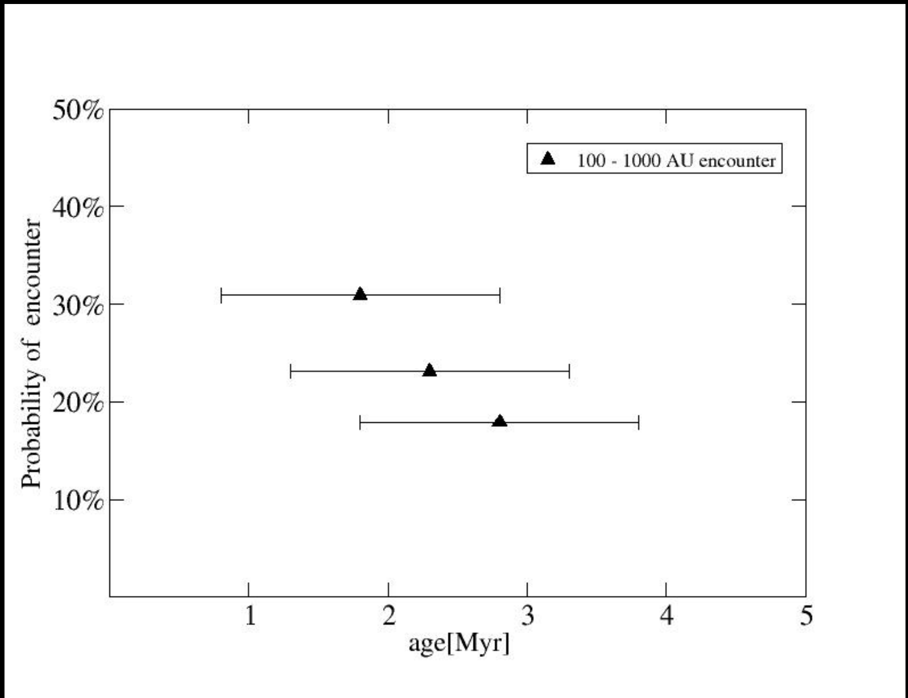
Meteorit composition	Supernova within 0.2pc 25 M_{sun} progenitor
30AU cut-off in mass distribution	Encounter or photo-evaporation Both require high stellar density If encounter with solar type star, then r_{min} =100-1000AU
Sedna orbit	Stellar density at solar system location
Circular orbits of planets	System undisturbed for solar system age > 30 Myr

Temporal evolution of young clusters
Cluster density



Pfalzner A&A 498, L37,2009

Resulting encounter history



Leaky cluster: $\rho_c \sim C\ t^{-3.7}$

Probabilty of encounter as function of solar system age

Probability of encounter decreases with cluster age

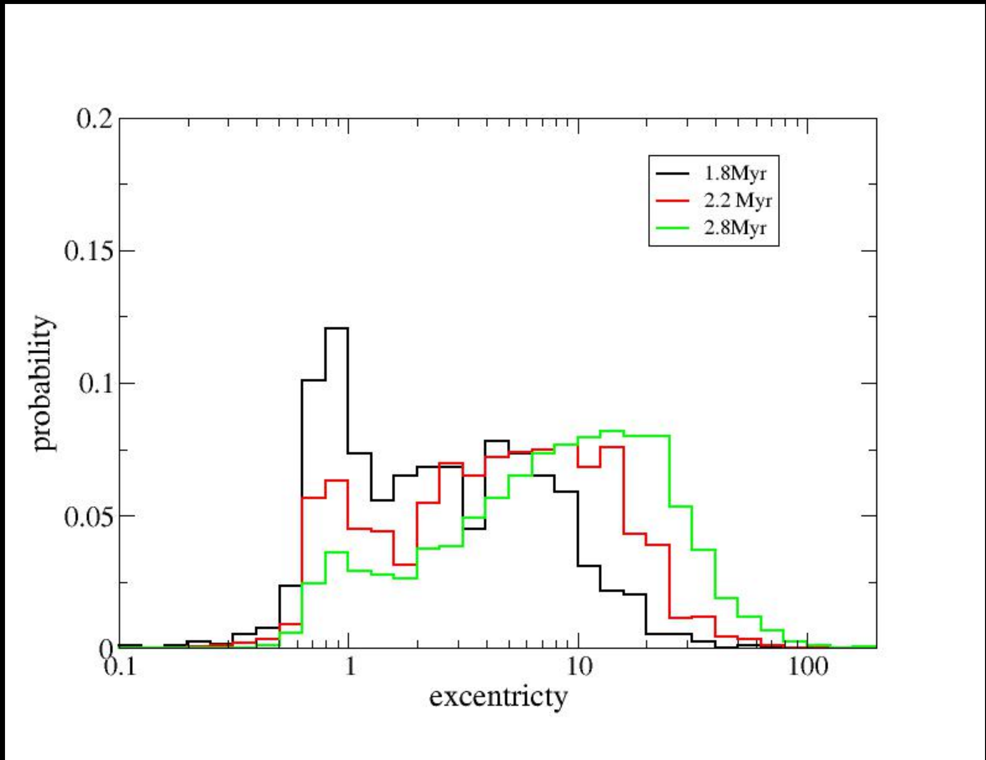
During 1st Myr after gas expulsion
30% chance of solar system forming encounter

Such an encounter likely event for solar-type star close leaky cluster center

After 3-4 Myr significantly reduced encounter probability

Solar system formed in the central regions of a leaky cluster

Encounter eccentricity history



Eccentricity of encounter function of cluster density

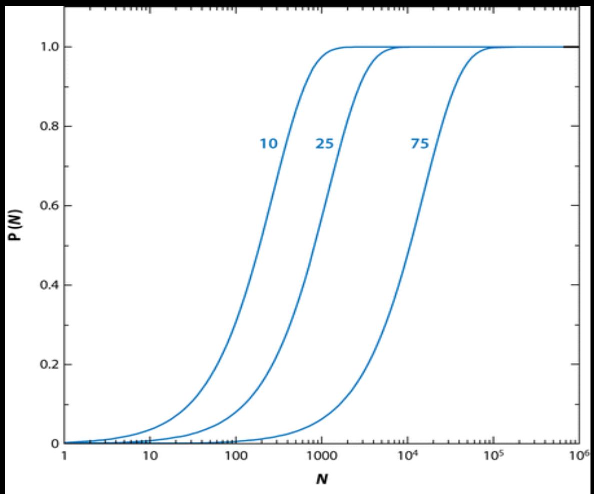
Dense clusters
Strongly hyperbolic encounters

Less dense clusters
nearly parabolic encounters

If encounter was early on in cluster developemnt (< 2Myr) then

Most likely strongly hyperbolic encounter

Infos from Meteorits

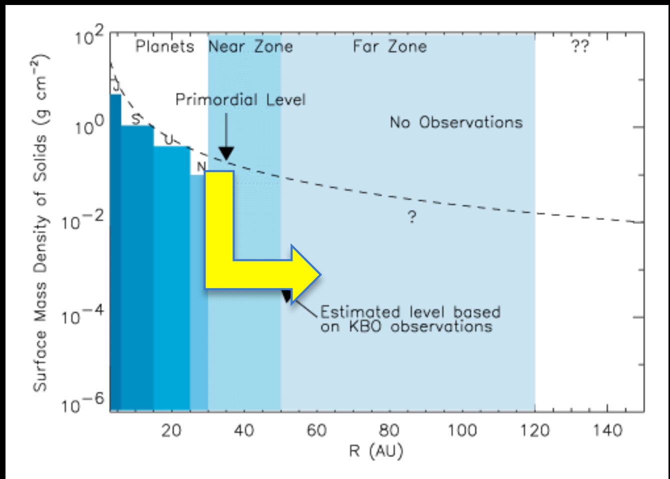


Adams FC. 2010.
Annu. Rev. Astron. Astrophys. 48:47–85

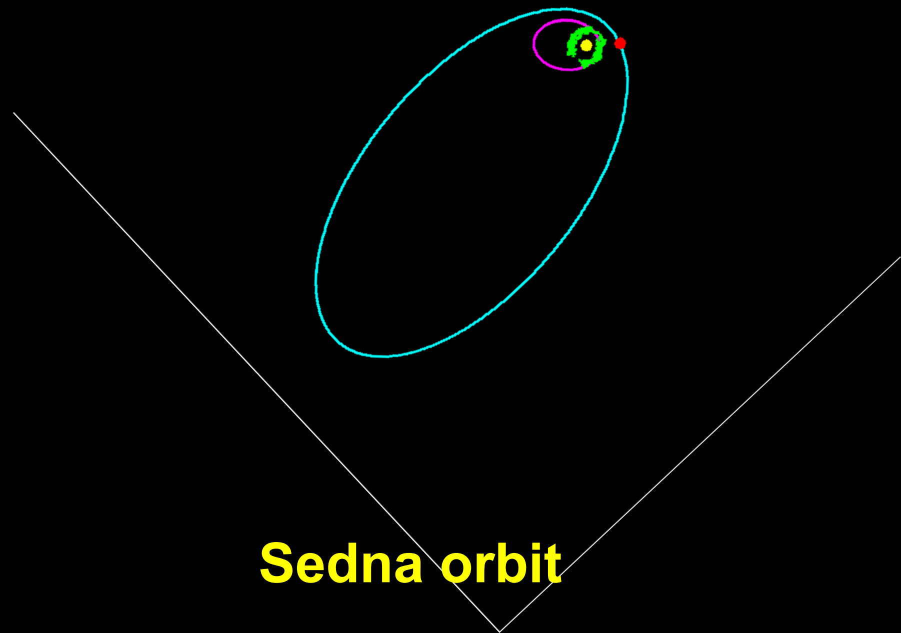
Solar system formed:

- **In vicinity of supernova with a 25 Msun progenitor**
- **Distance to supernova 0.2-0.3 pc**
- **N_{stars} > 1000 stars**

Relicts of the Solar System history: Mass distribution and Sedna orbit



30 AU drop in mass distribution



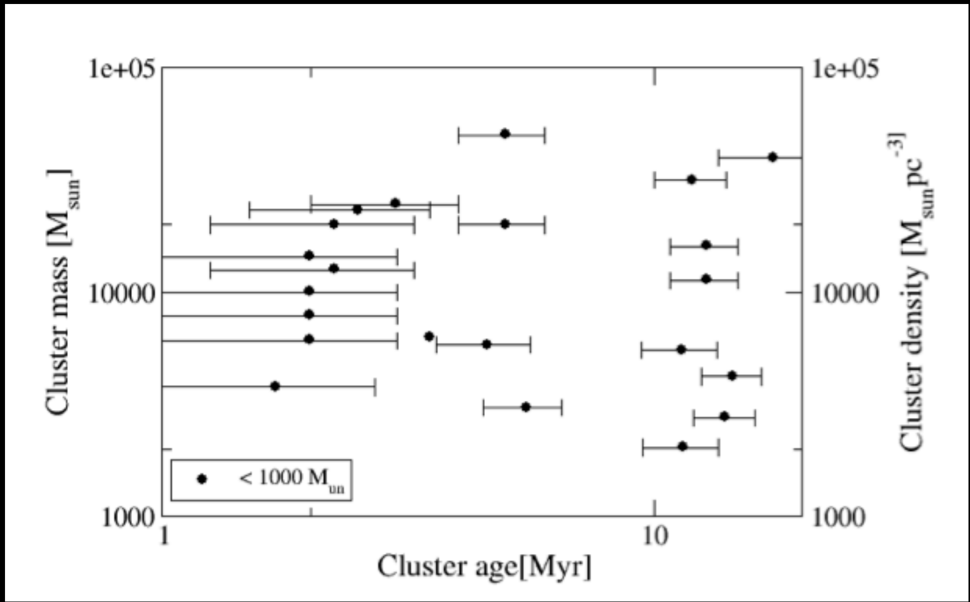
Sedna orbit

Likely cause: Encounter between 100-1000 AU during disc phase

(for summary see Adams 2010)

- solar-type star
- coplanar, prograde
- cut-off at 1/3 periastron

Young clusters with M > 10^3 M_{sun}



Note:
relatively large error bars for cluster age

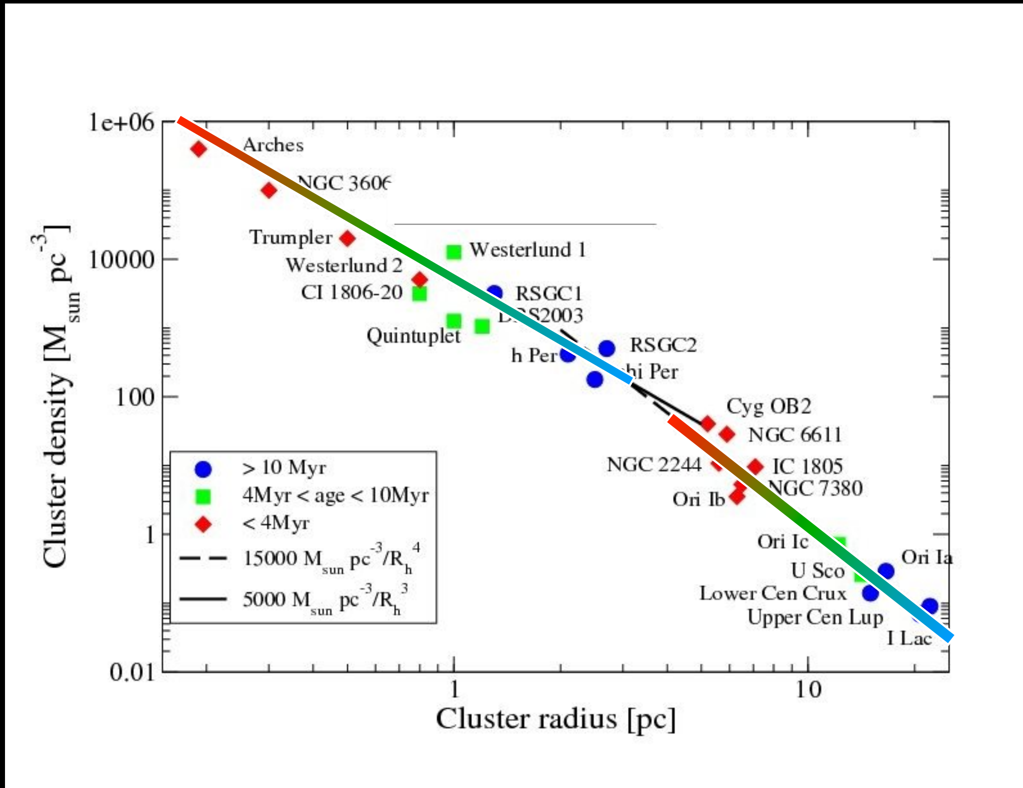
Most stars form in clusters
Lada & Lada (2003)

Many more clusters with ages < 10 Myr than at older ages for same time span

Clusters dissolve early on in development

Cluster with same mass as solar birth cluster mass exist today in Milky Way

2 types of clusters in solar birth cluster mass range



i) Star burst clusters

$\rho_c \sim R_c^{-3}$ Diffusion

ii) Leaky clusters
OB associations
or mass-loss clusters

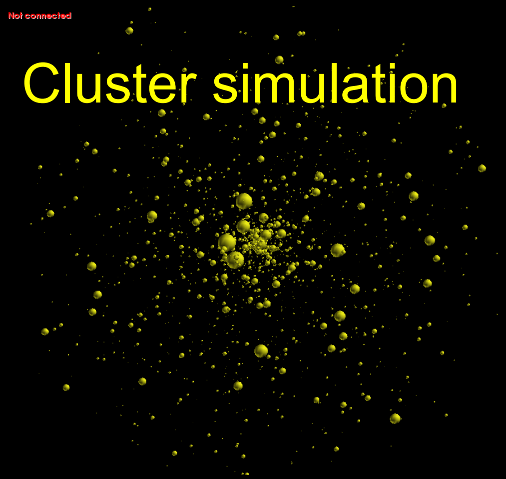
$\rho_c \sim R_c^{-4}$

Diffusion + Ejection

Sun formed in a leaky or starburst cluster

Which one is it?

Modelling of solar birth cluster

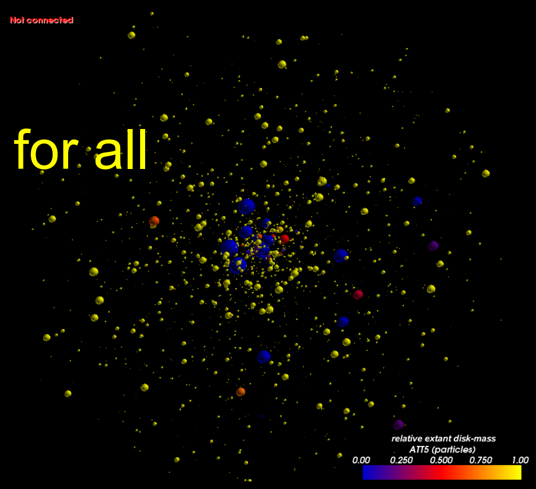


Cluster simulation

Encounter simulation

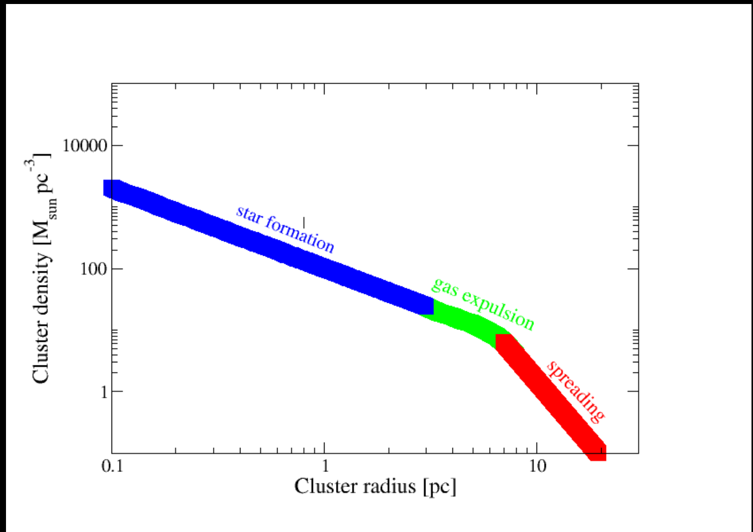
Dynamical model of clusters
single stars
no gas component
Code: NBODY6++
List of encounter parameters for all

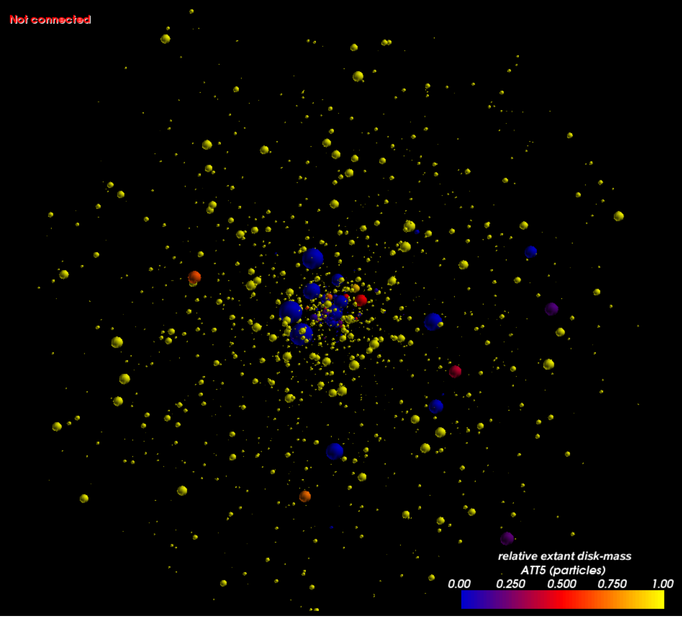
Only coplanar,
prograde encounters



Average encounter
effect on protoplanetare
Disc in cluster

Modelling of the solar birth cluster development





Gas expulsion at end of star formation probably resposible for **cluster expansion**

Uncertainities in gas expulsion process

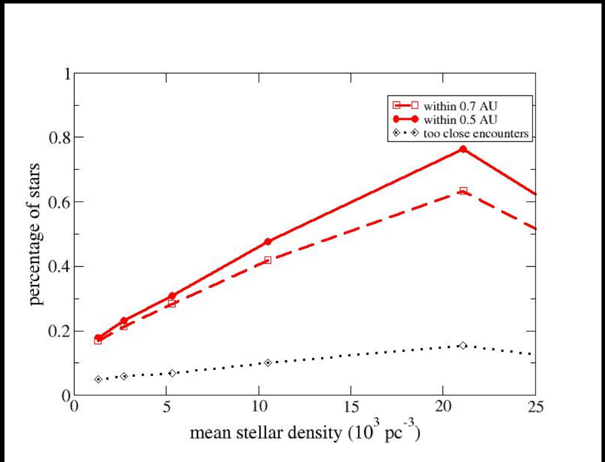
Instead:
Model clusters at different densities

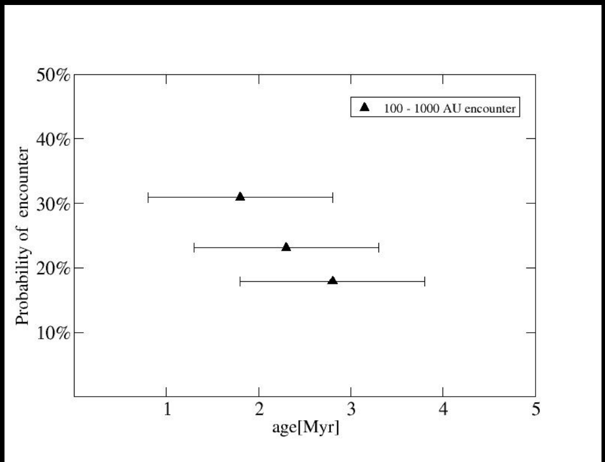
ONC-like cluster profile

Sun formed close to massive star

Solar-type stars close to cluster center

Probability of solar system forming encounter





Single encounter with 100 AU <r_{per}i< 1000 AU

Higher density = higher likelihood of encounter

But very high densities
Multiple or close encounters ➡ No solar system

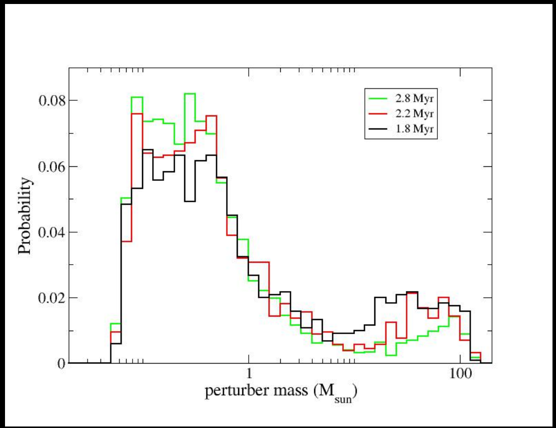
Leaky cluster: $\rho_c \sim C\ t^{-3.7}$

Probability of encounter decreases with cluster age

During 1st Myr after gas expulsion

30% chance of encounter with 100 AU <r_{per}i< 1000 AU

Encounter partner history



Solar-type stars mainly encounters with

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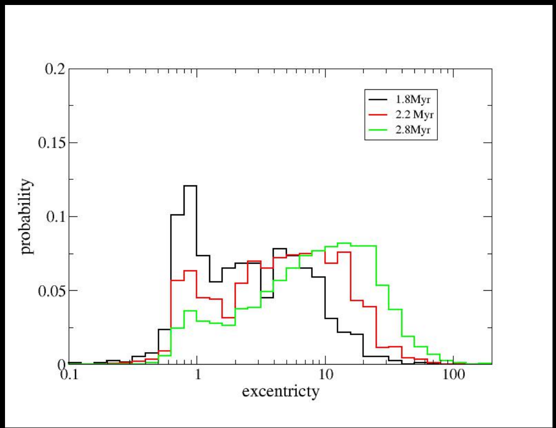
- **High-mass stars $m_{star} < 10\ M_{sun}$**

With a preference for low mass stars



Encounter orbit:

Dense clusters: strongly hyperbolic

Less dense clusters nearly parabolic

If encounter was early on in cluster developemnt (< 2Myr) then
Most likely strongly hyperbolic encounter