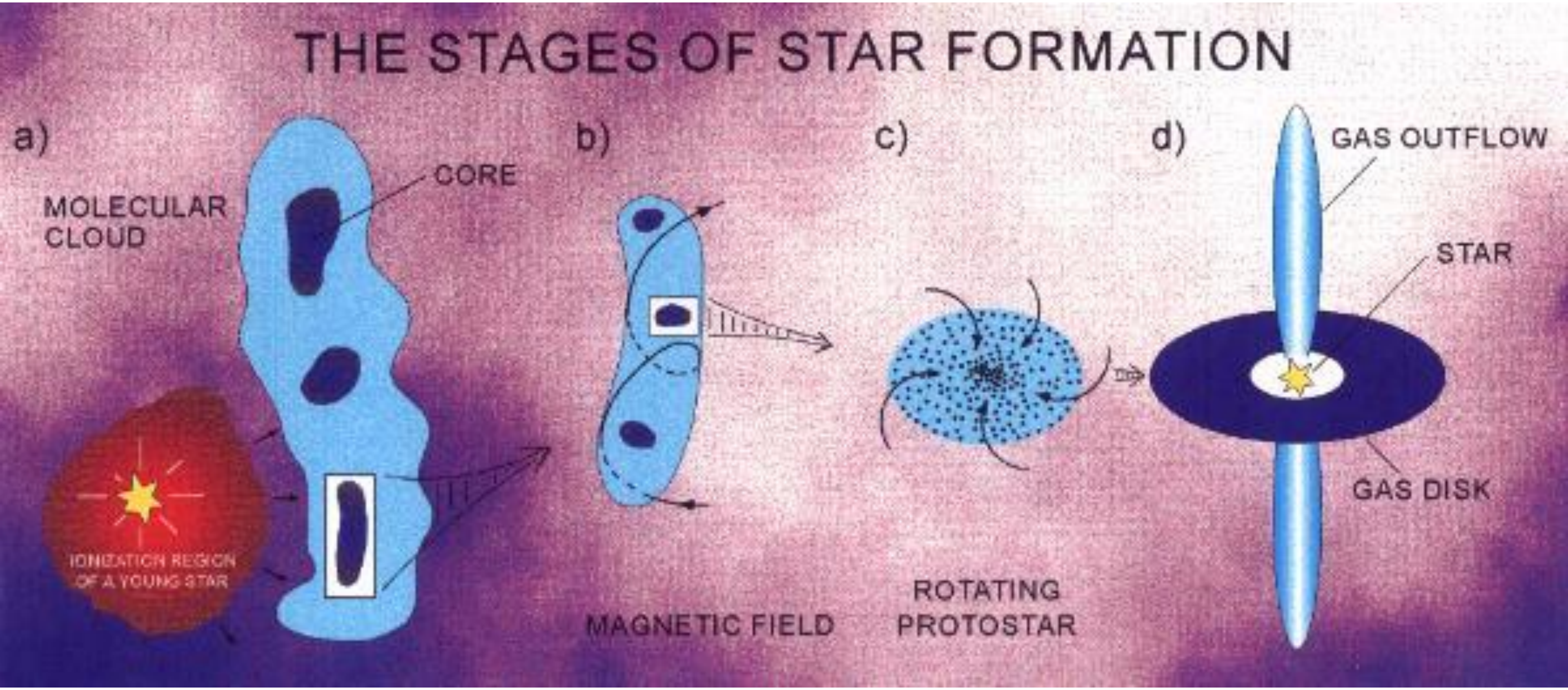
Jeans Length - When does Gravity win?

- $\boldsymbol{N}$ molecules of mass $\boldsymbol{m}$ in a box of size $\boldsymbol{L}$ (do not confuse with the luminosity) at temperature $\boldsymbol{T}$
- Gravitational Energy: $E_G \sim -\frac{G\,M^2}{L}$
- Thermal Energy: $E_T \sim N\,k\,T$
- Total mass: $M = N\,m \sim L^3\rho$
- Ratio: $\frac{E_G}{E_T} \sim \frac{G\,M^2}{L\,N\,k\,T} \sim \frac{G\,(\rho\,L^3)\,m}{L\,k\,T} = \left(\frac{L}{L_J}\right)^2$
- Jeans Length: $L_J \sim \sqrt{\frac{k\,T}{G\,\rho\,m}}$
- Gravity wins when $L > L_J$

Jeans Mass

- Jeans Length: $L_J \sim \sqrt{\frac{k\,T}{G\,\rho\,m}}$
- Jeans Mass: $M_J = L_J^3\,\rho = \rho\,\left(\frac{k\,T}{G\,\rho\,m}\right)^{3/2} \propto T^{3/2}\,\rho^{-1/2}$
- Lowest Jeans Mass for cool and dense clouds

Star formation



Gravitation „wins“ Magnetic field, Shock wave Protostar

← FREE GAS → ← NO FREE GAS →

Star formation

- The detection of free Gas in a Star Cluster is an excellent indicator for the time scale of continuous stellar formation

STAR-FORMING REGIONS

Region	⟨t⟩[a] (Myr)	Molecular Gas?	Ref. (age)
Coalsack	...	Yes	...
Orion Nebula	1	Yes	1
Taurus	2	Yes	1, 2, 3
Oph	1	Yes	1
Cha I, II	2	Yes	1
Lupus	2	Yes	1
MBM 12A	2	Yes	4
IC 348	1–3	Yes	1, 4, 5, 6
NGC 2264	3	Yes	1
Upper Sco	2–5	No	1, 6, 7
Sco OB2	5–15	No	8
TWA	~10	No	9
η Cha	~10	No	10

[a] Average age in Myr.

Star formation lasts 3 to 4 Myrs and is continuous

This is also the "intrinsic" error of an age determination

Hartmann et al., 2001, ApJ, 562, 852

Numerical simulation of star formation in Giant Molecular Clouds

- Hypothesis: the formation of all members of a star cluster is continuous for 3 to 4 Myrs within one GMCs
- Is this a realistic approach?
- Is it possible to simulation the formation of star clusters and compare the results with observational data within the solar vicinity?

Numerical simulation of star formation in Giant Molecular Clouds

- Detailed paper by Bate & Bonnell, 2005, MNRAS, 356, 1201
- Basis: Orion Nebula and Taurus star forming region
- “Complete” astrophysical numerical simulation including Shock Waves, dynamical parameters and 3D-Hydrodynamics, Jeans Mass < 1 M(sun)
- The numerical simulations are astonishing close to the observations

Numerical simulation of star formation in Giant Molecular Clouds

Input parameter:

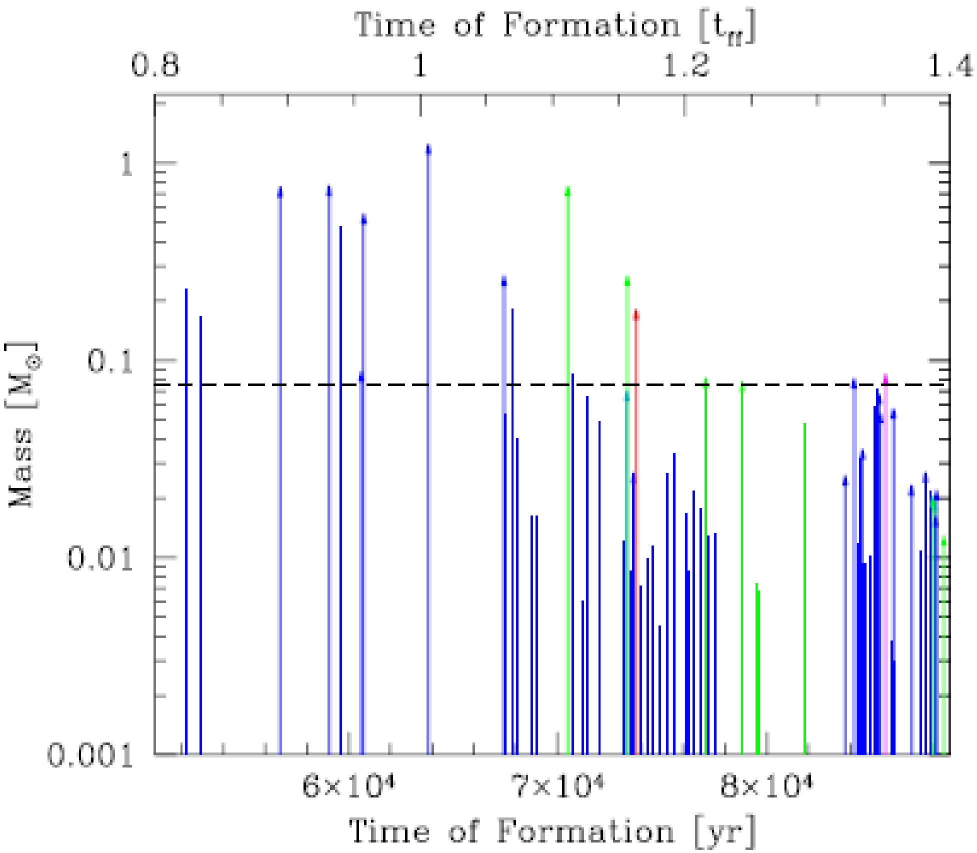
1. Mass (GMC) = 50 M(sun), limited by CPU time
2. Diameter = 0.375 pc, limited by CPU time
3. Time for the gravitational collapse: 19000 years
4. Random turbulence field with a 3D Gaussian distribution

Core	Initial Gas Mass $M_\odot$	Initial Size pc	Final Gas Mass $M_\odot$	No. Stars Formed	No. Brown Dwarfs Formed	Mass of Stars and Brown Dwarfs $M_\odot$	Star Formation Efficiency %
1	1.50 (0.15)	$0.04 \times 0.04 \times 0.03$	2.03 (1.04)	$\geq$13	$\leq$52	6.33	76 (86)
2	0.92 (0.16)	$(0.03 \times 0.01 \times 0.01)$	1.18 (0.50)	$\geq$4	$\leq$8	1.33	53 (73)
3	0.17 (0.06)	$(0.02 \times 0.01 \times 0.01)$	0.32 (0.08)	1	0	0.18	36 (69)
4	0.31 (0.07)	$(0.03 \times 0.01 \times 0.01)$	0.32 (0.06)	1	0	0.09	22 (60)
Cloud	50.0	$0.38 \times 0.38 \times 0.38$	42.1	$\geq$19	$\leq$60	7.92	16

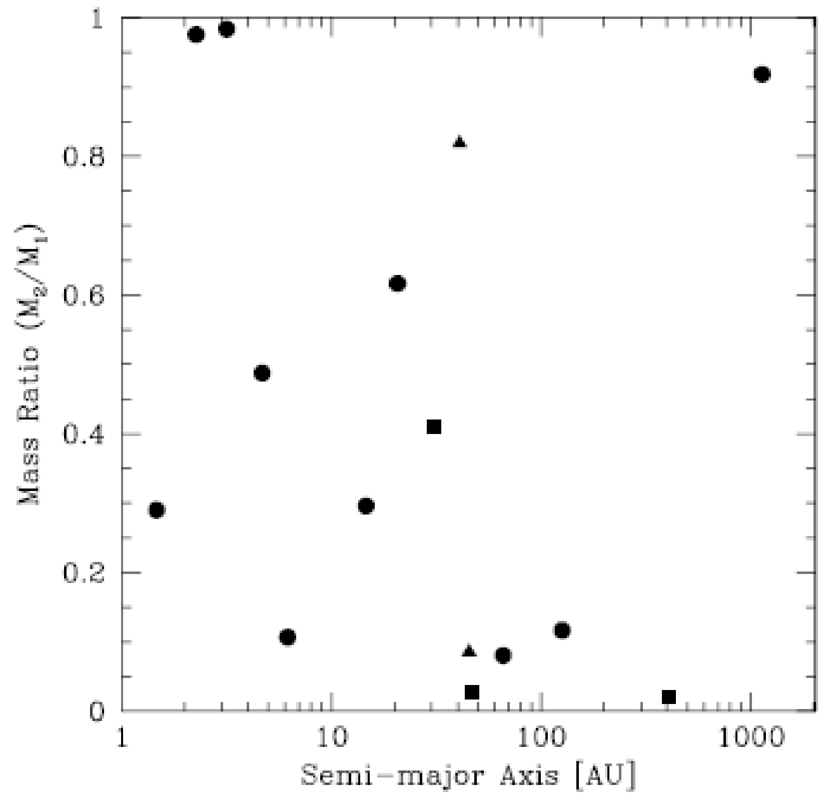
„Stars“: Mass > 0.084 M(sun)
Brown Dwarfs: Mass < 0.084 M(sun), no Hydrogen burning

More low mass stars formed due to the IMF

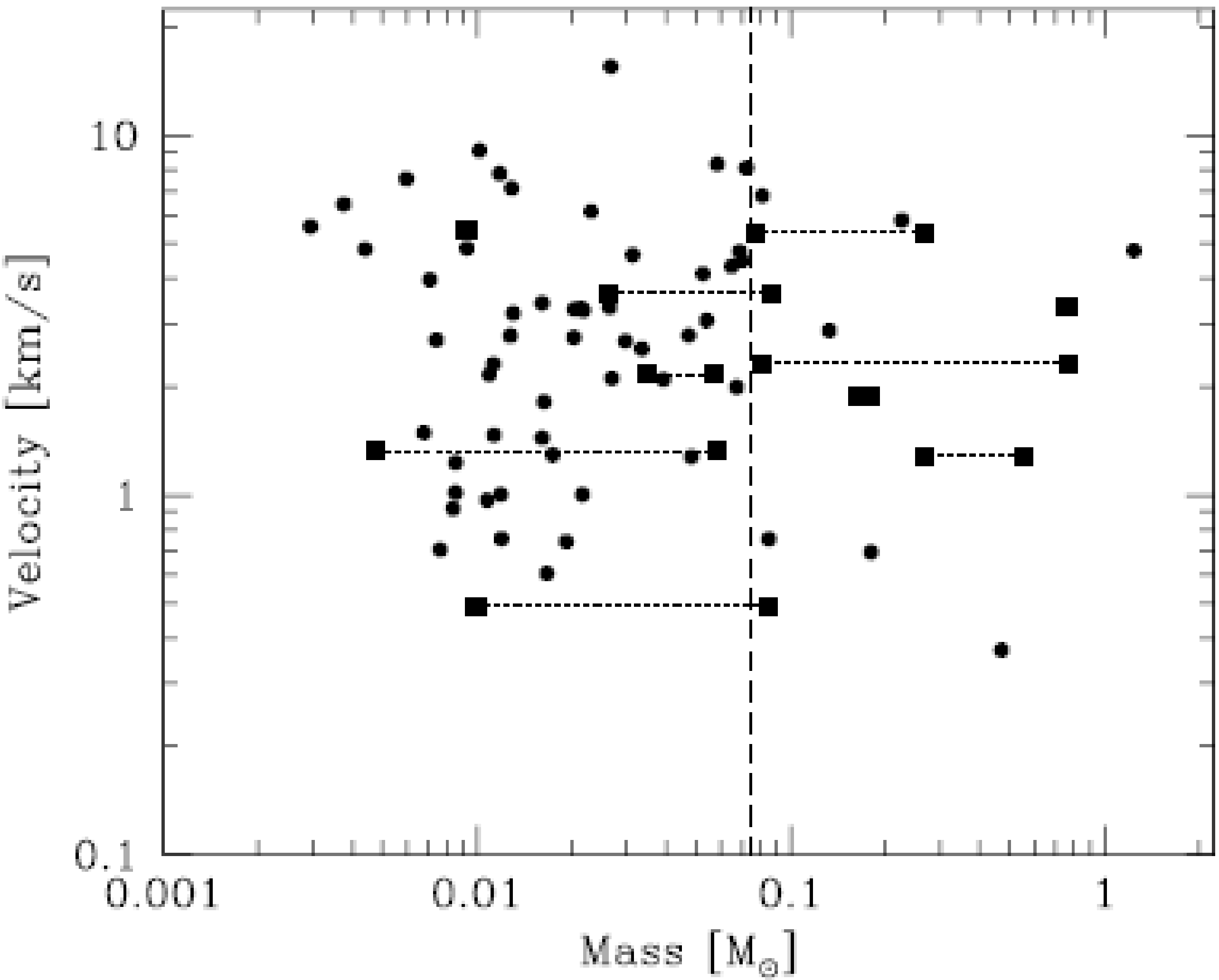
For star clusters it is essential to know the internal velocity distribution because of their evolution (see later)



Continuous star formation in time



The formation of Binary systems

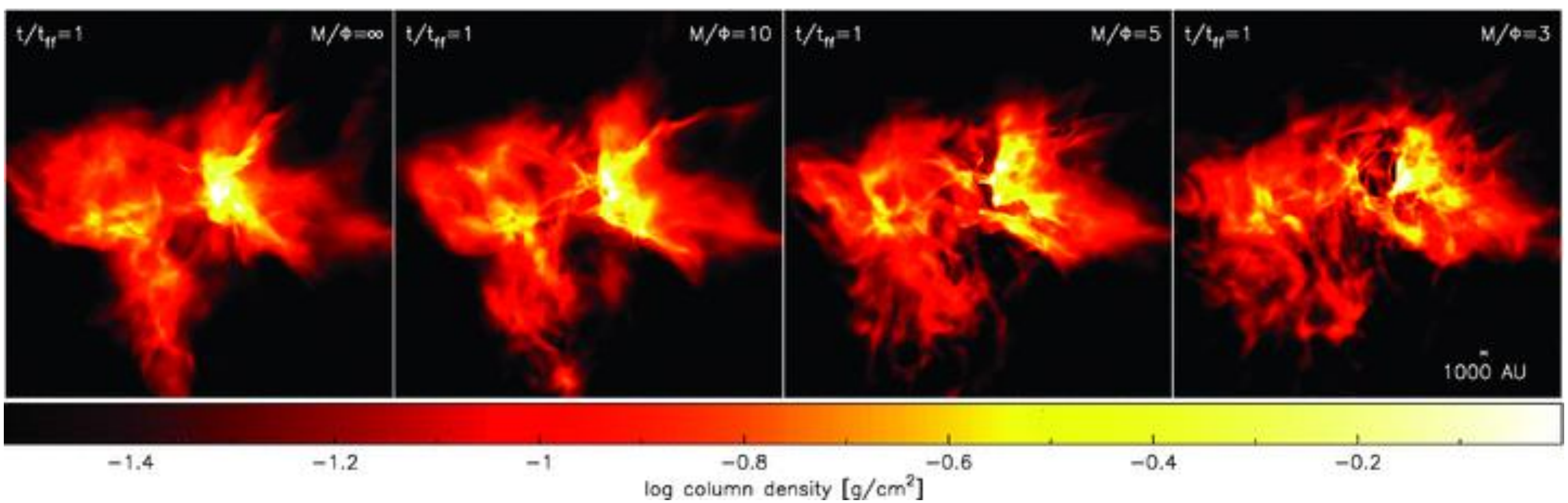


Binaries are connected with a line

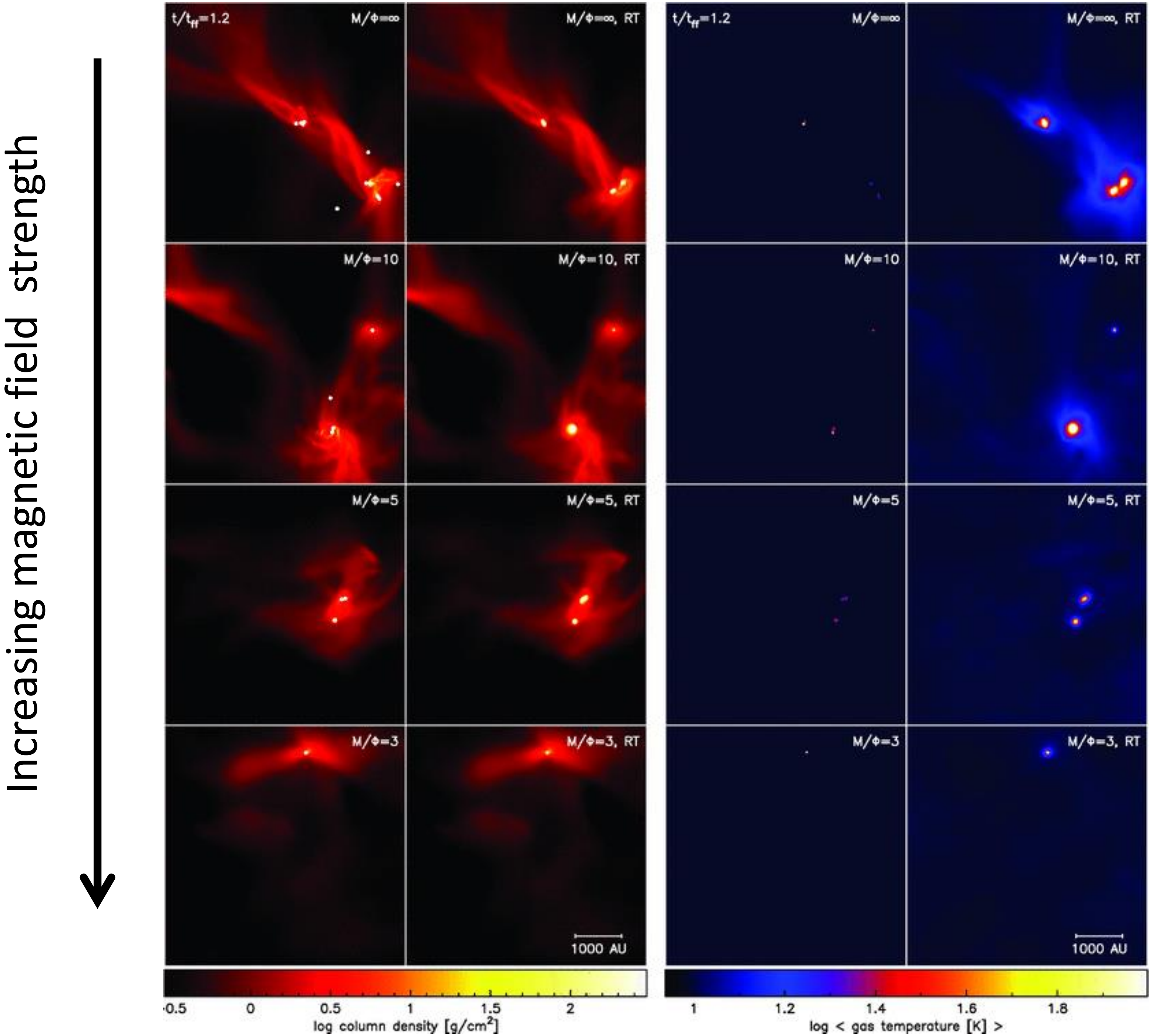
The rms velocity dispersion of the simulations is 4.3 km s^{-1}
Such observational data for d > 500 pc are still not available => Gaia satellite mission

Magnetic field – star formation

- Price & Bate, 2009, MNRAS, 398, 33
- Effects of magnetic pressure on fragmentation



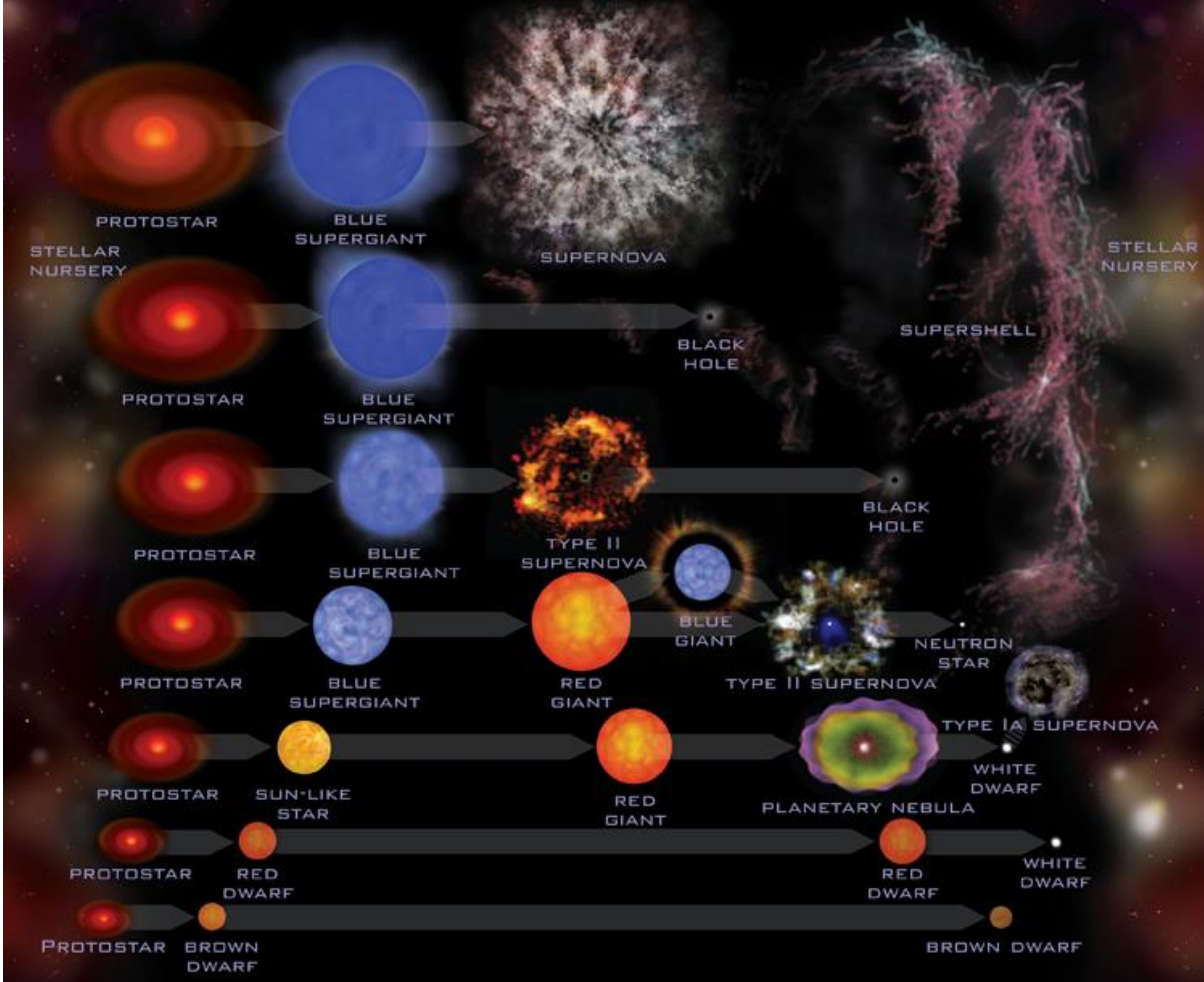
Increasing magnetic field strength


Increasing magnetic field strength
t/t_ff=1.2
M/Φ=∞
M/Φ=∞, RT
M/Φ=10
M/Φ=10, RT
M/Φ=5
M/Φ=5, RT
M/Φ=3
M/Φ=3, RT
1000 AU
-0.5
0
0.5
1
1.5
2
log column density [g/cm²]
1
1.2
1.4
1.6
1.8
log < gas temperature [K] >

Evolution of Star Clusters

- Star Clusters form with the following characteristics
    1. **Total Mass**: IMF
    2. **Metallicity**
    3. **Kinematics of the Cluster center**: location within the Galaxy
    4. **Internal velocity dispersion**
- How does a Star Cluster evolve with these starting parameters?

- Each member (= star) evolve “as an individual”, some important topics
  1. Binary Evolution
  2. Mass Loss (hot stars)
  3. AGB Evolution
  4. Planetary Nebula (cool stars)
  5. Supernovae explosions
- In Star Clusters, collisions are very uncommon (see later), almost no new multiple (binary) systems form during the later evolution
- Star Clusters, normally, follow Galactic Rotation


PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF