A Coronagraphic Search for Brown Dwarfs and Planets around Nearby Stars

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Outline

- Introduction to direct detection
  - Parameters that control detectability
- Dynamic range of instruments at VLT, and Subaru
- Strategies at VLT
- Our program at Subaru

Note that the focus of this talk is on high dynamic range and other efforts such as binary brown dwarf searches by adaptive optics are not included.

Also the focus is on comparison between VLT and Subaru.

Please comment on your own effort if I miss it during my talk.

Detectability of direct detection

I apologize that my talk is technical rather than astronomical.

- Direct detection of a planet: photometric
  - $\Delta m(M_*, M_p, s, d)$: dynamic range in mag

μ_*: star mass

μ_p: planet mass

s: separation in AU

d: distance in pc

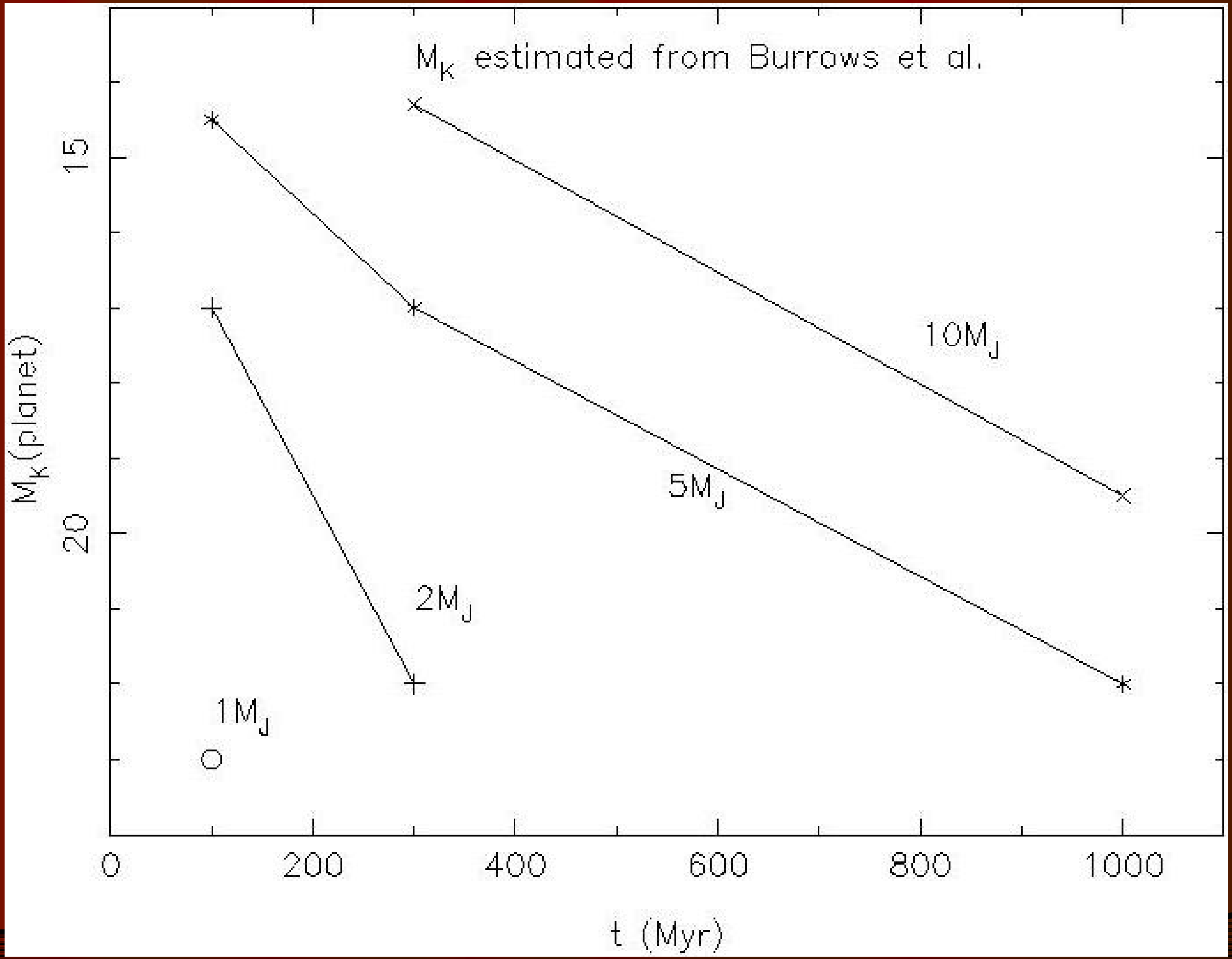
M_*: star abs. mag.

M_p: planet abs. mag.

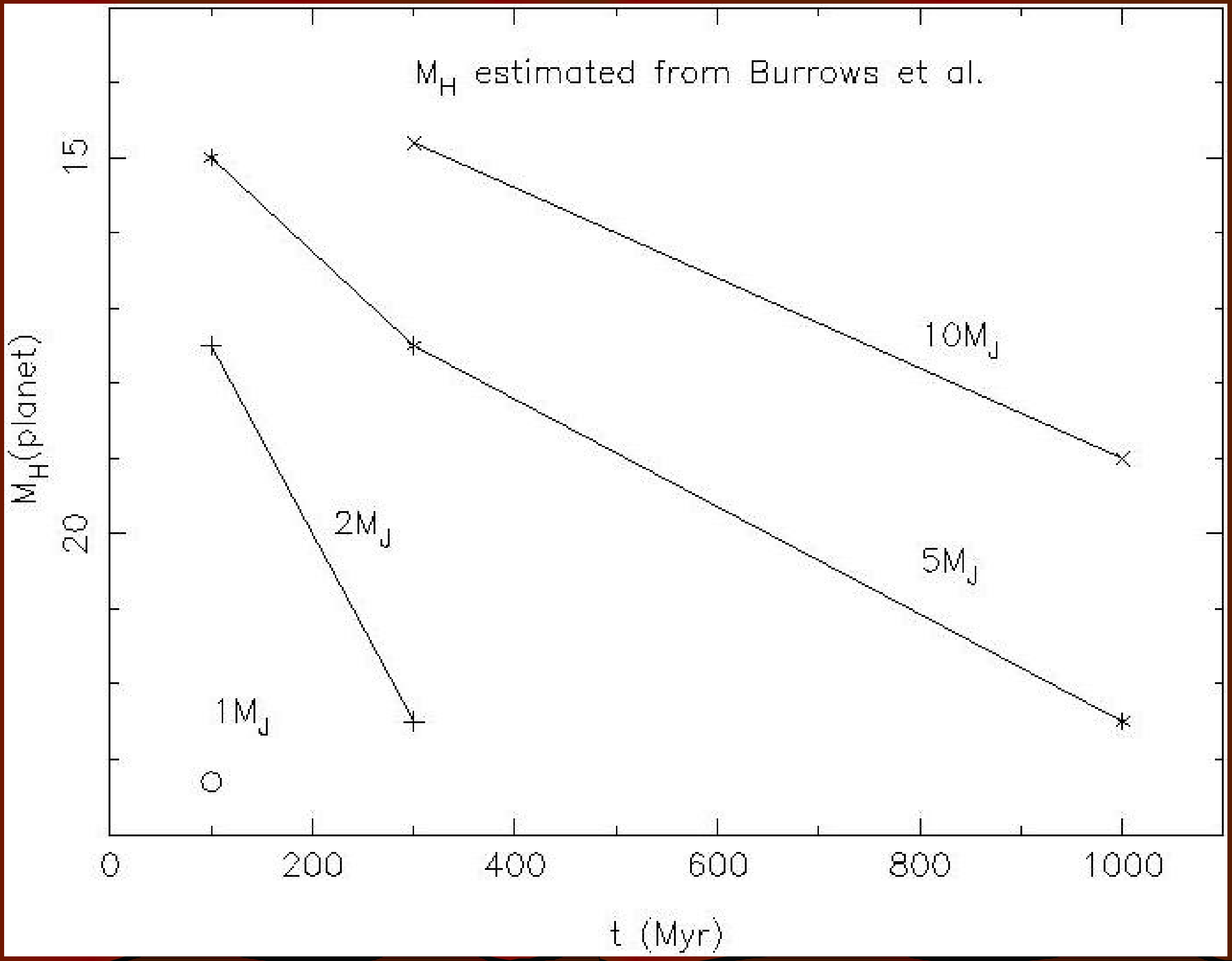
Parameters controlling dynamic range

- Giant planet detection by reflected light
  - Sun+Jupiter placed at 10pc
    - $\Delta m = 22.5$ at $\theta=0.5''$
    - No currently available instrument has this dynamic range
- Detection of self-luminous young planets
  - $M_p = M_p(\mu_p,t)$: dependences on mass and age
  - $M_* = M_*(\mu_*,t)$ if star is very young
  - $\Delta m = M_p - M_*$: small for small t
- Limiting mag of planet
  - $m_p(\text{limit})(\theta) = M_* + \Delta m(M_*,M_p,\theta=s/d) + 5\log(d/10)$
  - $M_p(\text{limit})(s) = M_* + \Delta m(M_*,M_p,s)$ at d=10pc

Absolute K mag of giant planets

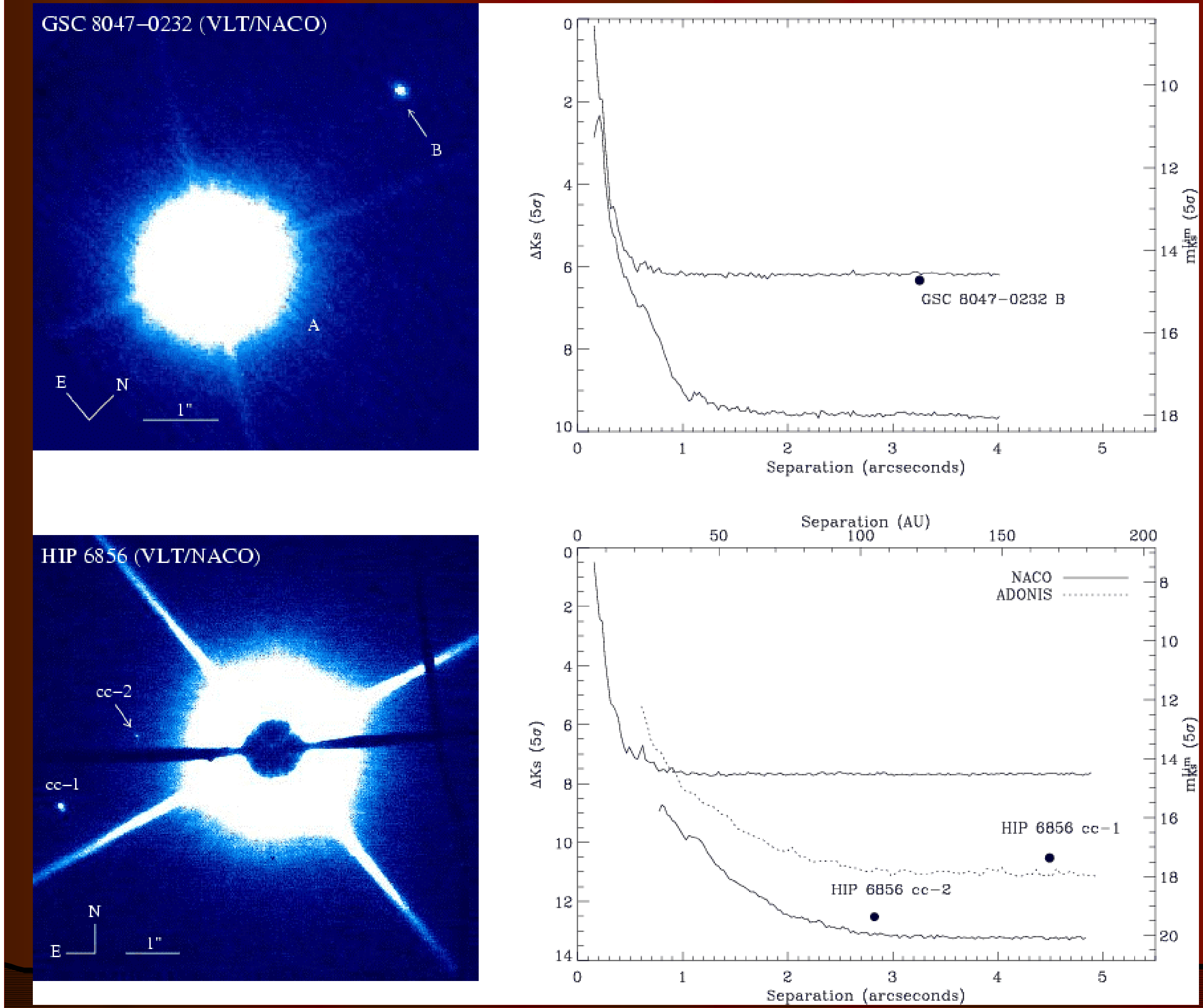


Absolute H mag of giant planets



Spectral band for which SDI of non-cooled coronagraph is effective.

Performance of VLT/NACO



$\Delta K = 6$ at 0.5”

= 9.5 at >1”

For a bright target

$\Delta K = 10$ at 0.5”
= 12 at 1.5”
= 13 at > 3”

For a fainter target

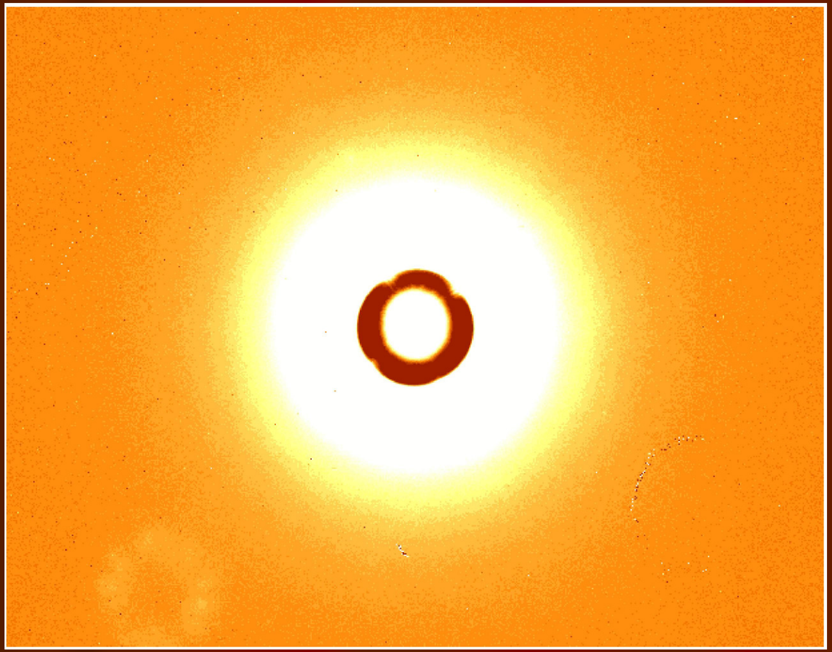
Chauvin et al. (2005)

Performance of VLT/SDI imaging

- Simultaneous Differential Imaging
  - Removes speckle noise and obtain high dynamic range at small angular separations.
- Simulated performance of SDI on VLT

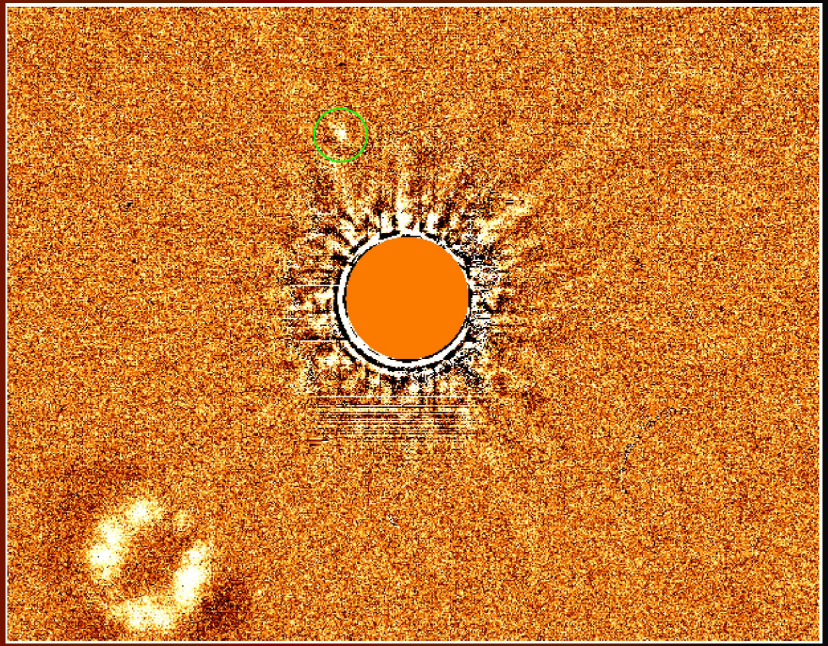
$\Delta H = 9.5$ at 0.5”, the highest value at small radii (ESO Messenger).

Performance of Subaru/CIAO



H=7 primary star (120s x 6)

d=10pc (2” diameter mask)



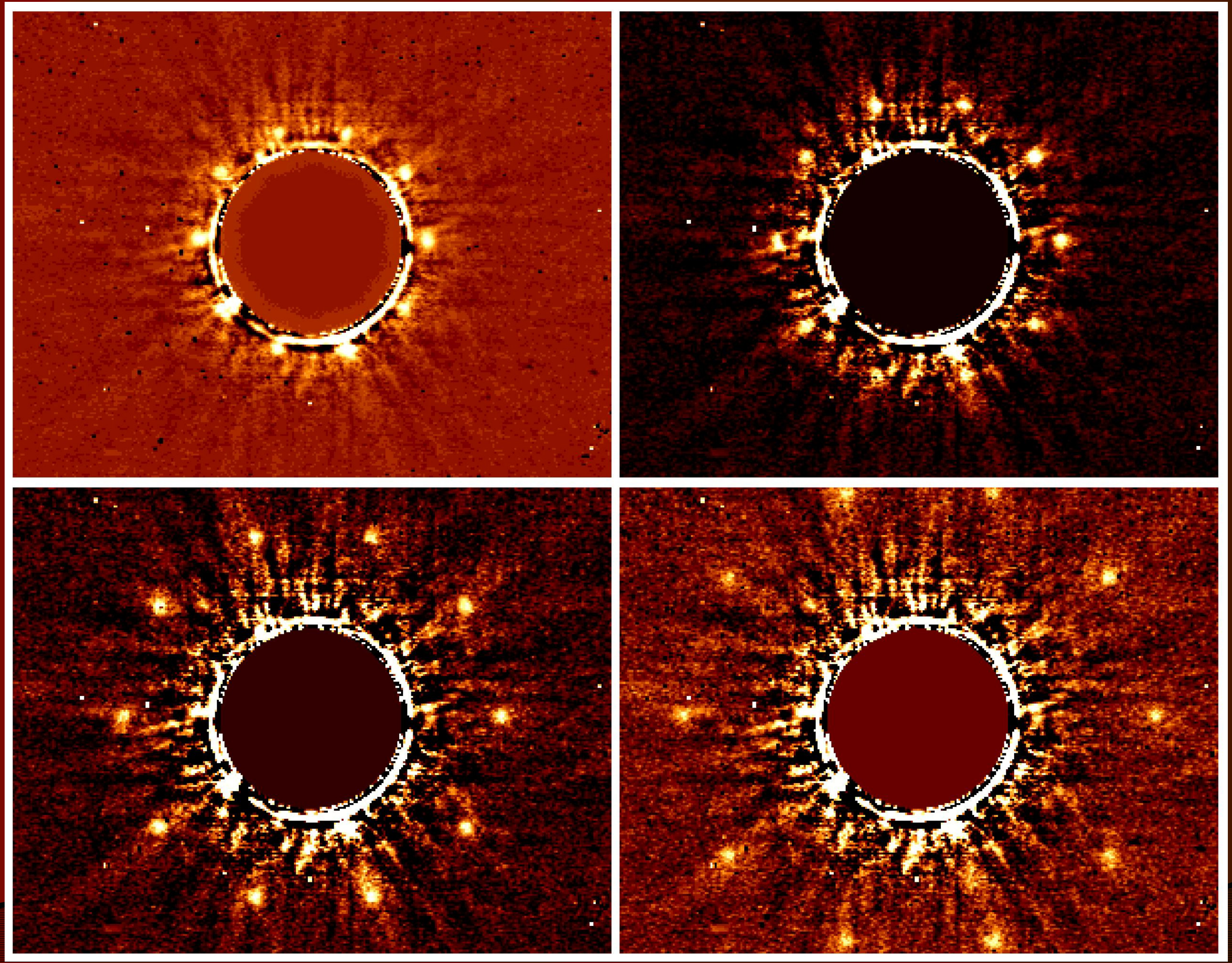
Primary PSF subtracted.

H=21 companion candidate detected at r=2.8”

$\Delta H = 14$ at r=2.8”

PSF subtraction is done real-time while observing.

Simulated planets on PSF subtracted CIAO image of a K=7 star



K=18
r=1.2”
ΔK=11

K=19
r=1.5”
ΔK=12

K=19.5
r=2.0”
ΔK=12.5

K=20
r=2.5”
ΔK=13

Performances of current instruments on VLT and Subaru

VLT/NACO (AO without coronagraph, Chauvin et al. & ESO Messenger)

Bright targets $\Delta K = 6$ at 0.5” (AO)

$\Delta H = 9.5$ (AO+SDI)

Faint targets $\Delta K = 10$ at 1.0”

= 13 at >3.0”

Subaru/CIAO (AO with coronagraph)

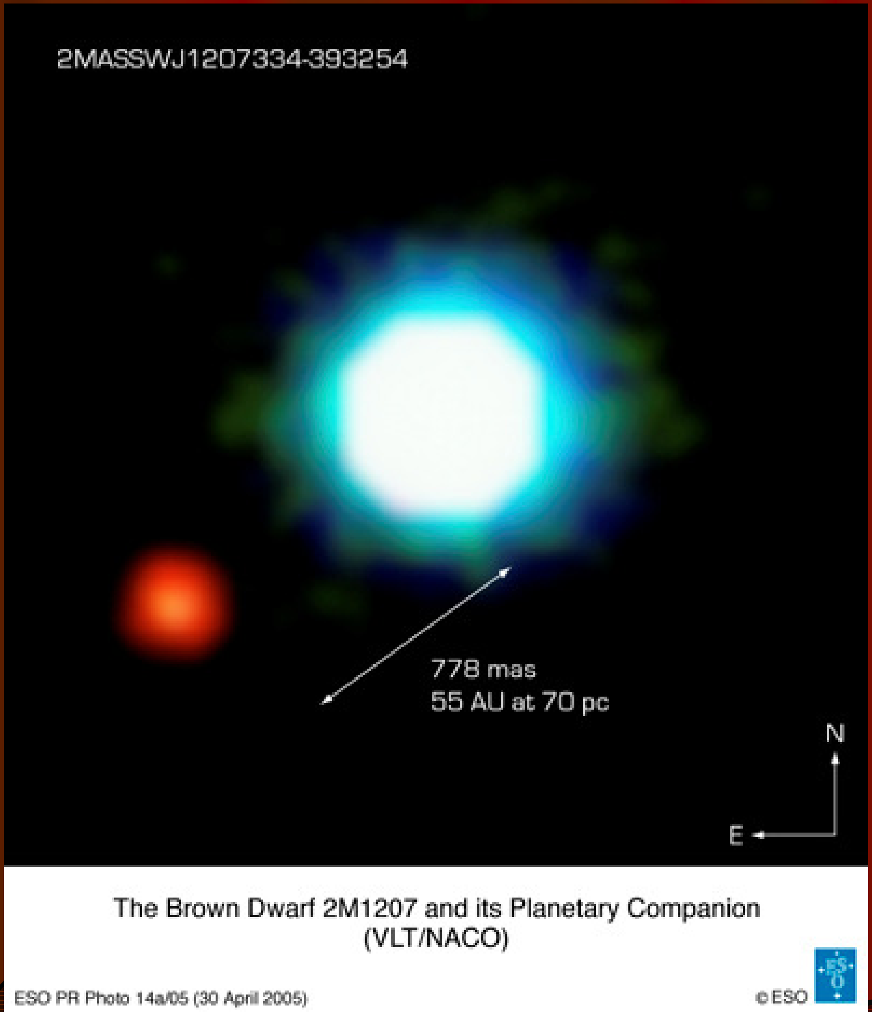
Faint targets $\Delta K = 11$ at 1.2”

= 13 at >2.5”

Strategies at VLT

- Select extremely young targets
  - t=1~8Myr
  - PMS stars or very young brown dwarf targets
  - Both primary and companion are bright.
  - d=140pc (Lupus, Neuhauser et al. 2005) or d=70pc (TW Hydra, Chauvin et al. 2004)
  - Necessary dynamic range is small: $\Delta K \sim 7$.
  - Physical separations are large: s>50AU.
- Targeting young BDs (Chauvin et al.)
  - IR wave front sensing (BDs are invisible at visible wavelengths).

Planet found by VLT



The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

VLT/NACOS AO w/out coronagraph

IR wavefront sensing --- low mass star targets

Primary: K=12 M8 brown dwarf in TW Hydra association (t=8Myr, d=70pc)

$M \sim 20M_J$

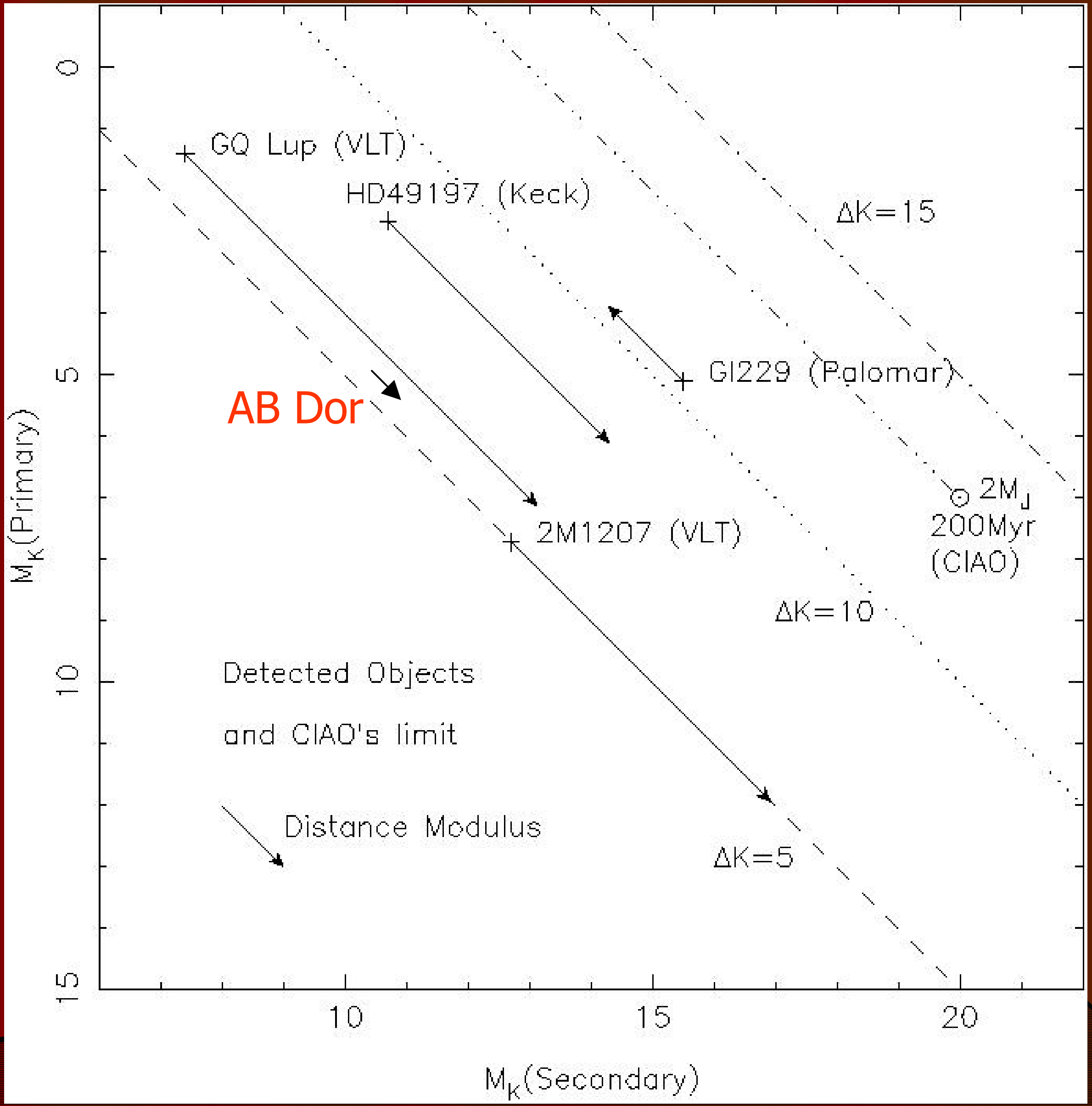
Secondary: K=17 L? dwarf

$M \sim 5M_J$, if the evolutionary model and temperature estimate are correct.

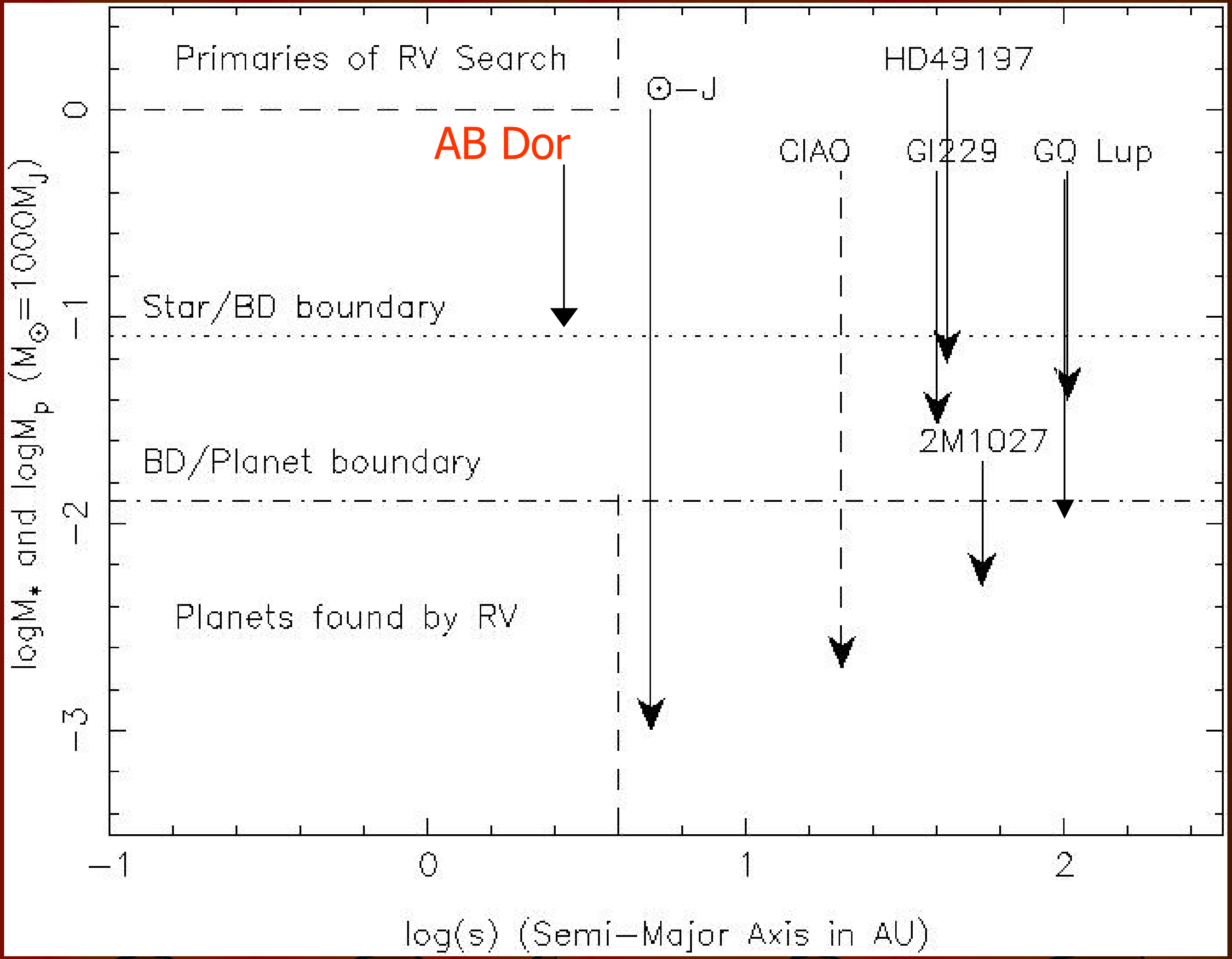
Separation: 0.8” or 55AU

Chauvin et al. (2004,2005)

ΔK of currently known objects



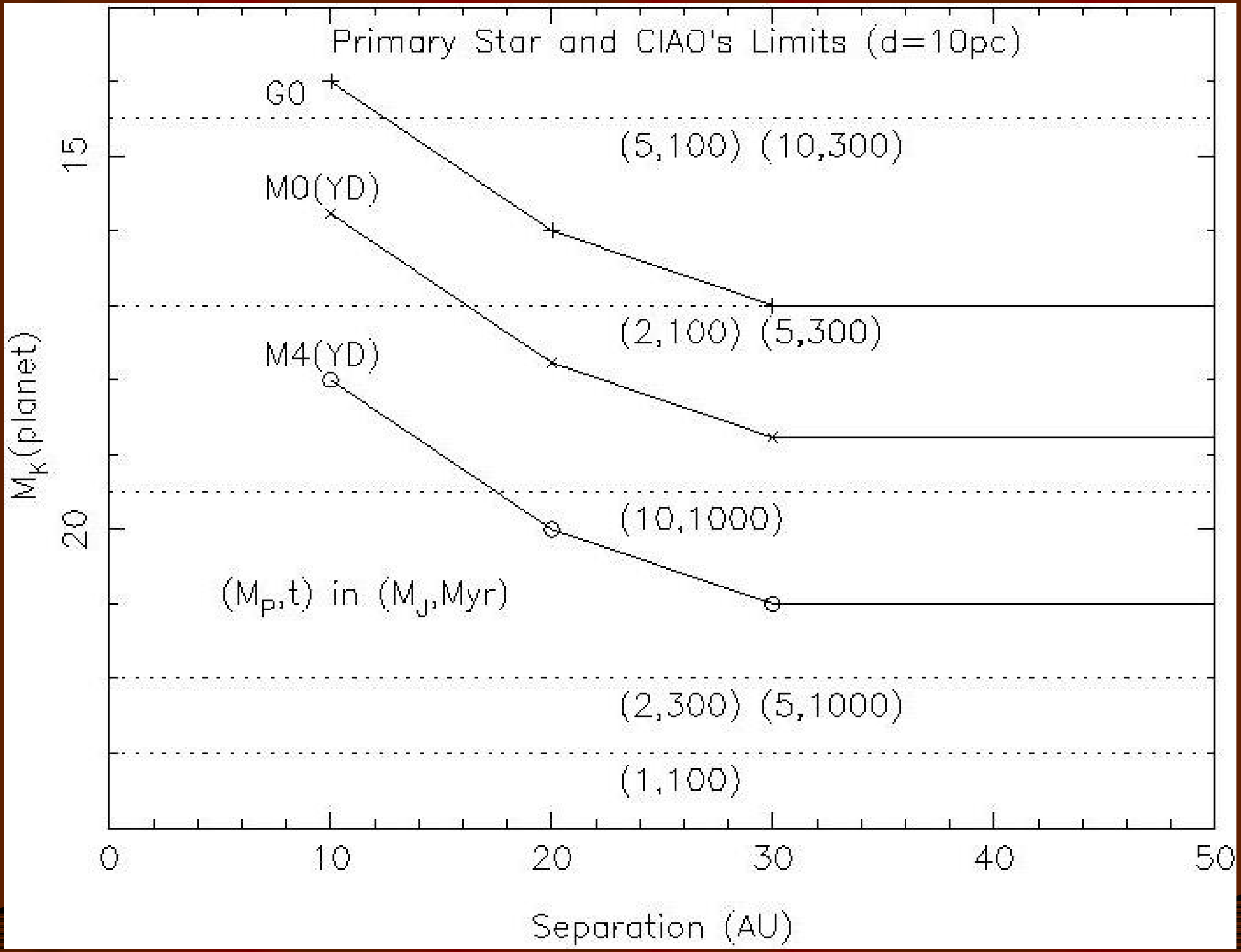
Mass-Separation Diagram



Our effort at Subaru

- To utilize $\Delta K > 13$ (or $K<20$) at $r>2.5''$
  - d ~ 10pc (<20pc) --- Physical separation > 20AU
  - Nearby stars are M+K dwarfs (0.5~0.2Mo)
- Kinematical age criteria
  - 3D kinematical information available for 500 M and K stars within 20pc (Reid et al. 2002)
  - Small random velocity with respect to LSR.
  - Small velocity deviation from a particular SKG.
- Mass limit for $M_K<20$ and $t<350$Myr
  - $M \sim 2M_J$

Target dependent detection limits of CIAO



(μ_p,t) in (M_J,Myr)

YD:Young disk star

Nearby stellar population

Henry (1998)

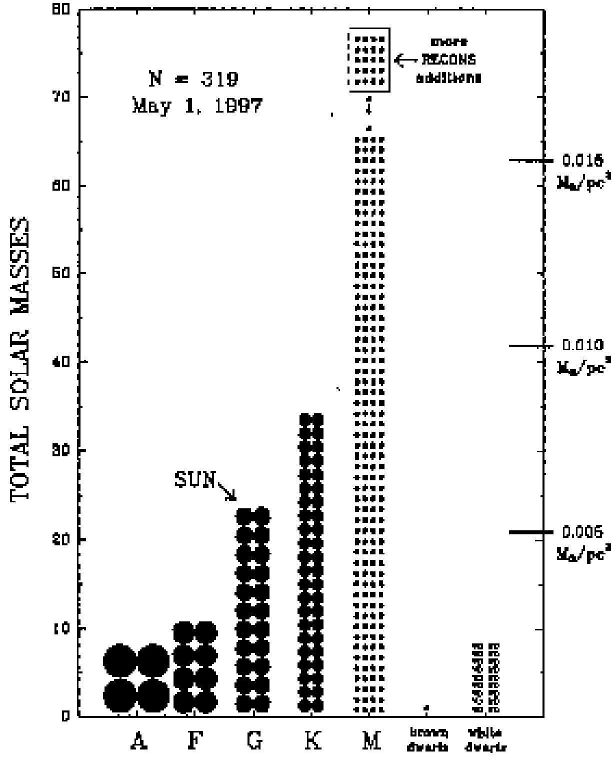


Figure 1. The complete sample of objects known within 10 pc of the Sun is shown, separated by spectral type. There are no O or B type stars, nor giants, in the sample. The sizes of the points correspond roughly to the actual sizes of the dwarfs (except for the white dwarfs). The heights of the piles represent the amount of mass contributed to the solar neighborhood by each type.

Age dating of stars

- Chromospheric activity (e.g. Hα)
  - Strong dependence on spectral type and 1/3 of M dwarfs show this ($t < 10/3 \sim 3$Gyr) .   This is not a strong constraint.
- Coronal activity (X-ray emission)
  - Sample is small and stars are at distances. ($d>20$pc).
- Kinematical age dating
  - Small deviation of (U,V,W) from $(U,V,W)_{LSR}$.
  - Particular (U,V,W) corresponding to a young stellar kinematical group.
  - At least one successful example exists --- Gl 229A

Kinematical age

- Velocity dispersion of stars w.r.t. local standard of rest increases as they age.
  - Time evolution of velocity dispersion is modeled by Fuchs and Wielen (1987)
- Our idea
  - Velocity deviation from V_{LSR} is obtained for each star.
  - Replace velocity dispersion with velocity deviation for each star and assign a particular age for each star.
  - Even if the age assigned to each star has an error, we should be able to define a statistically meaningful sample with some age limit.

Age-velocity relation based on a disk heating model

The age-velocity dispersion relation obtained by Fuchs and Wielen (1987) based on a diffusion equation with a velocity-time dependent diffusion coefficient is

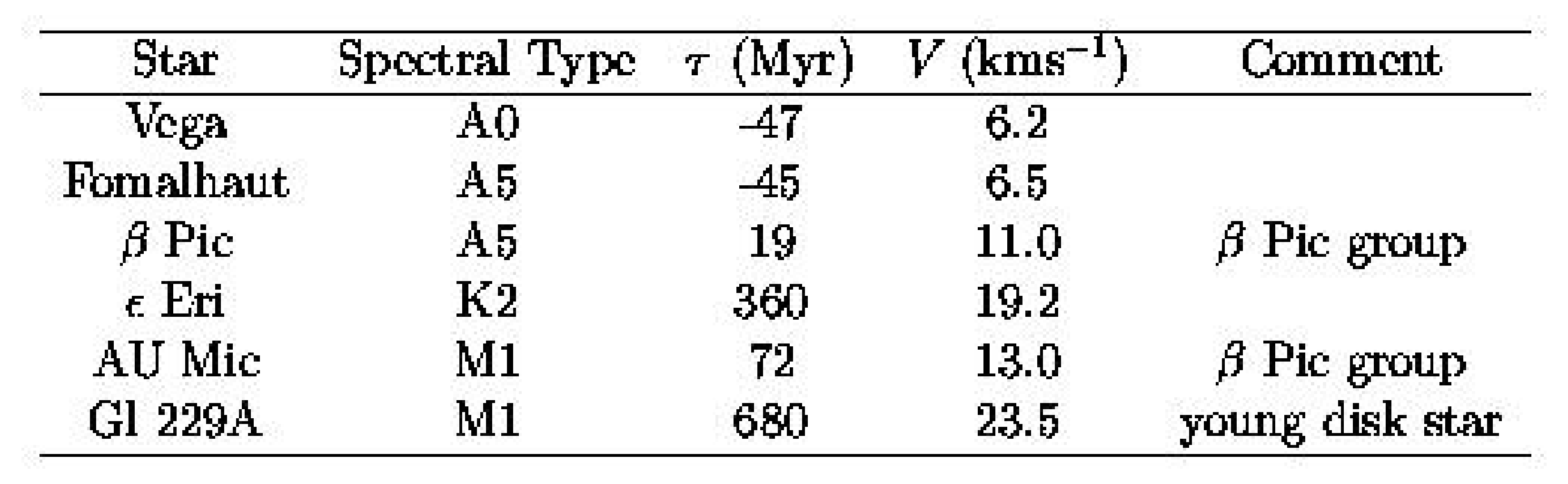
$$\sigma_V(\tau)^3 = \sigma_{V,0}^3 + \frac{3}{2}\alpha_V \delta_2 \mathrm{T}_\delta \left(\exp\frac{\tau}{\mathrm{T}_\delta} - 1\right), \quad (1)$$

where V is the total velocity in units of kms^{-1} with respect to the local standard of rest, σ_V is the velocity dispersion, τ is the age in year and

$$\begin{aligned} \delta_2 &= 3.7 \times 10^{-6}, \\ \mathrm{T}_\delta &= 5 \times 10^{9}, \\ \alpha_V &= 2.95, \\ \sigma_{V,0} &= 10. \end{aligned}$$

Eq.(1) is solved for τ and replace $\sigma_V(\tau)$ with $\Delta V = |\vec{V} - \vec{V}_{LSR}|$ to estimate a kinematical age of each star.

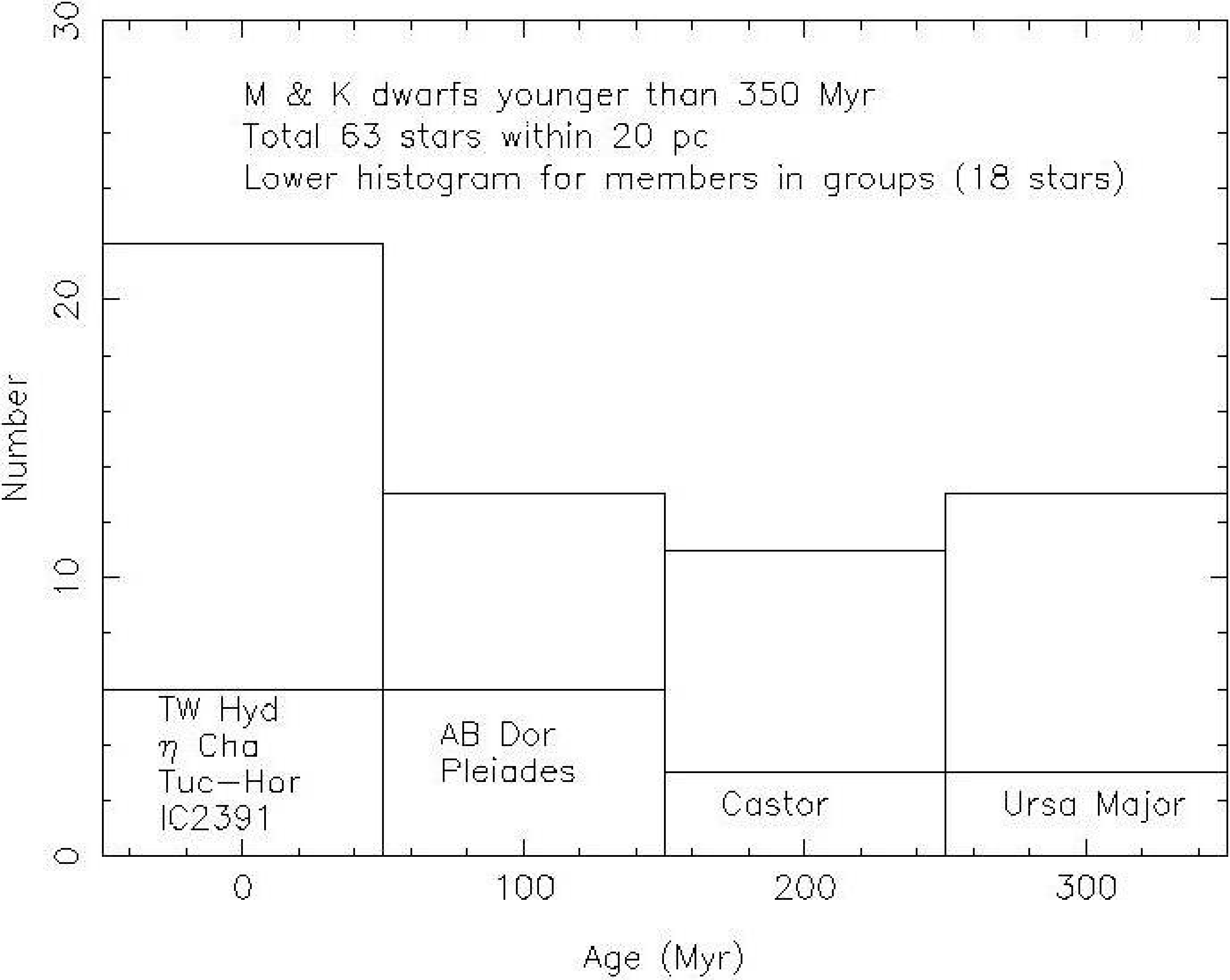
Kinematical Ages of Famous Stars



Star	Spectral Type	τ (Myr)	V (kms^{-1})	Comment
Vega	A0	-47	6.2	
Fomalhaut	A5	-45	6.5	
β Pic	A5	19	11.0	β Pic group
ϵ Eri	K2	360	19.2	
AU Mic	M1	72	13.0	β Pic group
Gl 229A	M1	680	23.5	young disk star

Note that zero-age velocity dispersion is assumed to be 10km/s by Fuchs and Wielen (1987).

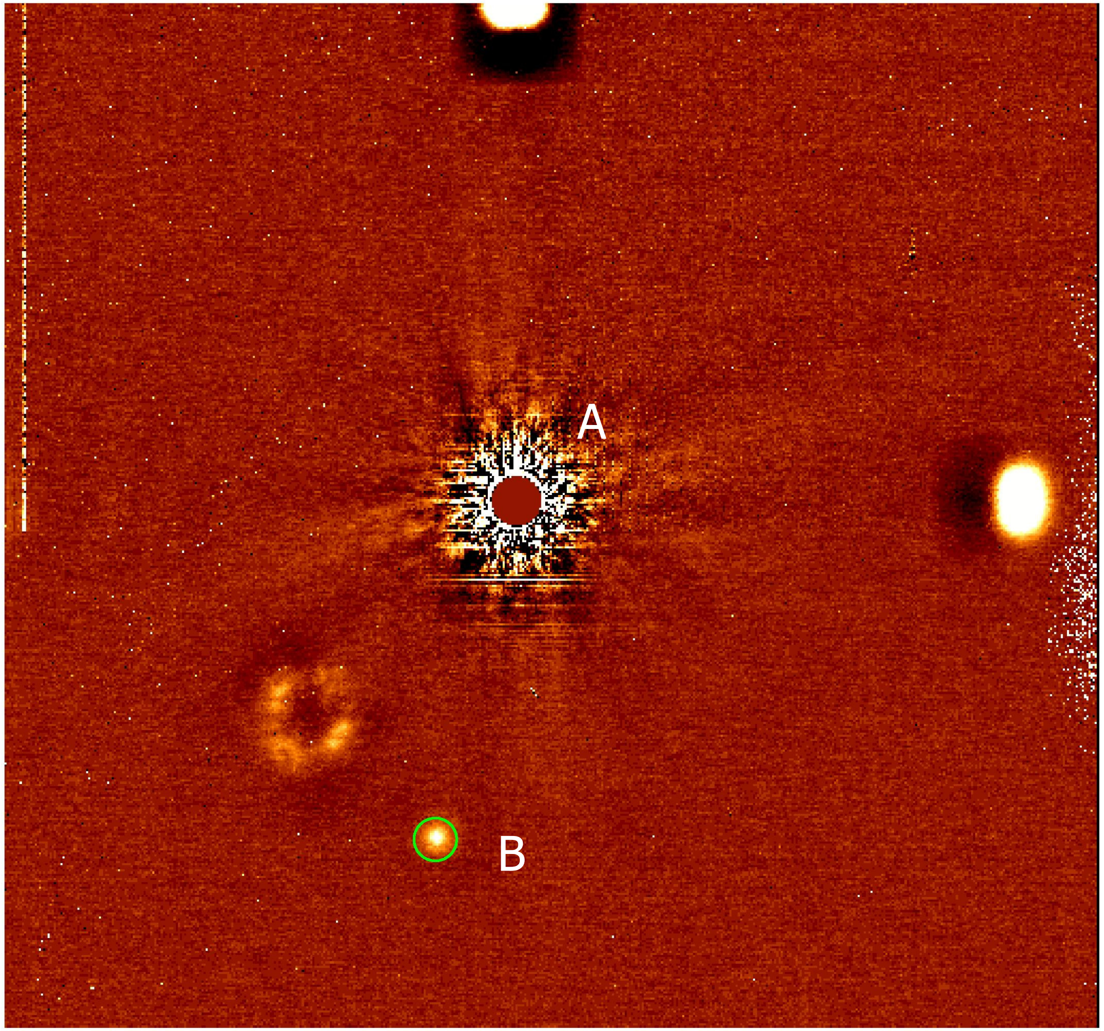
Age distribution of targets



Results since August 2004

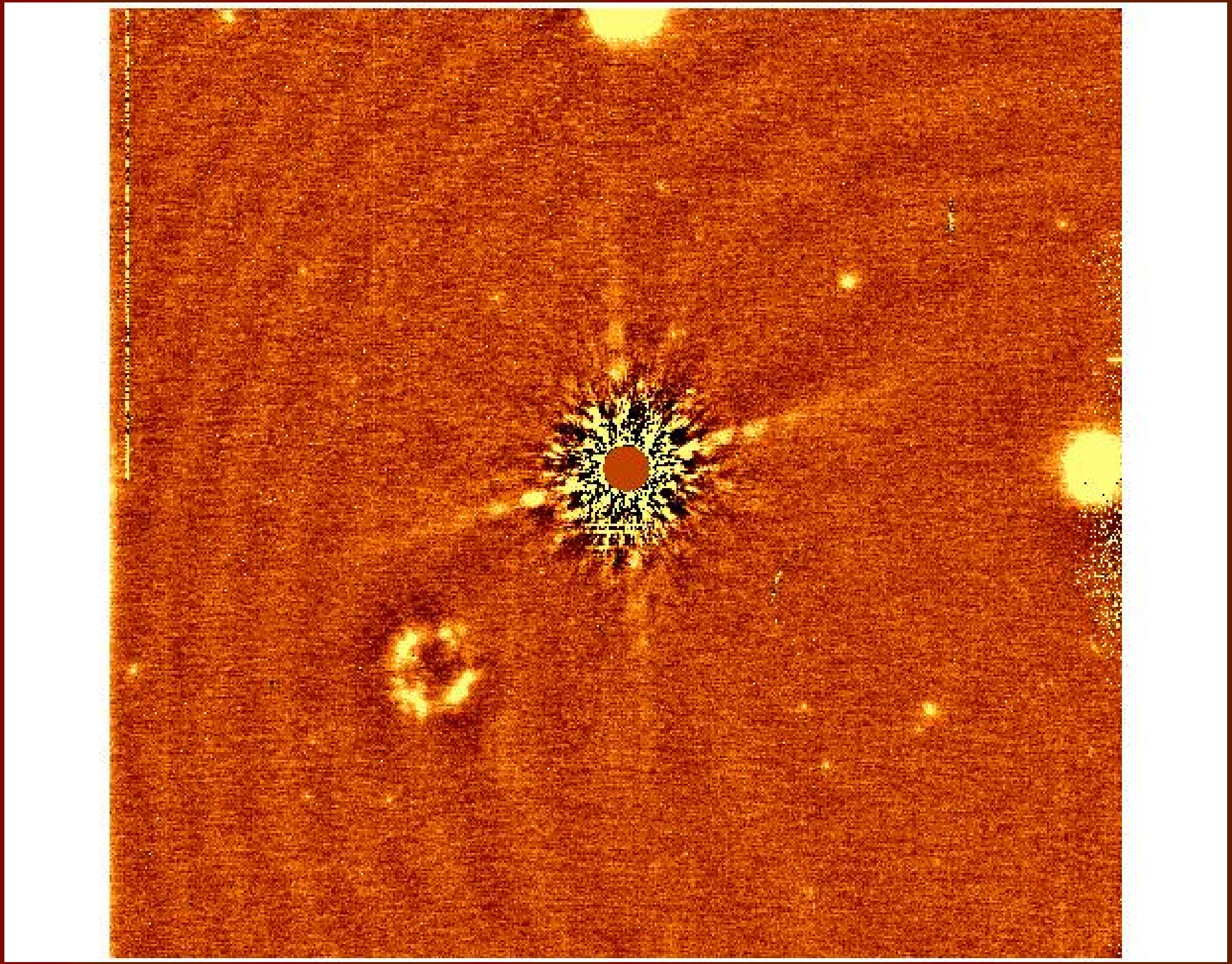
- Age criterion was not so strict for the targets observed in 2004.
  - Used CNS3 instead of Reid, Gizis & Hawley.
    - Information on kinematics was crude.
    - Age limit was about 700 Myr instead of 300 Myr.
  - Mass limit was about $5M_J$.
- 70 stars were observed (2nd epoch for limited targets).
  - ~20 stars were binaries.
  - Confirmed one known BD (Gl229B)
  - No planet confirmed so far.
- Massive giant planets ($> 5M_J$) may be rare around low mass primary stars (<0.5Mo).
  - Not yet a statistically significant statement.

Gl 229 system. No component C.



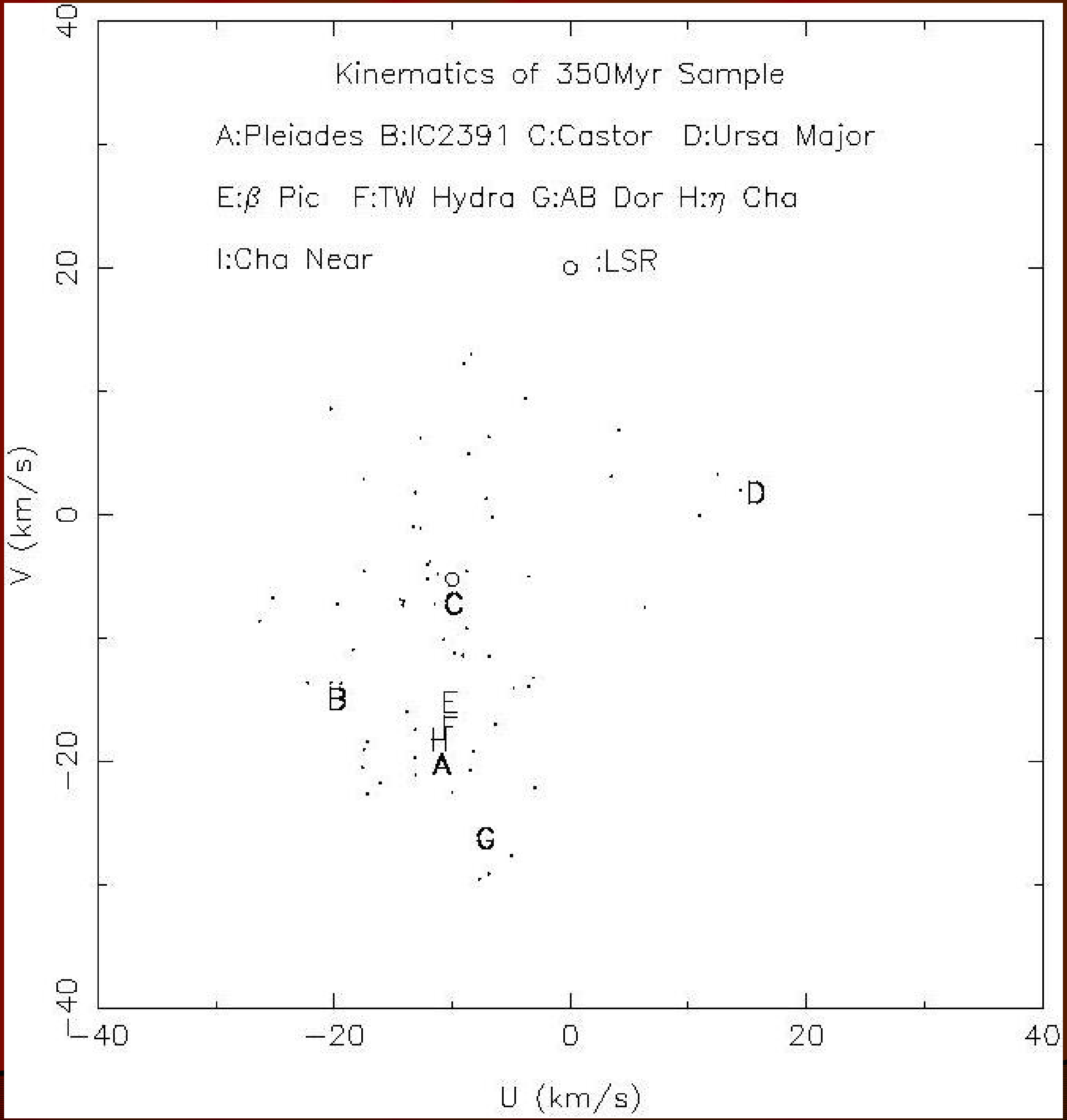
d=5.7pc FOV =114x114AU Mask=2” in diameter.

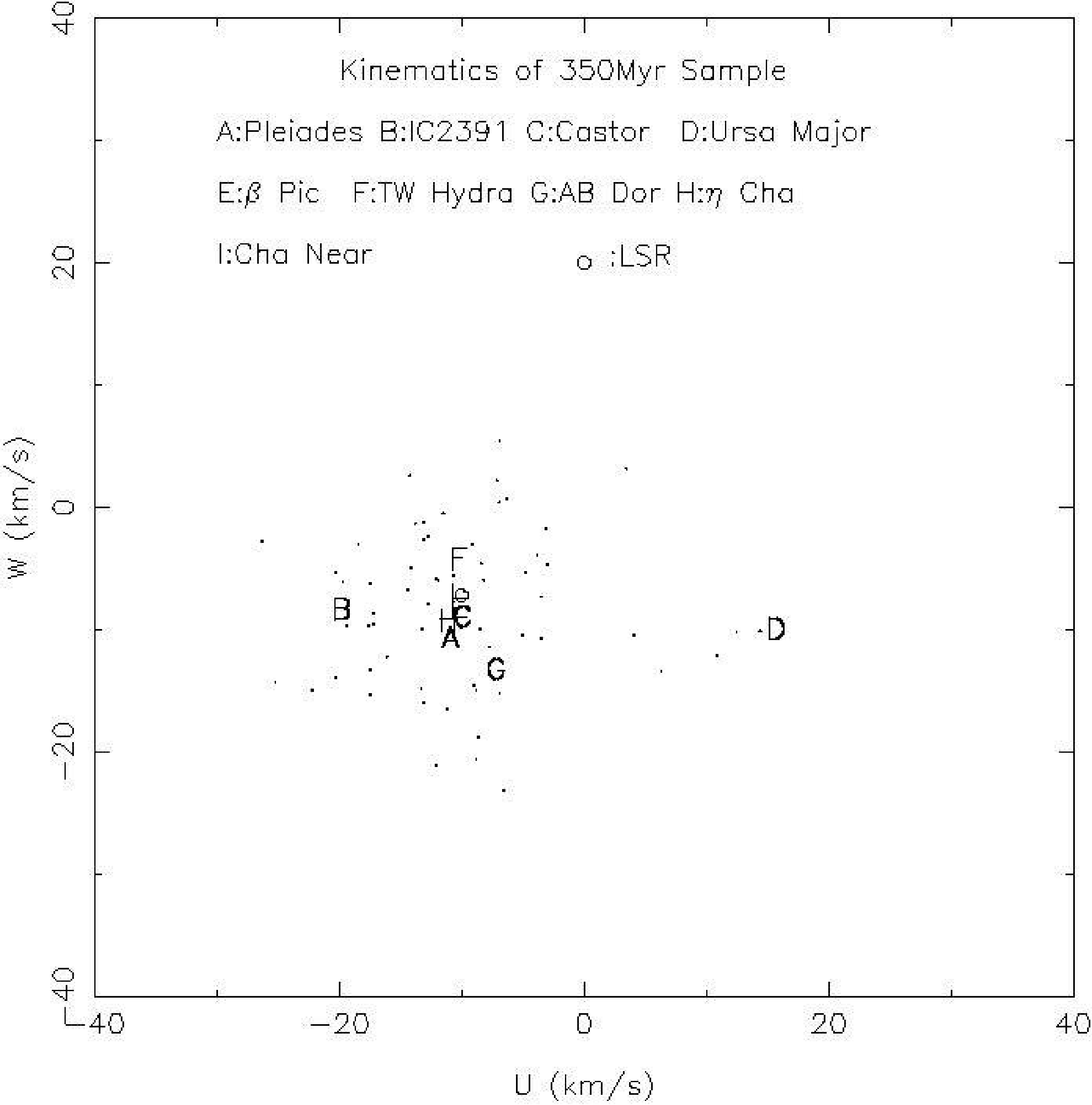
A target at 3pc with t<350Myr



$M_K<23$, Mask=3AU in diameter. FOV=60x60AU

2nd epoch observing in a week from now.


Kinematics of 350Myr Sample
A:Pleiades B:IC2391 C:Castor D:Ursa Major
E:β Pic F:TW Hydra G:AB Dor H:η Cha
I:Cha Near
o :LSR
A
B
C
D
E
F
G
H
V (km/s)
U (km/s)
40
20
0
−20
−40
−40
−20
0
20
40


Kinematics of 350Myr Sample
A:Pleiades B:IC2391 C:Castor D:Ursa Major
E:β Pic F:TW Hydra G:AB Dor H:η Cha
I:Cha Near
o :LSR
A
B
C
D
E
F
G
H
I
W (km/s)
U (km/s)
40
20
0
−20
−40
−40
−20
0
20
40