Evolution of Stellar Rotation:

Time for a New Viewpoint?

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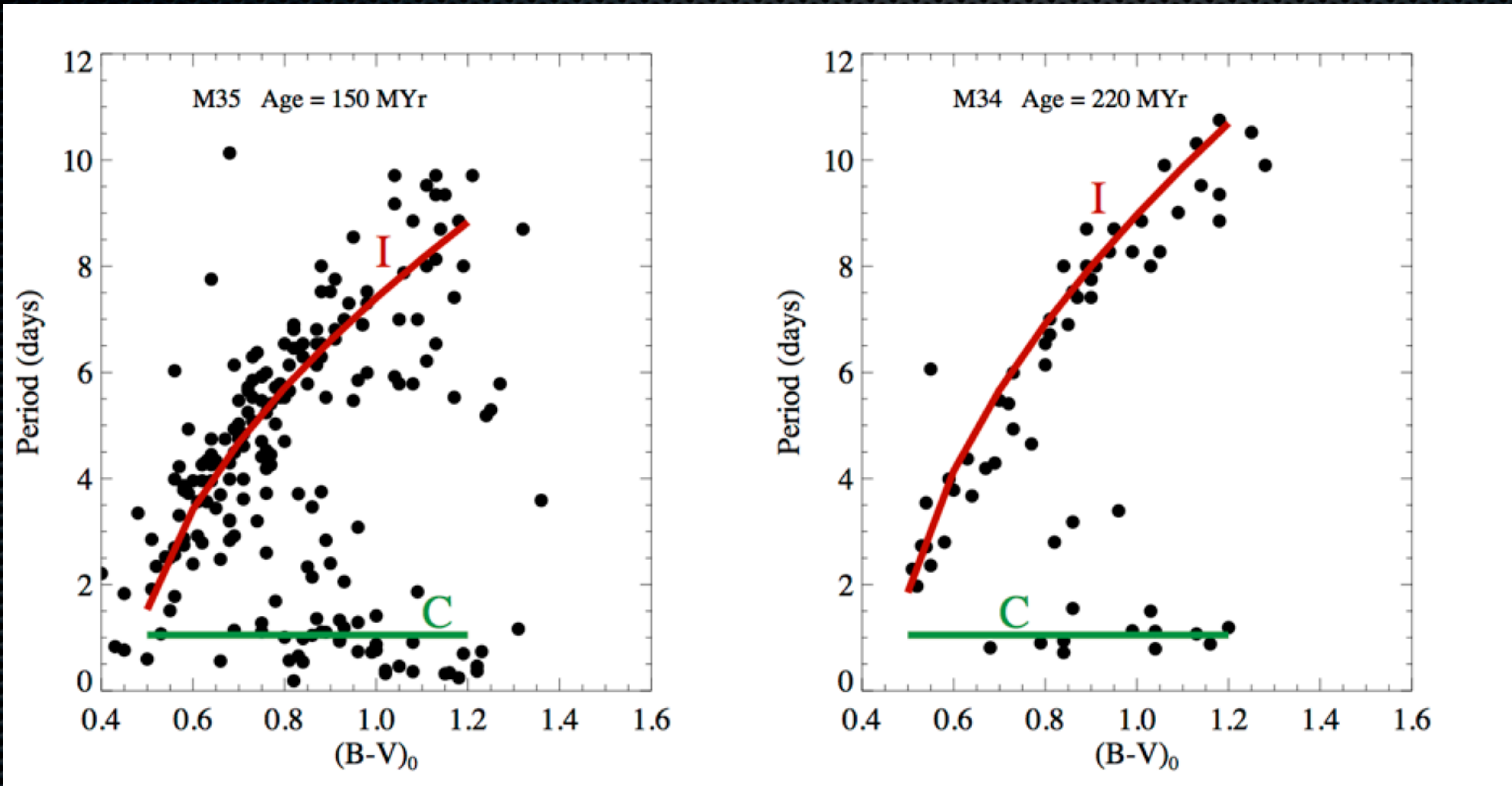


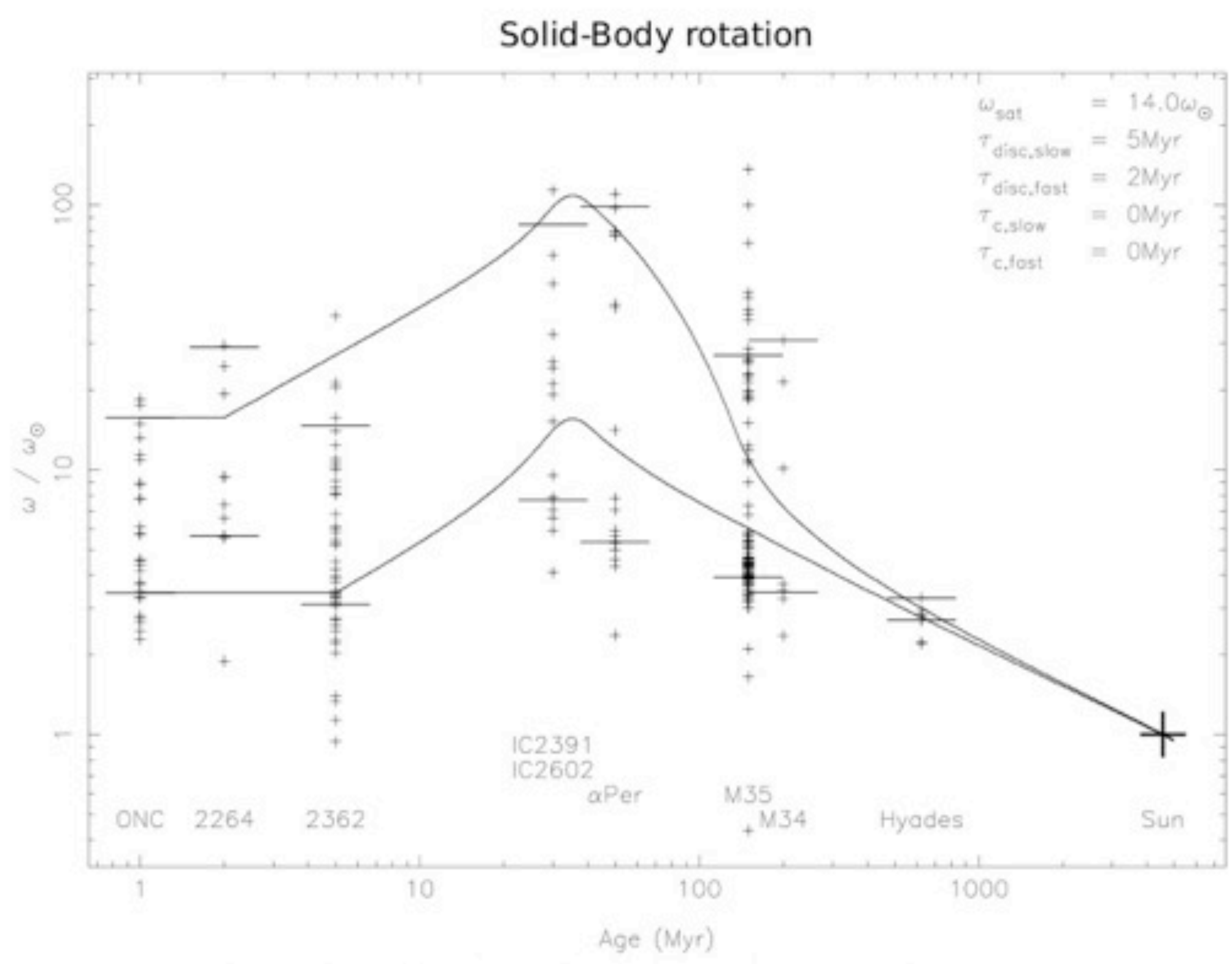
M35 Age = 150 MYr
M34 Age = 220 MYr
Period (days)
(B-V)0
I
C

Adopting this critical-frequency assumption, and taking $n = 3/2$ (monopole field configuration) in Kawaler's expression gives what is now the standard formulation of the wind torque law:

$$\frac{dJ}{dt} = -K_w \left(\frac{R}{R_\odot}\right)^{0.5} \left(\frac{M}{M_\odot}\right)^{-0.5} \begin{cases} \Omega^3 & \text{for } \Omega \leqslant \Omega_{\text{crit}}, \\ \Omega_{\text{crit}}^2\,\Omega & \text{for } \Omega > \Omega_{\text{crit}}, \end{cases}$$

With plausible (motivated by disk-locking) initial conditions and sensible stellar models, this leads to tracks showing $\Omega(t)$ that look like this:

Irwin & Bouvier, astro-ph 0901.3342v1 (2009)
in The Ages of Stars, IAU Symp 258



Trouble with slow rotators

Look again at the last graph -- there is a problem fitting the slow rotators with ages about 30 - 200 Myr. To produce stars with such long P_{rot} at such young ages requires implausibly long disk locking times, or long initial periods (small initial Ω), or both.

The proposed solution for this problem is to (mostly) decouple the rotation of the stellar convection zone from that of the interior. The CZ has much less inertia than the whole star, so spins down faster. Equilibrium P_{rot} is attained when torques balance across inner & outer boundaries of CZ.

To fit the data requires τ_c, the CZ-interior equilibration time, to be a function of mass, running from about 30 Myr for mass = 1.3 to abut 300 Myr for mass = 0.5
(If longer τ_c, the Sun would show such differential rotation, which it doesn't.)

Achieving such long equilibration times requires no magnetic coupling between the CZ and interior.

Irwin & Bouvier, astro-ph 0901.3342v1 (2009)
in The Ages of Stars, IAU Symp 258

Barnes's Symmetrical Empirical Model

Barnes (2010) and Barnes & Kim (2010) took a more explicitly empirical approach. They identified 2 sequences in the color/P_{rot} diagram -- the slowly-rotating *"I"* sequence, and the fast-rotating *"C"* sequence. Then for each sequence individually, $\Omega(t,mass) = 2\pi/P_{rot}(t,mass)$ is expressible as follows:

$$\frac{2\pi}{\Omega} = P_0 e^{t/T(B-V)}$$ for the C sequence

$$\frac{2\pi}{\Omega} = f(B-V) \times g(t),$$ for the I sequence

where $g(t) = t^{1/2}$ and the functions f(B-V) = f(mass), and T(B-V) = T(mass) may be estimated directly from cluster rotation data. With minor additional assumptions, these lead to two torque laws:

$$\frac{dJ}{dt} = -\begin{cases} \Omega I_C / T(B-V), & \text{for the C sequence} \\ \Omega^3 I_* f^2(B-V) / 8\pi^2, & \text{for the I sequence.} \end{cases}$$

where I* is the moment of inertia of the whole star, and I_C is the moment of inertia of (whatever is getting spun down) on the C sequence.

Barnes's Symmetrical Empirical Model

In Barnes (2010), two torque laws are combined into a single

period evolution expression for $dP/dt = -2\pi\ \Omega^{-2}\ d\Omega/dt$:

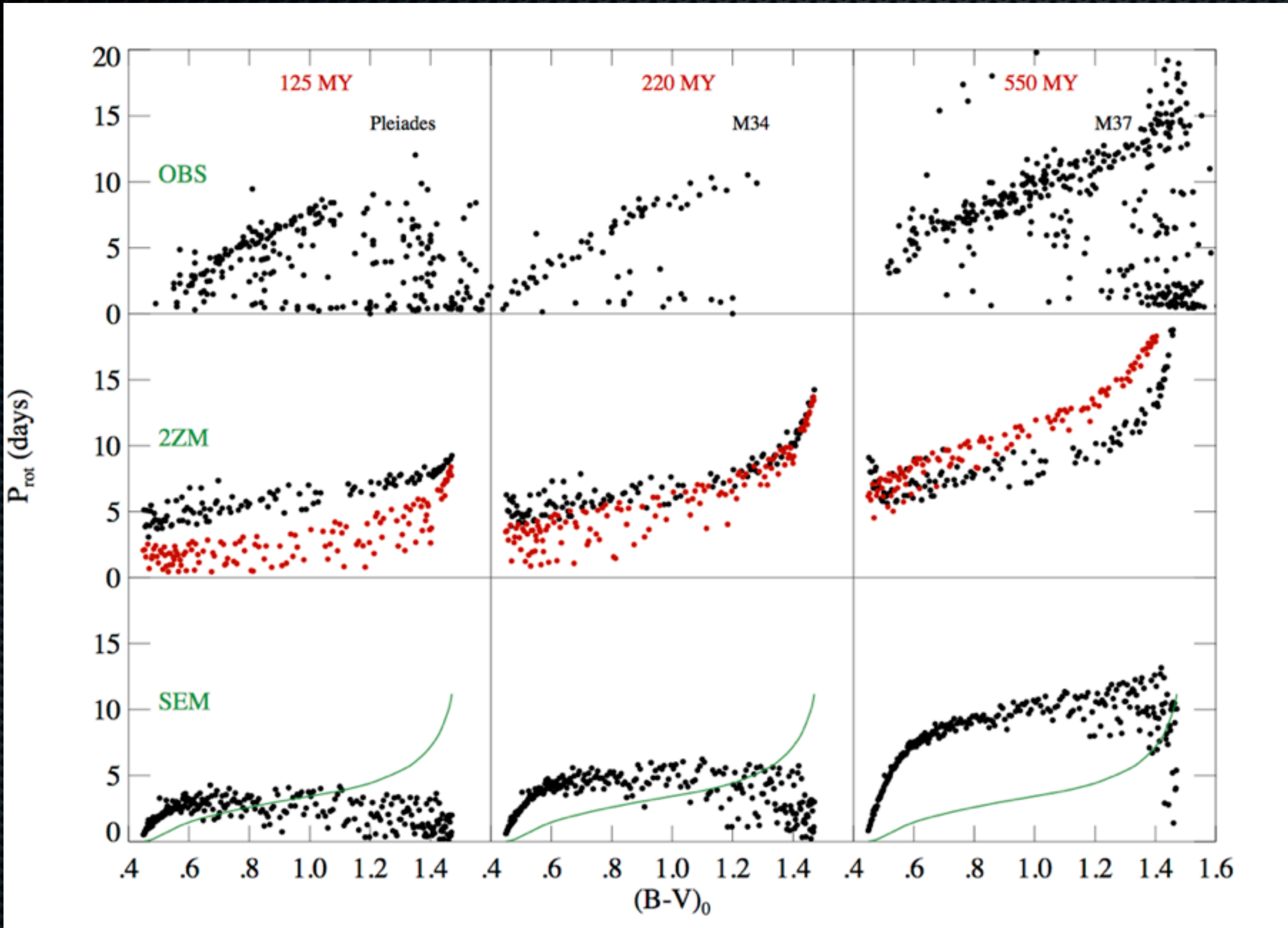
$$\frac{dP}{dt} = \left\{ \frac{k_I P}{\tau} + \frac{\tau}{k_C P} \right\}^{-1},$$

where k_I and k_C are constants to be fit, and τ is a mass-dependent timescale, which Barnes identifies as the star's convective turnover time.

By adopting a moment of inertia equal to that for the entire star, one may easily arrive at a solid-body torque law that combines the two sequences:

$$dJ/dt = -I^* (\Omega^2/2\pi) [(2\pi\ k_I/\tau\Omega) + (\tau\Omega/2\pi\ k_C)]^{-1}$$

All of the mass dependence of the torque law is contained in the single function τ(mass). If τ is taken as the convective turnover time, it happens to agree pretty well with the cluster-data-derived functions f(B-V) and T(B-V) from the last slide.


125 MY
220 MY
550 MY
Pleiades
M34
M37
OBS
2ZM
SEM
P_{rot} (days)
$(B-V)_0$
20
15
10
5
0
.4
.6
.8
1.0
1.2
1.4
1.6

Hypothesis
"Metastable Dynamo Model"

(1) Stars rotate like solid bodies, with little or no radial differential rotation.

(2) Stars obey a single mass- and Ω-dependent torque law, analogous to Barnes's prescription above for the I sequence:

$$dJ/dt = - K_M \Omega^3 f^2(B-V)$$

(3) However, the leading constant K_M may take one of two values:

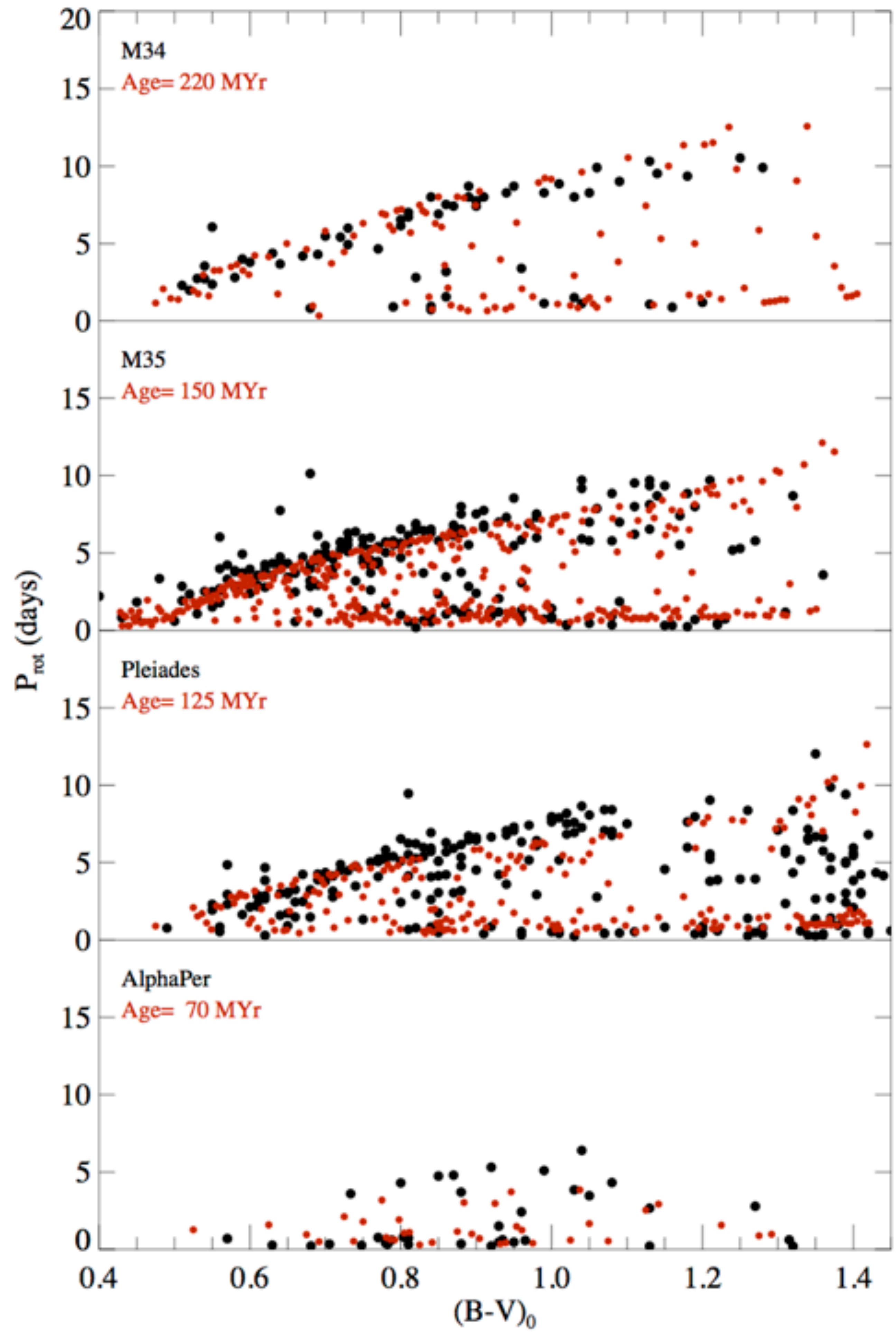
Stars are born with $K_M = K_{M0}$, which is very small compared to K_w.

Stars transition to $K_M = K_{M1}$ at random times, with a mass-dependent decay time proportional to Barnes's T(B-V). K_{M1} is the conventional leading constant in the Skumanich torque law.

To get good fits, need four parameters:

K_{M0}, K_{M1},
Transition timescale,
Shape exponent for *I* seq.

With these,
MDM works pretty well for youngish clusters.



What Might This Mean, Physically? (Speculation)

Torque on stars comes from a magnetized wind. To reduce the torque by a lot, we must mess with either the wind or the *B* field (or both).

My guess is the field. Recall Kawaler's form of the torque law:

$$\frac{dJ}{dt} = -K_W \Omega^{1+(4an/3)} \left(\frac{R}{R_\odot}\right)^{2-n} (\dot{M}_{14})^{1-(2n/3)} \left(\frac{M}{M_\odot}\right)^{-n/3}$$

where *n* has to do with the field geometry. For high multipoles, with many small-scale field structures, maybe little field leaks out into the stellar corona, hence the photosphere doesn't couple well to the distant stellar wind.

Observational Tests

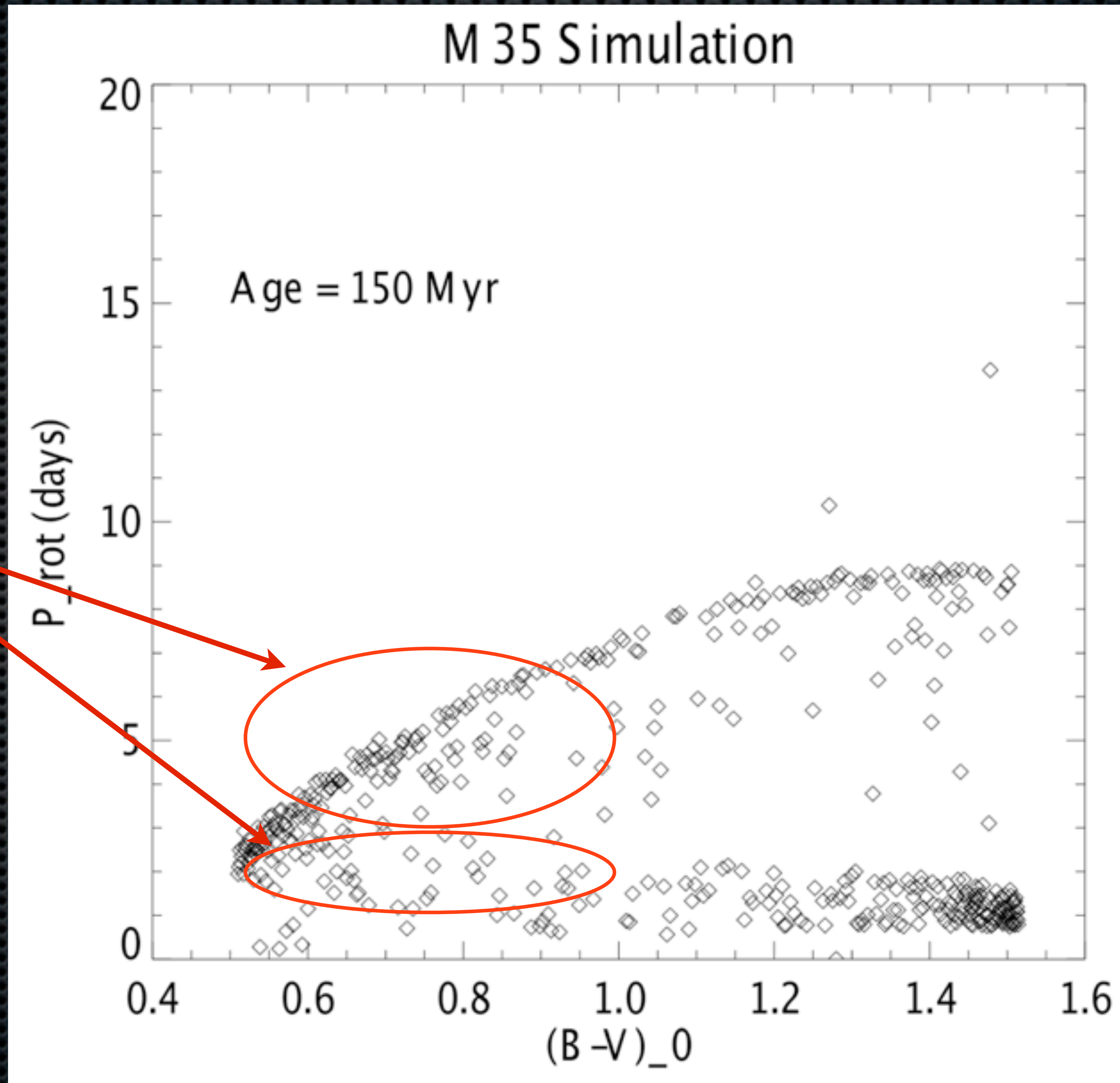
(1) Asterosesmology should be able to determine whether young-star CZs rotate at the same rate as their radiative interiors.
This is proving to be hard (magnetically active stars have lower pulsation amplitudes, larger noise than inactive ones), but should be possible with enough (space-based) data.

(2) Distribution of stars in P_{rot} at constant color distinguishes among models. In particular, the metastable dynamo model makes clear predictions, not too dependent on initial conditions. (next slide)

(3) The *B* - field morphology should differ between stars on the C-sequence and those at only slightly longer P_{rot}, if the metastable model is correct.

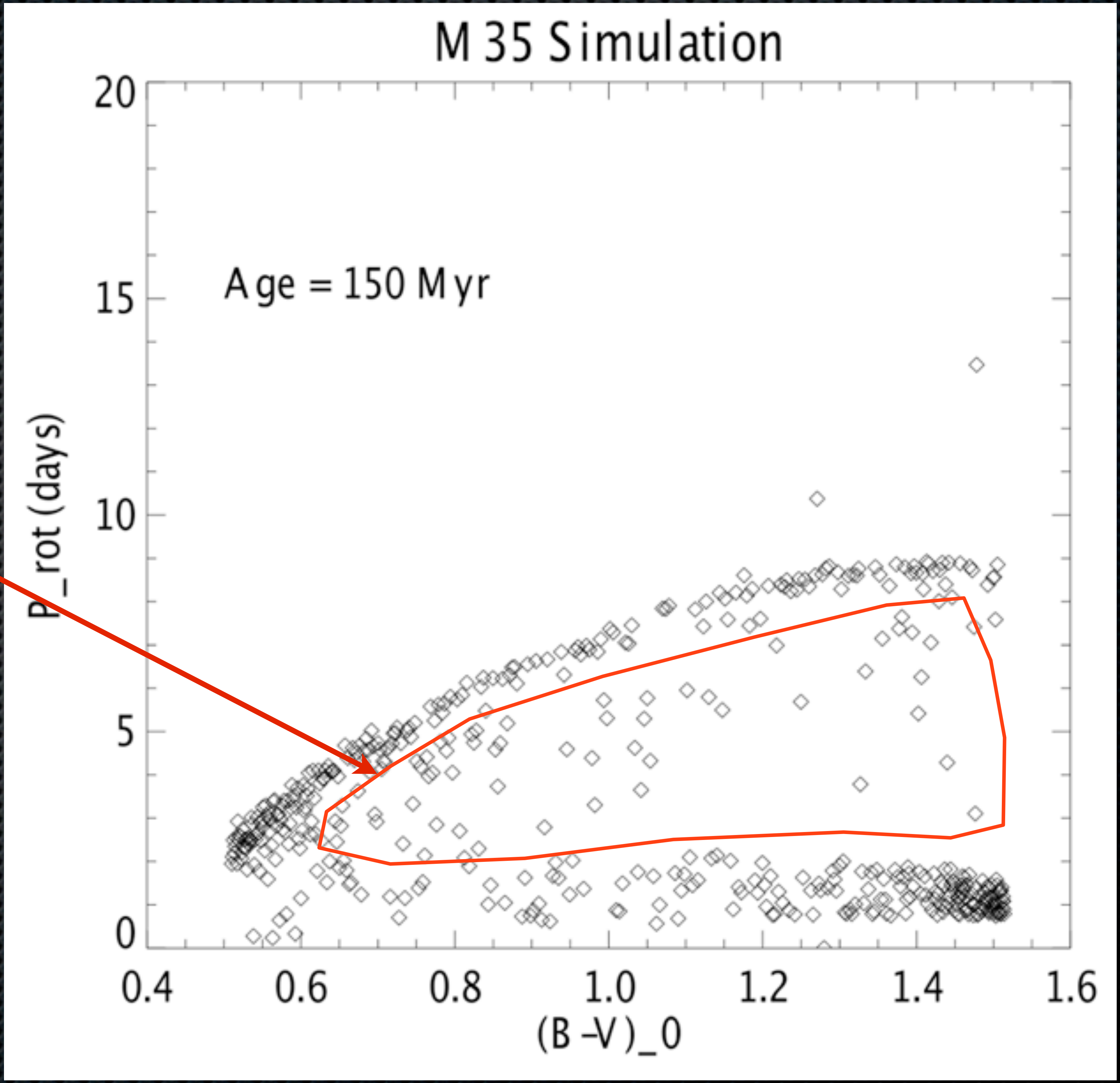
Asteroseismology:

If Pinsonneault et al. are correct, both these groups of stars should have rapidly-spinning interiors.



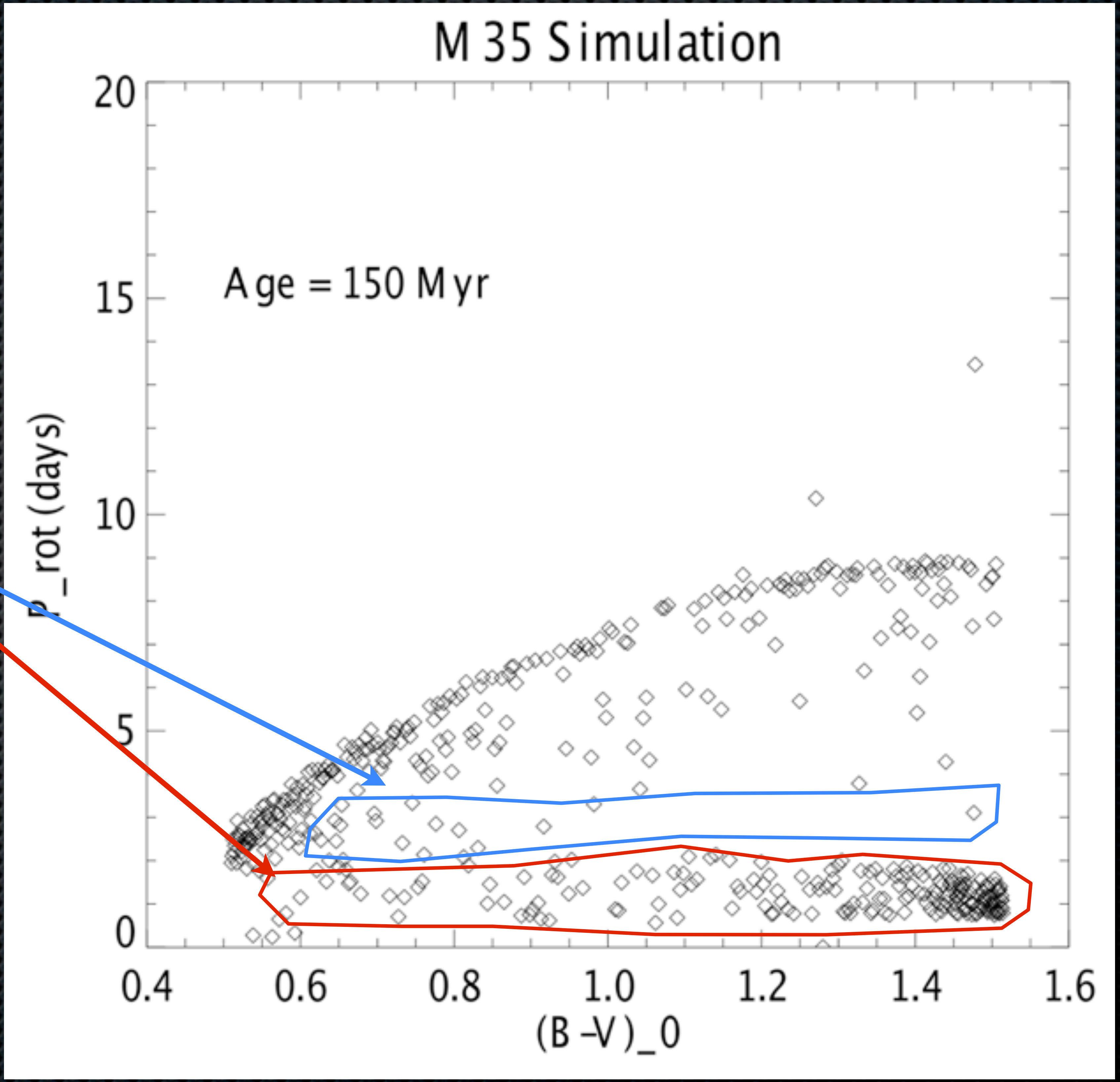
P_{rot} distribution:

Each of the 3 models discussed implies a different distribution of stars in this region.



B field morphology:

If metastable model is correct, the morphology of surface fields may differ significantly between these two groups of stars.



What Observations Are Needed?

Asteroseismology of young, active stars. Needs space photmetry.

More and better **color-P_{rot} diagrams.** Means long (months) dense (hours) time cadence precise (< 0.5%) photometry, backed up by spectroscopy for RV and classification.

Doppler imaging of activity on surfaces of selected stars, to look for differing field morphology. Spectro-polarimetry would be good, too.

These are demanding observations.

They require unusual facilities.

LCOGT

LCOGT

(Also other folks)

LCOGT's Main Things

A longitude-distributed network of telescopes, dedicated to time-domain astronomy.

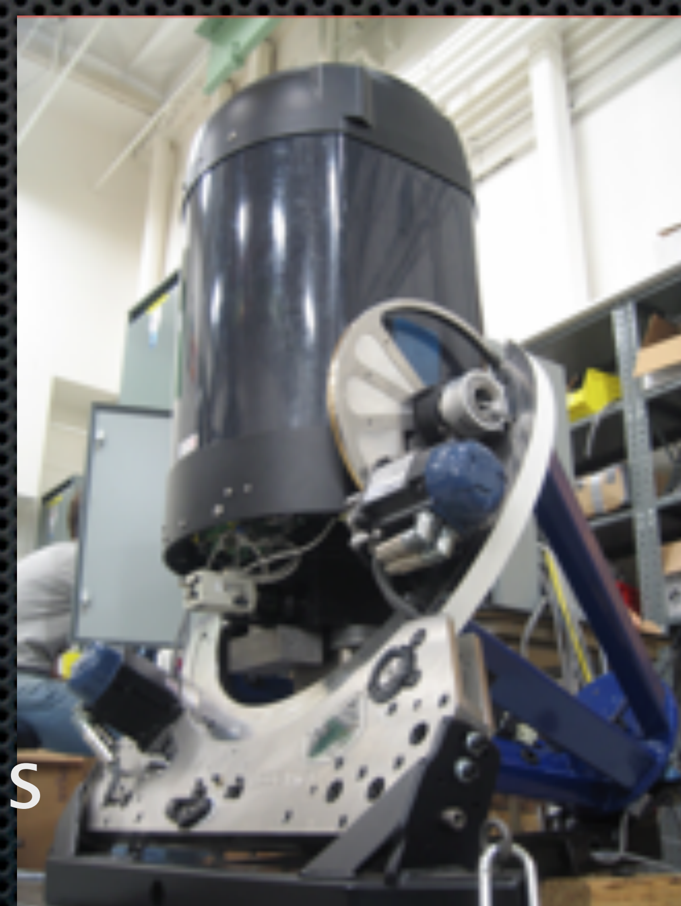
Telescopes, instruments, scheduling, and data acquisition are robotic.

(Like Hubble's "immaculate observing", but more so.)

moderate-aperture telescopes

10 x 1m telescopes
9 now operational
Future instumentation:
Sinistro imager +
NRES spectrographs

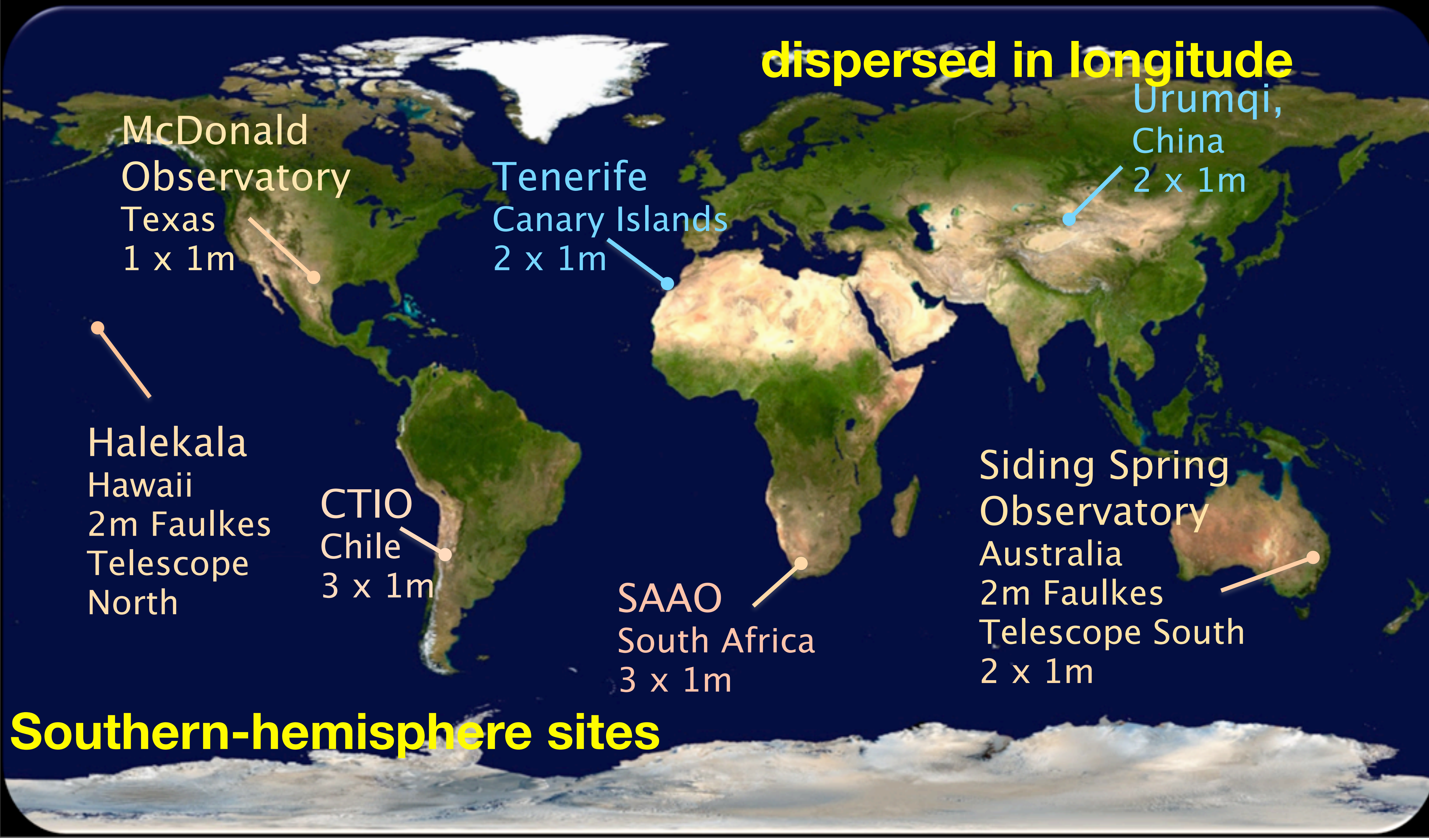
2 x 2m Faulkes telescopes operational imagers + FLOYDS low resolution spectrographs + lucky imaging



20 x 0.4m telescopes
Primarily for education.
Assembled, first ones being deployed

Current
Future
Possible future sites

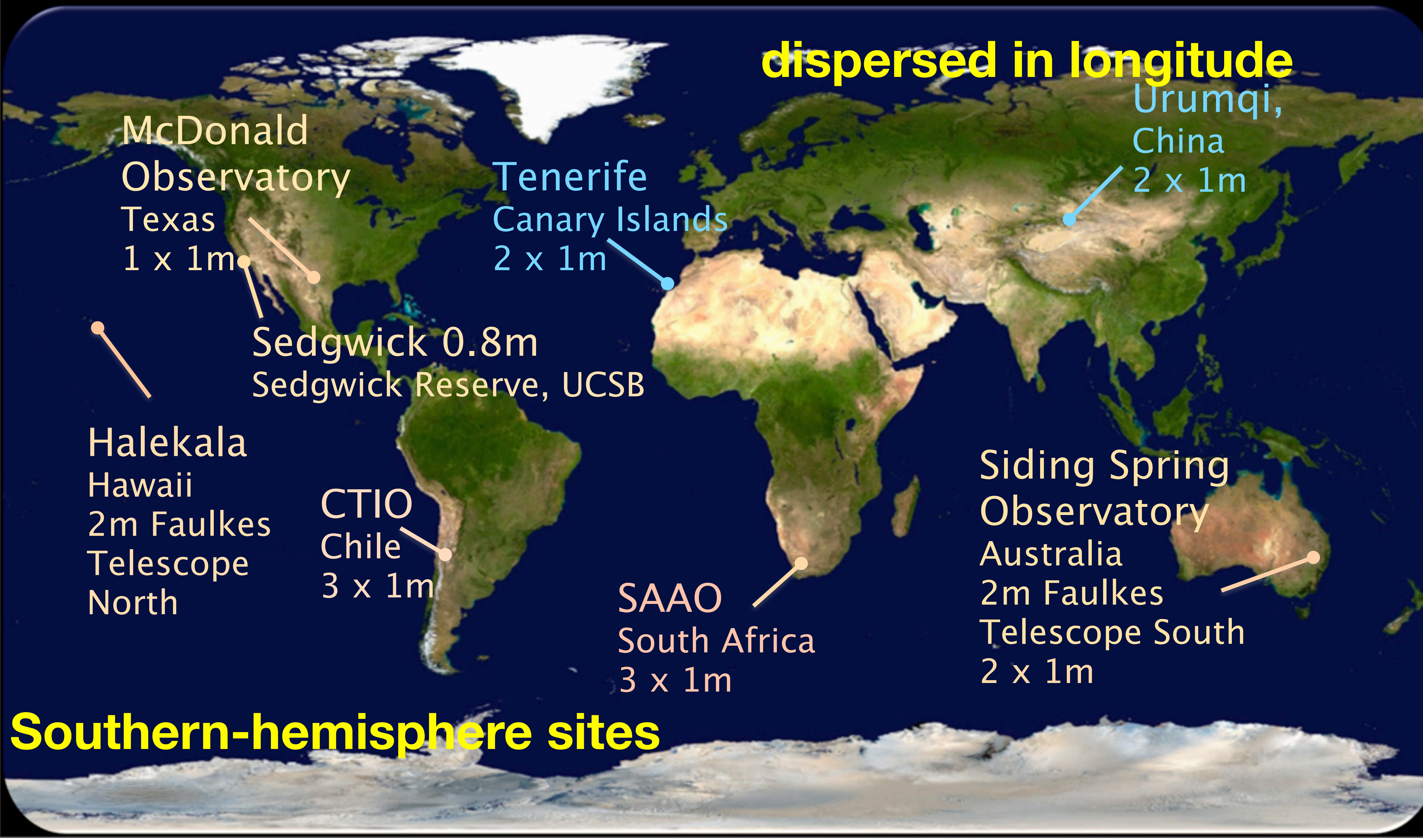
Most sites will also have 3-4 0.4m telescopes.



LCOGT.net

Current
Future
Possible future sites

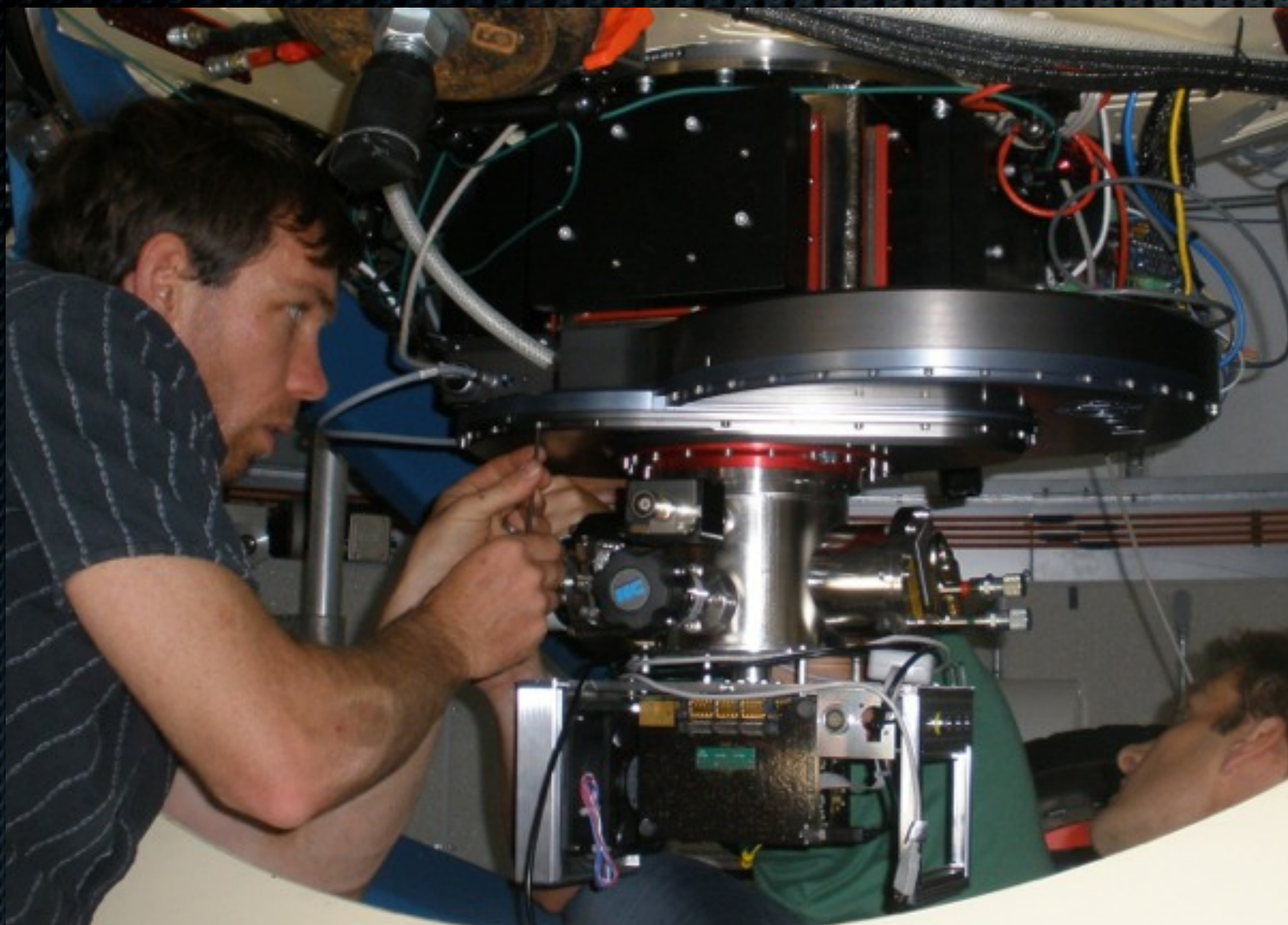
Most sites will also have 3-4 0.4m telescopes.

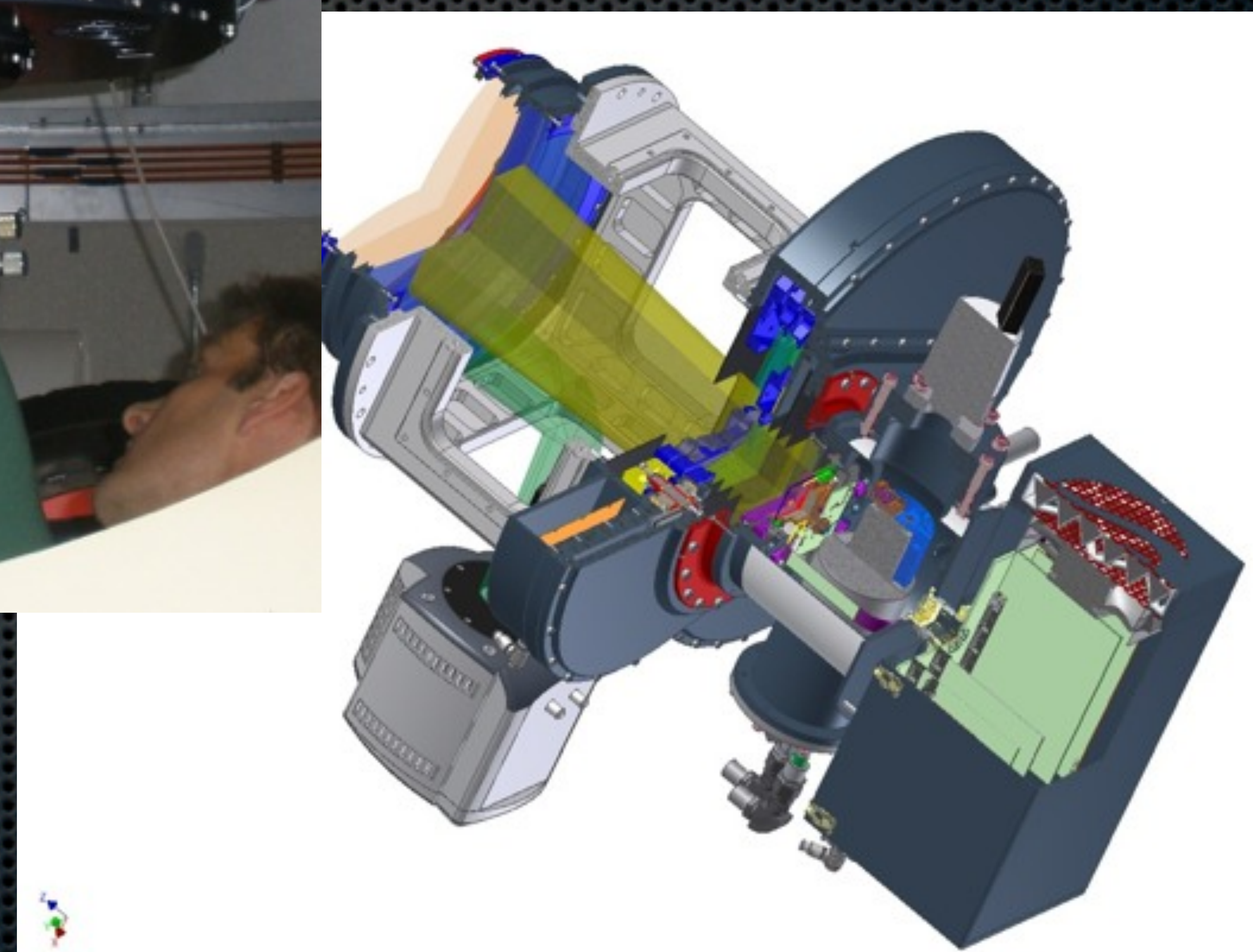


Instruments

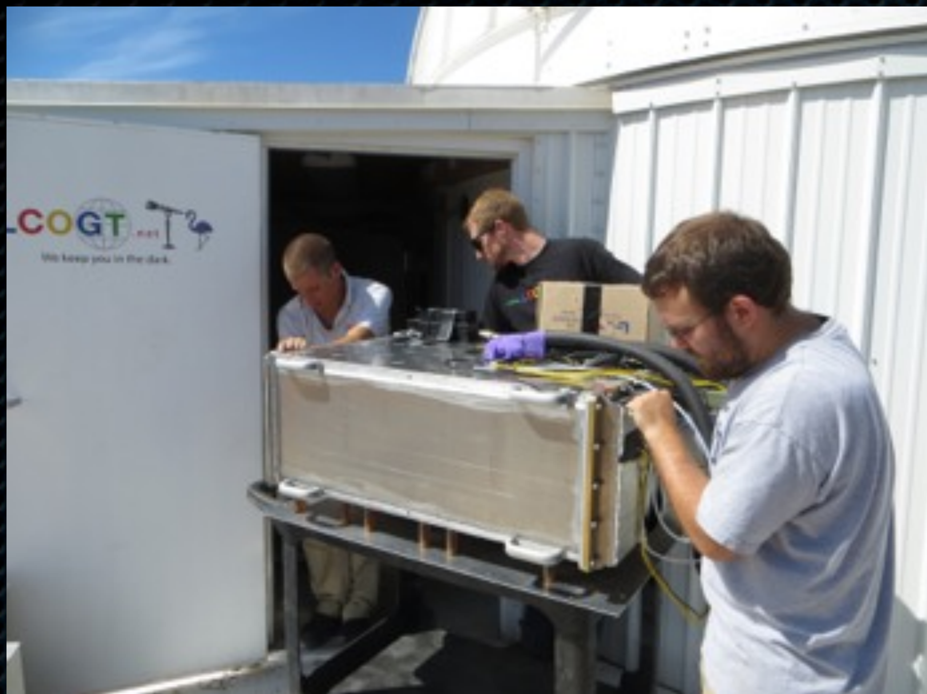
Sinistro

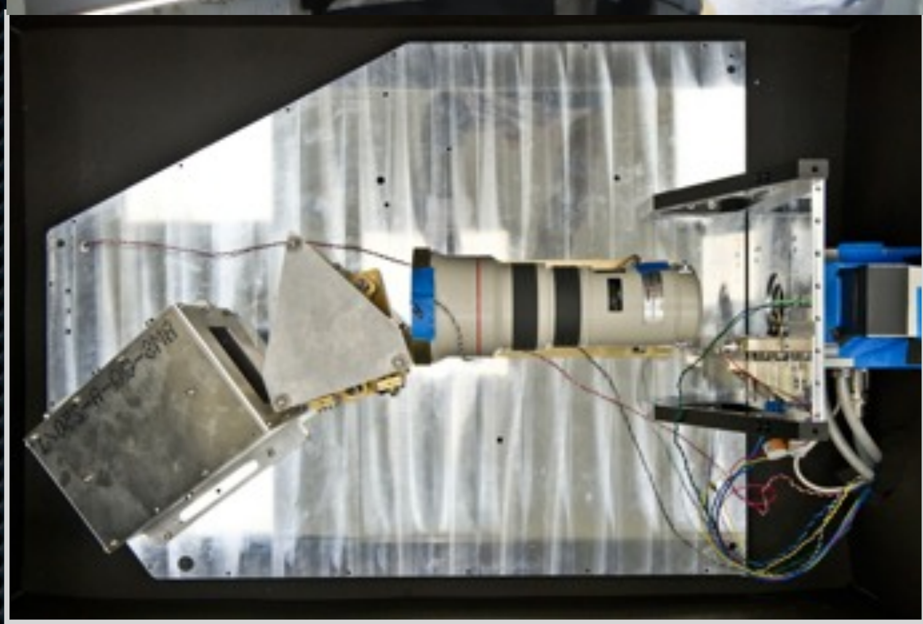
4K x 4K CCD
26 x 26 arcmin FOV
Many filters
Photometric shutter

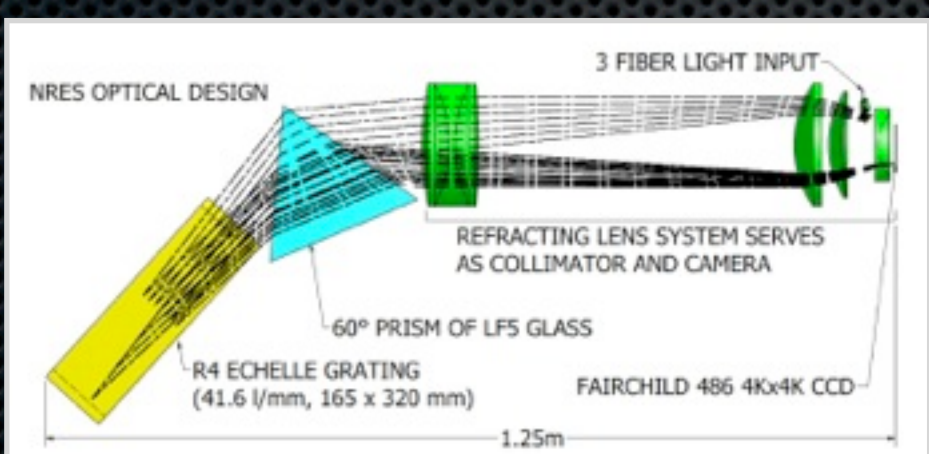




Network of Robotic Echelle Spectrographs (NRES)







Expect first light in 2014.

One at each 1m site, can be fiber-fed by two 1m telescopes

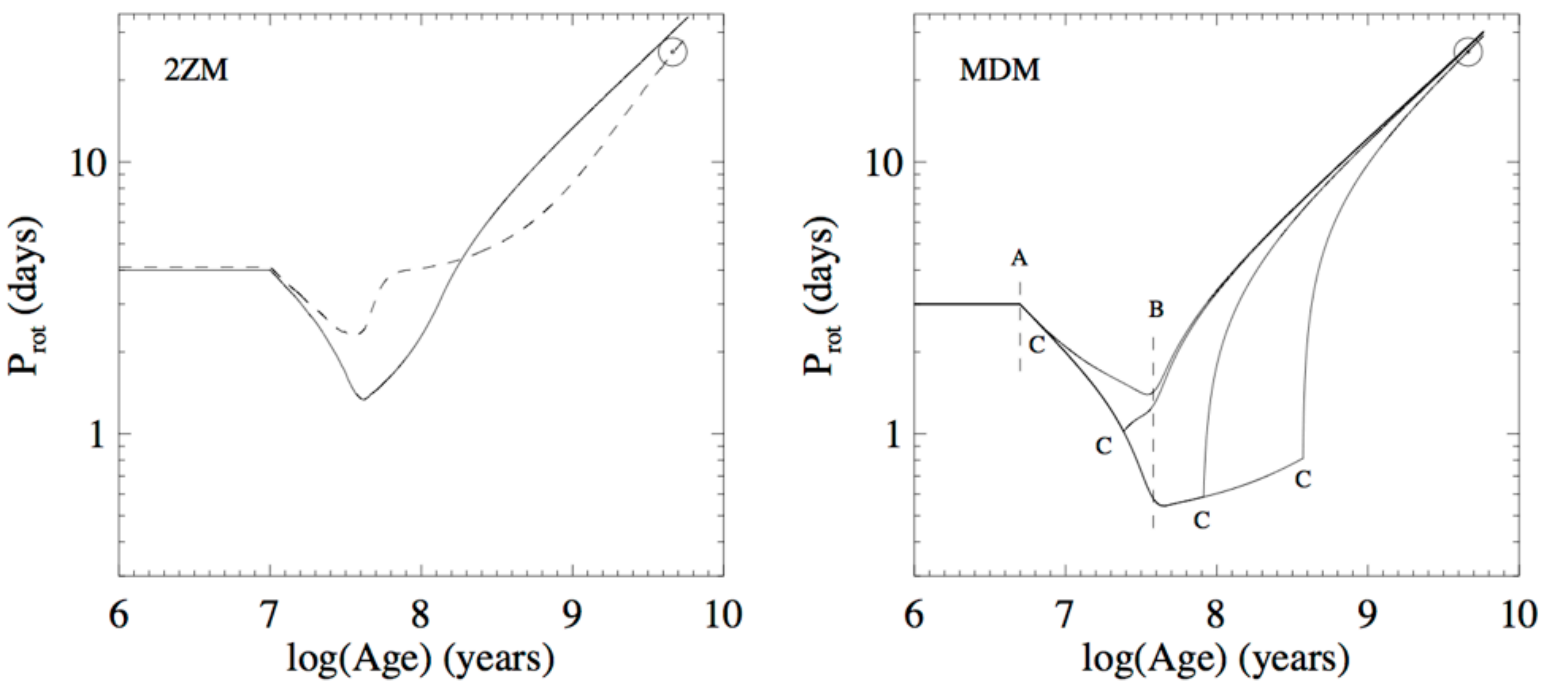
High-resolution (R~53,000), precise (≤ 3 m/s), optical (380-860 nm) echelle spectrographs

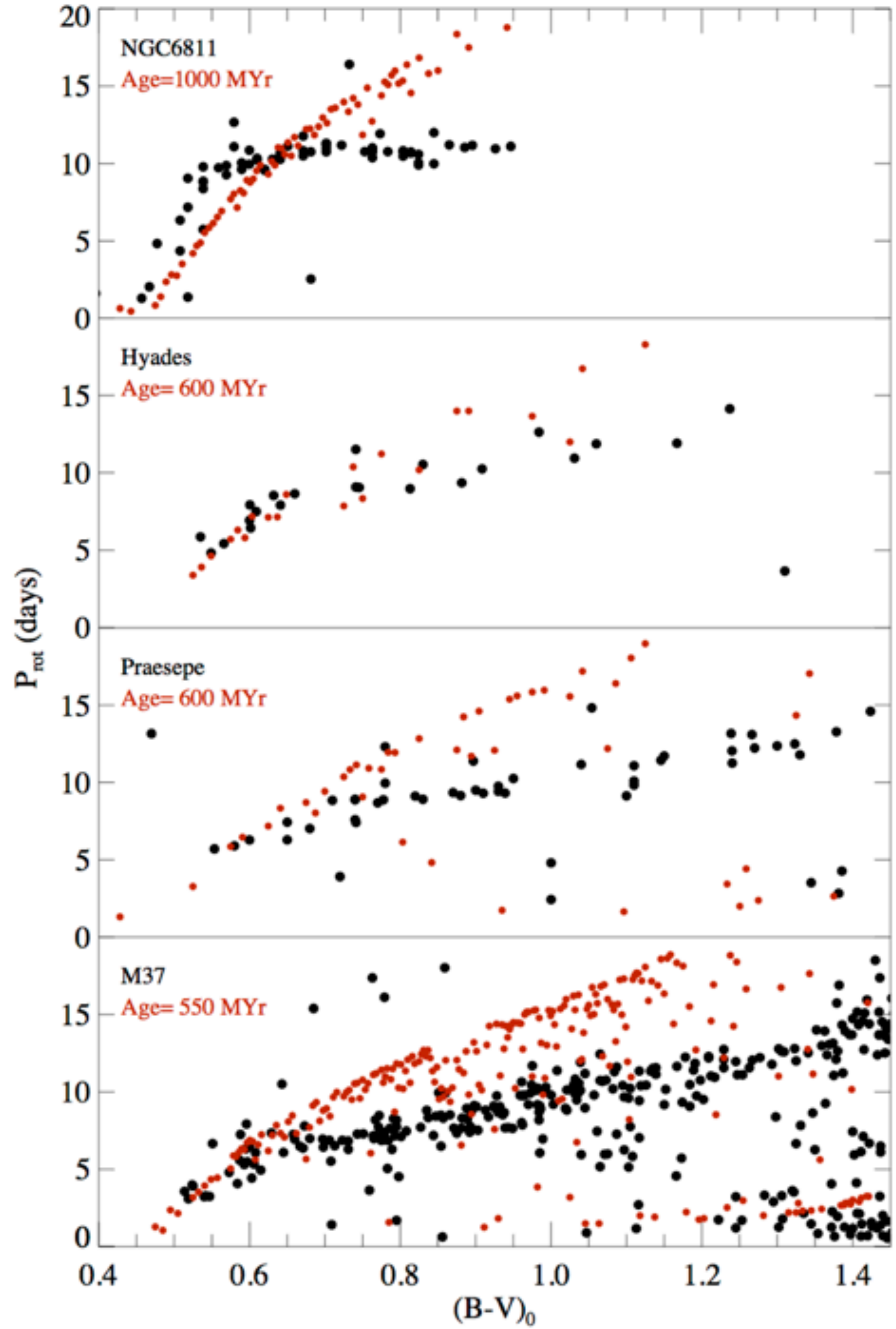
One at each site, fiber-fed (2.58" per fiber width) simultaneously by two 1 meter telescopes and a ThAr calibration source

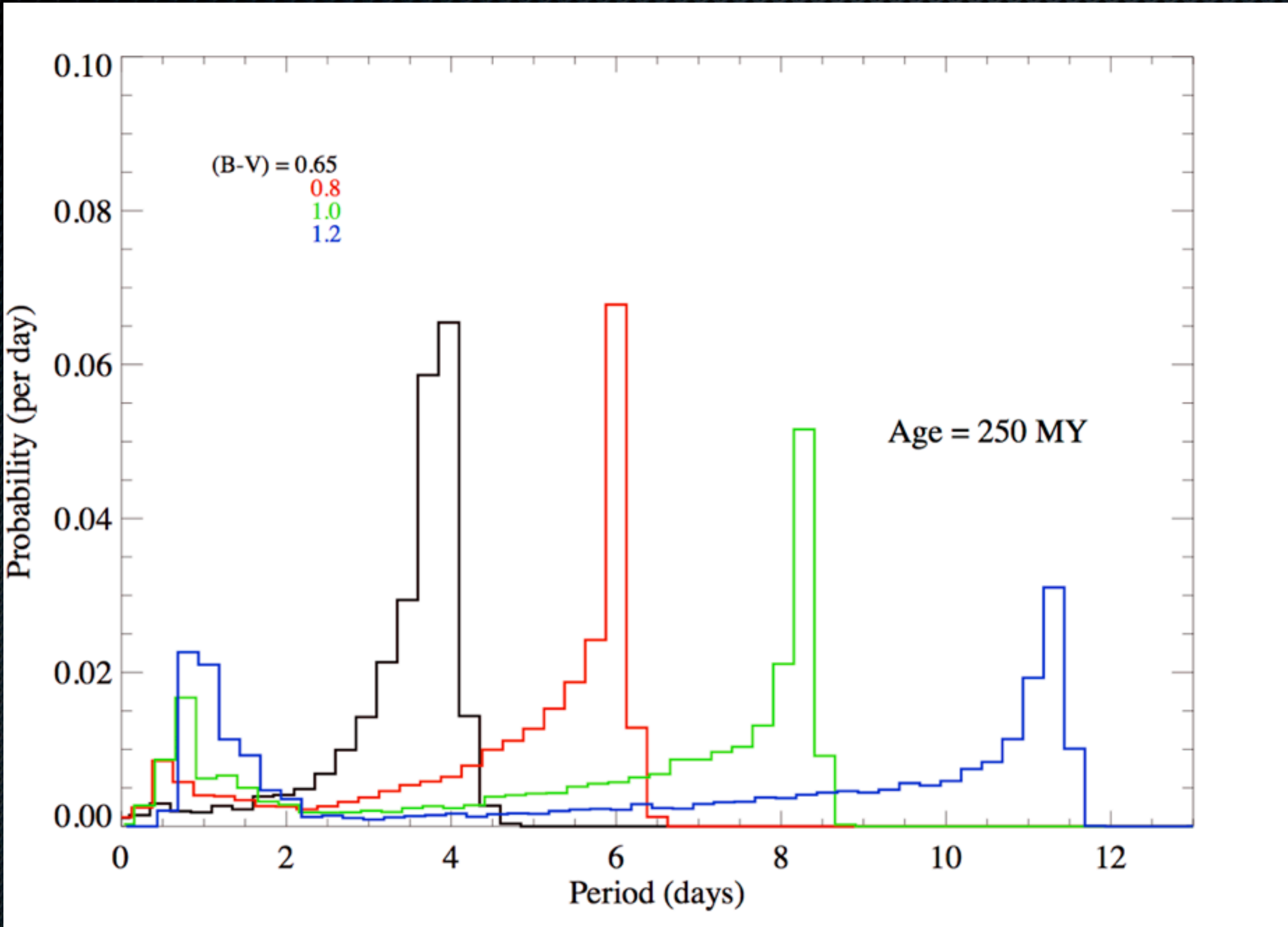
NRES will roughly double the radial velocity planet-vetting capacity nationwide and achieve accuracy better than 3 m/s in reasonable exposure times for stars brighter than V = 12

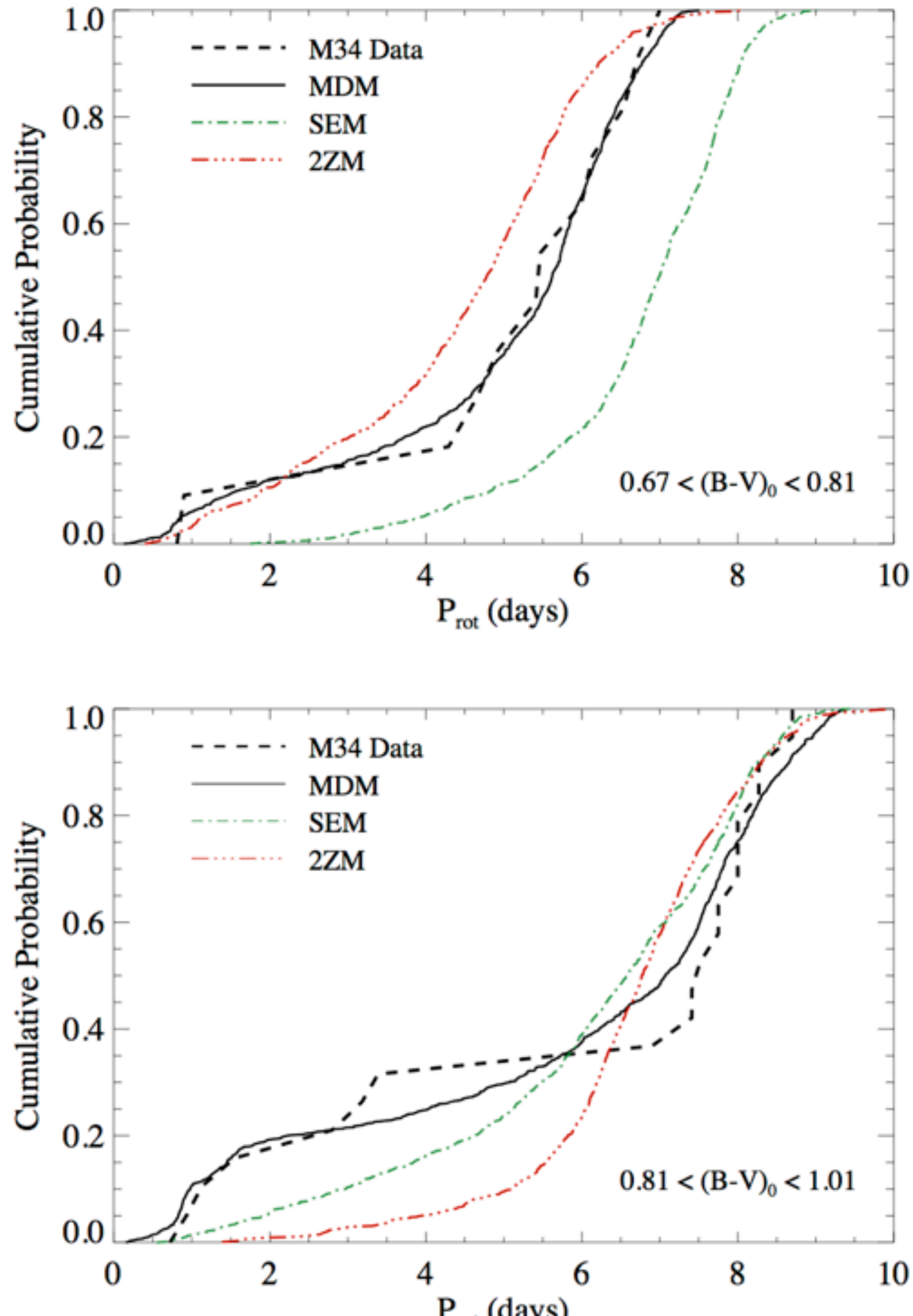
Have NSF grant to build 6, prototype is deployed at Sedgwick, saw 1st light Oct 7 2012.

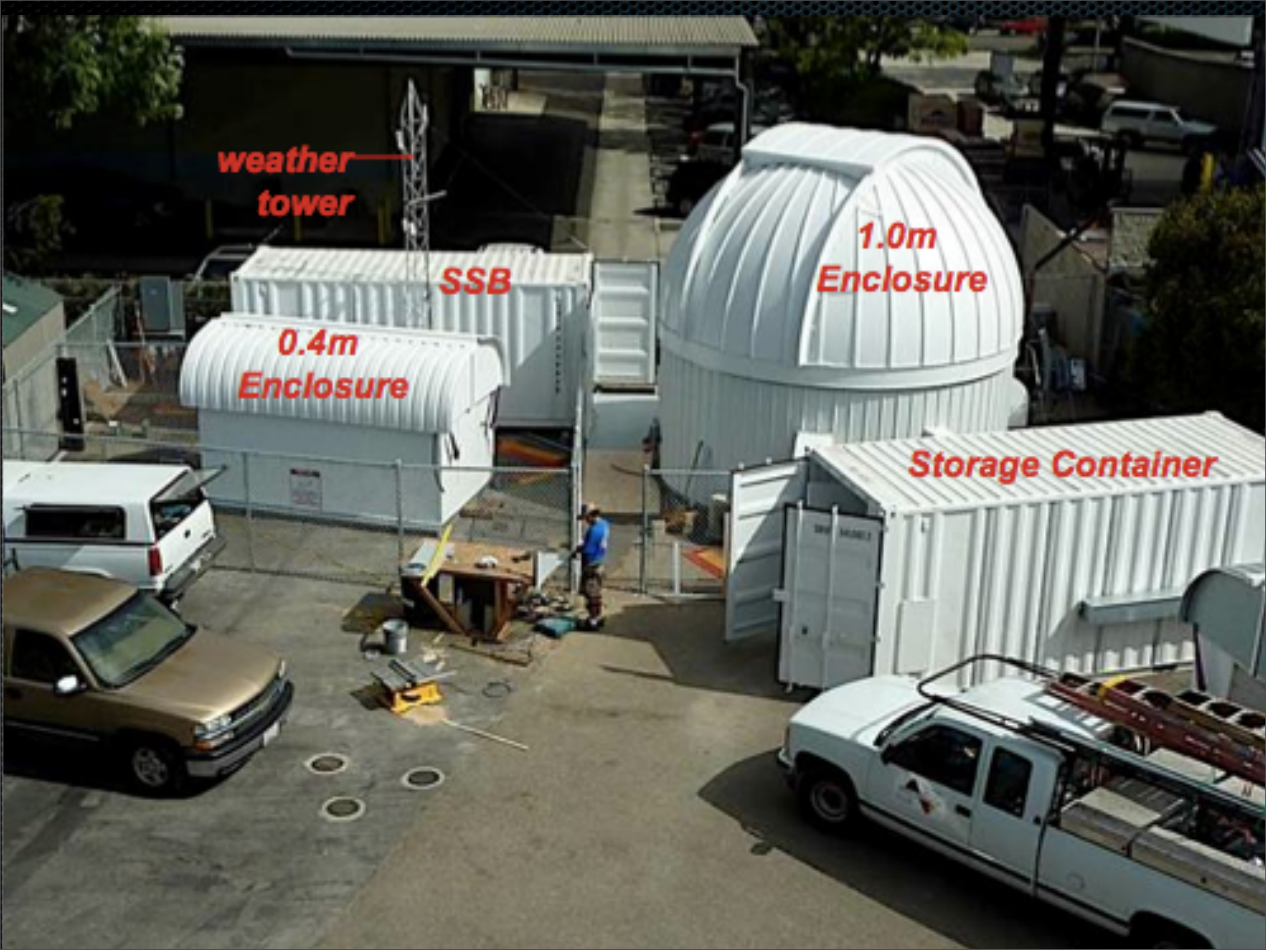
Extra Slides


2ZM
MDM
A
B
C
C
C
C
10
1
6
7
8
9
10
P_rot (days)
log(Age) (years)


NGC6811
Age=1000 MYr
Hyades
Age= 600 MYr
Praesepe
Age= 600 MYr
M37
Age= 550 MYr
P_rot (days)
(B-V)_0
0
5
10
15
20
0.4
0.6
0.8
1.0
1.2
1.4


0.10
0.08
0.06
0.04
0.02
0.00
Probability (per day)
(B-V) = 0.65
0.8
1.0
1.2
Age = 250 MY
0
2
4
6
8
10
12
Period (days)


M34 Data
MDM
SEM
2ZM
Cumulative Probability
0.67 < (B-V)0 < 0.81
P rot (days)
M34 Data
MDM
SEM
2ZM
Cumulative Probability
0.81 < (B-V)0 < 1.01
P rot (days)


weather tower
SSB
0.4m Enclosure
1.0m Enclosure
Storage Container