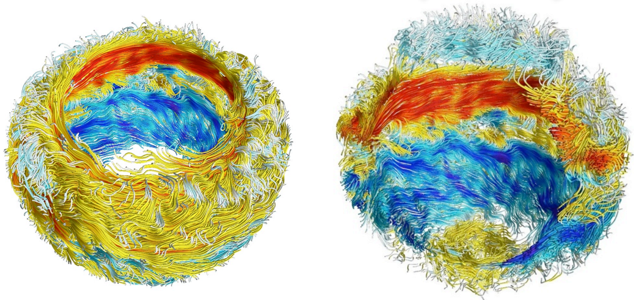
# ASTR 7500: Solar and Stellar Magnetism
## Hale CGEP Solar & Space Physics



Ben Brown, Prof. Juri Toomre & friends

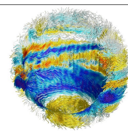
Lecture 20 Thurs 4 April 2013

http://zeus.colorado.edu/astr7500-toomre

# *Last time*

- We see signatures of magnetism on other stars
- Short-time-variable signatures include: photometry (spots; rotation period: days), ZDI magnetic maps (rotation period: days), **flares** (minutes-hours).
- Long-time-variable signatures include: chromospheric emission (e.g., Ca H&K; H-alpha), coronal X-ray emission, total surface flux.
- We see cycles on many other stars. Shortest is ~1.5 years; typical is ~10 years (similar to Sun).

# *This time*



- Catching flares on M-dwarf stars
- Global-scale dynamo action in stars like the Sun
- Emergence of large-scale flows (differential rotation) from rotation and convection; dynamo generation of organized magnetic field.
- These simulations suggest that large-scale, organized field can be built in the convection zone, can cyclicly reverse. All without relying on a tachocline as a fundamental component.

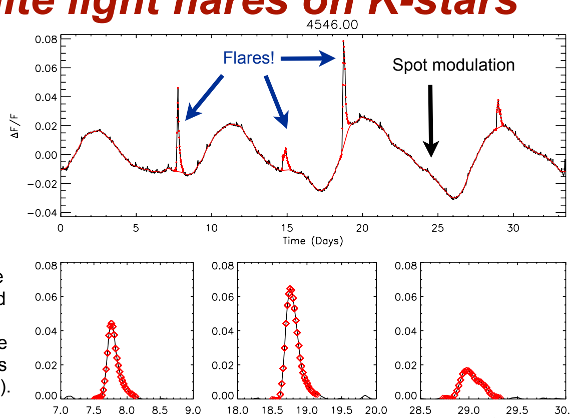
http://www.astro.wisc.edu/~bpbrown/Movies/

# *Stellar Flares*

- We see stellar flares on other stars
- M-dwarf "flare-stars" can be very active: major flares (solar X-class) every few hours/days
- Seen in X-rays; also seen in white light (optical). Optical emission thought to carry ~50% of total flare energy. Easier to see on K- and M-dwarfs.
- Photometric monitoring (1-4m class science) and spectral monitoring (4-10m class science) are possible; key is continuous coverage.
- Major source of variability for time-domain astronomy surveys. Especially LSST.

See work by: A. Kowalski, S. Schmidt, E. Hilton, J. Davenport, L. Walkowicz and other members of S. Hawley's extended group.

# *White light flares on K-stars*

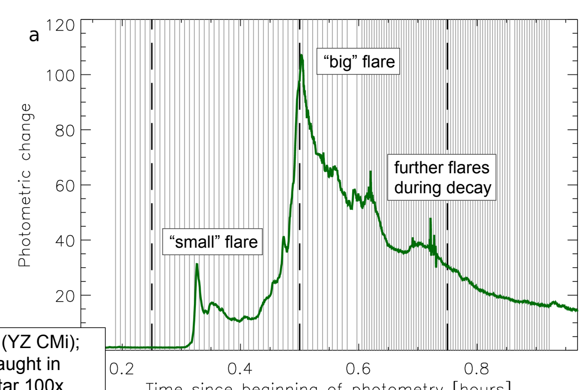



~5% change in broadband photometry (huge!); more in blue bands (can be 100x).

Contain about 50% of the energy released in flare.
Kepler sees on variety of K- and M-dwarf stars.

(Walkowicz et al 2011)

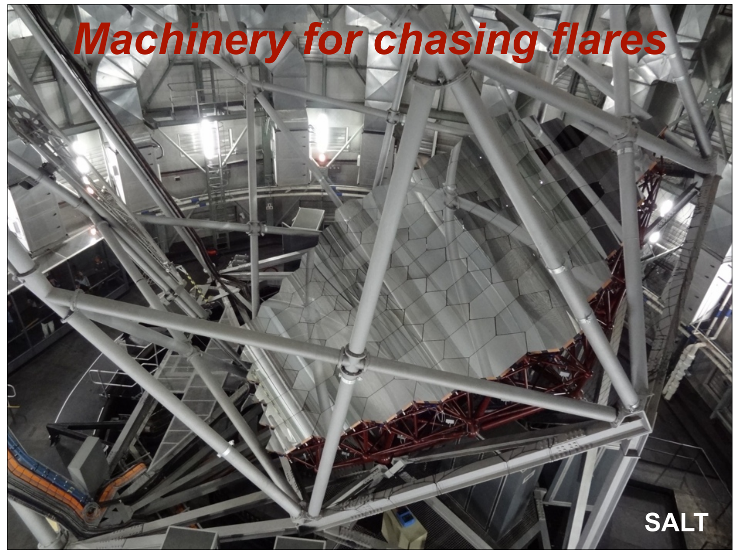
# *Megaflares on tiny stars*



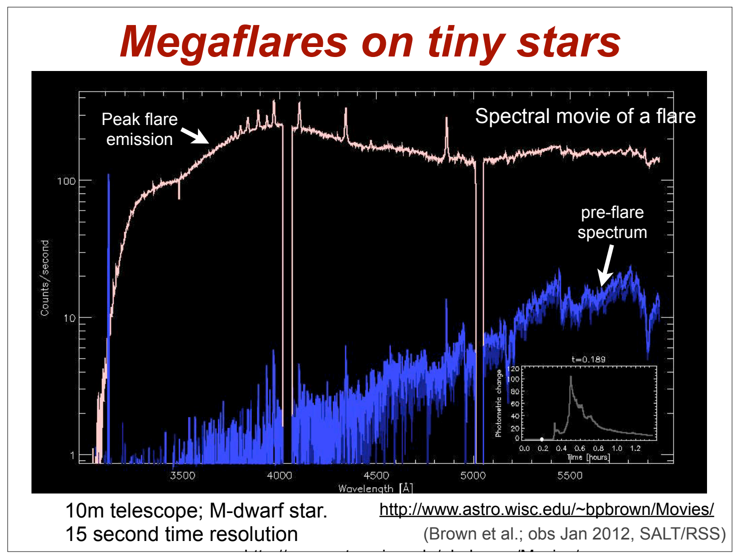

M-dwarf star (YZ CMi); major flare caught in Jan 2012. Star 100x brighter in U-band. Spectra taken at vertical grey lines.

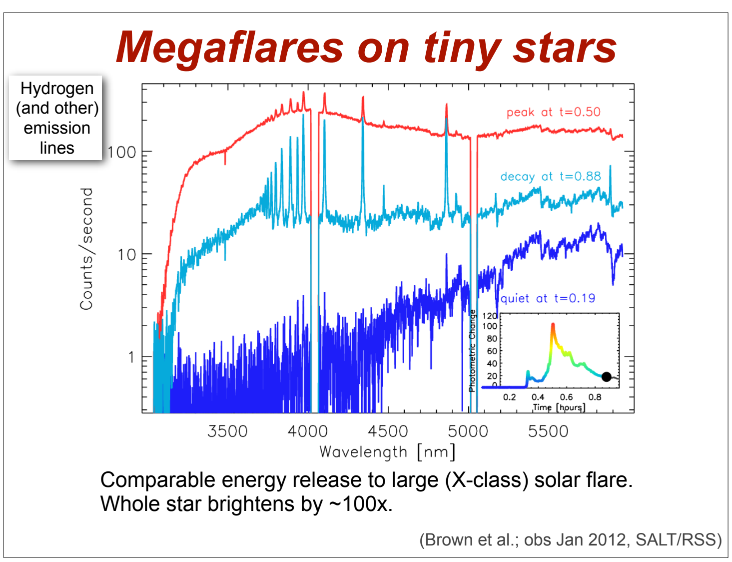
(photometry: Kowalski et al.; obs Jan 2012, WHT/La Palma; spectra Brown et al.; SALT/RSS)

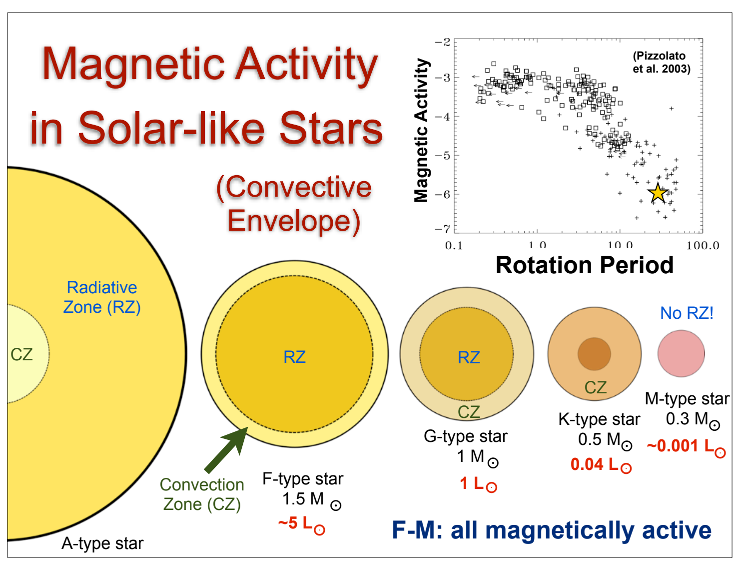

Machinery for chasing flares
SALT:
Southern African
Large Telescope
(~10m optical)


Machinery for chasing flares
SALT

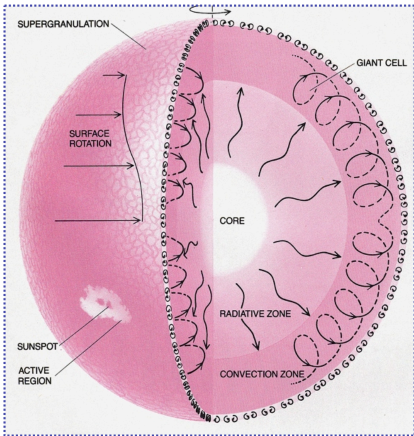

Machinery for chasing flares
SALT: spherical mirror, tracker with instruments at prime focus; like Arecibo

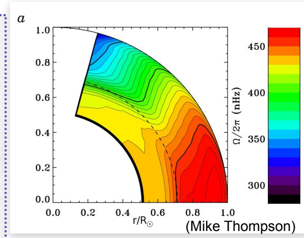

Megaflares on tiny stars
Peak flare emission
Spectral movie of a flare
pre-flare spectrum
Counts/second
Wavelength [Å]
10m telescope; M-dwarf star.
15 second time resolution
http://www.astro.wisc.edu/~bpbrown/Movies/
(Brown et al.; obs Jan 2012, SALT/RSS)


Megaflares on tiny stars
Hydrogen (and other) emission lines
peak at t=0.50
decay at t=0.88
quiet at t=0.19
Counts/second
Wavelength [nm]
Time [hours]
Comparable energy release to large (X-class) solar flare.
Whole star brightens by ~100x.
(Brown et al.; obs Jan 2012, SALT/RSS)


Magnetic Activity in Solar-like Stars
(Convective Envelope)
Magnetic Activity
(Pizzolato et al. 2003)
Rotation Period
Radiative Zone (RZ)
CZ
RZ
No RZ!
Convection Zone (CZ)
A-type star
F-type star 1.5 M⊙ ~5 L⊙
G-type star 1 M⊙ 1 L⊙
K-type star 0.5 M⊙ 0.04 L⊙
M-type star 0.3 M⊙ ~0.001 L⊙
F-M: all magnetically active

# Inside the Sun




***CONVECTION ZONE***
***VERY TURBULENT***
***(depth of 200 Mm)***
***Re ~ 10$^{15}$   Ro ~ 1***

**Stratified, Rotating and Magnetic**

# MHD Induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{B} + \eta \boldsymbol{\nabla} \times \boldsymbol{B})$$

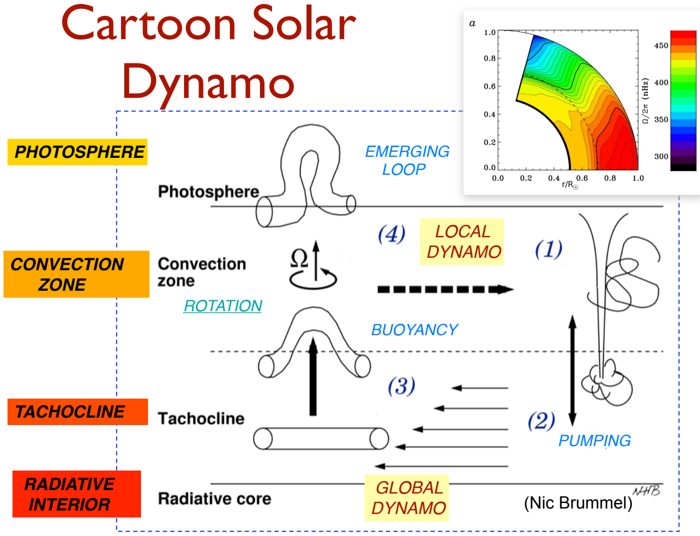
or, expanding the cross product:

$$\frac{\partial \boldsymbol{B}}{\partial t} = -(\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{B} - \boldsymbol{B}\,(\boldsymbol{\nabla} \cdot \boldsymbol{u}) + (\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \eta \nabla^2 \boldsymbol{B}$$

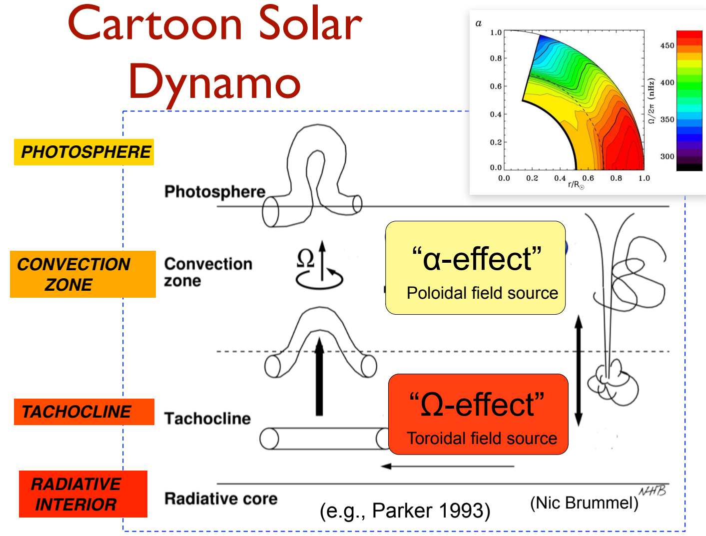
advection — compressibility — amplification of B by gradients of U — Ohmic diffusion

assuming $\eta$ is constant

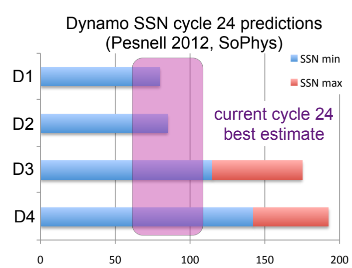
# Cartoon Solar Dynamo




# Cartoon Solar Dynamo




# Global Dynamo Models




## 2D: Mean-field models

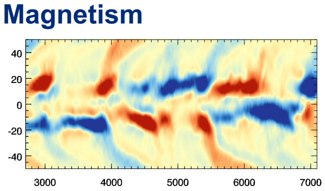
- $\alpha$–$\Omega$ type
- interface dynamos
- flux-transport and many variants (e.g. Babcock-Leighton)

Computationally inexpensive: simulate many cycles, try many ideas
In a position to try solar predictions (but parameterize convection)

## 3D: Convection, Rotation & Magnetism

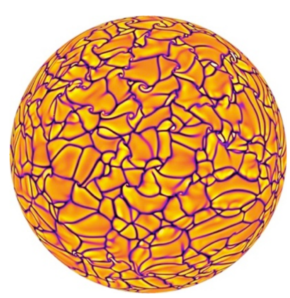
- global-scale flows, magnetism, coupling from first principles
- now achieving cyclic behavior, buoyant magnetic structures

Computationally expensive
Solar parameters well out of reach




# *Moving past cartoons: Simulations of Convective Dynamos*

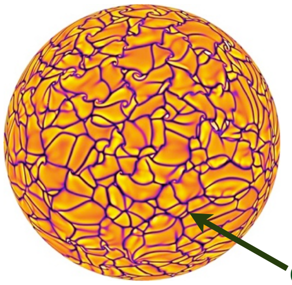
## *Anelastic Spherical Harmonic (ASH) code*



Solar convection
(Miesch et al. 2008)

- Capture 3-D MHD convection at high resolution on massively-parallel supercomputers (~1000 processors for ~1 year)
- Study turbulent convection interacting with rotation in bulk of solar CZ: 0.72 *R* - 0.97 *R*
- Realistic stellar structure
- Simplified physics: perfect gas, radiative diffusivity, **compressible**, overly large diffusions, MHD
- Correct global spherical geometry
- Study effects of more rapid rotation

## Importance of Sound-Proof Equations



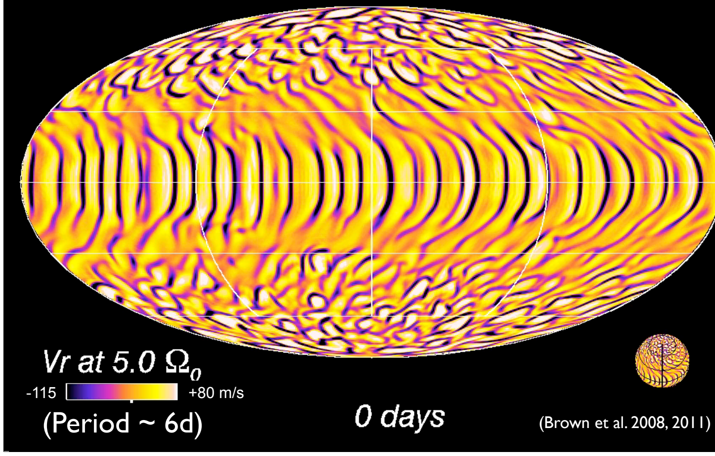
- What do we really mean by "**compressible**"?
- Want to capture effects of density stratification (~5 density scale heights between *0.72-0.98 R*; several thousand more to photosphere). Leads to up/down asymmetries in convection.

(broad upflows, narrow downflows)

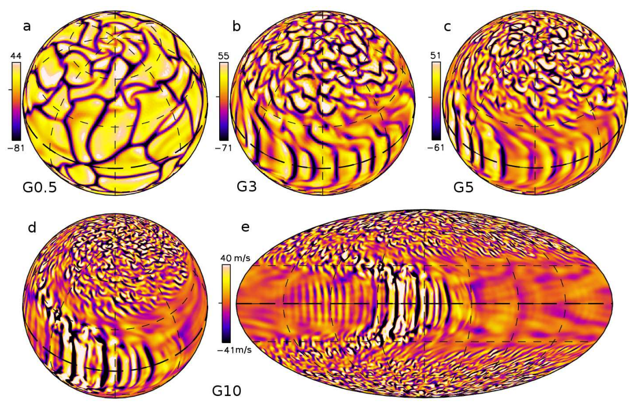
- Cannot afford to follow sound waves (deep flows are $10^{-4}$ slower than sound). Hence "anelastic" equations. These work great in stellar convection zones, can extend them for dynamics in stellar radiative zones.

(Brown, Vasil & Zweibel, 2012; Vasil et al. 2013)

## Rapidly Rotating Suns: Convective Flows



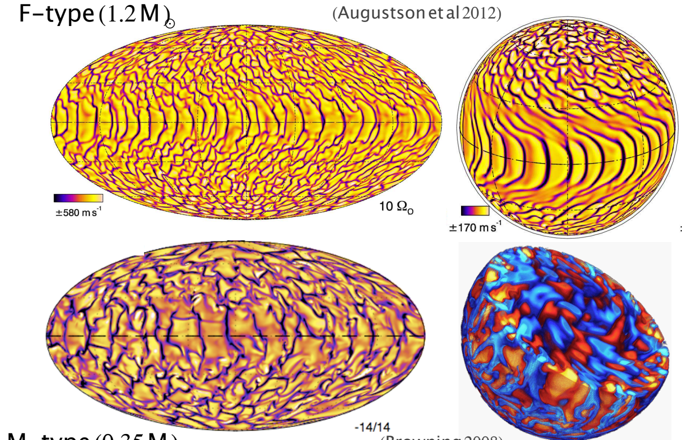

## Convection in G-type stars




(Brown et al. 2008)

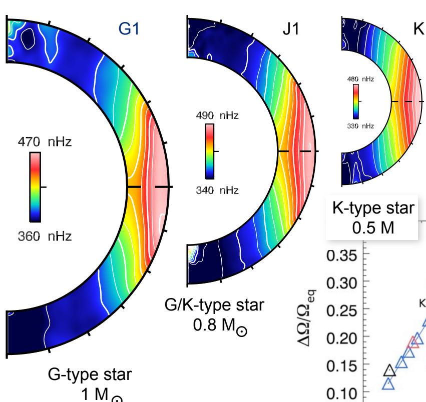
## Flows in F- and M-type stars

F-type (1.2 $M_\odot$) (Augustson et al 2012)

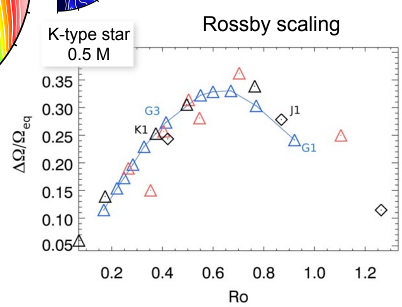



M-type (0.35 $M_\odot$) (Browning 2008)

## Differential Rotation in Other Stars

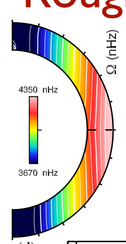



Different masses, same rotation rate



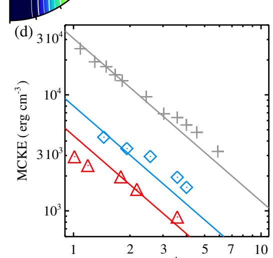

All three stars rotating at solar rate (P~28d)

## Rough Scaling laws (F- to G-stars)




$$\Delta\Omega \propto \left(\frac{M}{M_\odot}\right)^4 \left(\frac{\Omega_0}{\Omega_\odot}\right)^{0.5} \propto \mathrm{Ro}^{-1}$$

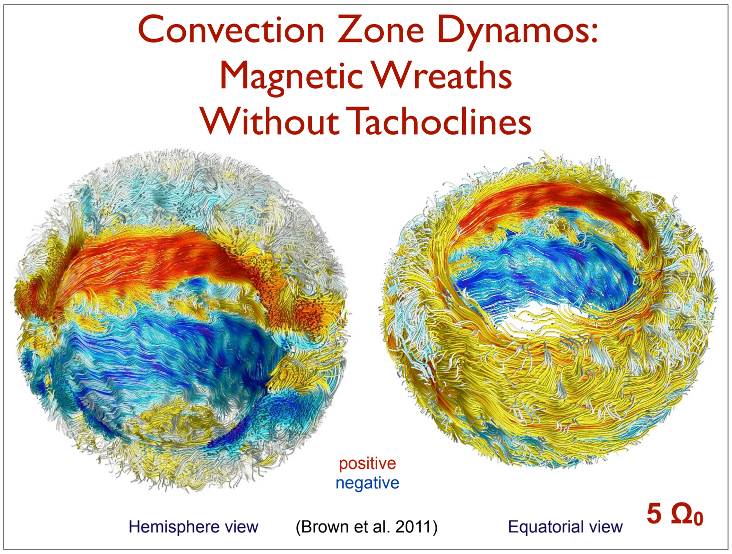
$$\mathrm{MCKE} \propto \left(\frac{M}{M_\odot}\right)^{-1} \left(\frac{\Omega_0}{\Omega_\odot}\right)^{-0.8} \propto \mathrm{Ro}$$

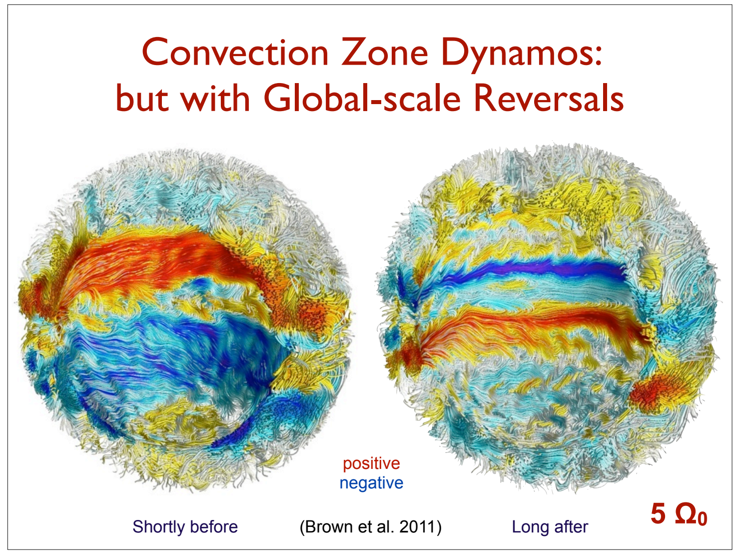


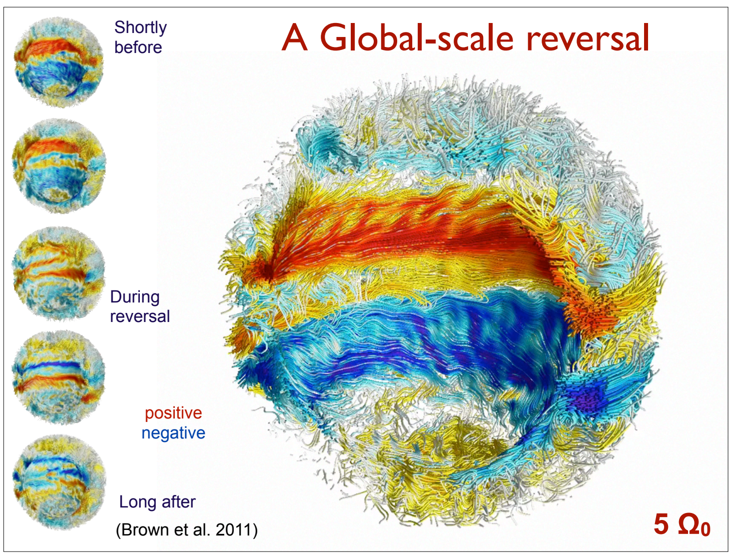

Extending now to K-, M-dwarfs.

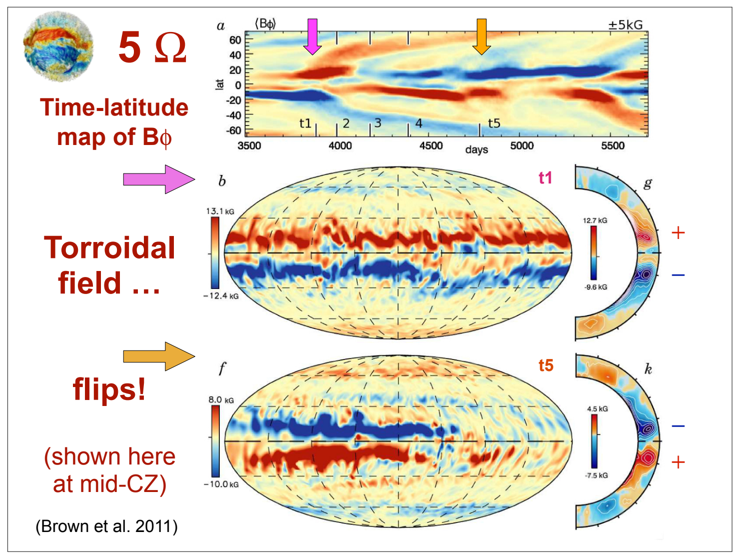
Caveat: parameter space is large; these sample a limited portion.

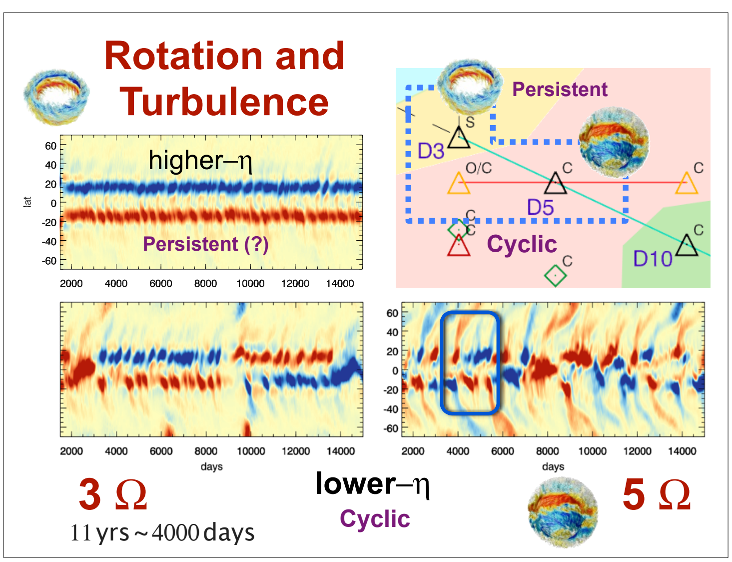
(Ballot et al. 2007, Brown et al. 2008, Augustson et al. 2012)

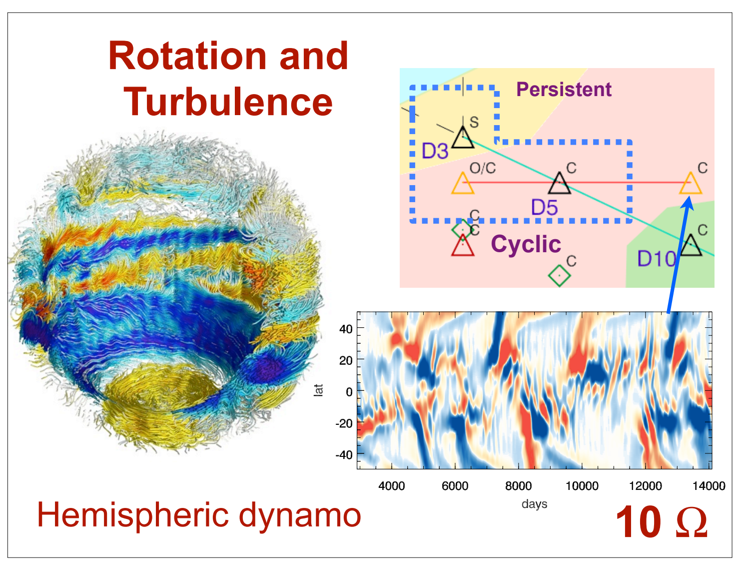

Convection Zone Dynamos:
Magnetic Wreaths
Without Tachoclines
positive
negative
Hemisphere view
(Brown et al. 2011)
Equatorial view
5 $\Omega_0$


Convection Zone Dynamos:
but with Global-scale Reversals
positive
negative
Shortly before
(Brown et al. 2011)
Long after
5 $\Omega_0$

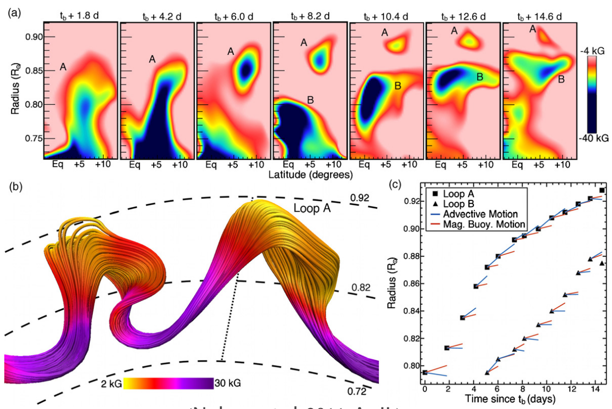

A Global-scale reversal
Shortly before
During reversal
positive
negative
Long after
(Brown et al. 2011)
5 $\Omega_0$


5 Ω
Time-latitude map of Bϕ
Torroidal field …
flips!
(shown here at mid-CZ)
(Brown et al. 2011)
t1
t5
days


Rotation and Turbulence
higher–η
Persistent (?)
Persistent
D3
O/C
D5
Cyclic
D10
days
3 Ω
11 yrs ~ 4000 days
lower–η
Cyclic
5 Ω

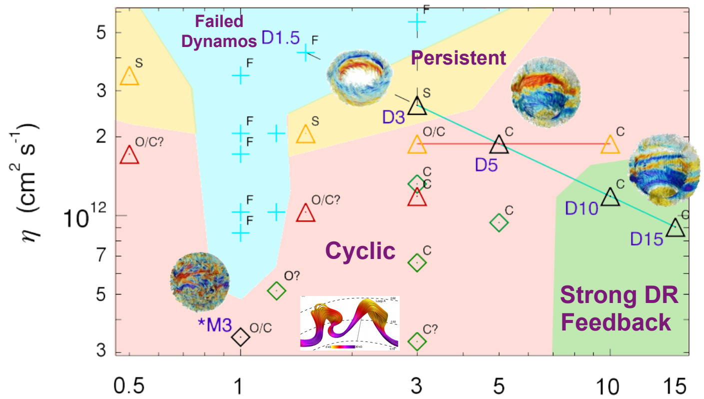

Rotation and Turbulence
Persistent
D3
O/C
D5
Cyclic
D10
days
Hemispheric dynamo
10 Ω

## Next Step: Sunspots and Buoyant Magnetic Loops?




(Nelson et al. 2011, ApJL)

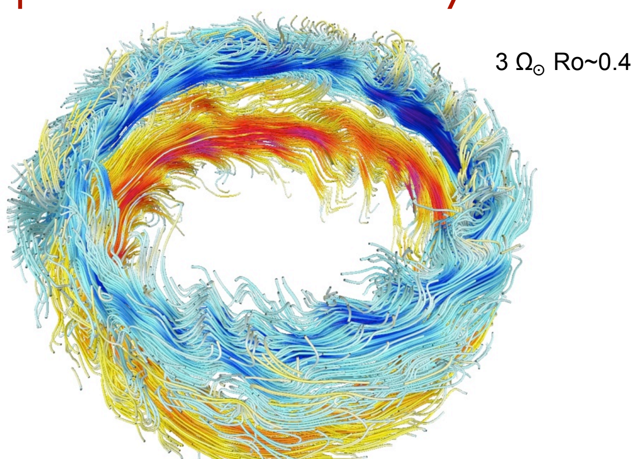
## Stellar Dynamos: Many flavors



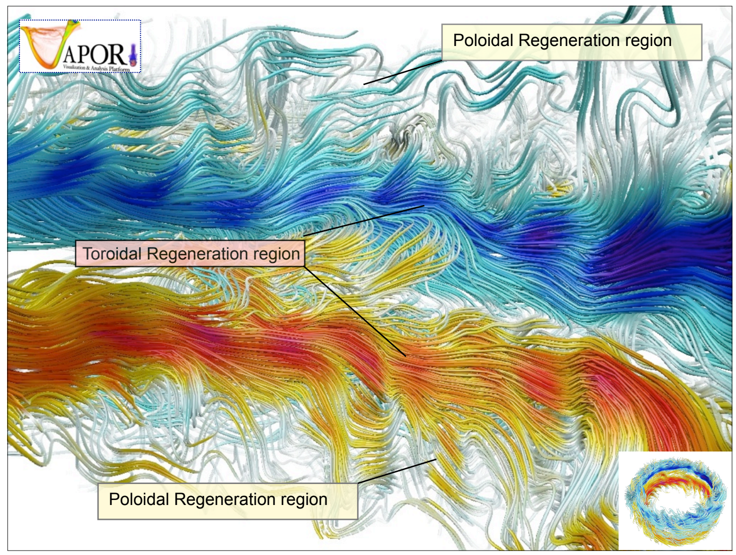

Also see Ghizaru et al. 2010, Racine et al. 2011

Brown et al. 2010, 2011 Nelson et al. 2011

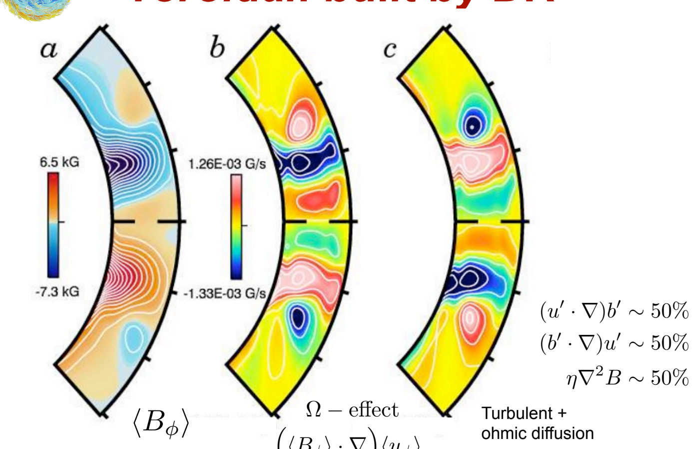
## A Special Case: Persistent Dynamos




(Brown et al. 2010)




## *Toroidal: built by DR*



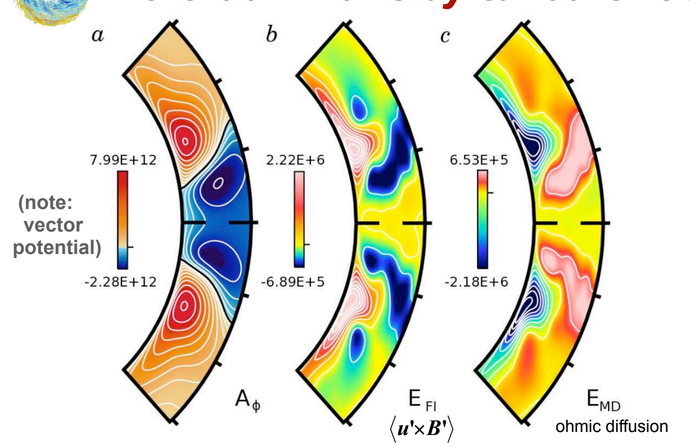

$(u' \cdot \nabla)b' \sim 50\%$

$(b' \cdot \nabla)u' \sim 50\%$

$\eta \nabla^2 B \sim 50\%$

(Brown et al. 2010)

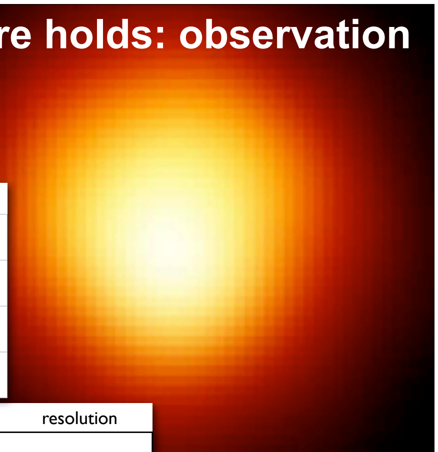
## *Poloidal: Built by turbulence*




(Brown et al. 2010)

# What the future holds: observation

So you want to see a star:



| Star | λ/D | size |
|---|---|---|
| τ Boo (F6IV)* | 1.4 R☉<br>15 pc | 0.8 mas |
| Vega (A0V) | 2.8 R☉<br>7.8 pc | 3.4 mas |
| Betelgeuse (M2I) | 1200 R☉<br>200 pc | 60 mas |
| α Cen (G2V) | 1.4 R☉<br>1.3 pc | 7.4 mas |

| Obs | λ/D | resolution |
|---|---|---|
| Hubble | 200-1700 nm<br>2.4 m | 15-150 mas |
| VLA | 7mm<br>36 km | 40 mas |

Betelgeuse with Hubble (APOD 6/5/99)

* exoplanet host: $R_{orb}$~ 7R*

# What the future holds: observation

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|---|---|---|
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| Obs | λ/D | resolution |
|---|---|---|
| Hubble | 200-1700 nm<br>2.4 m | 15-150 mas |
| VLA | 7mm<br>36 km | 40 mas |
| MRO or CHARA | 550 nm<br>~340 m | 0.3 mas |
| VLBI | 7mm<br>12000 km | 0.1 mas [1] |

Magdalena Ridge Interferometer

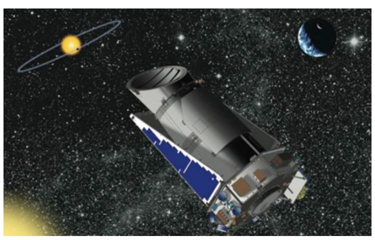
* exoplanet host: $R_{orb}$~ 7R*

[1] Bartell et al, Nature, 1988!

# What the future holds: observation

How about seeing *inside* a star:

Asteroseismology



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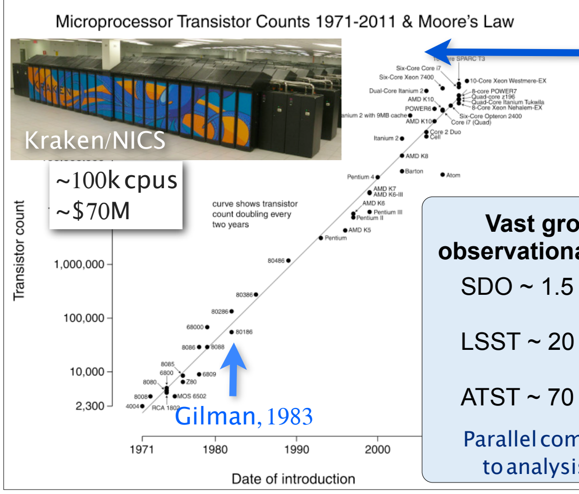
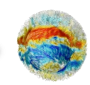
A PRECISE ASTEROSEISMIC AGE AND RADIUS FOR THE EVOLVED SUN-LIKE STAR KIC 11026764

T. S. Metcalfe[1], M. J. P. F. G. Monteiro[2], M. J. Thompson[3,1], J. Molenda-Żakowicz[4], T. Appourchaux[5], W. J. Chaplin[6], G. Doğan[7], P. Eggenberger[8], T. R. Bedding[9], H. Bruntt[10], O. L. Creevey[11,12], P.-O. Quirion[13], D. Stello[9], A. Bonanno[14], V. Silva Aguirre[15], S. Basu[16], L. Esch[16], N. Gai[16,17], M. P. Di Mauro[18], A. G. Kosovichev[19], I. N. Kitiashvili[20], J. C. Suárez[21], A. Moya[22], L. Piau[23], R. A. García[23], J. P. Marques[24], A. Frasca[14], K. Biazzo[25], S. G. Sousa[2], S. Dreizler[26], M. Bazot[2], C. Karoff[6], S. Frandsen[7], P. A. Wilson[27,28], T. M. Brown[29], J. Christensen-Dalsgaard[7], R. L. Gilliland[30], H. Kjeldsen[7], T. L. Campante[2,7], S. T. Fletcher[31], R. Handberg[7], C. Régulo[11,12], D. Salabert[11,12], J. Schou[19], G. A. Verner[32], J. Ballot[33], A.-M. Broomhall[6], Y. Elsworth[6], S. Hekker[6], D. Huber[9], S. Mathur[1], R. New[31], I. W. Roxburgh[10,32], K. H. Sato[23], T. R. White[9], W. J. Borucki[34], D. G. Koch[34], and J. M. Jenkins[35]

3-month program and associated conference at KITP
http://online.itp.ucsb.edu/online/asteroseismo-c11/

# What the future holds: computation



Brown et al 2011 (D5)

**Vast growth of observational datasets**

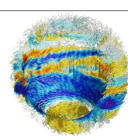
SDO ~ 1.5 TB/day

LSST ~ 20 TB/night

ATST ~ 70 TB/day (!)

Parallel computing key to analysis at scale.

# *What we learned today*



- M-dwarf stars have huge and frequent flares.
- Computation is permitting 3-D simulations of global stellar convection and dynamo action.
- Rotation and convection couple to build flows of differential rotation and meridional circulation.
- These simulations suggest that large-scale, organized field can be built in the convection zone, can cyclicly reverse. All without relying on a tachocline as a fundamental component.

# Learning more about stellar dynamos

"Astrophysical magnetic fields and nonlinear dynamo theory," Axel Brandenburg, Kandaswamy Subramanian, http://adsabs.harvard.edu/abs/2005PhR...417....1B

"Dynamo models of the solar cycle," Paul Charbonneau, http://solarphysics.livingreviews.org/Articles/lrsp-2010-3/

"Large-scale dynamics of the convection zone and tachocline," Mark Miesch. http://solarphysics.livingreviews.org/Articles/lrsp-2005-1/

Convection and wreath-dynamo movies

http://www.astro.wisc.edu/~bpbrown/Movies/

Next time: MHD waves (Brad Hindman)