Laboratory Astrophysics in the Stars and Stellar Evolution Astro2010 Panel

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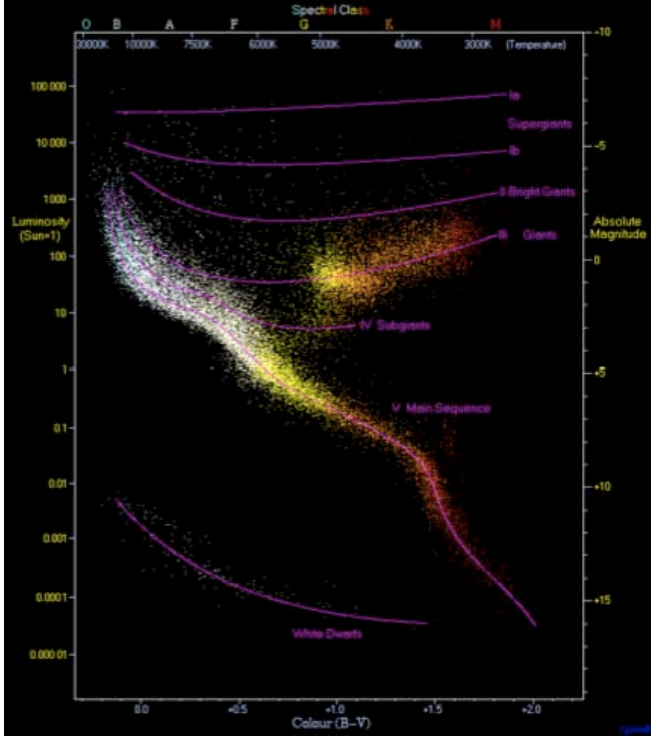
- The early success of SSE astrophysics was because stars are approximately 1-dimensional and emit in the optical

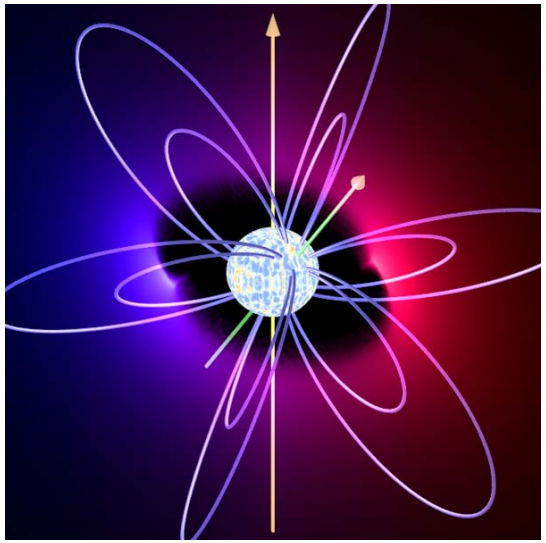
- More recent:

  Multiwavelength: cool L and T dwarfs (infrared); compact objects (X-rays); energetic phenomena

- Most recent:

  Now simulations and observations (precision, time domain) have developed to point where crucial 3-dimensional problems can be tackled





Model for σ Ori E[2]
magnetic Bp star

Goal: <u>a transition to models grounded in experimental data</u>

Precision Stellar Astrophysics

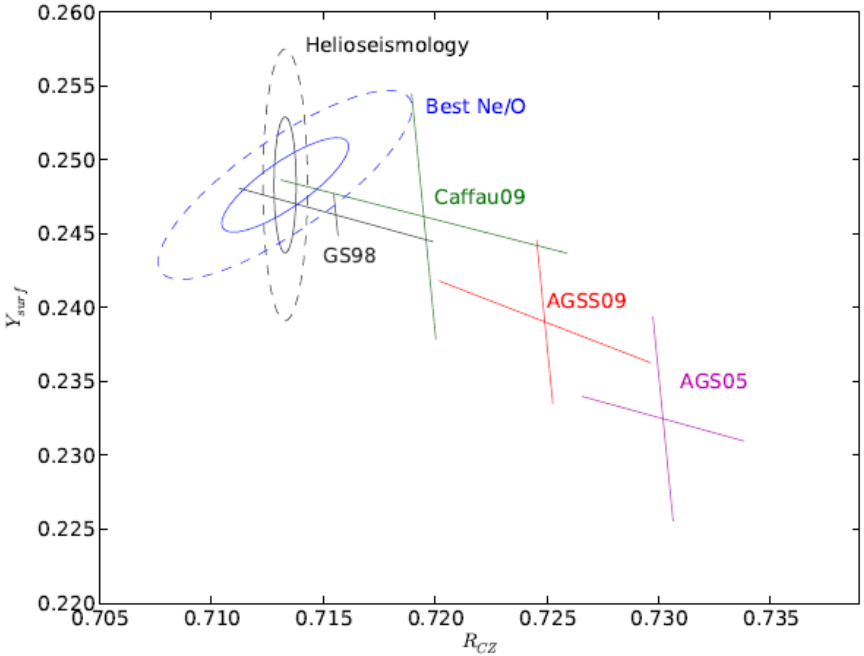
- Needed to decipher subtle effects
  - Opacities
  - Nuclear reaction rates
  - EoS
  - Transition probabilities

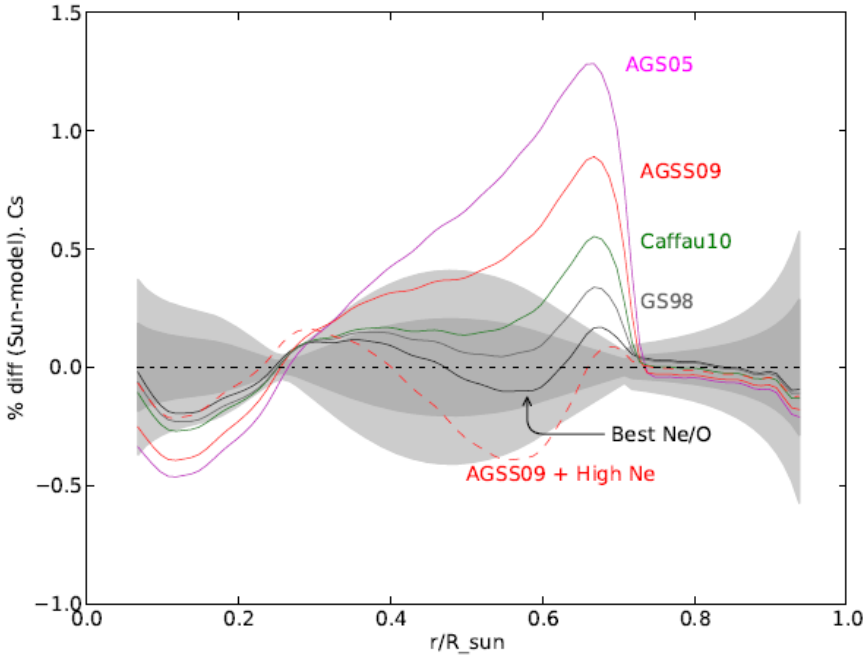
Frontier Topics

- Physical guidance from experiments
  - Explosive nucleosynthesis
  - Angular momentum transport
  - Generation of magnetic fields

Lab Astro and the Sun

- Solar Abundance problem:
  - New atmospheres models predict abundances at odds with interiors models
  - Interiors estimates rely on theoretical calculations
- Experimental opacity tests viable
- Solar neutrino experiments: solar core T, test of CNO
- **Payoff well beyond the solar case: near-field cosmology**





- **Questions:**

  How do Rotation and Magnetic Fields Affect Stars?

  What are Type Ia Supernovae?

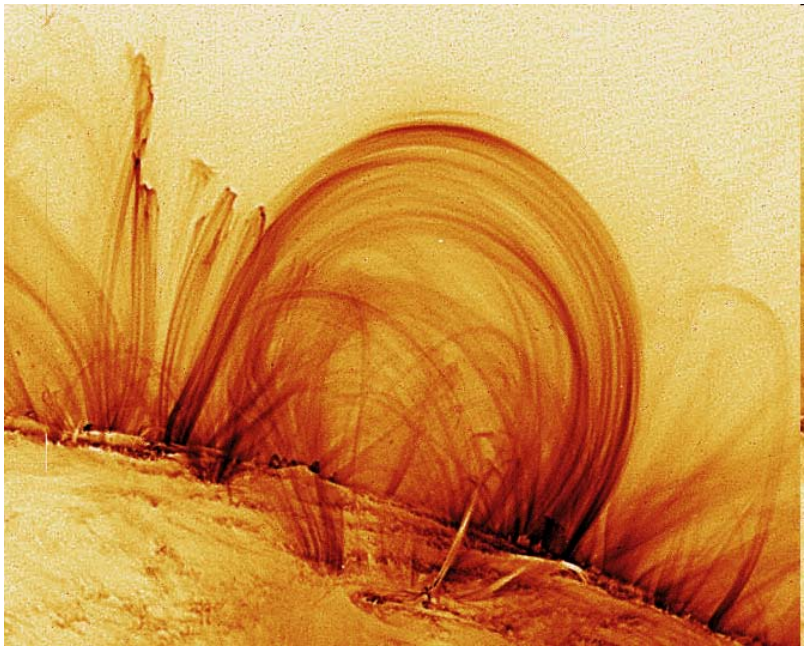
  How do Massive Stars end their Lives?

  What Controls the Masses, Spins, and Radii of Compact Stellar Remnants?

- **Discovery Area:**
  Large Time Domain Surveys

How do Rotation and Magnetic Fields Affect Stars?

- How are magnetic fields generated in stars?
- What is the surface and internal rotation of stars, and how do magnetic fields and convection shape it?
- What is the impact of rotation on stellar evolution?
- How are chromospheres and coronae heated?
- What is the origin of highly magnetized stars?



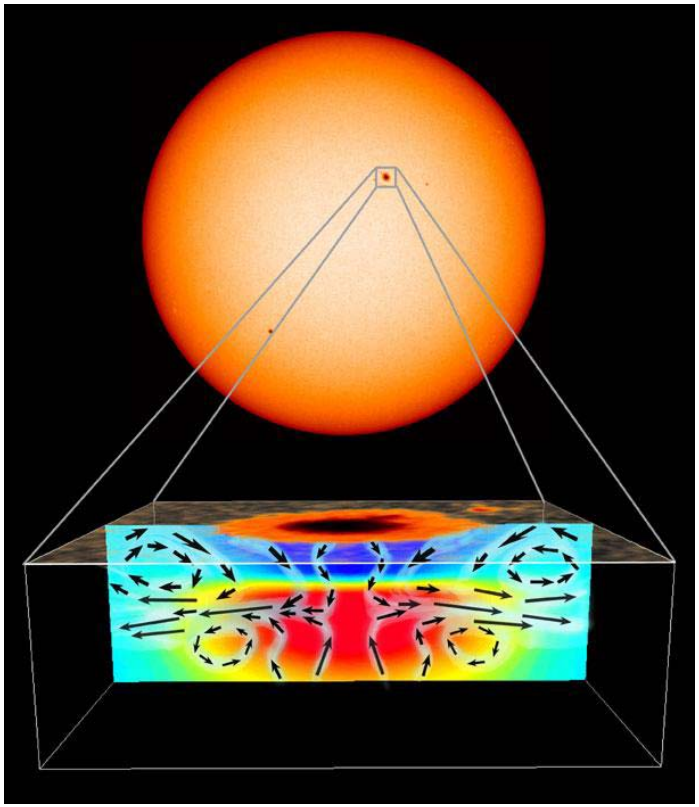
Broader Impact

- Precise solar constraints on dynamos, coronal & chromospheric heating, and convection
  - Sun as laboratory for astrophysics

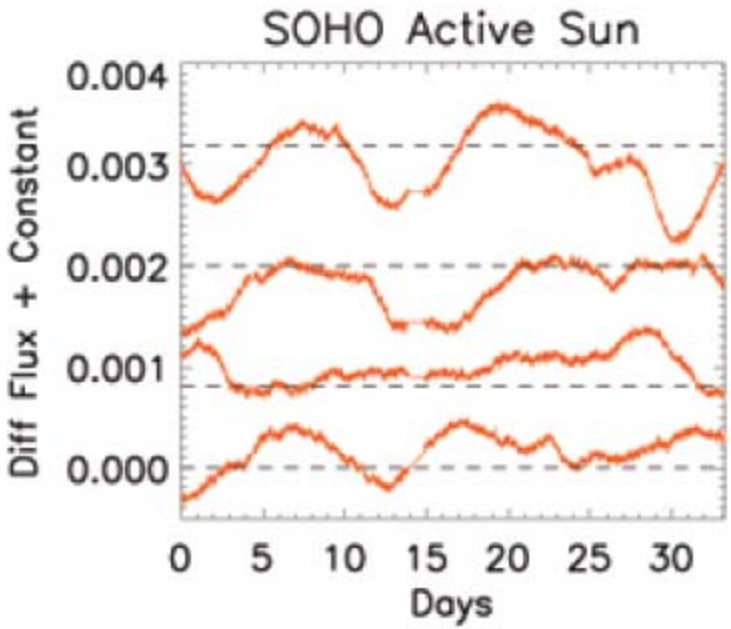
- Precise ages and abundances (for population studies)

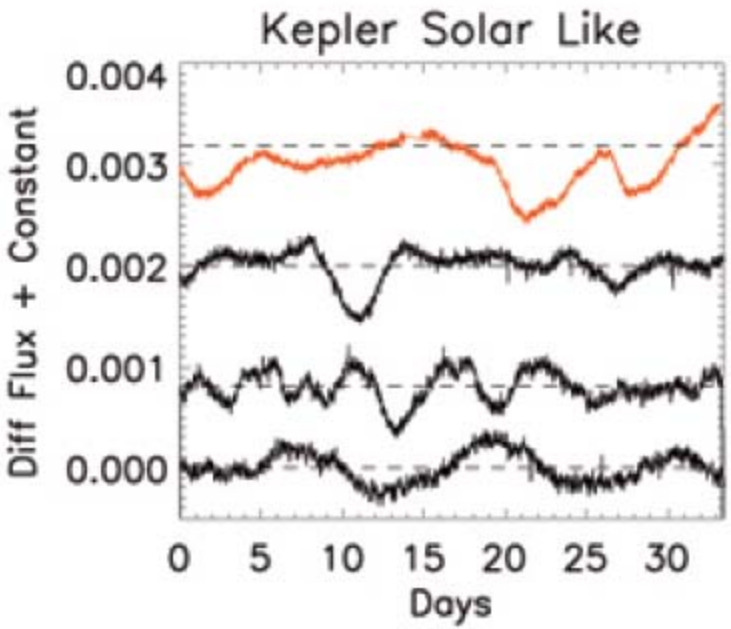
- Discovering the predominant mode of angular momentum transport in radiative regions

helioseismology



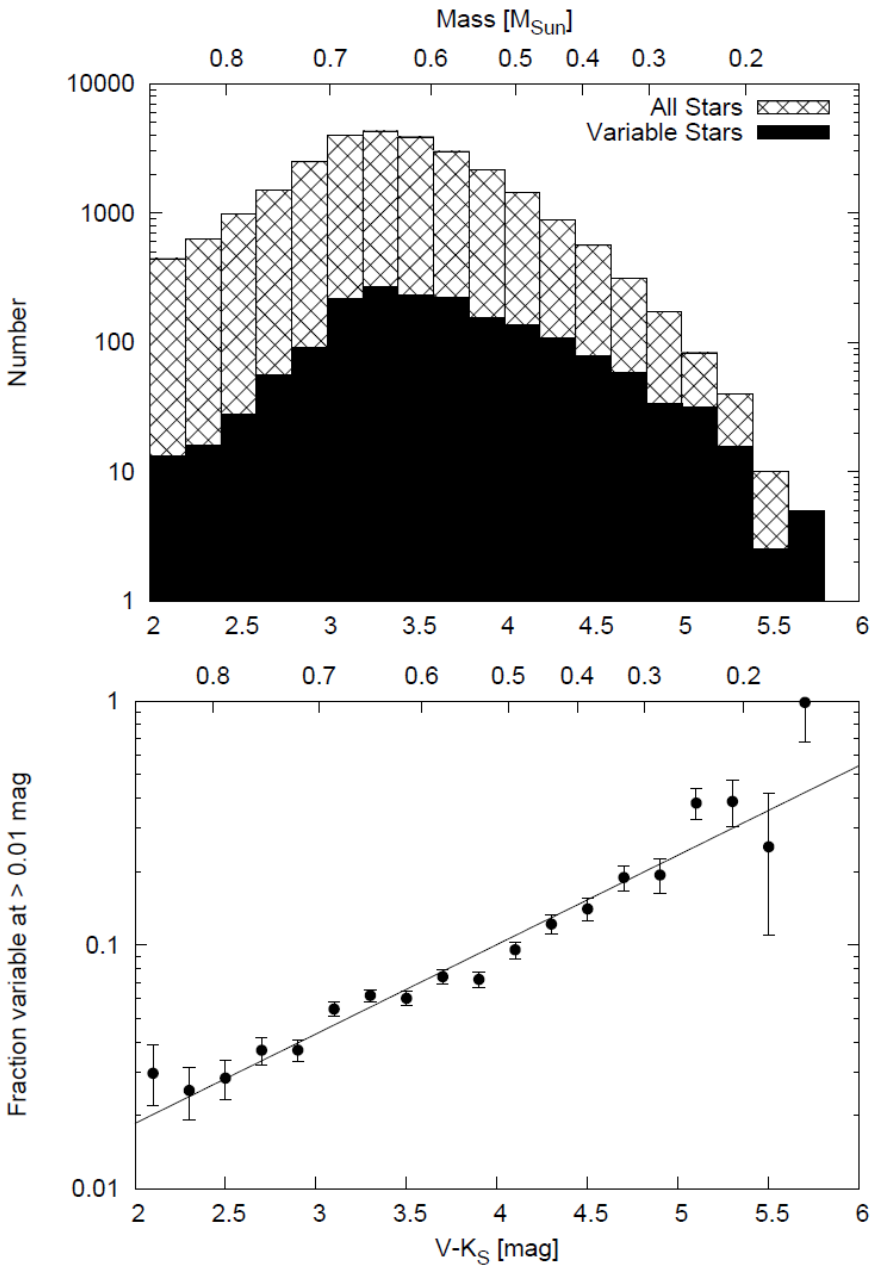
Photometric surveys: precise….





Basri et al. 2010 (astro-ph/1001.0414

…and large



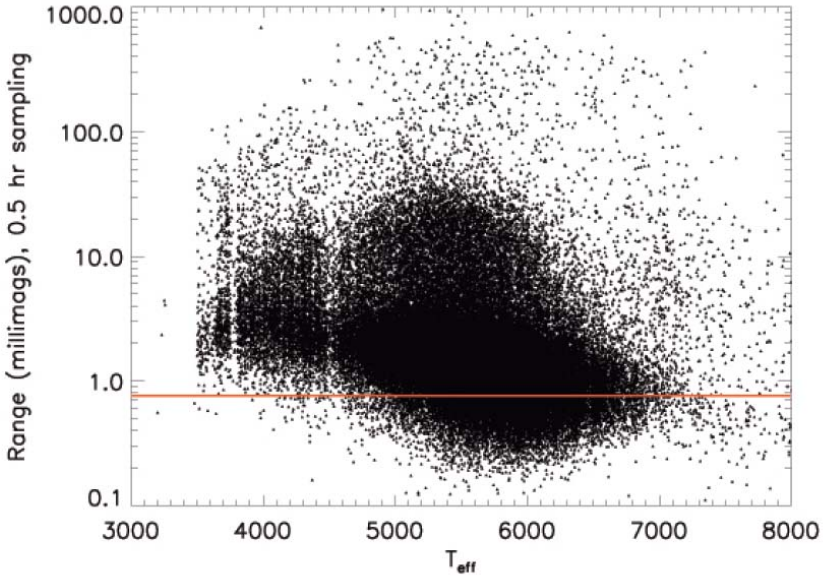
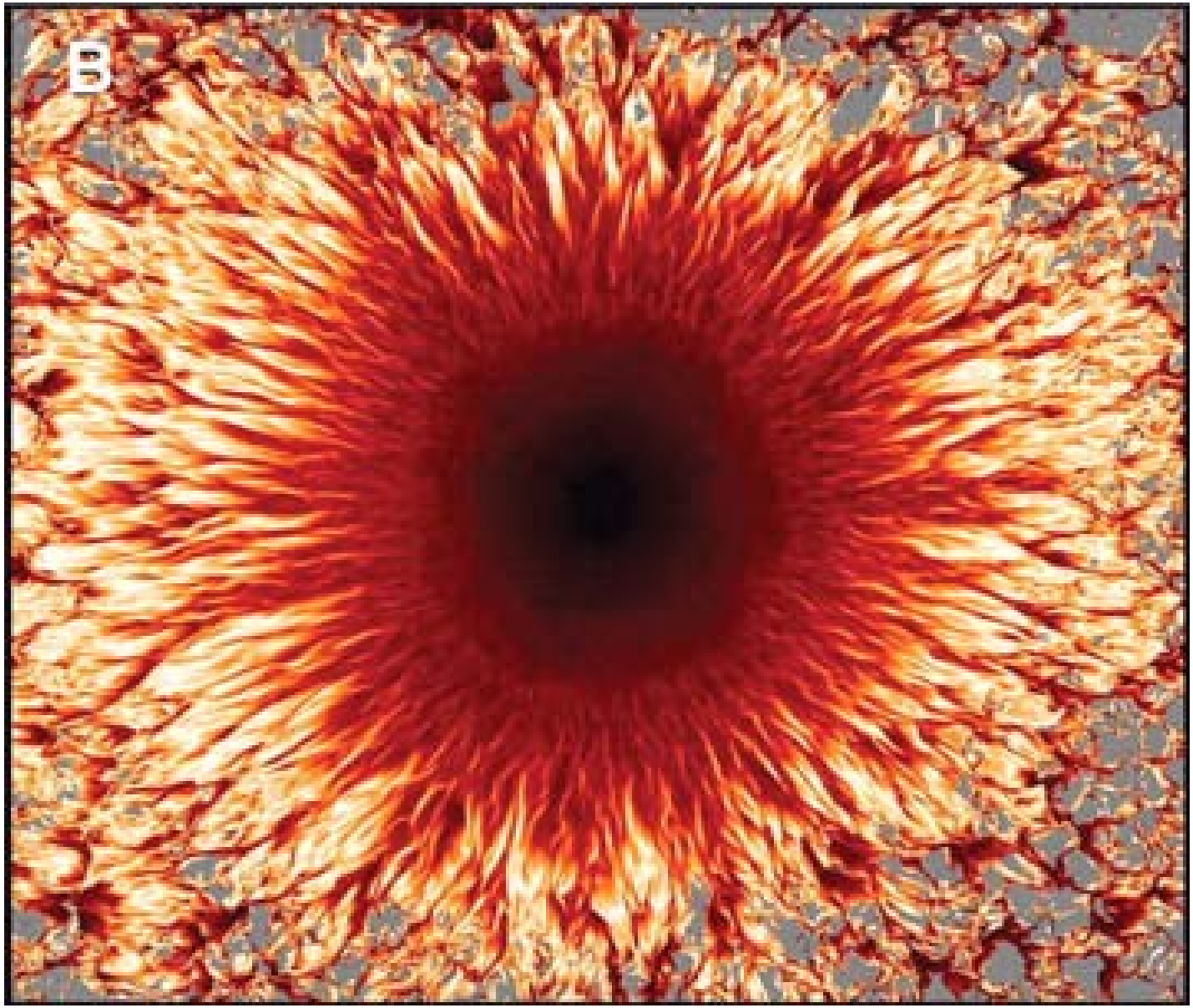


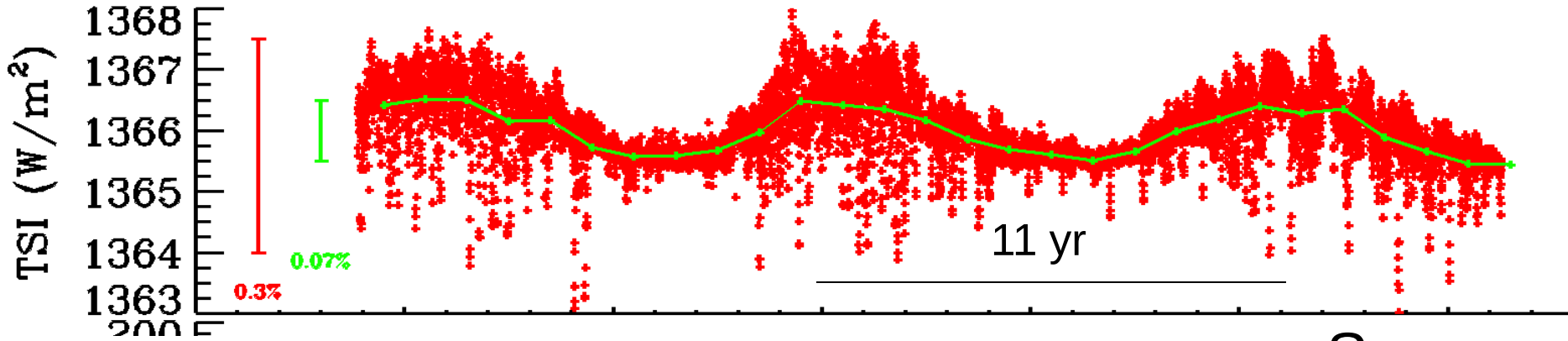
Fig. 3.— Effective temperature from the Kepler Input Catalogue versus the range of lightcurve variability. The red line gives the range value of the active Sun. The dearth of quiet stars at cool temperatures is evident in this figure; this is partly due to the faintness of cool dwarfs and measurement noise.

HADNET (Hartmann et al. 2010) and Kepler (Basri et al. 2010) data

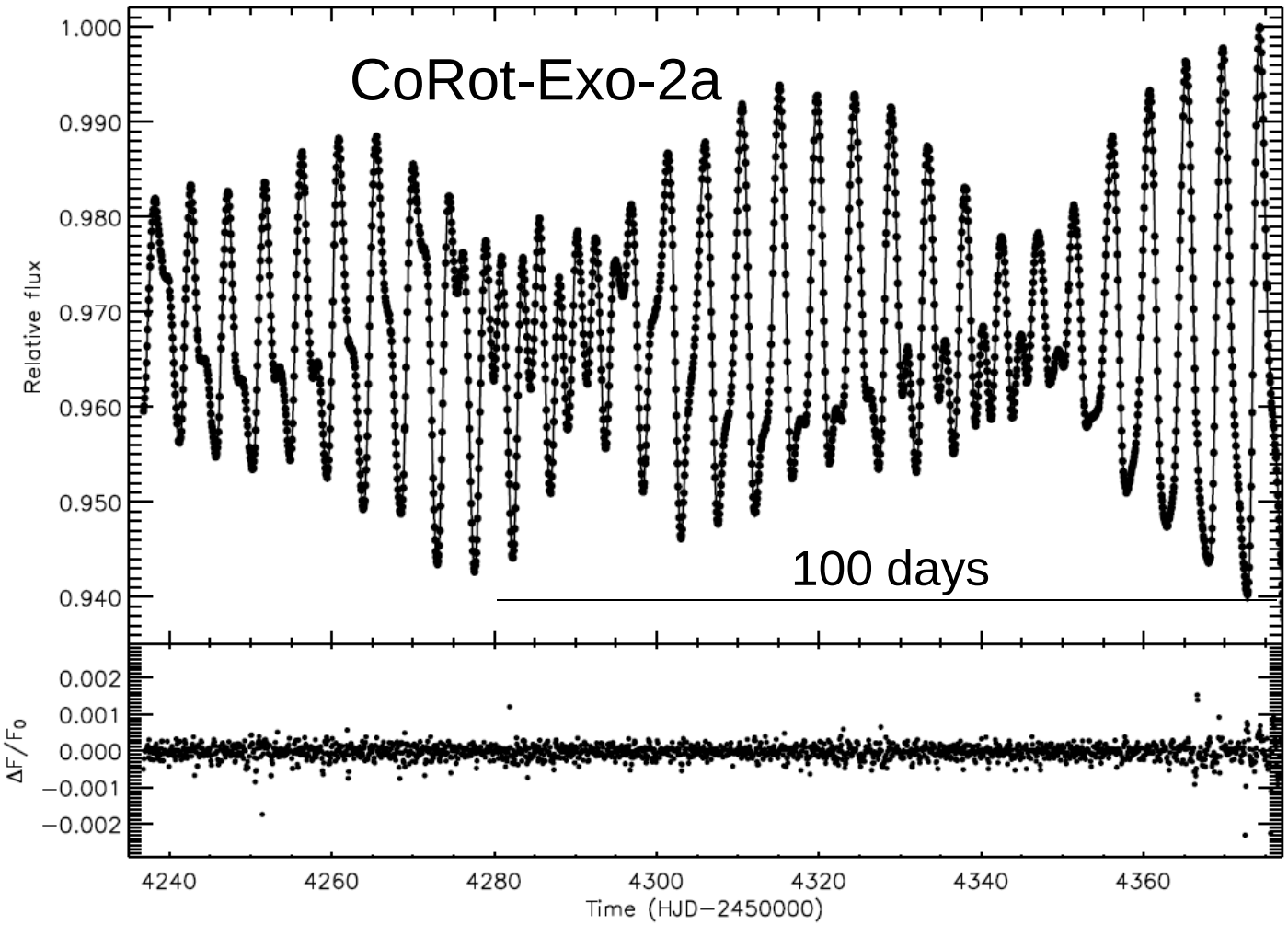
New Generation of Simulations



Rempel et al. 2009



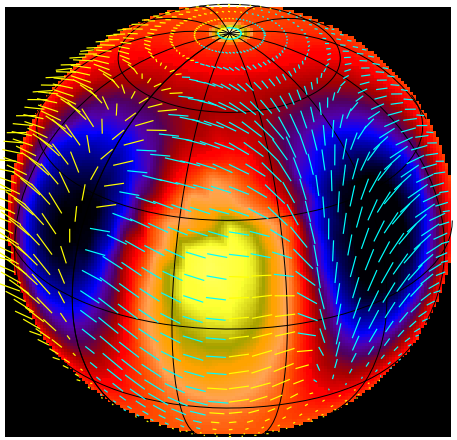
Sun



Detailed studies of spotted stars

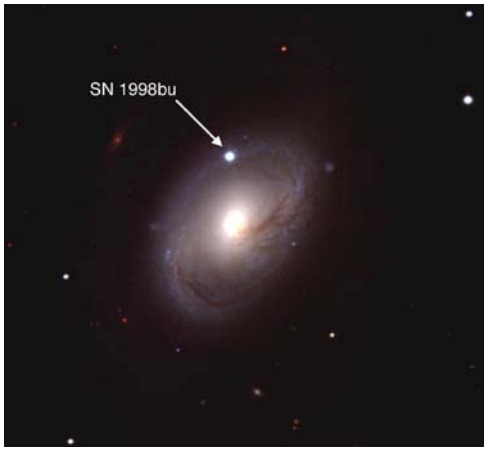
Key Roles for Laboratory Astrophysics

- Angular momentum transport in radiative interiors
- Reconnection and dynamos
- Improved microphysics essential for taking full advantage of next generation data sets
  - Interior Opacities

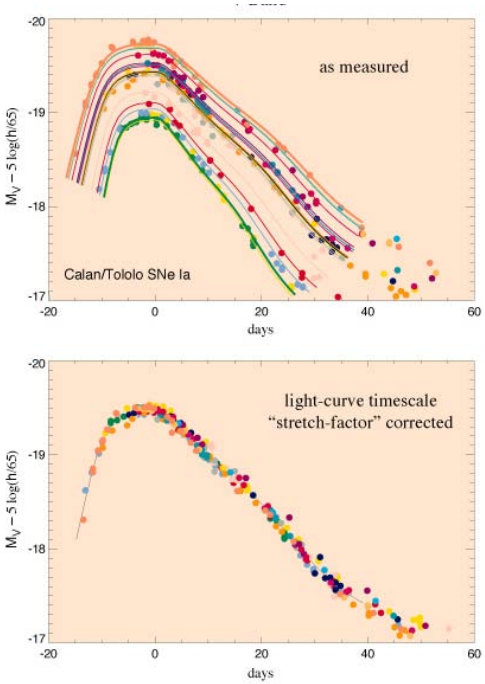


AU Mic
B field

What are Type Ia Supernovae?



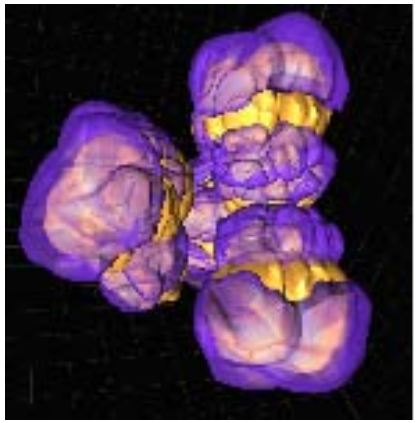
- What are the progenitors?
- How does the flame physics work (ignition, propagation, detonation)?
- Is more than one mechanism involved? (sub-M_{Ch}, merging WDs, super-M_{Ch}, effect of rotation)



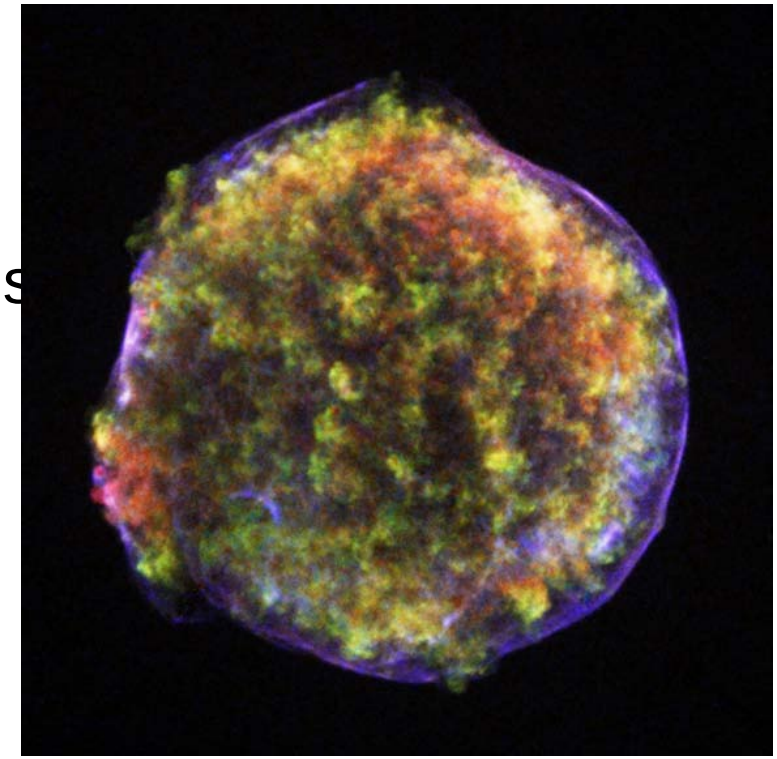
- How do properties vary with environment, binary properties, and metallicity?
- Can SN Ia be used to get distances to the accuracy necessary in an era of precision cosmology?

Needed to Make Advances (explosions)

- **Simulation** - a factor of 5 - 10 in resolution will allow realistic studies of thermonuclear ignition and flames
- **Surveys** - substantial increase in data on SN Ia will arise from major new surveys; spectra; studies of host galaxies

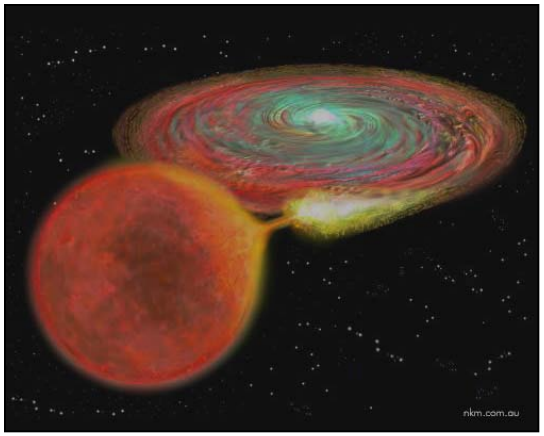


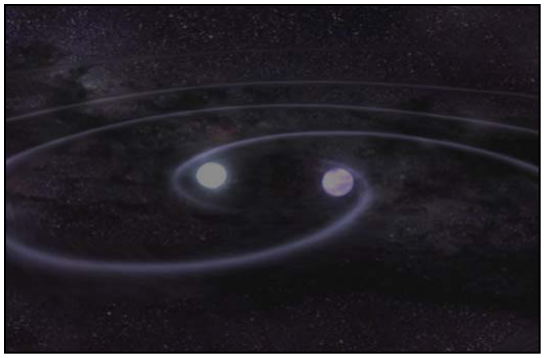
- **Experimental Data**:
  Atomic physics – interpretation of SN Ia spectra, nebular abundances
  Electron capture rates (e.g. FRIB)
  $C^{12}+C^{12}$ rate – crucial for ignition conditions (e.g. DUSEL)



Needed to Make Advances (Progenitors)

- White dwarfs in binaries
  - Optical surveys
  - Soft X-rays from accretion (X-ray surveys)
  - Models of binary evolution
- Diagnostics of companion
  - Entrained H from companion (optical spectra)
  - Radio and X-rays from interaction with wind
- Experimental Constraints:
  - X-ray transition probabilities
  - Accretion disk physics (MRI)





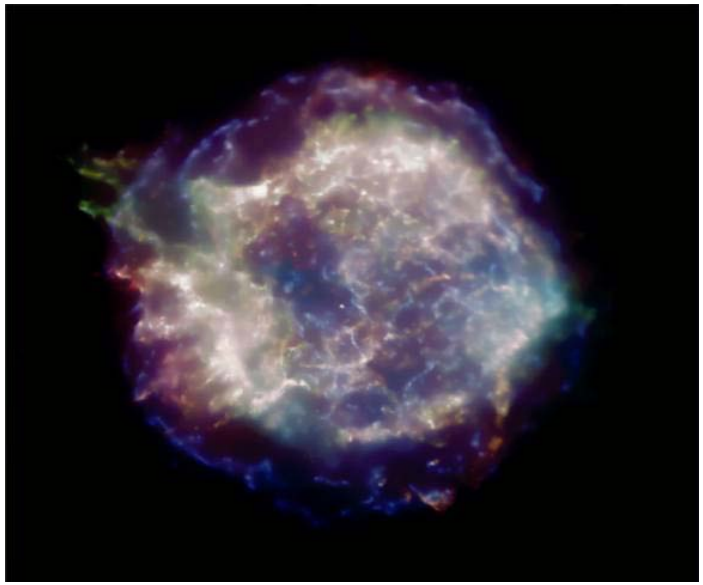
How do Massive Stars end their Lives?

- What are the progenitors of core-collapse SN?
  - pre-SN radii, masses, & rotation rates
  - pre-SN mass loss crucial; critically influences the WD/NS & NS/BH boundaries

- How do massive stars explode?
  - The neutrino mechanism, rotation & B-fields, pair instability
  - Connection to long-duration GRB and hyper-energetic SN
- What are the products of core-collapse SN?
  - What types of compact objects are produced by what mass stars?
  - Do core-collapse SN produce **the r-process elements**?
- Progenitors, explosions, & products through cosmic time?
  - How did the “first stars” die?
  - What is the role of metallicity?

Broader Implications

- The origin of the elements
- The chemical evolution of galaxies & the IGM and energy feedback
- Natural laboratories for neutrino physics
- Type IIP for cosmology?
- Initial properties of compact objects



Future Prospects

- 3-D simulations with realistic physics feasible in ~ 5-10 yrs
  - Multi-group neutrino transport, B-fields, rotation, …
  - Multi-D critical: convection, instabilities, asymmetries, jets, …

- Large optical surveys, including time domain
  - Rare supernovae; dependence on host galaxy; GRB “orphan” afterglows
  - Extreme metal poor stars (“first” supernovae)

- Progenitors and their mass loss environments
  - Observations of pre-SN Progenitors from surveys of nearby galaxies
  - Radio, X-ray, and optical emission from wind interaction
  - Shock breakout (X-ray transients)

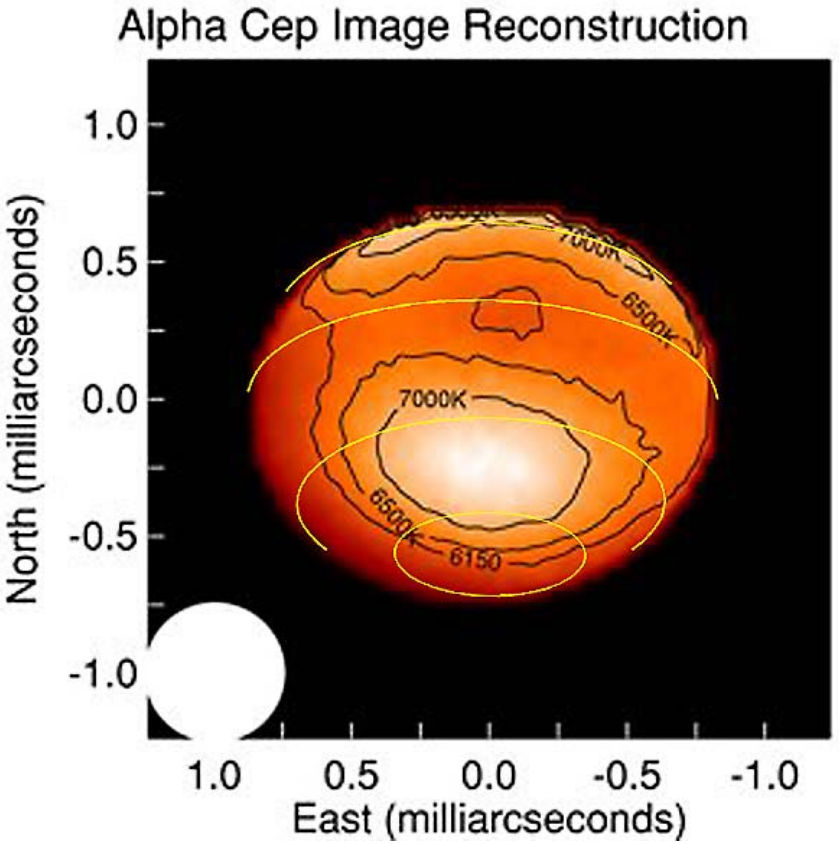
- Observational Tests of the explosion mechanism
  - Range of compact object properties (pulsar velocities,…)
  - Neutrino and/or gravity wave detections (lucky …)
  - Gamma-ray line observations w/ next generation mission (^{44}Ti)

Key Roles for Laboratory Astrophysics:Explosions

- Laboratory measurements of r-process nuclear physics (FRIB)
- Nuclear EoS (see below)
- Explosive nucleosynthesis cross-sections (FRIB, DUSEL)
- Opacities! (e.g. Metzger et al. 2010, astro-ph/1001.5029; r-process element opacities needed for NS+NS mergers)

Key Roles For Laboratory Astrophysics: Precursors

- Plasma physics in radiation-pressure dominated regimes (LBV mass loss?) – e.g. Z pinch, X-ray lasers
- Internal angular momentum transport



What Controls the Mass, Radius, and Spin of Compact Stellar Remnants*?

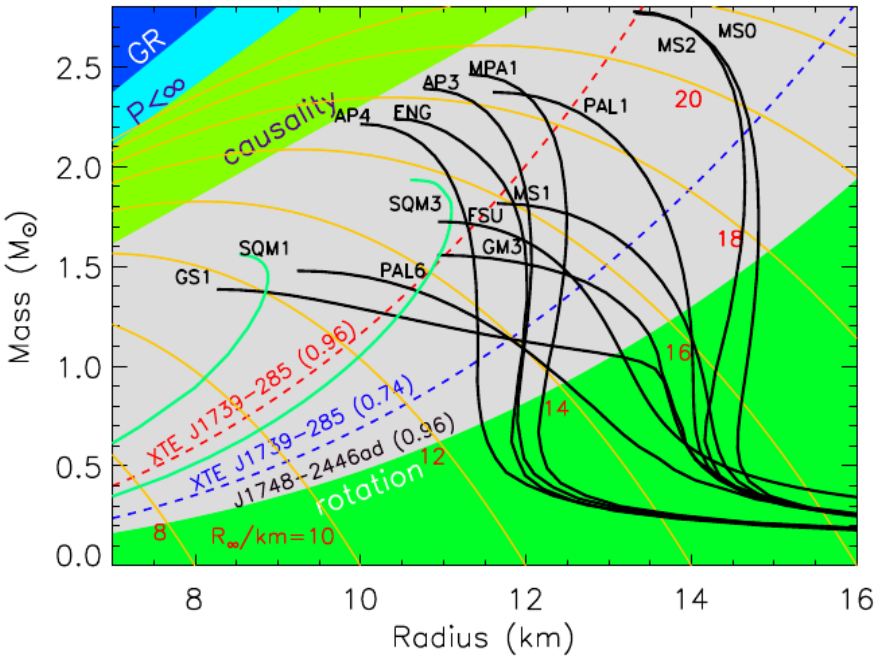
(* neutron stars, black holes, and white dwarfs)

- What is the **equation of state of ultradense matter**?
  - Astrophysics: NS interior and size, NS/BH mass boundary
  - Fundamental QCD and nuclear physics issues, inaccessible in lab
- What is the **spin distribution** and **maximum spin** of **neutron stars** and **black holes**?
  - Maximally spinning BH?
- What determines the **initial-final mass relation** connecting progenitors to **white dwarfs**?
  - Role of mass loss on the AGB
  - Physics of WD cooling needed to interpret observations

Why now and what's needed: Neutron Stars

- Evidence for **massive** (>1.6 $M_\odot$) NS and **sharp cutoff** (~750 Hz) in NS spin distribution
- Promising tracers of NS **radius** discovered in last decade (X-ray; double pulsar)
- Large radio surveys underway

From Lattimer & Prakash 2007



- What's needed:

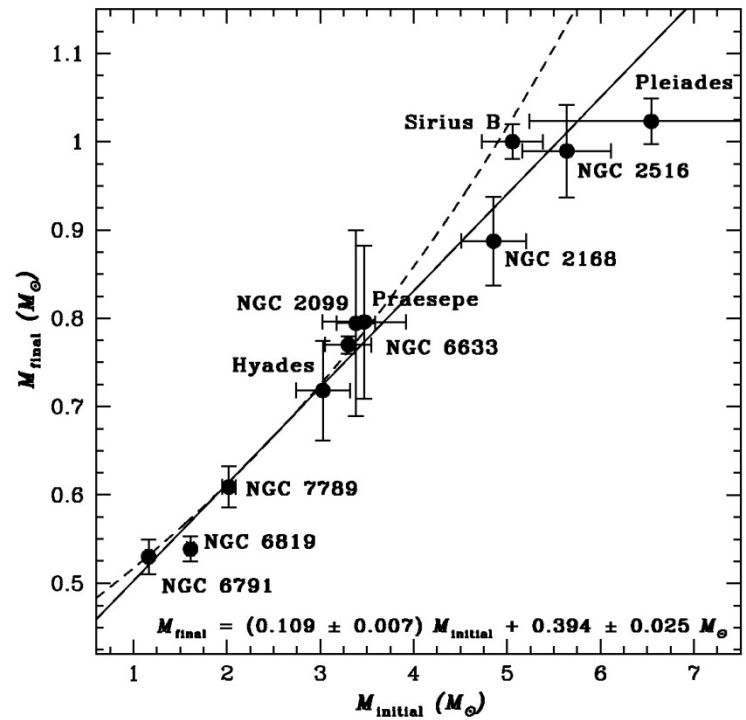
  Complementary studies of nuclear EoS in lab

  - Heavy Ion Collisions (FRIB)
  - Mass Measurements
  - Also important for CC Supernovae

Why now and what's needed: White dwarfs

- Empirical studies in open clusters
  - New large samples likely with upcoming surveys and missions
  - Precision cluster ages expected from GAIA
  - WD seismology constrains cooling ages
  - Direct imaging of AGB mass loss

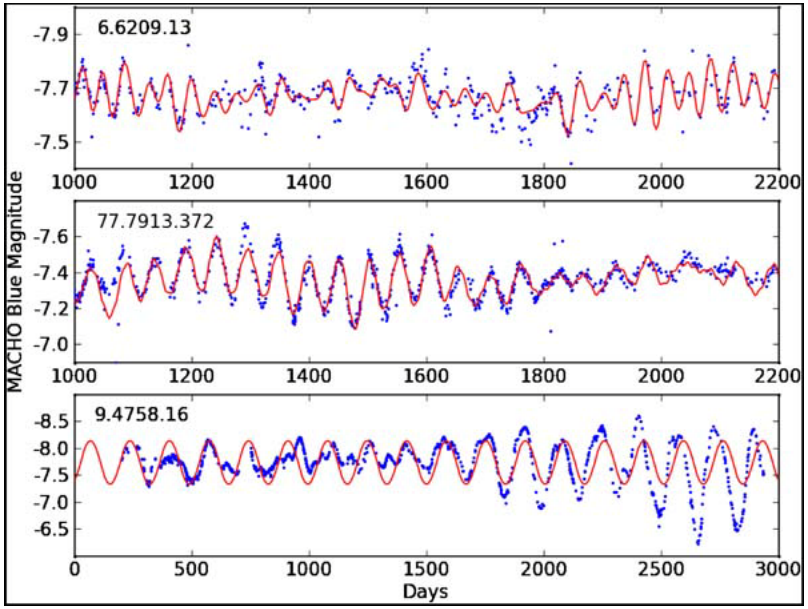
From Kalirai et al. 2008



- What's needed:
  - **Studies of WD cooling physics** (theory, asteroseismology)
  - **Molecular opacity/transition probabilities,** crucial for understanding mass loss in cool stars

Discovery Area: Large Time Domain Surveys

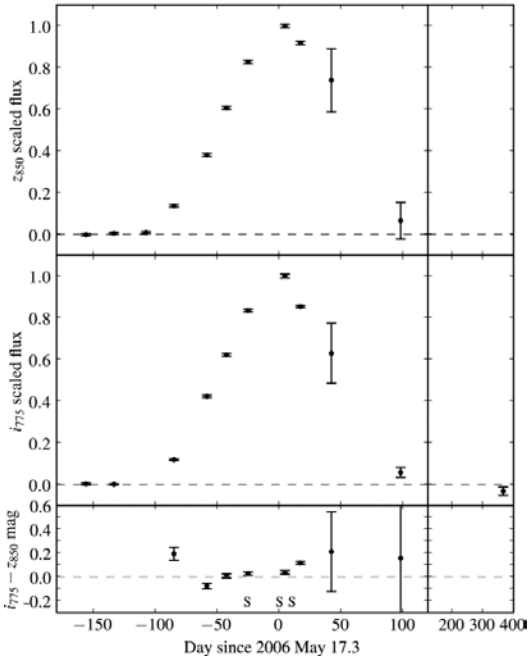
- Significant Fraction of the Sky
- Significant Fraction of the Time
- Many Wavelength Regimes
  - optical/NIR, radio, X-ray
- Large Numbers of Objects
- Accessible Databases
- Coordinated Follow-up



Long Period Variables (MACHO)

Frontier science

- Time domain surveys particularly benefit stellar astrophysics because stars vary on the scales they sample
  - Our 4 questions highlight the science opportunities requiring time domain survey data; also periodic variables, clouds and weather on brown dwarfs, episodic mass loss (e.g., LBVs), stellar flares,…
  - Expected, but previously unobserved phenomena, e.g., stellar mergers, GRB orphan afterglows,…
  - Serendipitous discoveries of previously unknown classes of objects



~200 day transient discovered in Hubble Cluster SN Survey

Summary

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