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Spin alignment of stars in old open clusters

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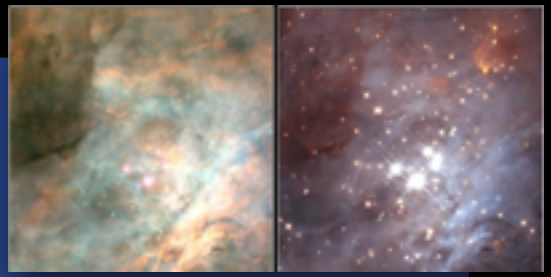
INTRODUCTION
STAR FORMATION

- **_Fundamental_** problem in Astrophysics
  SHU ET AL. 1987; MCKEE & OSTRIKER 2007
- Gravitational collapse of turbulent molecular clouds (MC)
- Dynamics of star forming regions (SFR)
- Origin of stellar mass distribution (IMF)
- Stars and planets formation rates
- Galaxy formation, structure, and evolution

BARNARD 68 DARK CLOUD. © ESO

Very difficult problem to investigate:

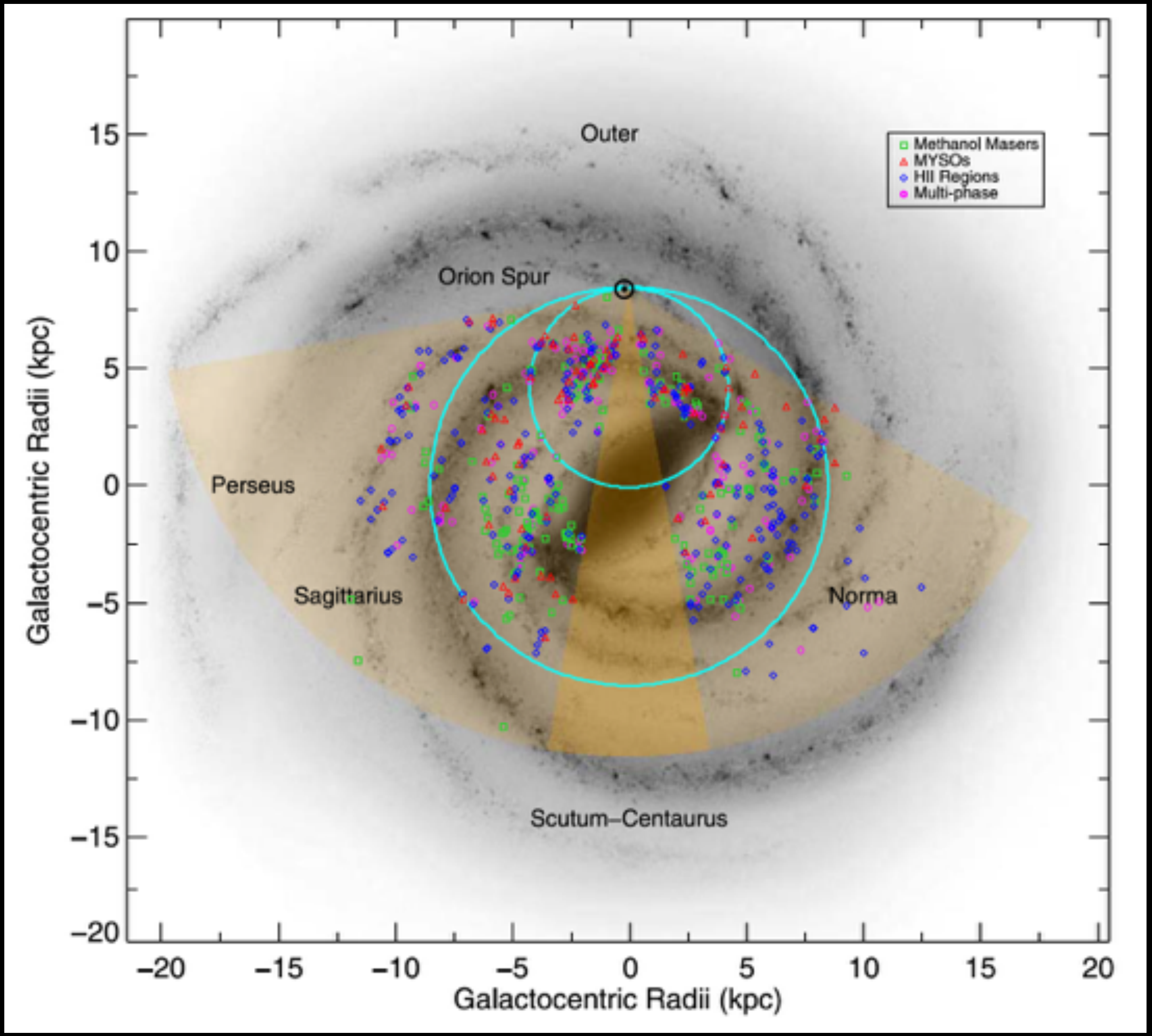
- SFR are dense and obscured by dust (only IR and Radio)
- MC change density by 10 orders - Hierarchical step approaches required



INTRODUCTION

STAR FORMING REGIONS

- Star formation diffused in entire Galaxy
- ~**1300** massive SFR identified with IR, sub-mm, Radio
  URQUHART ET AL. 2014
- Half star formation in Milky Way occurring in 24 giant MC (up to **10^7 M_{Sun}** each)
  LEE ET AL. 2012; LONGMORE ET AL. 2014



ATLASGAL © URQUHART ET AL. 2014

BENCHMARKS OF STAR FORMATION

OPEN CLUSTERS

- Giant MC can form hundreds of proto-clusters each with up to **10^5 M_{Sun}**
  LADA & LADA 2003; LONGMORE ET AL. 2014; URQUHART ET AL. 2014
- Stellar clusters are common
- Sun and Solar System are likely born from a cluster
  ADAMS 2010

OPEN CLUSTER NGC 265 © NASA/ESA

OPEN CLUSTERS

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  LADA & LADA 2003; LONGMORE ET AL. 2014; URQUHART ET AL. 2014
- Stellar clusters are common
- Sun and Solar System are likely born from a cluster
  ADAMS 2010
- Open clusters (OC) are **important**:

OPEN CLUSTER NGC 265 © NASA/ESA

1. **Can be observed in multi bands because no or little ISM**
   Not possible in SFR because covered by dust
2. **Stars are sparse (down to ~1 M_{Sun} pc^{-3}) —> precise follow-up of many stars possible**
   Not possible in e.g. Globular Clusters, too dense!
3. **Stars in cluster can preserve imprint of initial conditions of progenitor MC**
   Not possible with field stars because originate from dissolved small stellar systems

CLOUD'S ANGULAR MOMENTUM (AM)

OBSERVATIONAL RESULTS

- Evolution of cloud's AM not well understood
  E.G. SHU, ADAMS & LIZANO 1987; DONG LAI 2014

- Stellar-spin axis ***randomly distributed*** in nearby OC Pleiades and Alpha Persei (d ~ 150 pc, Age~80 Myr)
  JACKSON & JEFFRIES 2010

- Clouds' average AM scrambled by turbulence at different scales

PLEIADES WITH DSS © NASA/ESA

Imprint of cloud's global rotation lost during star formation because of turbulence

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PLEIADES WITH DSS © NASA/ESA

Imprint of cloud's global rotation lost during star formation because of turbulence

Only young active stars possible
Strong sensitivity to cluster distance
Prone to large systematics

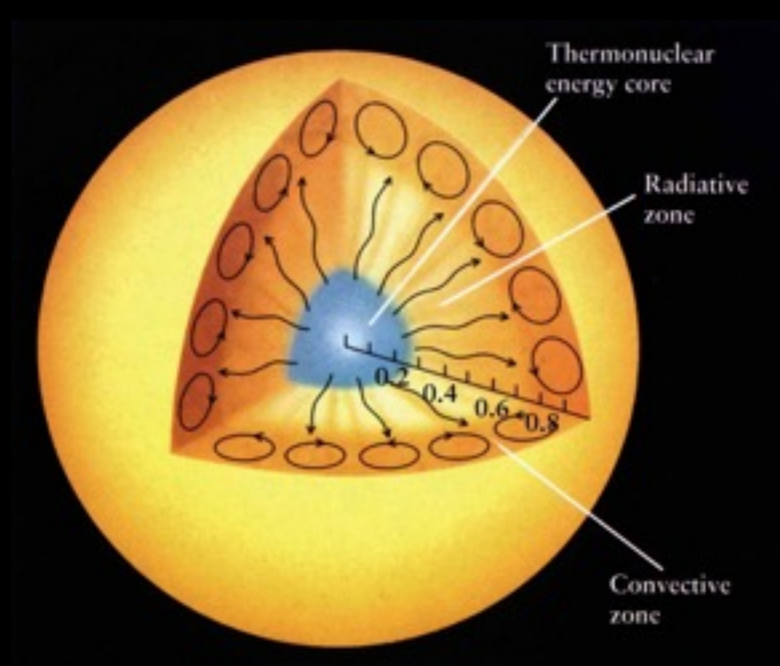
Spectroscopy **LC spot activity**

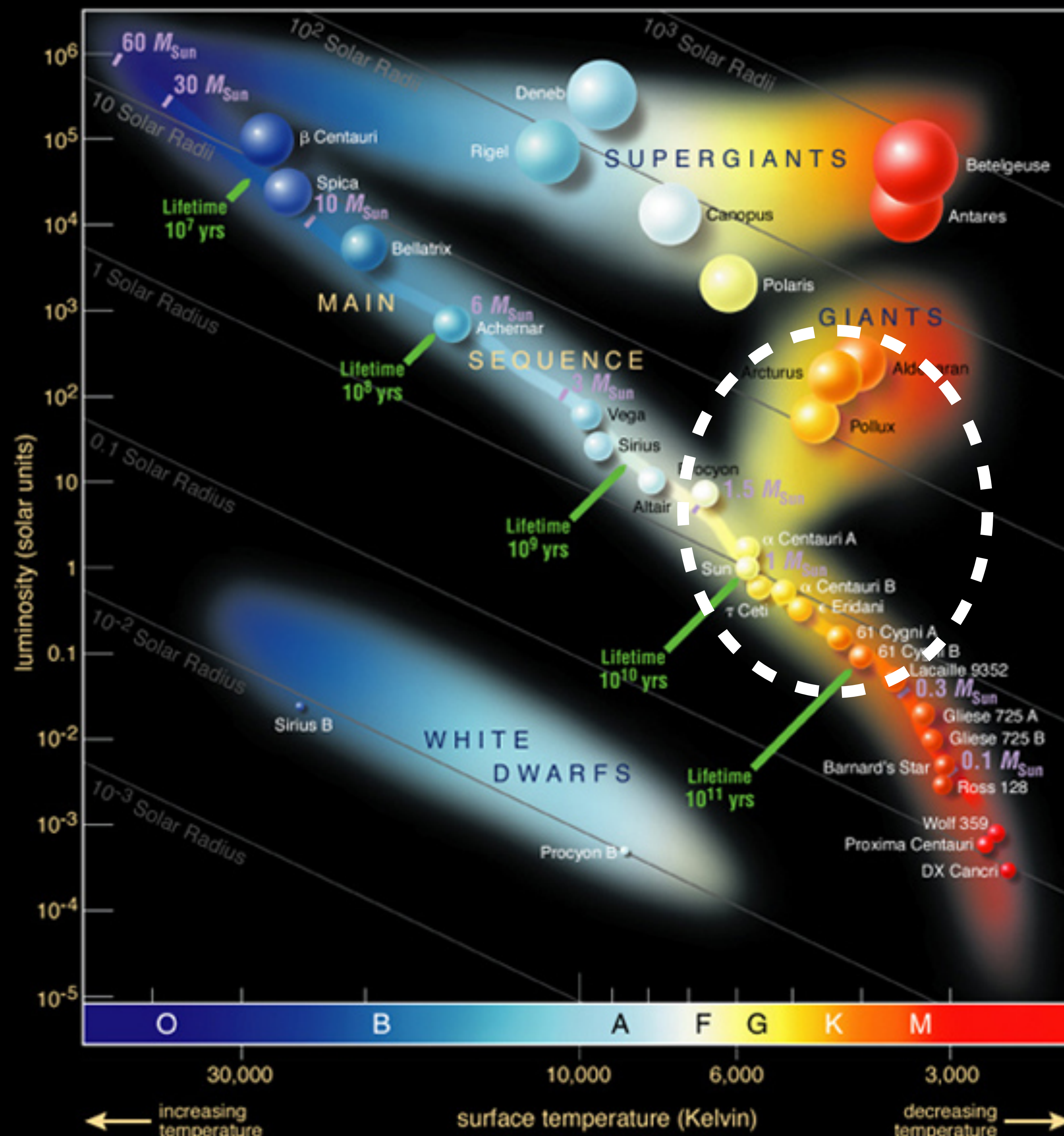
$$\sin\theta = \frac{v\sin\theta \, P_{\mathrm{rot}}}{2\pi R}$$

Angular diameter + parallax

ASTEROSEISMOLOGY

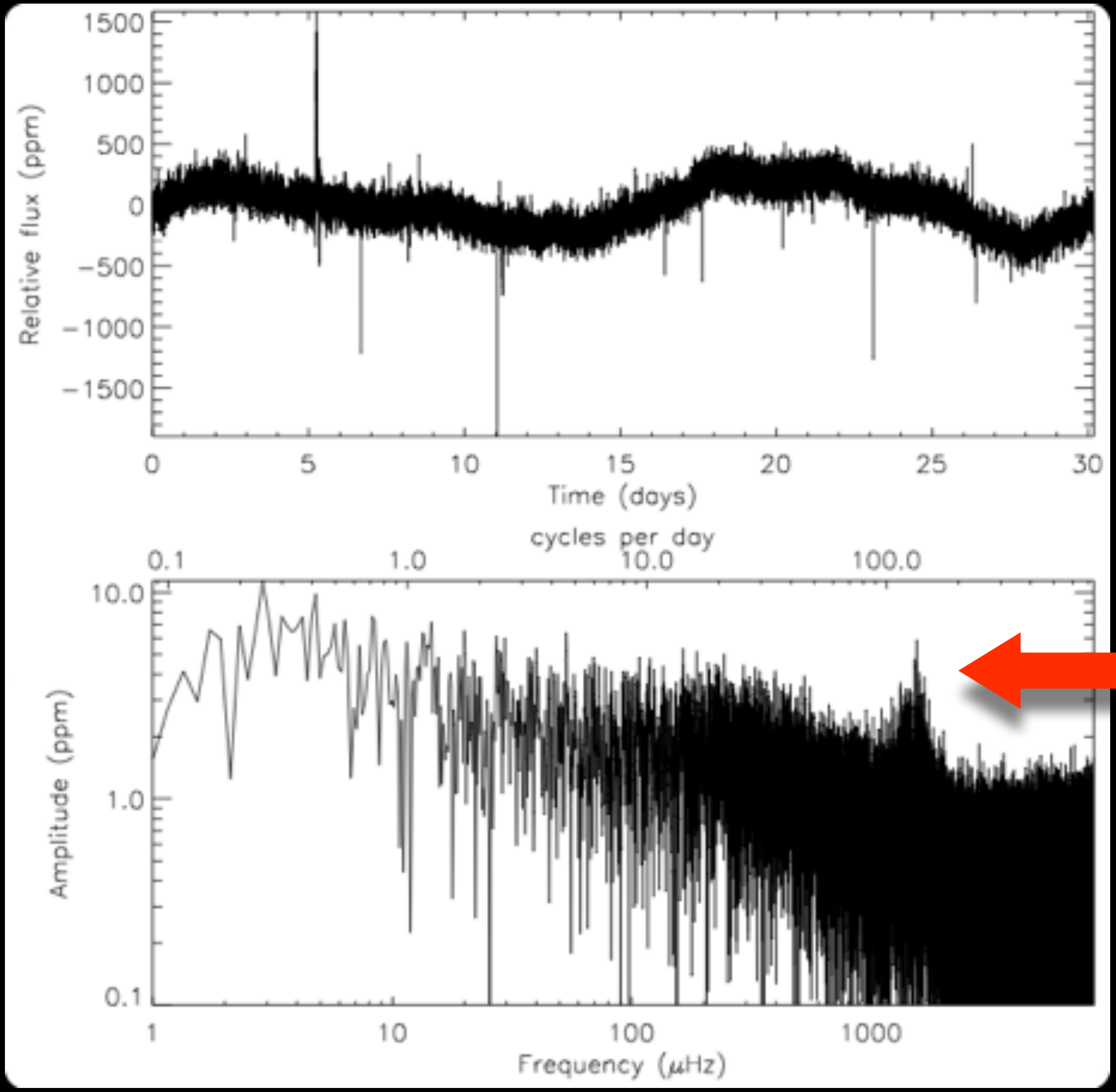
- Most stars with M ~ 1-3 M_{Sun} oscillate like the Sun (helioseismology)
  CHRISTENSEN-DALSGAARD 1987
- ~ 100 K known today
- Space missions MOST, CoRoT, NASA *Kepler* & K2
- More to follow: NASA TESS, ESA PLATO





SOLAR-LIKE OSCILLATIONS

- Acoustic waves produce tiny brightness variations (from few ppm)
- Fourier analysis (PS) reveals Gaussian envelope of oscillations



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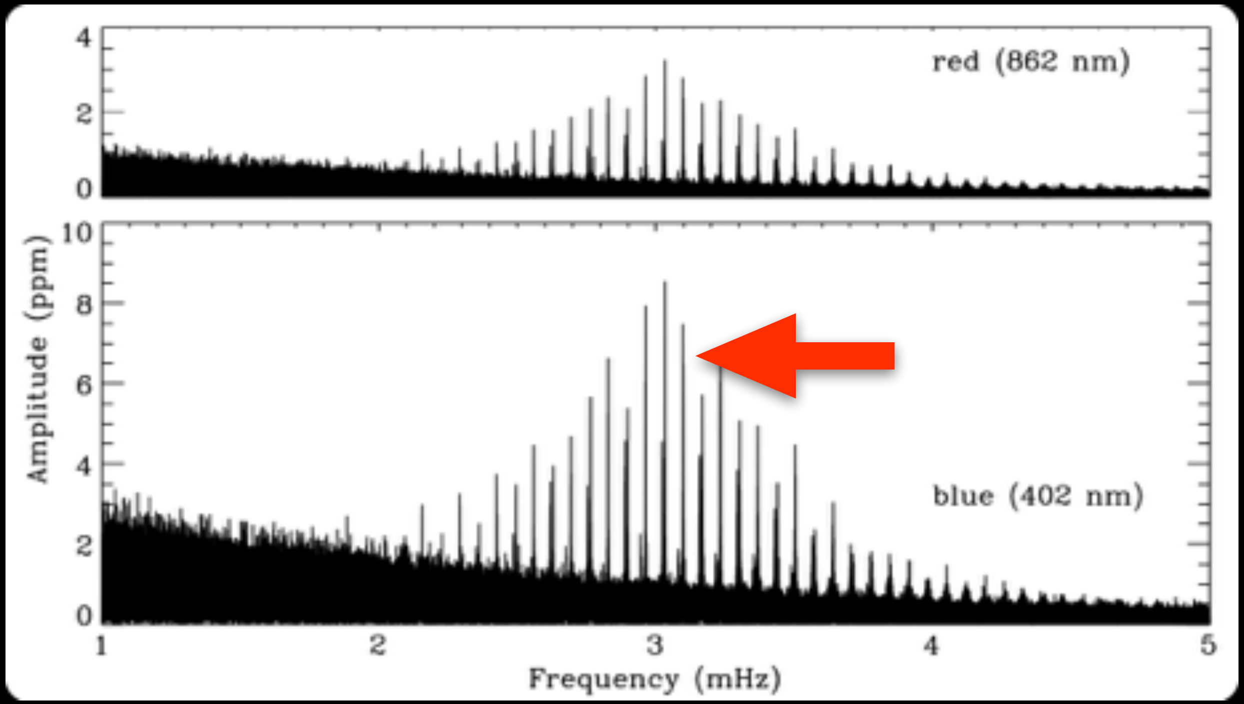

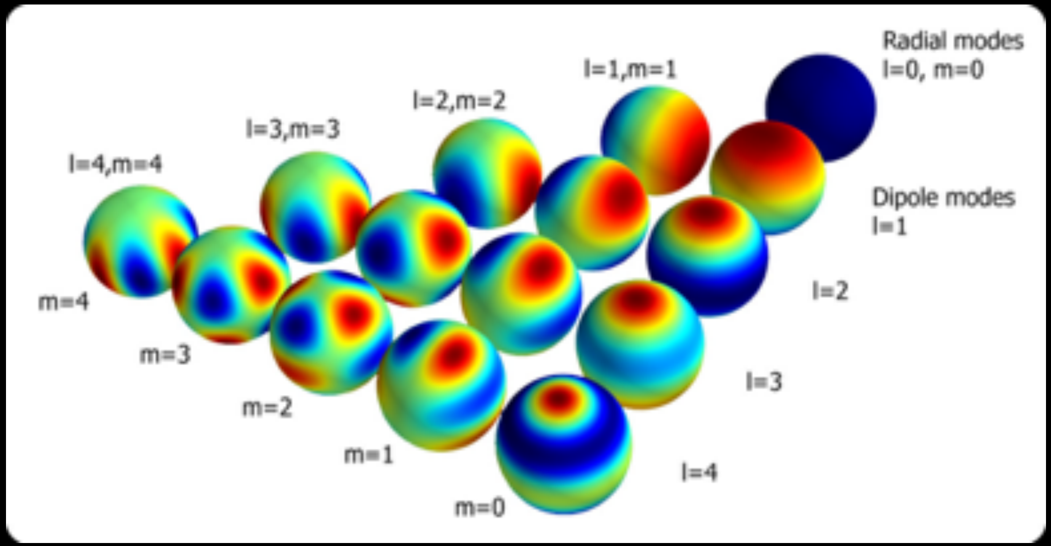

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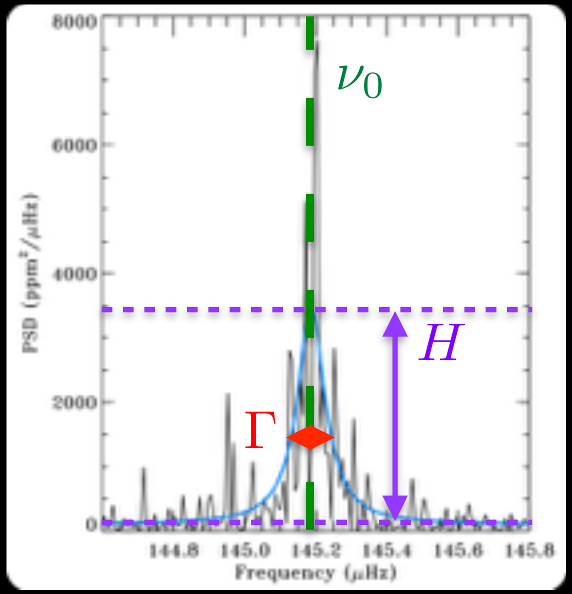
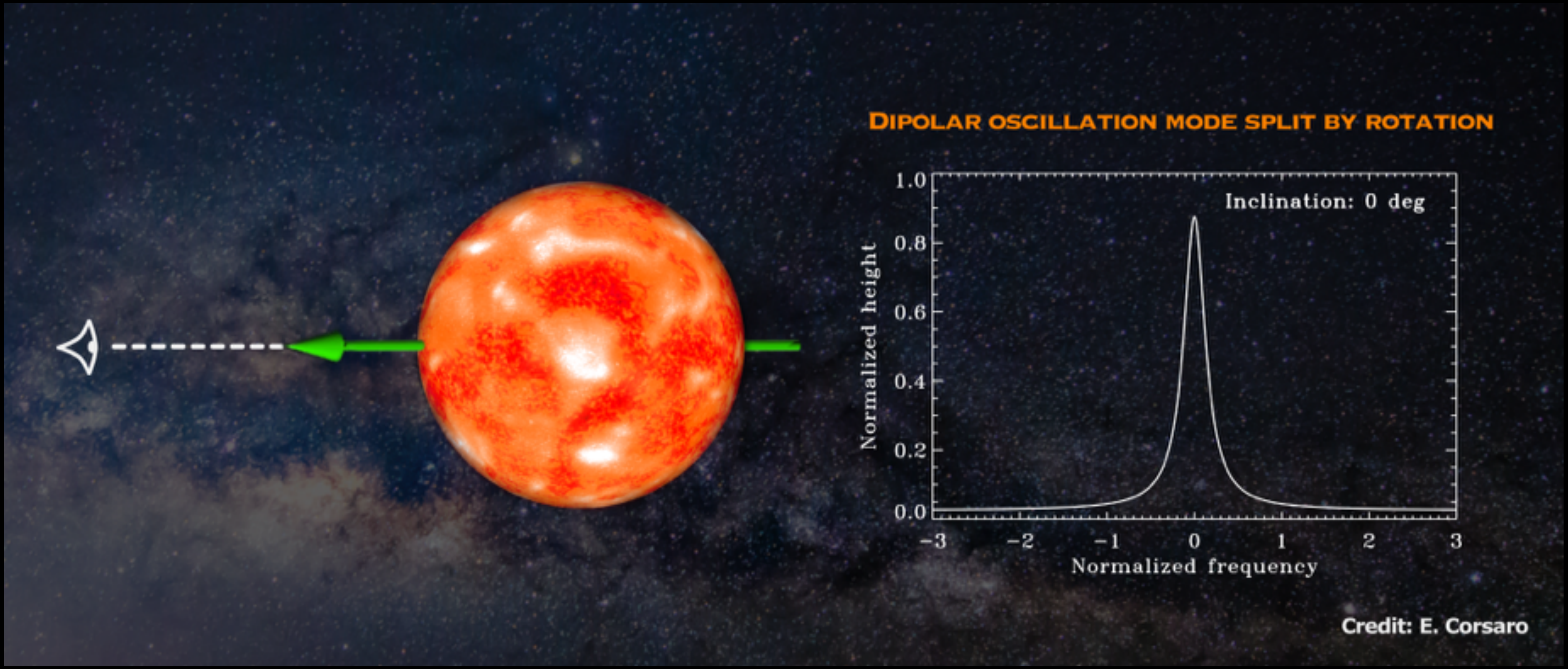
MEASURING STELLAR AM

SPIN INCLINATION ANGLE

- Stellar oscillations accurately probe spin axis inclination
  GIZON & SOLANKI 2003; BALLOT ET AL. 2006; BECK ET AL. 2012 NATURE; DEHEUVELS ET AL. 2012; HUBER ET AL. 2013 SCIENCE
- Rotational degeneracy of ℓ=1 (dipolar) modes gives $(2\ell + 1)$ *m*-components





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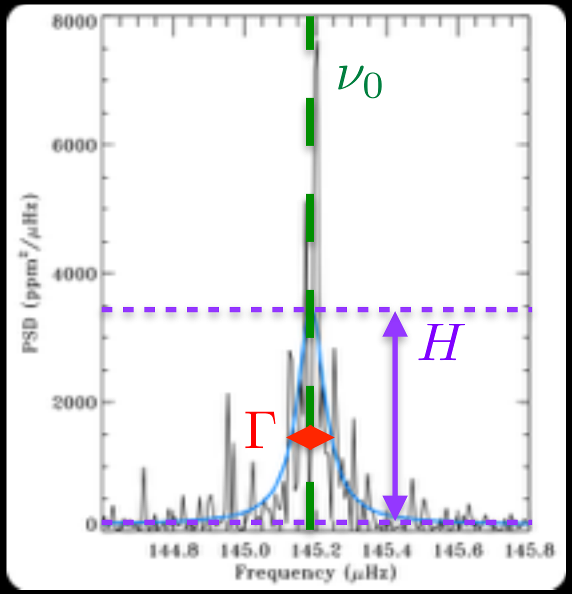

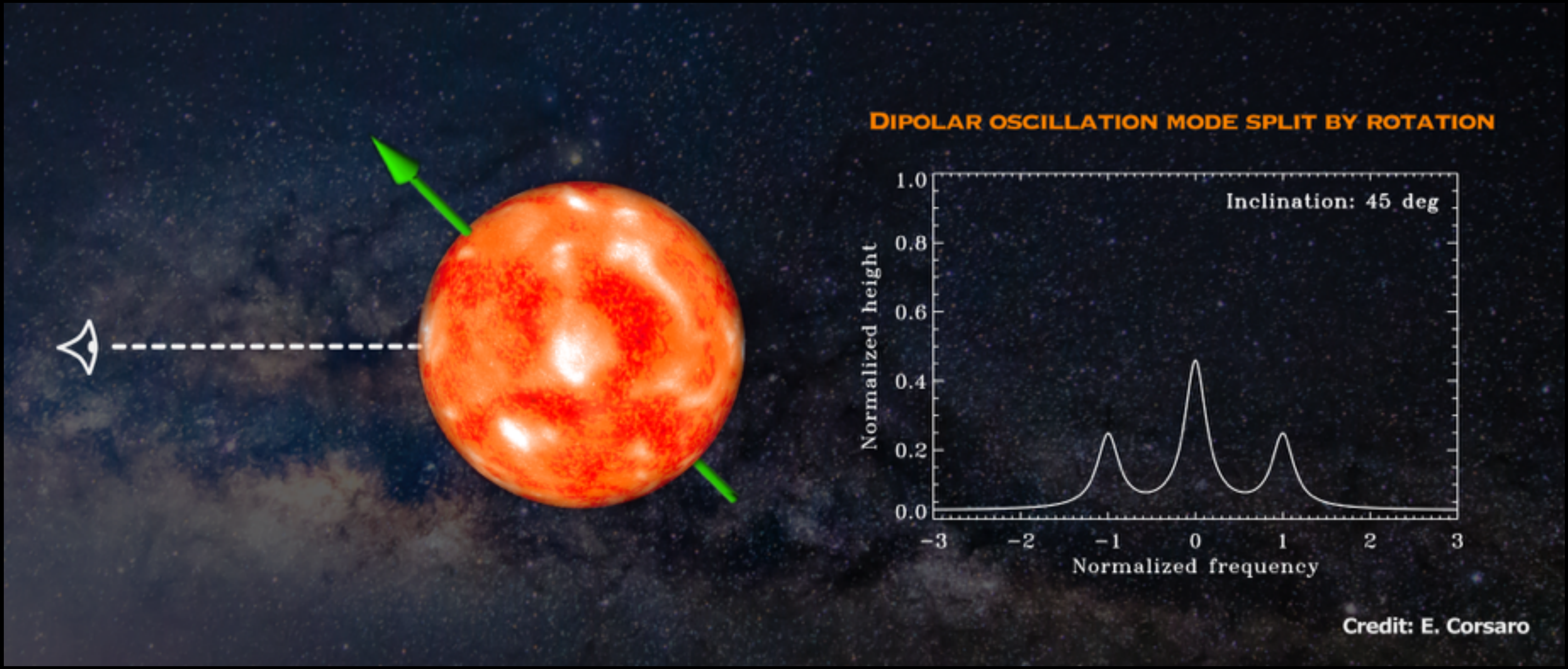

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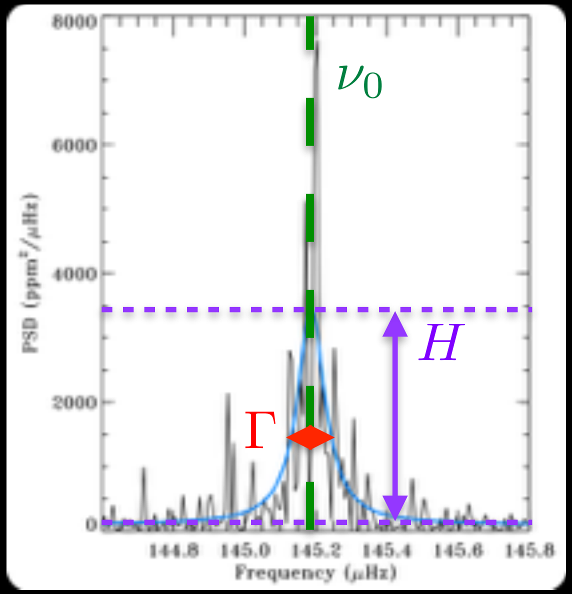
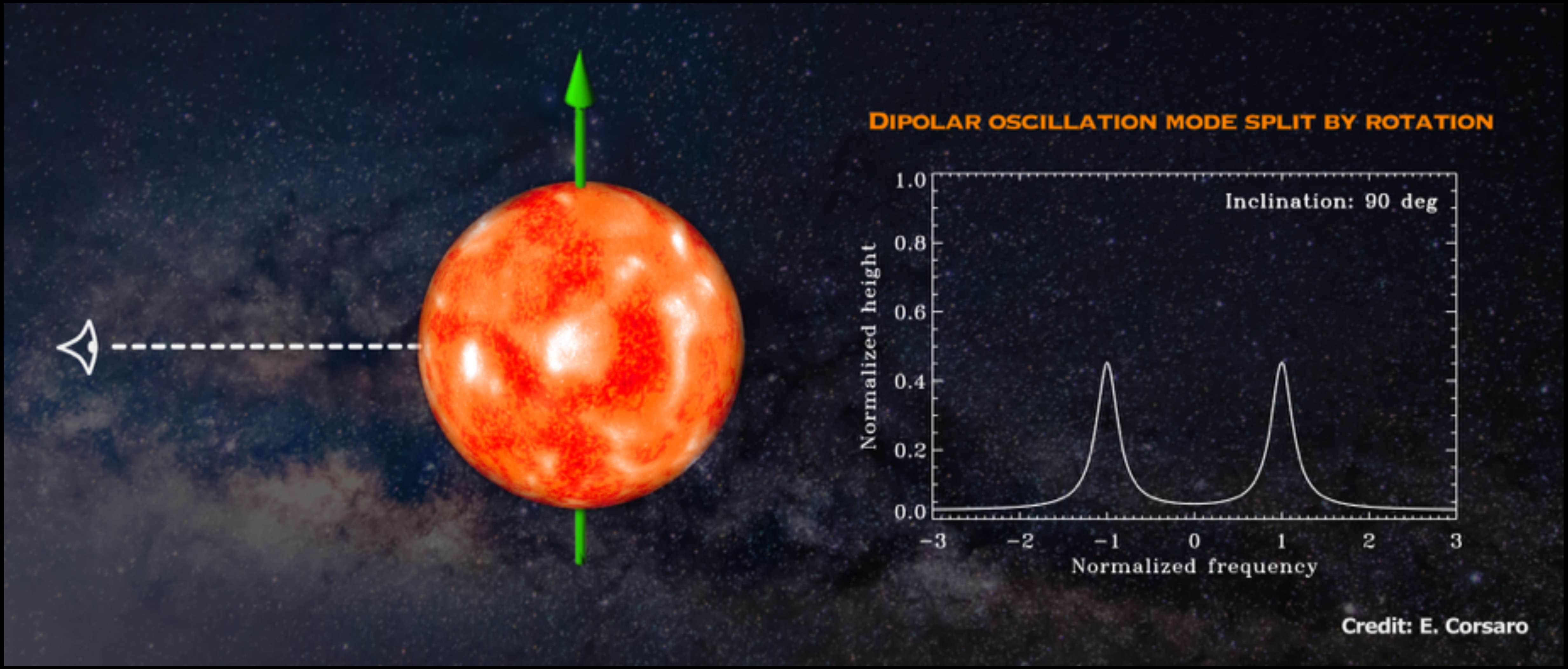


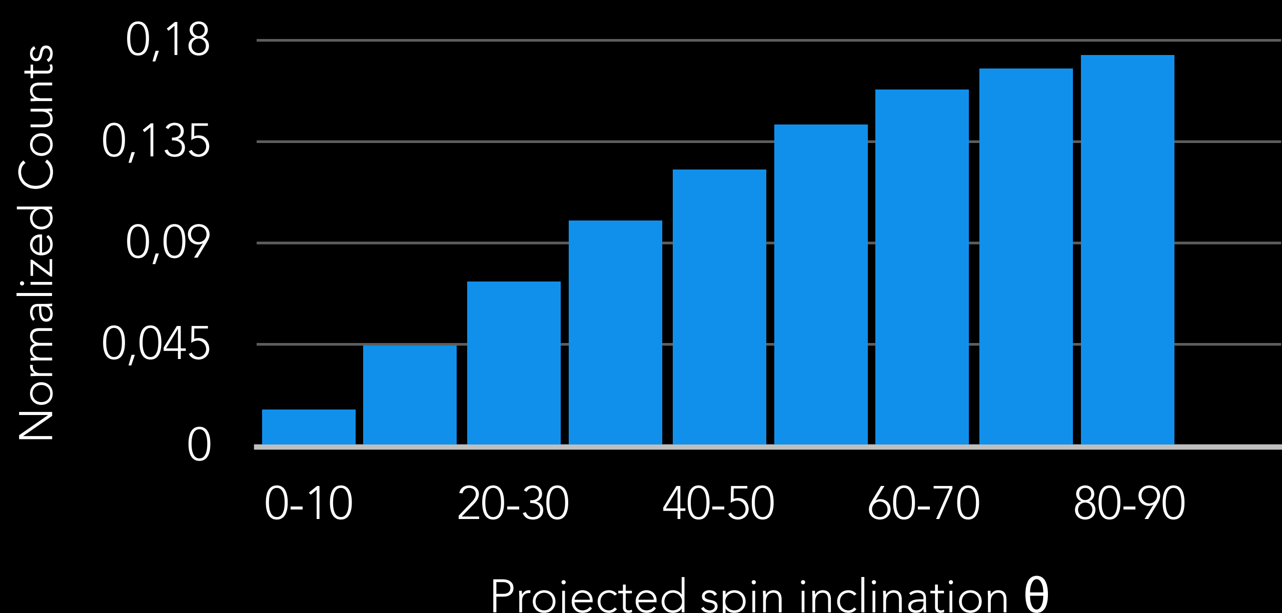


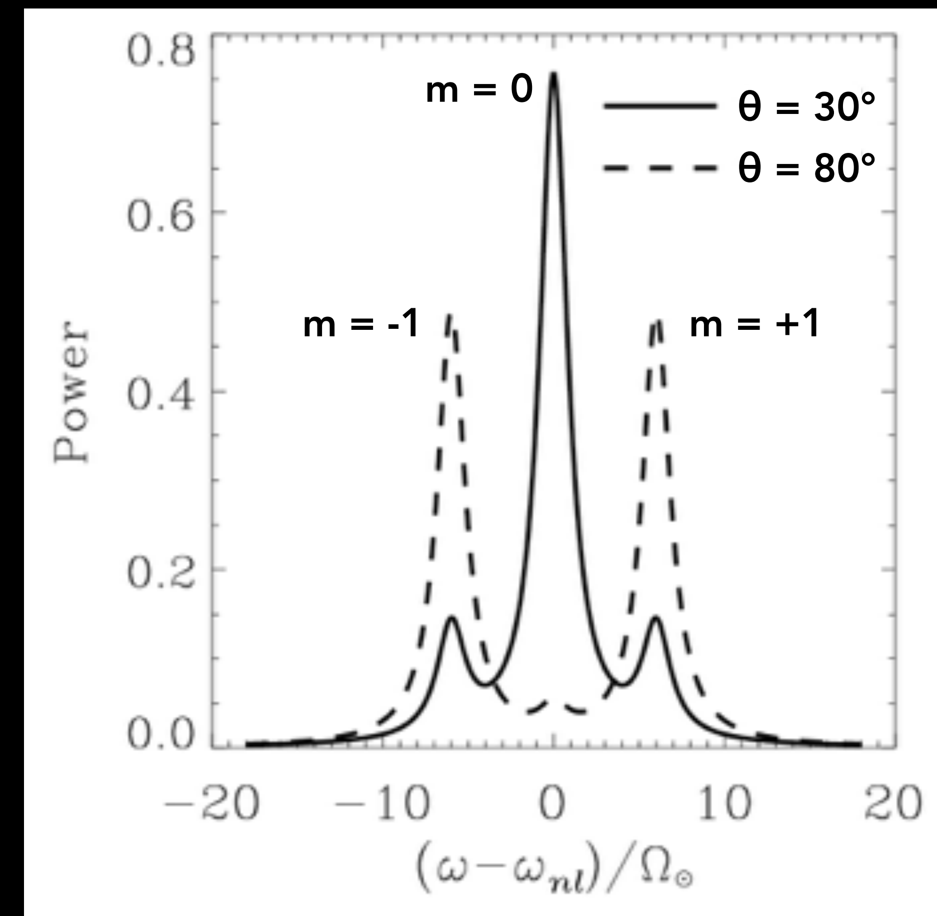
PROJECTION EFFECT

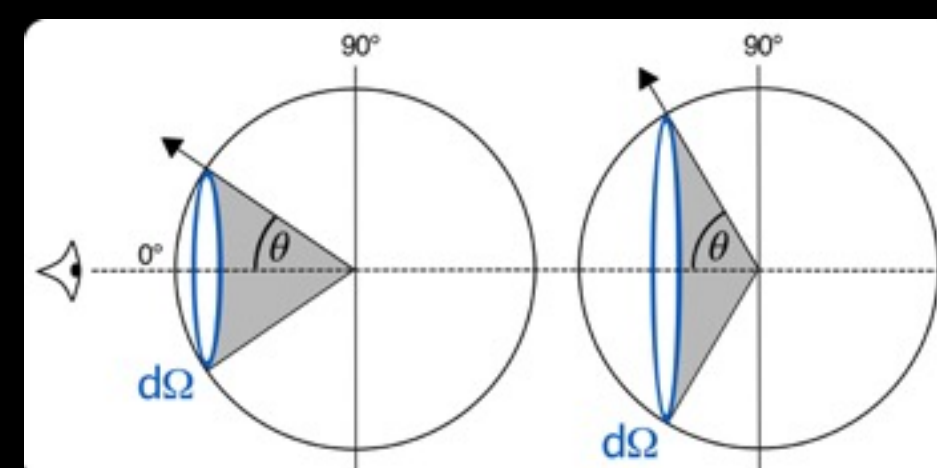
High angles are easier to observe
(projection effect from 3D space)

$$d\Omega = sin(\theta)d\theta$$

3D RANDOM DISTRIBUTION



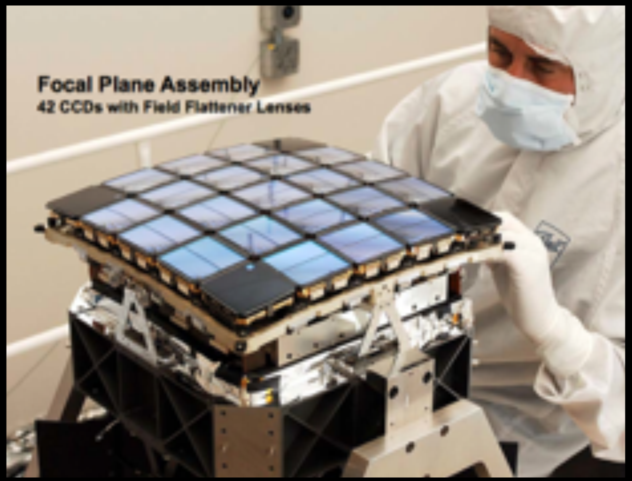


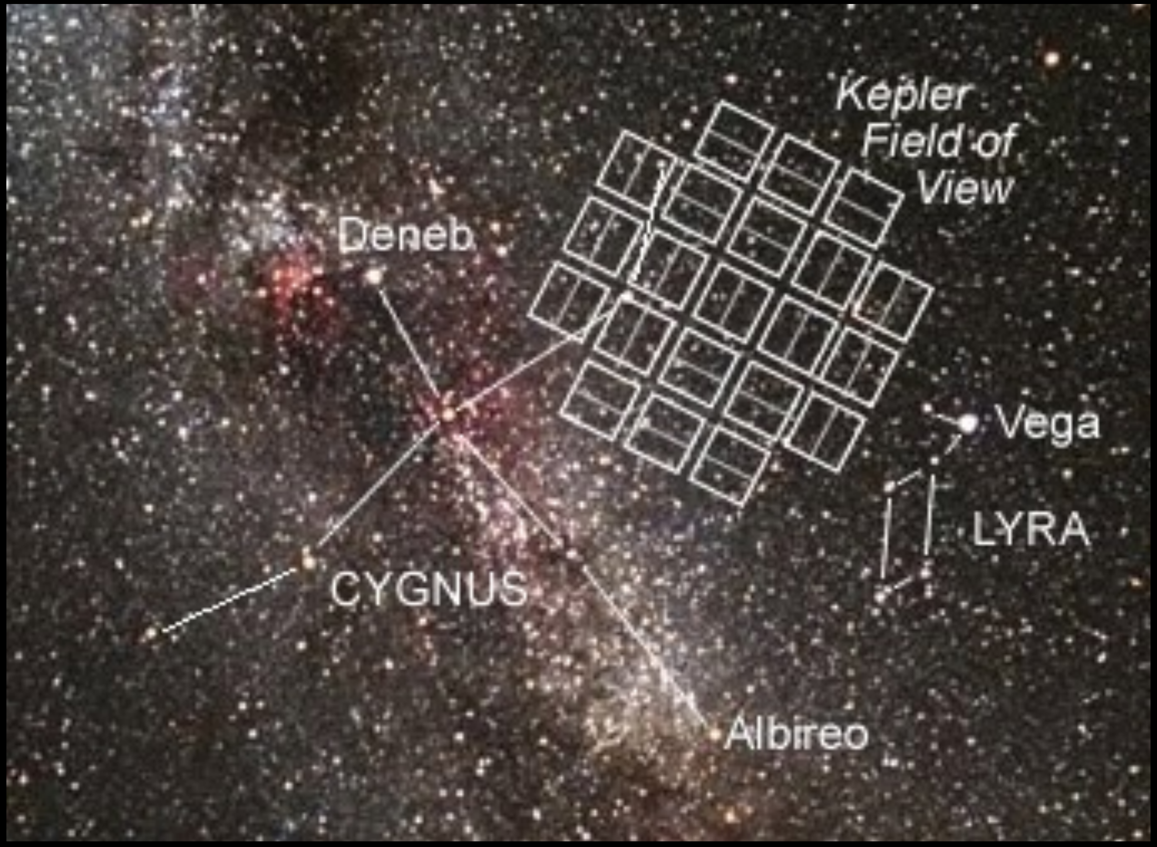


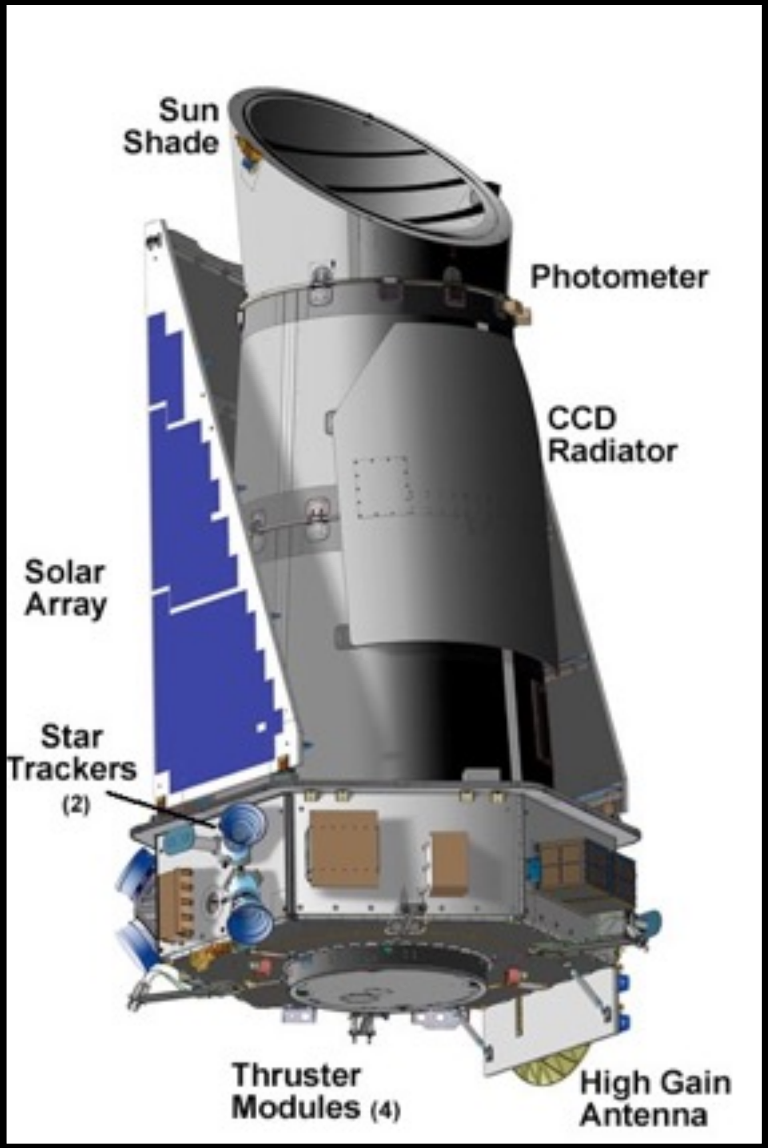
SPACE MISSION

NASA KEPLER

- Launched 2009 - End nominal mission in 2013
- Mission devoted to exoplanets discovery
- 150,000 stars observed in the Cygnus - Lyra constellations
- Kepler photometric band: 430-890 nm



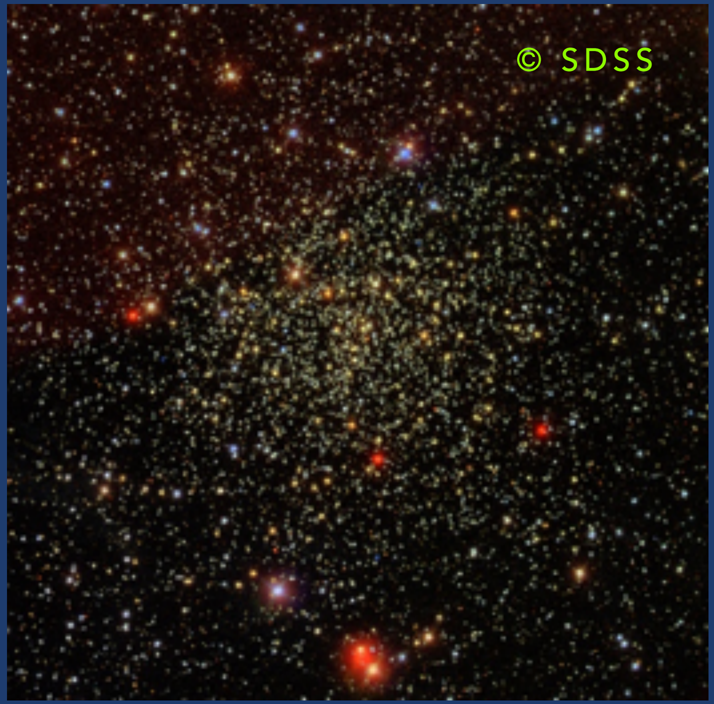




OBSERVATIONAL PROPERTIES

NGC 6791

- Total mass ~ 5000 M_{Sun}
  PLATAIS ET AL. 2011
- Distance ~ 4187 pc
  BASU ET AL. 2011
- Size ~ 10 pc
- Age ~ 8.3 Gyr
  BROGAARD ET AL. 2012
- M_{RG} ~ 1.1 M_{Sun}
  MIGLIO ET AL. 2012



4 YEARS PHOTOMETRY WITH NASA KEPLER

NGC 6819

- Total mass ~ 2600 M_{Sun}
  KALIRAI ET AL. 2001
- Distance ~ 2344 pc
  BASU ET AL. 2011
- Size ~ 7 pc
- Age ~ 2.4 Gyr
  BREWER ET AL. 2016
- M_{RG} ~ 1.7 M_{Sun}
  MIGLIO ET AL. 2012

CLUSTER RED GIANTS

DIAMONDS™ BAYESIAN SOFTWARE

- A sample of **~50 cluster RGs** studied with asteroseismology

CORSARO ET AL. 2012, APJ, 757, 190

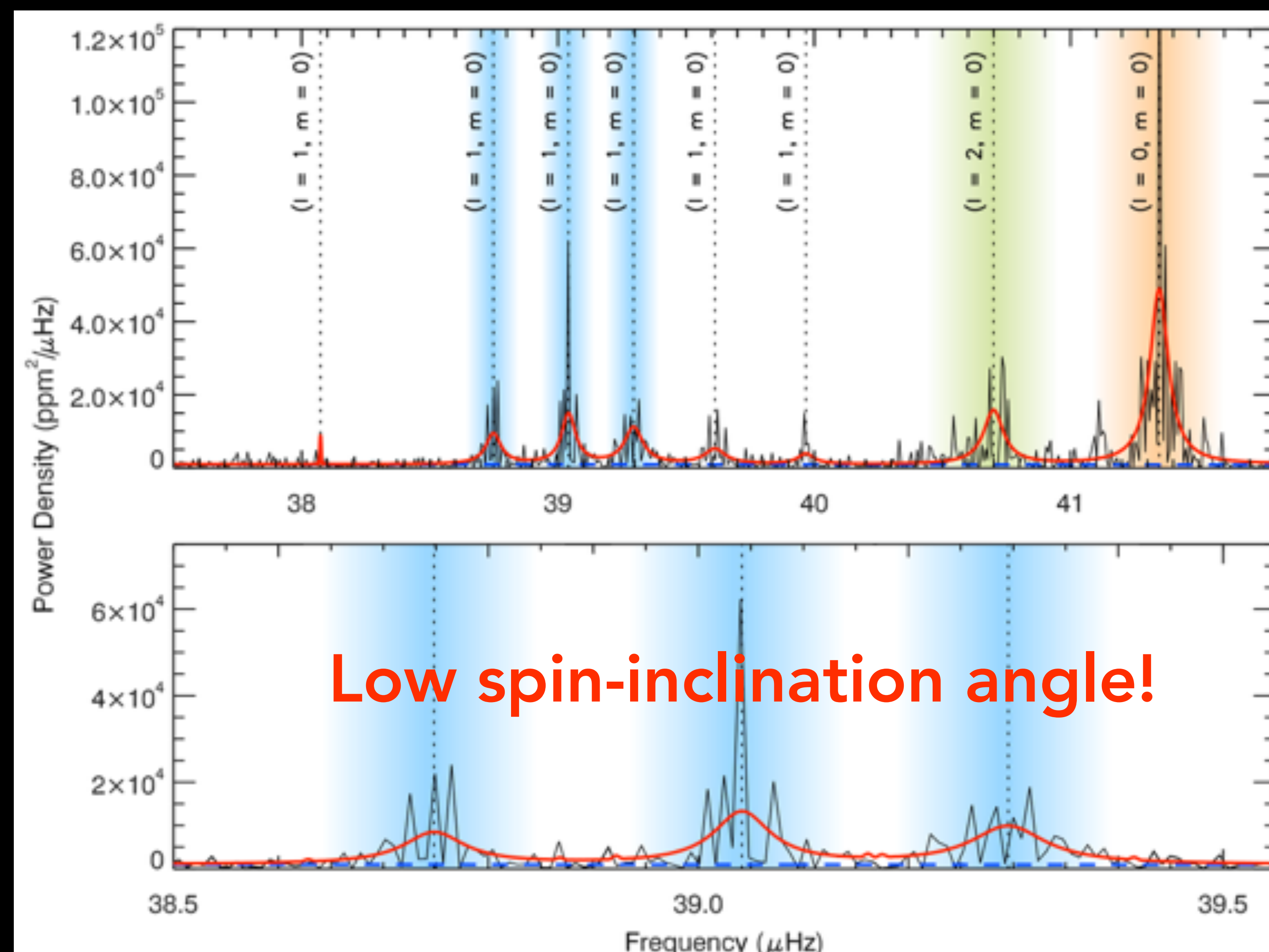
- Oscillation mode fitting using Bayesian inference code **DIAMONDS**

CORSARO & DE RIDDER, 2014, A&A, 571, 71;
CORSARO ET AL. 2015, A&A, 579, 83

- **3900** oscillation modes fitted and identified

CORSARO ET AL. IN PREP.

- **380** rotationally split $\ell=1$ modes used to measure spin-axis inclinations



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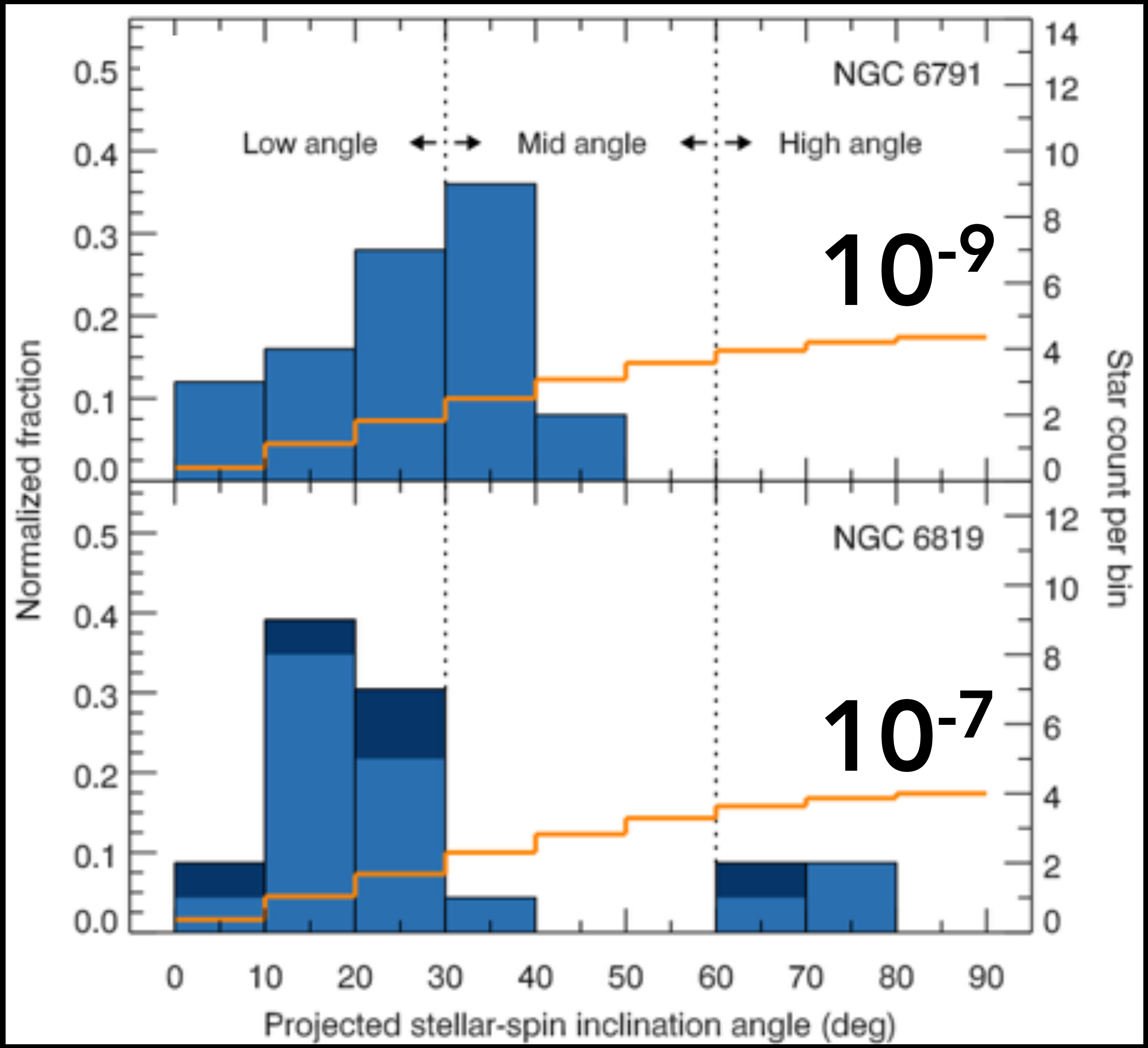
STELLAR-SPIN INCLINATION

STRONG DEGREE OF ALIGNMENT



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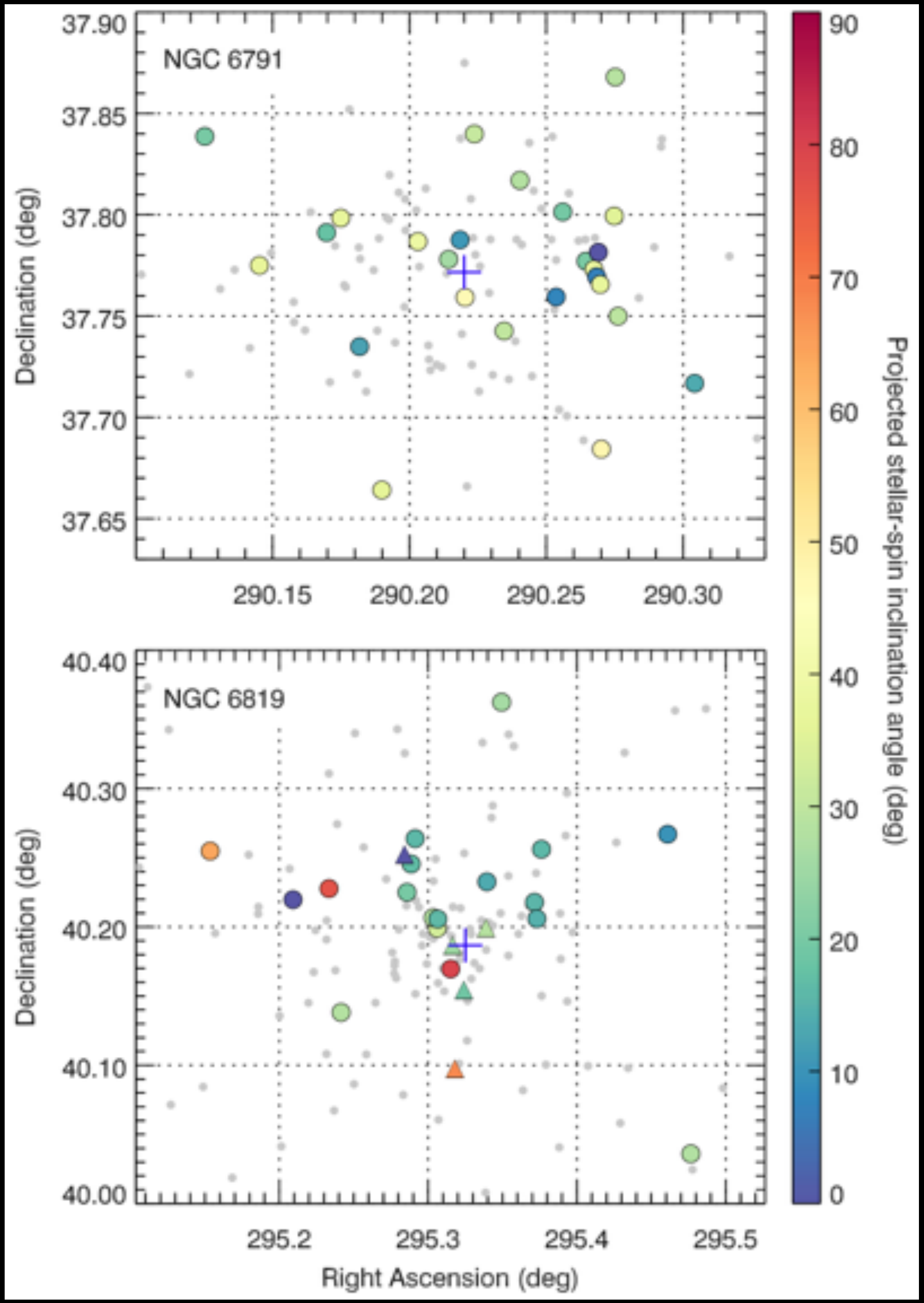

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N-BODY INTERACTIONS?

- Individual stars undergo spin down over time: magnetic braking, stellar winds, tidal friction
  MEIBOM ET AL. 2011 NATURE; VAN SADERS ET AL. 2016 NATURE; GELLER ET AL. 2013
- Main force influencing spin orientation is ***tidal***
- But OC stars are sparse (down to **~1 M_{Sun} pc^{-3}**)
  LADA & LADA 2003
- Effect from tidal forces negligible even after many Gyr!
  HUT 1981

$$\frac{d\theta}{dt} \propto \left(\frac{R}{a}\right)^6$$

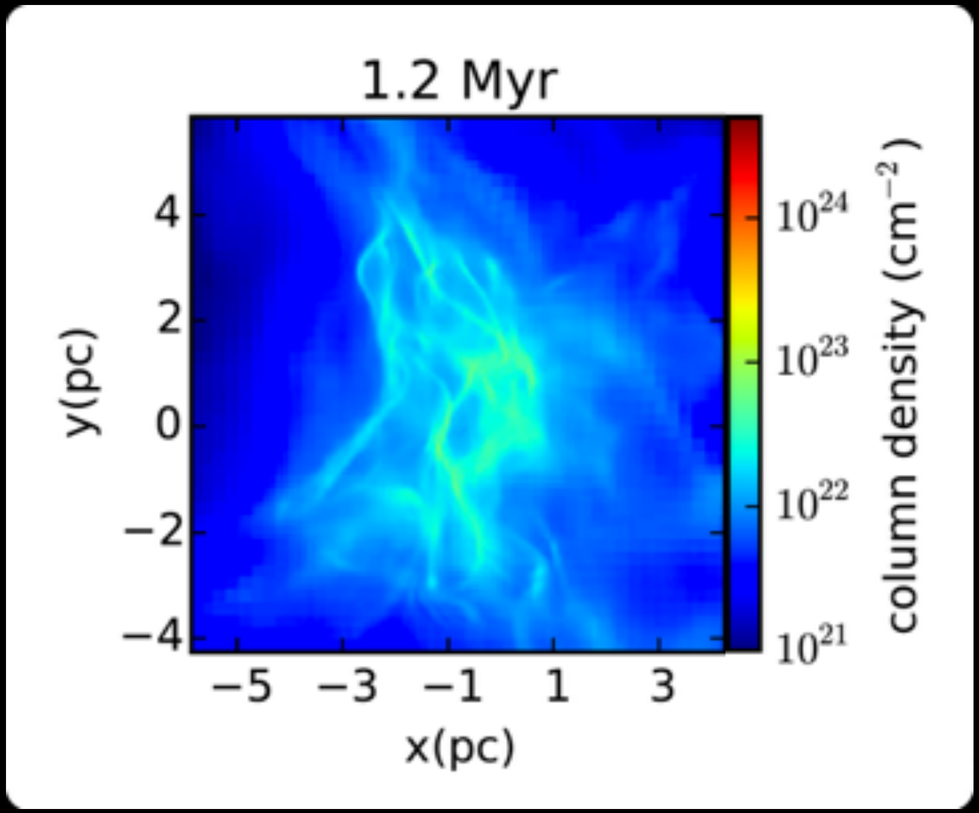
ORIGIN OF SPIN ALIGNMENT

PROTO-CLUSTER FORMATION

- Spin alignment possible ***only*** during cluster formation epoch
- MC evolution resolved with **RAMSES**: 3D MHD code with AMR
  TEYSSIER 2002; FROMANG ET AL. 2006
  LEE & HENNEBELLE 2016
- Evolution:

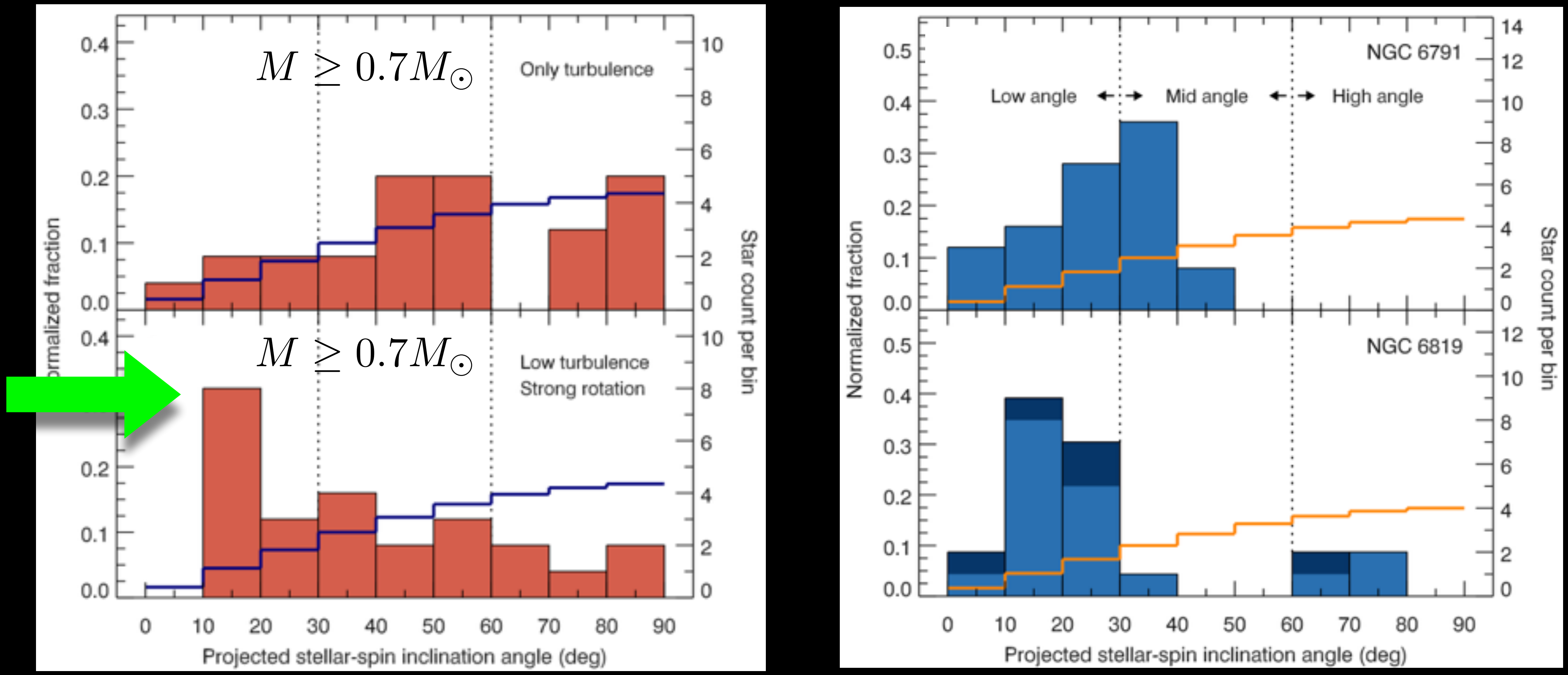
$$E_{\mathrm{kin}} = E_{\mathrm{tur}} + E_{\mathrm{rot}} \quad E_{\mathrm{grav}}$$

3D hydrodynamics



3D SIMULATION RESULTS

- If cloud rotation **absent** or **low**: no spin alignment (random) — $E_{rot}/E_{tur} < 1$
- If **strong** cloud rotation present: significant spin alignment — $E_{rot}/E_{tur} \simeq 1$
- Stars with **M < 0.7 M_{Sun}** show no alignment even with strong rotation



PROTO-CLUSTER FORMATION

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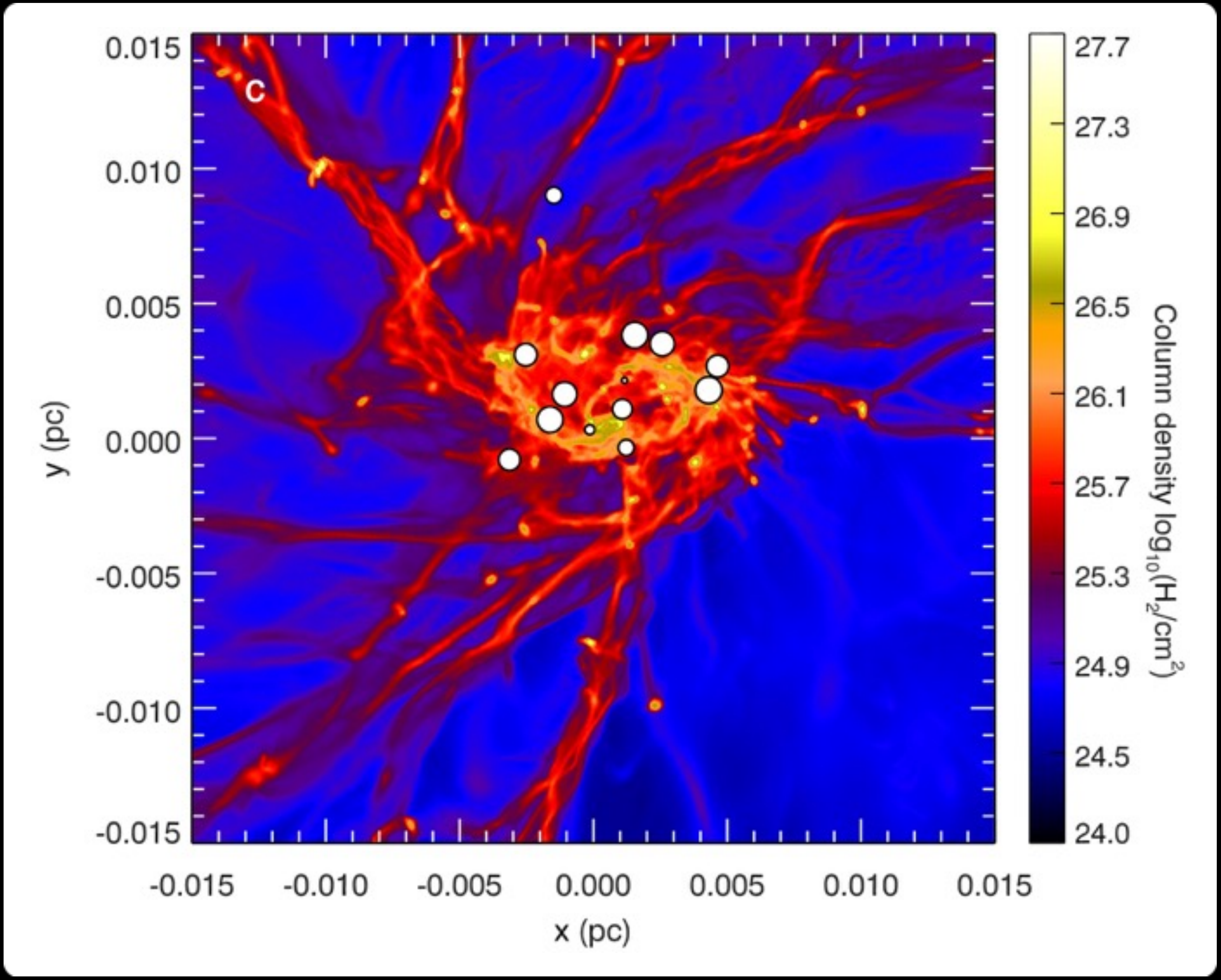

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SUMMARY & CONCLUSIONS

Direct observations

Strong stellar-spin alignment (~70%) within a stellar cluster → Detection through asteroseismology

+

3D hydrodynamics

Proto-cluster has strong rotational energy component

Proto-cluster AM efficiently passed down to individual stars

Imprint of cloud's global rotation has survived for more than 8 Gyr!

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Proto-cluster AM efficiently passed down to individual stars

Imprint of cloud's global rotation has survived for more than 8 Gyr!

$E_{\rm tur} > 2E_{\rm rot}$ **Proto-cluster**

$E_{\rm kin} = E_{\rm tur} + E_{\rm rot}$

NO Stellar spin-alignment

→

$E_{\rm rot} \gtrsim E_{\rm tur}$ **Proto-cluster**

$M \geq 0.7 M_\odot$ **Stars**

SIGNIFICANT Stellar spin-alignment

Thank you!

ENRICO CORSARO