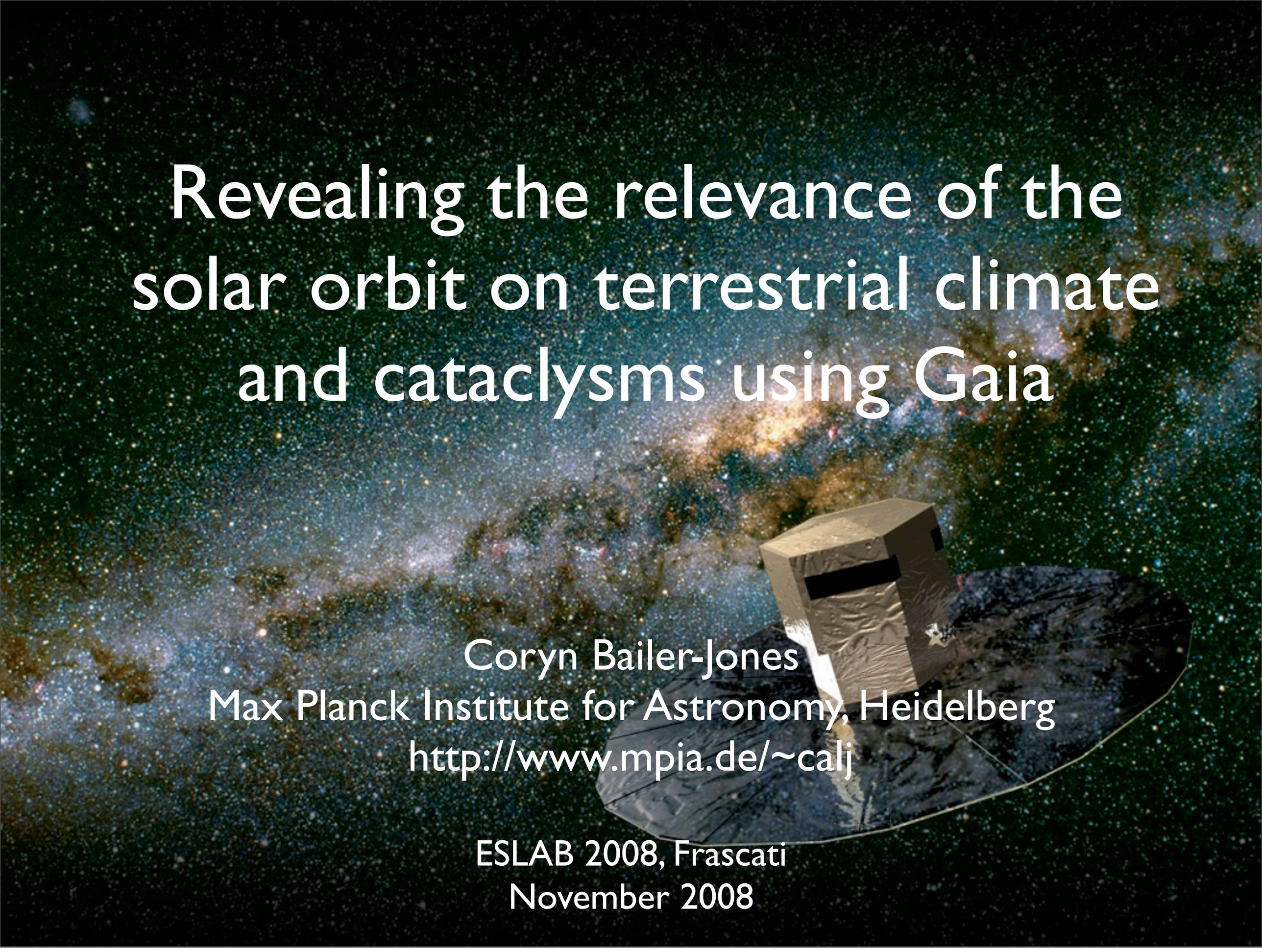
Revealing the relevance of the solar orbit on terrestrial climate and cataclysms using Gaia

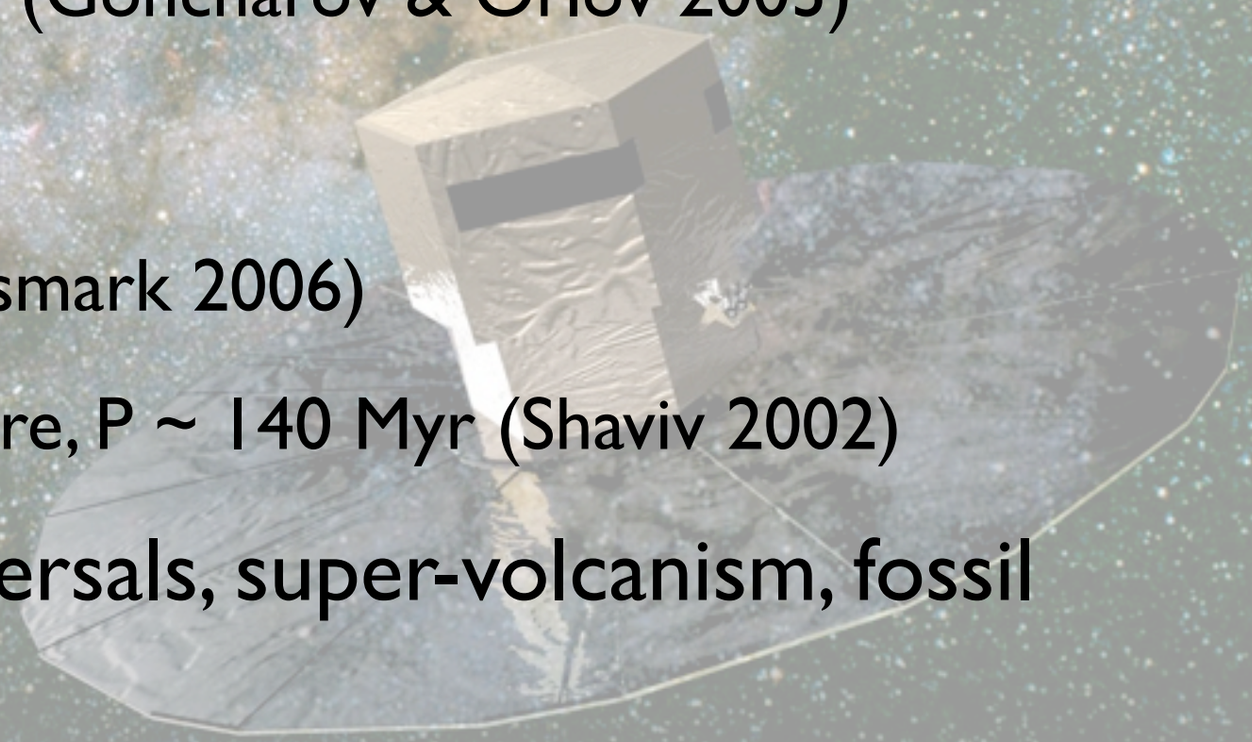


Coryn Bailer-Jones
Max Planck Institute for Astronomy, Heidelberg
http://www.mpia.de/~calj

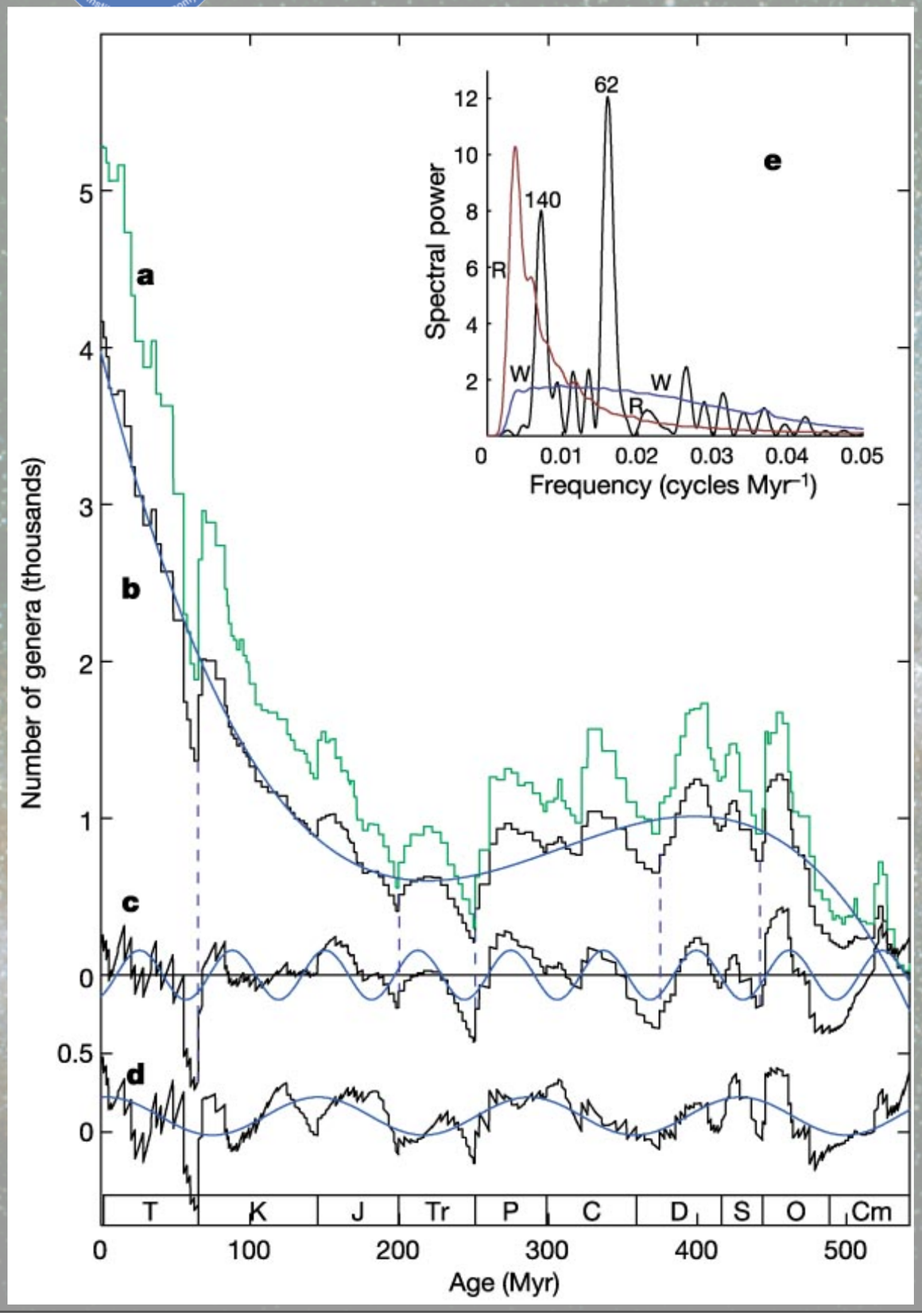
ESLAB 2008, Frascati
November 2008

Geological time series and period claims

- (Mass) extinctions
  - ✤ better fit by pulsed than continuous process (Raup 1986, Foote 2005)
  - ✤ P ~ 26 Myr in 10 events (Raup & Sepkoski 1984, 1986)
  - ✤ P = 183 ± 3 in Myr 13 events (Goncharov & Orlov 2003)
- Atmospheric temperature
  - ✤ ^{18}O proxy, P ~ 30 Myr (Svensmark 2006)
  - ✤ meteorite cosmic ray exposure, P ~ 140 Myr (Shaviv 2002)
- Cratering, geomagnetic reversals, super-volcanism, fossil diversity, ...



Periodicity in marine fossil diversity



- Rohde & Muller (2005)
- Sepkoski (2002) marine genera database (Phanerozoic)
- Calibrated on ICS 2004 timescale
- P = 62 ± 3 Myr
- P = 140 ± 15 Myr (weaker)

Coryn Bailer-Jones, MPIA Heidelberg

Possible extraterrestrial mechanisms of biological change

- Oort cloud perturbation (e.g. Wickramasinghe & Napier 2008)
  - ➡ asteroid/comet impacts ⇒ climate change
- Interstellar comet capture (e.g. Clube & Napier 1982)
  - ➡ comet impacts ⇒ climate change
- Cosmic rays (CRs) (e.g. Kirkby 2007, Svensmark 2007)
  - ➡ ionization ⇒ nucleation ⇒ cloud formation ⇒ global cooling
- SNe, GRBs (e.g. Ellis & Schramm 1995, Thomas et al. 2005)
  - ➡ direct extinction, global cooling

3 potentially relevant solar motions

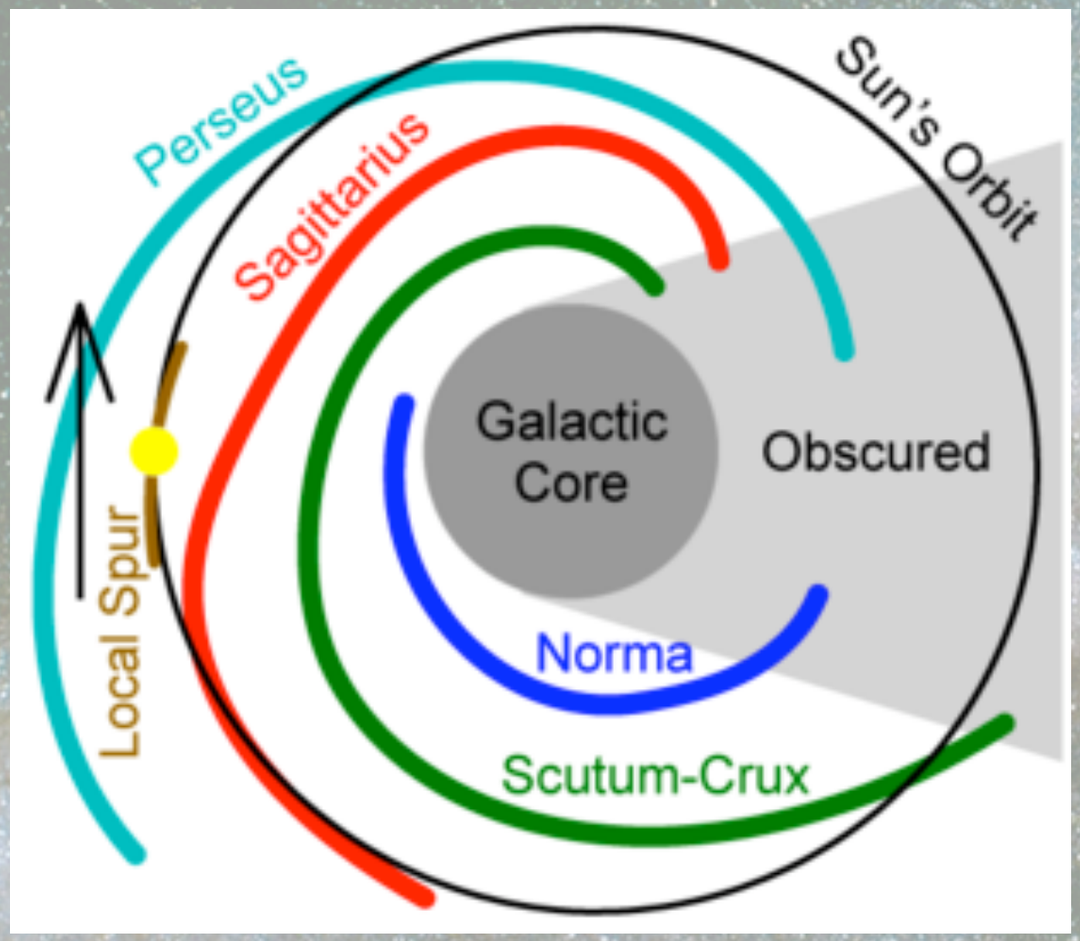


image: dailygalaxy.com

1. Azimuthal (through spiral arms) ($\dot{W}$)
   - P_{arm} ~ 140-180 Myr (if periodic)
   - increased exposure to SFRs, SNe (UV, X-ray, cosmic rays)
   - Napier & Clube (1980s), Leitch & Vasisht (1998), Shaviv (2003), Gies & Helsel (2005), Gilliam & Erenler (2007)

3 potentially relevant solar motions

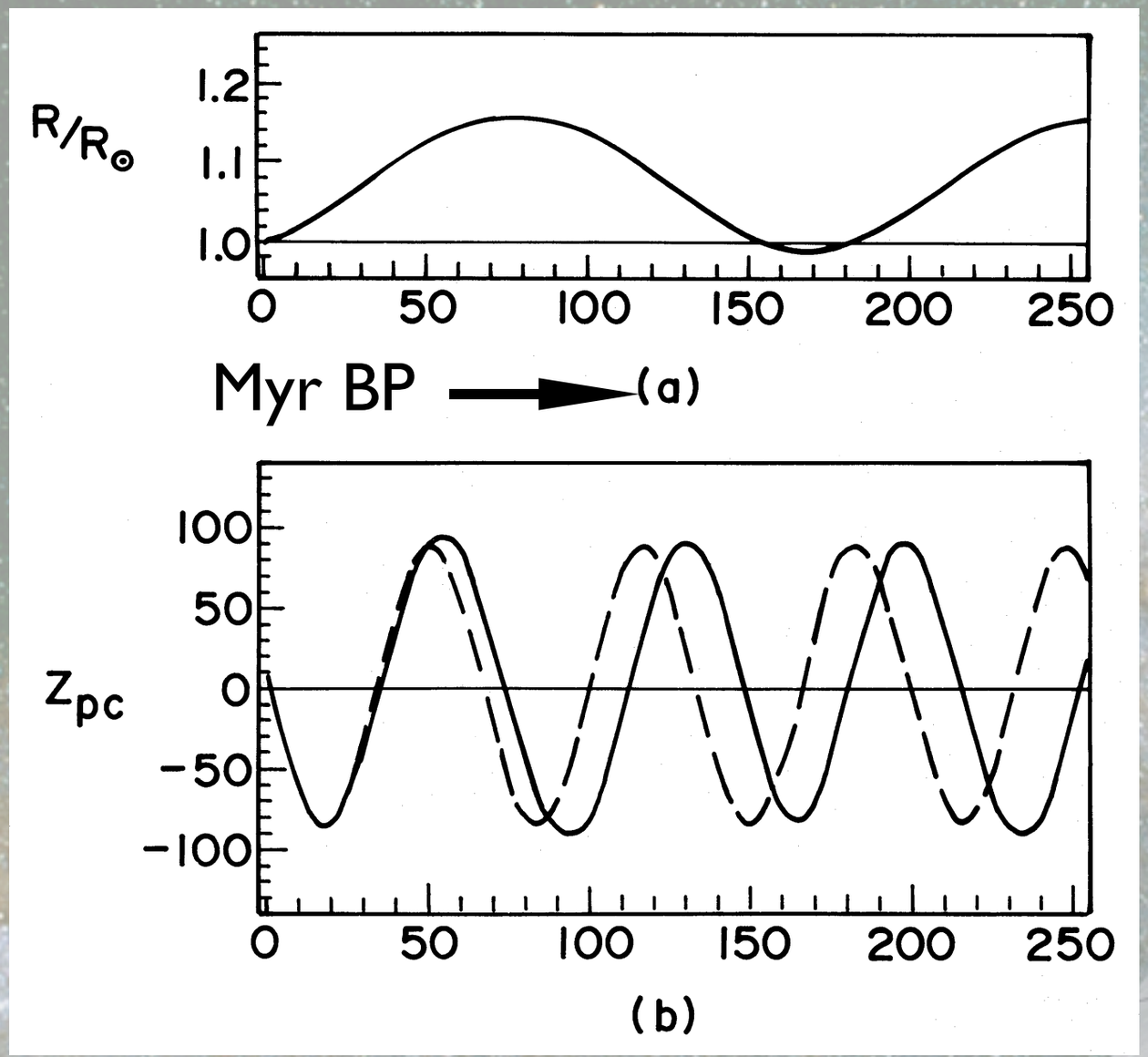
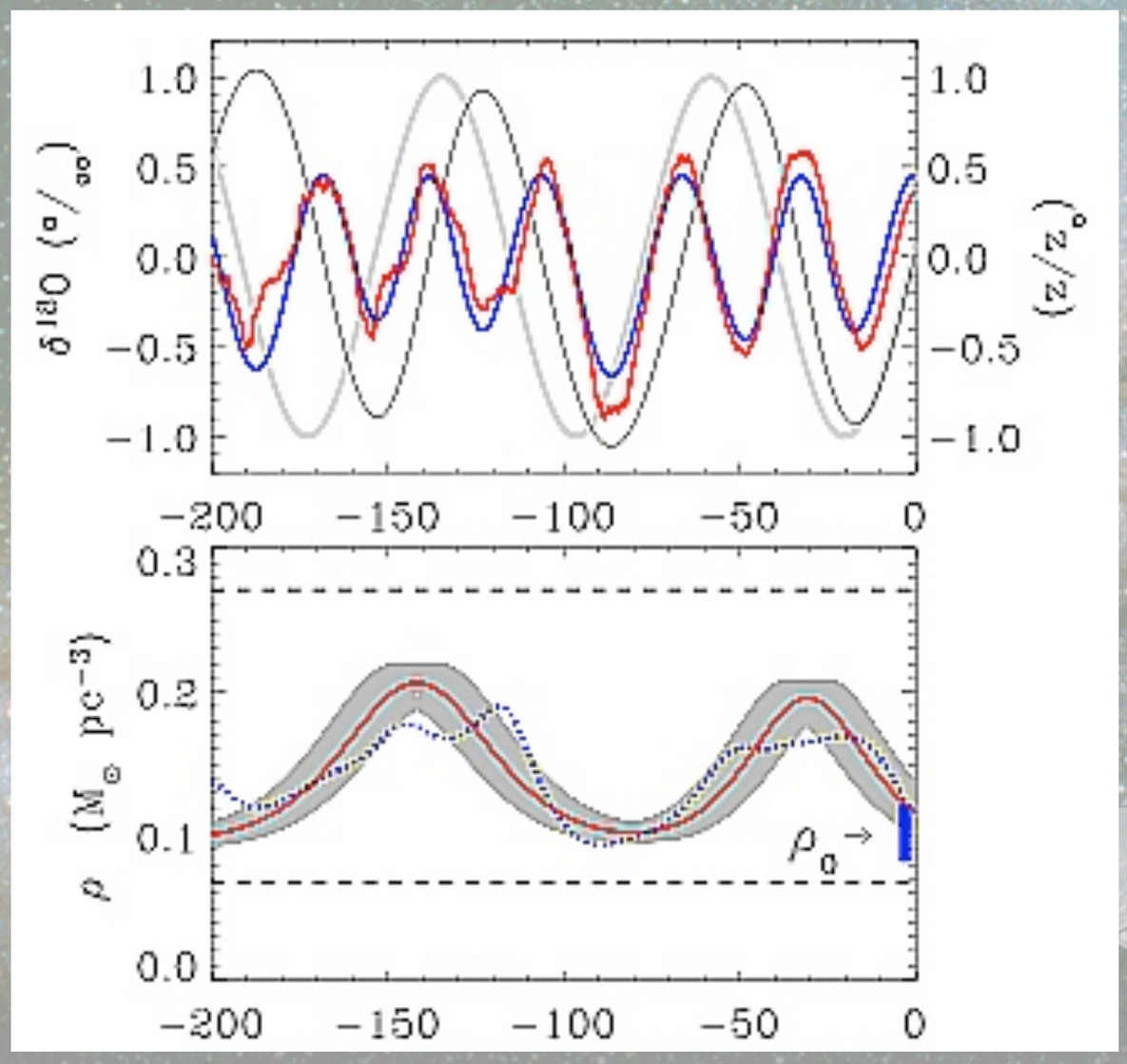


figure: Shuter & Klatt (1986)

2. Radial ($\dot{R}$)
   - ✤ P_R ~ 150-190 Myr
   - ✤ Goncharov & Orlov (2003)
3. Perpendicular to Galactic plane ($\dot{z}$)
   - ✤ P_z ~ 60 Myr
   - ✤ variable exposure to extragalactic cosmic rays, and/or
   - ✤ increased exposure to SFRs, SNe (cosmic rays)
   - ✤ Shuter & Klatt (1986), Svensmark (2006), Medvedev & Melott (2007)

Fit ż to temperature proxy data

red = $\delta^{18}O$ blue = T(z)
thin black = solar position (z)



Myr BP

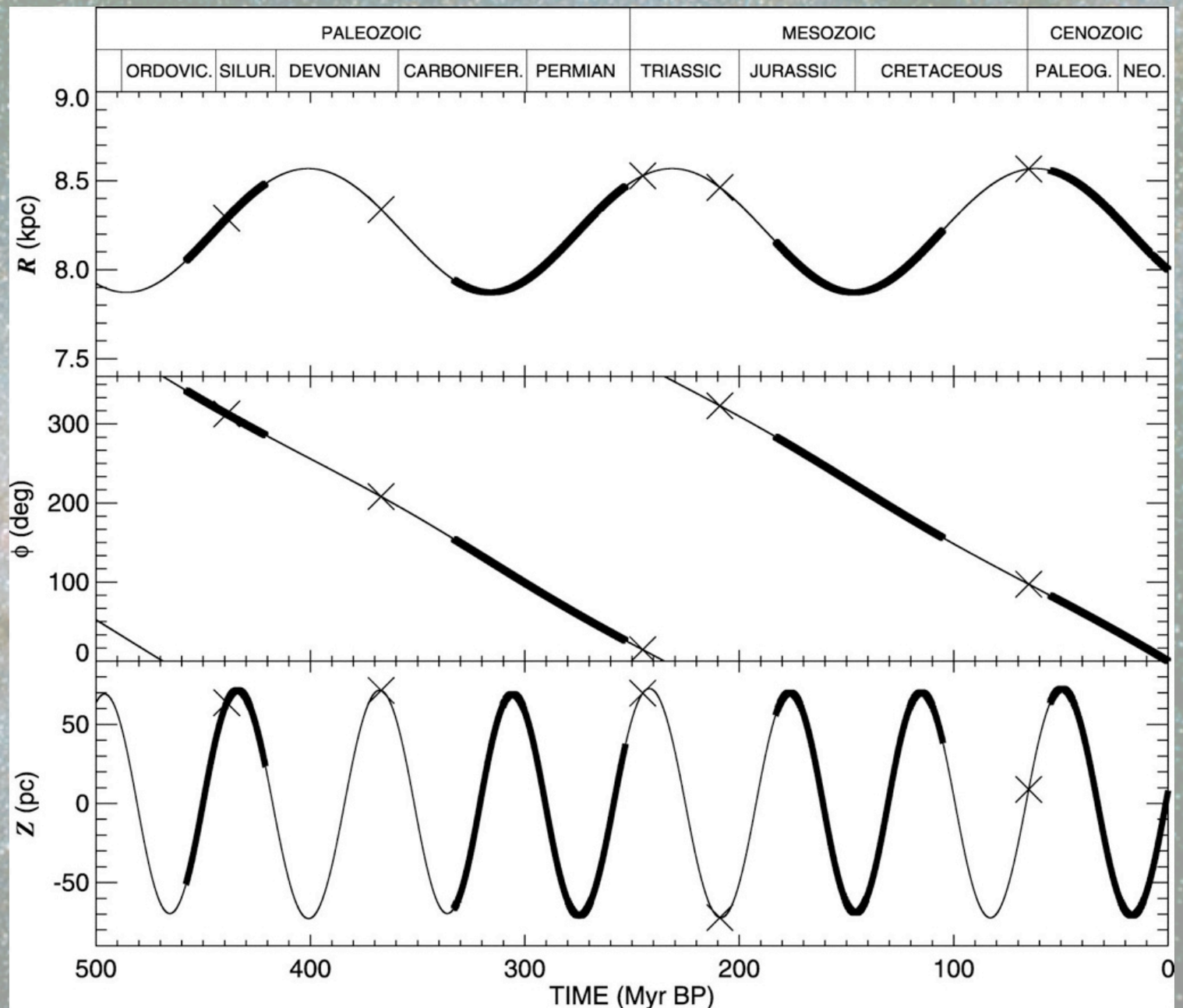
- Svensmark (2006)
- define model of solar z motion
- assume $T \sim z^2$ (T_{min} at z=0; CRs from SFRs cause cooling)
- fit to ^{18}O proxy (P ~ 30 Myr)
- potential with two spiral arms

➡ derives arm crossings at 31 and 142 Myr BP

Dynamical model of solar orbit

- Gies & Helsel (2005)
- Passage of Sun reconstructed from models of Dehnen & Binney (1998) based on *Hipparcos* data
- $P_z \sim 64$ Myr

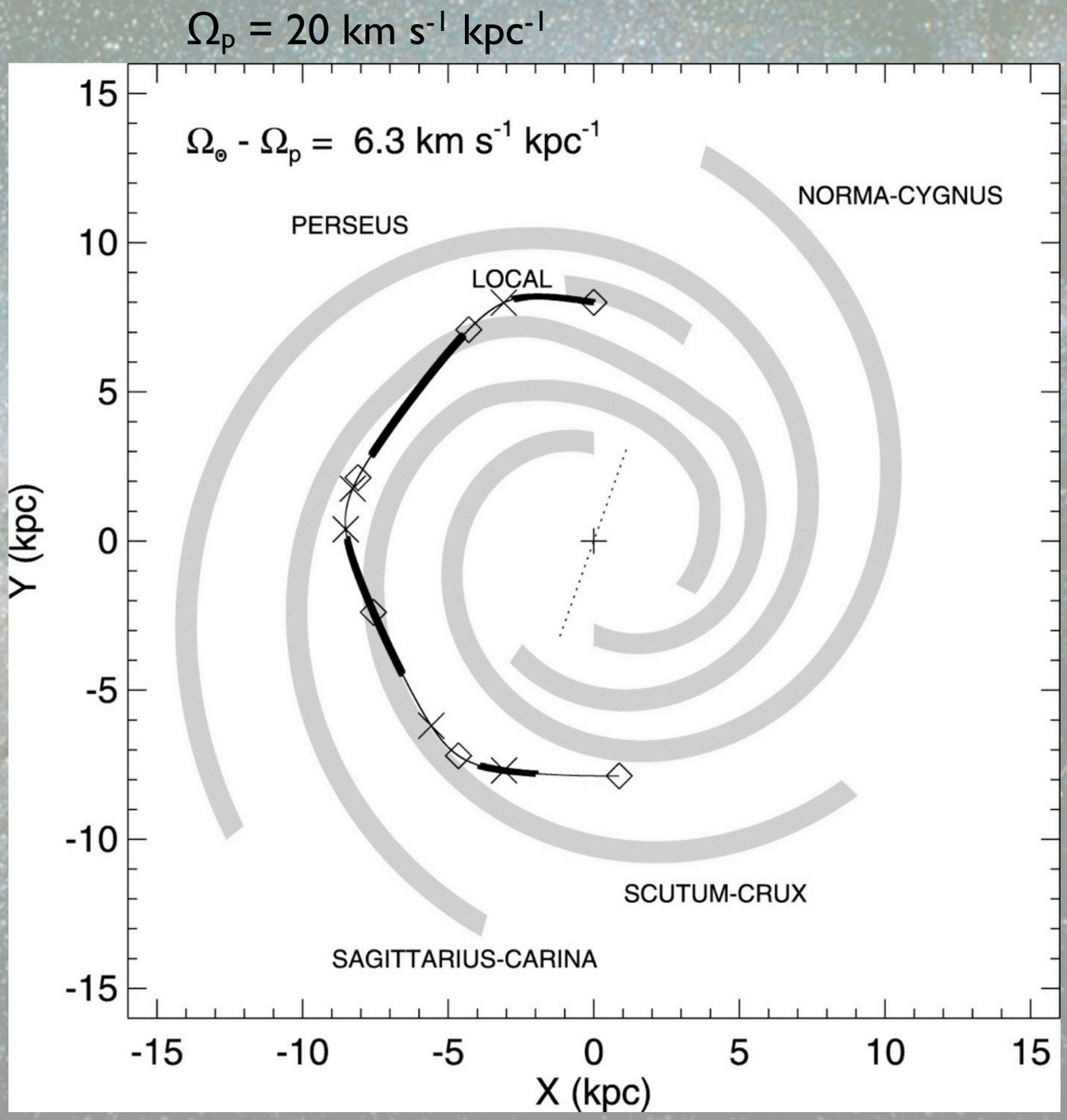
thick portions: ice ages
crosses: major extinctions



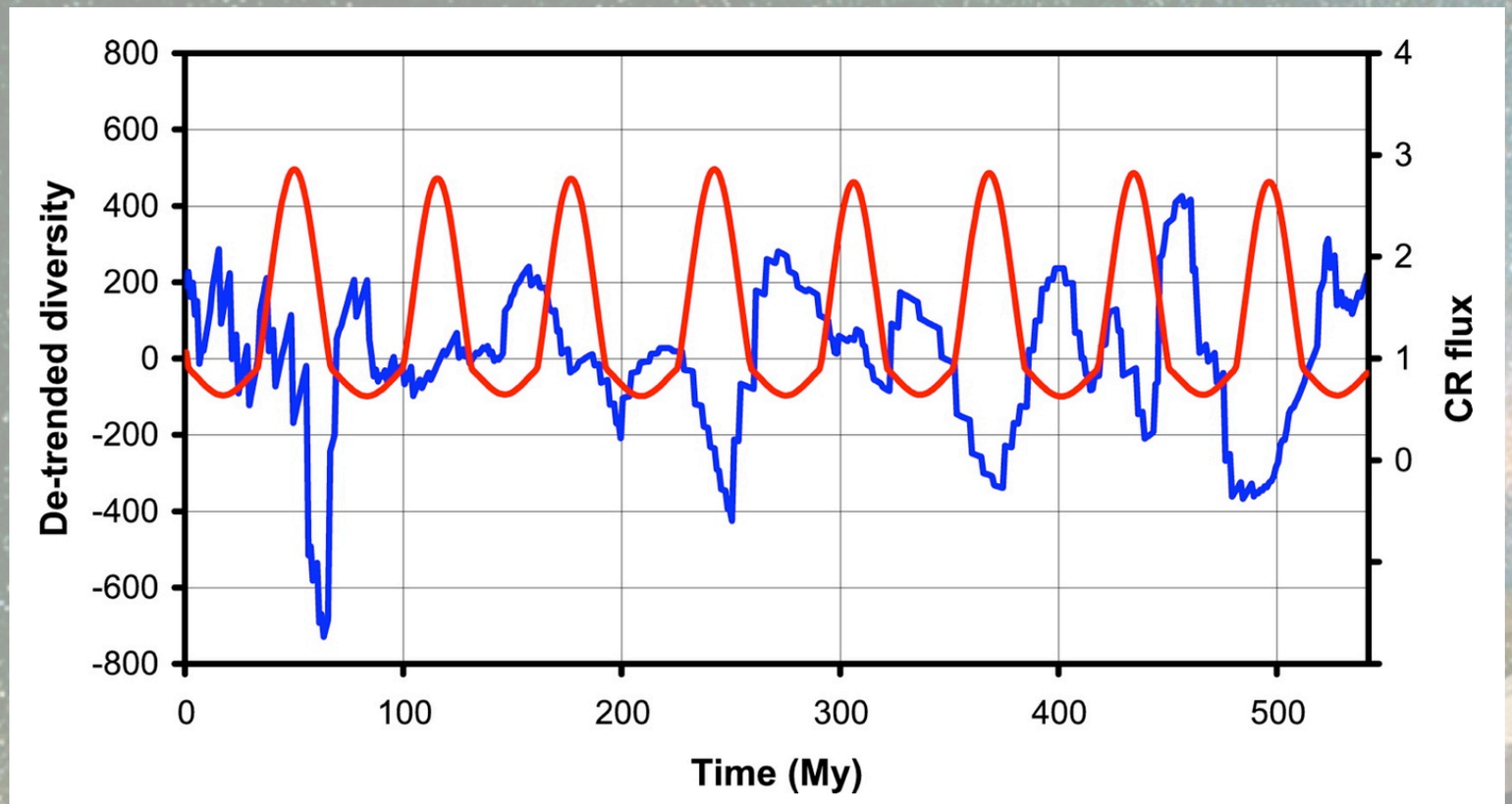
Coincidence with spiral arm crossings

- Solution depends on relatively poorly known arm pattern speed
  - ✤ Ω_p = 10 - 30 km s^{-1} kpc^{-1}
  - ✤ best fit with Ω_p = 14.4 km s^{-1} kpc^{-1}

thick portions: ice ages
crosses: major extinctions
diamonds: 100 Myr



Fossil diversity from extragalactic CRs?



red = CR flux

blue = fossil diversity data from Rohde & Muller (2005)

P ~ 60 Myr

- Medvedev & Melott (2007)
- 3D model of solar motion and extragalactic CR flux model
- Diversity minimum when Sun furthest north (CR flux max)

➡ Galactic bow shock and cosmic rays from Virgo cluster?

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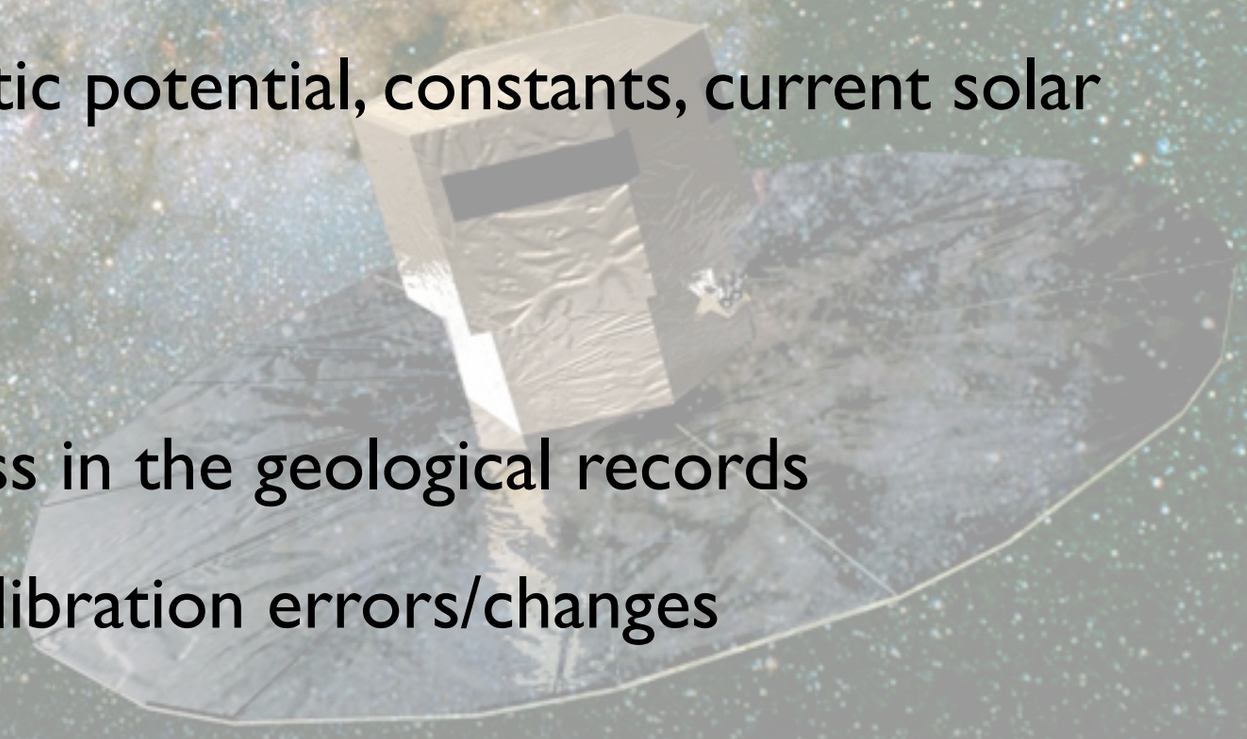
Summary of the evidence

- Apparent correlation between extinctions/fossil diversity and solar orbit
- Some evidence for 30 or 60 Myr period in geological record
  - ✤ close to solar z period (or half period)
  - ✤ data and plausible mechanisms only quasi-periodic
- Cosmic rays and SNe are oft-cited “cause”
  - ✤ no clear mechanism; CR effect controversial!
- Possibly more than one mechanism at work

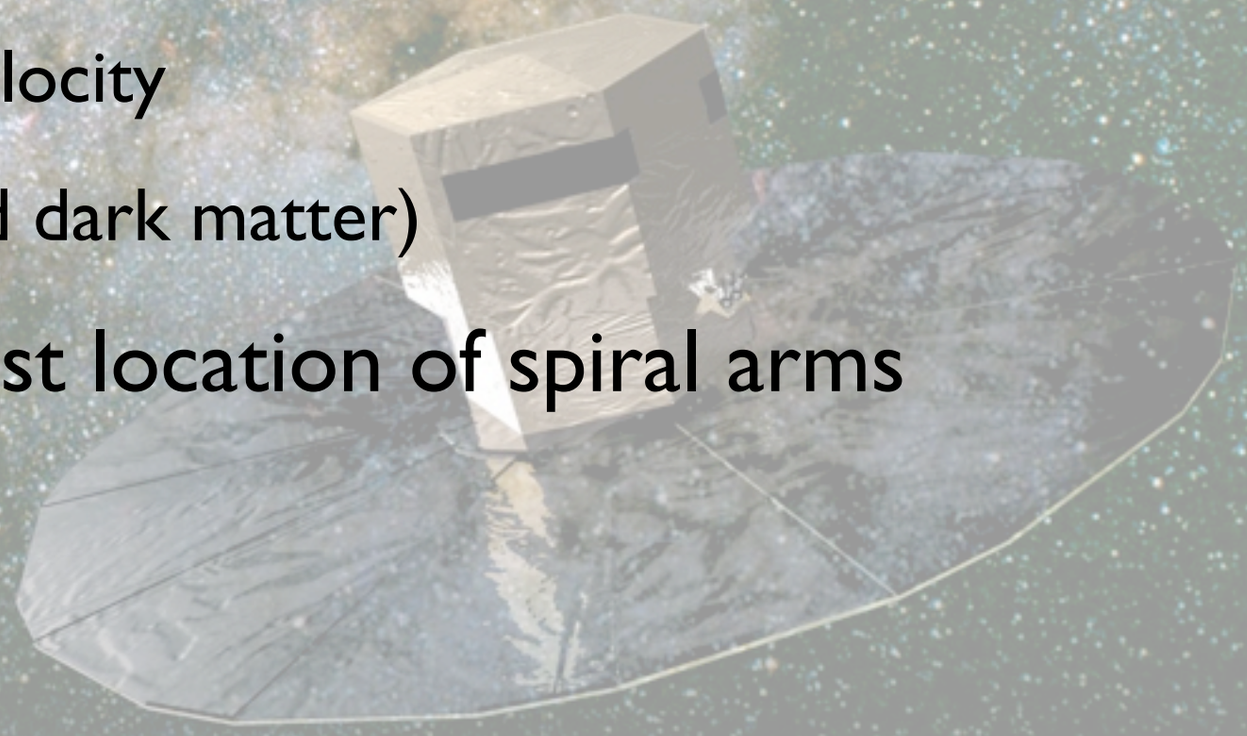
Can we reconcile different data and models?

- Studies have used different phenomena, data and models
  - ✤ fossil diversity, extinction and climate data not the same
  - ✤ data over different time periods (e.g. last 200 or 540 Myr)
  - ✤ strong dependency on Galactic potential, constants, current solar position/velocity
- Other problems
  - ✤ selectivity and incompleteness in the geological records
  - ✤ dating and geological time calibration errors/changes



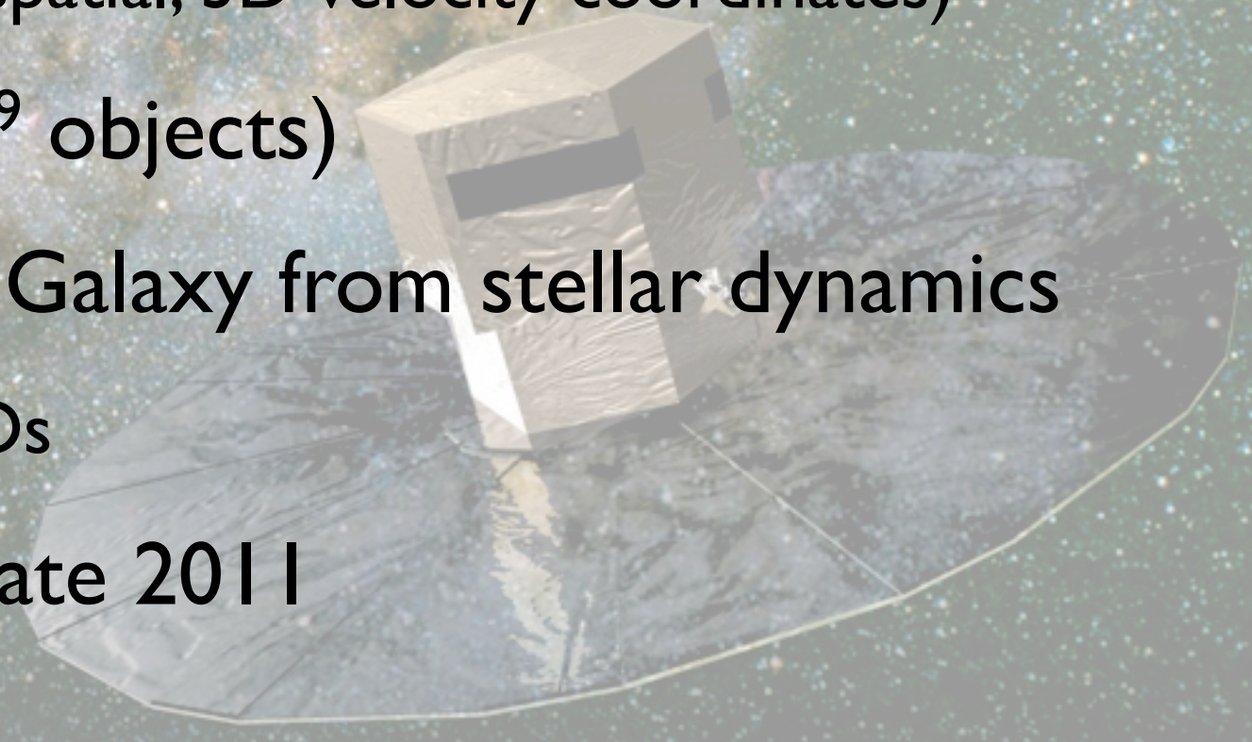
How can we improve the situation?

- Determine solar motion independently of geological record
- Better reconstruction of path of Sun
  - ✤ current solar position and velocity
  - ✤ Galactic potential (visible and dark matter)
- Better determination of past location of spiral arms



Gaia in a nutshell

- high accuracy stellar positions and velocities
  - ✤ parallax accuracy of 12-25μas at G=15, 100-300μas at G=20
  - ✤ radial velocities to a few km/s down to G=17
  - ✤ 6D phase space survey (3D spatial, 3D velocity coordinates)
- all sky survey to G=20 (10^9 objects)
- structure and evolution of Galaxy from stellar dynamics
  - ✤ but also exoplanets and NEOs
- ESA mission for launch in late 2011



Distance statistics

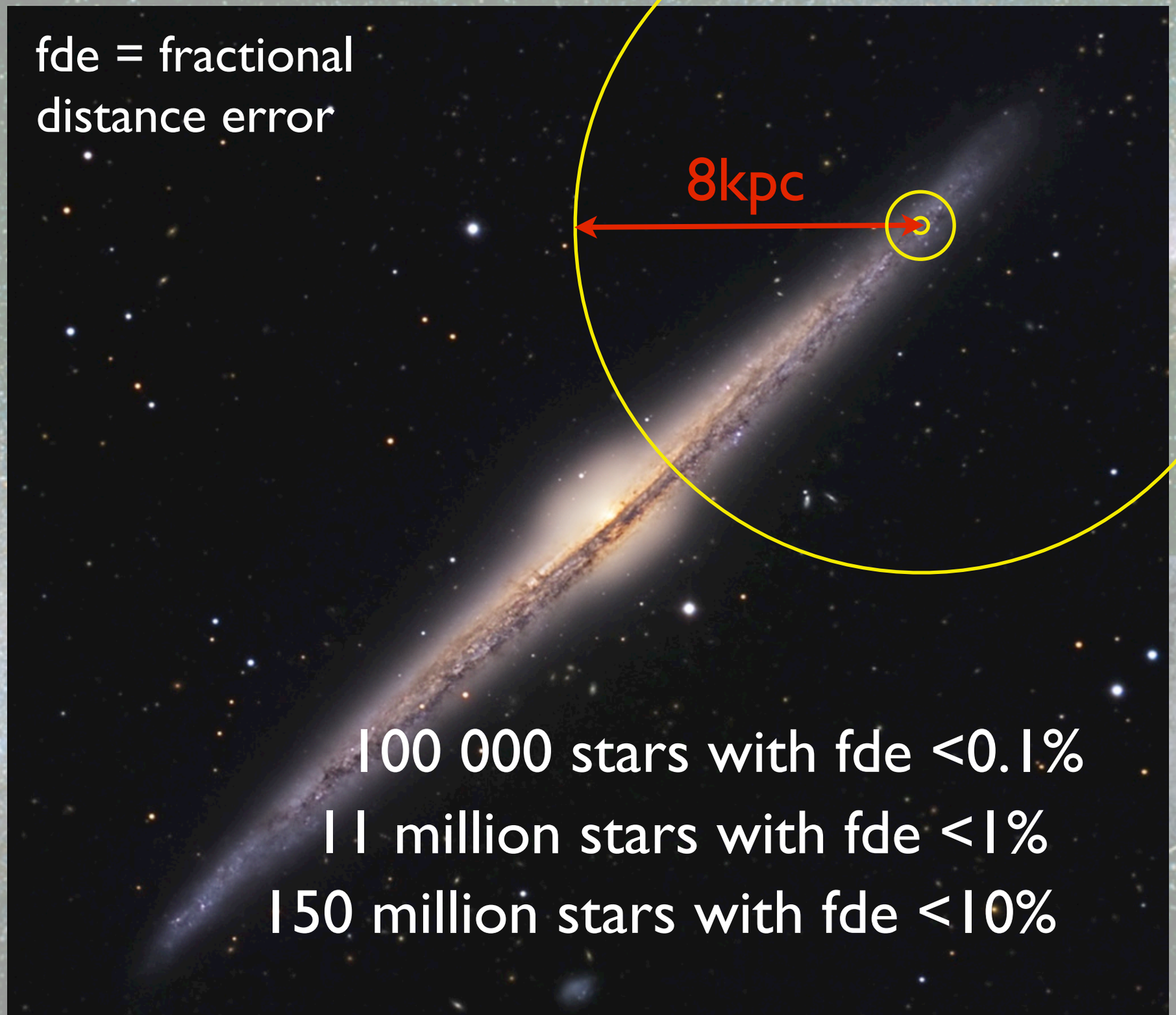


Image: NGC4565 from panther-observatory.com

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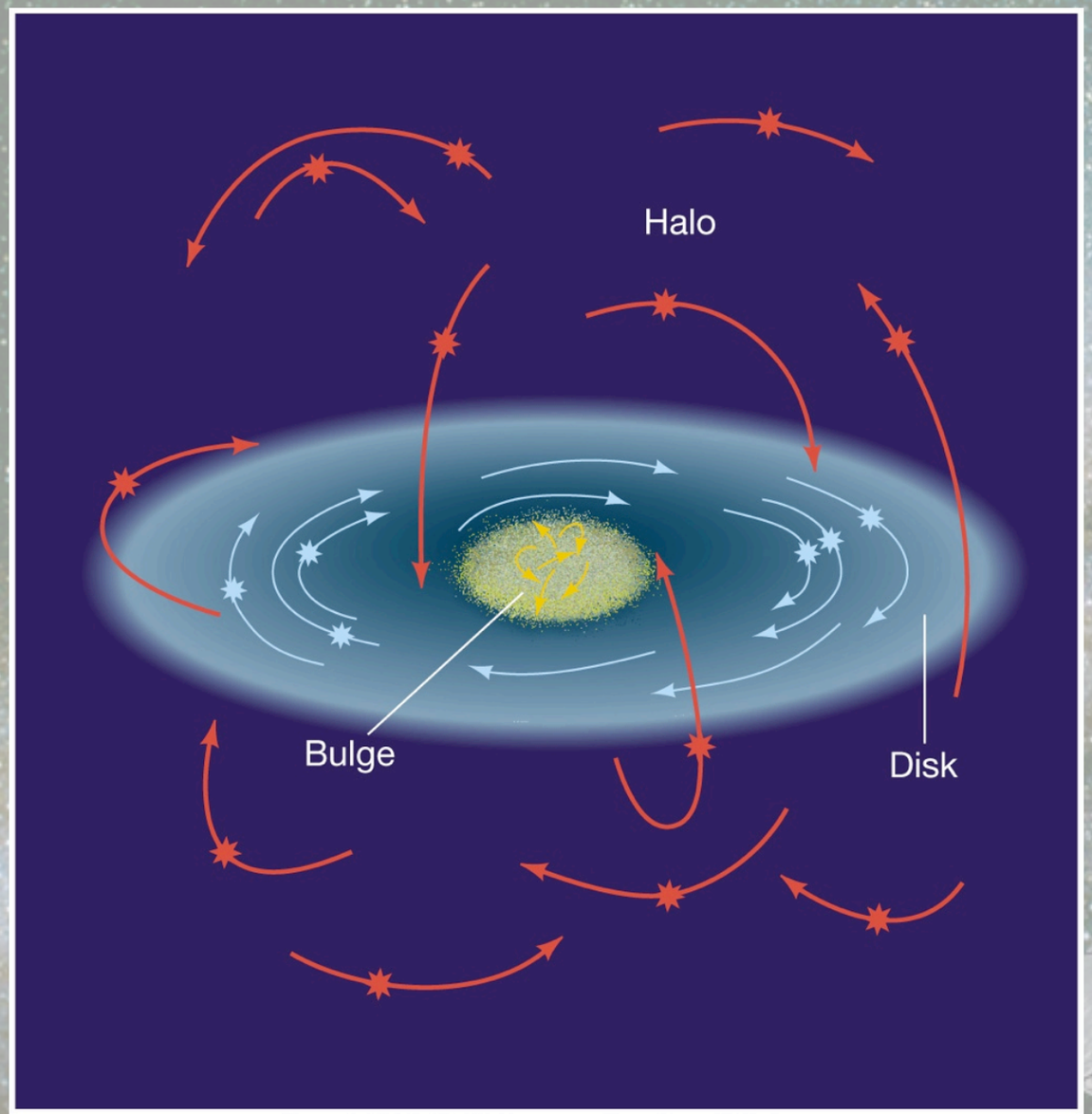
Infer Galactic gravitational potential from stellar kinematics



- K giant at 6 kpc (G=15)
  - ✤ σ(v) = 1 km/s (fde=2%)
- G dwarf at 2 kpc (G=16.5)
  - ✤ σ(v) = 0.4 km/s (fde=8%)

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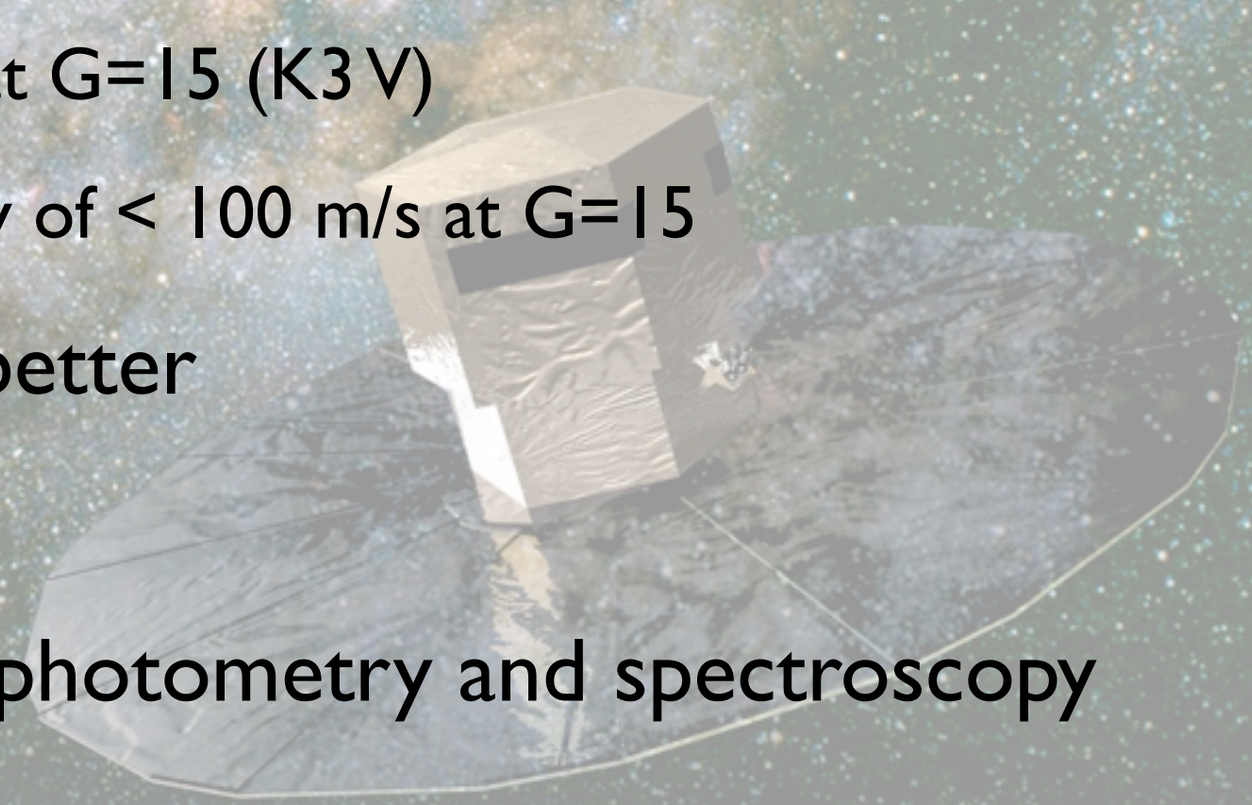
Open clusters and star forming regions

- use to trace disk rotation and sites of star formation
- hundreds with 1 kpc
  - ✤ individual distances to 1-2% at G=15 (K3V)
  - ✤ individual velocity uncertainty of < 100 m/s at G=15
- cluster parameters ~ $\sqrt{N}$ better
- ages from MSTO fitting
- abundances from onboard photometry and spectroscopy



Spiral structure

- map local spiral structure in 3D
  - without assuming M-L relation or extinction
- 3D velocities without assuming rotation curve
- OB star at d=5kpc with 4 mags extinction (G=15)
  - fractional distance error of 13%
  - transverse velocity error of ~ 1km/s
  - radial velocity error of a few km/s
  - ~ 50 000 OB stars

image: R. Hurt, SSC

Summary

- Evidence suggests a Galactic influence on terrestrial climate and/or biology
- We need better data to build a more accurate model of the Galaxy and the solar motion
  - ✤ fit model *independently* of geological data, then compare
- What Gaia will do
  - ✤ directly measure gravitational potential of Galaxy (inc. dark matter)
  - ✤ current solar position and velocity
  - ✤ position and velocity of spiral arms from OB stars and open clusters

Gaia and NEOs

- NEO: $q \leq 1.3$ AU, $Q \geq 0.98$ AU (Amors, Apollos, Atens)
- detect via rapid motion (plus accurate orbit for brighter ones)
- observe with 45 deg. of Sun
- characteristics (Mignard 2002)
  - ✤ 100% complete to H ~ 16 (2km diameter)
  - ✤ 50% complete to H ~ 18.5 (1km diameter)
  - ✤ 10 % complete to H ~ 20 (500m diameter)
  - ✤ expect ~ 2500 NEOs to H=21.5 (of 16 000 total population from Bottke et al. 2001)