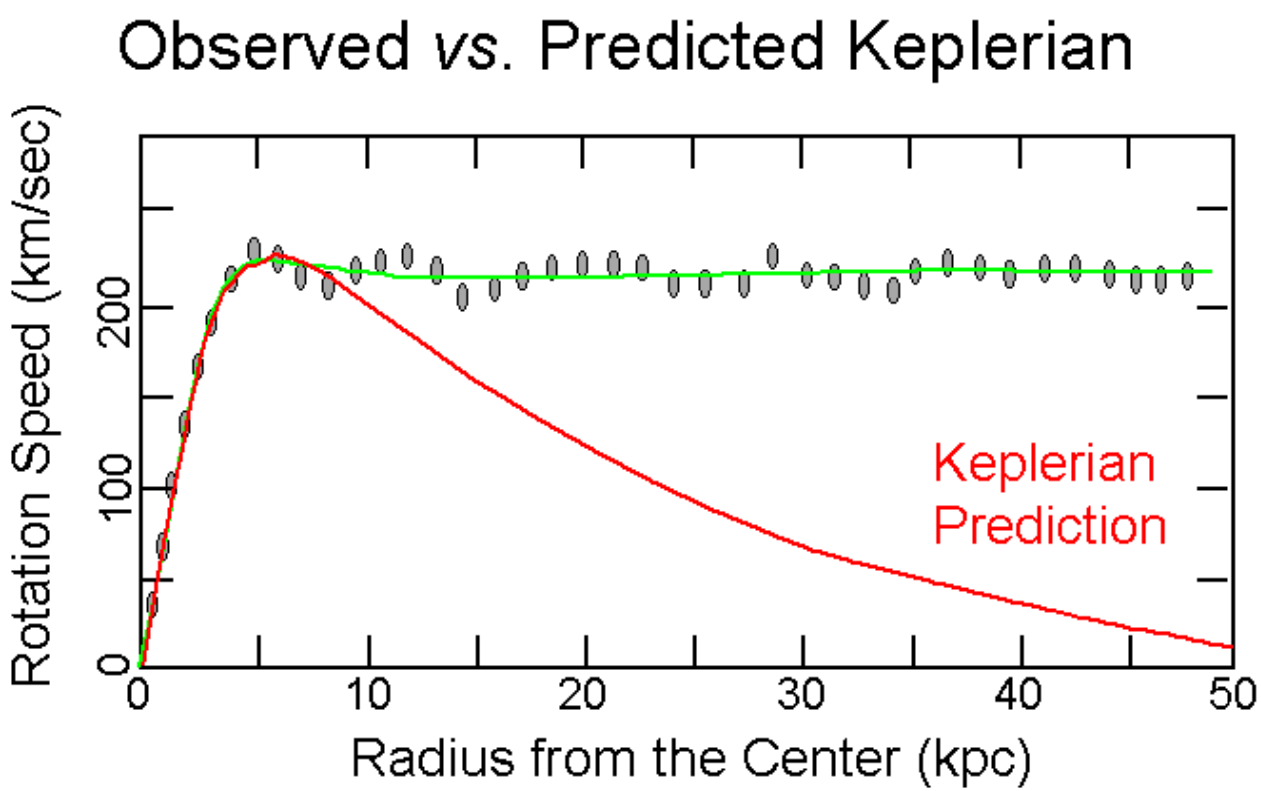
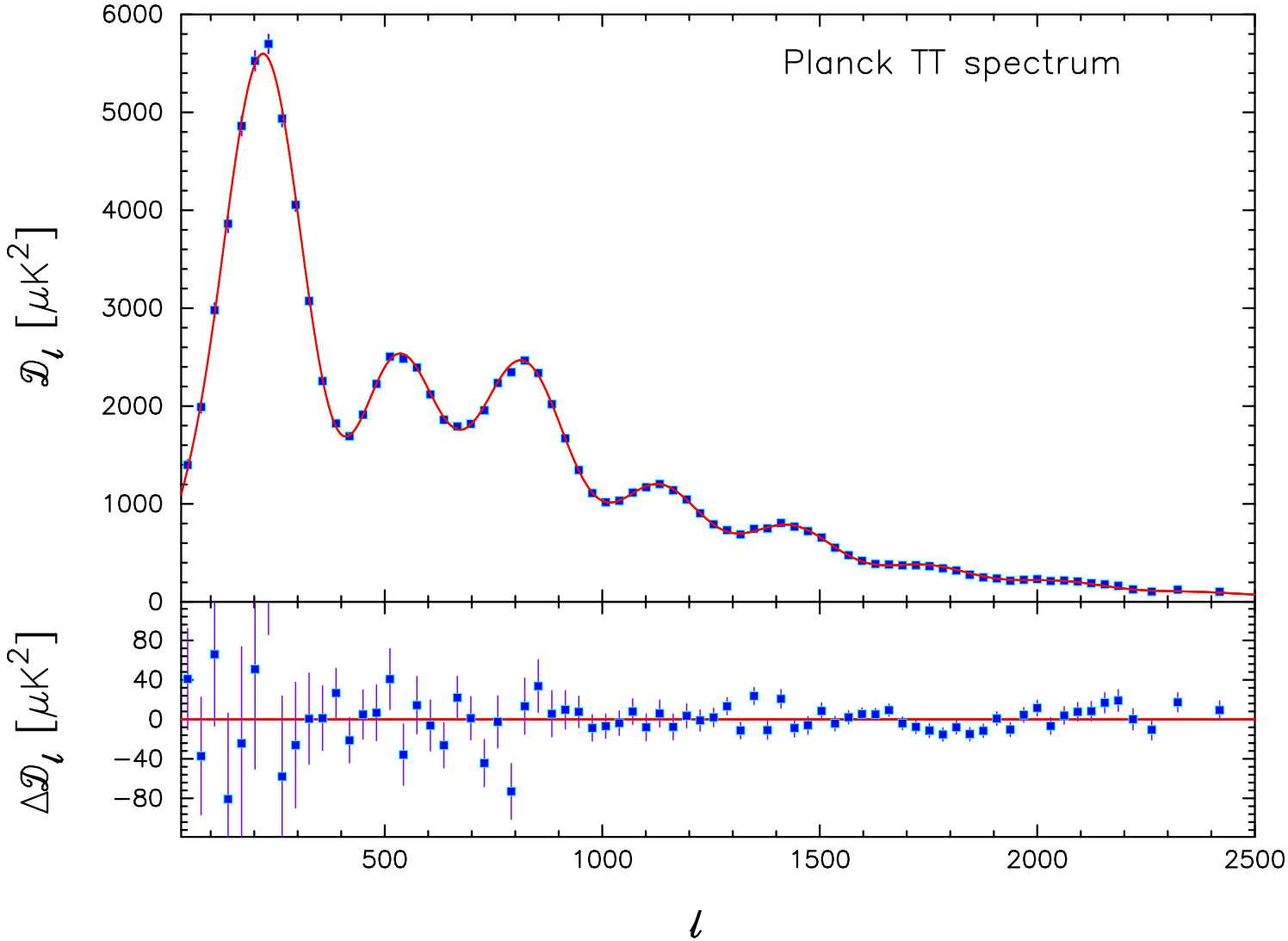
# *Astrophysics: Theory Motivation and Landscape*

- Dark Matter
- Solar Neutrinos
- Supernovae and Nucleosynthesis

# Dark Matter: Why Nuclear Physics Must Help…

- An outstanding opportunity for a fundamental breakthrough






ΛCDM comparison

Planck XVI $\Omega_m \sim 0.315 \pm 0.017$

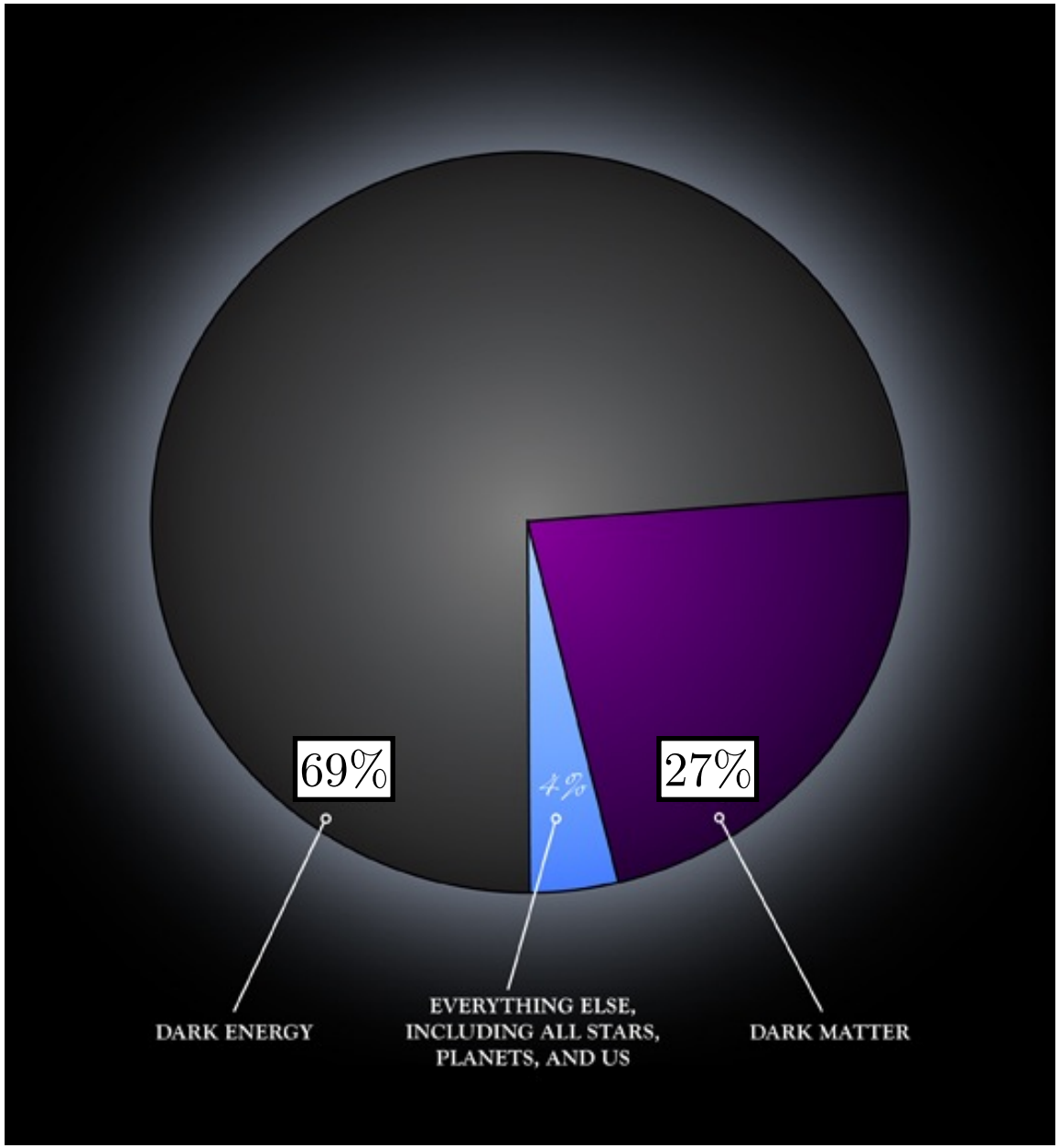
Required in simulations such as this (Bolshoi Collaboration) to reproduce observed cluster-cluster correlations*

$$\text{Calculated with } \Omega_m = \Omega_{DM} + \Omega_b = 0.27 \sim \Omega_m^{\text{WMAP9}} \sim 0.2865 \pm 0.0088$$

*Primack, Klypin, et al.

# Bullet Cluster

A collision between two clusters of galaxies, imaged by gravitational lensing, showing a separation of visible (pink) and dark (blue) matter




## Properties

Long lived or stable

Cold or warm — slow enough to seed structure formation

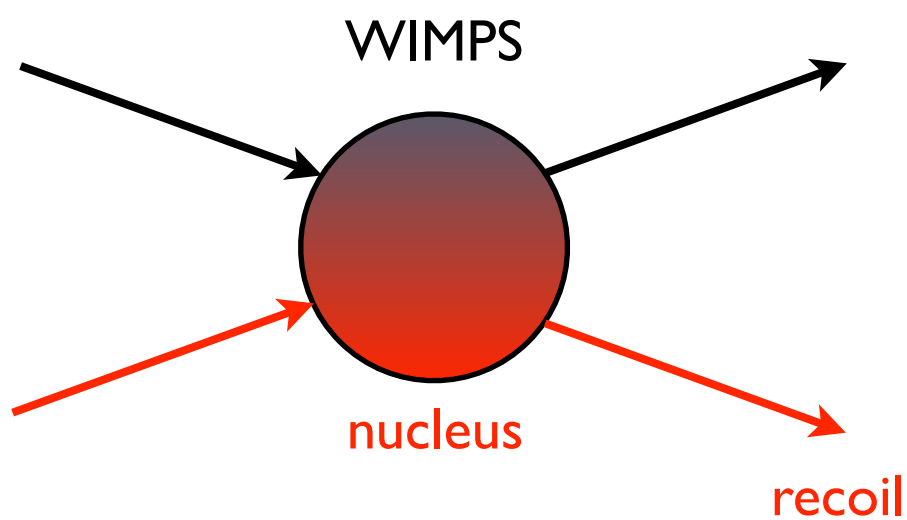
Gravitationally active

Lacking strong couplings to itself or to baryons

A great chance for discovery

Detection: their detection channels include (other than large scale structure)

- Collider searches
- Indirect detection: astrophysical signals
- Direct detection: Nuclear targets, low-energy techniques



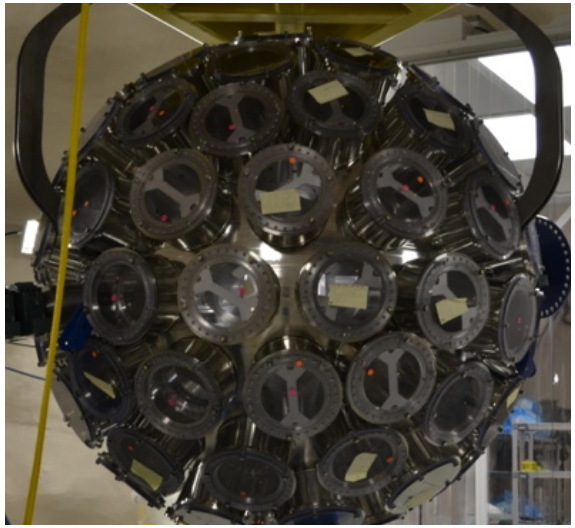
# Noble Gasses

## Single-phase detectors (scintillation light)

- Challenge: ultra-low absolute backgrounds
- LAr: pulse shape discrimination, factor $10^9$-$10^{10}$ for gammas/betas

XMASS-RFB at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished (RFB)
new run this fall -> 2013



CLEAN at SNOLab:

500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in 2014

DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

# Time projection chambers

## (scintillation & Ionization)

### XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
taking new science data

### LUX at SURF:

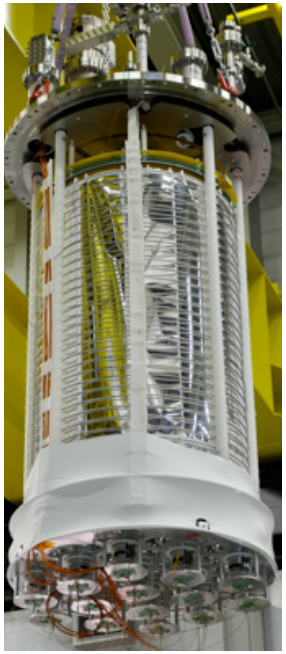
350 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run since spring 2013

### PandaX at CJPL:

125 kg LXe
(25 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
started in 2013



### ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

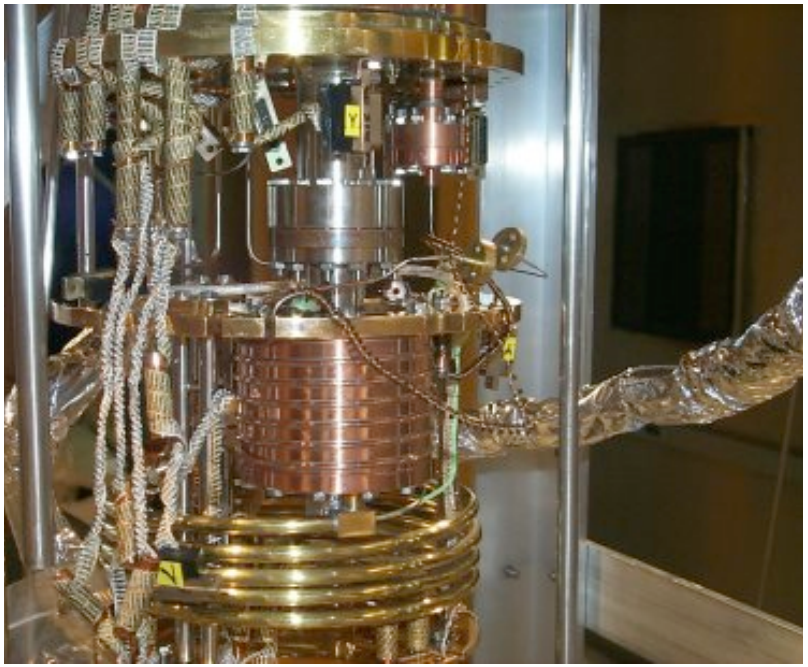
### DarkSide at LNGS

50 kg LAr (dep in $^{39}$Ar)
(33 kg fiducial)

38 3-inch PMTs
in commissioning
since May 2013
to run in fall 2013

# Crystals, Bubble Chambers, ...

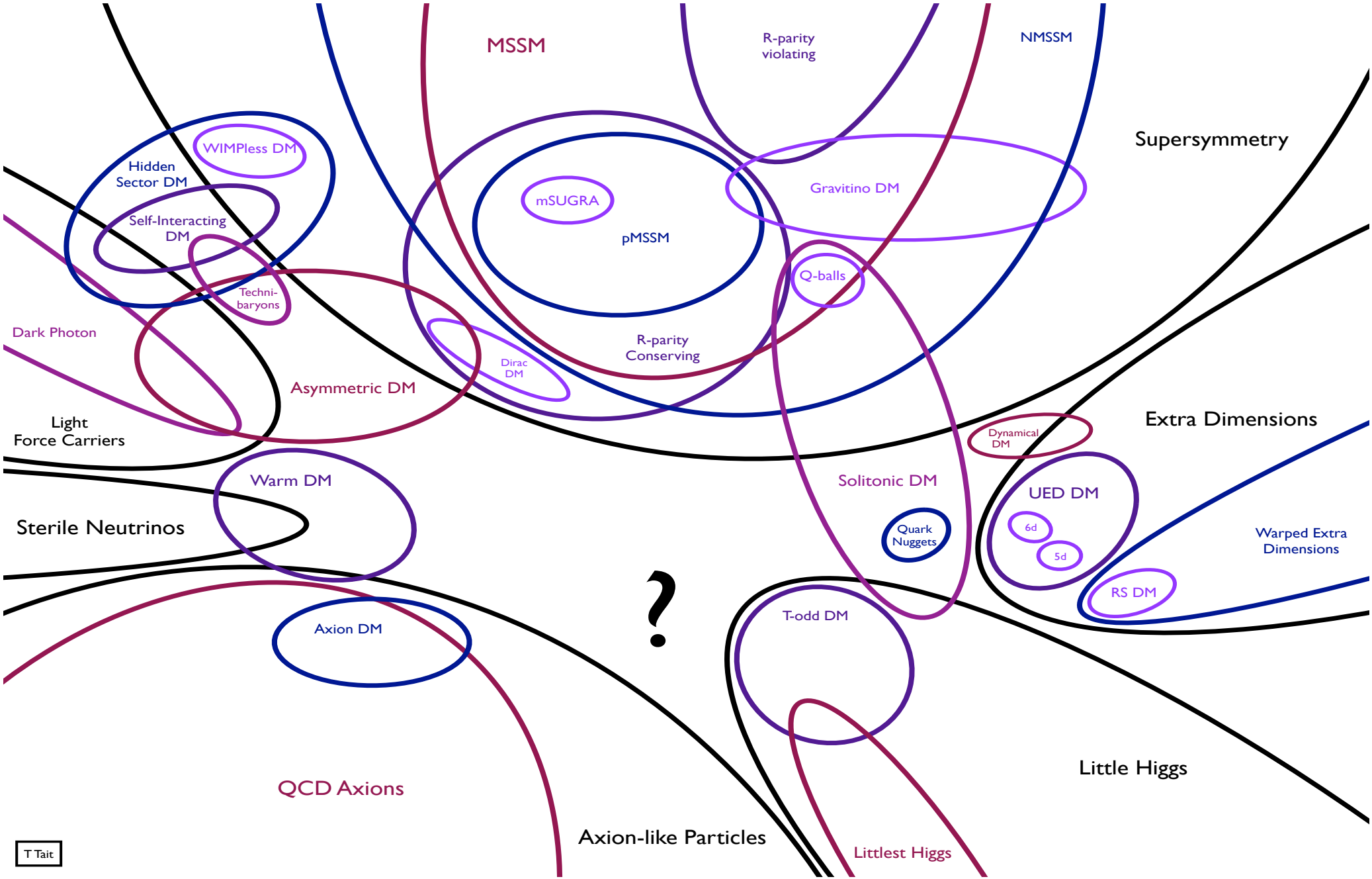
DAMA/LIBRA NaI



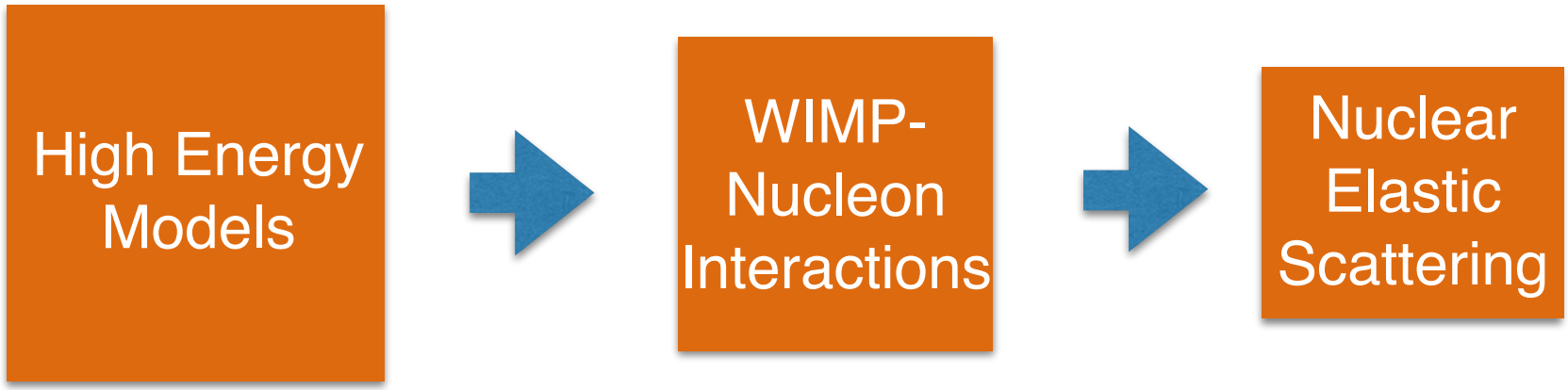
CDMS Si, Ge
CoGENT Ge

Coup $CF_3I$

# Ultimately these experiments are probing UV theories of DM



- But effective theory classifications provided a fully general framework for elastic scattering, a good starting point for nuclear treatments of the relevant many-body physics




- what nuclear responses are possible?
- how can we constrain them in nuclear experiments?
- how well can we calculate the unconstrained responses?

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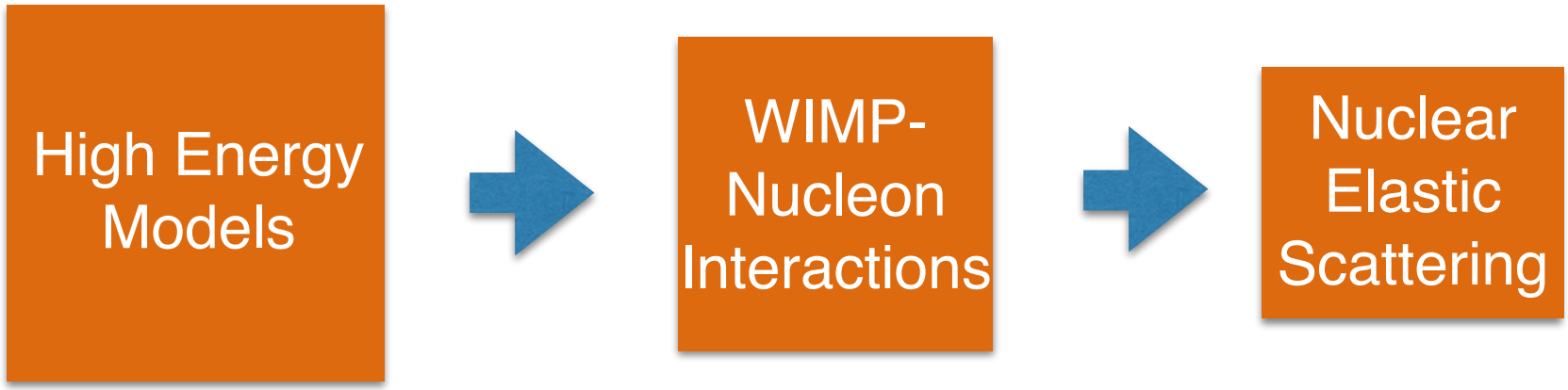


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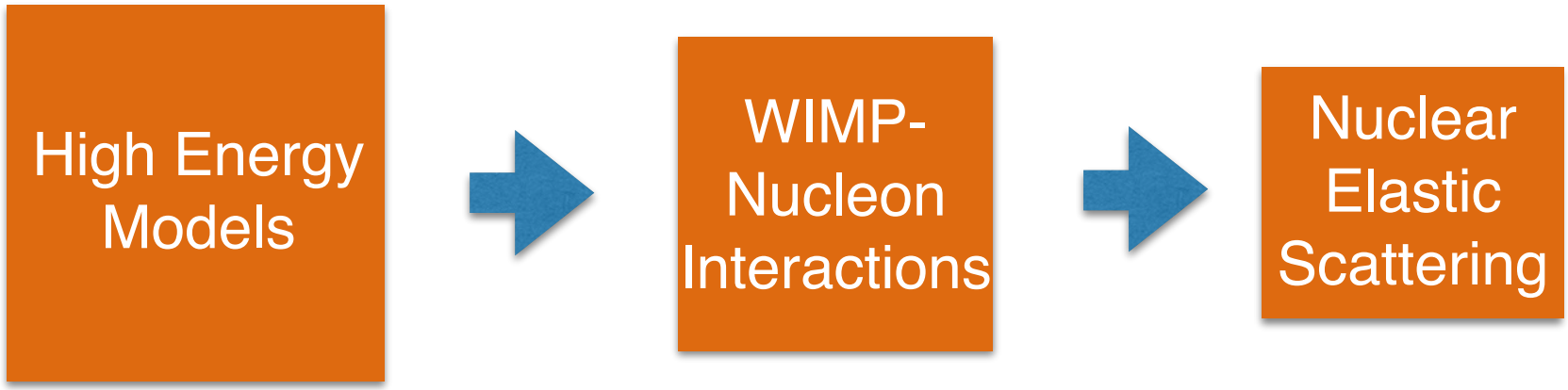


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- how can we constrain them in nuclear experiments?
- how well can we calculate the unconstrained responses?

Critical to experiment program: how many detectors, what are their distinct properties, and will the data mean?

## One example - velocity-dependent WIMP-nucleus interactions: $V_{WIMP}$??

- Half of ET operators: standard pt-nucleus treatment $\Rightarrow V_{WIMP}^2 \sim 10^{-6}$
- But such operators generate internal nuclear Jacobi momenta $\vec{\dot{v}}(i)$ that are o($10^{-1}$). These combine with the plane wave

$$e^{i\vec{q}\cdot\vec{r}(i)}\vec{\dot{v}}(i) \quad \text{where} \quad \vec{q}\cdot\vec{r}(i) \sim 1$$

- The two vector nuclear operators $\vec{r}(i),\ \vec{\dot{v}}$ generate interactions like

$$-\frac{1}{i}q\vec{r}\times\vec{\dot{v}} = -\frac{1}{i}\frac{q}{m_N}\vec{r}\times\vec{\dot{p}} = -\frac{q}{m_N}\vec{\ell}(i)$$

$\vec{\ell}(i)$ is a new dimensionless DM operator

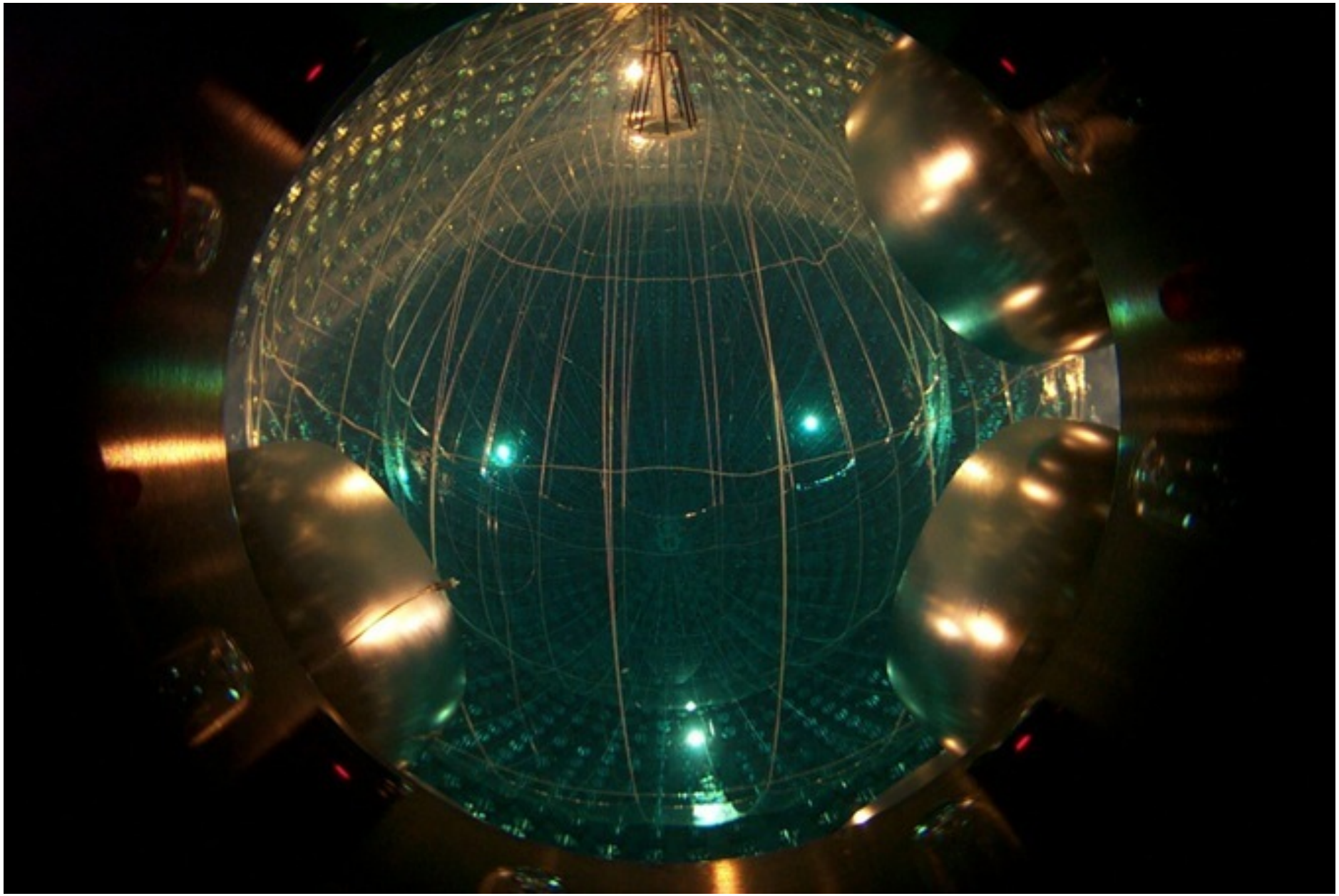
Bottom line: sensitivities to these interactions are $10^4$ times larger; new operators are involved; new detectors are needed; more variety in detectors required to avoid confusion

# Solar Neutrinos

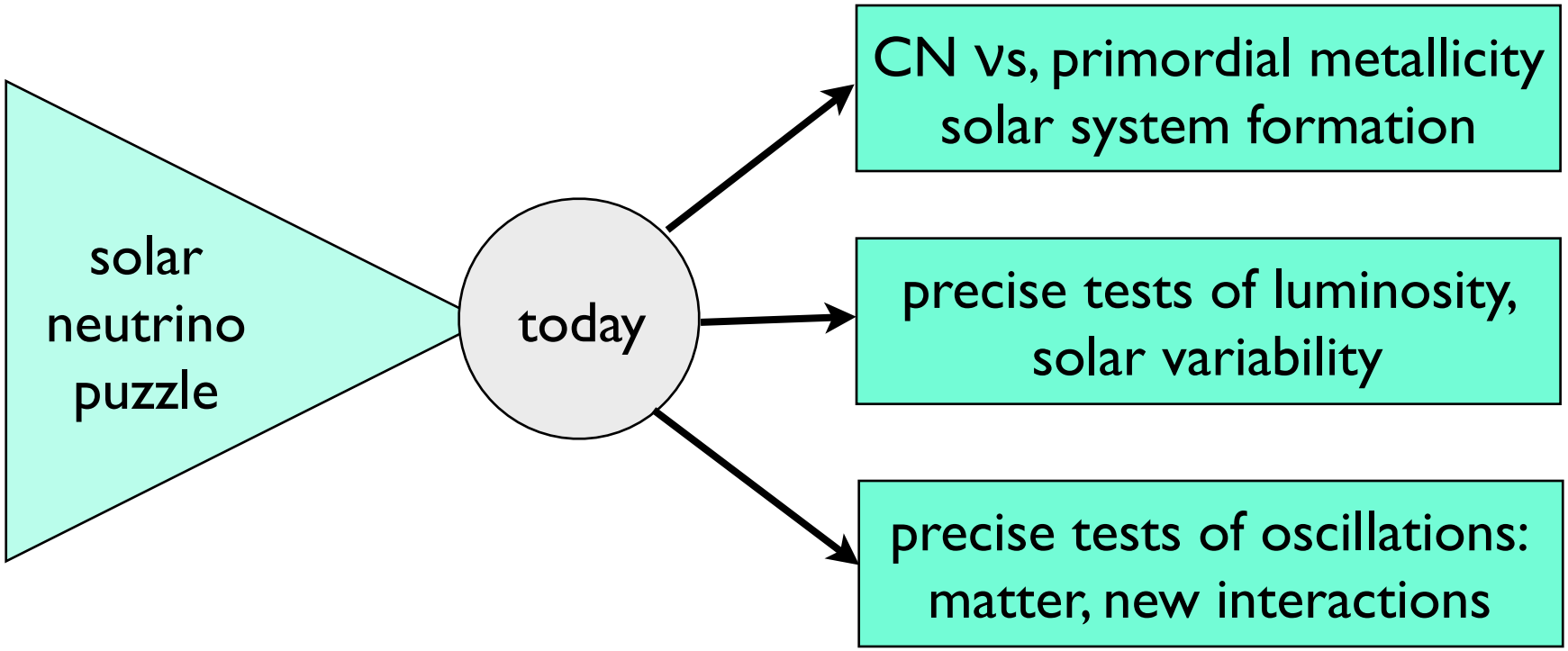
- A field that began with goal of using neutrinos as a direct probe of nuclear fusion in the solar core, to test our theory of main-sequence stellar evolution

- A marvelous diversion led to the discovery of neutrino mass, flavor oscillations, and the influence of matter on those oscillations

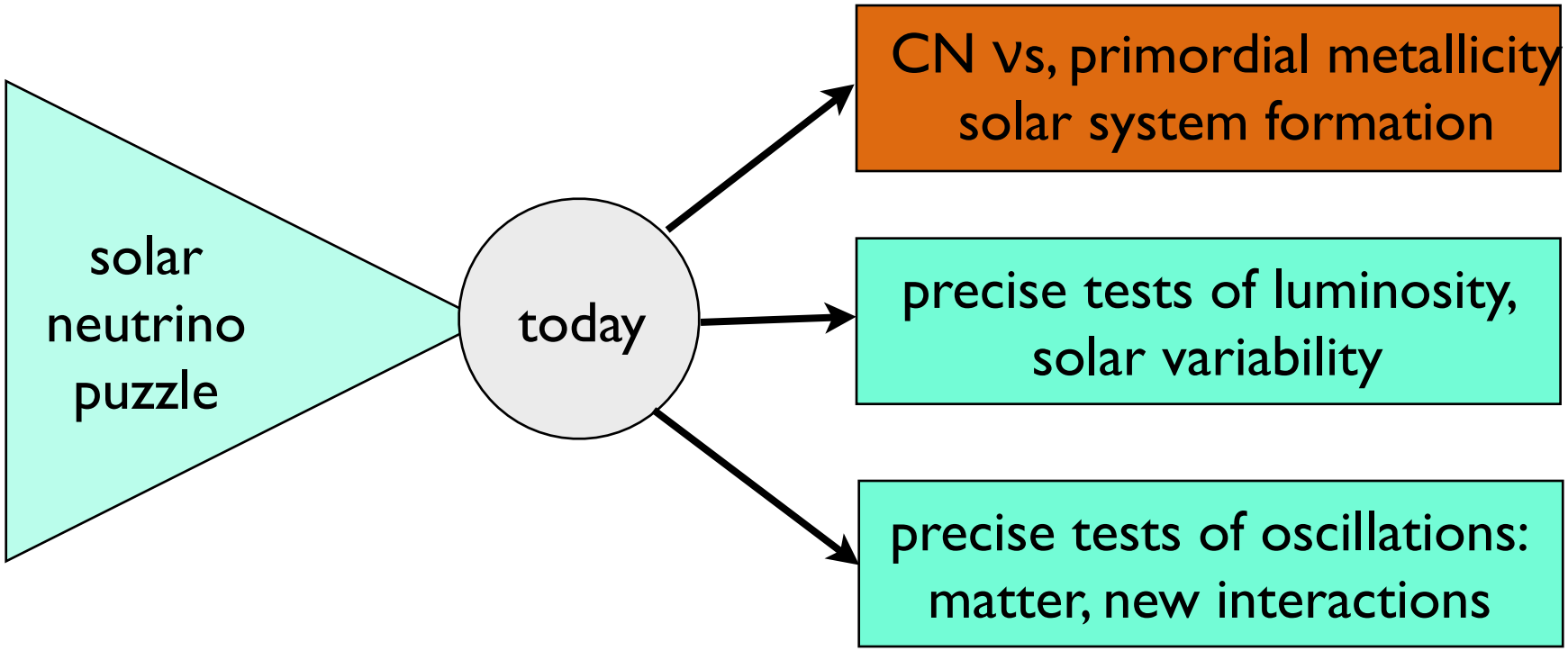
A milestone was reached last month with the first direct measurement of the pp neutrinos by Borexino



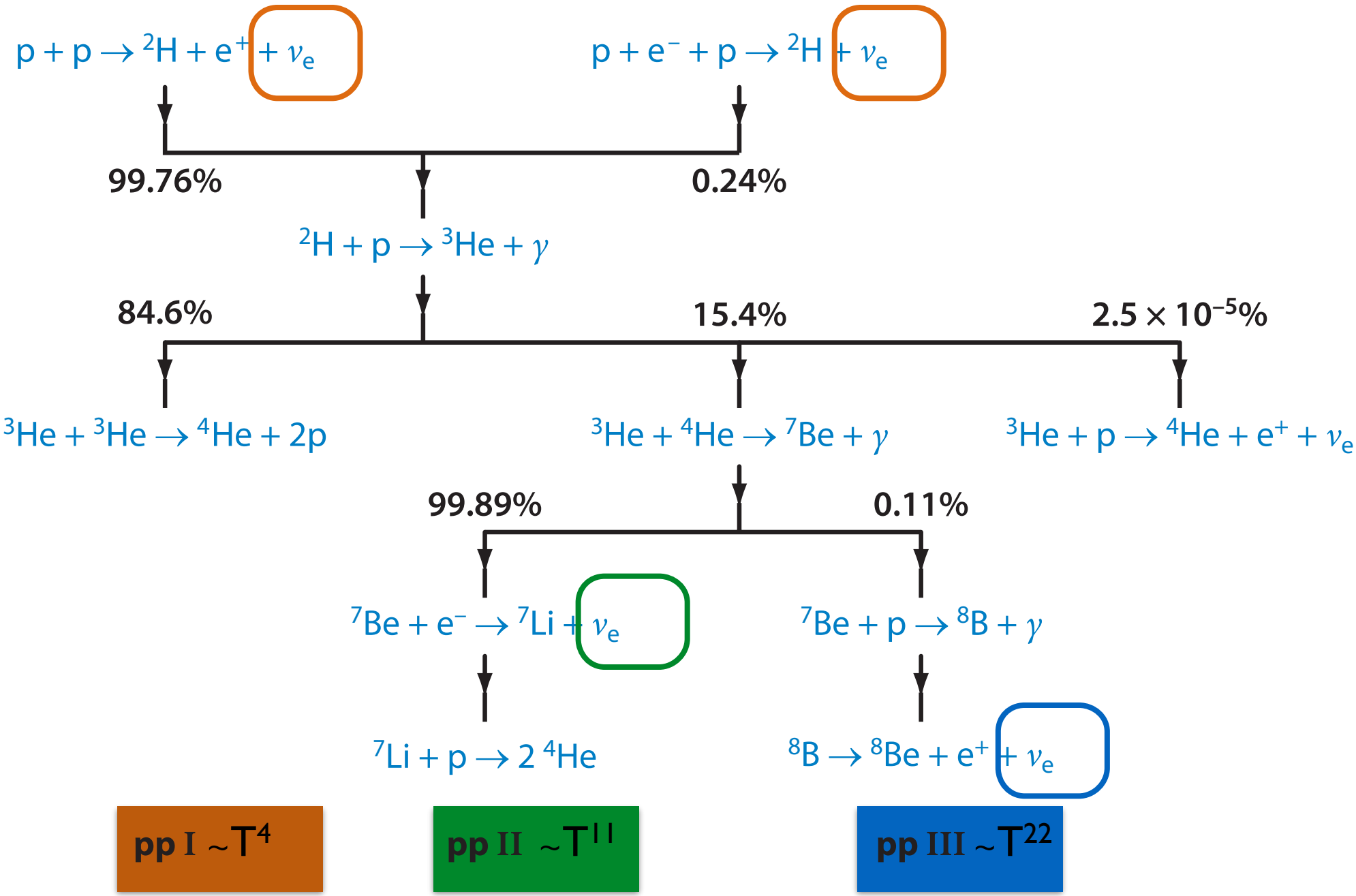
# three important future directions



# three important future directions



$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$



## Model tests:

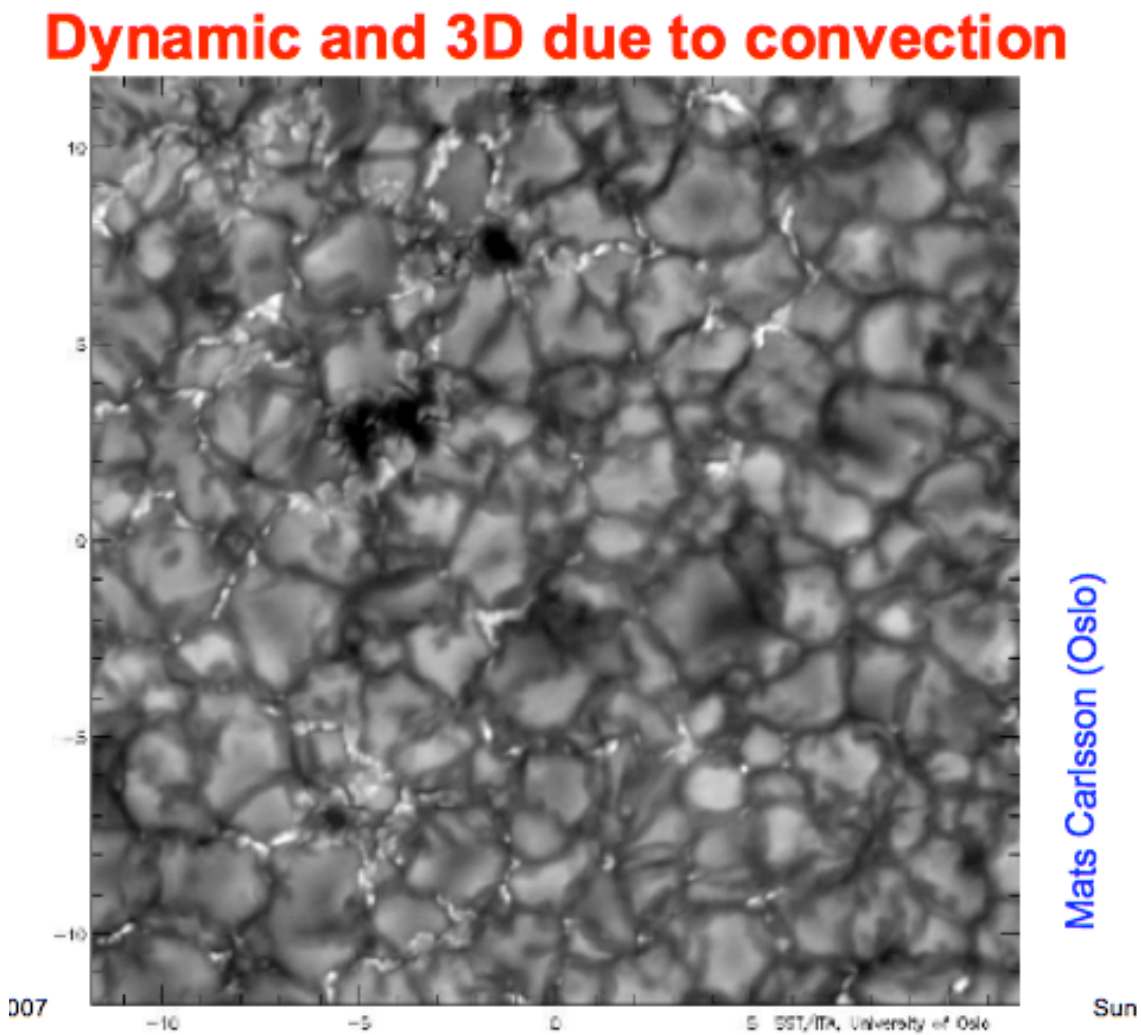
- Solar neutrinos: direct measure of core temperature to ~ 0.5%
  - once the flavor physics has been sorted out

- Helioseismology: inversions map out the local sound speed, properties of the convective zone

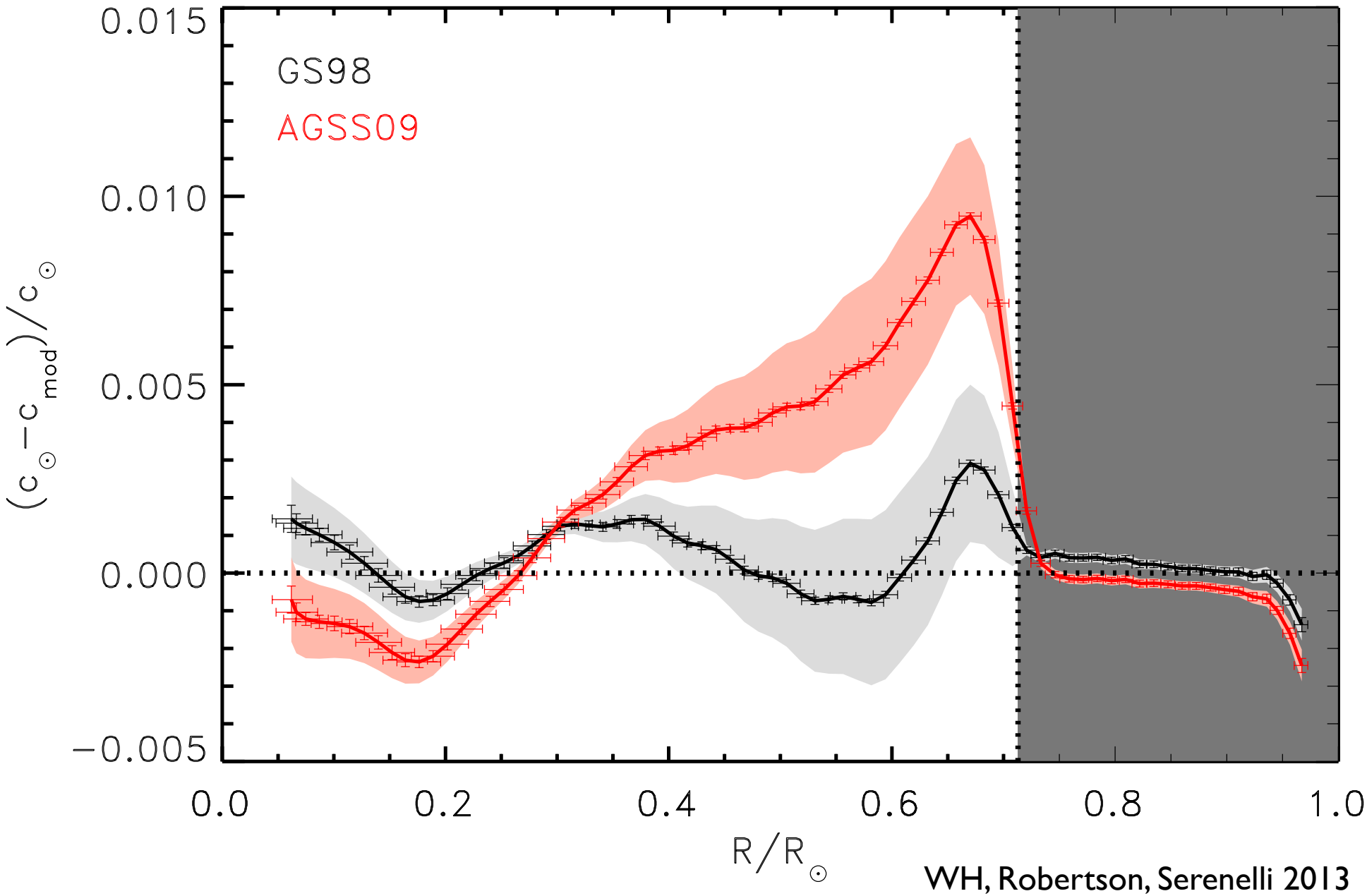
- Photospheric observations: luminosity, metallicity

The latter two probes give us two different solar models

Our best model of photosphere, based on 3D parameter-free methods, is used to interpret photo absorption lines, determining metal abundances



# But the resulting low metallicity leads to large deviations in helioseismology



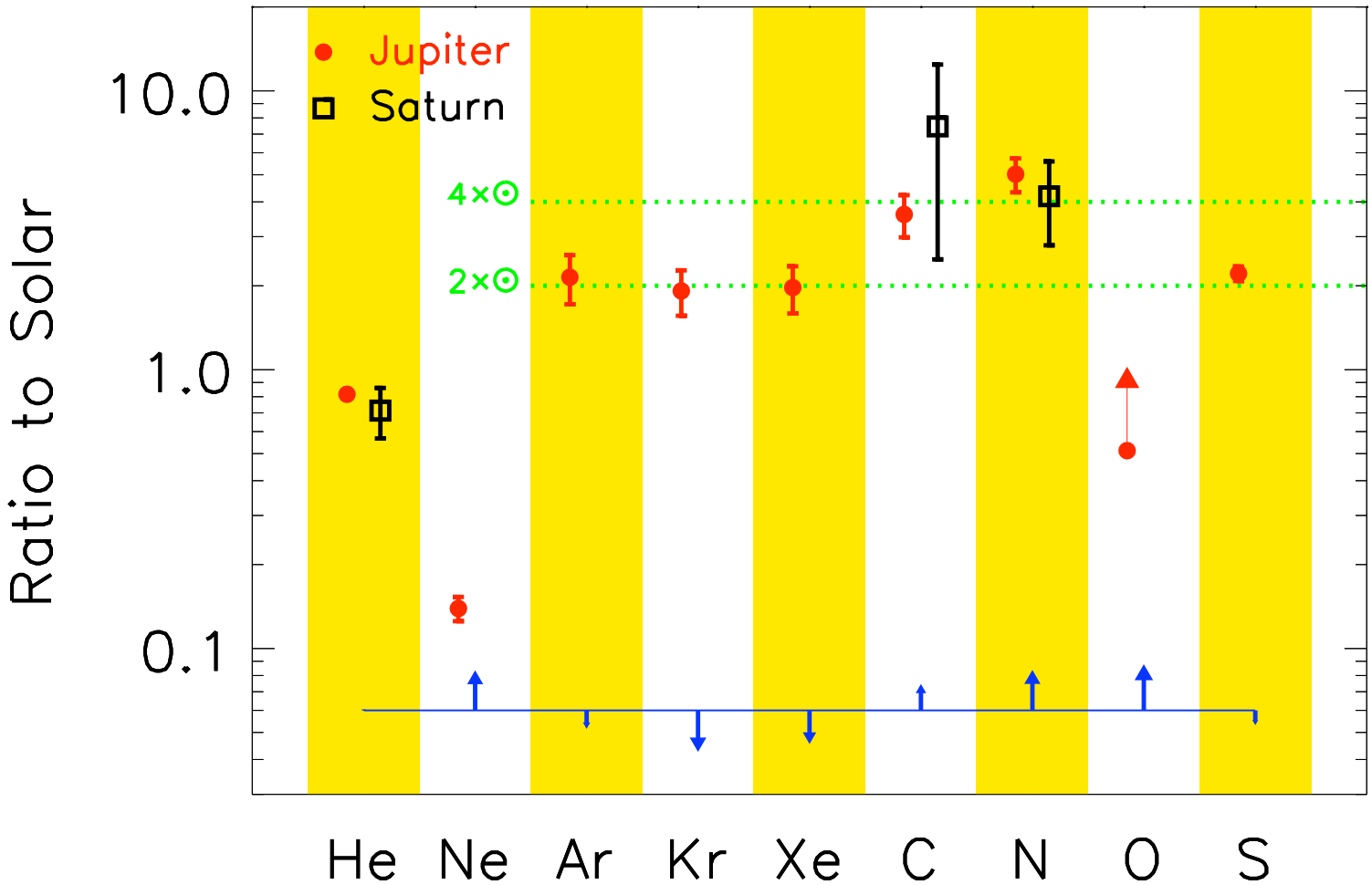

WH, Robertson, Serenelli 2013

Solar abundance problem: A disagreement between SSMs that are optimized to agree with interior properties deduced from our best analyses of helioseismology (high Z), and those optimized to agree with surface properties deduced from the most complete 3D analyses of photoabsorption lines (low Z).

Difference is ~ 40 $M_\oplus$ of metal, when integrated over the Sun's convective zone ( which contains about 2.6% of the Sun's mass)

This quantity of metal is familiar in another solar system context

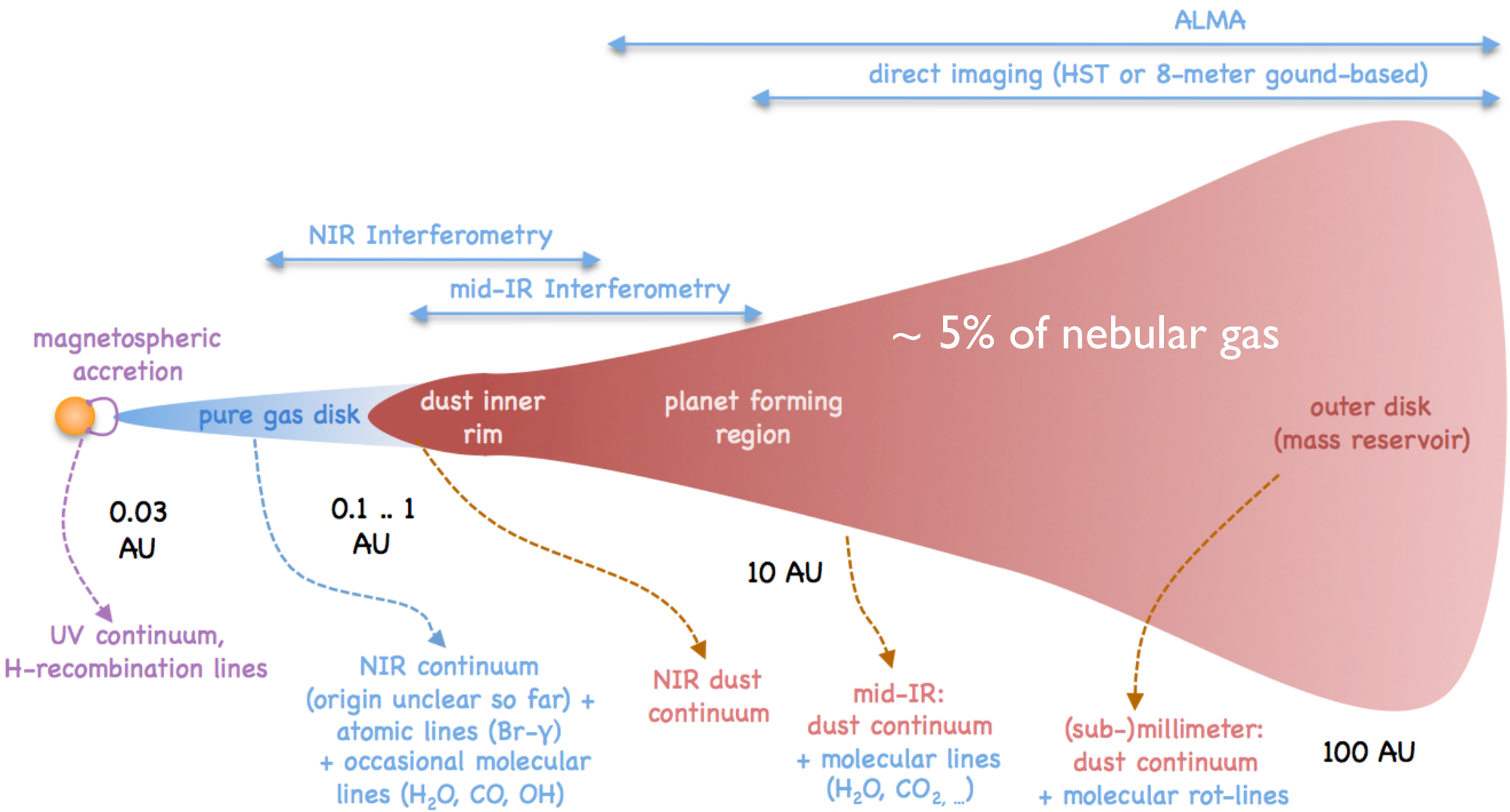
# Did the Sun form from a homogeneous gas cloud?




Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

# Contemporary picture of metal segregation, accretion




Dullemond and Monnier, ARA&A 2010

This (removal of ice, dust) from gas stream could alter Sun if

- processed gas - from which the elements we see concentrated in Jupiter were scrubbed - remains in the solar system, not expelled

- the Sun had a well-developed radiative core at the time of planetary formation (thus an isolated convective zone)

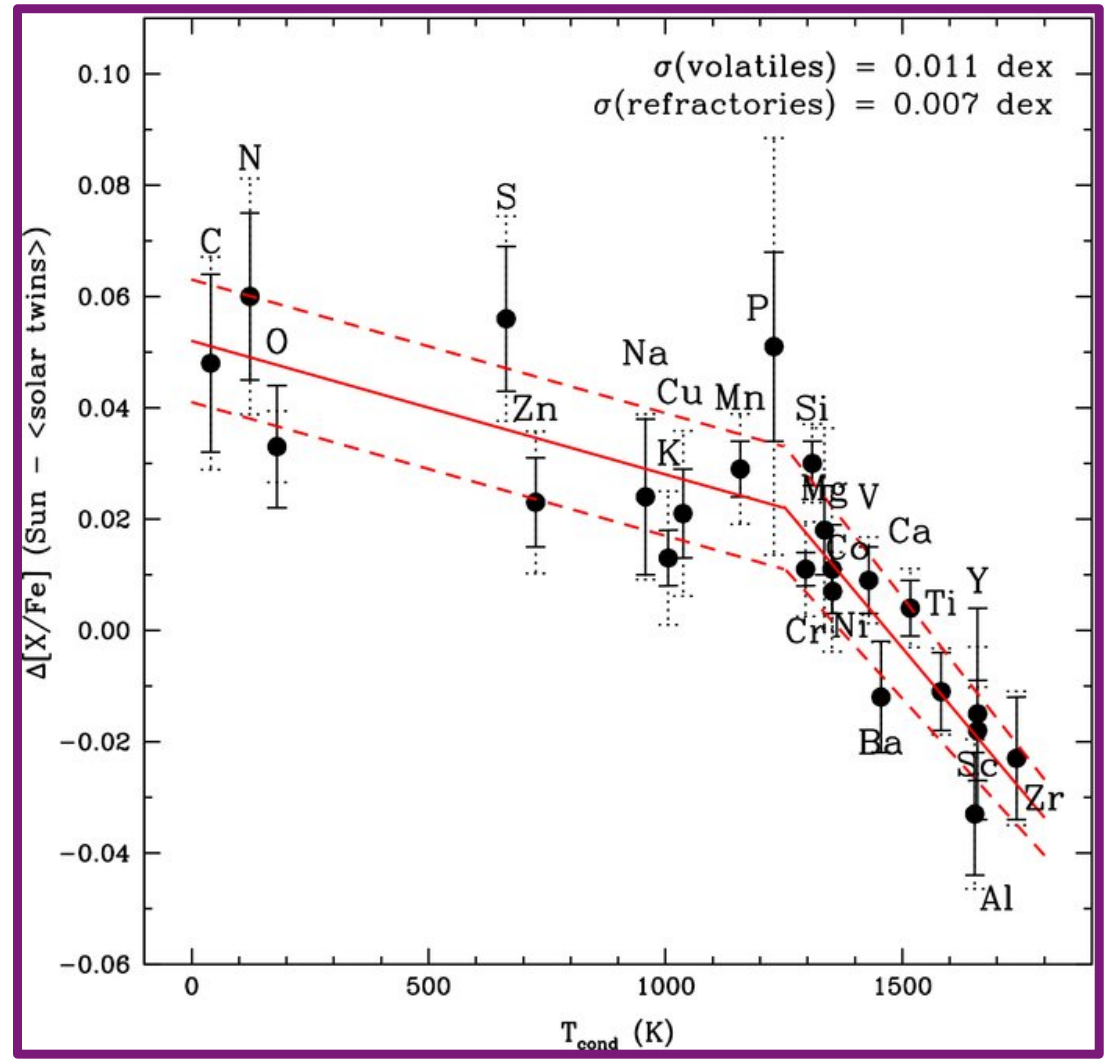
Numerically the mass of metals extracted by the protoplanetary disk is more than sufficient to account for the needed dilution of the convective zone (40-90 $M_\oplus$)

# Abundances in solar twins

This mechanism could explain another puzzling anomaly — the sun appears rich in volatiles compared to various nuclear twins

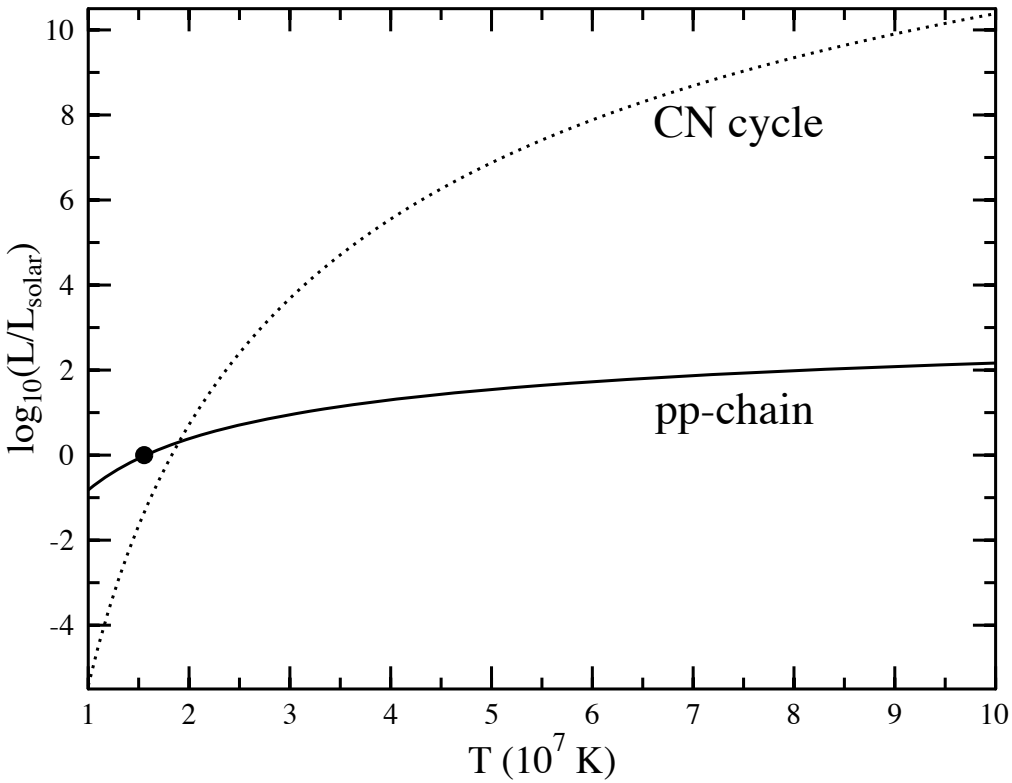
There is only one known way to probe interior metallicity:

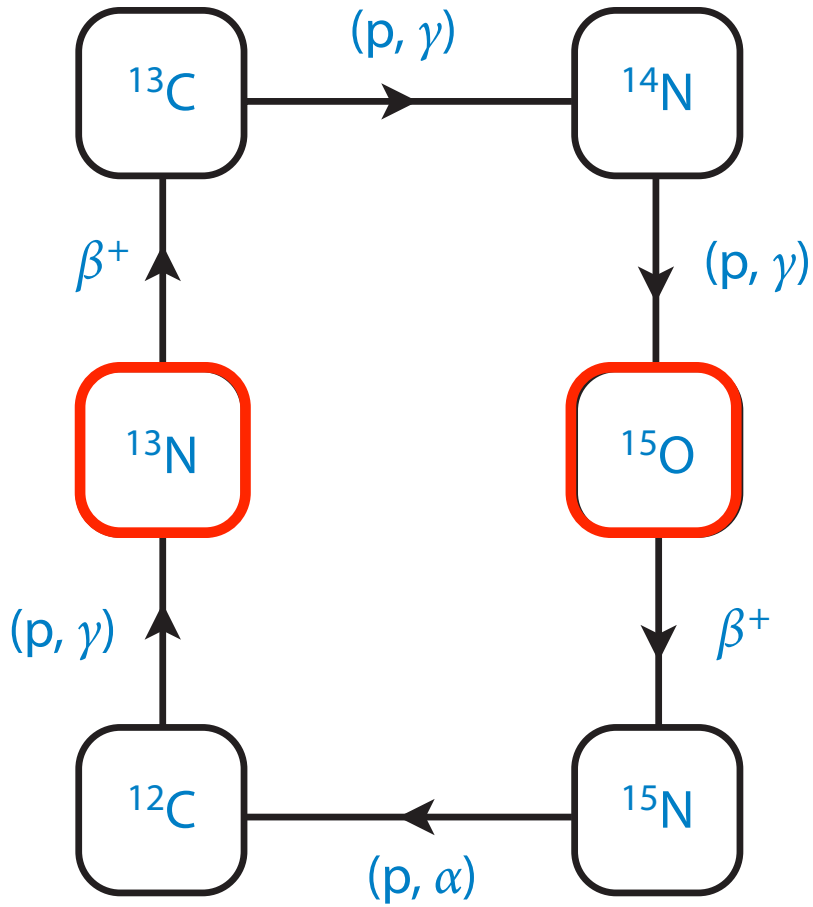
the CN solar neutrinos



# Using νs to Probe Solar Core Composition Directly

- pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except in the case of the first stars)



- measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199\ \mathrm{MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732\ \mathrm{MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on the total core C+N

There is a strategy to determine the metallicity of the core - the first gas to condense out of the primordial gas cloud - based on measuring these neutrinos

what we want to know: the primordial core abundance of C + N (in units of SSM best value)

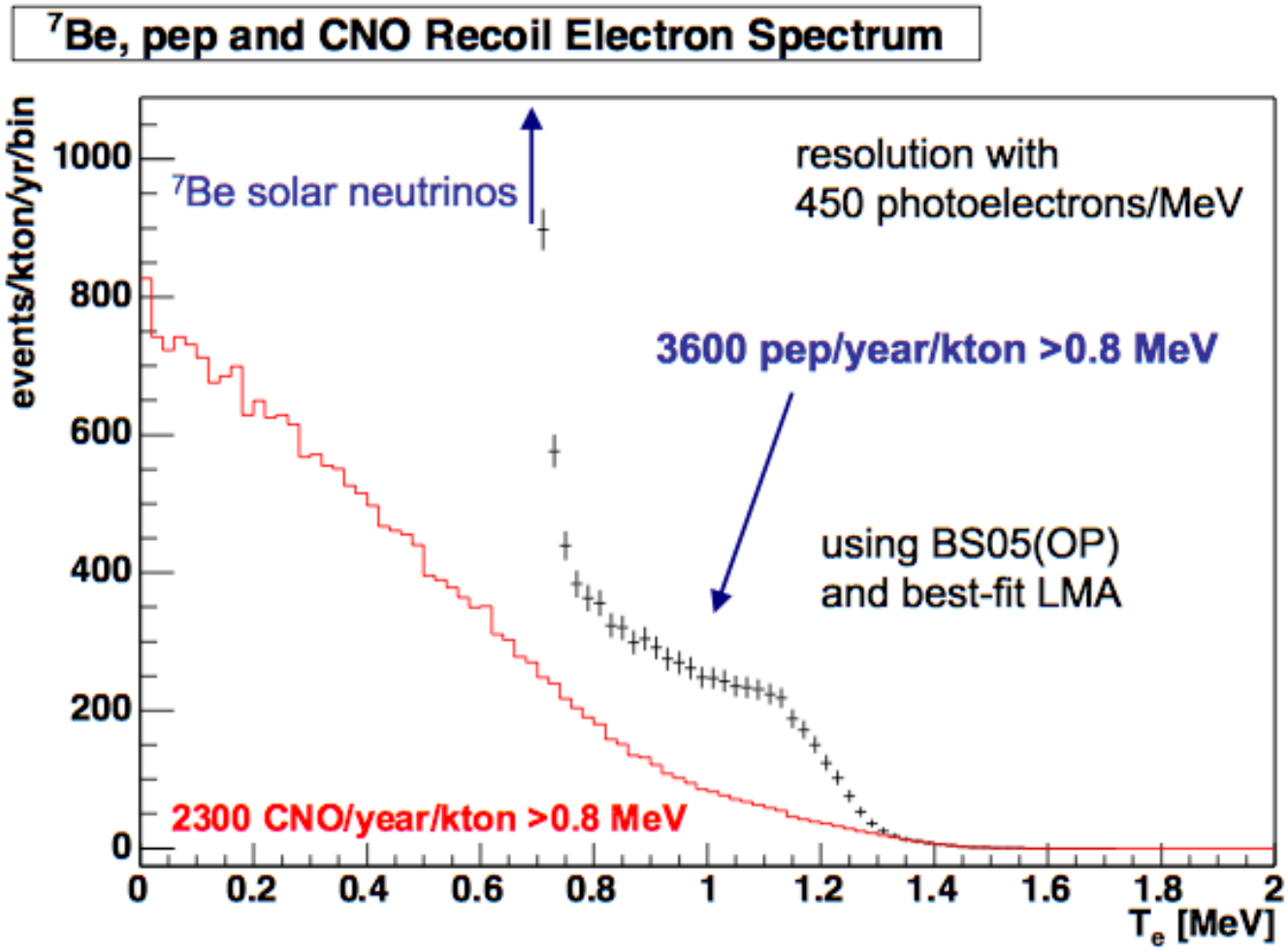
a future neutrino measurement:
Borexino, SNO+, JinPing....

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

We can make this measurement to 10%, to resolve a 30% problem in our Sun

a simulation of the expected SNO+ sensitivity



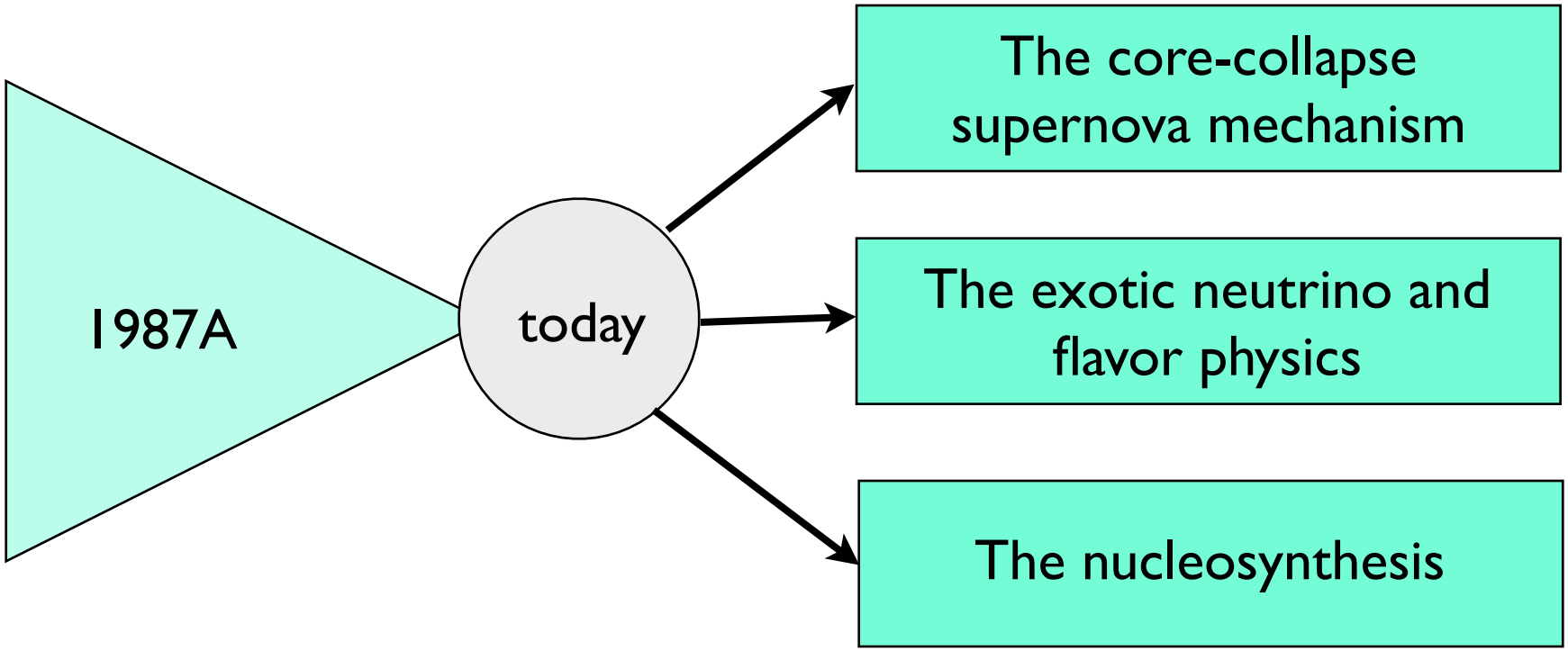

(from Mark Chen)

this measurement is fundamental

- ❑ probes the primordial gas from which our solar system formed
- ❑ the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions
- ❑ cannot overestimate the potential importance of demonstrating a link between host-star metallicity and the existence of exoplanets

And detectors with the right attributes, like SNO+, already exist

# SN Physics: Three Important Future Directions



from
Burrows

## The numerical challenges are daunting

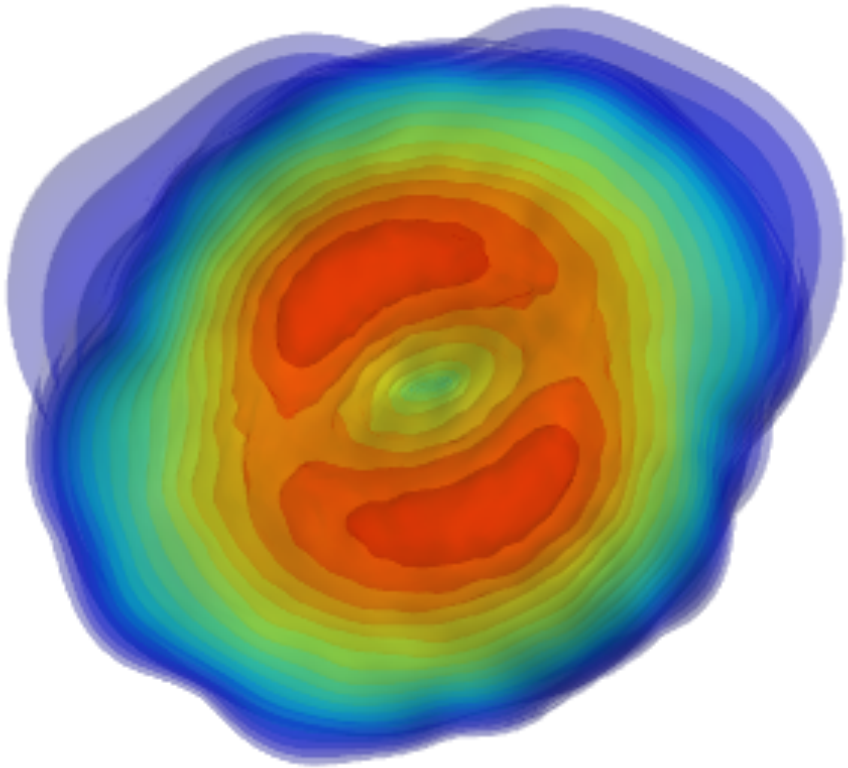
Full 3D modeling involving realistic neutrino transport, flavor physics, and nuclear microphysics

Reproduction of observations

- kinetic energies
- debris morphologies
- nucleosynthetic yields
- light curves
- remnant mass, spin, and velocity distributions
- and someday, neutrino yields

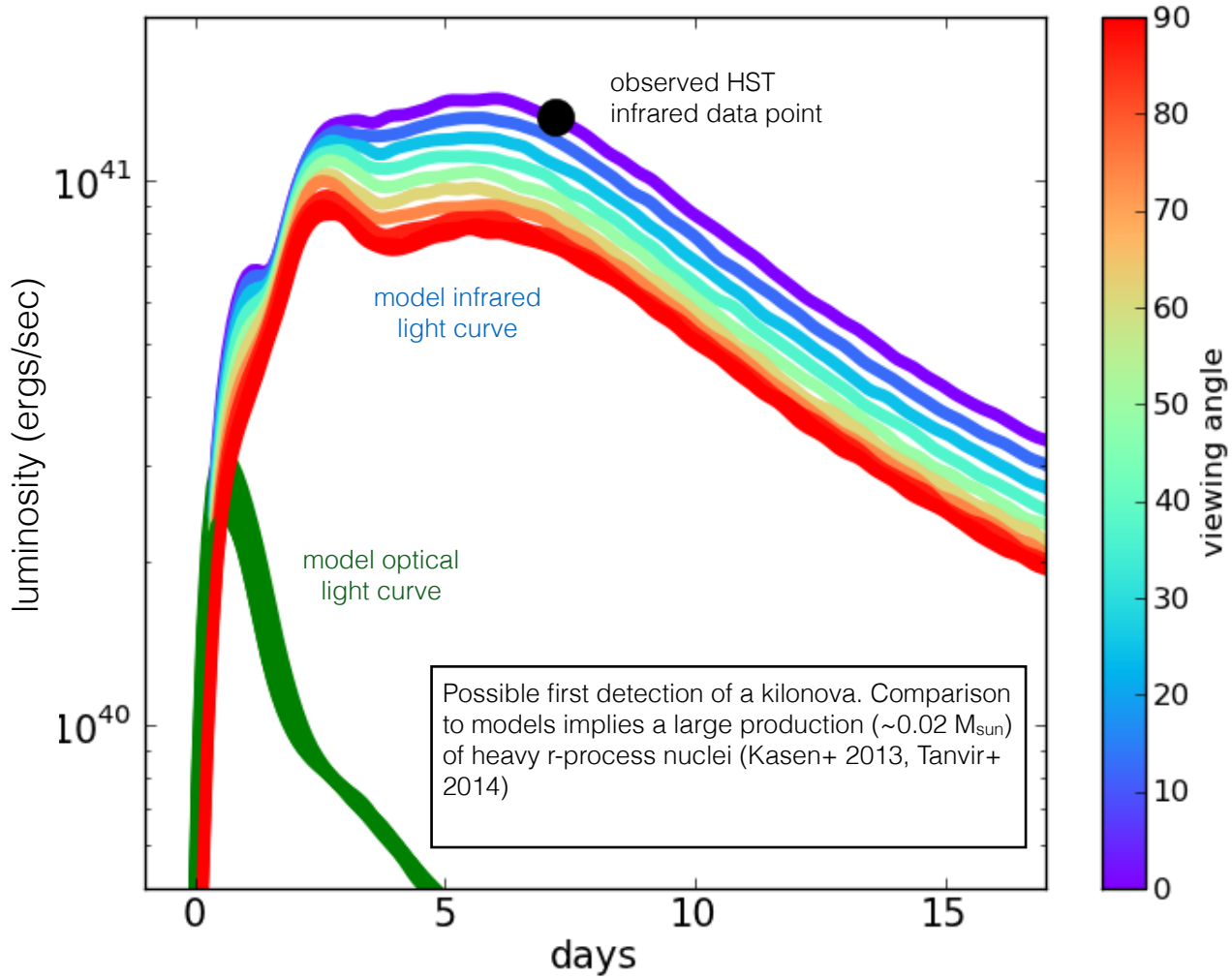
This is an open challenge, and even basic aspects of the explosion mechanism in 3D remain in dispute

# simulations of neutron star mergers and r-process nucleosynthesis



Simulations of neutron star mergers define the physical conditions under which r-process nuclei may be formed. High performance computing resources are needed to model the

- ✦multi-dimensional hydrodynamics and gravity
- ✦weak interactions and neutrino transport
- ✦nuclear equation of state
- ✦detailed nuclear reaction networks



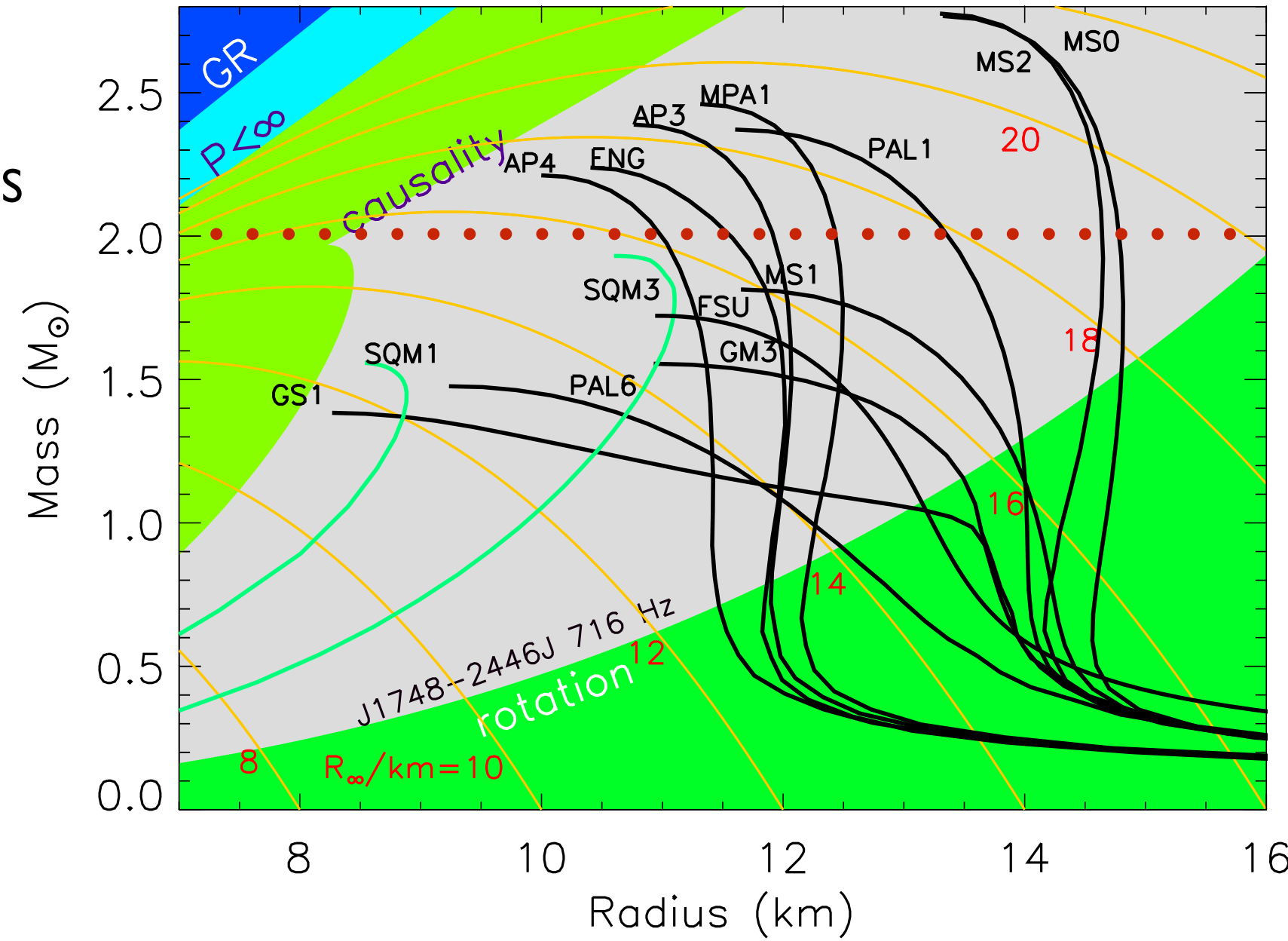

The decay of neutron-rich isotopes ejected in mergers will power a supernova-like transient (a *kilonova*). The color and brightness of a kilonova constrain the mass and composition of the ejecta, offering a direct observational window into *in situ* r-process nucleosynthesis.

Both mergers and SN dependent on the nuclear EOS

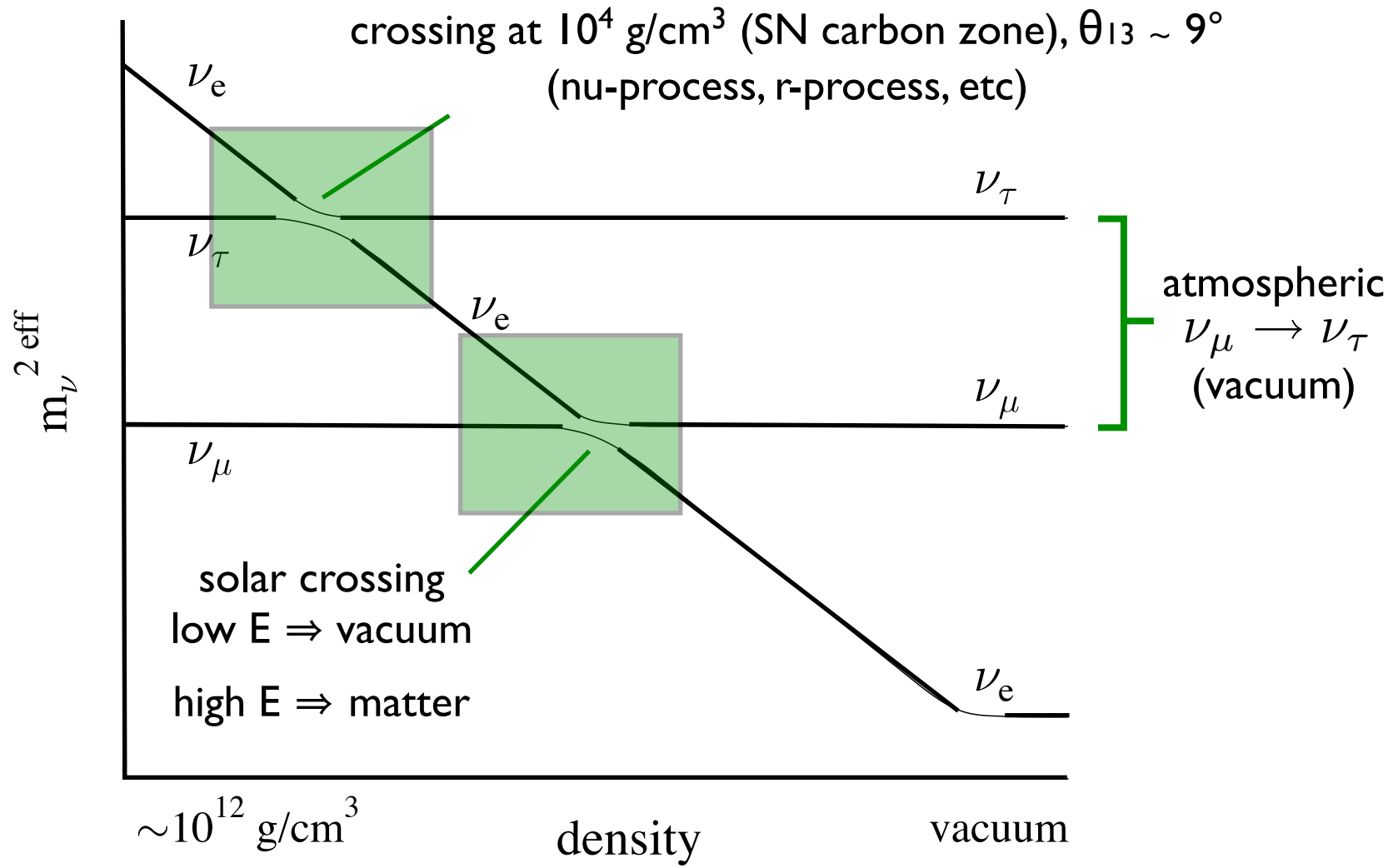
Progress from NS masses

Progress from theory

Important synergies with LIGO

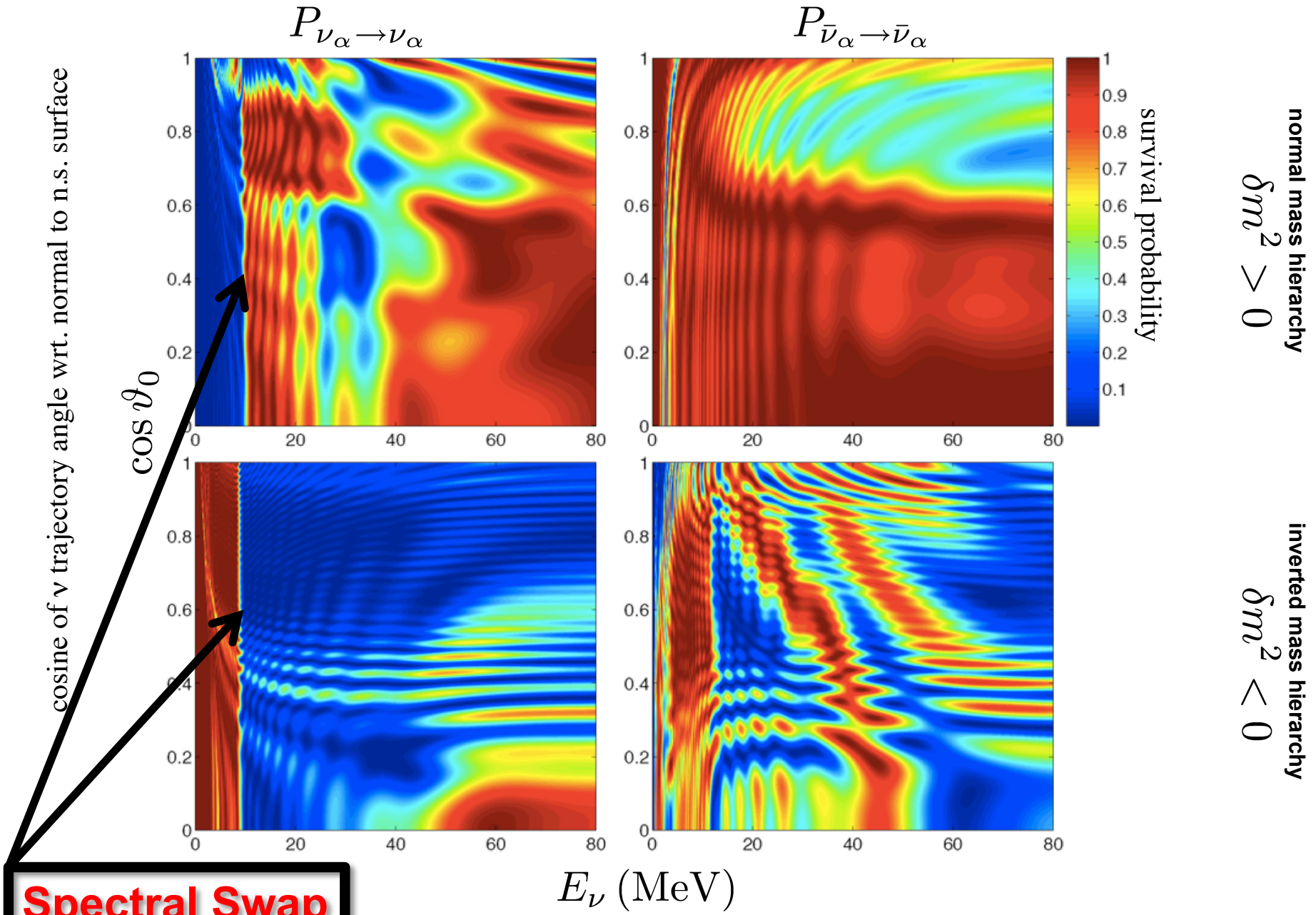


# Flavor Physics: A second MSW crossing, governed by $\theta_{13}$




So we can probe flavor physics not otherwise accessible — helped by the fact that SN are the ultimate neutrino factories

But in addition, the effective neutrino potential in a SN also depends on interactions with a sea of other neutrinos: a nonlinear process with surprising consequences




**Spectral Swap**

**consequences of neutrino mass and quantum coherence in supernovae**

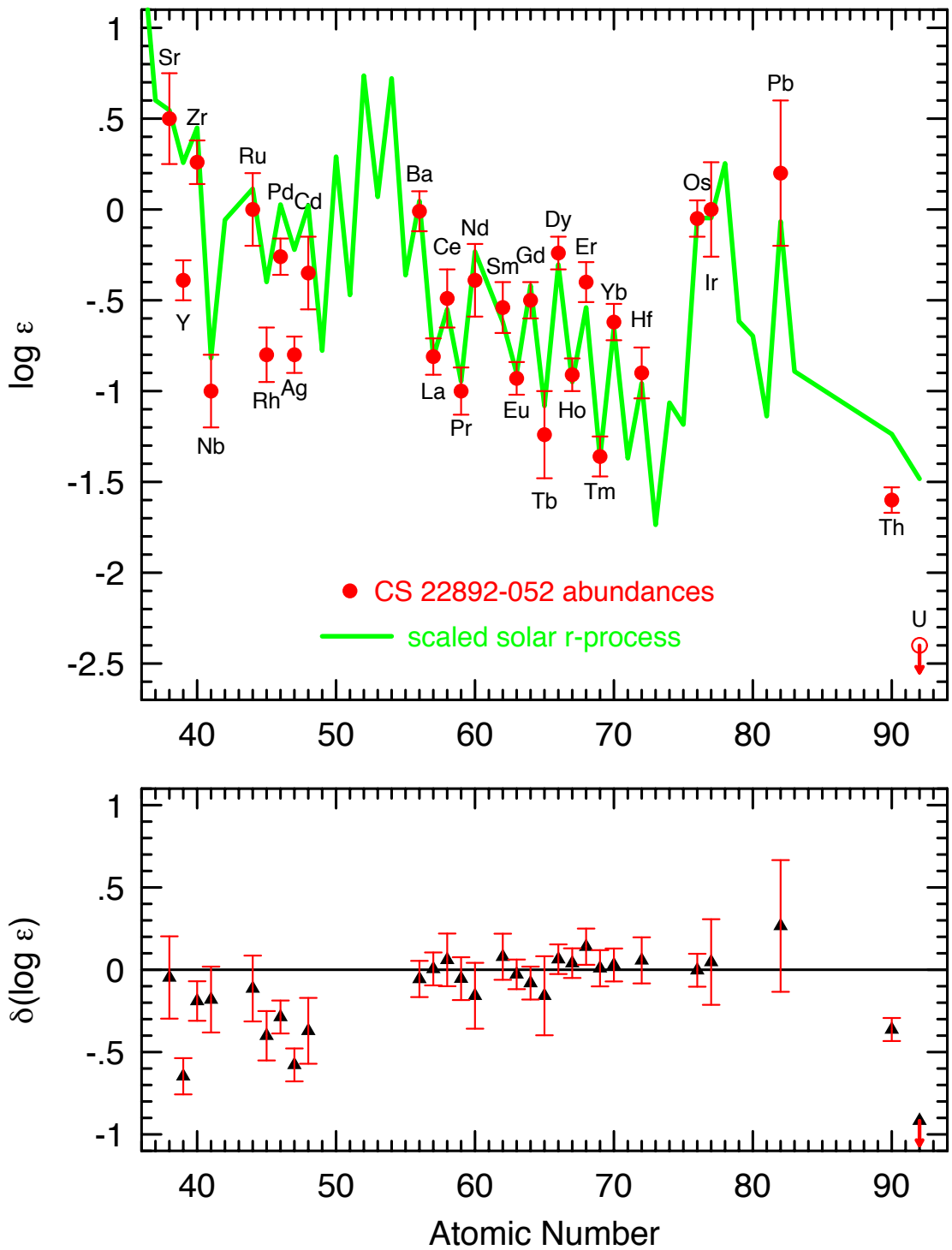
**H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian,** Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

Do such effects survive ν passage through the mantle?

- the supernova shock
- turbulence and density fluctuations
- neutrino direction-changing scattering

Do we have the modeling capabilities to treat this nonlinear process?

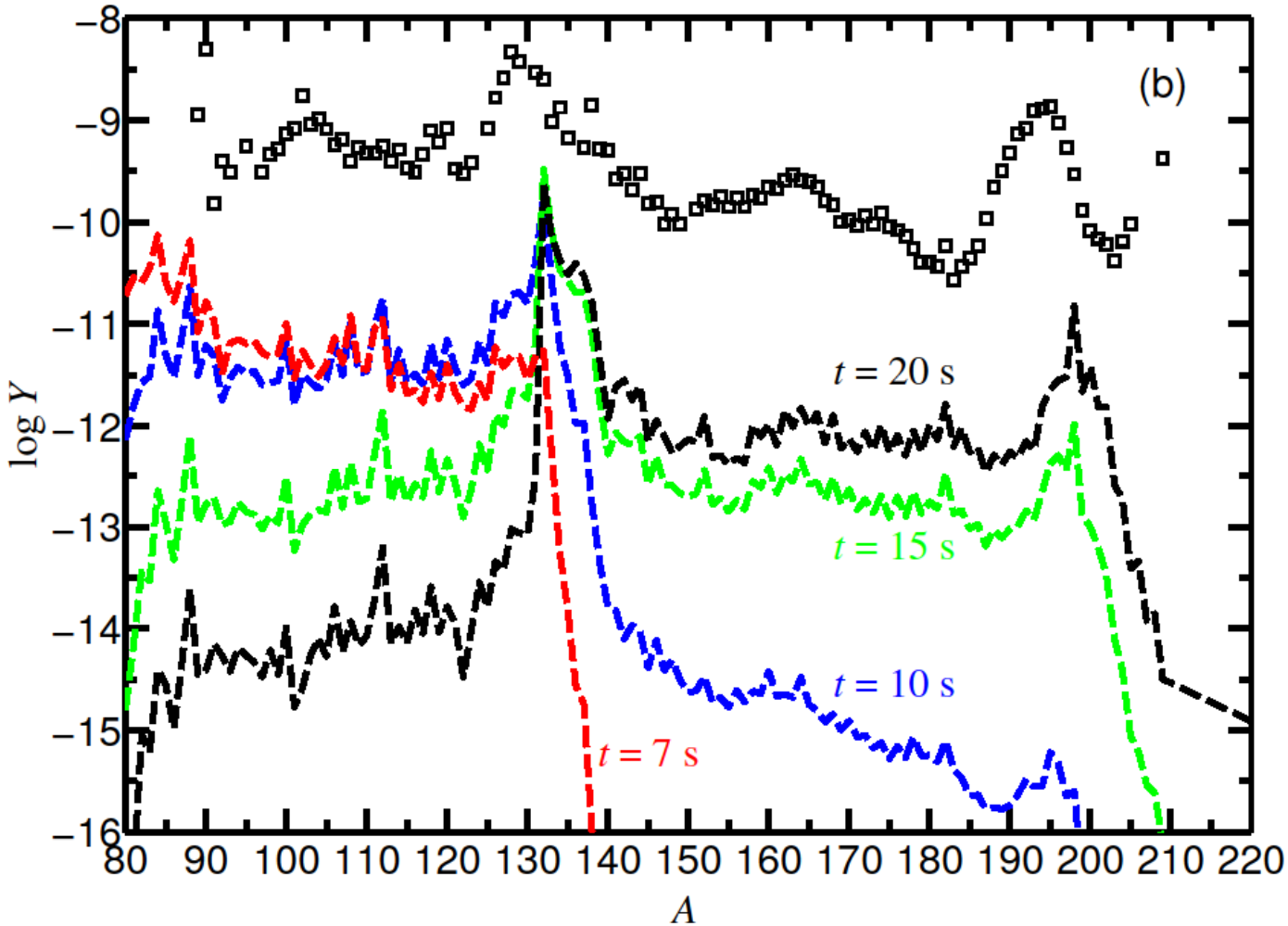
And nucleosynthesis, this field's important intersection with nuclear structure:




SN are major sources of new elements

much new information on the r-process coming from early, metal-poor stars

the production od r-process elements in such individual events scales well to solar r-process for A > Ba




An example: neutrino-driven slow and cold r-process that operates at low metallicity

Very active area, one of the key puzzles in the field:

- one vs multiple r-process sites, e.g., a neutrino-driven process in very low metallicity stars, neutron star mergers at higher metallicity?
- the nuclear physics along the paths for various r-processes?
- the observational signals?