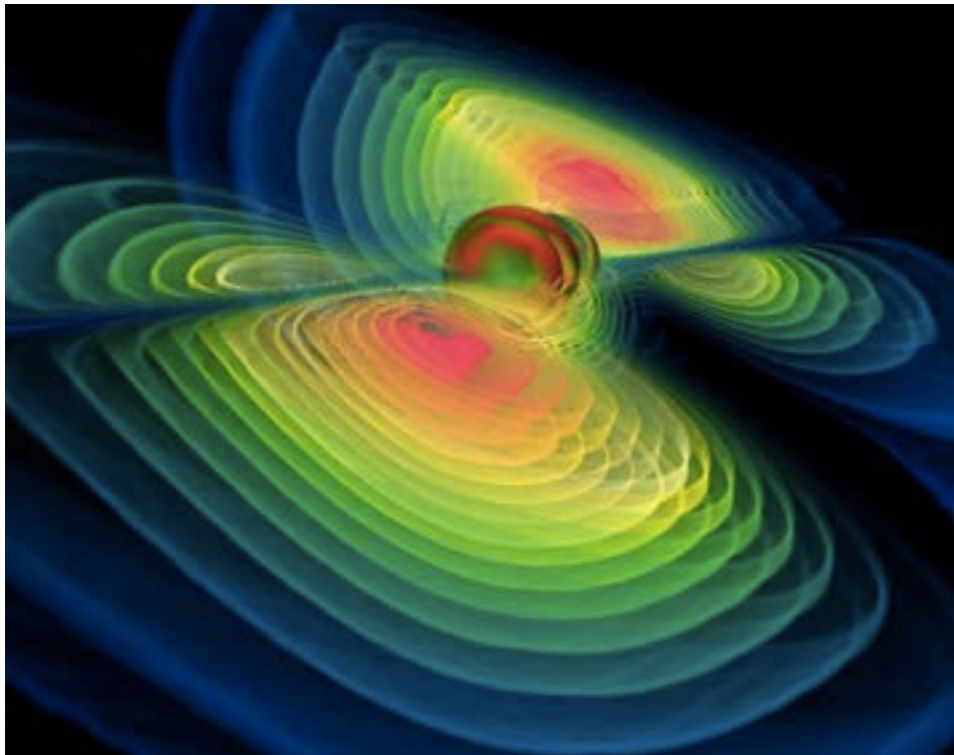# Gravitational Waves

Lec. 1: Neutron stars and their crusts.

Lec. 2: Supernovae.

Lec. 3: Nucleosynthesis and gravitational waves.

Questions: horowit@indiana.edu

C. J. Horowitz, Indiana University, National Nuclear Physics Summer School, Santa Fe, July 2012.

Neutron Rich Matter

- Compress almost anything to $10^{11}+$ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.

  - What are the high density phases of QCD?

  - Where did the chemical elements come from?

  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?

- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor ($T_c=10^{10}$ K!), superfluid, color superconductor...*

- *Focus on simpler liquid, solid, and gas phases.*
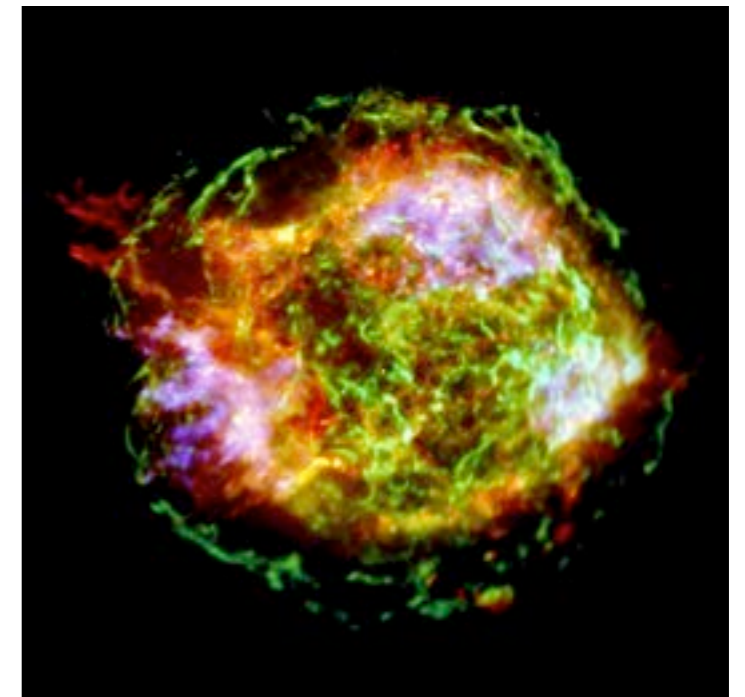
Supernova remanent Cassiopea A in X-rays
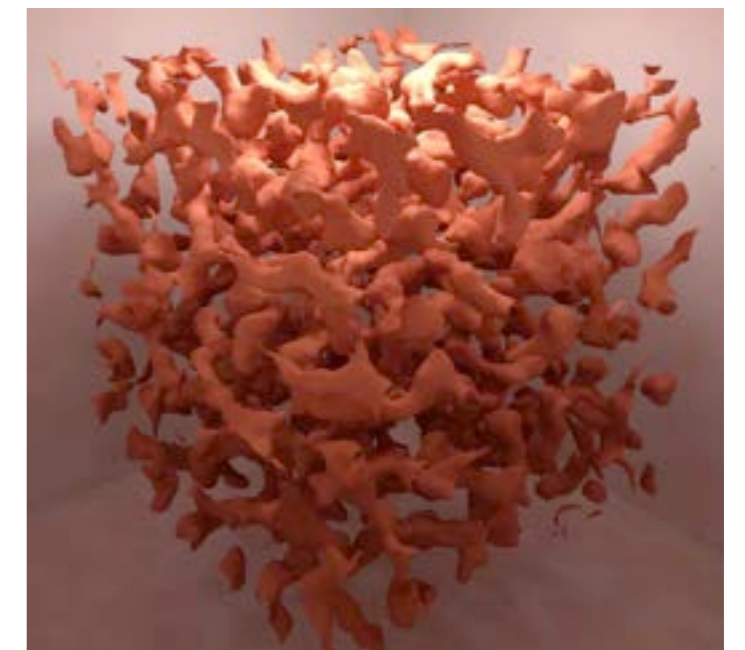
MD simulation of Nuclear Pasta with 100,000 nucleons

Limits on computations for cold dense matter

- Lattice QCD at finite T but finite density is presently very hard.
- Chiral pert theory only converges near nuclear density and below. Higher order contributions may be large at higher densities.
- Can do GFMC or other microscopic calculations at high densities. However, there may be important ambiguities in your hamiltonian.
- **Can't calculate properties of dense neutron rich matter, must observe!**

Probes of Neutron Rich Matter

- **Multi-Messenger Astronomy:** "seeing" the same event with very different probes should lead to fundamental advances. Often *photons* from *solid* netron star crust, supernova *neutrinos* from low density *gas*, and *gravitational waves* from energetic motions of *liquid* interior of neutron stars.

Large X-ray telescopes Chandra, XMM Newton are aging.

New powerful radio telescopes helped by advances in computers.
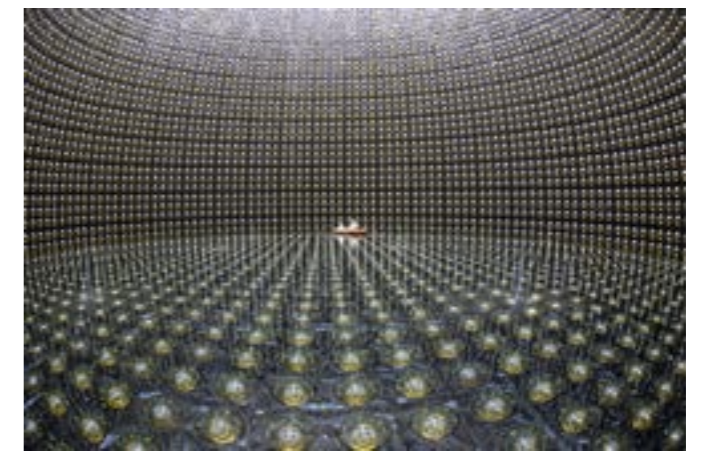

New detectors for SN neutrinos

GW detectors LIGO, VIRGO

Laboratory facilities such as FRIB to study neutron rich nuclei.

Nucleosynthesis

- Big bang made H, D, He, Li. Mass gaps at A=5 and 8 prevented binary nuclear reactions in low density early universe from making many heavier nuclei.

- Giant stars, in their high density cores, make C by three body rxn $^4He+^4He+^4He-->^{12}C+\gamma$. Hoyle predicted a 0^+ state in ^{12}C at just the correct E to enhance the rate of this rare 3 body rxn enough.

- Conventional 2-body thermonuclear fusion rxns in giant stars and SN can then make elements up to ^{56}Fe.

Solar Abundances
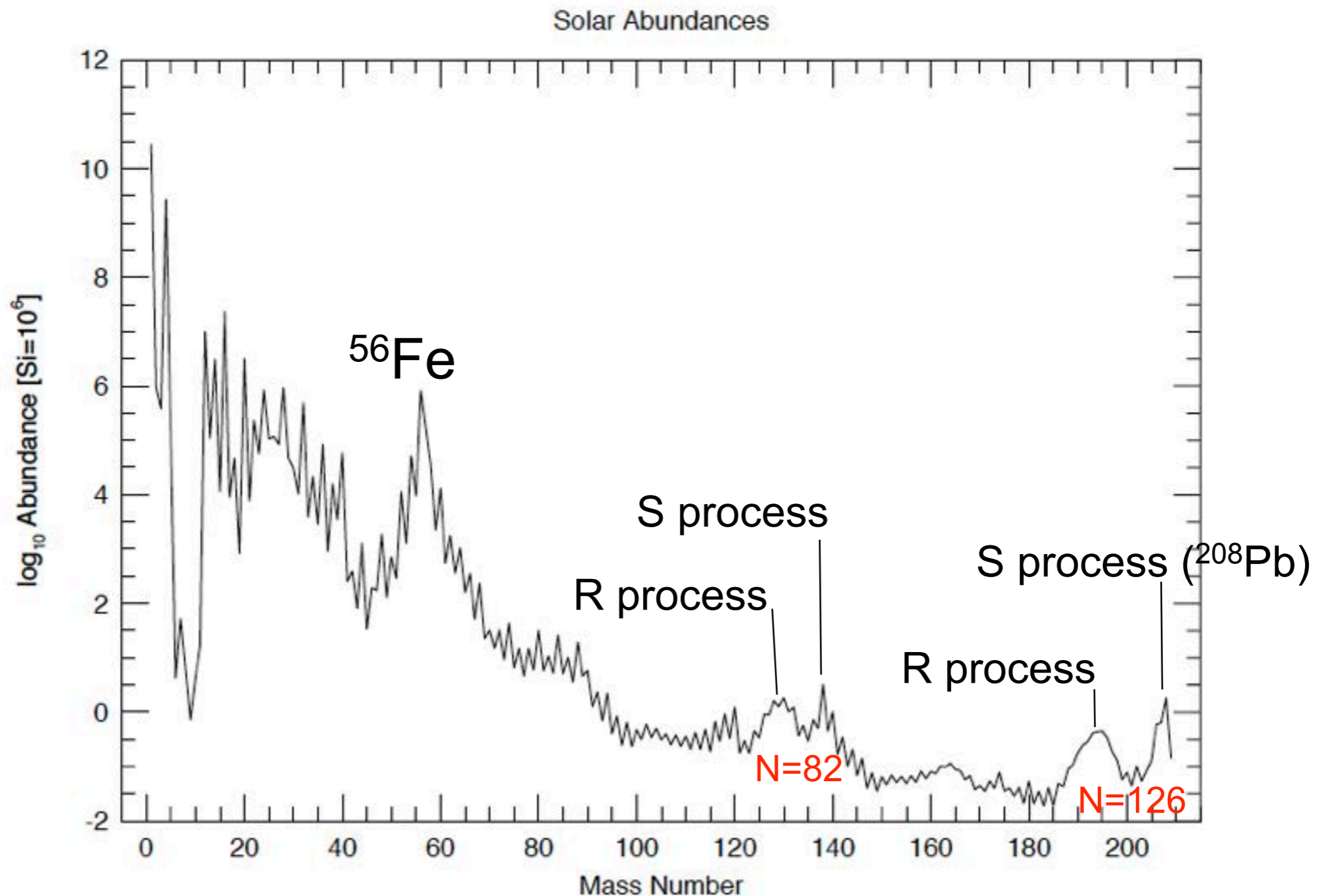
- Large peak near ^{56}Fe (most bound nucleus). IA SN make a lot of ^{56}Fe.

- Double peaks near A=135 and A=200.

- S process: slowly capture neutrons on a seed nucleus allowing time for beta decays to stable nuclei. Reach neutron closed shell N=126 at Z=82 to give doubly magic ^{208}Pb.

- R process: rapidly capture neutrons without enough time for full beta decay. Reach N=126 with less than Z=82 protons. Produces A=195 peak that includes gold.

# Synthesis of the Elements in Stars, Rev Mod Phys 1957 (B^{2}FH)

Burbidge, Burbidge, Fowler, Hoyle
Took the stars and made them toil:
Carbon, copper, gold, and lead
Formed in stars, is what they said

s-process

- Free neutrons act as a source of free energy. Energetically favorable to capture n on nuclei near ^{56}Fe even if it is not favorable to fuse two ^{56}Fe.

- Note hard to add free p at low T because of Coulomb barrier.

- In a giant star, a small supply of free n can be very slowly added to nuclei with plenty of time to beta decay so one stays in the valley of beta stability. Eventually one arrives arrives at doubly magic ^{208}Pb.

- In this s-process abundance of nuclei simply related to n capture cross sections. Furthermore involves stable nuclei so "easy" to measure n capture cross sections in lab.

- Can predict s-process abundances from known n capture cross sections and subtract them from total solar abundances to get r-process abundances.
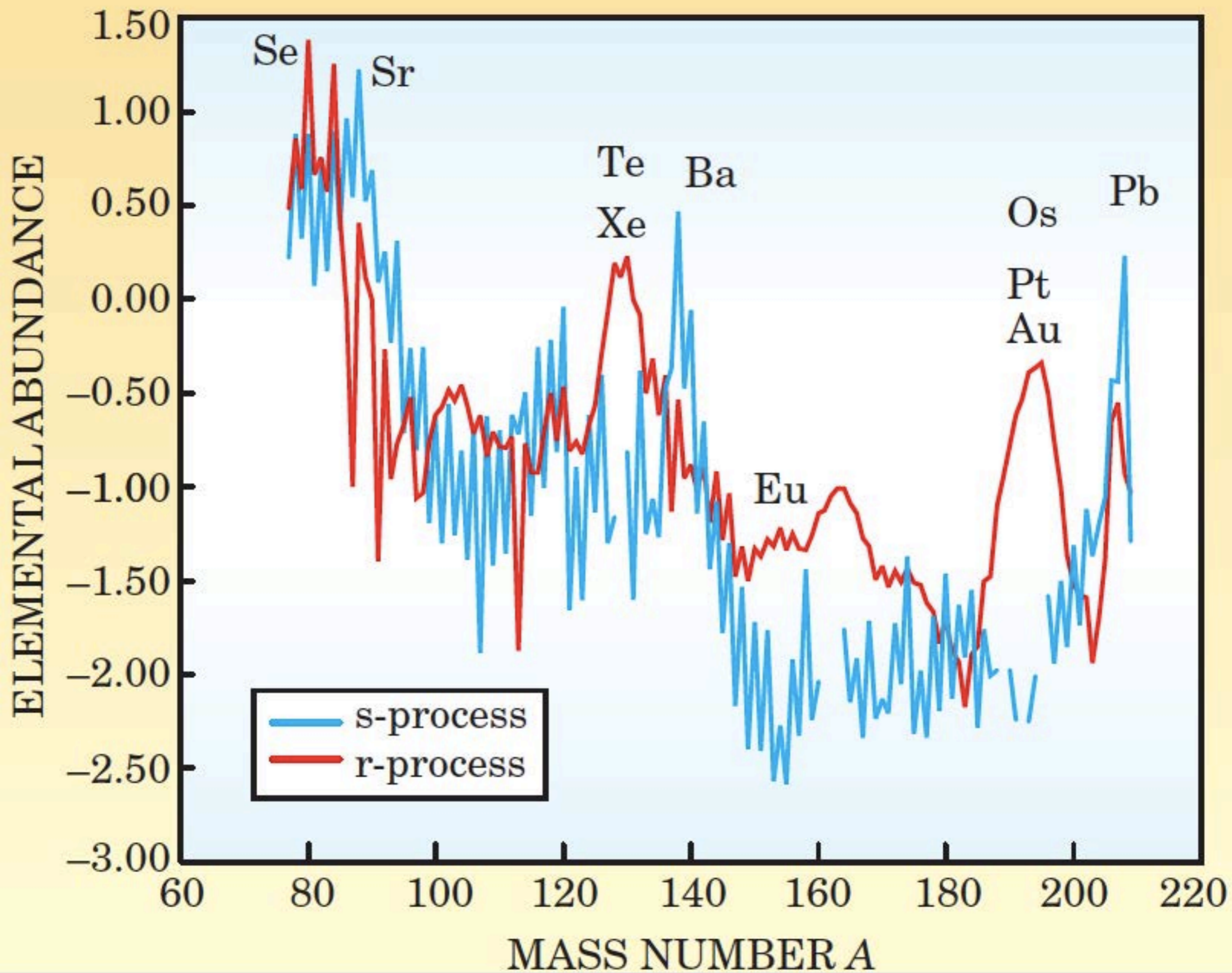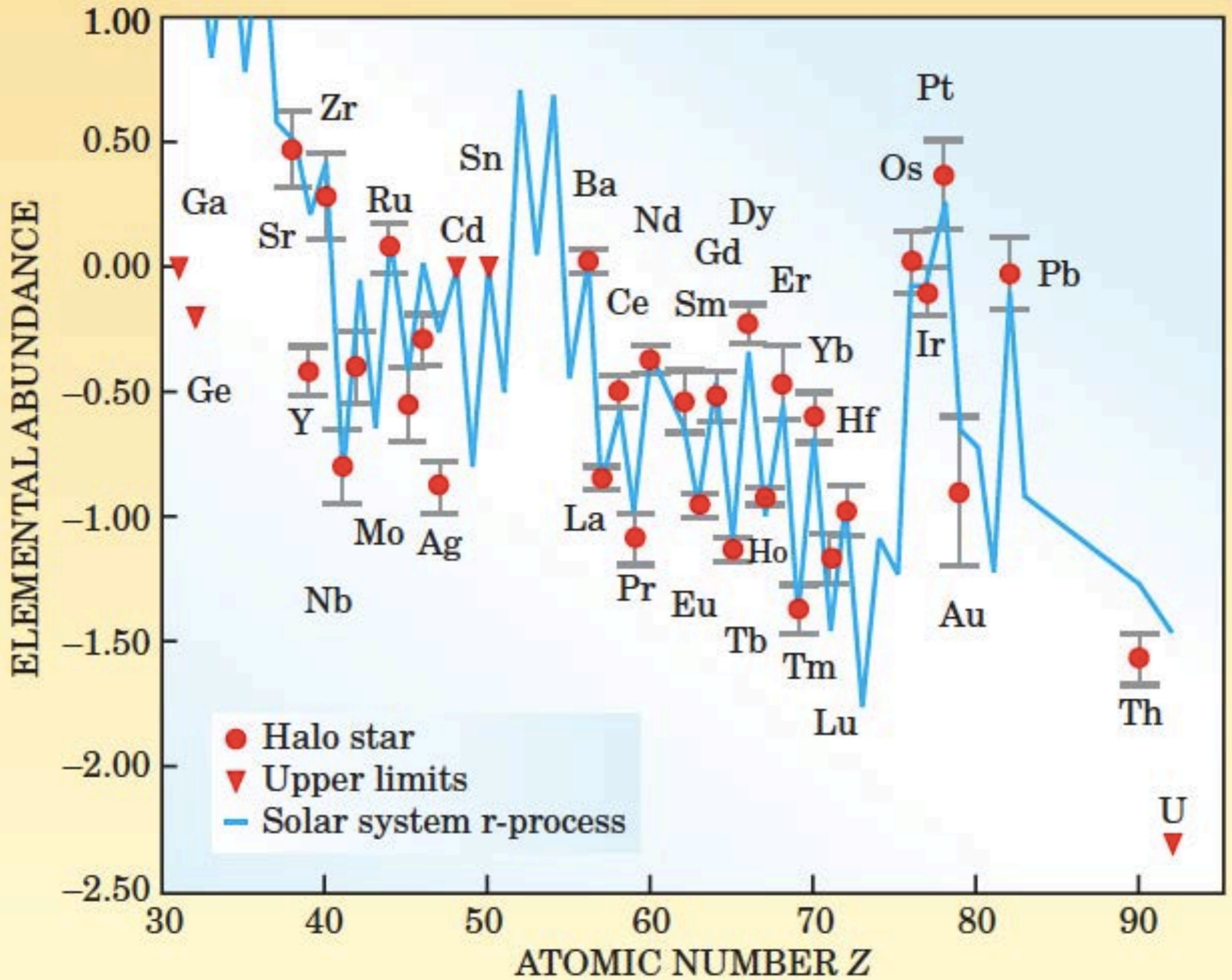
r-process

- Seed nucleus rapidly captures many neutrons and then beta decays several times back to stability.

- Depends on ratio of neutrons to seed nuclei.

- If you wish to make A=195 nucleus such as Au from ^{56}Fe seed nuclei **need 139 neutrons per seed nucleus.** Otherwise one will run out of neutrons before one reaches mass A=195.

- **Fundamental question: where do all the neutrons come from?**

- Note, one can make more neutrons (lower Y_p) or one can destroy more seed nuclei (raise the entropy) in order to increase the # of n per seed nucleus.

- *Two main possibilities for r-process site: core collapse SN and NS mergers.*

- Probe SN as r-process site with neutrinos, probe NS mergers with gravitational waves.
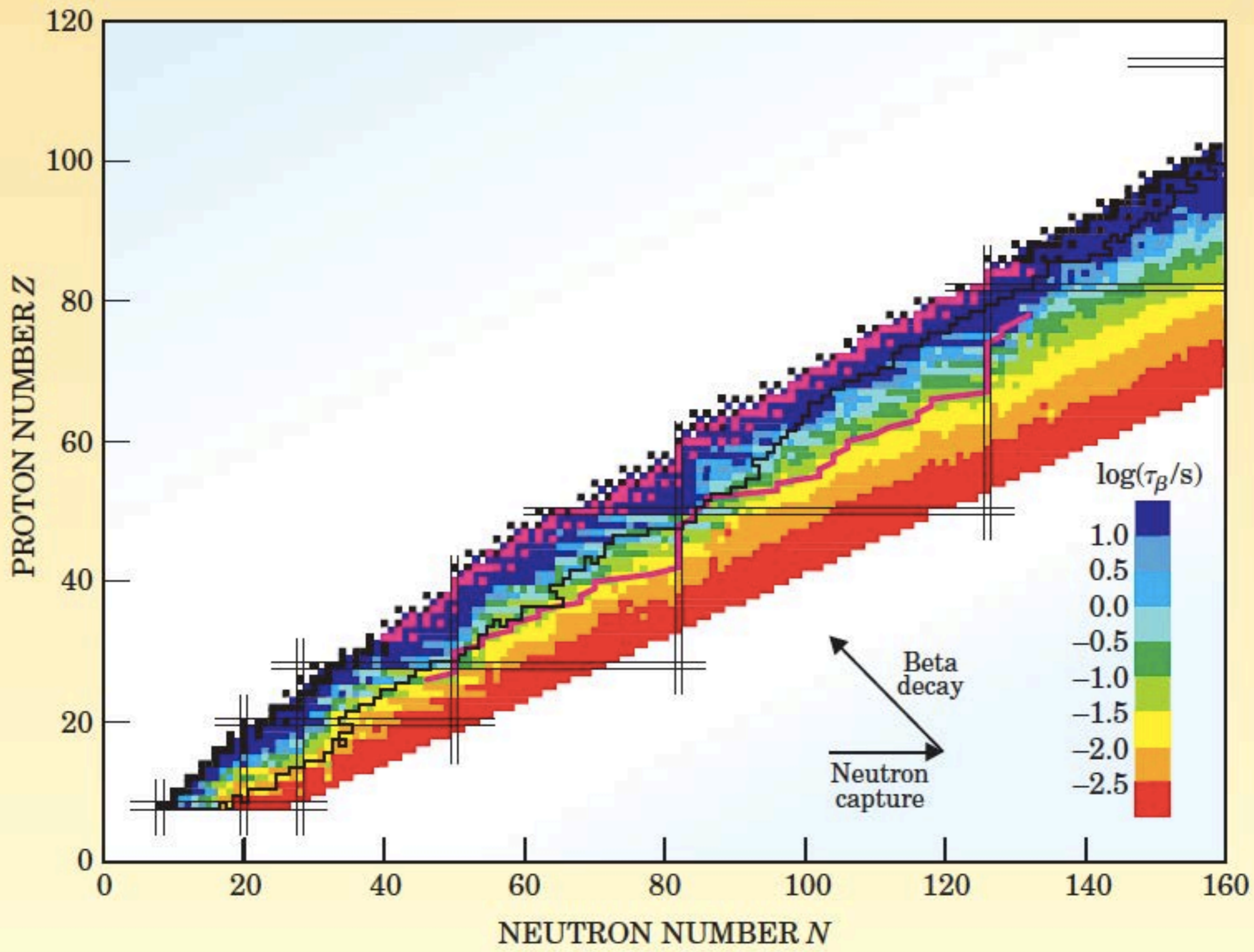
Neutrino probes of neutron-rich matter
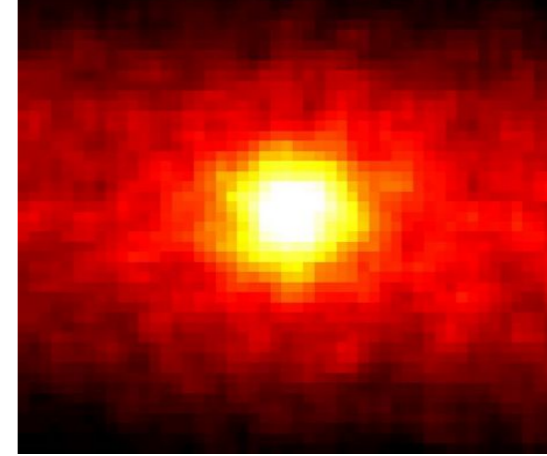
Sun in neutrinos

- Supernova neutrinos carry unique flavor information (some what complicated by oscillations) that may be closely related to composition and nucleosyntheis.

- New underground dark matter, solar nu,... experiments will be very sensitive to nu from the next galactic supernova (SN).

- Example: ton scale dark matter detectors very sensitive to SN neutrinos via nu-nucleus elastic scattering. Provides info on mu/tau nu spectra not available in Super-K. [CJH, K. Coakley, D. McKinsey, PRD**68**(2003)023005]

- Neutrinos are emitted from the low density $\sim 10^{11}$ g/cm^3 neutrino-sphere region. This gas phase can be described with a Virial expansion [CJH, A. Schwenk, NPA**776**(2006)55] and studied in the lab with HI collisions.
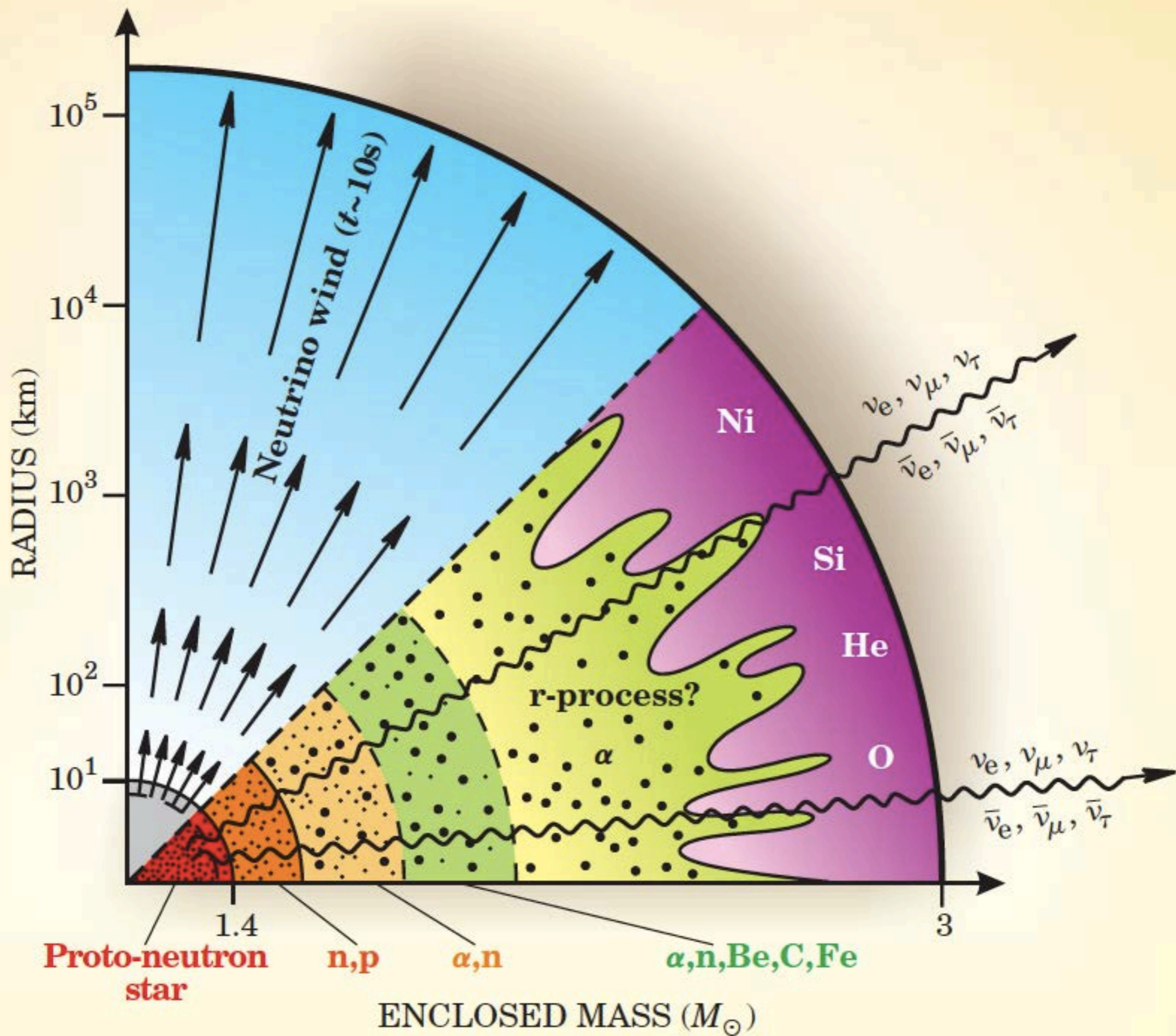
Neutrinos and r-process Nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Here seed nuclei rapidly capture many neutrons. Ratio of n to seed nuclei depends on n/p ratio (Y_p), entropy, expansion time scale.

- n/p ratio most important. This is set by capture rates that depend on neutrino / anti-neutrino energies

$$\nu_e + n \to p + e \qquad \bar{\nu}_e + p \to n + e^+$$
$$\Delta E = \langle E(\bar{\nu}_e) \rangle - \langle E(\nu_e) \rangle$$
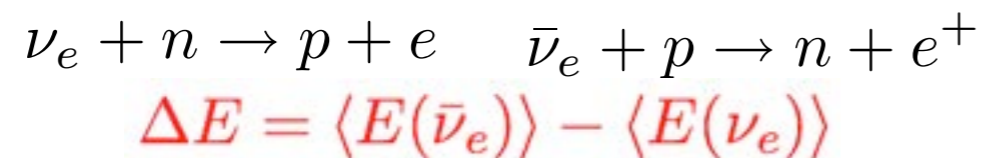
- Measure ΔE, difference in average energy for antineutrinos and neutrinos. If ΔE is large, wind will be neutron rich. If ΔE is small, wind will be proton rich and likely a problem for r-process. Hint of problem from SN1987a -- PRD**65** (2002) 083005

- SN was "best site" but simulations find too few neutrons because Y_p too high.

Searching for El Dorado
with supernova neutrinos

SN wind as r-proc. site

- **Advantages:** SN happen early and often in history of galaxy. Amount of material ejected by wind easy to reconcile with amount of r-process material needed. Entropy in wind relatively high (might like it to be somewhat higher).

- **Disadvantages:** Not enough neutrons. n/p ratio depends on simple neutrino physics and appears to be robustly low. Abundance pattern is not robust and depends sensitively on # of n.

- Observations of neutrinos from next galactic supernova including ΔE may either confirm the n/p ratio problem or discover some new ingredient which provides the neutrons.

Neutron Star Mergers

- Consider a binary system of two massive stars. Both stars end their lives as SN and producing two orbiting NS.

- Gravitational radiation slowly shrinks the orbit and the two NS will spiral together.

- Eventually the two NS will merge. Magnetic fields during the merger probably produce jets and a short gamma ray burst.

- Note gamma ray bursts longer than about 2 seconds are the most common and are though to arise from "collapsars". Rapidly rotating very massive stars that collapse to form a black hole and jets.

- NS mergers also produce a strong gravitational wave signal.
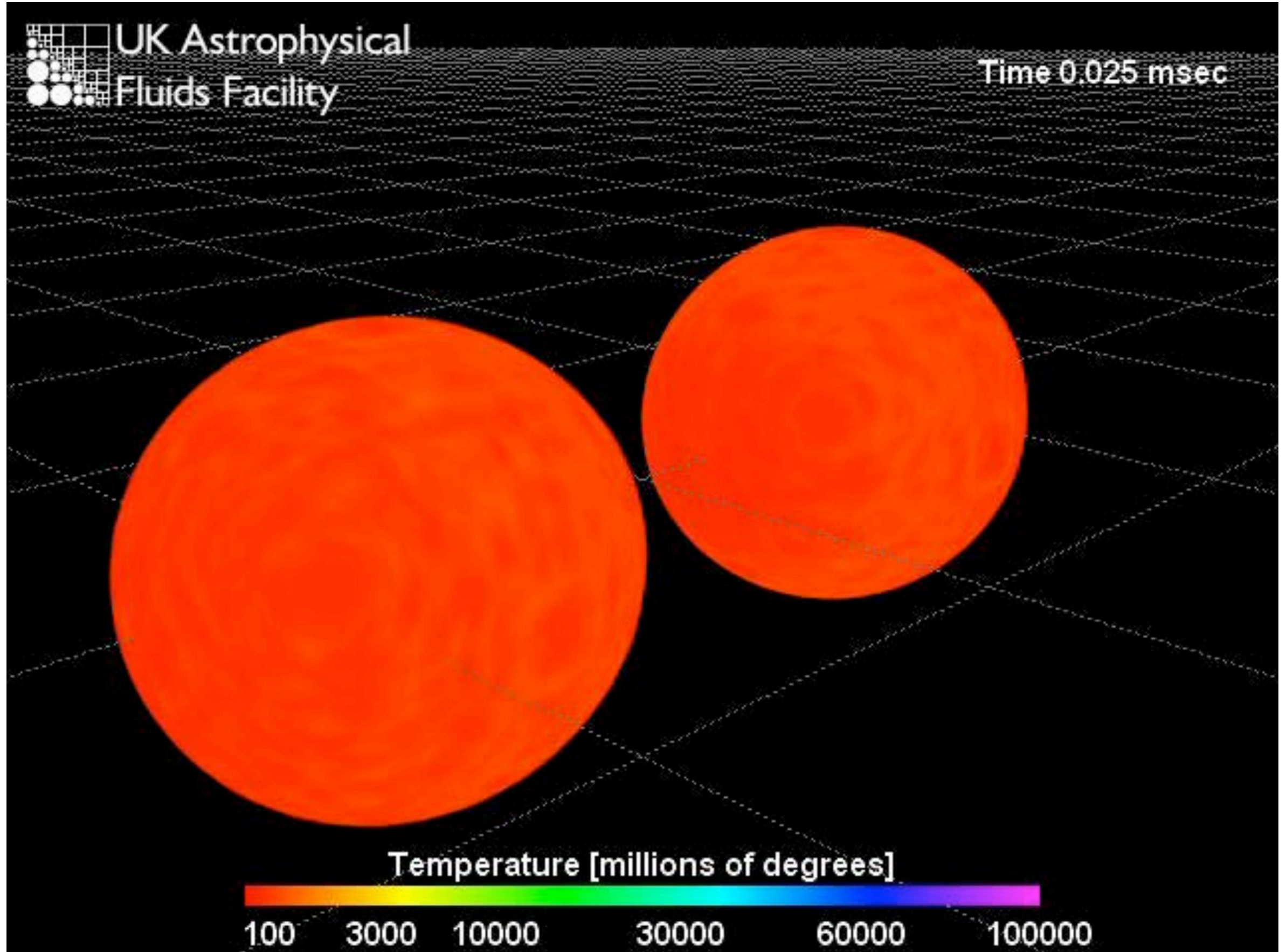
Swift

NS as source of neutrons?

- NS are robustly neutron rich (hence the name). High density squeezed electrons into protons to make neutrons.

- Can we use NS as a source of lots of n for the r-process?

- Problem: how to get n out? Escape velocity from a NS is significant fraction of speed of light. Furthermore need to get them out before they beta decay.

- Solution: tidal excitation during NS mergers.

Antenna Galaxy

- Tidal excitation during merger of two galaxies has ejected very long streams of gas and stars.

UK Astrophysical Fluids Facility

Time 0.025 msec

Temperature [millions of degrees]

100   3000   10000   30000   60000   100000

- Simulation by Stephan Rosswog, University of Leicester. Visualisation by Richard West, UKAFF.

r-process in mergers

- Simulations find ejected very n rich material that can form robust r-process.

- Abundance pattern may be insensitive to initial conditions.

- Note their may be still some numerical issues associated with difficulty resolving very low density matter near NS surfaces. What really is temperature history of ejected material?

- Mergers are rare so one needs more r-process material per merger than per SN.

r-process in mergers

- **Advantages:** plenty of neutrons. robust r-process producing abundances pattern that may be robust w.r.t. initial conditions.

- **Disadvantages:** mergers are rare (statistical fluctuations in amount of r-process material in old stars may be larger than observed?) and there may be a delay for NS to spiral together. Hard to explain r-process material in very Fe poor (old) stars?

- Perhaps galaxy built from mergers of globular clusters / dwarf galaxies that mixed material and reduced abundance fluctuations.?? Perhaps very Fe poor stars are not as old as we think??

- Gravitational wave observations will very soon tell us merger rates and merger populations. Radioactive decay of r-process material may power observable "mini supernova".

Gravitational waves and neutron rich matter

- We anticipate the historic detection of gravitational waves (osc. of space-time) in ~ 2016 with operation of Advanced LIGO.

- Gravitational waves provide info on n rich matter:
  - Neutron star mergers --> Eq. of state.
  - Collective r-mode osc of rotating NS --> dissipation from shear and bulk viscosity.
  - Mountains on rotating NS depend on shear modulus/ breaking strain of NS crust.

- First detection likely from NS mergers. Advanced LIGO has ~10 times sensitivity of LIGO, sensitive to 1000 times volume. Rate very likely more than few/Yr.
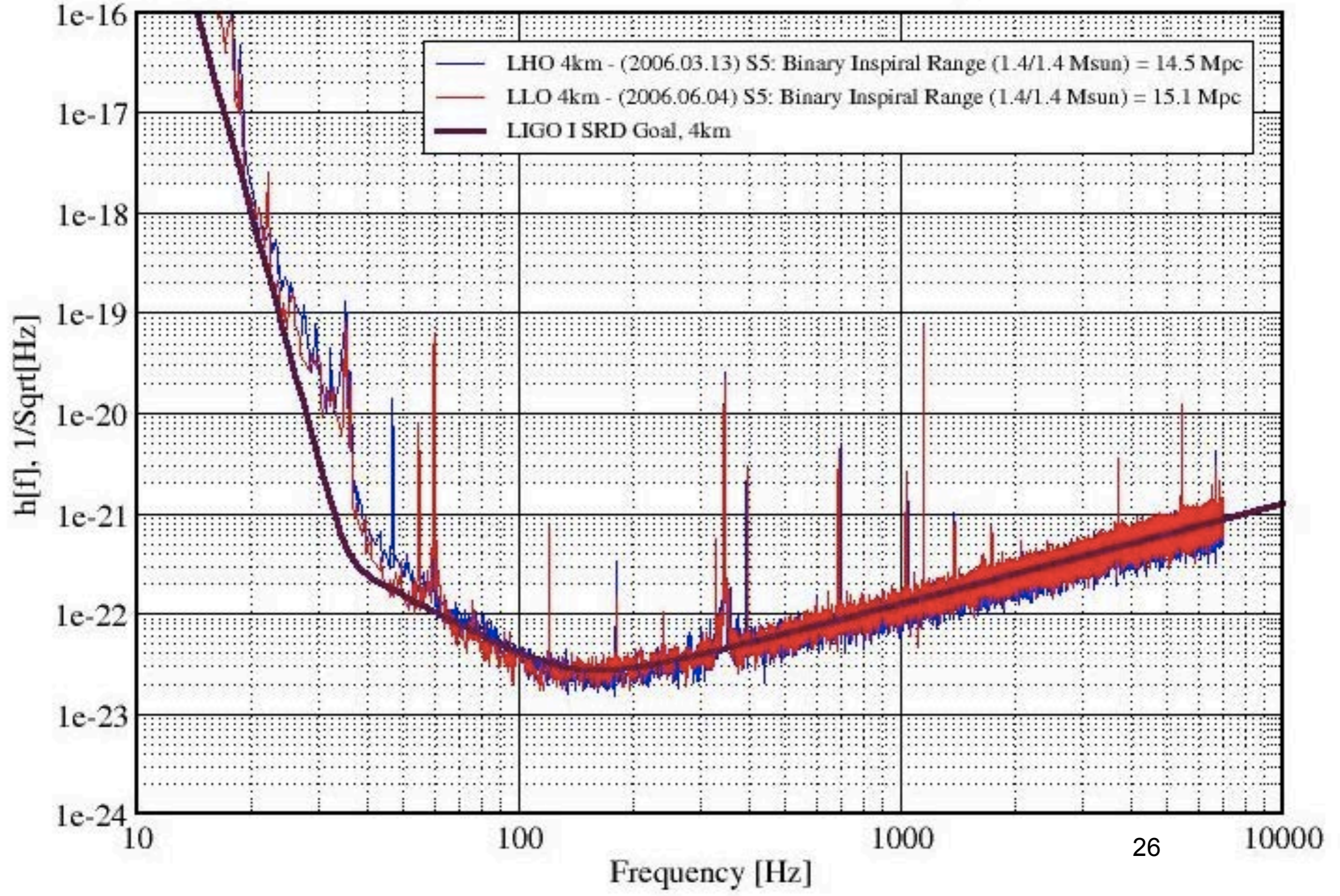

LIGO
Hanford

+ and x polarizations of GW

+ polarization

Time

0   T/4   T/2   3T/4   T

x polarization
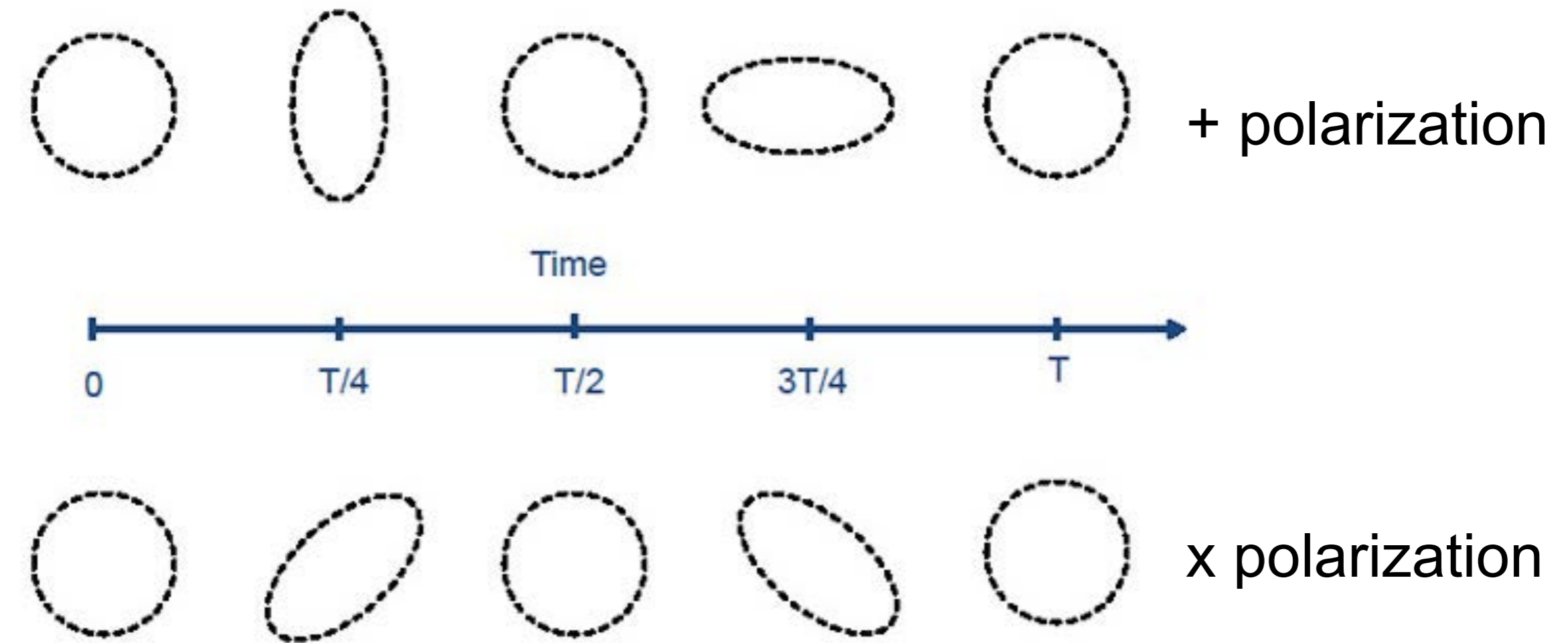
- Passage of GW distorts distances between circle of test bodies.

25

Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006   LIGO-G060293-00-Z

Legend:
- LHO 4km - (2006.03.13) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
- LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
- LIGO I SRD Goal, 4km

y-axis: h[f], 1/Sqrt[Hz]
x-axis: Frequency [Hz]

26

Noise sources


This graph courtesy of LIGO.
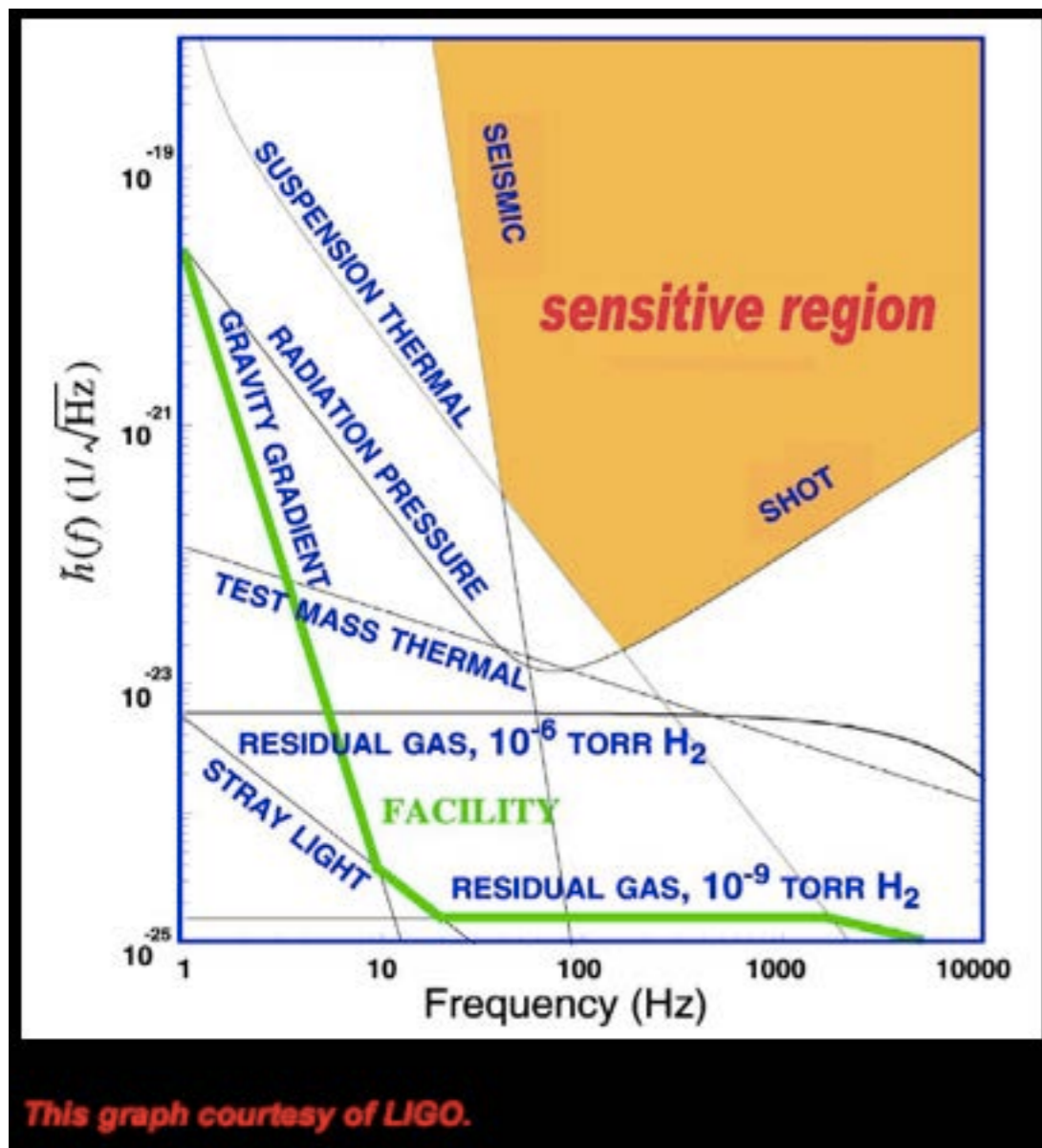
- seismic noise
  - mechanical vibrations carried through the earth
  - transmitted into interferometer via infrastructure
  - caused by plate tectonics, ocean tides, logging, cars, ...
- thermal noise
  - molecular motion associated with non-zero temperature
  - most problematic in the suspension system.
- photon shot noise
  - statistical fluctuations in number of photons measuring mirror position
  - can be reduced by increasing laser power

Advanced LIGO: Improve seismic isolation, improve suspensions, and increase laser power. Improves sensitivity by factor of ~10. See merger out to 150 instead of 15 Mpc.
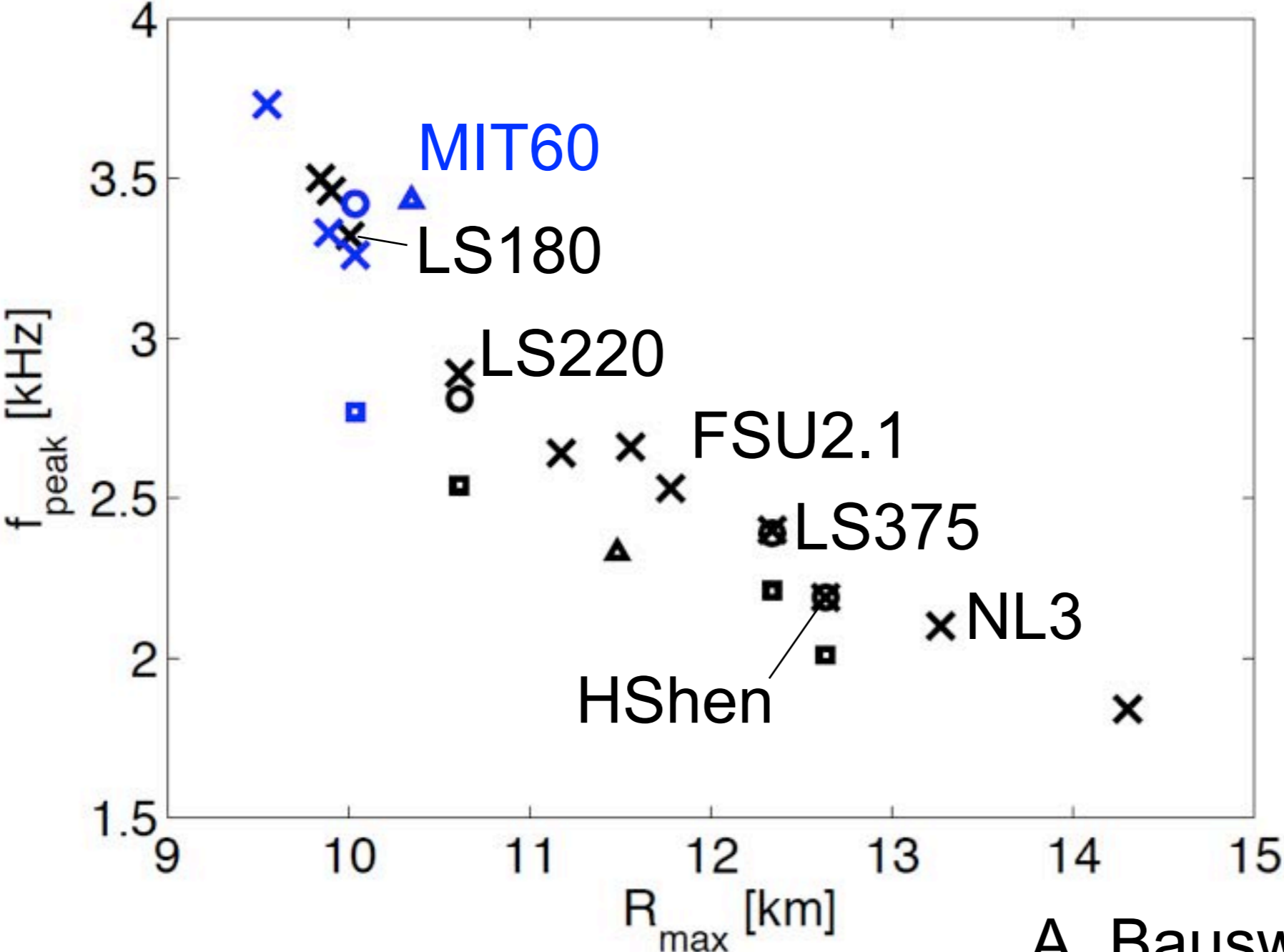
Wave form for merging NS

Chirp audio simulation from Ben Owen
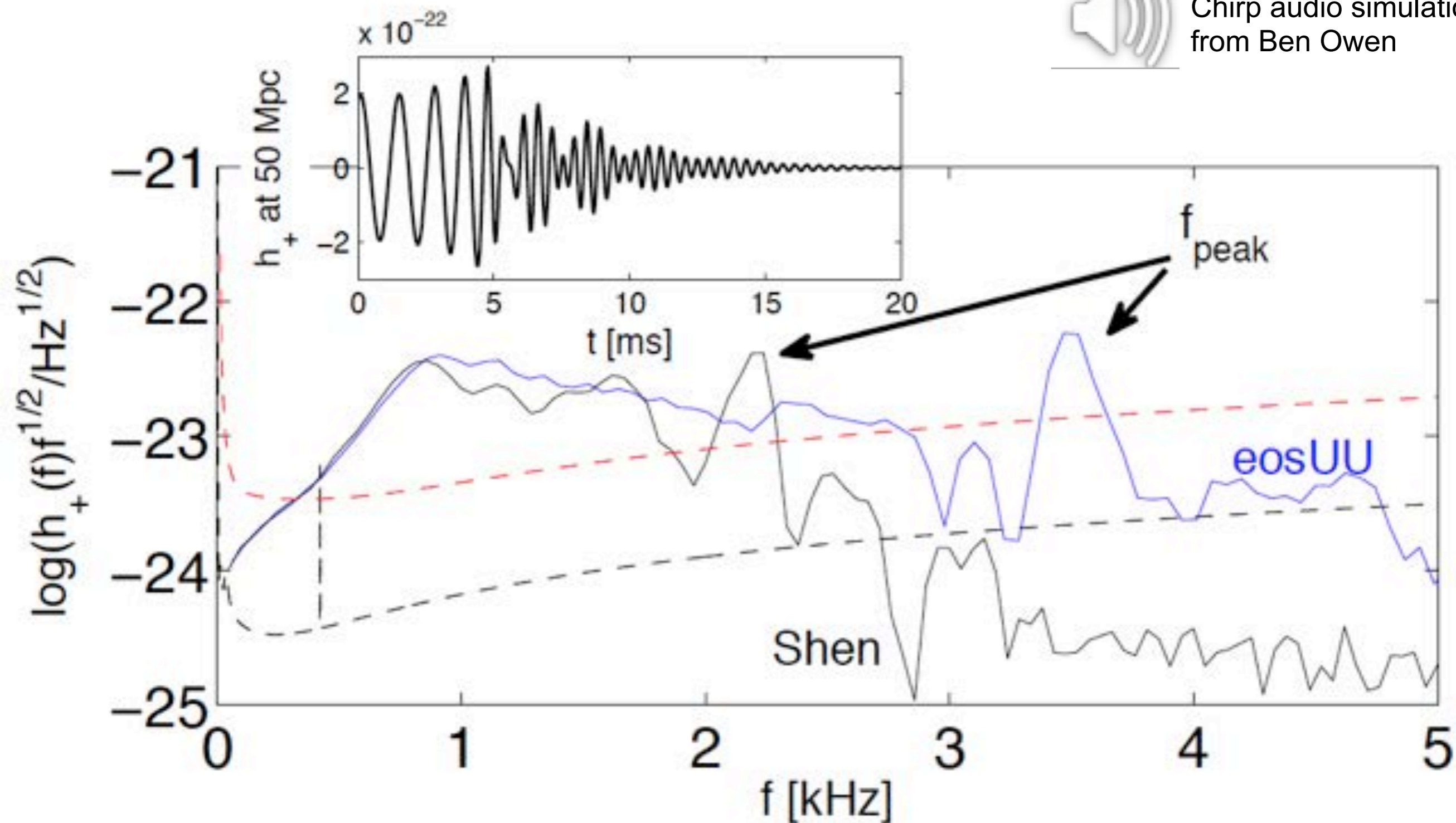
Gravitational Waves from NS mergers and EOS

Merger of two 1.35 M$_{sun}$ NS

Frequency of peak GW signal correlated with radius of max. mass star.

A. Bauswein + H. T. Janka

Continuous Gravitational Wave Sources and Neutron Star Crust

- Consider a large mountain (red) on a rapidly rotating neutron star. Gravity from the mountain causes space-time to oscillate, radiating gravitational waves. Fundamental question: *how do you support the mountain?*

- Strong GW source (at LIGO, VIRGO frequencies) places extraordinary demands on neutron rich matter, *and stress matter to limit.*
  -- Put a mass on a stick and shake vigorously.
  -- May need both a large mass and a strong stick.
  -- Let me talk about the strong stick.

- General Relativity asks fundamental (astro-)material science questions! Not just how strong is this material but what is the strongest possible material.

Mountain involves large mass undergoing large accelerations. Source can't be much larger and still radiate at 10+ Hz.

Neutron Star Quadrupole Moments and Gravitational Waves

- "Mountain" on a rotating NS very efficiently radiate GW. Maximum size of mountain depends on strength of NS crust.

- We perform large scale MD simulations of the crust breaking including effects of defects, impurities, and grain boundaries...

- We find neutron star crust is strongest material known: *10^{10} times stronger than steel.* Can support few cm tall mountains!

- Ongoing and near future searches for weak continuous GW signals by coherently integrating for long times. This is very computationally intensive! Einstein@home uses thousands of volunteer computers.

- Our strong crust can support ellipticities $\epsilon = (I_1 - I_2)/I_3$ up to 10^{-5}, best observational upper limits now 10^{-7} so mountains are detectable!

CJH, Kai Kadau, Phys Rev Let. **102**,191102 (2009)
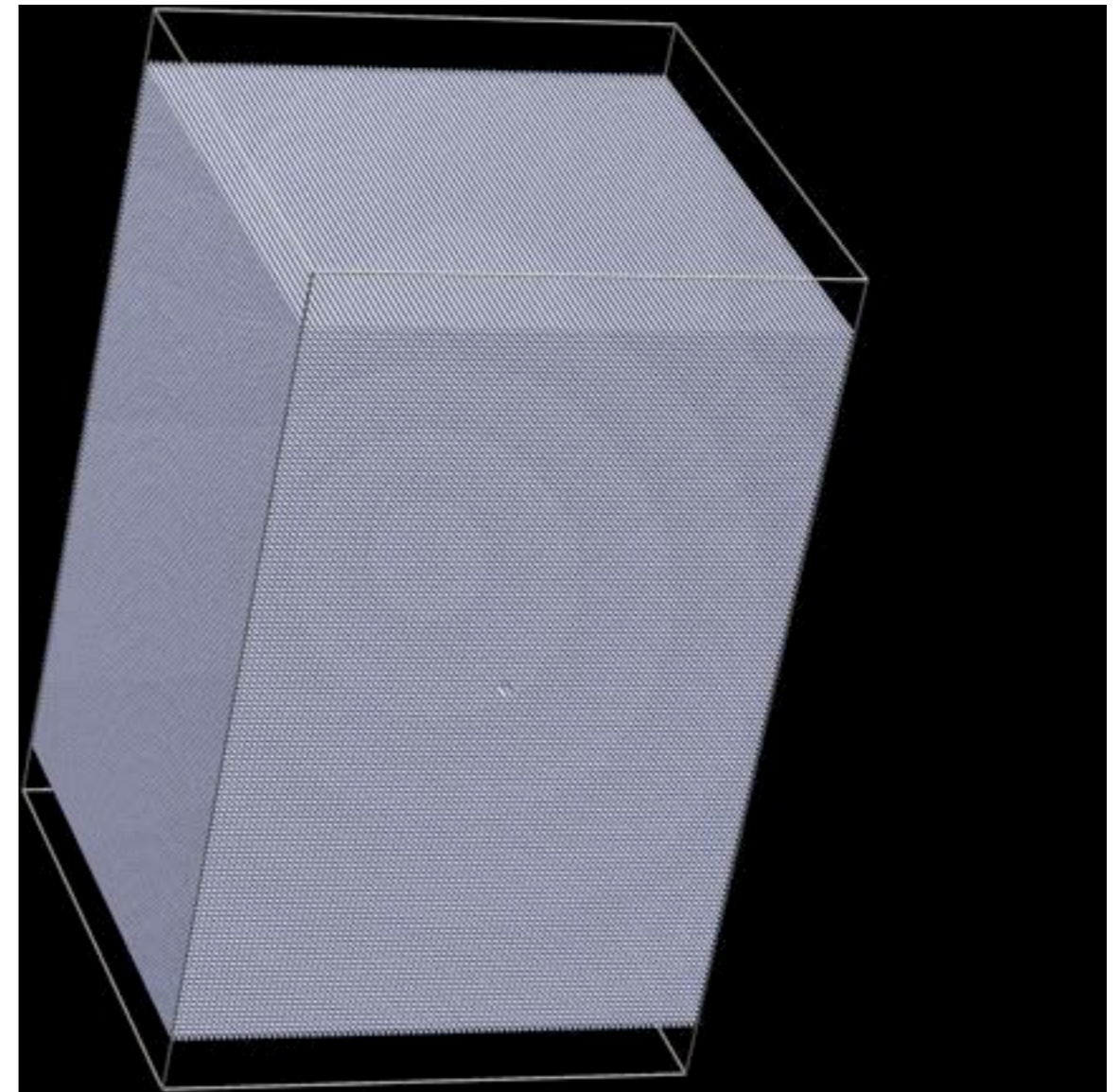
Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

Magnetars

--Bryan Gaensler

- **Soft Gamma Repeaters (SGRs)**
  and Anomalous X-ray Pulsars (AXPs)

  - occasional X-ray/γ-ray bursts
  - very rare giant γ-ray flares
  - slow X-ray periods ($P \sim$ 5–12 sec)
  - rapid spin-down, sudden changes in torque
  - low Galactic latitude, some in SNRs
  - not seen in radio, no companions

  $\rightarrow$ young neutron stars, but not
     ordinary pulsars, not accreting binaries

  $\Rightarrow$ *"magnetars",* isolated neutron stars
     with $B_{\text{surface}} \sim 10^{14}$–$10^{15}$ G

  (Duncan & Thompson 1992; Kouveliotou et al 1998)

- Rare objects: only ~12 magnetars known

  - active lifetimes ~10 kyr
  - ~10% of neutron star population?
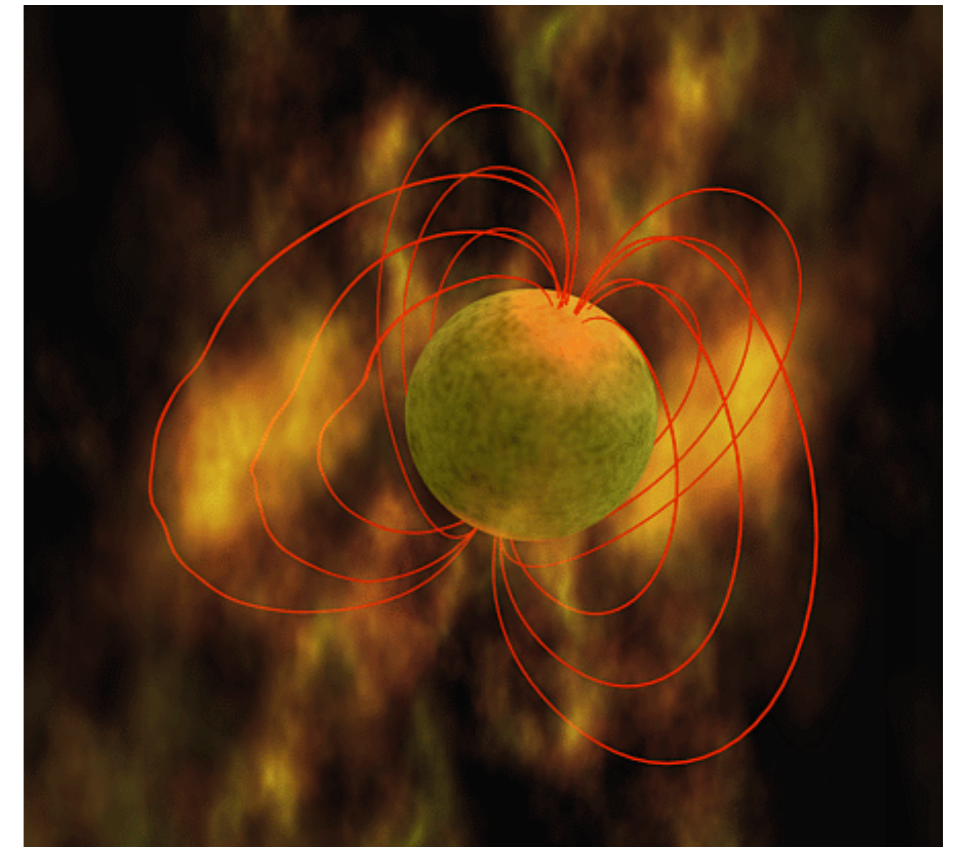
Robert S. Mallozzi, UAH / NASA MSFC
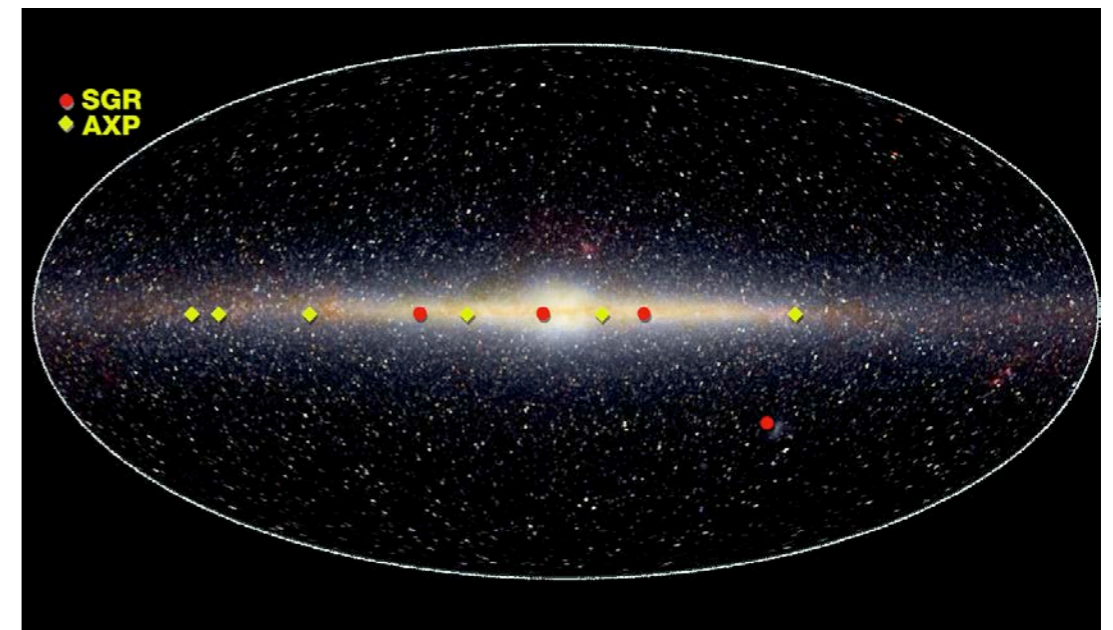

E. L. Wright (UCLA), COBE Project, Courtesy MSFC, NASA

The 2004 Giant Flare

- **27 Dec 2004 from SGR 1806-20**

  (Borkowski et al. 2004)

- 0.2 sec spike of γ-rays
  - $L_{peak} \sim 2 \times 10^{47}$ erg/s $\sim 1000 \times L_{MW}$
  - $E_{bol} \sim 4 \times 10^{46}$ erg $\quad \sim 300$ kyr $\times L_{\odot}$
  - fluence at Earth ~ 1 erg cm^{-2}
  - saturated all but particle detectors
  - created detectable disturbance
      in ionosphere (Campbell et al. 2005)
  - echo detected off Moon (Mazets et al. 2005)

- Fading 6-min tail with 7.6 sec pulsations
  (= known rotation period of star), similar
  intensity to tails in previous two giant flares

- Strength of spike reflects degree of reconnection;
 strength of tail indicates ability to trap particles

--Bryan Gaensler   33
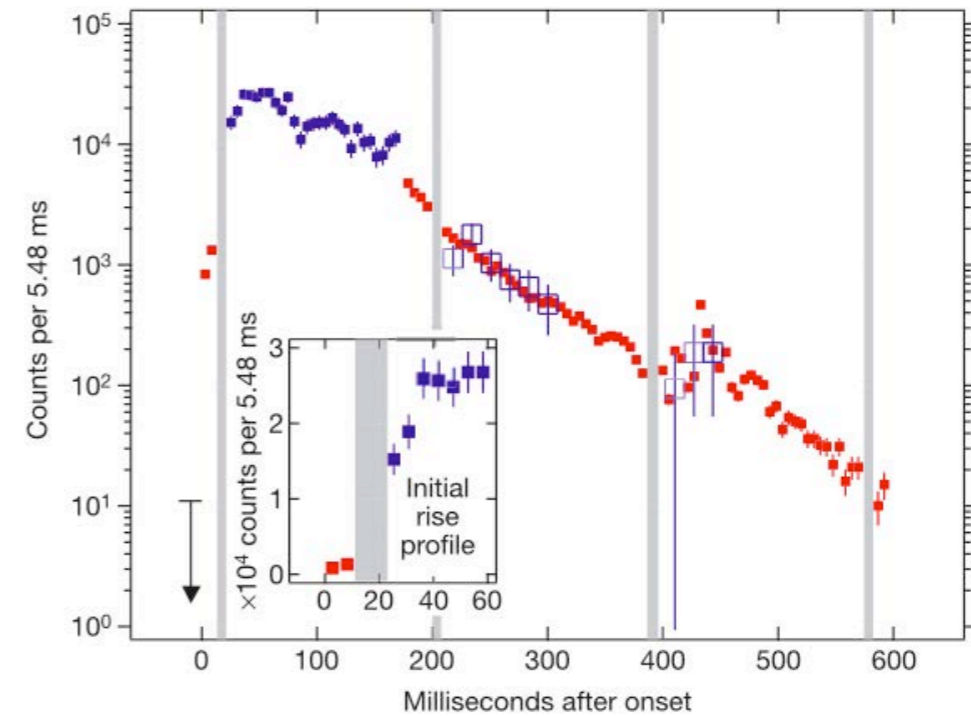
Terasawa et al. (2005)
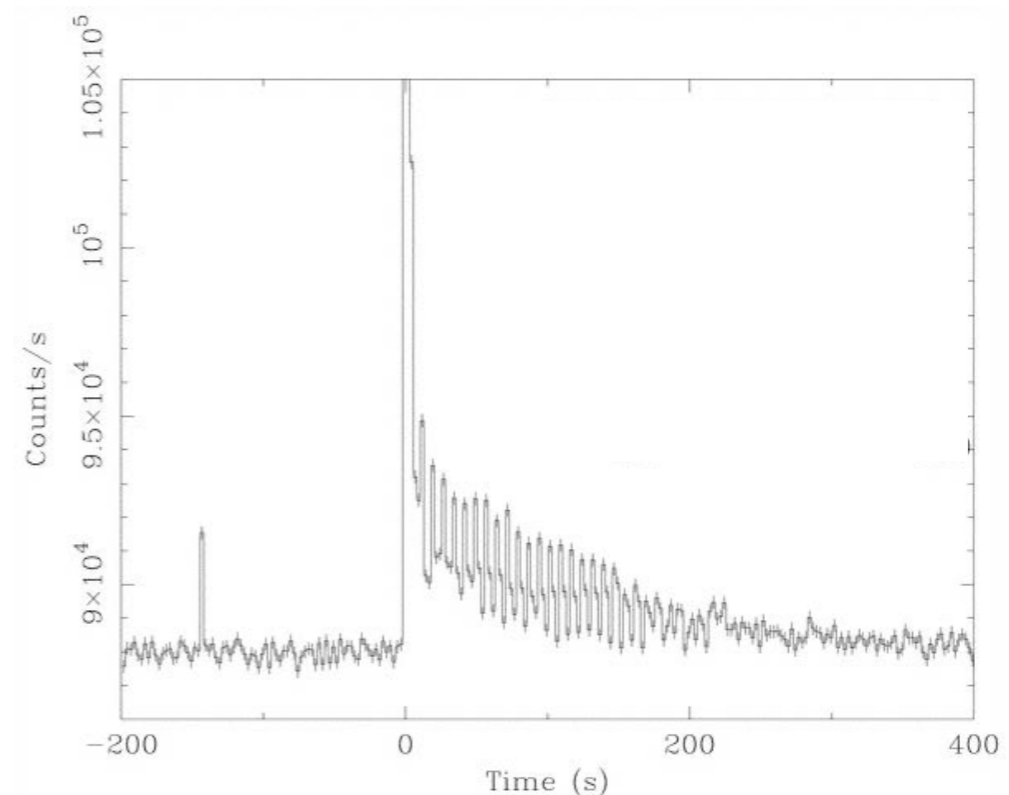
Meregetti et al. (2005)

# Curst Breaking Mechanism for Magnetar Giant Flares

- Twisted magnetic field diffuses and stresses crust. Crust breaks and moves allowing magnetic field to reconnect, releasing huge energy observed in giant flares.

- We find the crust is very strong and can control large energy in the magnetic field. Helps explain large10^{46} erg energy of 2004 flare from SGR1806.
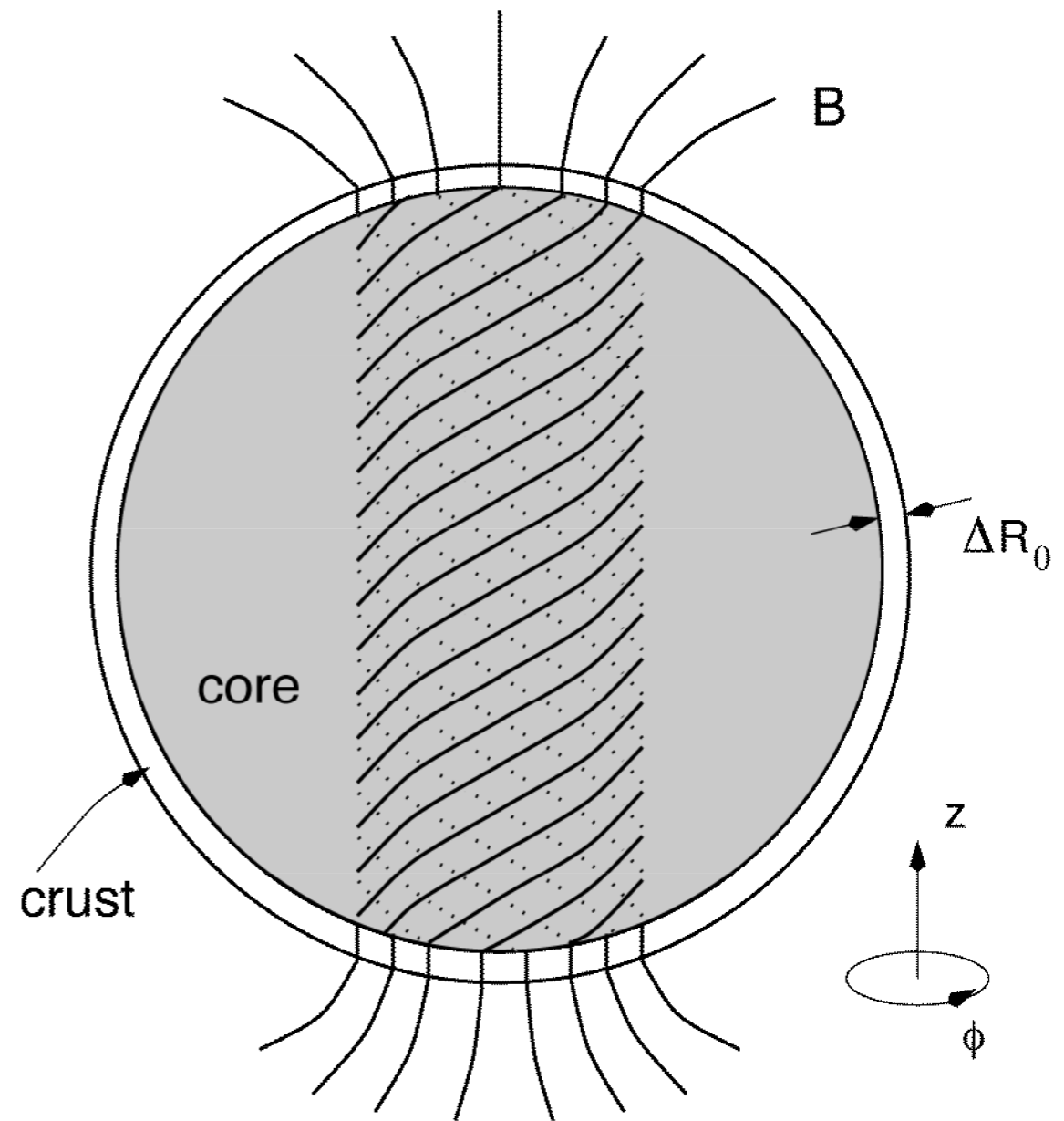
Thompson + Duncan

Rapidly rotating NS and r-modes

- r-modes: class of oscillation where restoring force is Coriolis force. May be unstable to GW radiation.

- GW radiation from r-modes potentially observable in LIGO.

- r-mode unstable if rate energy gained from GW radiation (tapping rotational E) greater than rate E lost from shear and bulk viscosities.

- Many calculations of **shear viscosity** of neutron rich matter, nuclear pasta (complex shapes), crust core boundary layer... and **bulk viscosity** of neutron rich matter, hyperons, quark matter,...

- *Dissipation from all of these sources does not appear to be enough.*
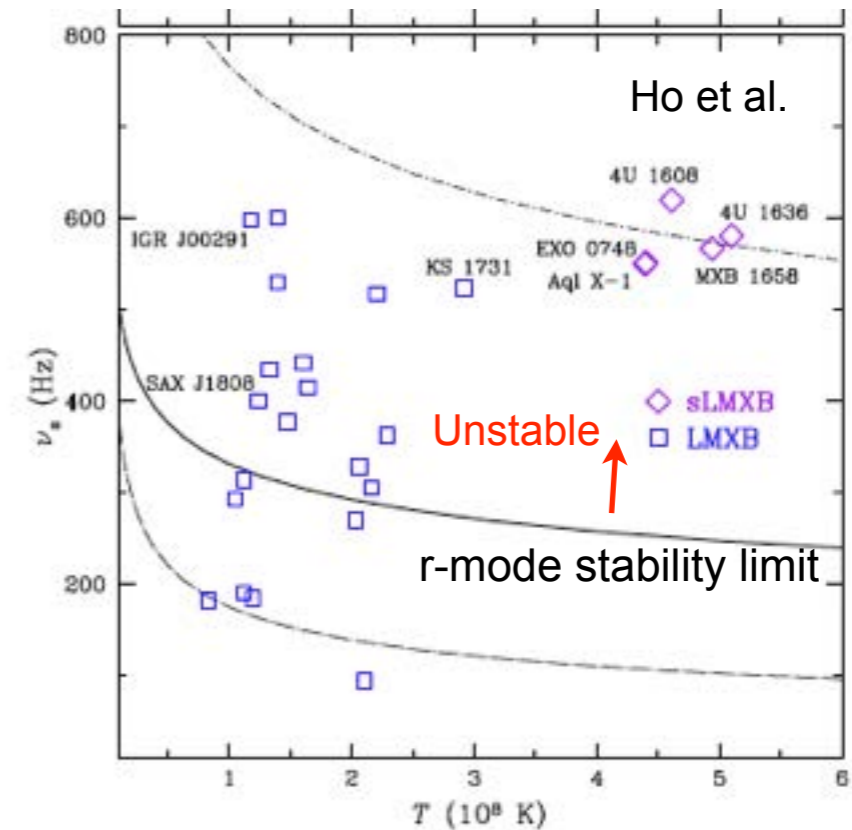
- **r-mode problem:** many observed NS are rotating so fast (above solid line) that they appear to be unstable to r-mode oscillations that would likely rapidly spin them down. --- Ho, Andersson, Haskell, PRL**107,** 101101(2011).

r-mode instability

- Consider a wave (green) moving counter-clockwise in stars frame, but clockwise in the lab frame.

- Gravitational wave back-reaction forces will act to slow the wave in the lab frame.

- This will actually increase the speed of the wave in the star's frame.

36
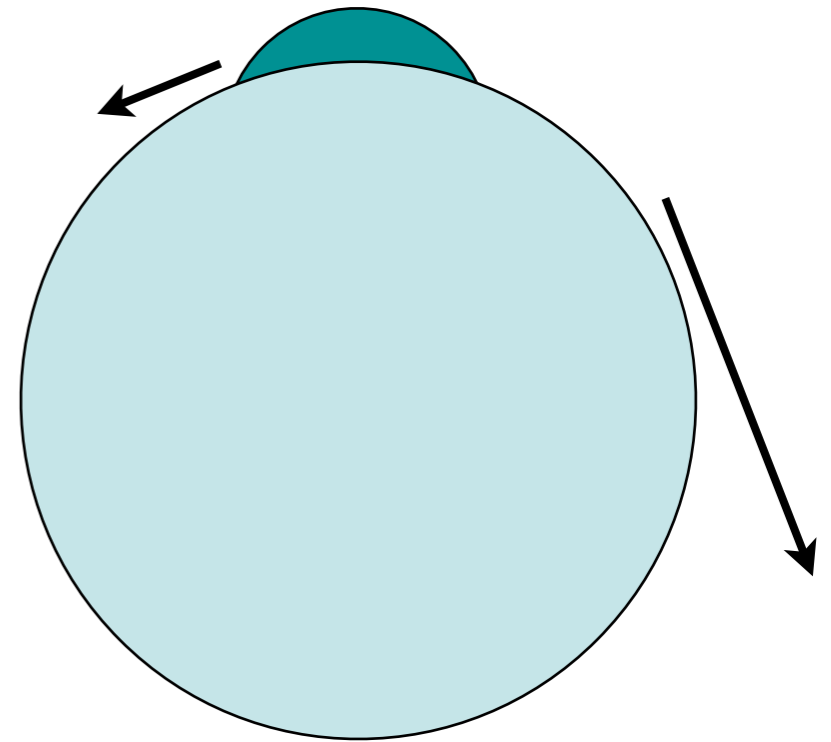
Dark matter in neutron stars

- If dark matter is weakly interacting massive particles (WIMPs) they will collect in neutron stars.

- Shear viscosity η_W of WIMP gas of density n_W is

$$\eta_W = \frac{1}{3}(3kTM_W)^{1/2}\lambda_W n_W$$

- WIMP-nucleon cross sections near present CDMS, XENON100 exp. limits may allow WIMP mean free path λ_W < size of star.

- η_W will exceed shear viscosity of conventional neutron rich matter if the number fraction of WIMPS to baryons $X_W = n_W/n_B > 10^{-10}$.

- *We speculate that WIMPs may enhance shear viscosity enough to solve r-mode problem.*

- Observations of NS spins may provide indirect information on dark matter.

  - Young NS with little dark matter unstable to r-modes can't spin fast

  - Old stars with more dark matter can spin fast. Indeed many old millisecond pulsars.

  - NS may be able to spin fastest in regions of galaxy with high dark matter density. Indeed fastest known NS near galactic center.

--- ArXiv:1205.3541

Einstein Telescope

- European proposal to follow up discovery of GW with next generation detector.

- Triangle 10 km on a side, underground to reduce noise.

- ~10 times sensitivity of Advanced LIGO.

- Very powerful astronomical observatory.

- Example see mergers 10 times farther again with 1000 times the rate.

Einstein Telescope
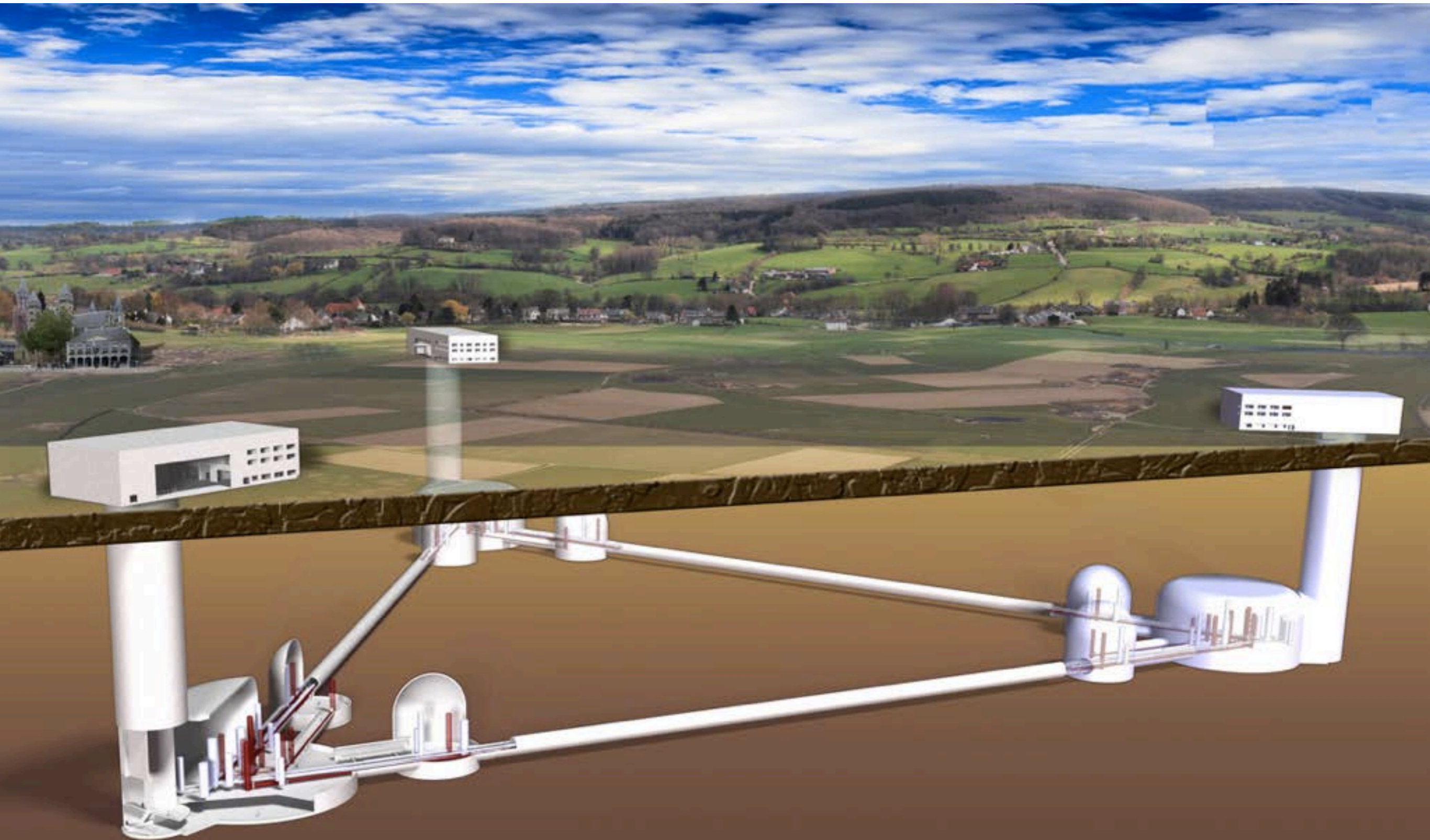
Multi-messenger Astronomy

- **Photons:** large scale radio searches will find many new pulsars. Observe NS thermal radiation and thermonuclear bursts in X-rays.

- **SN Neutrinos:** come from warm low density gas of neutron rich matter at the neutrino sphere. Carry unique flavor information related to nucleosynthesis.

- **Gravitational waves:** from mergers (sensitive to EOS), mountains (sensitive to shape of NS), collective modes (damping of neutron rich matter).

Conclusions

- **Multi-messenger astronomy**: Combine astronomical observations using photons, gravitational waves, and neutrinos to fundamentally advance our knowledge of the heavens.

- **Multi-messenger observations of neutron rich matter:** Combine astronomical observations using photos, GW, and neutrinos, *with laboratory experiments on nuclei, heavy ion collisions, radioactive beams...* to fundamentally advance our knowledge of the heavens, the dense phases of QCD, the origin of the elements, and of neutron rich matter.