Introduction to Supernovae for Heavy Ion Physicists

C. J. Horowitz, Indiana University

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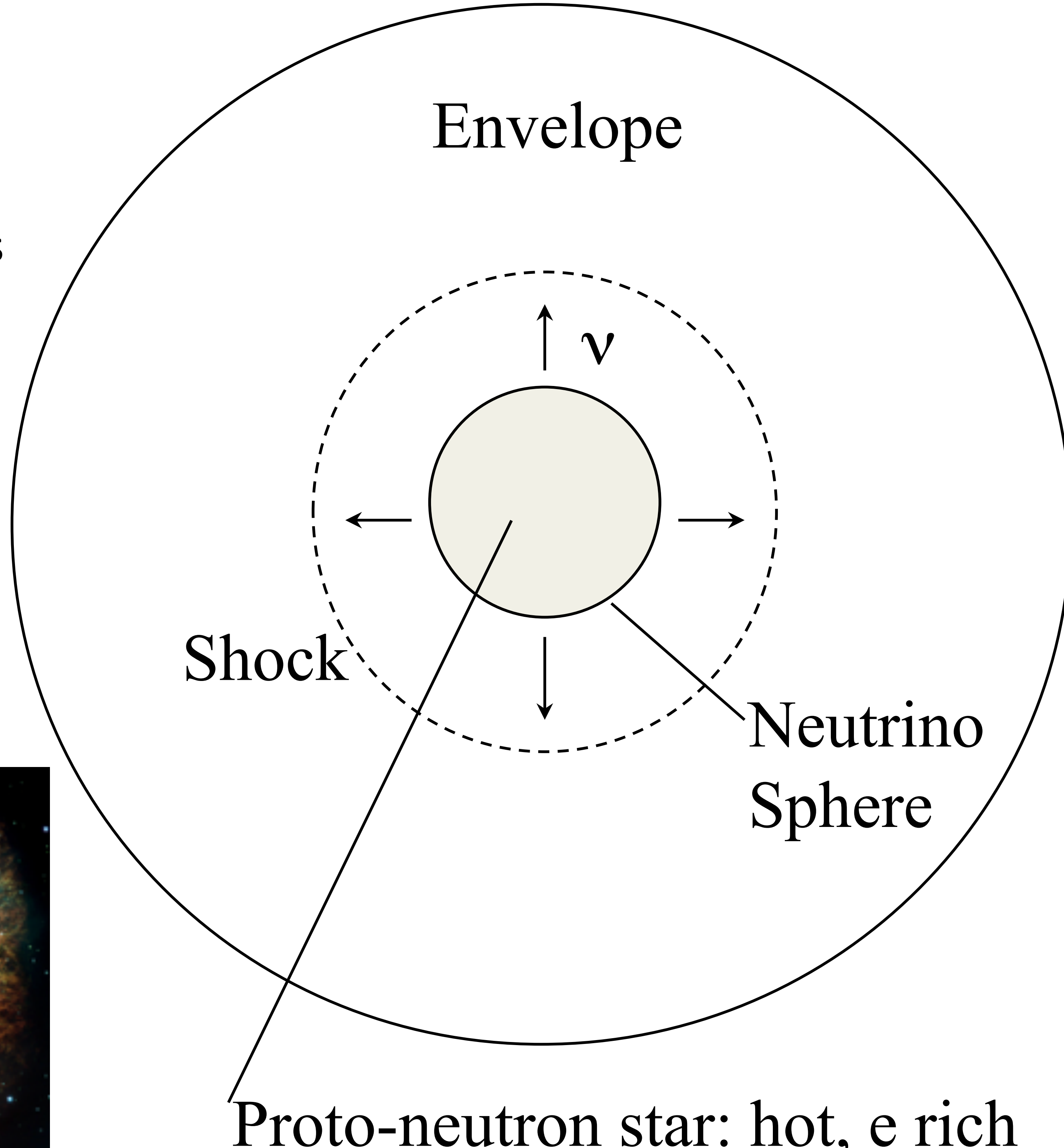
SN1987a

NS Born in Core Collapse Supernovae

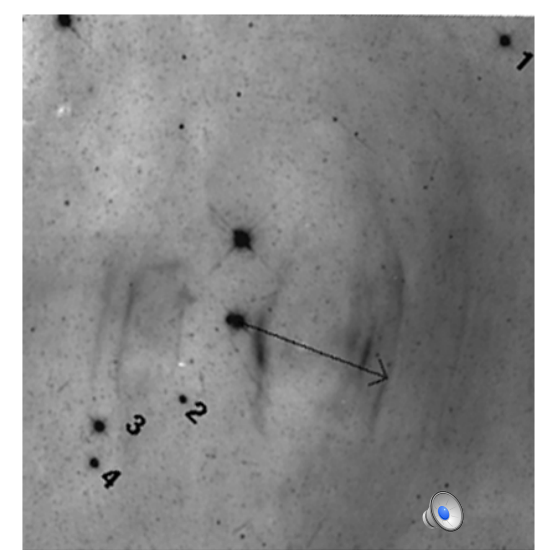
Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.



July 5, 1054

Crab nebula

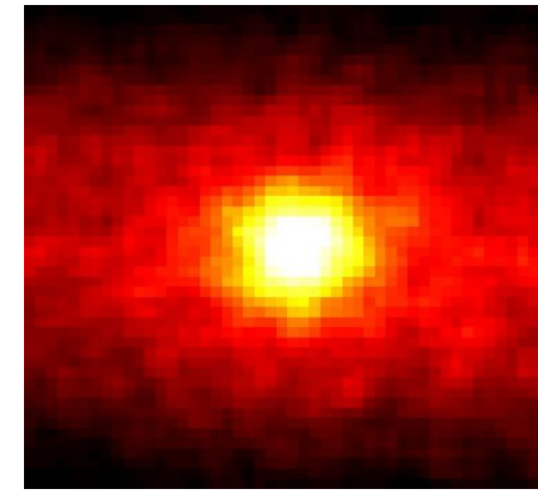
Crab Pulsar



Hubble ST

Audio: Jordal Bank

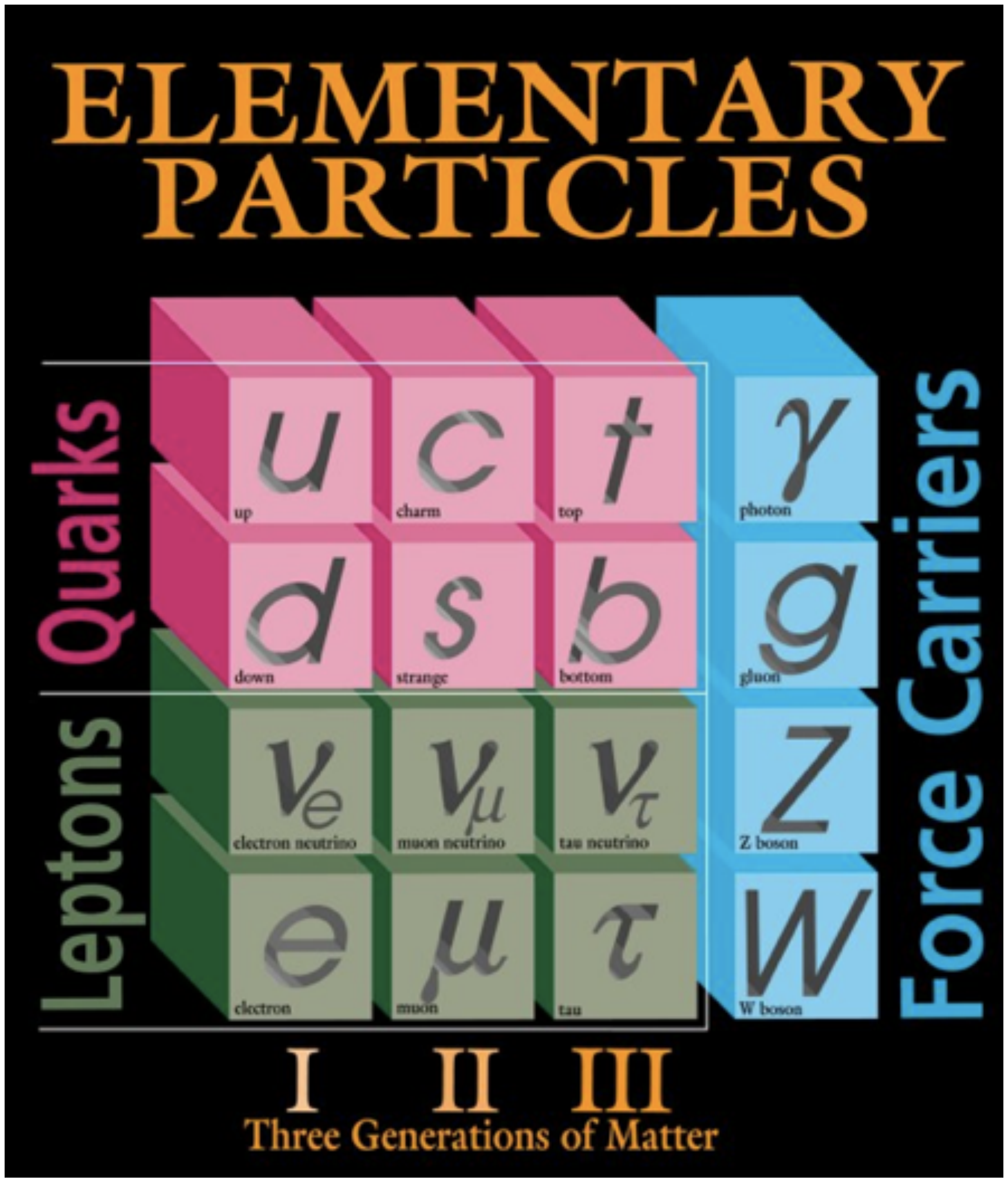
Astrophysical Neutrinos



Sun in neutrinos

- Core collapse supernova radiates gravitational binding energy of a neutron star ~ 0.2 $M_{sun}c^2$! in 10^{58} neutrinos of about 10 MeV each.
- ν_e, $\bar{\nu}_e$, along with mu and tau ν and $\bar{\nu}$ all radiated.
- Historic first detection of ~20 **supernova neutrinos** from SN1987A (acceptance x efficiency = 10^{-57}).
- New underground dark matter, solar nu,... experiments will be sensitive to nu from the next galactic supernova (SN).
- Expect ten thousand or more events from next galactic SN!
- SN radiates 10^{53} ergs in neutrinos, 10^{51} ergs in ejecta kinetic energy and much less in E+M radiation.
- Delayed nu mechanism where nu heating re-energizes stalled shock after 100s of msec. Need to tap 1% of nu energy.
- SN dynamics depends on EOS + nu interactions at LOW density!

Neutrino messengers



- All three flavors of neutrinos and their antineutrinos (electron, mu, tau) are radiated in core collapse supernovae.
- **Neutrinos cary unique flavor information all the way to earth.**
- Nu capture on n to make p, anti-nu convert p to n. Flavor info related to composition of SN matter and nucleosynthesis.
- Note, neutrinos are somewhat forgetful messengers because of oscillations.

SN neutrinos and r-process nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Seed nuclei captures many n and decay. **What makes all the neutrons?**
- **Neutrinos:** Important possible site for the r-process is the neutrino driven wind in core collapse supernovae.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino / anti-neutrino energies.

$$\nu_e + n \to p + e \quad \bar{\nu}_e + p \to n + e^+$$

$$\Delta E = \langle E(\bar{\nu}_e) \rangle - \langle E(\nu_e) \rangle$$

- 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.

Searching for El Dorado with supernova neutrinos

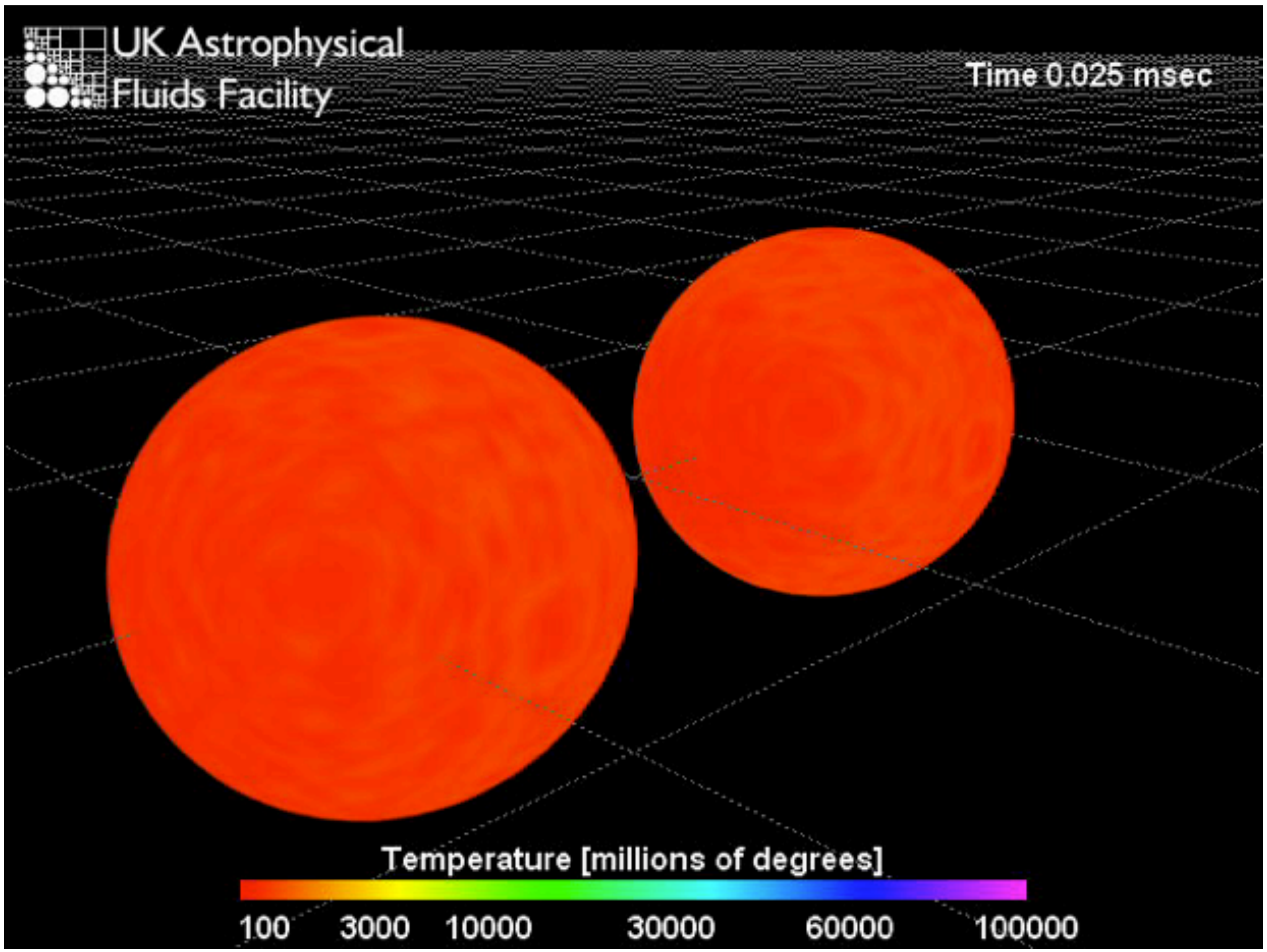
Important to measure energy of both anti-nu (SK) and neutrinos (liquid argon ELBNF, old LBNE).

ΔE depends on some nuclear physics including symmetry E at low densities.

However, present SN simulations find too few neutrons.

Neutron Star Mergers

Gravity: can make neutrons by compressing neutron star matter leading to electron capture. Tidal disruption during neutron star mergers can then eject neuron rich matter for alternative r-process site.



Simulations find very neutron rich matter ejected that undergoes successful r-process, so neutron rich it can fission cycle.

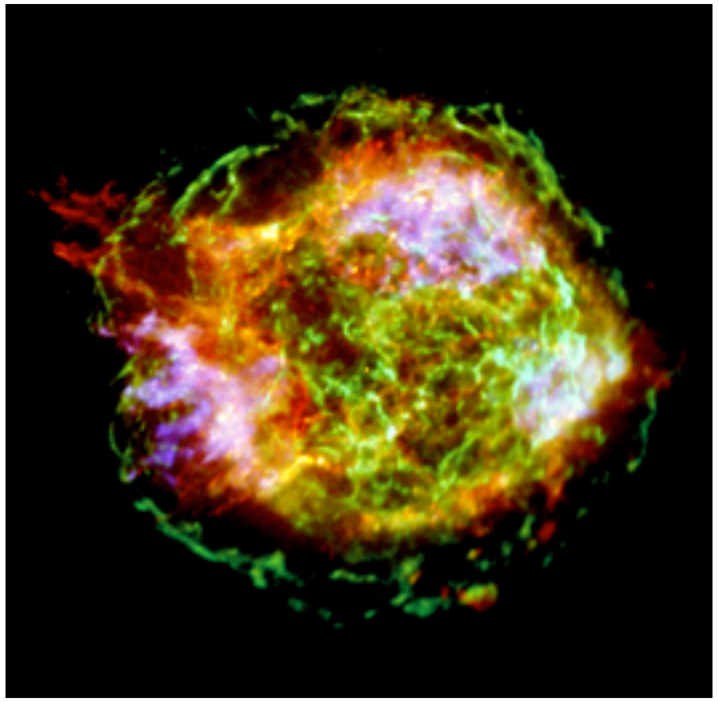
r-process yield is merger rate x amount ejected per merger.

LIGO/VIRGO soon observe rate with gravitational waves.

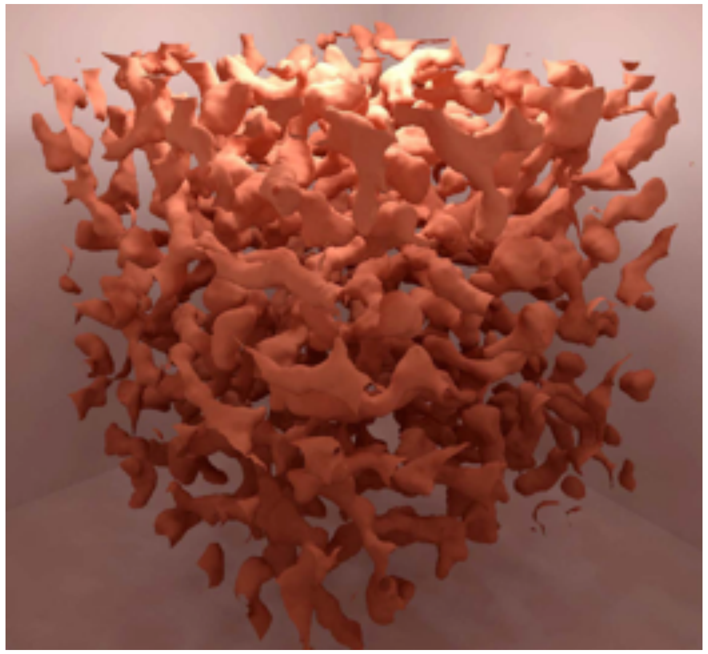
Simulation by Stephan Rosswog, University of Leicester. Visualisation by Richard West, UKAFF.

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

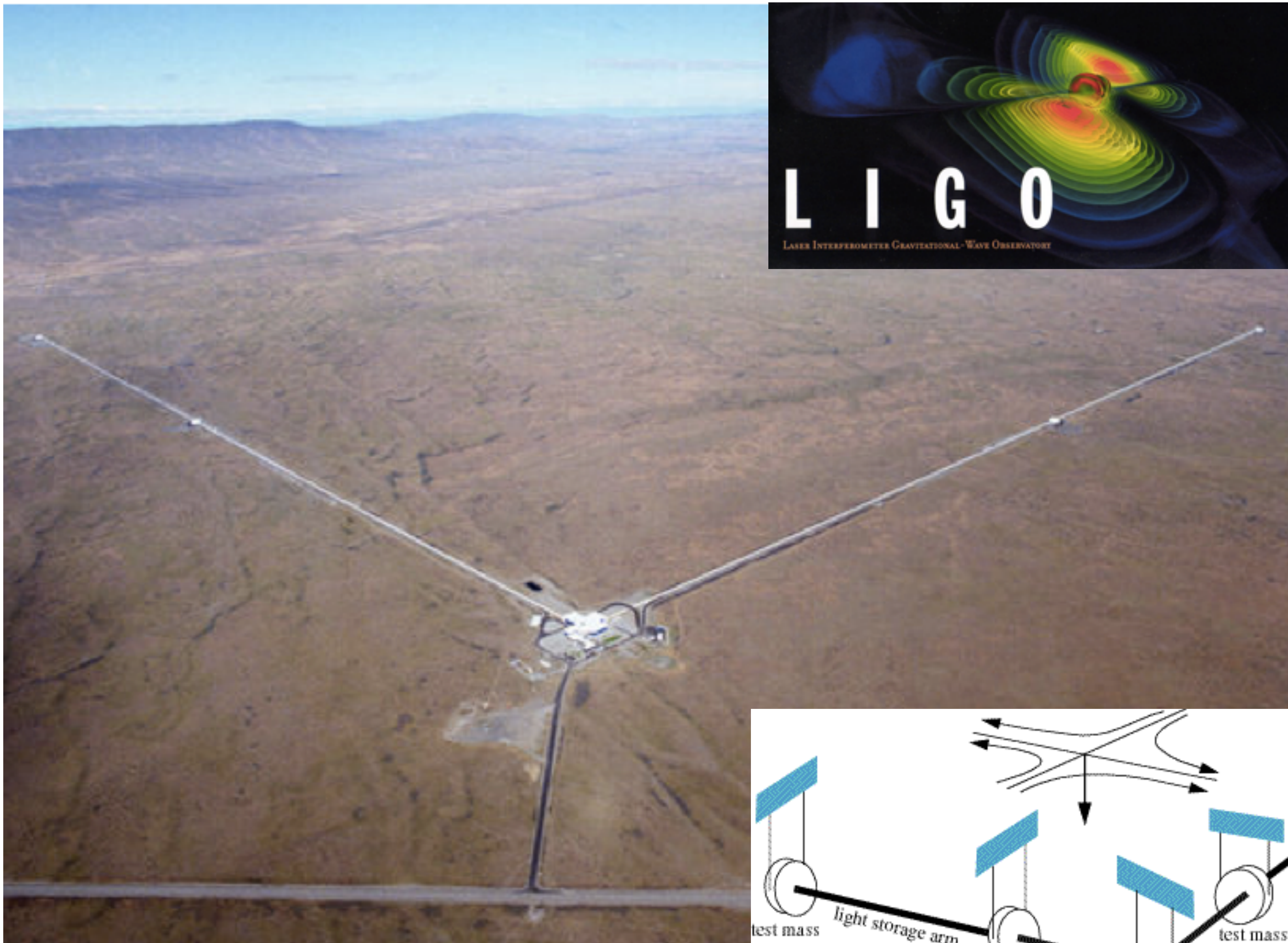


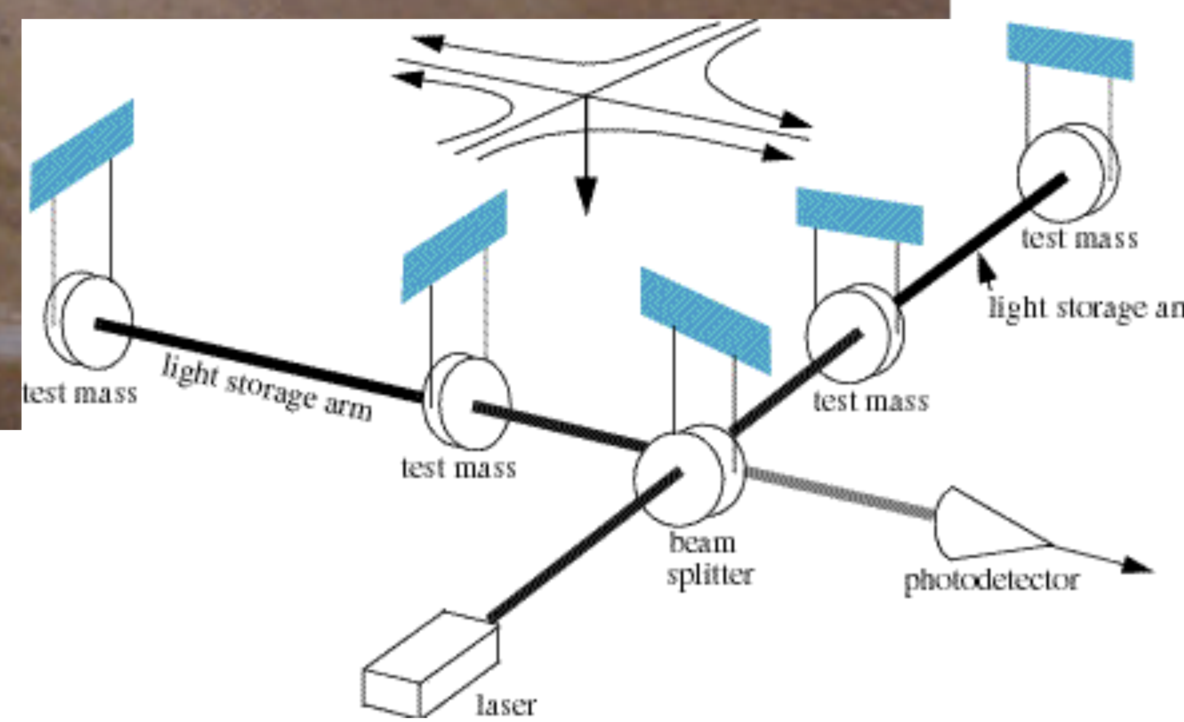
MD simulation of Nuclear Pasta with 100,000 nucleons

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* neutron star crust, supernova ***neutrinos*** from low density *gas*, and ***gravitational waves*** from energetic motions of *liquid* interior of neutron stars.
- **Laboratory:** Nuclei are liquid drops so most experiments probe liquid n rich matter. However one can also study vapor phase be evaporating nucleons.
  - Electroweak measurements, Heavy ion collisions, Radioactive beams of neutron rich nuclei...
- **Computational:** Important theoretical and computational advances aid in study of n rich matter.
  - Chiral effective field theory depends on important and poorly known *three neutron forces*.
  - Large scale computations: molecular dynamics, monte carlo, no core shell model, coupled cluster,

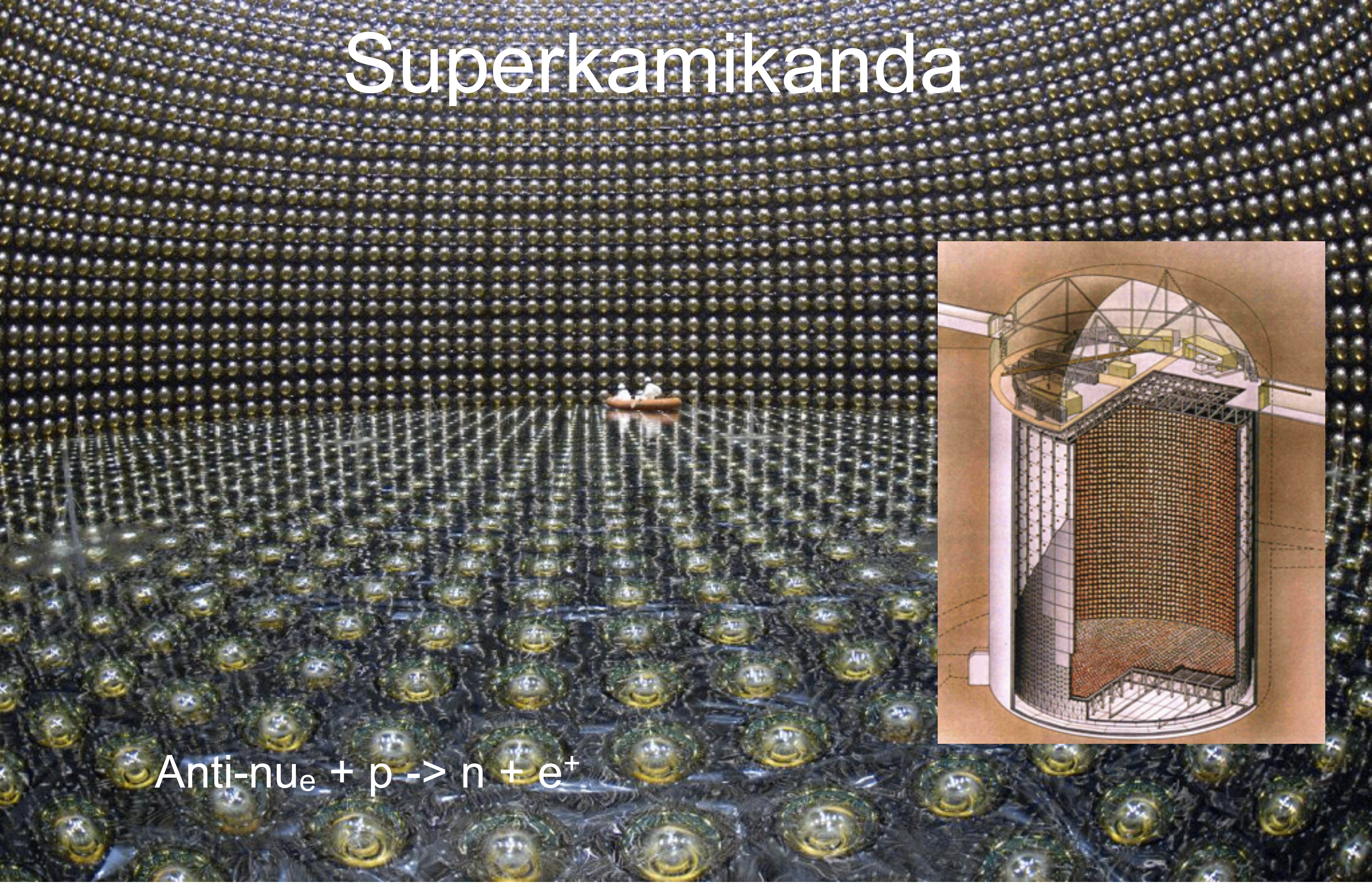
Review article: Multi-messenger observations of neutron rich matter, Int. J. Mod. Phys. E **20** (2011) 1.





Large scale gravitational wave detectors in Washington State, Louisiana, Italy (VIRGO) ...

Superkamikanda



Anti-ν_e + p -> n + e^+

- 32 kilotons of very clear water. Many large phototubes see light from e^+. Of order 10,000 events for galactic SN

ELBNF

~~Long Baseline Neutrino Experiment~~

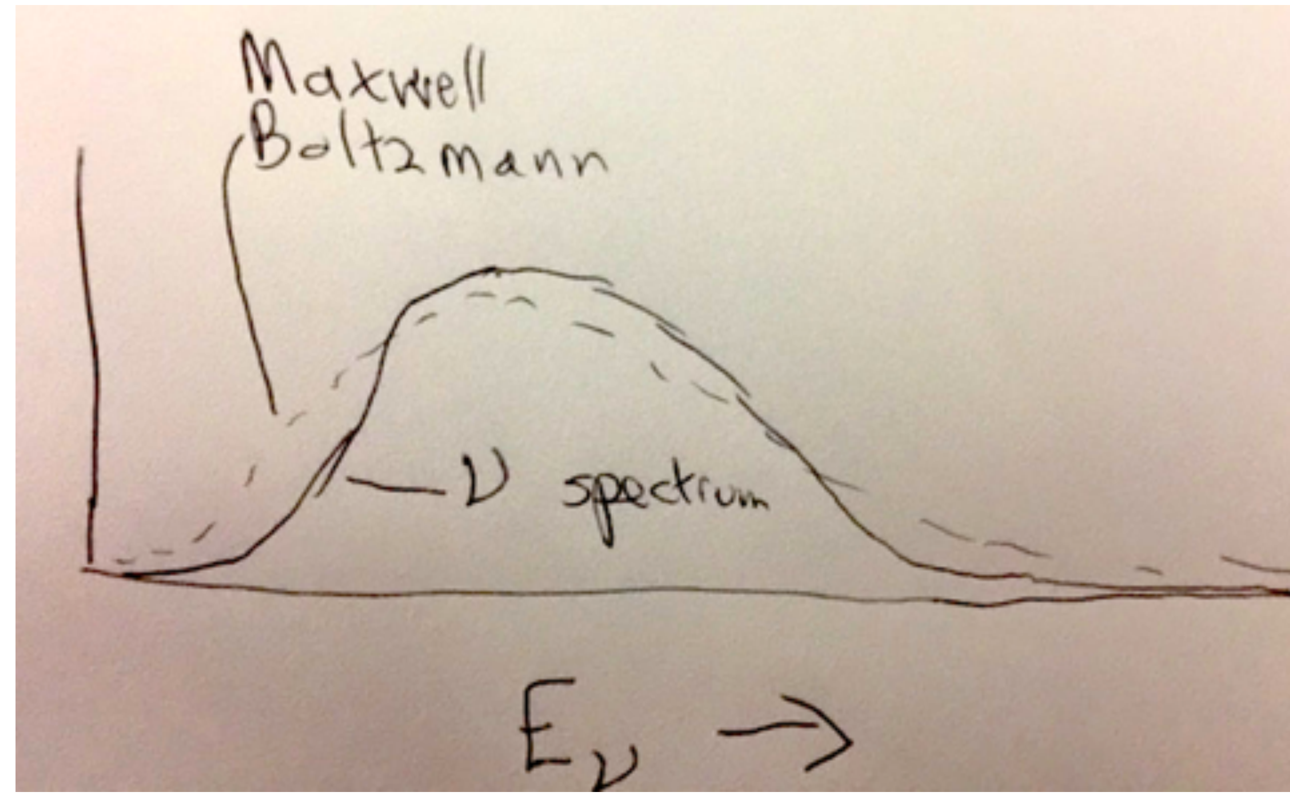
- Send neutrino and antineutrino beams from Fermilab (near Chicago) 1300 km to a large (34 kt) liquid Ar detector in the Homestake gold mine in South Dakota. Main goal: observe CP violation in neutrino oscillations.
- Powerful supernova detector that should be able to measure electron neutrino energies very well. $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
- Combine anti-nu E from Super K with nu E from LBNE to predict composition of neutrino driven wind and likely strongly disfavor r-process in wind.

Neutrino Spectra

- The stronger the neutrino interactions, the longer a neutrino stays in thermal equilibrium with matter to lower densities and temperatures, and the lower is the emitted neutrino energy.
- Mu and tau neutrinos have only neutral current reactions (not enough energy to make muons) and so decouple at highest energies.
- Electron antineutrinos capture on protons while neutrinos capture on neutrons. Matter is neutron rich so neutrinos have large opacity. Therefore electron neutrinos are emitted with lowest energy.
- Expect order E(mu, tau) > E(anti-nu_e) > E(nu_e).

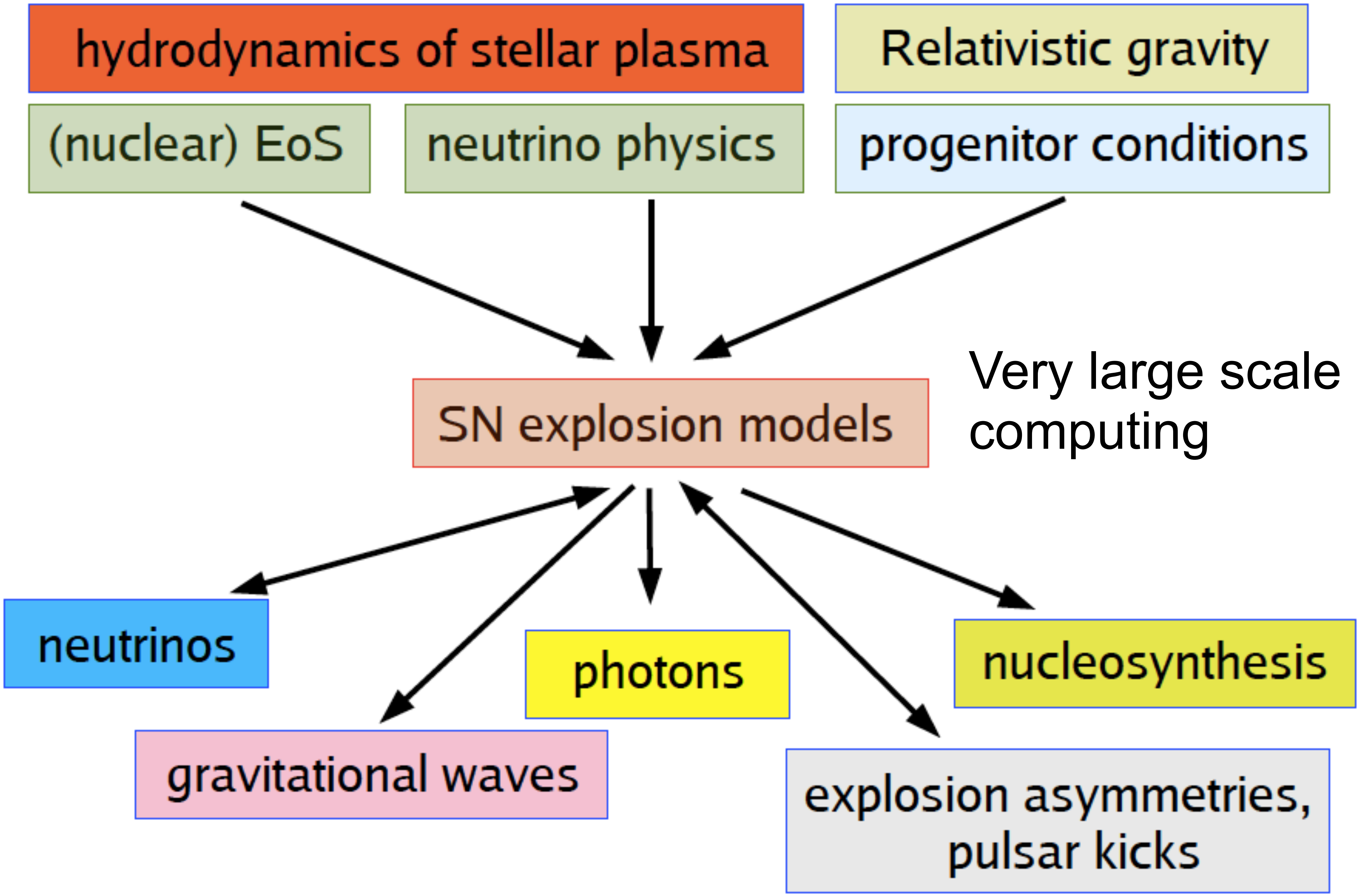
Particle Spectra

	SN nu	HIC
Thermal	Yes (~5 MeV)	Yes
Radial flow	No	Yes
Coulomb	No	Yes
Gravitational red shift	Yes ~15%	No
Pinched	Yes	No



* Pinched spectrum from large energy dependence of neutrino cross sections σ(E) that go as neutrino energy squared.
* High energy tail of Boltzmann spectrum stays in equilibrium longer to lower densities where matter is colder so high E tail of spectrum reduced in energy.
* Low E part of spectrum escapes from greater density where matter is hotter. Low E tail of spectrum increased in E.

Predictions of Signals from SN Core



NS properties mass, spin, magnetic field...

SN simulations status

- One dimensional simulations with realistic microphysics do not explode.
- Two dimensional simulations find convection helps. Many simulations explode with at least small energies, some with approx correct energy. Explosions are asymmetric.
- Three dimensional simulations with spectral (energy dependent) neutrino transport at limit of present computers. Some simulations find 3D less favorable to explosion than 2D. Unclear, at this time, how 3D explosions occur with correct energy. Better numerics may clarify.

“Femtonovae”

- Core collapse SN dominated by neutrinos. Much of the “action” occurs near the neutrinosphere (surface of last scattering) at temperatures of ~5 MeV, densities of 1/1000 to 1/10 ρ_0, and neutron rich compositions.
- A “Femtonova” is a very small new star. Suggested name for HI collisions applied to astrophysics, and in particular to recreate neutrinosphere conditons.
- Study in the laboratory the equation of state, symmetry energy, composition, and neutrino response … of neutrinosphere material.
  - Recreating ~5 MeV temperature is straight forward.
  - Recreating low densities occurs as system expands but it may be difficult to measure the density.
  - Recreating the very neutron rich conditions is harder. Perform HI collisions with proton rich and then neutron rich radioactive beams and extrapolate to very neutron rich conditions.

Chemical Freeze Out

- HI collisions create warm source regions that then expand with time.
- Nucleons in source regions interact to form light clusters D, ^{3}H, ^{3}He, ^{4}He.
- Source expands to such low densities that clusters stop interacting and the chemical composition freezes out.
- One can then measure this final composition which should correspond to the composition of equilibrium nuclear matter at the freeze out temperature and density.
- Several ways to measure freeze out temperatures (often near 5 MeV). For example looking at ratio of yields. $T_{HHe}=14.3/ \ln[1.59 (Y_D Y_{4He}/Y_{3H} Y_{3He})]$
- Measuring freeze out densities are more difficult. Example, can get source sizes from two-particle correlation functions.

Neutrinos and nuclear binding

- H_2O has bound neutrons and protons (in O) and free protons (but no free neutrons). Response dominated by antineutrino capture on free protons.
- Neutron rich neutrinosphere matter has “bound” protons (bound by symmetry energy) and free neutrons. Response dominated by neutrino capture on free neutrons.

Symmetry Energy shift

- Proton in n rich matter more bound than neutron because of symmetry energy.
- Symmetry energy at low density can be calculated exactly with virial expansion (with A. Schwenk). Find it is much larger than in some mean field models because of cluster formation.
- Neutrino absorption cross section increased by energy shift which increases energy and phase space of outgoing electron-> lowers E(nu).
- Consider $\boldsymbol{\nu}_e$ + n -> p + e

$$\Delta U = U_n - U_p = \lambda^3 T(n_n - n_p)(b_{pn} - \hat{b}_n)$$

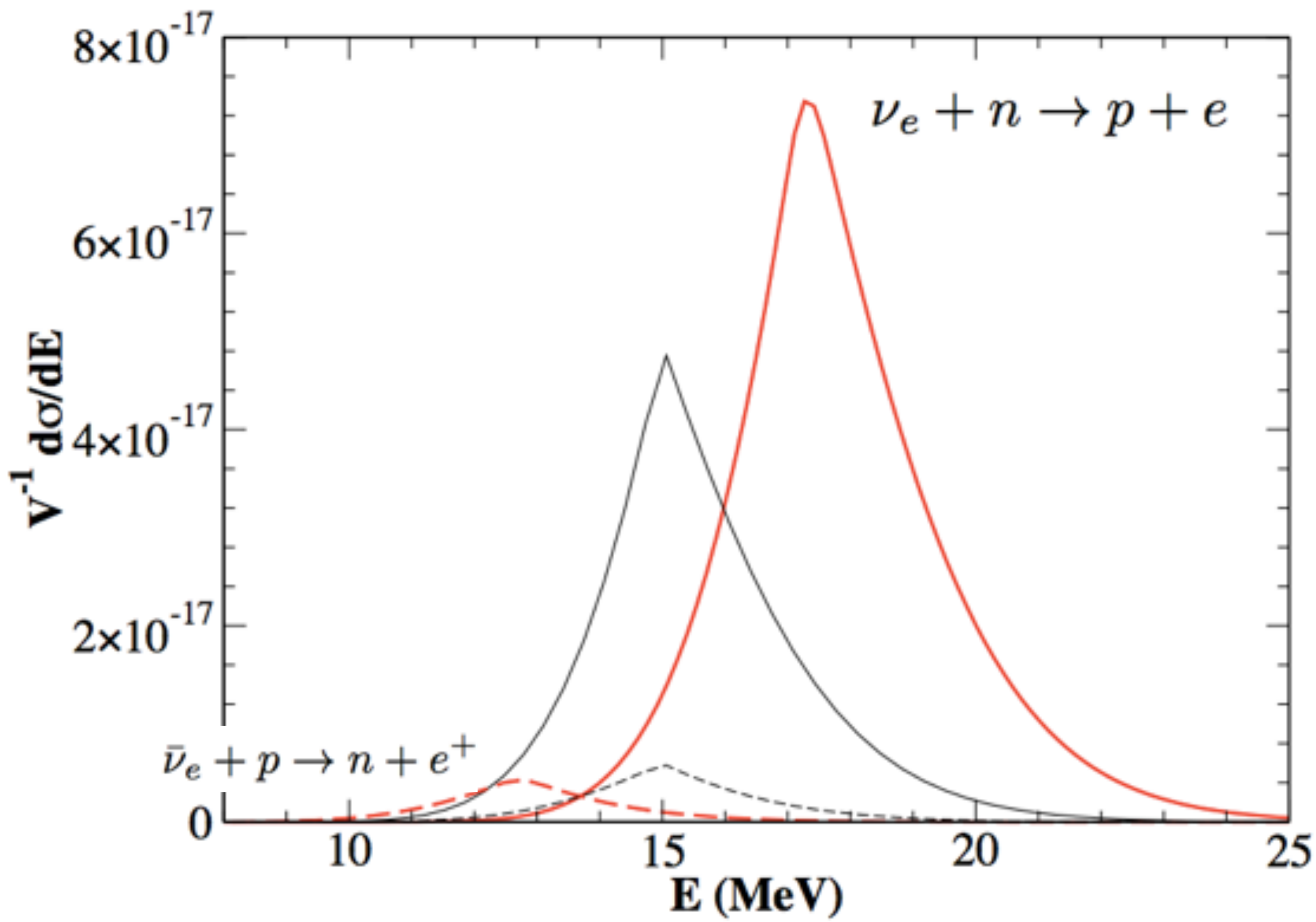
$$\frac{\sigma_{\nu_e}(\Delta U)}{\sigma_{\nu_e}(0)} = \frac{(E_\nu + \Delta U)^2[1 - f(E_\nu + \Delta U)]}{E_\nu^2[1 - f(E_\nu)]}.$$

- Effect opposite for anti-neutrino absorption and reduces cross section increasing E(anti-nu).
- Increases ΔE and makes wind somewhat more neutron rich. Probably not enough for r-process ?? But symmetry energy is relevant.

Idea due to L. Roberts, my work with G. Shen, C. Ott, E. O'Connor

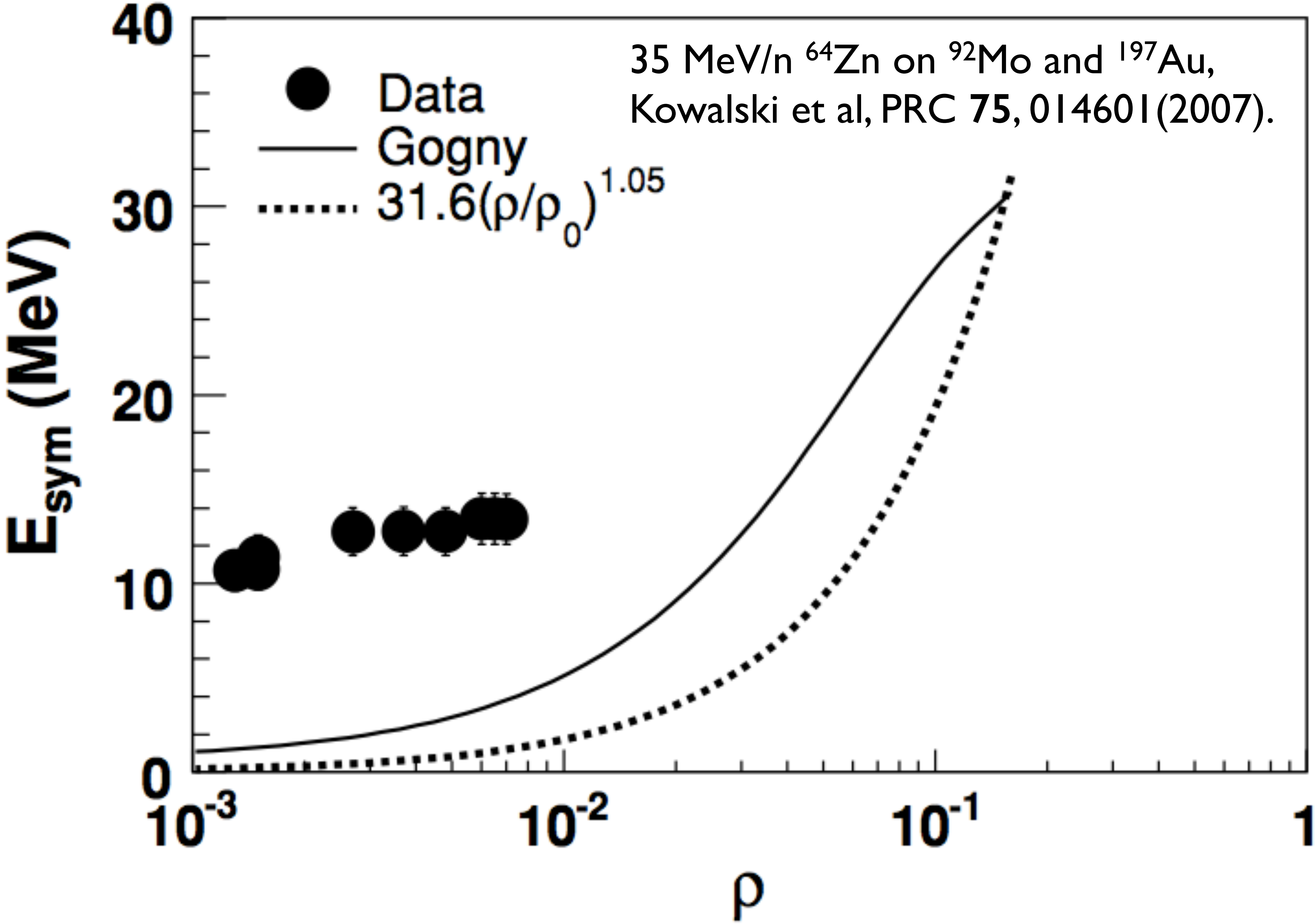
Neutrino and antineutrino cross sections

- Cross section for neutrino (anti-neutrino) absorption solid (dashed) vs energy of outgoing charged lepton without (black) and with (red) energy shift. E_{nu}=15 MeV, T=5 MeV and n=0.001 fm^{-3}.



- Effect decreases energy of emitted neutrinos because larger cross section keeps them in equilibrium to lower densities and temperatures.

- This change in neutrino spectra leads to a neutrino driven wind that is somewhat more neutron rich. However, probably still not neutron rich enough for the main r-process.



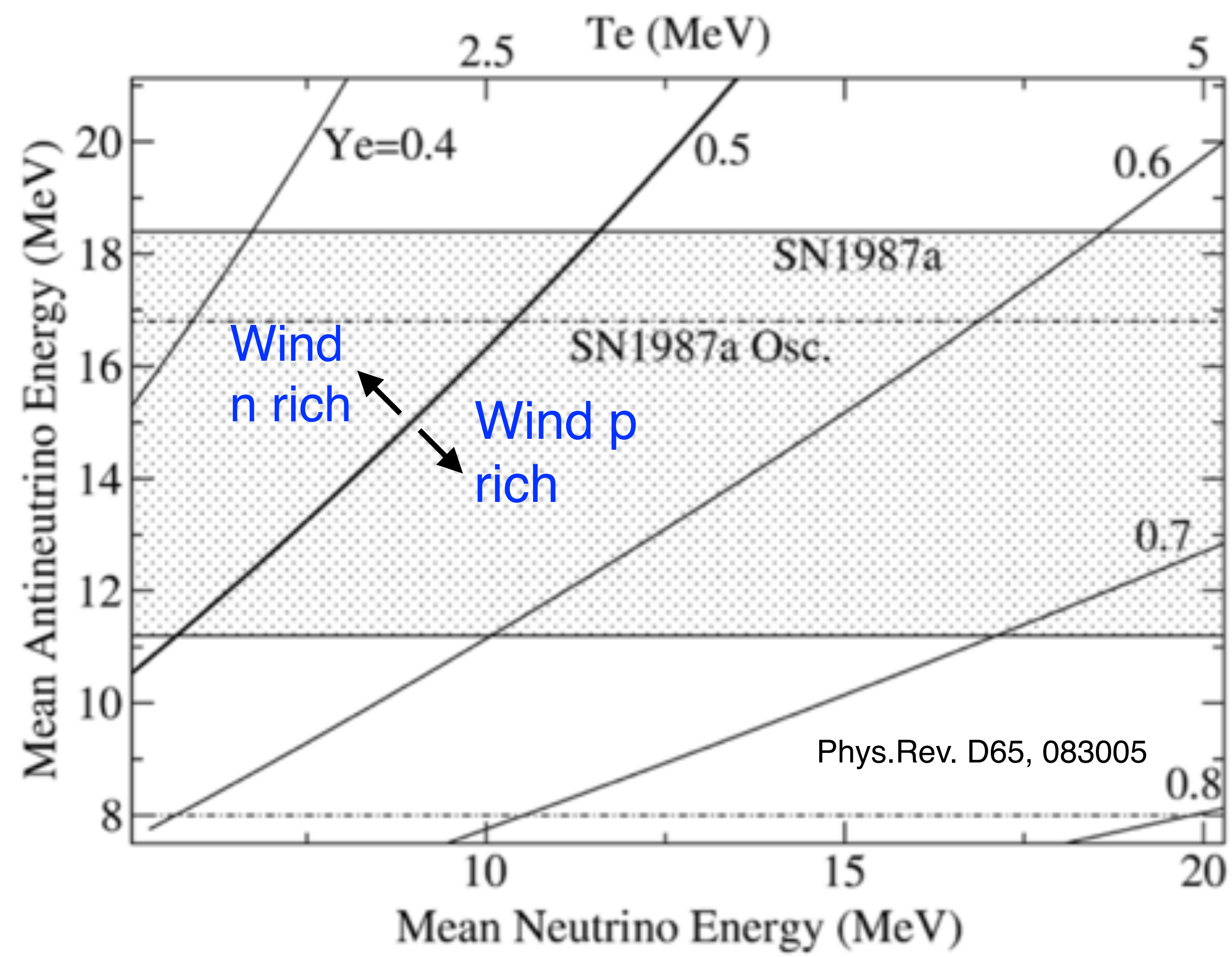
Symmetry energy from isoscaling analysis of ratio of yields of light clusters with different N/Z values. The temperature varies from about 4 MeV (lowest density) to 10 MeV (highest density)

SN neutrinos and r-process nucleosynthesis

- Important site for the r-process is the neutrino driven wind in SN.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

- Measure difference in average energy of **antineutrinos** and **neutrinos**. If large, wind will be neutron rich. If it is small, wind will be proton rich and likely a problem for r-process.
- Composition (Y_e) of wind depends on anti-neutrino energy (Y-axis) [results from ~20 SN1987A events shown] and energy of neutrinos (X-axis). Energy of neutrinos, not yet measured, depends on properties of n rich gas (nu-sphere).



ELBNF measures X axis and Super-K measures Y axis.

Present SN simulations find too few neutrons for (main or 3rd peak: Au, actinides) r-process. Suggests this is not r-process site.

- HIC measurements of neutrinosphere matter are important for SN neutrino spectra, neutrino detection, nucleosynthesis, and neutrino oscillations.

Next galactic supernova

- Has all ready occurred! (One just needs to view galaxy in correct reference frame.)
- "Check is in the mail".
- As I speak, astronomical numbers of neutrinos are racing towards earth, almost as fast as a European neutrino.

C. J. Horowitz, Indiana University, horowit@indiana.edu
Asy-EOS 2015, Piazza Armerina, Sicily, March 2015.

Femtonova Collaboration

- Use HIC to simulate neutrinosphere region of core collapse supernovae.
- Look at EOS, composition (light clusters), symmetry energy, neutrino response … of warm, low density, neutron rich matter.
- Reanalyze existing HI data.
- Consider new experiments with both stable and radioactive beams to extrapolate to very neutron rich conditions.
- Possible skype calls leading to a workshop.