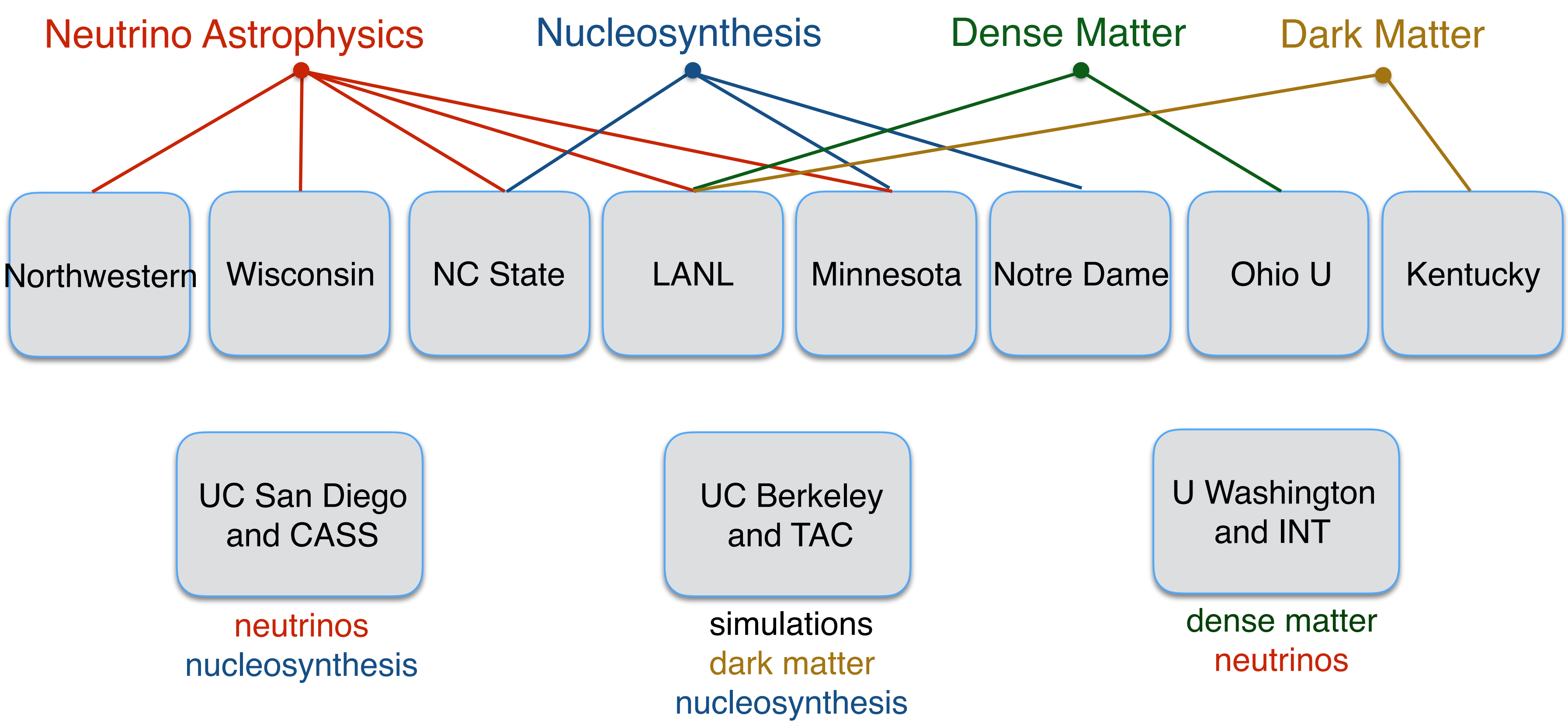
Our Science Collaborations and Mentoring

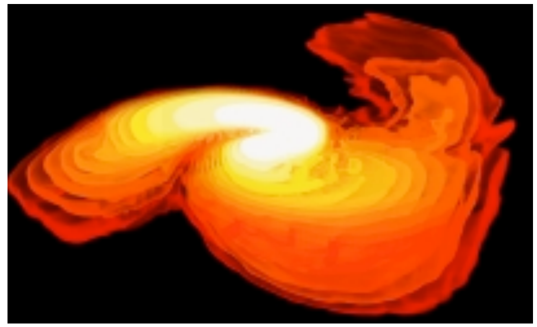
The Hub will be built around established collaborations involving leaders of the field, with strong records in mentoring young researchers:



Simulations and HPC

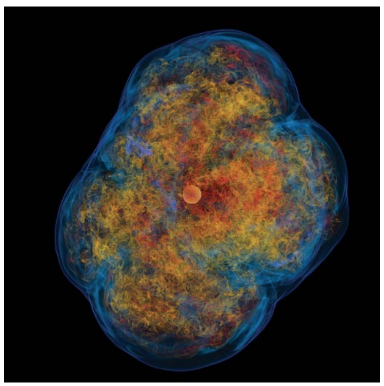
UC Berkeley and UCSD/CASS

shell model electroweak response codes BIGSTICK



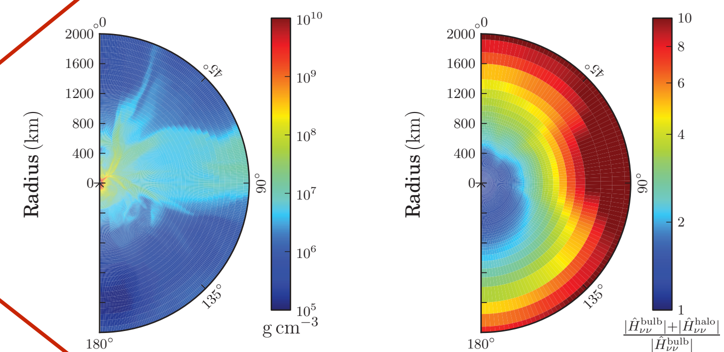
LANL, U Washington, Ohio U

Quantum Monte Carlo: nuclear EoS



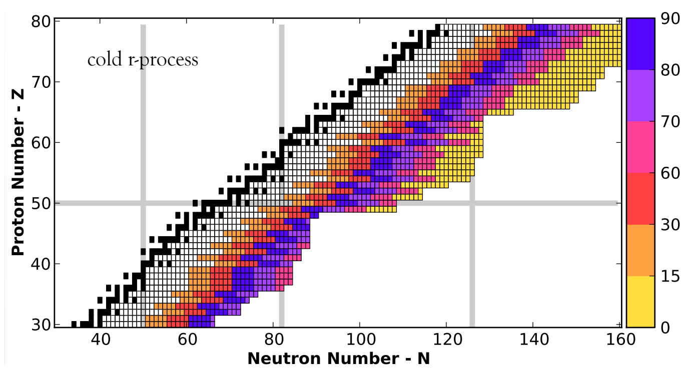
collapse and merger simulation codes: CASTRO/MAESTRO SEDONABox SpEC Spectre

UC Berkeley/NERSC
U Washington



stellar evolution: Kepler nucleosynthesis networks

Minnesota, Notre Dame, NC State, UC Berkeley



supernova neutrino propagation

UCSD, LANL, Minnesota, Wisconsin, U Washington

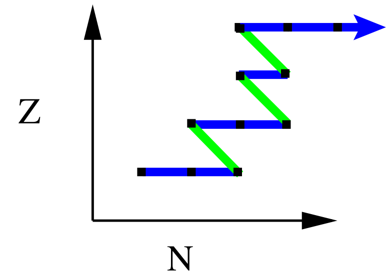
Nucleosynthesis – example *rapid neutron capture*

r-process

e. g. Uranium-238 Z=92, N=146 $\rightarrow$ need lots of neutrons

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$



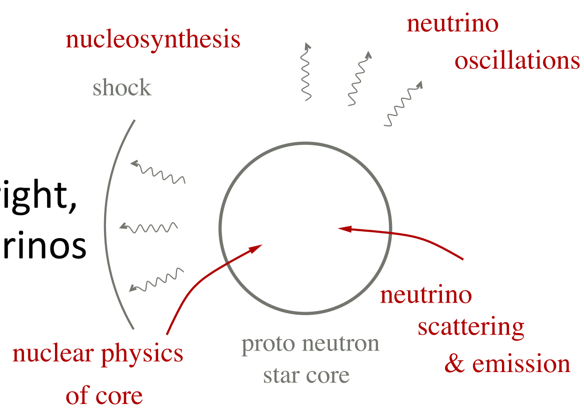
rapid neutron capture as compared with beta decay

in order to get the r-process nuclei, prefer a lot of neutrons

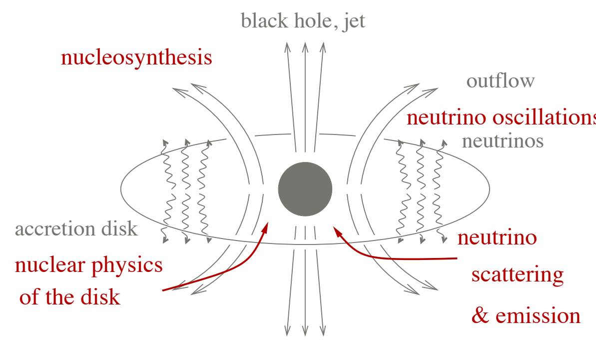
Compact Object Neutrino & Nuclear Physics

to understand these environments:
we need the nuclear-neutrino physics

Event rate,
amount of ejecta right,
troubles with neutrinos



standard core core collapse SN



compact object merger

Event rate?
Ejecta mass
per event?

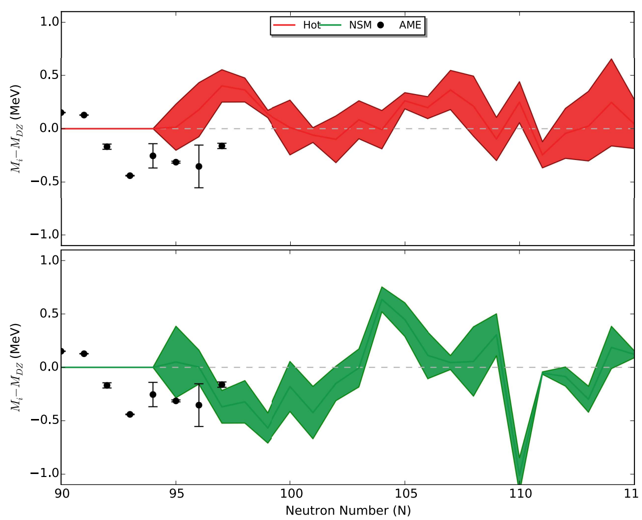
Single Core Collapse to *Hot* Neutron Star

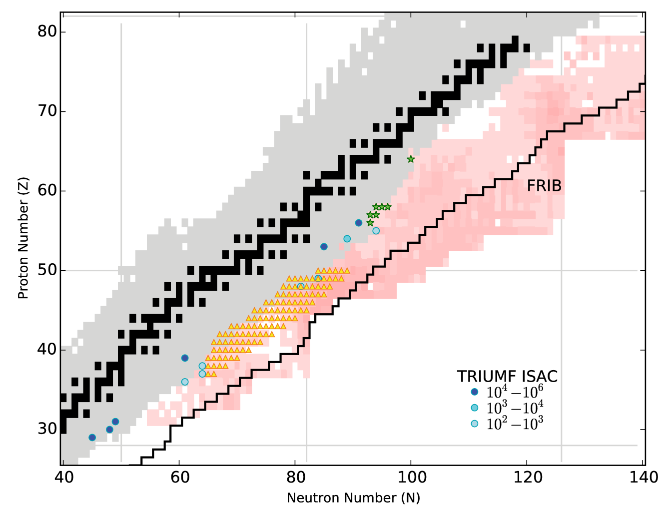
**Modest Initial Neutron Excess –
evolving toward ??**

Merging *Cold* Neutron Stars

***Very* Neutron-rich initially
– heating and evolving toward
lower n-richness in ejecta ? ?**

Neutrino physics, dense matter $\rightarrow$ improved predictions of r-process astrophysical conditions $\rightarrow$ FRIB predictions



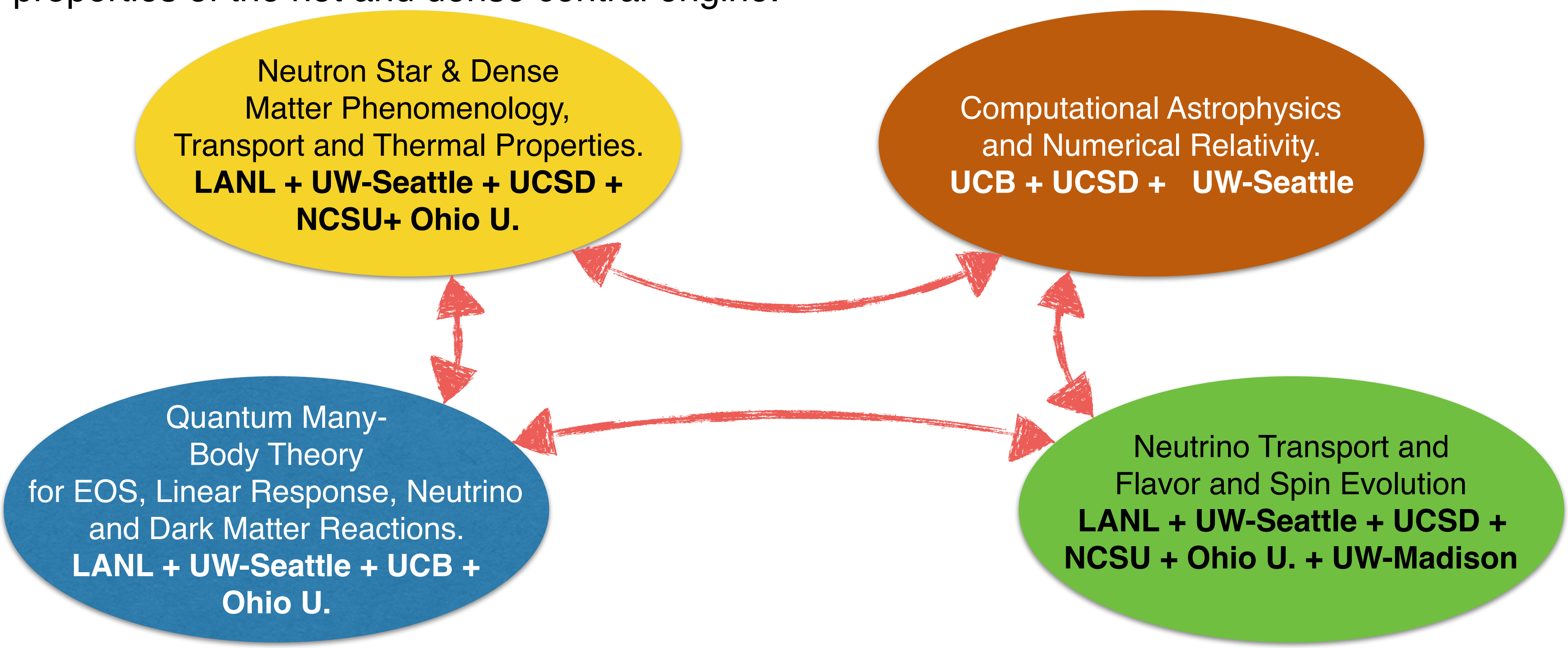


Predictions of the r-process required mass surface are different in supernova (top) and mergers (bottom) and within reach of radioactive beams (right).

Dense Matter Theory for Neutron Star Mergers and Supernovae

Multi-messenger signals are shaped by dense matter and neutrino physics

Gravitational waves from mergers: Neutron star mass, radius and tidal polarizability directly influence the observable waveform and normal mode frequencies of post-merger oscillations.
Supernova neutrino signal: Duration, spectrum, and flavor content of the signal is set by neutrino interactions at nuclear densities, and by neutrino oscillations.
R-process Nucleosynthesis: Composition of the ejecta in supernovae and neutron star mergers depends on the neutron star radius, neutrino spectrum, and neutrino oscillations.
Electromagnetic counterparts: The association between short-GRBs and neutron star mergers, and the mechanisms for late-time x-ray,optical and infra-red emission, rely on the properties of the hot and dense central engine.



Research & Collaborations

LANL + UW-Seattle

- EOS with quantifiable errors in Quantum Monte Carlo + 2 & 3-body nucleon-nucleon interactions.
- Linear response beyond perturbation theory, and its relation to transport properties of hot and dense matter.

LANL + Ohio U. + UW-Seattle

- Thermal properties of dense nuclear matter and the finite temperature EOS.
- Phase transitions and their impact on neutron star phenomenology.
- Two- and many-nucleon processes for neutrino and dark matter interactions in dense matter, and in heavy nuclei.
- EFT interactions and currents for Bremsstrahlung and related processes in dense matter.

UCB + UCSD + Ohio U. + UW-Seattle

- Improved treatment of nuclear and neutrino microphysics in merger and supernova simulations.
- The impact of improved microphysics on the amount and composition of ejecta and nucleosynthesis.
- Connecting electromagnetic signals to the central engines.

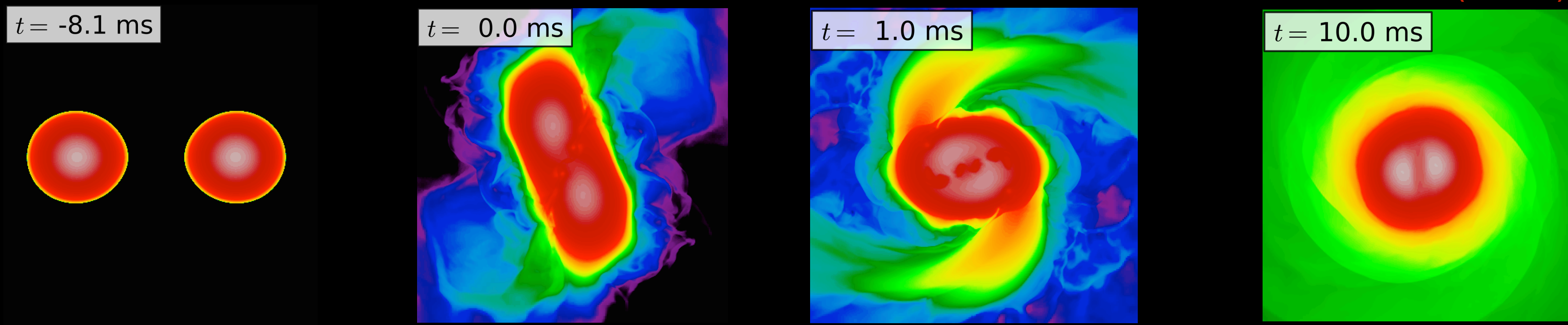
LANL + UCSD + NCSU + UW-Seattle + UW-Madison

- Unified description of incoherent scattering, and coherent flavor and spin evolution, of neutrinos at high density

Neutron Star Merger Dynamics

(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon

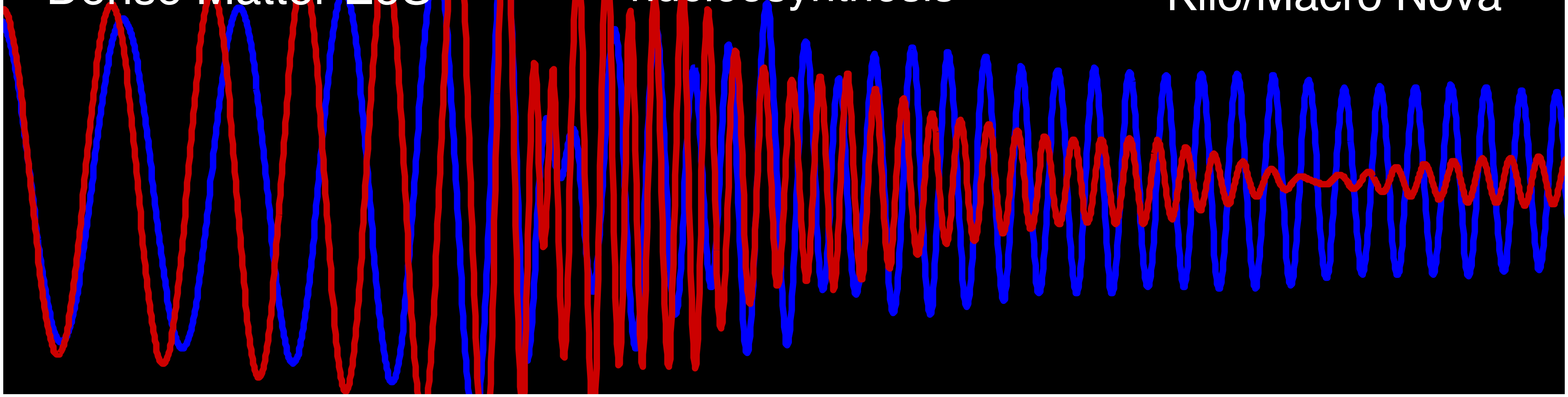
Simulations: Rezzola et al (2013)



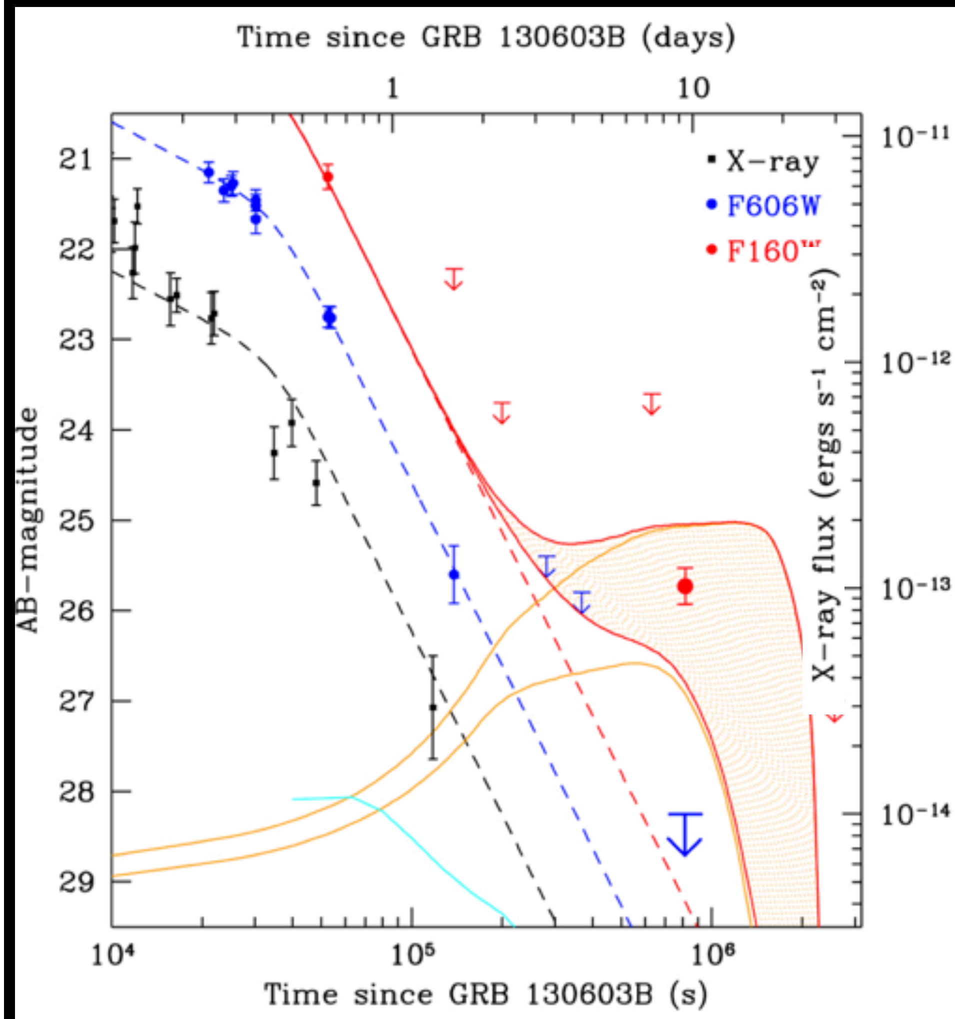
Inspiral:
Gravitational waves, Tidal Effects &
Dense Matter EoS

Merger:
Disruption, NS oscillations, ejecta and r-process nucleosynthesis

Post Merger:
Ambient conditions power GRBs, Afterglows, and Kilo/Macro Nova



Ejecta and GRB afterglow: Kilonova



Detection of a Kilonova

Tanvir et al. 2013

- Radioactive heavy elements synthesized and ejected can power an EM signal

Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011

- Magnitude and color of the optical emission is sensitive to the composition of the ejecta.

Kasen 2013

Neutrino Mean Free Paths in Dense Matter

Neutrinos couple to density and spin fluctuations in the medium.

$$\mathcal{L} = \mathsf{G_F}\ \bar{\nu}(\gamma_\mu - \gamma_\mu\gamma_5)\nu\ \sum_{\mathsf{i}} \bar{\psi}_{\mathsf{i}}(\mathsf{c}^{\mathsf{i}}_{\mathsf{V}}\gamma^\mu - \mathsf{c}^{\mathsf{i}}_{\mathsf{A}}\gamma^\mu\gamma_5)\psi_{\mathsf{i}}$$

Neutrino wavelength is comparable to correlation lengths in the medium.

Strong and electromagnetic correlations between hadrons, quarks (if present), and leptons alter neutrino transport properties.

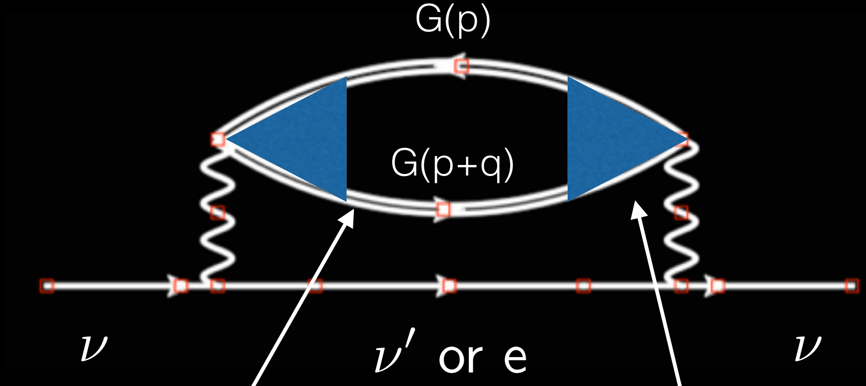
dressed quasi-particles

Linear response theory:

$$\mathsf{d}\sigma \propto\ \mathsf{G}^2_{\mathsf{F}}\ \mathsf{L}_{\mu\nu}\ \mathsf{Im}\ \Pi^{\mu\nu}(\mathsf{q}_0, \mathsf{q})$$

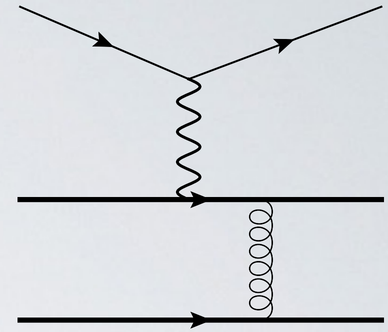
lepton tensor

hadronic polarization tensor

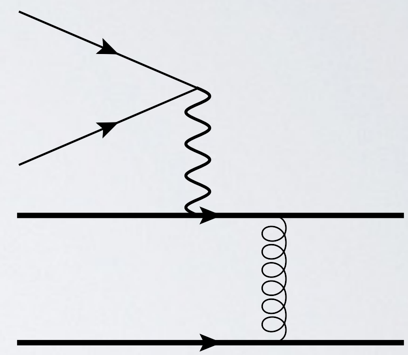


MULTI-PARTICLE EXCITATIONS

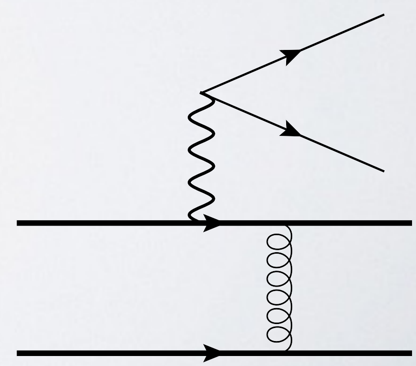
- Excitation of 2 particle-2 hole states enables pair-processes and larger energy transfer during scattering.
- In strongly coupled systems leads to significant smearing of the single particle and collective strength.
- Especially important for the spin response because spin is not conserved in nuclear interactions.
- Can enhance the charged current rate at small Y_e.



$$\nu + n + n \rightarrow n + n + \nu$$



$$\nu + \bar{\nu} + n + n \rightarrow n + n$$



$$n + n \rightarrow n + n + \nu + \bar{\nu}$$

Raffelt & Seckel (1995)

Neutrino *Mass*/*Flavor*/*Spin* Physics in the Early Universe & Compact Objects

Balantekin (UW-Madison); Carlson (LANL); Cirigliano (LANL); Fuller (UCSD); McLaughlin (NC State); Qian (Minnesota); Reddy (INT/UW)

Nonlinear **Many Body (**$10^{57} - 10^{87}$ **particles!) problem driven by the *Weak Interaction***

Quantum Kinetic Equations for ν flavor/spin

Vlasenko (NC State); Fuller (UCSD); Cirigliano (LANL)

$$D\mathcal{F} = -i\,[\mathcal{H},\mathcal{F}] + \{\mathcal{C}_{\mathrm{GAIN}}, 1-\mathcal{F}\} - \{\mathcal{C}_{\mathrm{LOSS}}, \mathcal{F}\}$$

Vlasov operator (convective derivative plus force terms)

Vacuum + coherent forward scattering Hamiltonian

Flavored Boltzmann terms with gain-loss structure

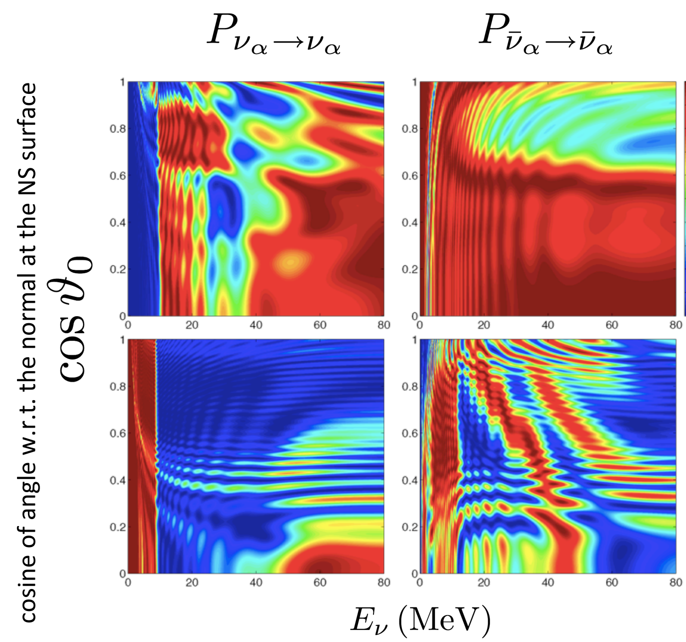
$$\mathcal{F} = \begin{pmatrix} f & \phi \\ \phi^\dagger & \bar{f}^T \end{pmatrix} \qquad \mathcal{H} = \begin{pmatrix} H & H_\phi \\ H_\phi^\dagger & -\bar{H}^T \end{pmatrix}$$

6 x 6 matrix containing neutrino and antineutrino densities & spin coherence

Usual Hamiltonian, plus helicity mixing term of O(m/E)

Saturday, April 25, 15

Coherent,
ν-ν forward scattering implies nonlinear, ***collective oscillations***

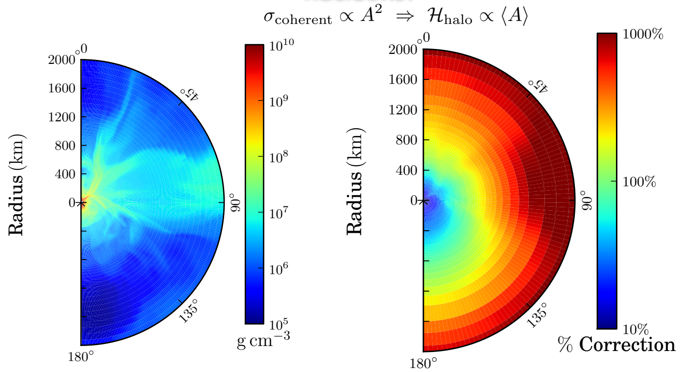


H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

add effects of direction-changing scattering (1 ν in 10^3 !!)
the ***HALO*** - now we have a ***boundary value problem***
Instead of an initial value problem – couples in ***nuclear composition*** In a new way

How large is the Halo effect for free nucleons?

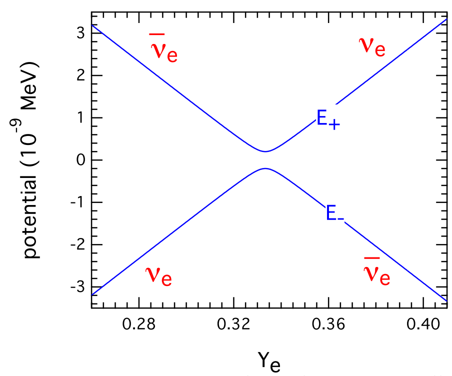
$\sigma_{\mathrm{coherent}} \propto A^2 \Rightarrow \mathcal{H}_{\mathrm{halo}} \propto \langle A \rangle$



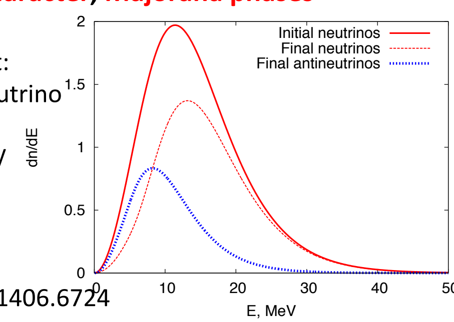
J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

A.~Malkus, J.~P.~Kneller, G.~C.~McLaughlin and R.~Surman, Phys. Rev. D86, 085015 (2012)

Anisotropy in neutrinos/matter : *Spin Coherence*
***neutrino-antineutrino* transformation**
Like 0νββ-decay, depends on absolute ν-mass
Majorana/Dirac character, Majorana phases

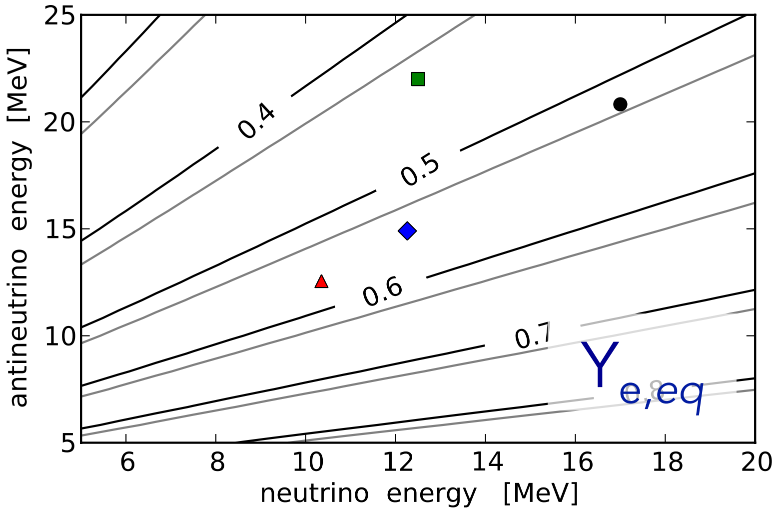


Netronization burst:
Neutrino-to-antineutrino Conversion. Here neutrino mass=1 eV



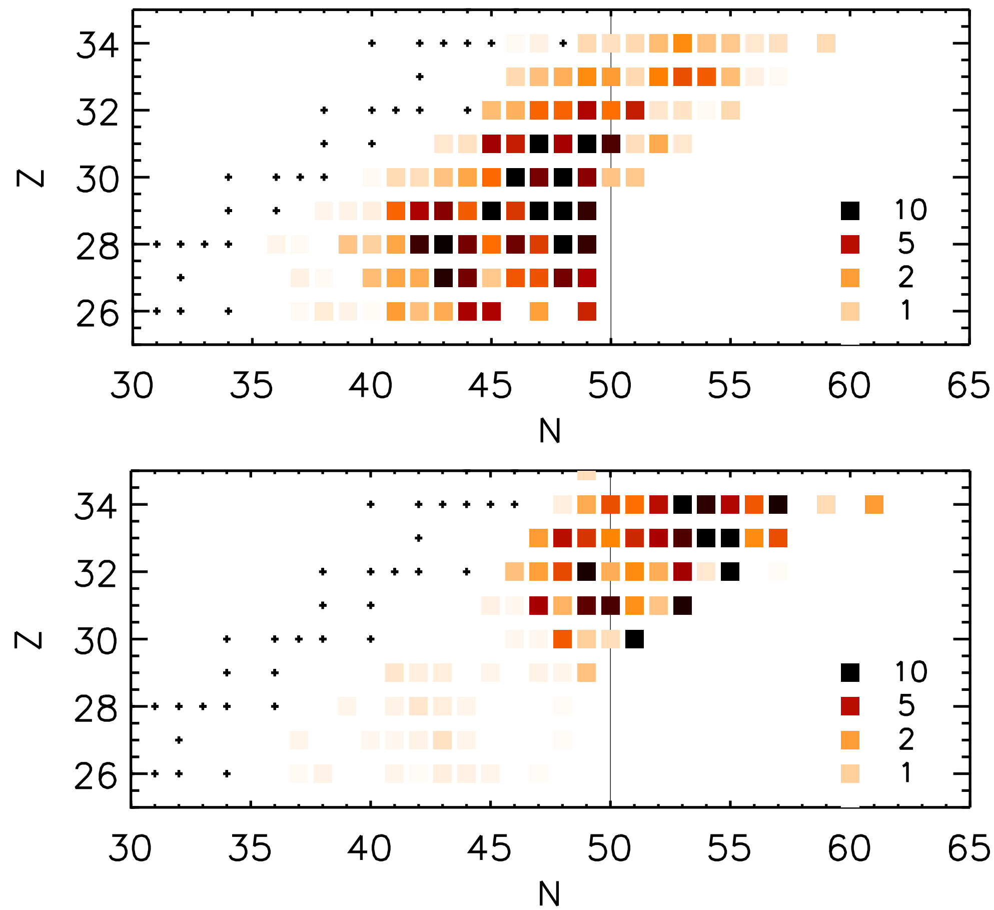
A. Vlasenko, G. M. Fuller, V. Cirigliano ArXiv:1406.6724

Arcones & Montes (2011), adapted from Qian & Woosley (1996)



Our proposed dense matter and neutrino flavor transformation calculations will clarify the range of nucleosynthesis possible in supernovae and mergers. From there we will work to identify the key nuclear data uncertainties that influence the most likely nuclear pathways in each environment.

Connection to nuclear experiment and FRIB

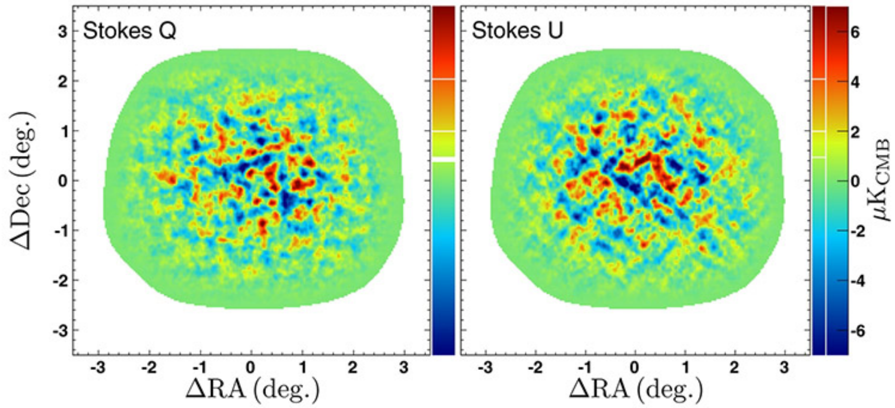


Surman, Mumpower, Sinclair, Jones, Hix, McLaughlin (2014)

Balantekin, Fuller, McLaughlin, Gardner

neutrino mass and *neutrino physics* will be key science drivers for ***Stage IV Cosmic Microwave Background***

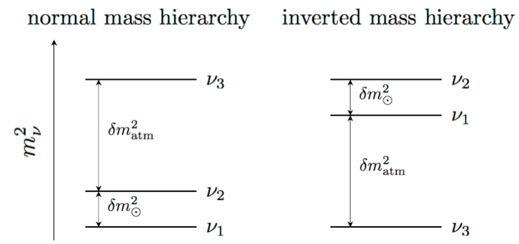
UCSD – Simons Array



Stage IV CMB (~ 500,000 detectors):

Neutrino Mass — 15 meV sensitivity for Σm_ν at 1σ.

Radiation Energy Density – Neutrino energy spectrum — 0.02 sensitivity for $N_{\rm eff}$ at 1σ.

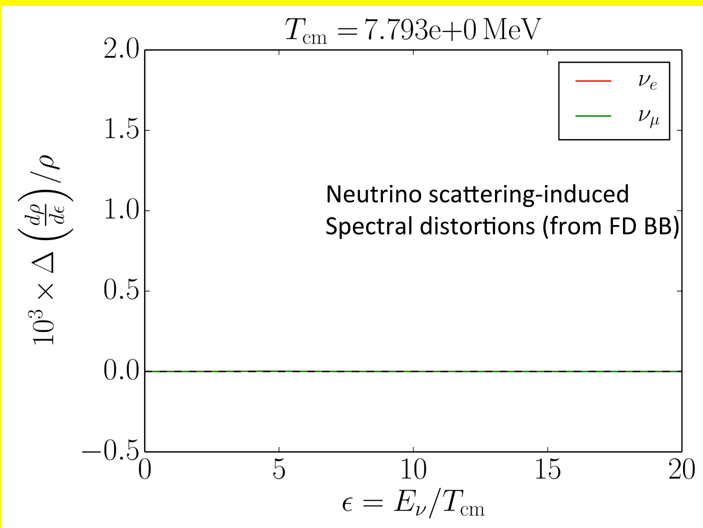


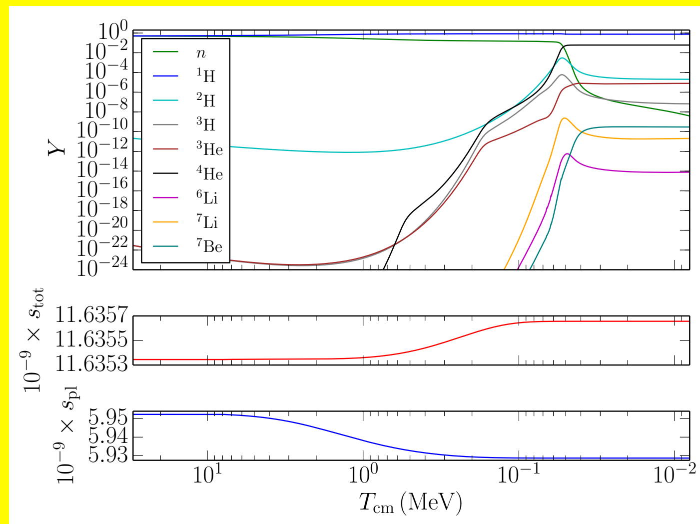
history of the early universe through *weak decoupling*/*freeze-out*, BBN, γ-decoupling

Sets up restrictive probe of neutrino sector and other BSM physics

e.g., “Majorana Neutrino Magnetic Moment and Neutrino Decoupling in Big Bang Nucleosynthesis”, N. Vassh, E. Grohs, A. B. Balantekin, G. M. Fuller , Phys. Rev. D **92**, 125020 (2016).

Coupled Boltzmann/QKE neutrino transport and weak and nuclear reactions in weak decoupling/ BBN – E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko arXiv:1512.02205





ions

$, N) + \gamma$

$T \sim 1$ M

NSE

$T \sim 10$

d $N_{\rm eff}$

$T_\gamma \approx 0.2$ e

$z \approx 1100$

$z \sim 3$

and

deuterium abundance *(~ 2% precision with 30-m class telescopes)*

The Nuclear Physics of Dark Matter

Kentucky, LANL, UCB, UCSD

Physics of dark sectors

Dark Photon, Dark Z, ...
Self-Interacting DM (EFT)
Composite DM (+Inelastic)
Sterile Neutrinos

Milky Way Evolution
(cf. Stellar Feedback)

Fixed Target Experiments
(JLab, FNAL)

UCB, LANL, Kentucky

Nuclear Responses

Direct Detection EFT
EM (+ inelastic) responses
for non-"WIMP"searches

Fixed Target Experiments (JLab, FNAL)

LANL, Kentucky

WIMP-like: UV <-> IR

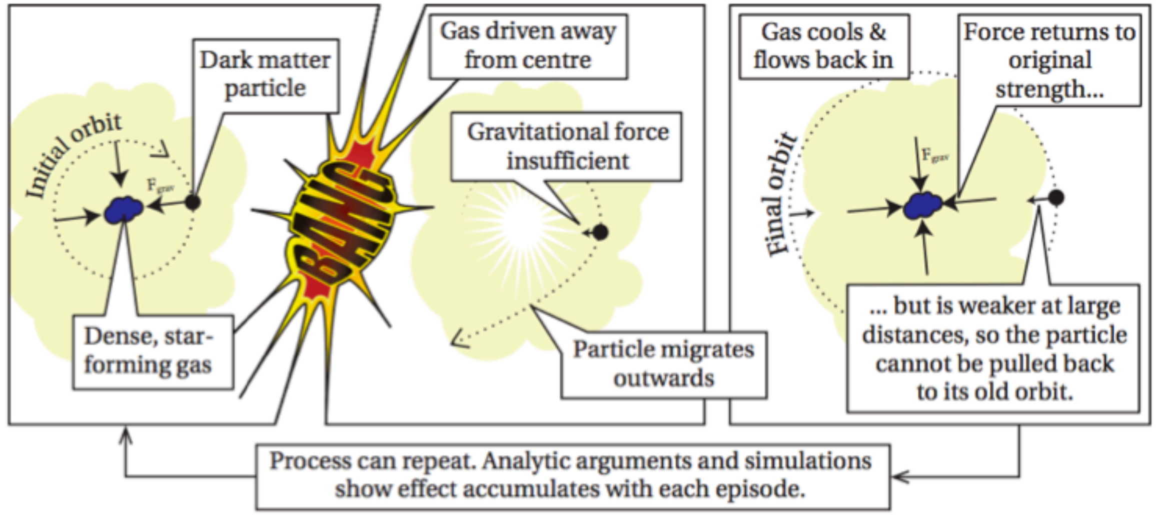
QCD matching
RNG (+ EW) evolution

Lattice QCD (LANL, LLNL)

Dark Matter Issues

Problem: DM simulations produce cusps in galaxy cores   Solution: Baryon feedback??

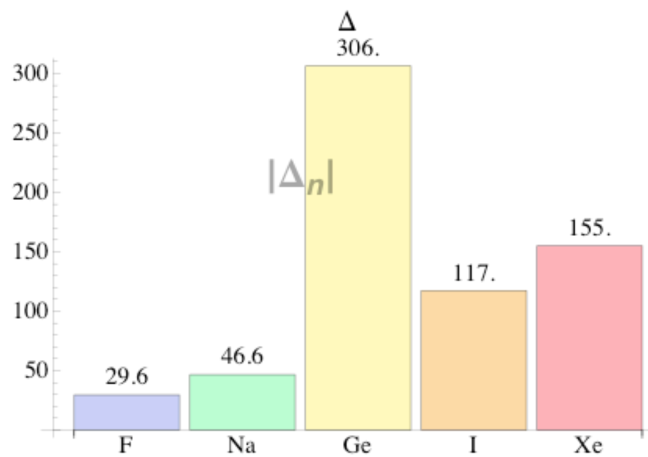
nuclear physicists:
study the stellar evolution, the SN explosions, and the integrated nucleosynthesis that constrains rates

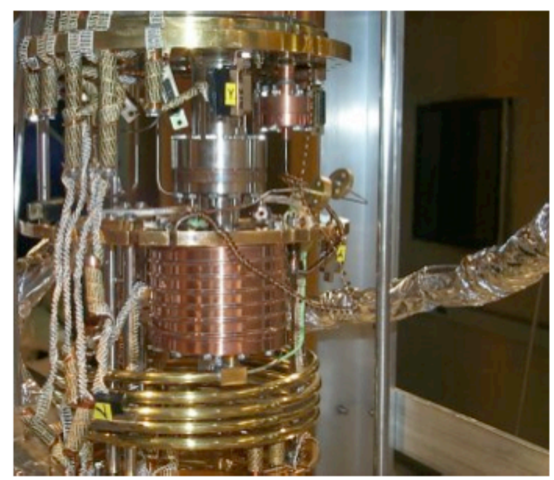


From Pontzen & Governato, 2014

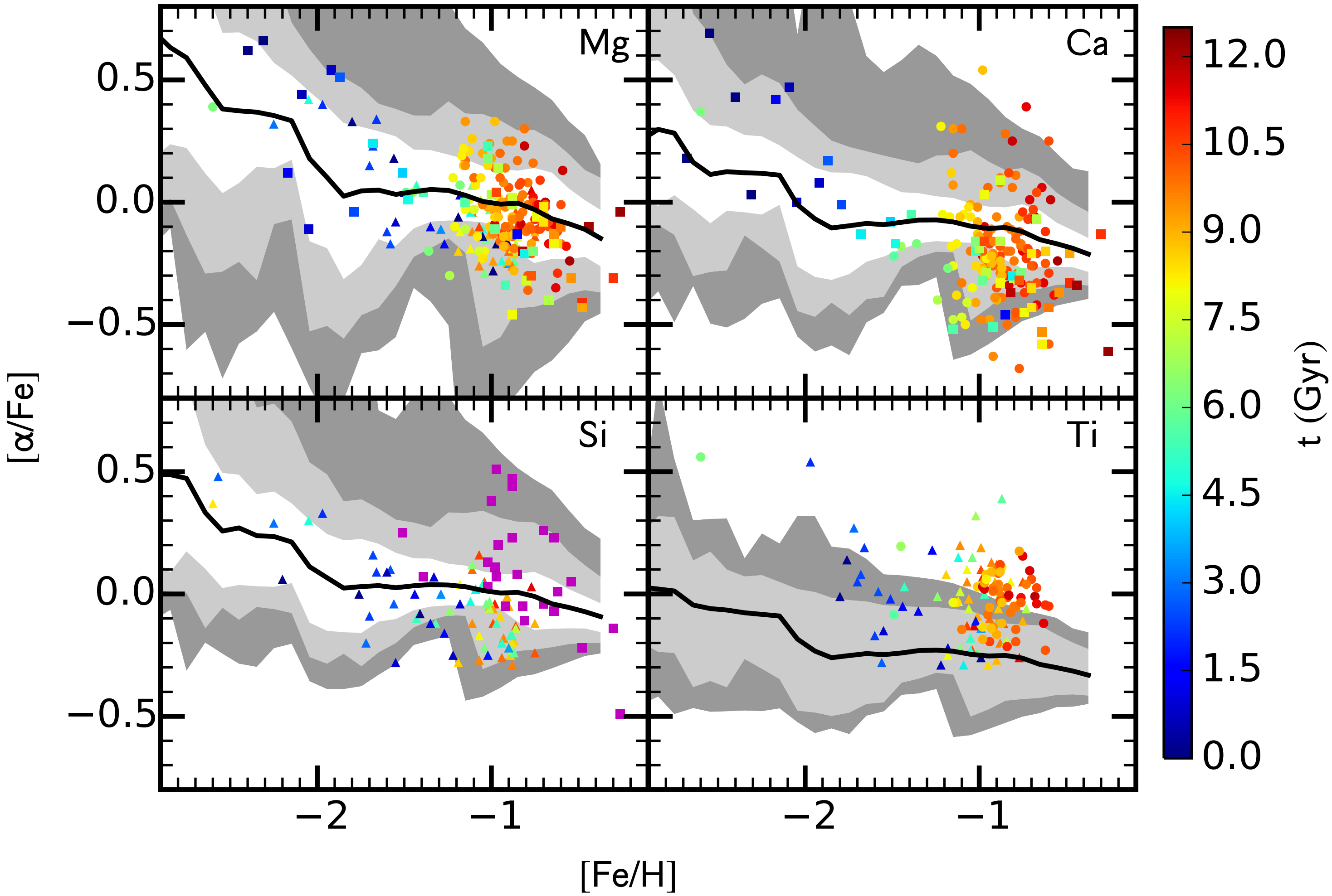
Problem: What are dark matter direct detection limits telling us?

nuclear physicists:
characterize the nuclear responses in EFT, and evaluate the nuclear form factors using SM and other techniques





Chemical evolution of dwarf galaxies ---



-- hangs on many of the nucleosynthesis objectives of our proposal
-- insights into the effectiveness of baryonic feedback
-- insights into the nature of dark matter and the origin of structure

Our collaboration has a strong record of mentoring young scientists, many of whom are now leaders in the field

-- see list in proposal

-- attract the best young people to our field

-- golden opportunity to grow our field
   compelling, exciting science