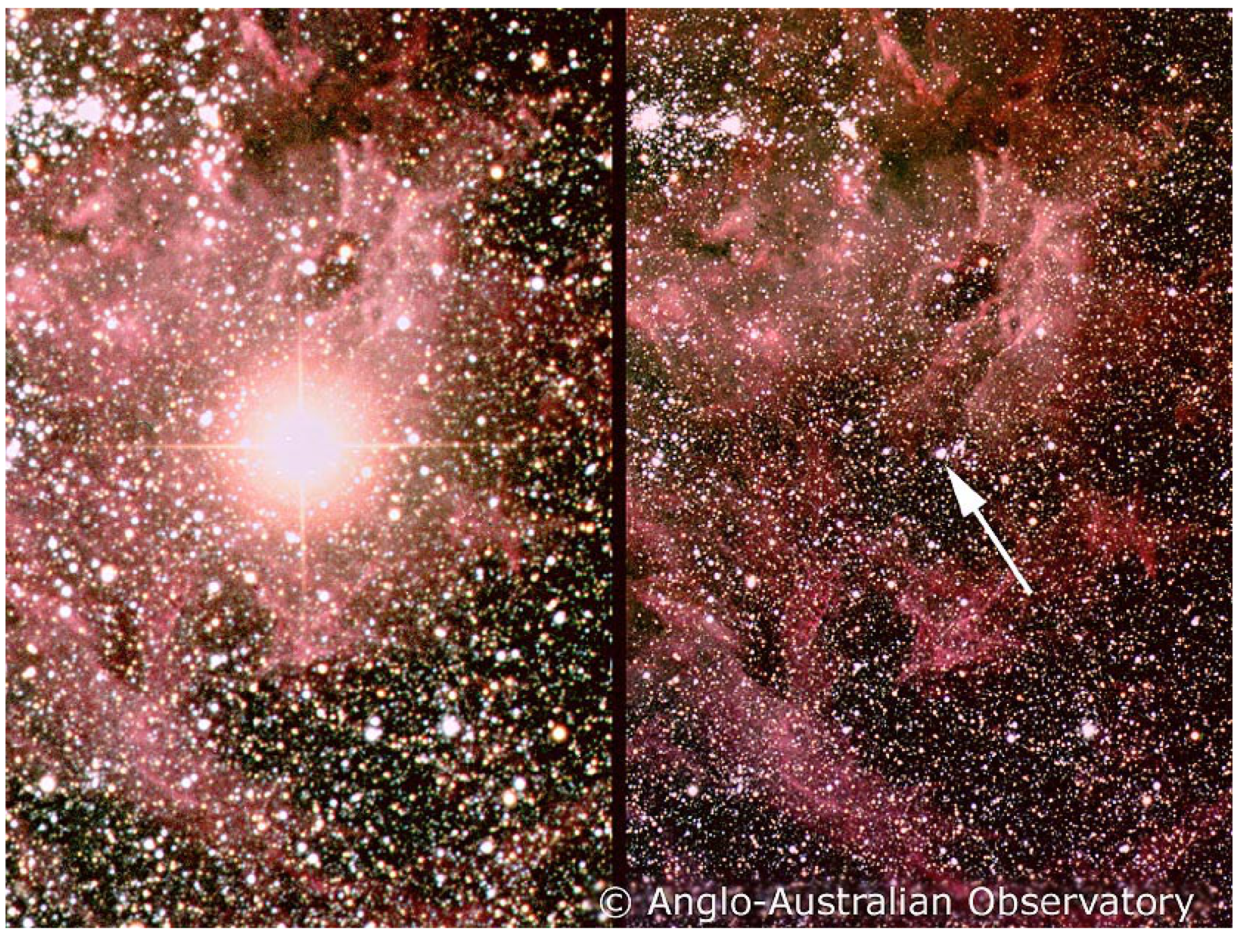
Summary 6
Low energy neutrino scattering



✓Supernova Neutrino
- Theory - H.Suzuki
- Experiment - K.Ishidoshiro

✓Neutrino interaction
- Theory - J.Carlson
- Experiment - K.Scholberg

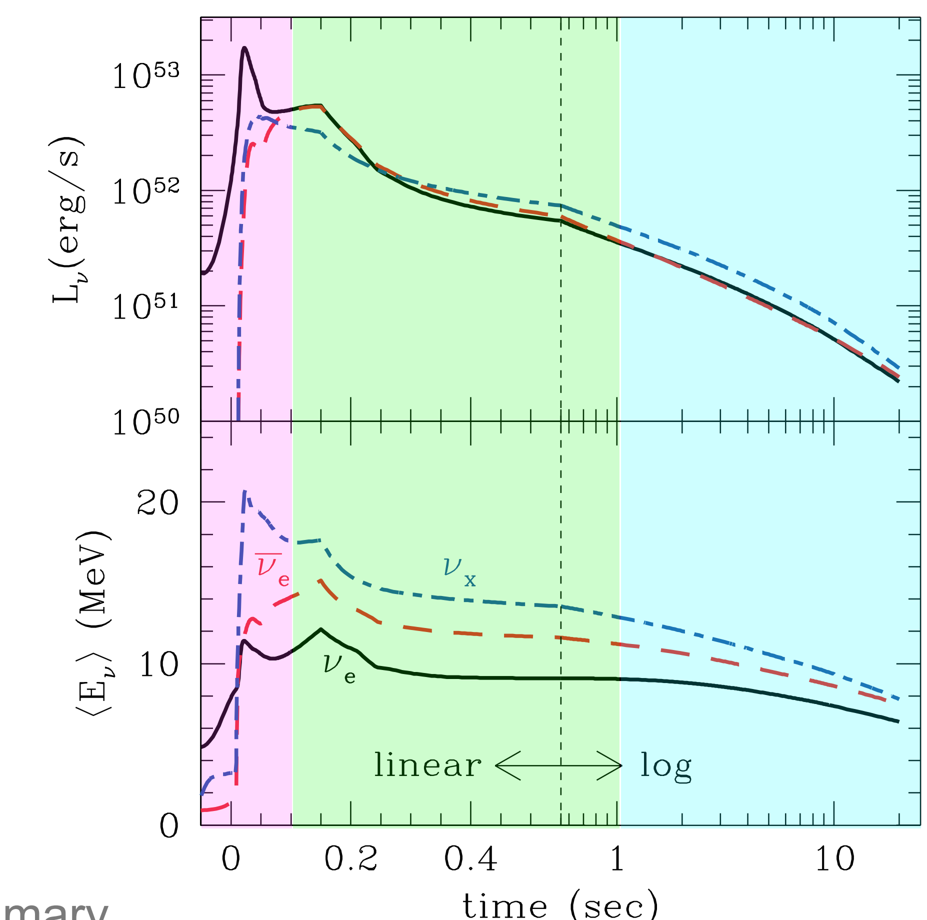
Yusuke Koshio / Gerry Garvey

Supernova neutrino : Theory

Review of the neutrino emission by Supernova burst

Supernova neutrinos can be roughly divided into 3 phases (while they are continuous).

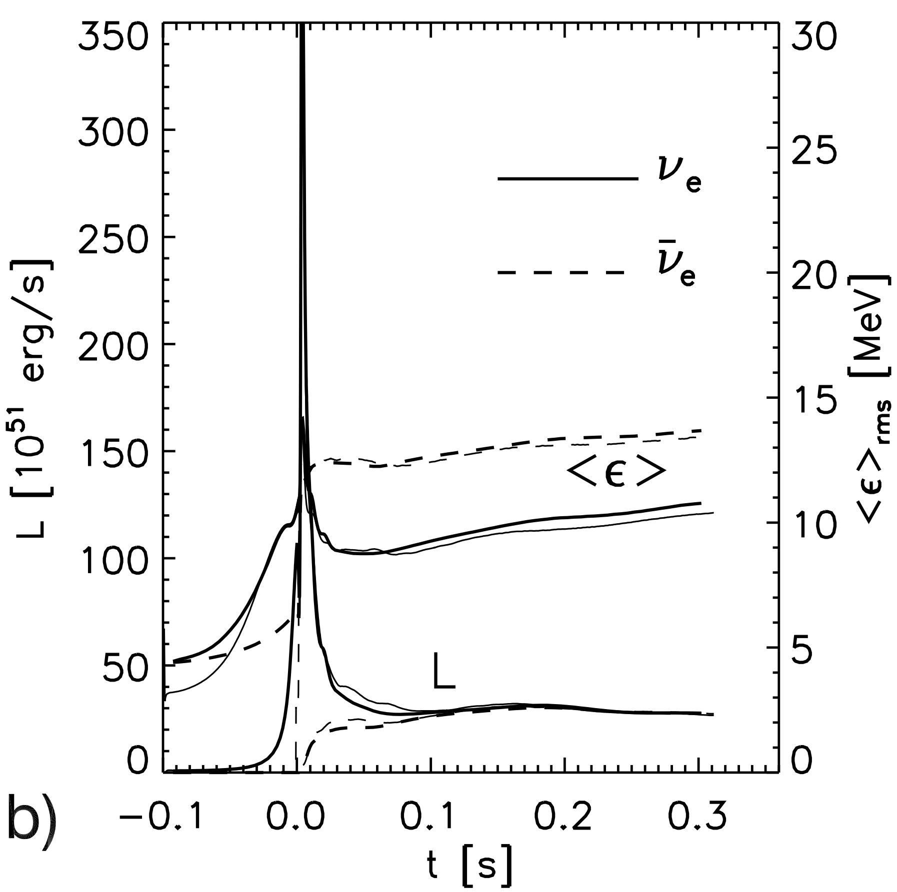
1. collapse and bounce phase: ($O(10)$msec), $O(10^{51})$erg
   core collapse, inner core bounce, shock launch
2. accretion phase: ($O(1)$sec), $O(10^{53})$erg
   shock wave propagation, stall, revival (leading to explosion) or BH formation
3. cooling phase: ($O(10)$sec), $O(10^{53})$erg
   Proto Neutron Star (PNS) cooling



Supernova neutrino : Theory

1. Collapse and bounce phase

- neutronization burst of ν_e
  shocked region: $\mathrm{A} \to \mathrm{p}, \mathrm{n}$, $\sigma_{\mathrm{e-cap}}(\mathrm{p}) > \sigma_{\mathrm{e-cap}}(\mathrm{A}) \Rightarrow \mathrm{e}^- \mathrm{p} \to \nu_e \mathrm{n}$
  When the shock wave passes the neutrinosphere, the emitted ν_e's behind the shock front can escape from the core immediately
  $\Rightarrow$ **neutronization burst** of ν_e.
  $L_{\nu_e} > 10^{53}$erg/sec, the time scale of the shock propagation through the neutrinosphere $\Delta t \lesssim O(10)$msec $\to E_{\nu_e} \sim L_{\nu_e} \Delta t \sim O(10^{51})$erg



b)

Supernova neutrino : Theory

2. Accretion phase

Modern simulations with GR 1D Boltzmann ν-transfer

canonical models: no explosion

Neutrino Interactions (minimal standard: Bruenn'85)

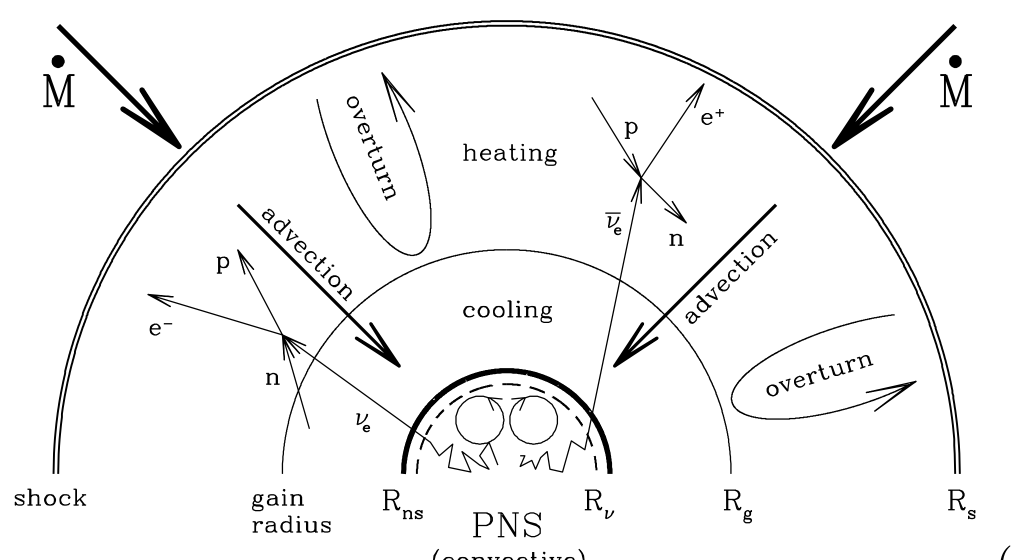
$\mathrm{e}^-\mathrm{p} \longleftrightarrow \nu_\mathrm{e}\mathrm{n}$ $\mathrm{e}^+\mathrm{n} \longleftrightarrow \bar{\nu}_\mathrm{e}\mathrm{p}$ $\mathrm{e}^-\mathrm{A} \longrightarrow \nu_\mathrm{e}\mathrm{A}'$ $\mathrm{e}^+\mathrm{A} \longrightarrow \bar{\nu}_\mathrm{e}\mathrm{A}'$

$\mathrm{e}^-\mathrm{e}^+ \longleftrightarrow \nu\bar{\nu}$ $\mathrm{plasmon} \longleftrightarrow \nu\bar{\nu}$ $\mathrm{NN} \longrightarrow \mathrm{NN}\nu\bar{\nu}$ $\nu_\mathrm{e}\bar{\nu}_\mathrm{e} \longleftrightarrow \nu_x\bar{\nu}_x$

$\nu\mathrm{N} \longrightarrow \nu\mathrm{N}$ $\nu\mathrm{A} \longrightarrow \nu\mathrm{A}$ $\nu\mathrm{e}^\pm \longrightarrow \nu\mathrm{e}^\pm$ $\nu\nu' \longrightarrow \nu\nu'$

e-cap, ν emission, photodissociation $\rightarrow$ shock wave weakens and stalls

Multidimensional effects to revive the shock wave



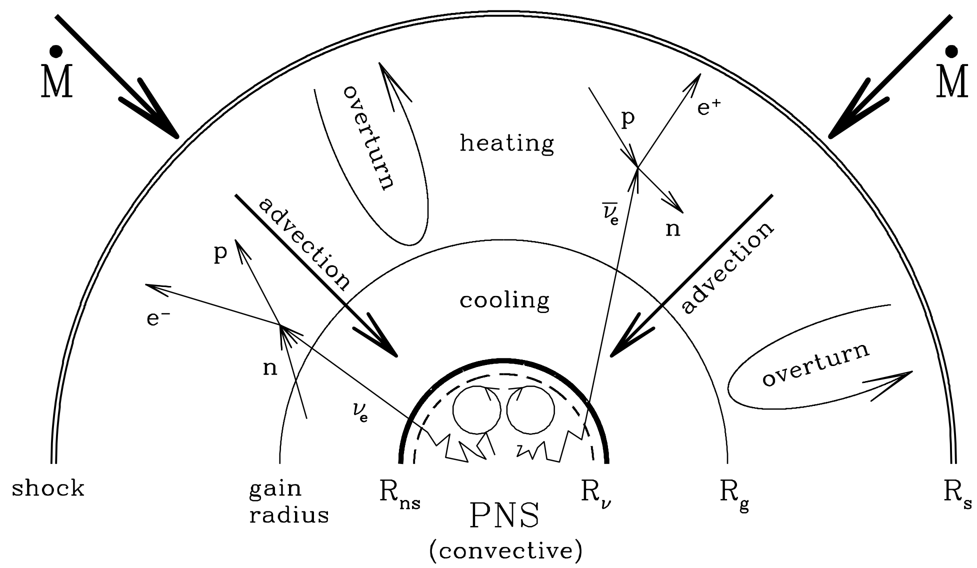
(Janka 1997)

- PNS convection inside neutrinosphere
  increase neutrino luminosity $\rightarrow$ more heating
- instability between shock front and neutrinosphere
  - neutrino convection
    (bottom of gain region is heated by ν's)
  - SASI (Standing Accretion Shock Instability)
    stay long in gain region: Δt(gain region) $\nearrow$
    $\Delta Q(\nu\text{ heating}) \sim \dot{Q}\Delta t(\text{gain region}) \nearrow$

Supernova neutrino : Theory

2. Accretion phase

Multidimensional effects to revive the shock wave



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    stay long in gain region: Δt(gain region) $\nearrow$
    $\Delta Q(\nu$ heating$) \sim \dot{Q}\Delta t$(gain region) $\nearrow$

2D/3D simulations $\rightarrow$ explosions
(but $E_{\rm exp} \lesssim$ obs. $O(10^{51})$erg)

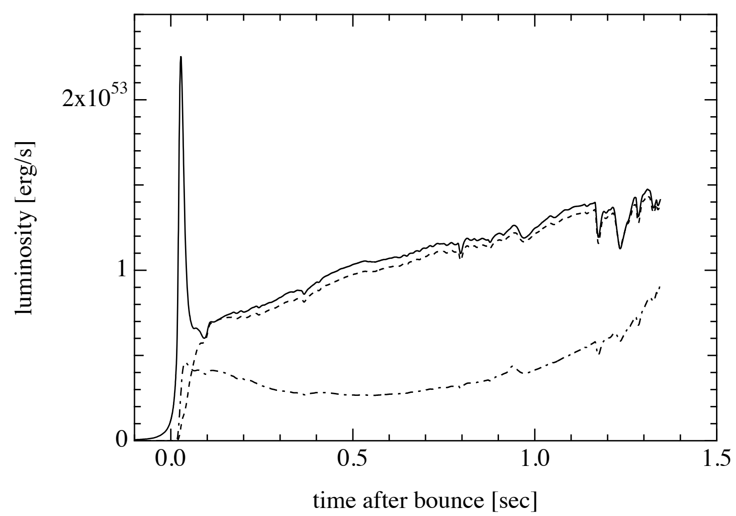
key physics is still unclear
Neutrino Heating, Standing Accretion Shock Instability, Convection, Rotation, Magnetic Field, Acoustic Wave ?

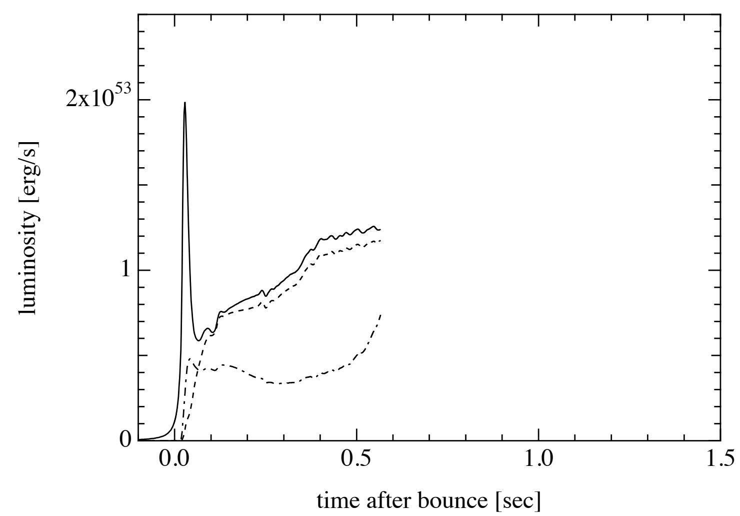
Supernova neutrino : Theory

2. Accretion phase

Failed supernovae (Black Hole formation)
1D implicit GR hydrodynamics + Boltzmann ν transfer code

Sumiyoshi, Yamada, Suzuki, Chiba PRL97(2006) 091101





L_ν increases due to matter accretion
$\nu_x < \nu_e, \bar{\nu}_e$ from accreted matter
Burst duration time strongly depends on EOS!

Progenitor $40M_\odot$, left: Shen EOS (stiffer), right: Lattimer-Swesty EOS 180 (softer)

Supernova neutrino : Theory

3. Cooling phase

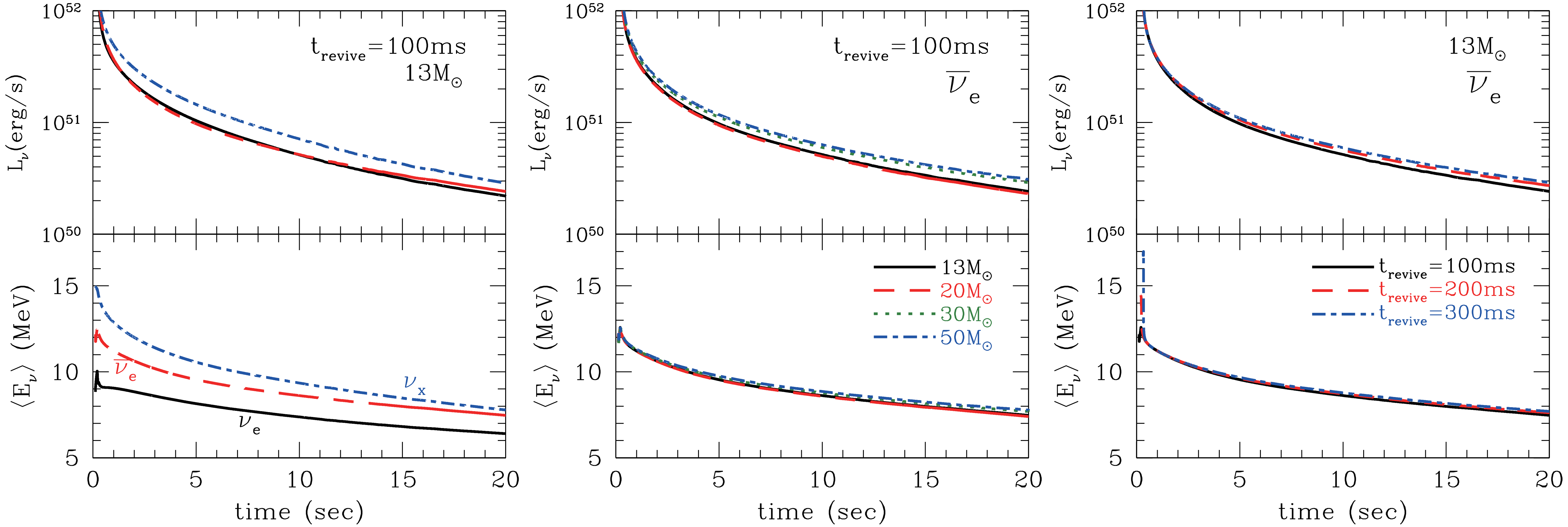


Figure 13. Same as Figure 12 but from the PNSC simulations. In the left panel, signals of ν_e (solid lines), $\bar{\nu}_e$ (dashed lines), and ν_x (dot-dashed lines) are shown for the model with $(M_{\rm init}, Z, t_{\rm revive}) = (13\,M_\odot, 0.02, 100\text{ ms})$. In the central panel, $\bar{\nu}_e$ signals are shown for the models with $(Z, t_{\rm revive}) = (0.02, 100\text{ ms})$ and $M_{\rm init} = 13\,M_\odot$ (solid lines), $20\,M_\odot$ (dashed lines), $30\,M_\odot$ (dotted lines), and $50\,M_\odot$ (dot-dashed lines). In the right panel, $\bar{\nu}_e$ signals are shown for the models with $(M_{\rm init}, Z) = (13\,M_\odot, 0.02)$ and $t_{\rm revive} = 100$ ms (solid lines), 200 ms (dashed lines), and 300 ms (dot-dashed lines).

Nakazato *et al.*, 2013, 1D simulations

Our new SN neutrino database (`http://asphwww.ph.noda.tus.ac.jp/snn/`)
Nakazato *et al.*, ApJS205 (2013) 2

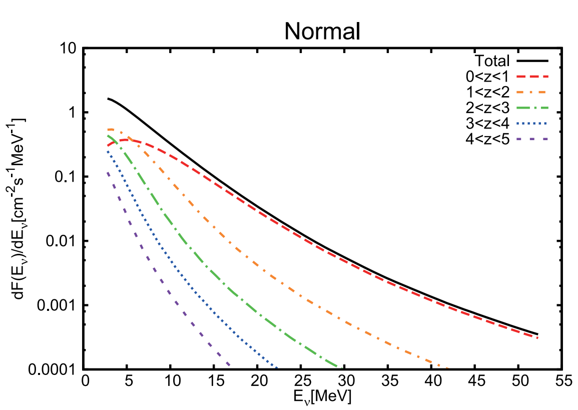
Supernova neutrino : Theory

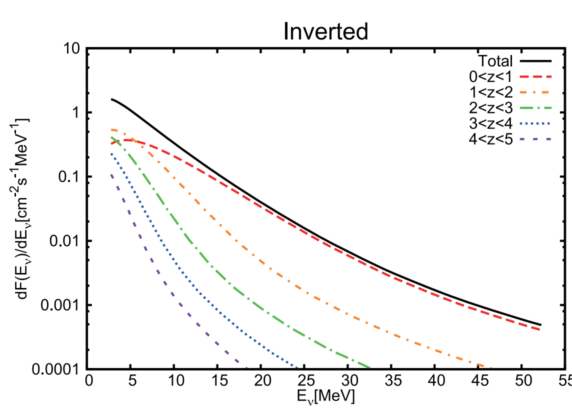
Supernova Relic Neutrino (SRN)
Diffuse Supernova Neutrino Background (DSNB)

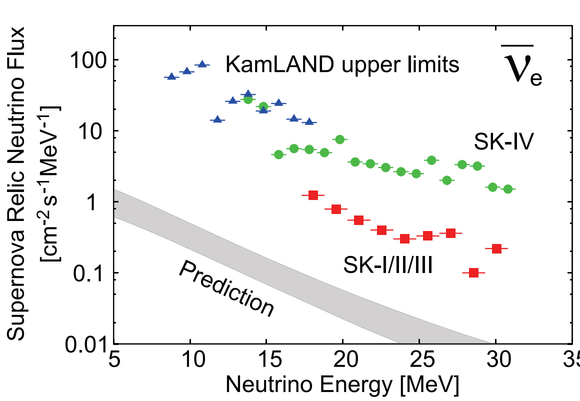
- Core-Collapse Supernova Rate $R_{\mathrm{CC}}(z, M, Z)$
  $\Leftarrow$ Star Formation Rate(SFR), Initial Mass Function (IMF), metallicity evolution
- Energy spectra from individual supernova $\frac{dN_\nu(E'_\nu, M, Z)}{dE'_\nu}$
  using our SN neutrino database
- Cosmic expansion

$$\frac{dF_\nu(E_\nu, t_0)}{dE_\nu} = c \int_0^{t_0} \int_{M_{\min}}^{M_{\max}} \int_0^{Z_{\max}} \frac{d^2 R_{\mathrm{CC}}(z, M, Z)}{dM dZ} dZ dM \frac{dN_\nu(E'_\nu, M, Z)}{dE'_\nu} \frac{dE'_\nu}{dE_\nu} dt$$

$$dt = -\frac{dz}{(1+z)H(z)}, \quad dE'_\nu = (1+z) dE_\nu$$







contributions from $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, $4 < z < 5$, Nakazato *et al.*, 2015

Numerical data are available at `http://asphwww.ph.noda.tus.ac.jp/srn/`

Supernova neutrino : Theory

Summary

- Collapse and bounce phase: neutronization burst of ν_e

  uncertainty is relatively small

  because the multidimensional effects do not have enough time to grow substantially and because the uncertainty of nuclear EOS is small around the nuclear density (density at which the core bounce occurs).

- Accretion and core explosion phase:

  state-of-the-art 1D simulation: light core explodes weakly, canonical cores do not explode.

  2D/3D simulations: explosion mechanism is still unknown, neutrinos will give us information.

  Instability like SASI might cause time variation of neutrino luminosity.

  At the shock revival, matter accretion onto inner core ceases and the neutrino luminosity drops.

  3D simulations with full general relativity and 3D neutrino transfer are required.

- Cooling phase: after the core explosion (cooling stage of the new-born protoneutron star), differences among neutrino species are small.

- We provide numerical data of the time evolution of emitted neutrino spectra obtained by our 1D models of supernova explosion and of the formation of a black hole.

  Neutrinos from failed supernovae are good probe to high density matter

Supernova neutrino : Experiment

Detection of supernova neutrinos

2010s

Several large detectors: sensitive to galactic SNe

Super-Kamiokande, IceCube, KamLAND, Borexino, LVD, DayaBay, HALO, XMASS, (SNO+)

Supernova neutrino : Experiment

Science of supernova neutrinos

Larger statistics than SN1987 events

Particle physics

- **Neutrino mass**
- **Neutrino mass hierarchy**
- **Axion**
- **Collective oscillation**
- **Cross section measurement**

Astrophysics

- **Explosion mechanisms**
- **Tomography of massive starts**
- **Early alarm to astronomical telescope**
- **Origin of heavy element**

Supernova neutrino : Experiment

What we want for future detectors

- Massive detector
  O(Mton), sensitive for Mpc
- Low-background rate in MeV range
  ⇒ Underground detectors

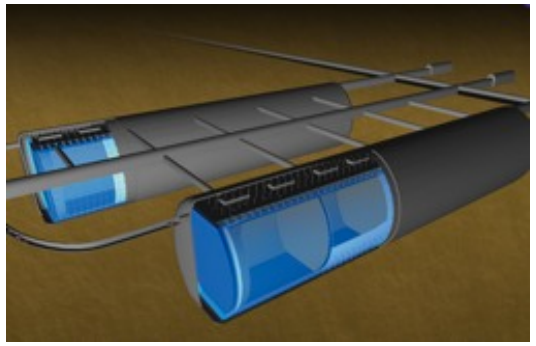
- Multi color observations
(ν_e, $\overline{\nu}_e$, and ν_x simultaneous observations)
- Timing resolution
- Energy resolution
- Directional measurement

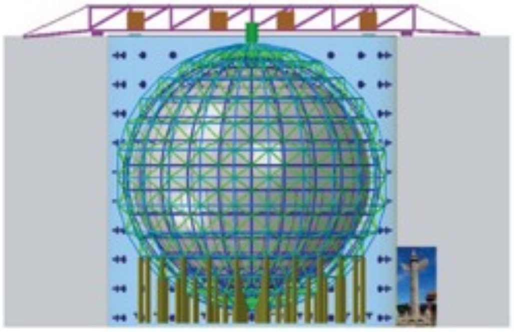
A single detector can not cover all.
⇒ Complementary observations with different detectors

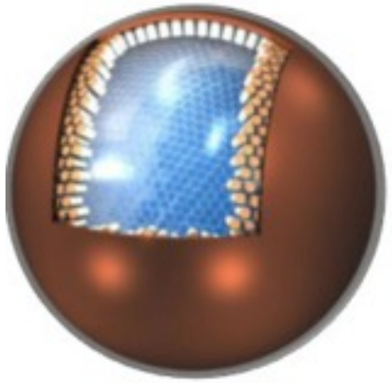
Supernova neutrino : Experiment

Detector type

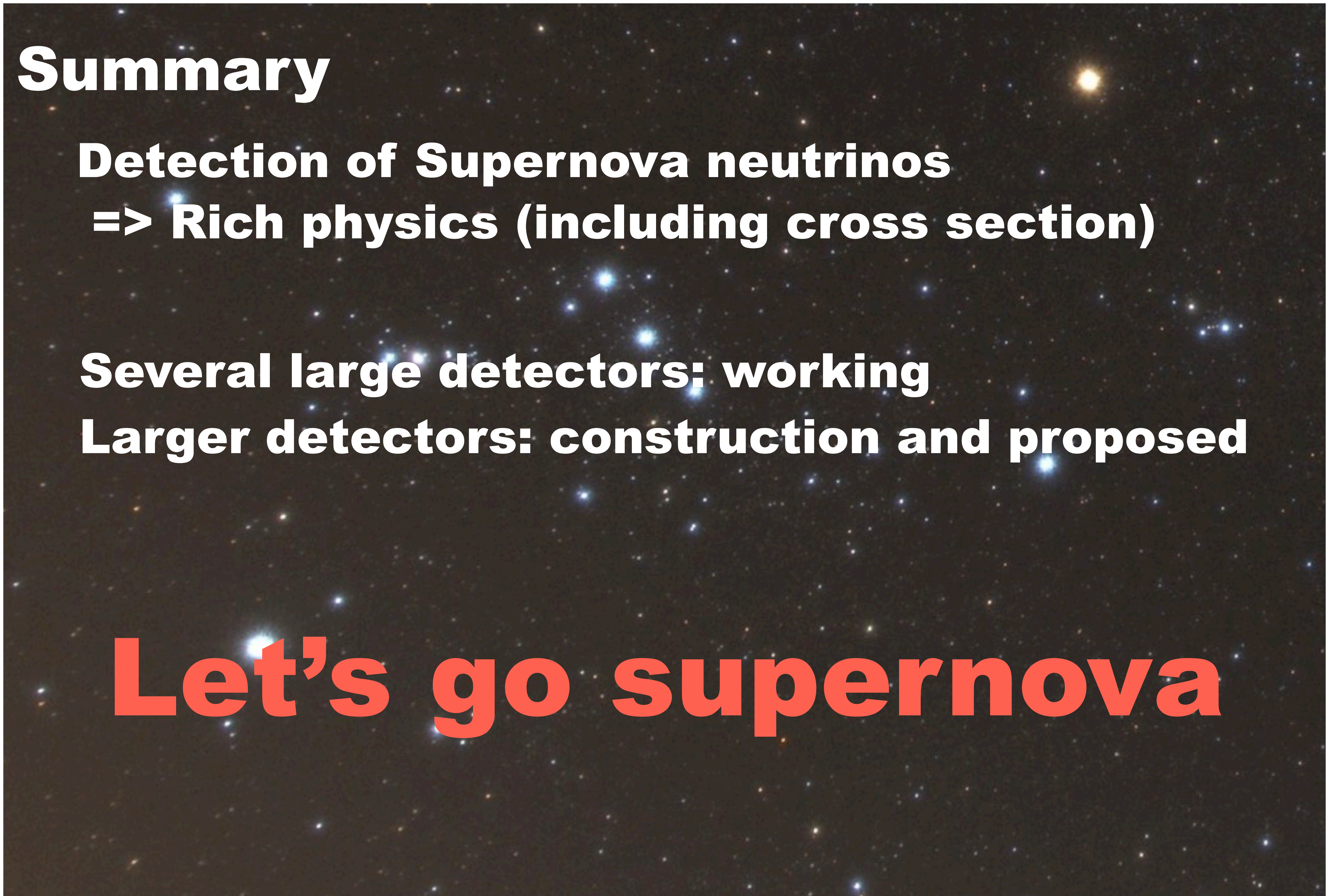
- **Water-Cherenkov detectors**
- **Liquid-scintillator detectors**
- **Liquid-Argon detectors**
- **Other detectors (Lead & Xe)**







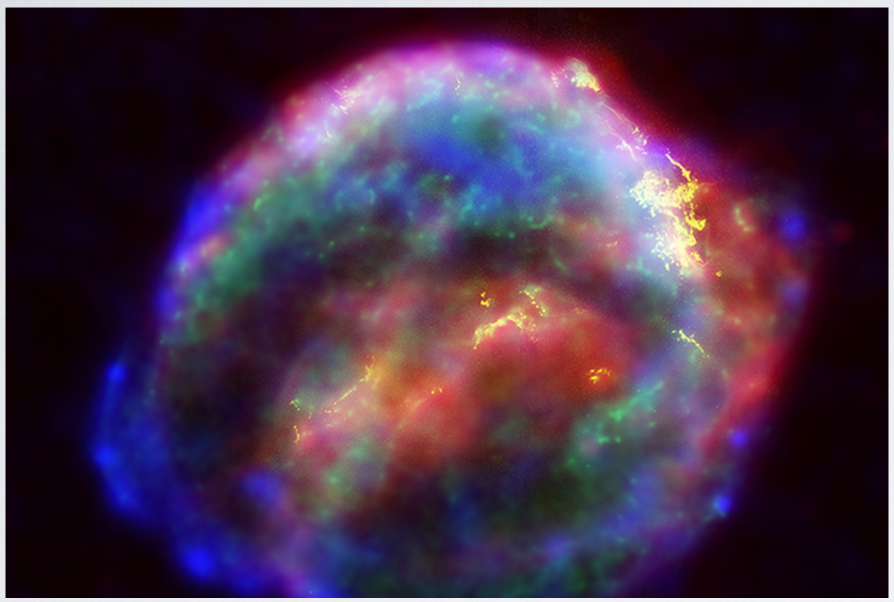
Supernova neutrino : Experiment

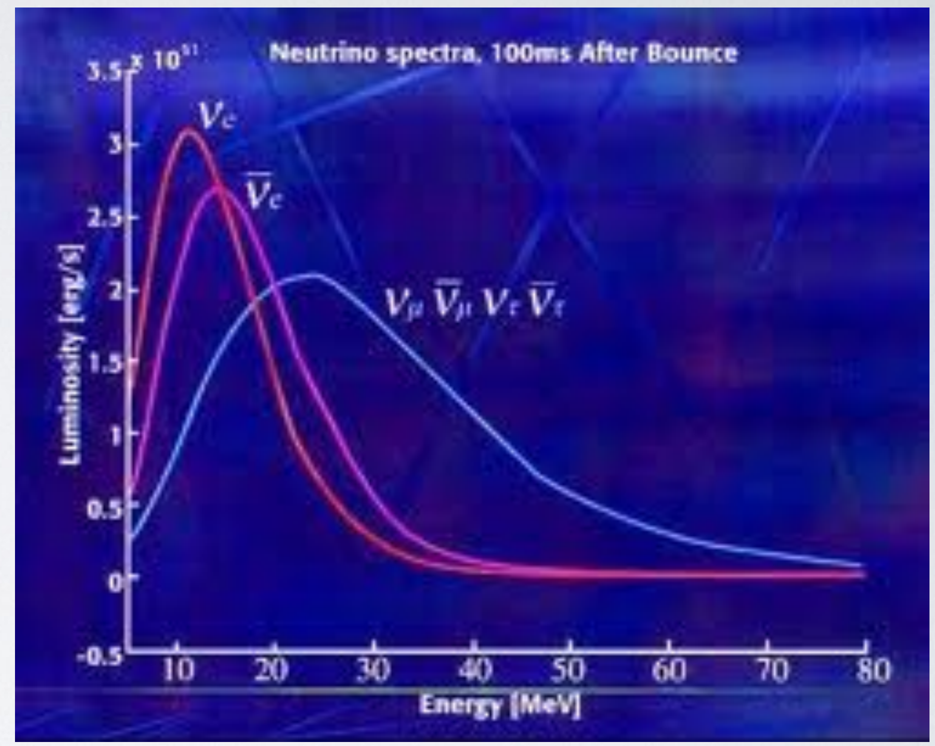


Neutrino interaction : Theory

Supernovae and Astrophysical Neutrinos

Different Sources, time dependence, different epochs





Kepler Supernova

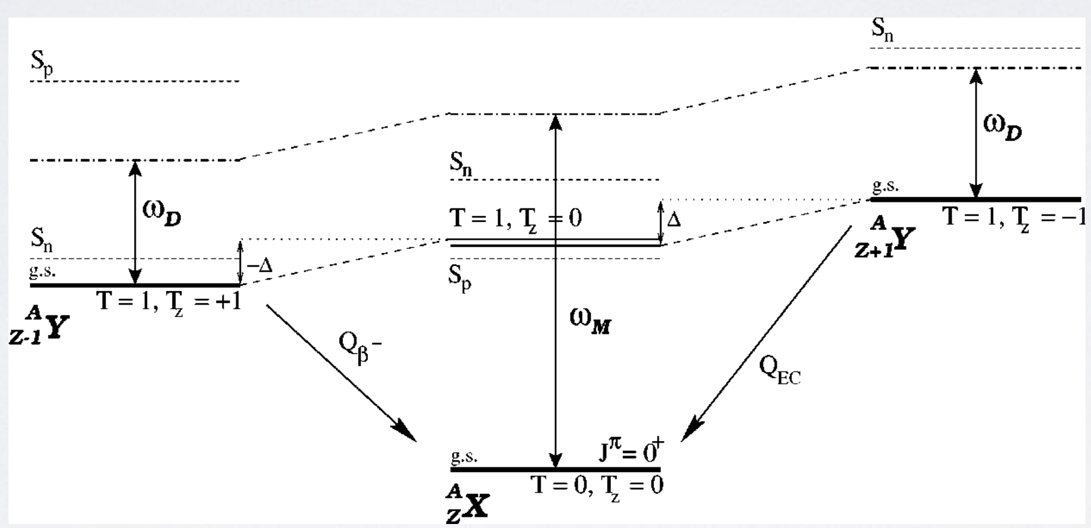
Can we make r-process nuclei in supernovae; and/or neutron-star mergers ?
Need to understand low energy neutrinos in matter

Neutrino interaction : Theory

Neutrino Scattering from Nuclei

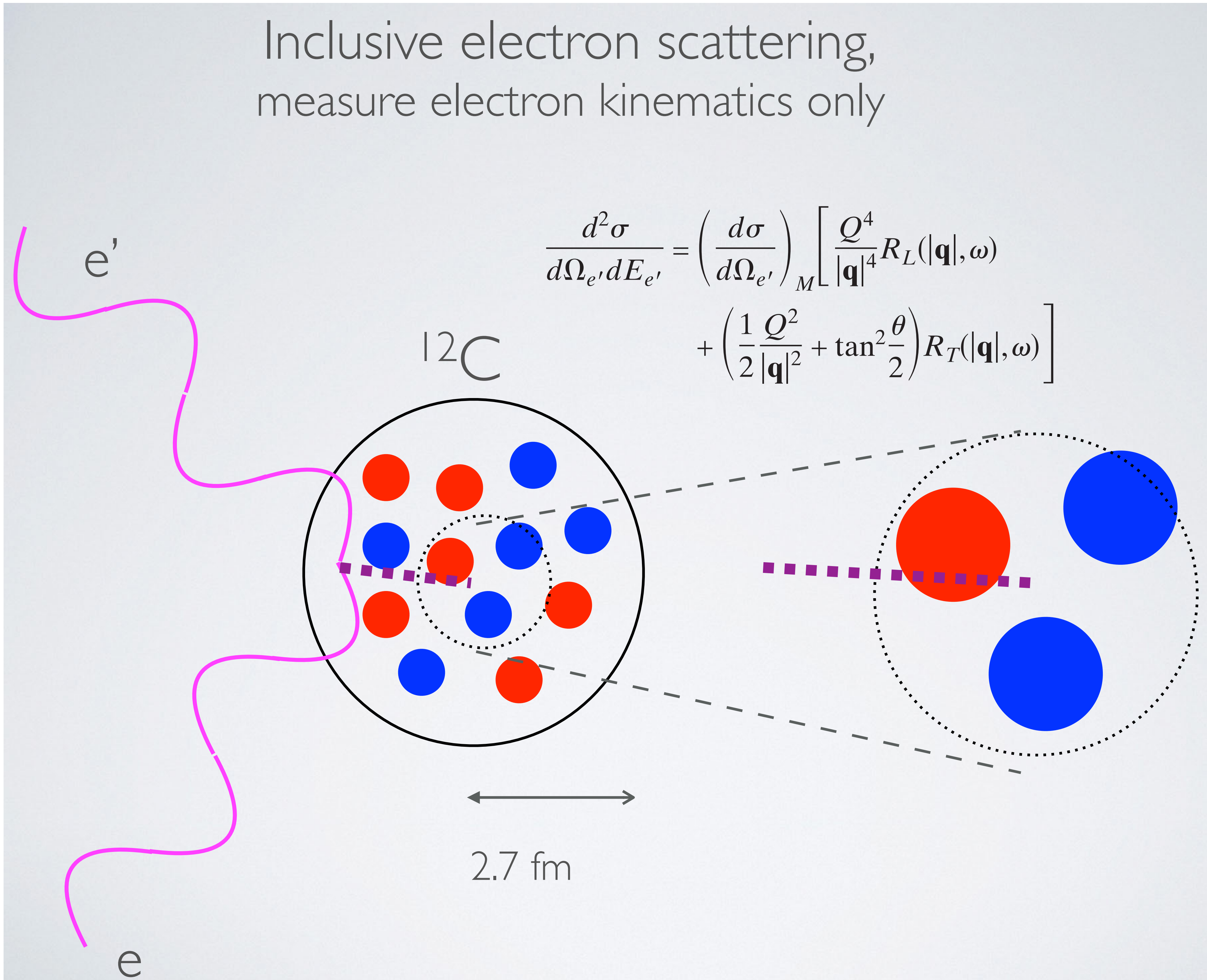
Impacts explosion mechanism, r-proces, ….
Necessary for interpreting neutrino observations
How well do we understand it?

Energies 50 MeV
Typically going to excited states or low in the continuum



Generic Neutral and Charged-Current Processes
Momenta ~ 50-100 MeV/c = 0.25 - 0.5 fm^{-1}

Neutrino interaction : Theory

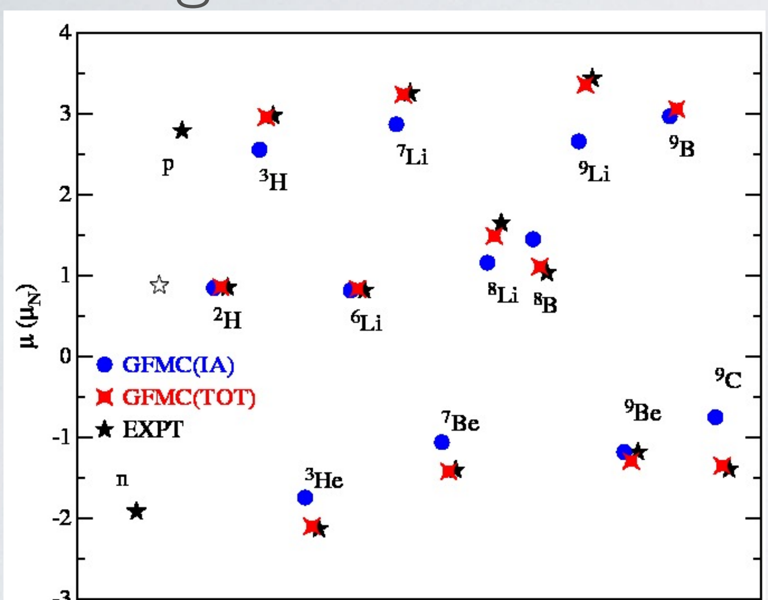


Neutrino interaction : Theory

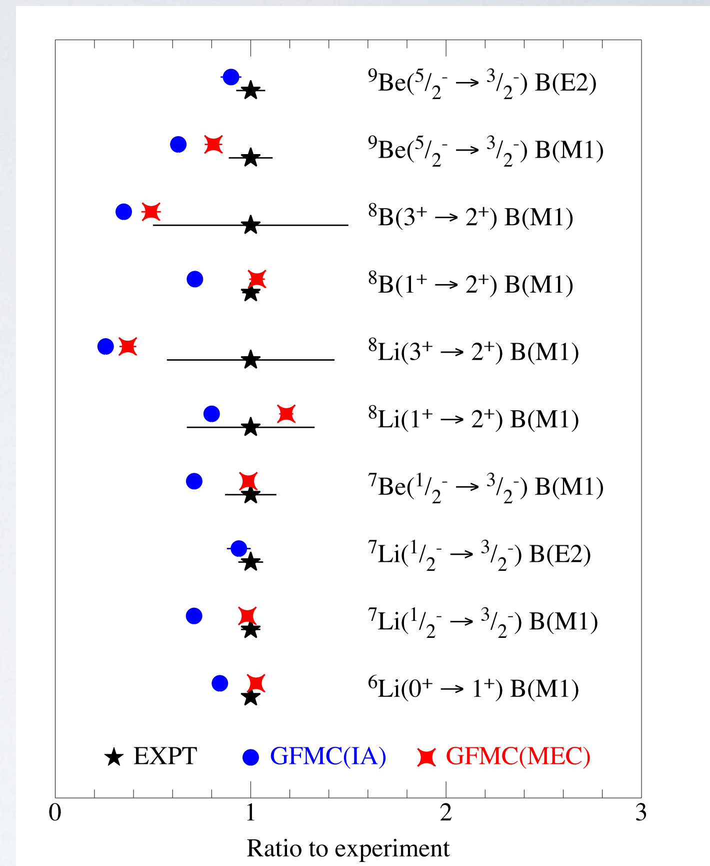
2-Nucleon Currents and Low-Energy Transitions

Magnetic Moments

A < 10



EM transitions



Combination of correlations and currents

p = 2.792 n = -1.913
^{3}H = 2.979 ^{3}He = -2.128

Pastore, Pieper, Schiavilla, Wiringa: arXiv 1406.2343, 1302.5091

Neutrino interaction : Theory

Conclusions/Outlook

- Supernovae neutrinos can teach us a lot about both neutrinos and supernovae
- Microscopic theory important for decoupling and propagation in the supernovae; and hence for energy deposition and potentially r-process
- Basic Theory ingredients understood
- More data essential - very limited at present
- Advances in many-body theory and computing essential
- Close relationship with many important issues
    - Quasi-Elastic neutrino scattering
    - Double-beta decay (Majorana neutrinos)
    - Astrophysical Sources (neutron star mergers,…)

Neutrino interaction : Experiment

This is a (somewhat) gentler regime than most topics at NuInt...

~GeV+ neutrinos can create a quite a mess ...

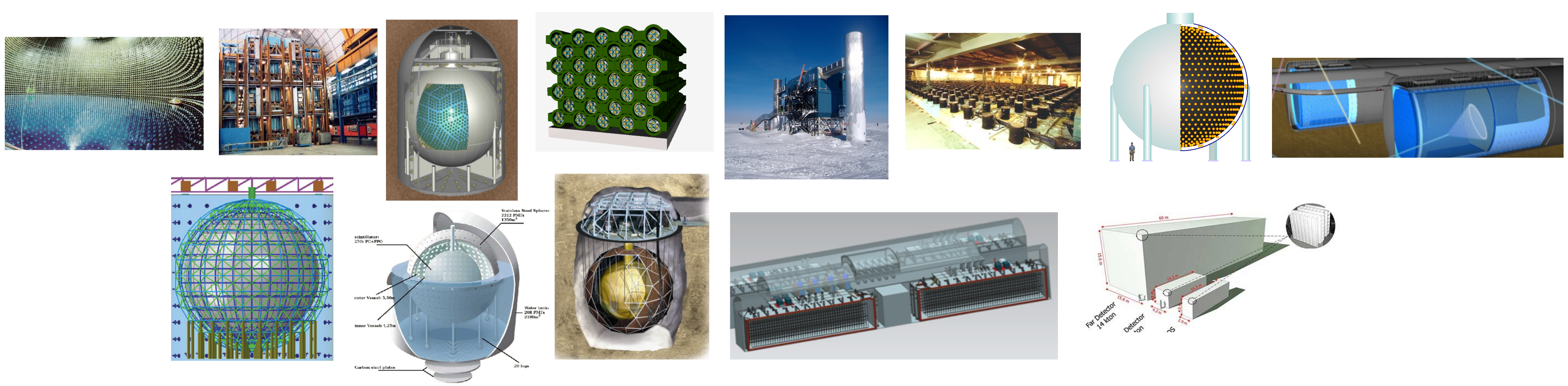
~tens of MeV neutrinos are not as disruptive, but still leave non-trivial debris ...

Neutrino interaction : Experiment

Nuclei of particular interest for SN detection

carbon
oxygen
argon
lead

detector materials for current and future supernova neutrino detectors

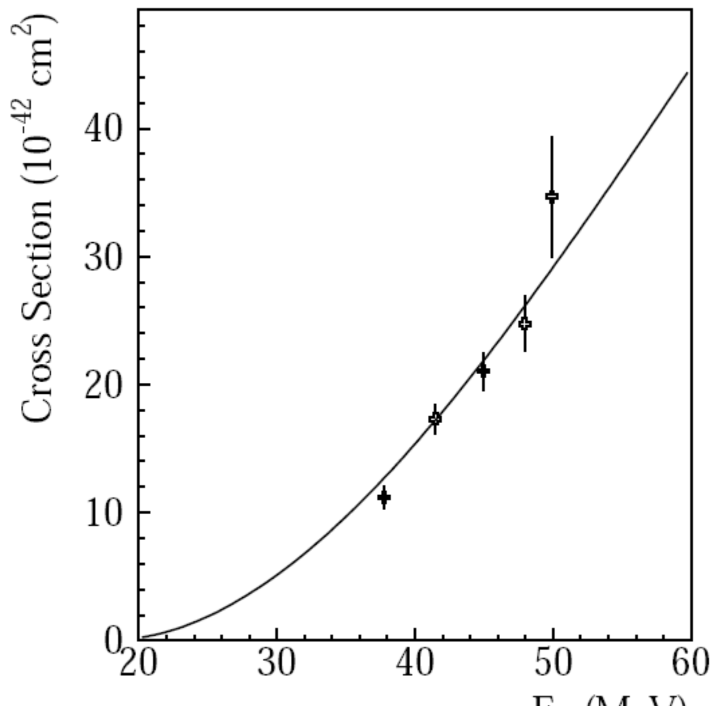


(These are not the only nuclei:
additional nuclei are of interest for other detectors;
supernova explosion physics, supernova nucleosynthesis)

Neutrino interaction : Experiment

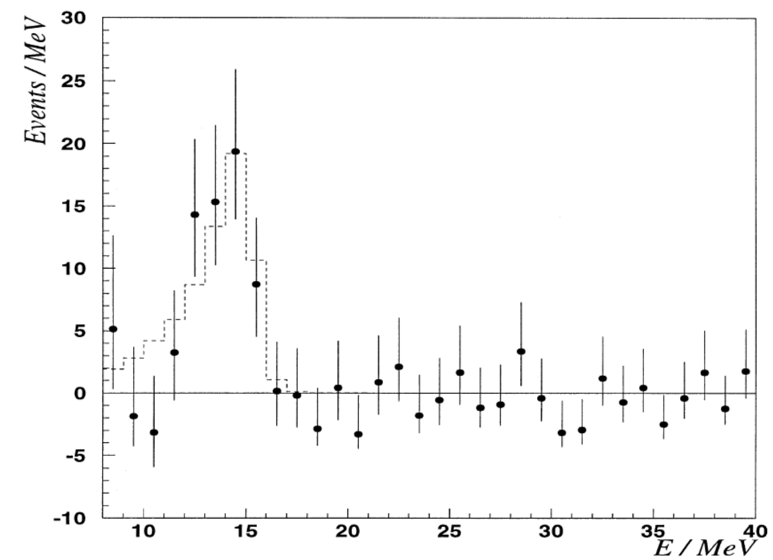
.. but so far ^{12}**C is the *only* heavy nucleus** with ν interaction x-sections well (~10%) measured in the tens of MeV regime

e.g. **LSND** Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen Phys. Lett. B 423 (1998) 15-20



$$^{12}\mathrm{C}(\nu_\mu \nu'_\mu)\,^{12}\mathrm{C}^*(1^+,1;15.1\ \mathrm{MeV})$$

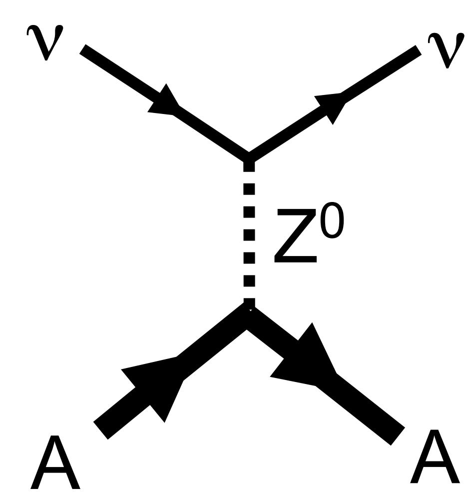
Need: oxygen (water), lead, argon, ...

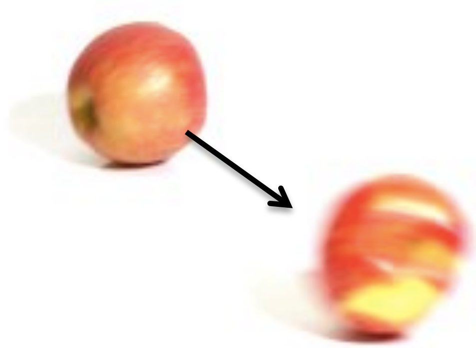
Neutrino interaction : Experiment

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



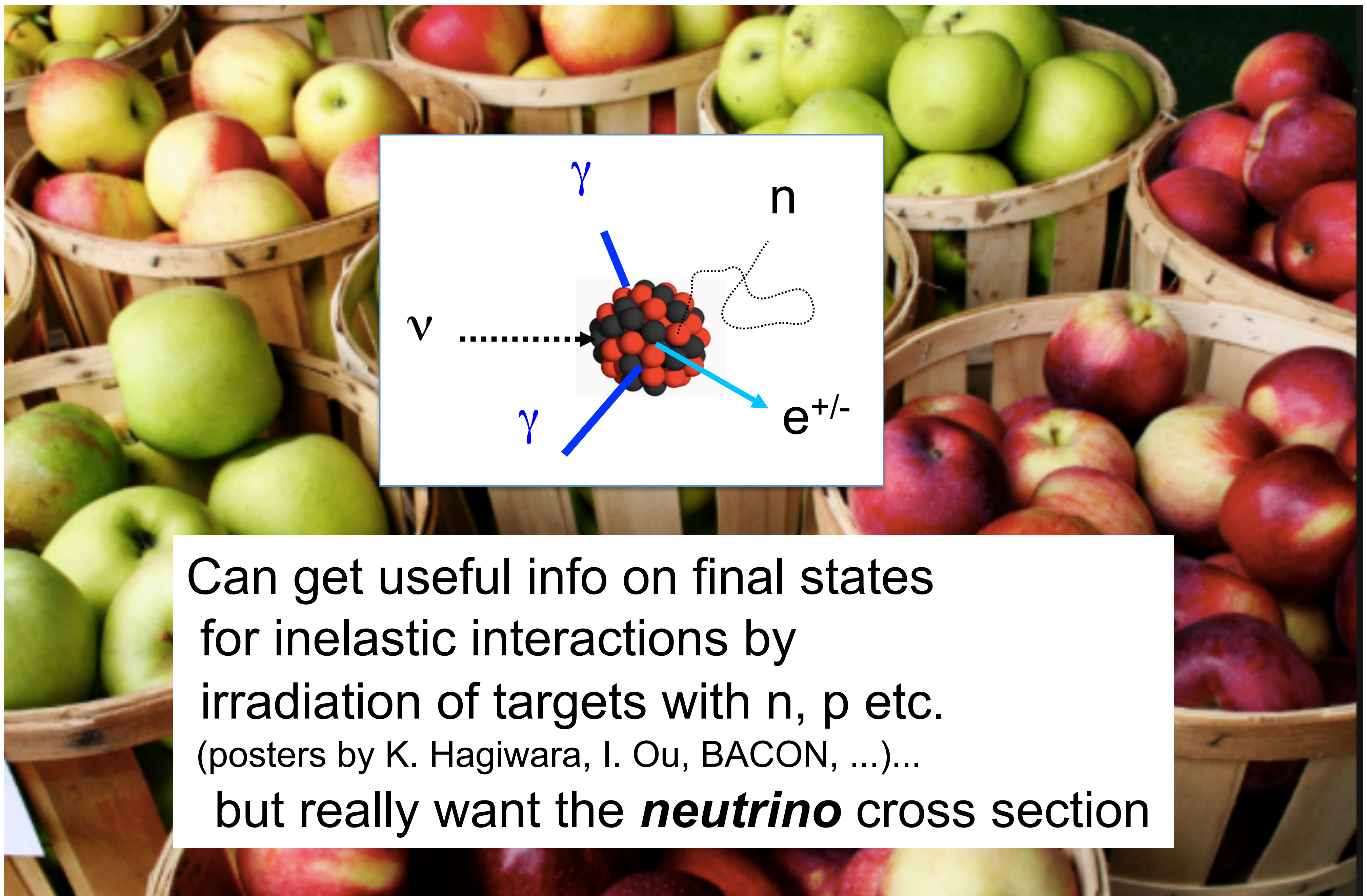


- Important in **SN processes & detection**
- Well-calculable cross-section in SM:
  SM test, probe of neutrino NSI
- Dark matter direct detection background
- Possible applications (reactor monitoring)

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2) \quad \boxed{\propto N^2}$$

Neutrino interaction : Experiment

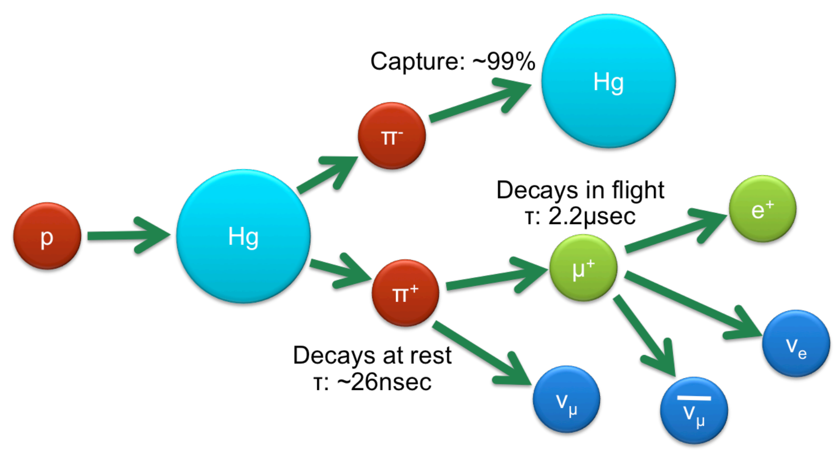
How can we *measure* these cross sections?

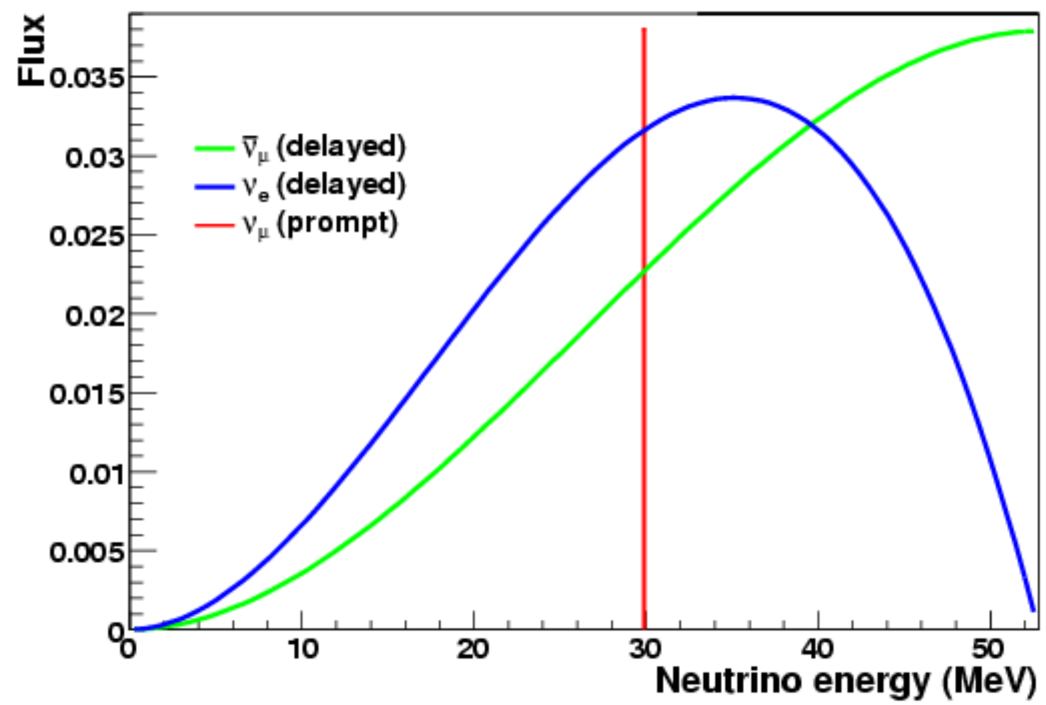


Can get useful info on final states
for inelastic interactions by
irradiation of targets with n, p etc.
(posters by K. Hagiwara, I. Ou, BACON, ...)...
but really want the ***neutrino*** cross section

Neutrino interaction : Experiment

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Neutrino interaction : Experiment

Experiments at stopped-π neutrino sources

Location	Past	Ongoing	Future/ Proposed
LANSCE	LSND		
ISIS	KARMEN		
J-PARC MLF (JSNS)			E56, KPIPE
FNAL BNB			CENNS, CAPTAIN-BNB
SNS		COHERENT	OscSNS, CAPTAIN
CSNS			Liquid scint?
ESS			Concepts

Look in more detail at these

Neutrino interaction : Experiment

Summary

Cross sections on nuclei in the few tens-of-MeV regime
are poorly understood (theoretically and experimentally)
... **especially relevant for SN neutrinos**

Stopped-pion ν sources offer opportunities for these measurements

CEvNS also never before measured (SM test, DM bg); now within reach with WIMP detector technology

COHERENT@ SNS and **CENNS@BNB** going after this
... next measurement may be **NINs on lead**
(bg for CEvNS and of SN relevance in itself)

Need for more measurements! Ar, O, ...